BSM Theory: The SM and Beyond

Patrick "PaDDy" Fox

Fermilab

Bugs and Features

Hierarchy (Naturalness) problem

$$\mathcal{L}_2 = \pm\mu^2|H|^2$$

Why is μ so much smaller than M_{GUT}, M_{Pl}?

Unlike fermions (and gauge bosons) no symmetry protects scalar mass parameter

1. Nature is fine-tuned (anthropics?)
2. The SM has no high scales (gravity?, unification?)
3. New dynamics/symmetries keeps mass scale low

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Why is μ sc

> There is something fascinating about science. One gets such wholesale returns of conjecture out of such a trifling investment of fact.
>
> —Mark Twain

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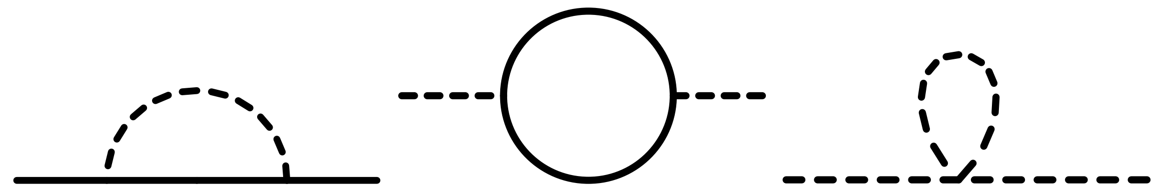
Hierarchy (Naturalness) problem

$$\mathcal{L} = |\partial_\mu \phi|^2 + \overline{\psi} i \partial\!\!\!/ \psi - m_f \overline{\psi}\psi - y\phi\overline{\psi}\psi - \mu^2 |\phi|^2 - \lambda |\phi|^4$$



etc

$$\Delta m_f \sim -\frac{y^2}{16\pi^2} m_f \log\left(\frac{\Lambda}{m_f}\right)$$

$$\Delta \mu^2 \sim \frac{\lambda - y^2}{16\pi^2}\Lambda^2 - \frac{y^2}{16\pi^2} m_f^2 \log\frac{\Lambda}{m_f}$$

Scalars are sensitive to the highest scale in the theory!

Expect new physics (Λ) at $\frac{4\pi}{g} m_h$

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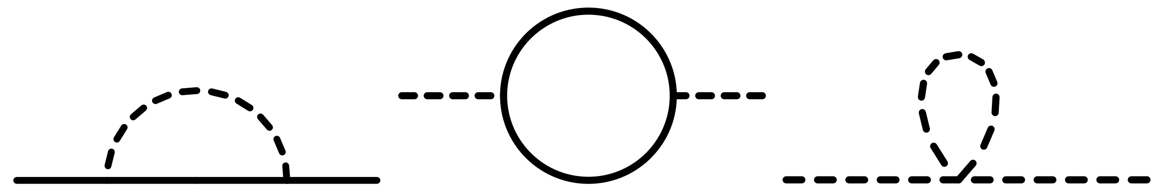

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Possible solution?

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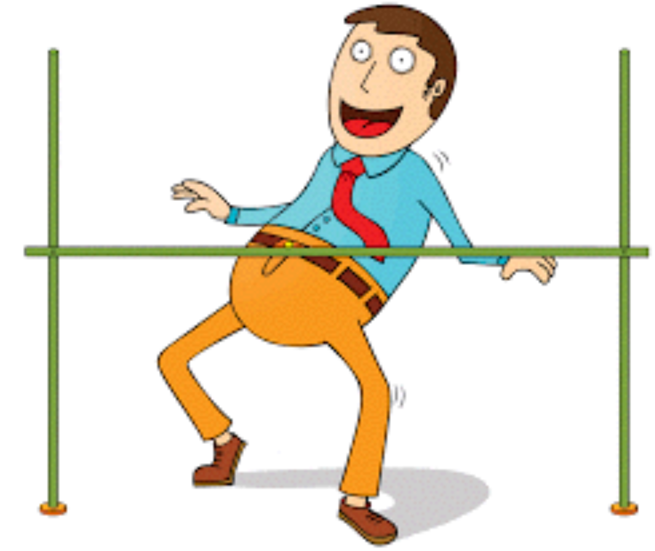


SM Higgs sensitivity (how low ~~can you~~ go)

$$\delta m_h^2 = \alpha_t \Lambda_t^2 + \alpha_g \Lambda_g^2 + \alpha_h \Lambda_h^2$$

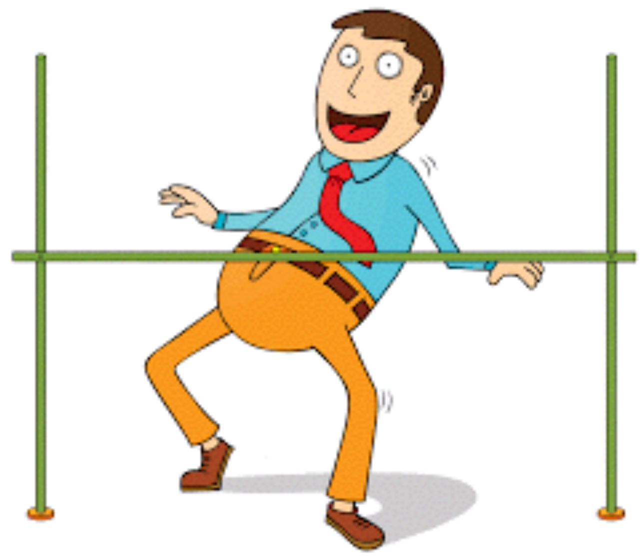
$$\alpha_t = \frac{3m_t^2}{4\pi^2 v^2}, \quad \alpha_g = -\frac{6m_W^2 + 3m_Z^2}{16\pi^2 v^2}, \quad \alpha_h = -\frac{3m_h^2}{16\pi^2 v^2}$$

(One) Measure of fine tuning: $D_i(m_h) \equiv \left| \frac{\partial \log m_h^2}{\partial \log \Lambda_i^2} \right| = \frac{|\alpha_i| \Lambda_i^2}{m_h^2}$

No guaranteed discovery, unlike Higgs mechanism

Should not stop us looking!!

Hierarchy (Naturalness) problem



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Supersymmetry…a BSM case study

Bosons ⟷ Fermions

(more than) Doubling of the spectrum

SM Field	$SU(3)$	$SU(2)$	$U(1)$	MSSM partner	Superfield
q_i (LH quarks)	3	2	$\frac{1}{6}$	$\tilde{q}_i$ (LH squarks)	Q_i
u_i^c (RH top, charm, up)	$\bar{3}$	1	$-\frac{2}{3}$	$\tilde{u}_i^c$ (RH stop, scharm, sup)	U_i^c
d_i^c (RH bottom, strange, down)	$\bar{3}$	1	$\frac{1}{3}$	$\tilde{d}_i^c$ (RH sbottom, sstrange, sdown)	D_i^c
ℓ_i (LH leptons)	1	2	$-\frac{1}{2}$	$\tilde{\ell}_i$ (LH sleptons)	L_i
e_i^c (RH tau, muon, electron)	1	1	1	$\tilde{e}_i^c$ (RH stau, smuon, selectron)	E_i^c
h_u (h_d) (up-type (down-type) Higgs)	1	2	$\frac{1}{2}$ $(-\frac{1}{2})$	$\tilde{h}_u$ $\left(\tilde{h}_d\right)$ (up-type (down-type) higgsino)	H_u (H_d)
gluino	8	1	0	gluino	
W/Z	1	3	0	Wino/Zino	
B/photon	1	1	0	bino/photino	

Superpartners have the same couplings as SM partners

If SUSY (softly) broken they have different masses

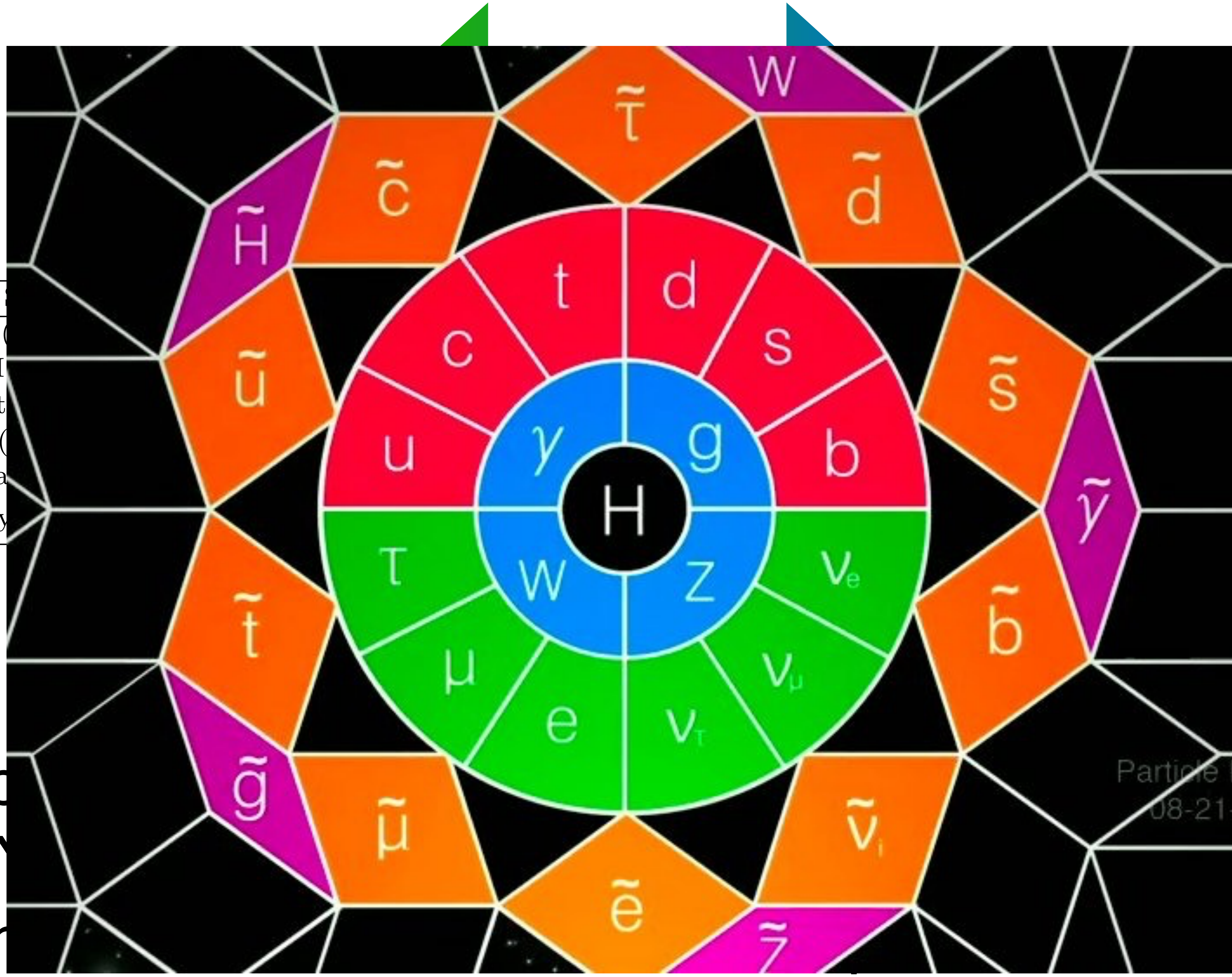
Many new interactions…>100 new parameters!

Many constrained by flavour, CP-violation

SUSY breaking models (GMSB, AMSB ,….) predict relations

Supersymmetry…a BSM case study

	Superfield
q_i (	Q_i
u_i^c (RH	U_i^c
d_i^c (RH bot	D_i^c
ℓ_i (	L_i
e_i^c (RH ta	E_i^c
h_u (h_d) (up-ty)	H_u (H_d)



Superp … artners
If SUSY … s
Many r

Many constrained by flavour, CP-violation
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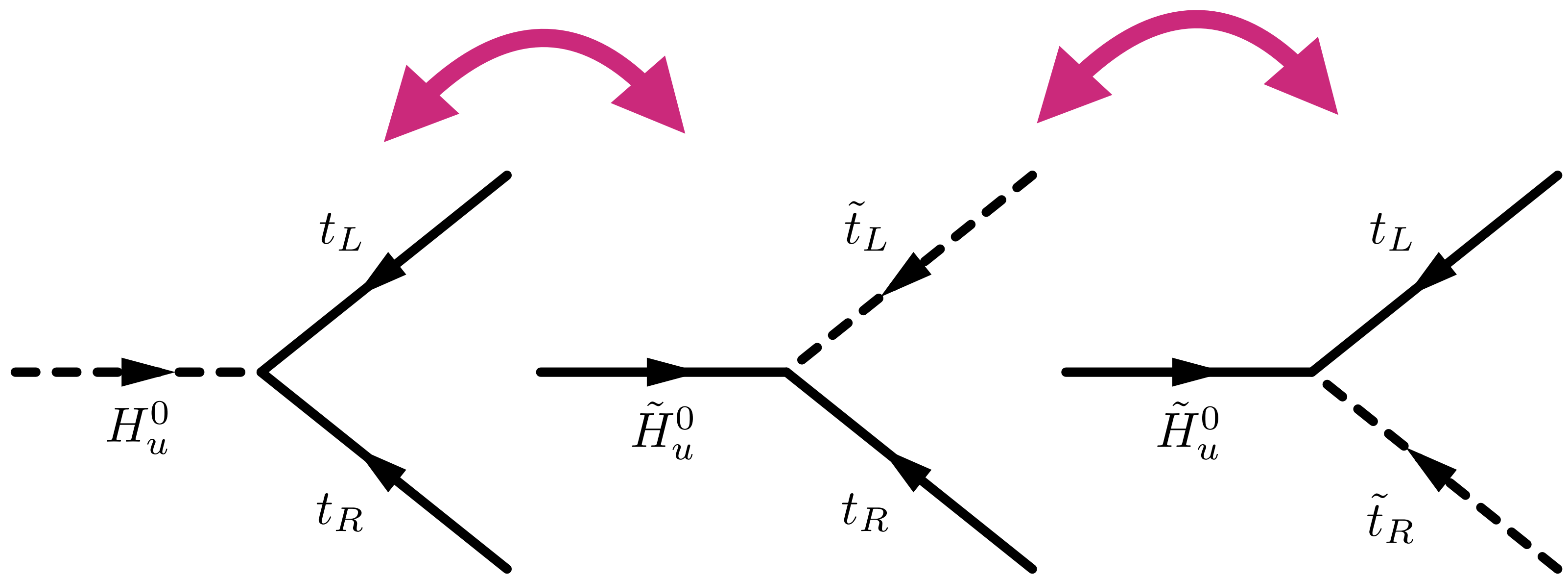
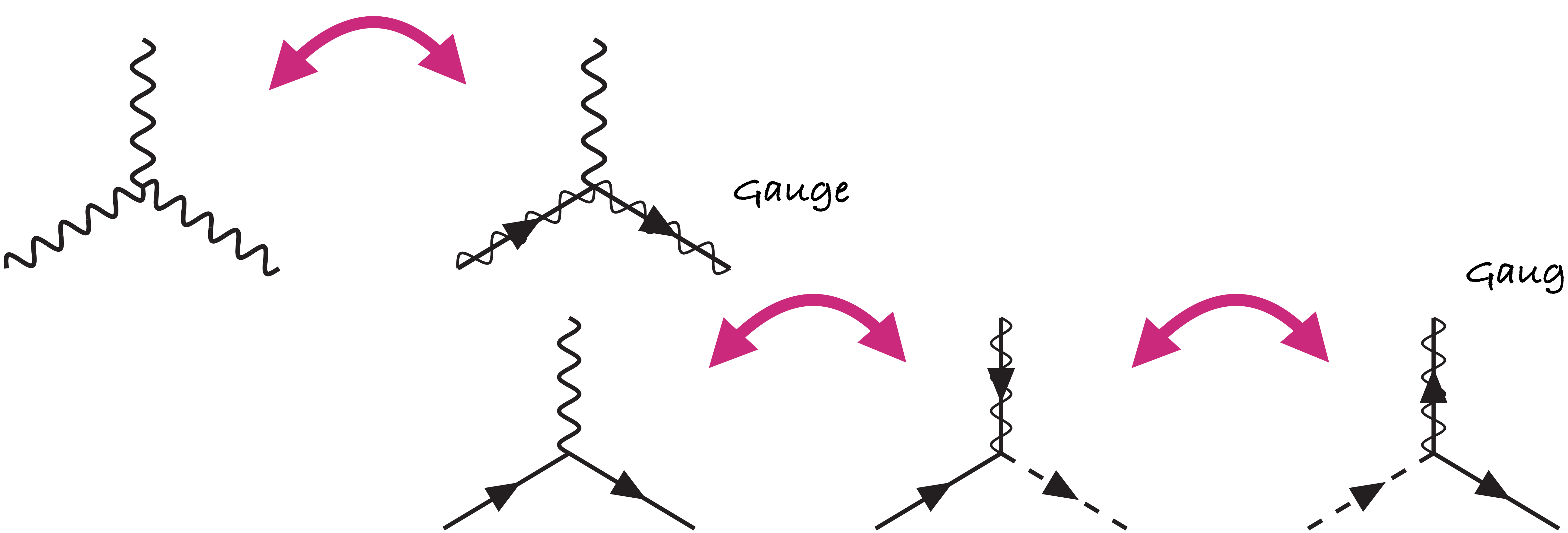
Supersymmetry

