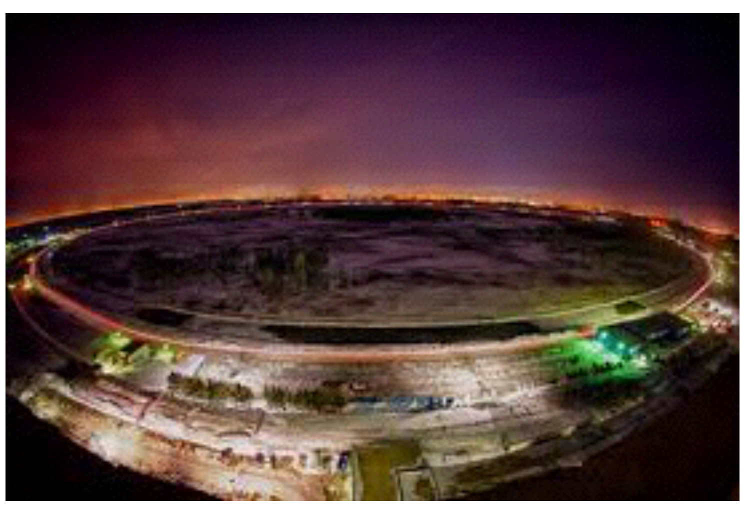
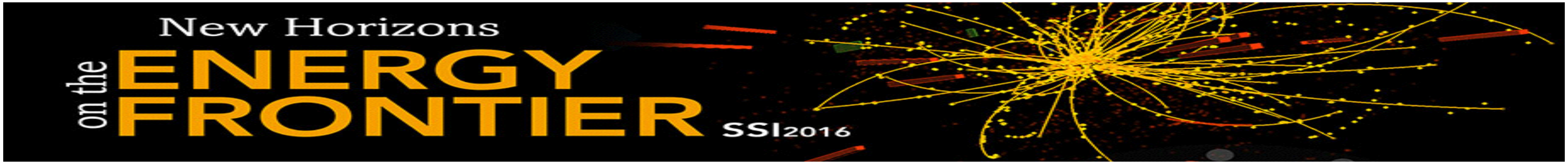
Cosmic Frontier-Collider Complementarity

Patrick Fox
Fermilab





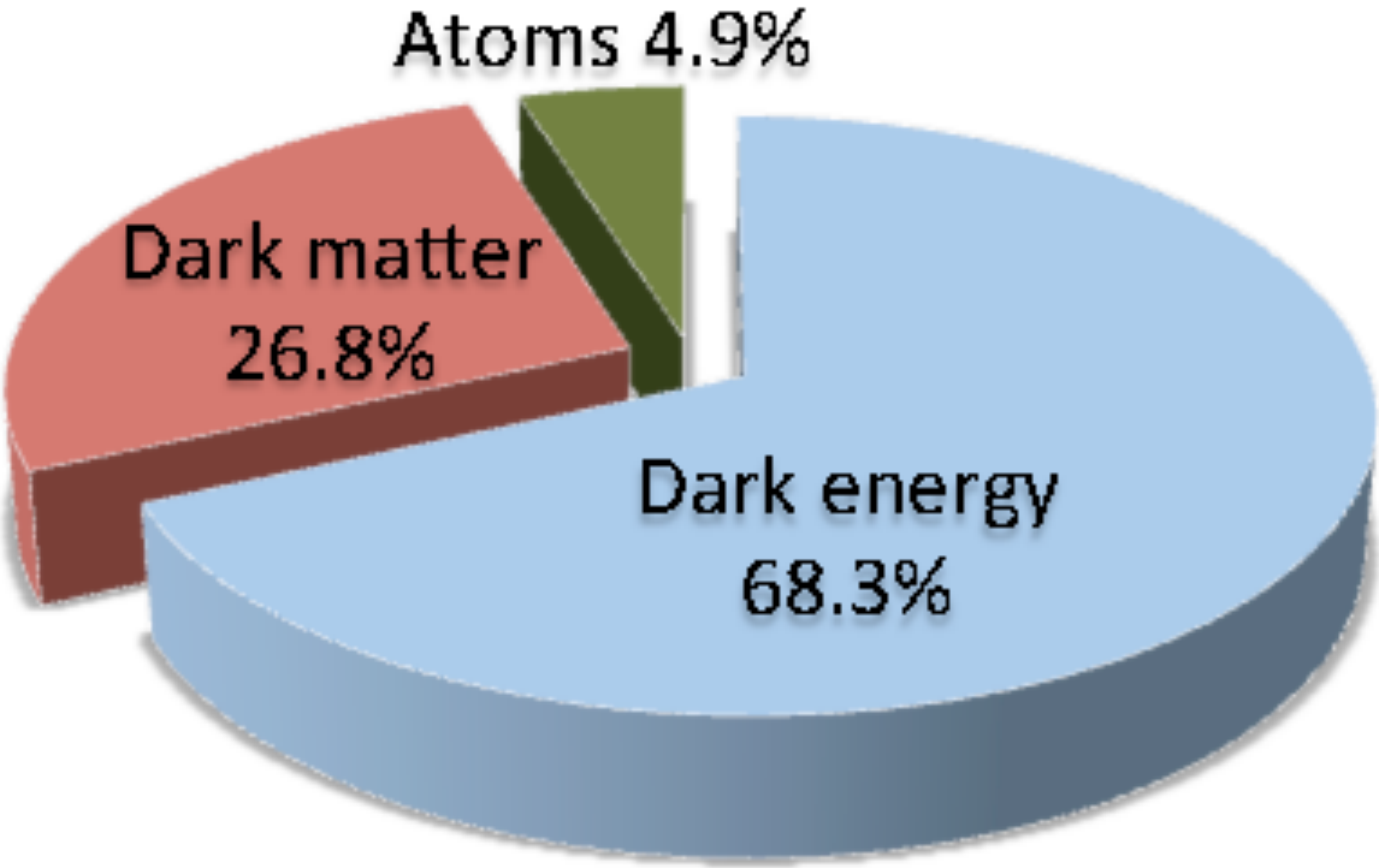
Outline

- Overview of dark matter's properties
- Overview of WIMP's properties
- Direct, Indirect searches
- Collider searches

Lecture II

- Electroweakinos, a case study
- Light mediators, light dark matter
- Conclusions

HEP's dark secret



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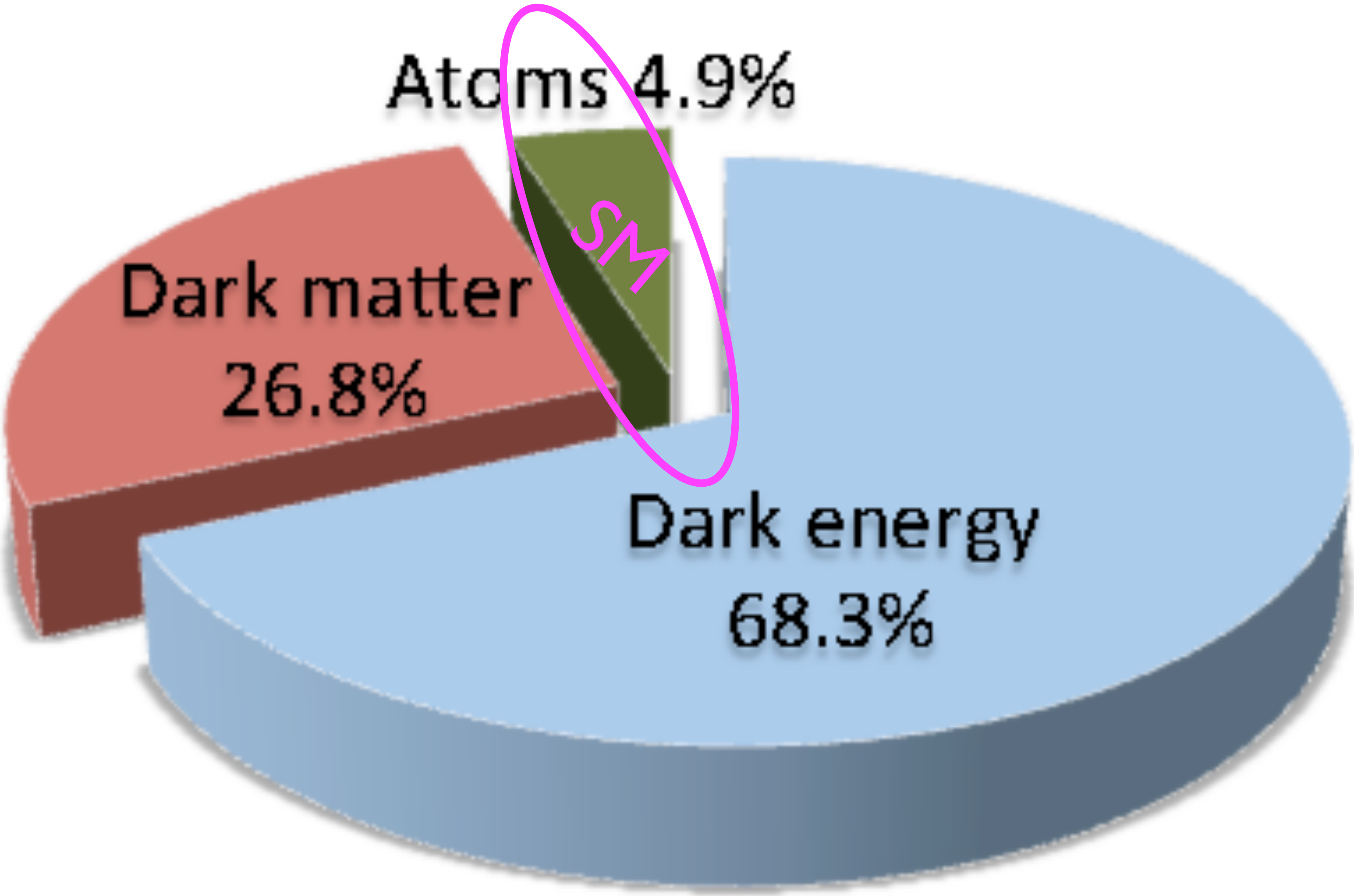

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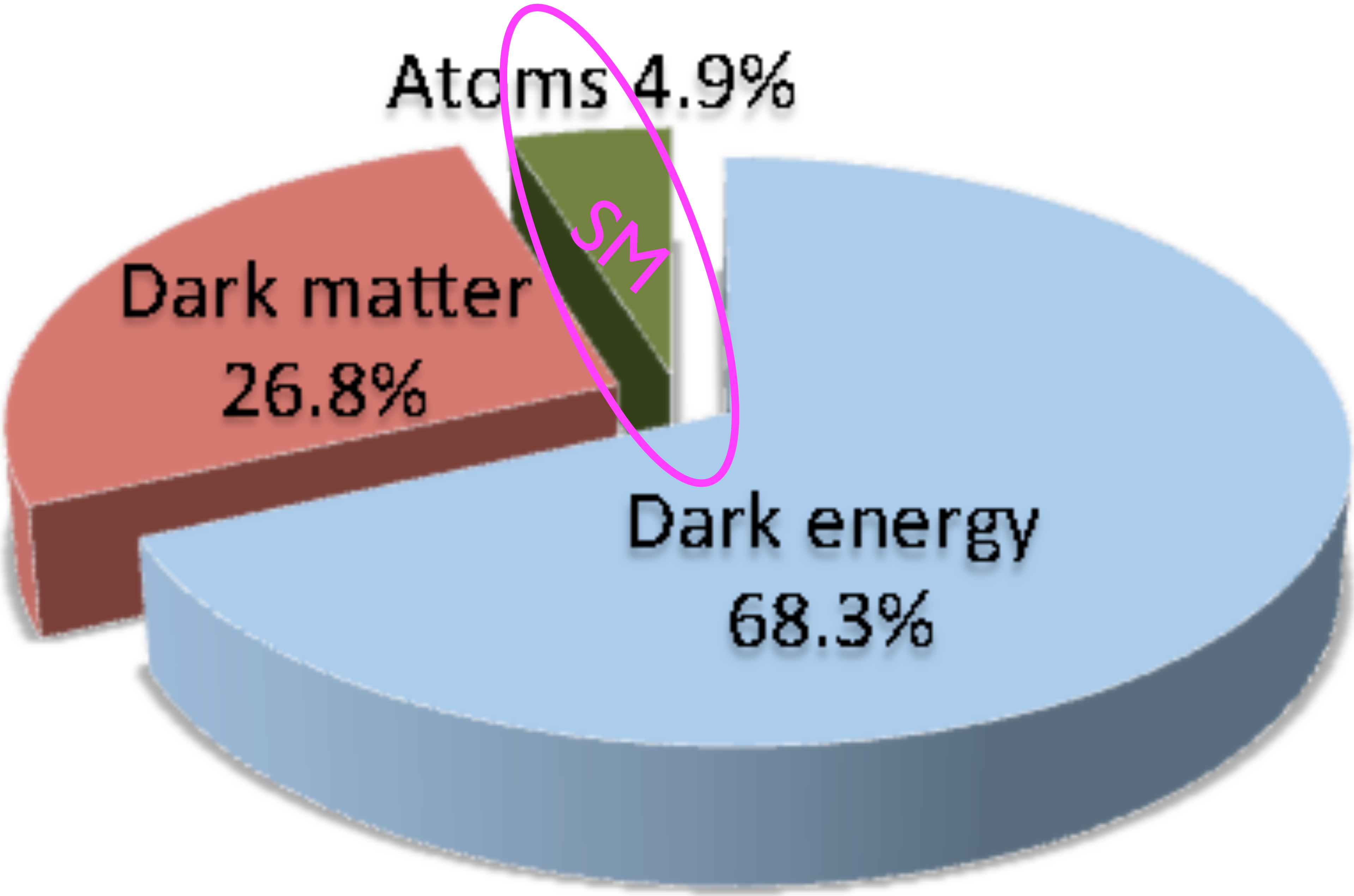
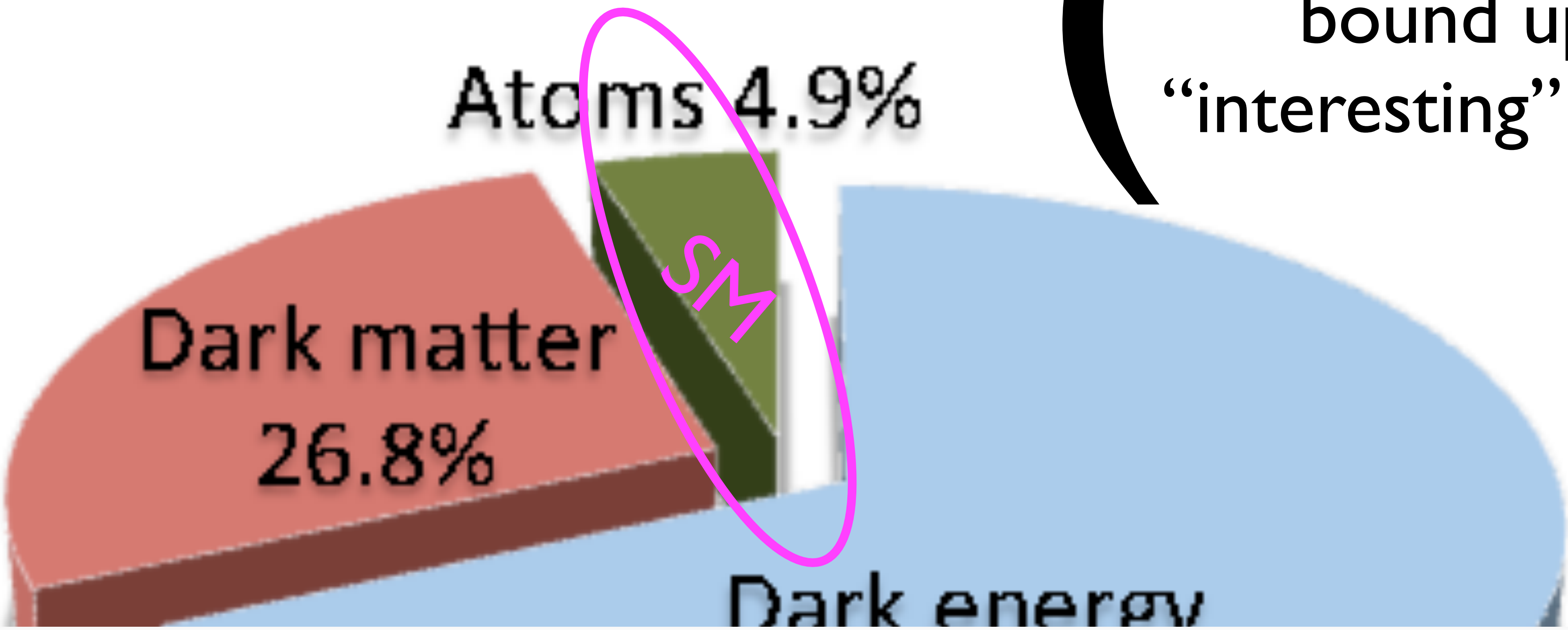
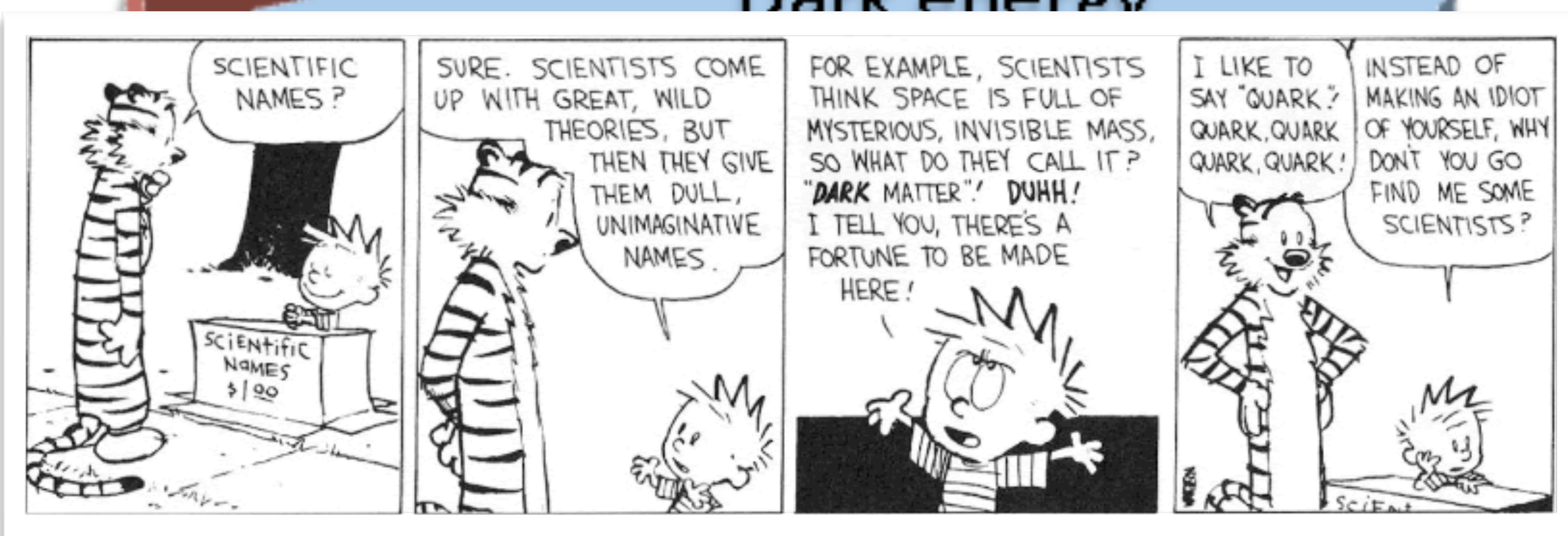


How did we arrive at this?

HEP's dark secret

(Only ~10% of this is bound up in "interesting" objects)

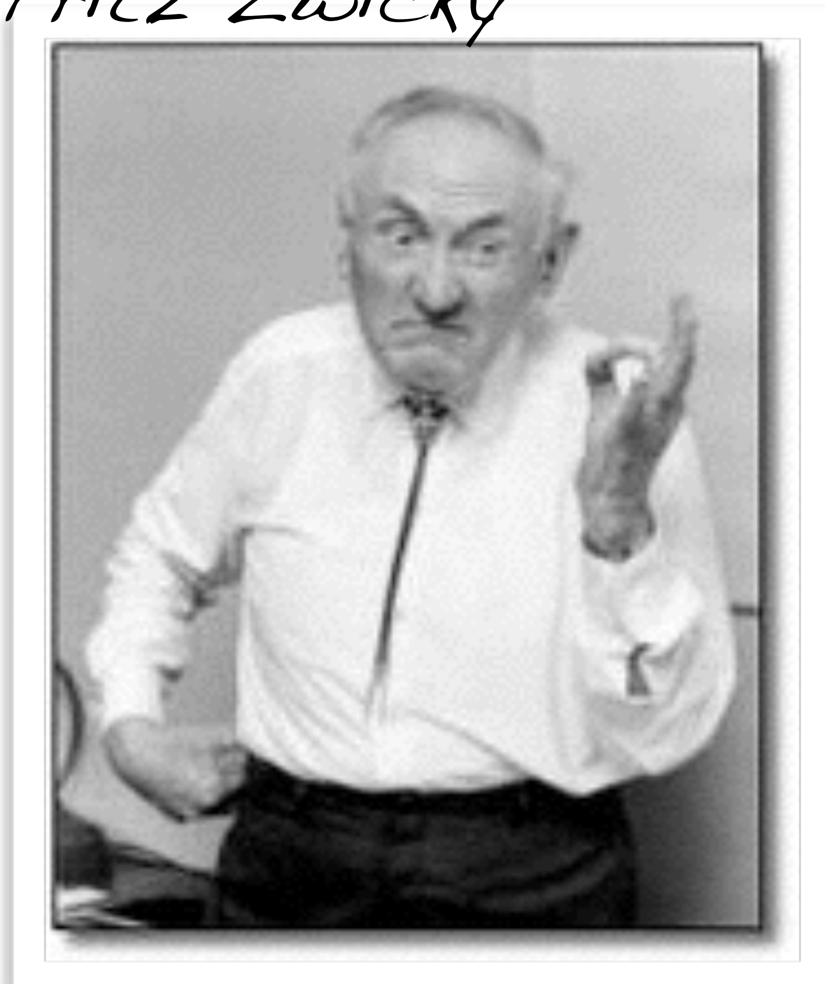




How did we arrive at this?

“You spin me right round…”

Fritz Zwicky



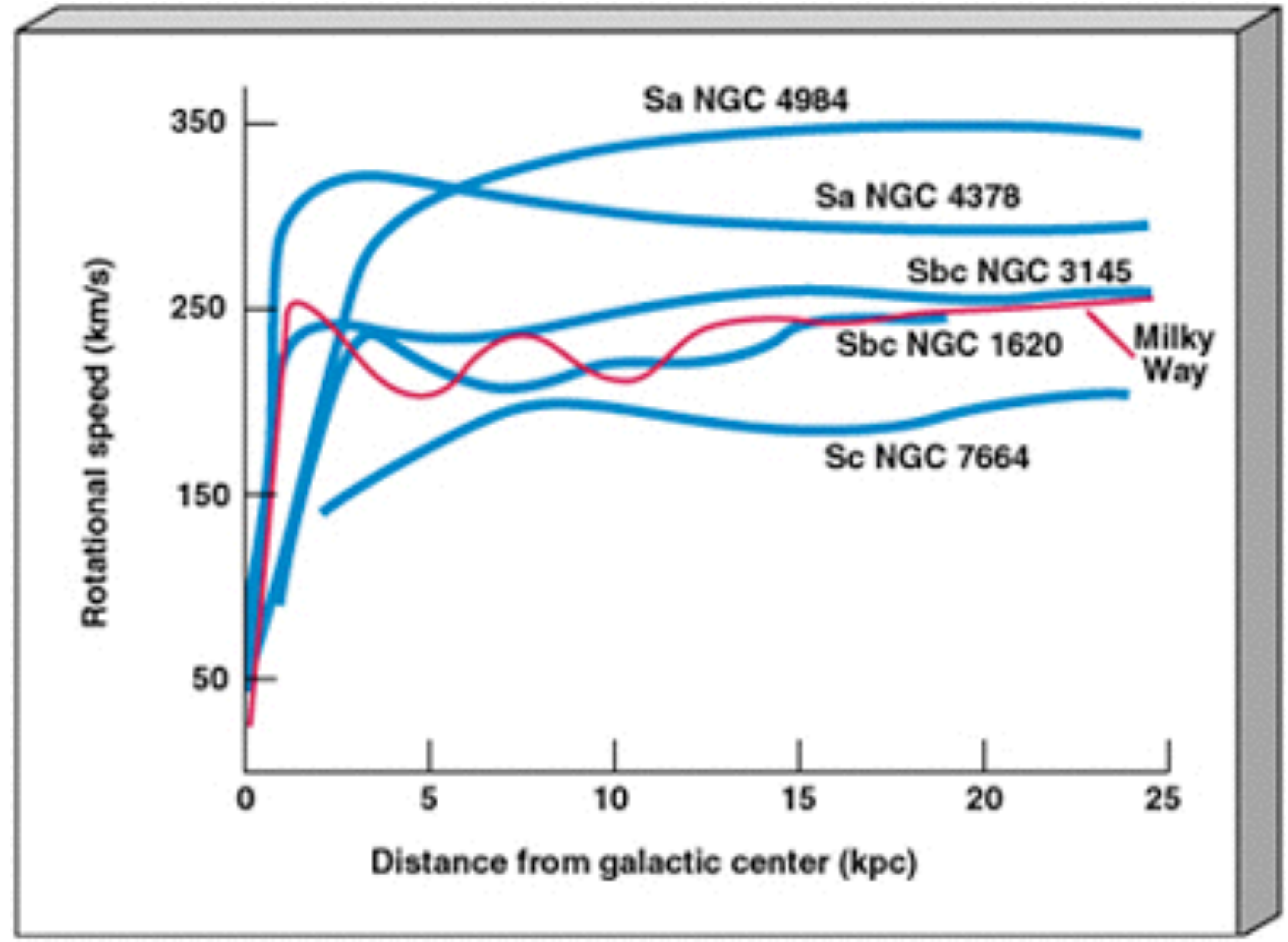
Coma Cluster

Virial theorem: $2\langle K\rangle = -\langle V\rangle$

$$M = \frac{v^2 R}{G_N}$$

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

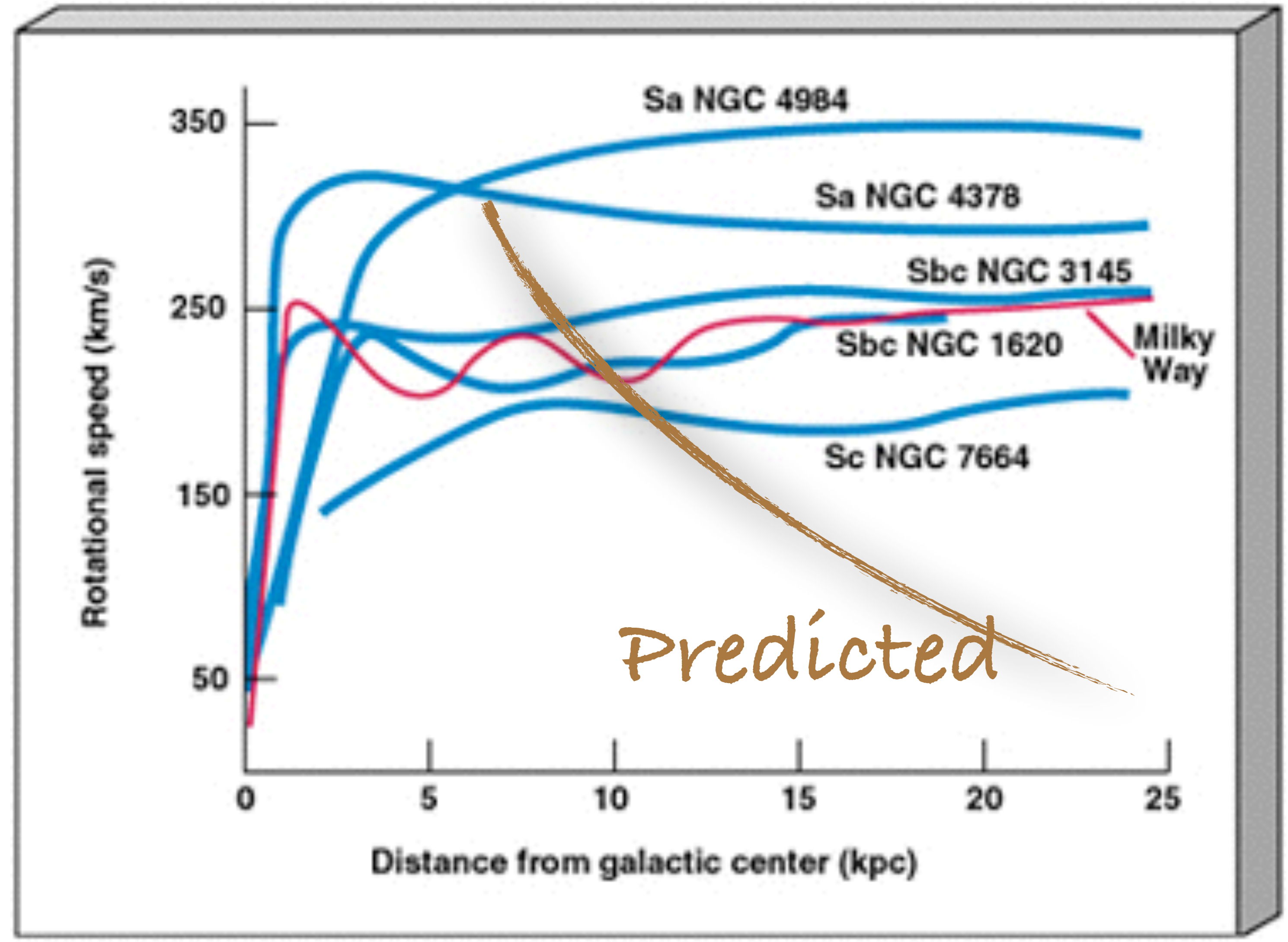
Vera Rubin



Something invisible is holding stars in orbit

Has been repeated in many systems on many scales.
Alway same result: never enough stuff

Vera Rubin



$$\frac{v^2}{r} = \frac{G_N M}{r^2}$$

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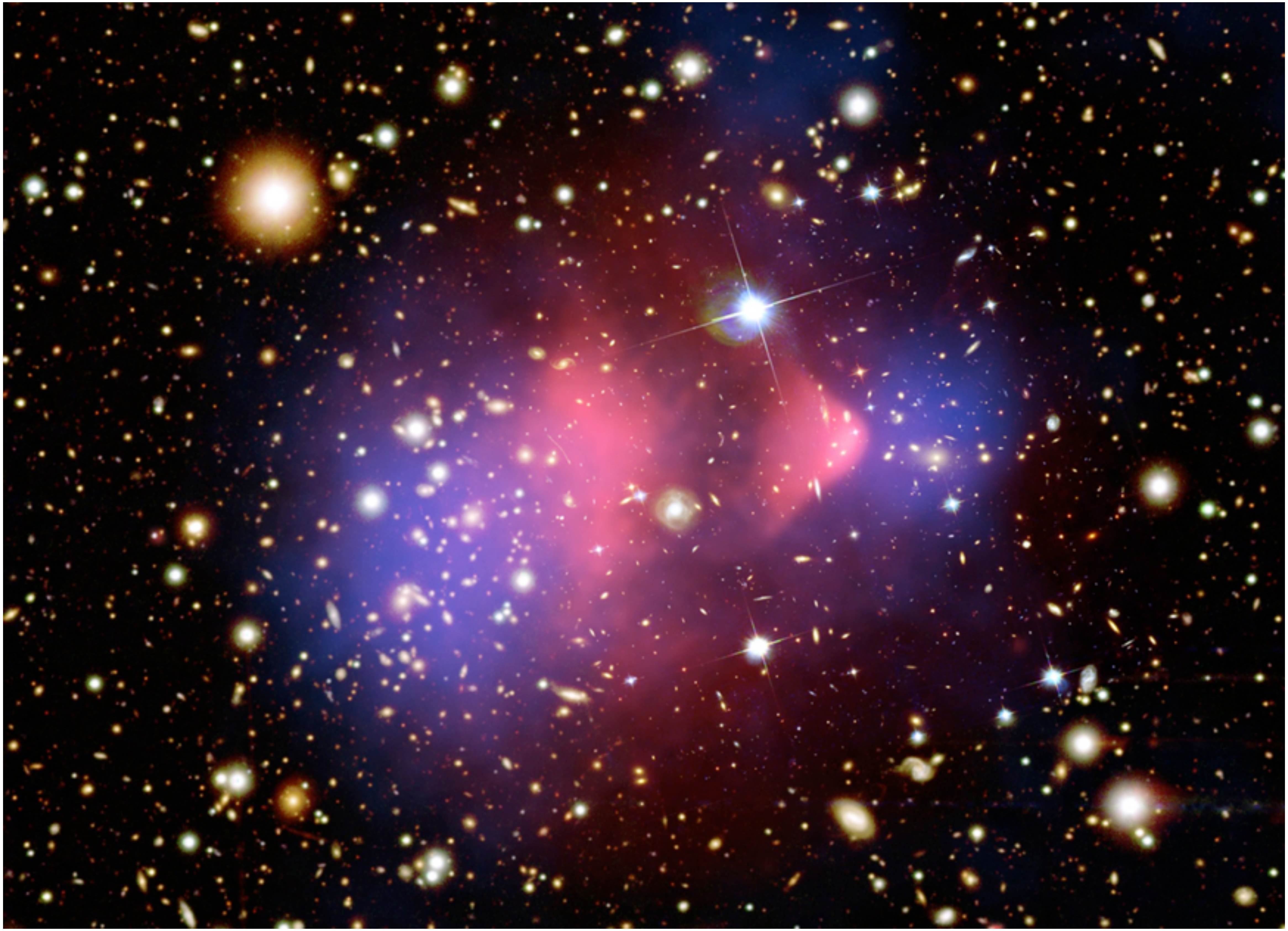
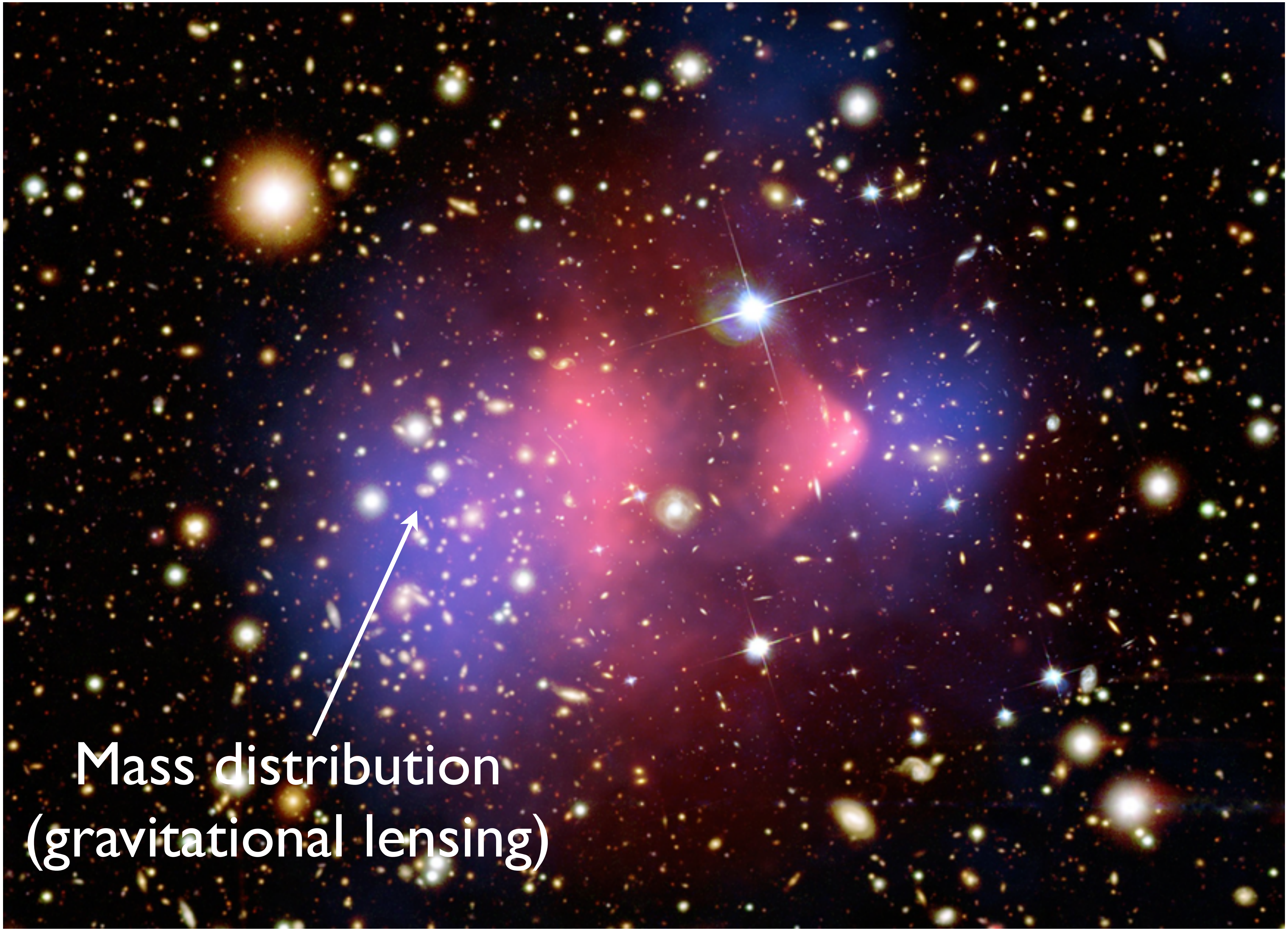
Alway same result: never enough stuff

Evidence for Dark Matter



The Bullet Cluster

Evidence for Dark Matter



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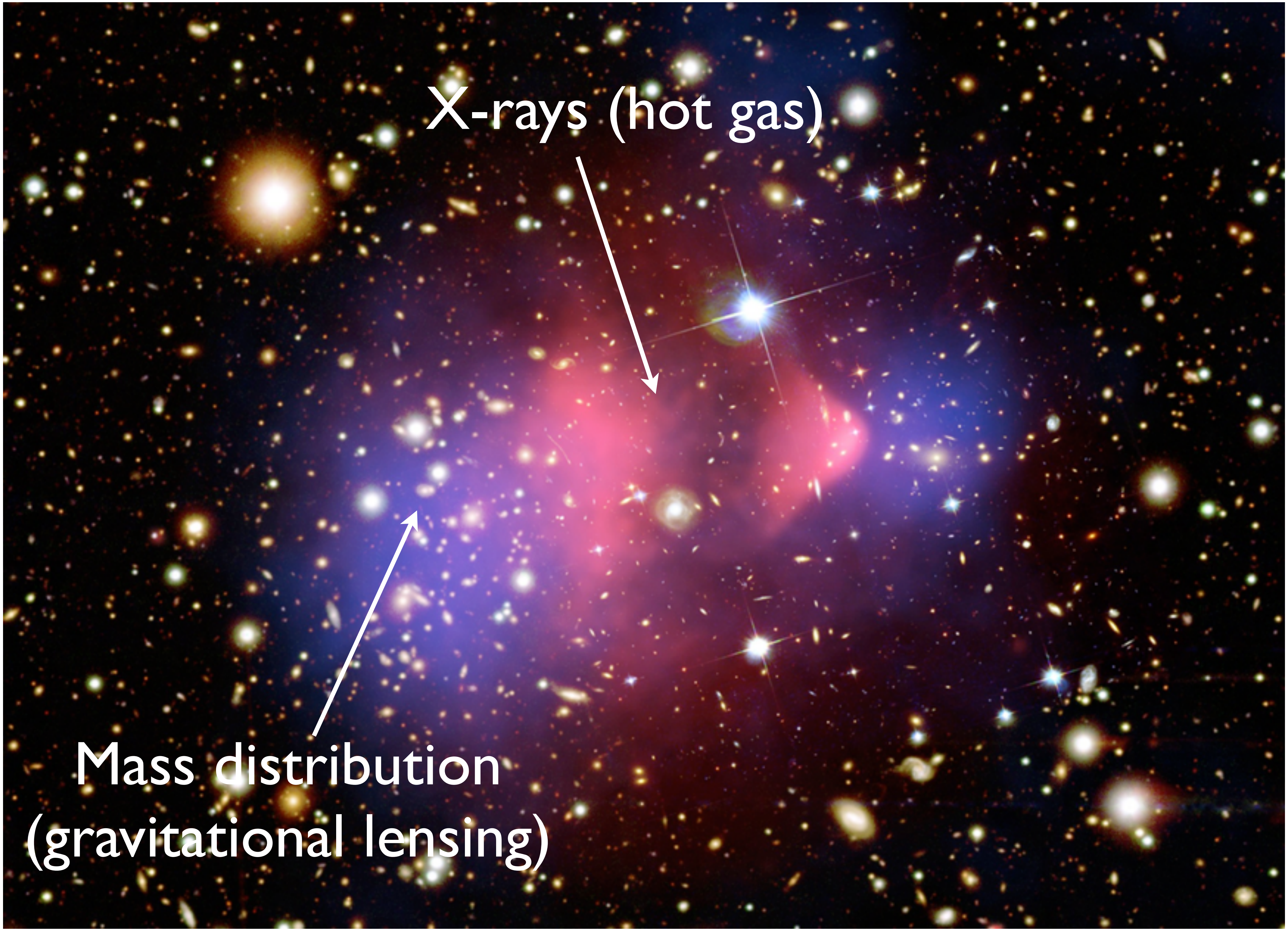

