Dark Matter Intro

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PI · SNOLAB · TRIUMF

TRISEP

"Roadmap"

- The story of DM
  - Evidence
  - Basic properties
- Relic abundance
  - Thermal relics/WIMPs
  - Non-WIMPs
  - Non-thermal relics
- Indirect Detection
- Direct Detection
- DM@Colliders
- DM self interactions
- Conclusions

“Roadmap”

- The story of DM
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See Mina’s lectures next week

“Roadmap”

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    - Evidence
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- Dire…
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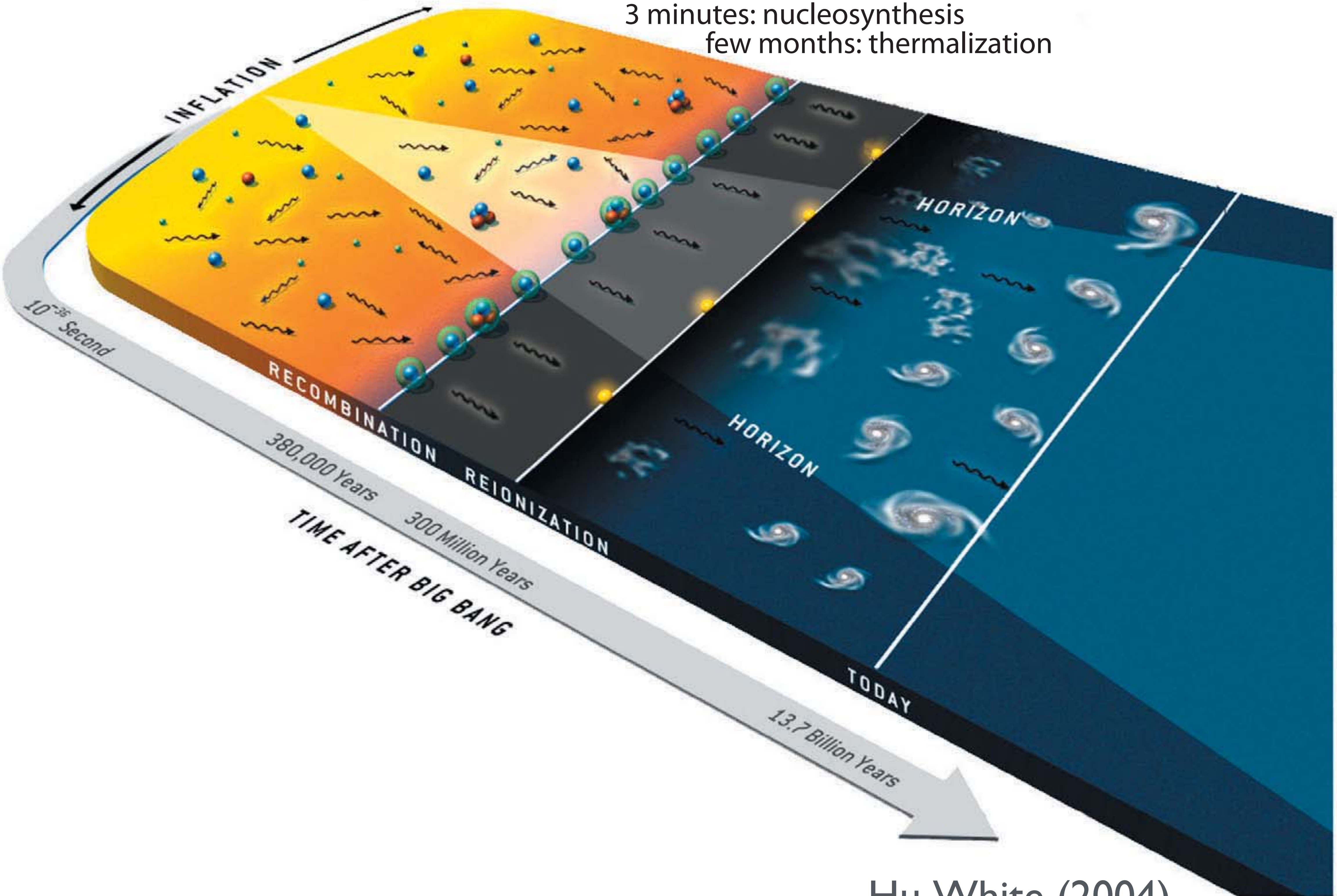
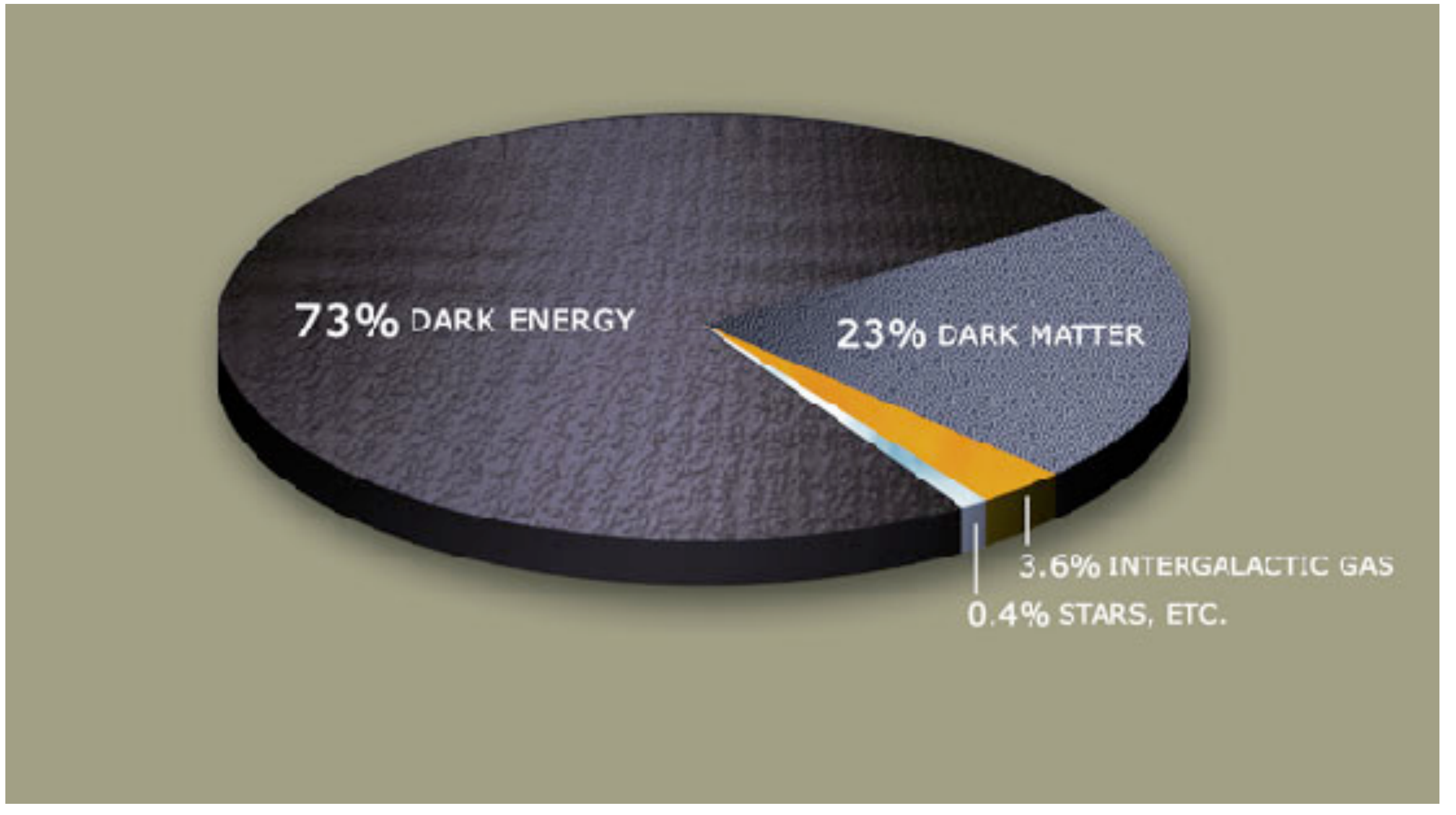
See Rick’s lectures next week

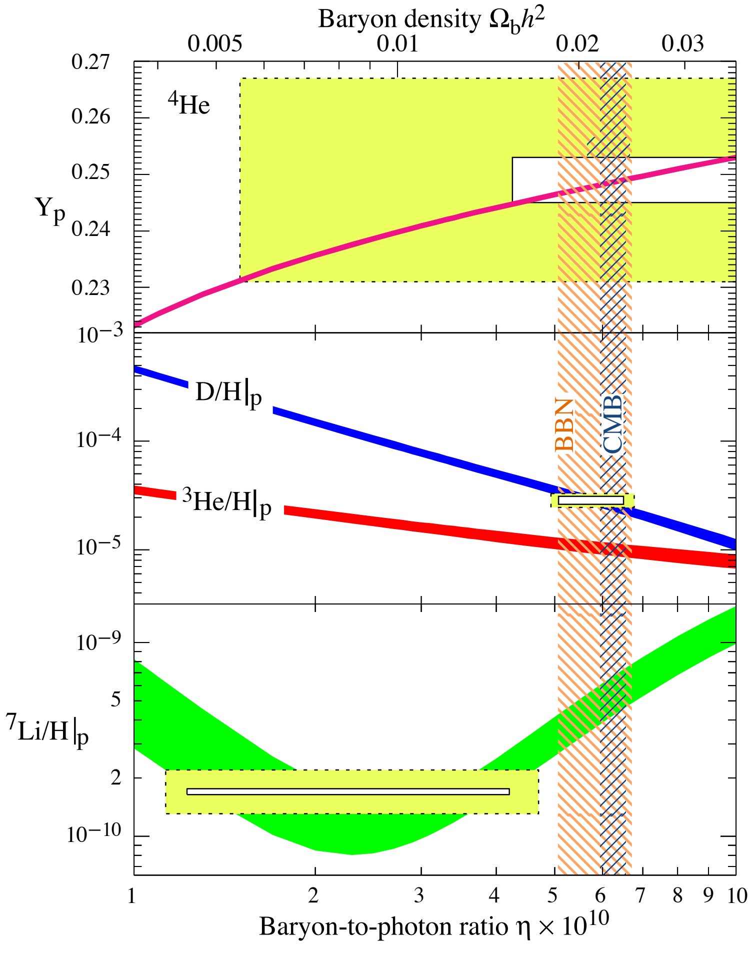


Hu, White (2004)

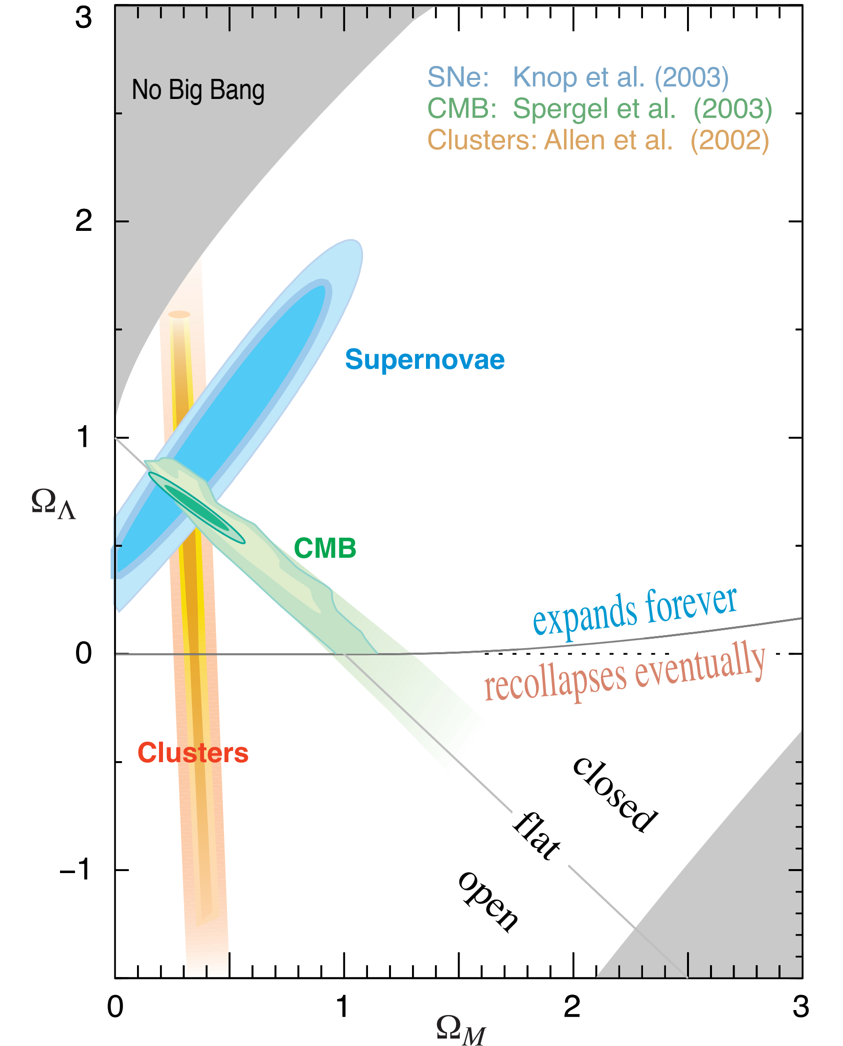
Extra stuff



73% DARK ENERGY
23% DARK MATTER
3.6% INTERGALACTIC GAS
0.4% STARS, ETC.

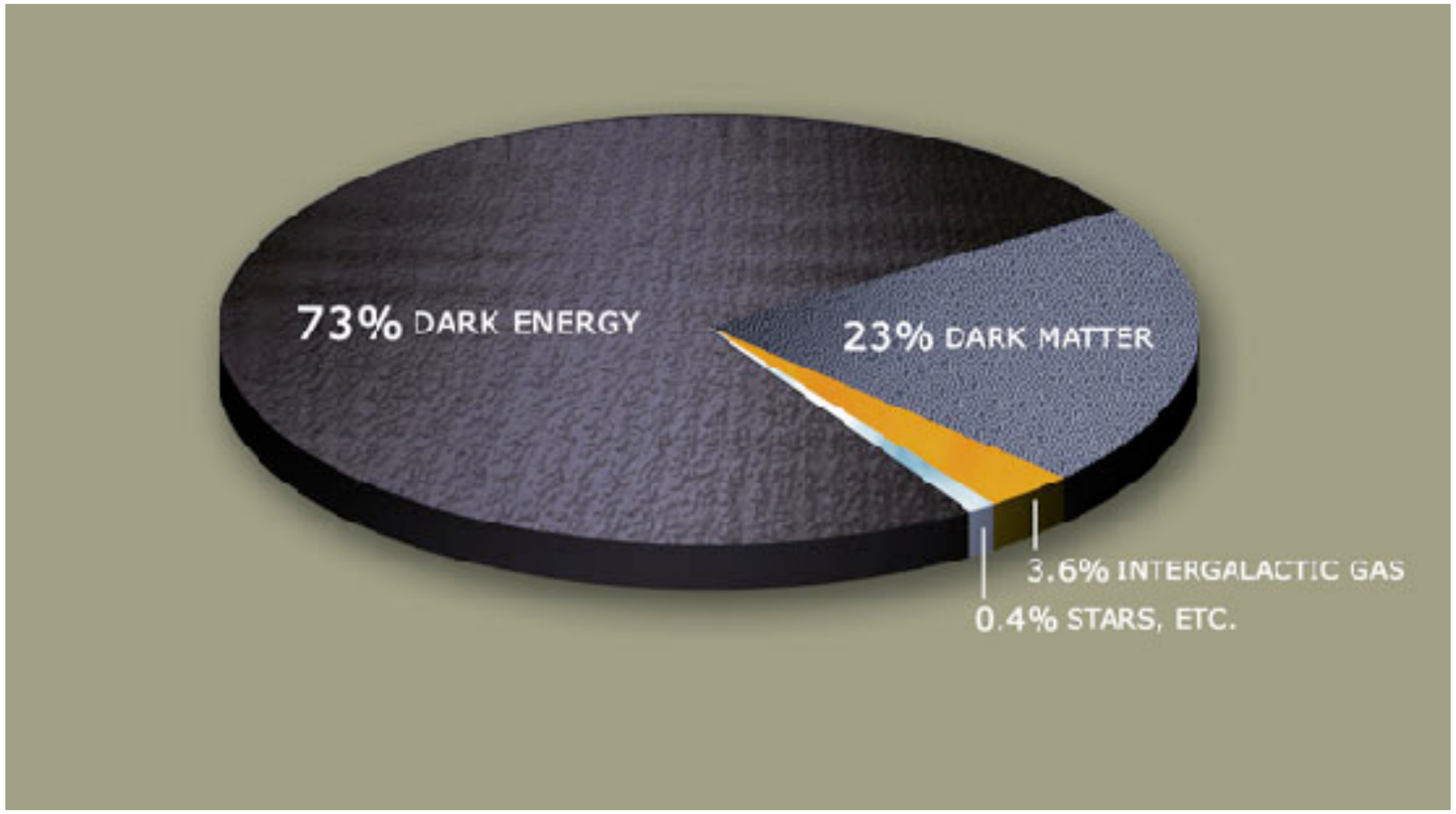


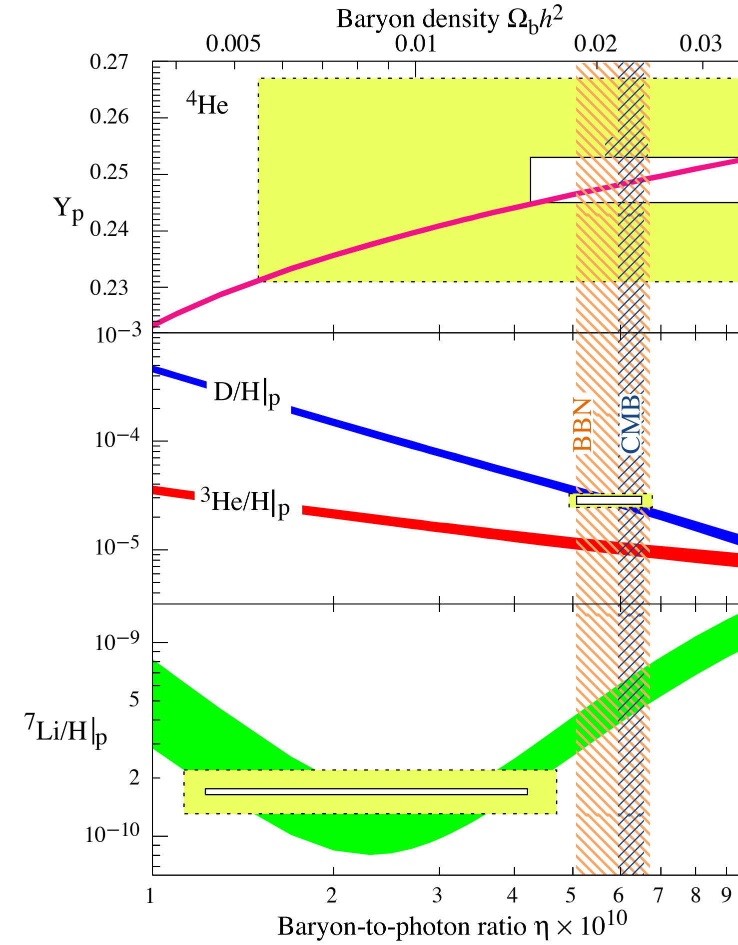
Baryon density $\Omega_b h^2$
0.005
0.01
0.02
0.03
0.27
0.26
0.25
0.24
0.23
Y_p
^{4}He
10^{-3}
10^{-4}
10^{-5}
D/H|p
^{3}He/H|p
BBN
CMB
10^{-9}
5
2
10^{-10}
^{7}Li/H|p
1
2
3
4
5
6
7
8
9
10
Baryon-to-photon ratio $\eta \times 10^{10}$

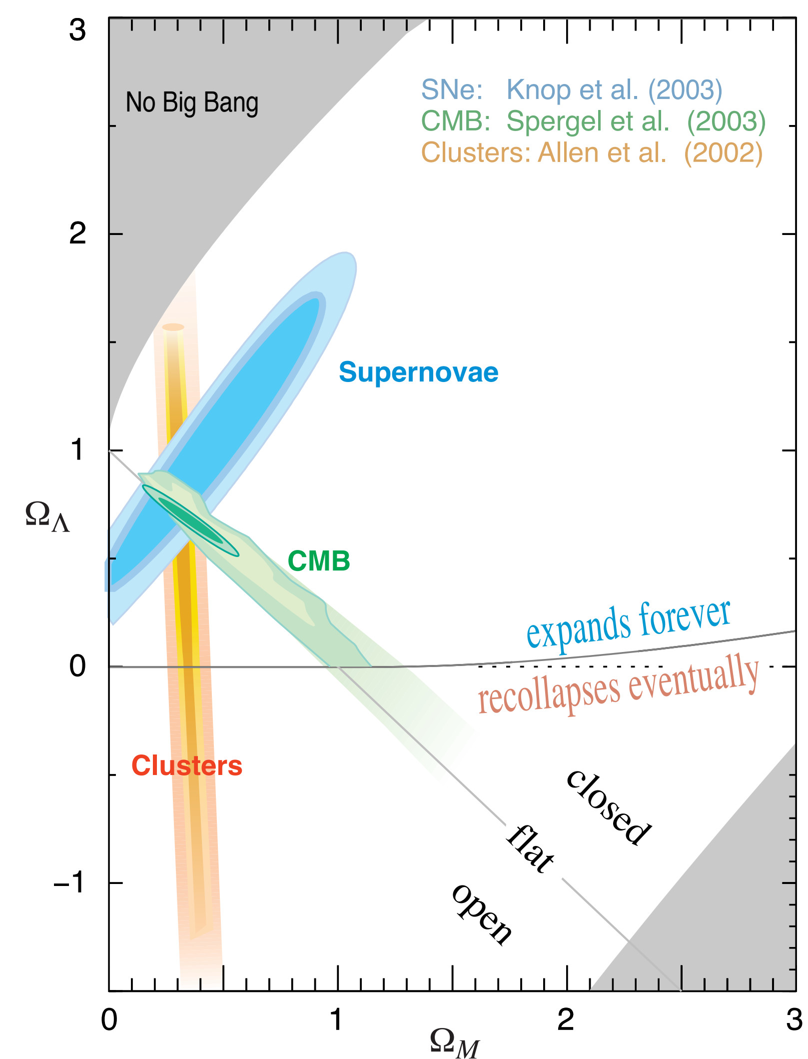


No Big Bang
SNe: Knop et al. (2003)
CMB: Spergel et al. (2003)
Clusters: Allen et al. (2002)
Supernovae
CMB
Clusters
expands forever
recollapses eventually
closed
flat
open
Ω_Λ
Ω_M
3
2
1
0
−1
0
1
2
3

Extra stuff







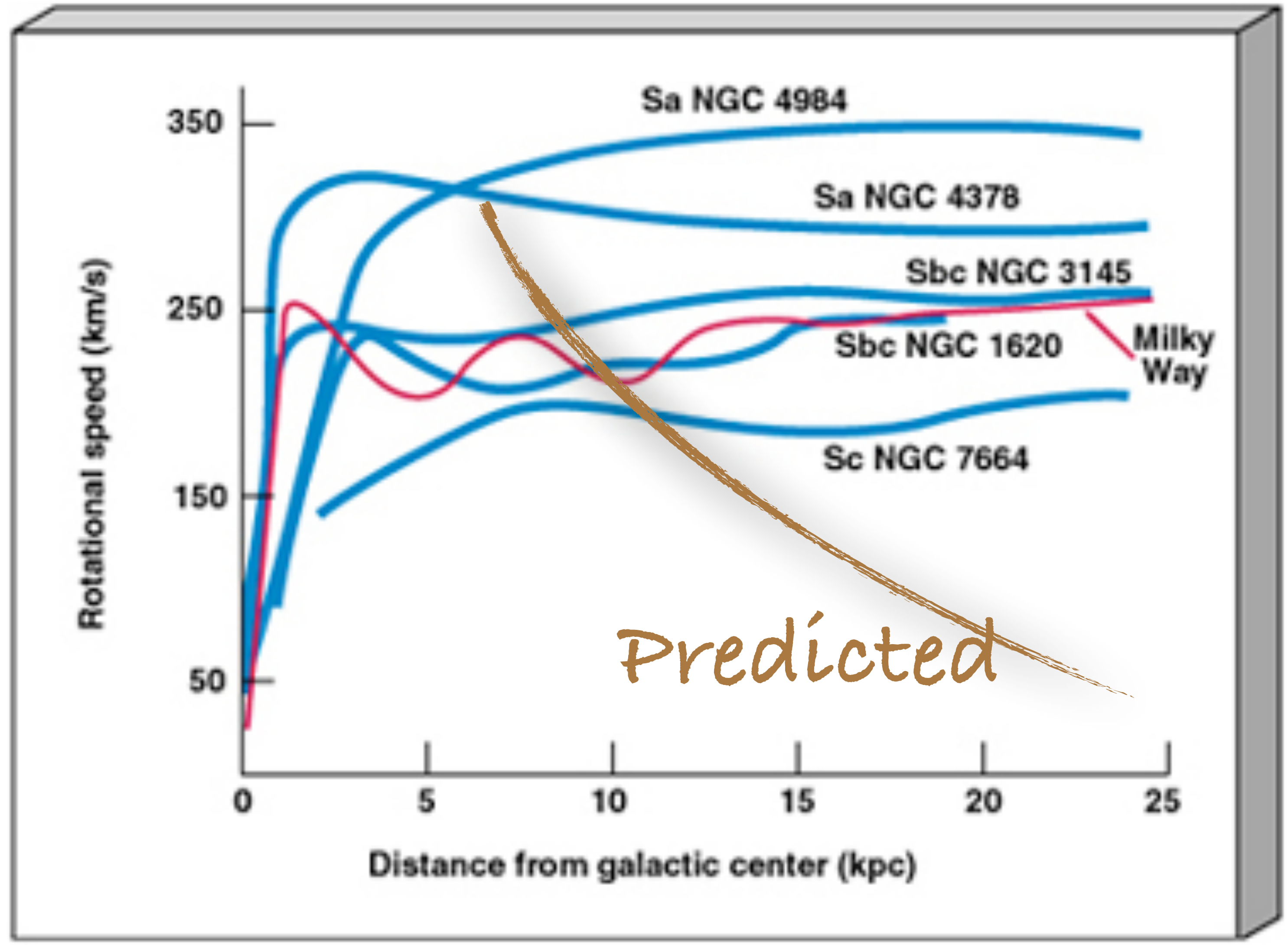
- 23% of universe energy/matter is a new type of (non-baryonic) matter
- 73% is a new type of energy (cosmological constant)
- SM is 4%

Evidence for Dark Matter

Coma Cluster

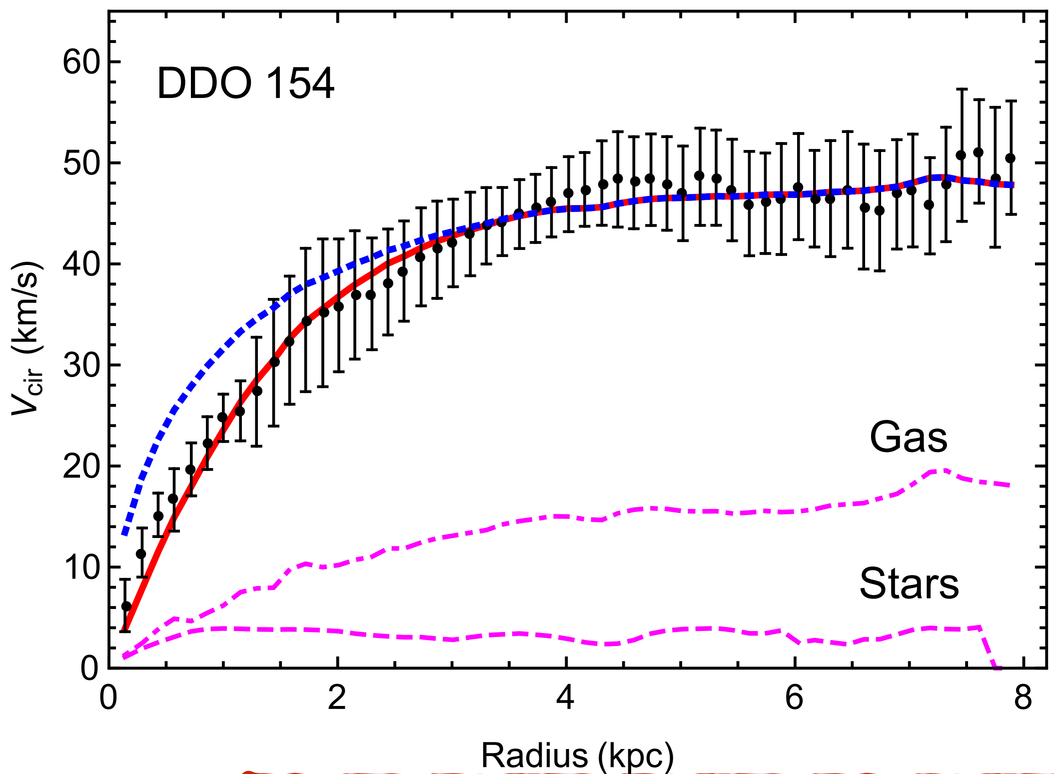
90% of the matter in the cluster doesn't shine

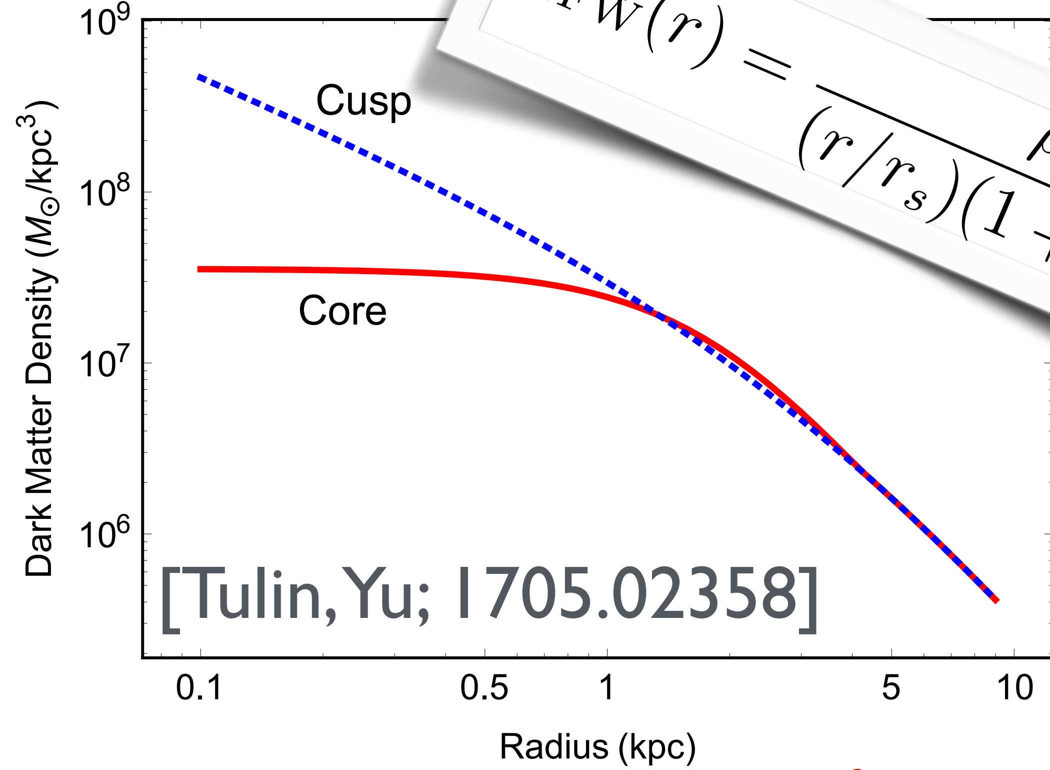
Evidence for Dark Matter



HW: predict the shape of this curve

Something invisible is holding stars in orbit

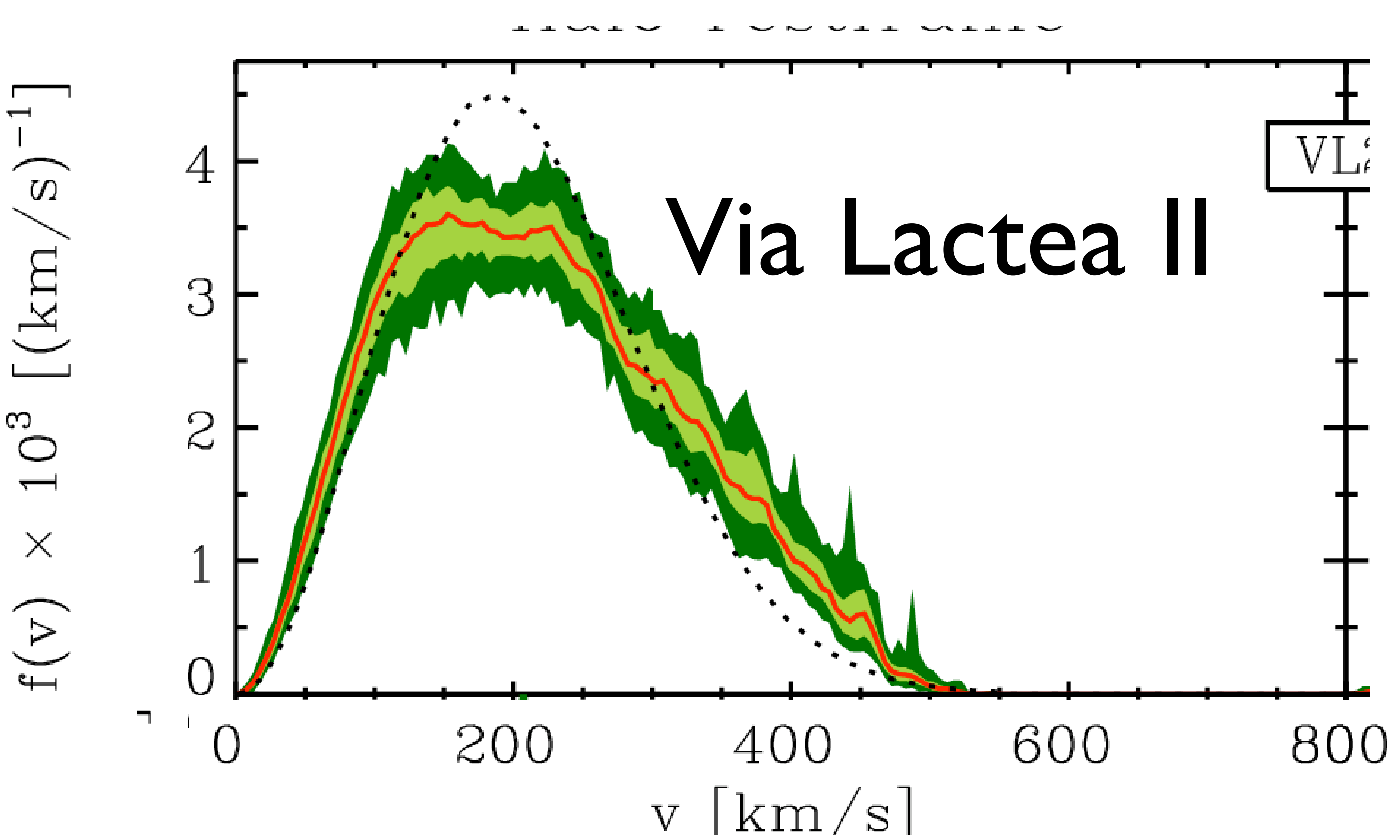




$$\rho_{\rm NFW}(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}$$

$$\rho_{\rm DM}^{\rm local} = (0.39 \pm 0.03) \cdot (1.2 \pm 0.2) \cdot (1 \pm \delta_{\rm triax}) \, \frac{\rm GeV}{\rm cm^3}$$

<0.2

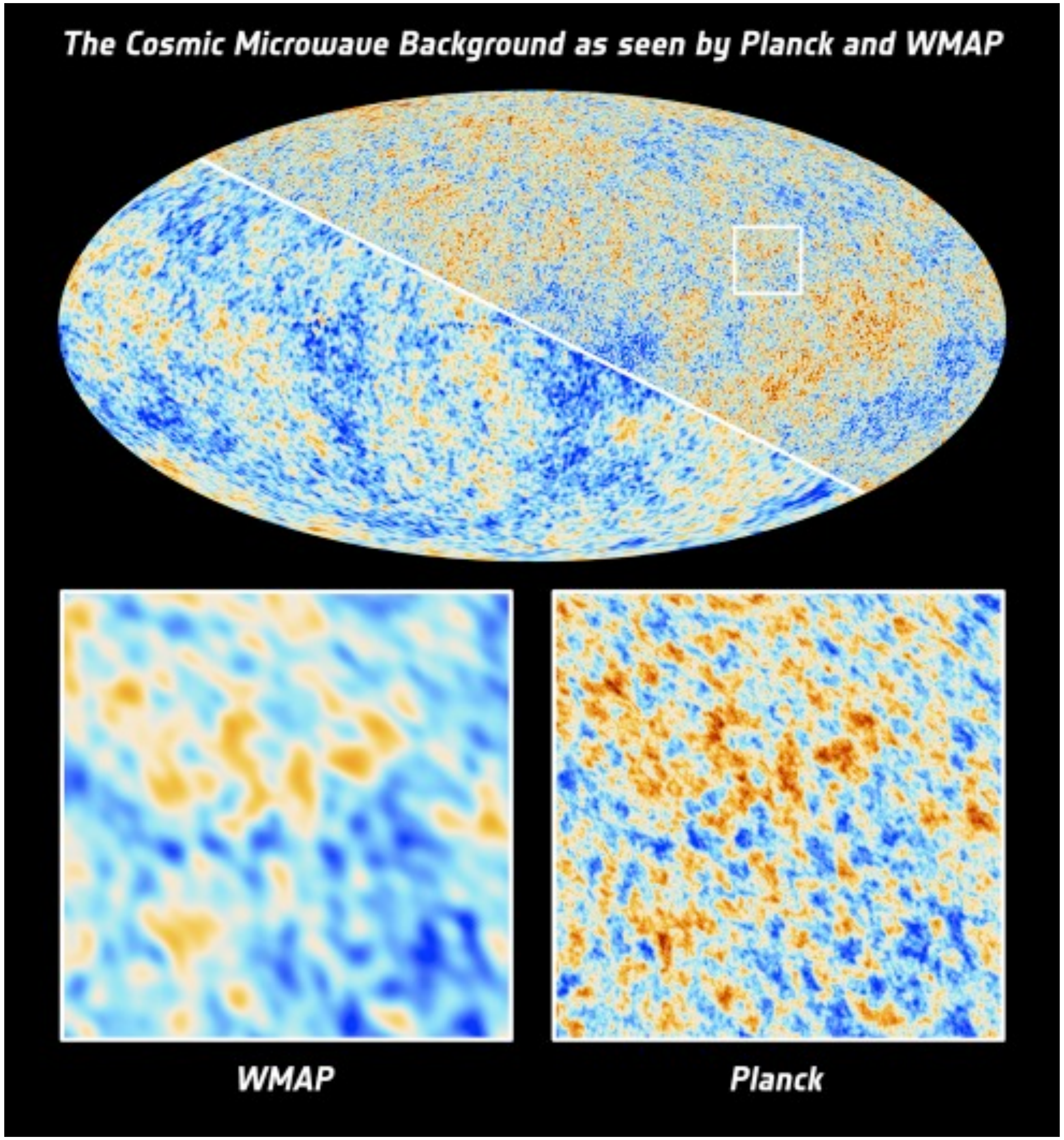


$$f(v) \propto d^3v \; e^{-(v/v_0)^2}$$

$$v_0 = 220 \text{ km s}^{-1}$$

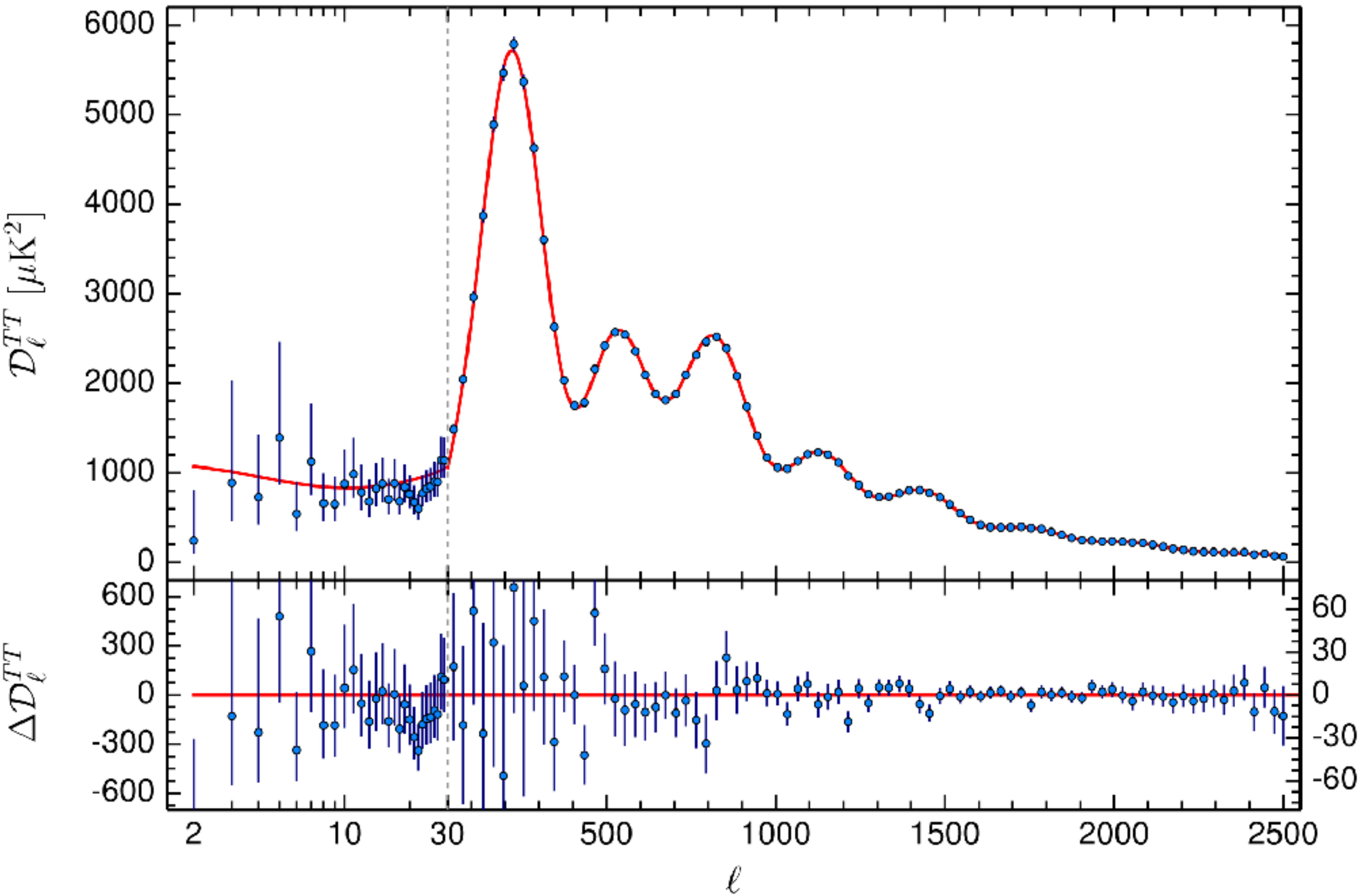
$$498 \text{ km/s} \leq v_{esc} \leq 608$$

Evidence for Dark Matter



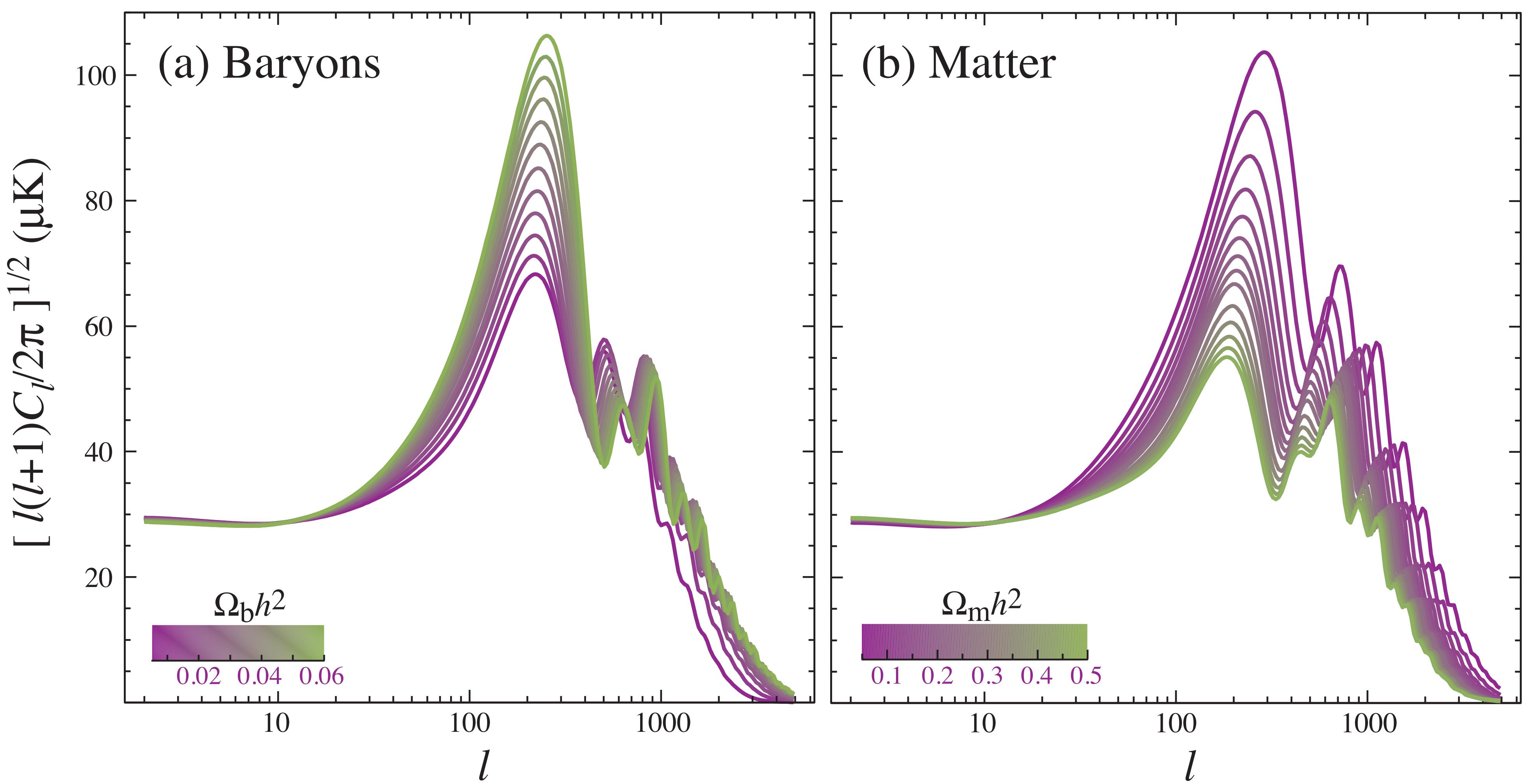
Hot plasma of hydrogen atoms and photons, and DM and cc

Planck Collaboration

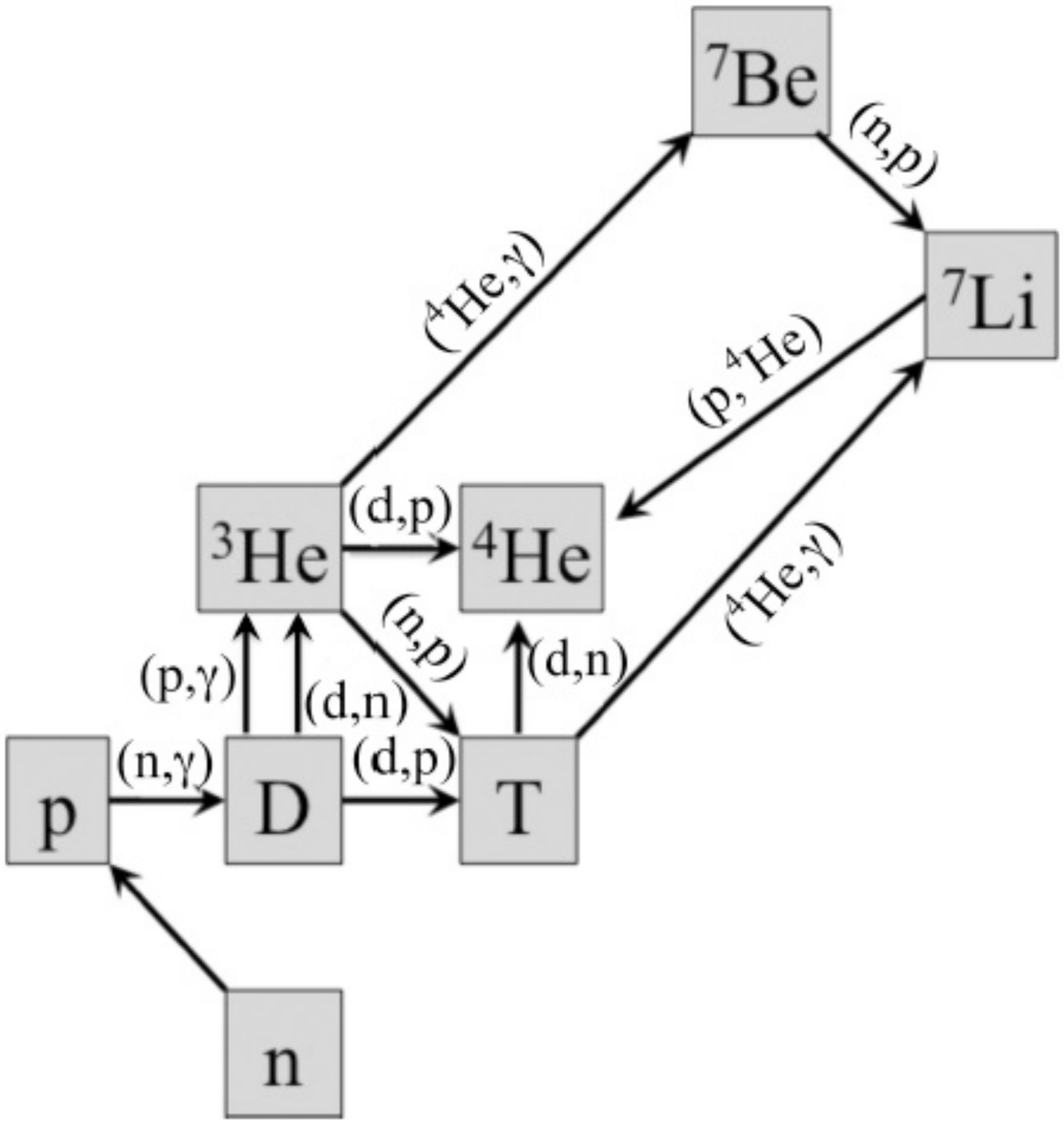


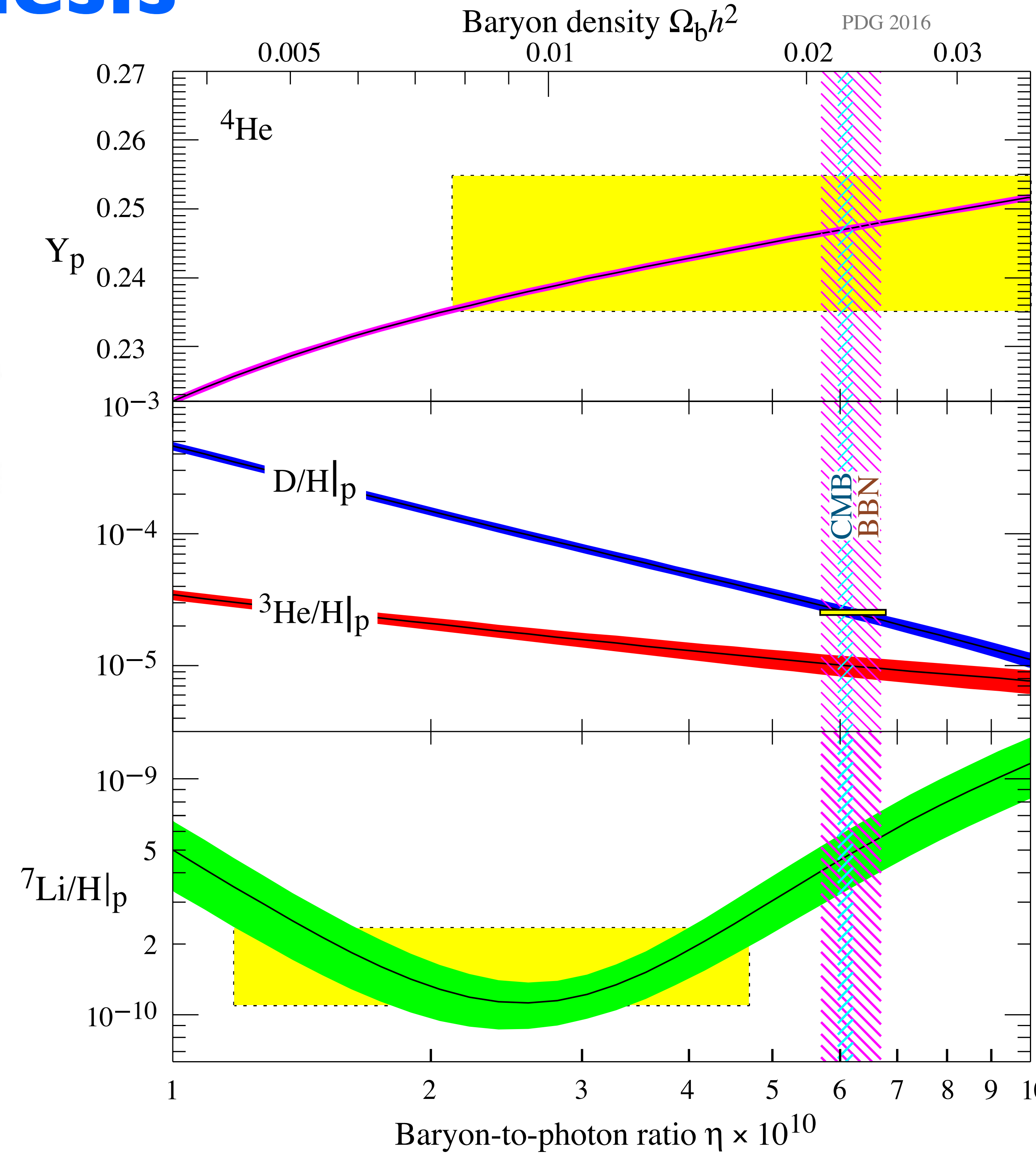
- CMB well described by ~10 parameters
- Linear modes, caused by gravitational instabilities of coupled baryon-photon fluid, seeded by 10^{-5} fluctuations
- Adiabatic, gaussian
- Requires on DM, baryons and dark energy
- Polarization, higher ℓ, black body spectrum, BAO,…

Hu 0802.3688



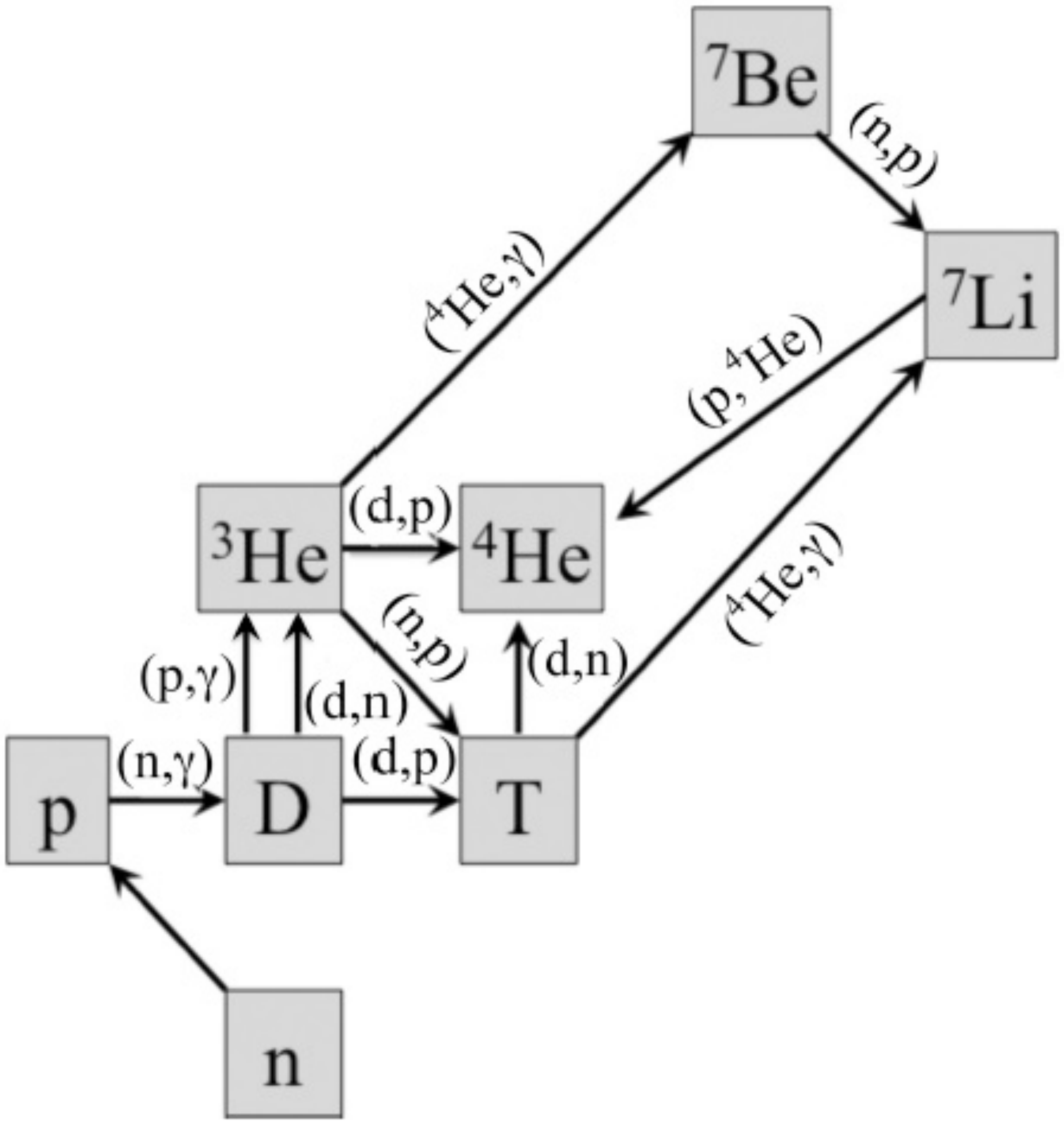
Big Bang Nucleosynthesis

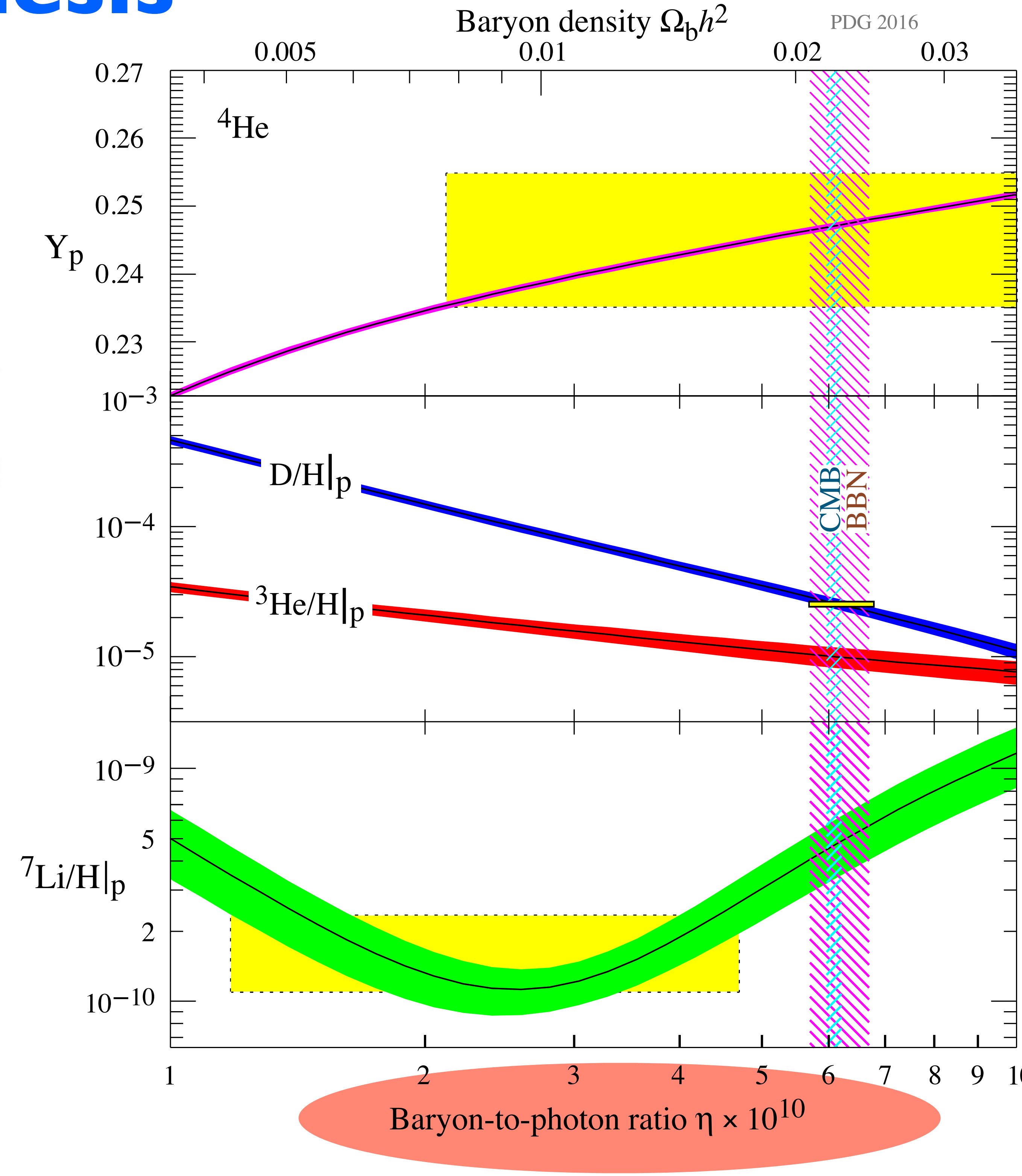




Hot soup of protons and neutrons, can predict light element abundance

Big Bang Nucleosynthesis





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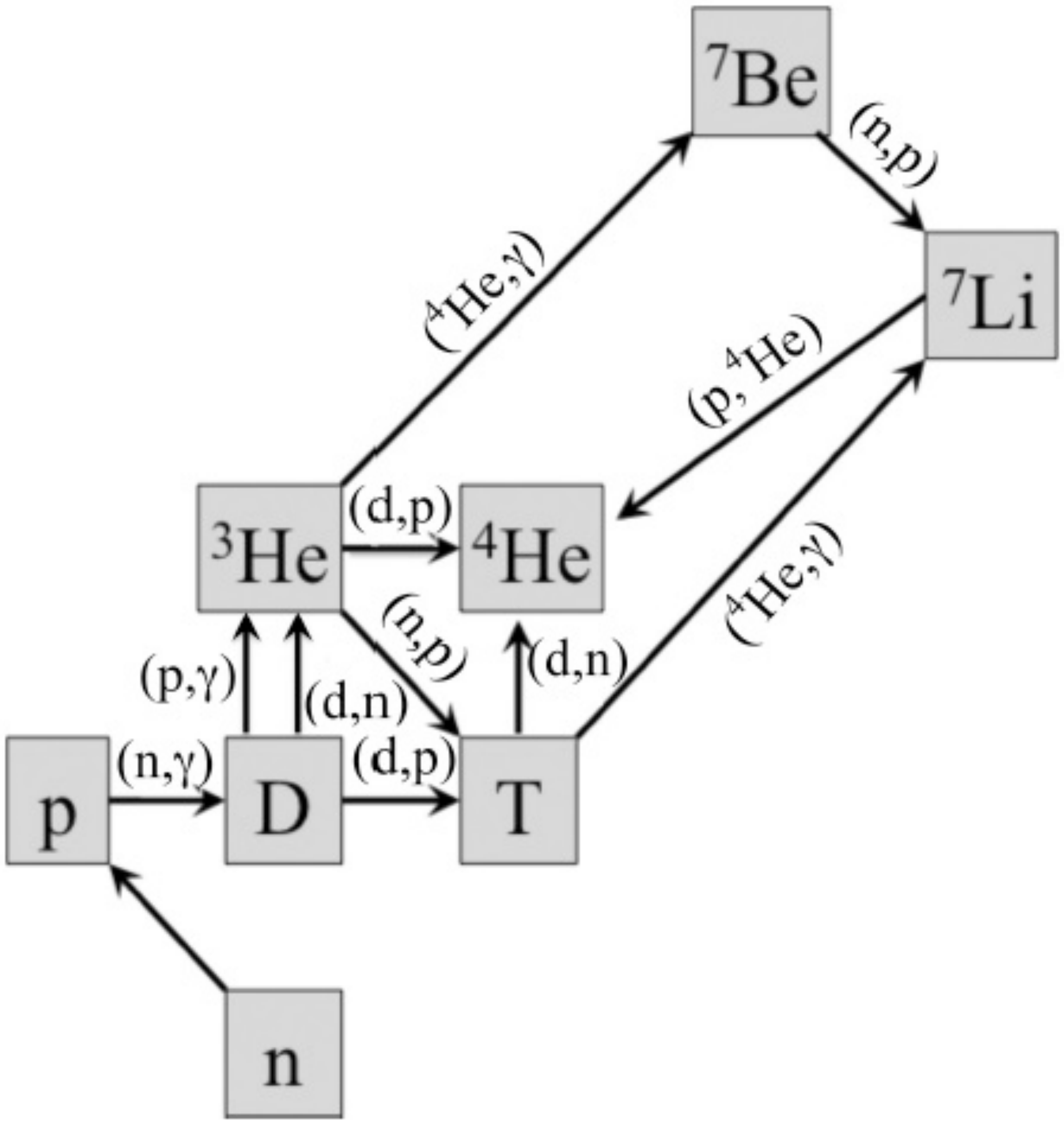
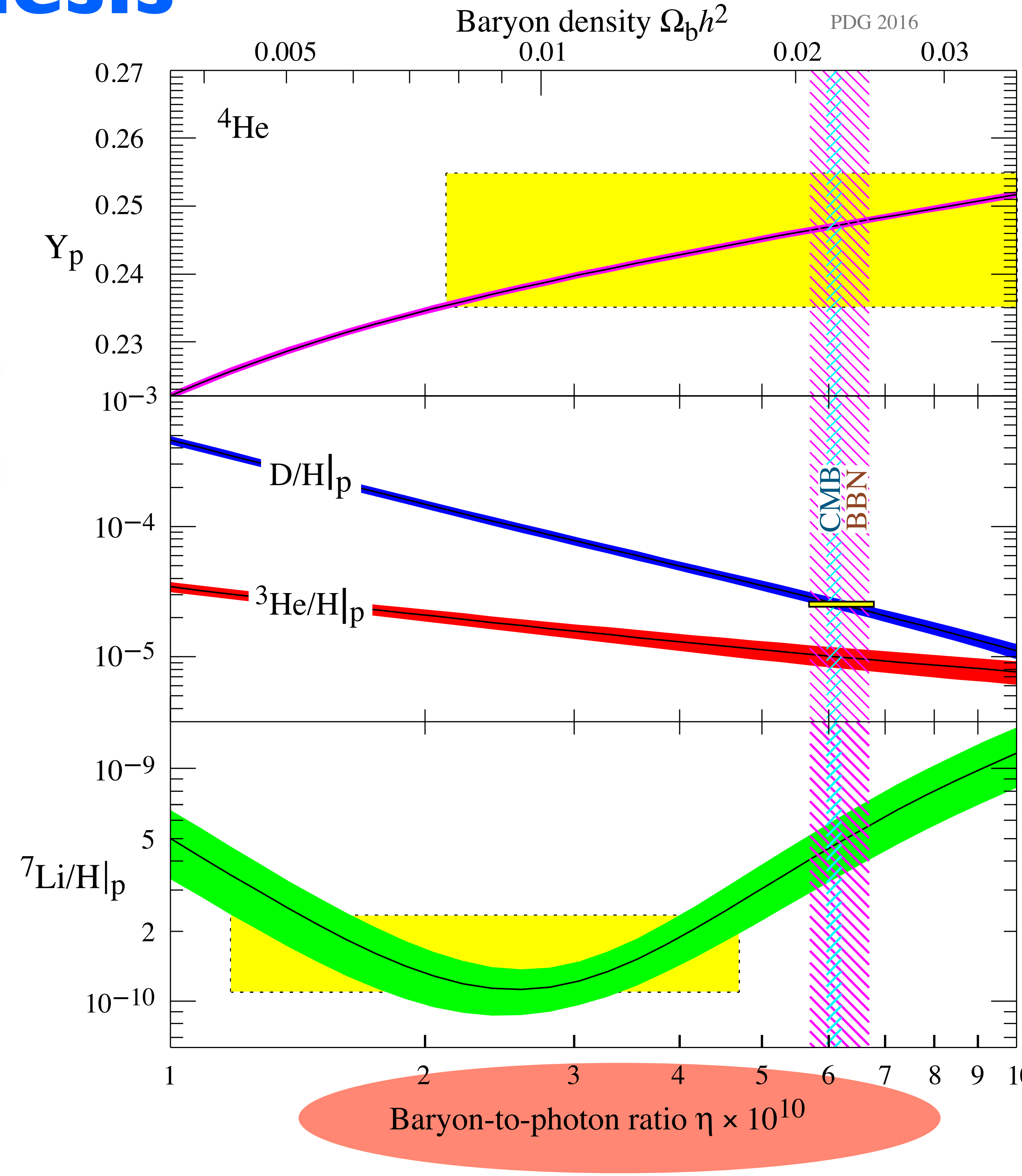




Hot soup of protons and neutrons, can predict light element abundance

~5% in baryons

BBN@LO

- Freeze out occurs when weak interactions decouple

$$G_F^2 T^5 \sim H \sim \frac{T^2}{M_{pl}}$$

$$T \sim 1\,\mathrm{MeV}$$

- Neutron:Proton ratio determined by thermodynamics

$$\frac{n}{p} \sim e^{-\Delta m/T} \sim 1/6$$

- Reaction rates determined by single parameter

$$\eta_b = \frac{n_b}{n_\gamma} \sim 6 \times 10^{-10}$$

- BBN begins when temp. far enough below Deuterium b.e.