$$W_{MSSM} = \mathbf{Y_U} U^c Q H_u - \mathbf{Y_D} D^c Q H_d - \mathbf{Y_E} E^c L H_d + \mu H_u H_d$$

Flip two



Yukawa



Supersymmetry

Extended Higgs sector
Higgs modifications

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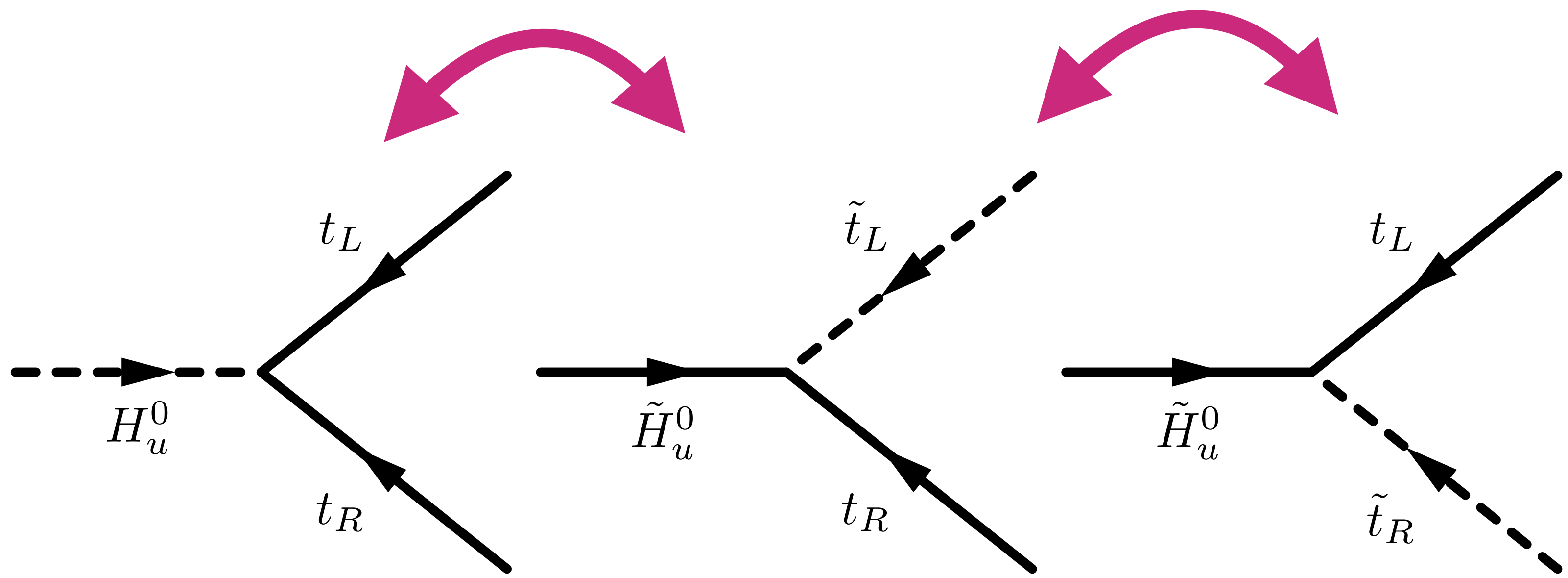

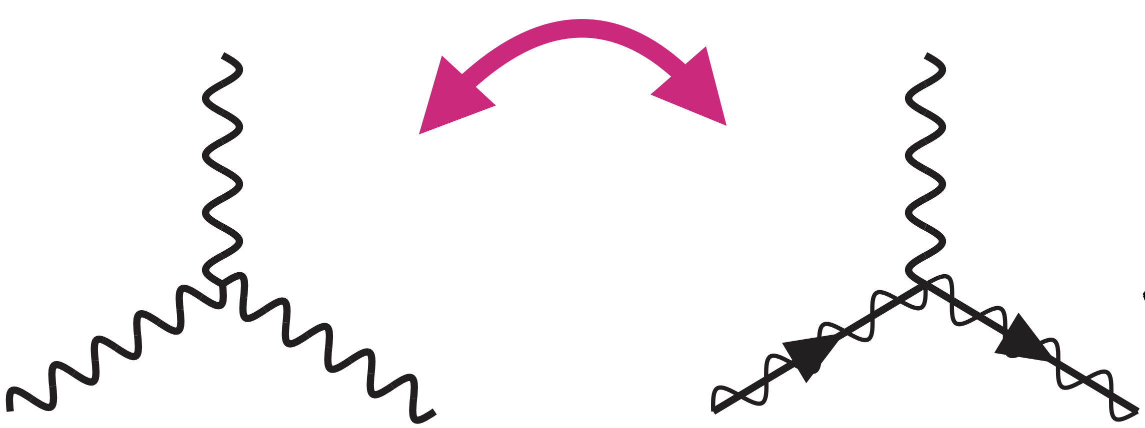

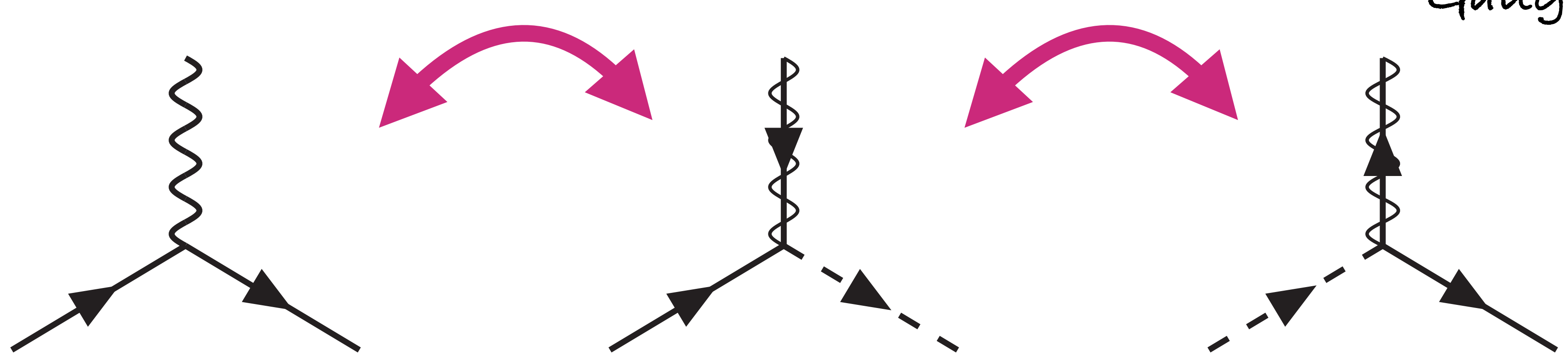

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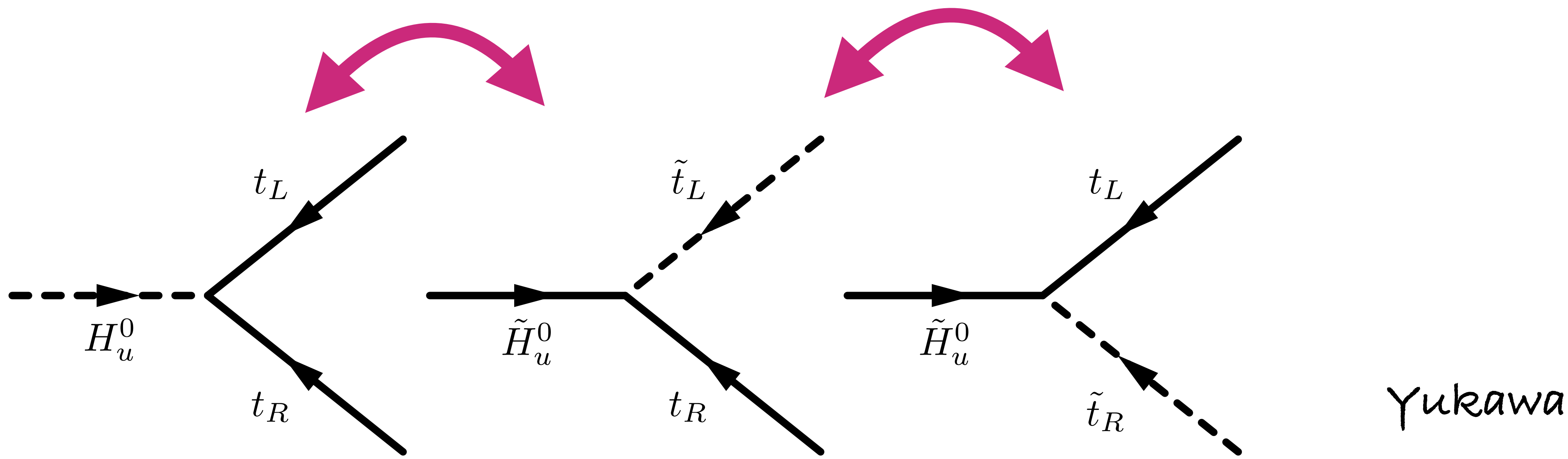

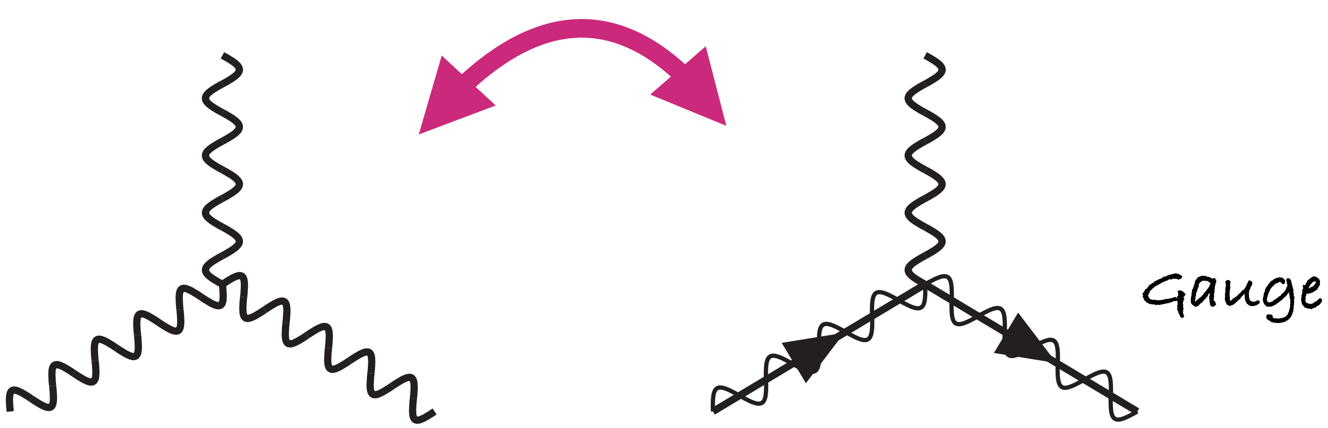

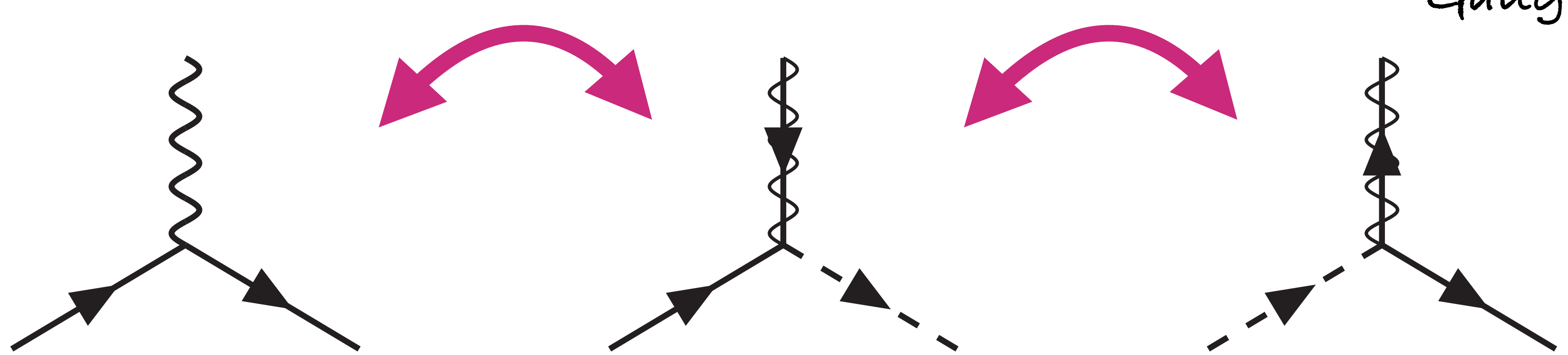

Supersymmetry

New fields allow for new interactions (EFT philosophy)

$$\overset{\Delta L = 1}{} \qquad \overset{\Delta L = 1}{} \qquad \overset{\Delta L = 1}{} \qquad \overset{\Delta B = 1}{}$$

$$W_{\Delta B,L} = \cancel{\kappa_1^{ijk} Q_i L_j D_k^c} + \cancel{\kappa_2^{ijk} L_i L_j E_k^c} + \cancel{\kappa_3^{i} L^i H_u} + \cancel{\kappa_4^{ijk} D_i^c D_j^c U_k^c}$$

Proton lifetime: $\Gamma \sim \frac{\kappa_1 \kappa_4}{16\pi} \frac{m_p^5}{m_{\tilde{q}}^4}$ $\qquad \kappa < 10^{-12}!$

Forbid these (RPV) operators with a parity (R-parity)

$$SM \to SM \qquad\qquad BSM \to -BSM$$

LPOP

1. SM and partners don't mix
2. SUSY states pair produced
3. Lightest parity odd particle stable (DM?)

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More later....