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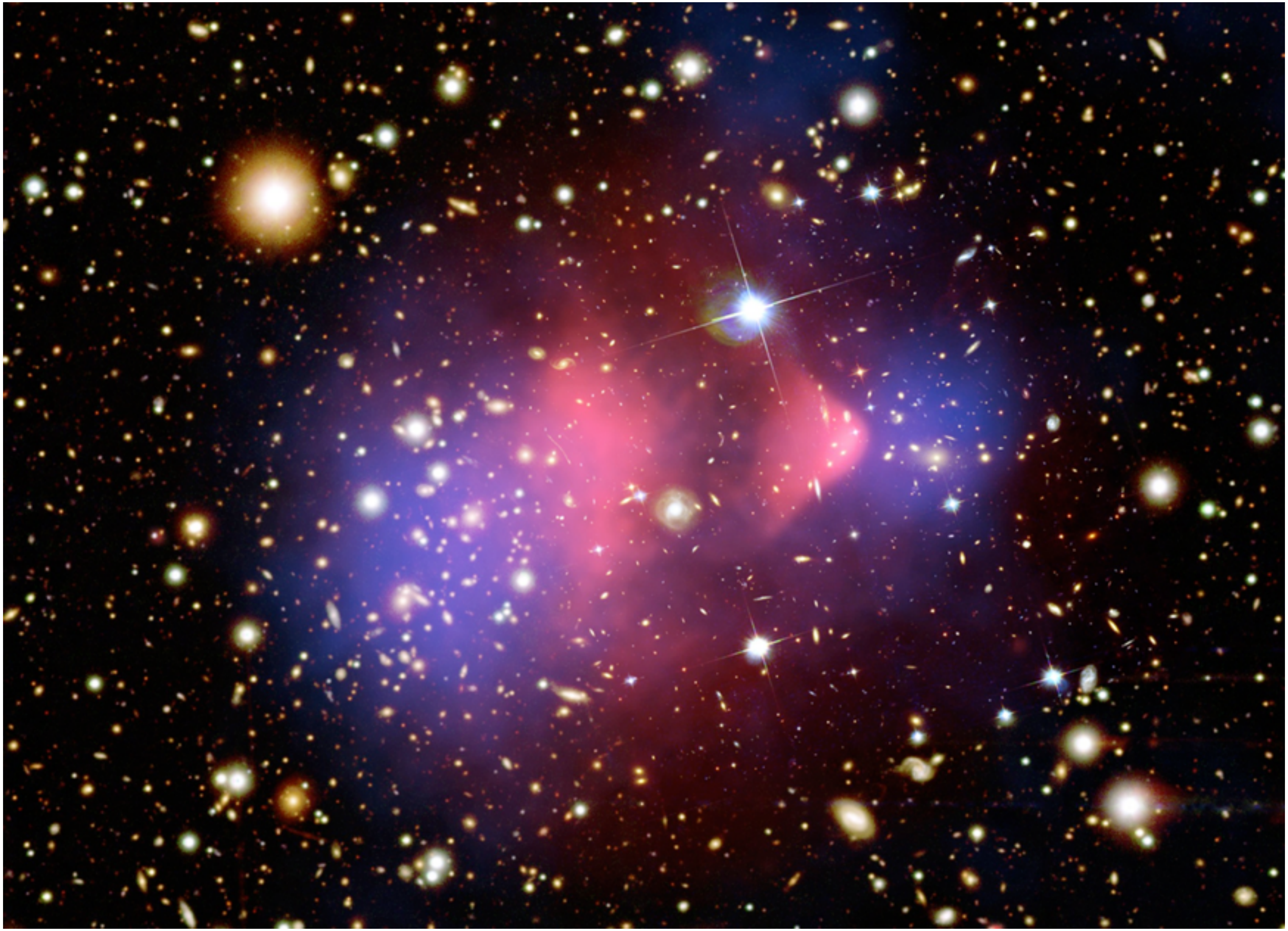

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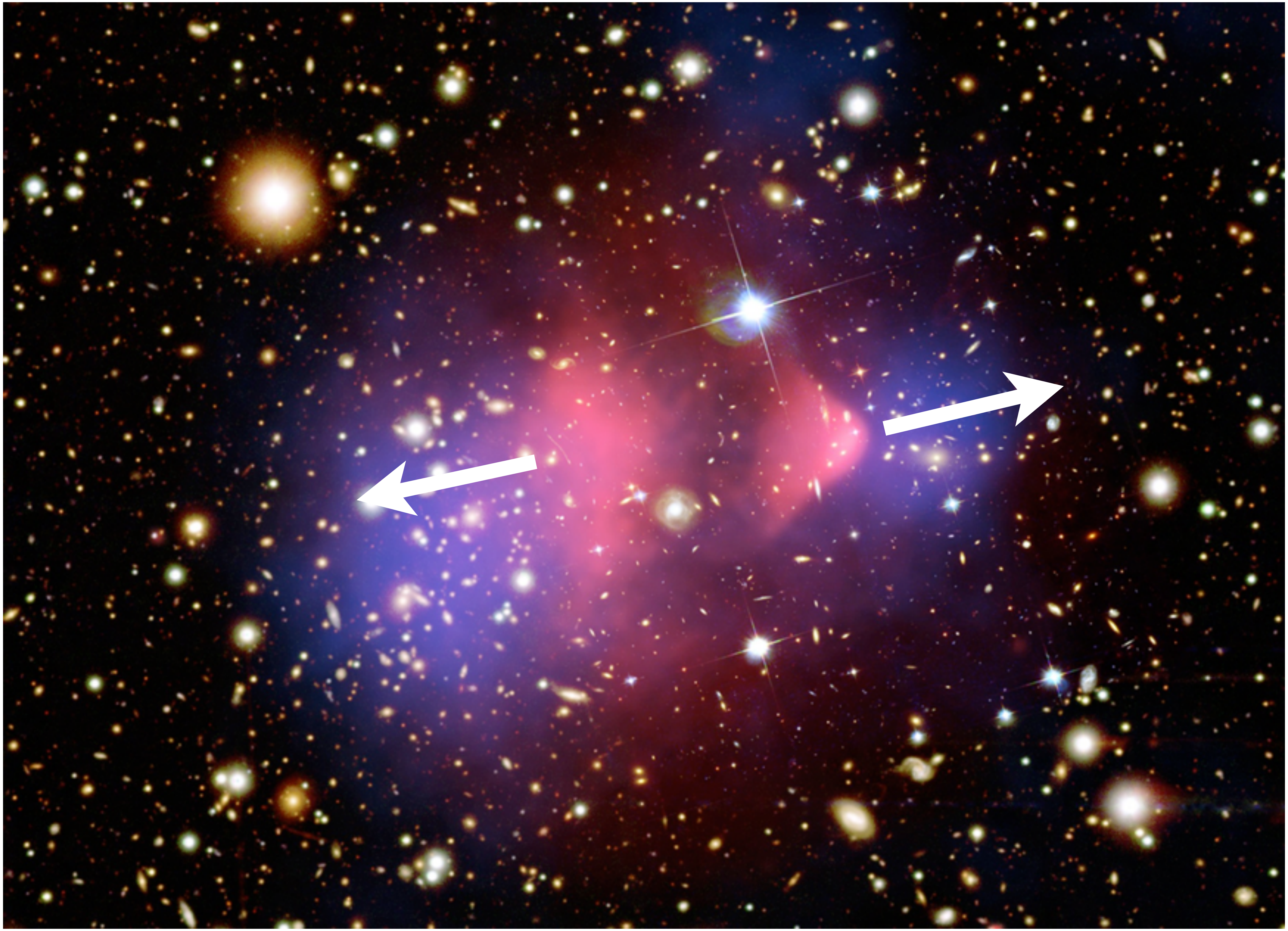

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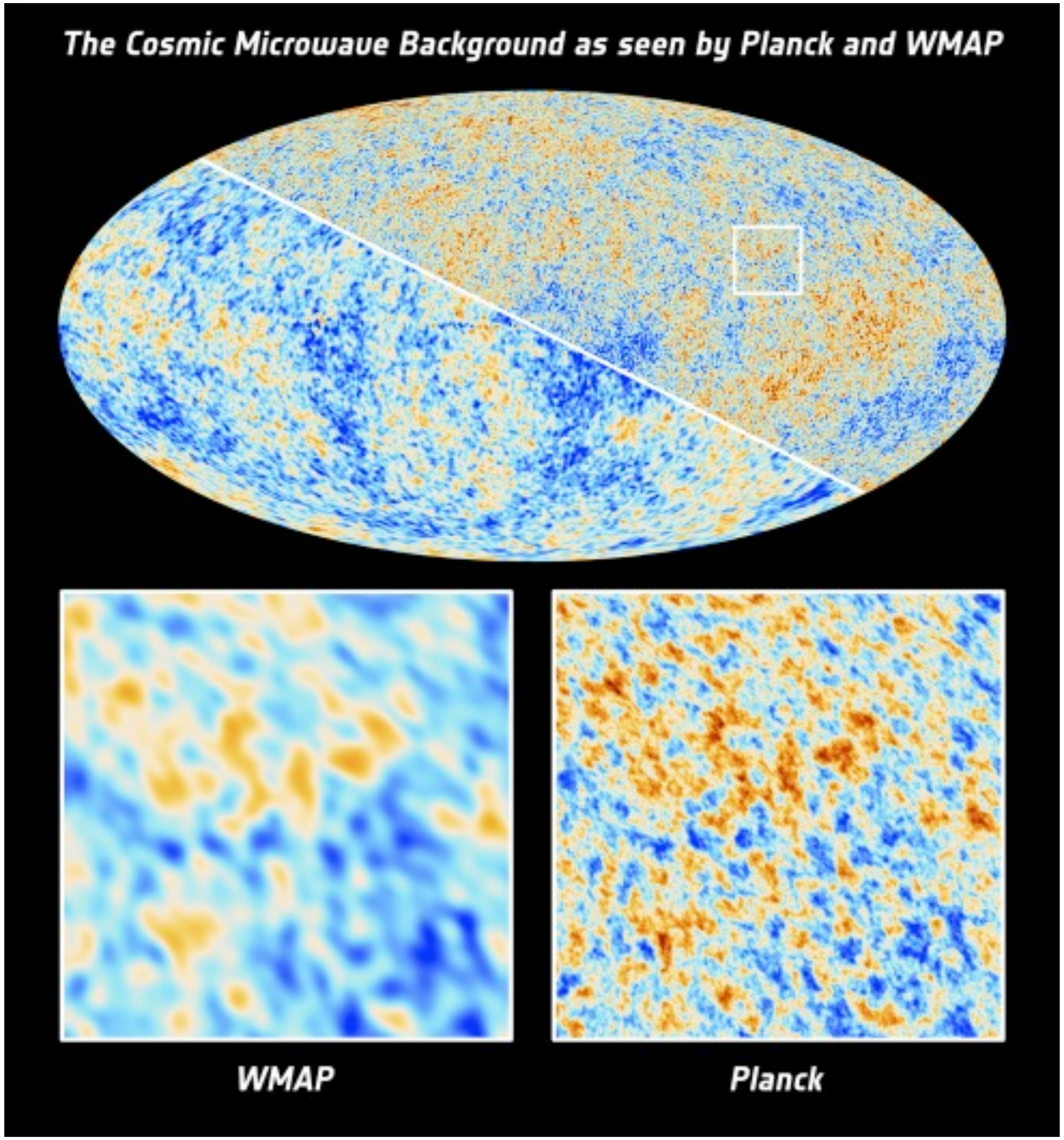
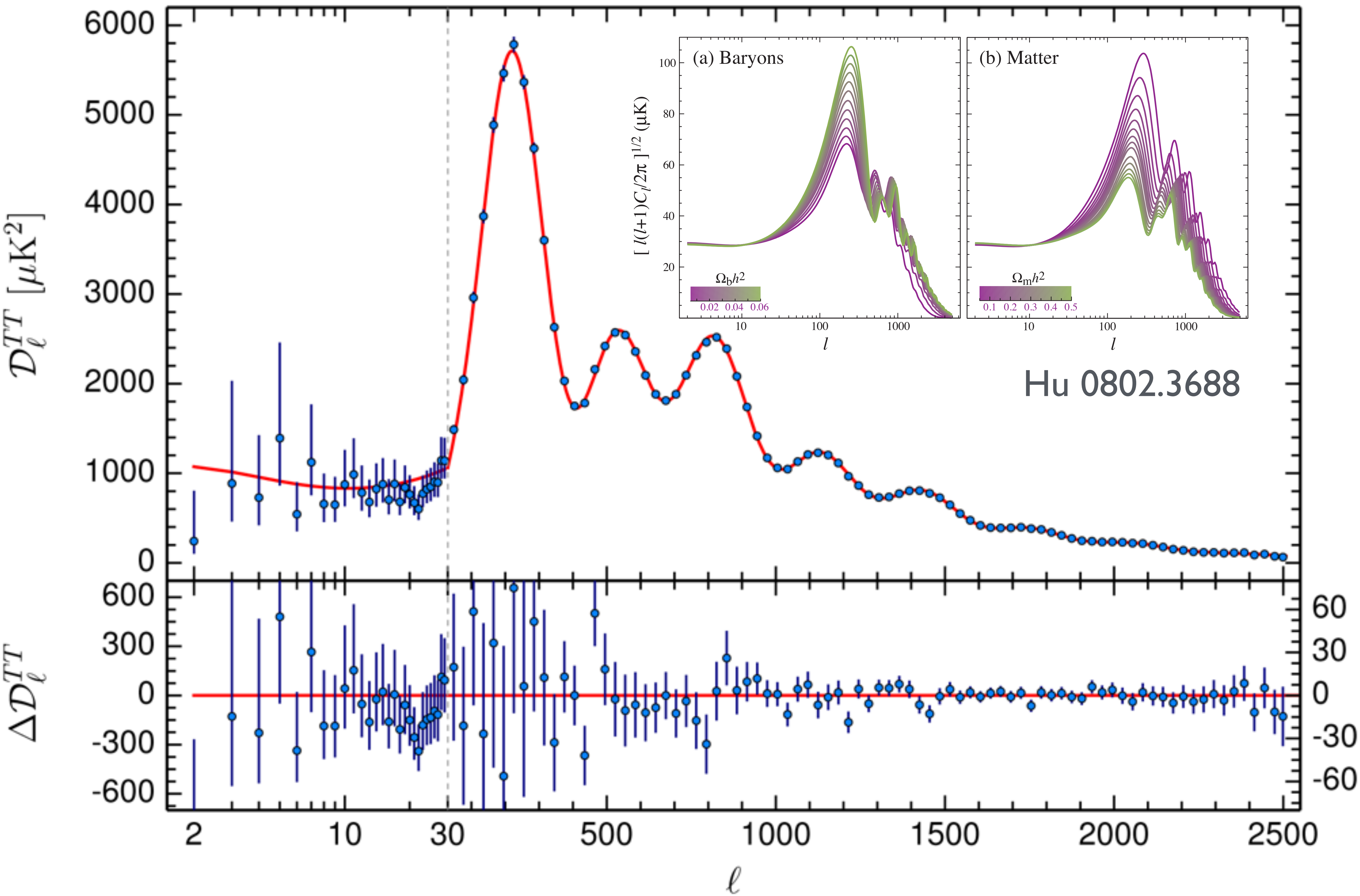
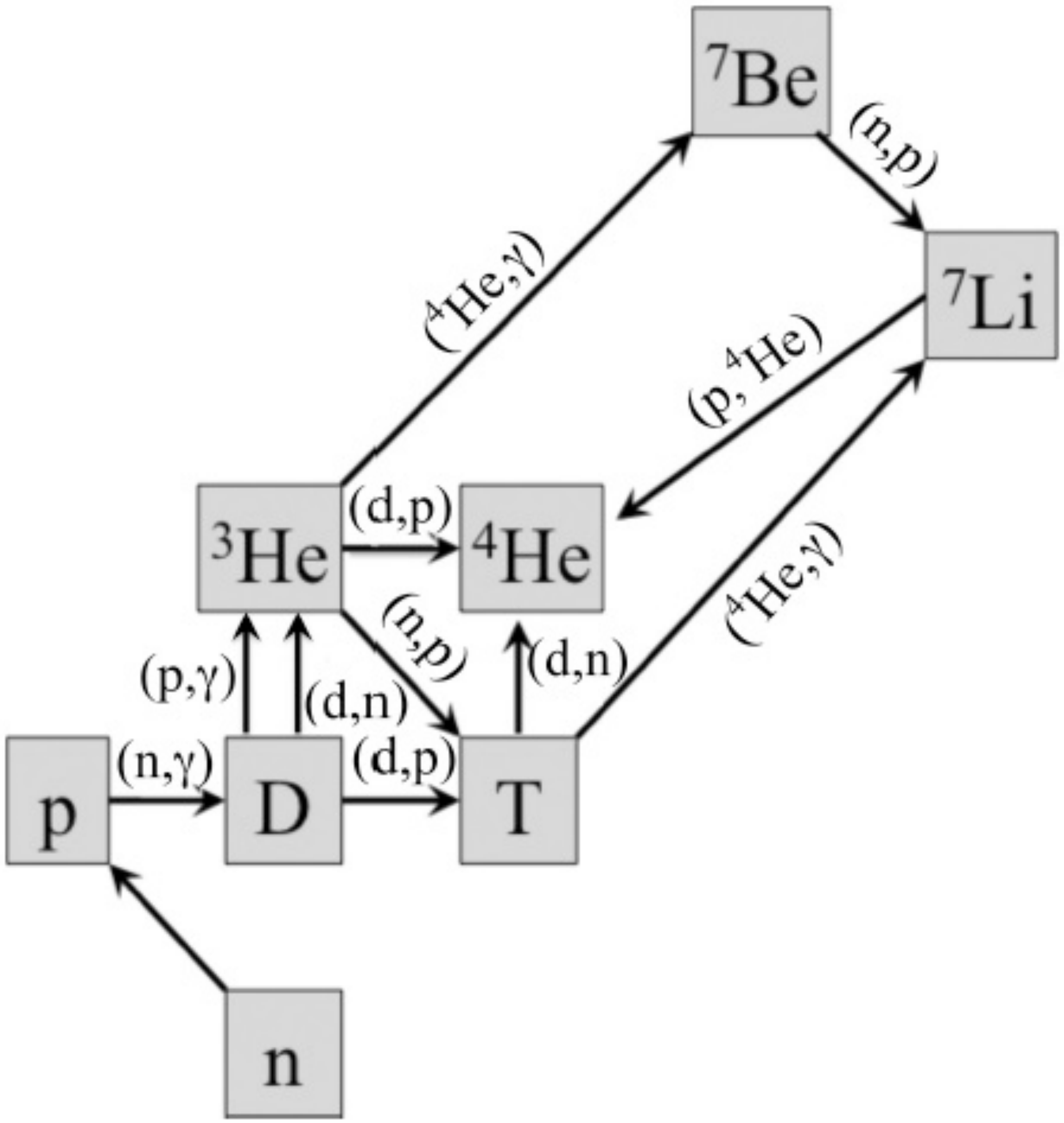


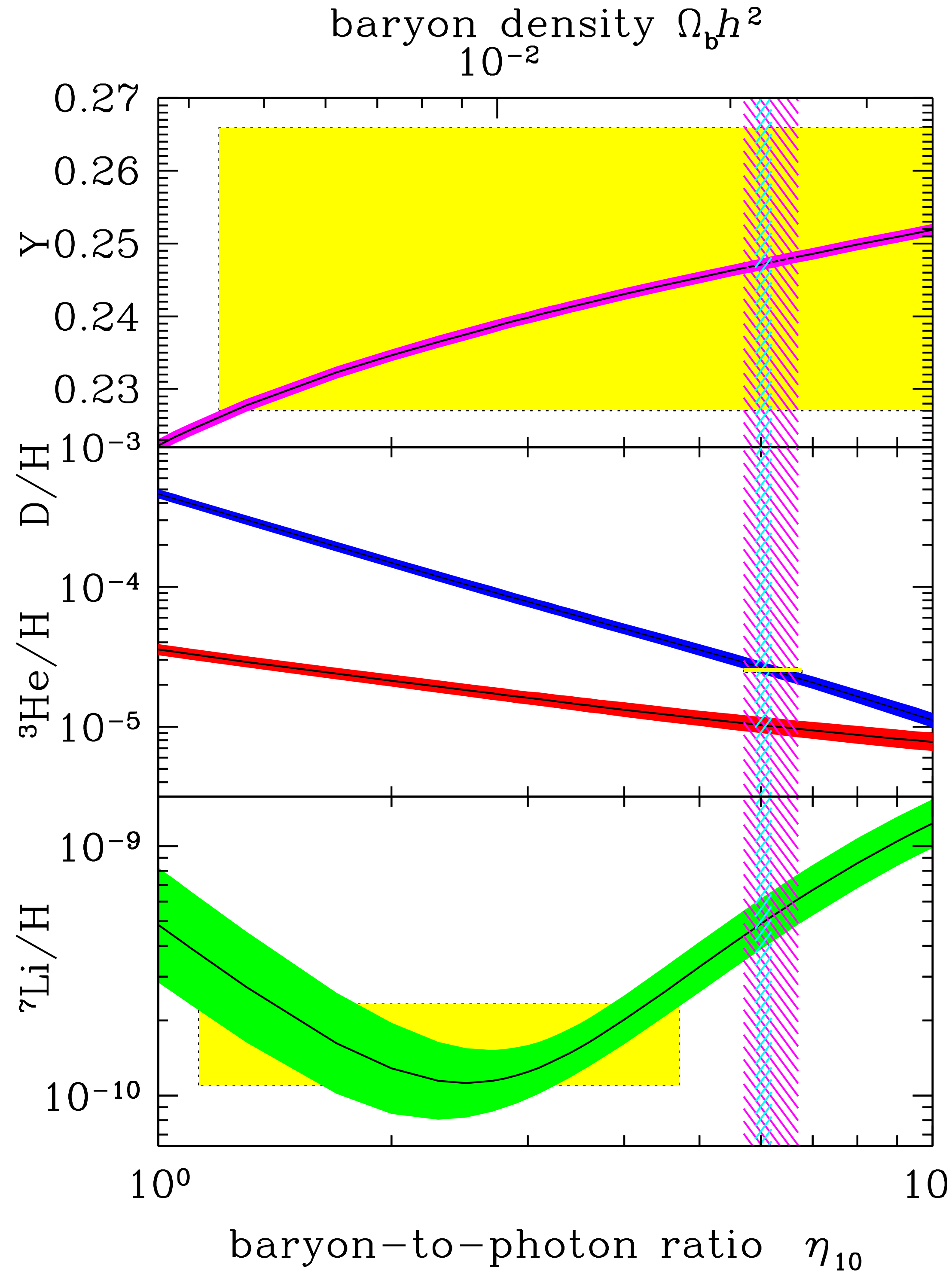
Hot plasma of hydrogen atoms and photons,
and DM and cc

Planck Collaboration



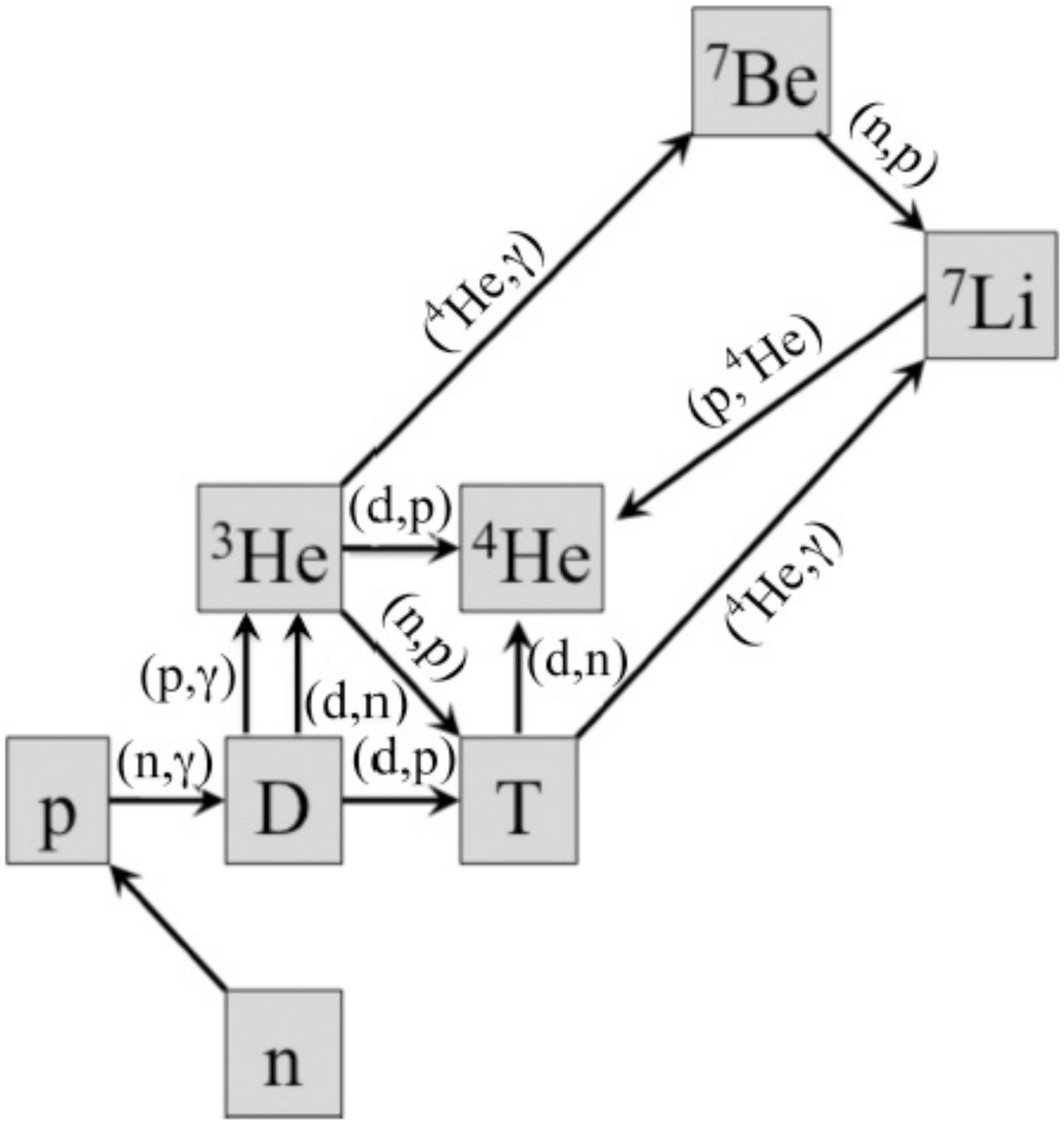
Big Bang Nucleosynthesis

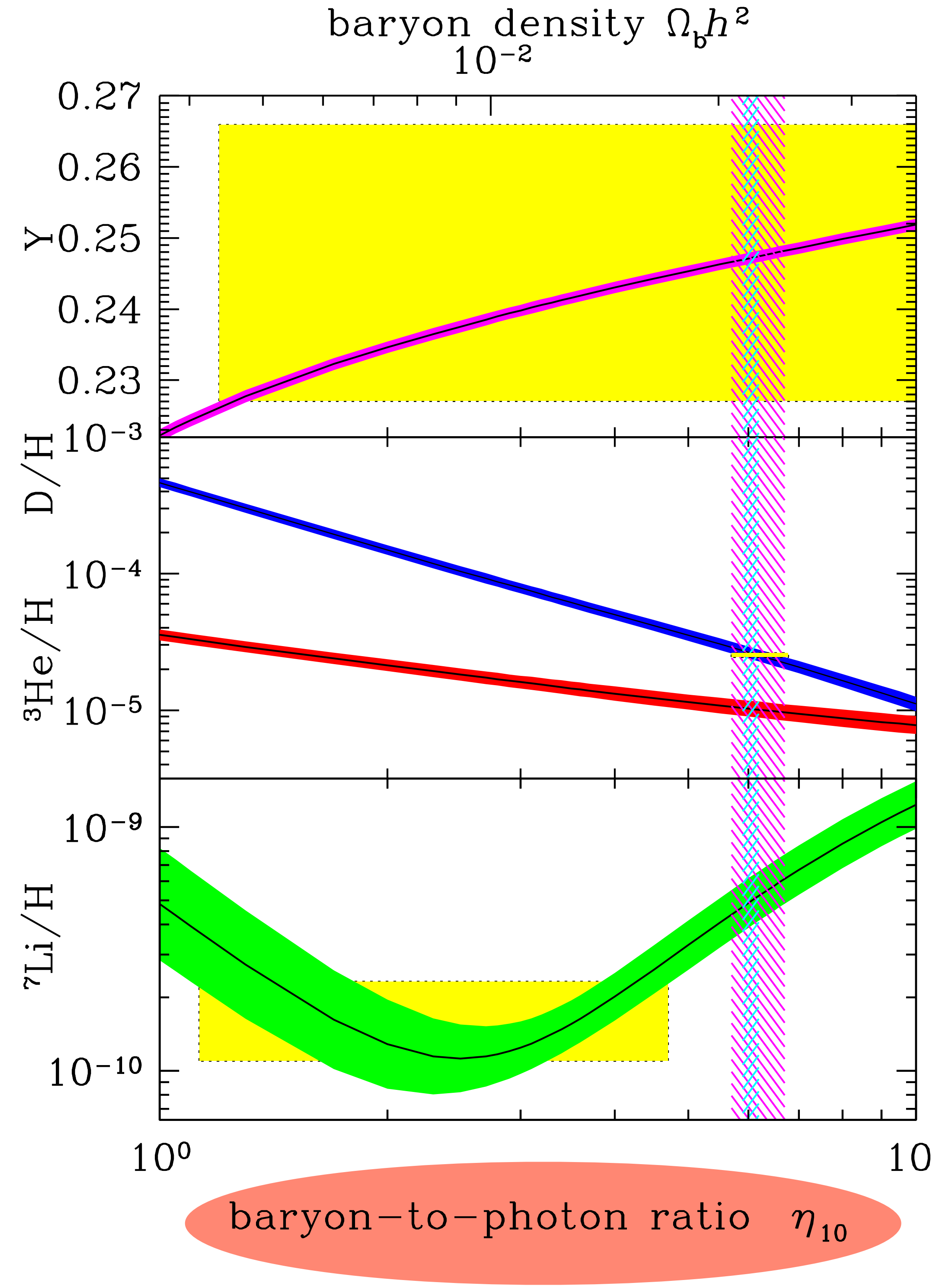




Hot soup of protons and neutrons, can predict light element abundance

Big Bang Nucleosynthesis





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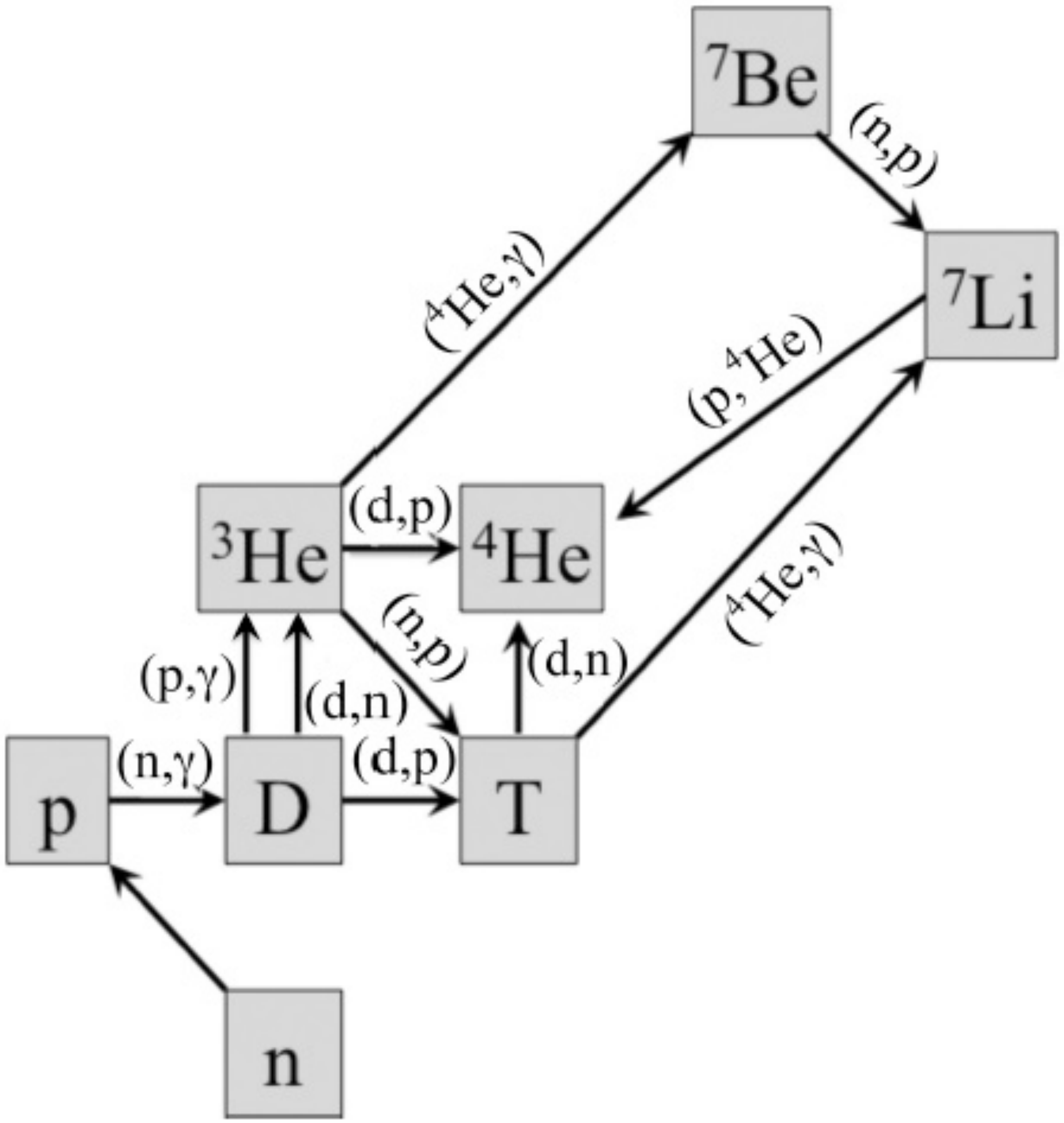
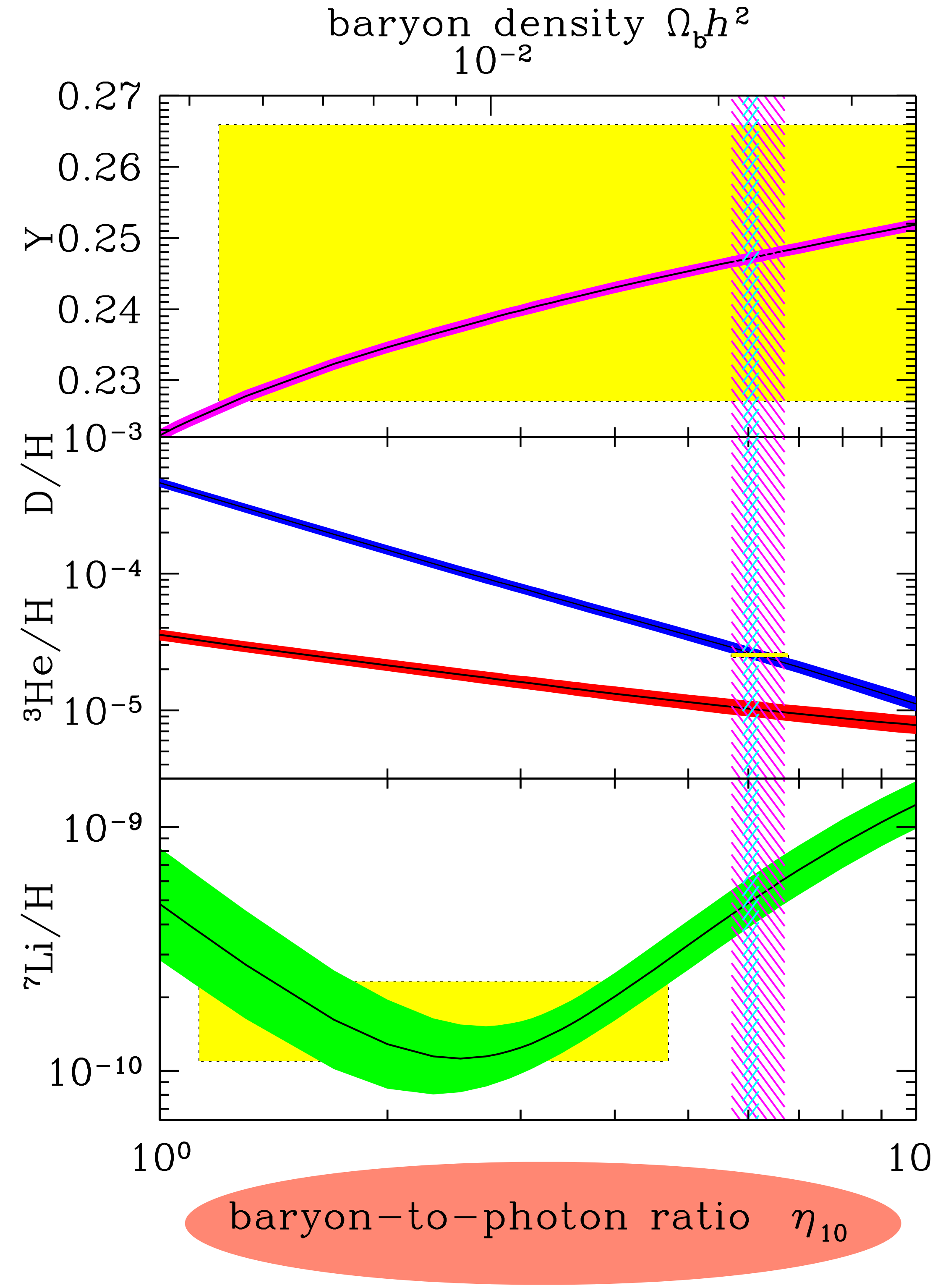




Hot soup of protons and neutrons, can predict light element abundance

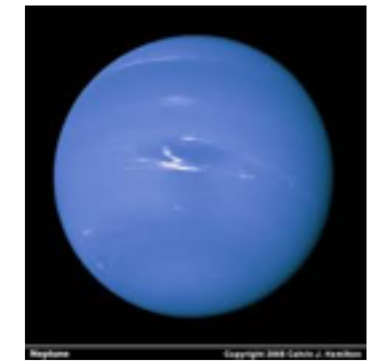
~5% in baryons

So far all probes have been gravitational in nature

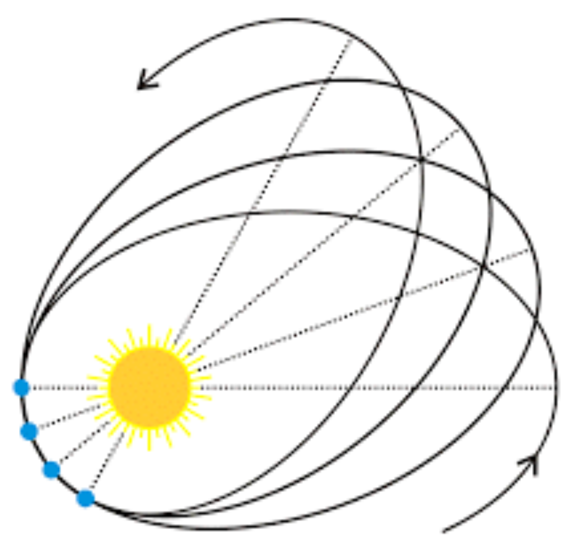
What about other interactions?

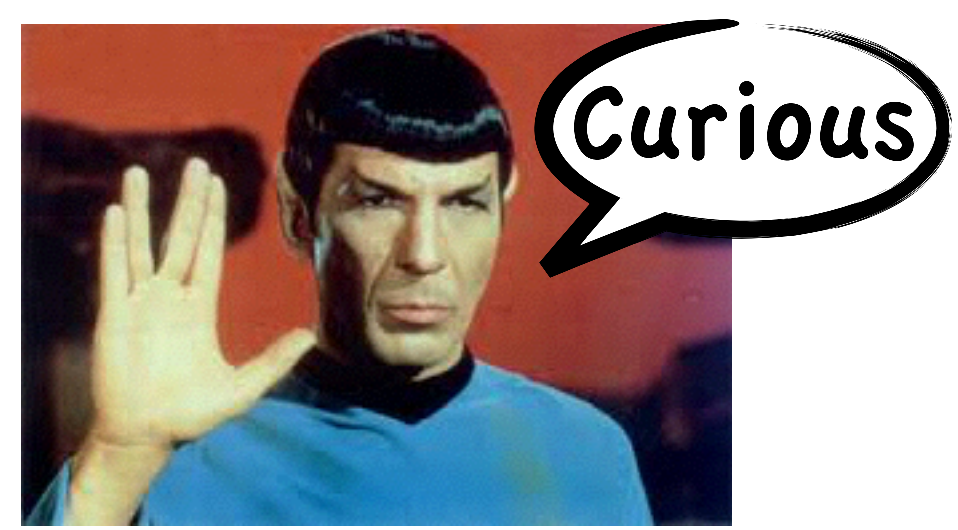
History Lesson

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!)
—MOND??