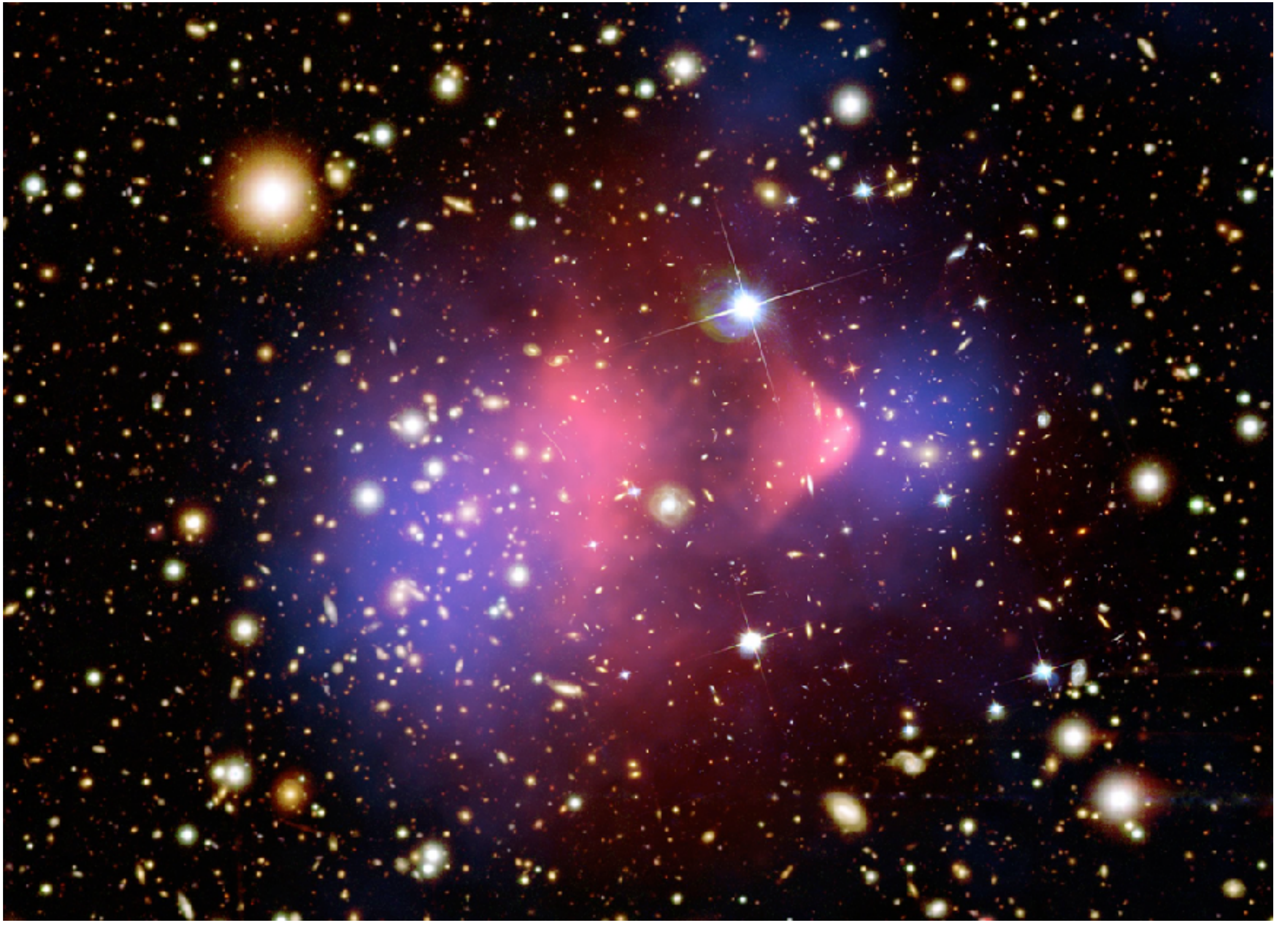
$$\eta^{-1} e^{-\Delta_D/T} \sim 1$$

- At L.O. all nuclei are H or He

$$\frac{n}{p} = \frac{1}{6} \xrightarrow{\tau_n} \frac{1}{7}$$

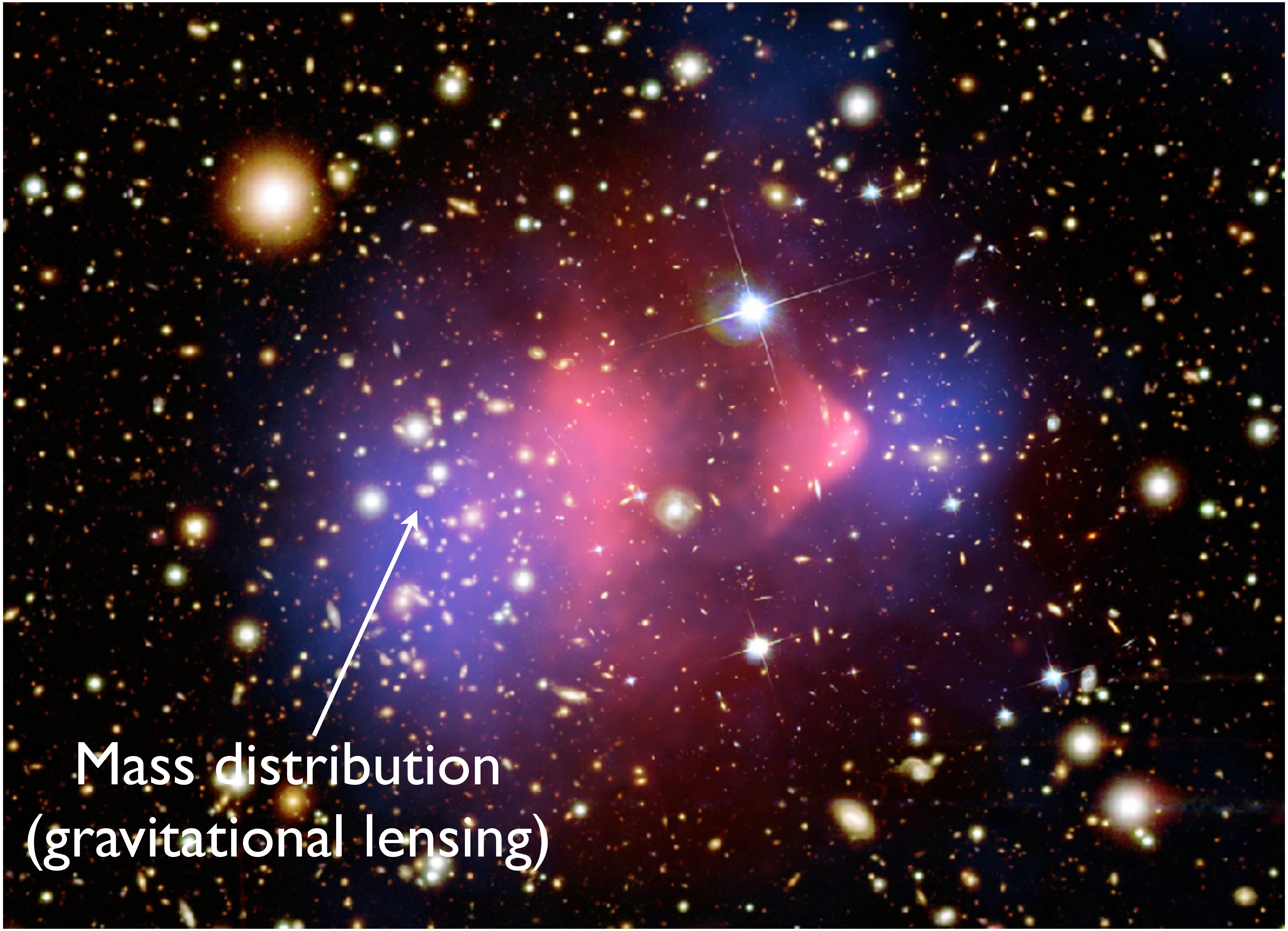
$$Y_{\mathrm{p}} = \frac{2(n/p)}{1+n/p} \simeq 0.25$$

Evidence for Dark Matter



The Bullet Cluster

Evidence for Dark Matter



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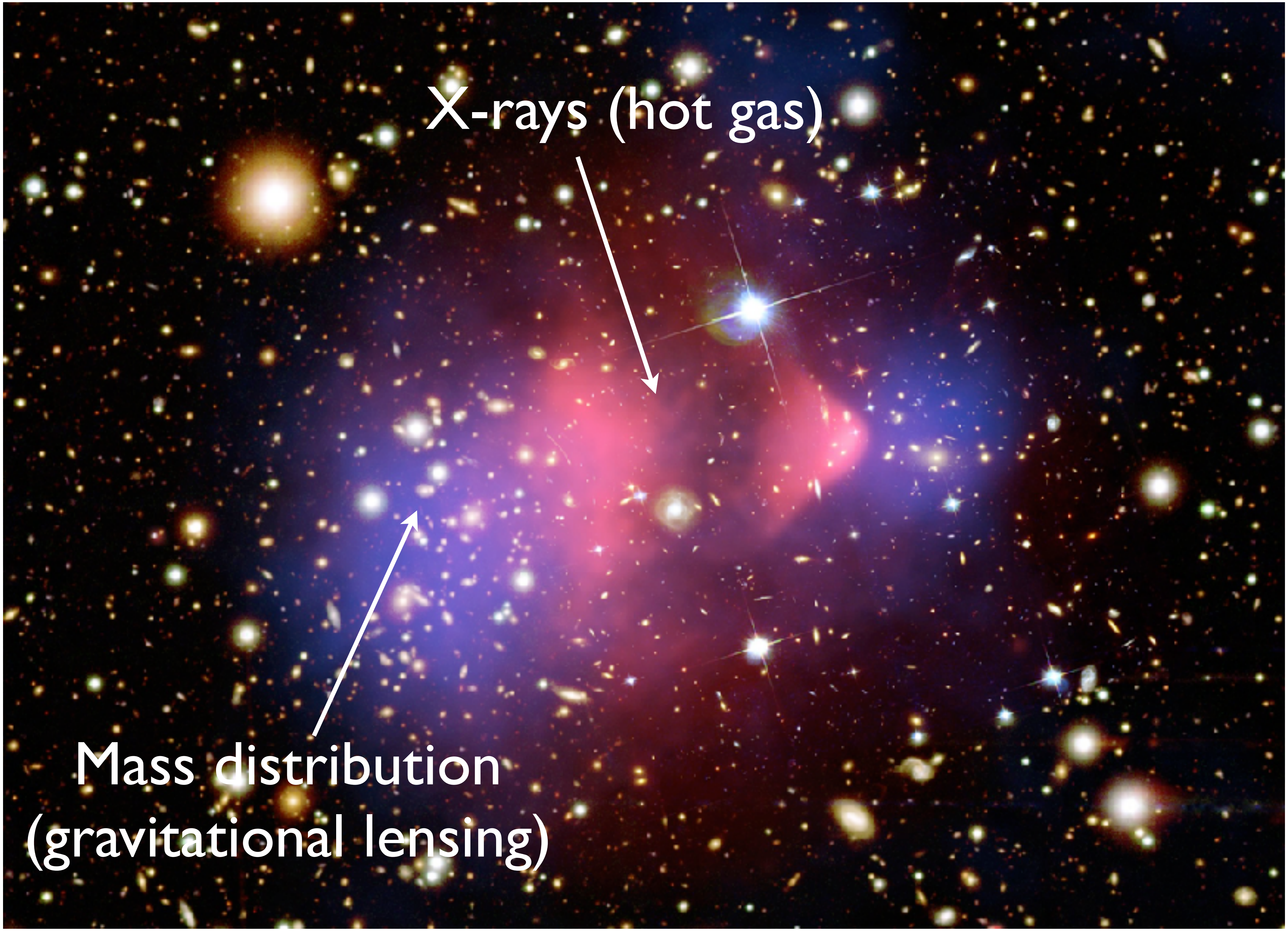

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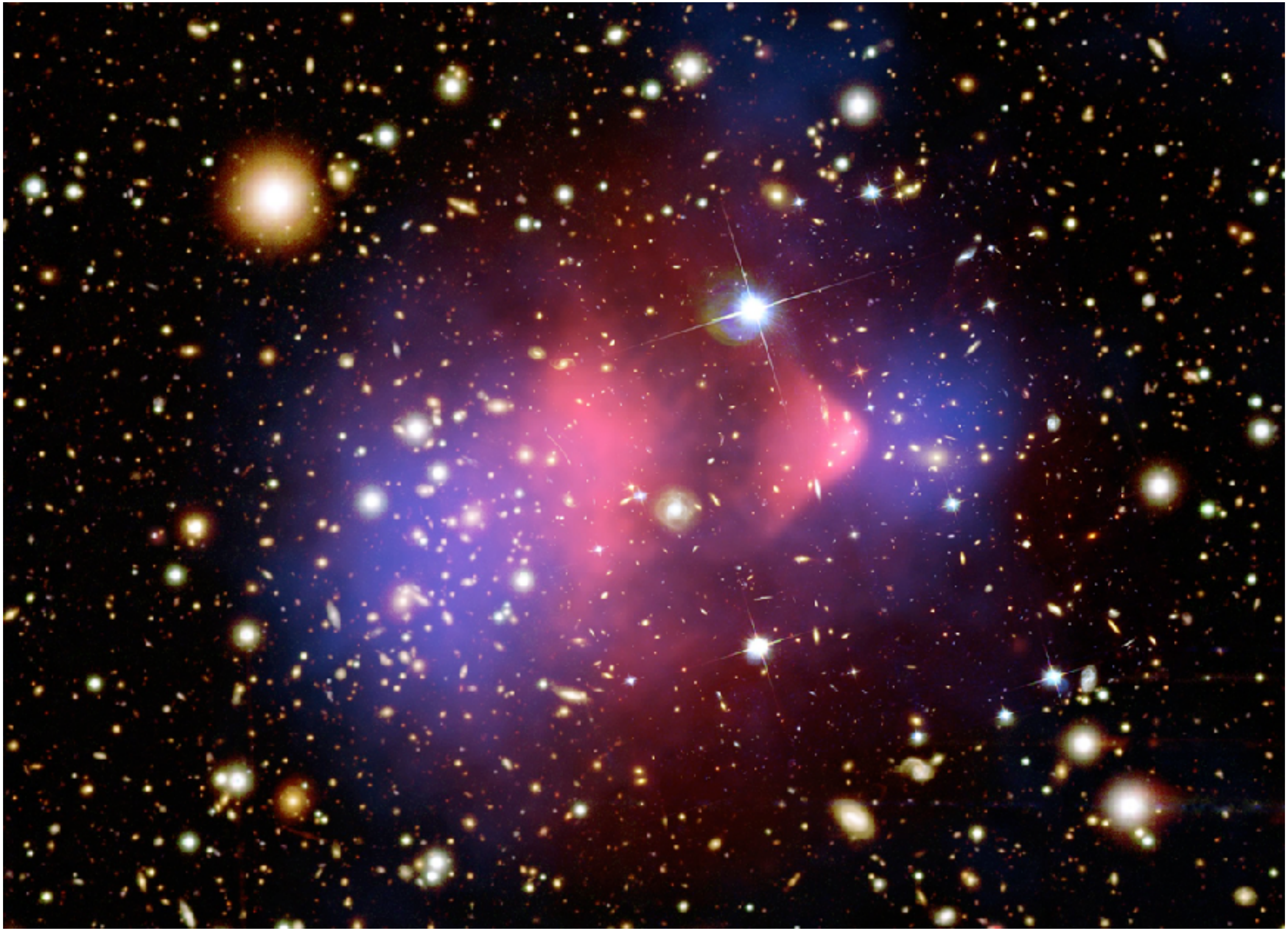

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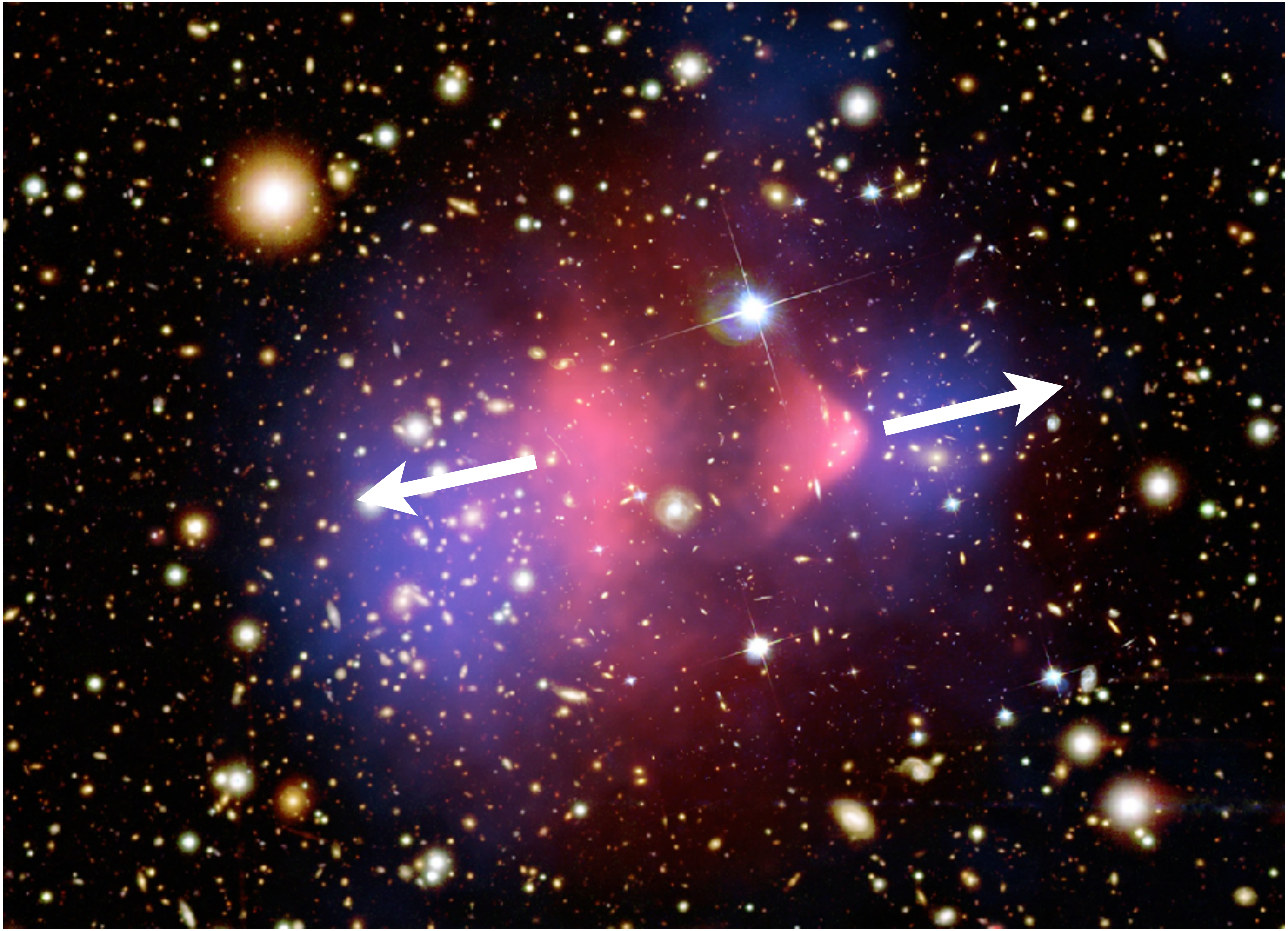

Recap on DM's (gross) properties

- DM makes up 23% of the universe
- Gravitates like ordinary matter, but is non-baryonic
- Is dark i.e. neutral under SM (not coloured, or charged)
- Does not interact much with itself $\frac{\sigma_{\chi\chi}}{m_\chi} \lesssim 3\,\mathrm{GeV}^{-3}$
- Does not couple to massless particle
- Was non-relativistic at time of CMB
- Is long lived

Decay Channel	τ Lower Limit	Experiment
$q\bar{q}$	10^{27} s	PAMELA antiprotons
e^+e^- or $\mu^+\mu^-$	2×10^{25} s $\left(\frac{\mathrm{TeV}}{m_{\mathrm{DM}}}\right)$	PAMELA positrons
$\tau^+\tau^-$	10^{25} s $\left(1+\frac{\mathrm{TeV}}{m_{\mathrm{DM}}}\right)$	EGRET + PAMELA
WW	3×10^{26} s	PAMELA antiprotons
$\gamma\gamma$	2×10^{25} s	PAMELA antiprotons
$\nu\bar{\nu}$	10^{25} s $\left(\frac{m_{\mathrm{DM}}}{\mathrm{TeV}}\right)$	AMANDA, Super-K

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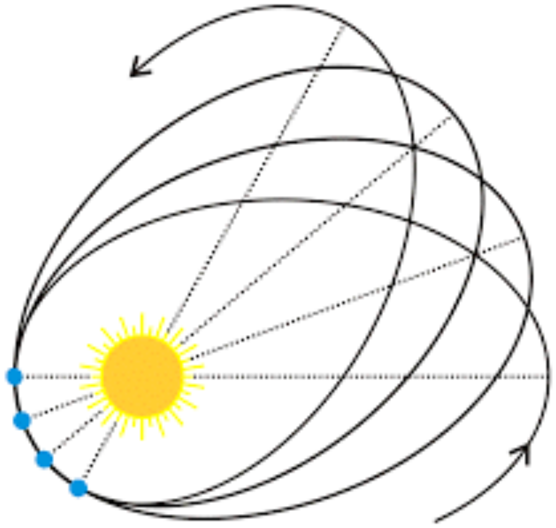
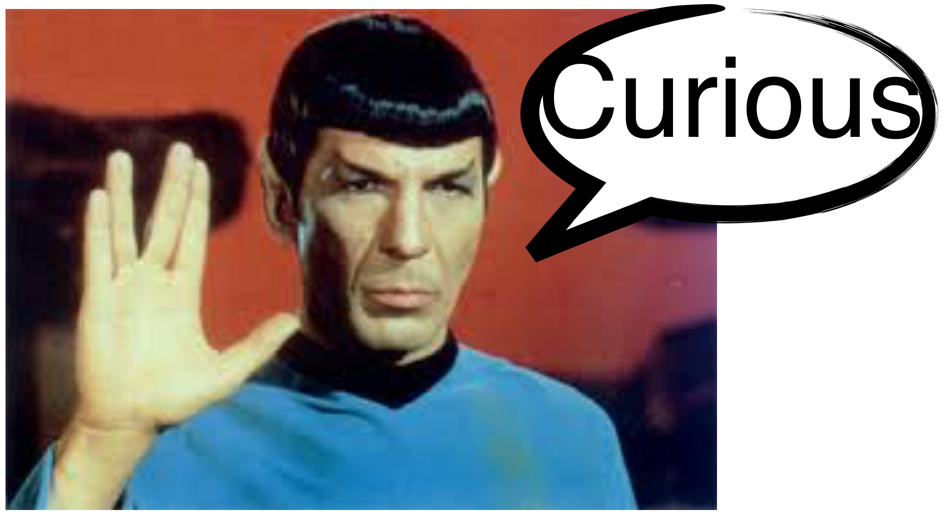
No such particle exists in the SM

So far all probes have been gravitational in nature

Neptune discovered by wobble in orbit of Uranus —original DM!

Advance in Perihelion of Mercury needed new physics (general relativity) to explain it. (Originally thought to be planet Vulcan!)





What about other interactions?

So far all probes have been gravitational in nature

What about other interactions?

Relic abundance

DM as a thermal relic

"The weak shall inherit the Universe"

If there are DM-SM couplings leading to annihilation/ production, DM will be produced in the hot early universe

$$T \gg m_\chi : \; n_\chi^{eq} \sim T^3 \qquad \chi\chi \leftrightarrow \bar{f} f$$

$$T \lesssim m_\chi : \; n_\chi^{eq} = g \left(\frac{m_\chi T}{2\pi} \right)^{3/2} e^{-m_\chi / T} \qquad \chi\chi \to f \bar{f}$$

Universe is expanding while this is happening

Need to solve Boltzmann equation

$$\frac{dn_\chi}{dt} + 3 H n_\chi = - \langle \sigma v \rangle \left(n_\chi^2 - n_{eq}^2 \right)$$

$$H = \frac{\dot{a}}{a} \sim \frac{T^2}{M_{pl}}$$

DM as a t[h...]

...nherit the Universe”

If there are D... ...nnihilation/
production, D... ...ot early universe

$$T \gg m_\chi \; : \quad n \qquad \chi\chi \leftrightarrow \bar{f}f$$

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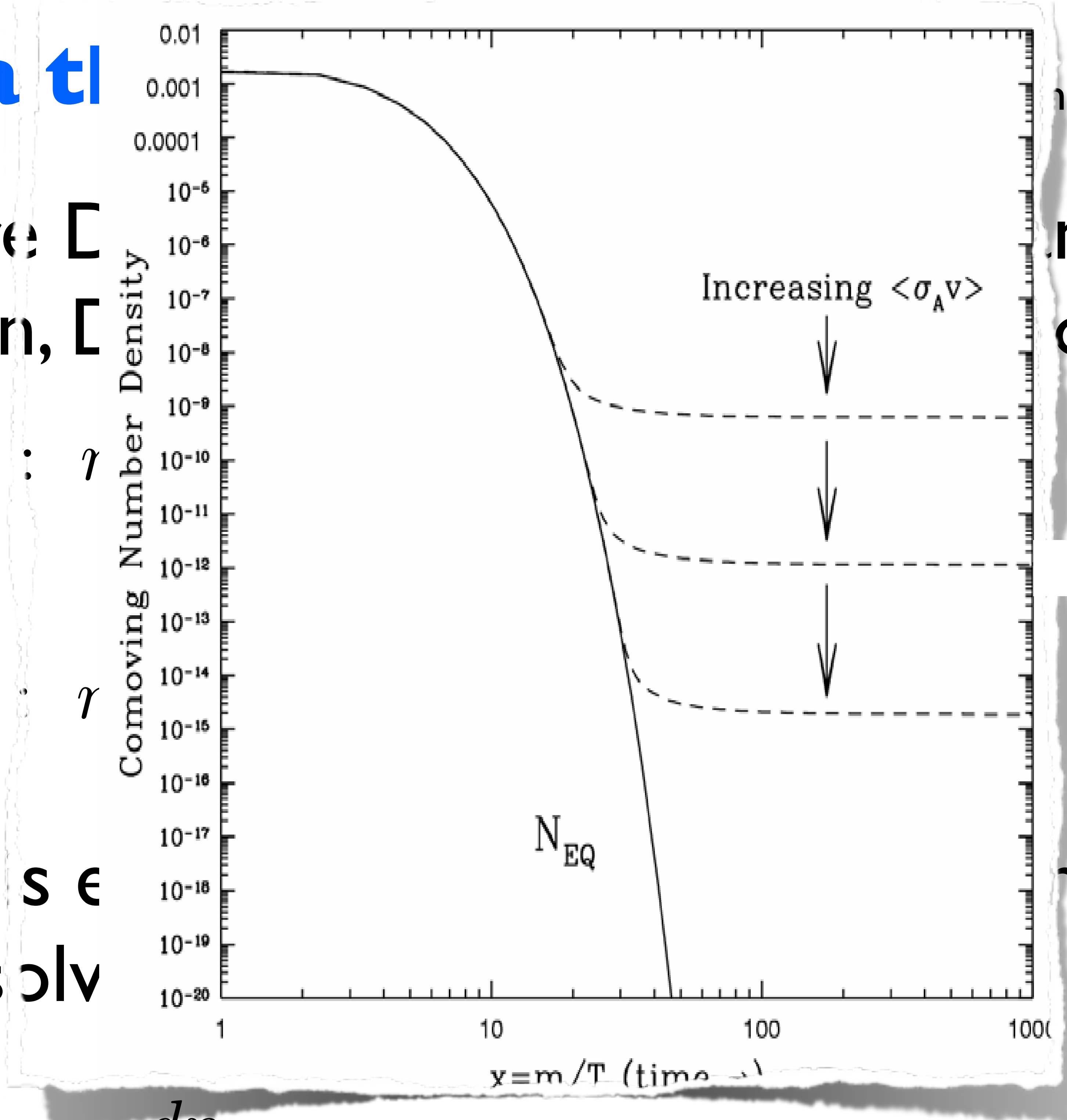

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Boltzmann equation

Useful to define $Y = \frac{n}{s}$ and $x = m_\chi/T$

$$s = \frac{2\pi^2}{45} g_* T^3 \qquad sa^3 = \text{const}$$

HW: Derive this

$$\frac{dY}{dx} = -\sqrt{\frac{\pi}{45 G_N}} \frac{g_*^{1/2} m_\chi}{x^2} \langle \sigma v \rangle \left(Y^2 - Y_{eq}^2 \right)$$

Some examples

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma v \rangle \left(n_\chi^2 - n_{eq}^2\right)$$

$$\langle \sigma v \rangle = const$$

Freeze out occurs when

$$\left(\frac{m_\chi T}{2\pi}\right)^{3/2} e^{-m_\chi/T} \sim \frac{T_f^2}{M_{pl}\langle \sigma v \rangle}$$

Numerical solution show x=20..30

$$\rho_c = \frac{3H^2}{8\pi G_N} = 8 \times 10^{-47} h^2 \mathrm{GeV}^{-4}$$

$$\Omega_\chi = \frac{m_\chi n_0}{\rho_c} \sim \frac{T_0^3}{\rho_c} \frac{x}{M_{pl}\langle \sigma v \rangle}$$

Some examples

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle \left(n_\chi^2 - n_{eq}^2\right)$$

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Numerical solution show x=20..30

$$\rho_c = \frac{3H^2}{8\pi G_N} = 8 \times 10^{-47} h^2 \mathrm{GeV}^{-4}$$

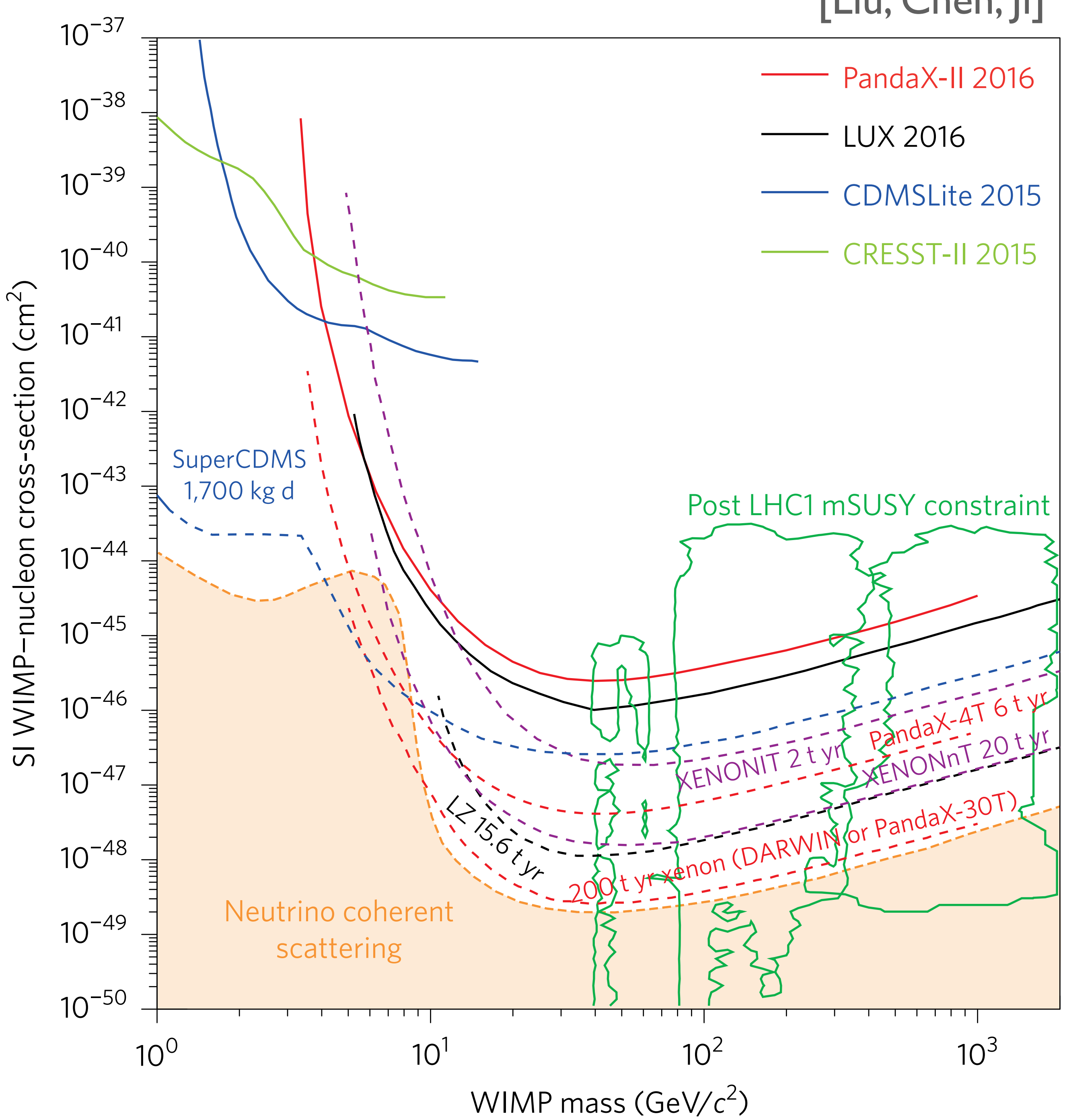
$$\Omega h^2 \approx 0.1 \left(\frac{m/T}{20}\right) \left(\frac{g_*}{80}\right)^{-1} \left(\frac{3\times 10^{-26}\mathrm{cm}^2\mathrm{s}^{-1}}{\sigma v}\right)$$

HW: Repeat this for baryons. Why does there need to be an initial asymmetry?
HW: Repeat for a state coupled to the Z. (The Lee-Weinberg bound)

WIMP

- DM interacts through weak (or weak scale) couplings
- Lee-Weinberg and Unitarity constrain mass range
  - ~1 GeV —~10 TeV
- Usually consider a thermal relic

[Liu, Chen, Ji]



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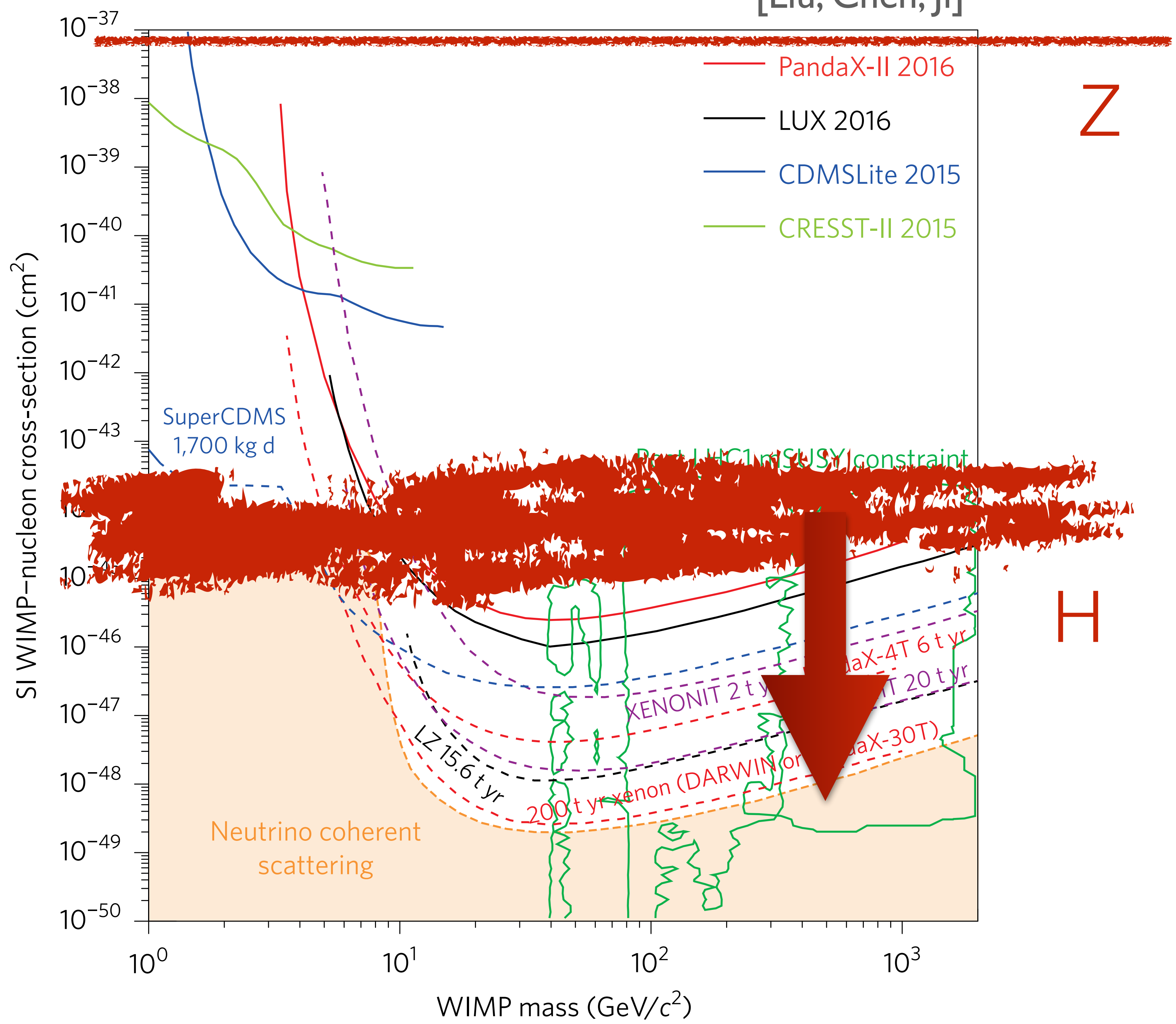

Hidden sector DM

- DM interacts through *new* mediators
  - “dark photon”, U-boson, Z’, secluded mediator,….
  - dark Higgs
  - pseudo scalars, ALPs
  - ….
- Portal interactions
- Thermal relic, now can annihilate within the dark sector
- Allows for lighter DM
  - ~1 keV — ~100 TeV
- Search for all dark sector particles
  - Direct, indirect, collider, self-coupling

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$$\frac{\epsilon}{16\pi^2} F'_{\mu\nu} B_Y^{\mu\nu}$$

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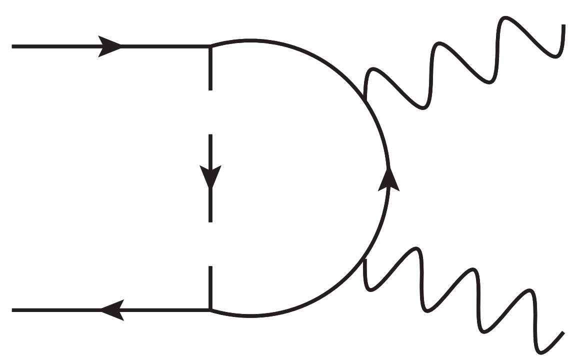
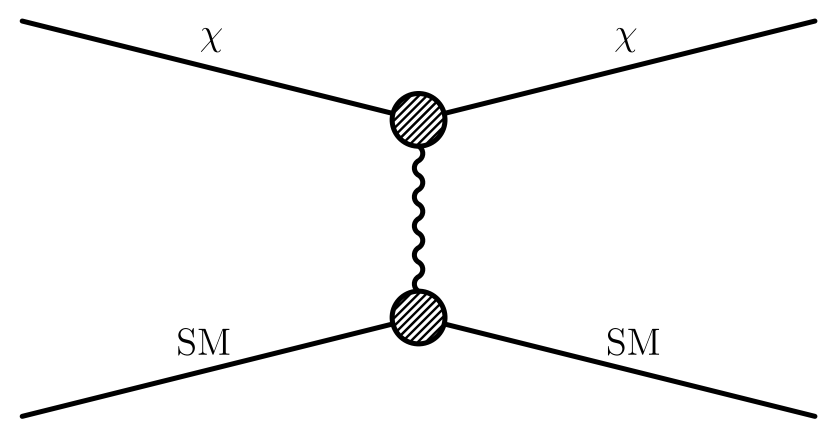
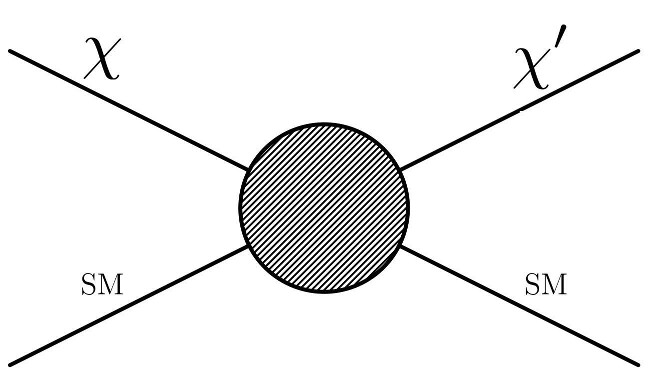
Hidden sector DM—interesting dynamics

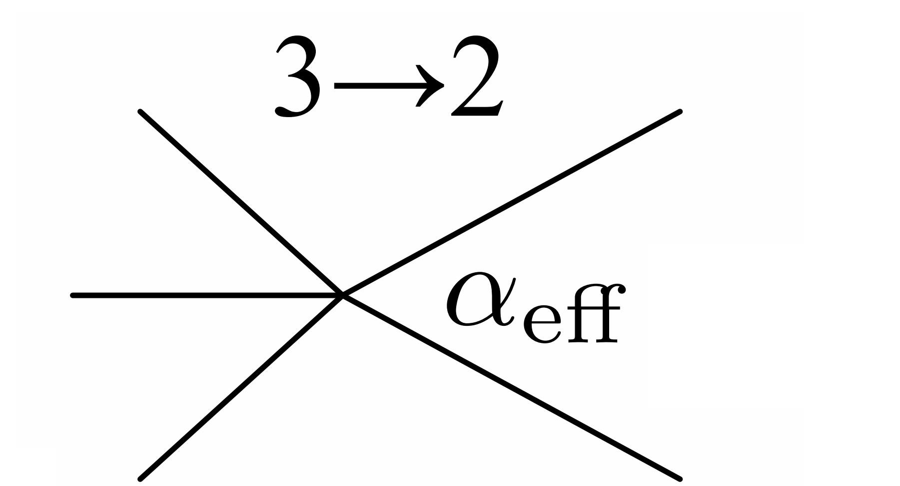
Hidden sector dynamics, new force carriers

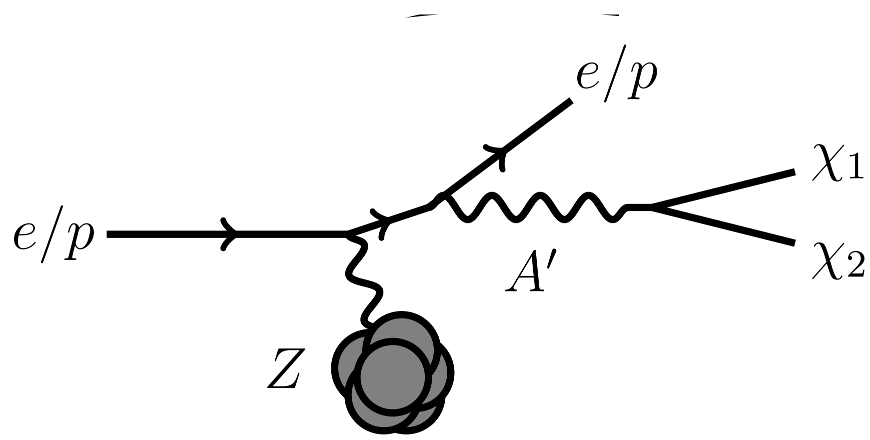
Composite dark matter, cannibalisation, DM form factors, inelastic splittings, dipole couplings, atomic DM, DM-DM self interactions,…



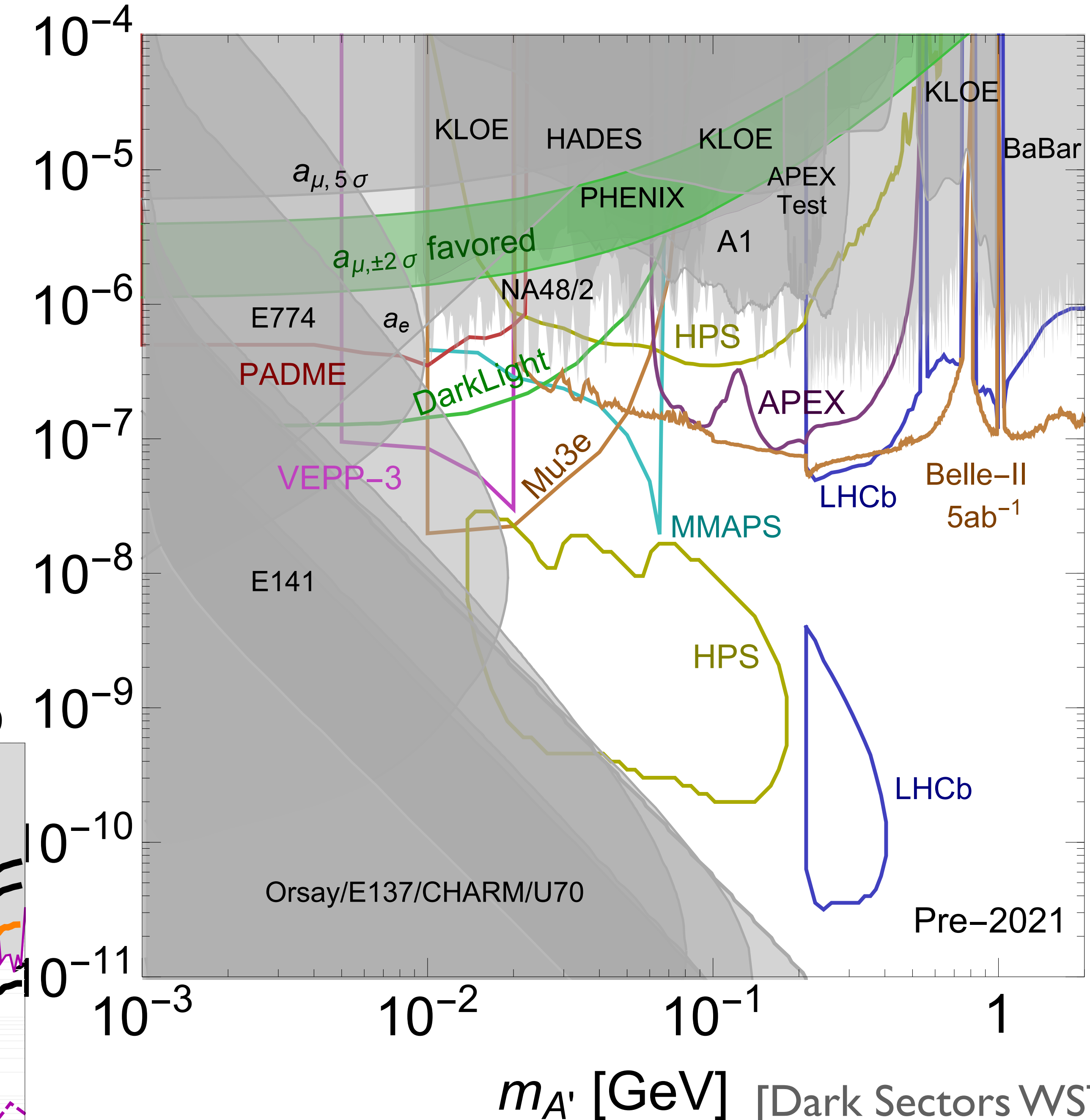




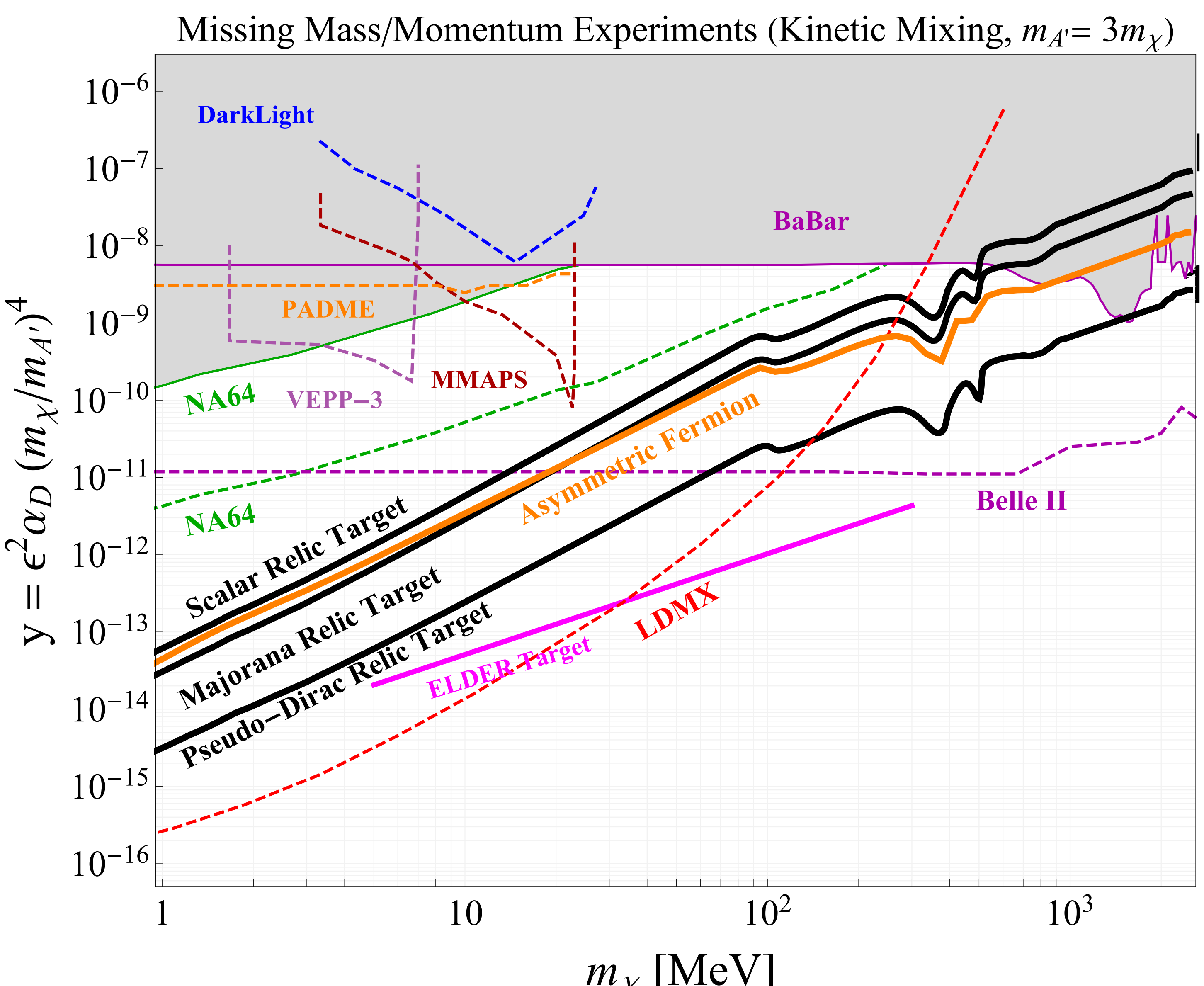




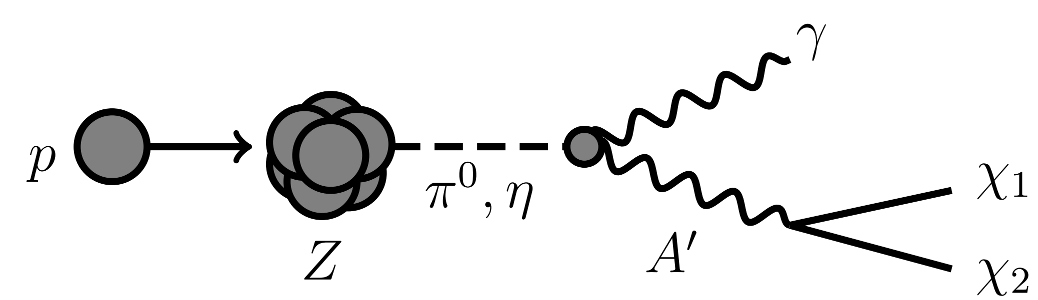
e/p
e/p
A′
χ1
χ2
Z



KLOE
HADES
KLOE
KLOE
BaBar
APEX Test
PHENIX
A1
$a_{\mu,5\sigma}$
$a_{\mu,\pm2\sigma}$ favored
NA48/2
E774
a_e
PADME
DarkLight
HPS
APEX
VEPP-3
Mu3e
MMAPS
LHCb
Belle-II 5ab^{-1}
E141
HPS
LHCb
Orsay/E137/CHARM/U70
Pre-2021
ϵ^2
$m_{A'}$ [GeV]
[Dark Sectors WS]



Missing Mass/Momentum Experiments (Kinetic Mixing, $m_{A'} = 3m_\chi$)
DarkLight
BaBar
PADME
MMAPS
NA64
VEPP-3
NA64
Asymmetric Fermion
Belle II
Scalar Relic Target
Majorana Relic Target
Pseudo-Dirac Relic Target
ELDER Target
LDMX
$y = \epsilon^2\alpha_D (m_\chi/m_{A'})^4$
m_χ [MeV]

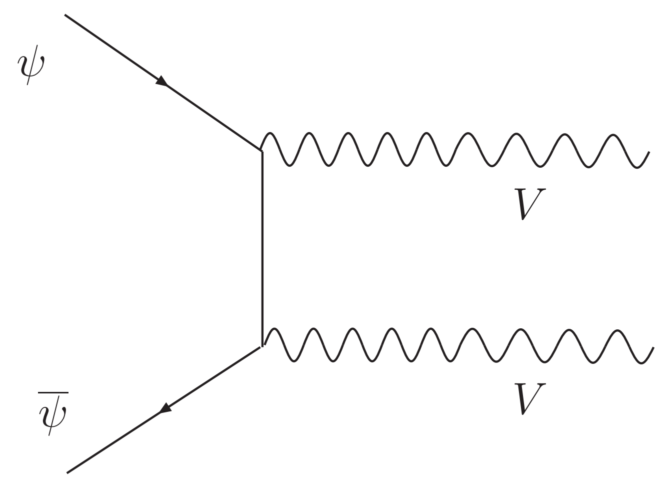


p
Z
π^0, η
γ
A′
χ1
χ2

Hidden sector DM—thermal relics

[Pospelov, Ritz, Voloshin]

Secluded DM $m_\chi > m_{A'}$



Decouples direct detection from thermal history

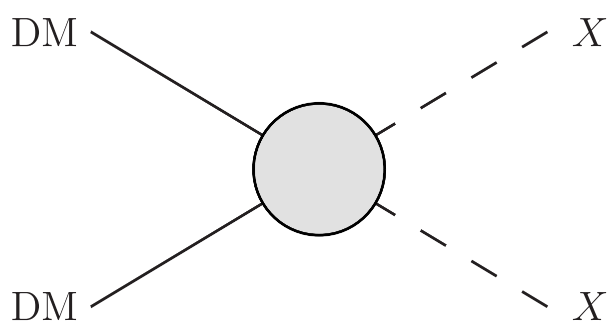
Light DM and CMB

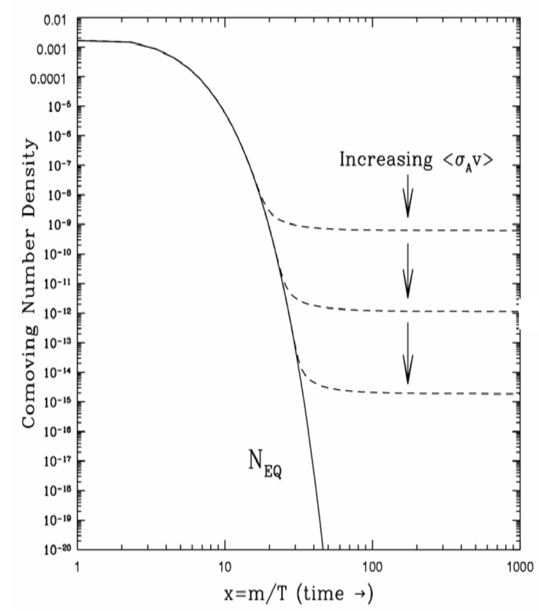
$$p_{CMB} = f_{off} \frac{\langle \sigma v \rangle_{T \sim eV}}{m_\chi} < 3.5 \times 10^{-11} \mathrm{GeV}^{-3}$$

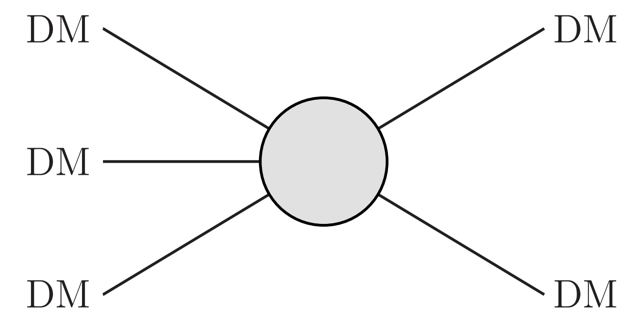
P-wave (Majorana fermions), asymmetric, co-annihilation w/ suppressed species

Hidden sector DM—thermal relics

Leads to interesting changes in cosmology



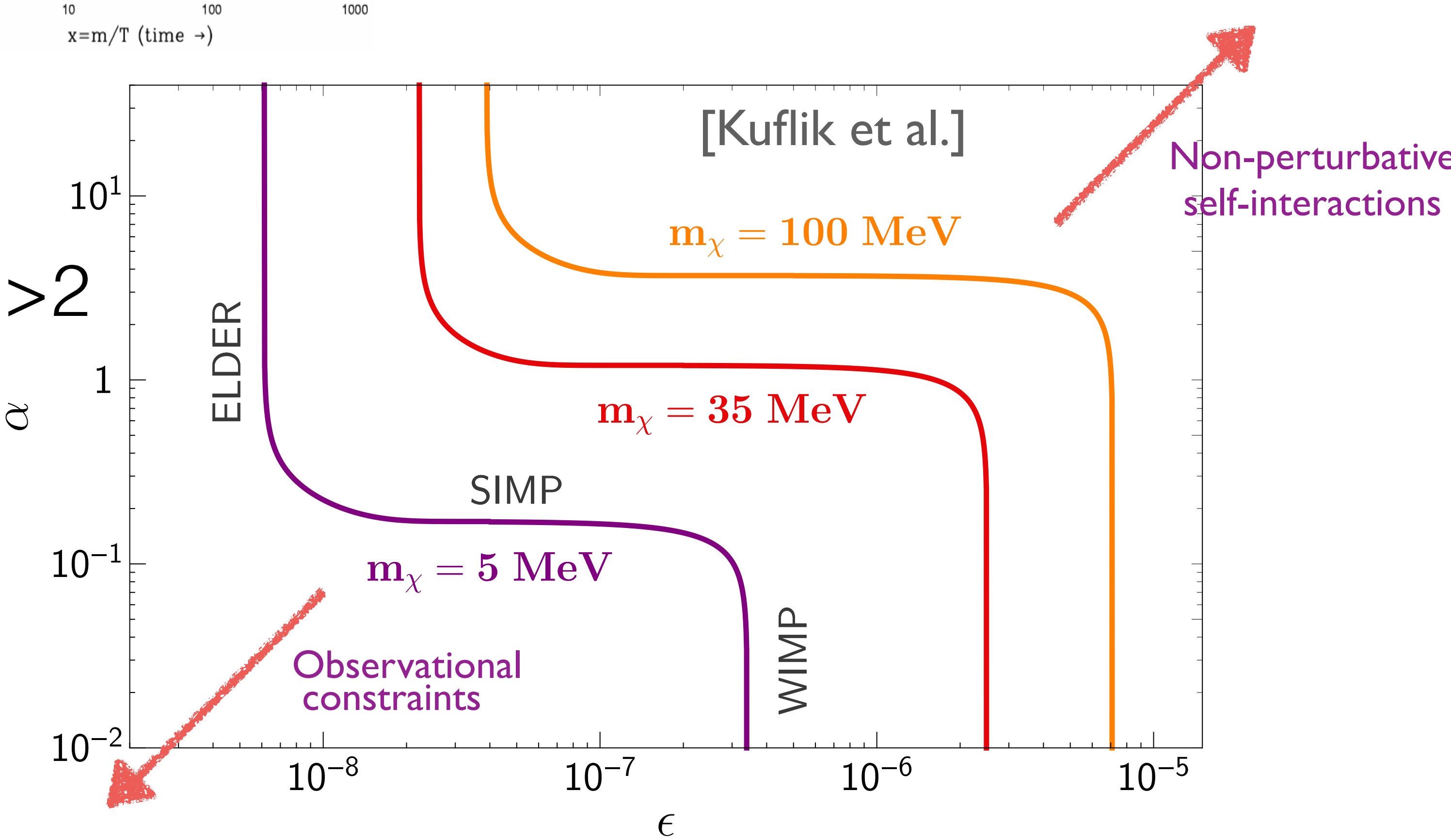




cannibalization

WIMPless-miracle
(1-100 MeV scale)
SIMP-miracle
ELDER…
all smoothly connected
in parameter space

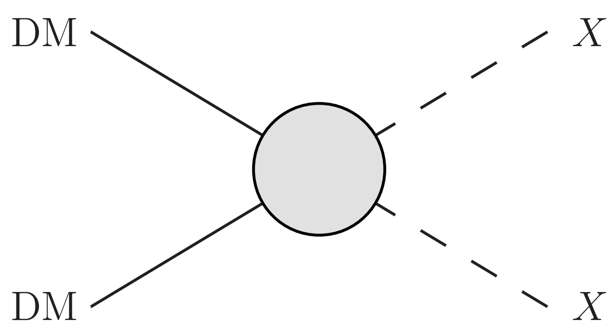
3->2

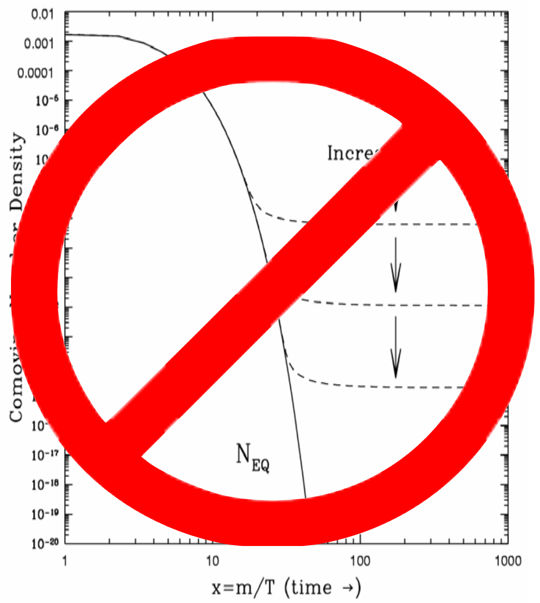


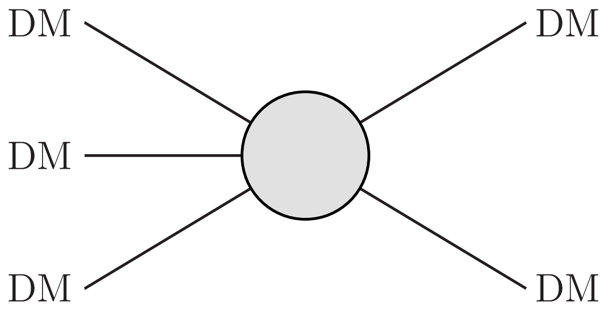
DM-SM elastic scatter

Hidden sector DM—thermal relics

Leads to interesting changes in cosmology







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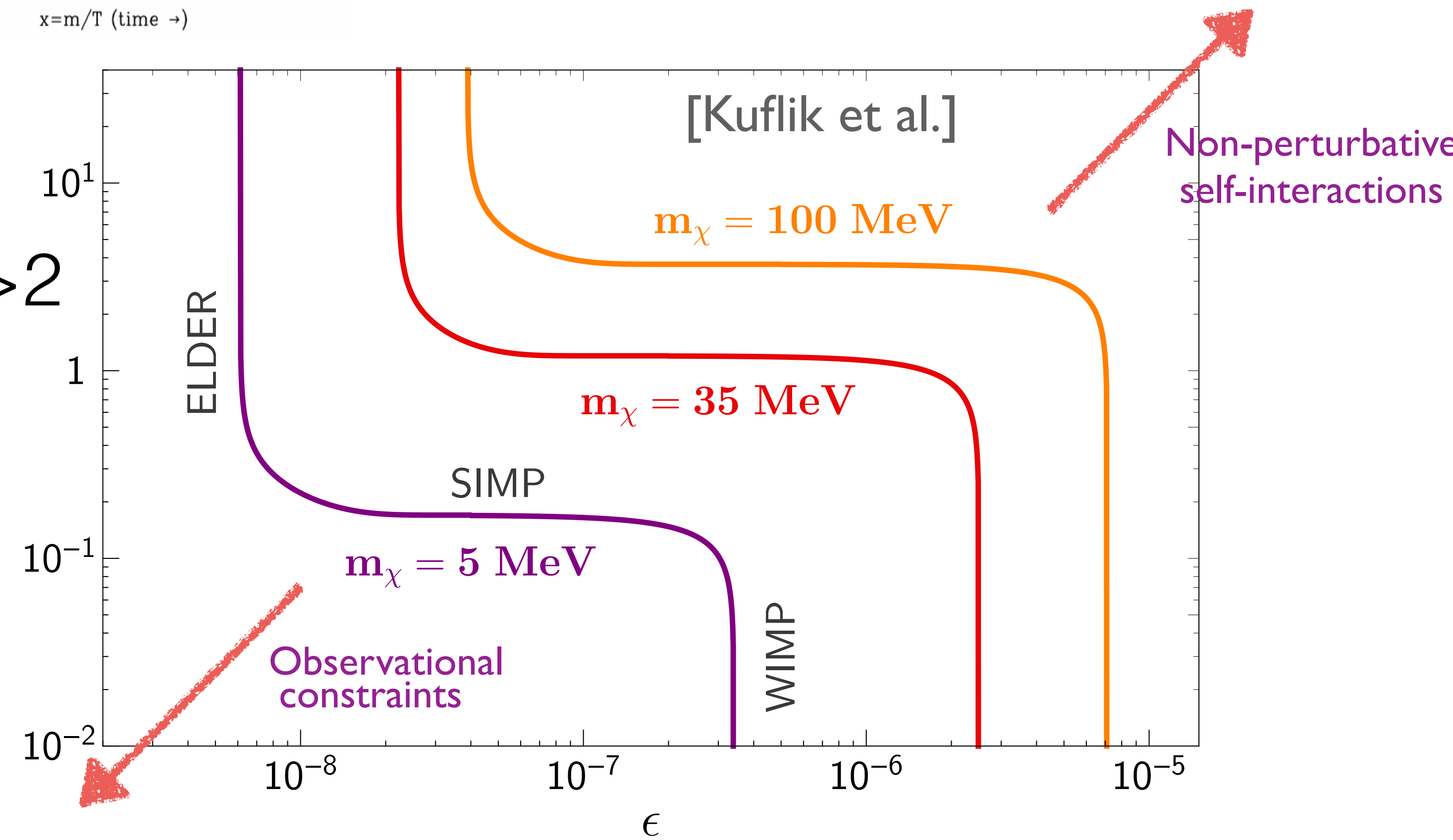

DM-SM elastic scatter

Non-thermal relics

- Late decaying massive particle e.g. modulus
- Asymmetric DM [See Petraki and Volkas review]
  - Similar to baryon-antibaryon asymmetry
  - Explains $\Omega_{\rm DM} \simeq 5\,\Omega_{\rm VM}$
  - Decouples cosmological history from possible signals
  - Indirect detection?
  - Many examples of “cogenesis”
- Misalignment mechanism to produce ultralight (<eV) cold relic
  - QCD relic

- DM makes up 23% of the universe
- Gravitates like ordinary matter, but is non-baryonic
- Is dark i.e. neutral under SM (not coloured, or charged)
- Does not interact much with itself
- Does not couple to massless particle
- Was no relativistic at time of CMB
- Is long lived

IF DM is a thermal relic:

- A weak scale annihilation x-sec gives correct abundance
- Mass range is $10\ \mathrm{MeV} \lesssim m_\chi \lesssim 70\ \mathrm{TeV}$

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WIMPs

IF DM is a thermal relic:

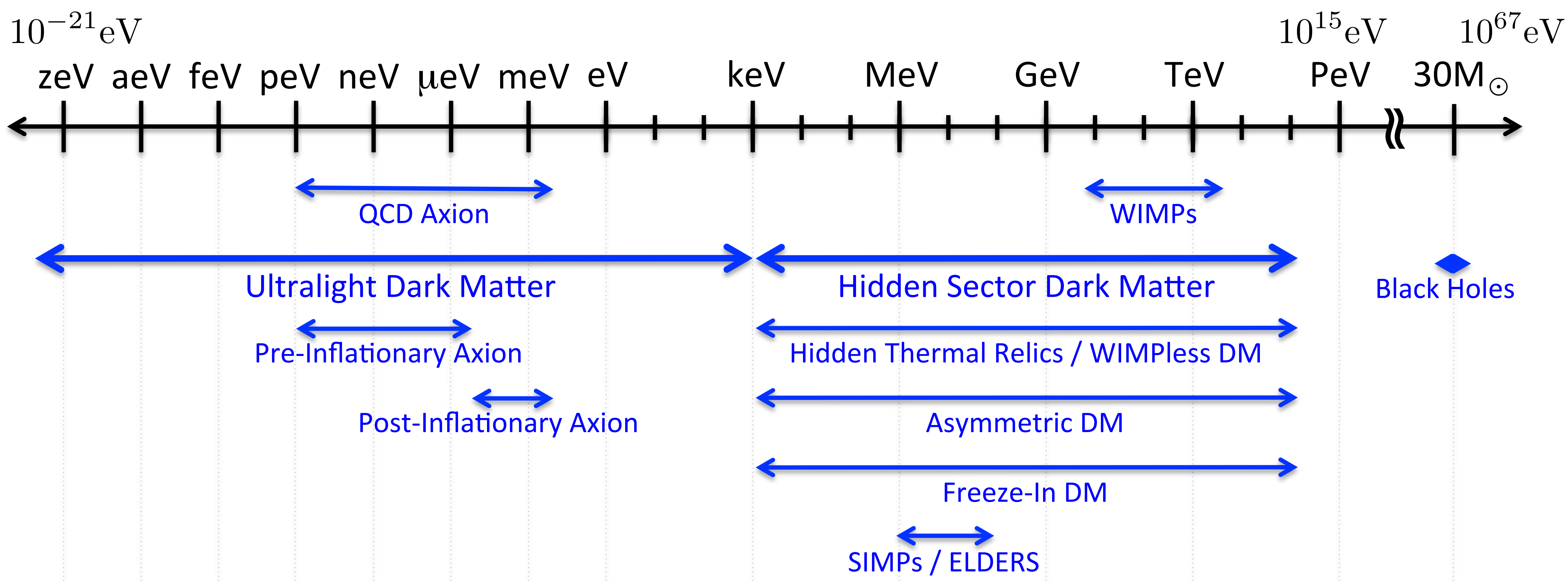
- A weak scale annihilation x-sec gives correct abundance
- Mass range is $10\ \mathrm{MeV} \lesssim m_\chi \lesssim 70\ \mathrm{TeV}$

WIMPs and BSM physics

- Higgs hierarchy problem "predicts" new states at weak scale with/without SM charge
- Flavour constraints require high scale (1000 TeV) suppression of FCNC operators
- "New physics parity"
- LPOP often has possibility to be a DM WIMP

- WIMPs e.g. SUSY neutralino, KK-mode of UED, techni-baryons, lightest T-odd little Higgs particle, LPOPs....