Supersymmetry

Complicated spectrum, details depend on model

GMSB, Effective/Natural SUSY, Dirac gauginos….

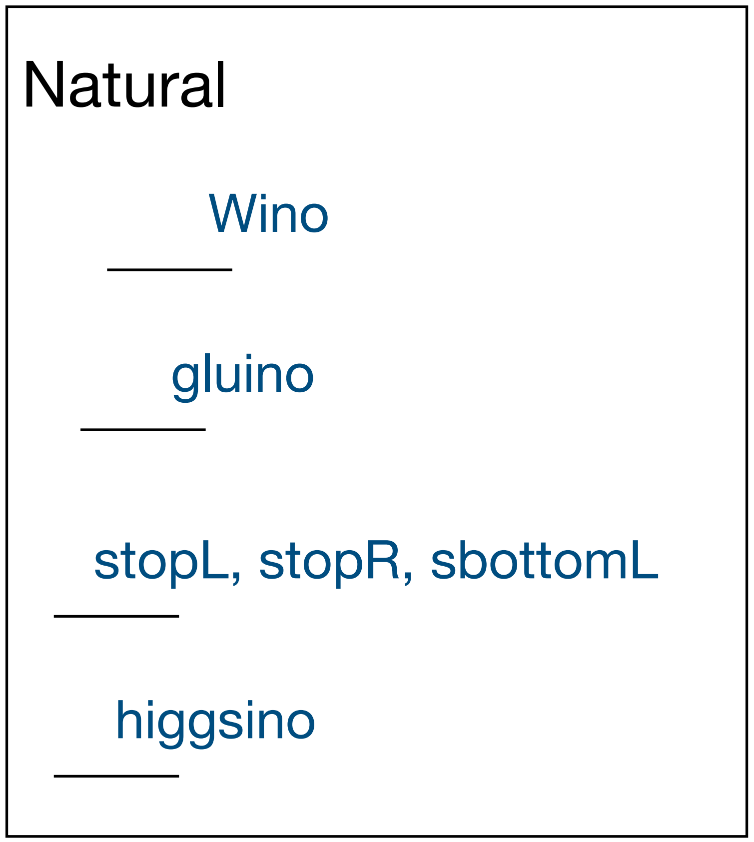
Many, many interesting collider signatures

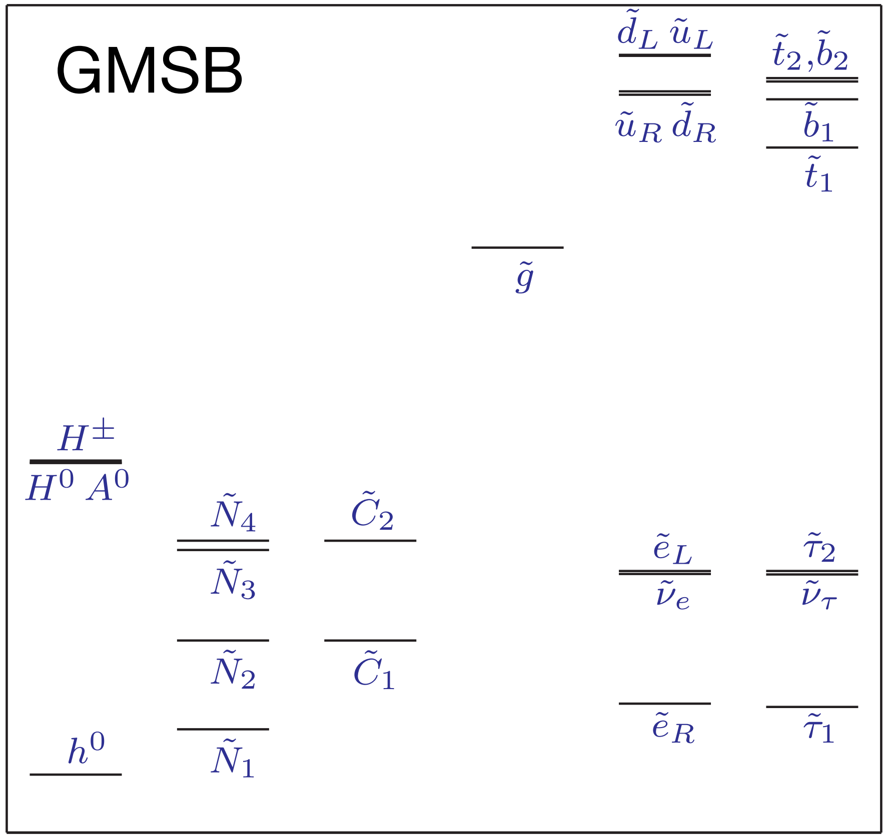
Lightest coloured states made first, decays involve MET

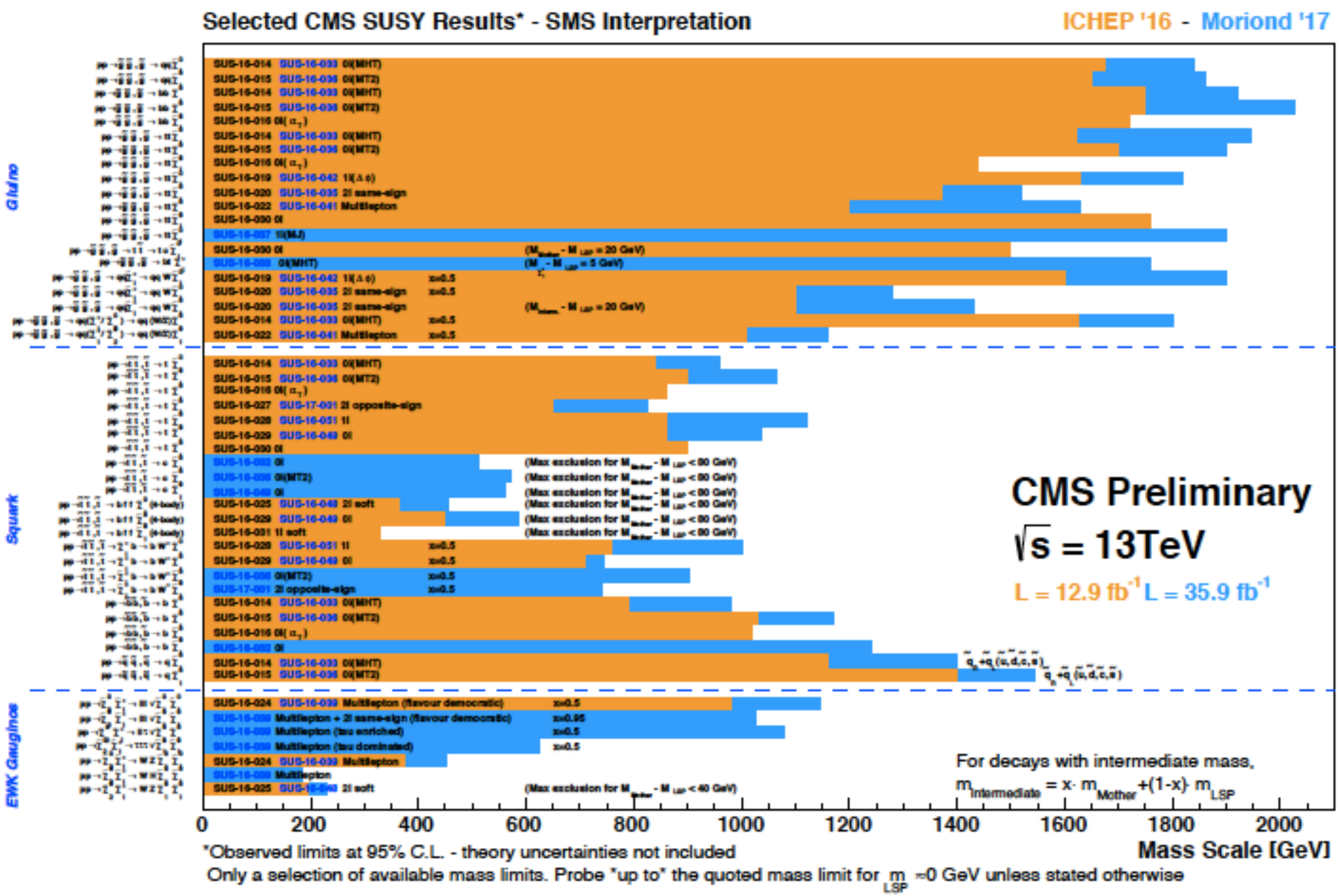
Compressed/Stealth spectra can hide SUSY (a little)

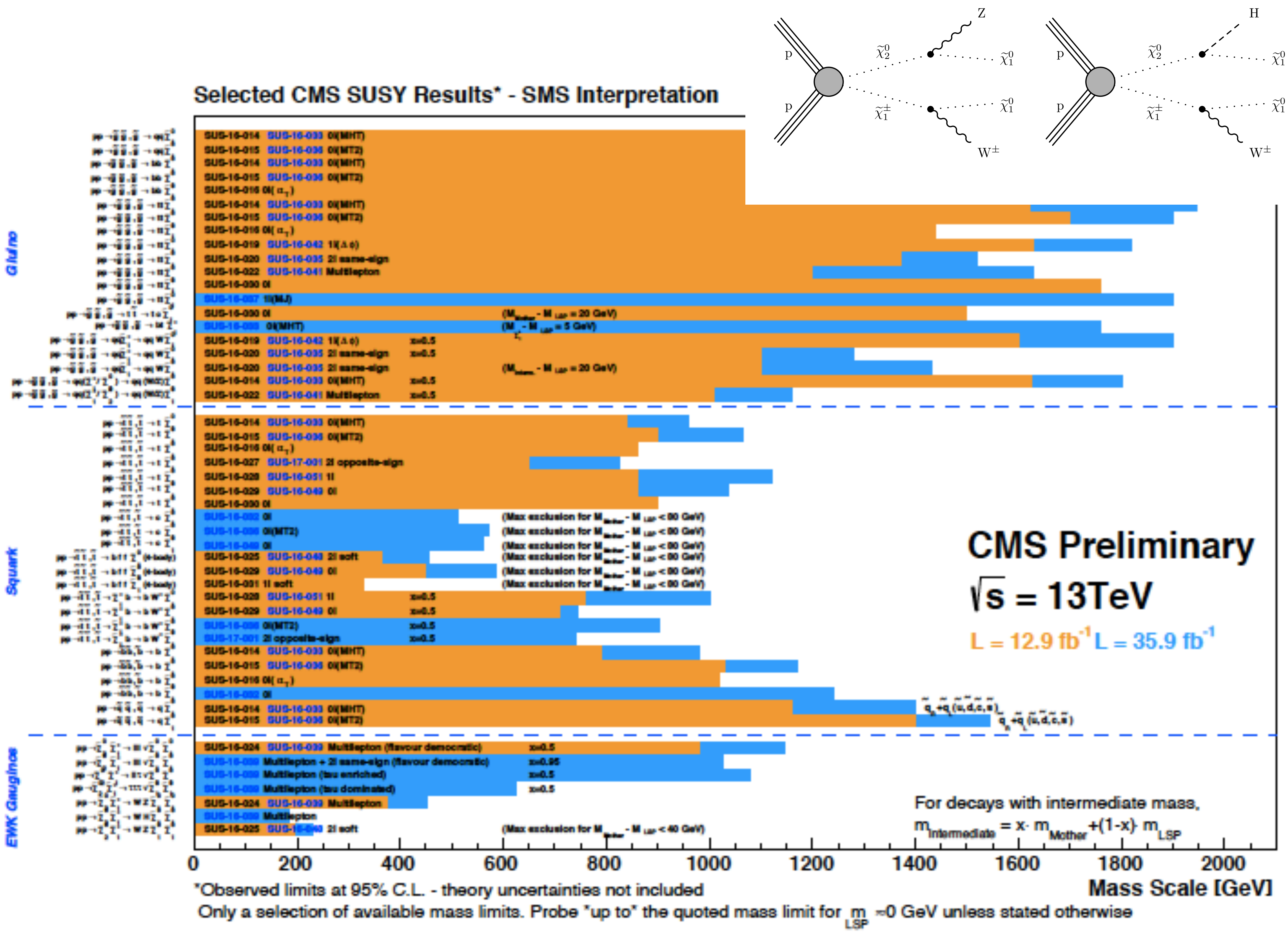
Electroweakino sector starting to be probed (DM)