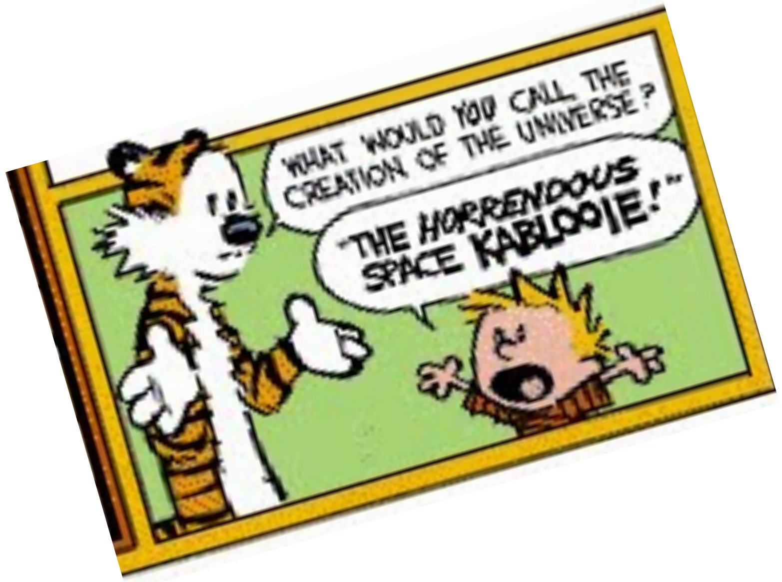


DM as a thermal relic

"The weak shall inherit the Universe"

A weak scale particle (WIMP) freezes out to leave the correct relic abundance - the WIMP "miracle"

$$\chi\chi \leftrightarrow \bar{f}f$$



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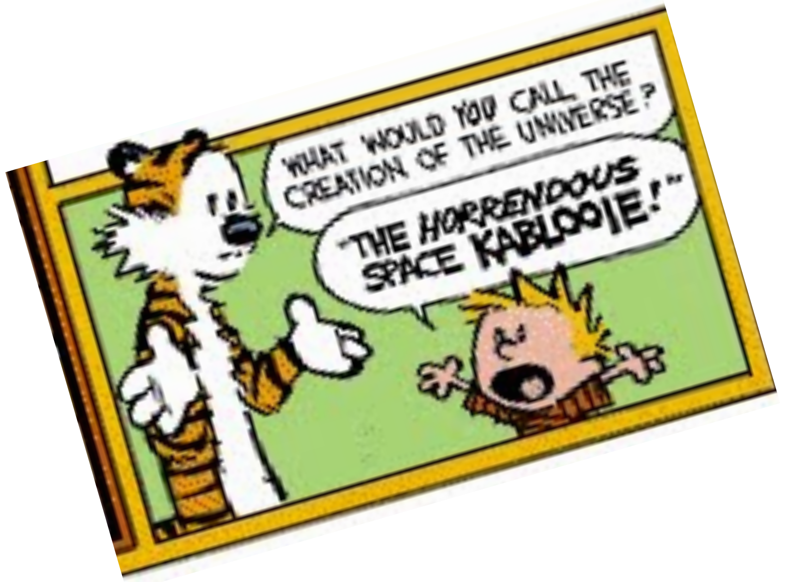
"Freeze out": $$n\langle\sigma v\rangle \sim H \sim \frac{T^2}{M_{pl}}$$



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

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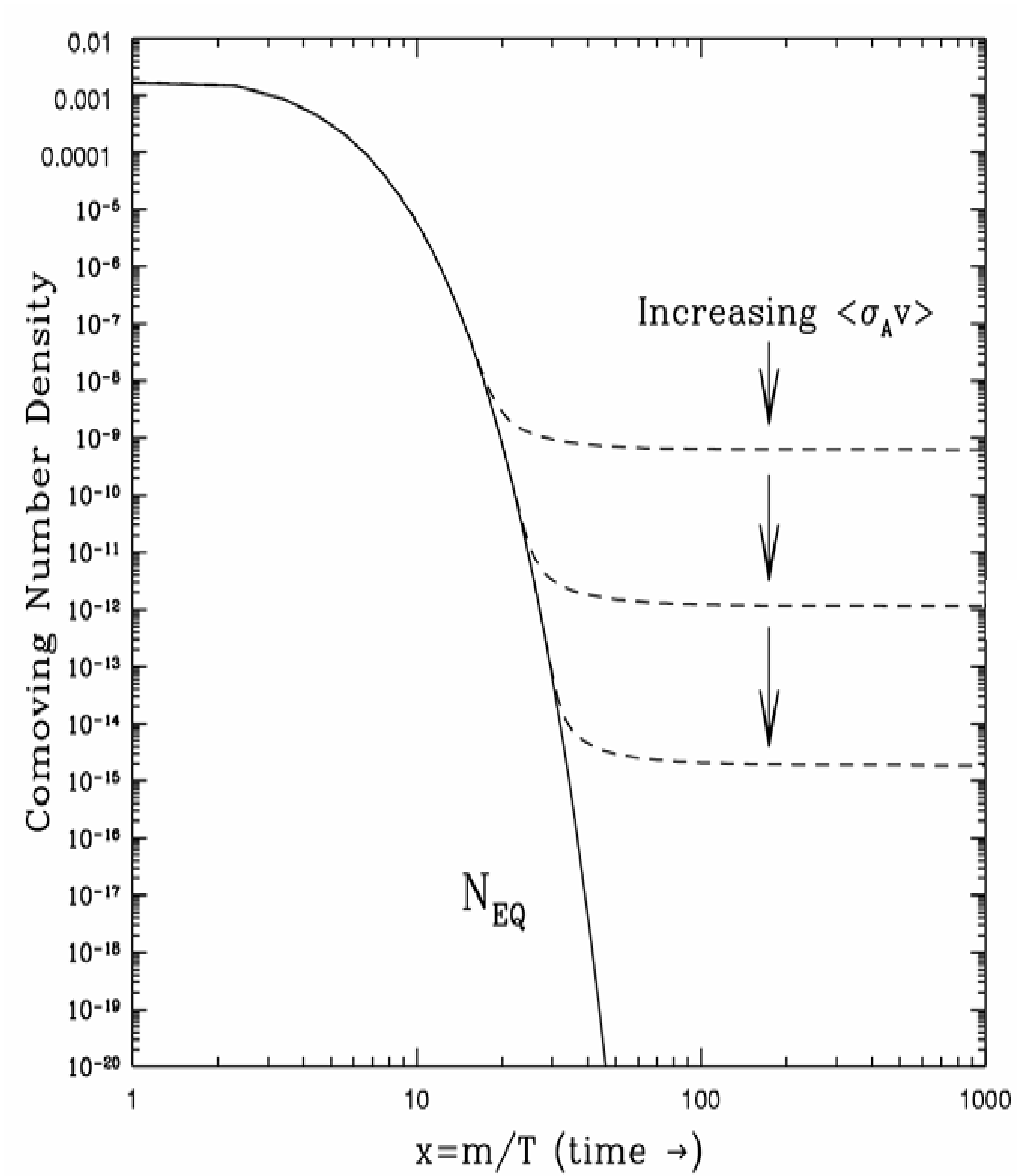

$$\chi\chi \leftrightarrow \bar{f}f$$

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

Amazing (misleading?) fact:

$$\langle\sigma v\rangle \sim \frac{\alpha_W^2}{M_W^2} \sim 1\,\mathrm{pb} \sim 3\times 10^{-26}\mathrm{cm}^2\mathrm{s}^{-1}$$

DM, the story so far

- 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 not relativistic at time of CMB
- Is long lived
- Is BSM physics

IF DM is a thermal relic:

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

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$$\frac{\sigma}{m} \lesssim 1\mathrm{cm}^2/g \sim \mathrm{barn}/\mathrm{GeV}$$

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WIMPs

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LPOPs

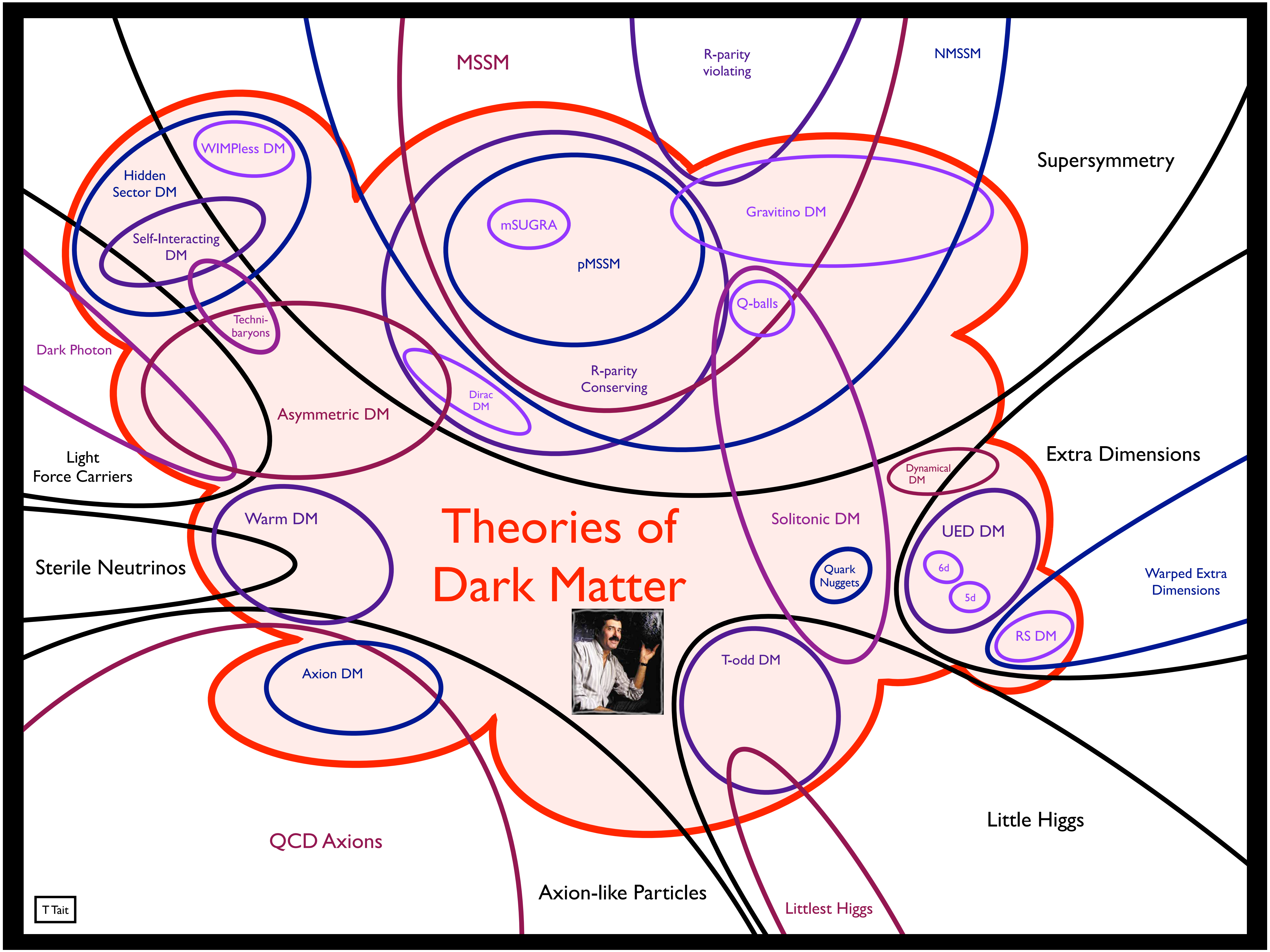
Many models of BSM physics contain a parity

$$\mathrm{SM} \to \mathrm{SM} \qquad\qquad \mathrm{BSM} \to -\mathrm{BSM}$$

e.g. R-parity in SUSY (proton decay)
T-parity in little higgs models (precision EW observables)
KK-parity in extra-dimensional models
…..

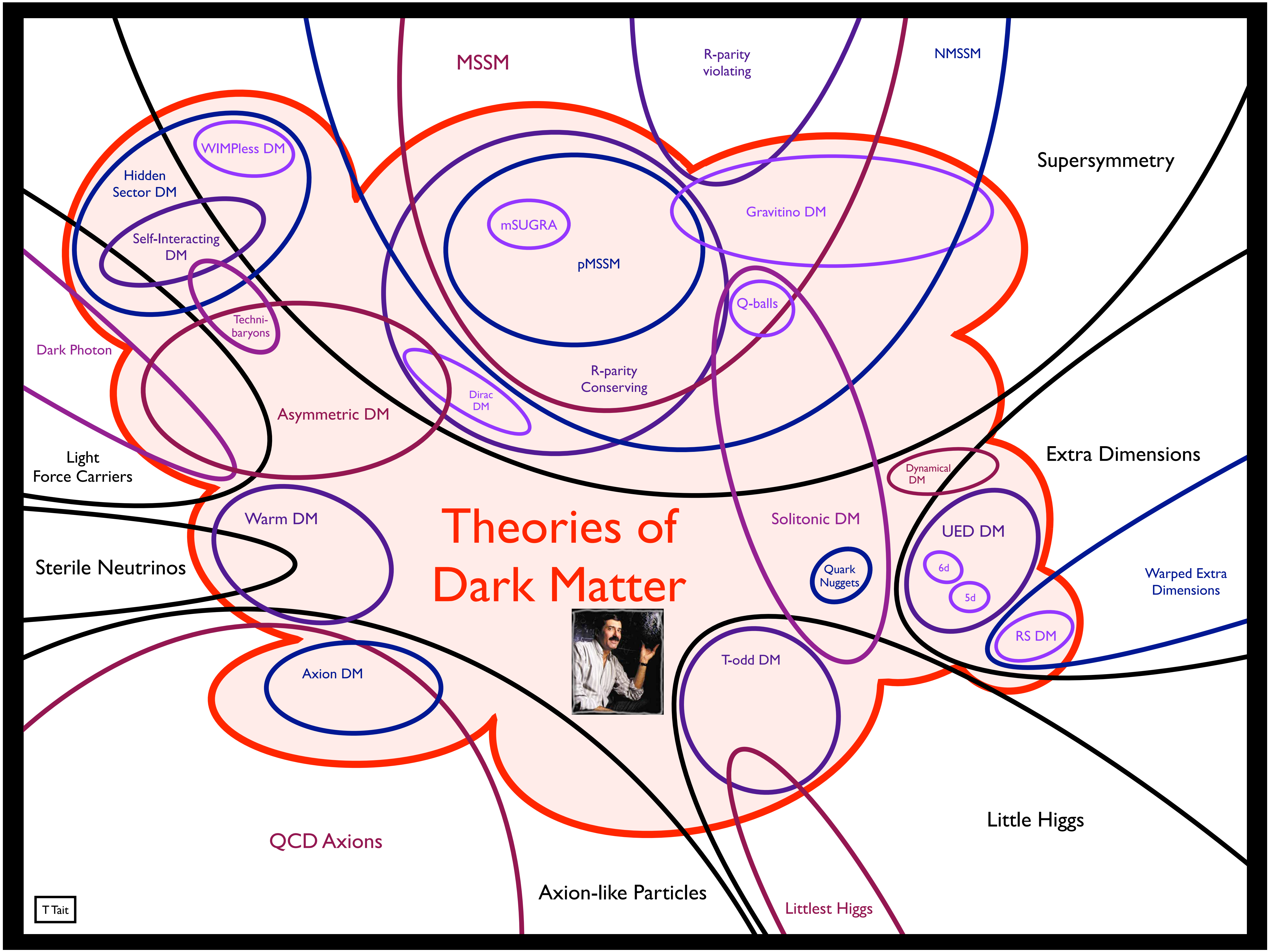
Lightest **P**arity **O**dd **P**article is stable, may be a DM candidate

Always produced in pairs and leaves detector as MET



MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
Techni-baryons
mSUGRA
pMSSM
Gravitino DM
Q-balls
R-parity Conserving
Dark Photon
Asymmetric DM
Dirac DM
Light Force Carriers
Extra Dimensions
Dynamical DM
Theories of Dark Matter
Warm DM
Solitonic DM
UED DM
Sterile Neutrinos
Quark Nuggets
6d
5d
Warped Extra Dimensions
RS DM
Axion DM
T-odd DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait

But such particles exist in **MANY** BSM models



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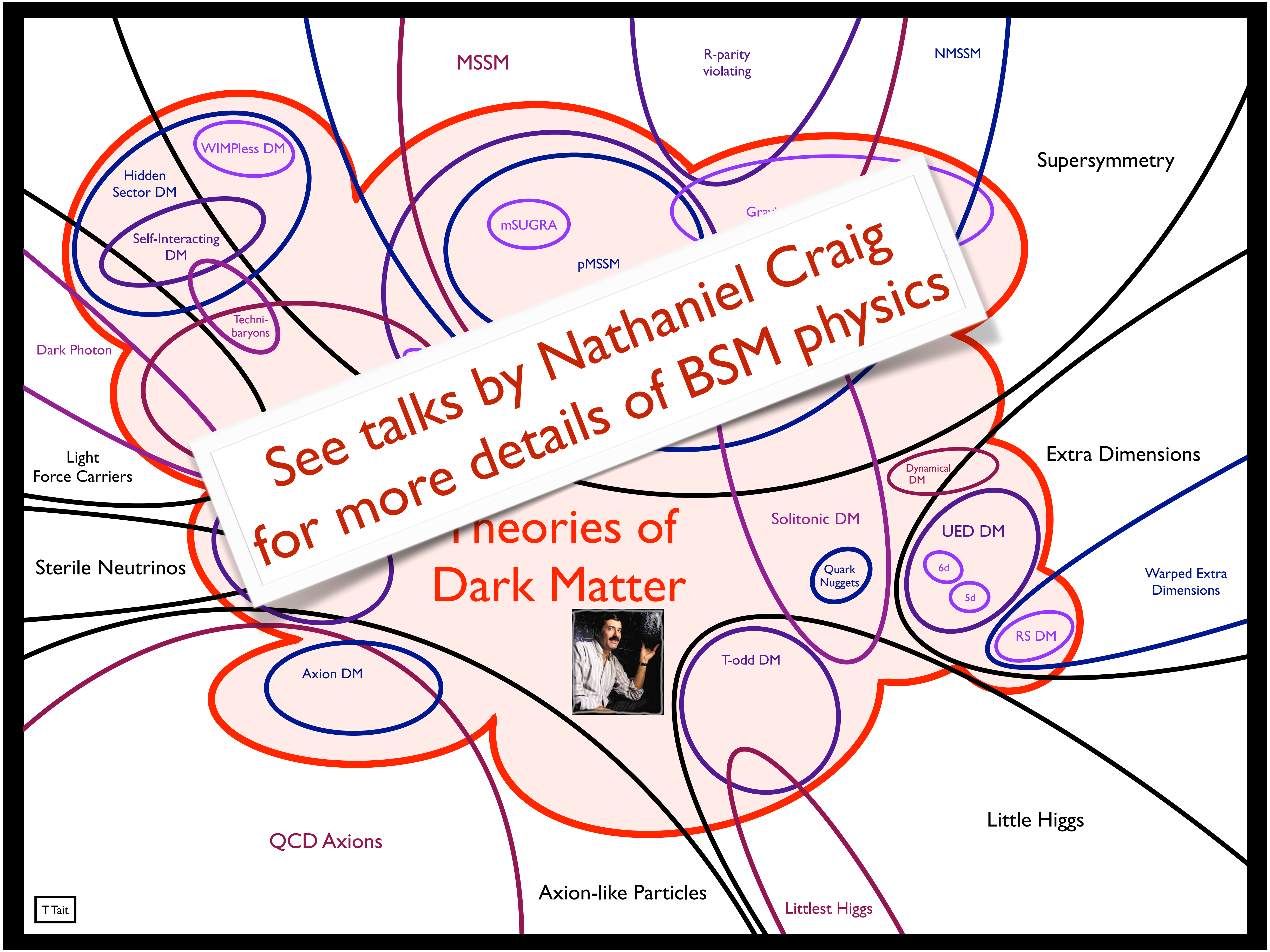
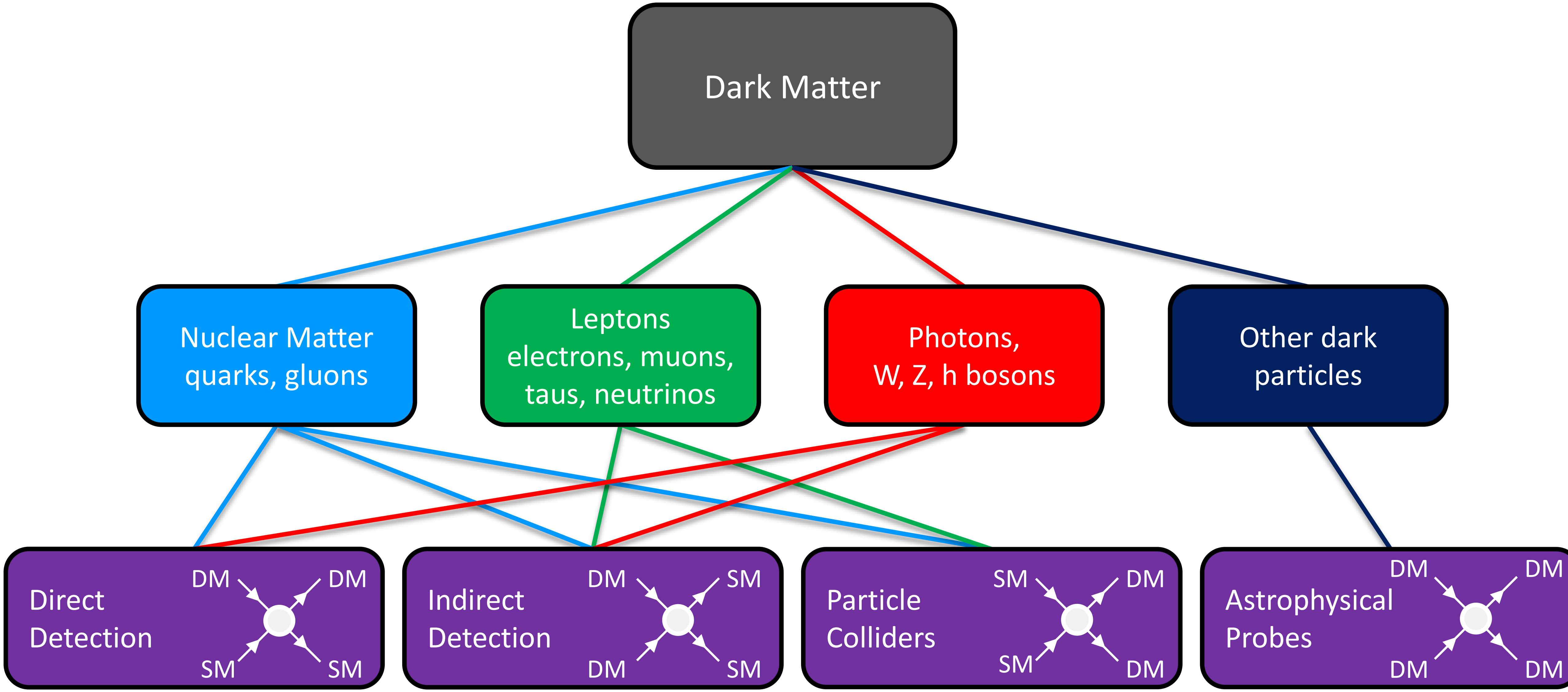
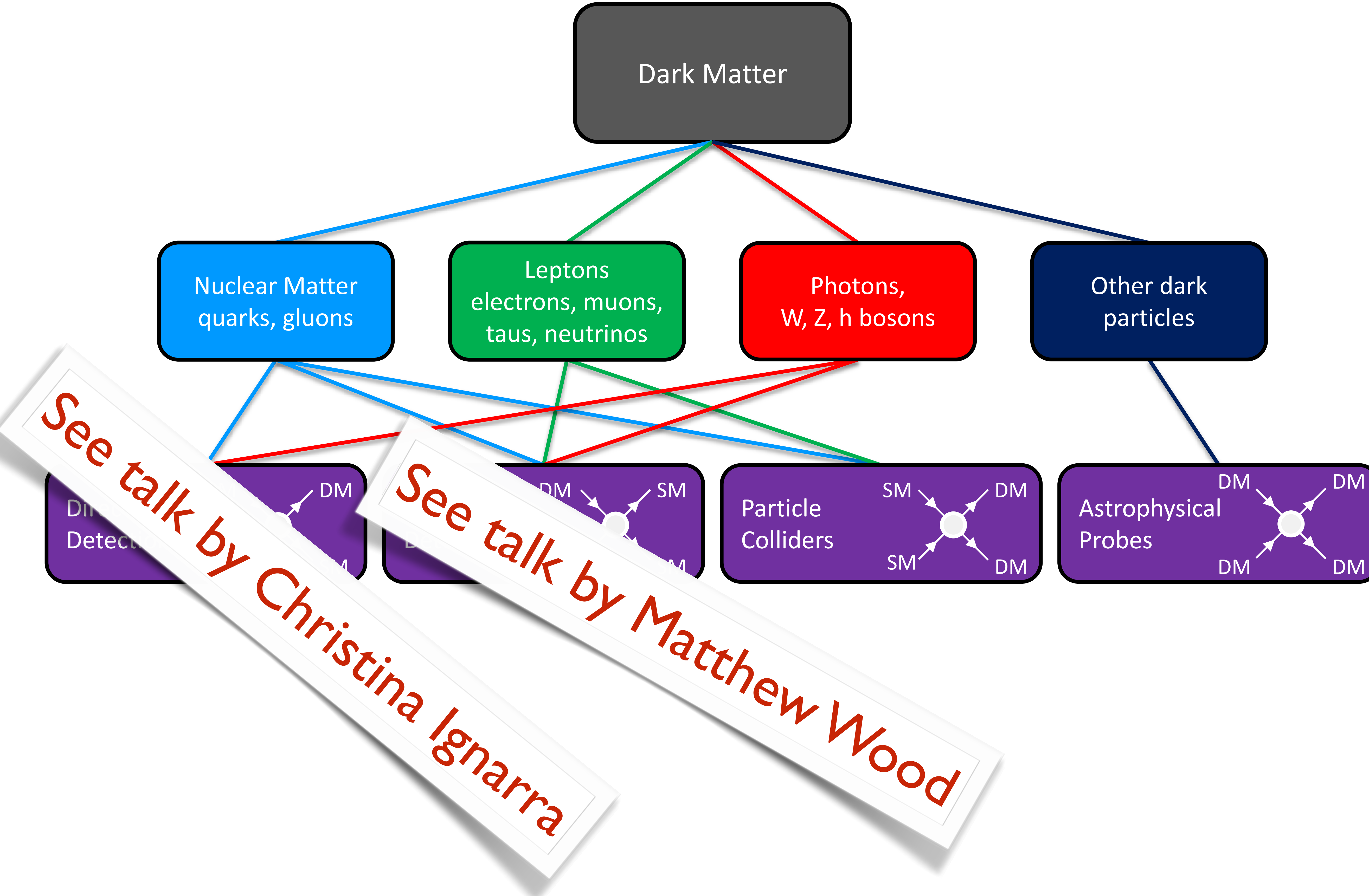




Dark Matter
Nuclear Matter
quarks, gluons
Leptons
electrons, muons,
taus, neutrinos
Photons,
W, Z, h bosons
Other dark
particles
Direct
Detection
DM
DM
SM
SM
Indirect
Detection
DM
SM
DM
SM
Particle
Colliders
SM
DM
SM
DM
Astrophysical
Probes
DM
DM
DM
DM



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particles
DM
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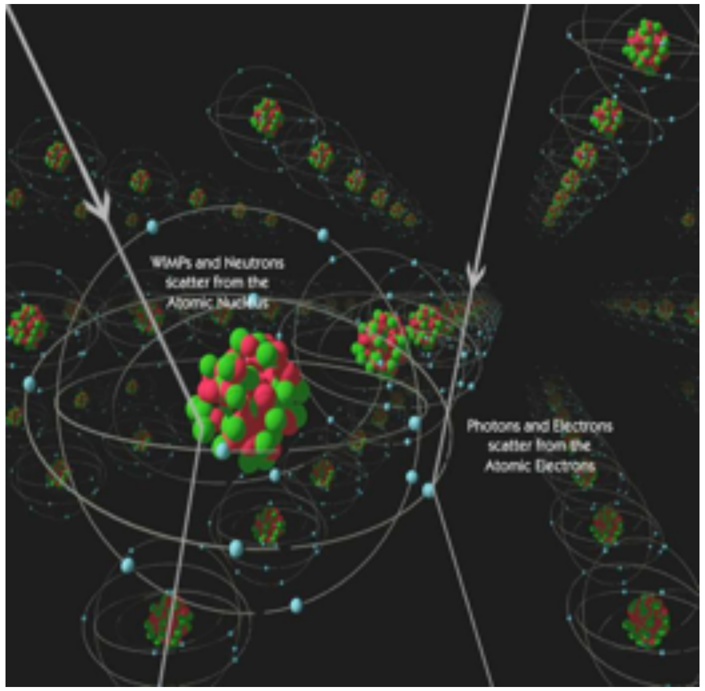
SM
DM
Astrophysical
Probes
DM
DM
DM
DM
See talk by Christina Ignarra
See talk by Matthew Wood

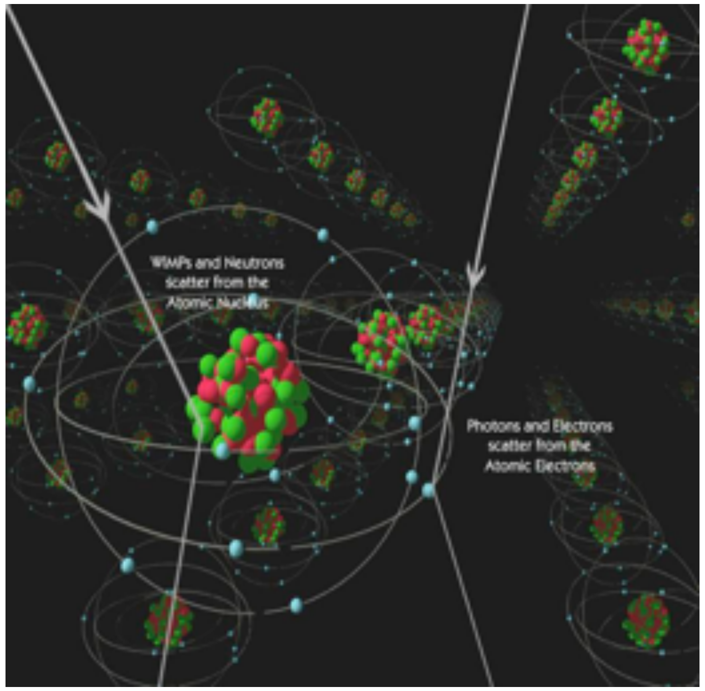
Q: Are these different search strategies separate, redundant, complementary, relatable,….?

Direct Detection "Master formula"



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

Direct Detection "Master formula"



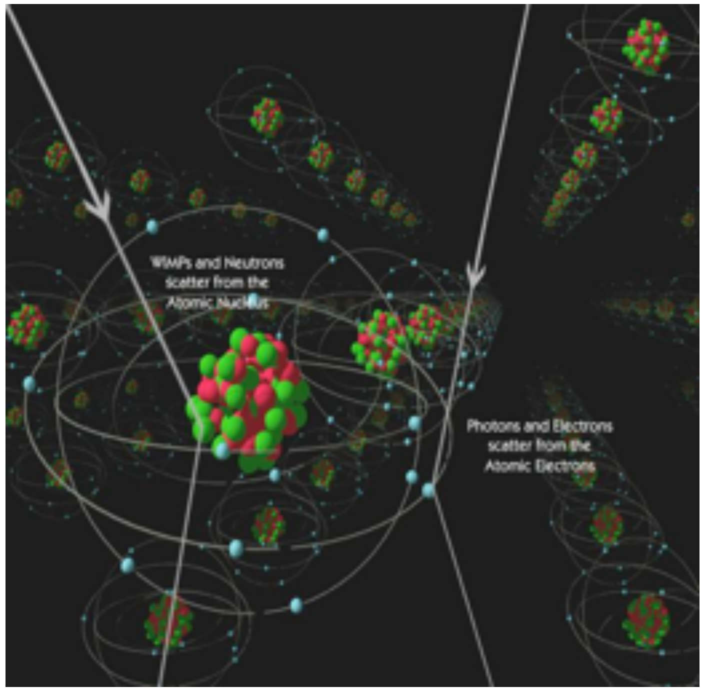
Recoil rate as a function of recoil energy

Depends on how much DM is around...

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

Number of targets in experiment

Direct Detection "Master formula"



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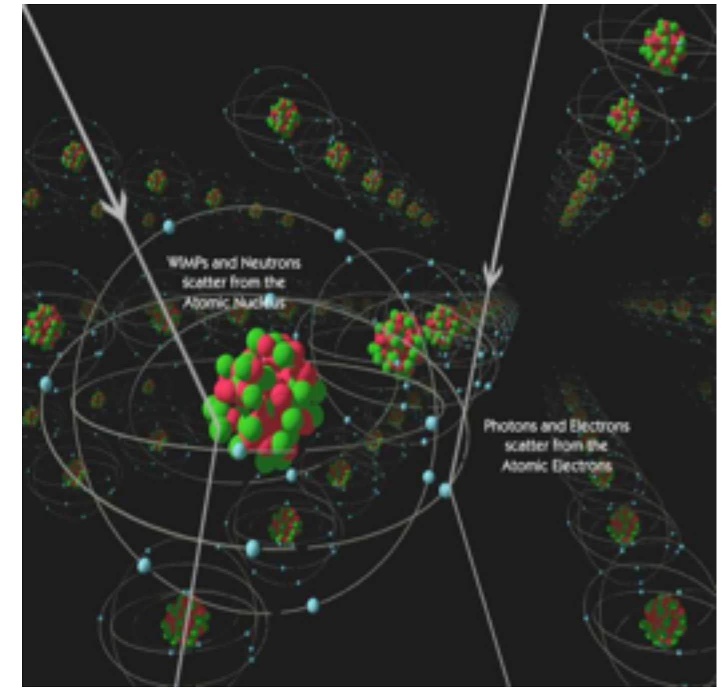
Number of targets in experiment

...and how it's moving...

Direct Detection “Master formula”



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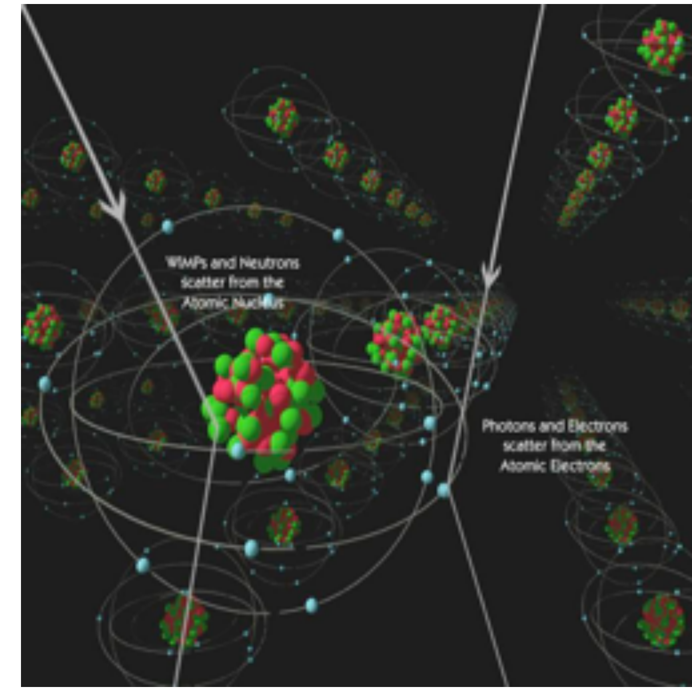
Number of targets in experiment

...and how it’s moving...

...and how it interacts with nuclei.

Direct Detection "Master formula"



Recoil rate as a function of recoil energy

Depends on how much DM is around...

"In theory there is no difference between theory and practice. But in practice there is.--Yogi Berra"

Number of targets in experiment

...and how it's moving...

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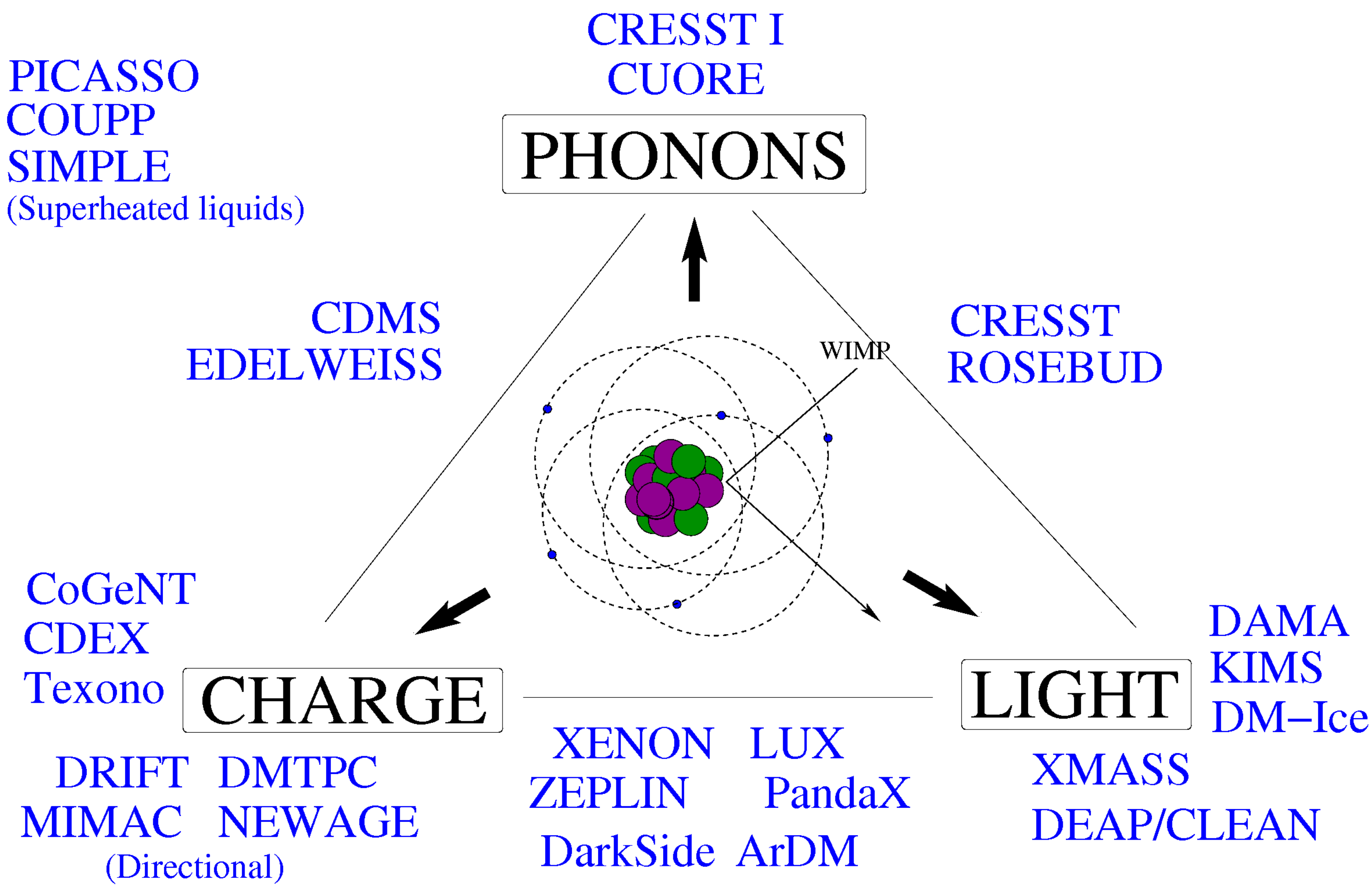
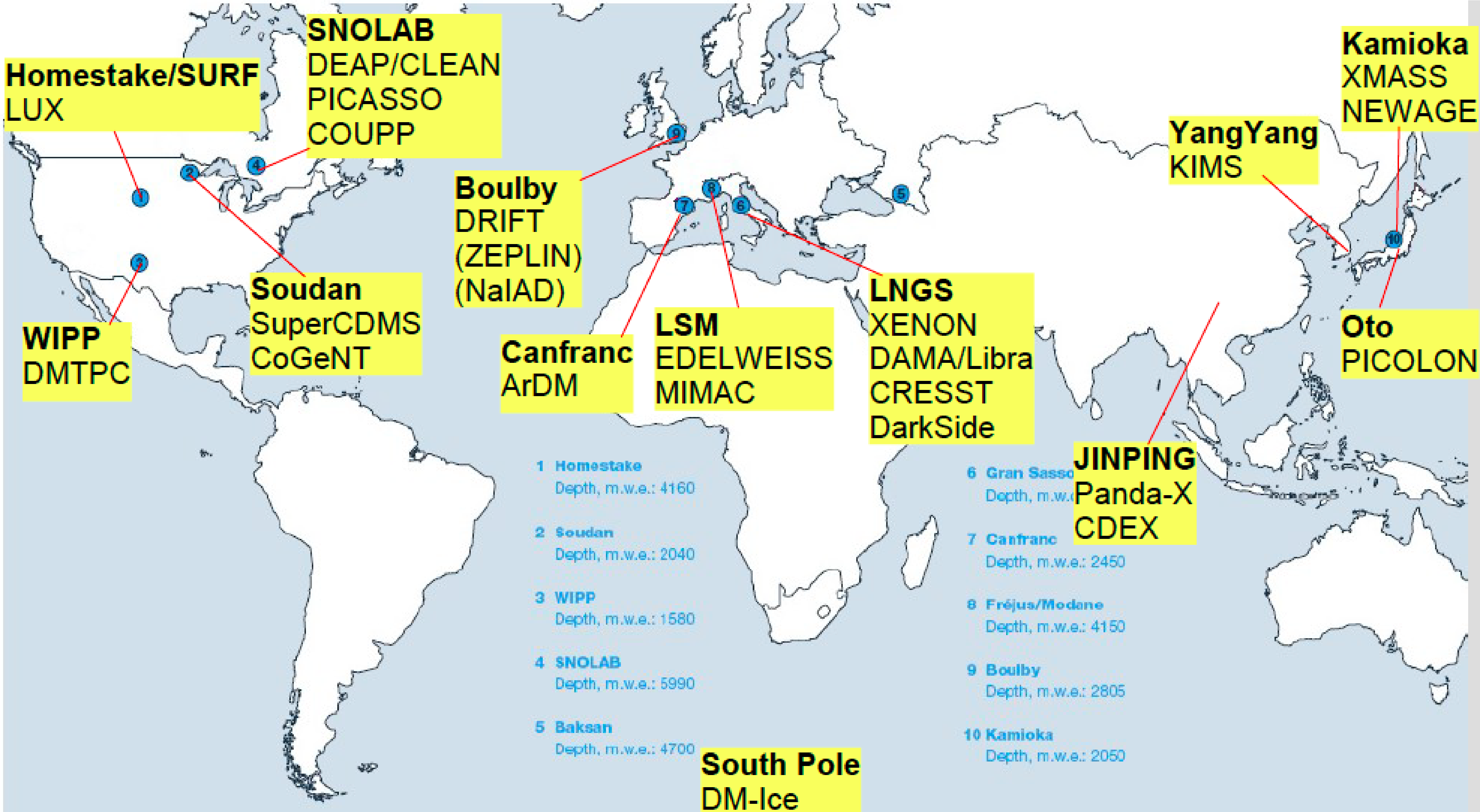
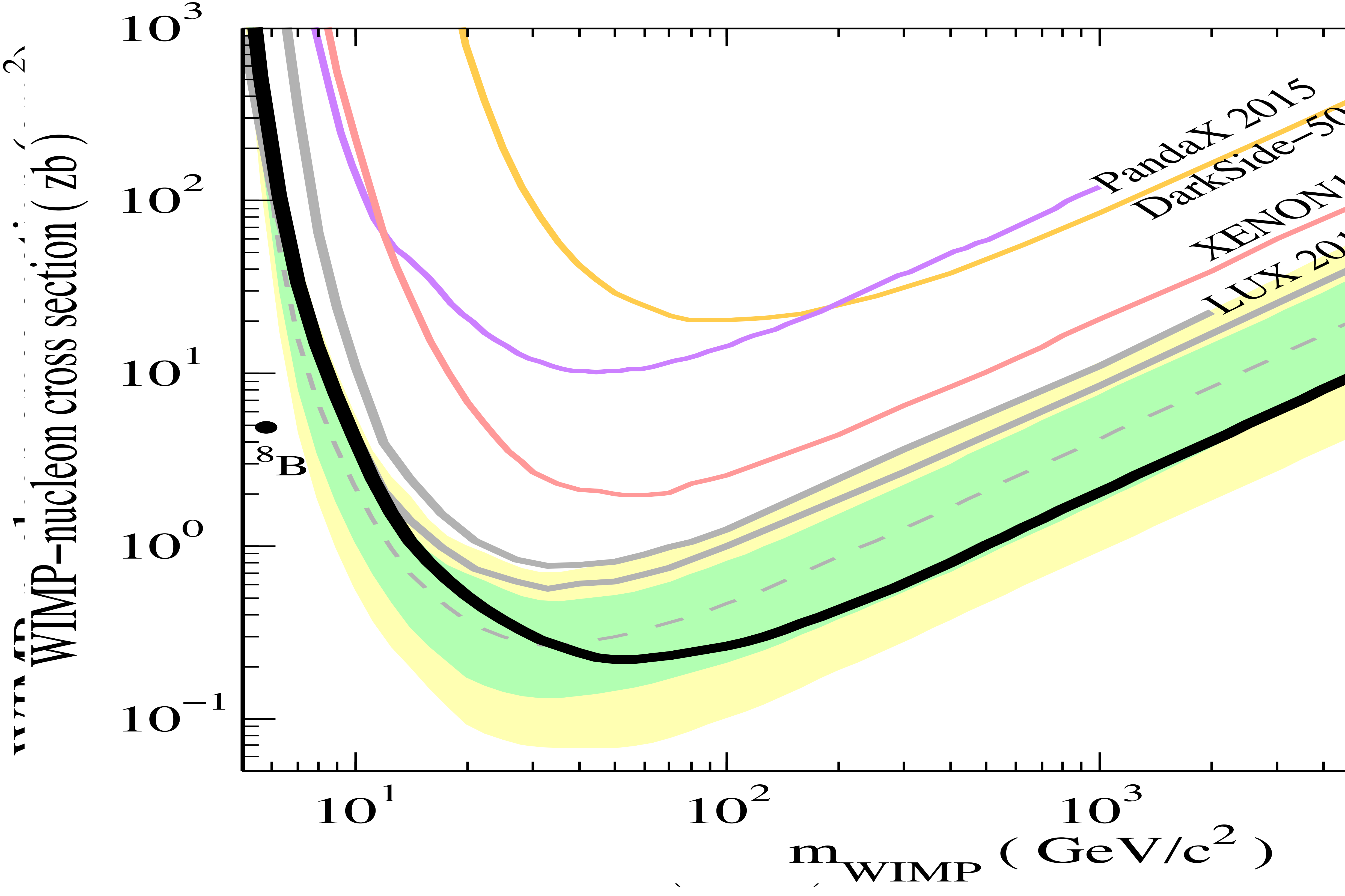
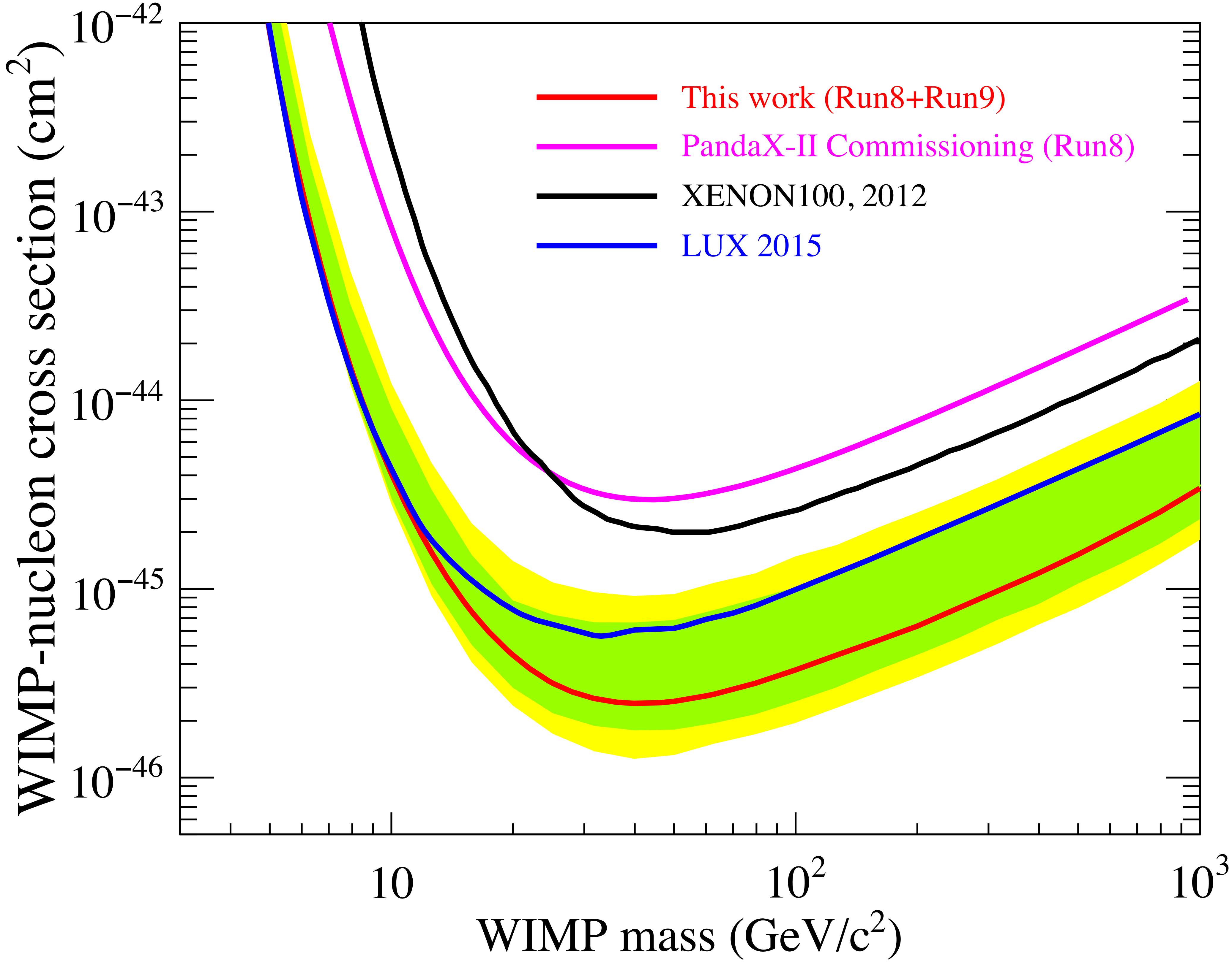