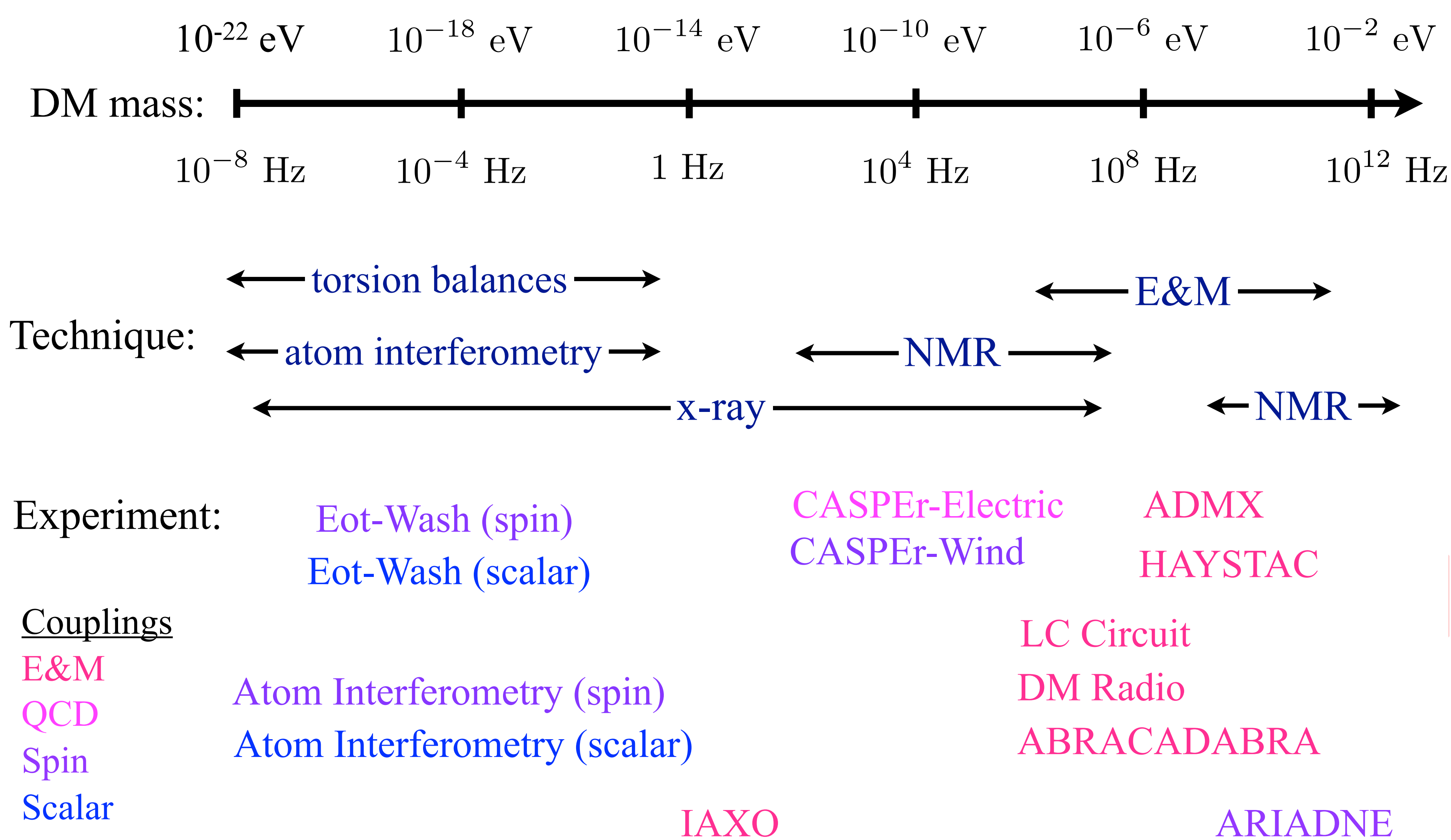
Particle theories



[Feng-US Cosmic Visions White papers]

sub-keV DM

- Very light DM is bosonic
- Heavier than $10^{-22}\,\mathrm{eV}$
- More appropriately thought of as semiclassical wave, large n
- Or, absorption of DM, linear coupling to matter



[US Cosmic Visions White papers]

QCD Axion

see talk by Semertzidis

Axionic DM best thought of as a coherent oscillation with high occupancy

$10^{-12}\mathrm{eV}$ m_a $10^{-2}\mathrm{eV}$ $1\mathrm{eV}$

$f \sim M_{pl}$ SN1987A Hot DM

PQ broken
after inflation

Axion starts osc.
too late, too much DM

$10^{-5}\mathrm{eV}$ $1\mathrm{eV}$

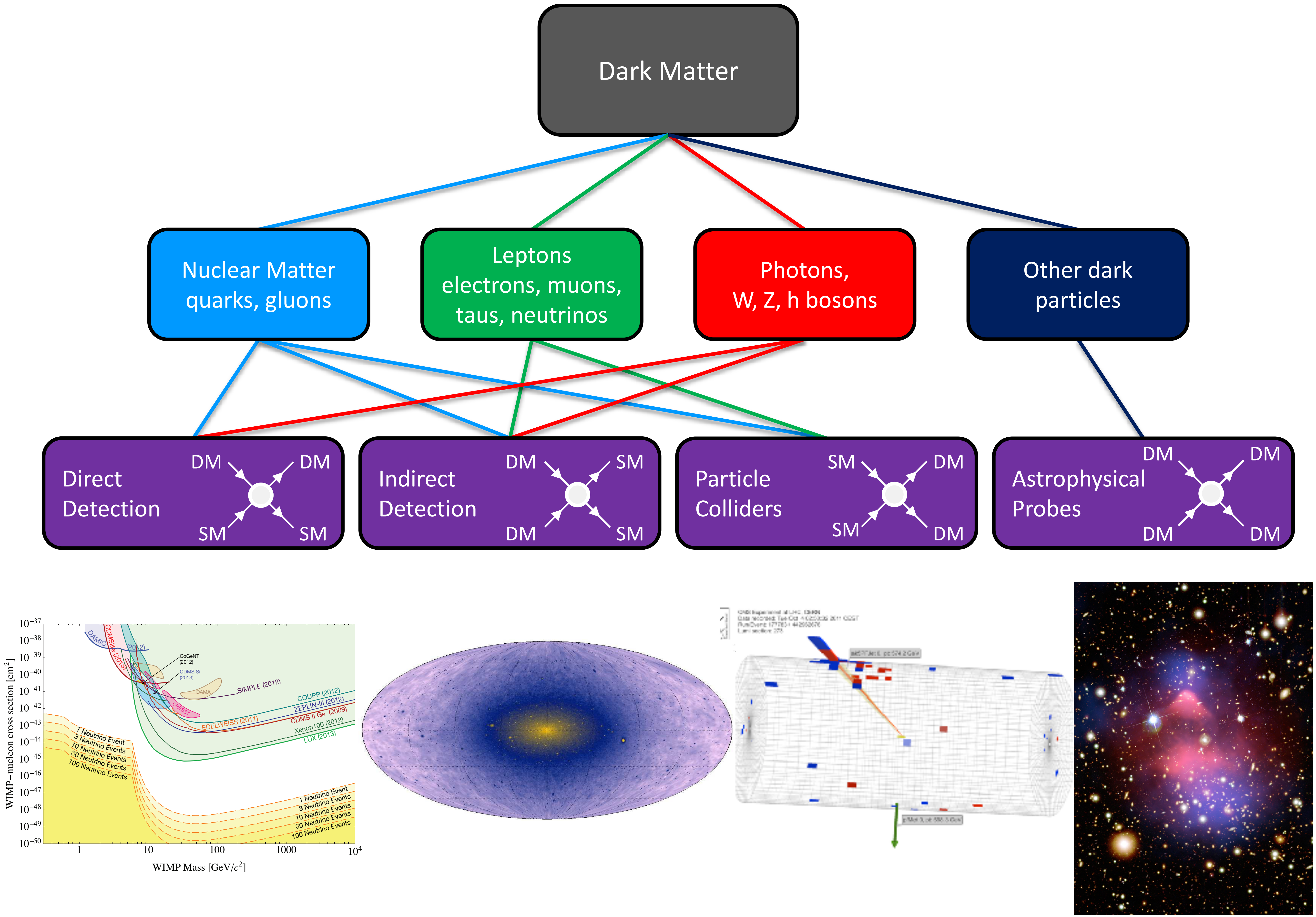
PQ broken
before inflation

DM abundance requires small θ_{init} Anthropics?

Isocurvature modes $(H_I/f)^2$

B-modes $(H_I/M_{pl})^2$

connections to inflation
[PF, Pierce, Thomas]

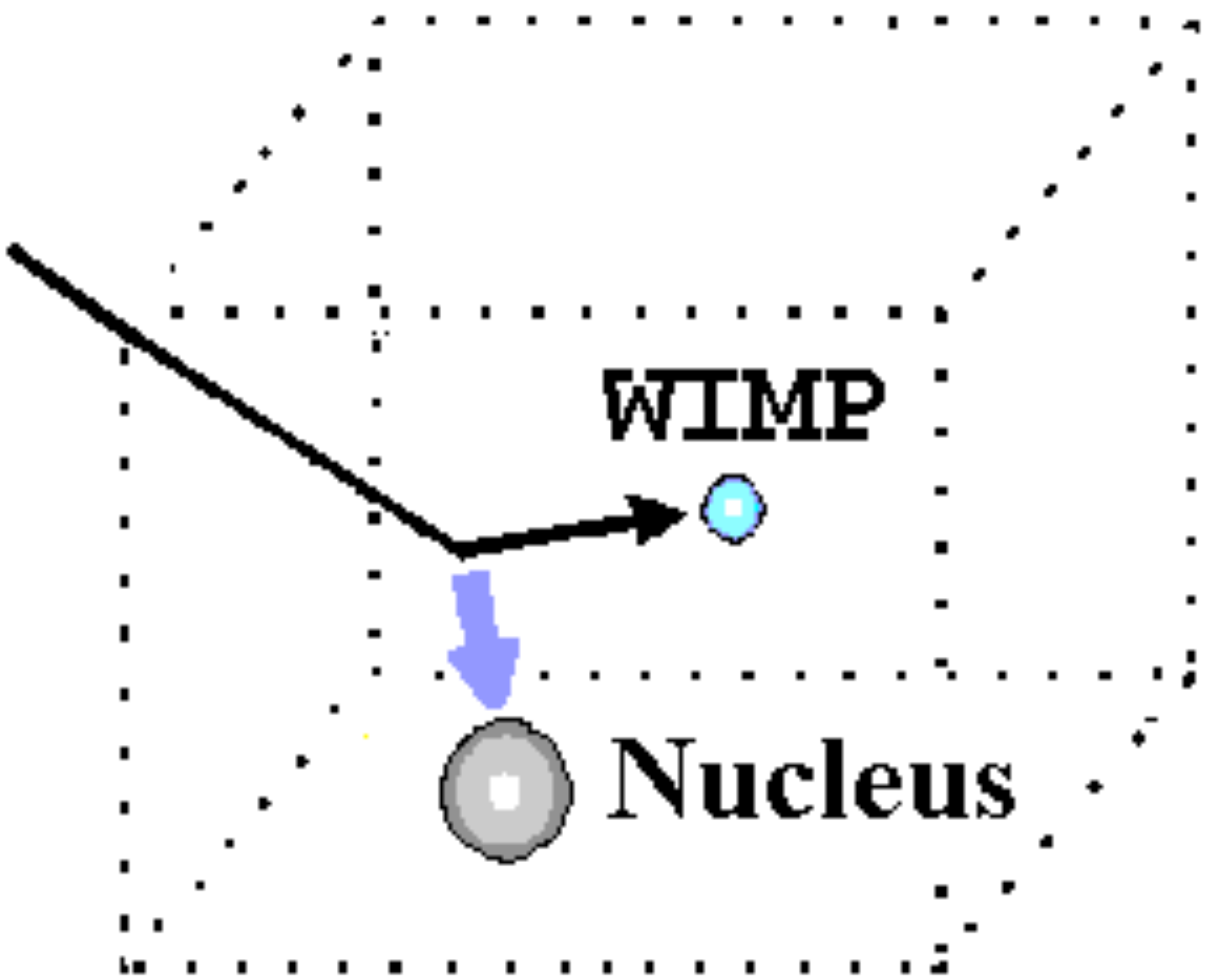


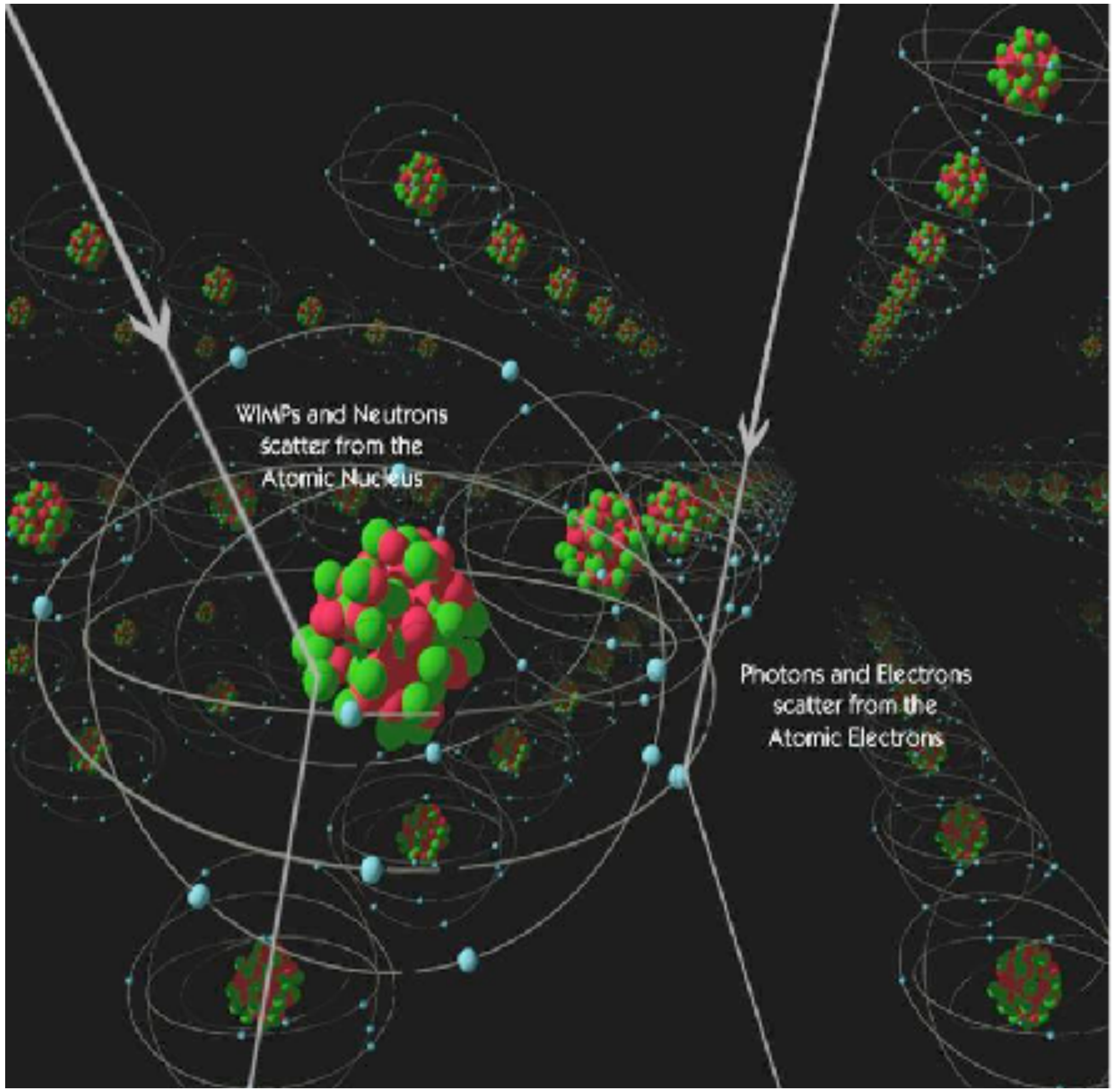
Dark Matter
Nuclear Matter
quarks, gluons
Leptons
electrons, muons,
taus, neutrinos
Photons,
W, Z, h bosons
Other dark
particles
Direct
Detection
DM
DM
SM
SM
Indirect
Detection
DM
SM
DM
SM
Particle
Colliders
SM
DM
SM
DM
Astrophysical
Probes
DM
DM
DM
DM
WIMP–nucleon cross section [cm²]
WIMP Mass [GeV/c²]
SIMPLE (2012)
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
Xenon100 (2012)
LUX (2013)
EDELWEISS (2011)
DAMA
CRESST
CoGeNT
(2012)
CDMS Si
(2013)
1 Neutrino Event
3 Neutrino Events
10 Neutrino Events
30 Neutrino Events
100 Neutrino Events

Direct Detection

Dark Matter Direct Detection

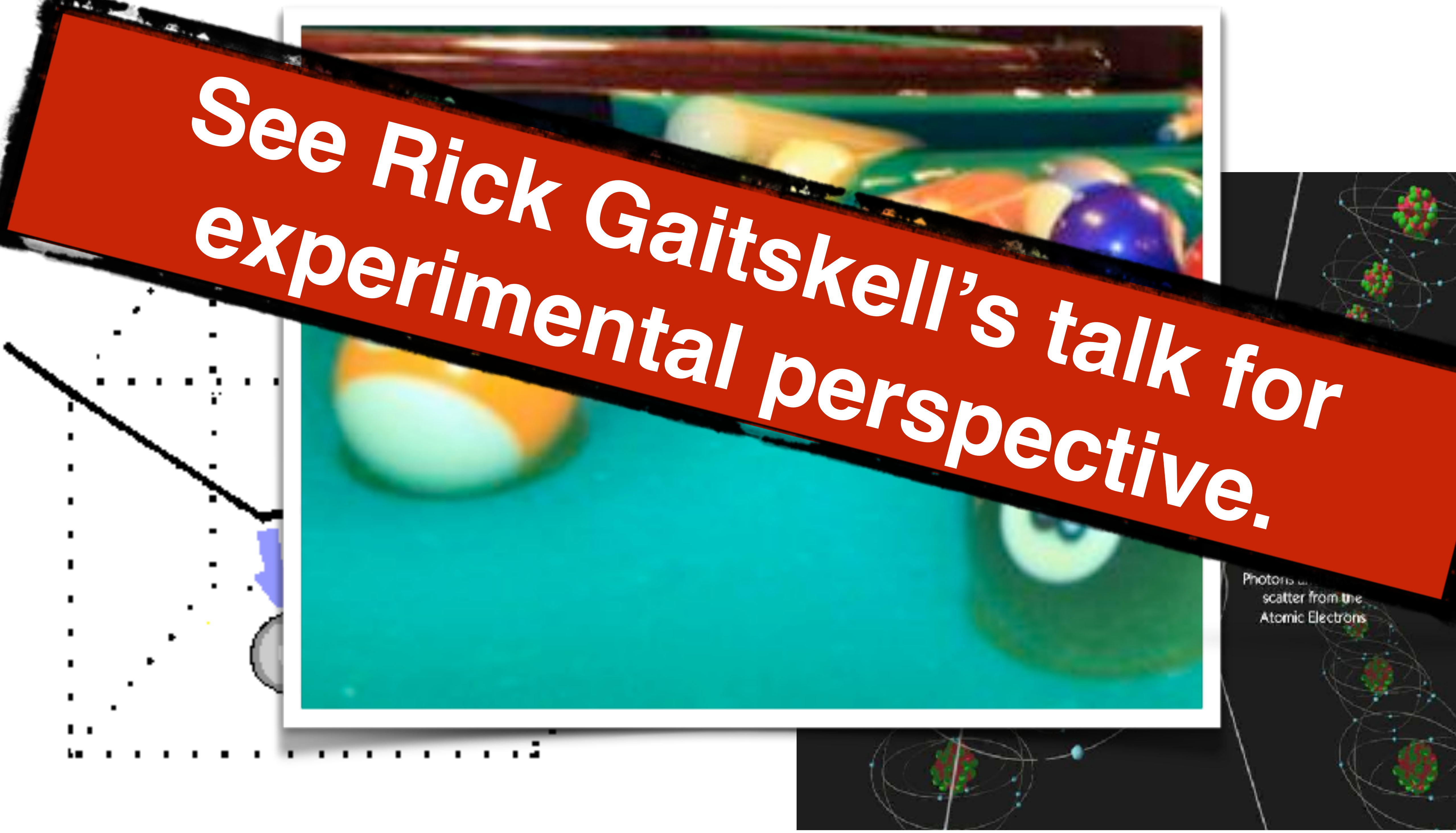
(the theorist's perspective)



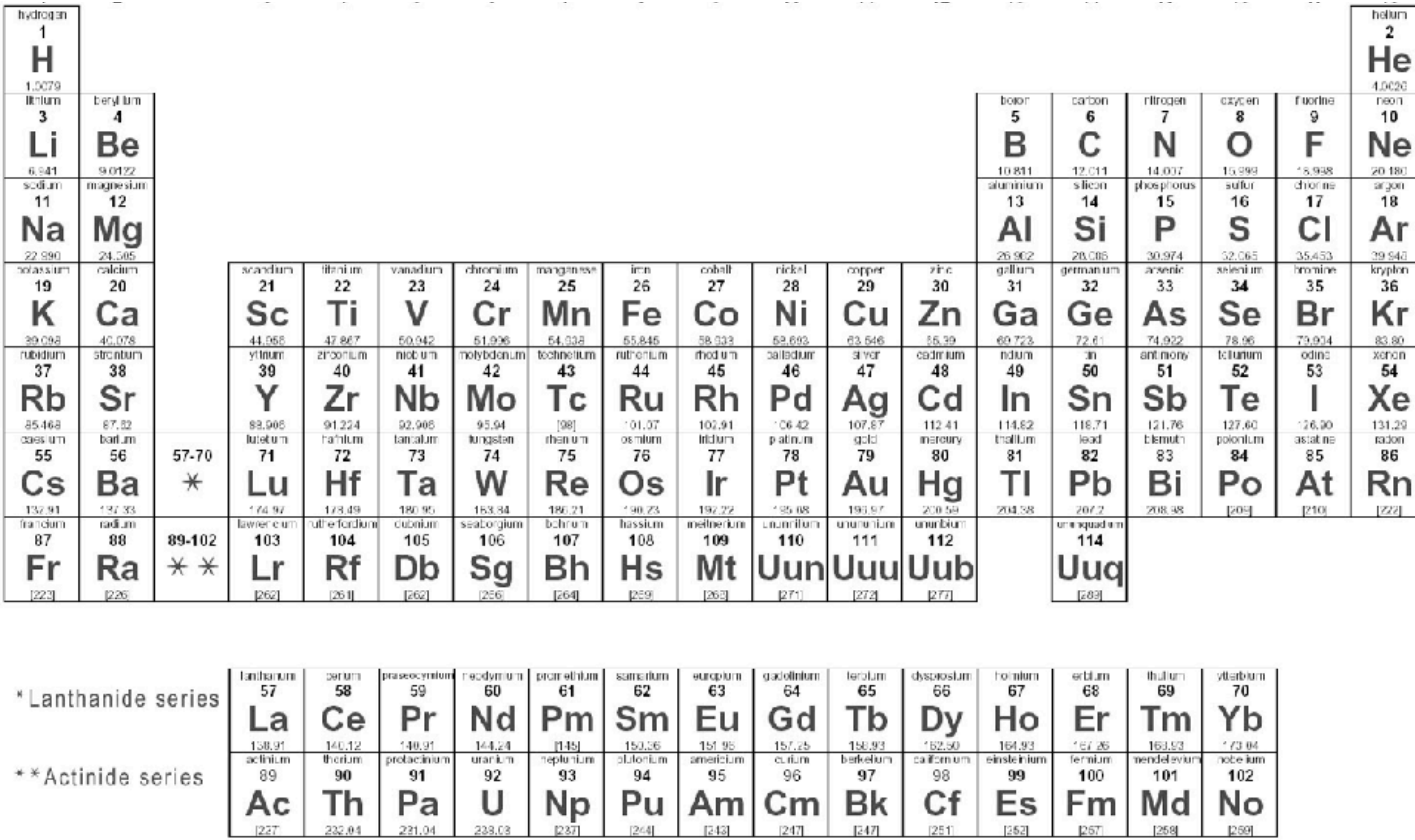


Dark Matter Direct Detection

See Rick Gaitskell's talk for experimental perspective.



An exciting time, many experiments



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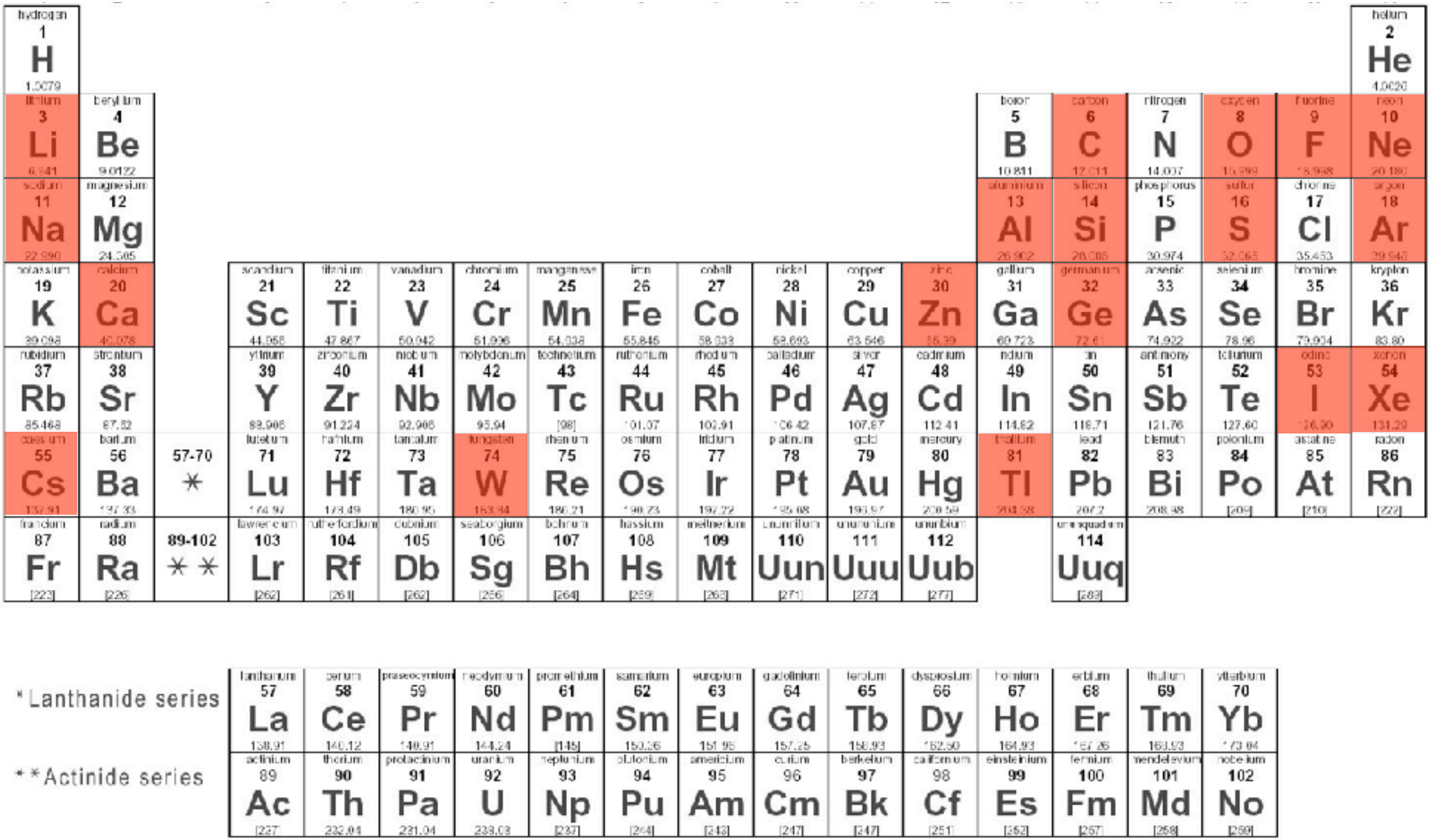
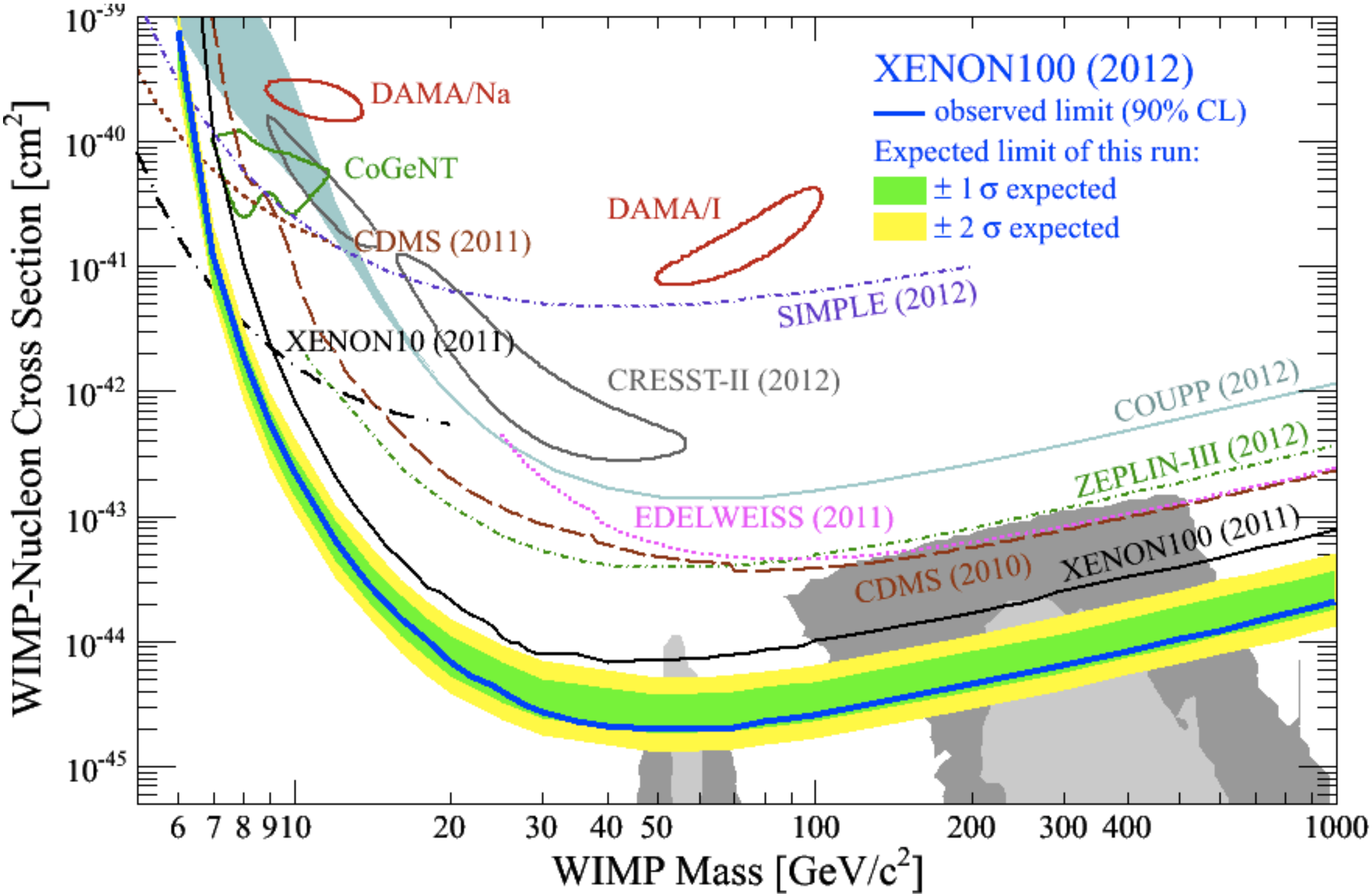


Aim: to understand everything that goes into this plot



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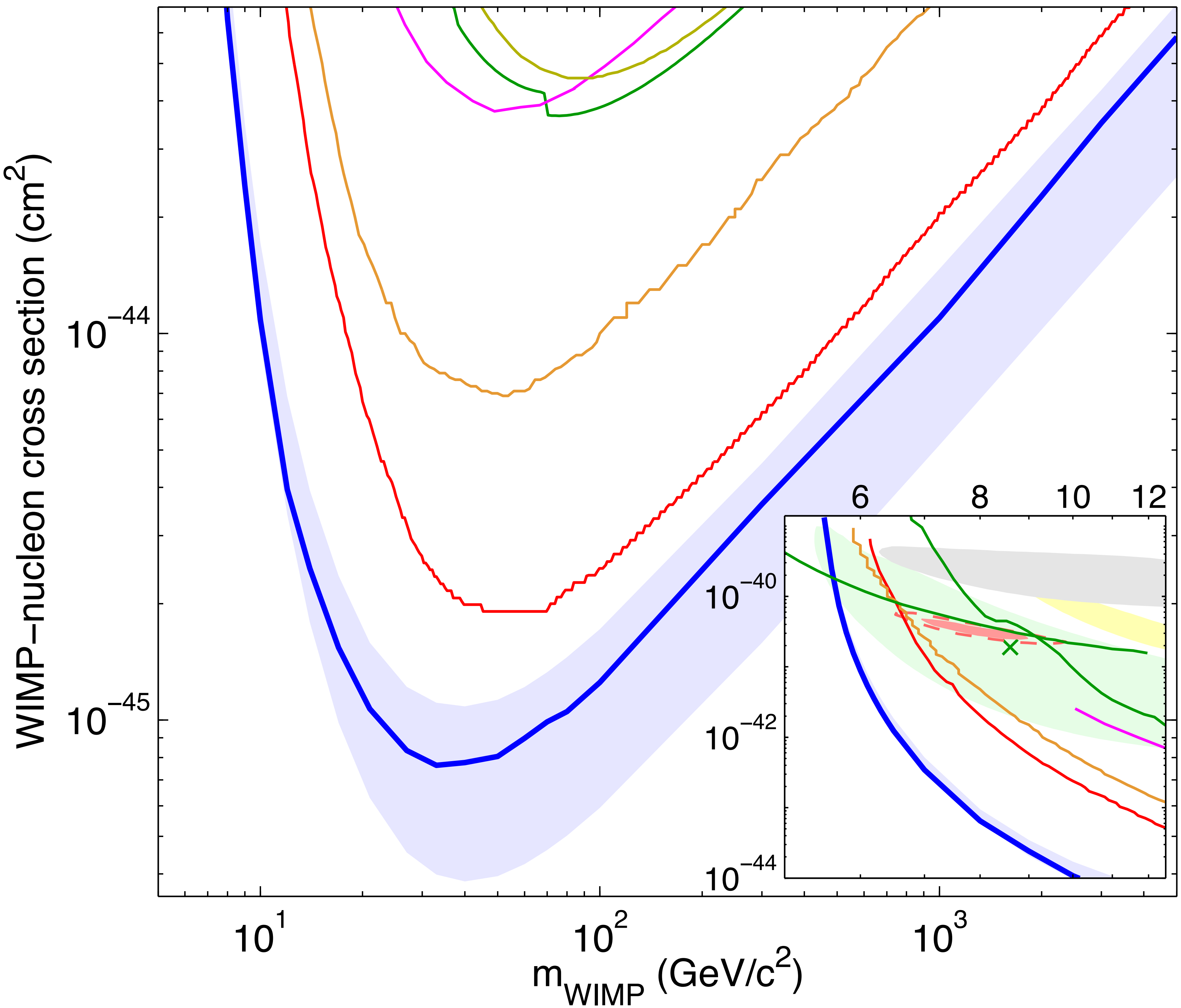
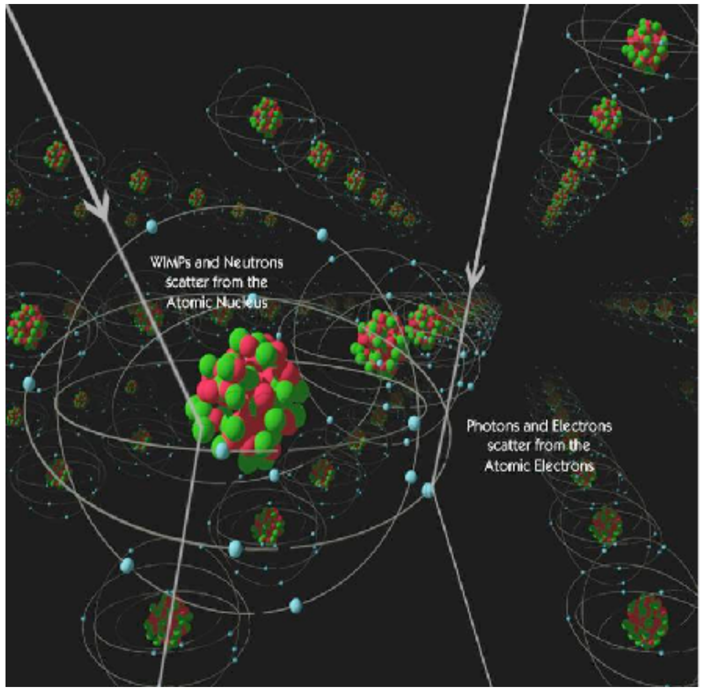
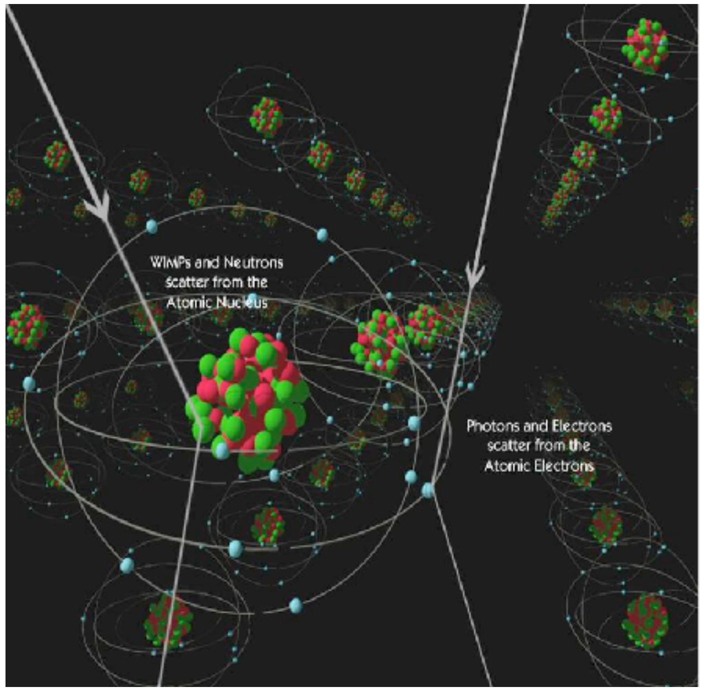


“The Master formula”



$$\frac{dR}{dE_R} = \frac{N_T \rho}{m_\chi} \int_{v_{\min}}^{v_{\max}} d^3v\, f(v(t))\, \frac{d\sigma |v|}{dE_R}$$

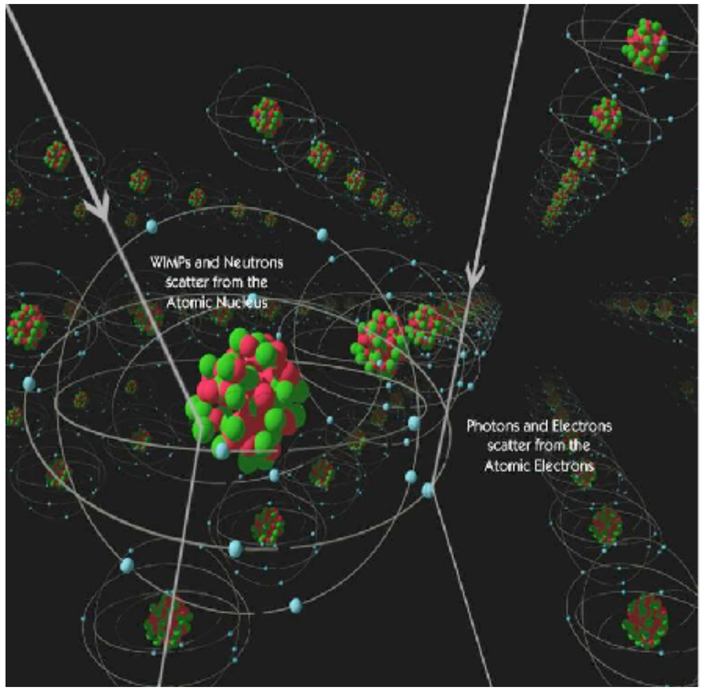
“The Master formula”



Recoil rate as a function of recoil energy

$$\frac{dR}{dE_R} = \frac{N_T \rho}{m_\chi} \int_{v_{\min}}^{v_{\max}} d^3v\, f(v(t)) \frac{d\sigma |v|}{dE_R}$$

“The Master formula”



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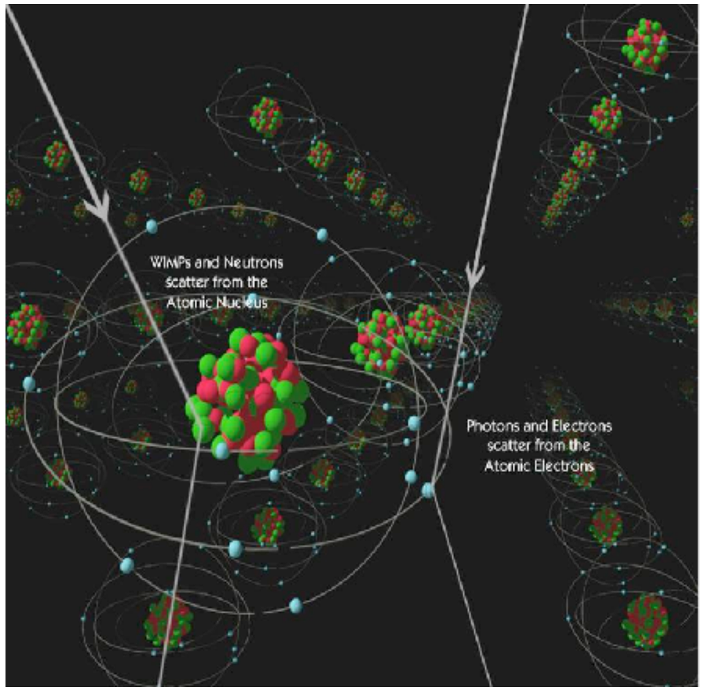
Number of targets in experiment

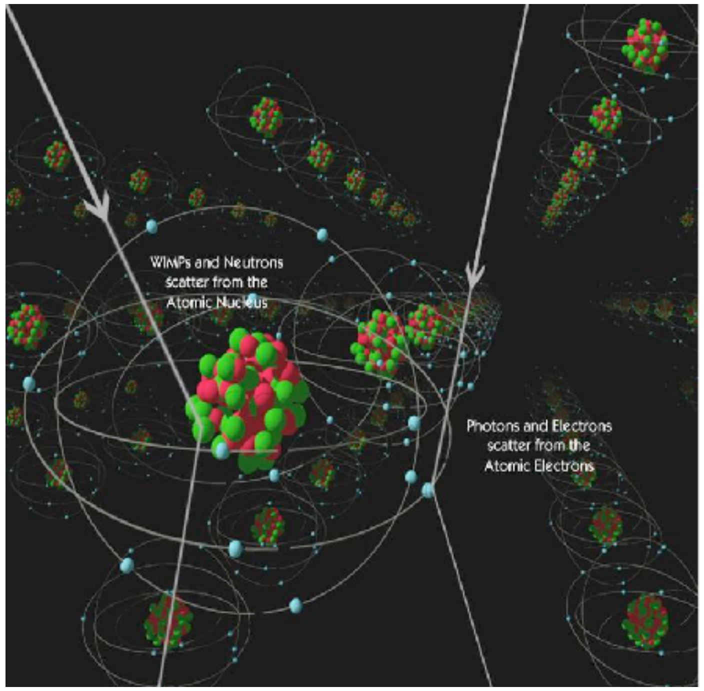
“The Master formula”



Depends on how much DM is around...

$$\frac{dR}{dE_R} = \frac{N_T \rho}{m_\chi} \int_{v_{\min}}^{v_{\max}} d^3v \, f(v(t)) \frac{d\sigma |v|}{dE_R}$$

“The Master formula”



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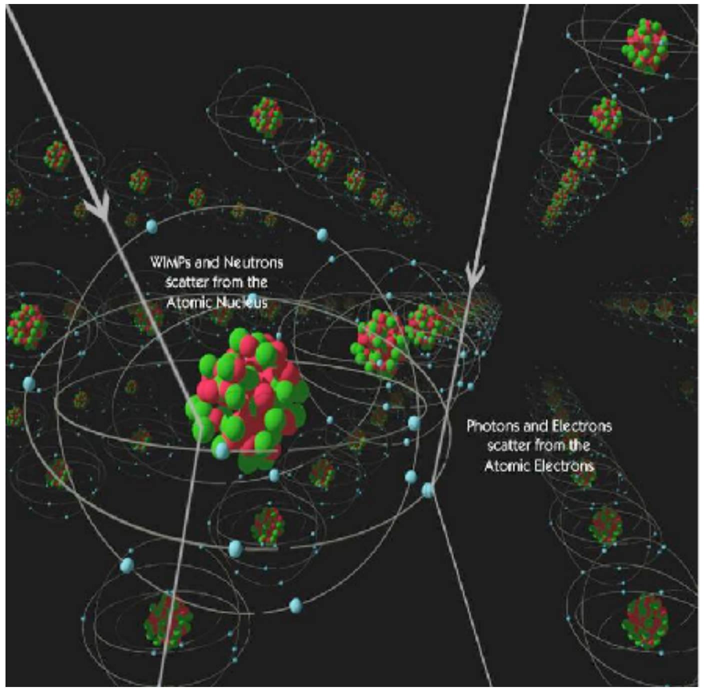
...and how it’s moving...

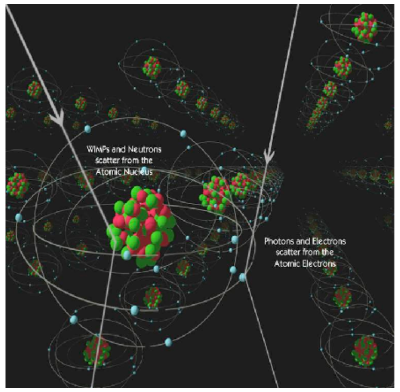
"The Master formula"



$$\frac{dR}{dE_R} = \frac{N_T \rho}{m_\chi} \int_{v_{\rm min}}^{v_{\rm max}} d^3v\, f(v(t)) \frac{d\sigma |v|}{dE_R}$$

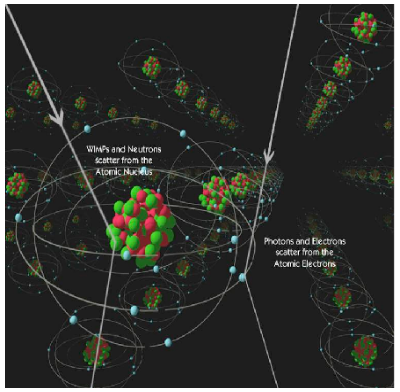
...and how it interacts with nuclei.

“The Master formula”



$$\frac{d\sigma}{dE_R} = F_N^2(E_R) F_\chi^2(E_R) \frac{m_N}{\mu v^2} \sigma_N$$

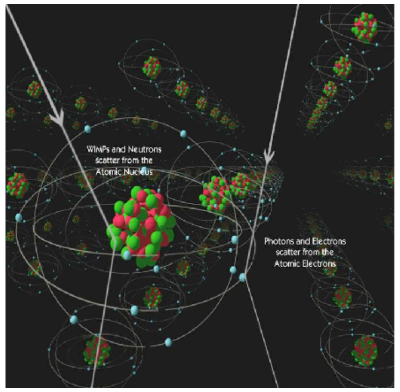
“The Master formula”



Differential
cross section

$$\frac{d\sigma}{dE_R} = F_N^2(E_R) F_\chi^2(E_R) \frac{m_N}{\mu v^2} \sigma_N$$

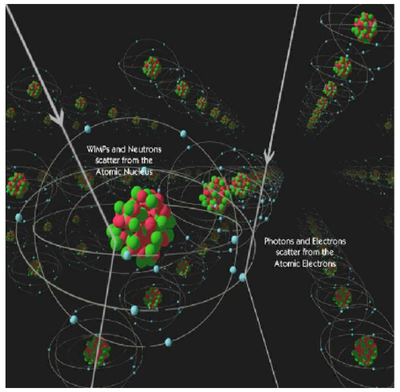
“The Master formula”



$$\frac{d\sigma}{dE_R} = F_N^2(E_R) F_\chi^2(E_R) \frac{m_N}{\mu v^2} \sigma_N$$

Form factor
(nuclear)

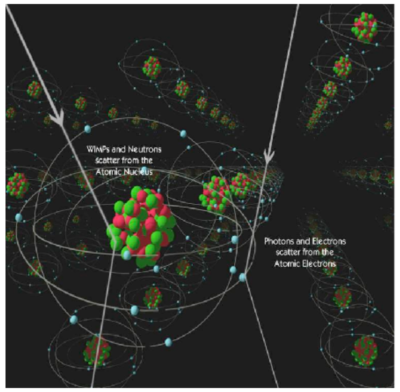
“The Master formula”



Form factor
(DM)

$$\frac{d\sigma}{dE_R} = F_N^2(E_R) F_\chi^2(E_R) \frac{m_N}{\mu v^2} \sigma_N$$

“The Master formula”



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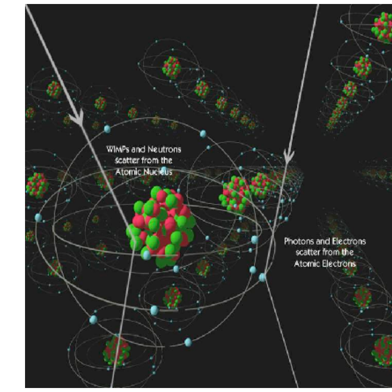
Cross section

“The Master formula”



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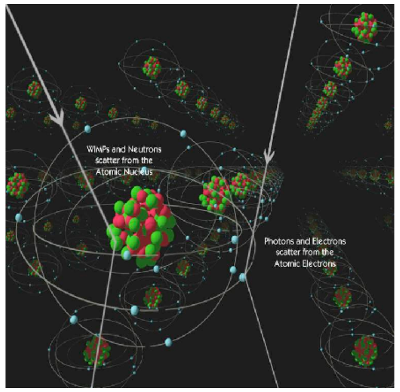
$$\sigma^{\rm SI} = \frac{[Z f_p + (A - Z) f_n]^2}{f_p^2} \frac{\mu_{\chi N}^2}{\mu_{\chi p}^2} \sigma_p^{\rm SI}$$

“The Master formula”



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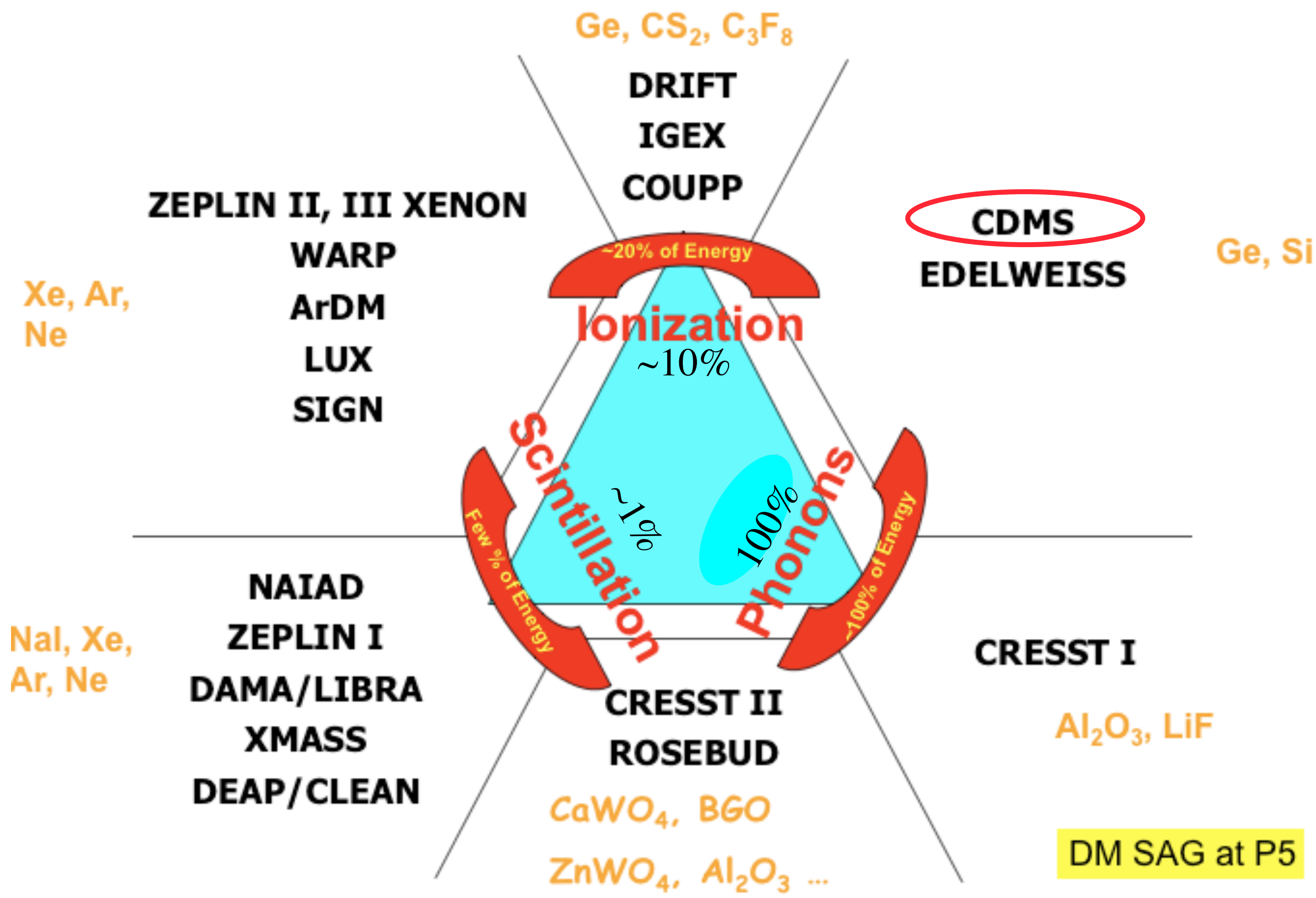
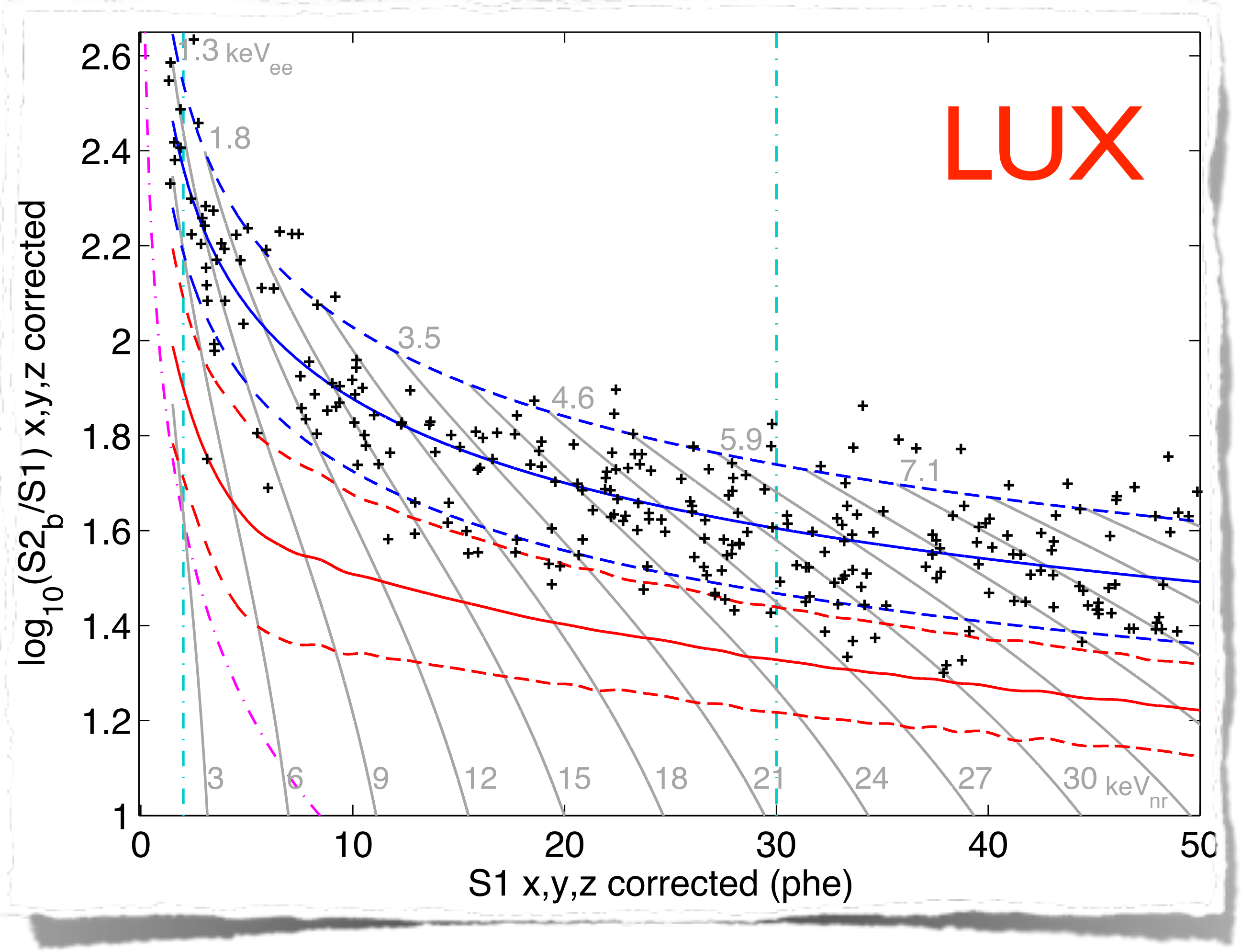
$$\sigma^{\mathrm{SD}} S(E_d) = \frac{4\mu_{\chi N}^2 \pi}{3\mu_{\chi p}^2 a_p^2 (2J+1)} [a_0^2 S_{00}(q) + a_0 a_1 S_{01}(q) + a_1^2 S_{11}(q)] \sigma_p^{\mathrm{SD}}$$