SUSY is a great signal generator






Selected CMS SUSY Results* - SMS Interpretation
ICHEP '16 - Moriond '17
Gluino
Squark
EWK Gauginos
CMS Preliminary
√s = 13TeV
L = 12.9 fb⁻¹ L = 35.9 fb⁻¹
For decays with intermediate mass,
m_Intermediate = x· m_Mother +(1-x)· m_LSP
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Mass Scale [GeV]
*Observed limits at 95% C.L. - theory uncertainties not included
Only a selection of available mass limits. Probe "up to" the quoted mass limit for m_LSP ≈0 GeV unless stated otherwise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0 200 400 600 800 1000 1200 1400 1600 1800 2000
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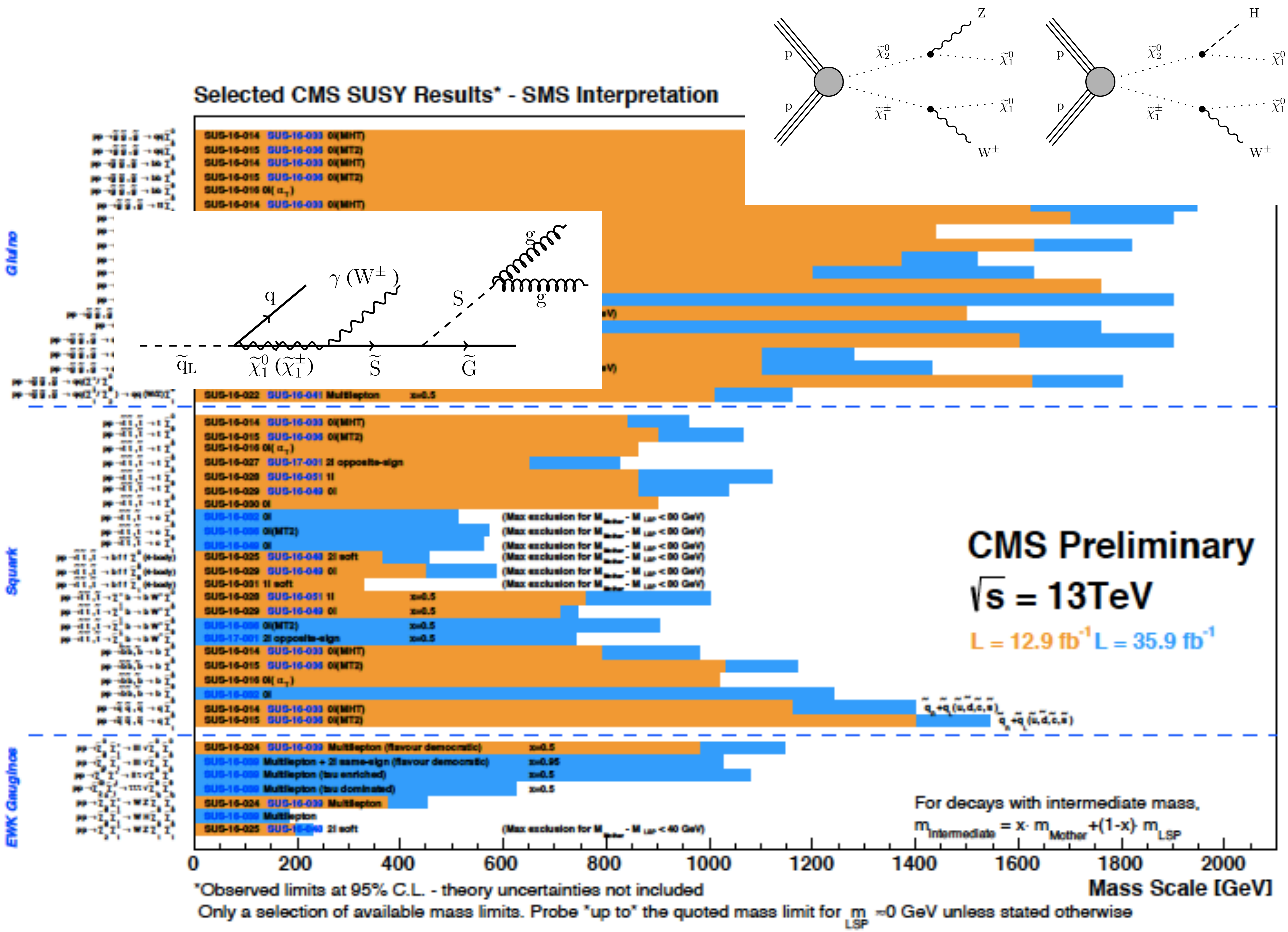

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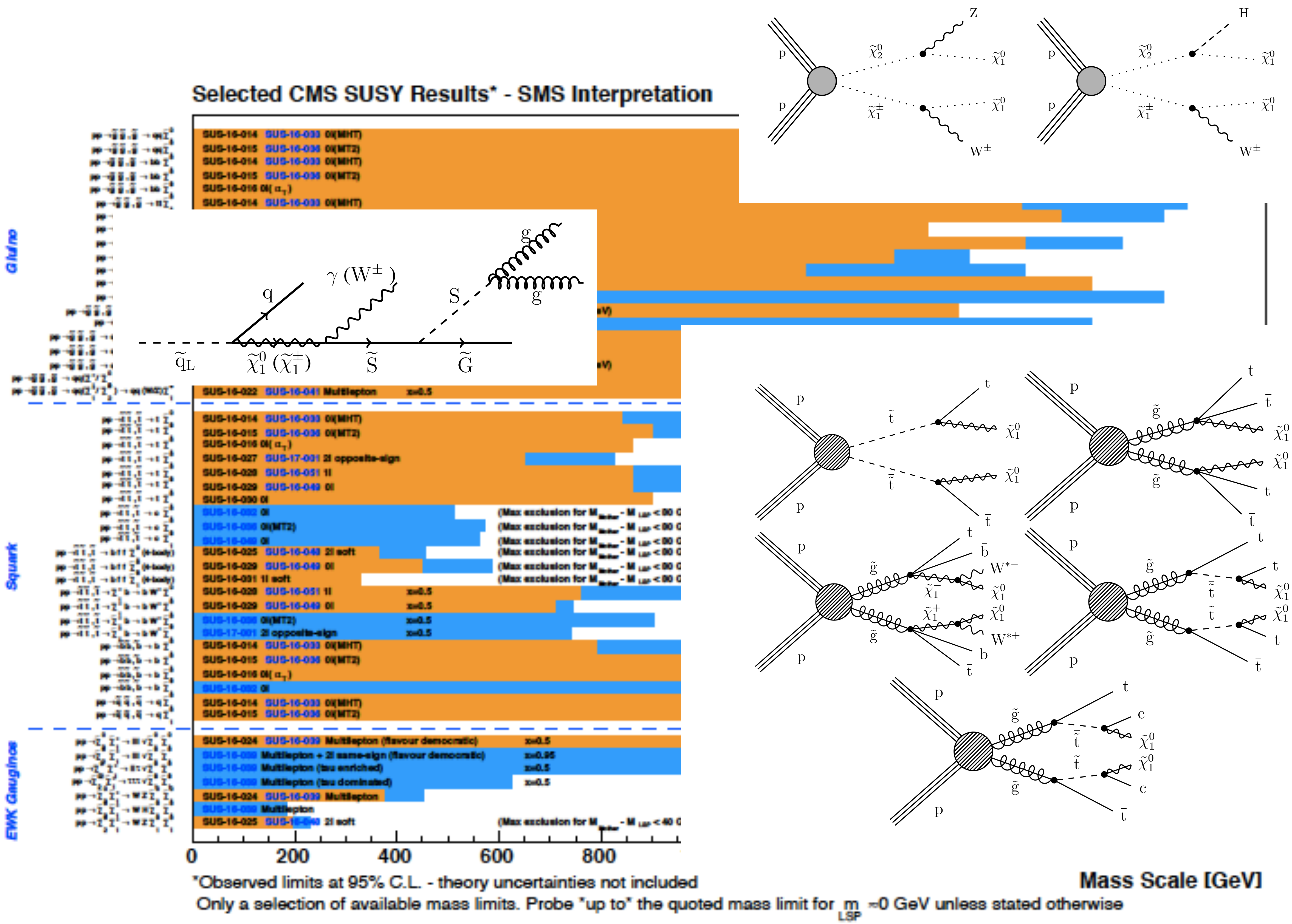
p
p
Z
H
W±
q
γ (W±)
S
g



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General BSM lessons

Top partners (fermions/bosons)
Higgs sector modifications
LPOPs, parity, DM, MET
Extra matter in fundamental and adjoint reps.

New gauge groups?
Lighter, more weakly coupled particles?
Resonances?

General BSM lessons

Composite Higgs

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Randall Sundrum

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Little Higgs

Twin Higgs

[Chacko, Goh, Harnik]

$\mathrm{SM}_A \times \mathrm{SM}_B \times \mathbb{Z}_2$

$$\mathcal{L} \supset y\, Q_A H_A U_A^c + y\, Q_B H_B U_B^c$$

Higgs is a PNGB, and Higgs potential is O(8) symmetric

$$V = -m^2 H^\dagger H + \lambda \left(H^\dagger H\right)^2$$

$O(8) \to O(7)$:7 Goldstone bosons, 3 eaten by B gauge bosons

$$H = \begin{pmatrix} H_A \\ H_B \end{pmatrix} = e^{i h^a t^a / f} \begin{pmatrix} 0 \\ 0 \\ 0 \\ f \end{pmatrix}$$

Twin Higgs

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Twin Higgs

Gauge and Yukawa interactions explicitly break the O(8)

Mass for Higgs?

$$\frac{3}{8\pi^2}\Lambda^2\left(y_A^2 H_A^\dagger H_A + y_B^2 H_B^\dagger H_B\right)$$

$$Z_2 \Rightarrow y_A = y_B$$

$$\frac{3}{8\pi^2}\Lambda^2 y^2 H^\dagger H$$

Loop corrections to mass is O(8) symmetric, does not lead to *quadratically divergent* Higgs mass

EFT aside

Low energy degrees of freedom, non-linearly realized symm.

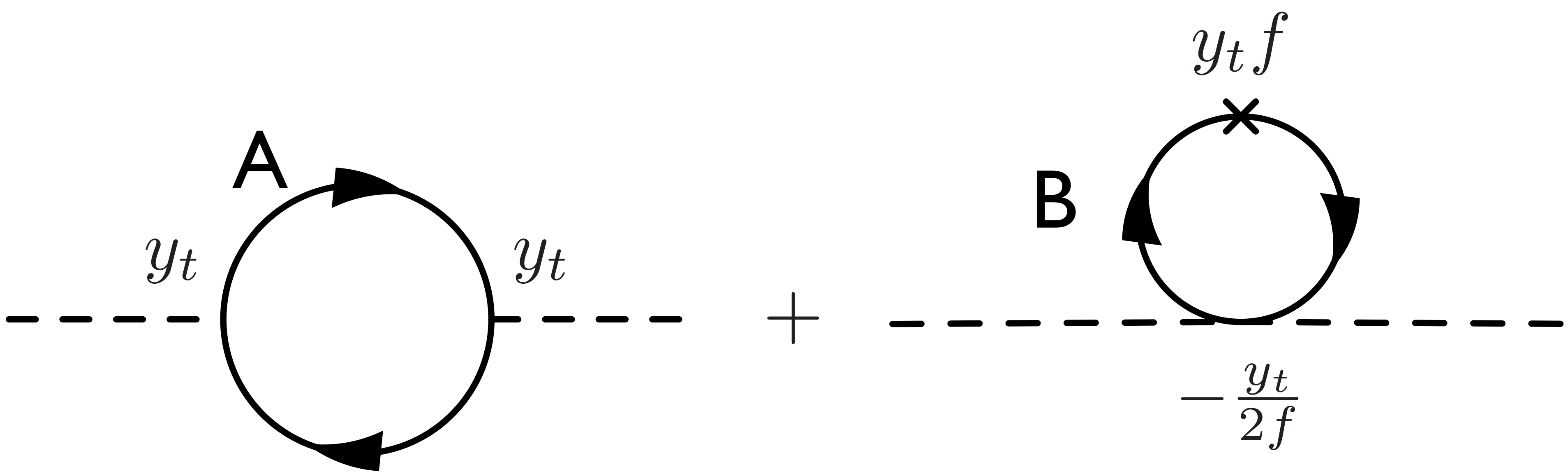
$$H = \begin{pmatrix} H_A \\ H_B \end{pmatrix} = e^{i h^a t^a / f} \begin{pmatrix} 0 \\ 0 \\ 0 \\ f \end{pmatrix}$$

$$\vdots$$

$$H = \begin{pmatrix} \mathbf{h} \frac{i f}{\sqrt{\mathbf{h}^\dagger \mathbf{h}}} \sin \frac{\sqrt{\mathbf{h}^\dagger \mathbf{h}}}{f} \\ 0 \\ f \cos \frac{\sqrt{\mathbf{h}^\dagger \mathbf{h}}}{f} \end{pmatrix} = \begin{pmatrix} i\mathbf{h} \\ 0 \\ f - \frac{1}{2f} \sqrt{\mathbf{h}^\dagger \mathbf{h}} \end{pmatrix} + \ldots$$

Top sector

$$\mathcal{L} \sim y\, Q_A H U_A^c + y\, Q_B \left(f - \frac{|H|^2}{2f^2} \right) U_B^c$$



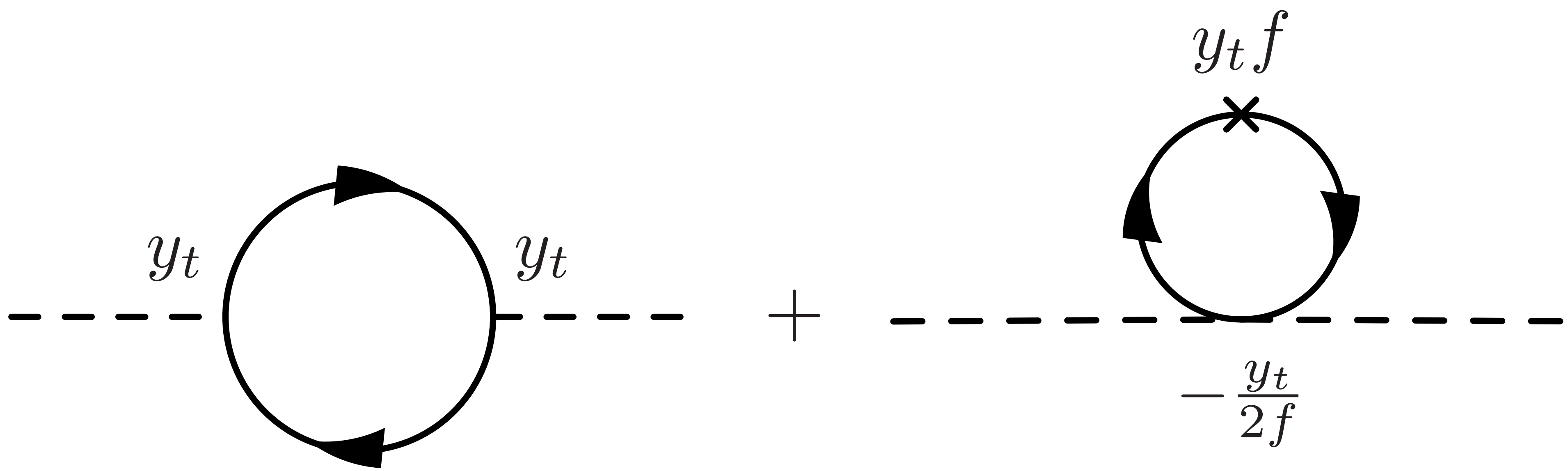
Quadratic divergences cancel, states running in loop have no SM charge, same spin