CRESST I
CUORE
PHONONS
PICASSO
COUPP
SIMPLE
(Superheated liquids)
CDMS
EDELWEISS
CRESST
ROSEBUD
WIMP
CoGeNT
CDEX
Texono
CHARGE
LIGHT
DAMA
KIMS
DM–Ice
XENON
LUX
ZEPLIN
PandaX
DarkSide
ArDM
XMASS
DEAP/CLEAN
DRIFT
DMTPC
MIMAC
NEWAGE
(Directional)

Underground laboratories

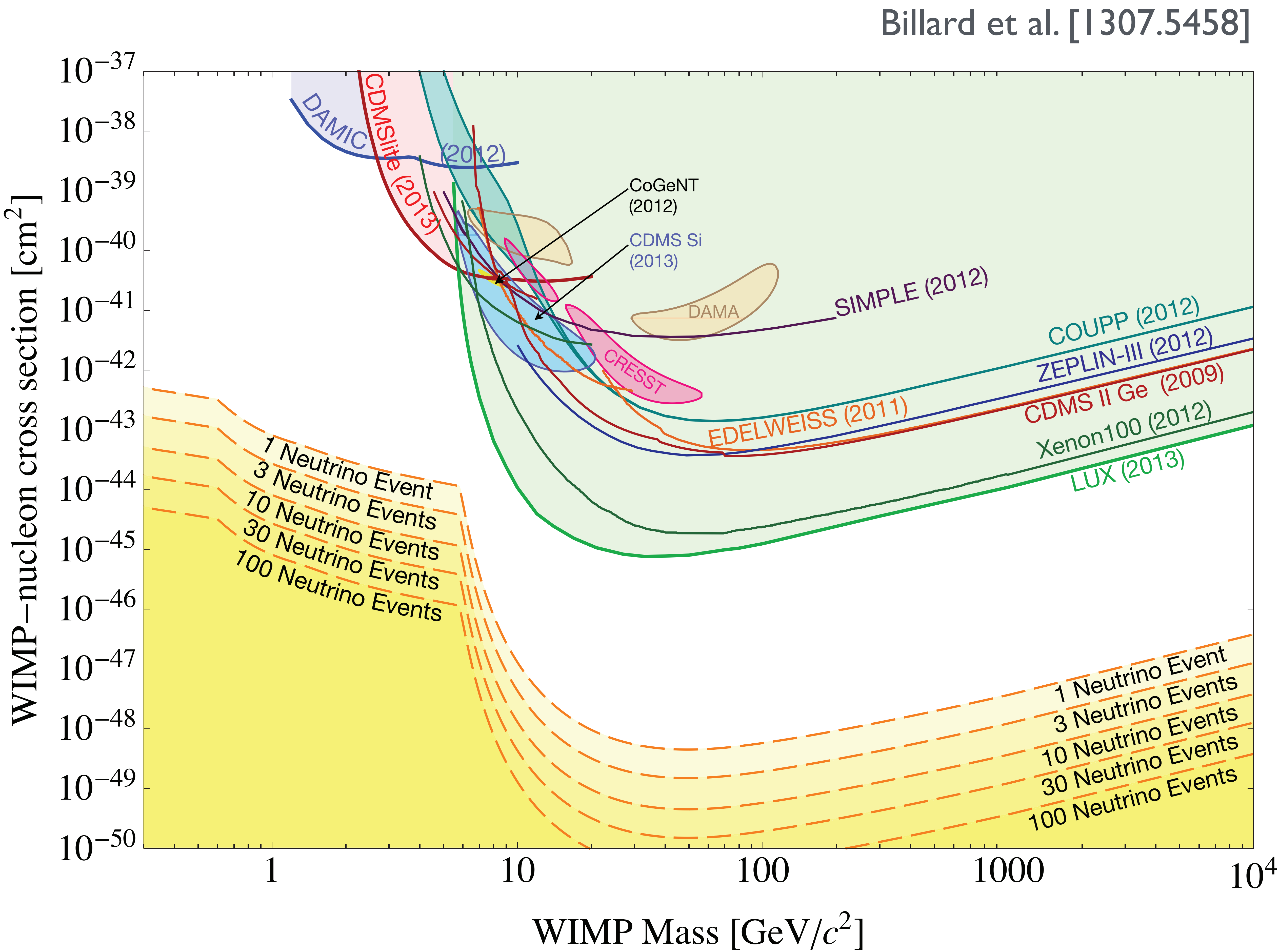




WIMP-nucleon cross section (zb)
10^3
10^2
10^1
10^0
10^{-1}
^{8}B
PandaX 2015
DarkSide-50
XENON1
LUX 201
10^1
10^2
10^3
m_{WIMP} (GeV/c^2)



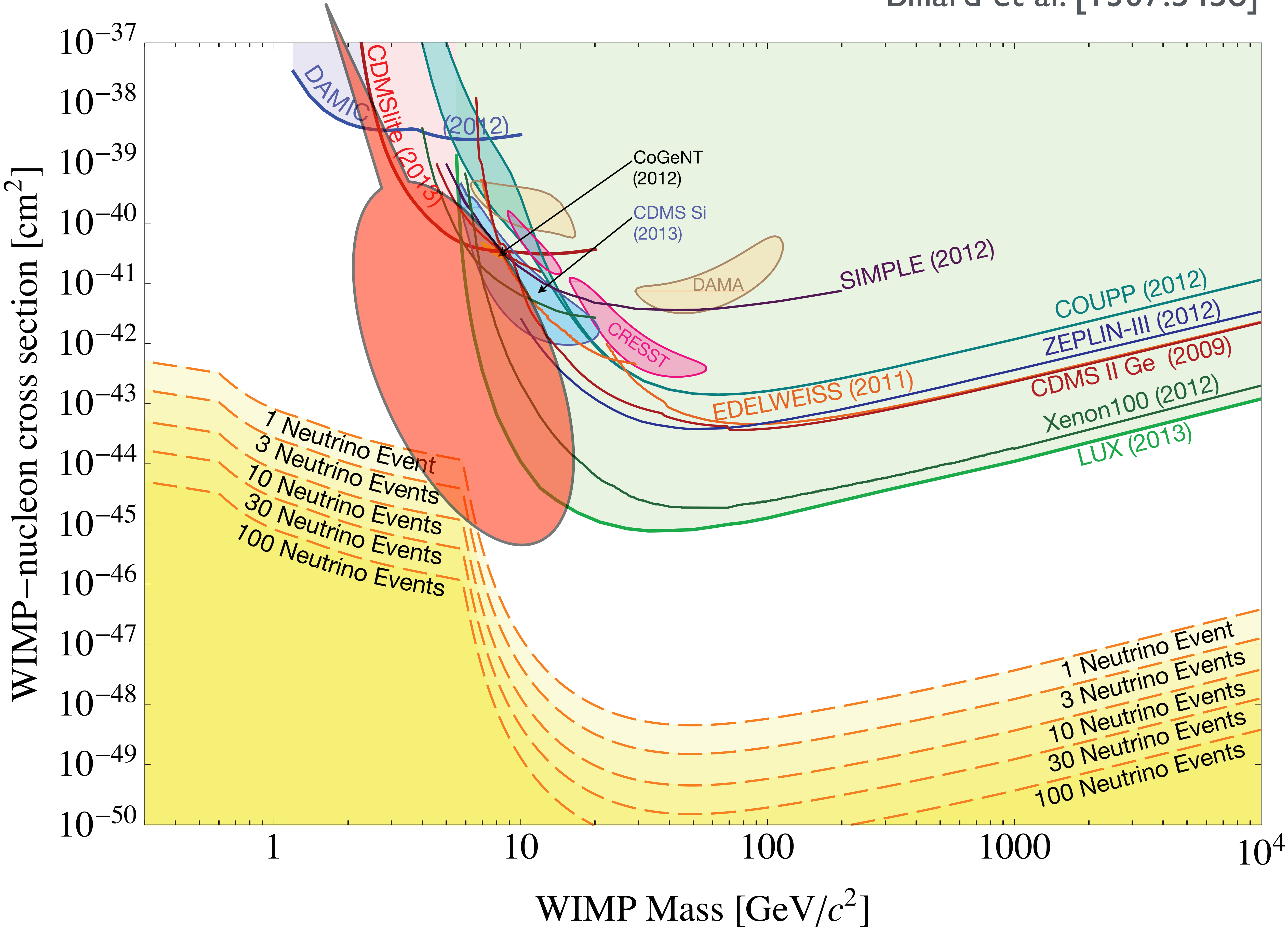
This work (Run8+Run9)
PandaX-II Commissioning (Run8)
XENON100, 2012
LUX 2015
WIMP-nucleon cross section (cm^2)
WIMP mass (GeV/c^2)
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10
10^2
10^3



Billard et al. [1307.5458]
WIMP–nucleon cross section [cm^2]
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
10^{-50}
1
10
100
1000
10^4
WIMP Mass [GeV/c^2]
DAMIC
(2012)
CDMSlite (2013)
CoGeNT (2012)
CDMS Si (2013)
DAMA
SIMPLE (2012)
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
CRESST
EDELWEISS (2011)
Xenon100 (2012)
LUX (2013)
1 Neutrino Event
3 Neutrino Events
10 Neutrino Events
30 Neutrino Events
100 Neutrino Events
1 Neutrino Event
3 Neutrino Events
10 Neutrino Events
30 Neutrino Events
100 Neutrino Events

Threshold cuts off

Billard et al. [1307.5458]



Threshold cuts off

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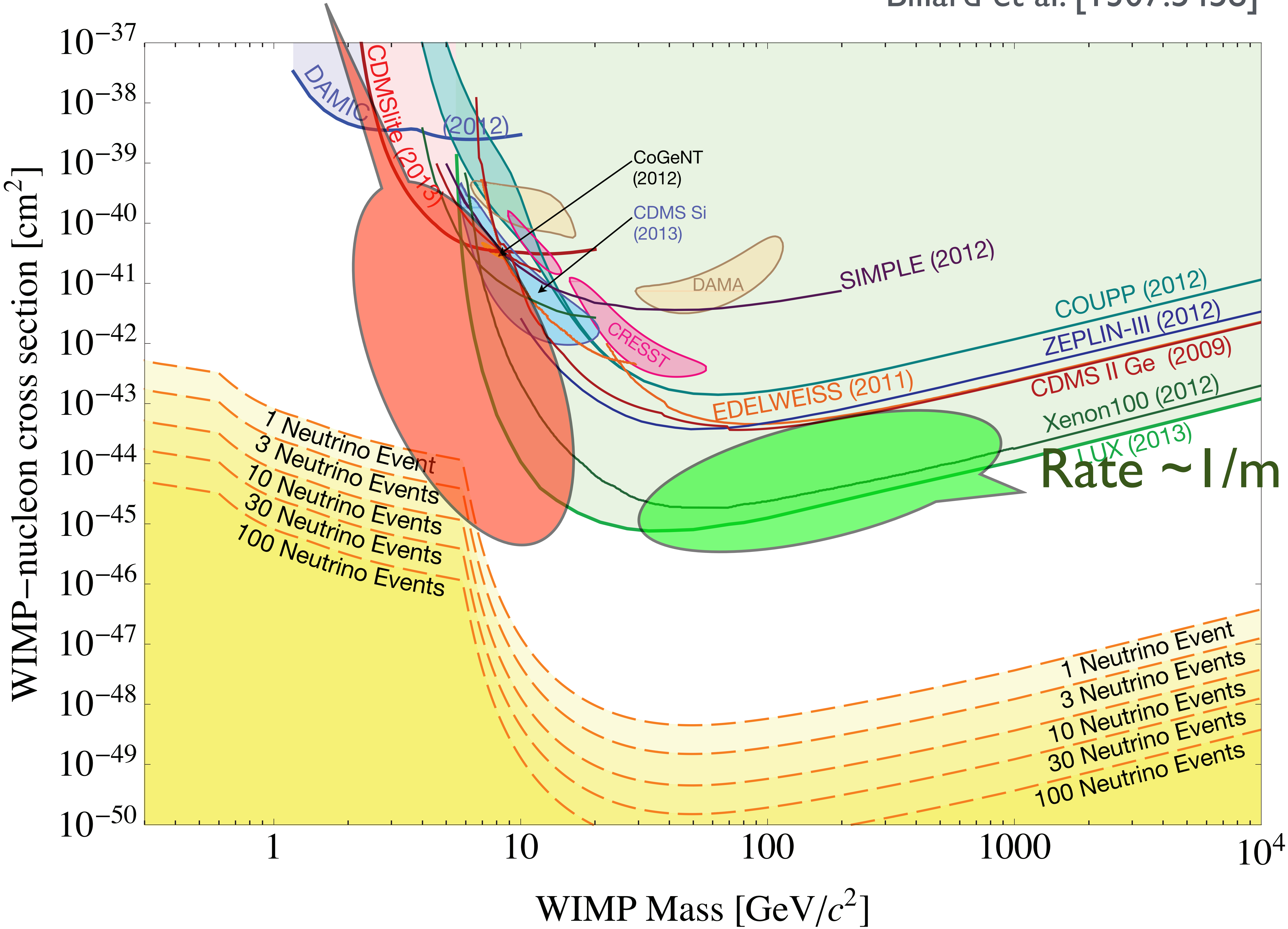
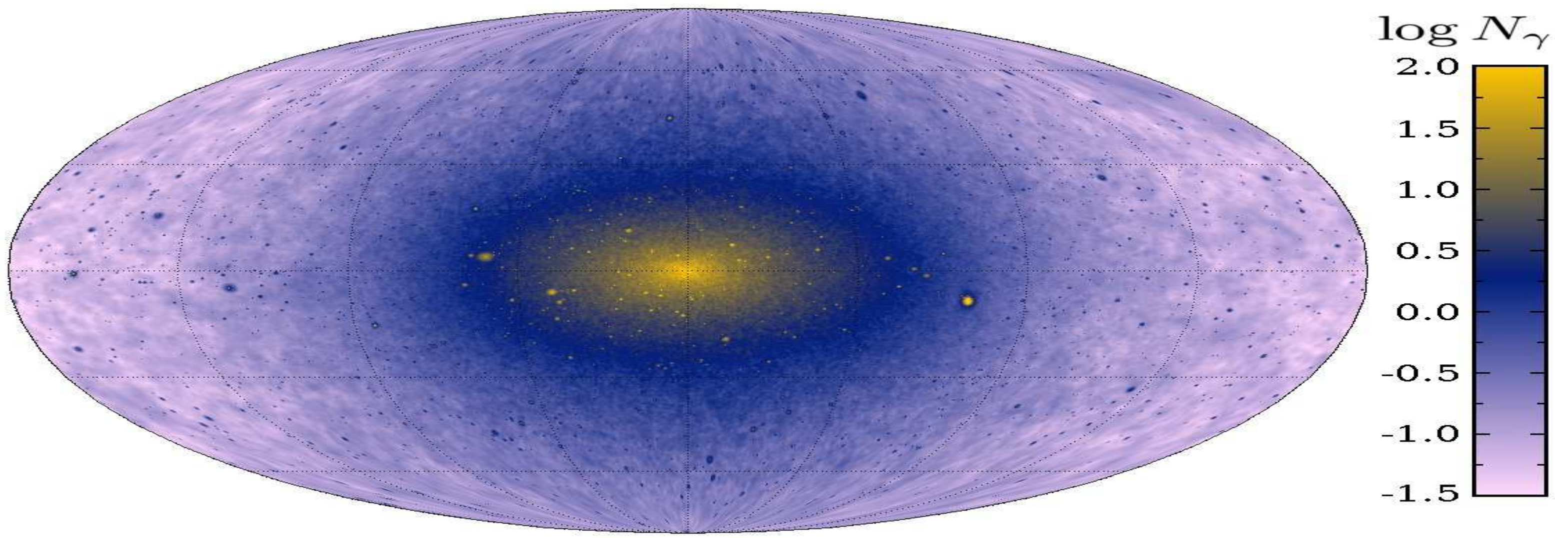


Indirect Detection "Master formula"



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

Spectrum of particles in final state

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

Line of sight integral

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

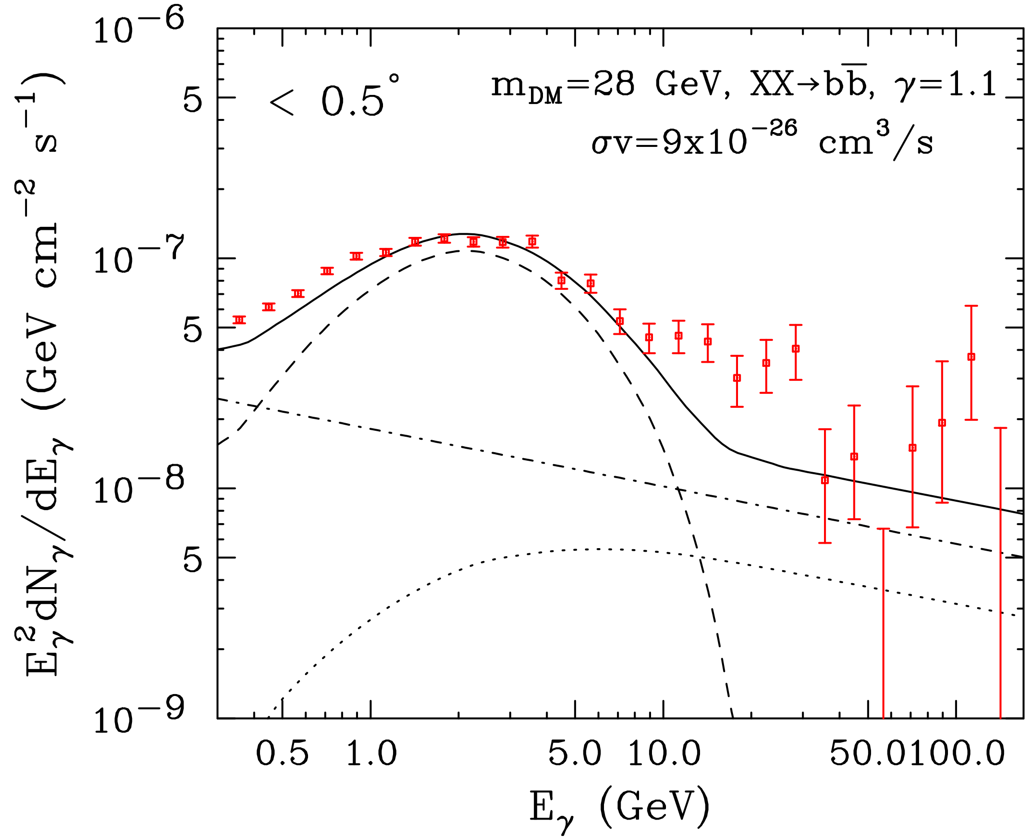
$\chi\chi \to \gamma\gamma$

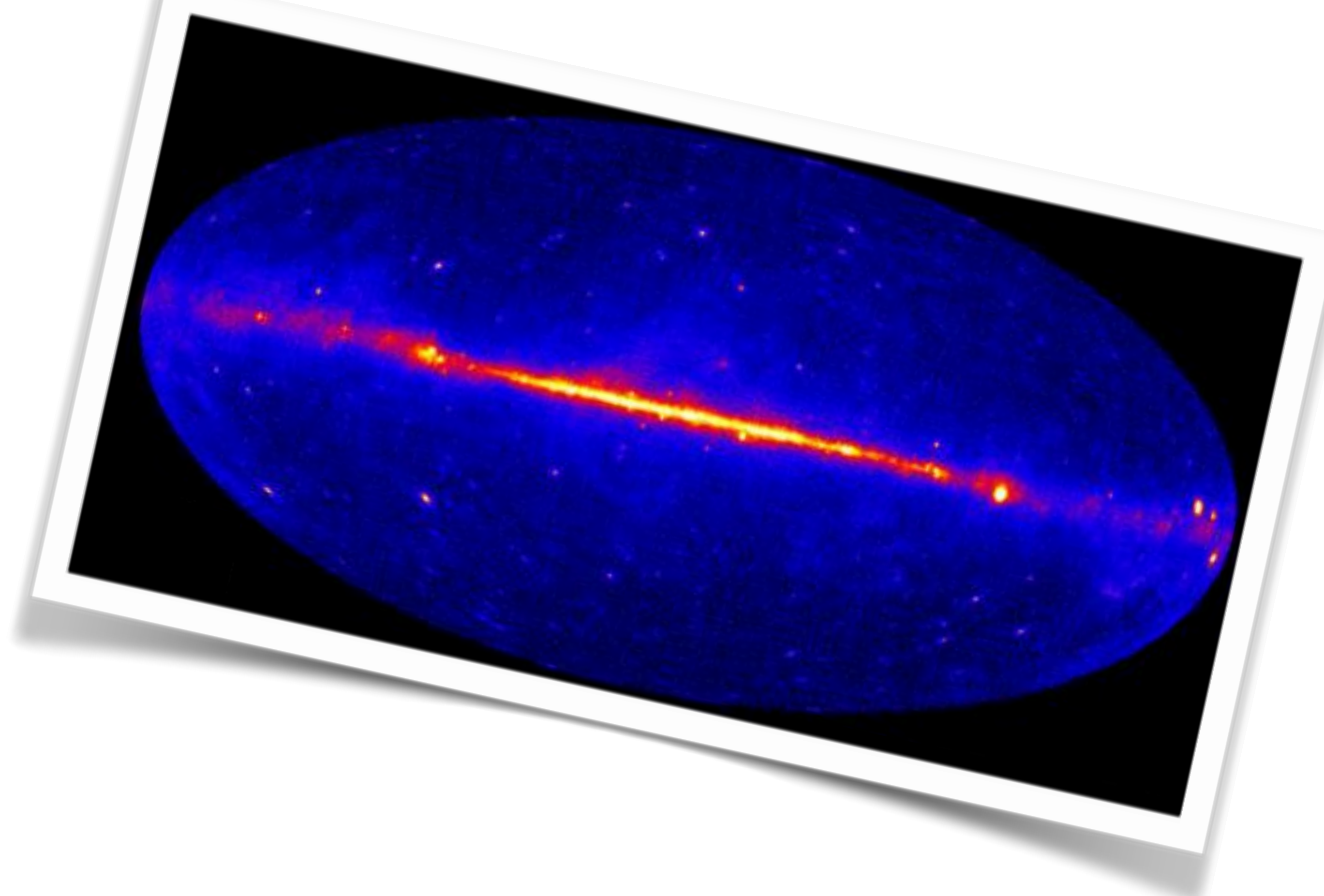
Point back to source, spectral line, low rate
Fermi, HESS

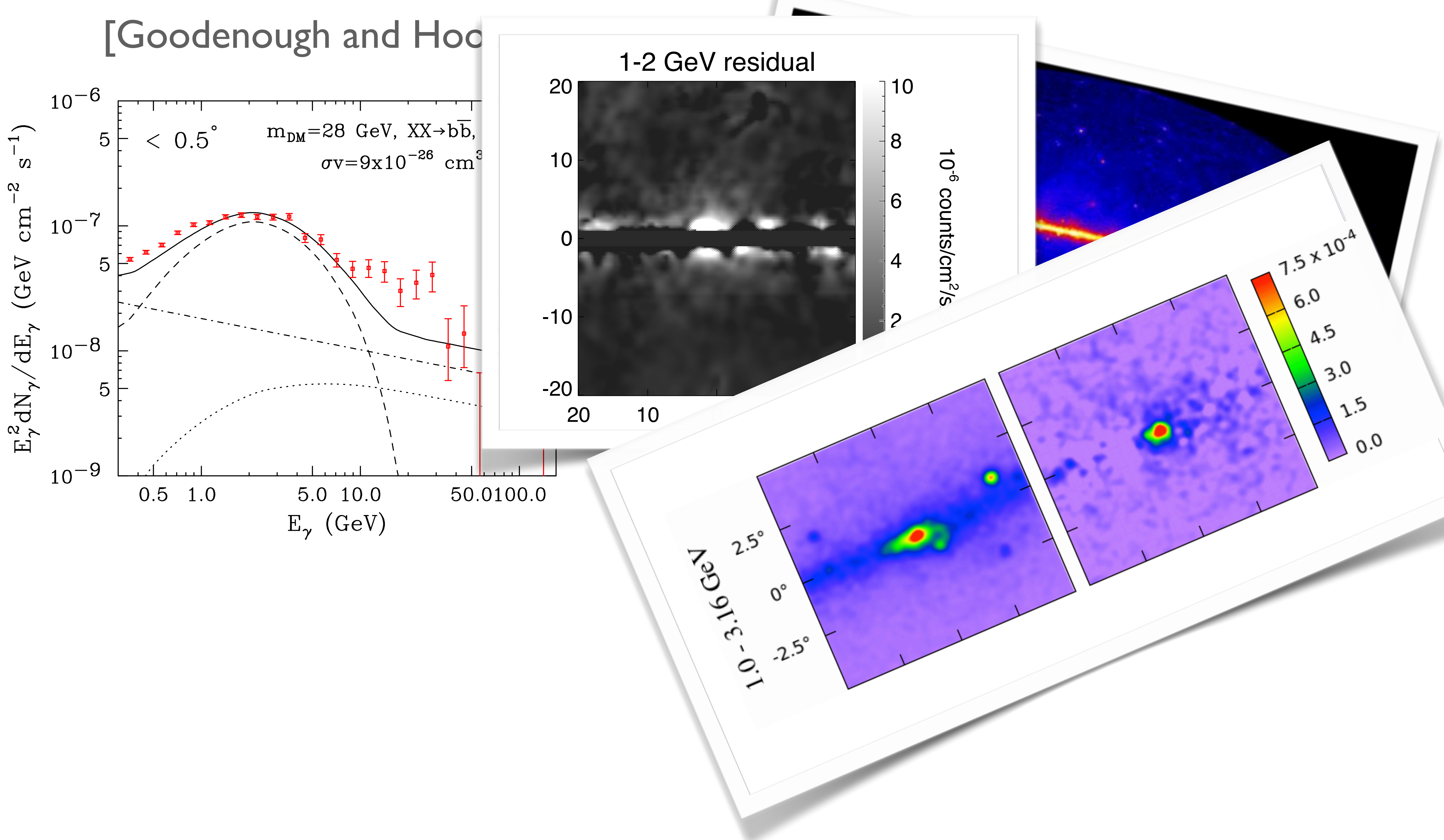
$$\chi\chi \to \mathrm{SM\ SM} \hookrightarrow \ldots + \gamma\gamma$$

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

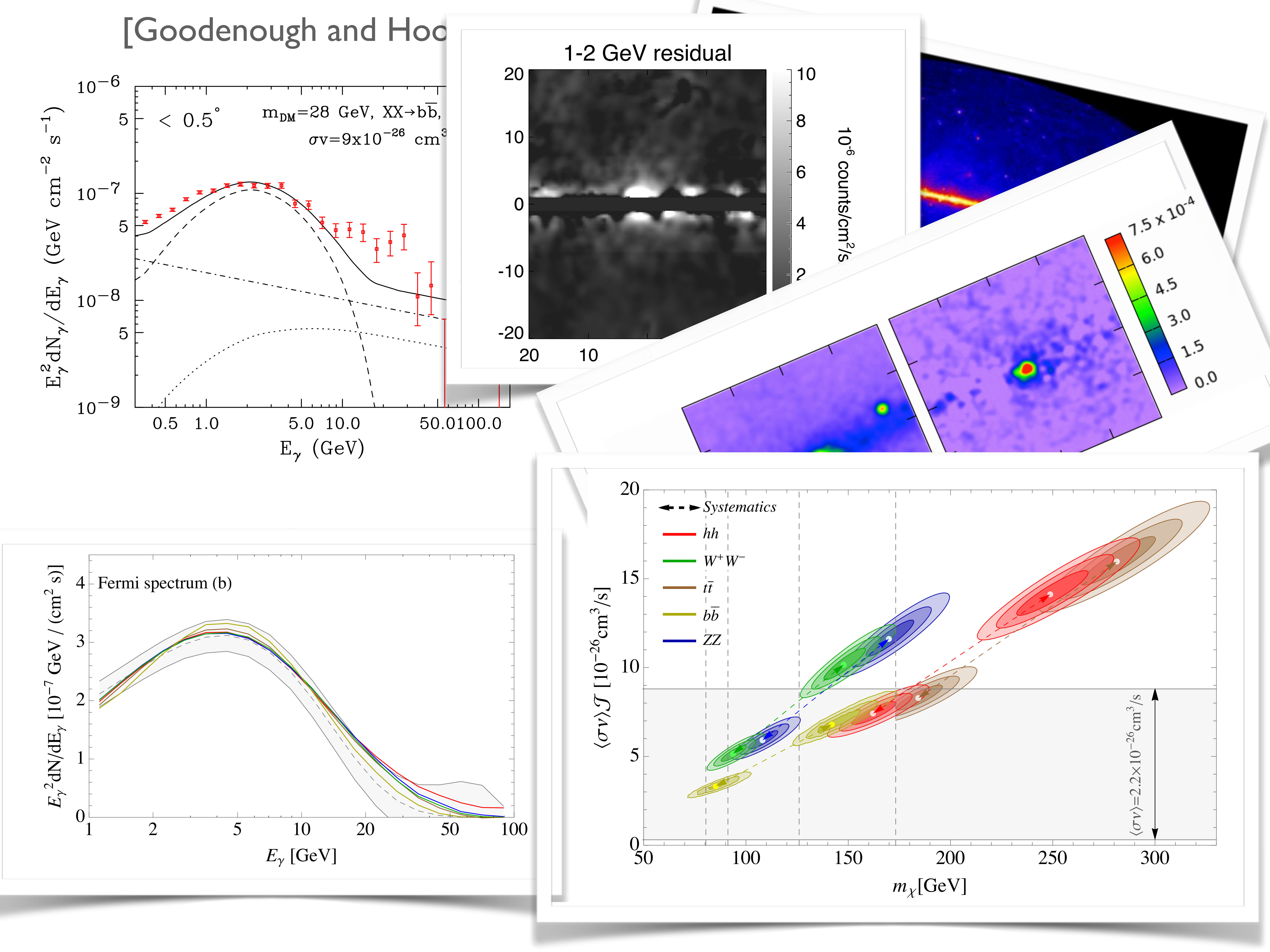
[Goodenough and Hooper, 2009]





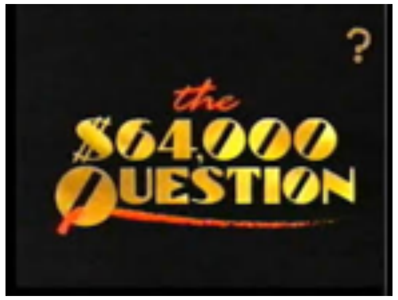

[Goodenough and Hoo
< 0.5°
m_{DM}=28 GeV, XX→$b\bar{b}$,
σv=9x10^{-26} cm
$E_\gamma^2 dN_\gamma/dE_\gamma$ (GeV cm^{-2} s^{-1})
E_γ (GeV)
1-2 GeV residual
10^{-6} counts/cm^2/s
7.5 x 10^{-4}
6.0
4.5
3.0
1.5
0.0
2.5°
0°
-2.5°
1.0 - 3.16 GeV

[Goodenough and Hoo



Are the excess photons from the Galactic centre DM?