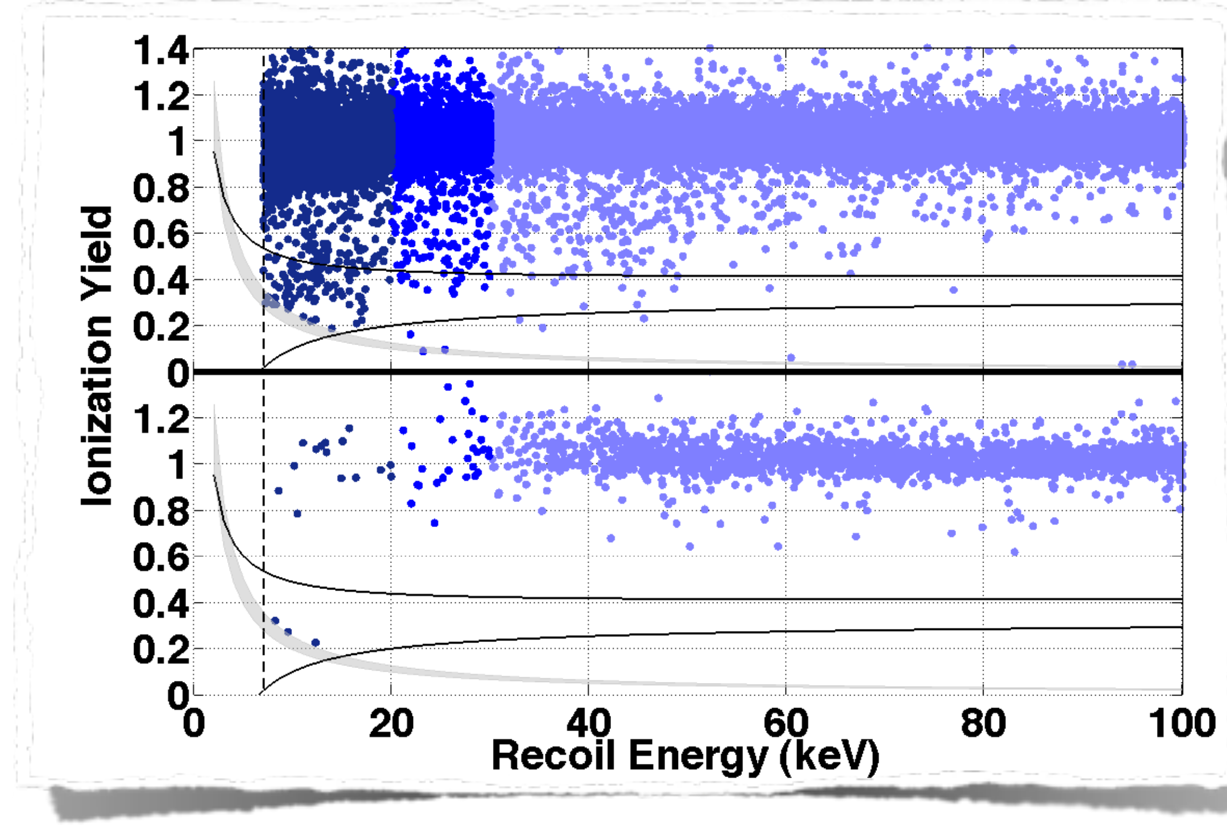
Of course, don't actually measure DM recoils directly

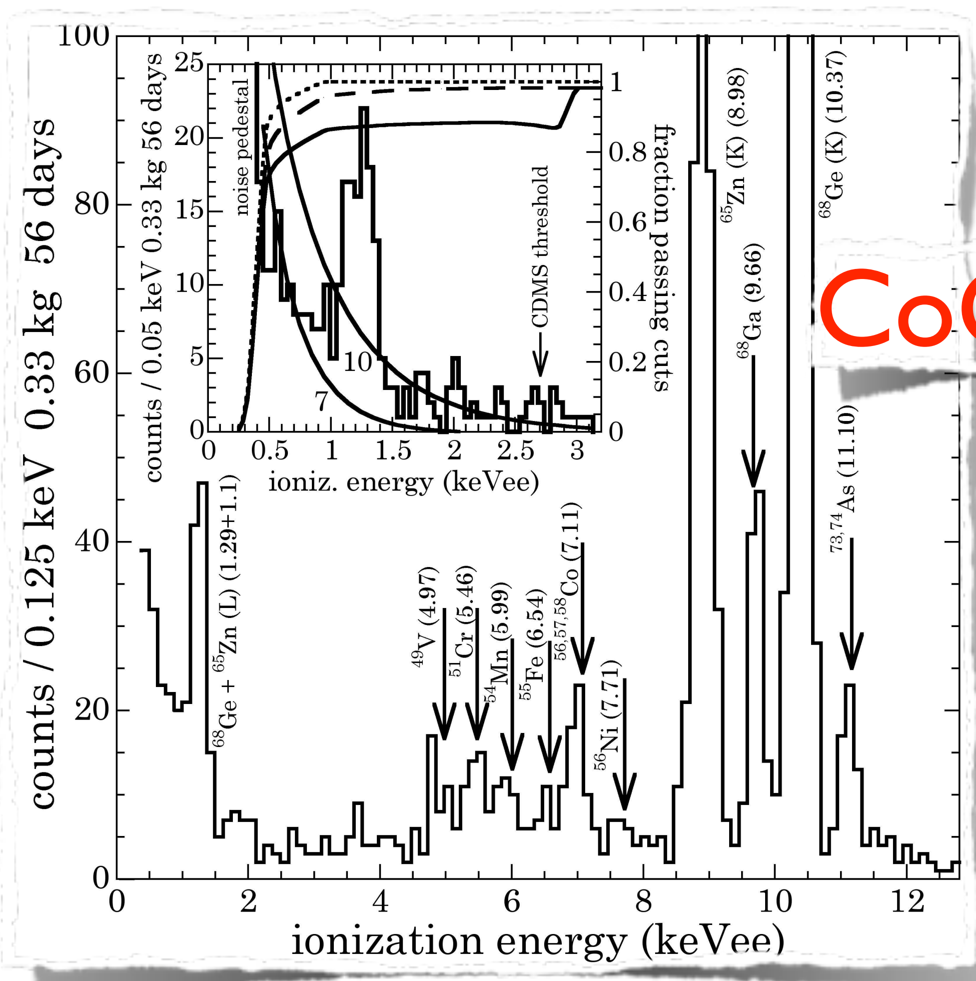
In reality also have to include backgrounds and combine with detector effects

e.g. energy resolution, quench factors, target composition, deadtime etc etc



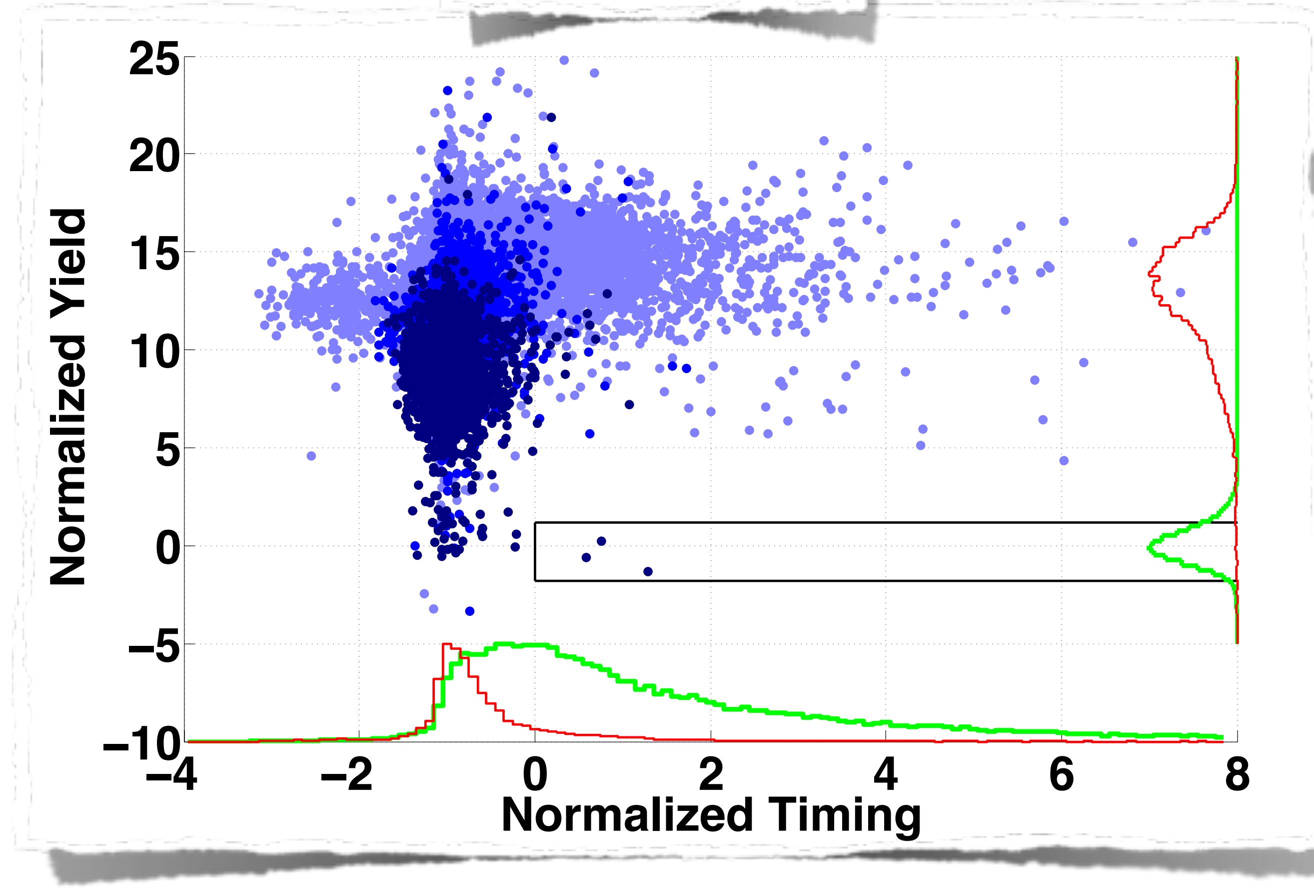




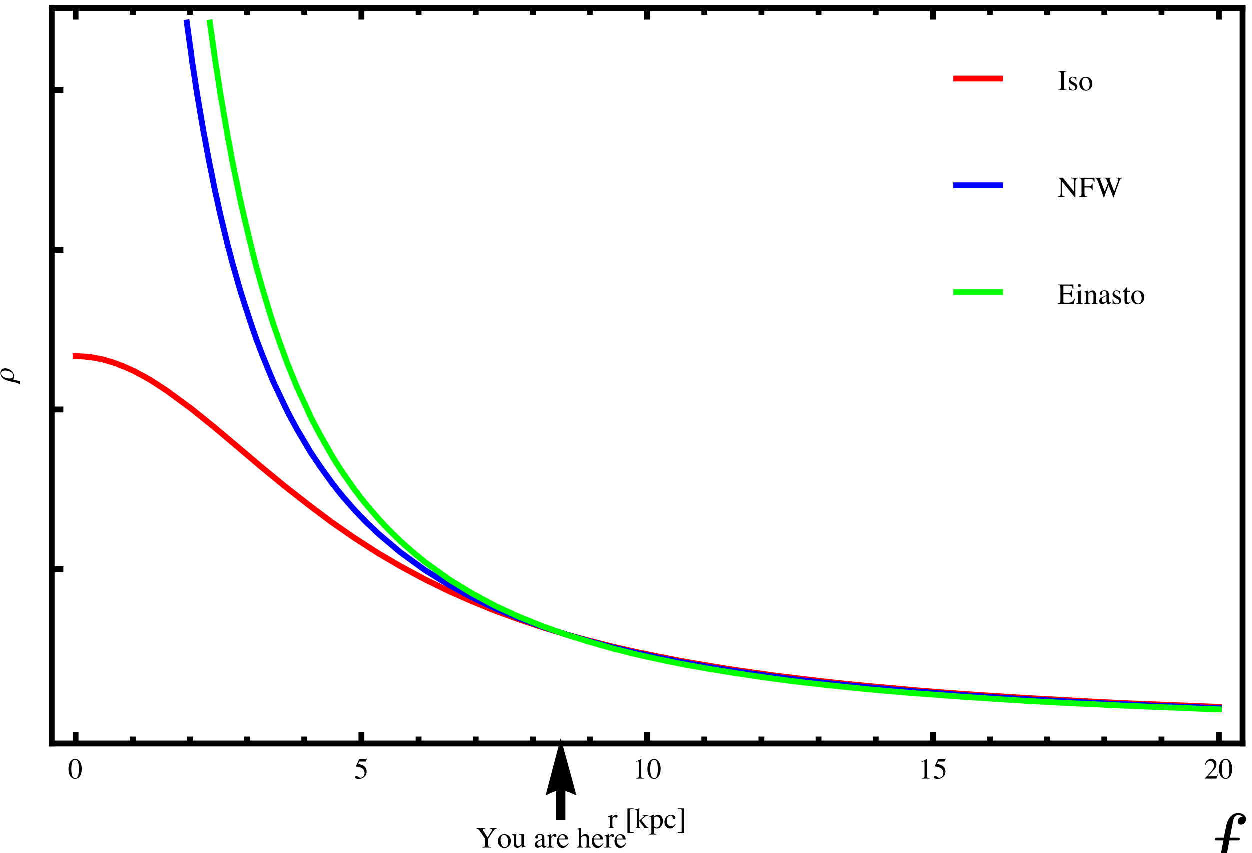


CoGeNT

CDMS-Si



DM's local properties (?)

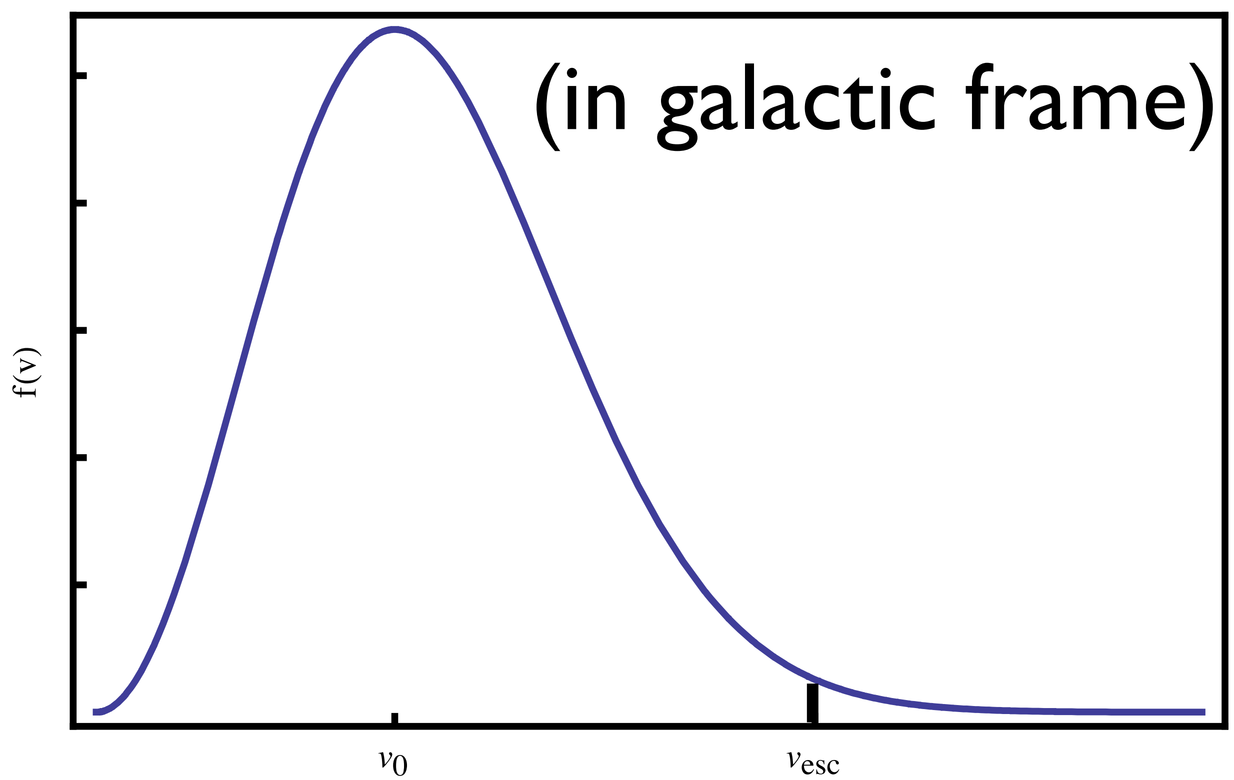


Overall scaling by local density

*$\rho_{DM} \sim 0.3 \text{ GeV cm}^{-3}$

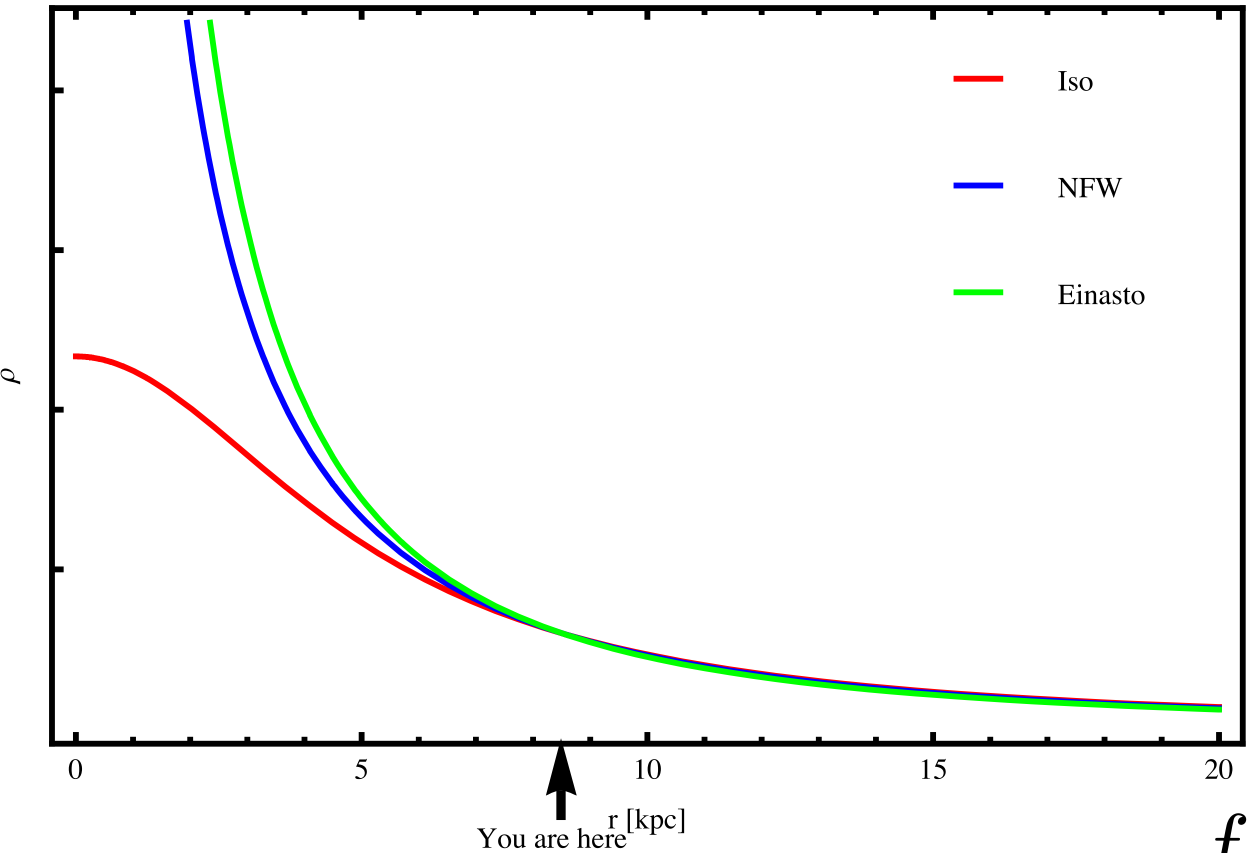
*$\pm$ a factor of two

$$f(v) \propto \left(e^{-v^2/v_0^2} - e^{-v_{esc}^2/v_0^2}\right) \Theta(v_{esc} - v)$$



Maxwell Boltzmann distribution
or
Standard Halo Model

DM's local properties (?)



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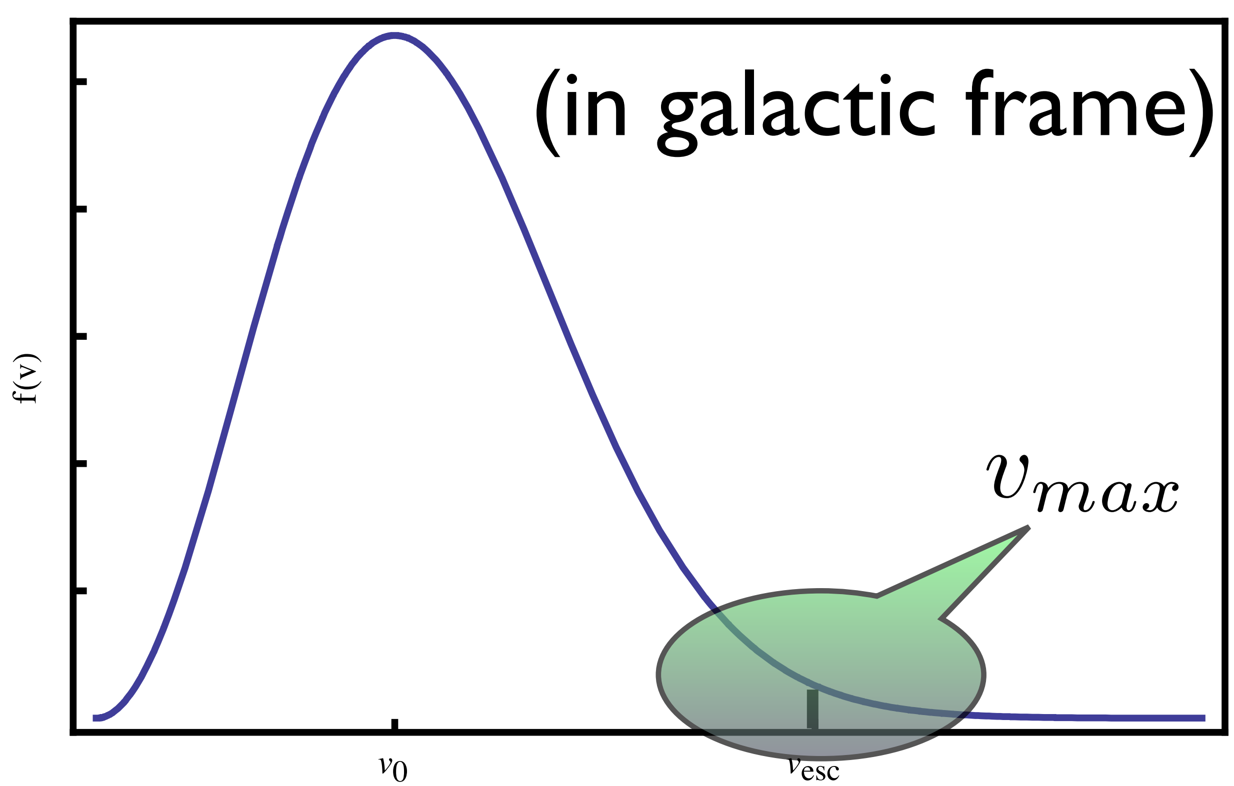
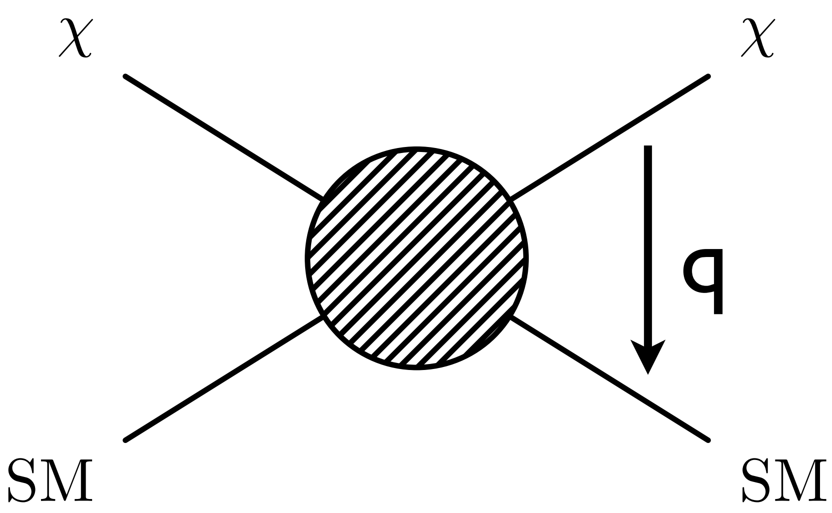


Maxwell Boltzmann distribution or Standard Halo Model

Kinematics



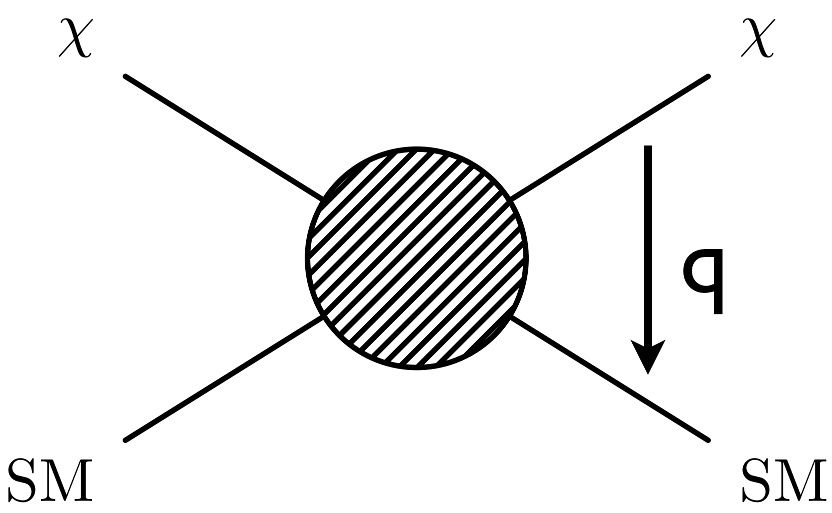
$$q^2 = 2\mu_{N\chi}^2 v^2 (1 - \cos\theta)$$

$$E_R = \frac{q^2}{2m_N}$$

Minimum speed DM must have to give recoil energy Er

$$v_{min} = \sqrt{\frac{m_N E_R}{2\mu_{N\chi}^2}}$$

Kinematics



$$q^2 = 2\mu_{N\chi}^2 v^2 (1-\cos\theta) \sim (100\,\mathrm{MeV})^2$$

$$E_R = \frac{q^2}{2m_N} \sim 10\,\mathrm{keV}$$

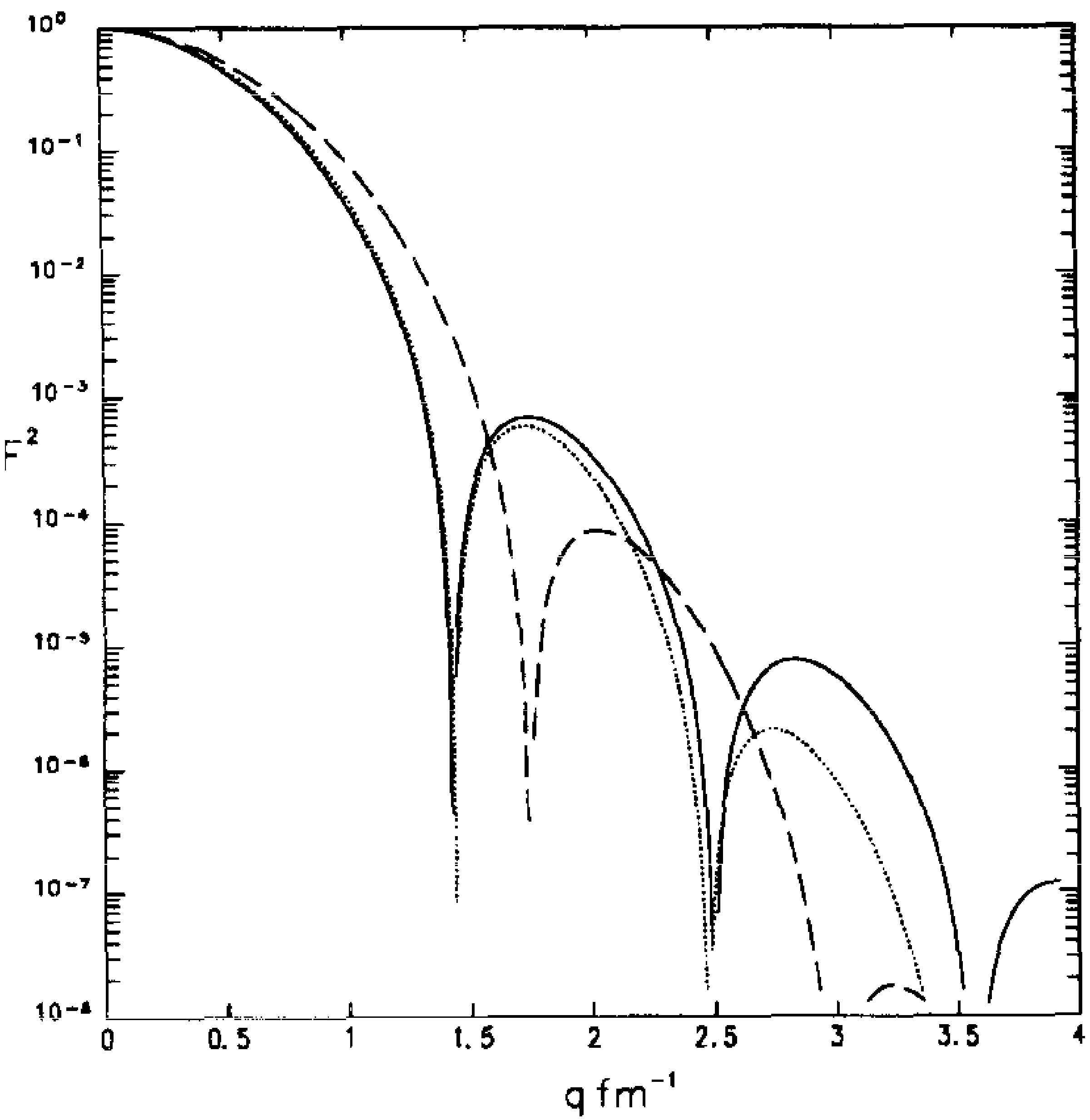
Minimum speed DM must have to give recoil energy Er

$$v_{min} = \sqrt{\frac{m_N E_R}{2\mu_{N\chi}^2}}$$

Nuclear Physics

Nuclear radius $r_N \sim A^{1/3} fm$

[Lewin and Smith]



SI:Helm, or Fermi distribution

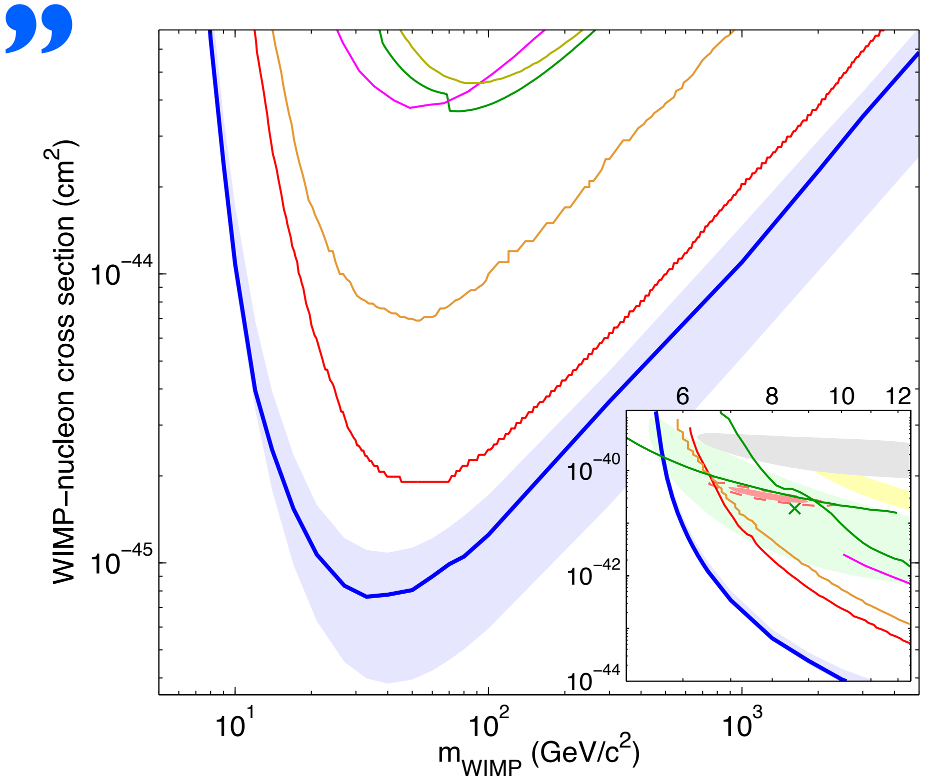
SD:

$$S(q) = a_0^2 S_{00}(q) + a_0 a_1 S_{01}(q) + a_1^2 S_{11}(q)$$

Converting nuclear to nucleon x-sec

$$\sigma^{\rm SI} = \frac{[Zf_p + (A-Z)f_n]^2}{f_p^2} \frac{\mu_{\chi N}^2}{\mu_{\chi p}^2} \sigma_p^{\rm SI}$$

Some "standard candles"

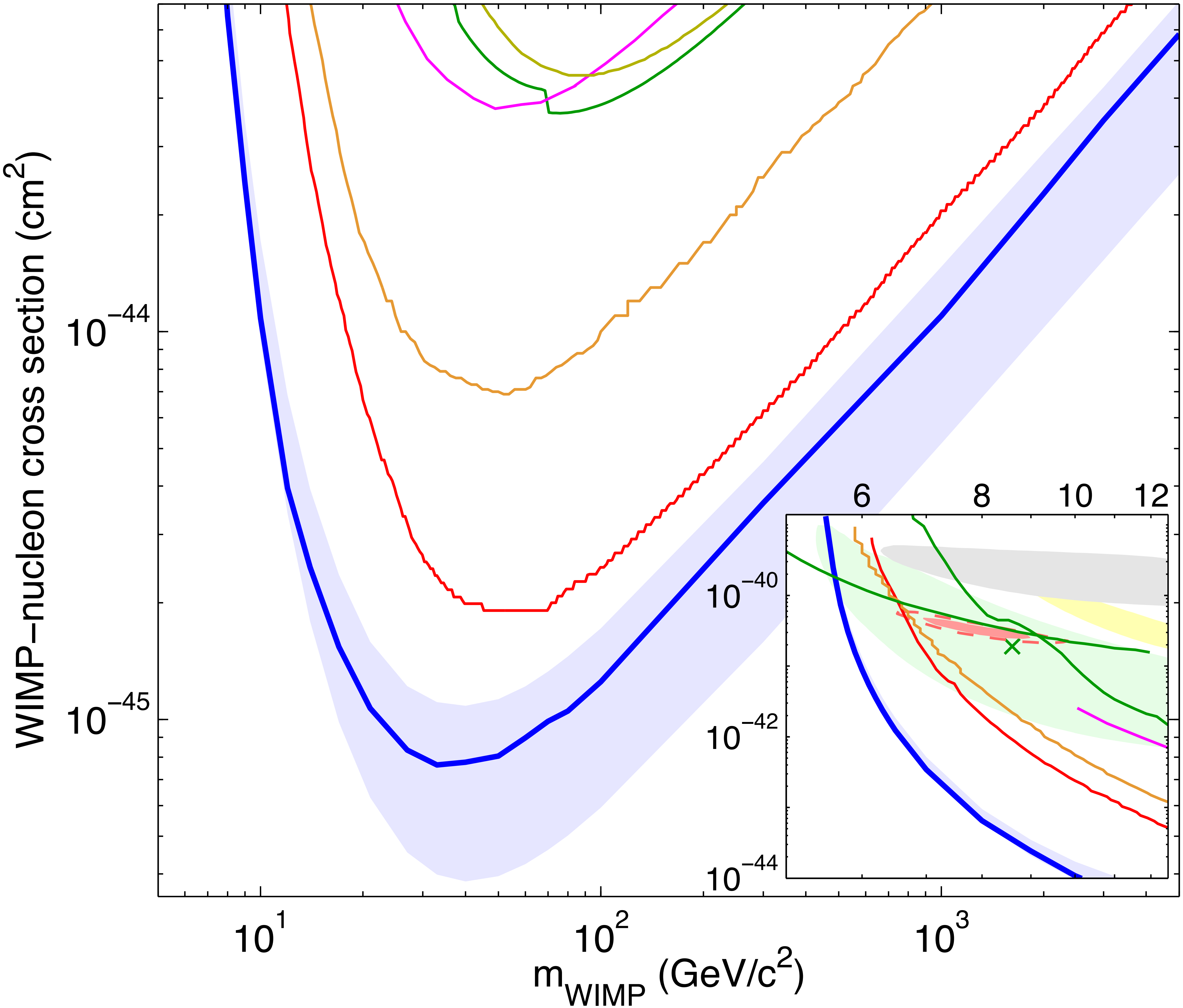


Z-exchange

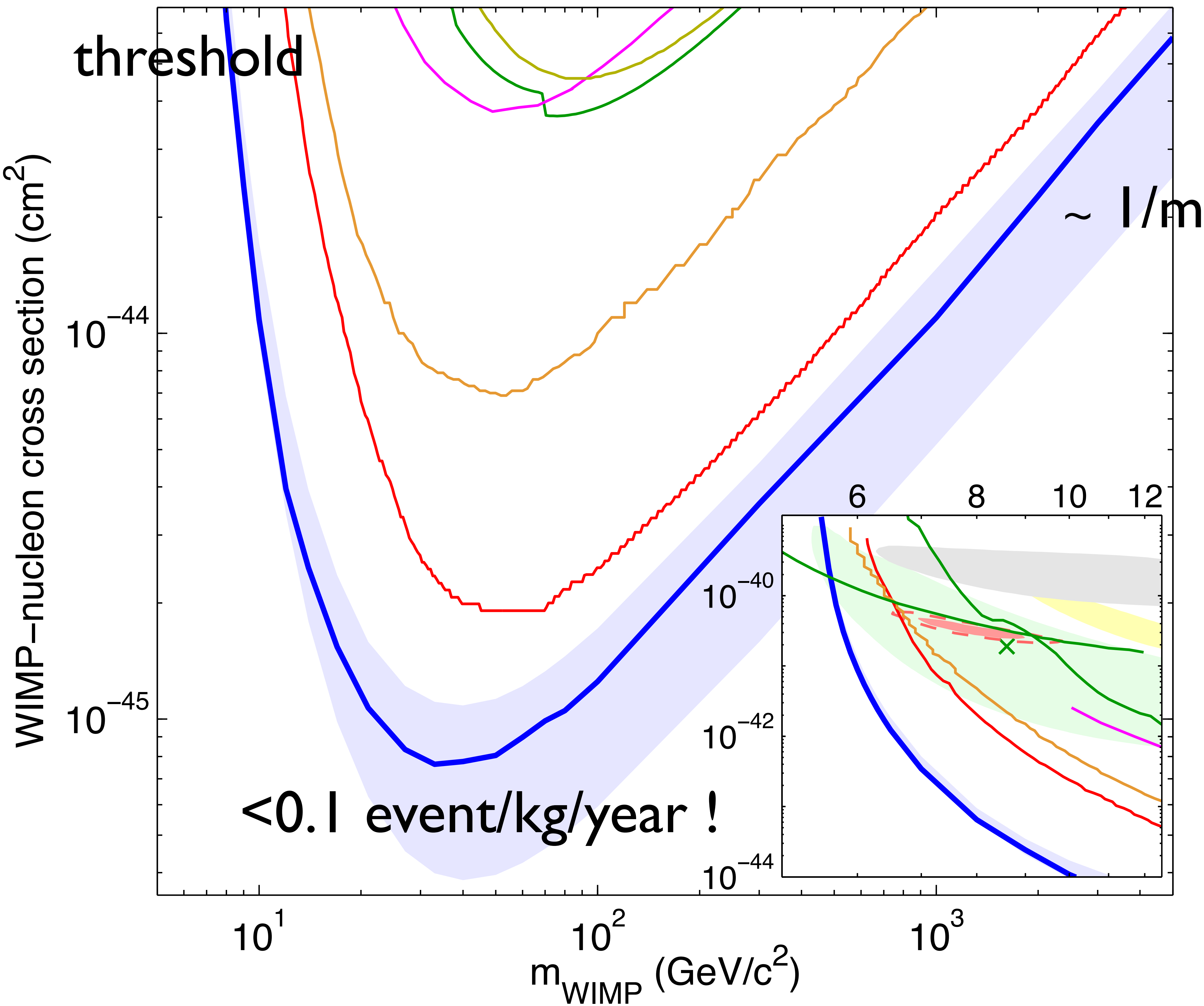
$$\sigma_p \sim \frac{G_F^2 \mu^2}{2\pi} \frac{\left[(1-4s_W^2)Z + (A-Z)\right]}{A^2} \approx 10^{-39}\,\mathrm{cm}^2$$

H-exchange $\lambda S^2 |h|^2$

$$\sigma_p \sim \frac{\lambda^2 v^2}{16\pi m_h^4} \left|\langle p| \sum y_q \bar{q} q |r\rangle\right|^2 \frac{m_p^2}{(m_\chi + m_p)^2} \approx \lambda^2 \left(\frac{100\ \mathrm{GeV}}{m_\chi}\right)^2 \times 10^{-43}\,\mathrm{cm}^2$$



WIMP–nucleon cross section (cm^2)
10^{-44}
10^{-45}
10^{1}
10^{2}
10^{3}
m_{WIMP} (GeV/c^2)
6
8
10
12
10^{-40}
10^{-42}
10^{-44}



threshold
~ 1/m
<0.1 event/kg/year !
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10^{-44}
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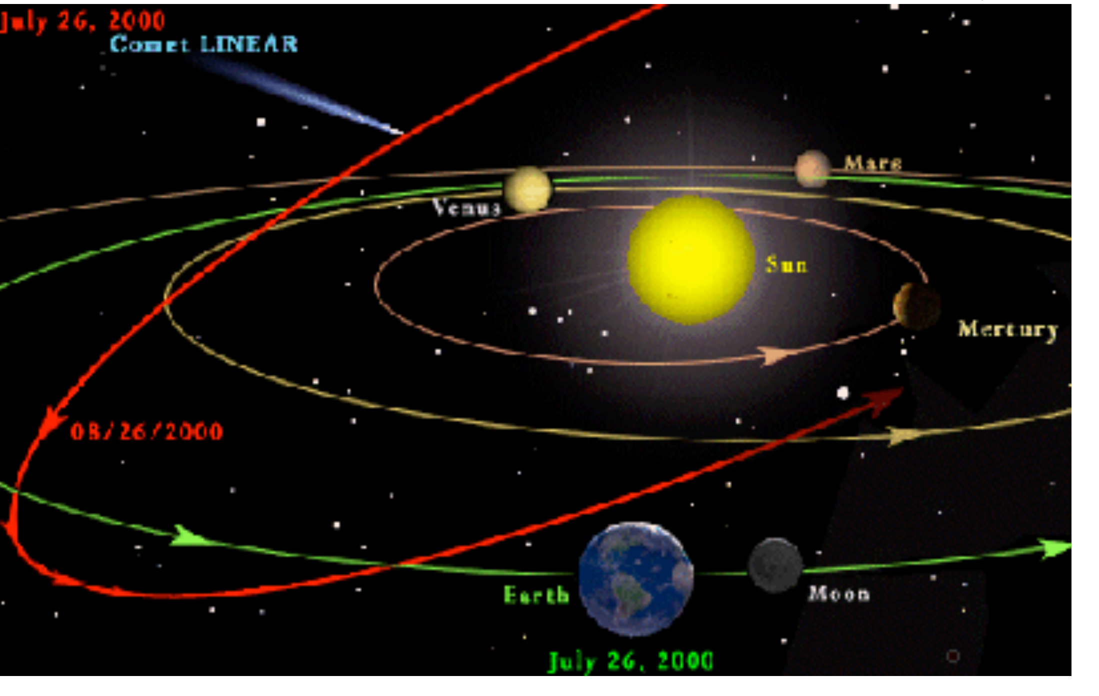
Annual Modulation

Another Way:

DAMA uses this to eliminate background, other expts. can look at modulation once they acquire enough data



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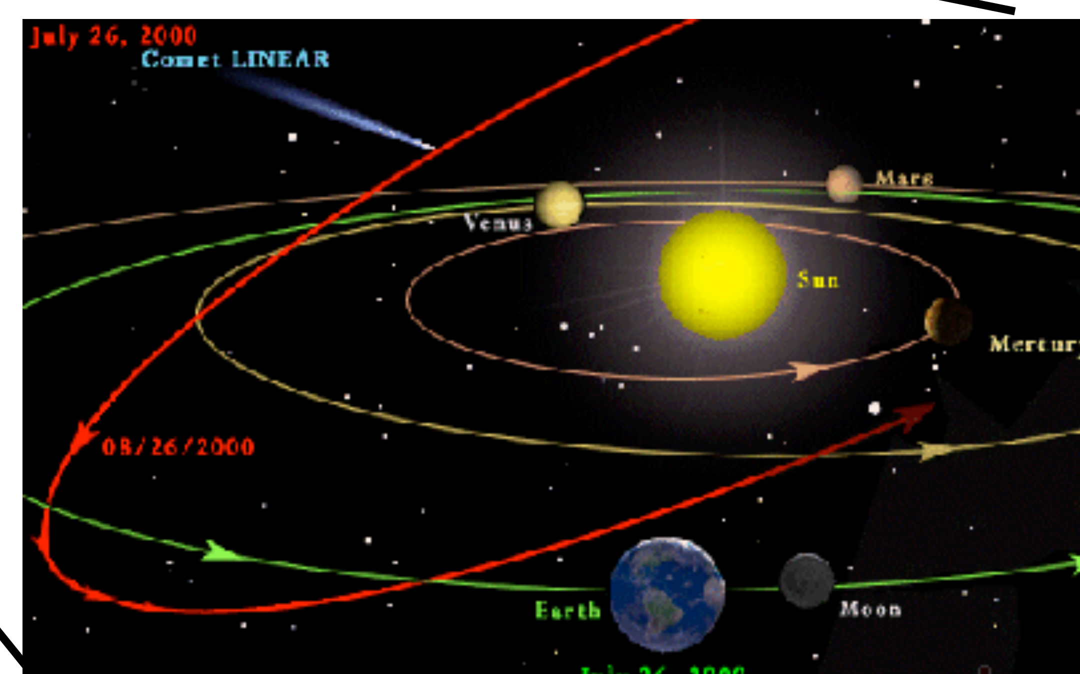

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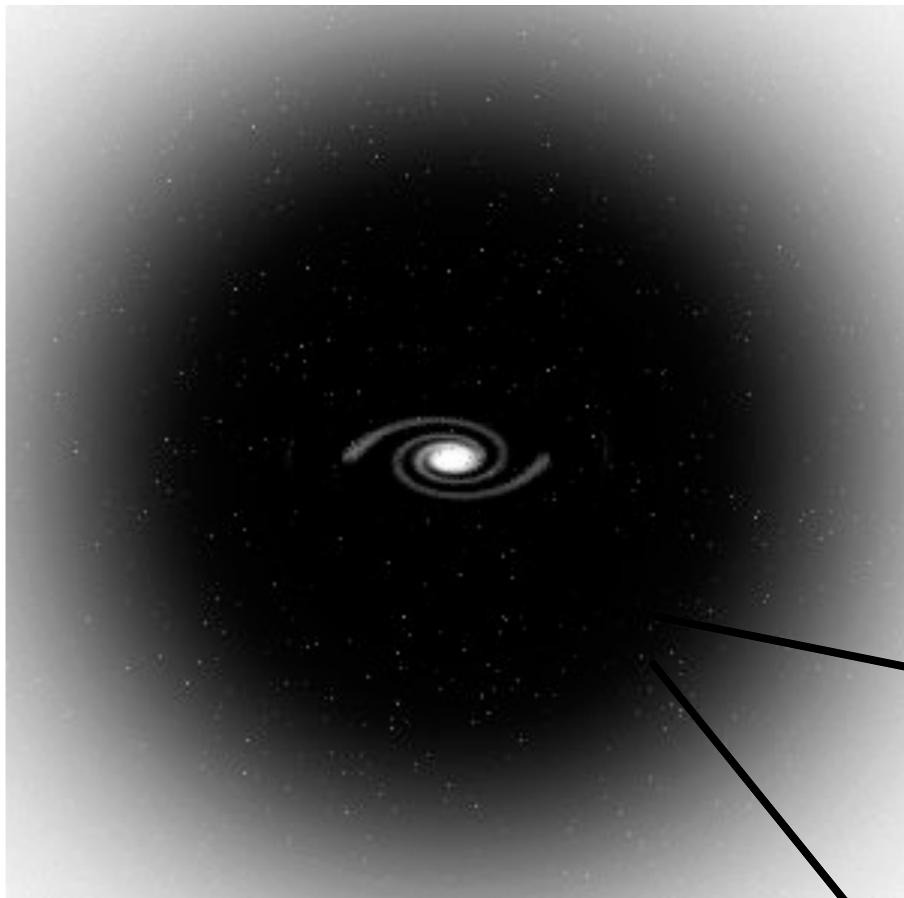

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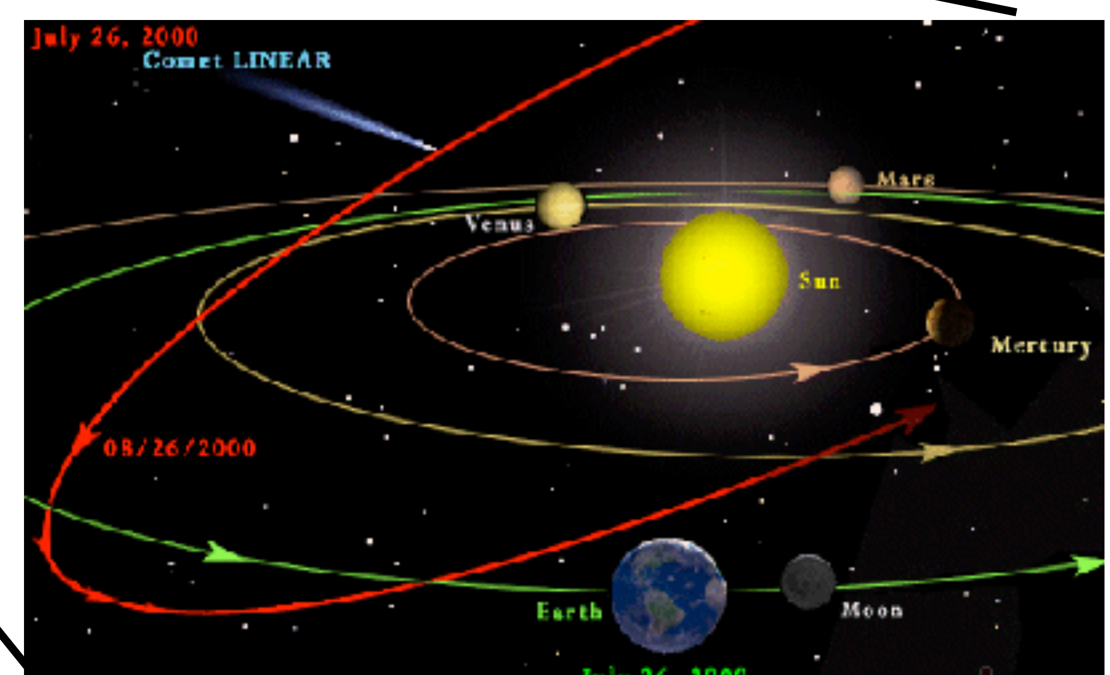


Annual Modulation

In galactic frame:

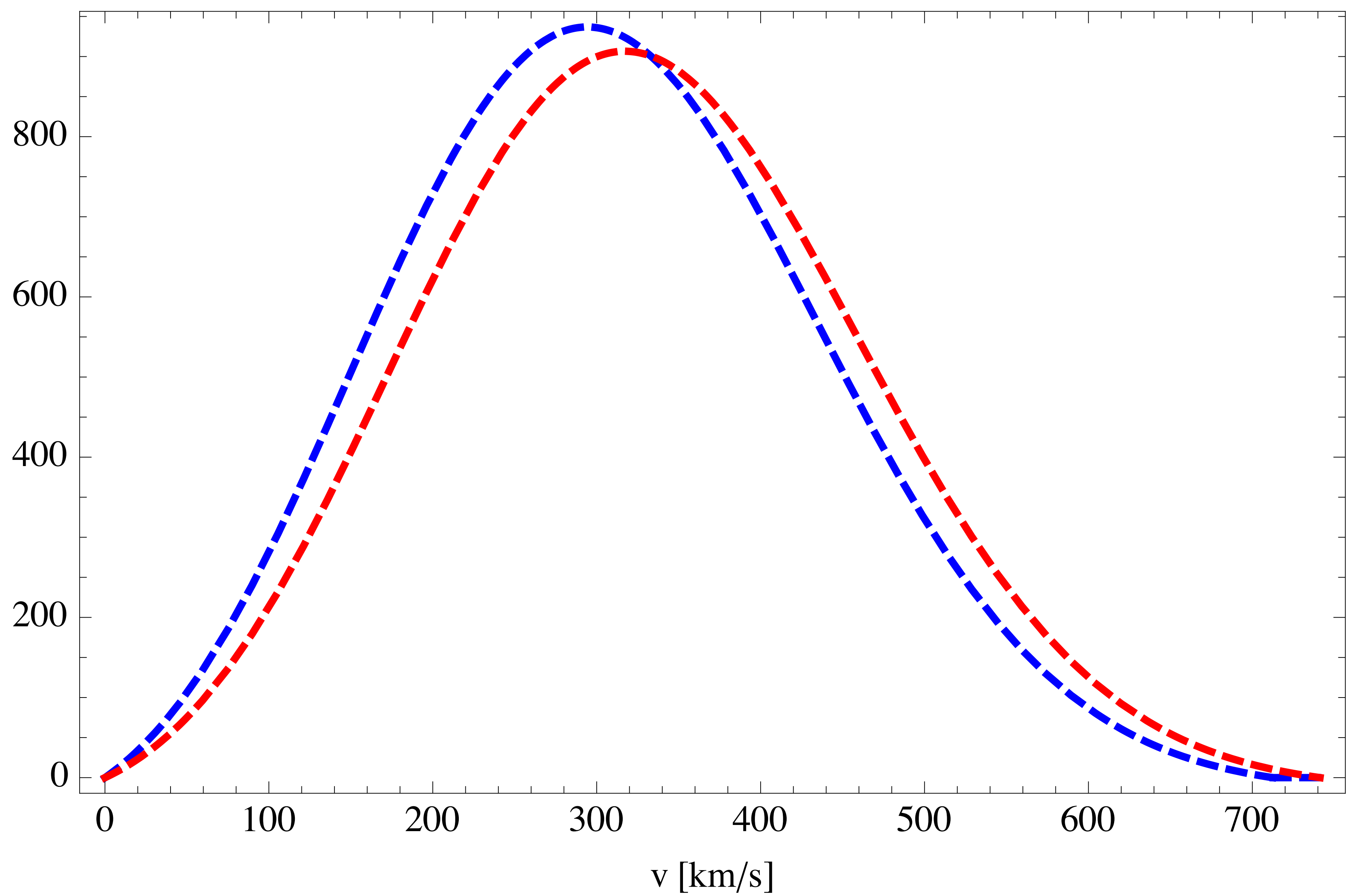
$$f(v) = \frac{1}{(\pi v_0^2)^{3/2}} e^{-v^2/v_0^2}$$

$$498 \text{ km/s} \leq v_{esc} \leq 608$$

In Earth's frame:

$$f(\vec{v}, \vec{v}_E) = \frac{1}{(\pi\, v_0^2)^{3/2}}\, e^{-(\vec{v}+\vec{v}_E)^2/v_0^2}$$

$$v_E \approx 227 + 14.4 \cos\left[2\pi \left(\frac{t-t_0}{T}\right)\right] \quad t_0 = \text{June } 2^{\text{nd}}$$



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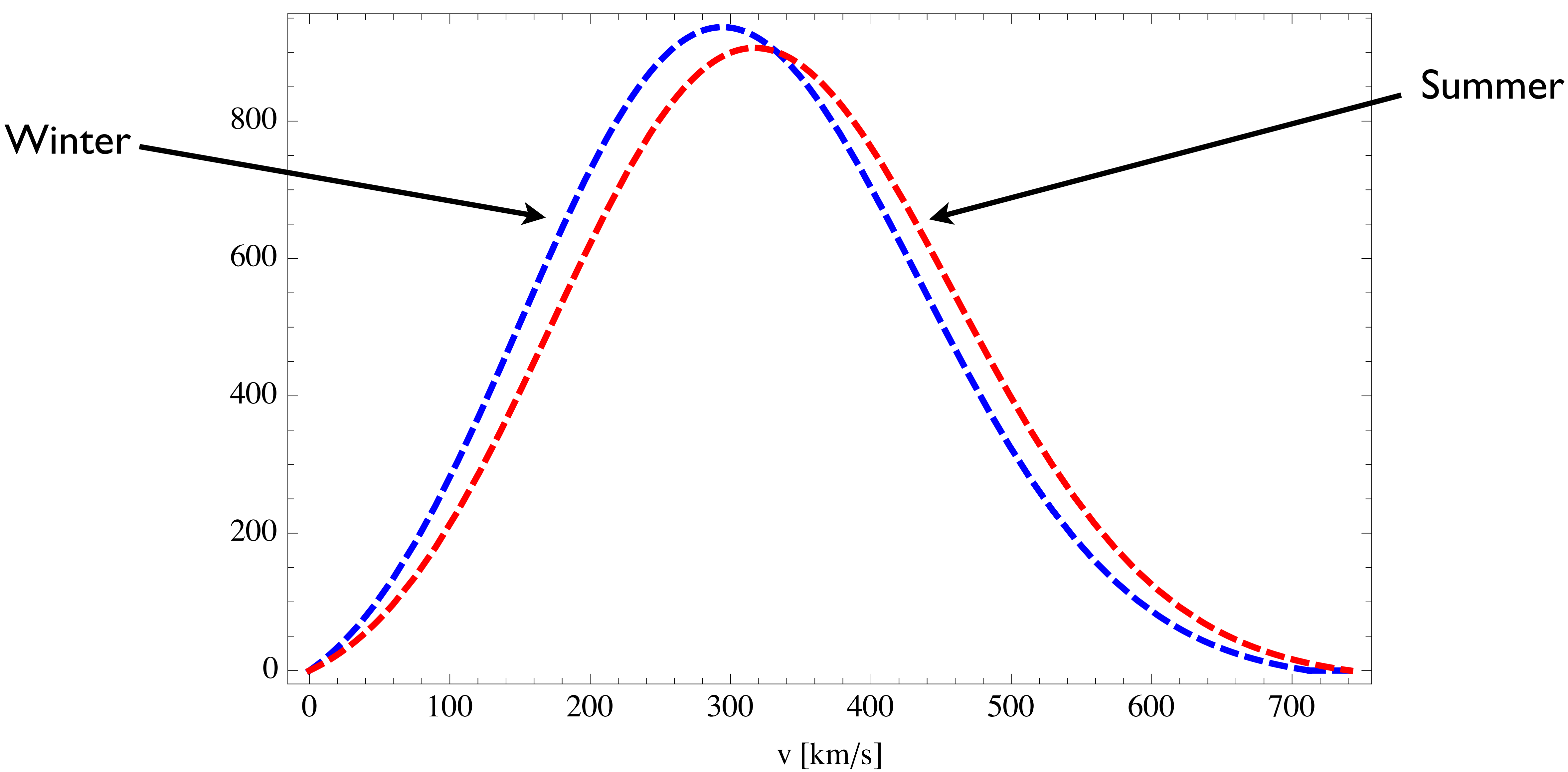

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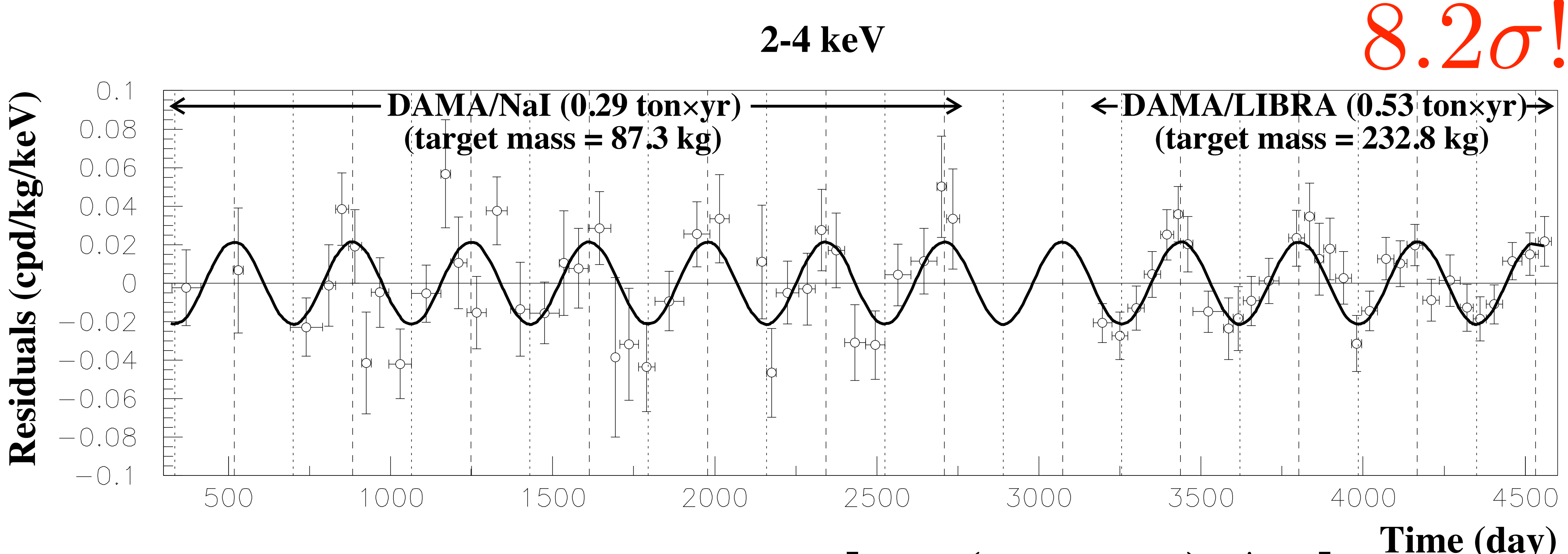
$8.2\sigma!$



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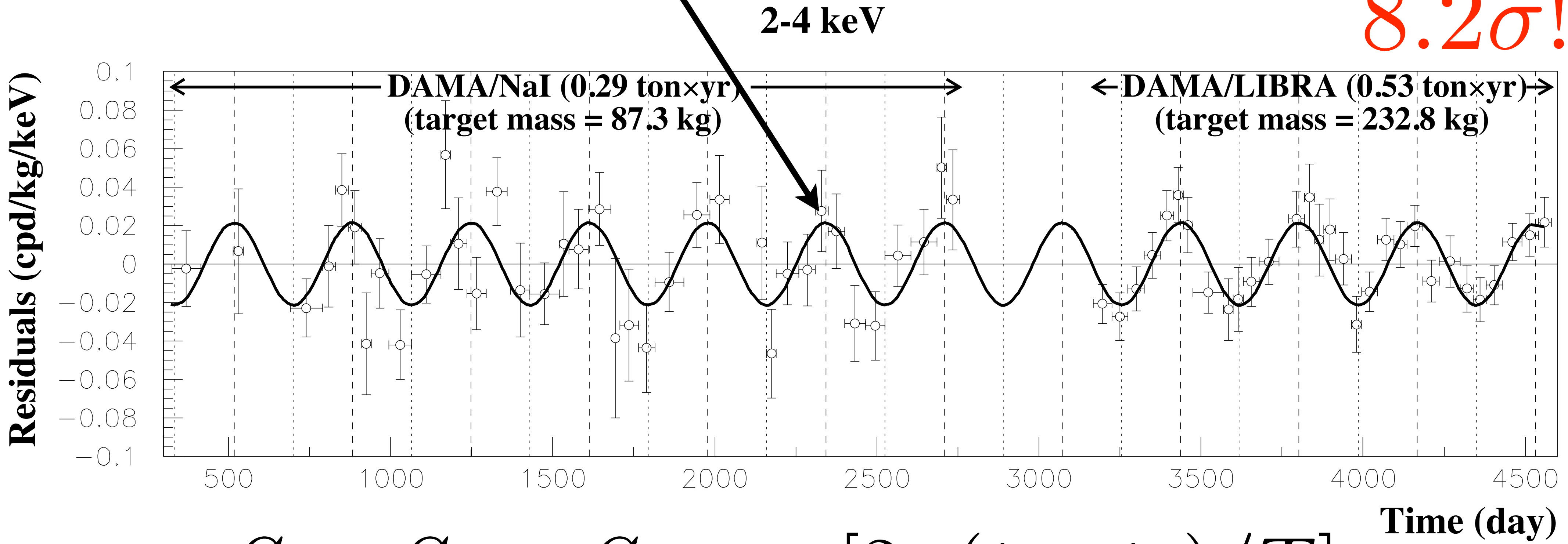

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Does annual modulation = discovery of DM?

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Many things modulate on a year timescale:

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But, very few line up year-on-year with June 2nd

DM models pre-DAMA

DM models pre-DAMA


DM models pre-DAMA


DM models pre-DAMA
DAN
direct detection
experimentalist?