(3 is just a number)

Cancelling states not coloured: small production x-sec at LHC

To separate v and f and make the SM Higgs lie mostly in A introduce soft breaking $\mu_A^2 |H_A|^2$

$$\langle H_A \rangle = v_{SM} \ll \langle H_B \rangle = f \sim 1\,\mathrm{TeV}$$



Tuning grows with f/v

$$\delta m_h^2 \sim \frac{3 y_t m_t^2}{4\pi^2} \left(\frac{f}{v} \right)^2 \log \frac{\Lambda v}{m_t f}$$

$$\Delta = \left| \frac{2 \delta m_h^2}{m_h^2} \right|^{-1}$$

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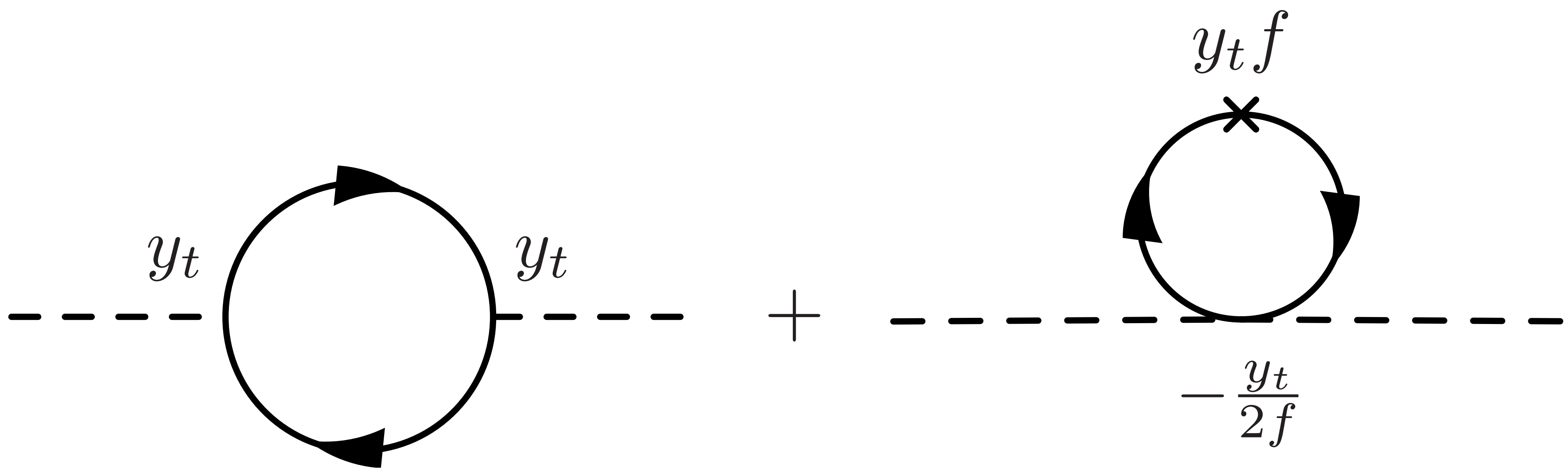

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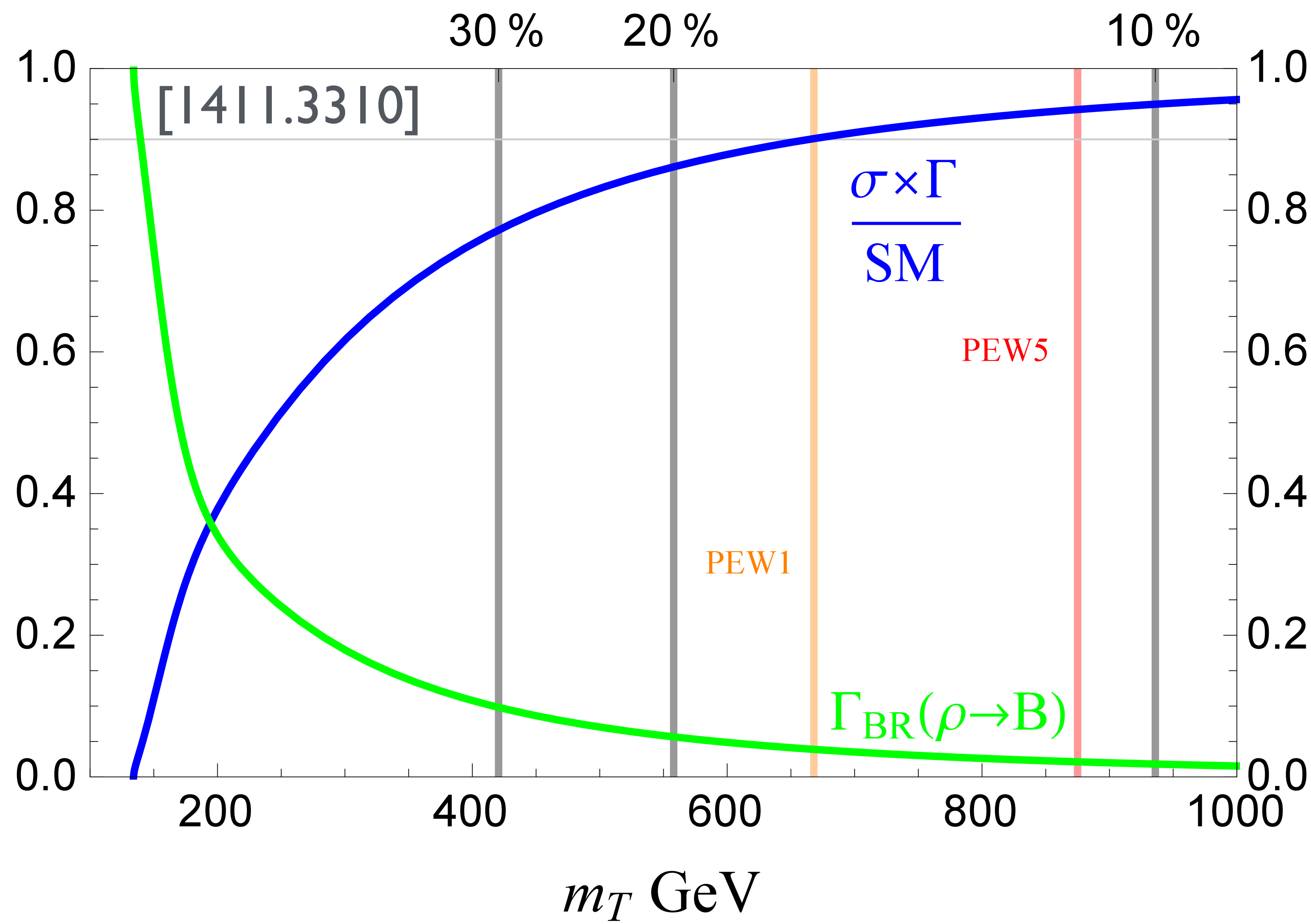
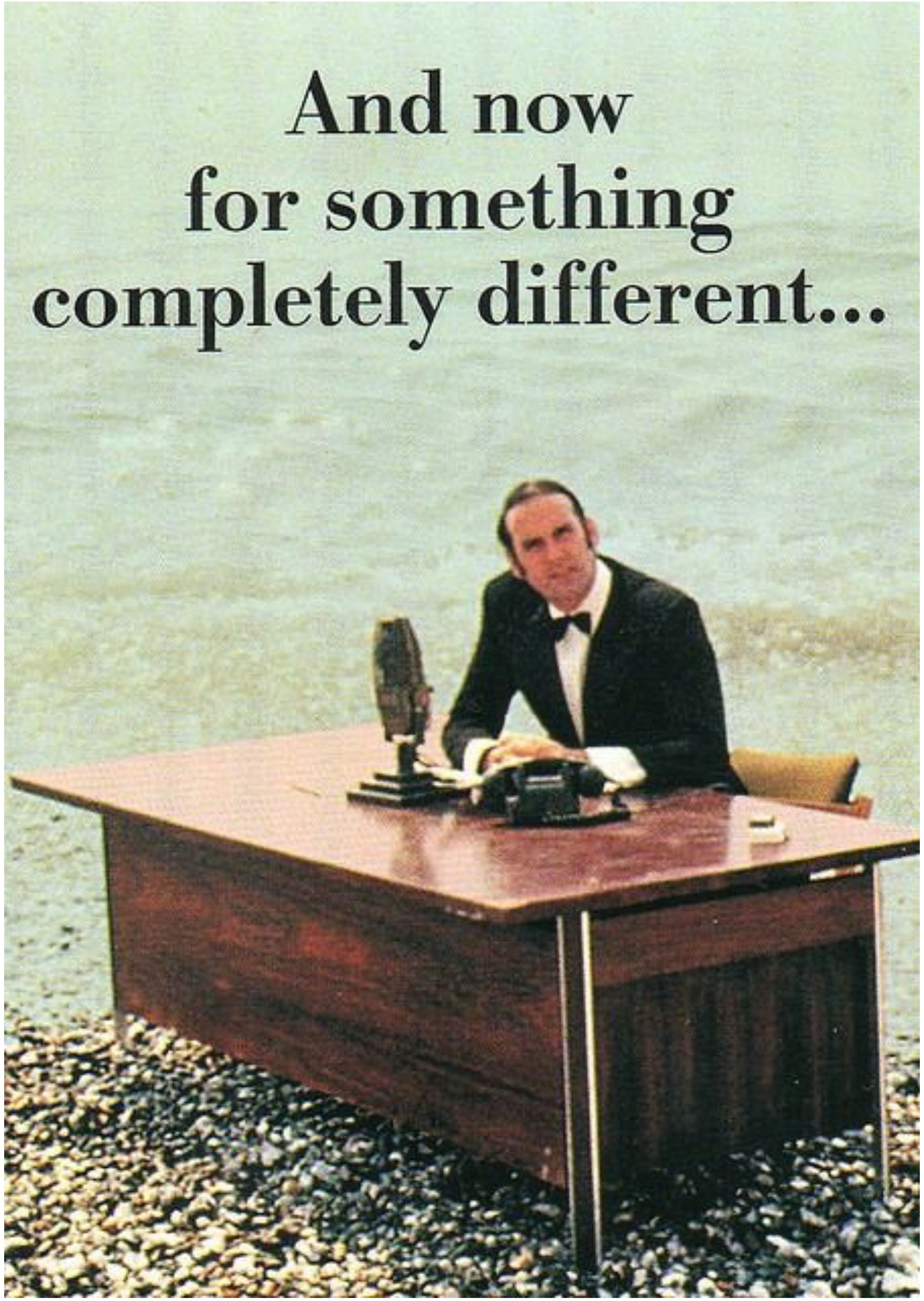
f/v~3-5

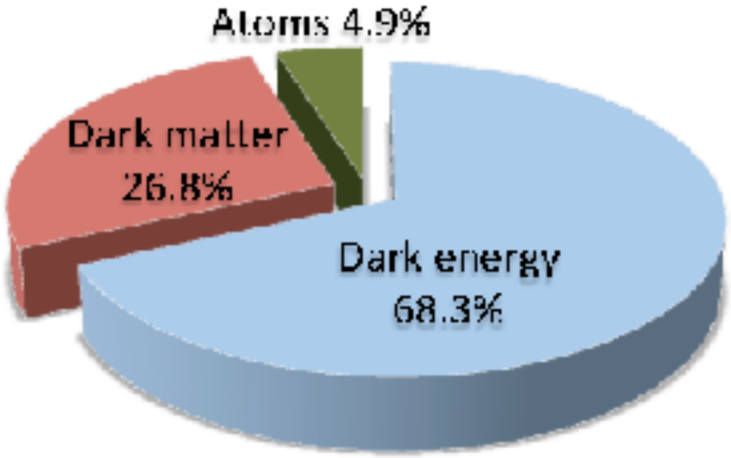
$$V = -m^2\left(H_A^\dagger H_A + H_B^\dagger H_B\right) + \lambda\left(H_A^\dagger H_A + H_B^\dagger H_B\right)^2$$

Higgs portal between A and B sectors

- Higgs mixing and corrections to Higgs pheno at $\frac{v^2}{f^2}$
- Higgs invisible decay width, to light B sector stuff




And now
for something
completely different...


Atoms 4.9%
Dark matter
26.8%
Dark energy
68.3%

“You spin me right round…”