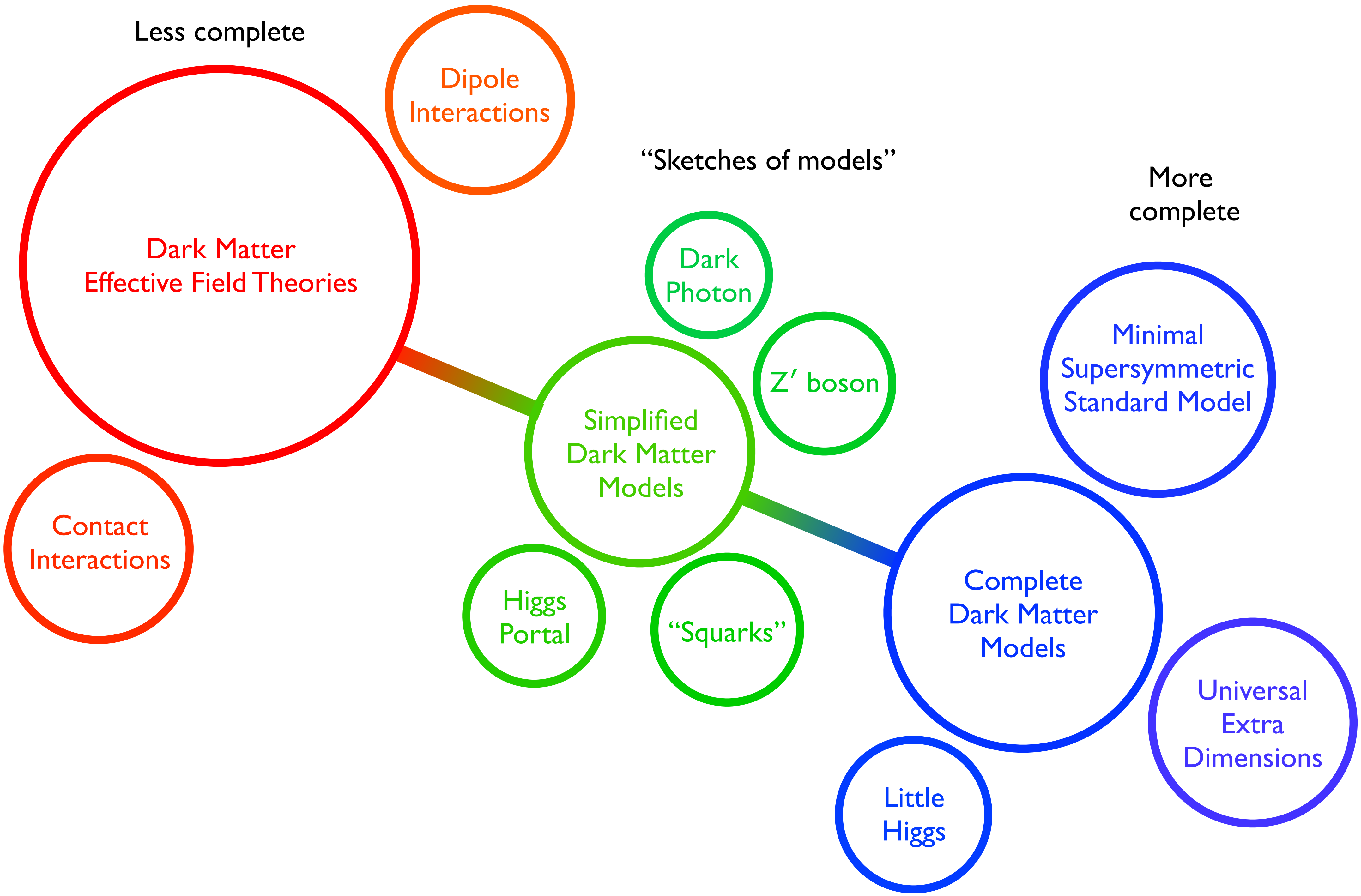
- Source is spherical, with the expected radial dependence
- Cross section is close to thermal
- Centred in the right place
- Statistical significant, and Fermi-team sees it too



- 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)

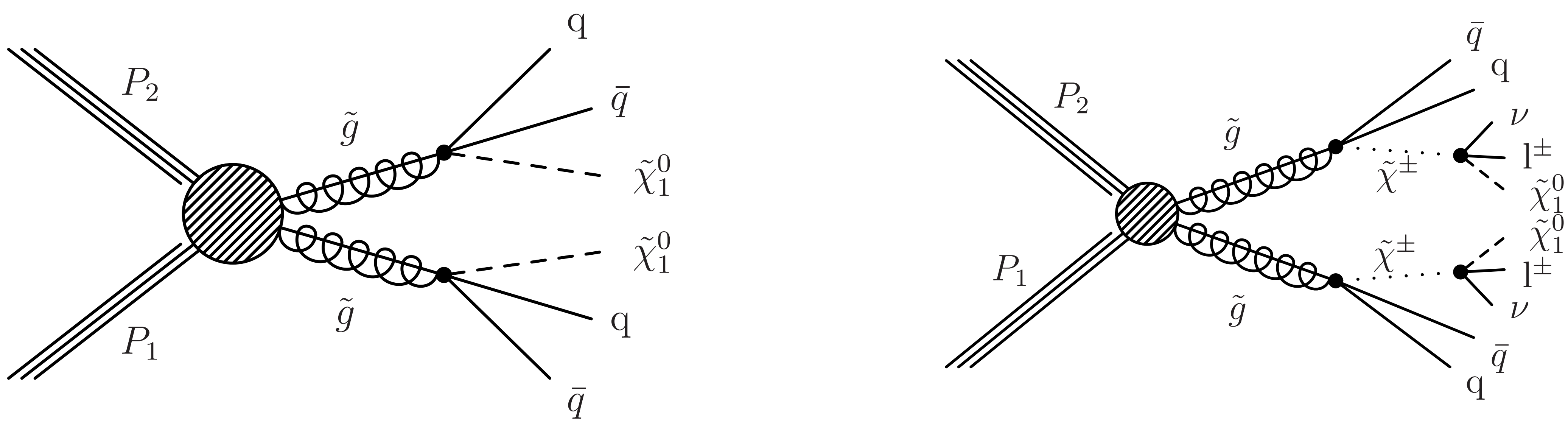
- Look at other DM "bright spots"--dwarf galaxies
- Cosmic ray anti-particles
- Correlated signals, LHC, direct detection
- **Interesting times ahead**

Ways to search for DM at colliders

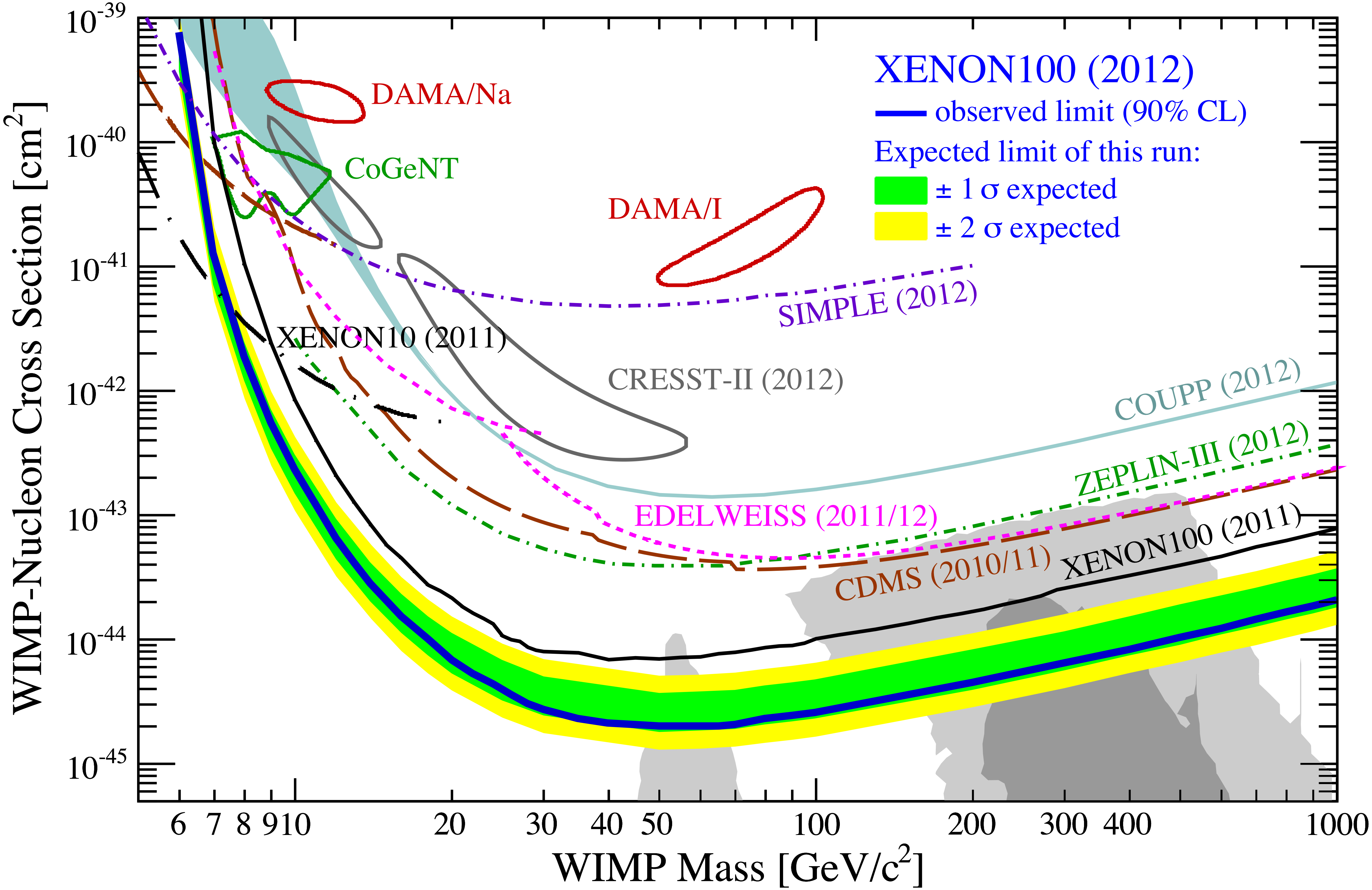


Ways to search for DM at colliders

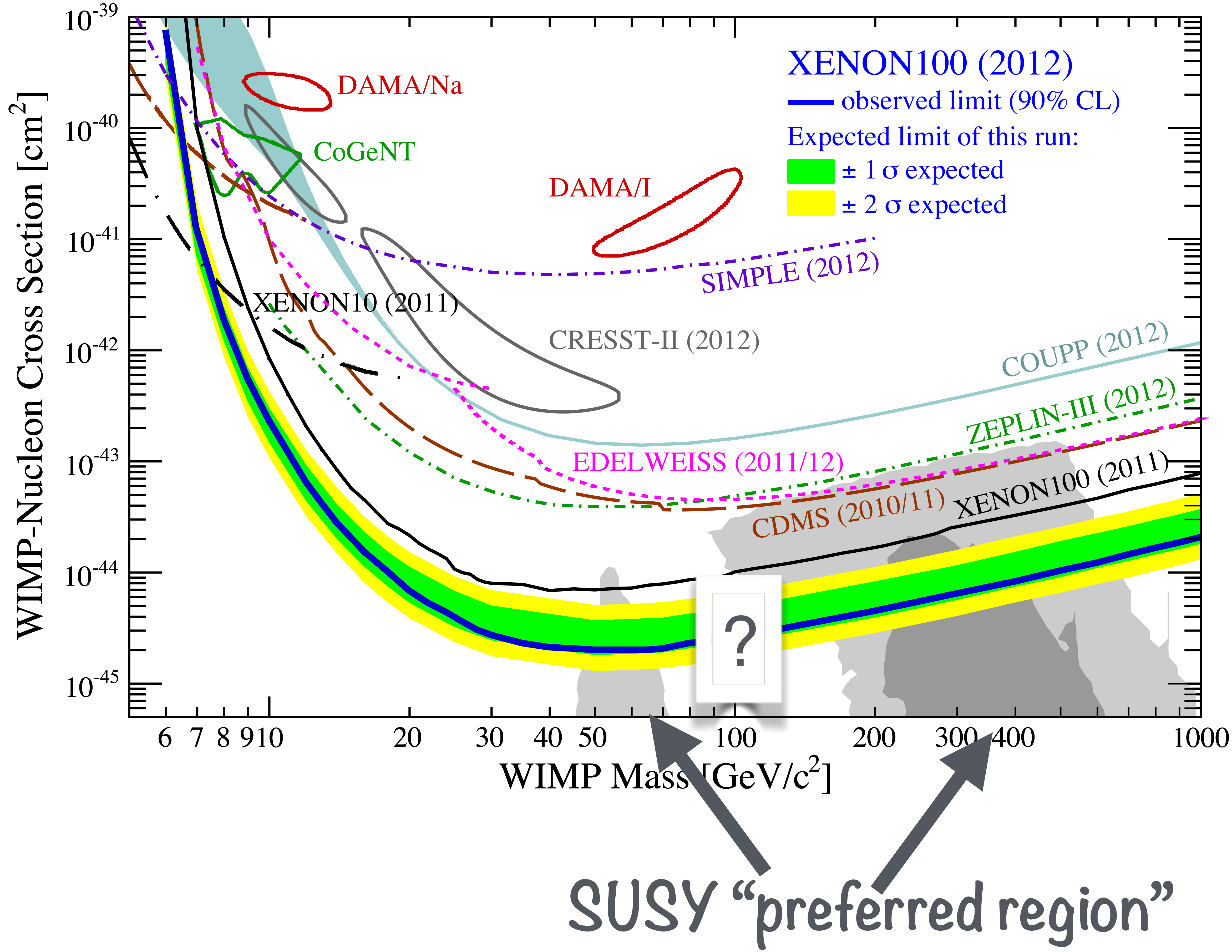
Use a full UV model (e.g. SUSY)



Complicated/interesting final state.
Tuned analyses
No clear relation between different search strategies



XENON100 (2012)
observed limit (90% CL)
Expected limit of this run:
± 1 σ expected
± 2 σ expected
DAMA/Na
CoGeNT
DAMA/I
SIMPLE (2012)
XENON10 (2011)
CRESST-II (2012)
COUPP (2012)
ZEPLIN-III (2012)
EDELWEISS (2011/12)
CDMS (2010/11)
XENON100 (2011)
WIMP-Nucleon Cross Section [cm^2]
WIMP Mass [GeV/c^2]
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
6 7 8 910 20 30 40 50 100 200 300 400 1000



XENON100 (2012)
observed limit (90% CL)
Expected limit of this run:
± 1 σ expected
± 2 σ expected
DAMA/Na
CoGeNT
DAMA/I
SIMPLE (2012)
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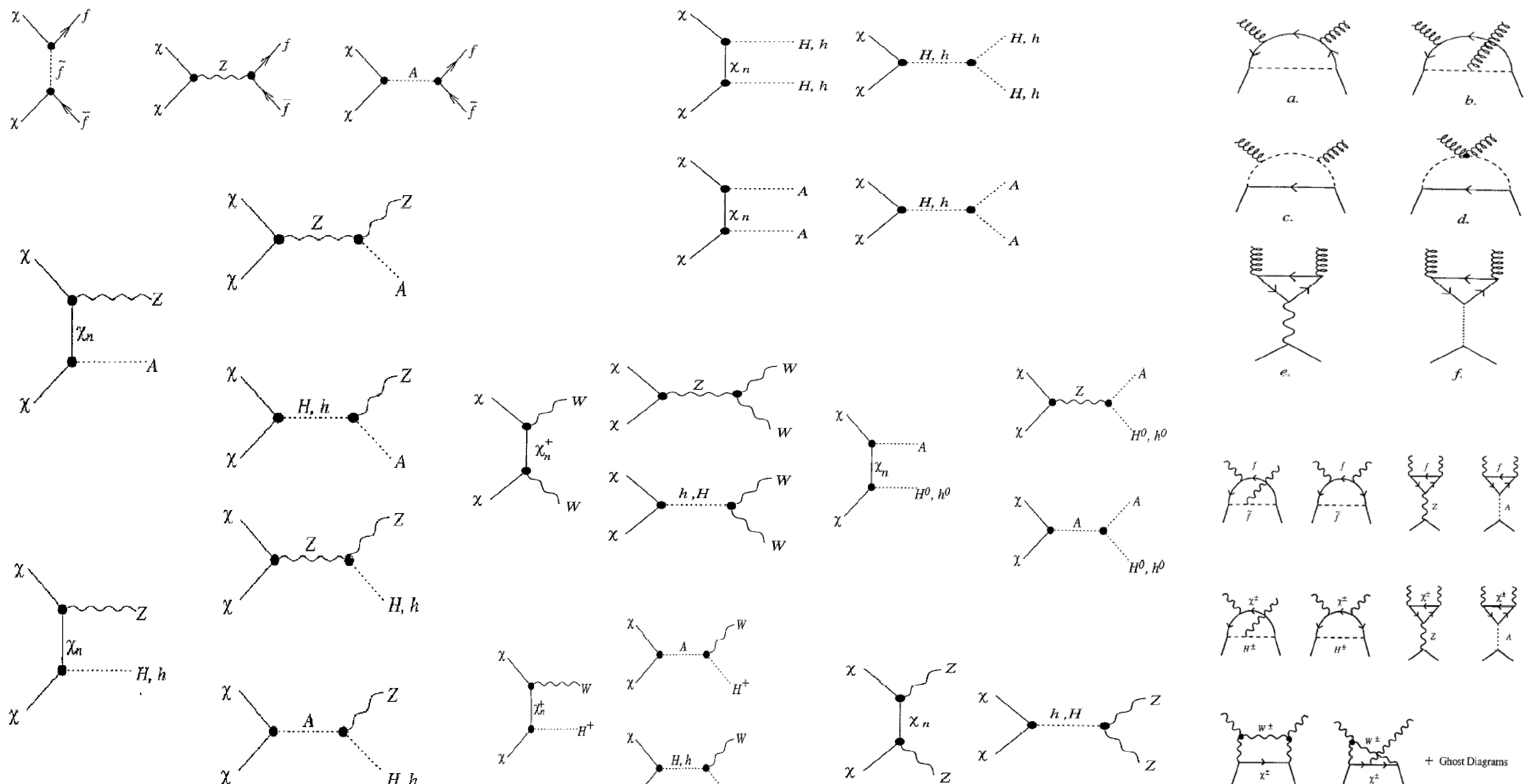
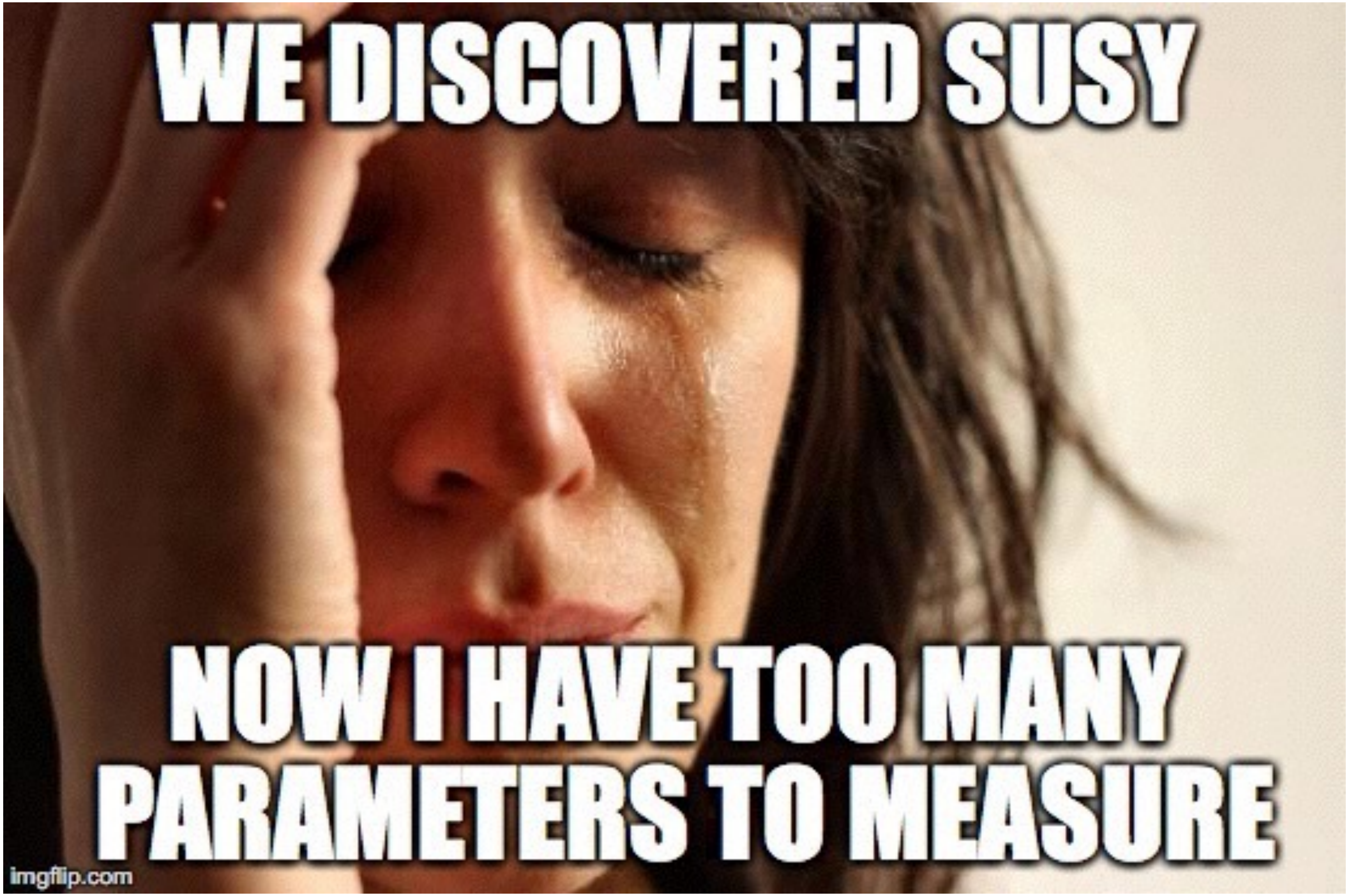
ZEPLIN-III (2012)
EDELWEISS (2011/12)
CDMS (2010/11)
XENON100 (2011)
WIMP-Nucleon Cross Section [cm^2]
WIMP Mass [GeV/c^2]
SUSY "preferred region"



Jungman, Kamionkowski, Griest (1995)


WE DISCOVERED SUSY
NOW I HAVE TOO MANY PARAMETERS TO MEASURE
imgflip.com

Q: Are these different search strategies separate, redundant, complementary, relatable,….?

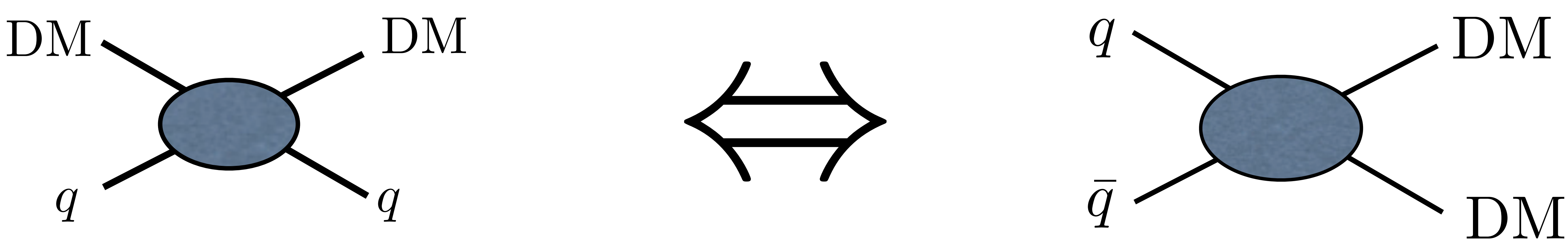
A: traditionally there was no clear way to relate them

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)

Ways to search for DM at colliders

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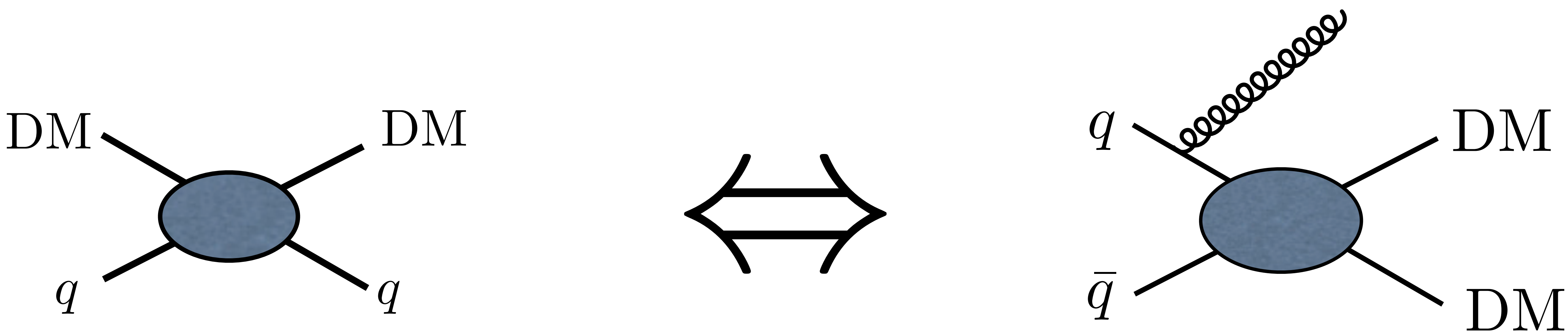
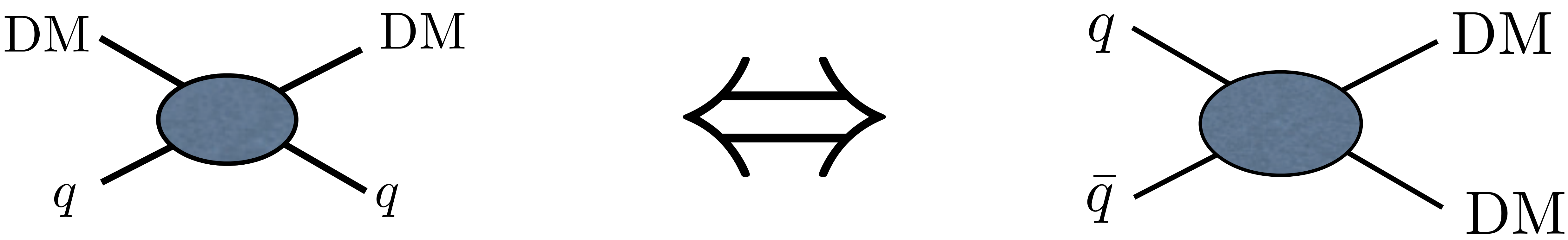


"Monojet", monophoton, mono-top, mono-X,....

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

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

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

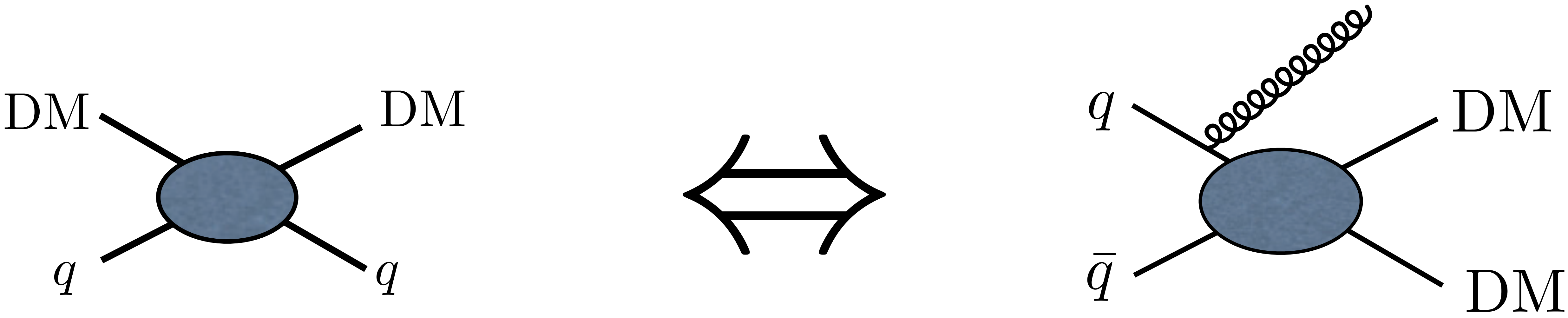
SI, scalar exchange

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

SI, scalar exchange

Typically consider each operator separately

Operators



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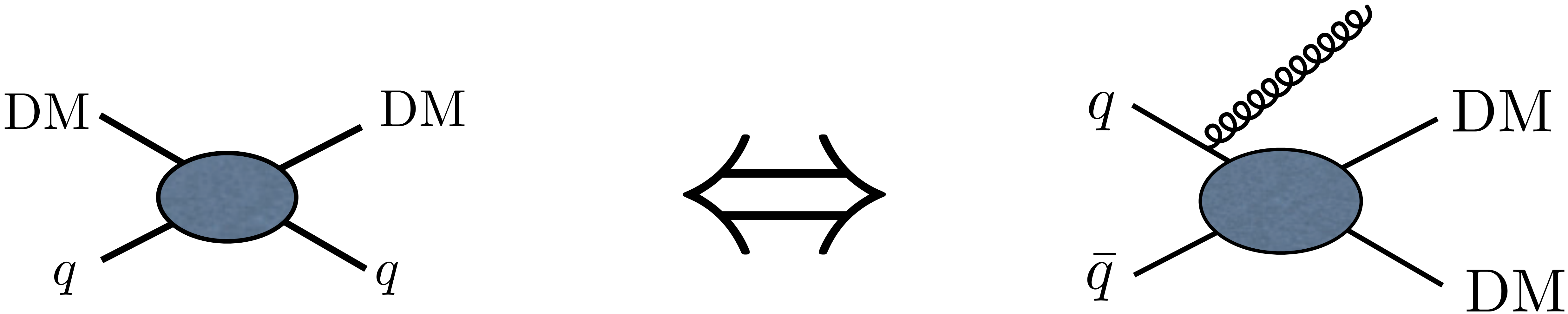
Operators



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

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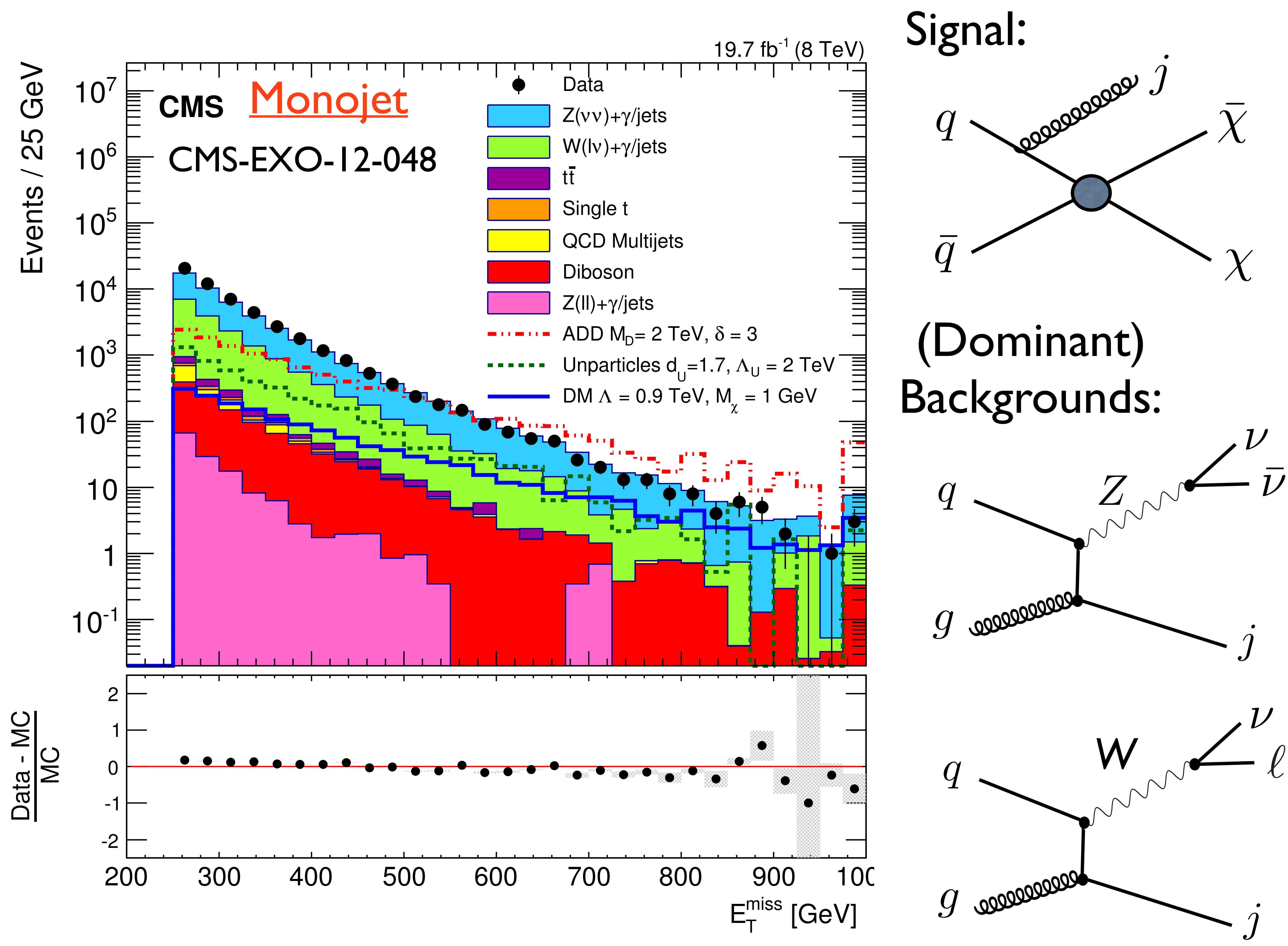
$$\mathcal{O}_t = \frac{(\bar{\chi}P_R q)(\bar{q}P_L \ldots}{\Lambda^2} \ldots \leftrightarrow R)\,,$$ SI, scalar exchange

$$\mathcal{O}_g = \alpha_s\frac{(\bar{\chi}\chi)\,(G^a_{\mu\nu}G^{a\mu\nu})}{\Lambda^3}$$ SI, scalar exchange

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

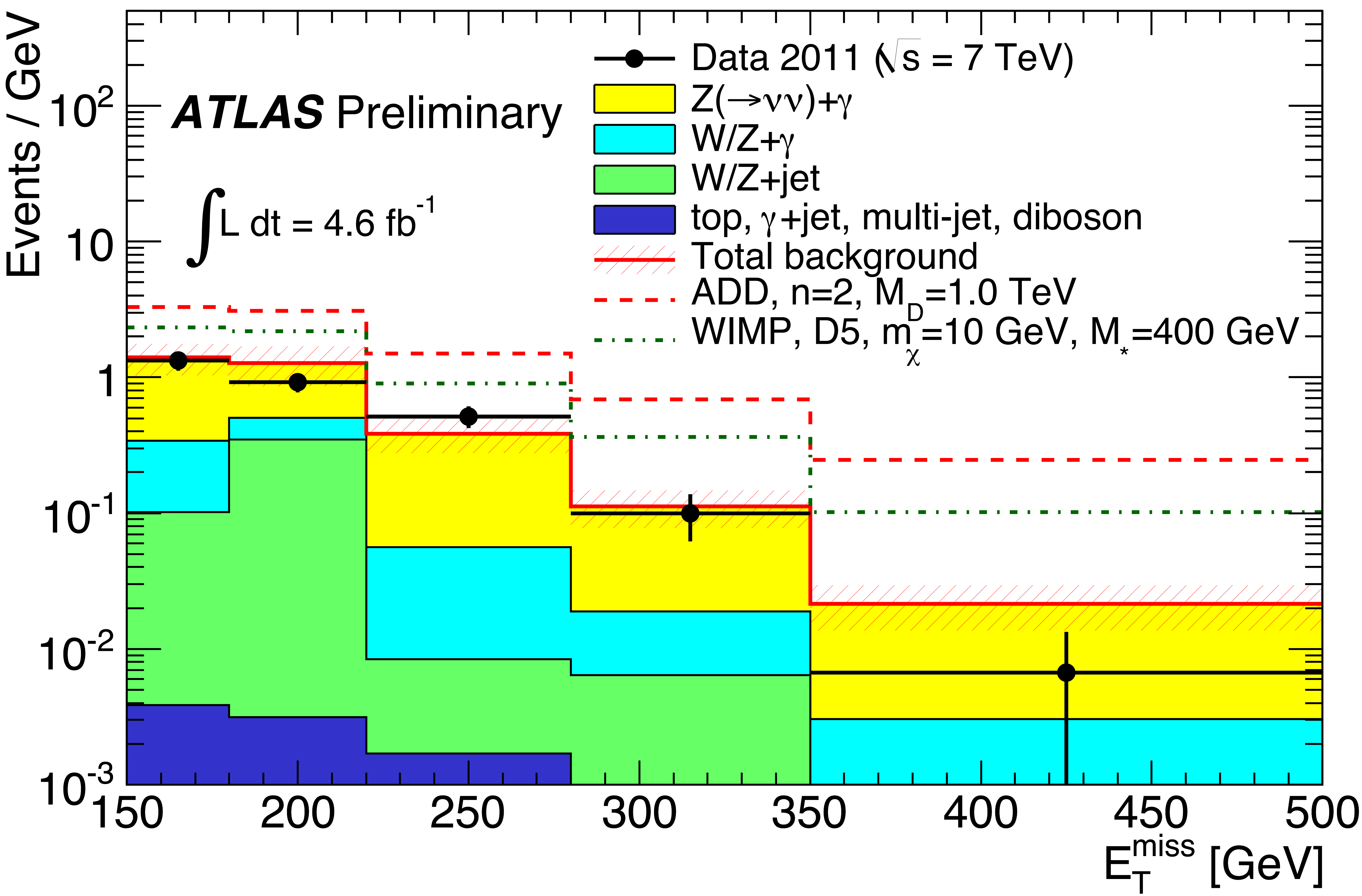
Typically consider each operator separately



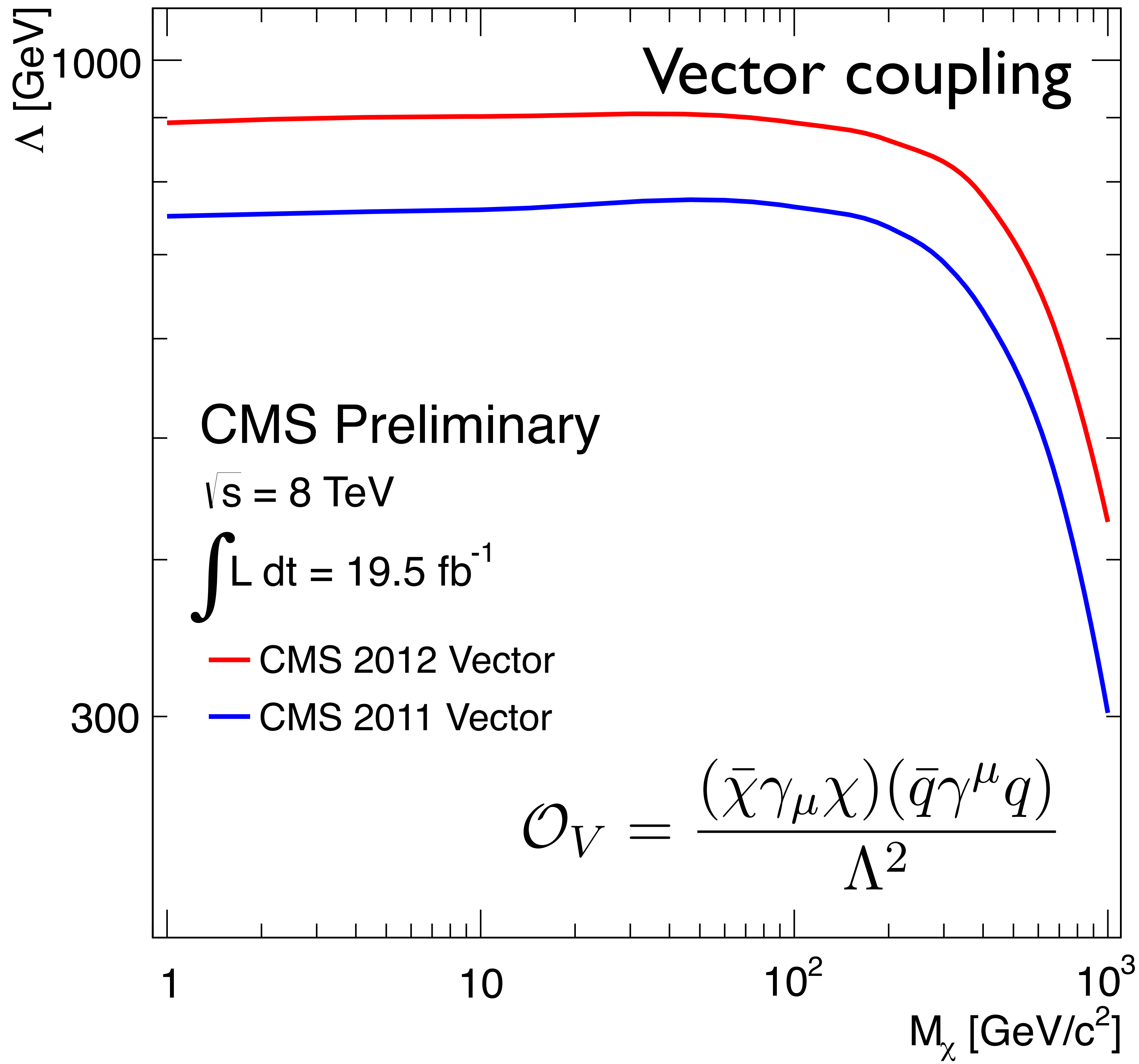
19.7 fb^{-1} (8 TeV)
CMS
Monojet
CMS-EXO-12-048
Data
Z(νν)+γ/jets
W(lν)+γ/jets
$t\bar{t}$
Single t
QCD Multijets
Diboson
Z(ll)+γ/jets
ADD M_D= 2 TeV, δ = 3
Unparticles d_U=1.7, Λ_U = 2 TeV
DM Λ = 0.9 TeV, M_χ = 1 GeV
Events / 25 GeV
$\frac{\text{Data - MC}}{\text{MC}}$
E_T^{miss} [GeV]
Signal:
q
$\bar{q}$
j
$\bar{\chi}$
χ
(Dominant) Backgrounds:
q
g
Z
ν
$\bar{\nu}$
j
q
g
W
ν
ℓ
j

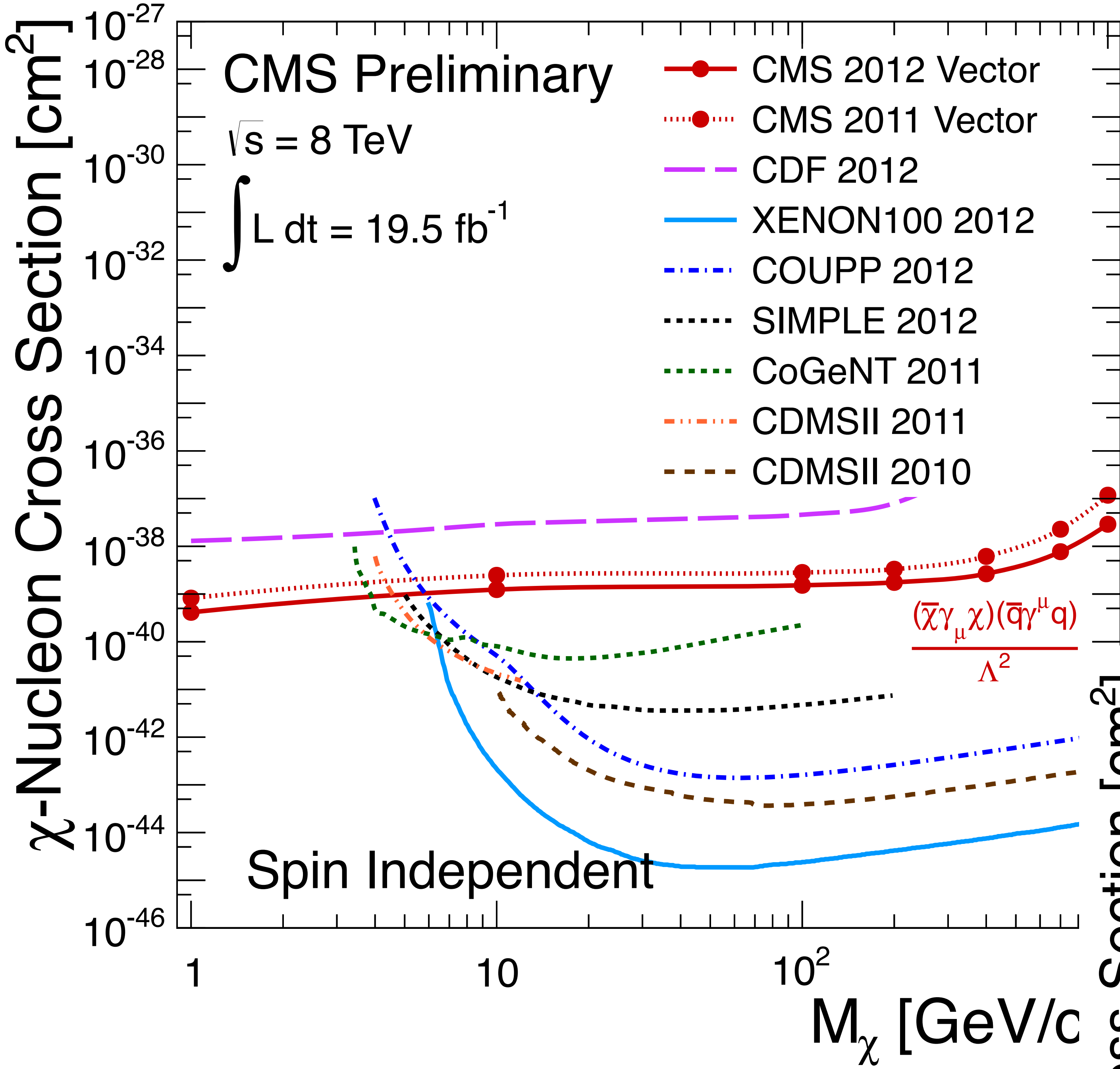
ATLAS-CONF-2012-085

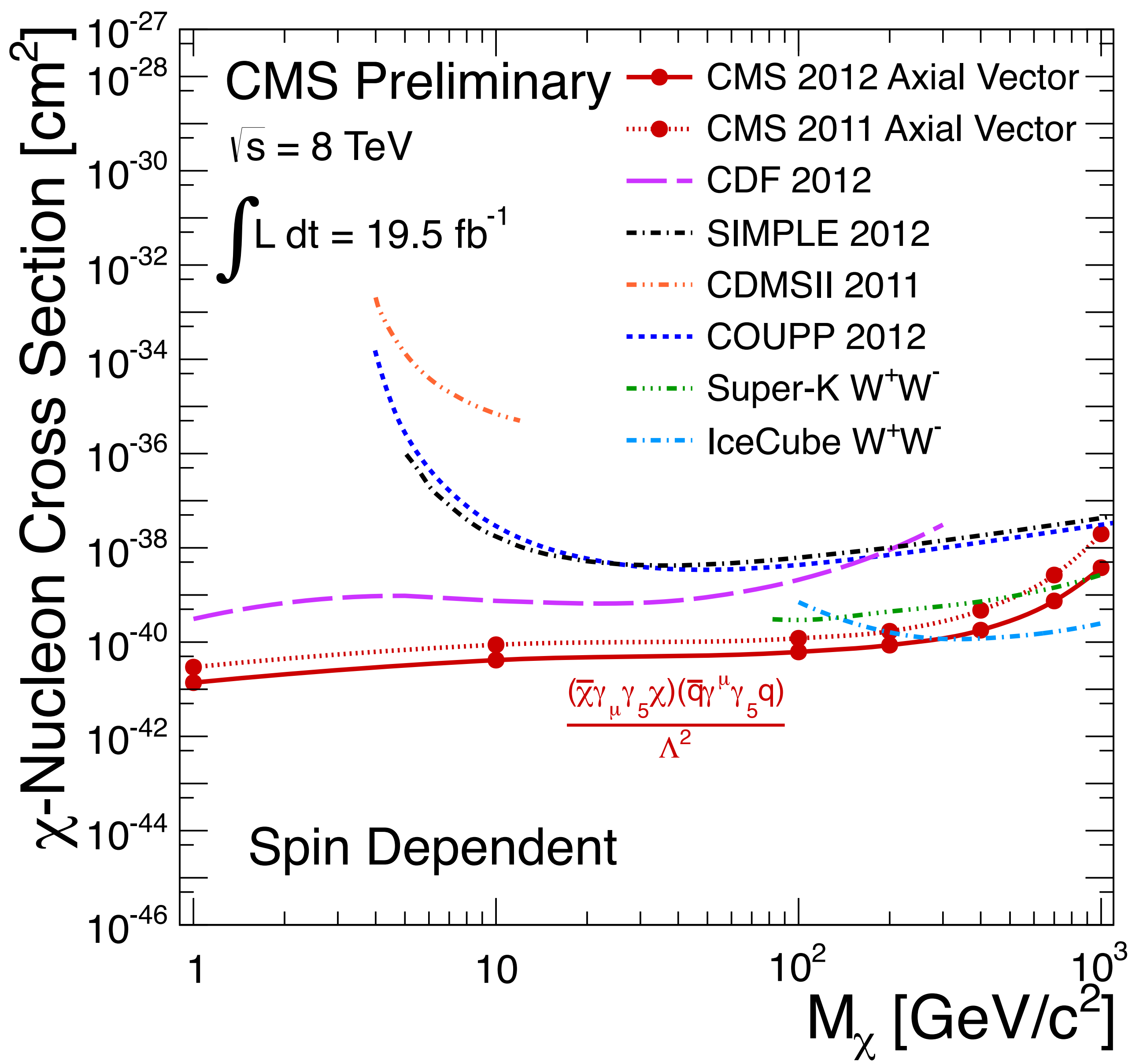
Monophoton



How to quantify nothing?