Possible explanations

- Low mass dark matter with channelling, M~10 GeV
- Leptophilic DM
- Inelastic Dark Matter (iDM)
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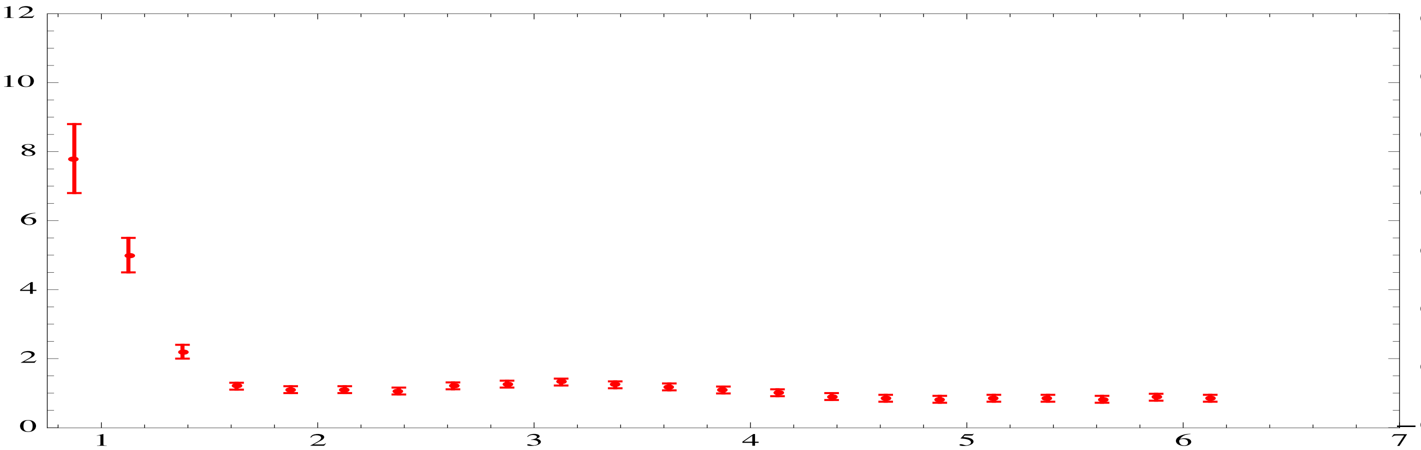

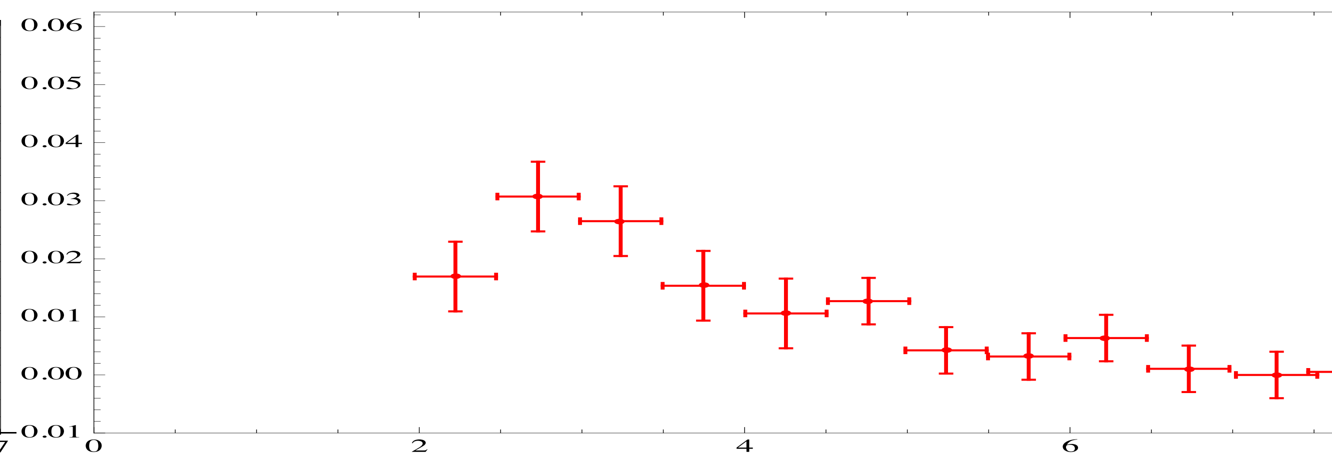

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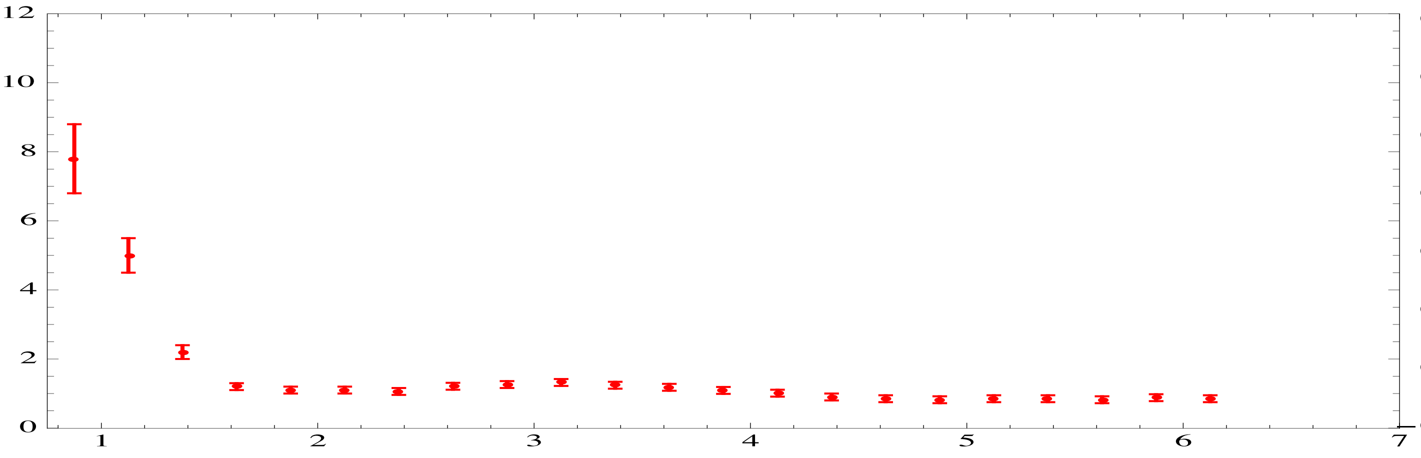

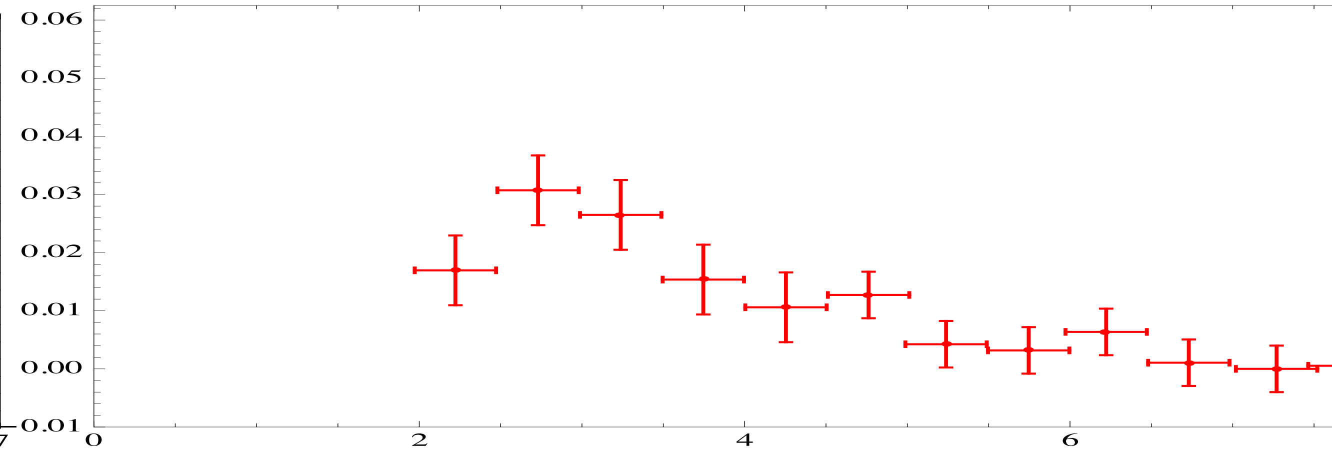

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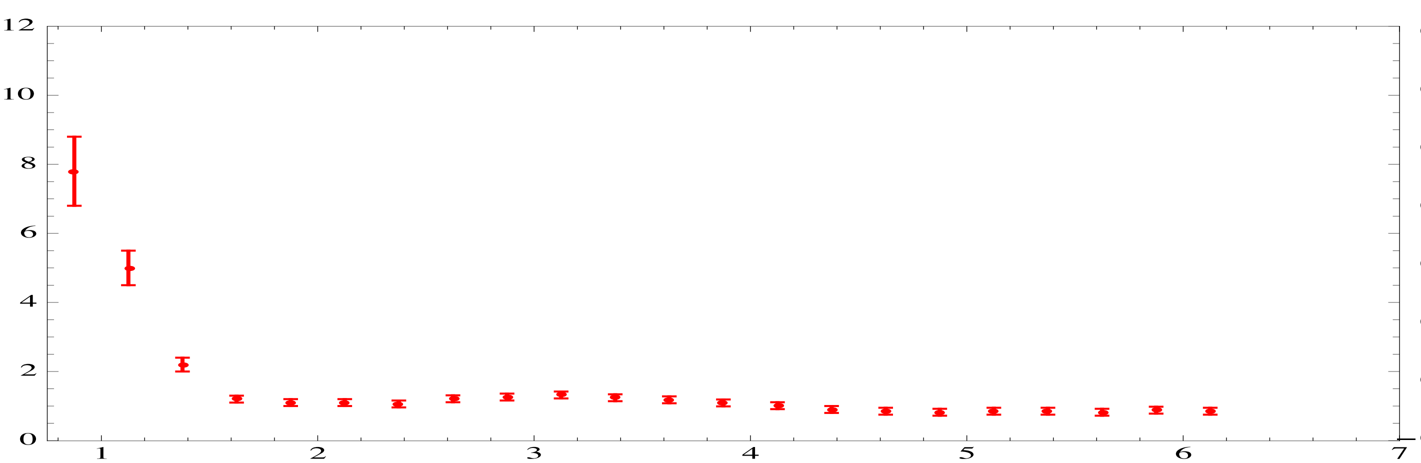

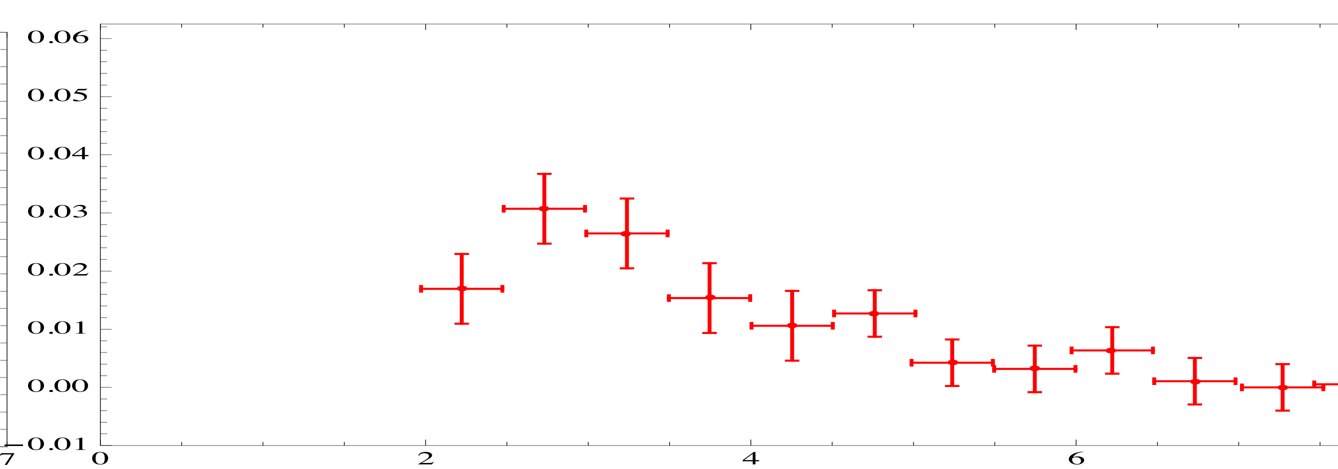

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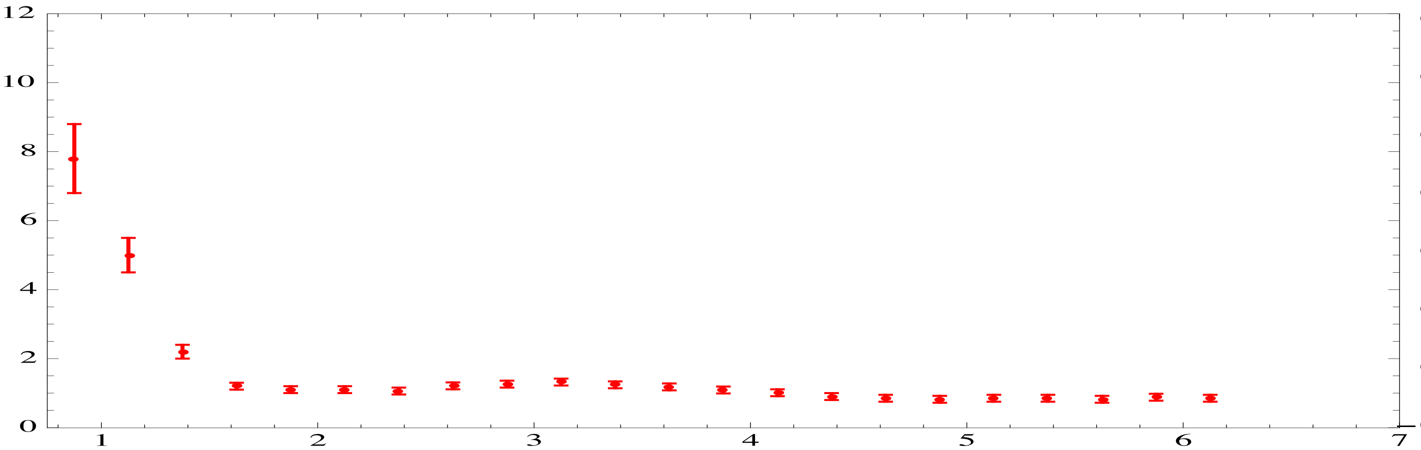

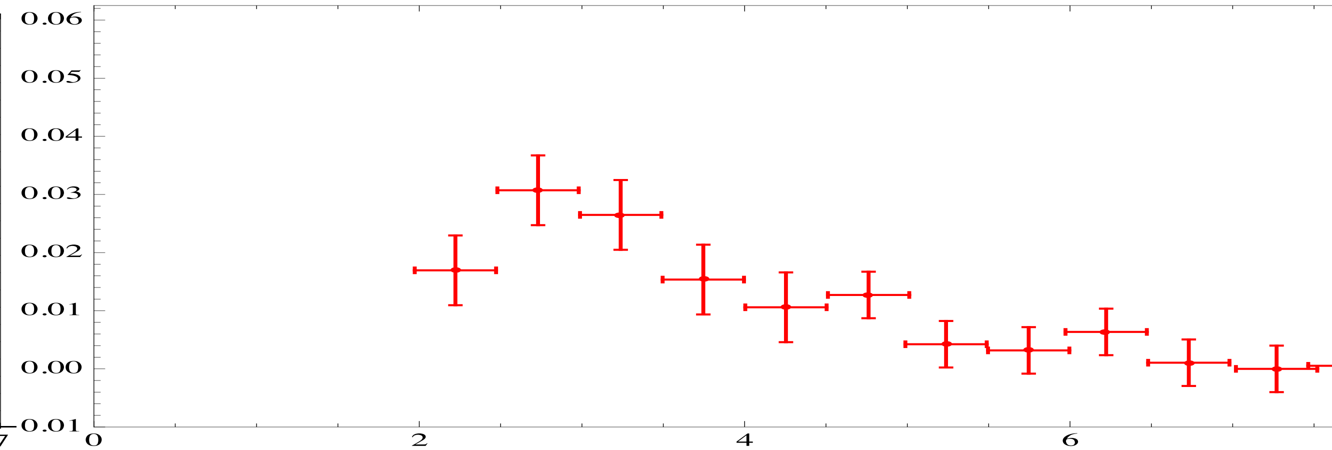

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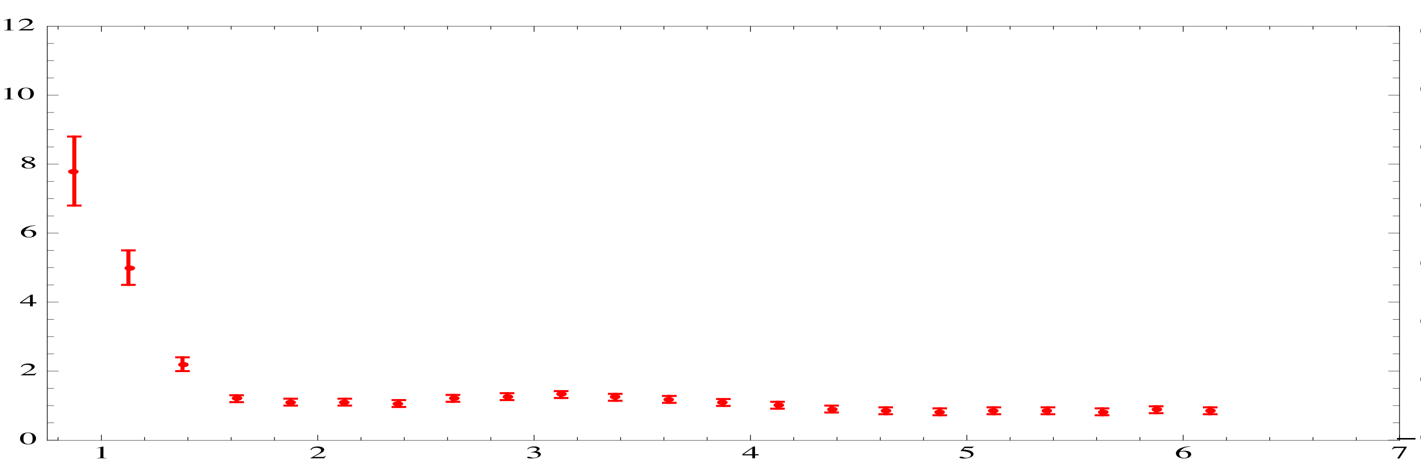

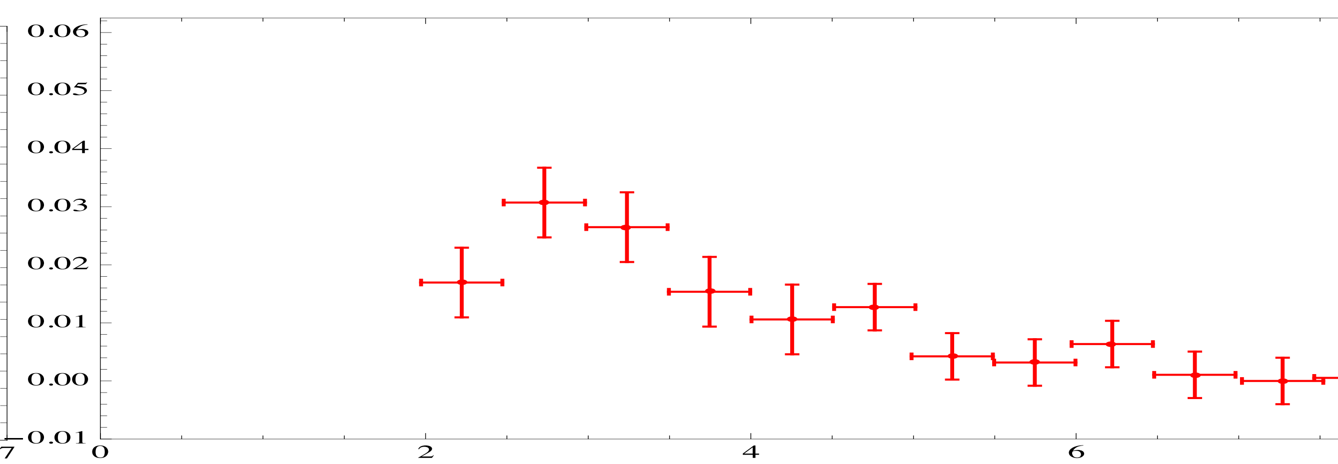

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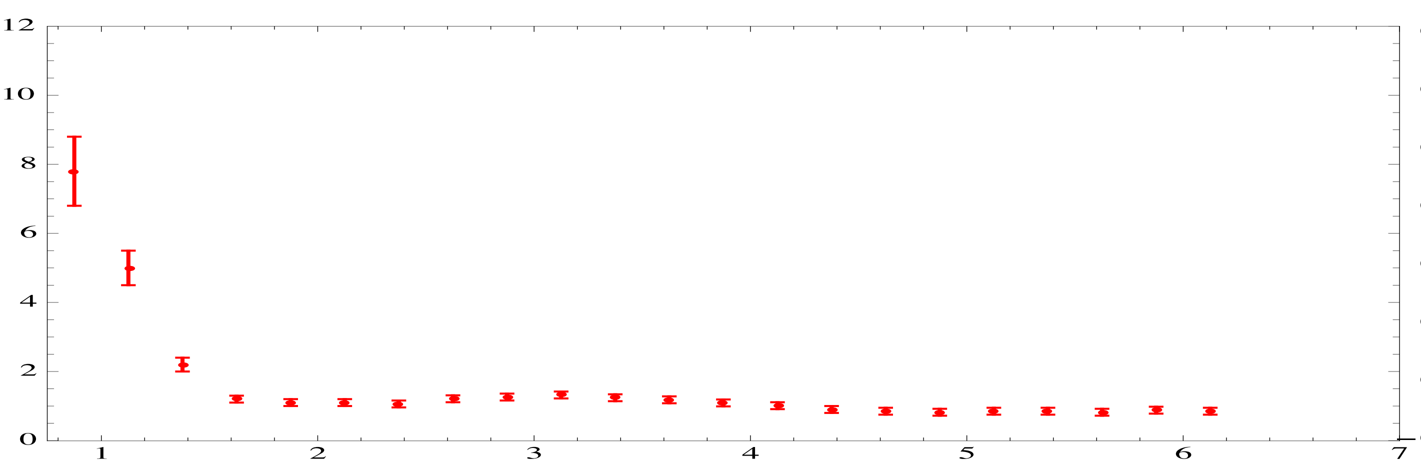
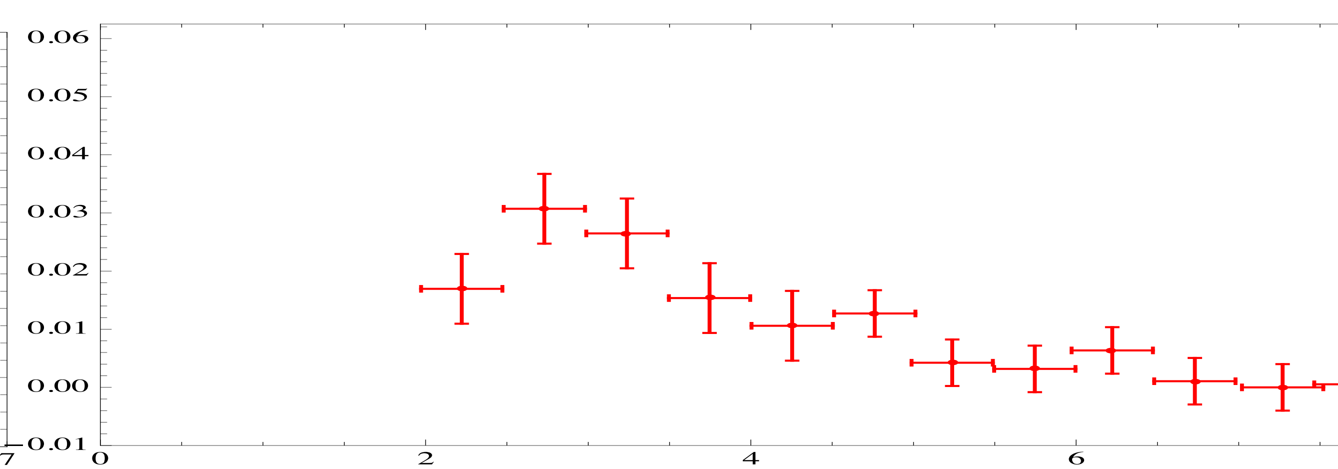




DM: a phenomenologist's playground

Explore the landscape of possible ways DM can interact with the SM

Experiments originally designed for a ~100 GeV SUSY WIMP, but there are many more possibilities

Thankfully many experiments and clever experimentalists

Light Dark Matter

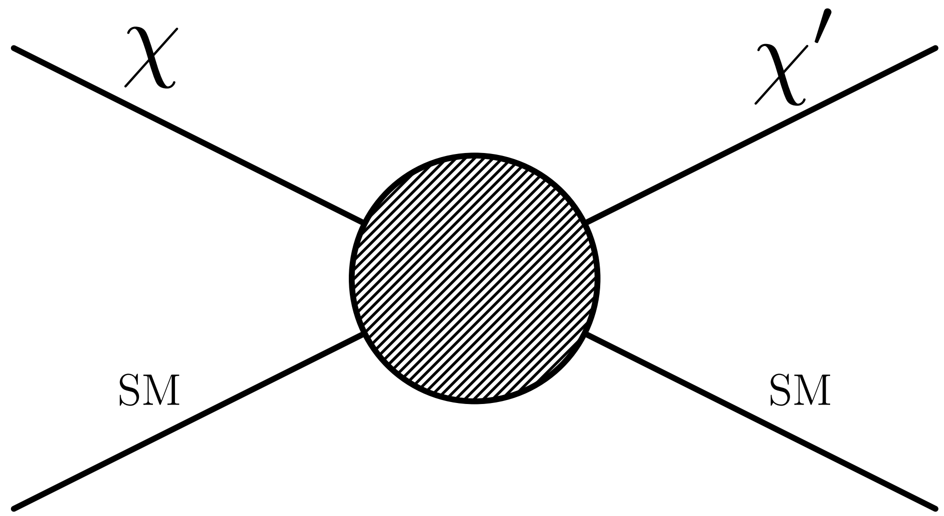
Motivated by fact that $\Omega_{DM} \sim 5\ \Omega_b$

If baryon and DM abundance related then expect DM to be (5-10) x proton mass

Also, hard for direct detection because of thresholds, backgrounds, etc (ask Rick ☺️)

Inelastic Dark Matter (iDM)

[Weiner and Tucker-Smith]



$$\frac{dR}{dE_R} = \frac{N_T\, m_N\, \rho_\chi}{2\, \mu_{N\chi}^2\, m_\chi} \int_{v_{min}}^{v_{max}} d^3\vec{v}\, \frac{f(\vec{v}, \vec{v}_E)}{v}\, \sigma_N\, F^2(E_R)$$

$$v_{min} = \sqrt{\frac{1}{2 m_N E_R}} \left(\frac{m_N E_R}{\mu_{N\chi}} + \delta \right)$$

$$m_\chi - m_{\chi'} = \delta \sim 100\,\text{keV}$$

- Requires "large" momentum exchange to upscatter
- Favours high velocity tail of MB distribution
- Increased modulation
- Prefers heavy targets e.g. iodine, xenon, tungsten,..
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All of the above helped to make DAMA consistent with CDMS, predicts events at other heavy element detectors

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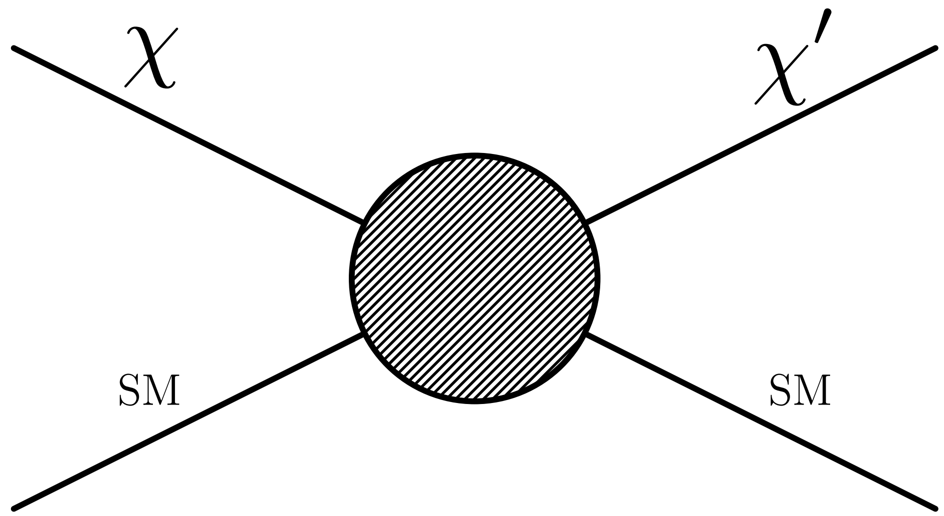

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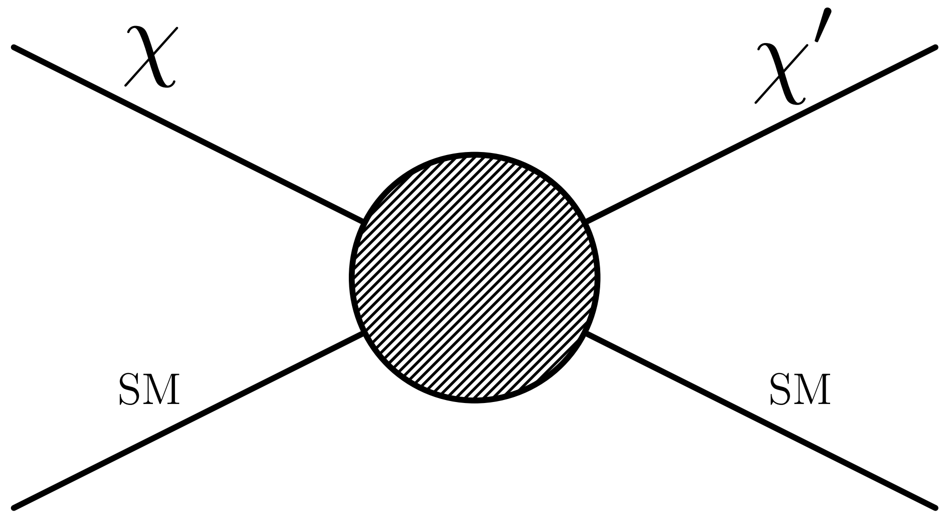
Exothermic DM (exoDM) [Graham, Harnik, Rajendran, Saraswat]

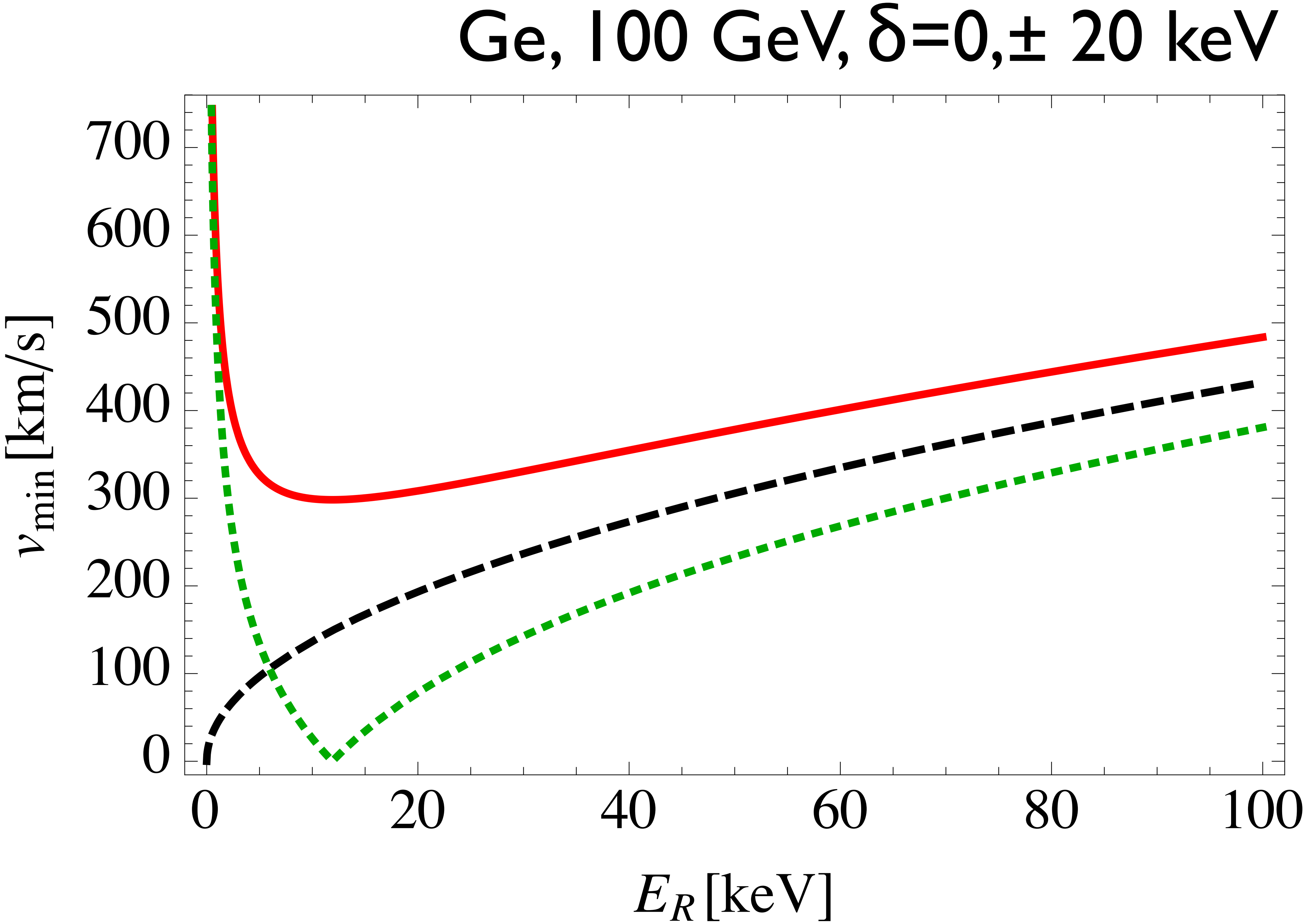


$$m_\chi - m_{\chi'} = \delta \sim -10\,\mathrm{keV}$$

$$v_{\min} = \frac{1}{\sqrt{2 m_N E_R}} \left| \frac{m_N E_R}{\mu_{N\chi}} + \delta \right|$$

- Can deposit energy even at zero speed
- Decreased (but still some) modulation
- Prefers light targets
- Recoil spectrum has a peak

e/i/exo-DM


Ge, 100 GeV, δ=0,± 20 keV
700
600
500
400
300
200
100
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$v_{\min}$ [km/s]
0
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40
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E_R [keV]

Form Factor DM

[Chang, Weiner, Pierce and Feldstein, Fitzpatrick, Katz]

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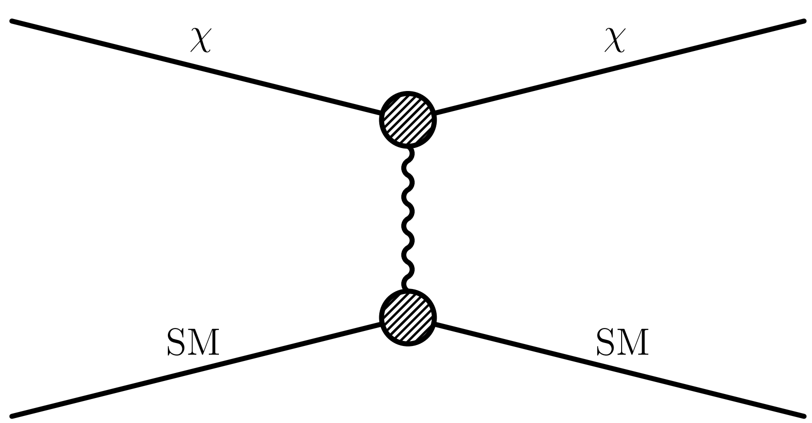
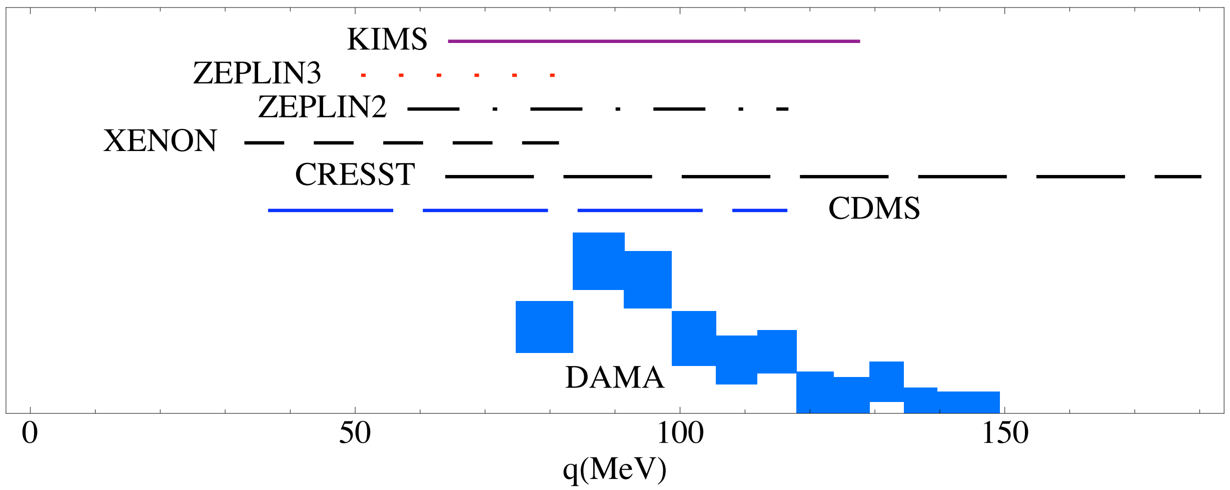
DM has a form factor, dipole coupling to light gauge boson

$$\frac{1}{\Lambda^2} D_\mu \phi^\dagger D_\nu \phi F^{\mu\nu}$$





[arXiv:0908.2991]

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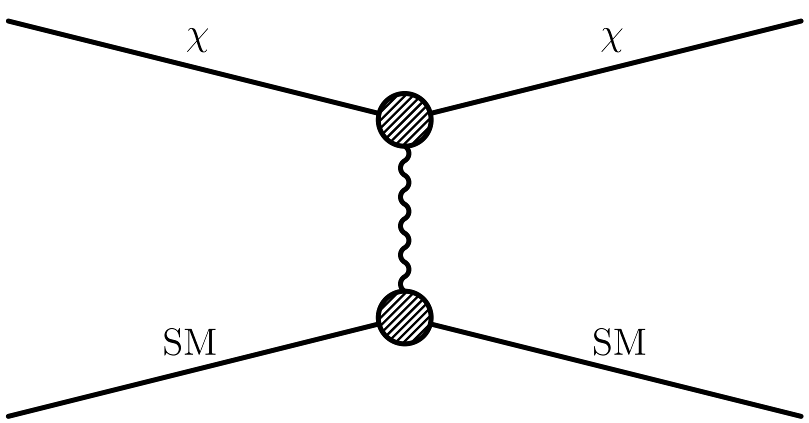

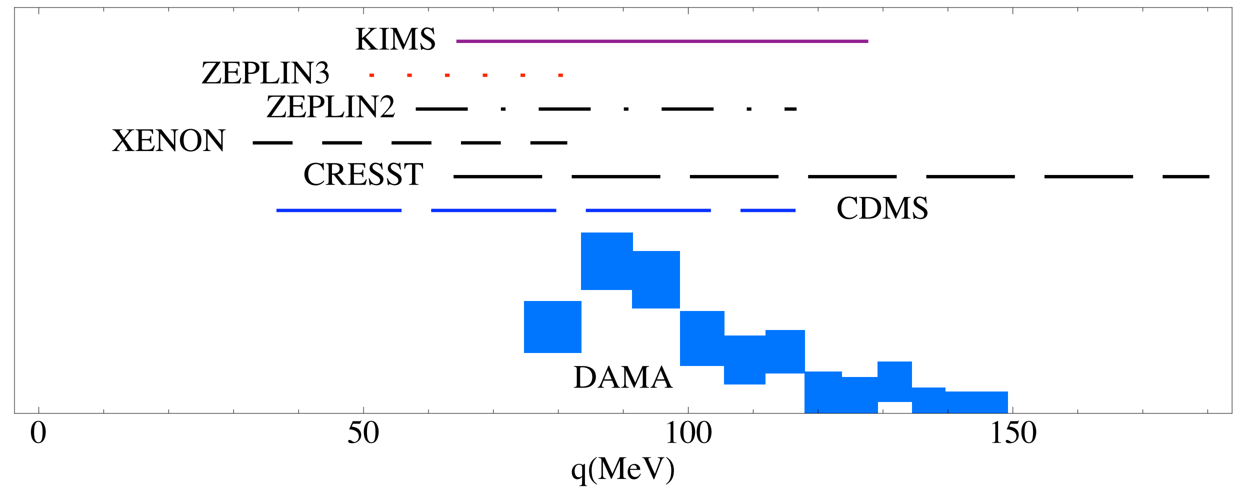

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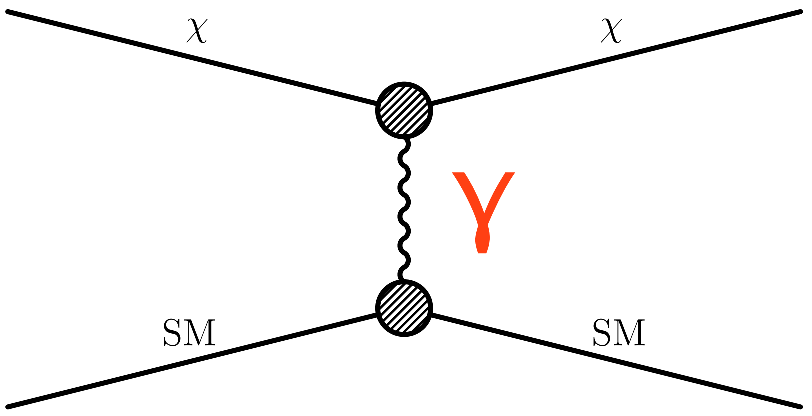
A moment with the photon

[Pospelov and ter Veldhuis]



Although DM is electrically neutral it can have higher electromagnetic moments e.g. EDM, MDM, quadropoles, anapole, charge radius,...

DM couples to nucleus through photon exchange

Leads to interesting momentum dependence e.g.

$$\frac{d\sigma_{EDM}}{dE_R} = \frac{1}{4\pi}\mathtt{d}_\chi^2 Z^2 e^2 \frac{(S+1)}{3S}\frac{1}{v_r^2}\frac{1}{E_R}|G_E(\boldsymbol{q}^2)|^2$$

Isospin dependent DM [Kurylov and Kamionkowski; Feng and Kumar]

Typically assume fn~fp

But different elements have different ratios of p/n

Can remove some of the strongest constraints if

$$\frac{f_n}{f_p} \approx -0.7$$

Isospin dependent DM [Kurylov and Kamionkowski; Feng and Kumar]

$$\sigma^{\rm SI} = \frac{[Zf_p + (A-Z)f_n]^2}{f_p^2}\frac{\mu_{\chi N}^2}{\mu_{\chi p}^2}\sigma_p^{\rm SI}$$

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Resonant Dark Matter (rDM)

[Bai and PJF]

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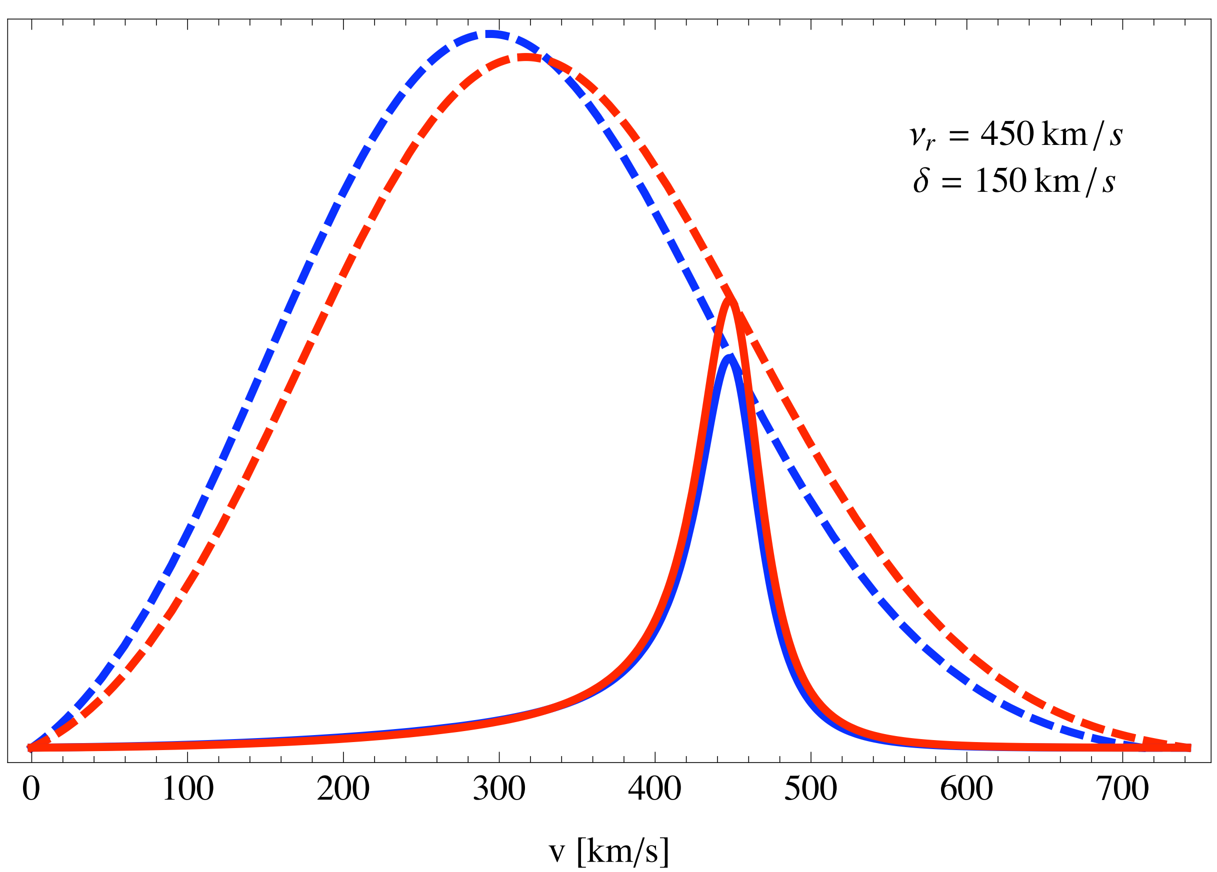
- Cross section is velocity dependent
- In particular the velocity dependence is "resonant"
- Picks out small range of velocities
- Increases modulation
- In our particular model realisation scattering is highly element dependent



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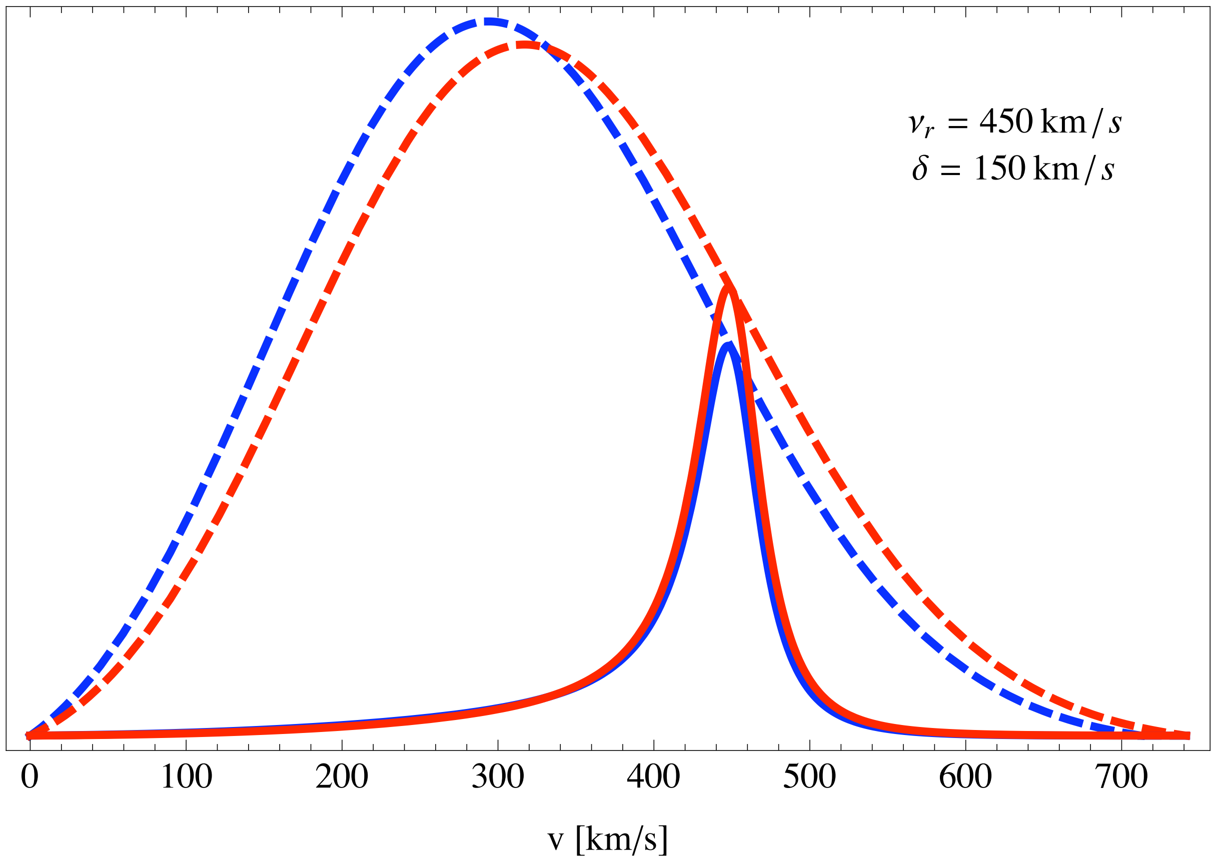
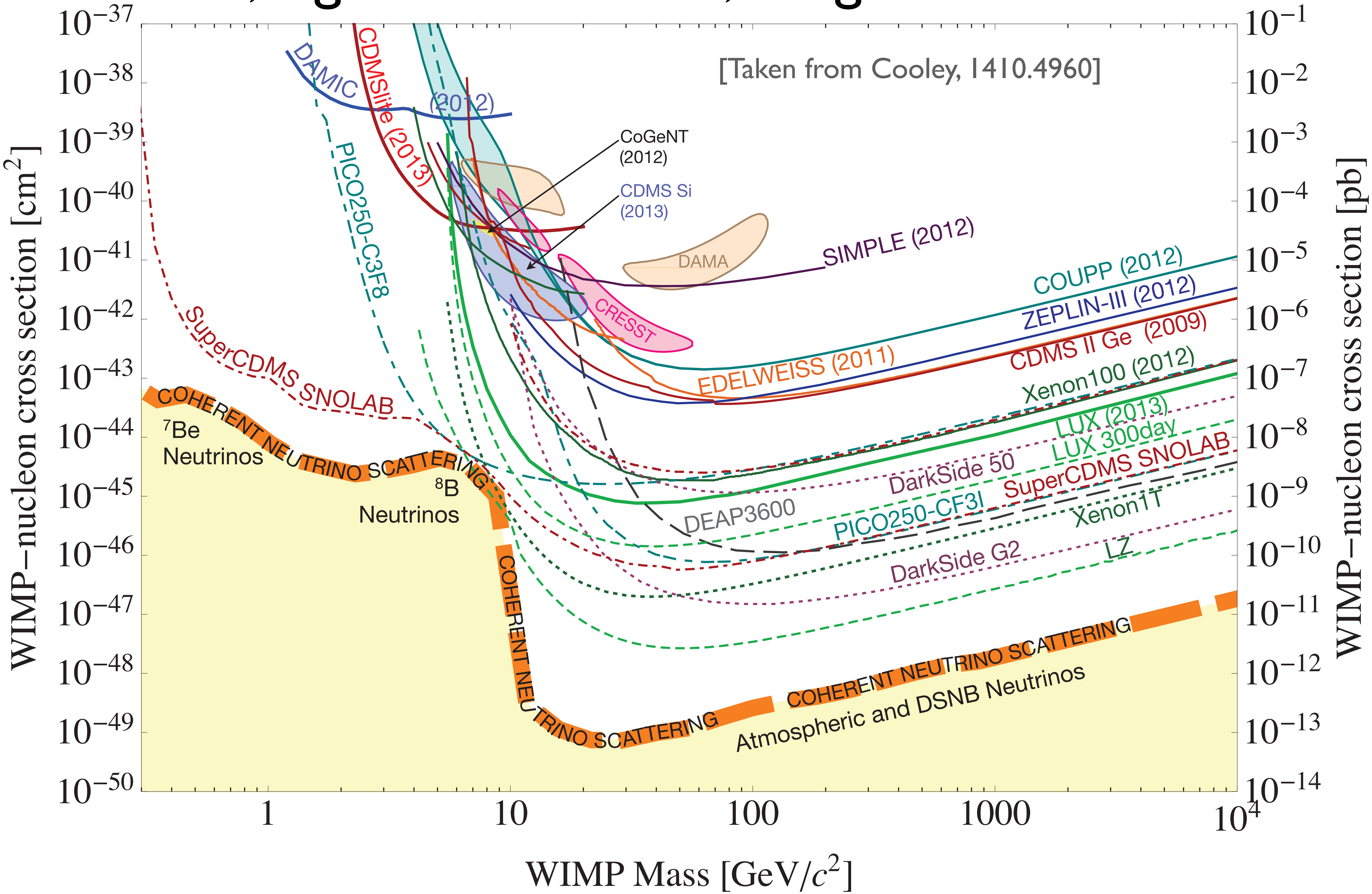
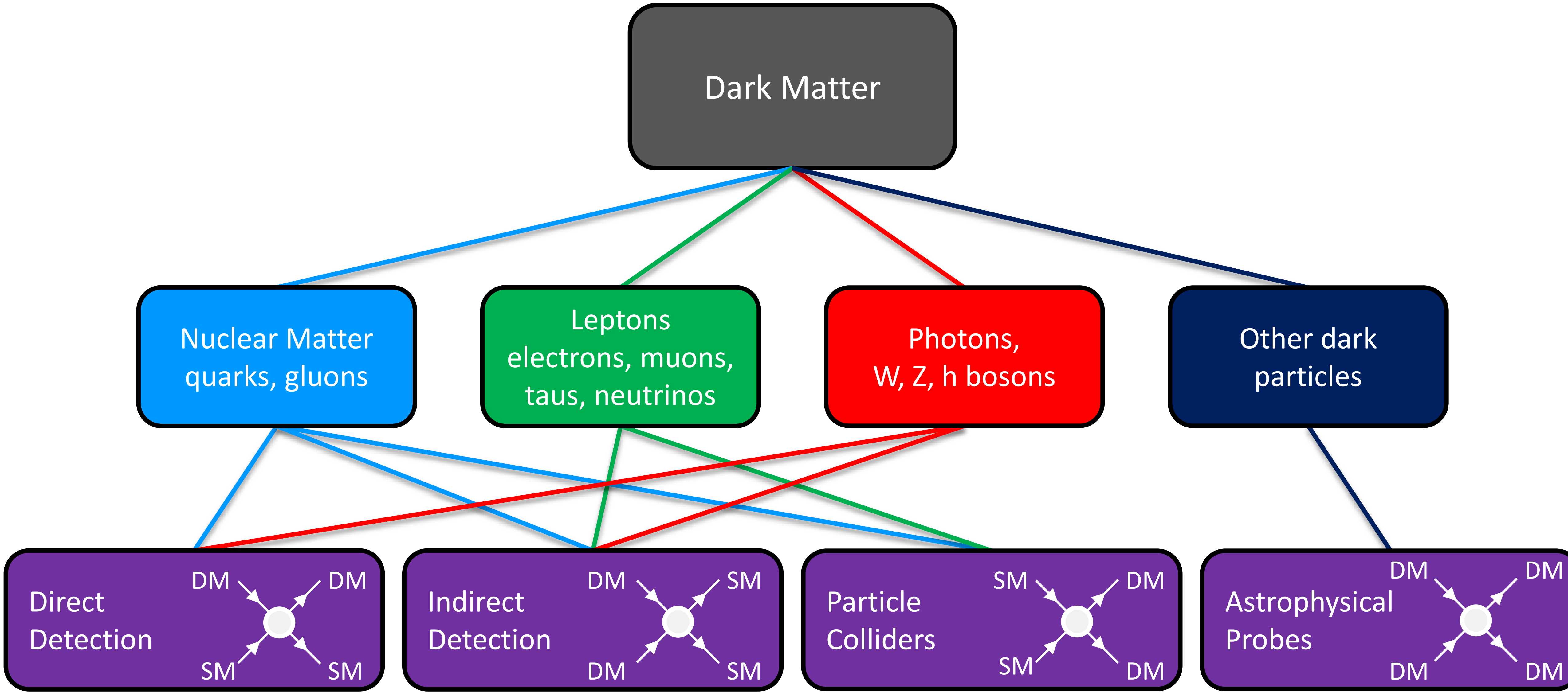


How low can we go?

Billard, Figueroa-Feliciano, Strigari



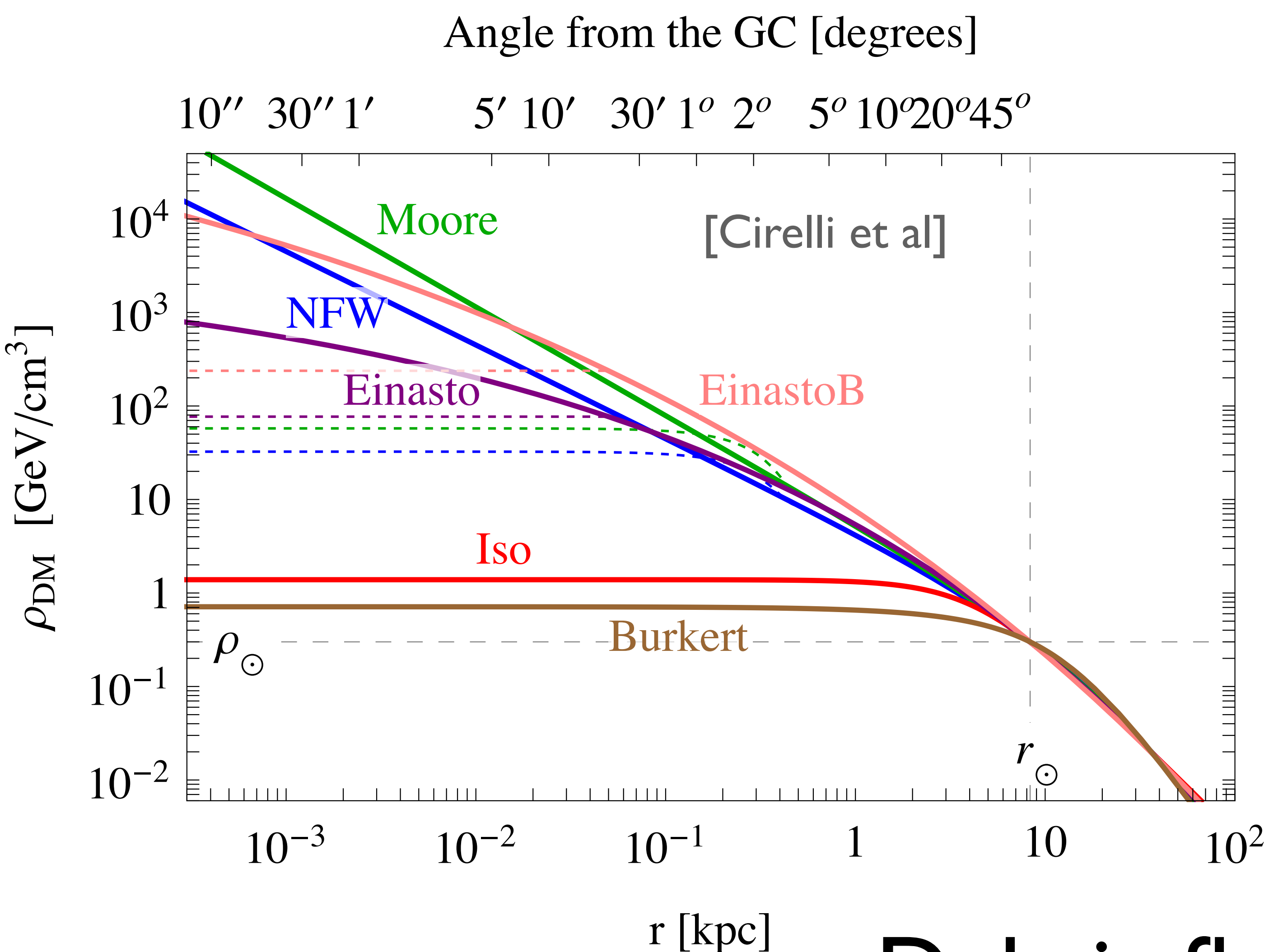
Indirect Detection

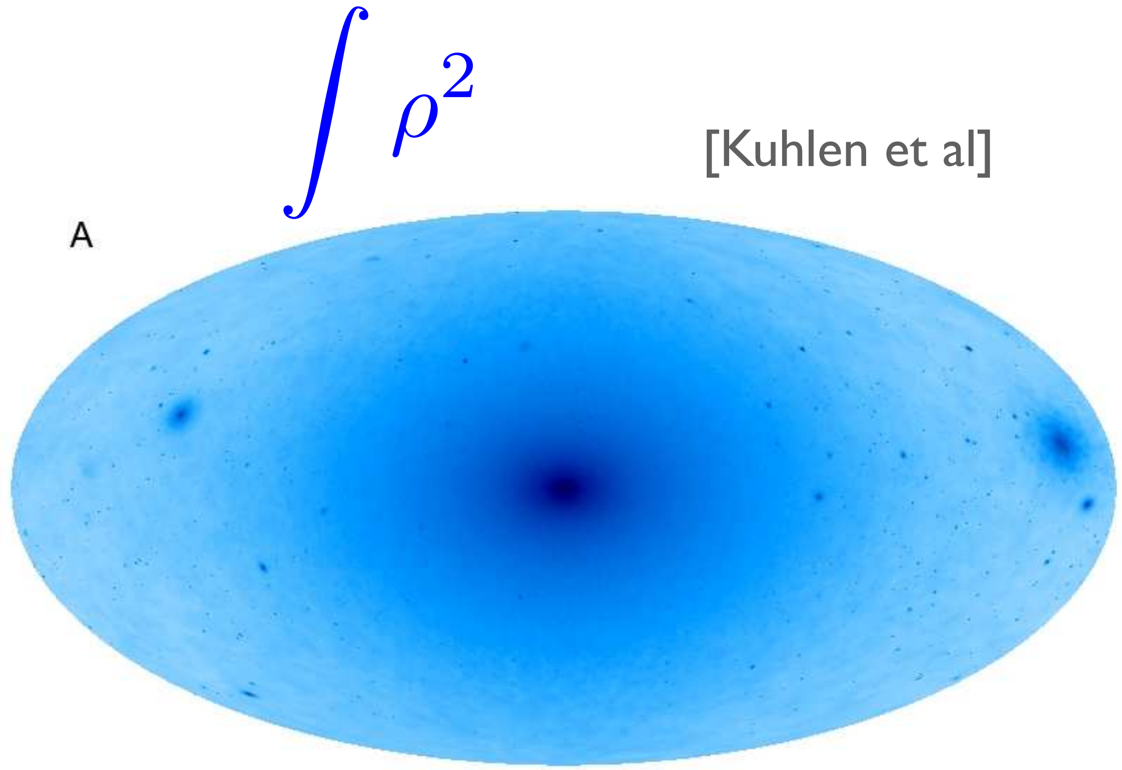


Usually refers to DM annihilation/decay products in Galaxy (or extra-galactic), or from capture + annihilation in Sun, Earth,…

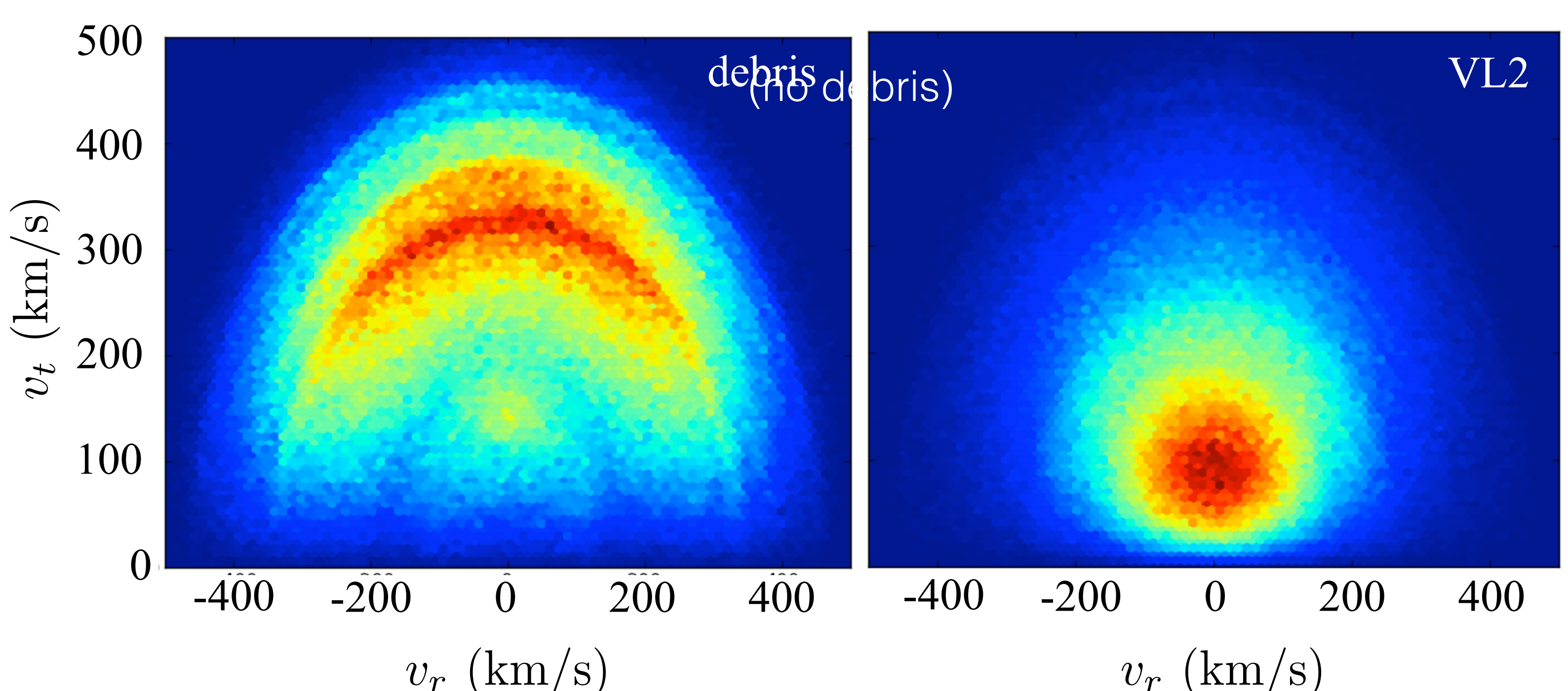
Not present for asymmetric DM

DM profiles



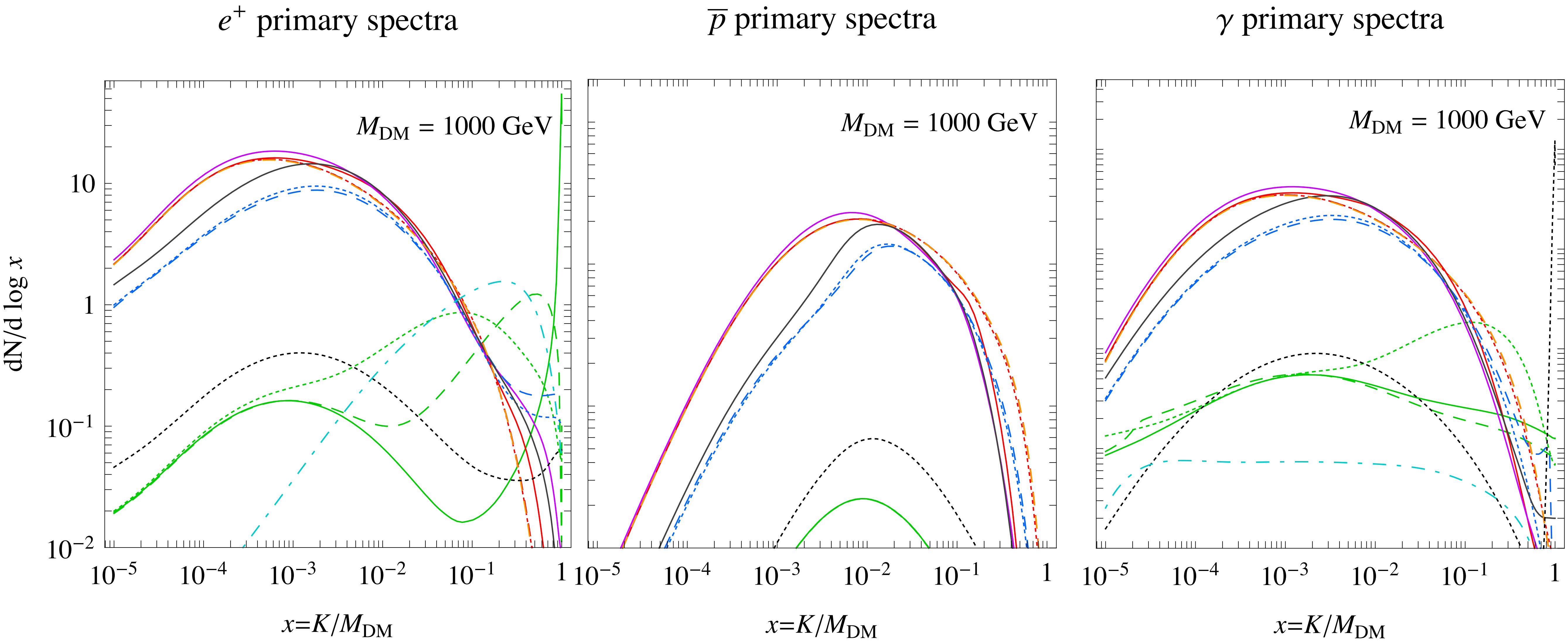


Debris flow, Lisanti et al.