Fritz Zwicky

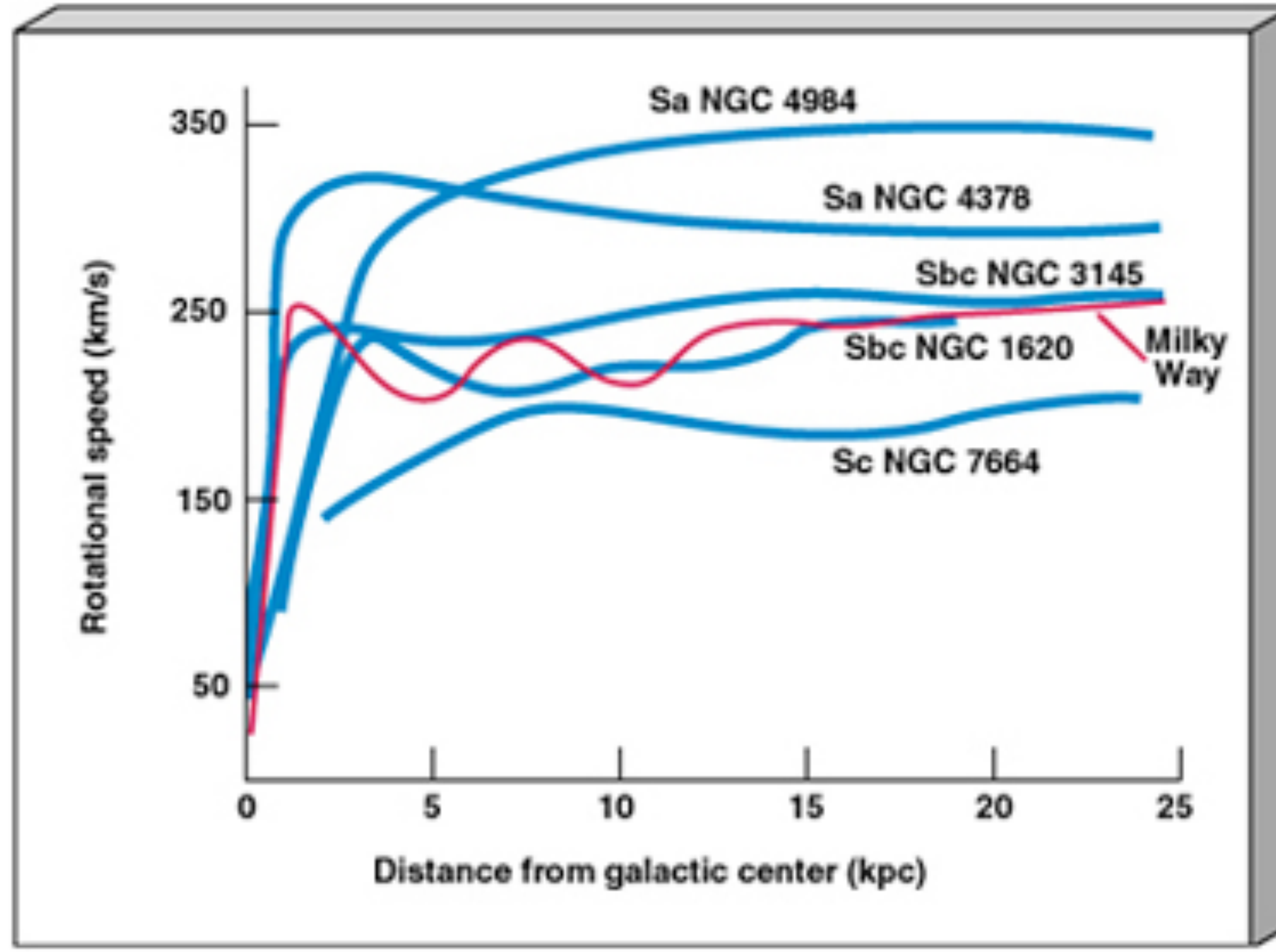
Coma Cluster

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

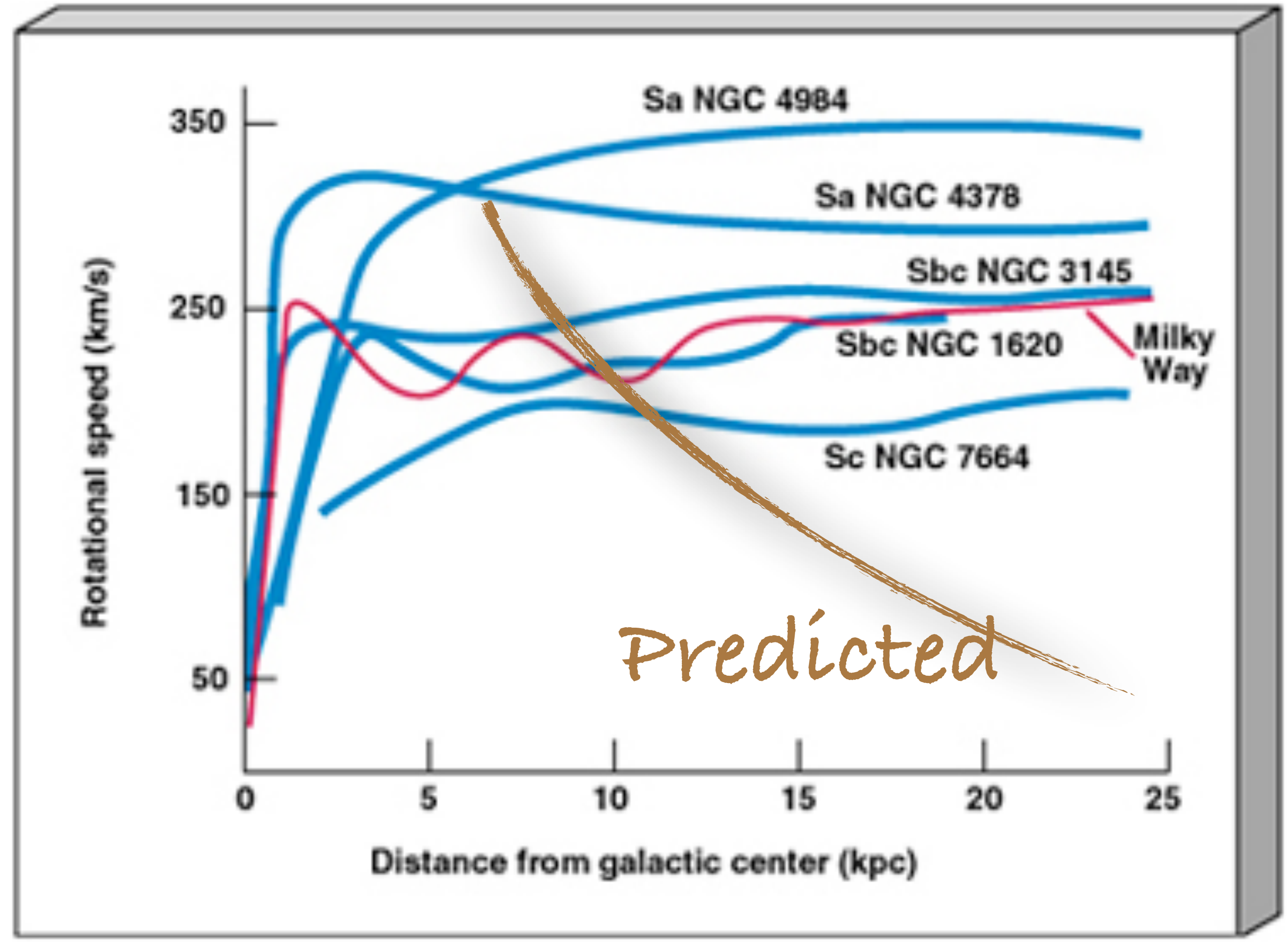
Vera Rubin



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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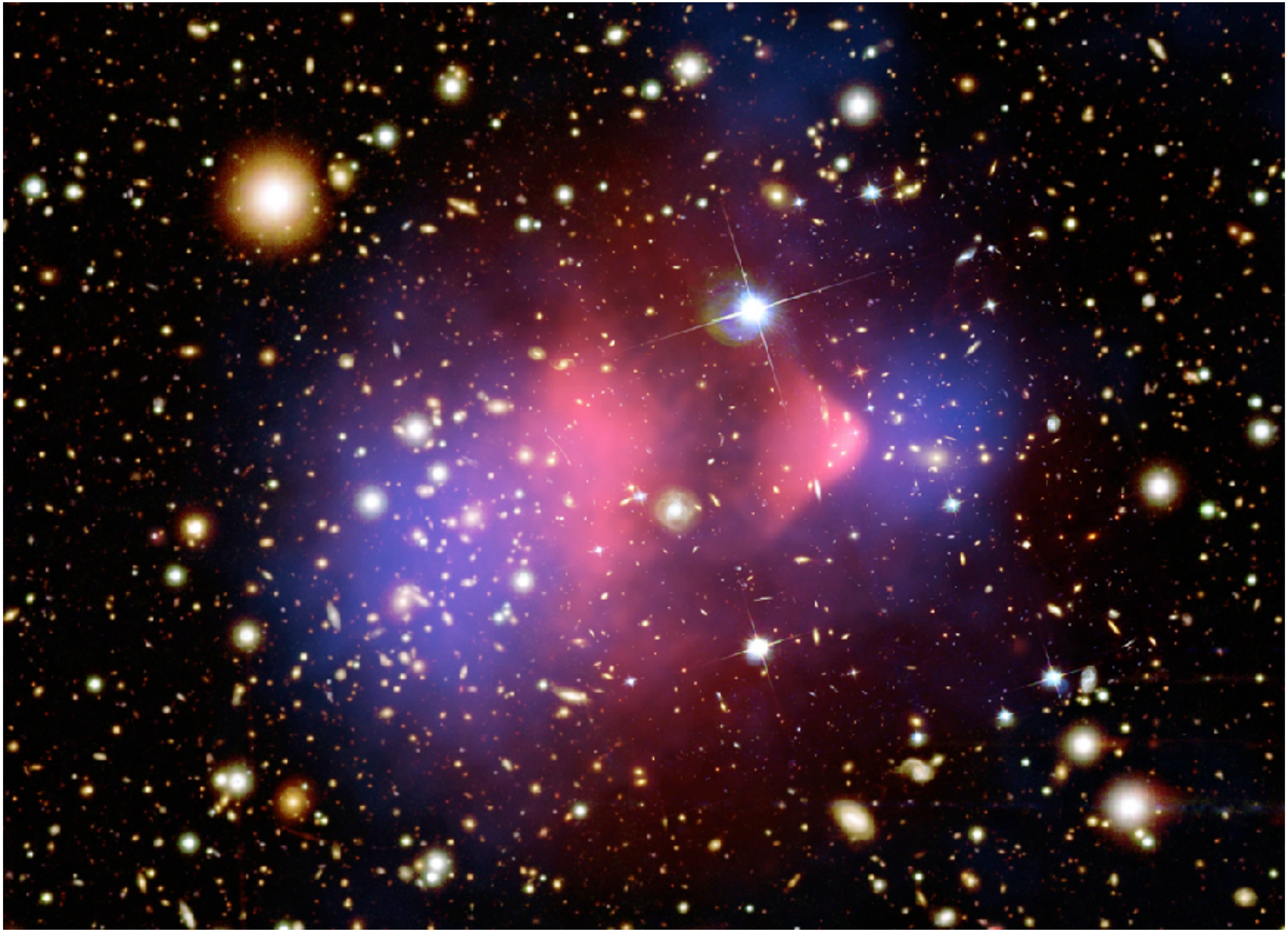
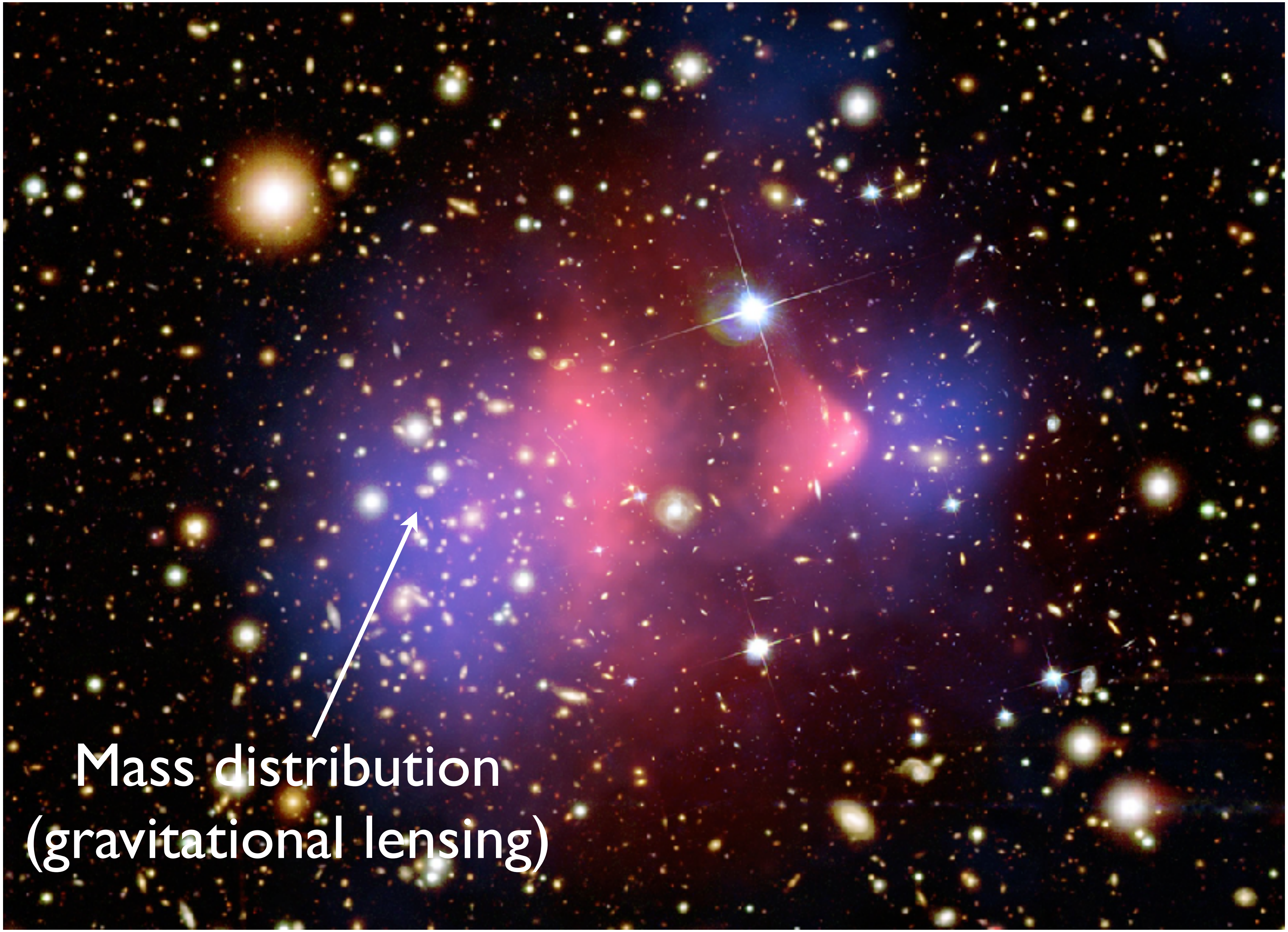
Evidence for Dark Matter