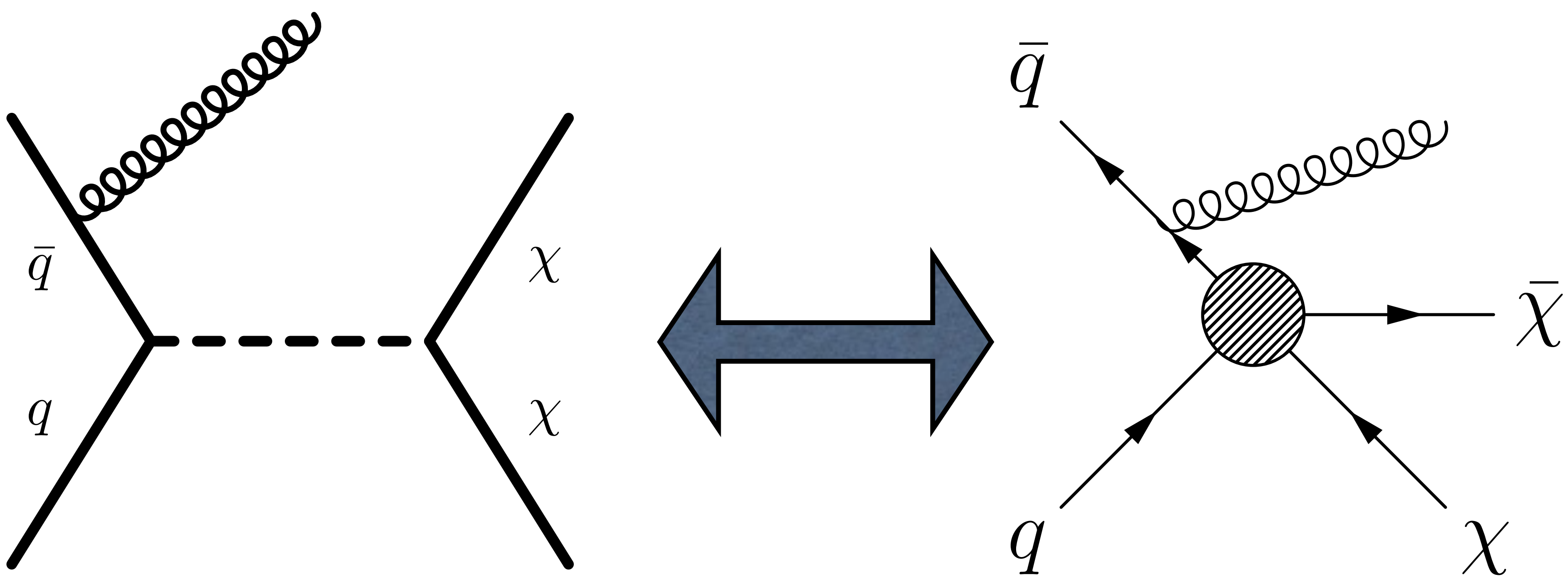
Colliders give complementary constraint at low mass and for SD

Light Mediators

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

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

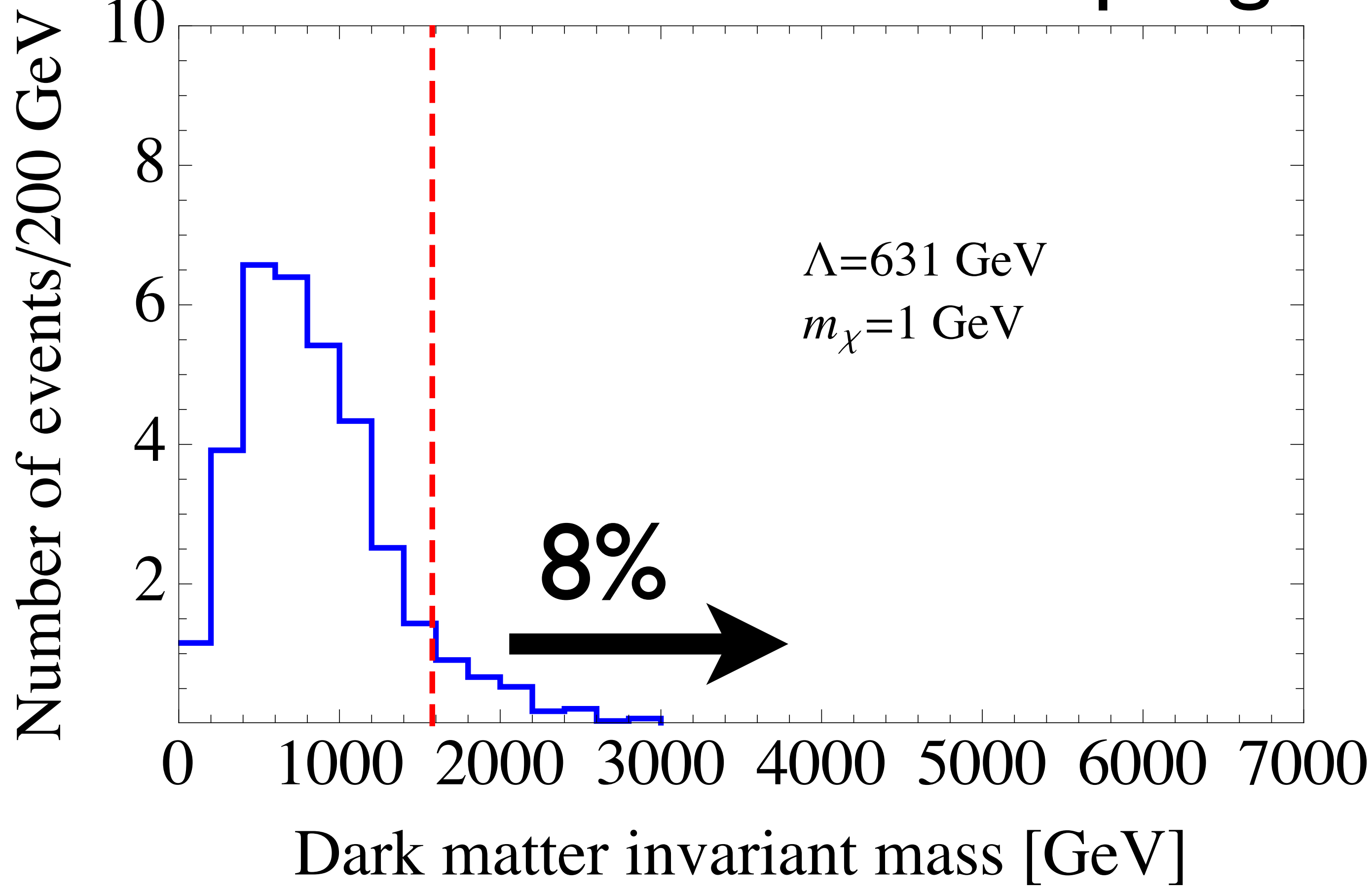
What fraction of collider events have momentum transfers sufficient to probe the UV completion?



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

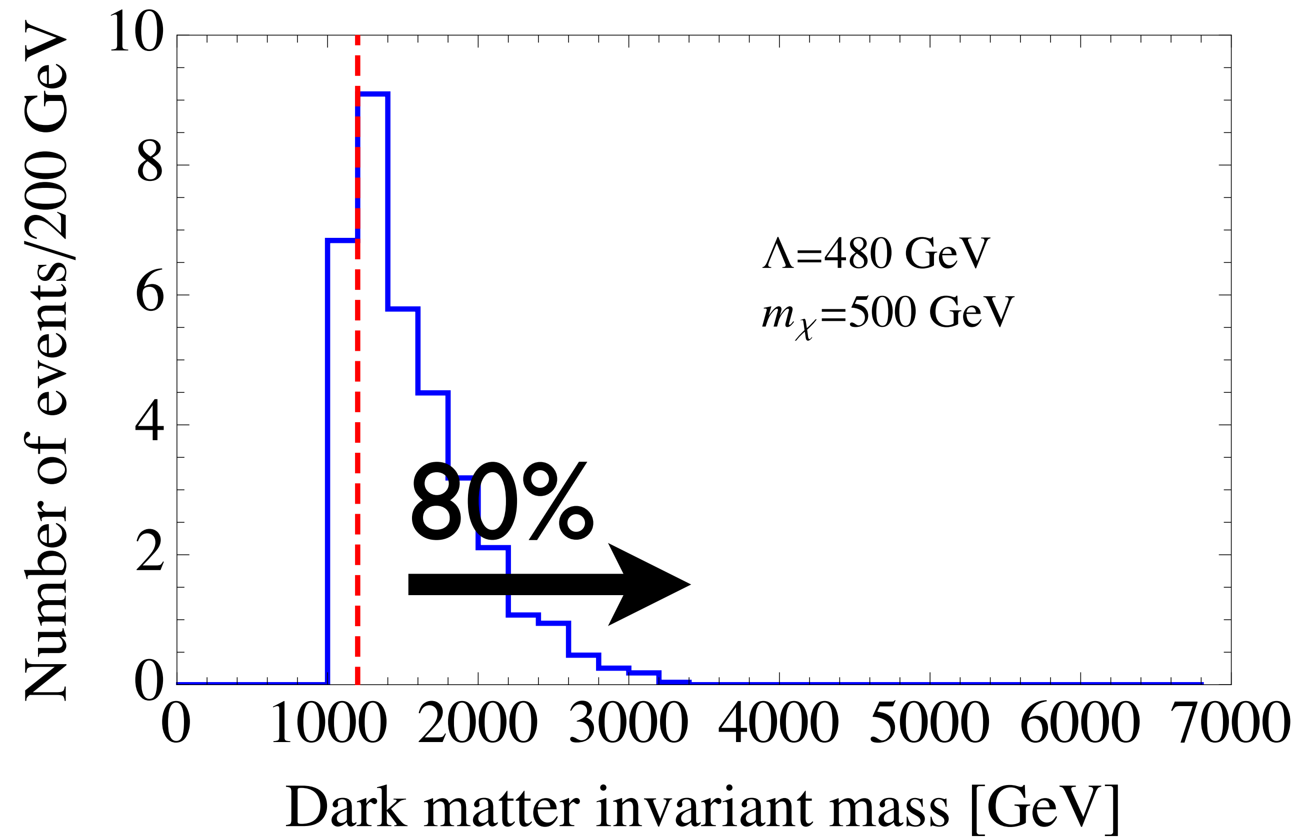
[PJF et al, 1203.1662]

Vector coupling



Unitarity bound $m_{\chi\chi} < \frac{\Lambda}{0.4}$

[Shoemaker and Vecchi, 1112.5457]

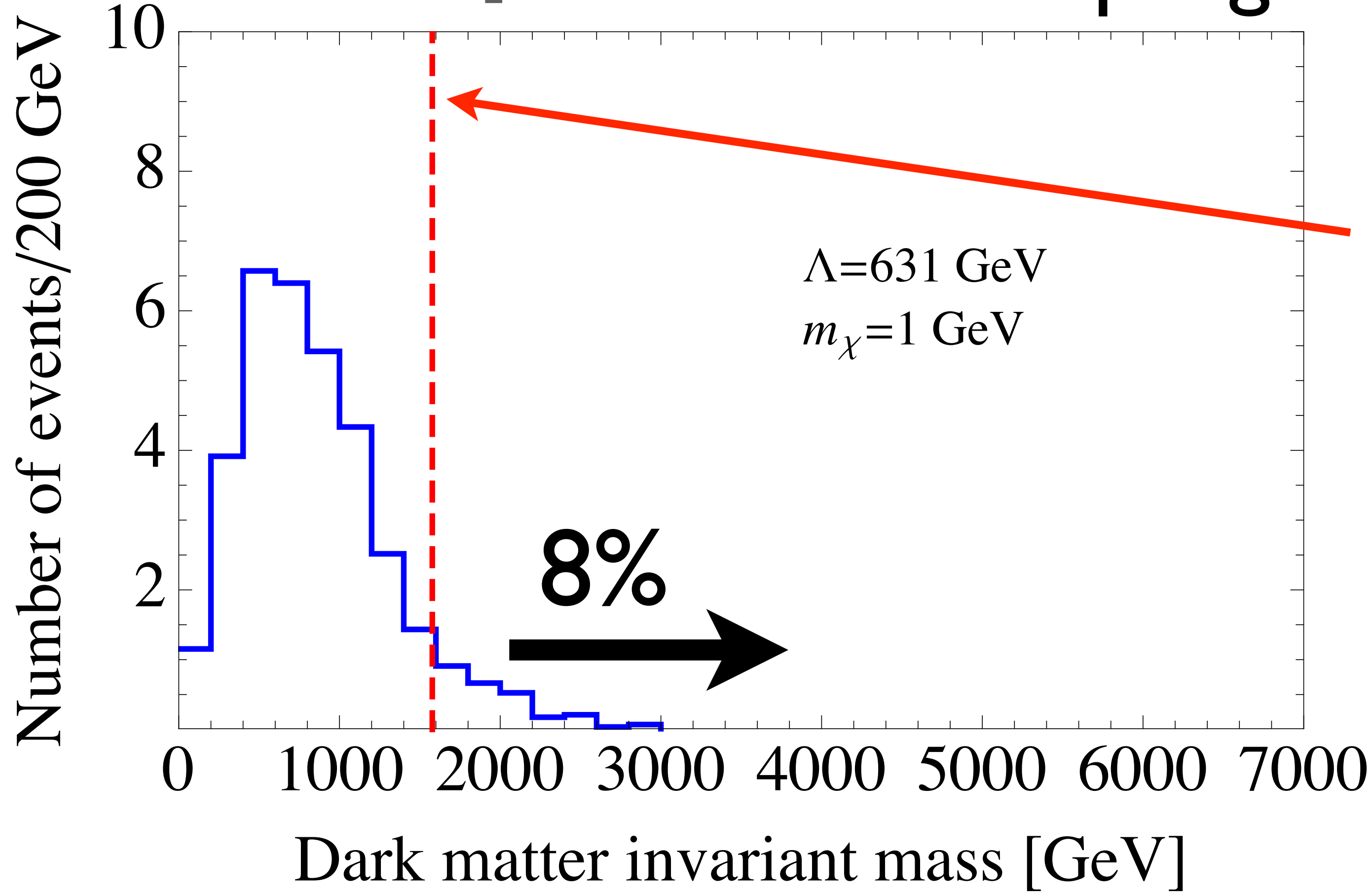


Fraction of events where EFT breaks down may be non-negligible

Depends on DM mass

[PJF et al, 1203.1662]

Vector coupling



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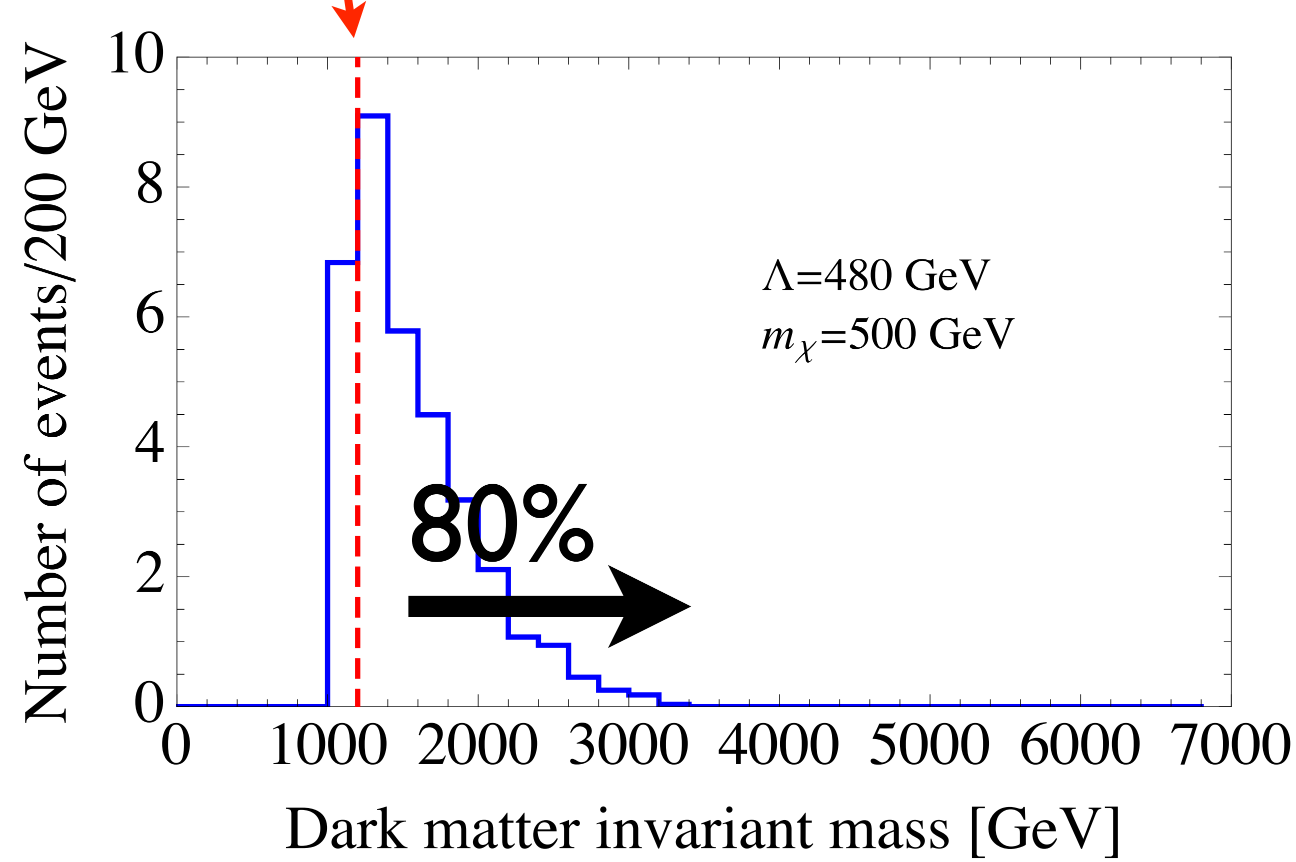

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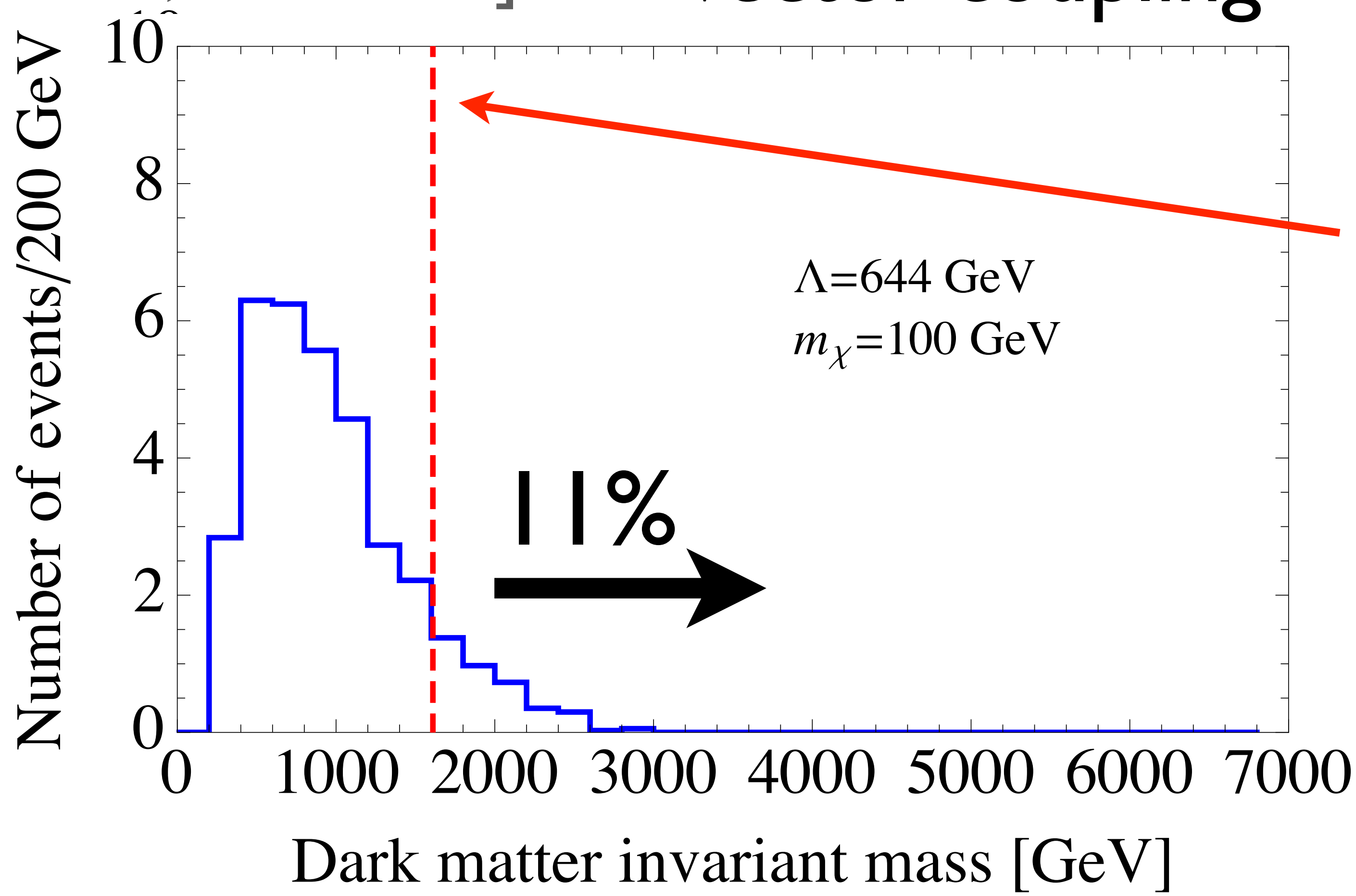

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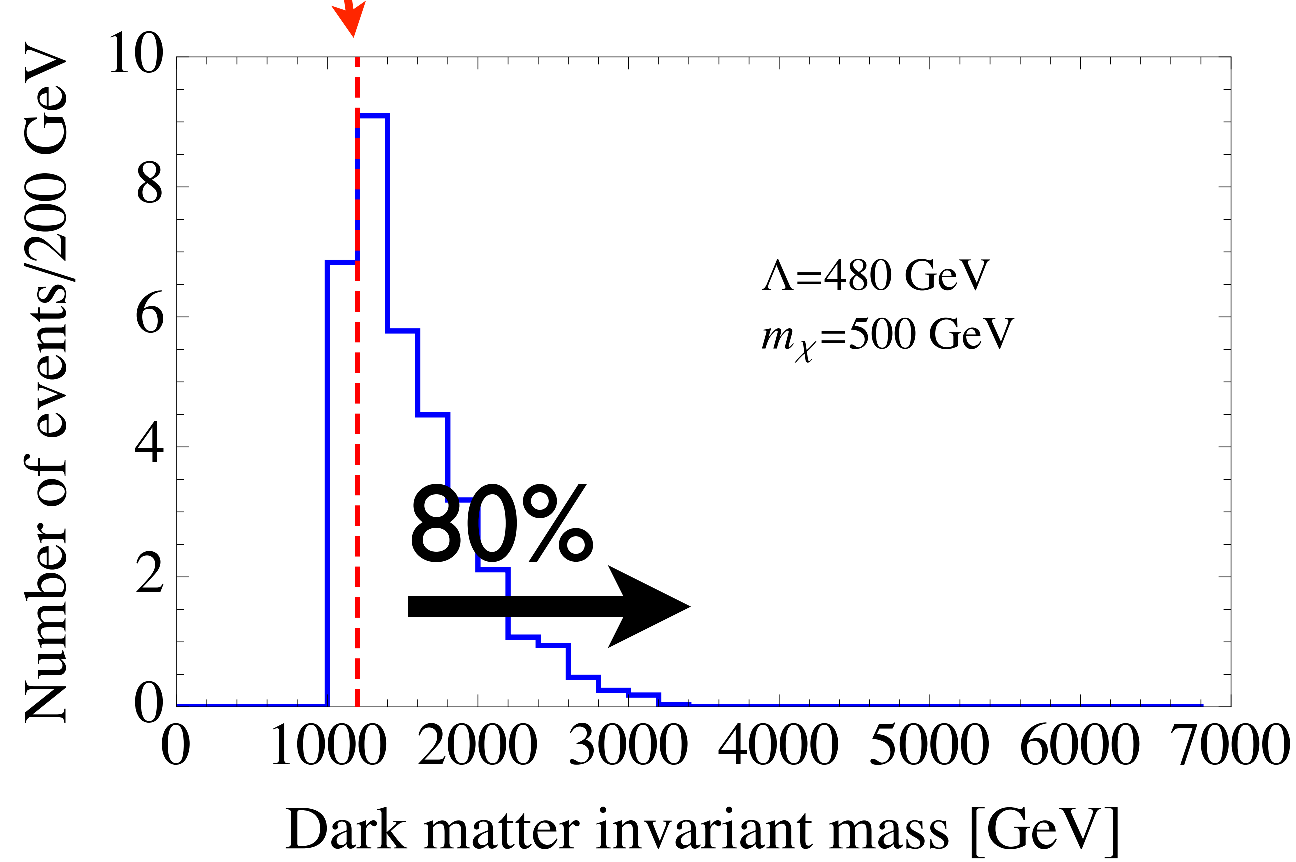


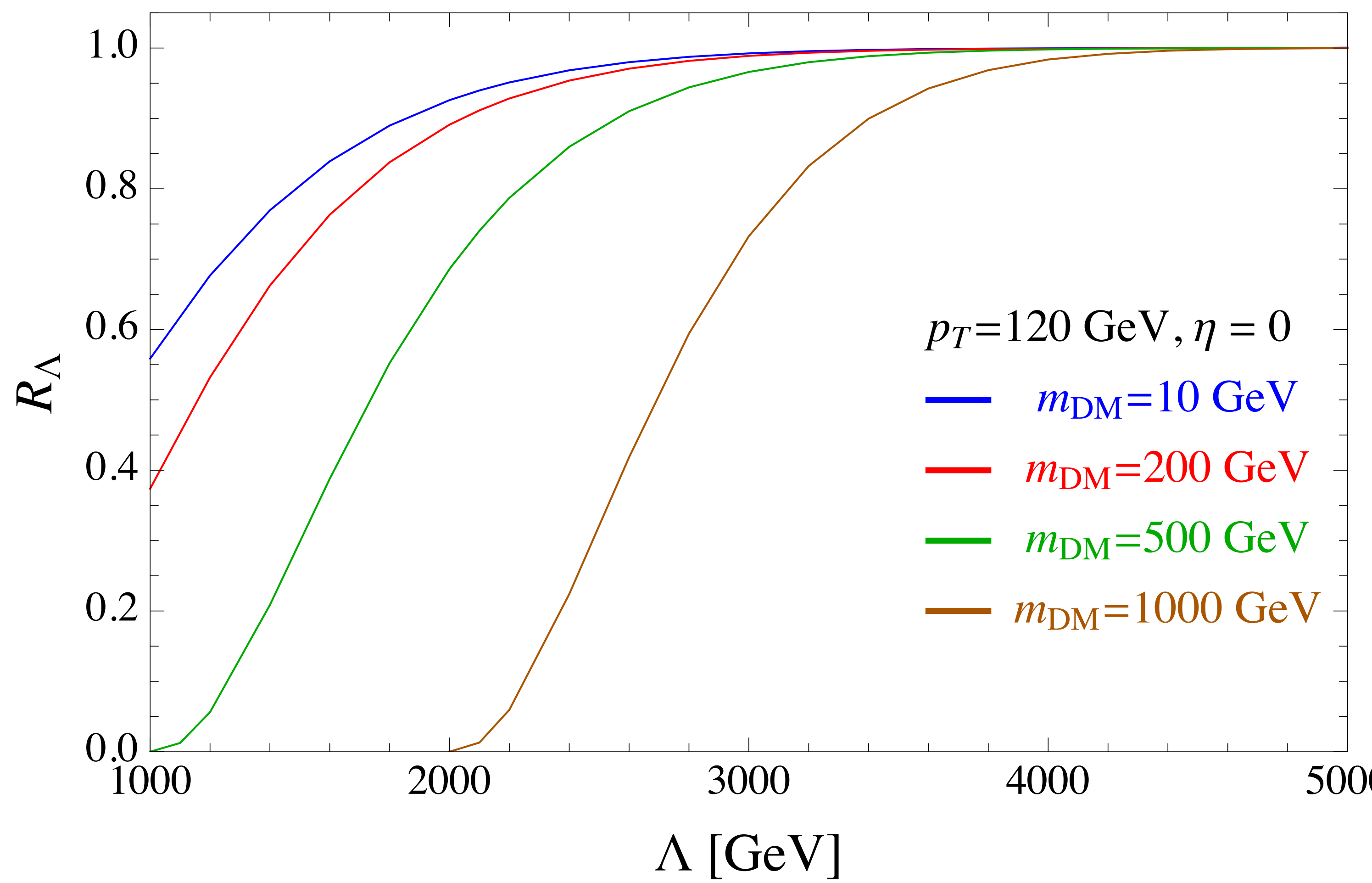
Fraction of events where EFT breaks down may be non-negligible

Depends on DM mass

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

[Busoni, De Simone, Morgante, Riotto, 1307.2253, 1402.1275, 1405.3103]

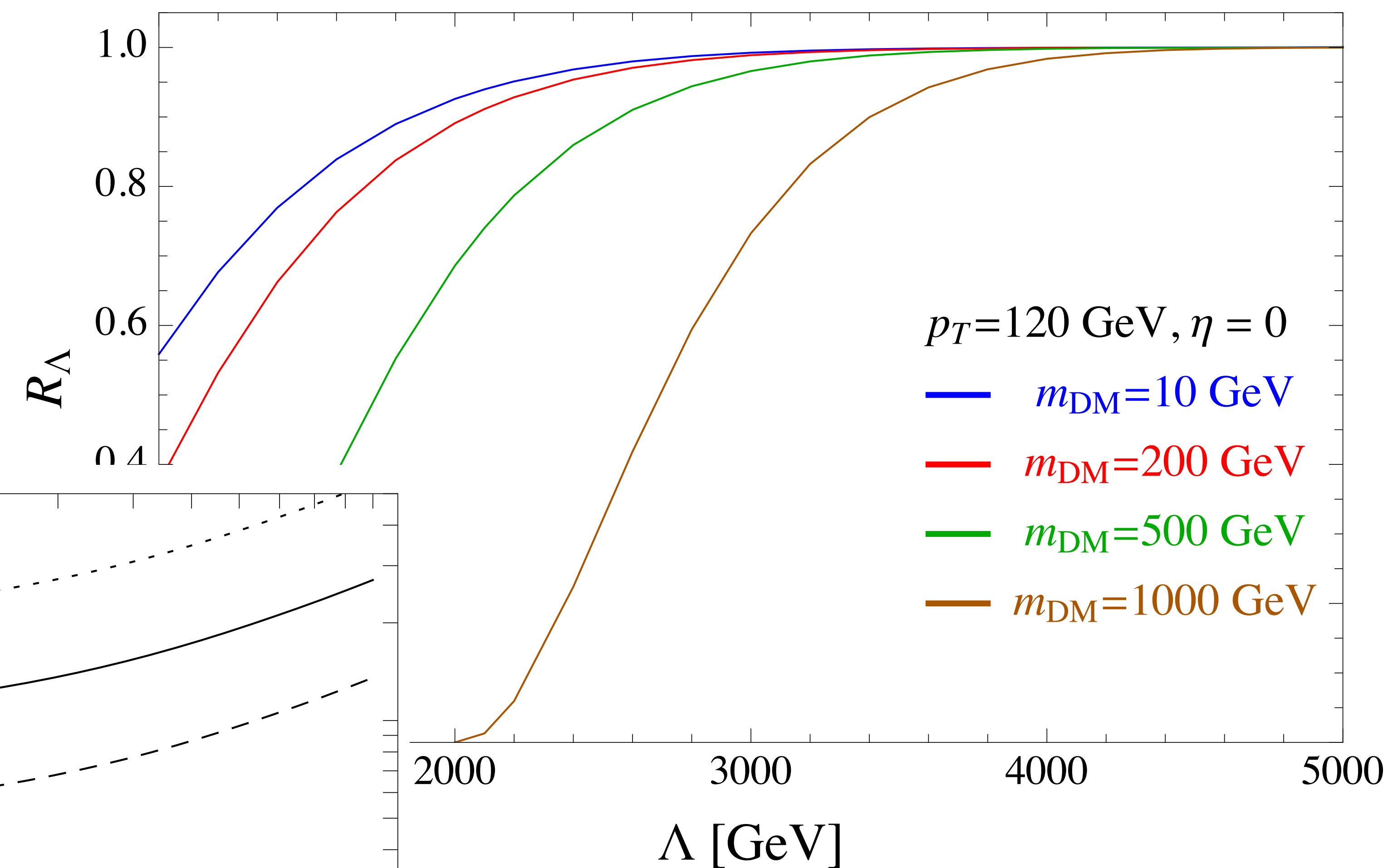
$$R_\Lambda \equiv \frac{\left.\dfrac{\mathrm{d}^2\sigma_{\mathrm{eff}}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}\eta}\right|_{Q_{\mathrm{tr}}<\Lambda}}{\dfrac{\mathrm{d}^2\sigma_{\mathrm{eff}}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}\eta}}$$

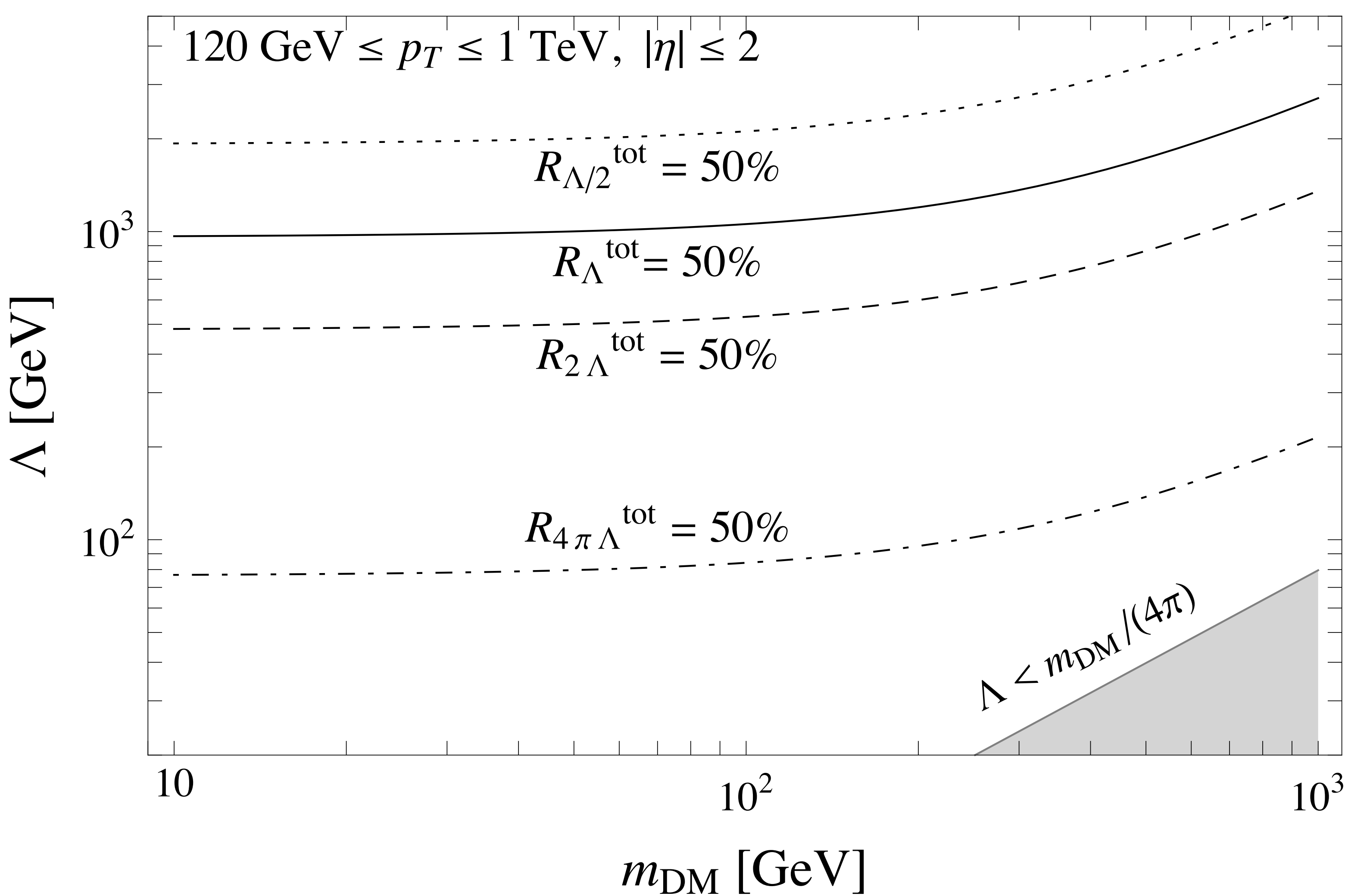


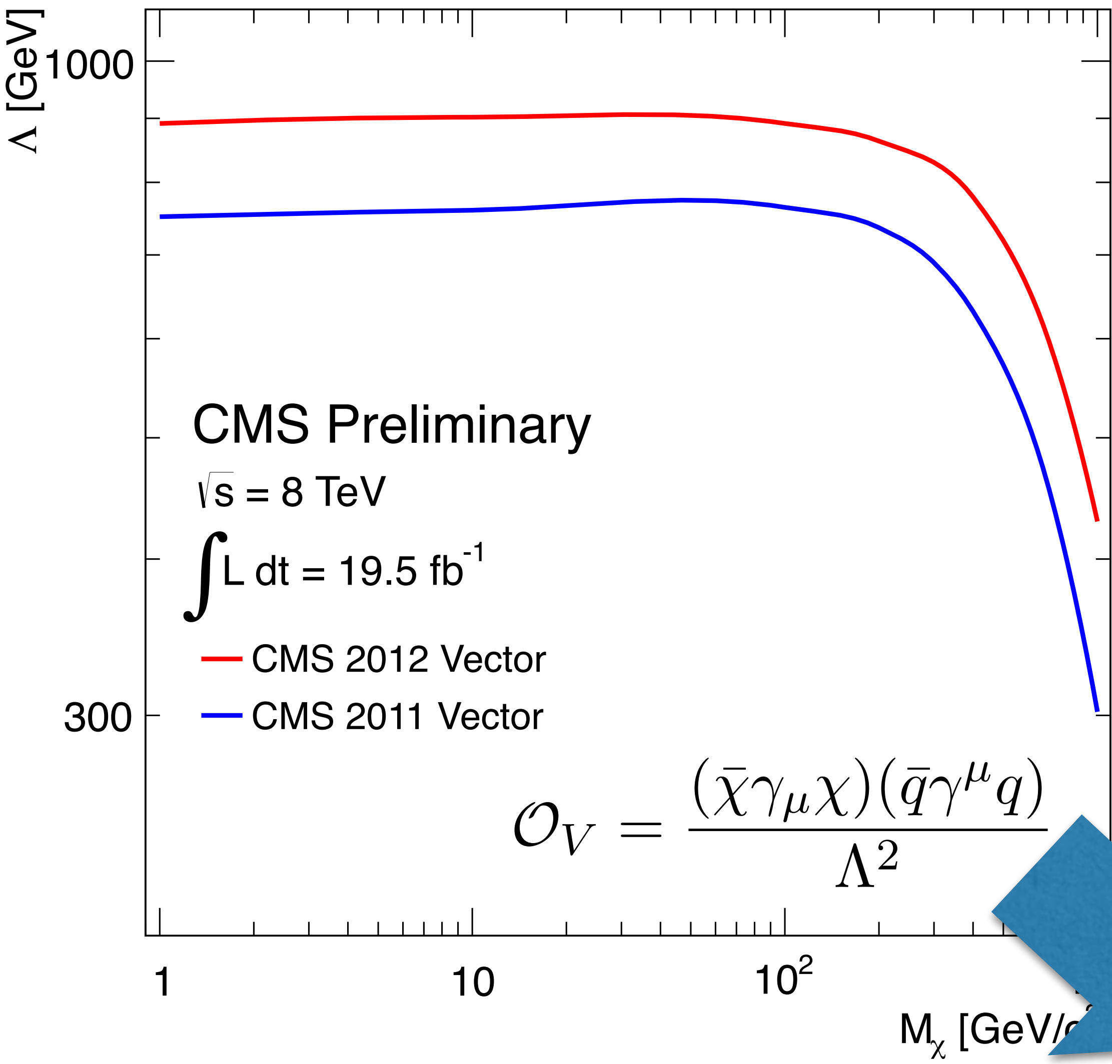
What fraction of events have momentum transfers sufficient to probe the UV completion?