DM annihilation/decay modes

[Cirelli et al]



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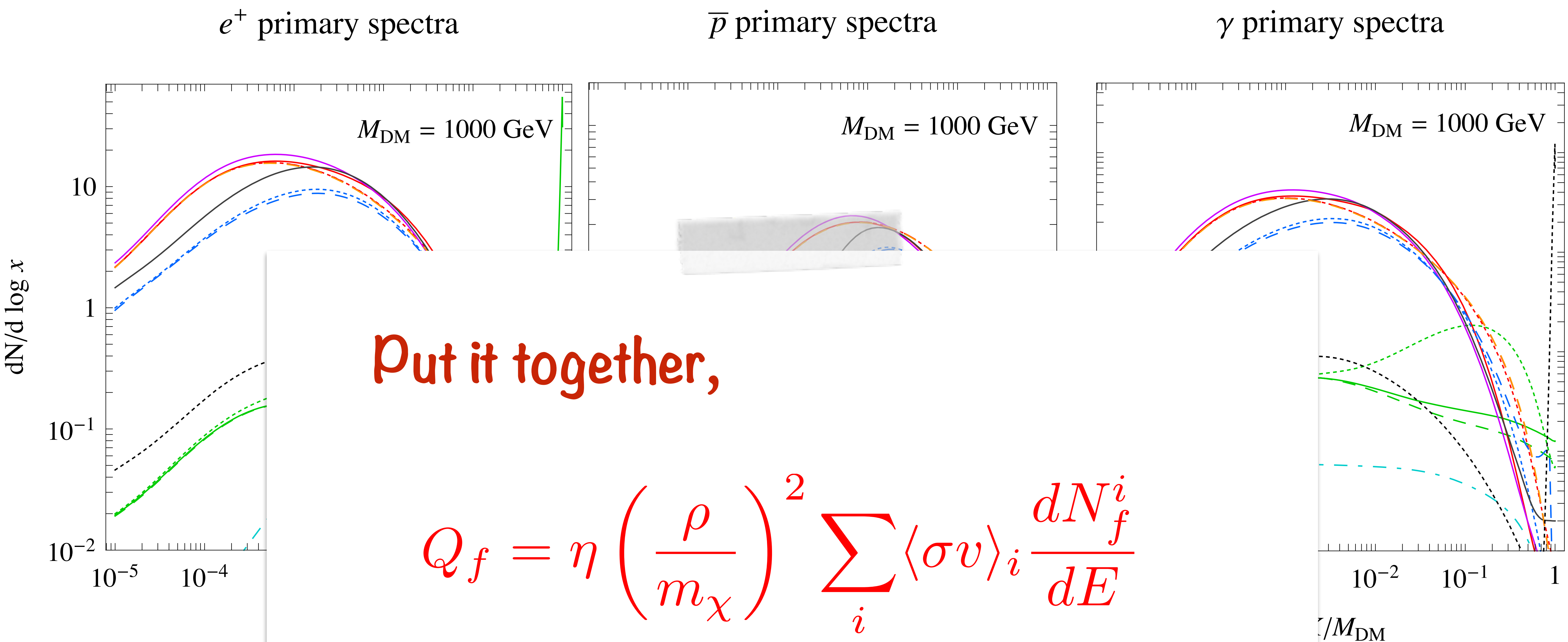
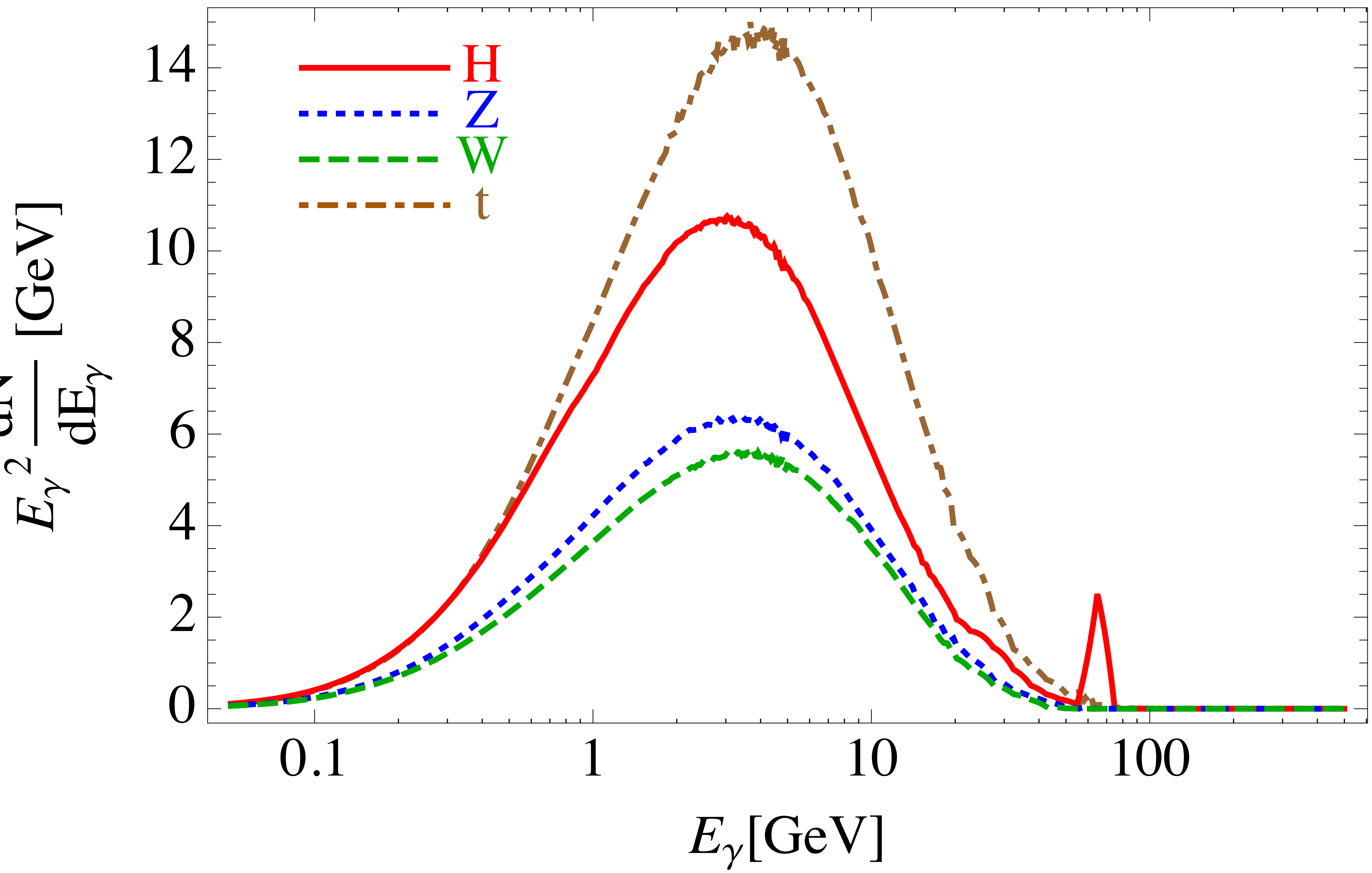


Put it together,

$$Q_f = \eta \left(\frac{\rho}{m_\chi} \right)^2 \sum_i \langle \sigma v \rangle_i \frac{dN_f^i}{dE}$$

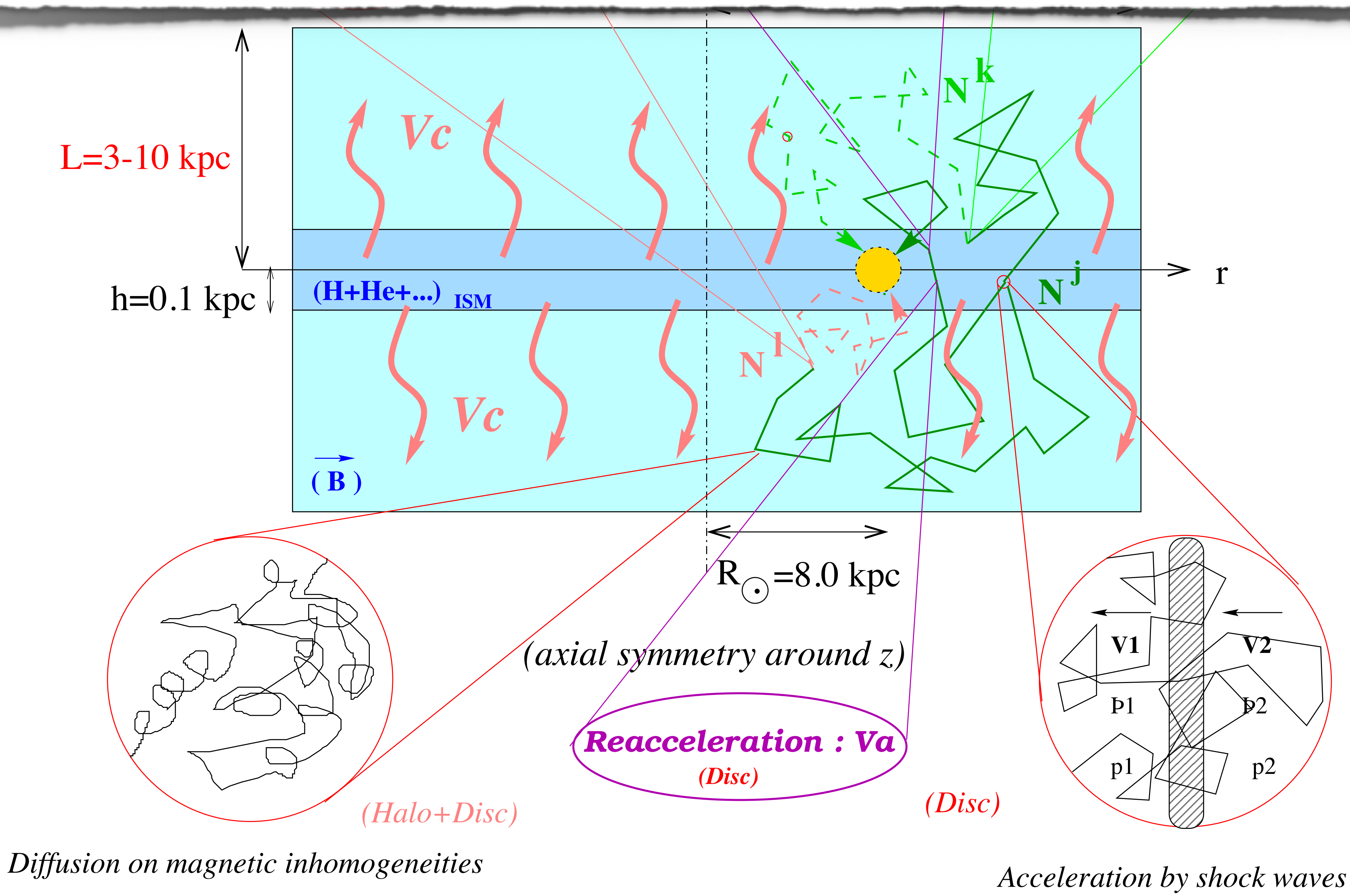
Often plotted weighted by E^2 :



[Figure from Maurin et al: 0212111]

Diffusion-loss equation

$$\frac{\partial f}{\partial t} - \nabla\left(\kappa(E,\vec{x})\nabla f\right) - \frac{\partial}{\partial E}\left(b_{loss}(E,\vec{x})f + K_{EE}\frac{\partial f}{\partial E}\right) + \frac{\partial}{\partial z}\left(sgn(z)V_c f\right) = Q$$



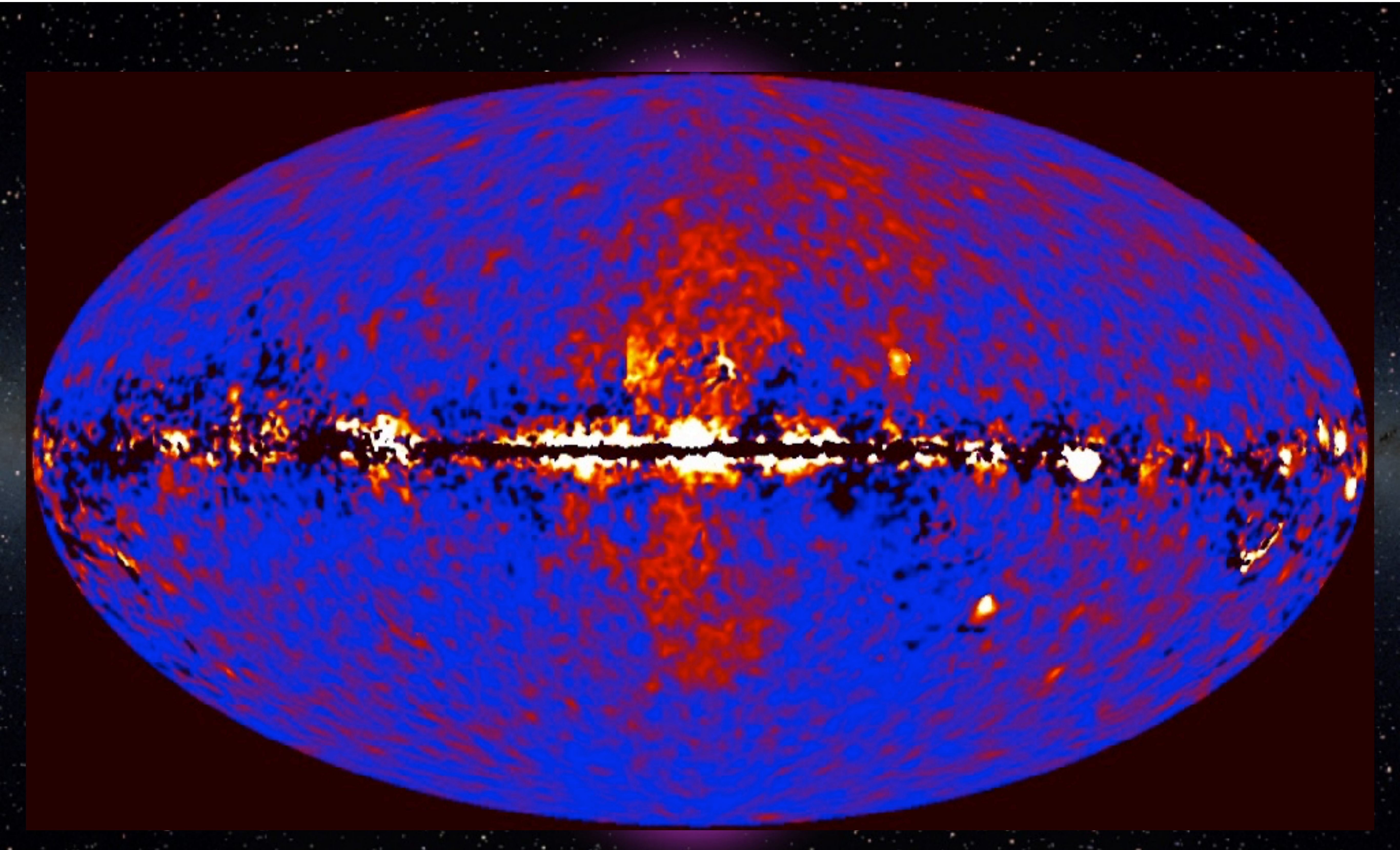
Propagation

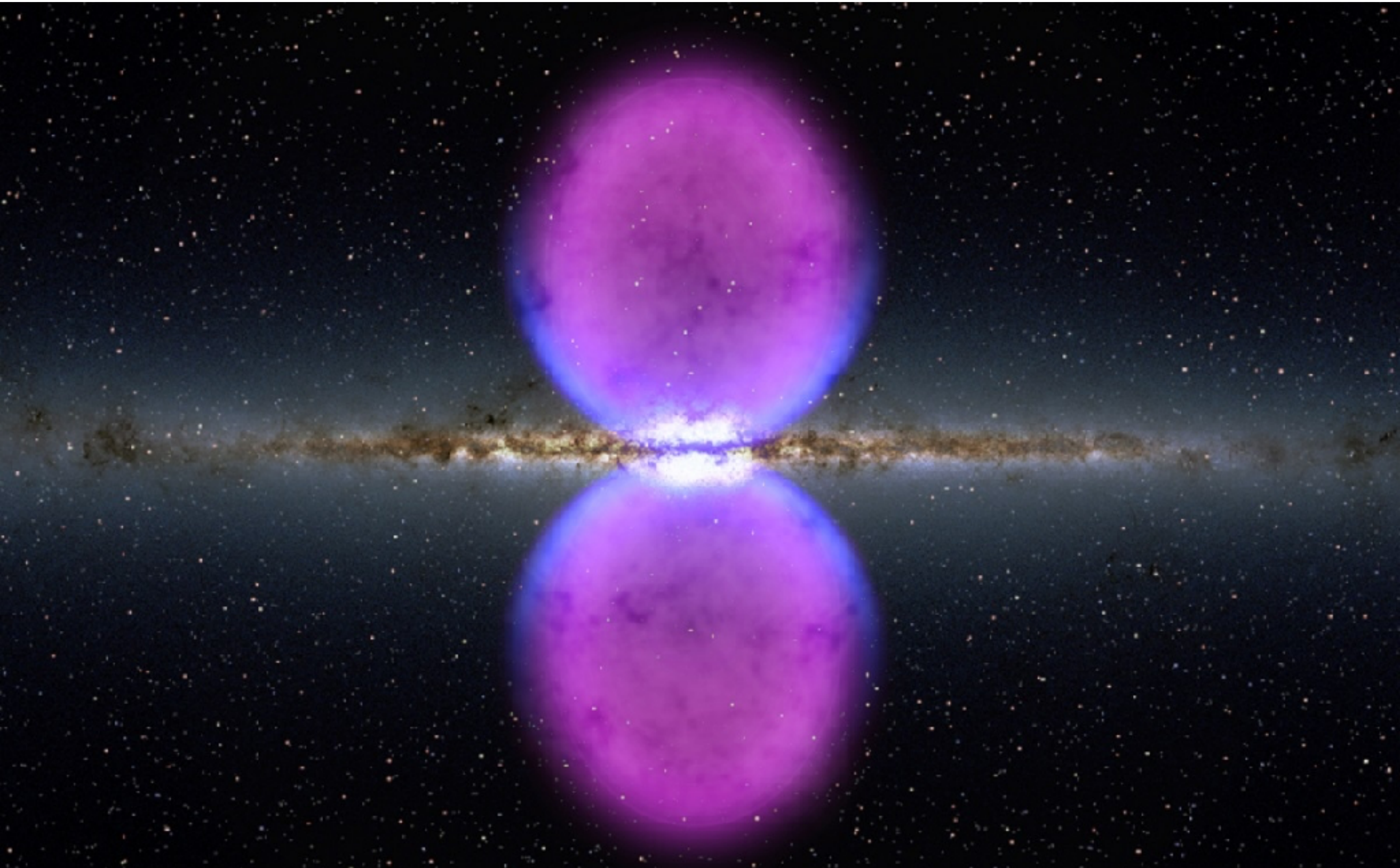
- Assume steady state, simplifying geometry, cylindrical symmetry
- Diffusion coefficient determined by random magnetic fields

$$\kappa = \kappa_0 \left(\frac{E}{\mathrm{GeV}} \right)^{\delta}$$

- Losses due to synchrotron, ICS, spallation etc. Depends on distribution of magnetic fields, starlight, matter etc in galaxy
- Many complexities, parameters. Use GALPROP

	Electrons or positrons		Antiprotons (and antideuterons)			
Model	δ	$\mathcal{K}_0$ [kpc^2/Myr]	δ	$\mathcal{K}_0$ [kpc^2/Myr]	V_{conv} [km/s]	L [kpc]
MIN	0.55	0.00595	0.85	0.0016	13.5	1
MED	0.70	0.0112	0.70	0.0112	12	4
MAX	0.46	0.0765	0.46	0.0765	5	15





Dark Matter Indirect Detection

DM annihilates in our galaxy, or nearby dwarf galaxy e.g.

$\chi\chi \to p\bar{p}, e^+e^-$

Look for antimatter in cosmic rays, does not point back to source, limited range.
PAMELA, AMS02, Fermi

$\chi\chi \to \nu\bar{\nu}$

Point back to source, low cross section.
IceCube, ANTARES, Super-K

$\chi\chi \to \gamma\gamma$

Point back to source, spectral line, low rate
Fermi, HESS

$\chi\chi \to \mathrm{SM\ SM}$
$\hookrightarrow \ldots + \gamma\gamma$

Point back to source, continuum with edge, backgrounds
Fermi, HESS

Experiments

- Balloons, satellites, space stations
- Need magnetic field to distinguish charges

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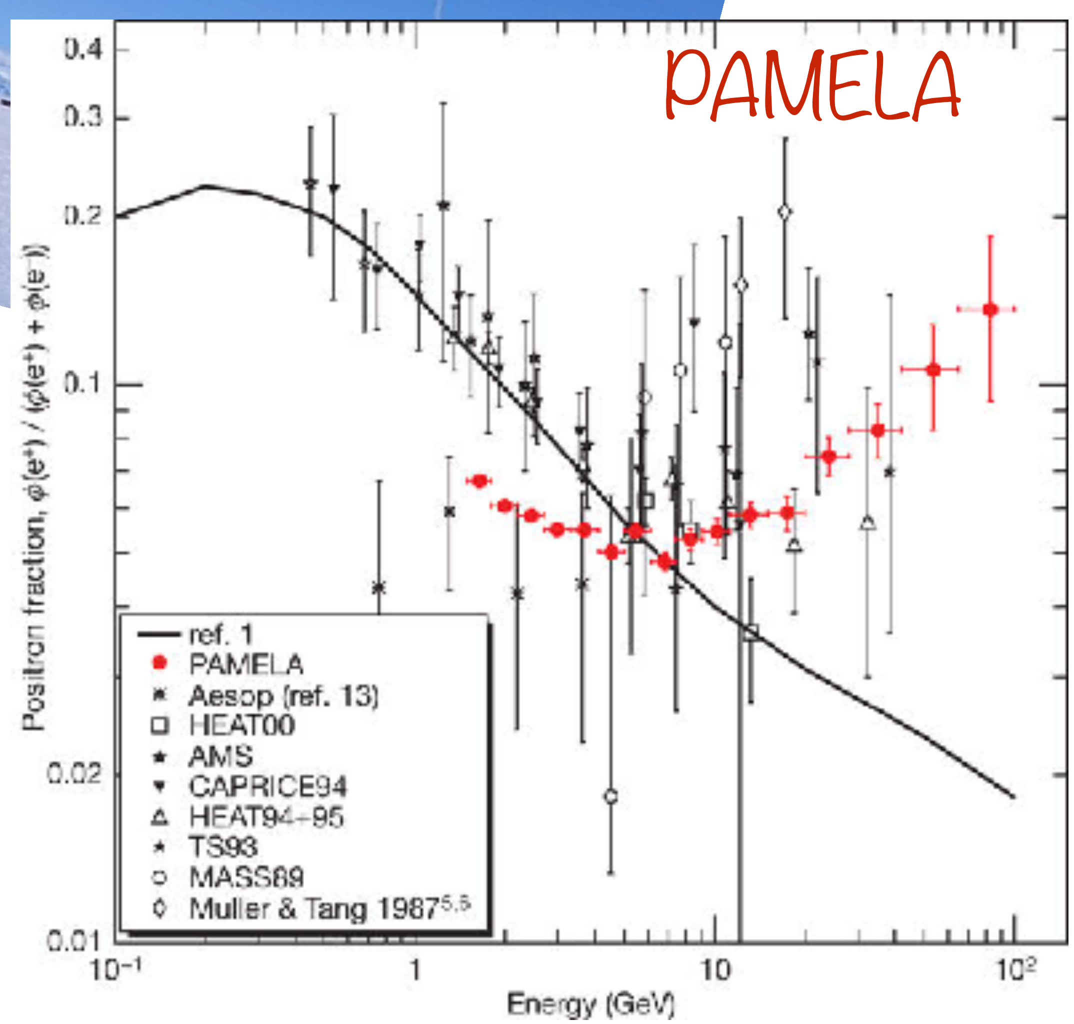
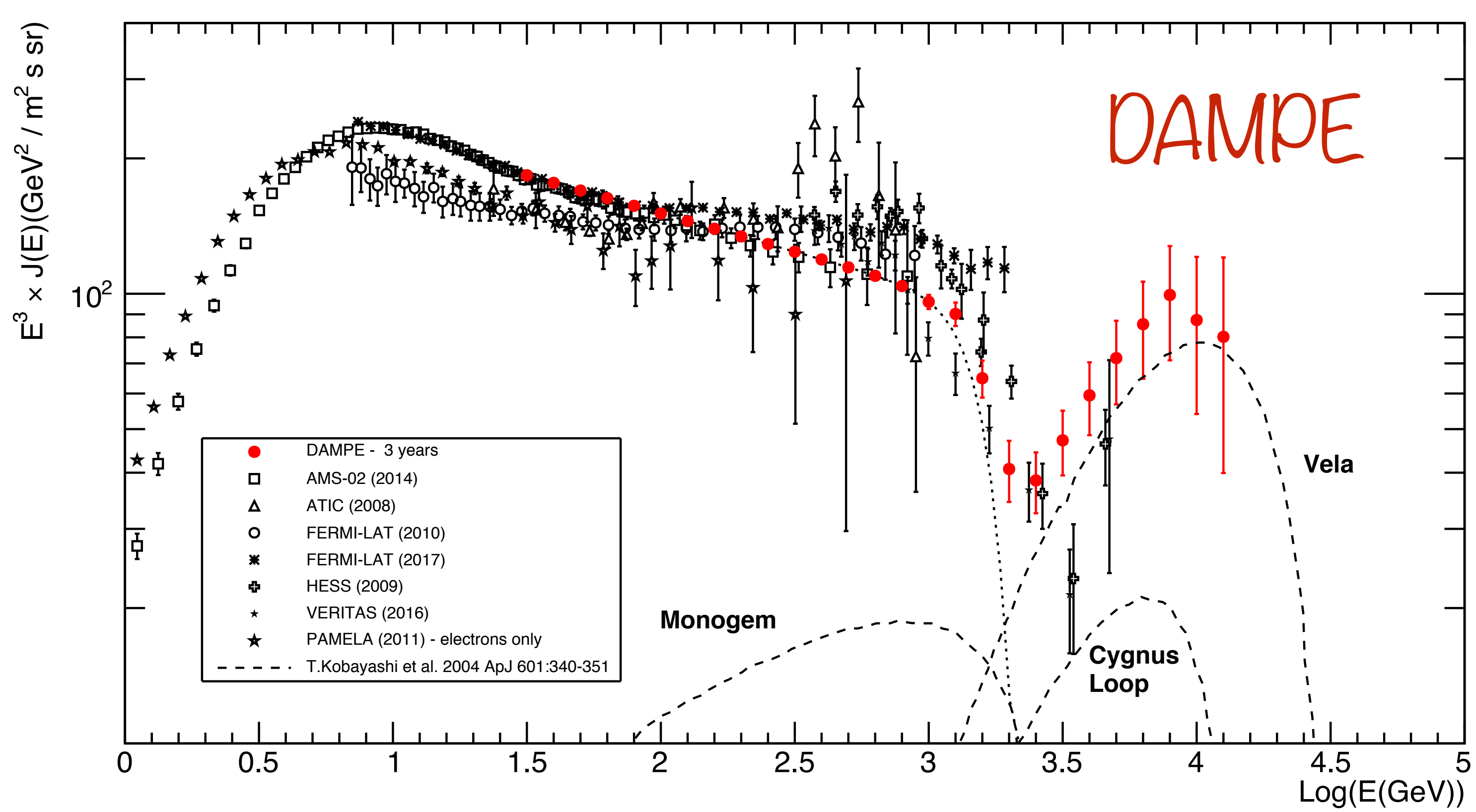
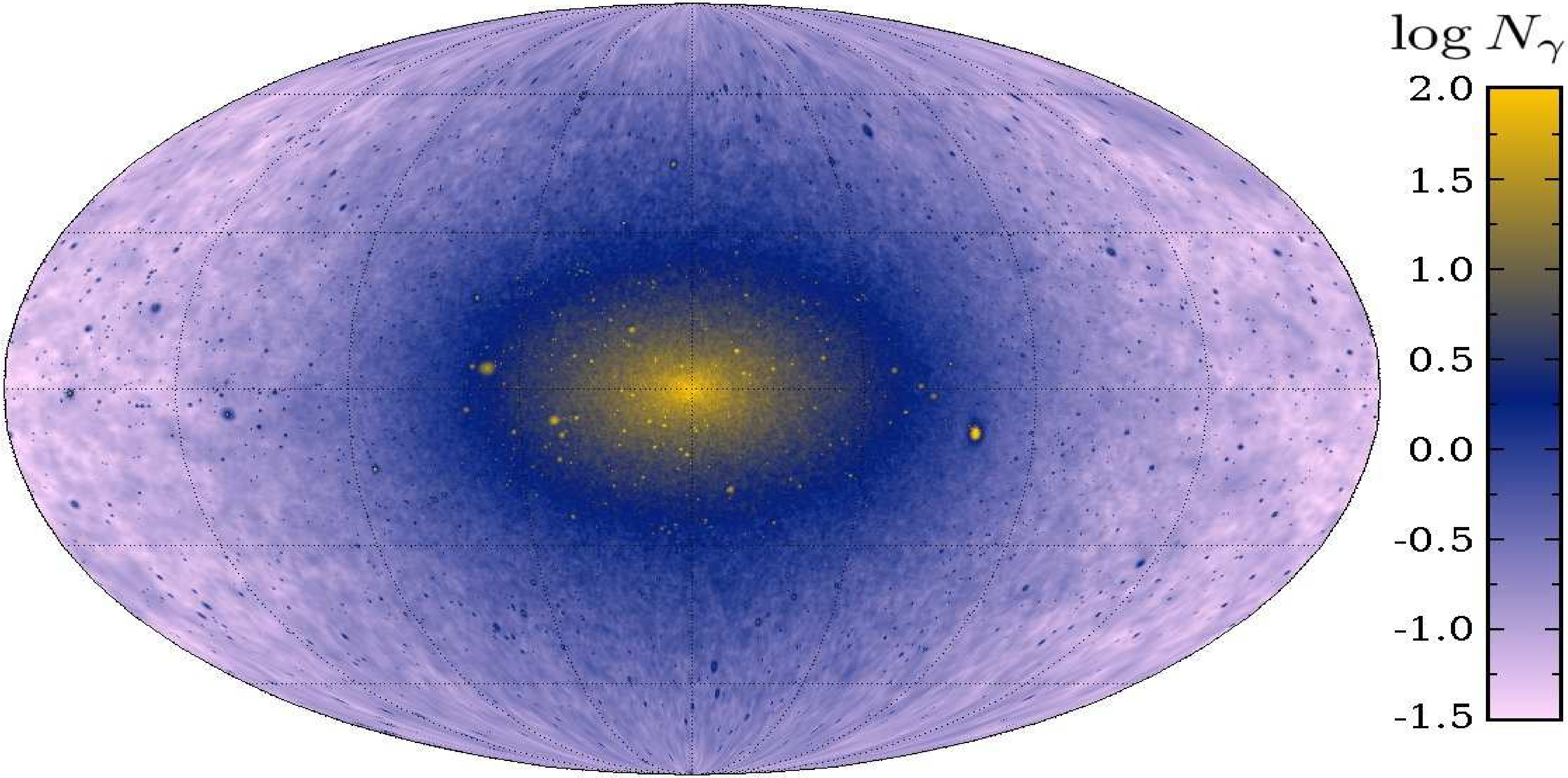




Simulation of DM photon signal in our galaxy

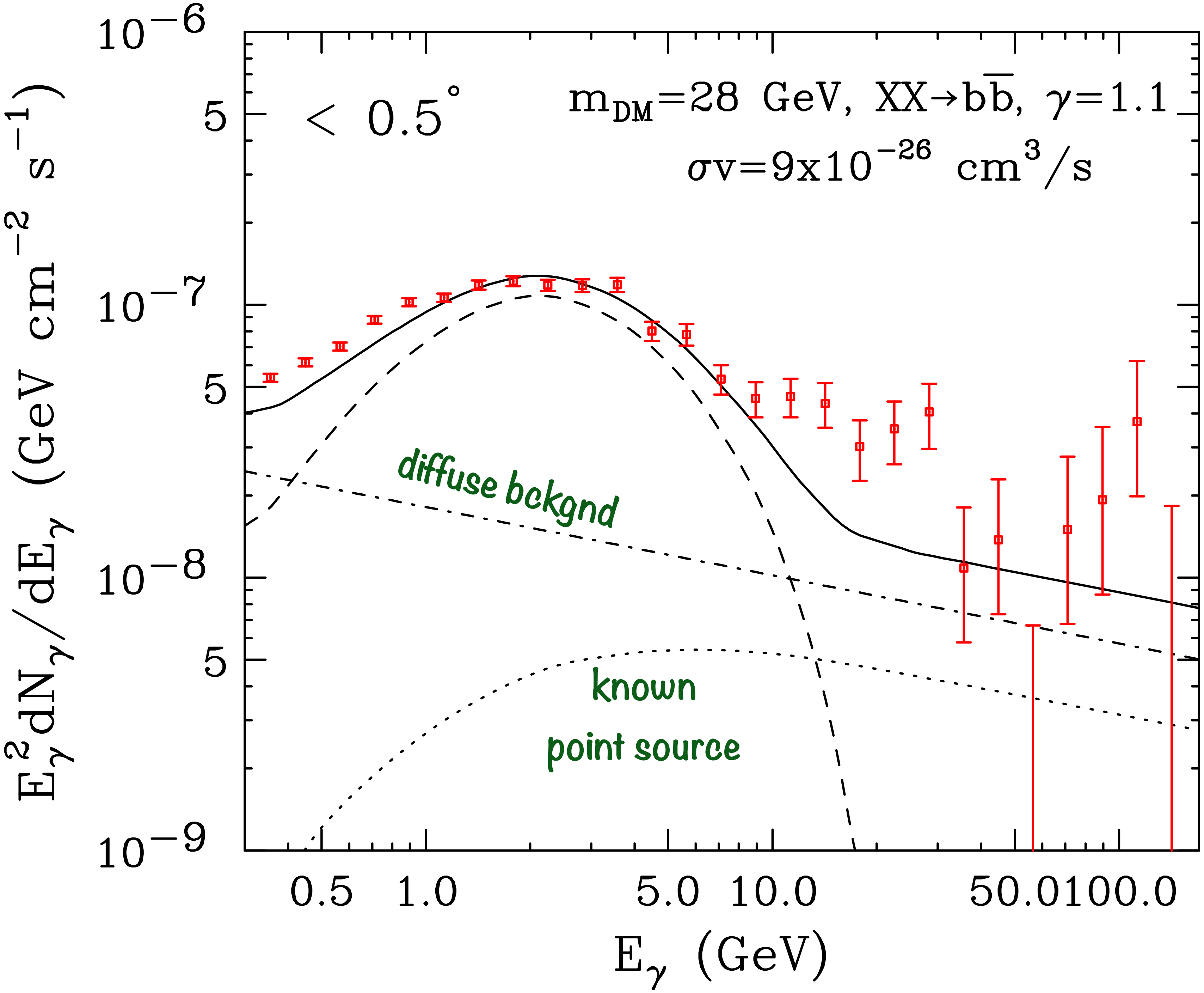


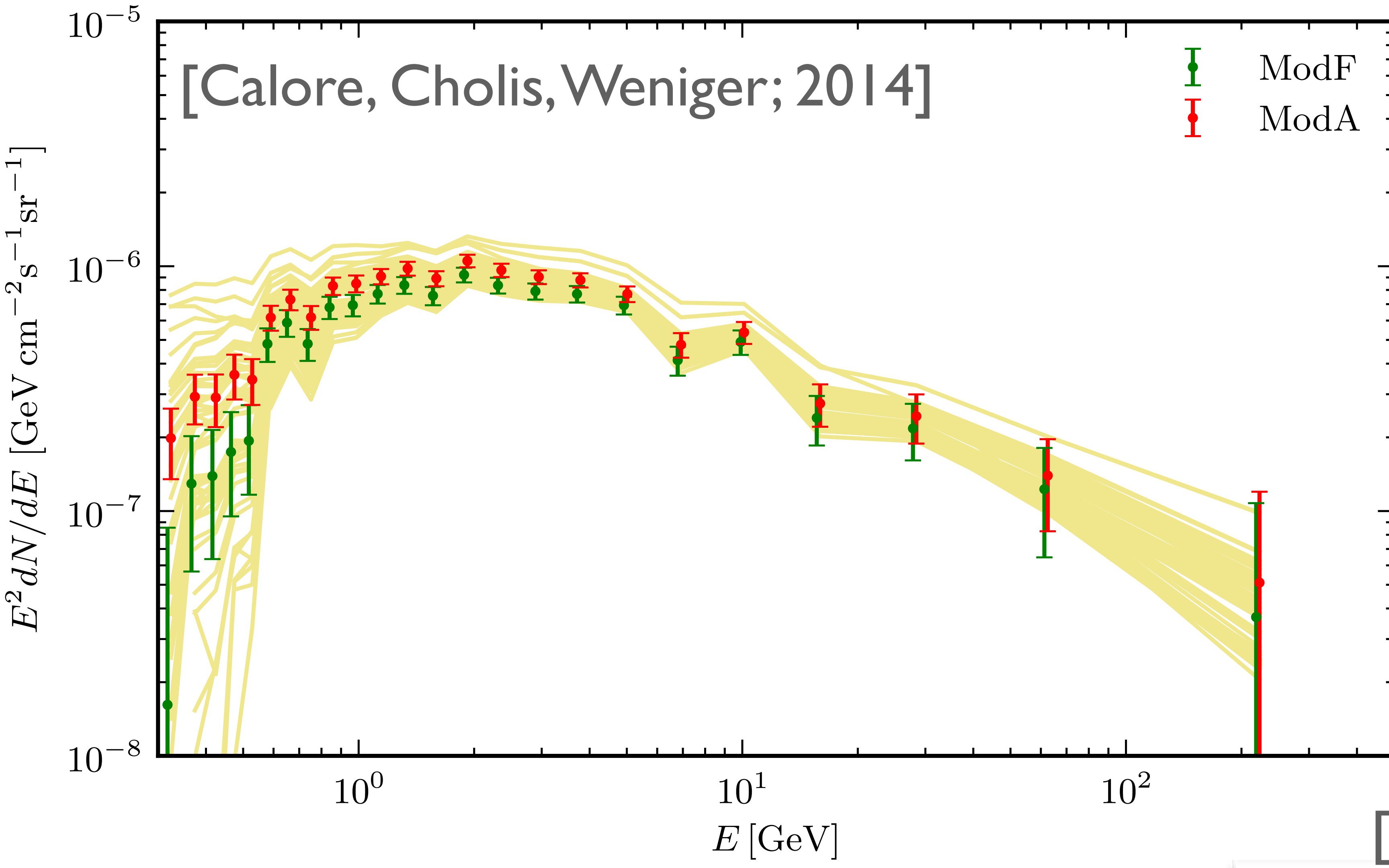
$$\frac{dN}{d\Omega dE}(\psi) = \frac{1}{4\pi\eta}\frac{f_\chi^2 J(\psi)}{m_\chi^2}\sum_i \langle\sigma v\rangle_i \frac{dN^i}{dE_\gamma}$$

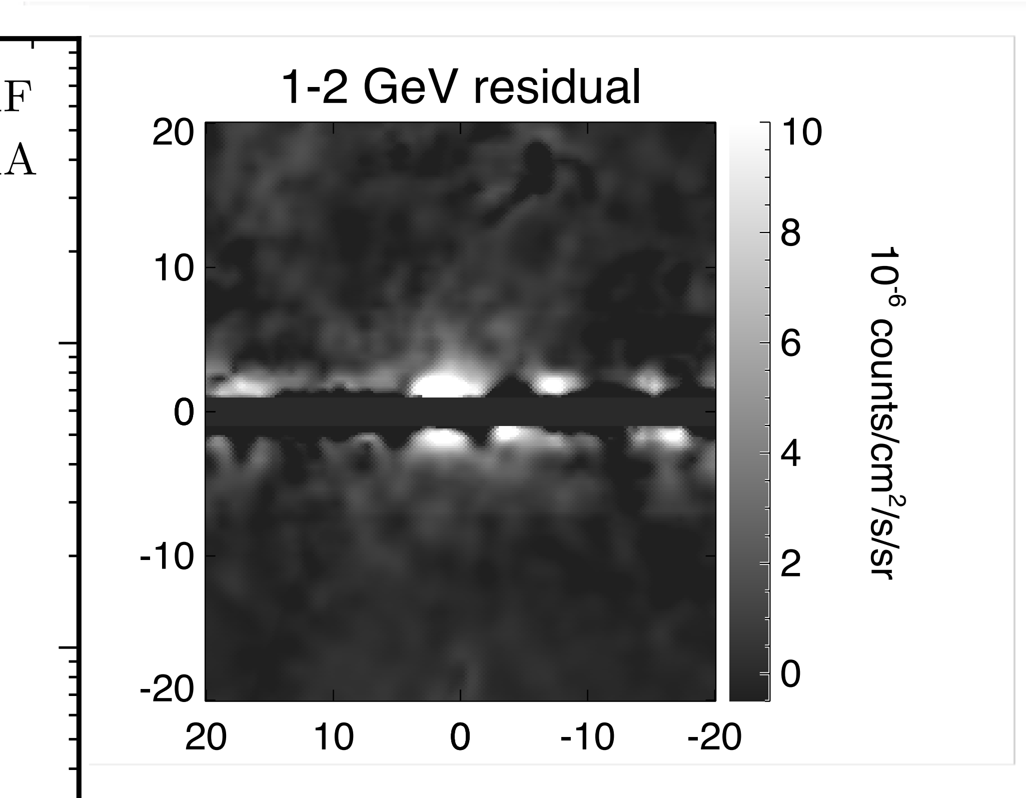
$$J(\psi) = \int_{\rm l.o.s.} ds\, \rho(r)^2$$

GCE (Gooperon)

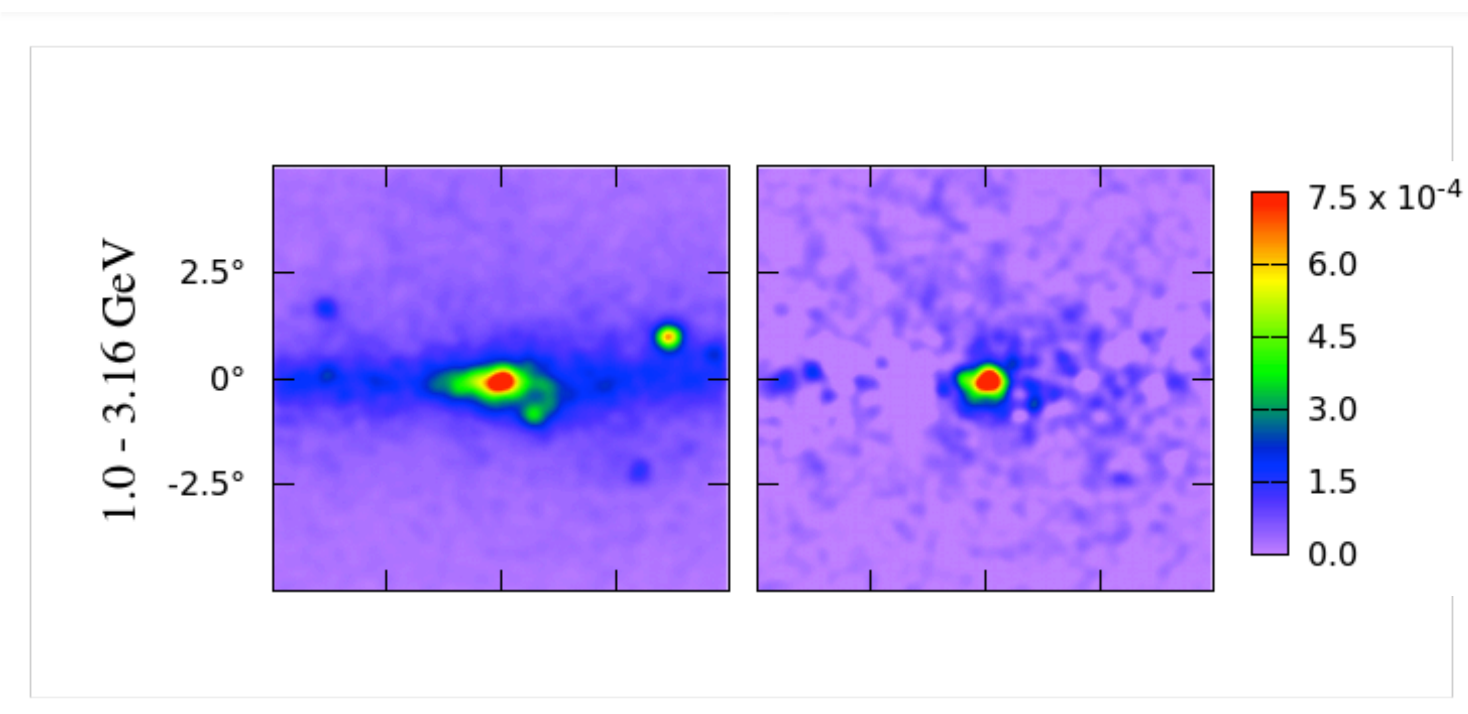
[Goodenough and Hooper, 2009]

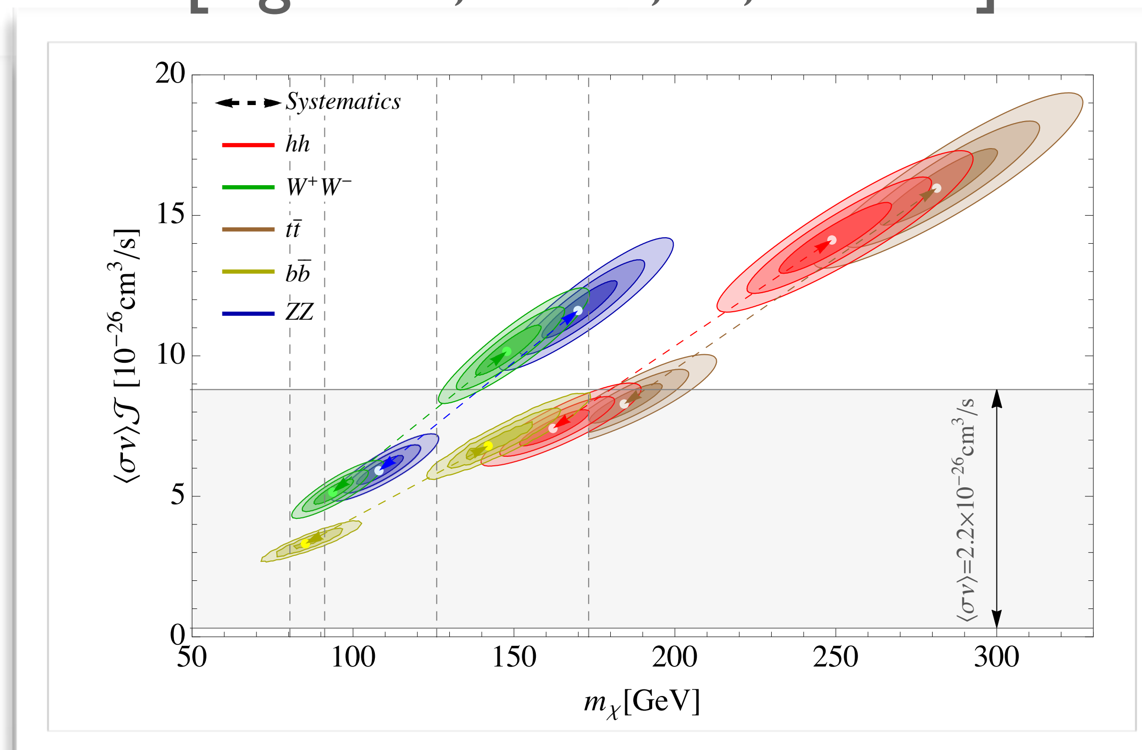






[Agrawal, Batell, PF, Harnik]





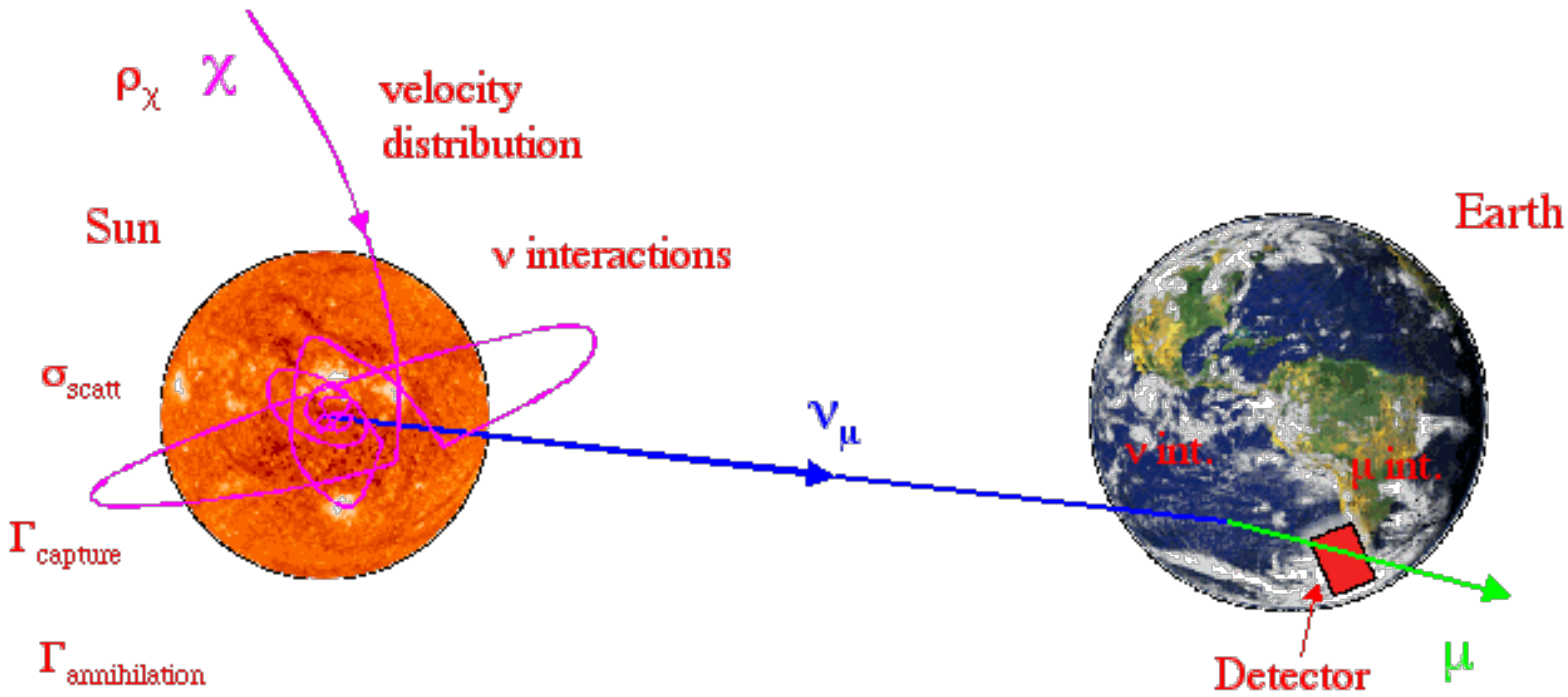
Are the excess photons from the Galactic centre DM?

- Source is spherical, with the expected radial dependence
- Cross section is close to thermal
- Centred in the right place
- Statistical significant, and Fermi-team sees it too

- Galactic centre is a confusing place
- Not as clear as a spectral line
- Milli-second pulsars (but we would have seen more, also spectrum different from those observed)

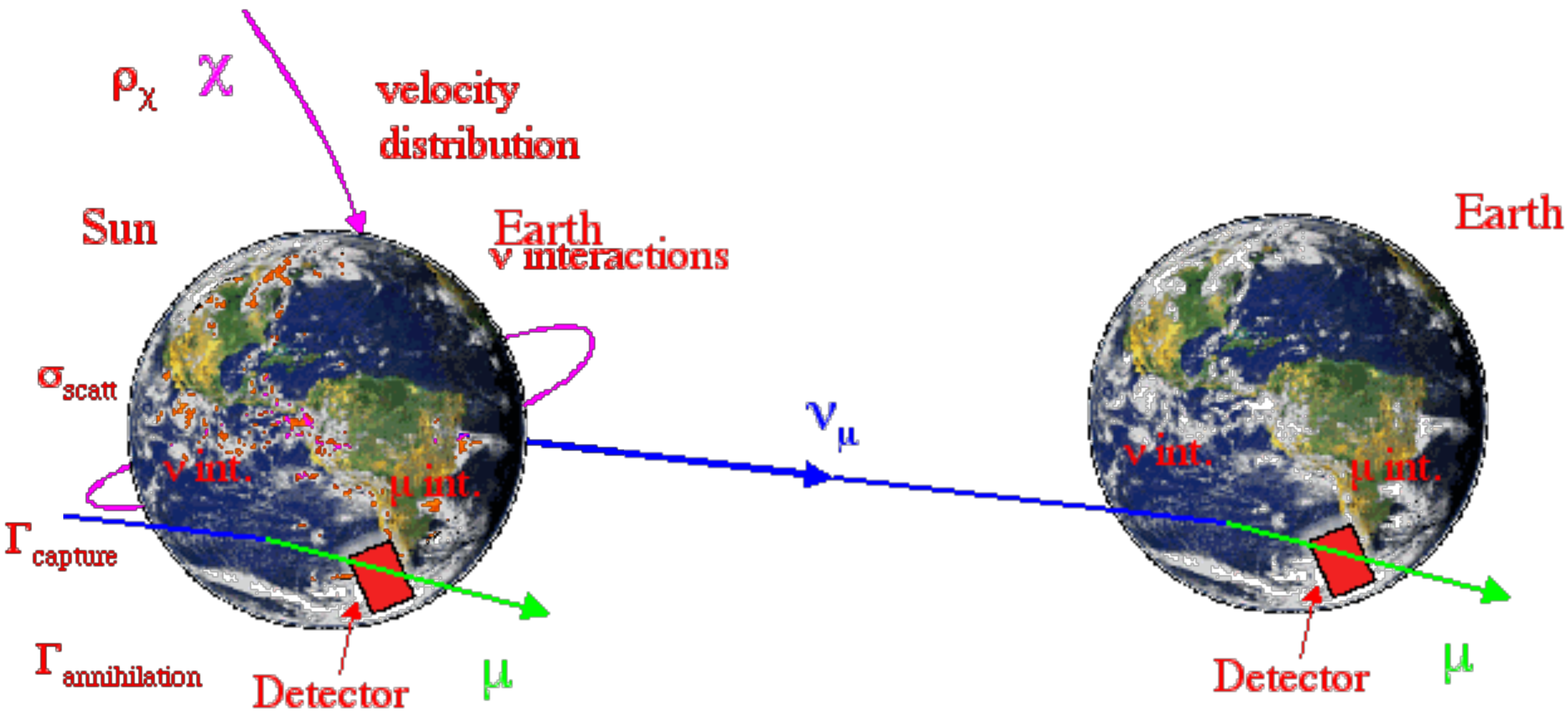
- Look at other DM "bright spots"--dwarf galaxies
- Cosmic ray anti-particles
- Correlated signals, LHC, direct detection
- **Interesting times ahead**

Other "indirect" signals



[Figure by Joakim Edsjo]

Other "indirect" signals



[Figure by Joakim Edsjo]

Rate

$$\frac{dN}{dt} = \Gamma_{\rm capt} - 2\Gamma_{\rm ann} - \Gamma_{\rm evap}$$

$$\Gamma_{\rm ann} = \int n^2 \langle \sigma v \rangle$$

$$n \sim e^{-m_\chi \phi(r)/T} \xrightarrow{\rm const.\rho} n_0\, e^{-r^2/r_\chi^2} \approx 0.01 R_\odot \sqrt{\frac{100\ \rm GeV}{m_\chi}}$$

$$\Gamma_{ann} = N^2 \frac{\langle \sigma v \rangle}{2} \left(\frac{G_N m_\chi \rho_\odot}{3 T_\odot} \right)^{3/2}$$

$$\Gamma_{\rm ann} = \frac{\Gamma_{\rm capt}}{2} \tanh^2 \left(\frac{t}{\tau} \right) \overset{t \gg \tau}{\simeq} \frac{\Gamma_{\rm capt}}{2}$$

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Capture Rate

[Gould, 87; Cirelli et al. 1312.6408]

$$\Gamma_{\rm capt} = \frac{\rho_{\rm DM}}{M_{\rm DM}} \sum_i \sigma_i \int_0^{R_\odot} dr\ 4\pi r^2\ n_i(r) \int_0^\infty dv\ 4\pi v^2 f_\odot(v) \frac{v^2 + v^2_{\odot\rm esc}}{v} \wp_i(v, v_{\odot\rm esc})$$

- DM abundance
- Target abundance in Sun (typically dominated by H, He)
- Scattering cross section (SI, SD)
- DM speed distribution in Sun's frame
- Capture probability—favours slow moving DM

$$\wp_i(v, v_{\odot\rm esc}) = \frac{1}{E\,\Delta_{\rm max}} \int_{E\,\Delta_{\rm min}}^{E\,\Delta_{\rm max}} {\rm d}(\Delta E)\,|F_i(\Delta E)|^2,$$

$$\Gamma_{\rm capt} \simeq \frac{5.90 \cdot 10^{26}}{\rm sec} \left(\frac{\rho_{\rm DM}}{0.3\,\frac{\rm GeV}{\rm cm^3}}\right) \left(\frac{100\,{\rm GeV}}{M_{\rm DM}}\right)^2 \left(\frac{270\,\frac{\rm km}{\rm sec}}{v_0^{\rm eff}}\right)^3 \frac{\sigma_{\rm SD} + 1200\,\sigma_{\rm SI}}{\rm pb}$$

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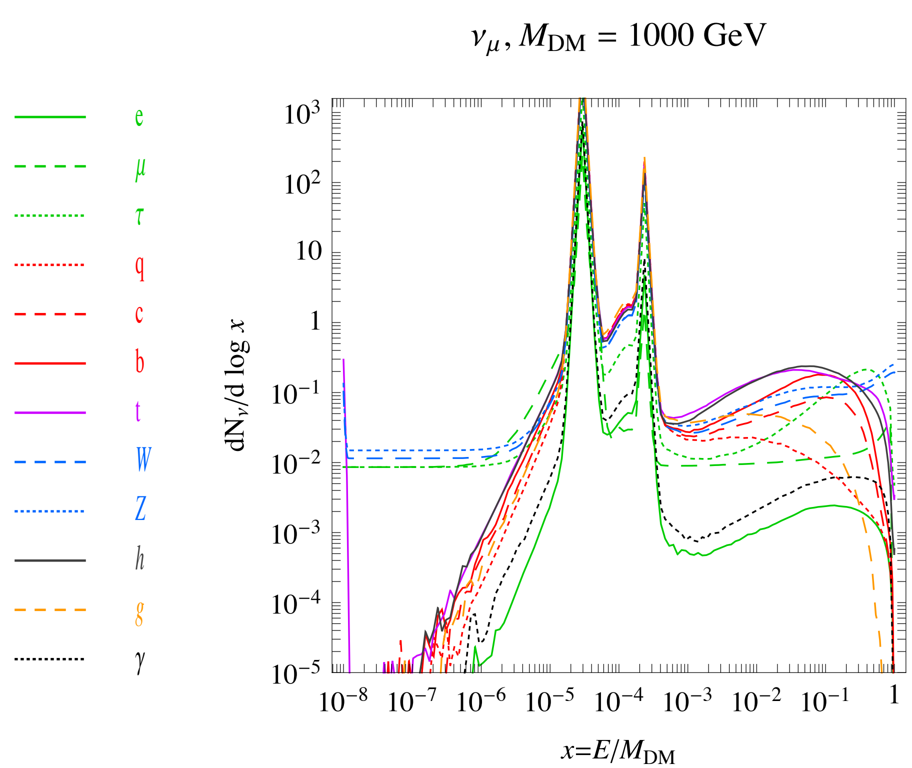
Annihilation signal

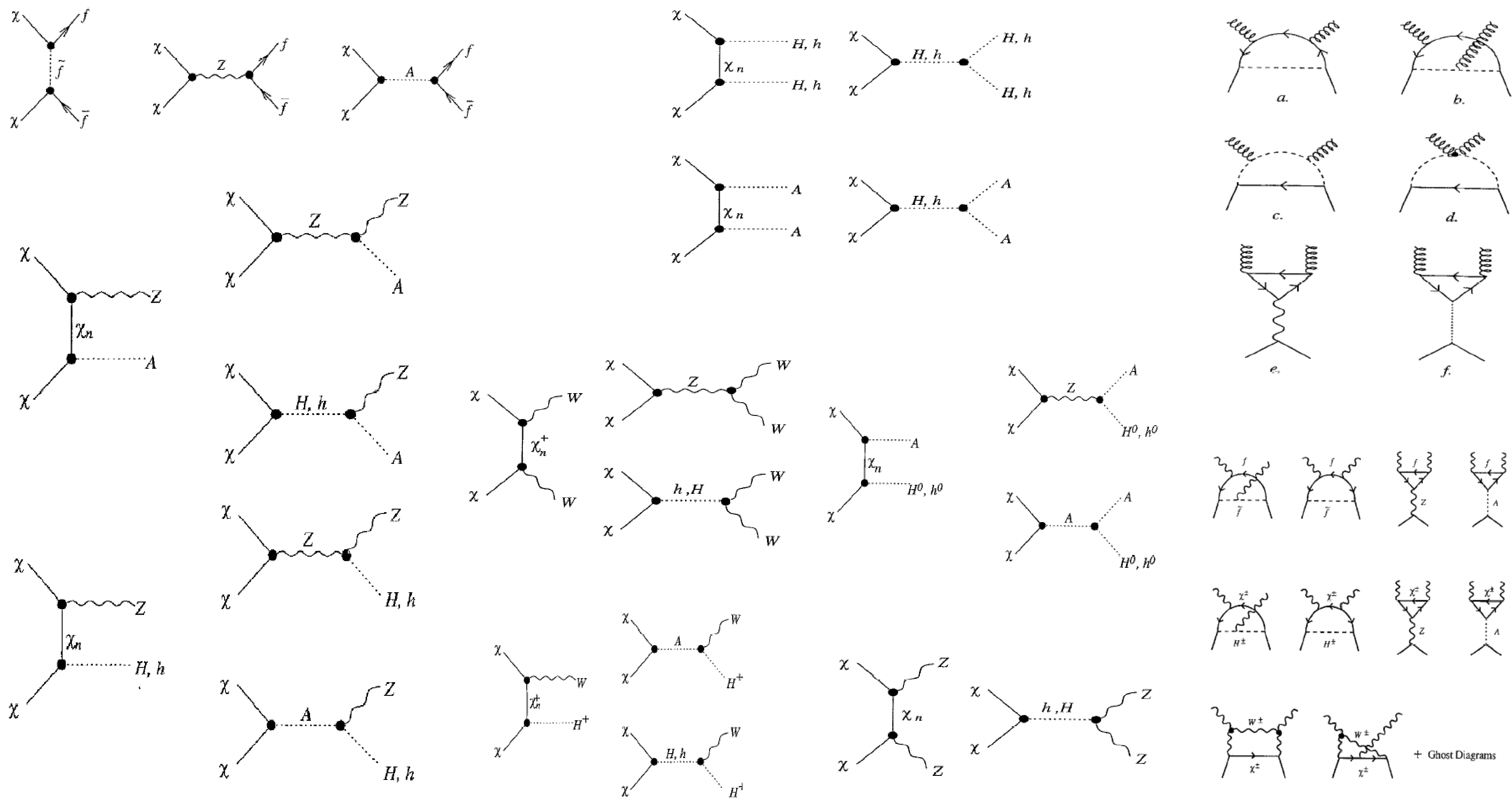
(not present for asymmetric DM)

- Neutrinos made from DM annihilation or decays of annihilation products (long-lived dark mediators?)
- Decay in flight (eg tau) better than decay after stopping (eg muon)
- Need to take into account oscillations through Sun, across 1AU and through Earth
- Use pointing to suppress atmospheric neutrino background



$$\frac{d\Phi^{\mathrm{P}}_{\mu}}{dE_{\mu}} = \int_{E_\mu}^{\infty} dE_\nu \frac{d\Phi_\nu}{dE_\nu}\left[\frac{d\sigma^p_\nu(E_\nu, E_\mu)}{dE_\mu}\rho_p + (p \to n)\right] \times R_\mu(E_\mu) + (\nu \to \bar{\nu}) \ ,$$

DM@Colliders



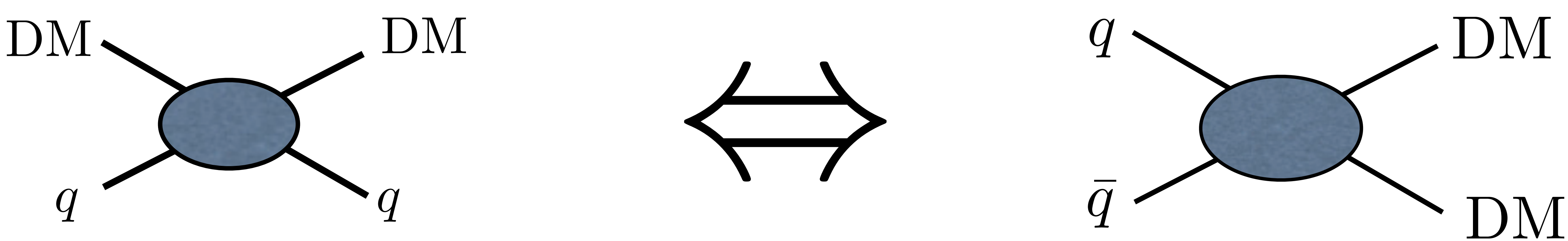
Jungman, Kamionkowski, Griest (1995)

Ways to search for DM at colliders

Beltran et al. [1002.4137]

Consider only the DM is light "Maverick DM", or EFT

Straightforward relationship between DD and collider



"Monojet", monophoton, mono-top, mono-X,....