The Bullet Cluster

Evidence for Dark Matter



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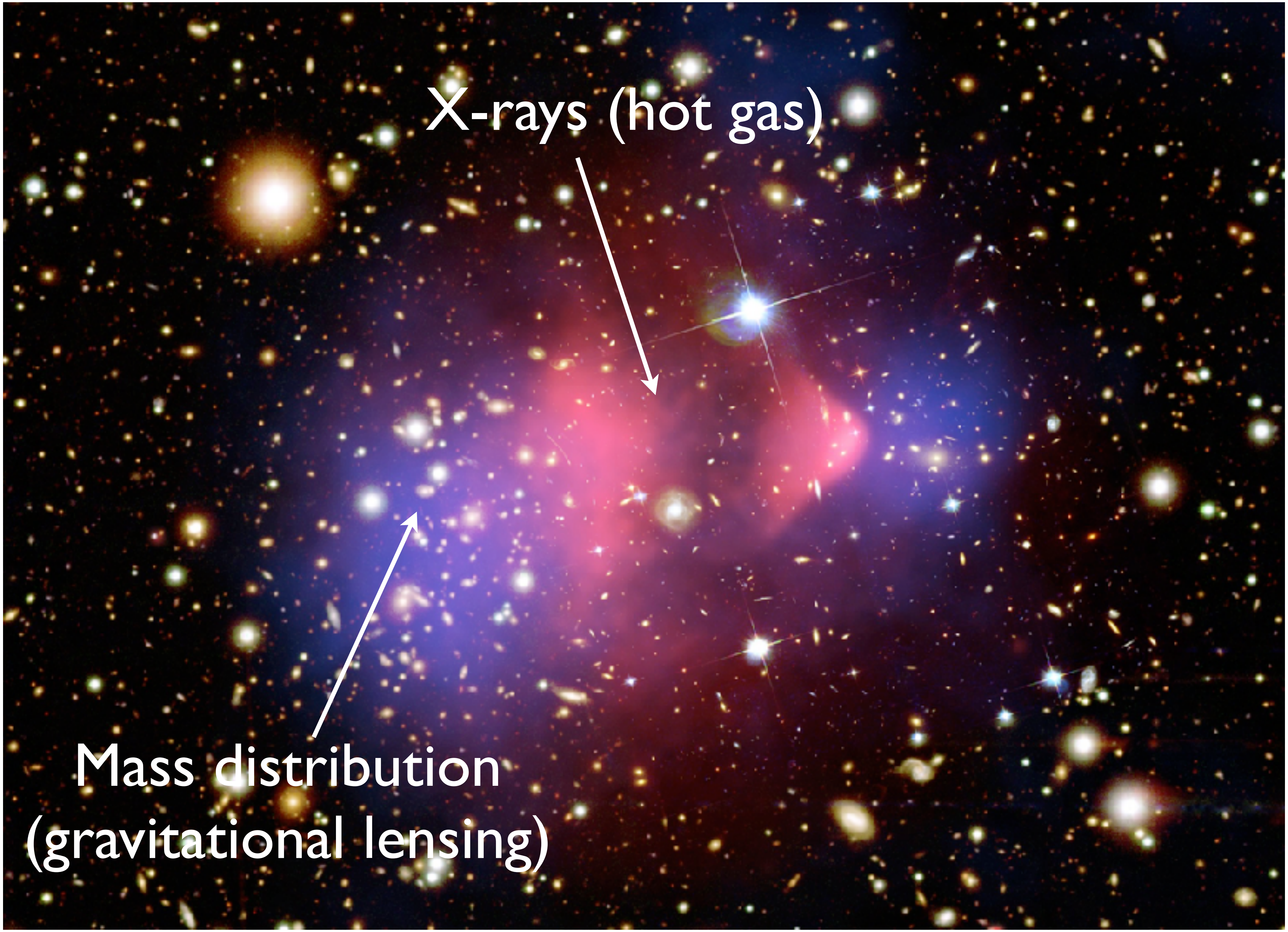

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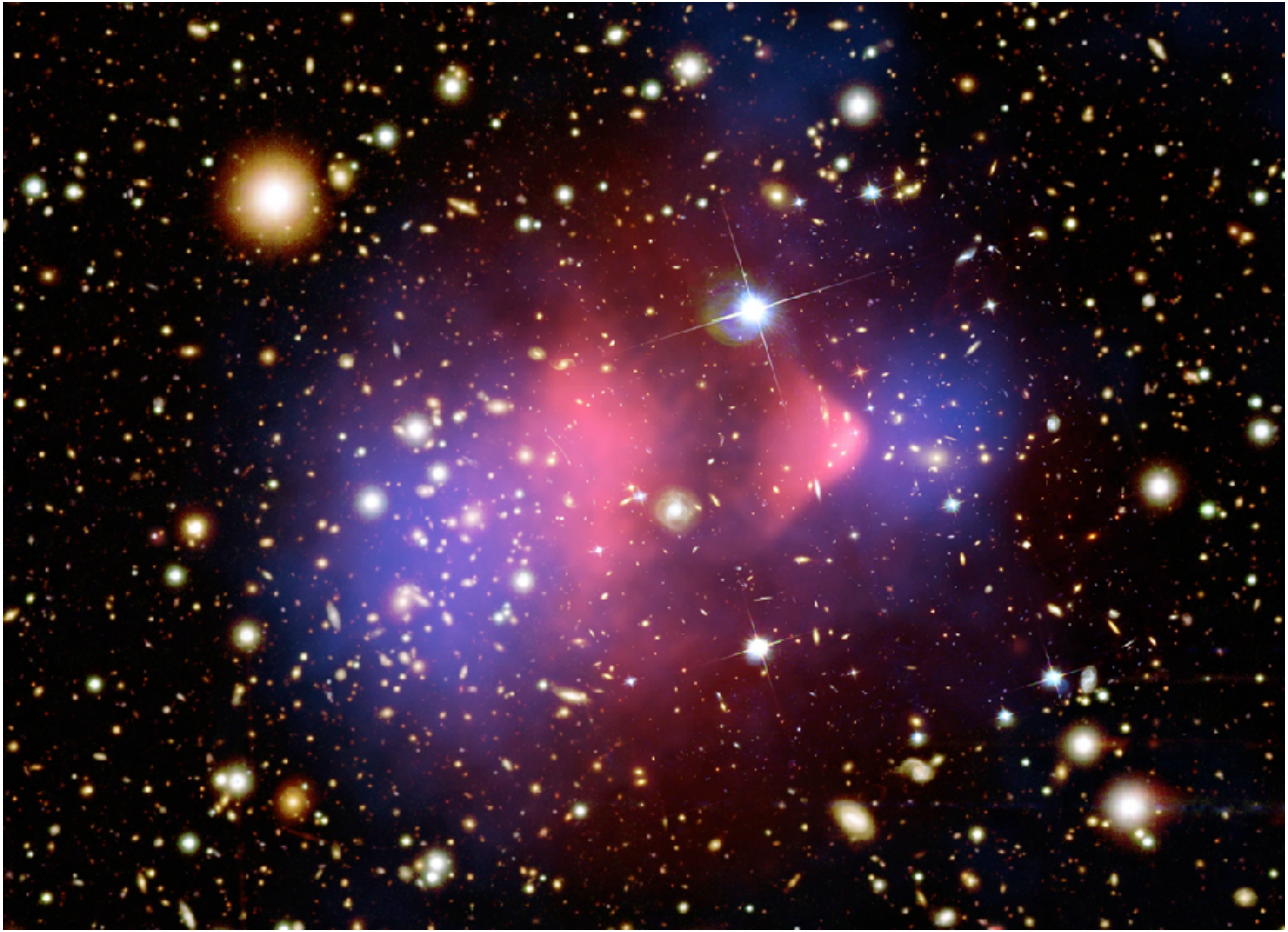

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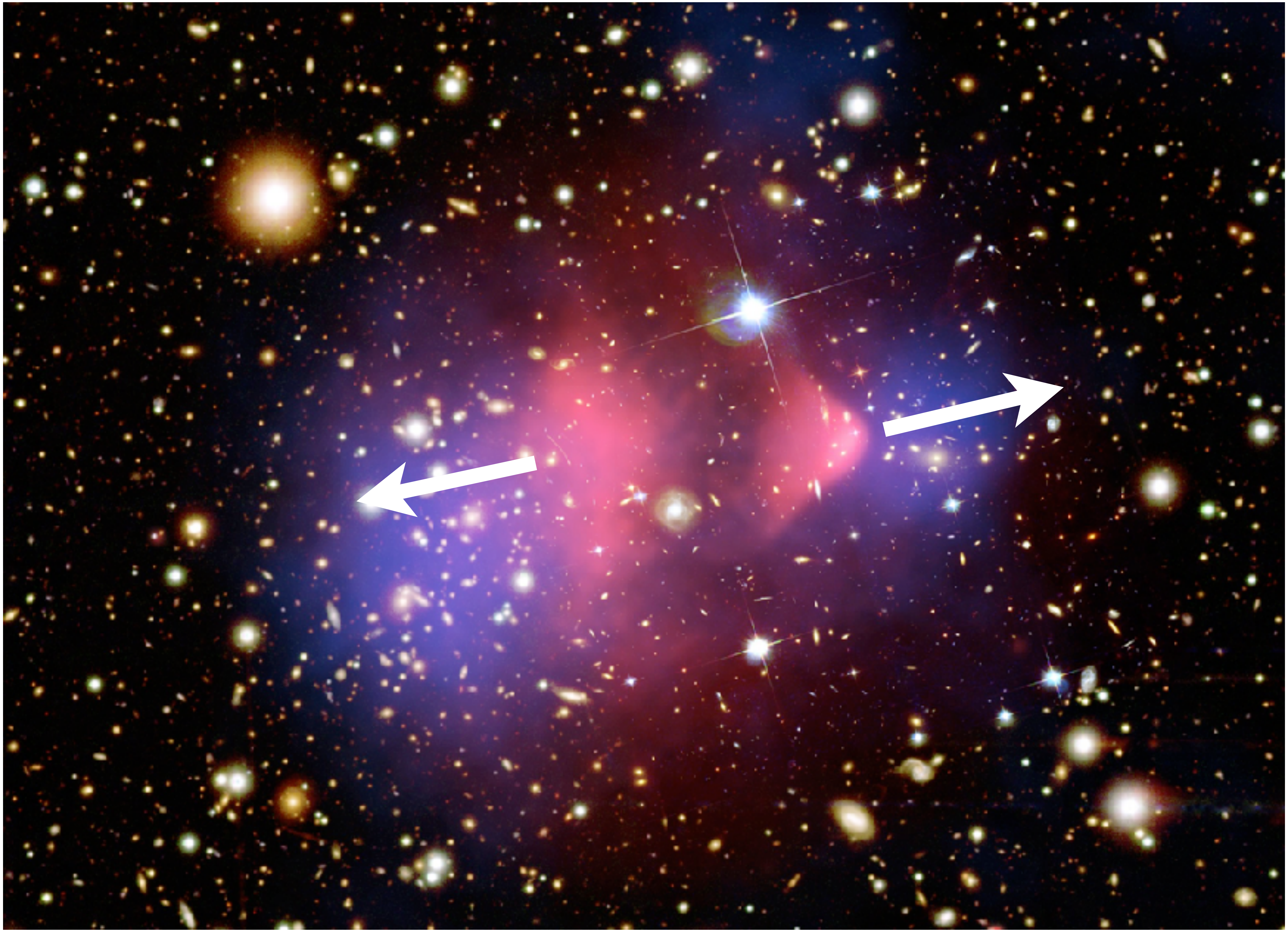

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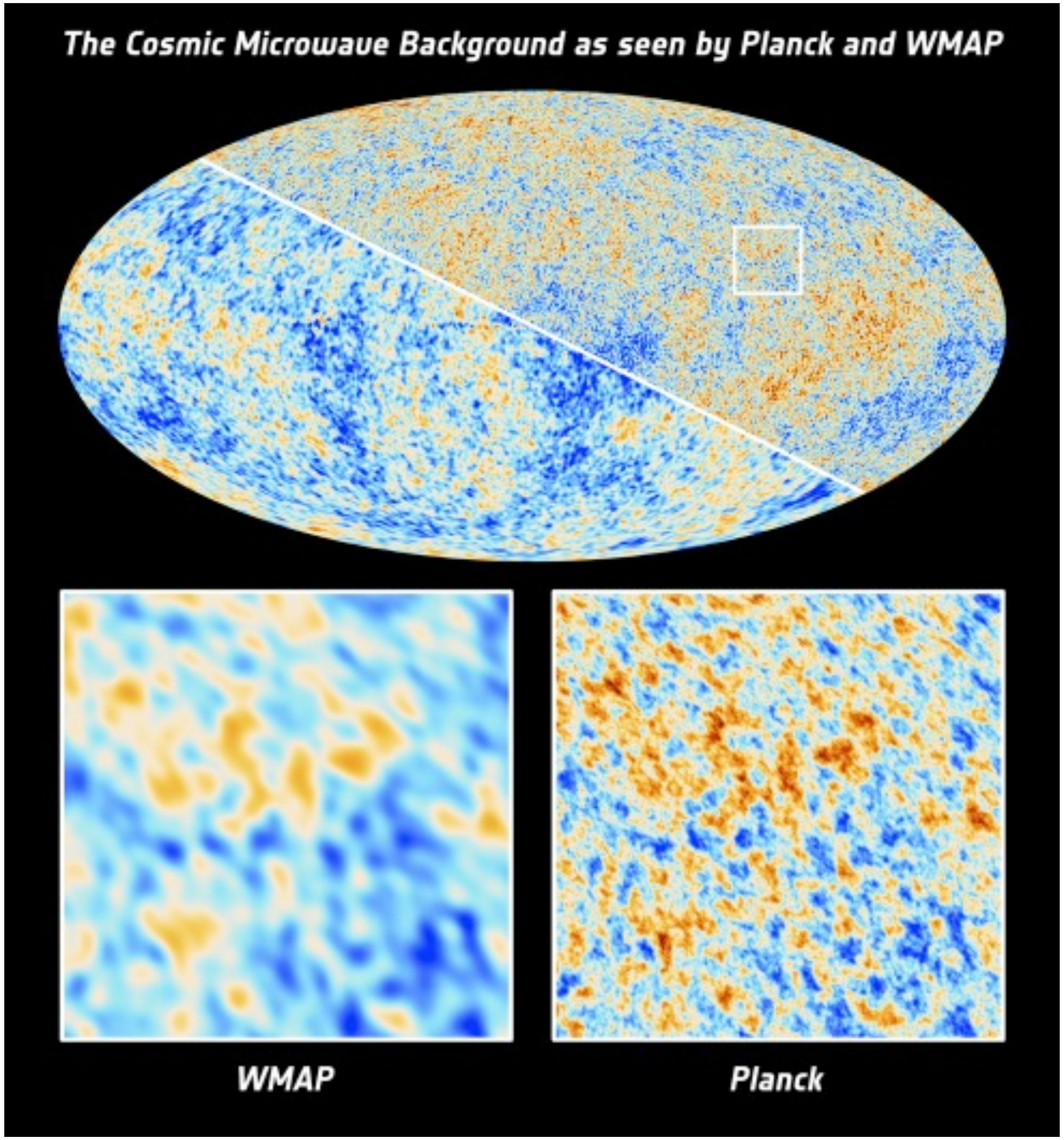
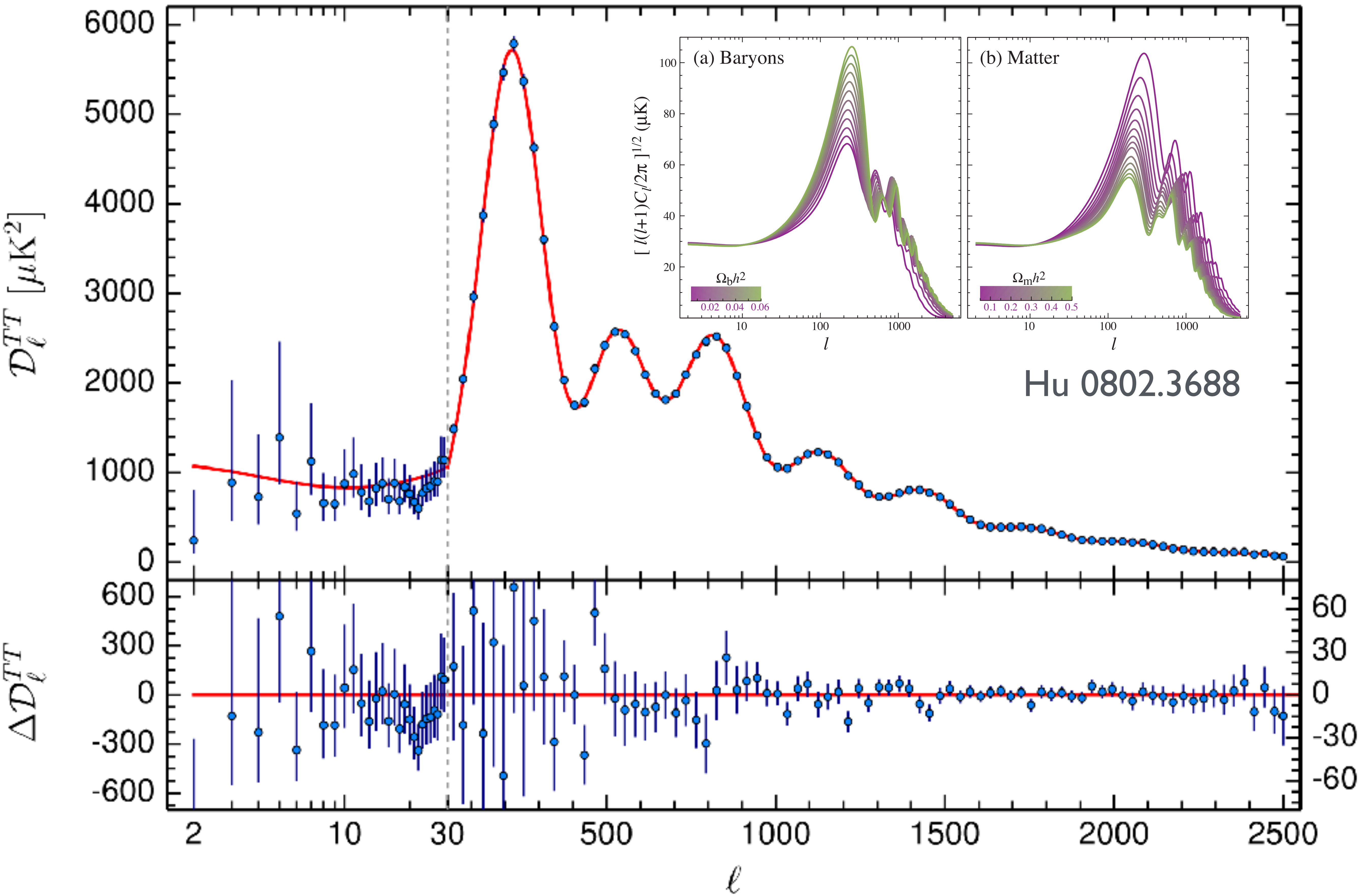