[Busoni, De Simone, Morgante, Riotto, 1307.2253, 1402.1275, 1405.3103]

$$R_\Lambda \equiv \frac{\left.\dfrac{\mathrm{d}^2\sigma_{\rm eff}}{\mathrm{d}p_{\rm T}\mathrm{d}\eta}\right|_{Q_{\rm tr}<\Lambda}}{\dfrac{\mathrm{d}^2\sigma_{\rm eff}}{\mathrm{d}p_{\rm T}\mathrm{d}\eta}}$$

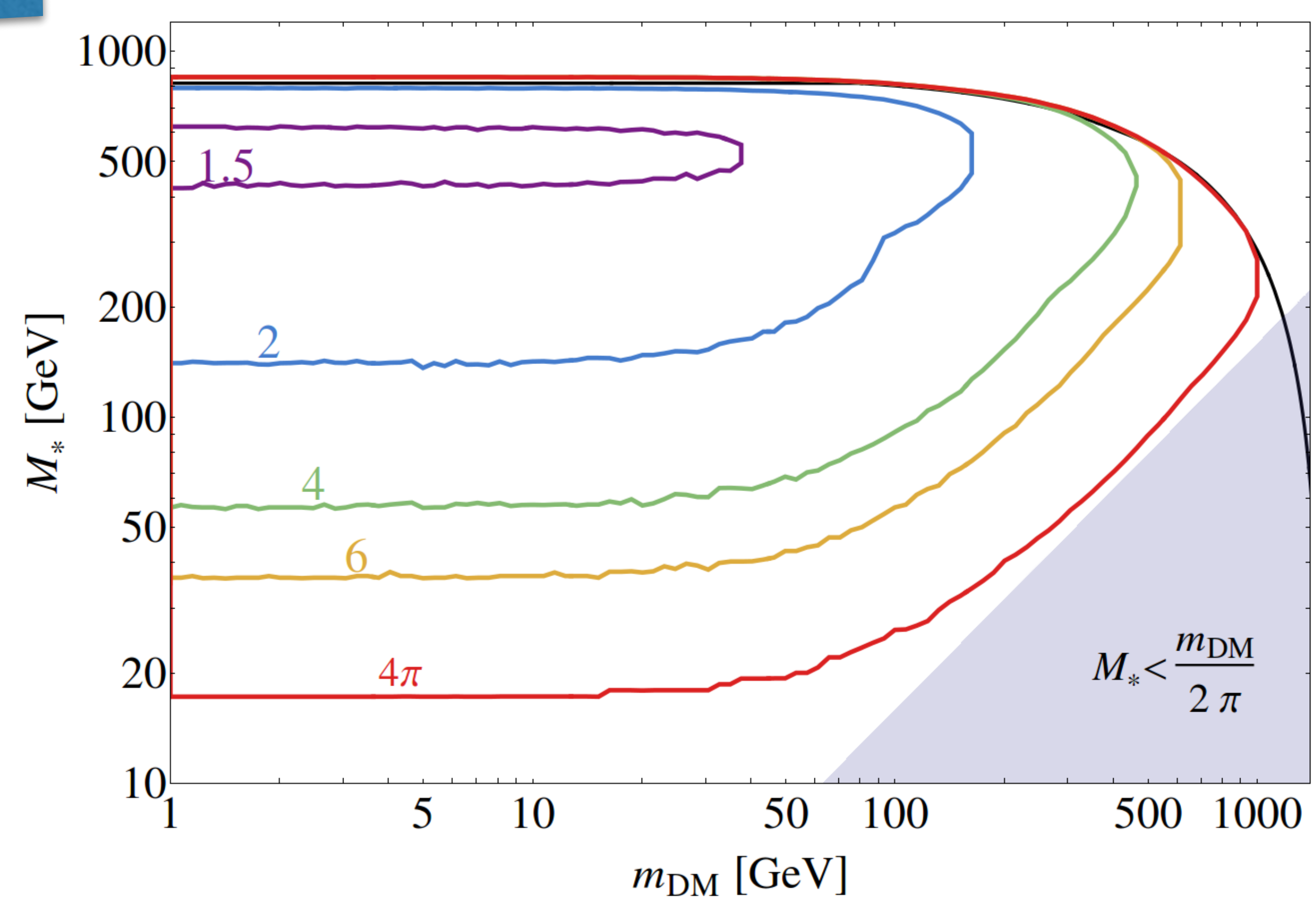






Cutting off theory at the mediator mass scale alters the bounds

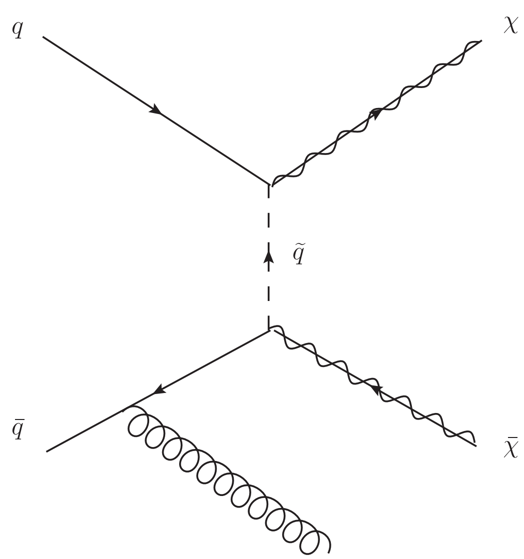
Racco, Wulzer, Zwirner [1502.04701]



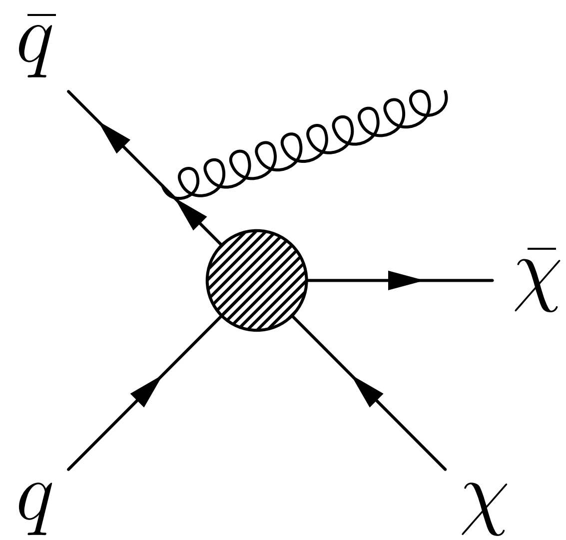
Simplified Models

"Integrate in" the mediator

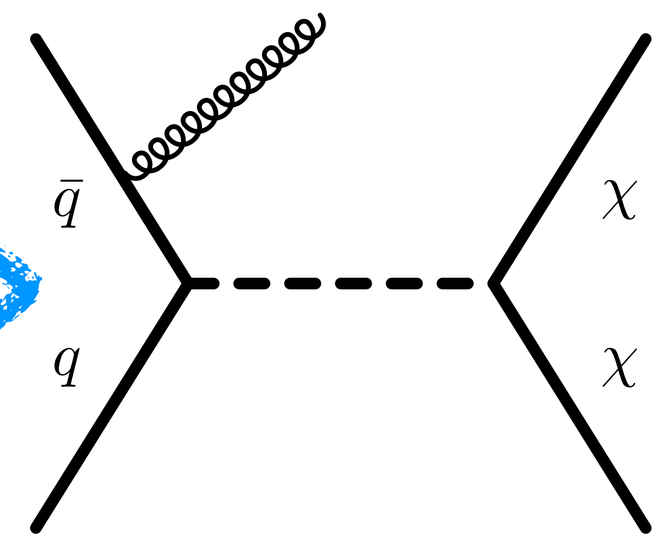
t-channel



EFT



s-channel



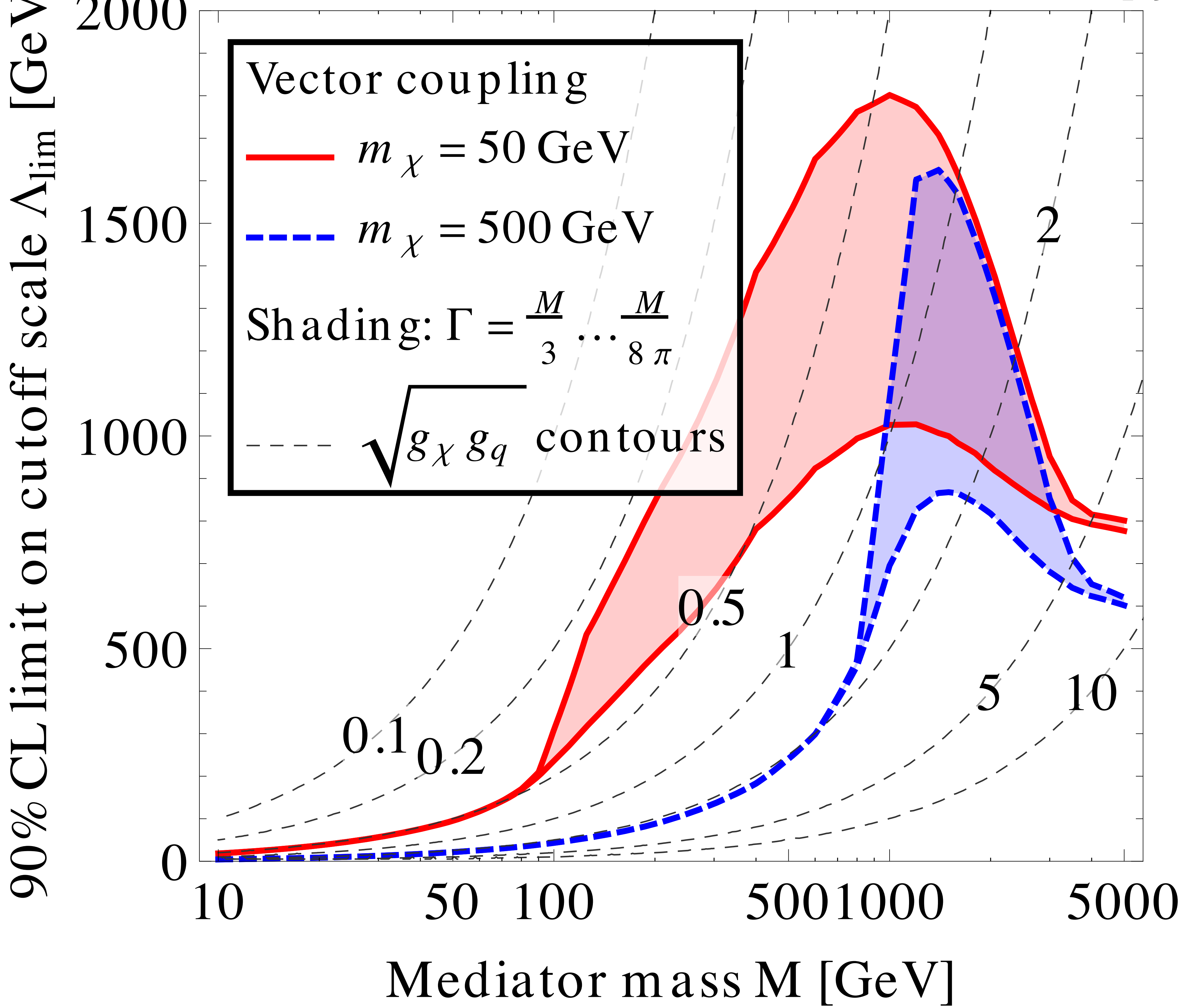
$$\Lambda,\ m_\chi \longrightarrow m_\chi,\ M,\ \Gamma,\ \sqrt{g_q g_\chi}$$

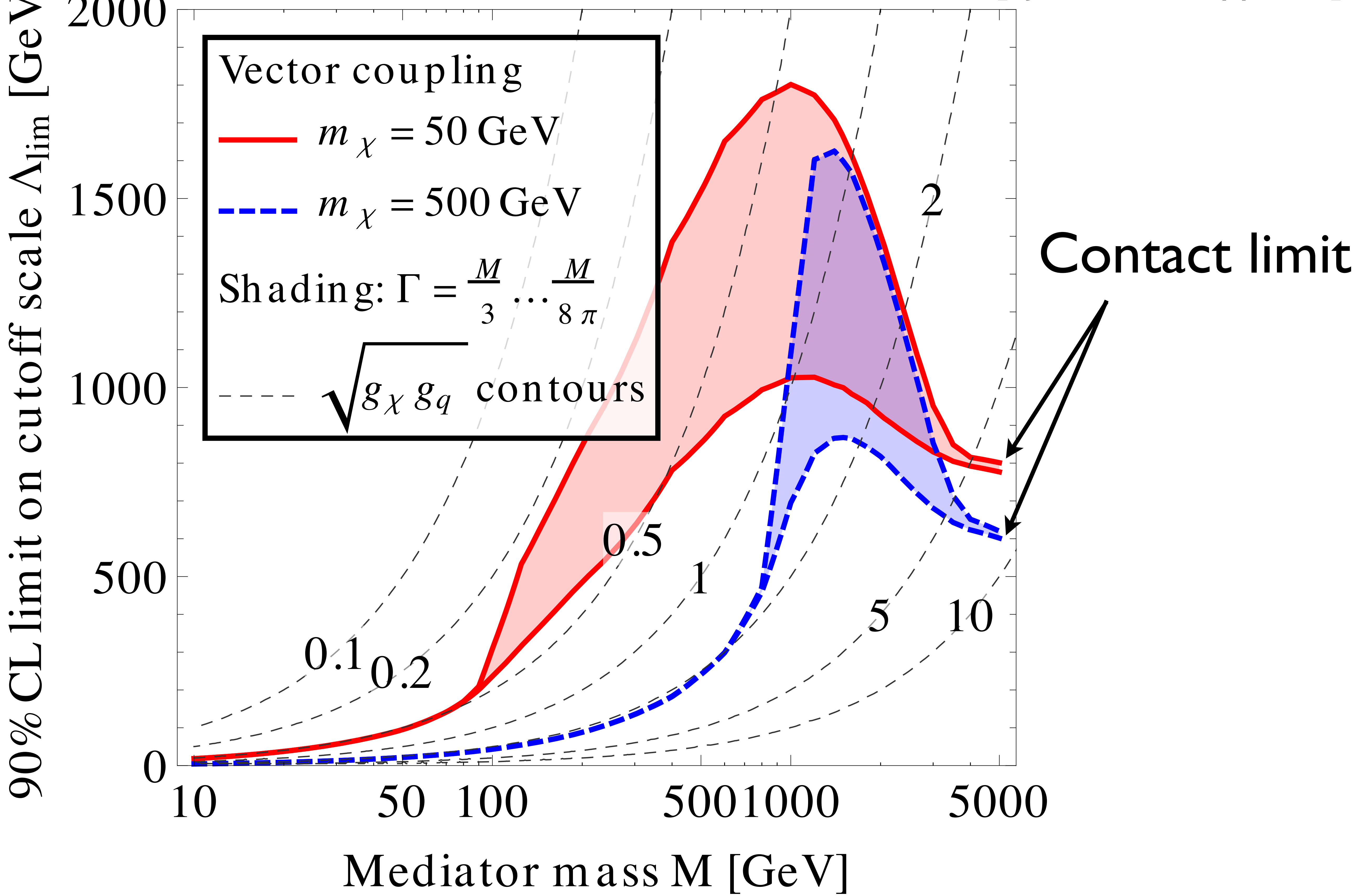
New channels to search for!

Collider only sensitive to all 4 parameters over a narrow range

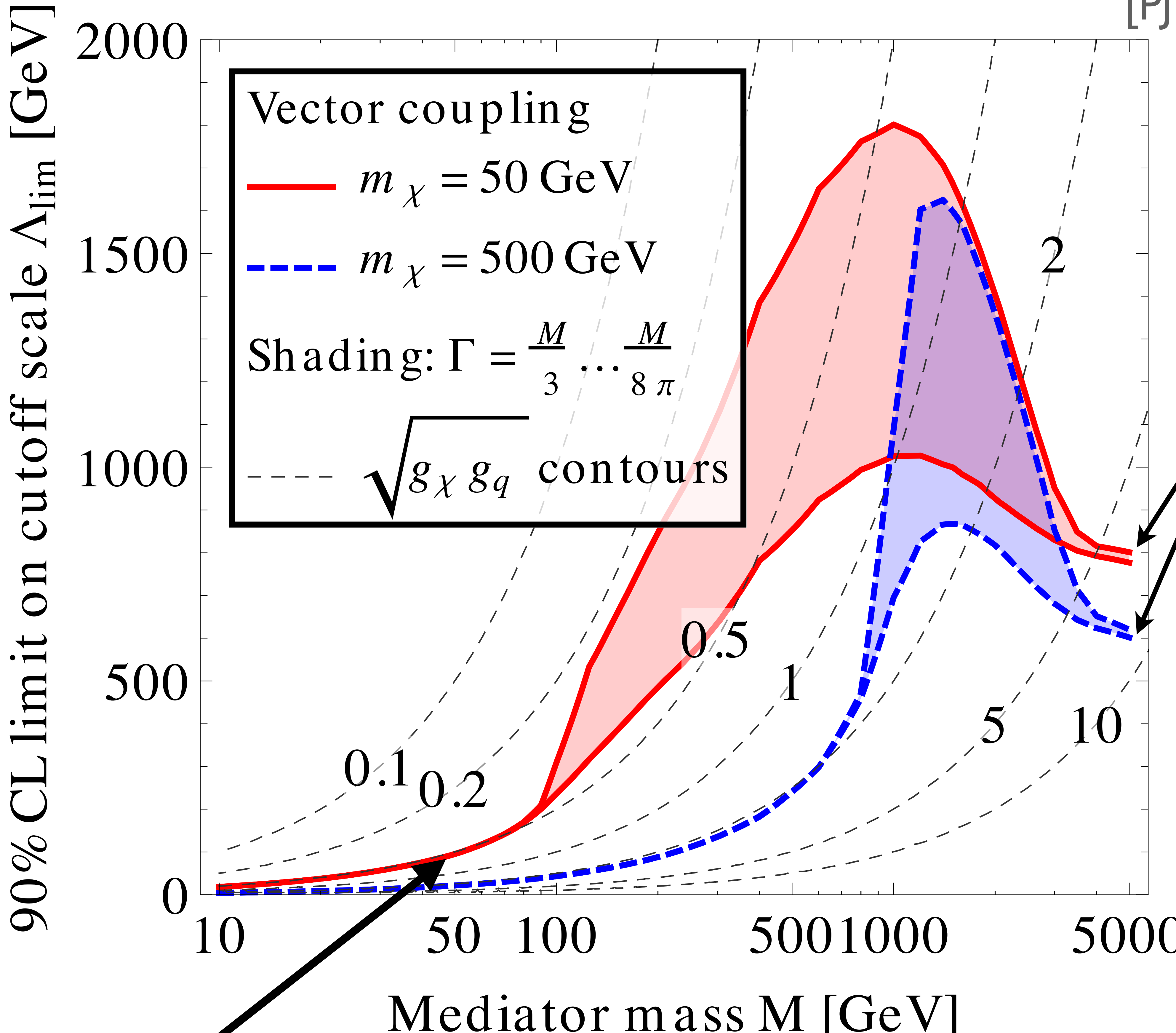
But mapping collider constraints to direct/indirect detection now requires assumptions

[PJF,Harnik,Kopp,Tsai]





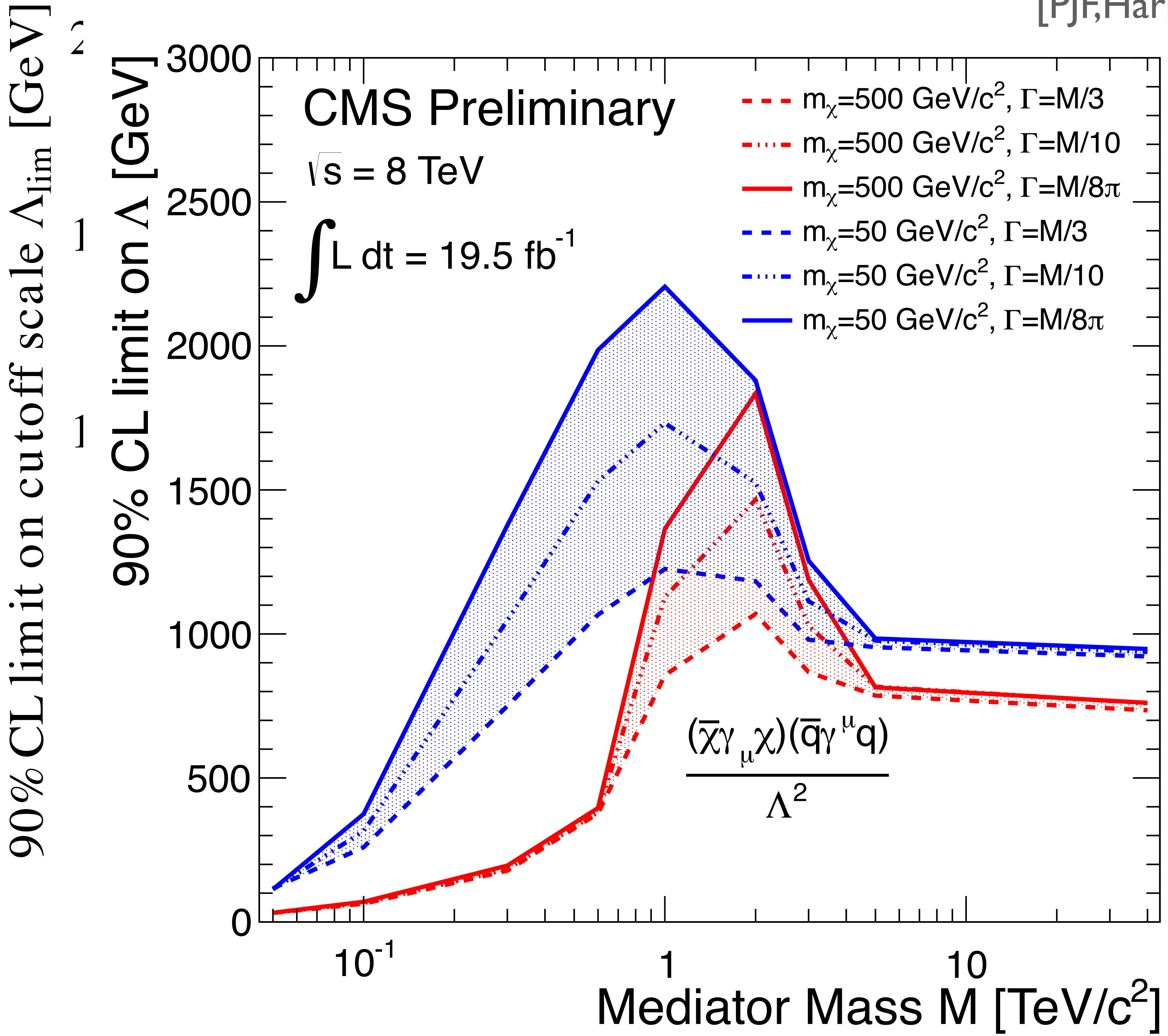
90% CL limit on cutoff scale $\Lambda_{\rm lim}$ [GeV]
2000
1500
1000
500
0
10
50
100
500
1000
5000
Mediator mass M [GeV]
Vector coupling
$m_\chi = 50$ GeV
$m_\chi = 500$ GeV
Shading: $\Gamma = \frac{M}{3} \ldots \frac{M}{8\pi}$
$\sqrt{g_\chi g_q}$ contours
0.1
0.2
0.5
1
2
5
10
Contact limit



Contact limit

Light mediator severely weakens limit

[PJF,Harnik,Kopp,Tsai]

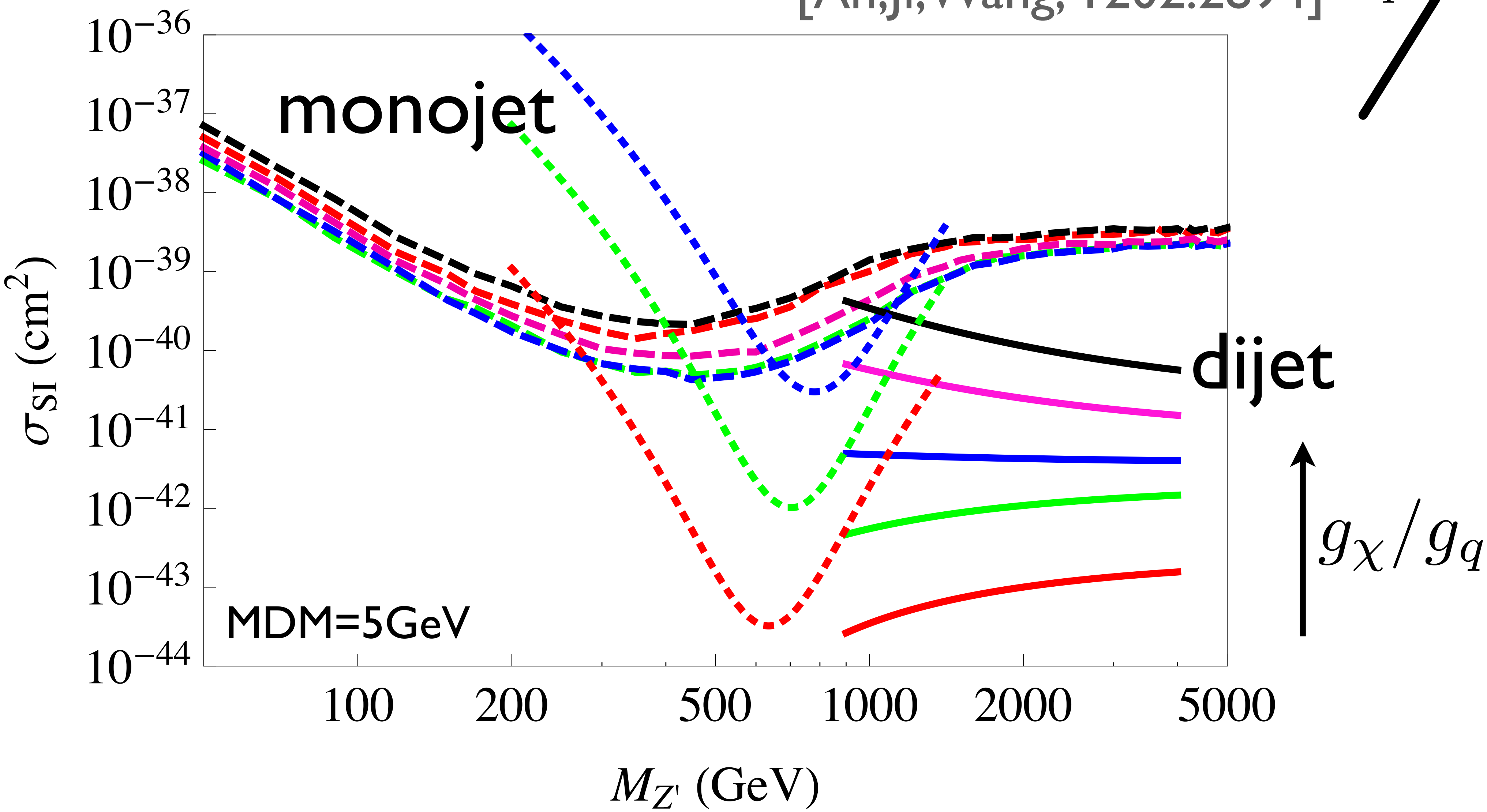


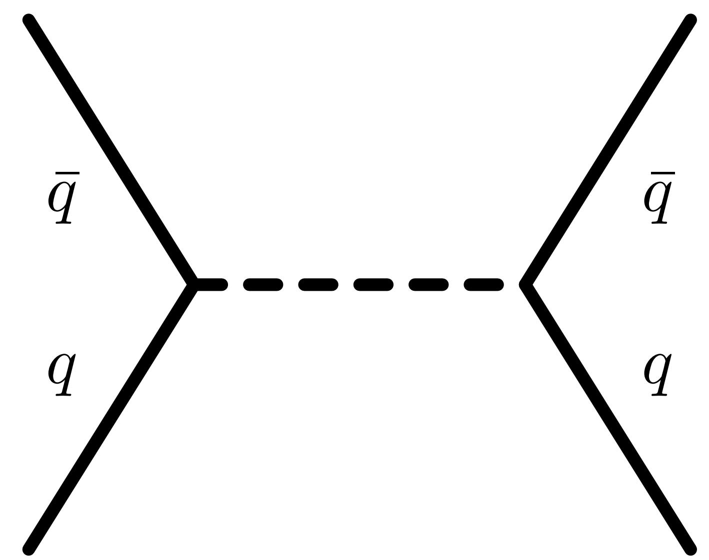
Light Mediators

[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]

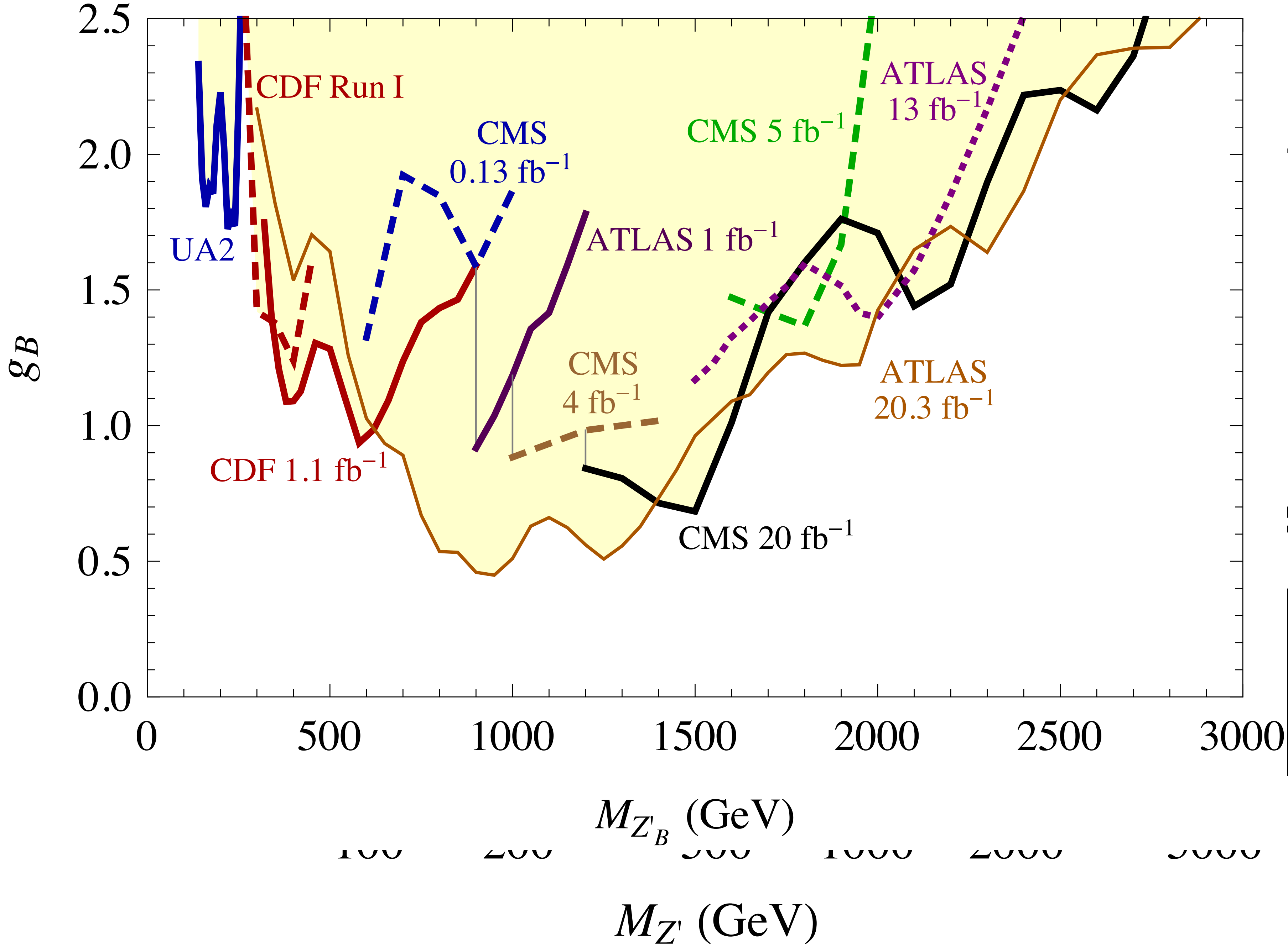


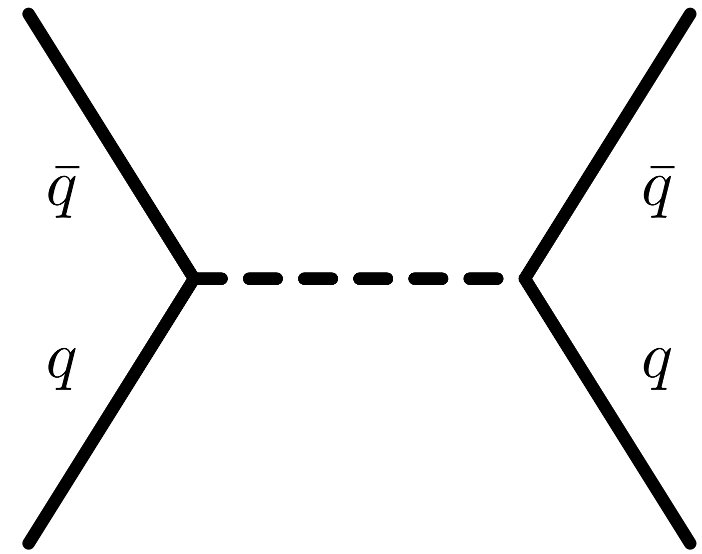


Light Mediators

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

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





-]

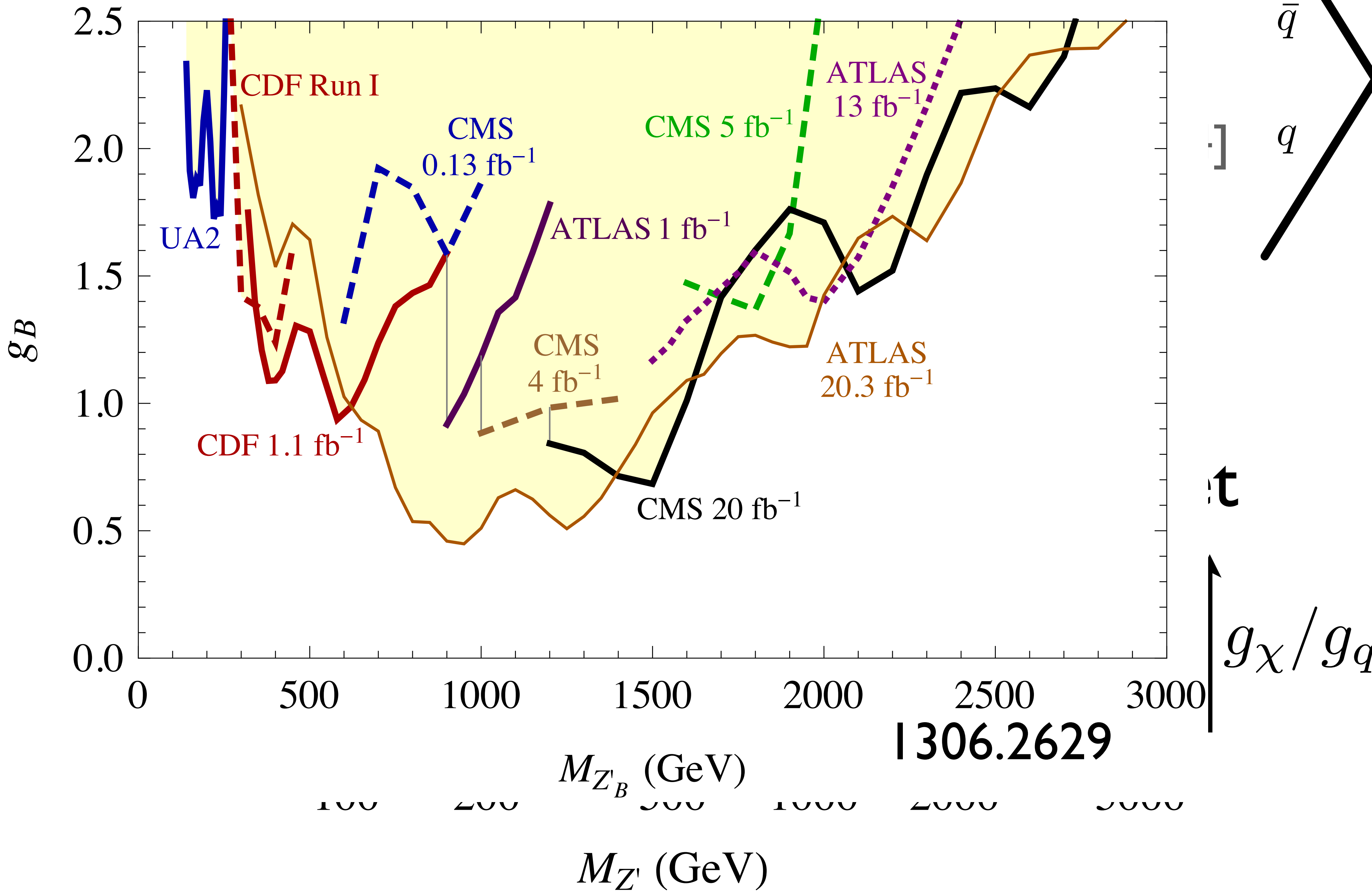
et

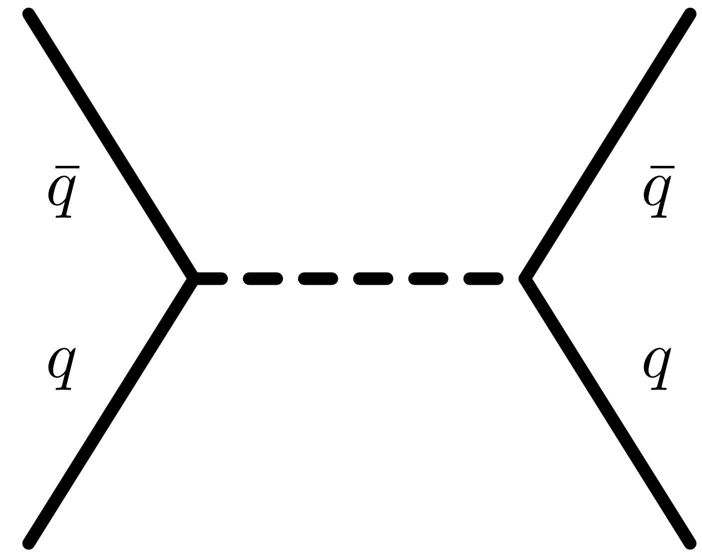
g_χ / g_q

Light Mediators

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

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

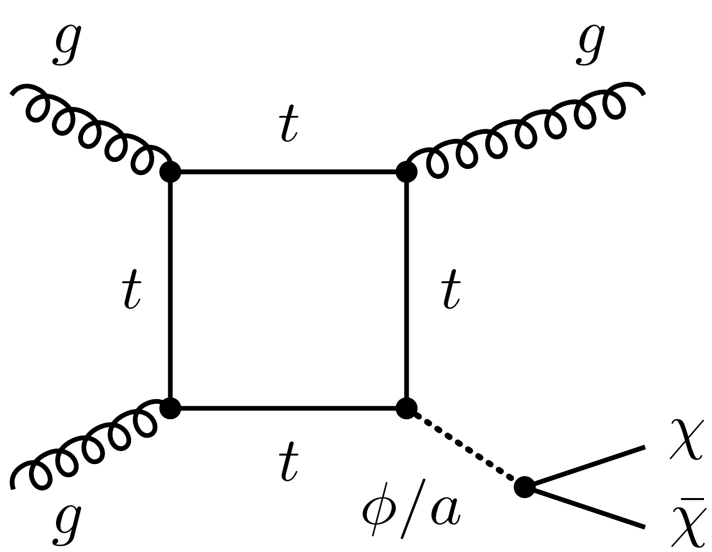




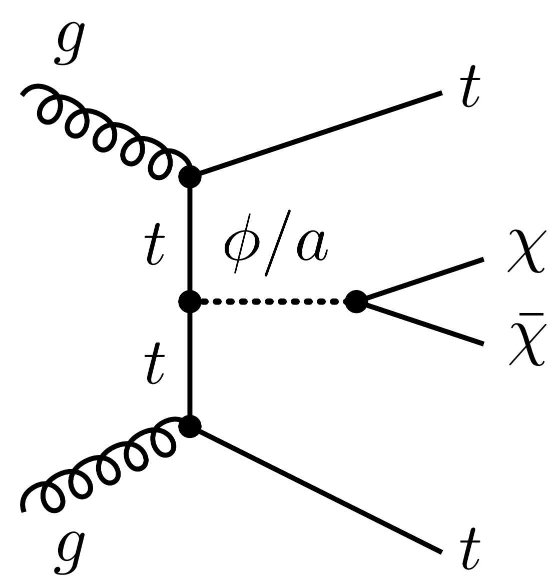
Types of Simplified models

s-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

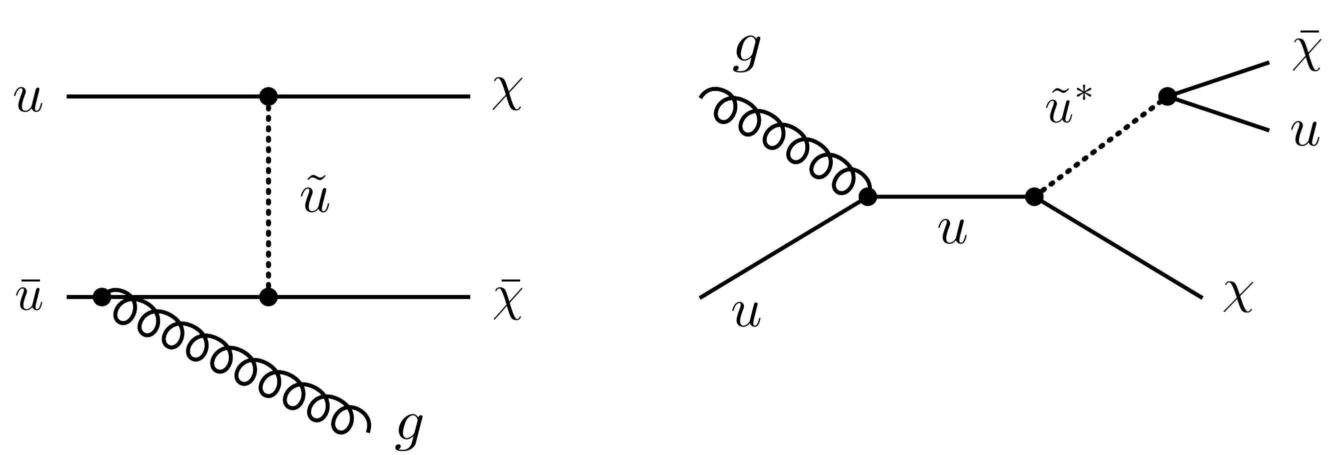
- Scalars have helicity suppressed annihilation, and SI DD
- Pseudo scalars do not, and have SD momentum suppressed DD