(really up to 2 jets, with 2 jets not back to back)

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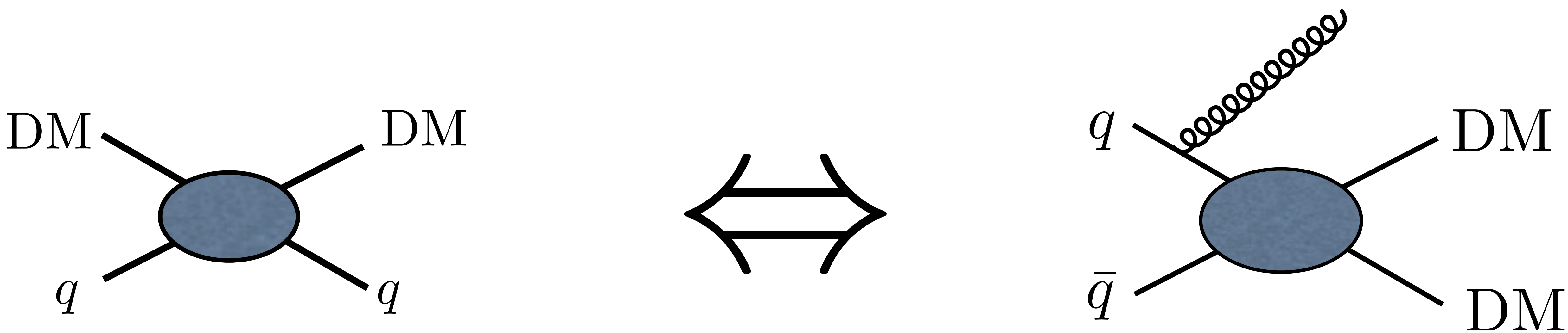

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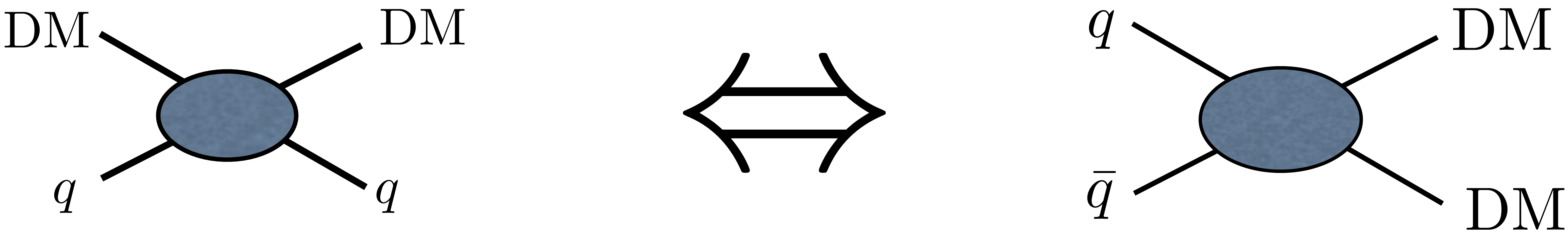
Mono-mania at the LHC

Operators



$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}\,,$$

SI, vector exchange

$$\mathcal{O}_A = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2}\,,$$

SD, axial-vector exchange

$$\mathcal{O}_t = \frac{(\bar{\chi}P_R q)(\bar{q}P_L\chi)}{\Lambda^2} + (L \leftrightarrow R)\,,$$

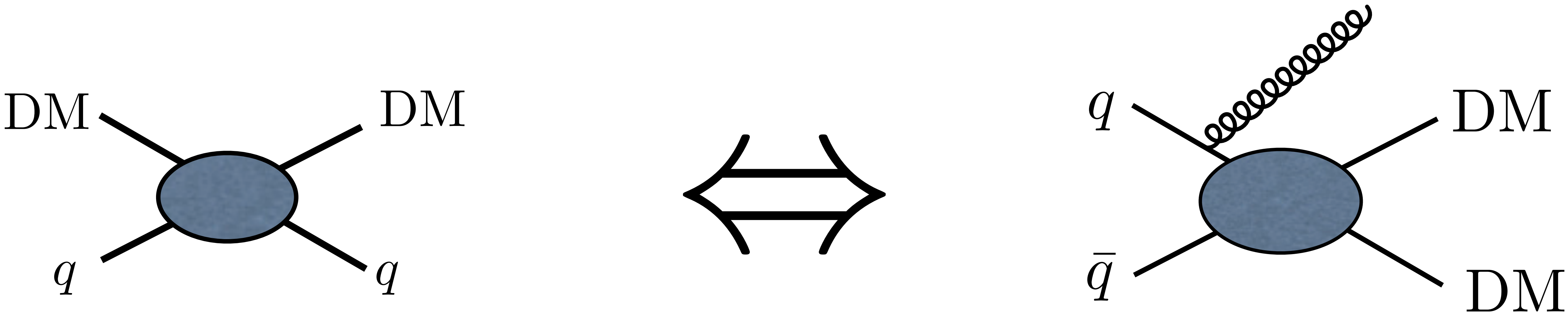
SI, scalar exchange

$$\mathcal{O}_g = \alpha_s \frac{(\bar{\chi}\chi)\left(G^a_{\mu\nu}G^{a\mu\nu}\right)}{\Lambda^3}$$

SI, scalar exchange

Typically consider each operator separately

Operators



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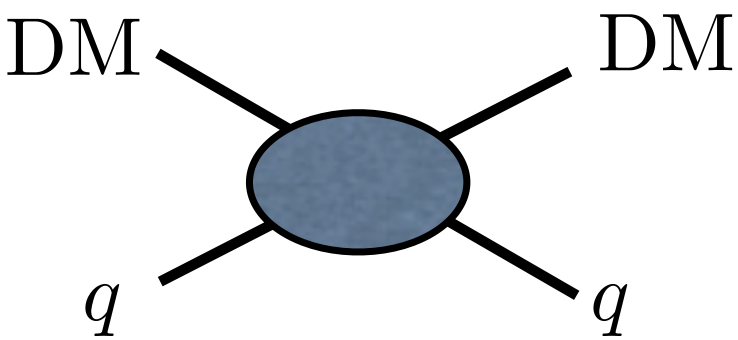
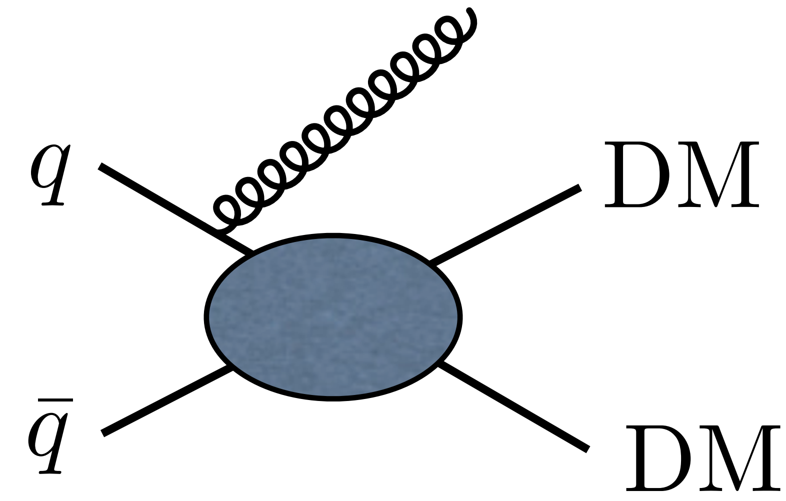


$\Leftrightarrow$



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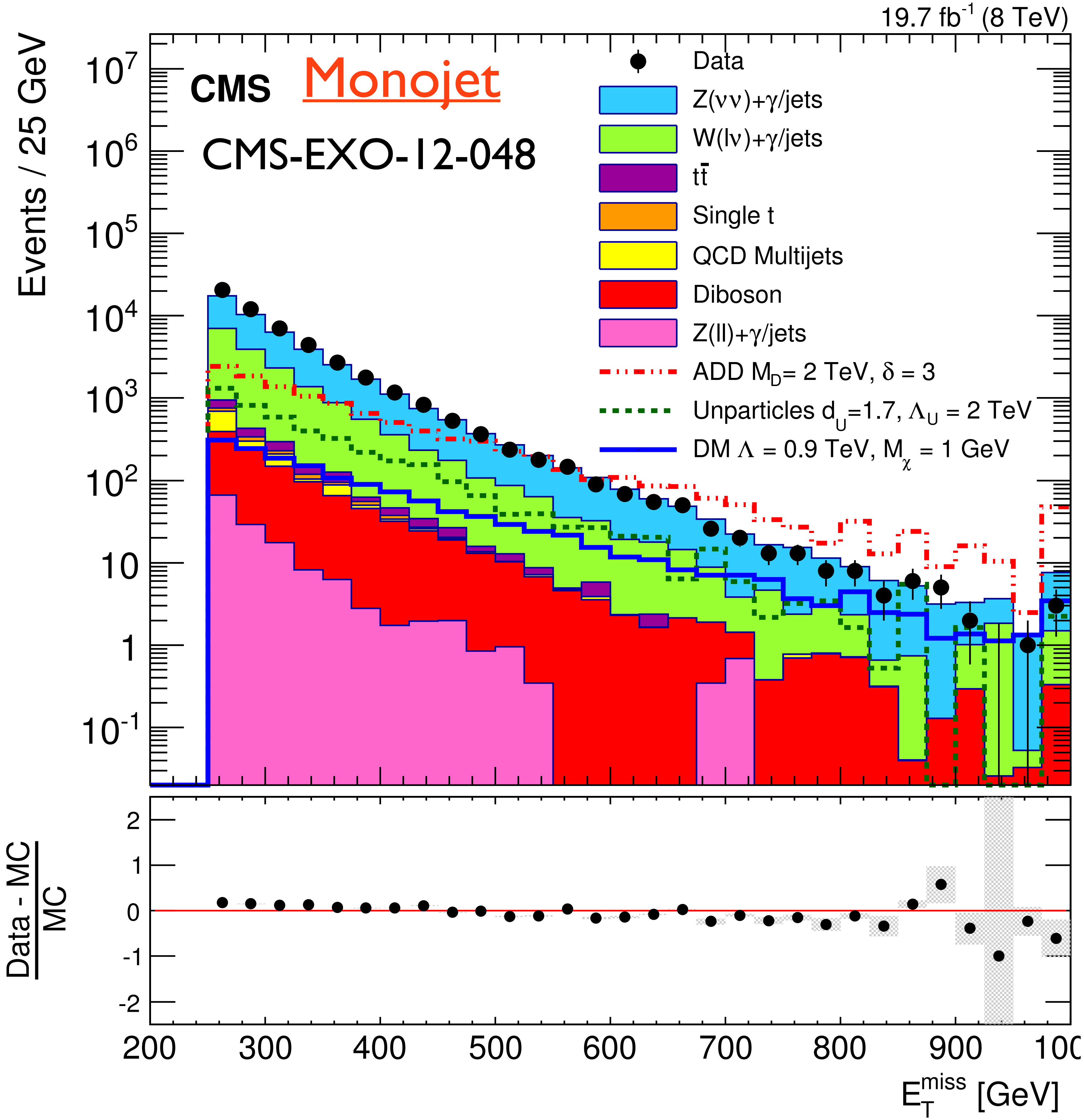
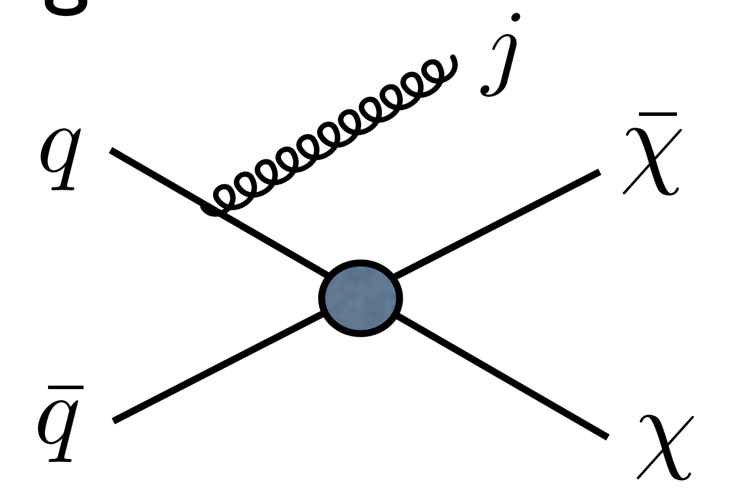
SI, scalar exchange

See Goodman et al. [1008.1783] for more complete list

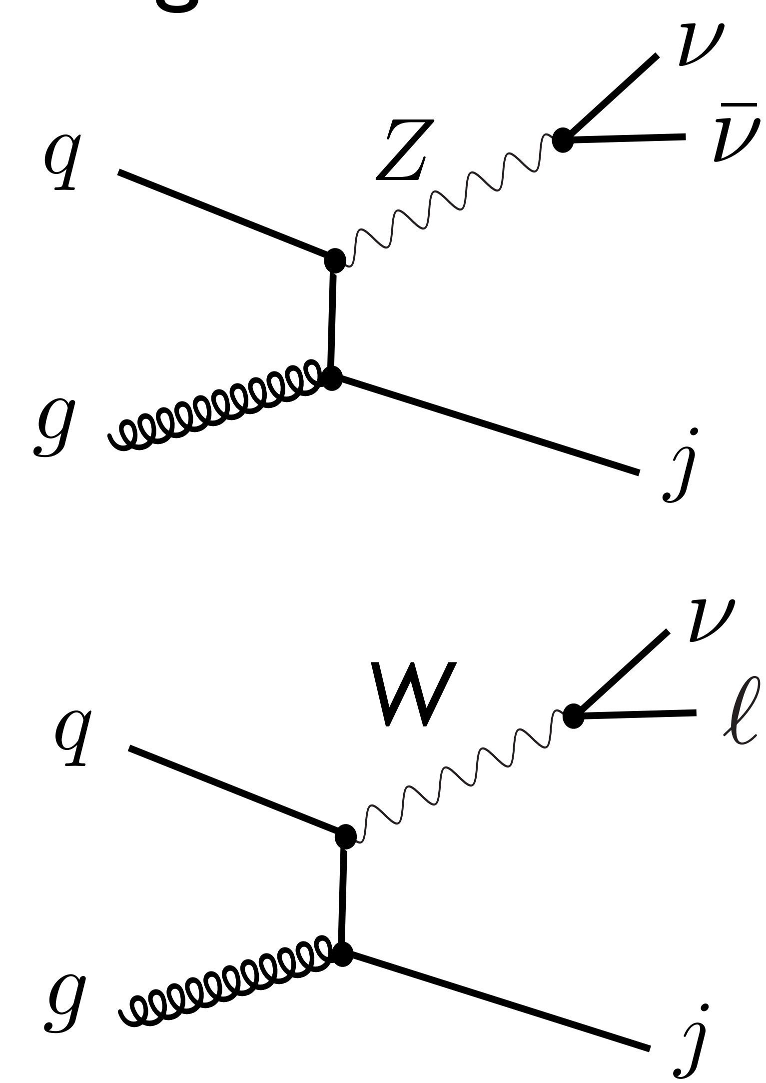
Typically consider each operator separately



Signal:



(Dominant) Backgrounds:



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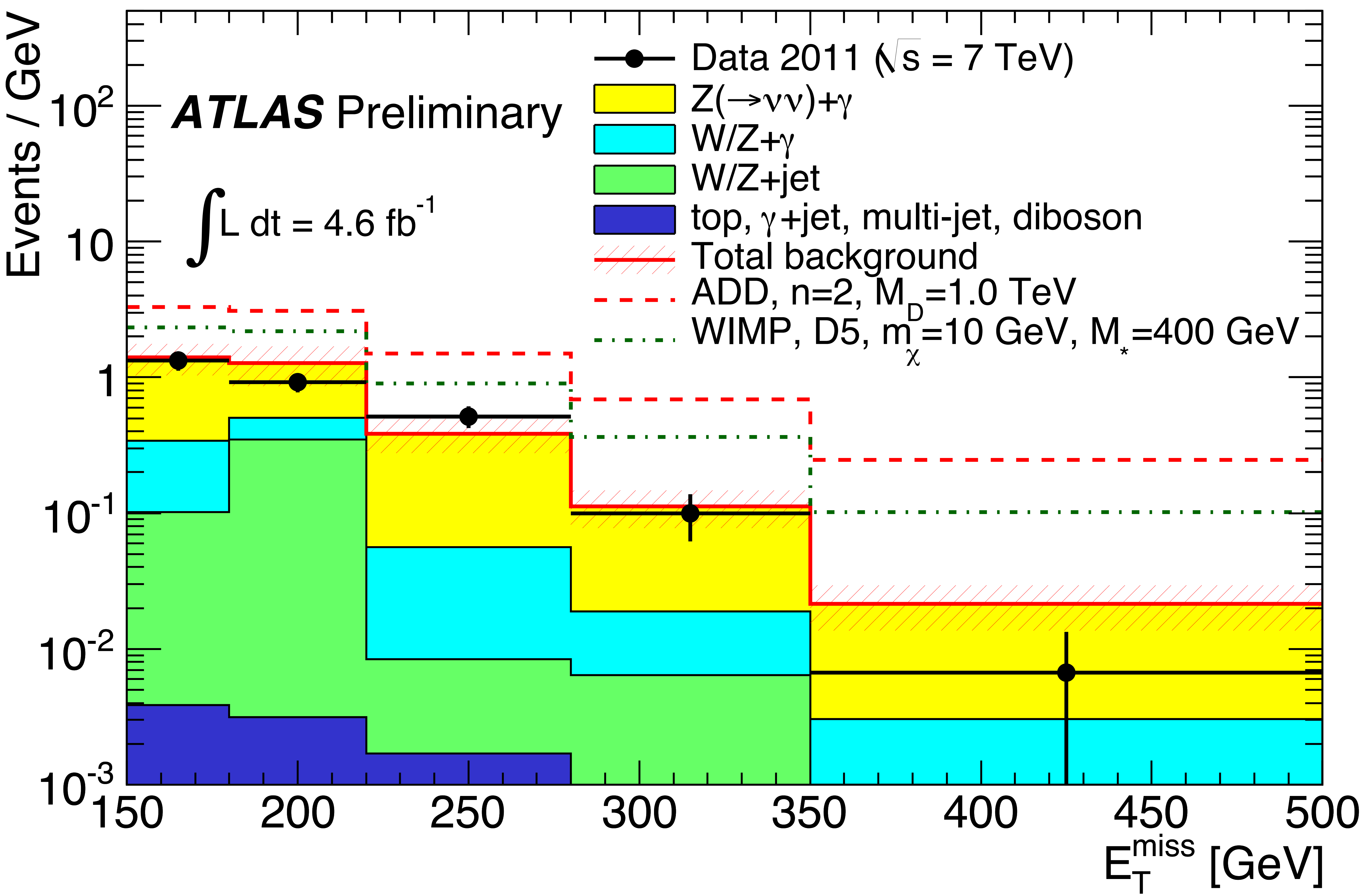
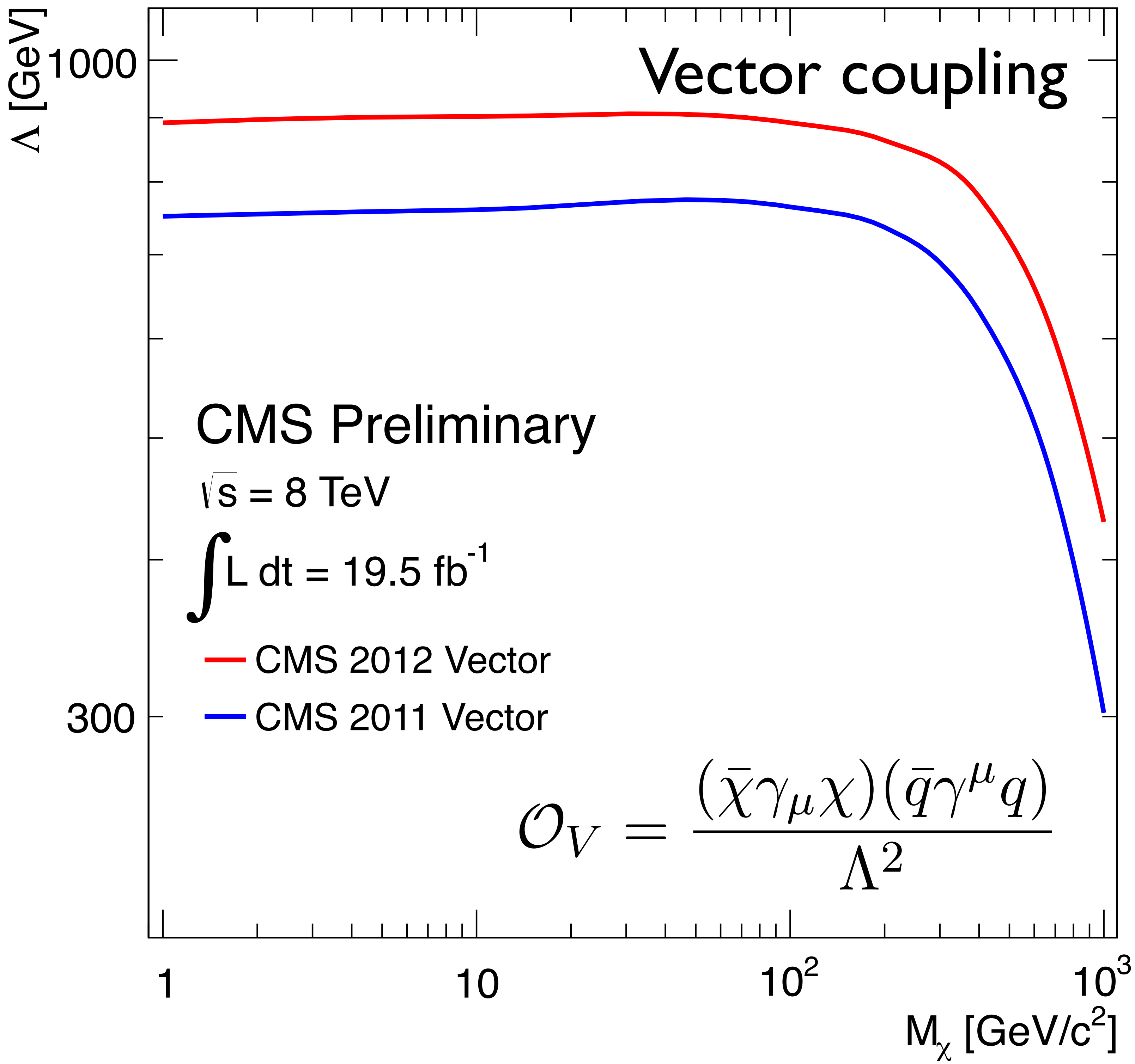
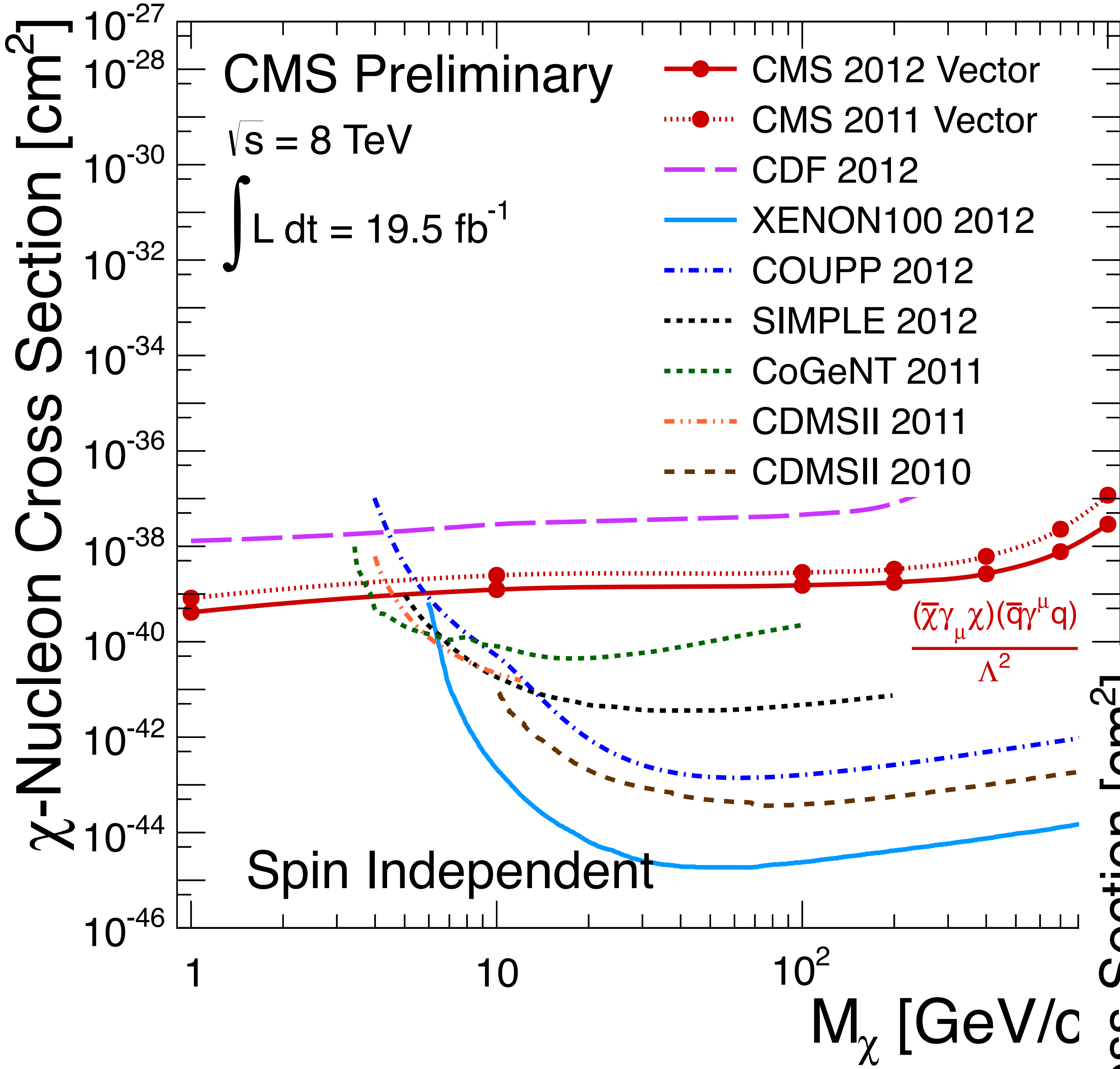
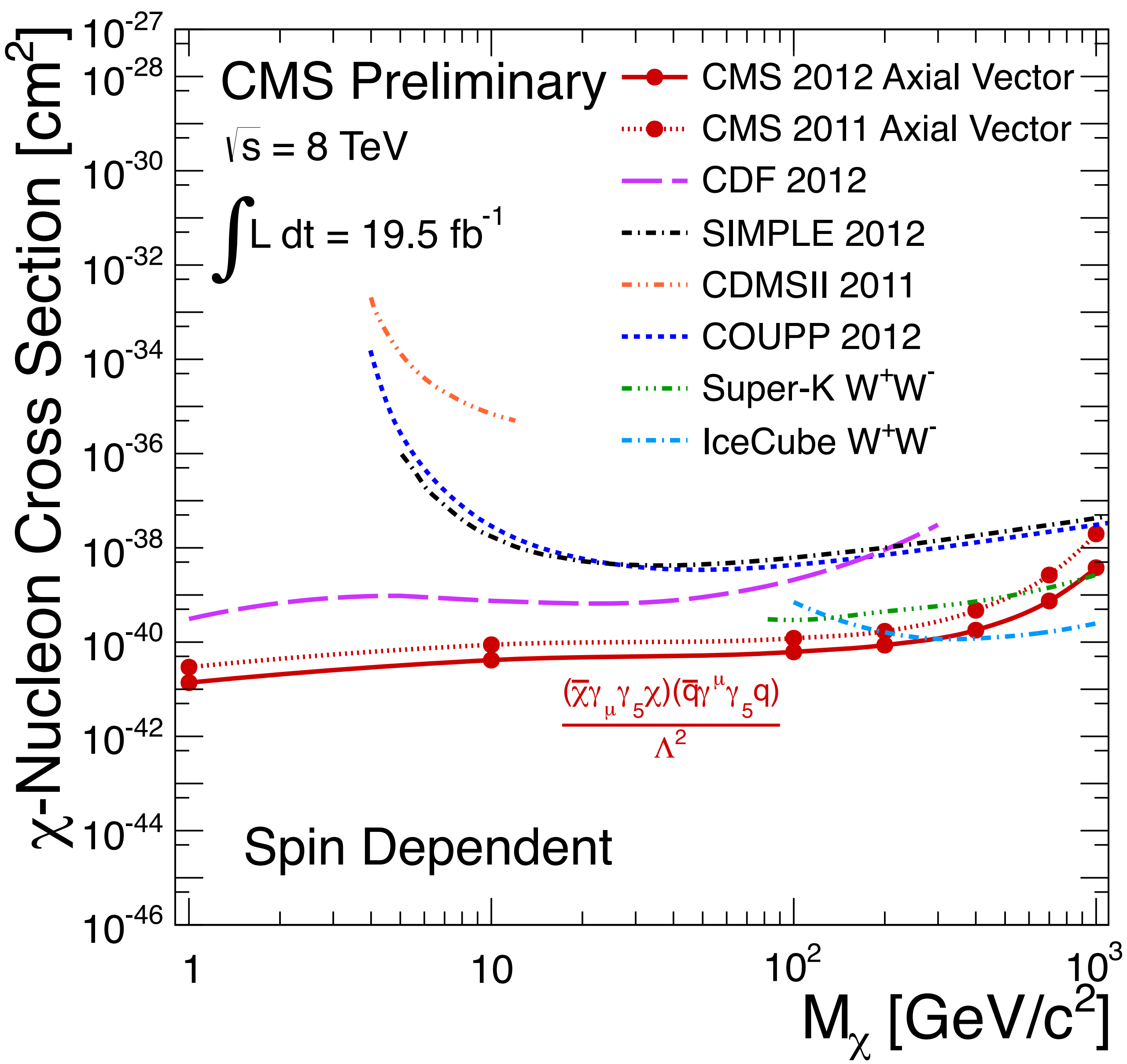
Monophoton



How to quantify nothing?







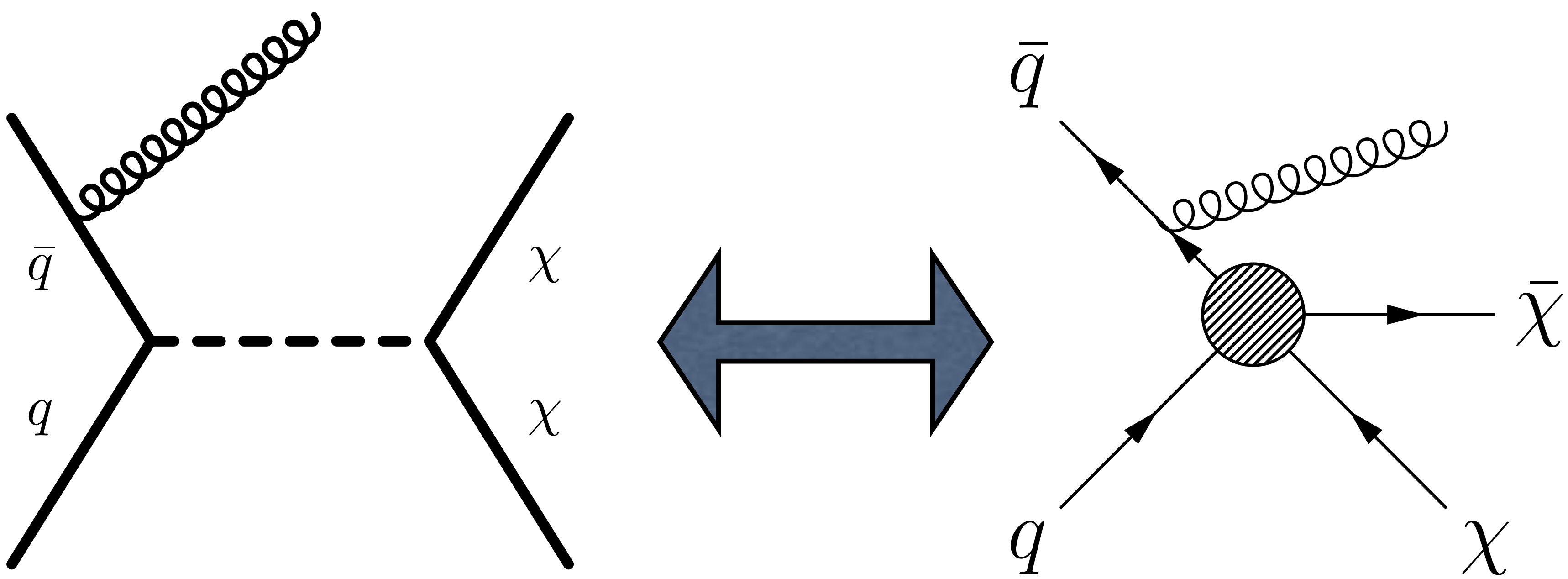
Colliders give complementary constraint at low mass and for SD

Light Mediators

For all but the lightest mediators EFT is good for direct detection

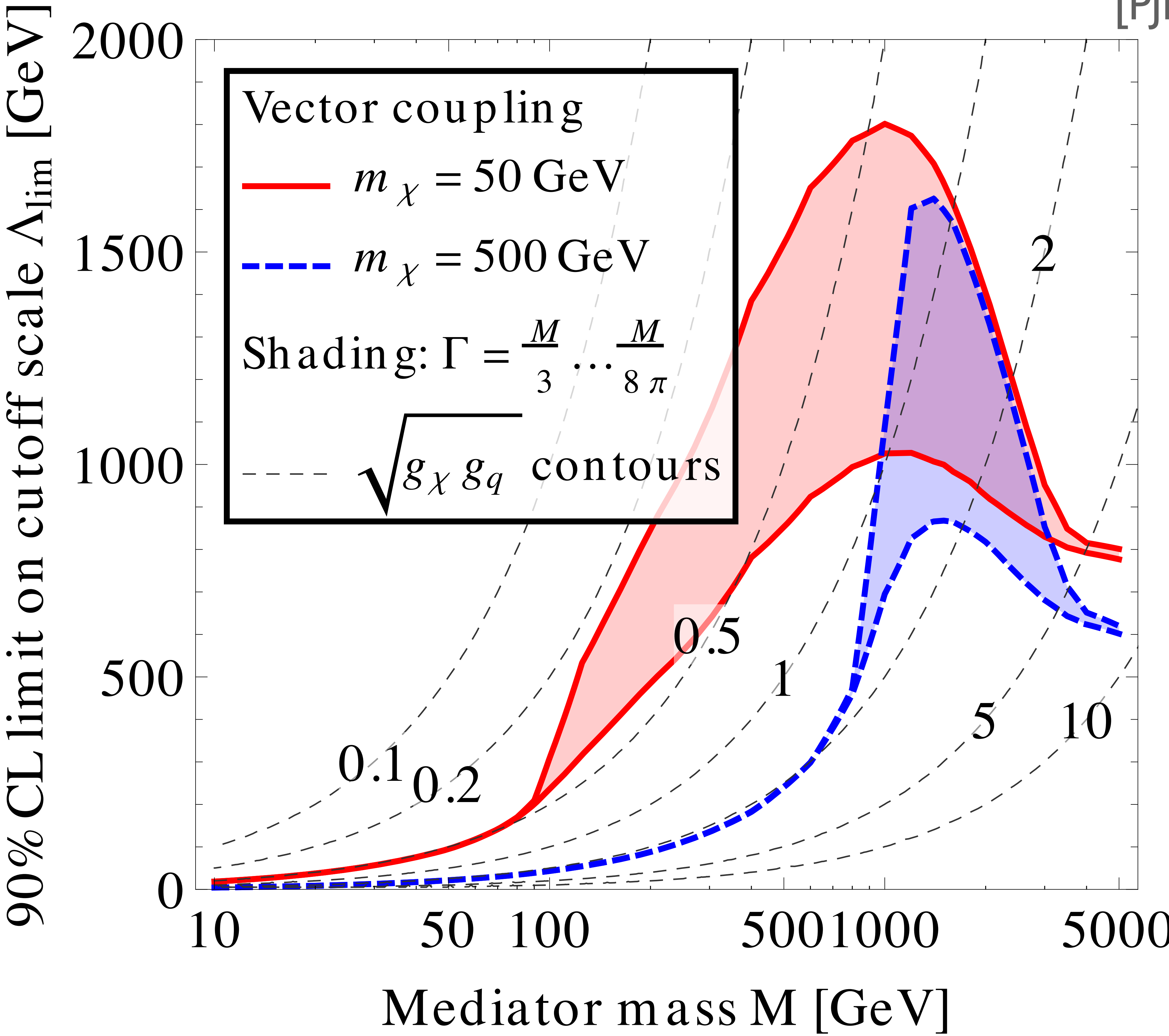
$$\sigma(\chi N \to \chi N) \sim \frac{g_q^2 g_\chi^2}{M^4} \mu_{\chi N}^2$$

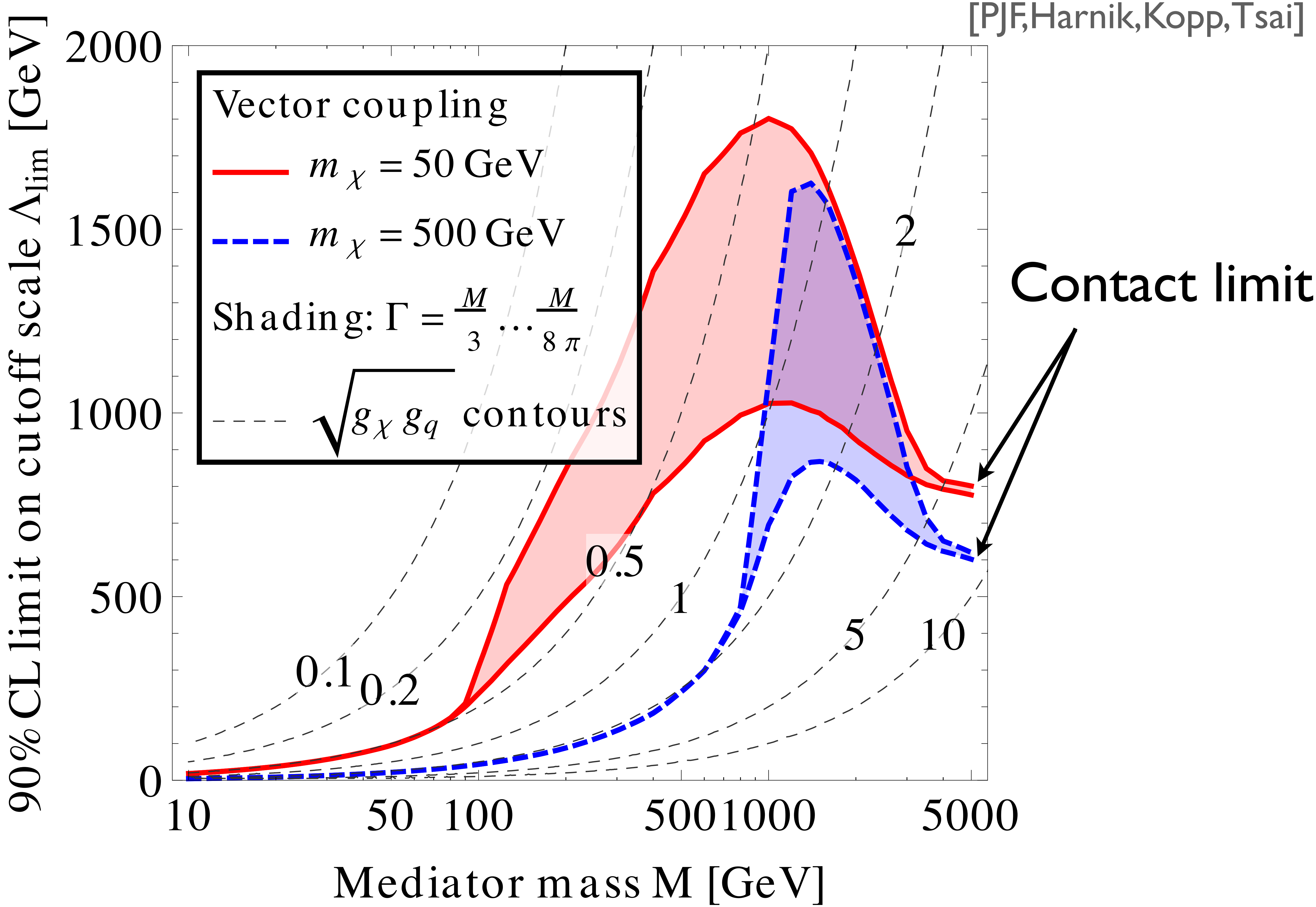
What fraction of collider events have momentum transfers sufficient to probe the UV completion?



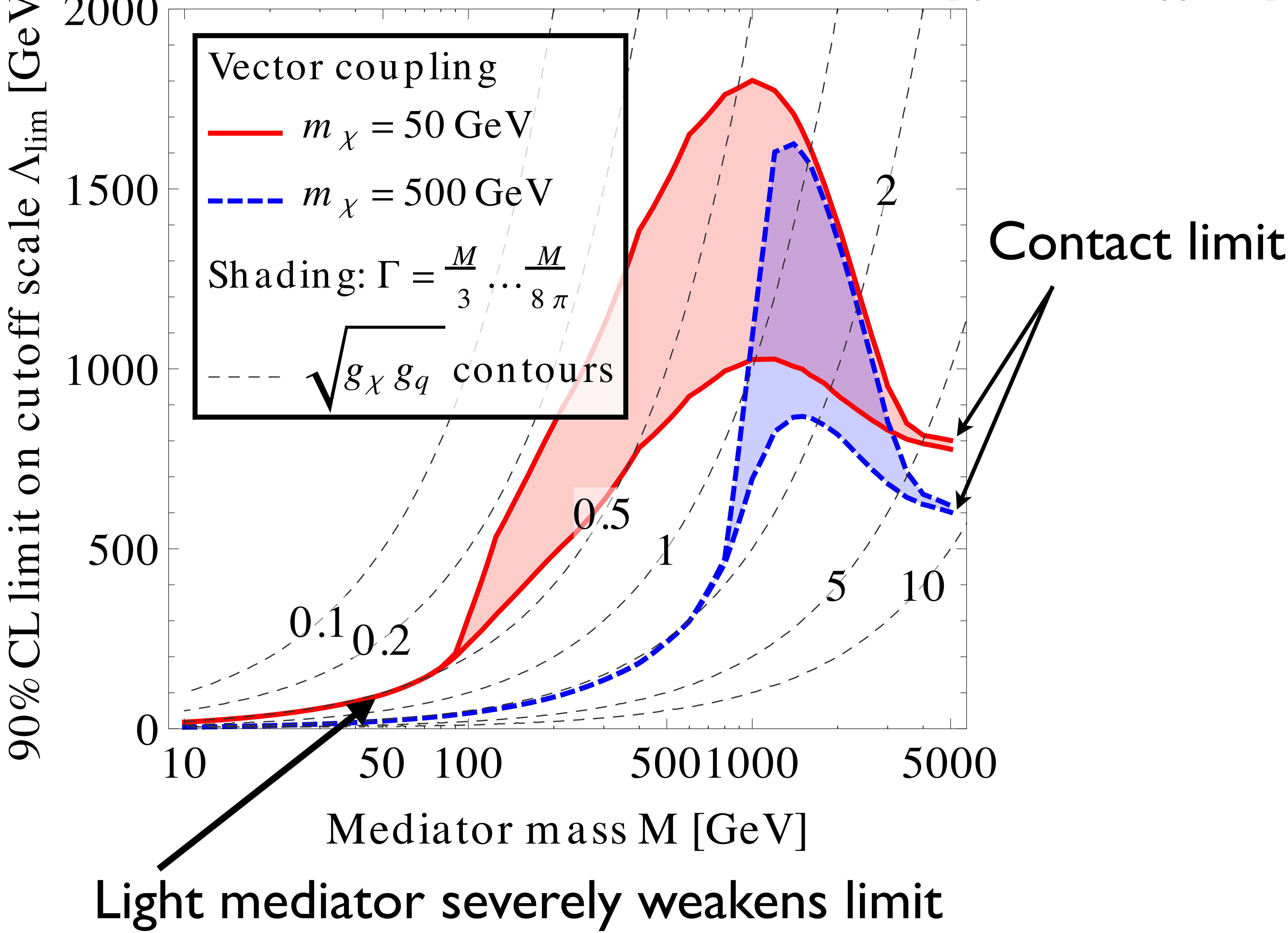
$$\frac{g_q g_\chi}{q^2 - M^2} \xrightarrow{q^2 \ll M^2} \frac{1}{\Lambda^2} \qquad \Lambda^2 = \frac{M^2}{g_q g_\chi}$$

[PJF,Harnik,Kopp,Tsai]





[PJF,Harnik,Kopp,Tsai]
Vector coupling
$m_\chi = 50$ GeV
$m_\chi = 500$ GeV
Shading: $\Gamma = \frac{M}{3} \dots \frac{M}{8\pi}$
$\sqrt{g_\chi g_q}$ contours
0.1
0.2
0.5
1
2
5
10
Contact limit
90% CL limit on cutoff scale $\Lambda_{\rm lim}$ [GeV]
Mediator mass M [GeV]
0
500
1000
1500
2000
10
50
100
500
1000
5000



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2000
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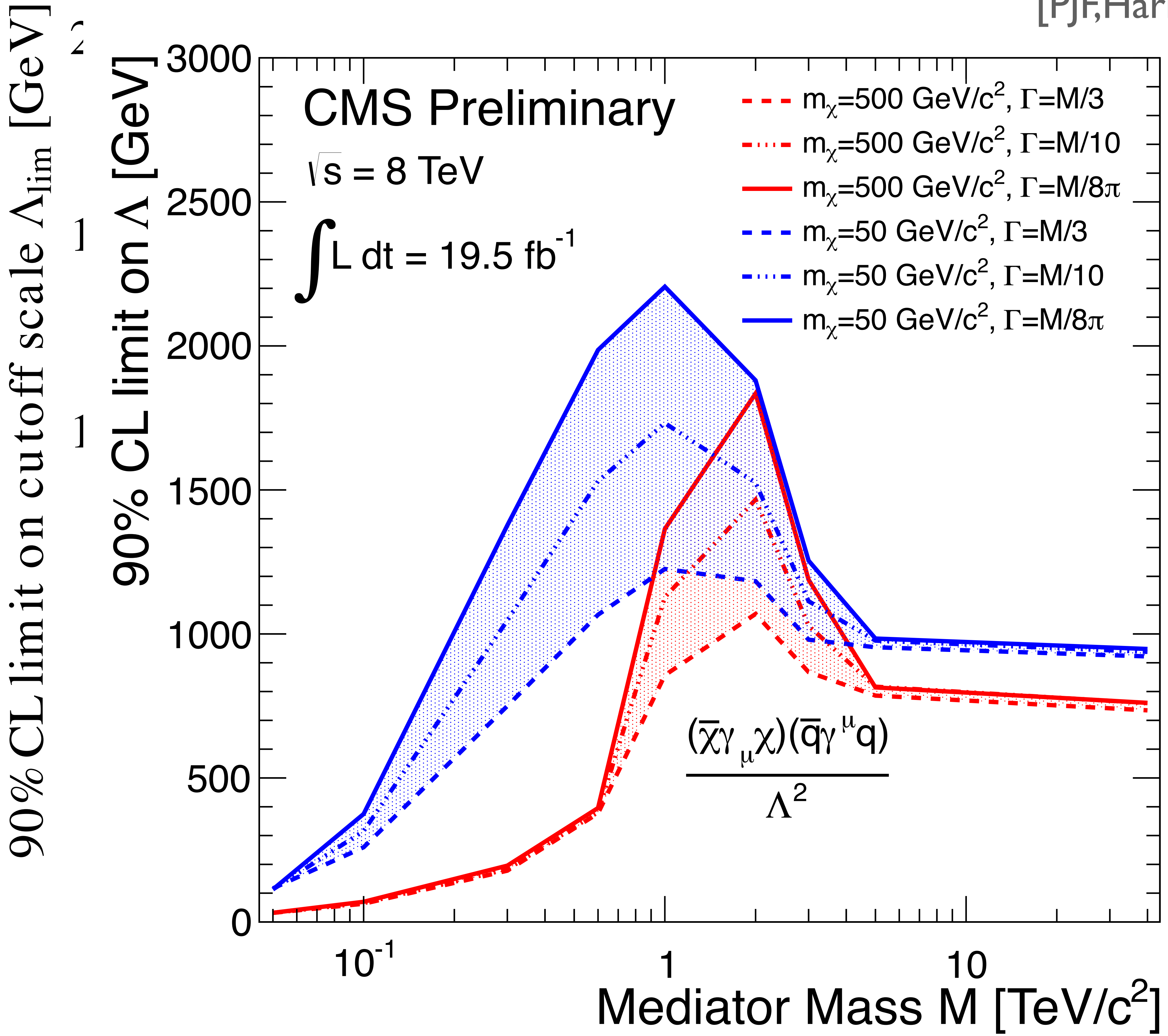
1000
500
0
10
50
100
500
1000
5000
Mediator mass M [GeV]
0.1
0.2
0.5
1
2
5
10
Contact limit
Light mediator severely weakens limit

[PJF,Harnik,Kopp,Tsai]



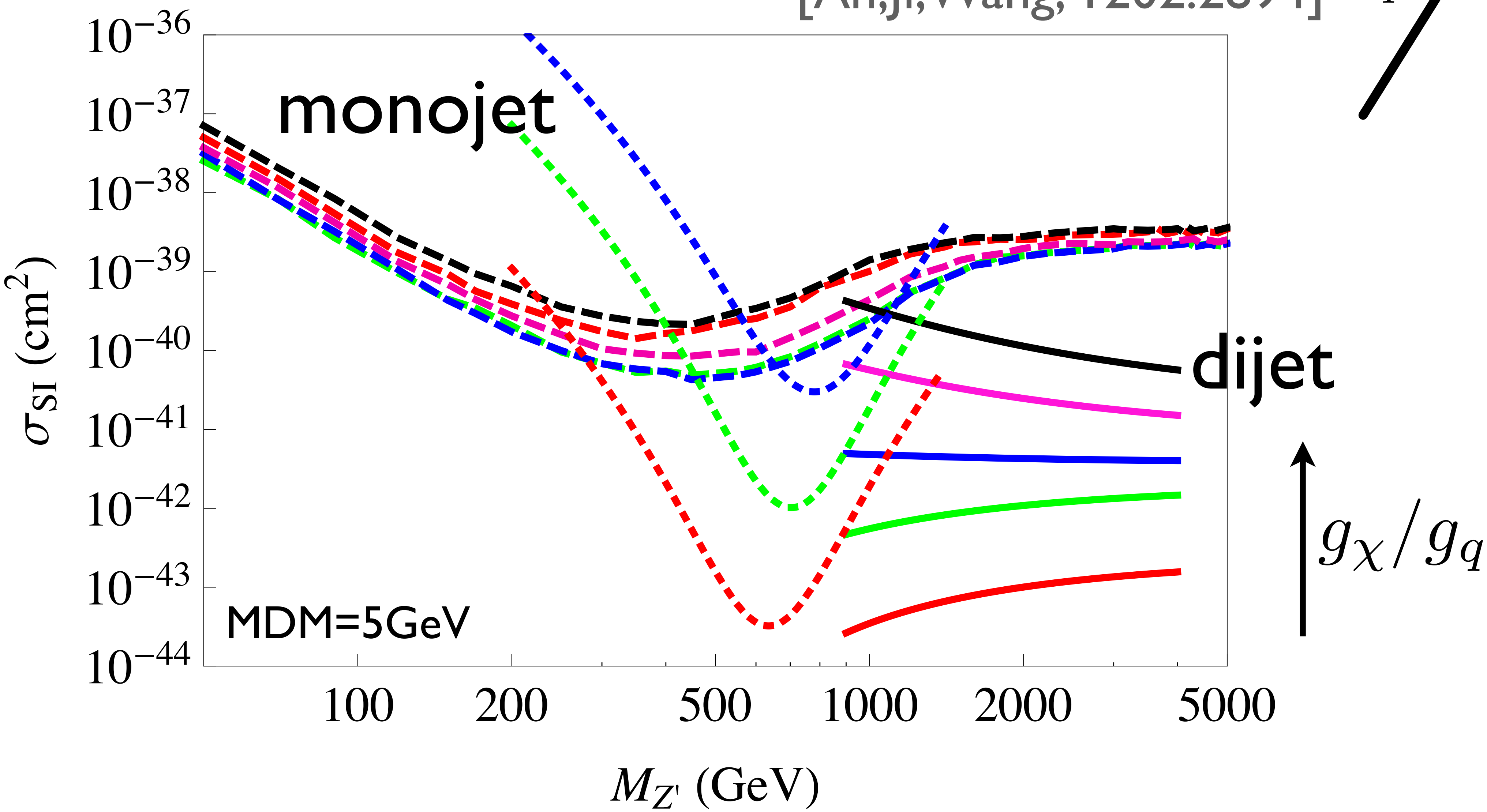
ıtact limit

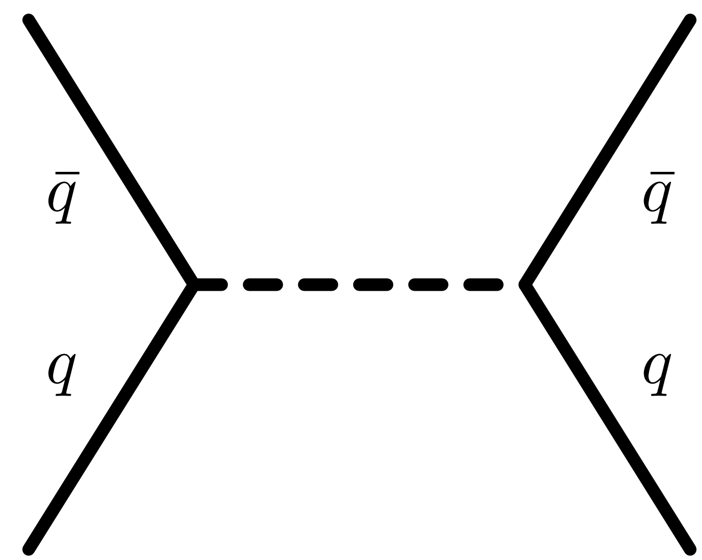
Light Mediators

[An,Ji,Wang:1202.2894;March-Russell, Unwin,West: 1203.4854]

Look for the light mediator directly-dijet resonance/angular distributions

[An,Ji,Wang, 1202.2894]





Light Mediators

[An,Ji,Wang:1202.2894;March-Russell, Unwin,West: 1203.4854]

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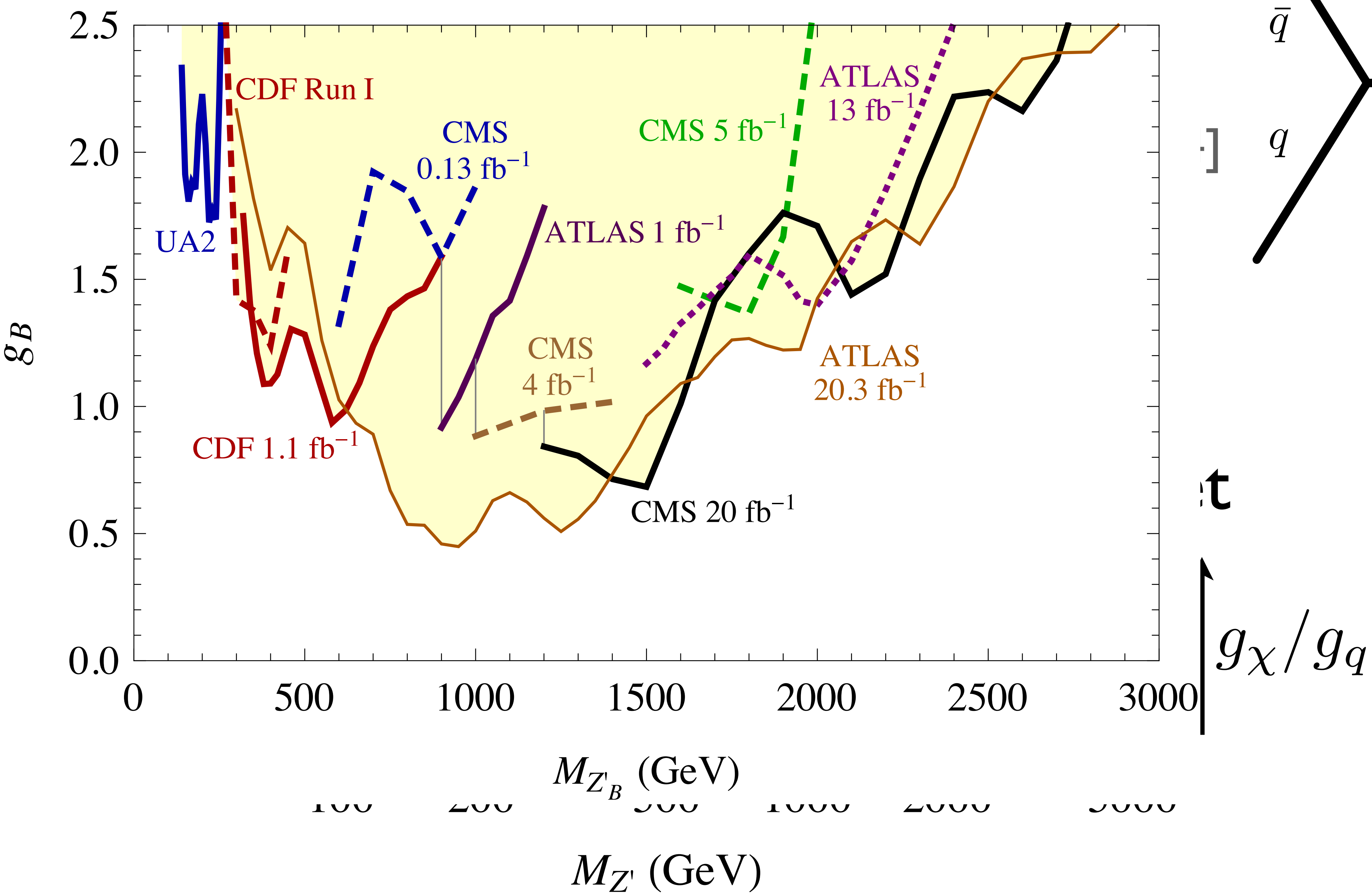

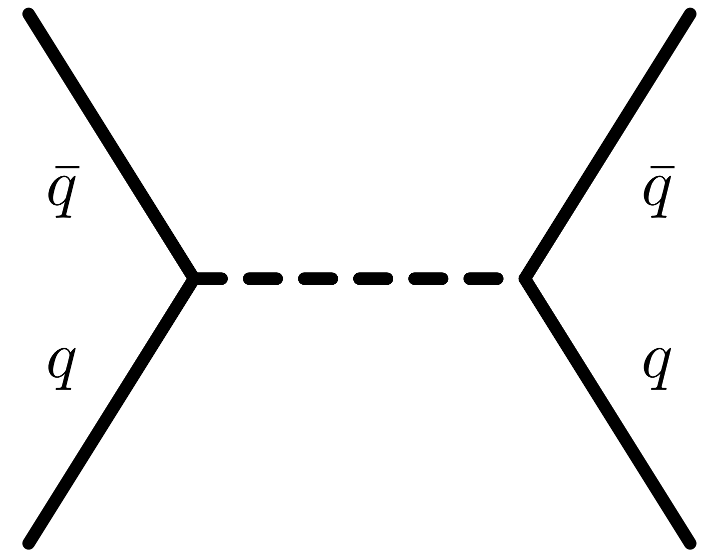

Light Mediators

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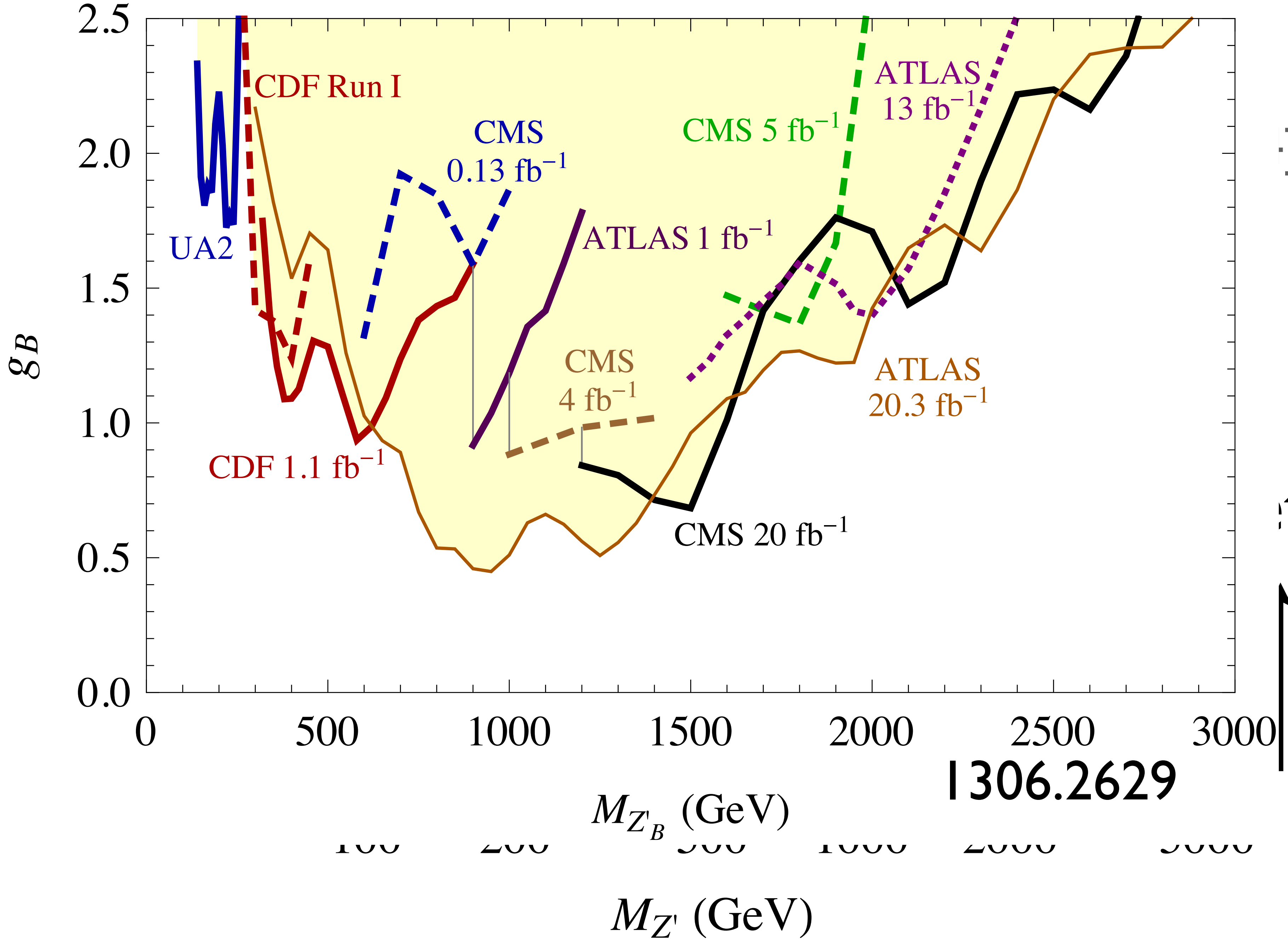

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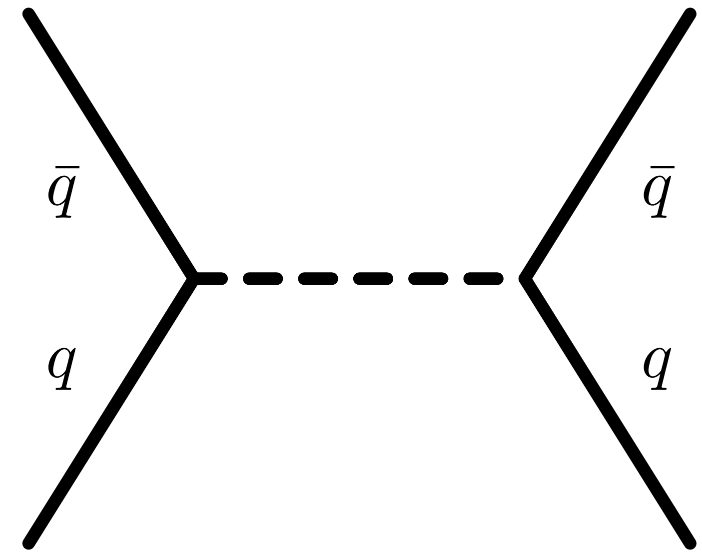
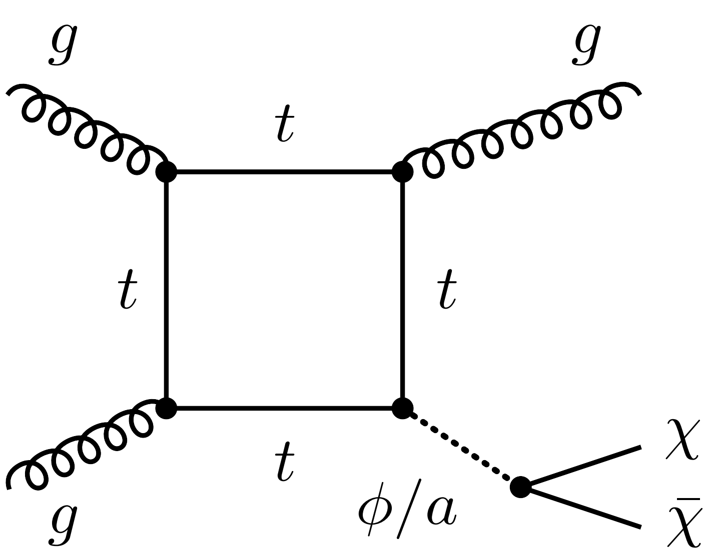


g_χ/g_q

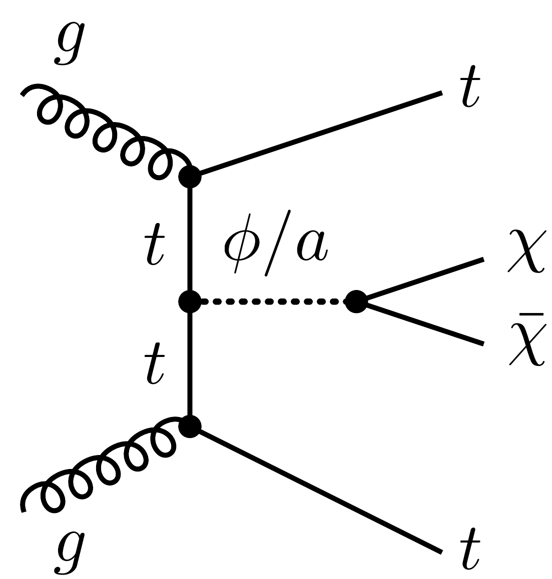
Types of Simplified models

-channel scalar/psuedo-scalar

MFV: $\lambda_\chi \phi \bar{\chi}\chi + \lambda_U \phi \left(Y_U^{ij} Q_i H U_j^c \right)$ Physics dominated by top



monojet



tops + MET

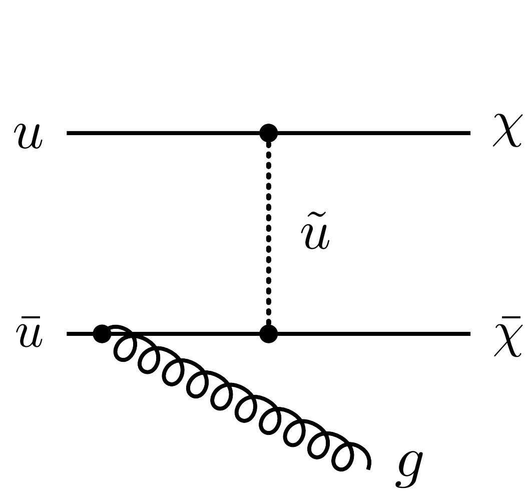
- Scalars have helicity suppressed annihilation, and SI DD
- Pseudo scalars do not, and have SD momentum suppressed DD

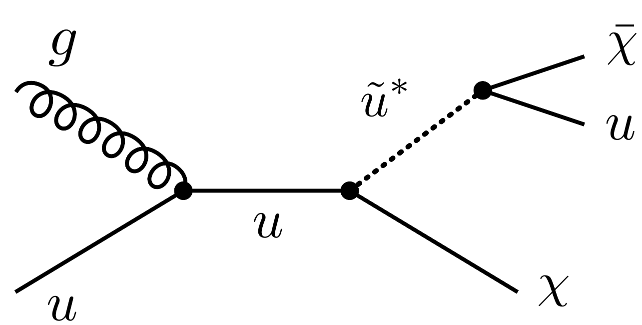
Types of Simplified models

-channel scalar/psuedo-scalar

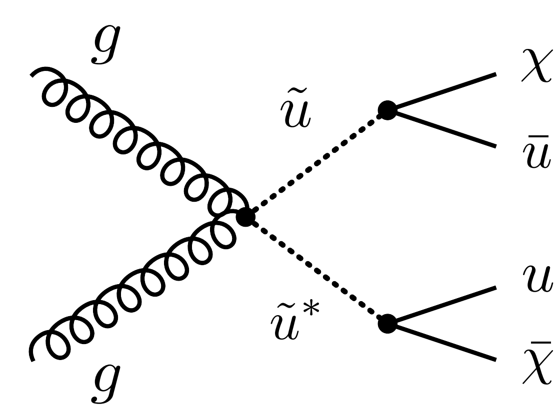
MFV requires DM or mediator to carry flavour $\lambda \phi_i \bar{\chi} q_i$

(Like in SUSY MFV allows for separation of 1,2 from 3 gen.)





monojet



jets+MET

Majorana has only SD, Dirac has both
Dirac cannot be a thermal relic, Majorana can if > 100 GeV

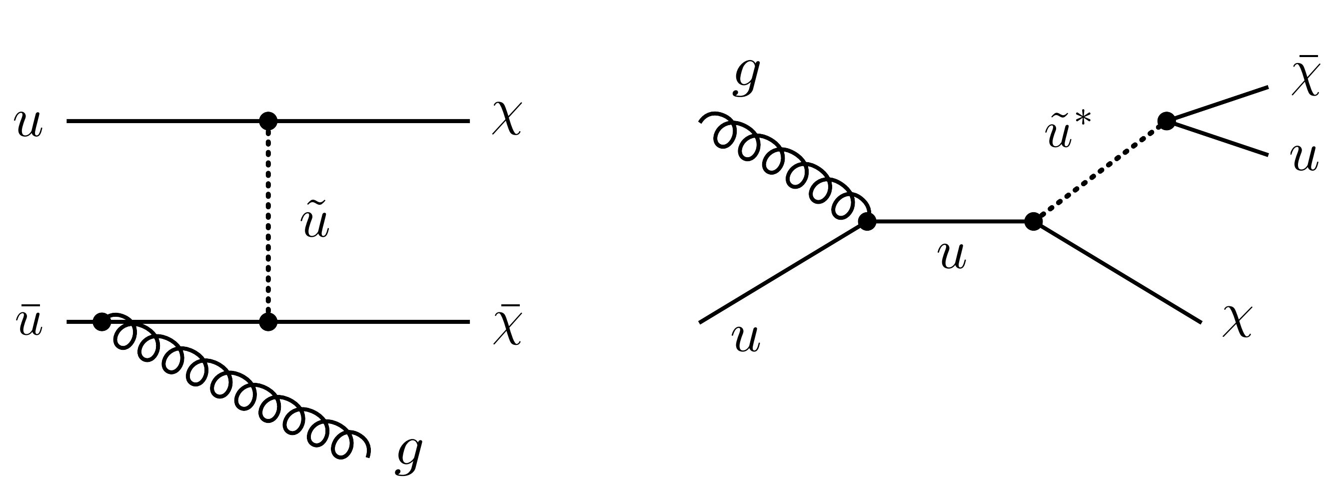
Types of Simplified models

-channel scalar/psuedo-scalar

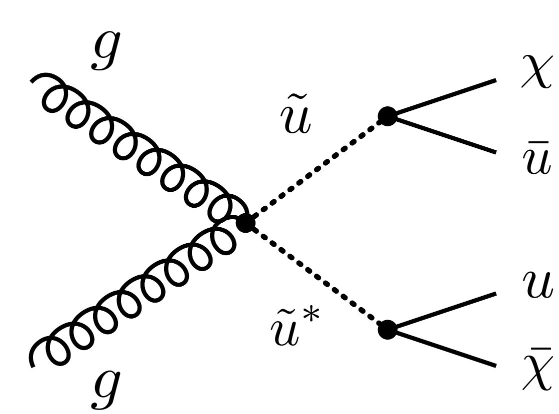
“squarks” w/o SUSY prior

MFV requires DM or mediator to c … flavour $\lambda\phi_i\bar{\chi}q_i$

(Like in SUSY MFV allows for separation of 1,2 from 3 gen.)



monojet



jets+MET

Majorana has only SD, Dirac has both

Dirac cannot be a thermal relic, Majorana can if > 100 GeV

Types of Simplified models

s-channel vector/axial-scalar

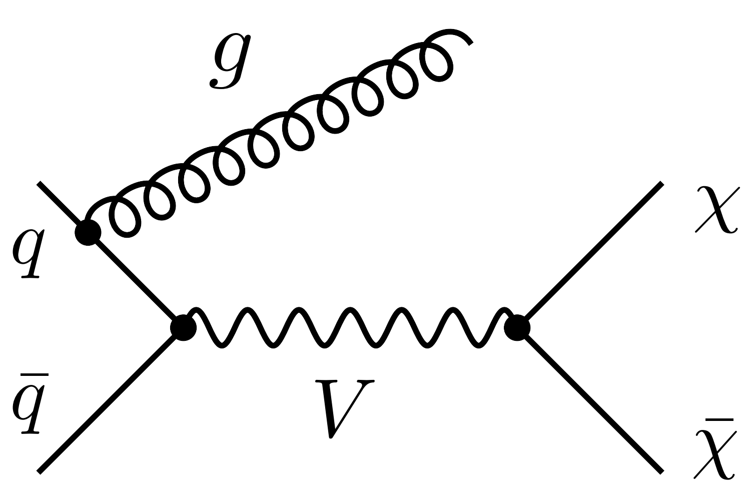
Spontaneously broken $U(1)'$

(Higgs mode may be accessible, can alter physics)

Consistency of model? How does DM get mass, anomalies…

$$m_\chi \lesssim \frac{\sqrt{4\pi}}{g_\chi^A} M_V$$

Bounds on dileptons, leptophobic Z'



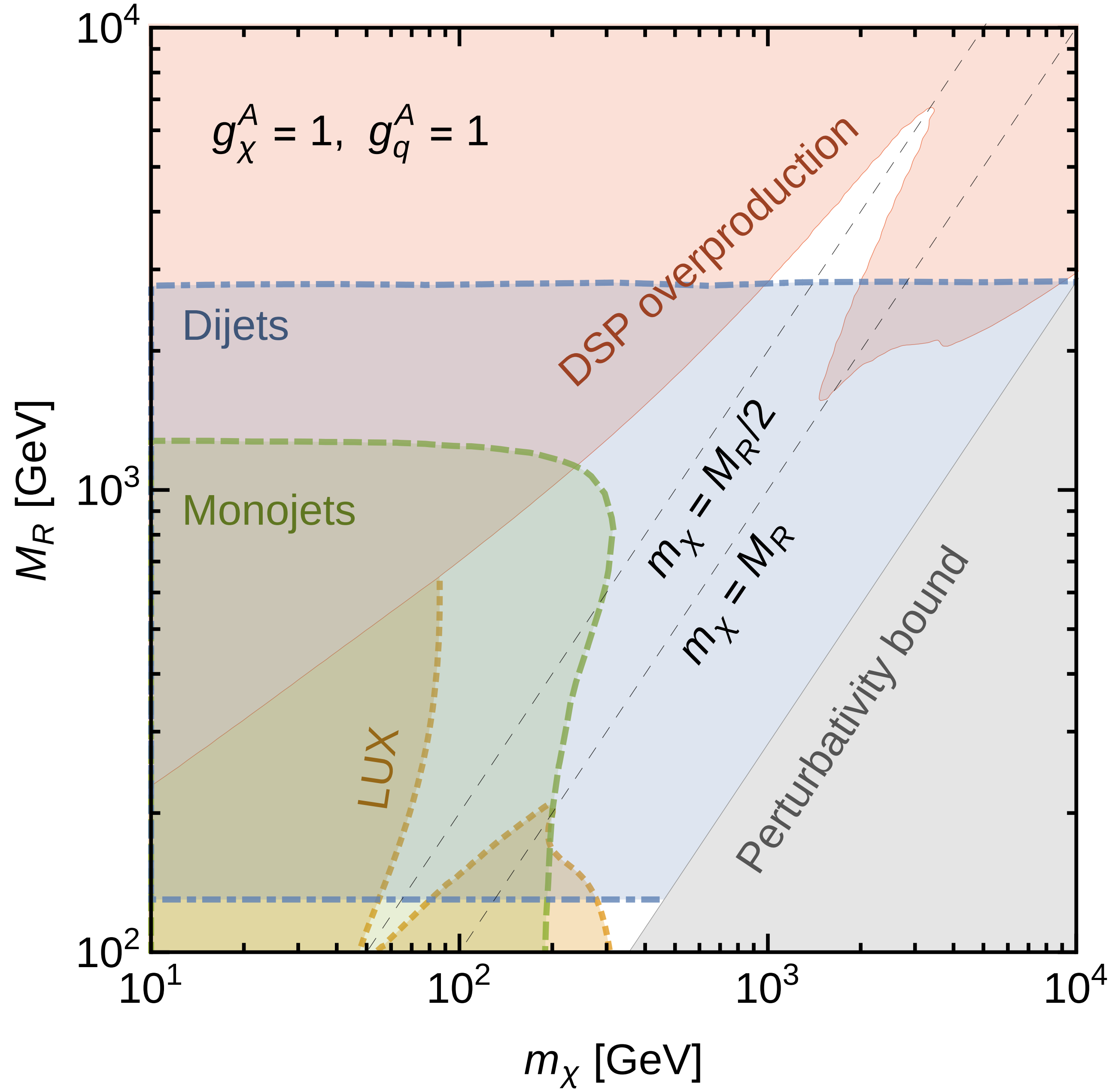
monojet

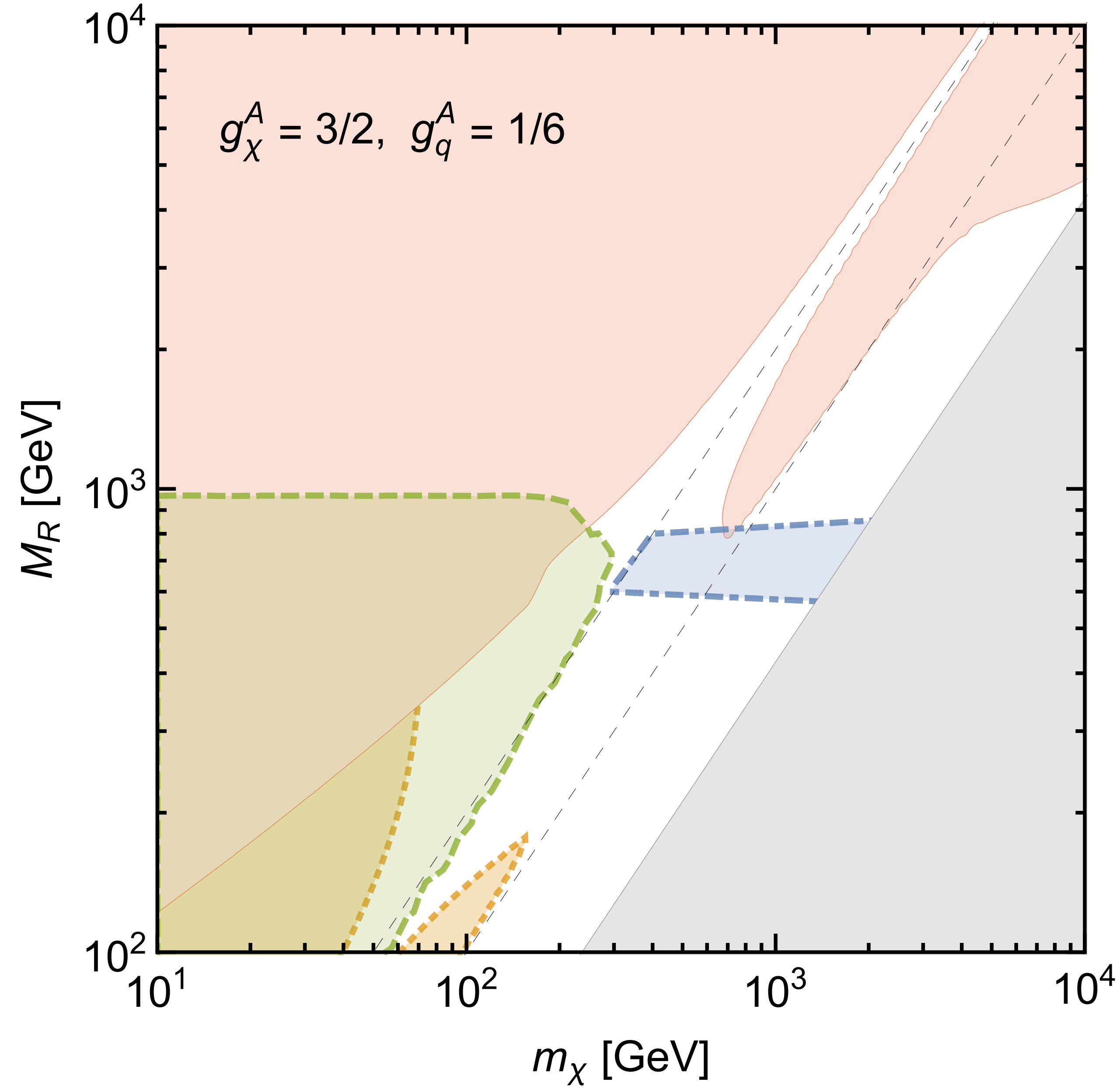
- Vectors are SI
- Axial vectors SD
- If thermal often underproduced

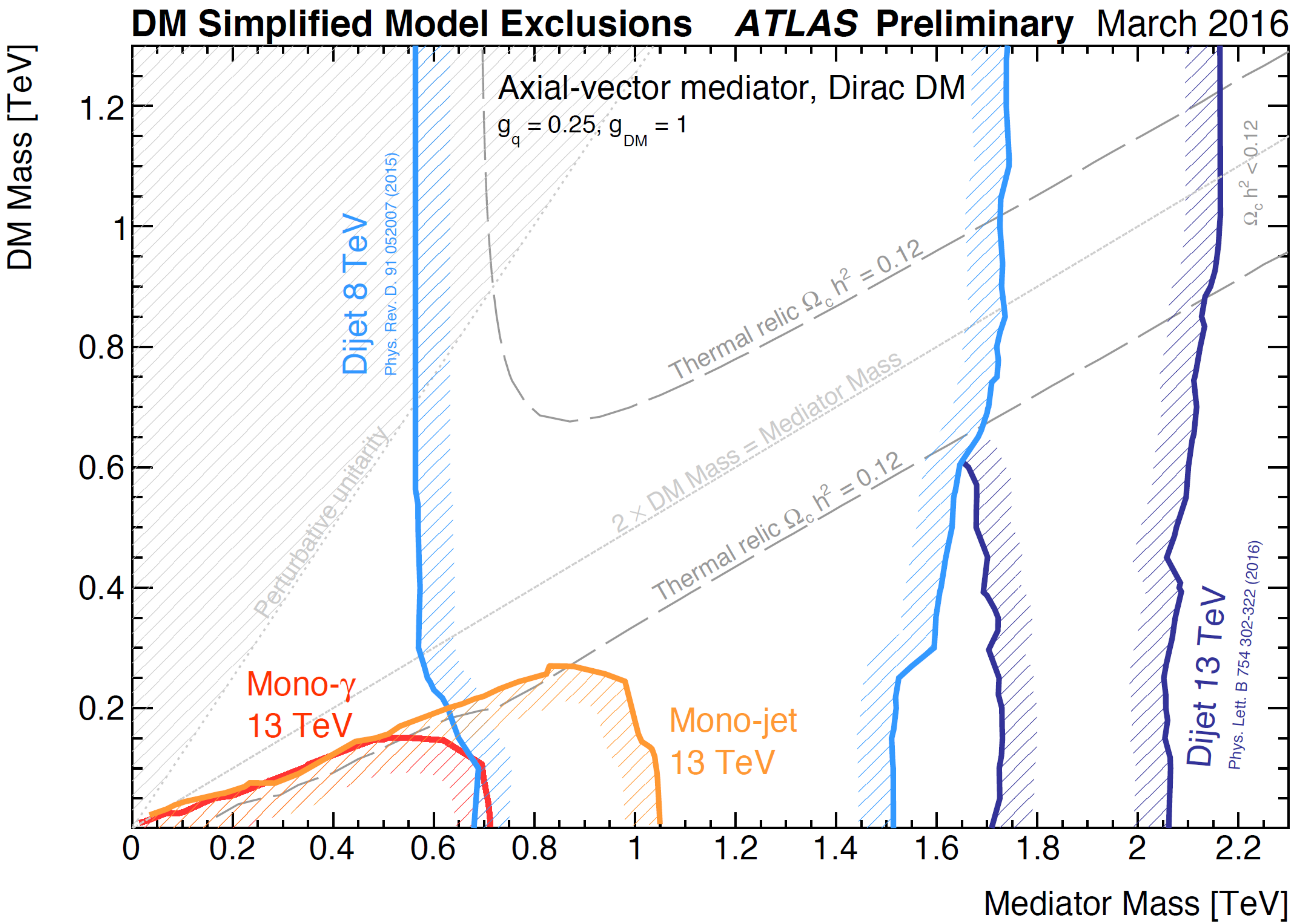
Types of Simplified models

- Landscape of simplified models is broad and varied
- Spin/parity of DM and mediator
- MFV
- Kinetic mixing
- Higgs portal
- Vector DM
- Other dark sector states alter thermal history & BRs
- Electroweak-inos, singlet-doublet DM, etc

[Chala, Kahlhoefer, McCullough, Nardini, Schmidt-Hoberg]



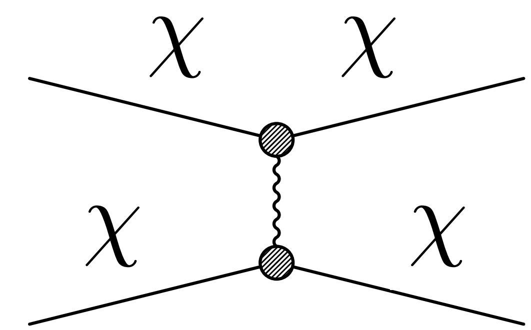




DM Simplified Model Exclusions
ATLAS Preliminary
March 2016
Axial-vector mediator, Dirac DM
g_q = 0.25, g_DM = 1
DM Mass [TeV]
Mediator Mass [TeV]
Dijet 8 TeV
Phys. Rev. D. 91 052007 (2015)
Dijet 13 TeV
Phys. Lett. B 754 302-322 (2016)
Mono-γ
13 TeV
Mono-jet
13 TeV
Thermal relic Ω_c h² = 0.12
2 × DM Mass = Mediator Mass
Perturbative unitarity
Ω_c h² < 0.12

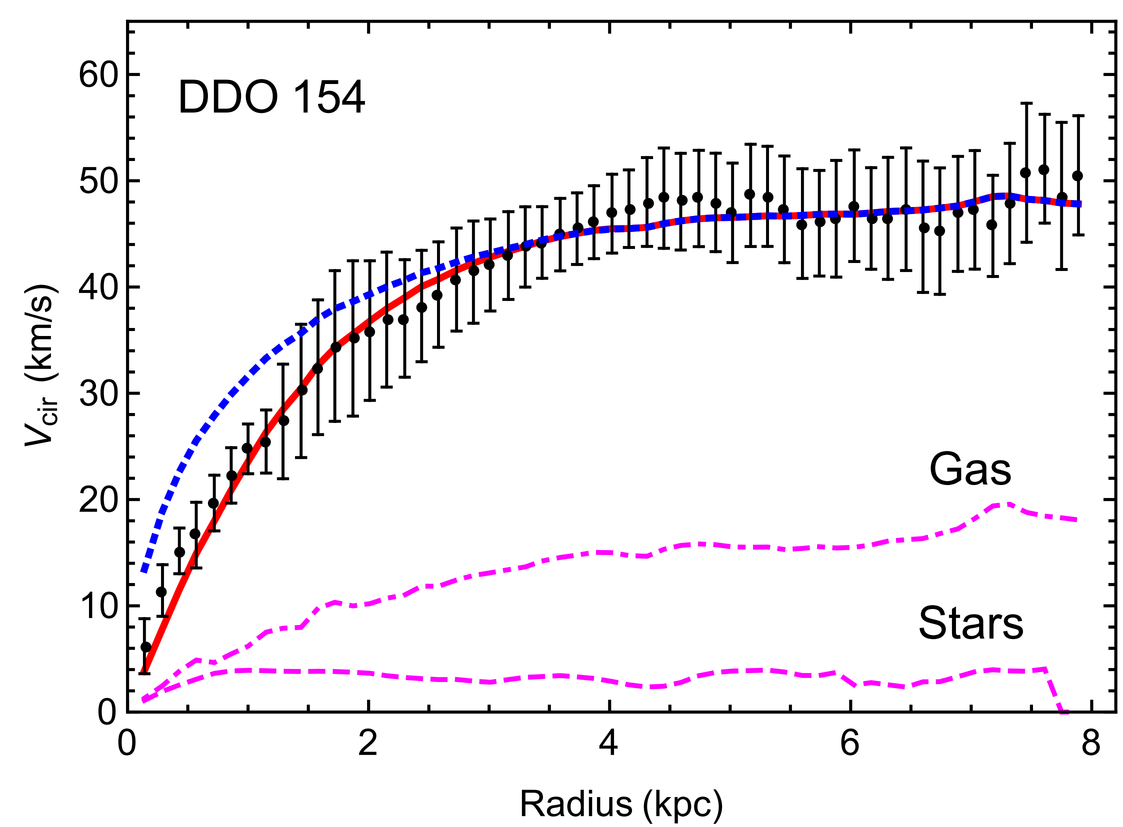
DM—DM couplings

- Dark sector models have DM-DM interactions
- SIMPs, velocity dependence?



Positive observations	σ/m	$v_{\rm rel}$	Observation
Cores in spiral galaxies (dwarf/LSB galaxies)	$\gtrsim 1$ cm^2/g	$30 - 200$ km/s	Rotation curves
Too-big-to-fail problem			
Milky Way	$\gtrsim 0.6$ cm^2/g	50 km/s	Stellar dispersion
Local Group	$\gtrsim 0.5$ cm^2/g	50 km/s	Stellar dispersion
Cores in clusters	~ 0.1 cm^2/g	1500 km/s	Stellar dispersion, lensing
Abell 3827 subhalo merger	~ 1.5 cm^2/g	1500 km/s	DM-galaxy offset
Abell 520 cluster merger	~ 1 cm^2/g	$2000 - 3000$ km/s	DM-galaxy offset
Constraints			
Halo shapes/ellipticity	$\lesssim 1$ cm^2/g	1300 km/s	Cluster lensing surveys
Substructure mergers	$\lesssim 2$ cm^2/g	$\sim 500 - 4000$ km/s	DM-galaxy offset
Merging clusters	$\lesssim$ few cm^2/g	$2000 - 4000$ km/s	Post-merger halo survival (Scattering depth $\tau < 1$)
Bullet Cluster	$\lesssim 0.7$ cm^2/g	4000 km/s	Mass-to-light ratio

- Core-vs-Cusp, too big to fail, missing satellites,…



(NO) Conclusions

DM is not just your advisor's WIMP model!

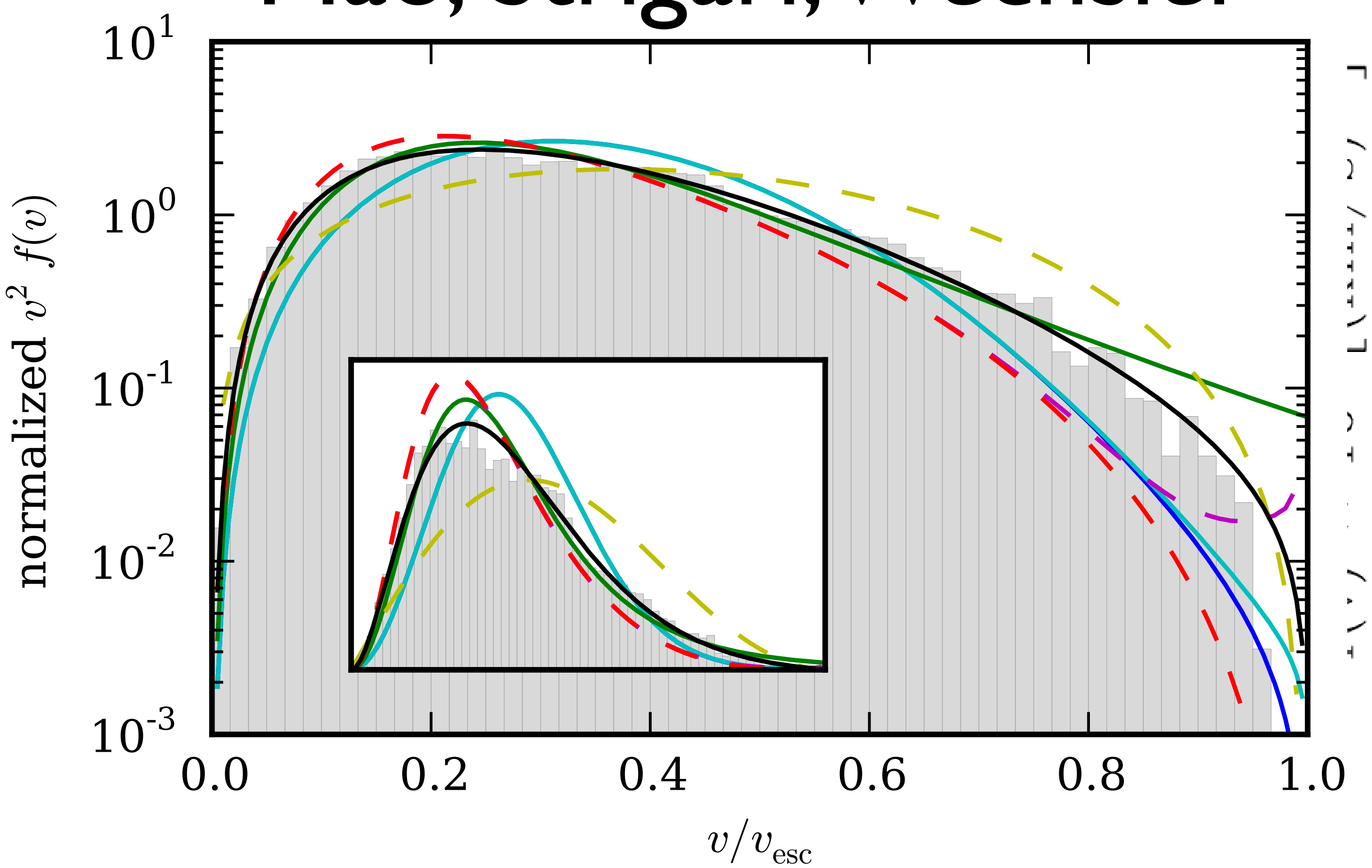
There are interesting anomalies in multiple search techniques

Many unexplored regions that can be explored soon/NOW!

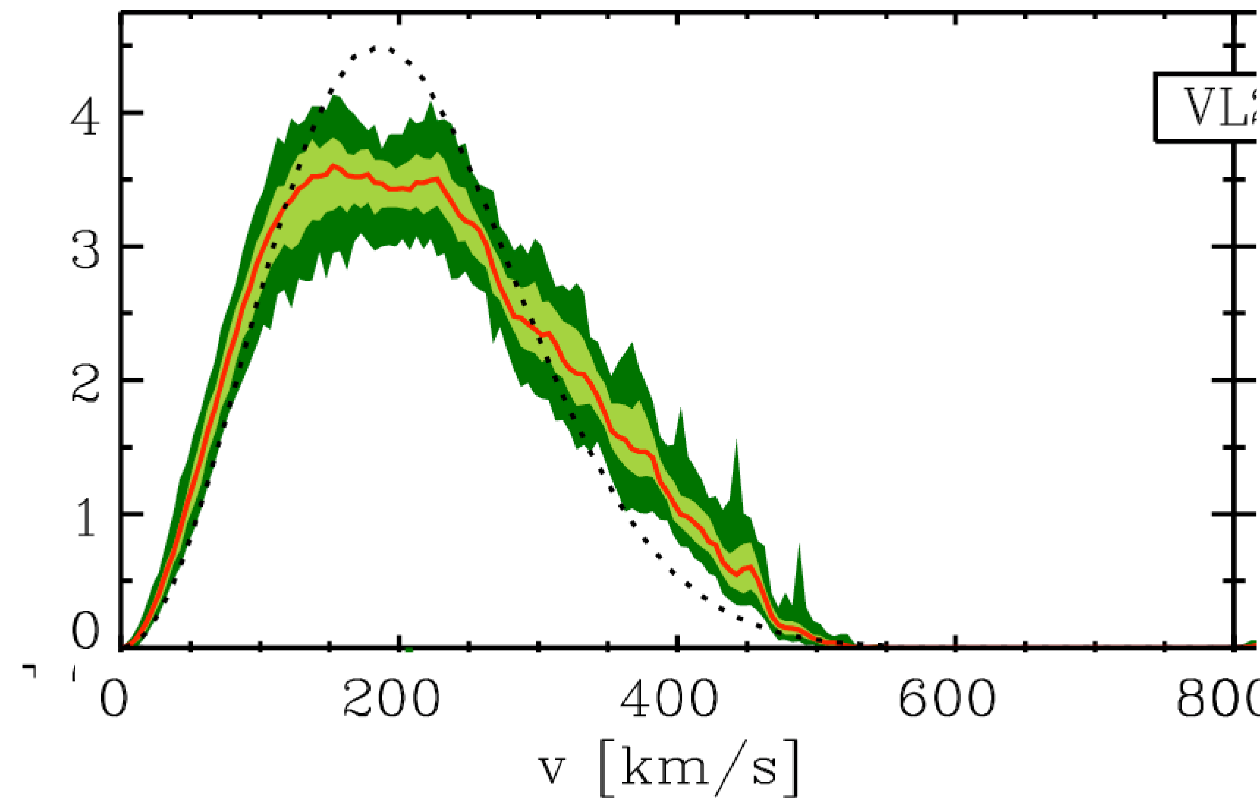
Extras

Winds, streams and flows

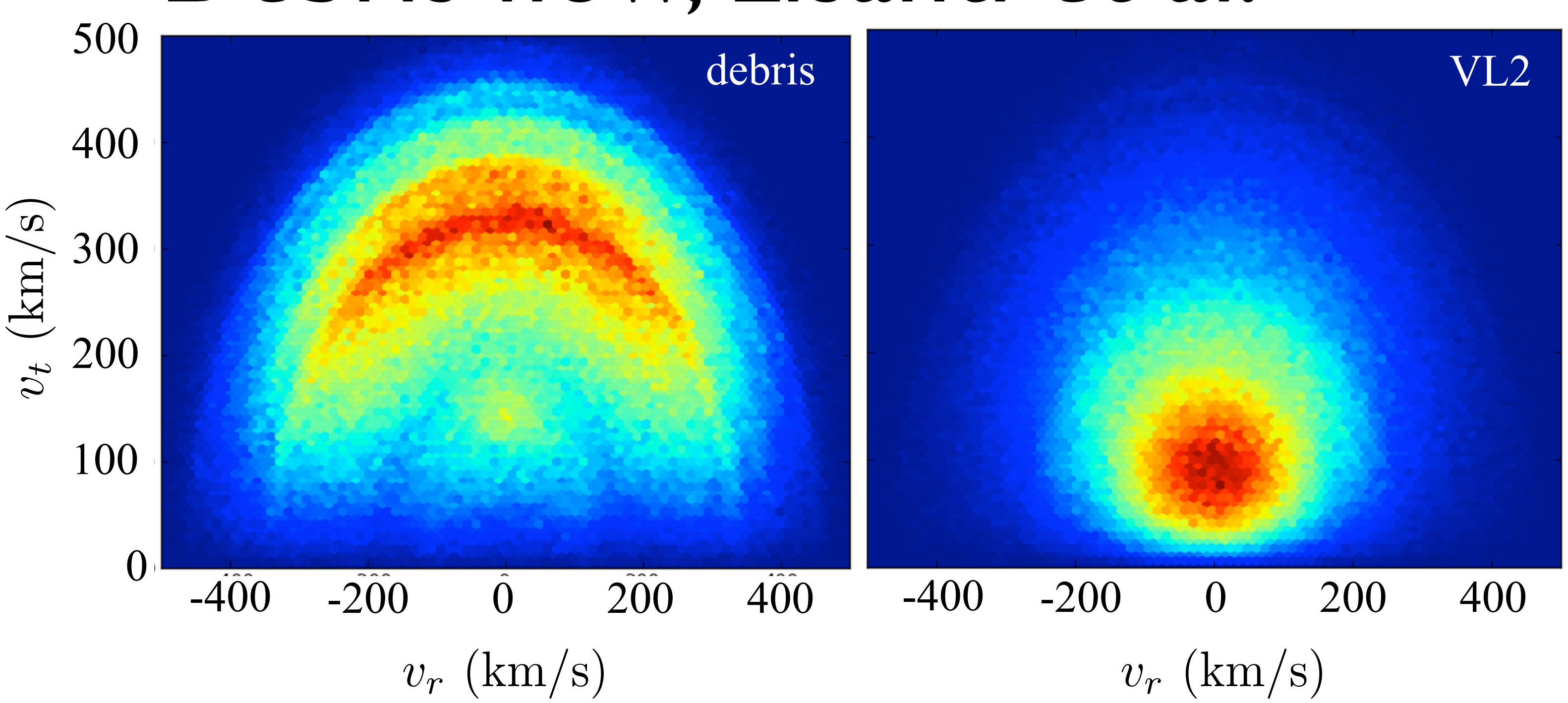
Mao, Strigari, Wechsler



Via Lactea II



Debris flow, Lisanti et al.



Local abundance and velocity distribution are inputs into the interpretation of direct detection experiments

Only way to measure these things is through direct detection experiments

[PJF, Kribs, Tait]

$$f_1(v_{\min}(E_R)) = -\frac{4\mu^2 E_R^2}{m_N^2 E_R^2 - \mu^2\delta^2}\frac{1}{\mathcal{N}\sigma_0(v_{\min}(E_R))F_\chi^2(E_R)}\left(\frac{d\mathcal{R}}{dE_R} - \mathcal{R}\frac{1}{F_\chi^2(E_R)}\frac{dF_\chi^2(E_R)}{dE_R}\right)$$

f-condition: $f(v) \geq 0$

(Deconvoluted) rate is a monotonically decreasing function, or there is non-standard particle physics e.g. inelastic or a increasing DM form factor

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$$f_1(v) = \int d\Omega f(\vec{v}).$$

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"Deconvoluted" rate

$$f_1(v) = \int d\Omega f(\vec{v}).$$

$$\mathcal{R} \equiv \frac{1}{F_N^2(E_R)}\frac{dR}{dE_R}$$

f-condition: $f(v) \geq 0$

(Deconvoluted) rate is a monotonically decreasing function, or there is non-standard particle physics e.g. inelastic or a increasing DM form factor

Two experiments allow us to test particle physics independent of astrophysics

1) Make hypothesis about DM e.g. elastically scattering DM with mass 100 GeV and x-sec 10^{-40} cm^2
2) Use experiment A to extract astrophysics i.e. rho x f(v)
3) Use these extracted astrophysics properties to predict result at experiment B
4) Compare to B's measurement/bound
5) Rule in our out each particle physics hypothesis

Doesn't allow extraction of "unique" x-sec, mass
Need relatively large statistics ~10's events
Experiments must run over same part of year
Other uncertainties (nuclear, atomic etc not addressed)

Halo model independence

[PJF, Liu, Weiner]

$$\frac{dR}{dE_R} = \frac{N_T M_T \rho}{2 m_\chi \mu^2} \underbrace{\int_{v_{min}}^{v_{max}} d^3\vec{v} \frac{f(\vec{v}, \vec{v_E})}{v}}_{g(v)} \sigma(E_R)$$

$$\frac{dR}{dE_R} = \frac{N_T M_T}{2\mu^2} \frac{\rho\sigma}{m_\chi} g(v)$$

$$v_{min} = \sqrt{\frac{M_T E_R}{2\mu^2}}$$

Recoil energy uniquely determines **minimum** DM velocity

Halo model independence

[PJF, Liu, Weiner]

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$g(v)$

$$\frac{dR}{dE_R} = \frac{N_T M_T}{2\mu^2} \frac{\rho\sigma}{m_\chi} g(v)$$

Target specific

$$v_{min} = \sqrt{\frac{M_T E_R}{2\mu^2}}$$

Recoil energy uniquely determines **minimum** DM velocity

Halo model independence

[PJF, Liu, Weiner]

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Target specific

Target independent

$\tilde{g}(v_{\rm min})$

$$v_{min} = \sqrt{\frac{M_T E_R}{2\mu^2}}$$

Recoil energy uniquely determines **minimum** DM velocity

Using vmin space

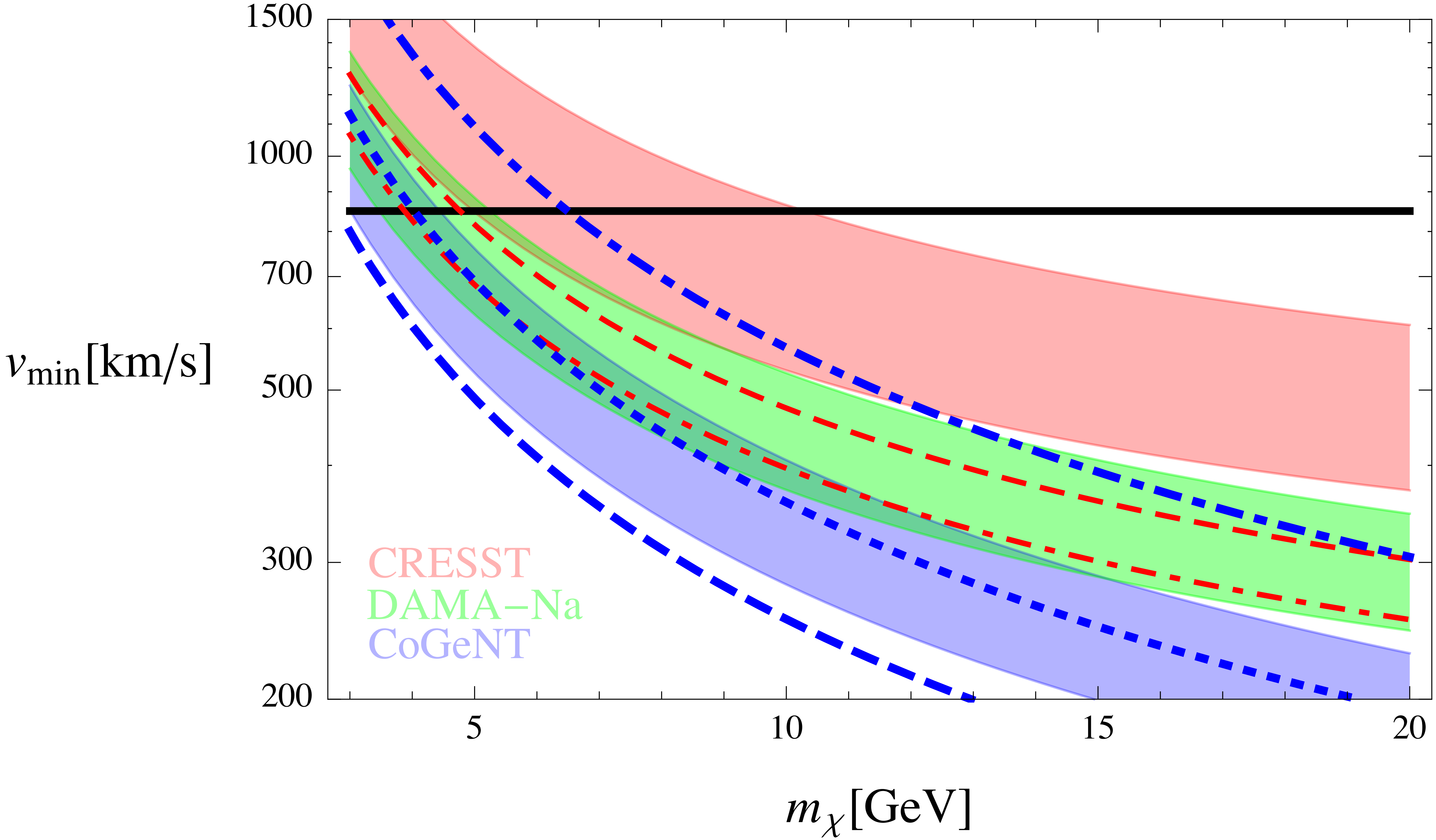
Experiment 1 $\longleftrightarrow$ Experiment 2

$$[E^{(1)}_{low}, E^{(1)}_{low}] \Longleftrightarrow [v^{low}_{min}, v^{high}_{min}] \Longleftrightarrow [E^{(2)}_{low}, E^{(2)}_{high}]$$

$$[\mathrm{E}^{(2)}_{\mathrm{low}}, \mathrm{E}^{(2)}_{\mathrm{high}}] = \frac{\mu_2^2 M_T^{(1)}}{\mu_1^2 M_T^{(2)}} [\mathrm{E}^{(1)}_{\mathrm{low}}, \mathrm{E}^{(1)}_{\mathrm{high}}]$$

Bin	CoGeNT	Ge	Na (Q=0.3)	Si	O	Xe
1	[0.5,0.9] 0.90 ± 0.72	[2.3,3.8] 0.23 ± 0.18	[1.5,2.5] 0.078 ± 0.062	[4.5,7.6] 0.035 ± 0.028	[5.8,9.9] 0.011 ± 0.009	[1.4,2.3] 0.72 ± 0.58
2	[0.9,1.5] 0.37 ± 0.55	[3.8,6.1] 0.1 ± 0.149	[2.5,4.0] 0.035 ± 0.052	[7.6,11.9] 0.015 ± 0.023	[9.9,15.6] 0.005 ± 0.008	[2.3,3.7] 0.31 ± 0.46
3	[1.5,2.3] 0.48 ± 0.22	[6.1,8.9] 0.136 ± 0.063	[4.0,5.8] 0.049 ± 0.022	[11.9,17.5] 0.021 ± 0.01	[15.6,22.8] 0.007 ± 0.003	[3.7,5.4] 0.41 ± 0.19
4	[2.3,3.1] 0.27 ± 0.23	[8.9,11.6] 0.08 ± 0.068	[5.8,7.6] 0.029 ± 0.025	[17.5,22.8] 0.013 ± 0.011	[22.8,29.8] 0.004 ± 0.004	[5.4,7] 0.23 ± 0.2

Using vmin space



Halo model independence

$$N_T = \kappa N_A m_p / M_T$$

Solve for g(v)

$$g(v_{min}) = \frac{2 m_\chi \mu^2}{N_A \kappa \, m_p \, \rho \, \sigma(E_R)} \frac{dR_1}{dE_1}$$

$$\frac{dR_1}{dE_1} \Longleftrightarrow g(v_{min}) \Longleftrightarrow \frac{dR_2}{dE_2}$$

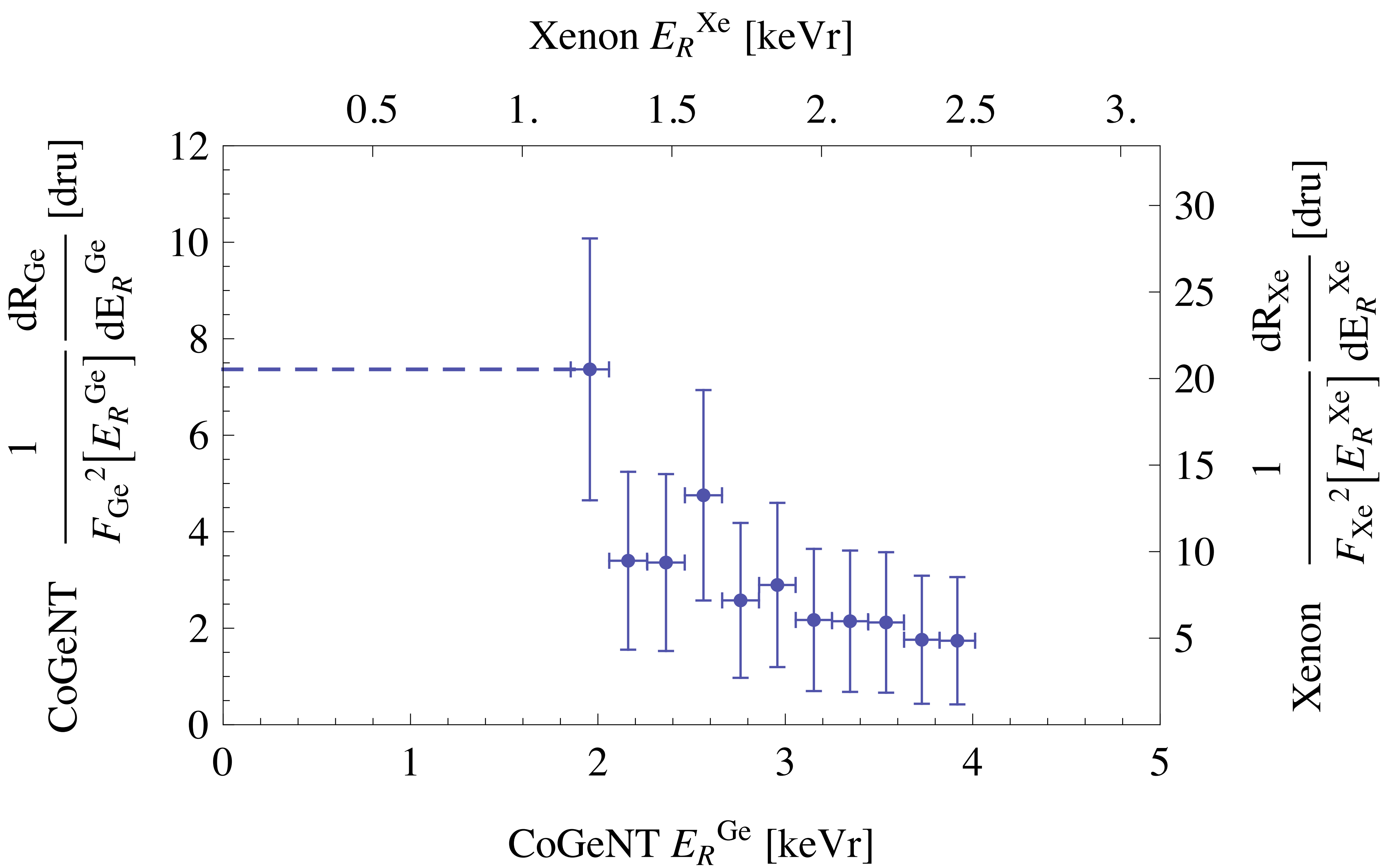
The master formula (SI):

$$C_T^{(i)} = \kappa^{(i)} \left(f_p \, Z^{(i)} + f_n \left(A^{(i)} - Z^{(i)} \right) \right)^2$$

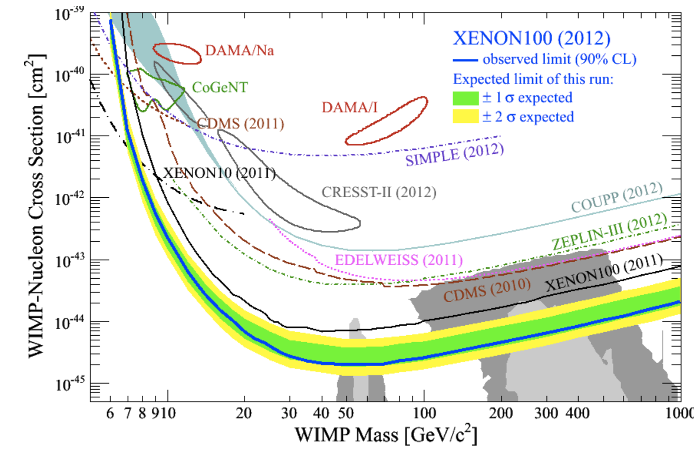
$$\frac{dR_2}{dE_R}(E_2) = \frac{C_T^{(2)}}{C_T^{(1)}} \frac{F_2^2(E_2)}{F_1^2 \left(\frac{\mu_1^2 \, M_T^{(2)}}{\mu_2^2 M_T^{(1)}} E_2 \right)} \frac{dR_1}{dE_R} \left(\frac{\mu_1^2 \, M_T^{(2)}}{\mu_2^2 \, M_T^{(1)}} E_2 \right)$$

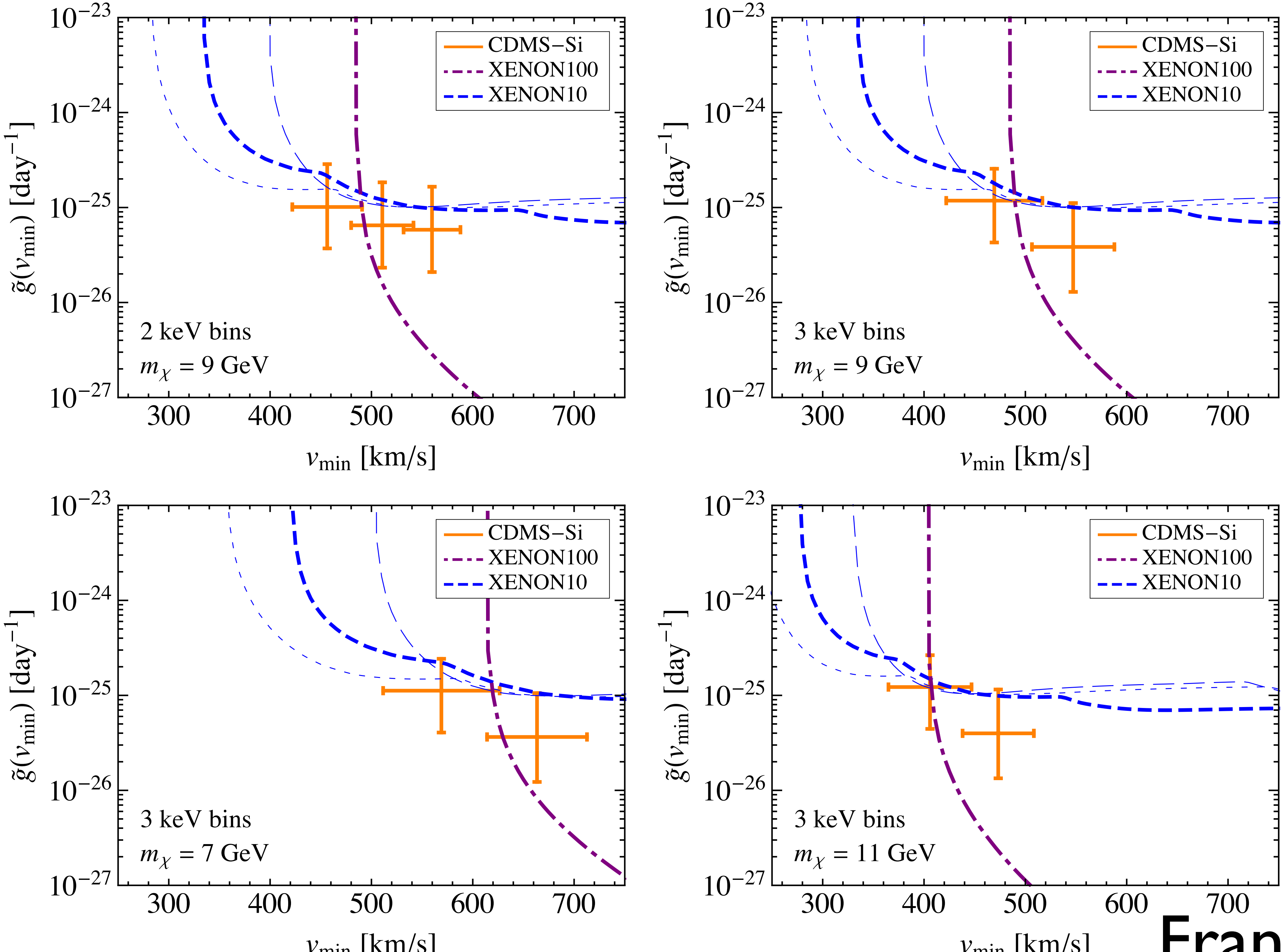
CoGeNT and XENON10

$$m_\chi = 10\,\text{GeV}$$



A new plot





Frandsen et al.

Axions

Solution to strong CP problem:

$$\frac{\theta}{32\pi^2}\mathrm{tr}\ \epsilon_{\alpha\beta\gamma\delta}F^{\alpha}\beta F^{\gamma\delta}$$

Contributes to neutron edm (<10^-26 ecm)

$$d_n \sim 10^{-16}\theta ecm \quad \longrightarrow \quad \theta \lesssim 10^{-10}$$

Why so small??

Axions

Solution to strong CP problem:

$$\frac{\theta}{32\pi^2}\mathrm{tr}\ \epsilon_{\alpha\beta\gamma\delta}F^{\alpha}\beta F^{\gamma\delta}$$

Contributes to neutron edm (<10^-26 ecm)

$$d_n \sim 10^{-16}\theta ecm \quad \longrightarrow \quad \theta \lesssim 10^{-10}$$

Why so small??

Perhaps a symmetry?

Peccei Quinn axion

Axions

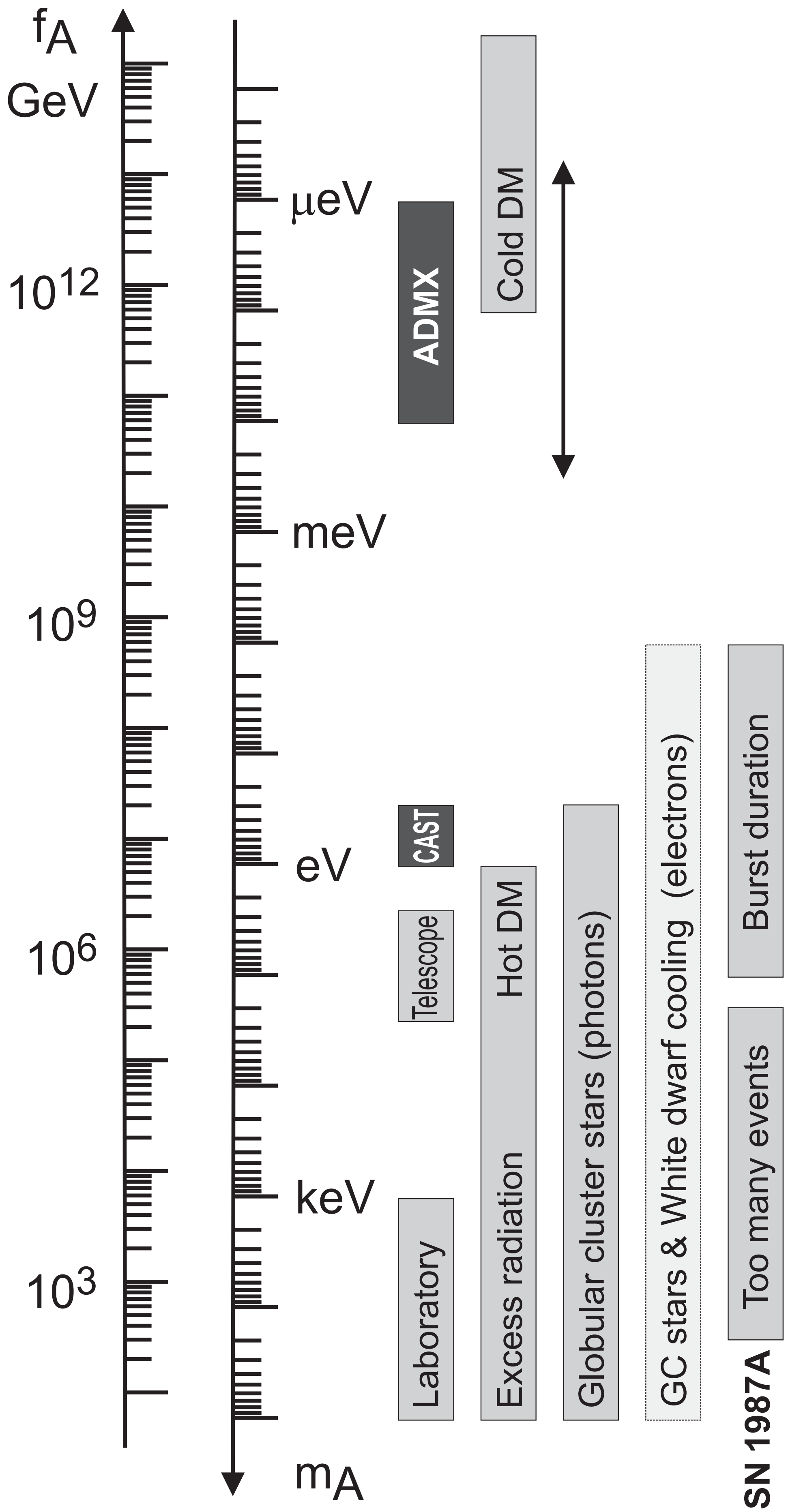
Axion is goldstone boson of spontaneously broken U(1)

$$\mathcal{L} = \frac{1}{2}(\partial a)^2 + \frac{1}{32\pi^2}\frac{a}{f}F\tilde{F} + \dots$$

Picks up a mass from QCD instantons

$$\mathcal{L} = \frac{1}{2}(\partial a)^2 - m_a^2 f_a^2 (1 - \cos a/f_a)$$

$$m_a^2 f_a^2 \sim m_\pi^2 f_\pi^2$$



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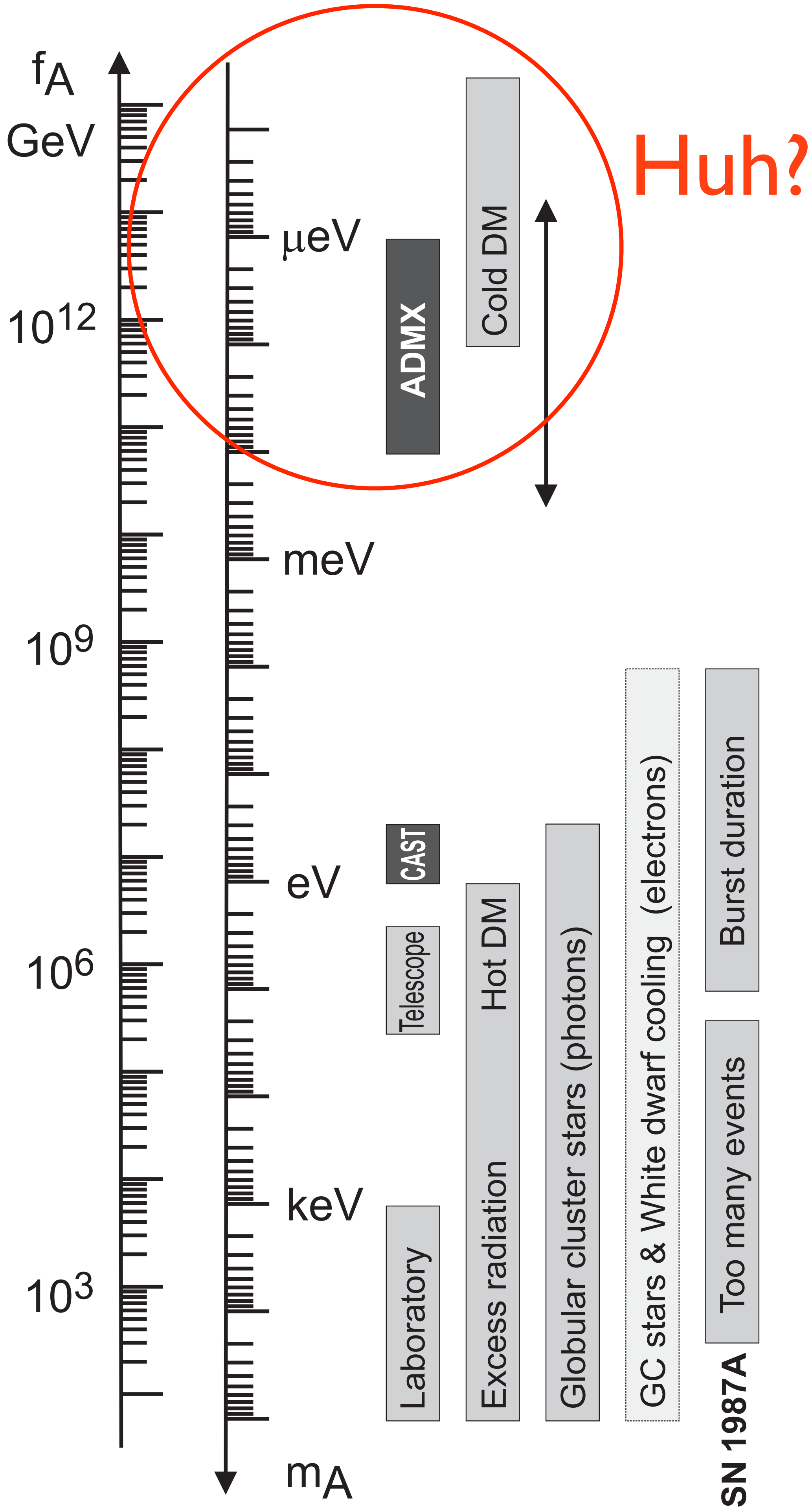
- Can be CDM candidate despite mass <eV
- Search for in very different ways from WIMP DM



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Misalignment mechanism

Axion evolution $\ddot{a} + 3H\dot{a} + m_a^2(T)a = 0$

Axions start to oscillate when $3H \approx m_a(T)$

$$\frac{m_a(T)}{m_a} = 0.018 \left(\frac{\Lambda_{\rm QCD}}{200\rm MeV}\right)^{1/2} \left(\frac{\Lambda_{\rm QCD}}{T}\right)^4$$

$$T_{\rm osc} = 150{\rm Mev} \left(\frac{\Lambda_{\rm QCD}}{200\rm Mev}\right)^{3/4} \left(\frac{10^{16}\rm GeV}{f_a}\right)^{1/6}$$

$$\Omega_a h^2 \sim 2 \times 10^4 \left(\frac{200\rm MeV}{\Lambda_{\rm QCD}}\right)^{3/4} \left(\frac{f_a}{10^{16}\rm GeV}\right)^{7/6} \theta_i^2 \gamma$$

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Axion searches

Microwave cavities, take advantage of axion-photon coupling