Types of Simplified models

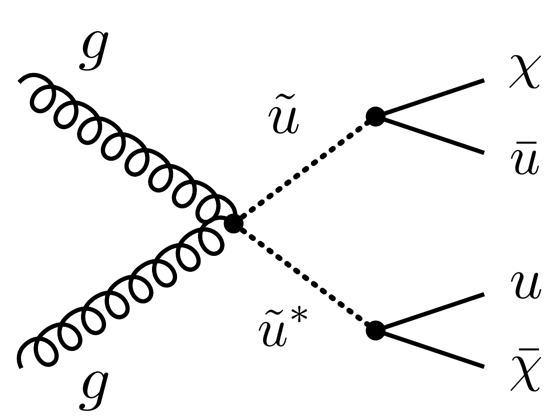
t-channel scalar/psuedo-scalar

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

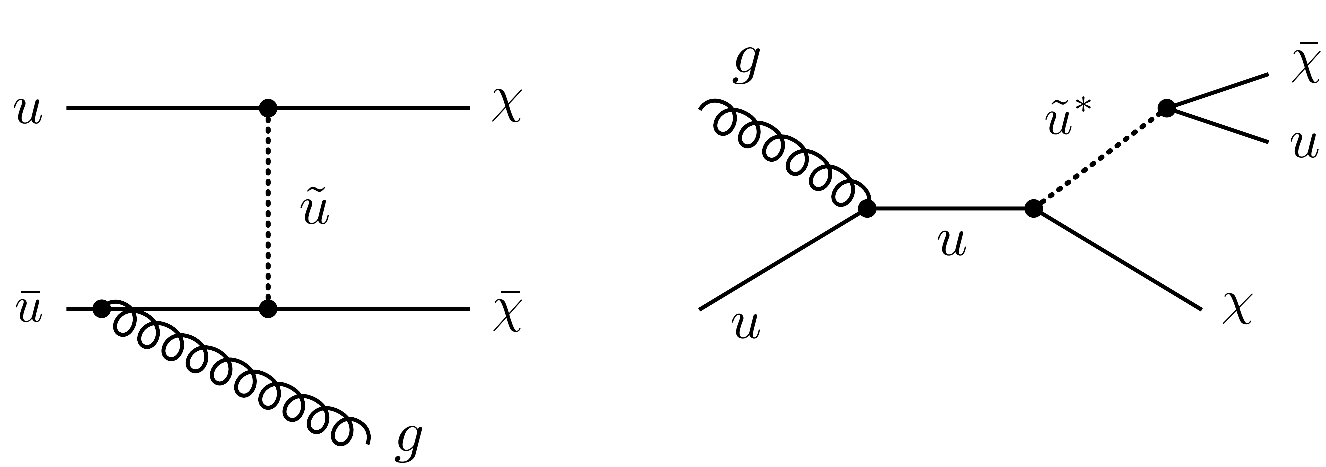
Types of Simplified models

t-channel scalar/psuedo-scalar

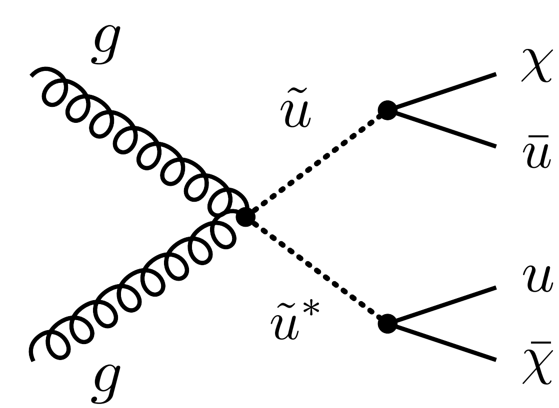
“squarks” w/o SUSY prior

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

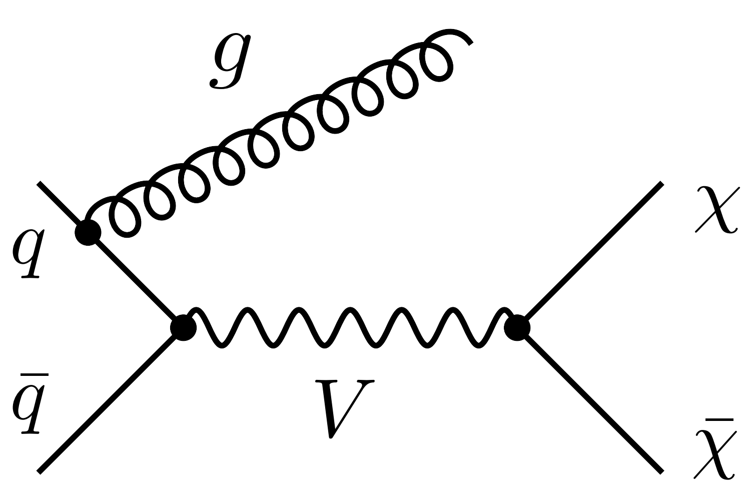
Spontaneously broken $U(1)'$

(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'



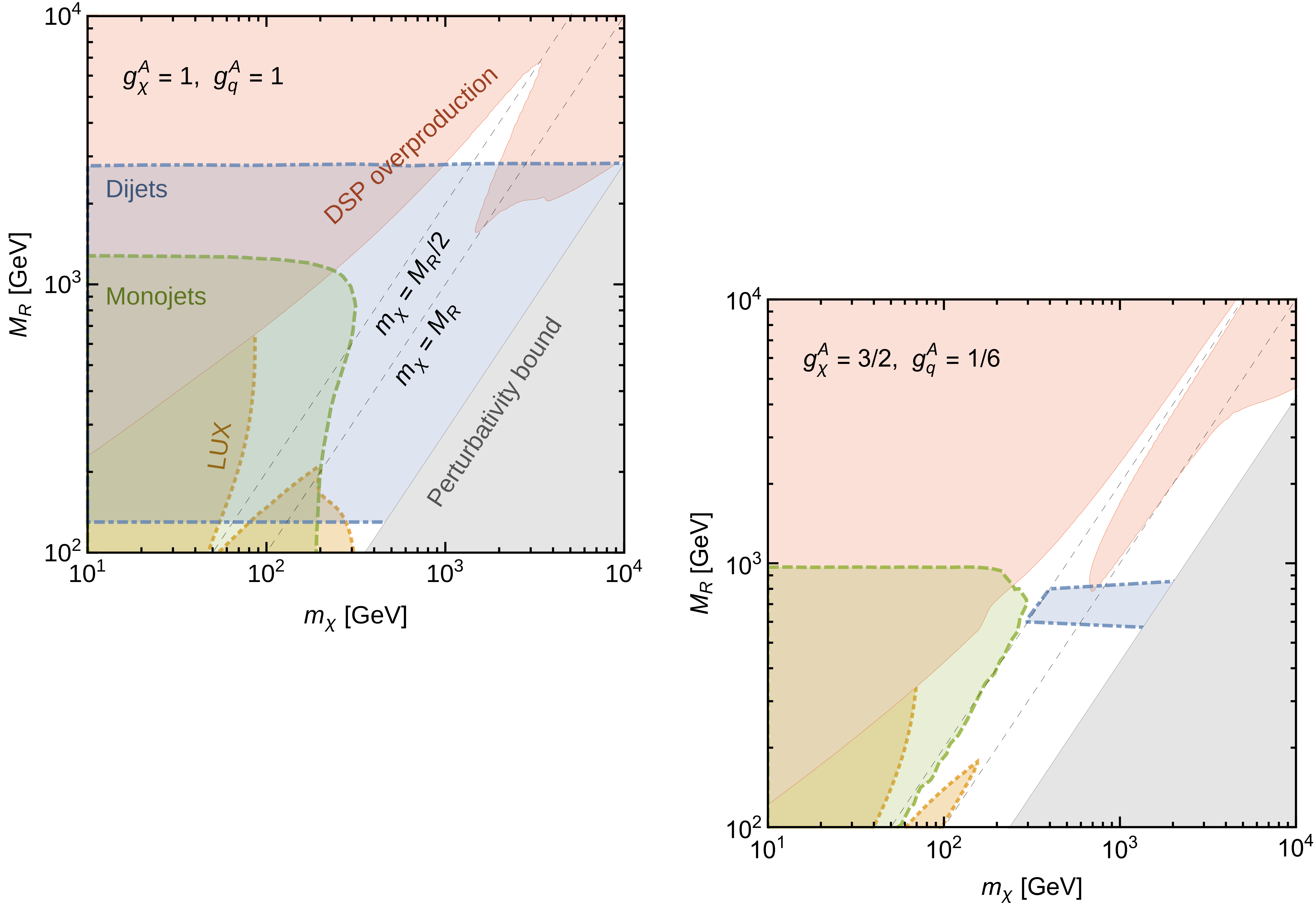
monojet

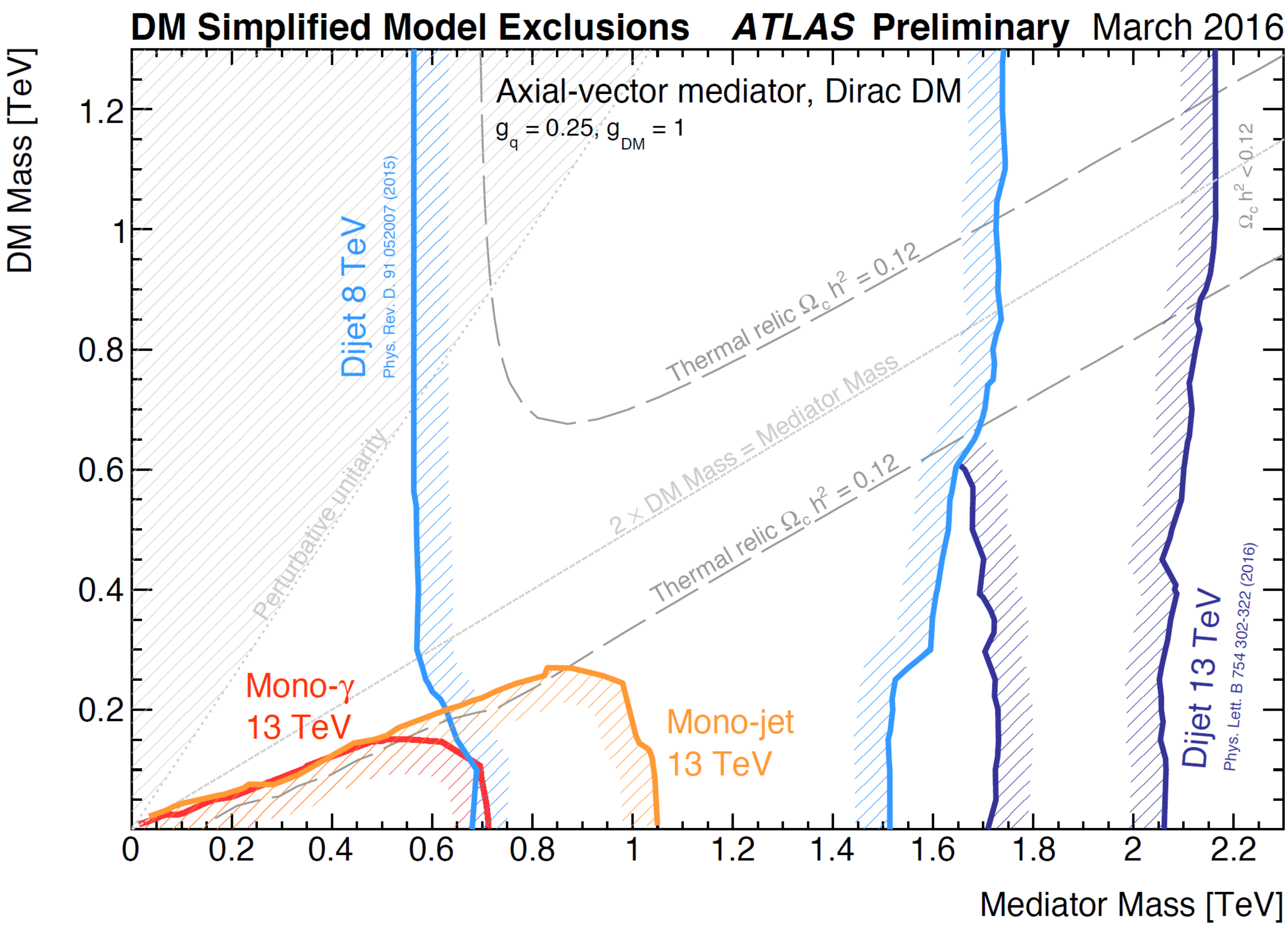
- Vectors are SI
- Axial vectors SD
- If thermal often underproduced

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
$g_q = 0.25$, $g_{DM} = 1$
Dijet 8 TeV
Phys. Rev. D. 91 052007 (2015)
Perturbative unitarity
Thermal relic $\Omega_c h^2 = 0.12$
$2 \times$ DM Mass = Mediator Mass
Thermal relic $\Omega_c h^2 = 0.12$
$\Omega_c h^2 < 0.12$
Mono-γ
13 TeV
Mono-jet
13 TeV
Dijet 13 TeV
Phys. Lett. B 754 302-322 (2016)
DM Mass [TeV]
Mediator Mass [TeV]

Higgs and DM

[Fox, Harnik, Kopp, Tsai]

- The Higgs exists. DM exists.
- The Higgs is a motivated candidate for mediator of DM interaction. a.k.a. the **Higgs Portal**.
- Assuming Standard Higgs production:

Limit on invisible Higgs.

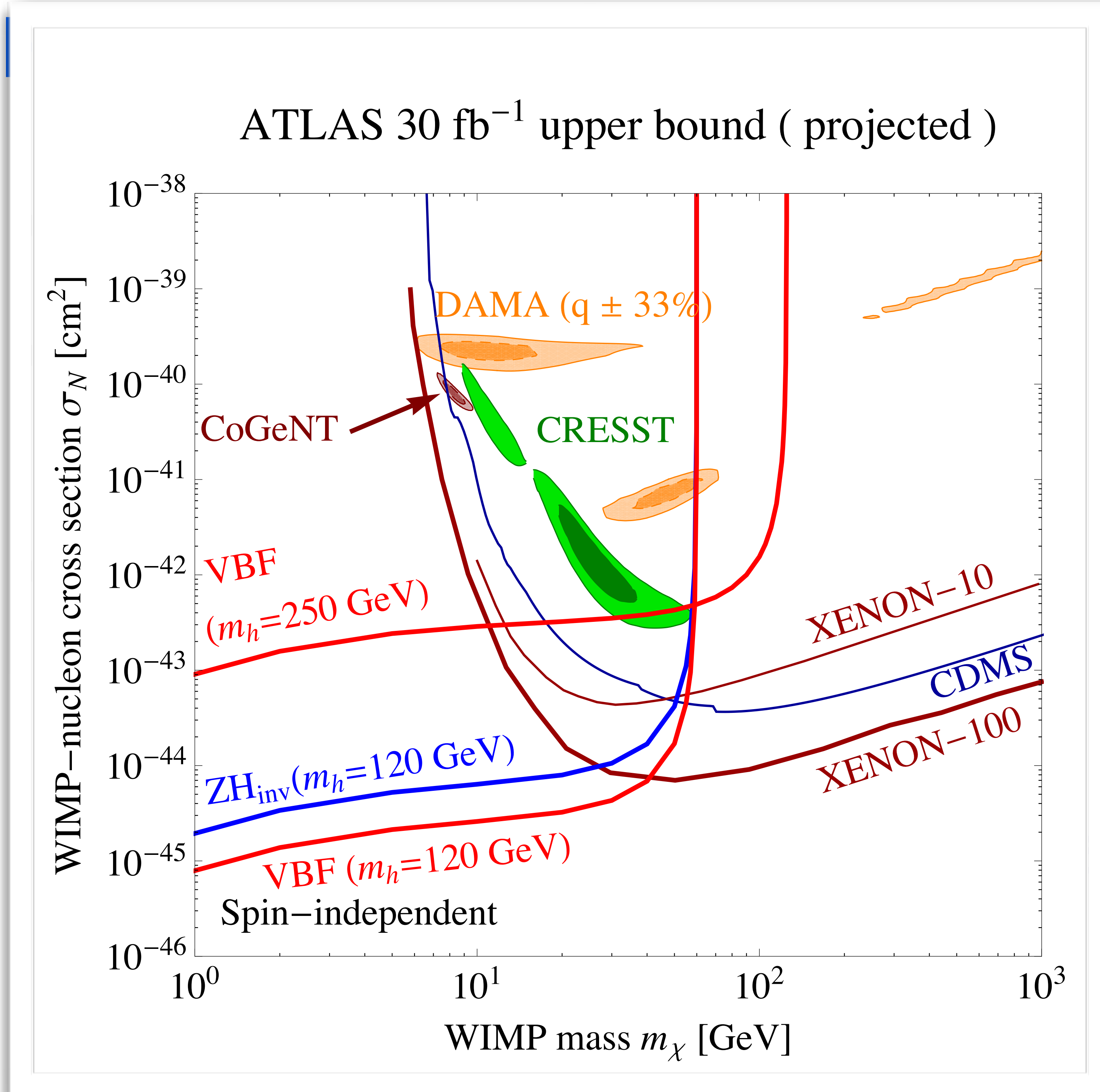
↓

Limit on Higgs-DM coupling.

↓

Limit on direct detection.

[Fox, Harnik, Kopp, Tsai]



or mediator of DM

:

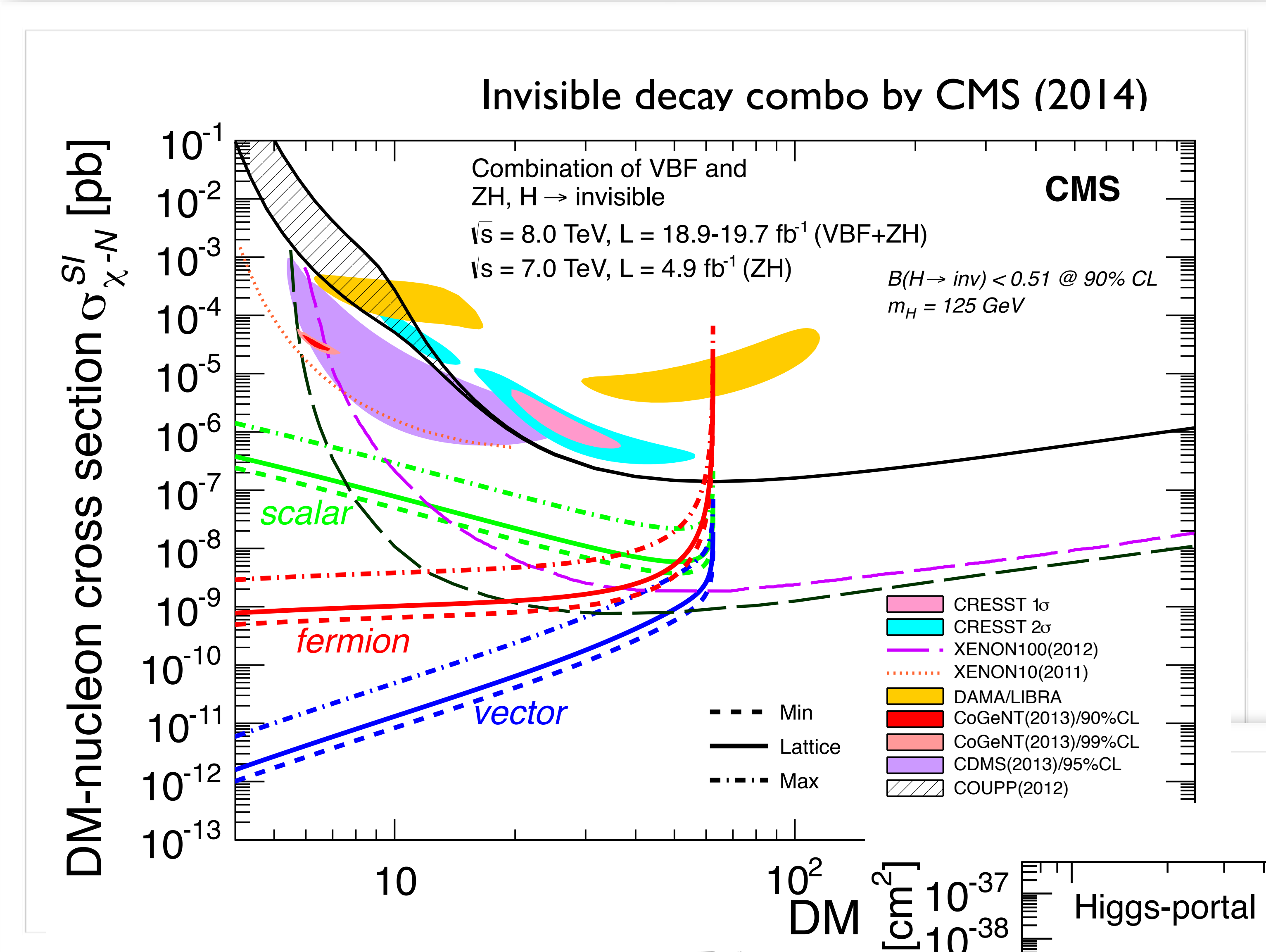
Higgs.

Limit on Higgs-DM coupling.

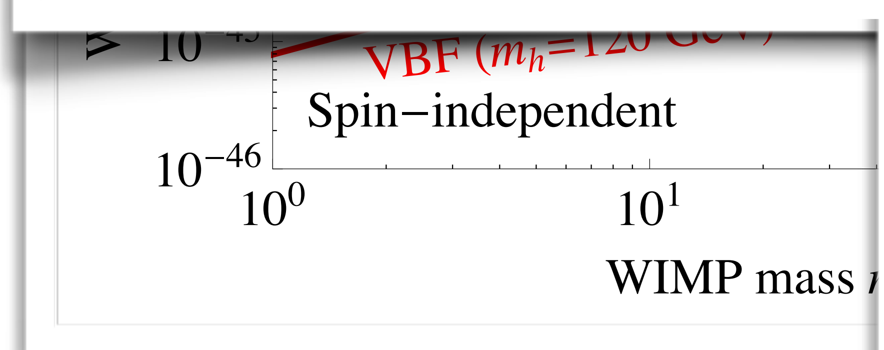
↓

Limit on direct detection.

[Fox, Harnik, Kopp, Tsai]



r mediator of DM



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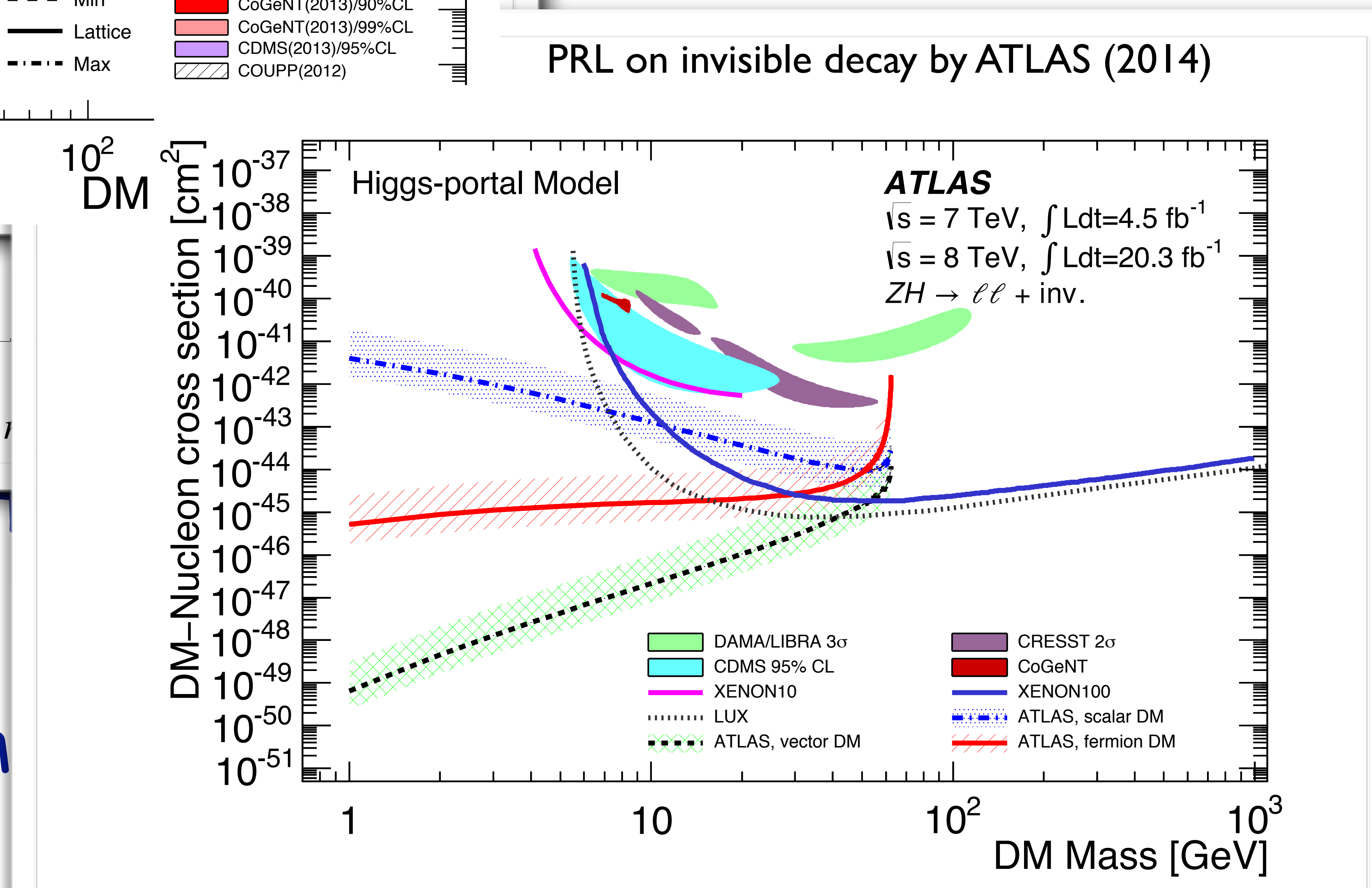


What next?

"Mono" searches: $\Delta\phi(j_1, j_2) < 2.5 \quad N_{jet} \leq 2$

LHC is a jets "factory", can we do better?

Steal from SUSY jets+MET analyses

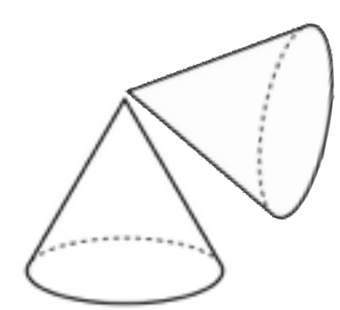
[Rogan 1006.2727]

$$M_R = \sqrt{(E_{j_1} + E_{j_2})^2 - (p_z^{j_1} + p_z^{j_2})^2}$$

$$M_R^T = \sqrt{\frac{\not{E}_T(p_T^{j_1} + p_T^{j_2}) - \vec{\not{E}}_T \cdot (\vec{p}_T^{j_1} + \vec{p}_T^{j_2})}{2}}$$

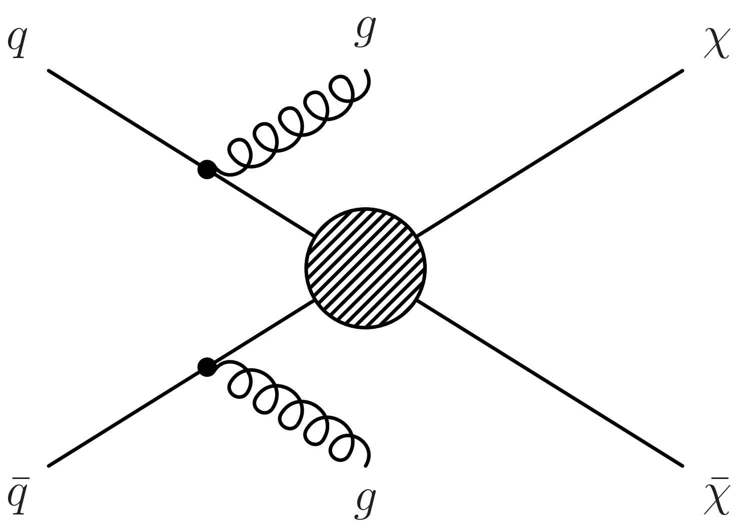
$$R = \frac{M_R^T}{M_R}$$

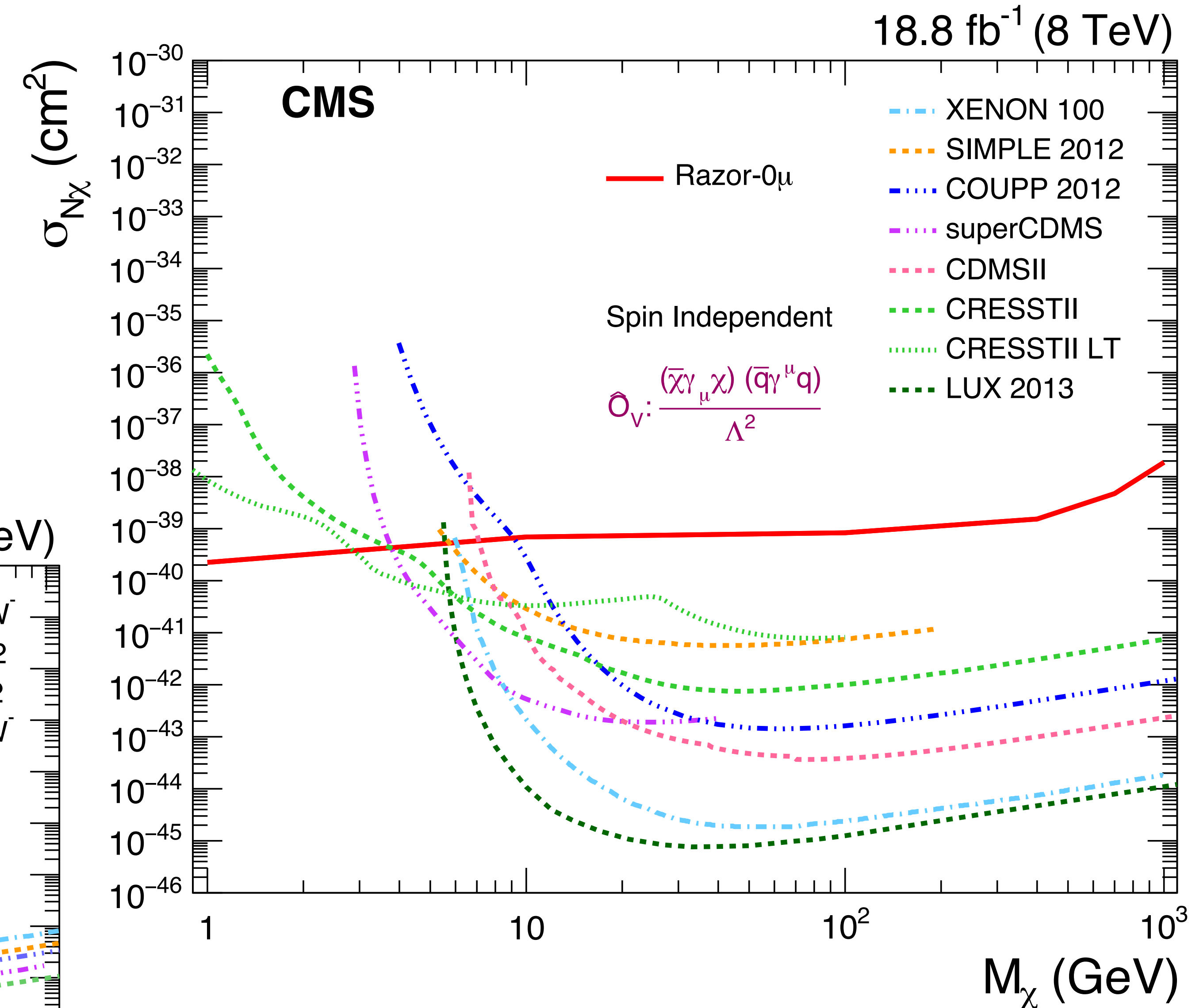
Small R

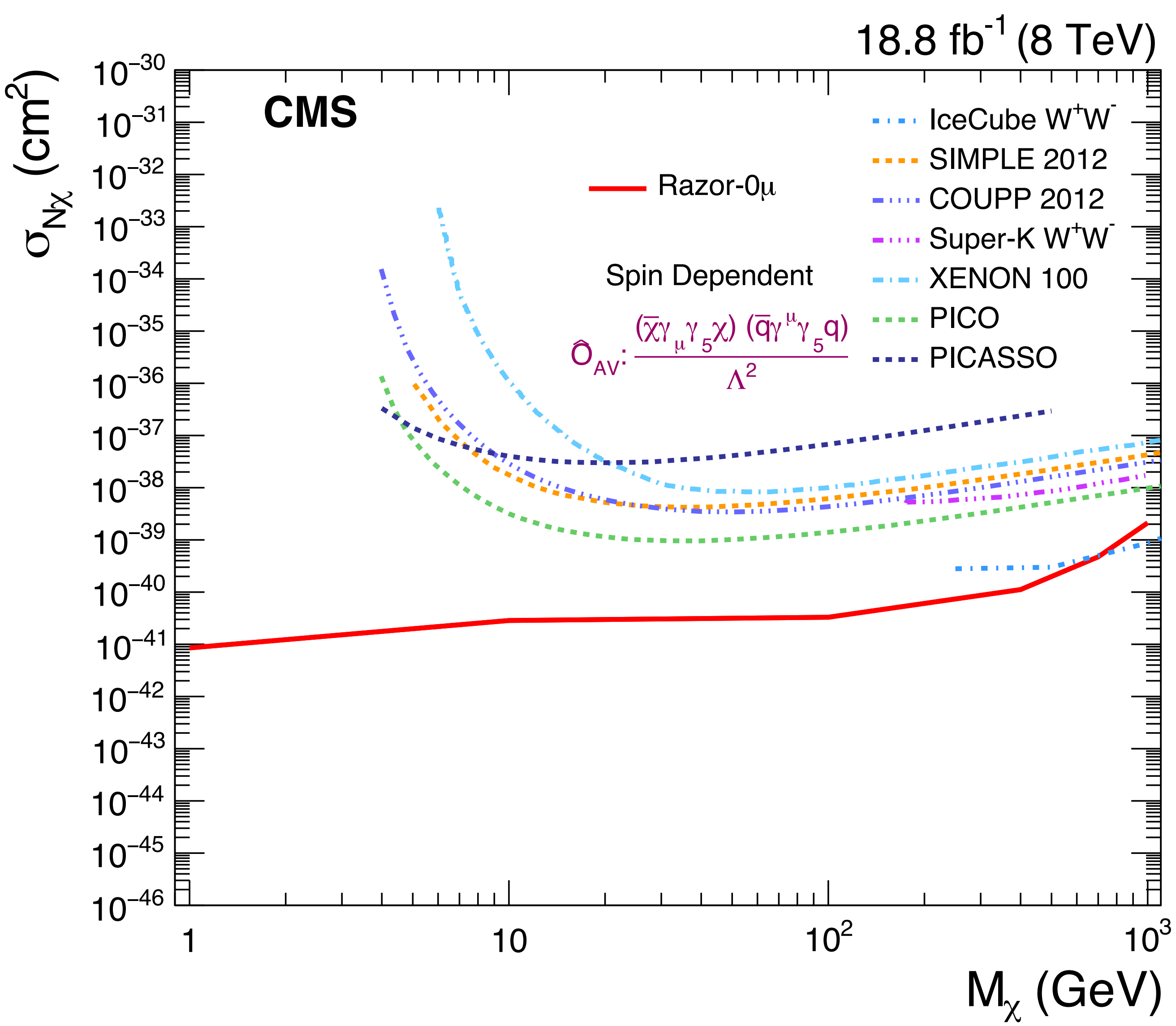


Large R

CMS dedicated razor DM search





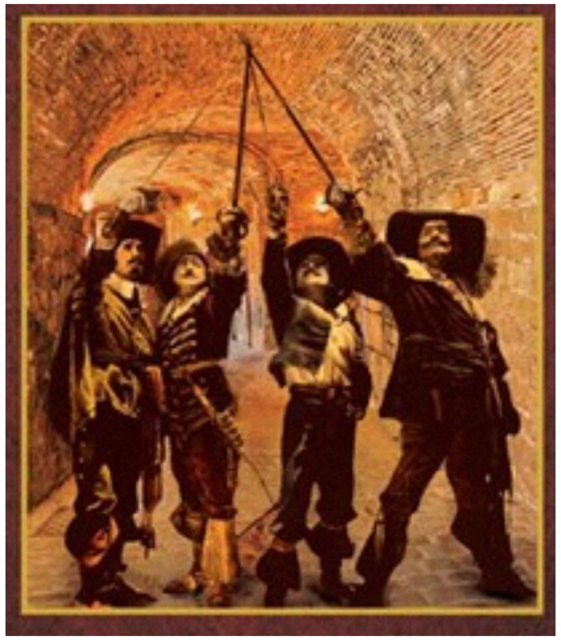


Similar sensitivity but more inclusive set of events

Complementarity

- Direct detection limited to DM above GeV, needs DM nearby moving in the right way
- No upper limit on mass probed, learn about DM in cosmos
- Indirect detection very sensitive to astrophysics
- Halo shapes can probe DM-DM interactions
- Collider searches have kinematic upper limit, no astrophysics systematics, but many others

Complementary taken together provide complete picture



Complementarity

Many exciting new ideas for probing light DM e.g. scattering off electrons in semi/super conductors

- Direct detection
- mass probed, learn about DM in cosmos
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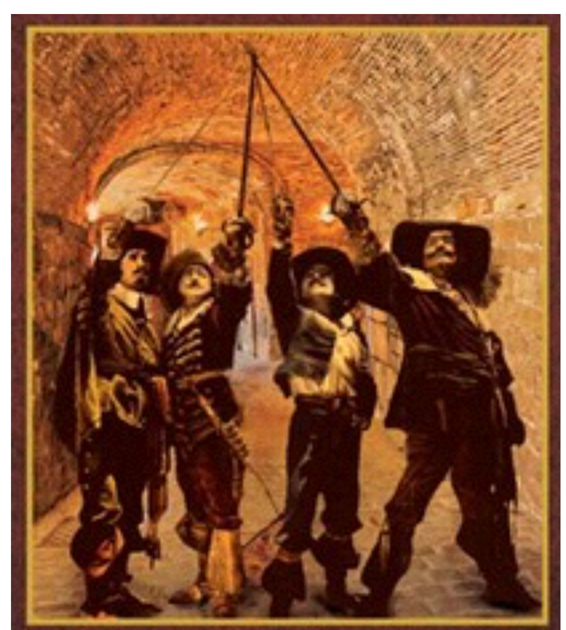

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