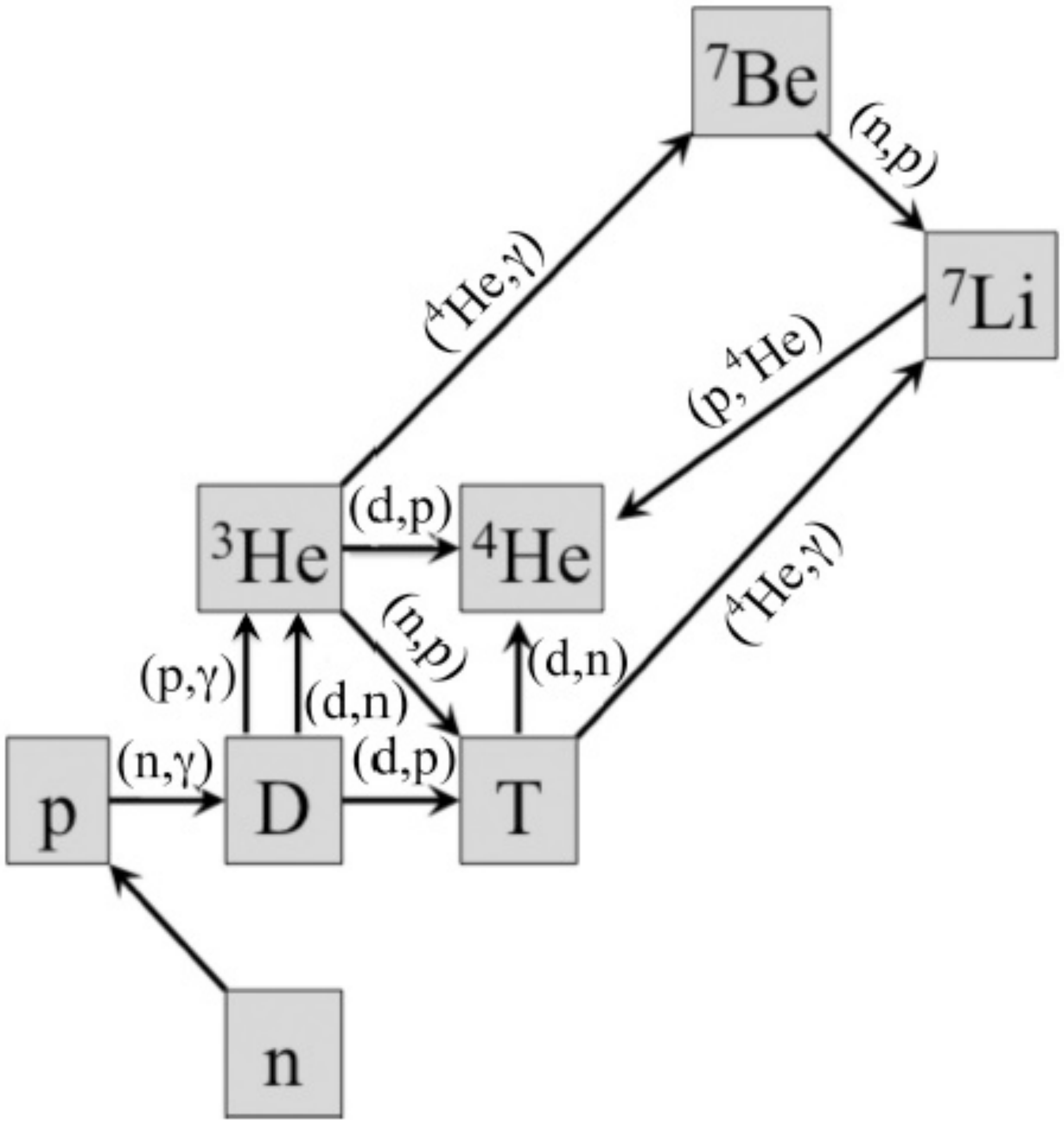
Hot plasma of hydrogen atoms and photons,
and DM and cc

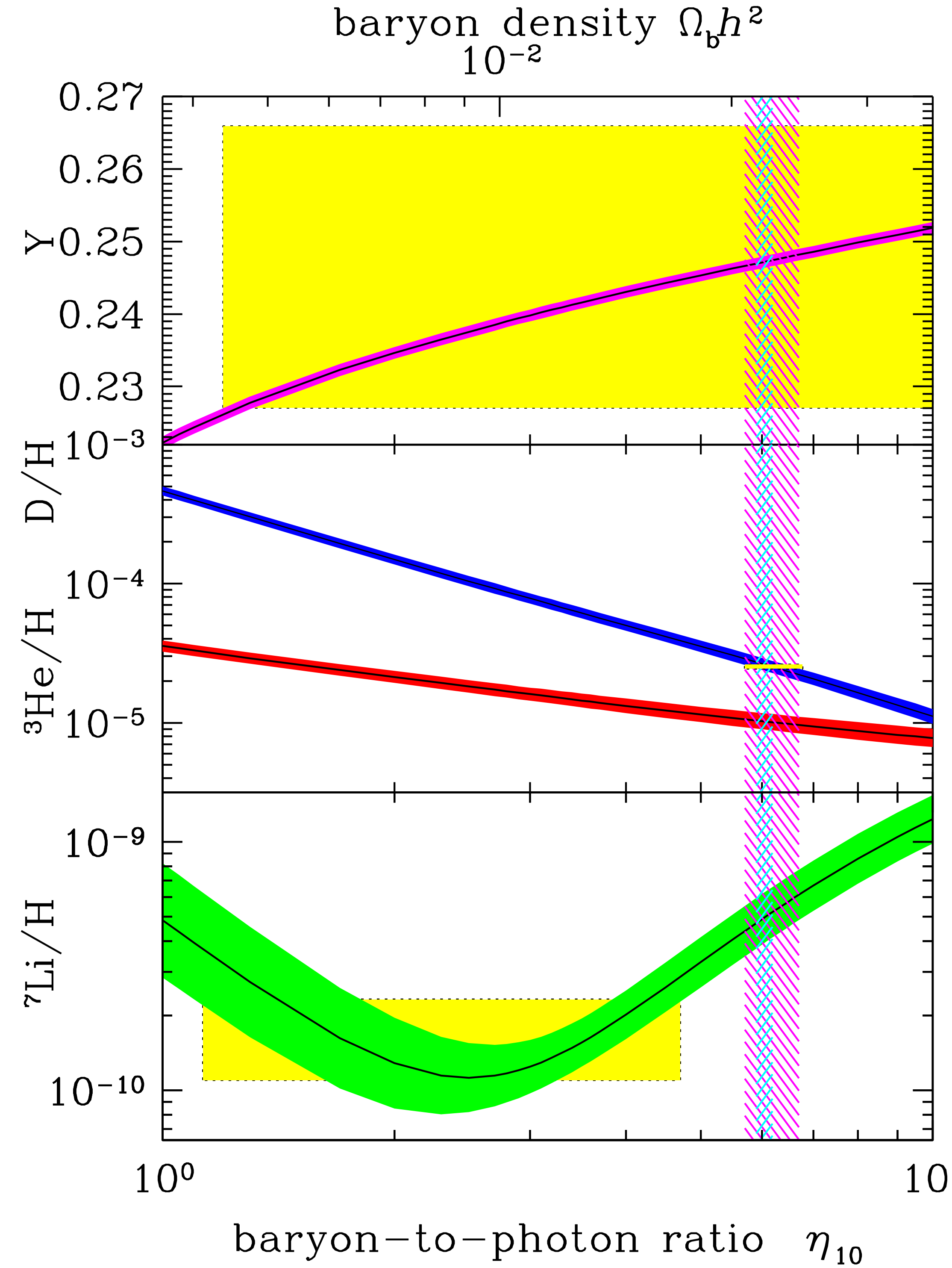
Planck Collaboration



Hu 0802.3688

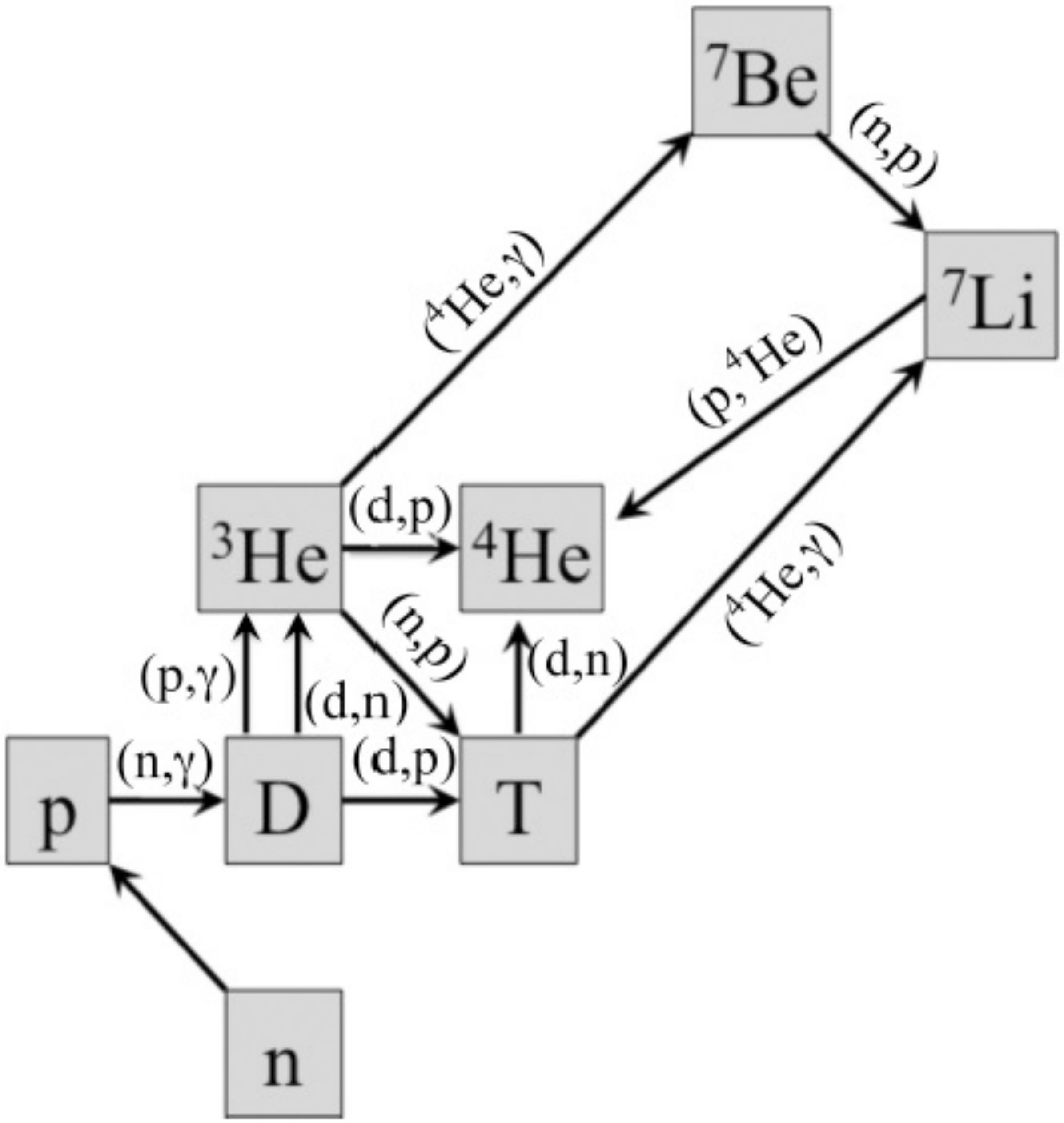
Big Bang Nucleosynthesis

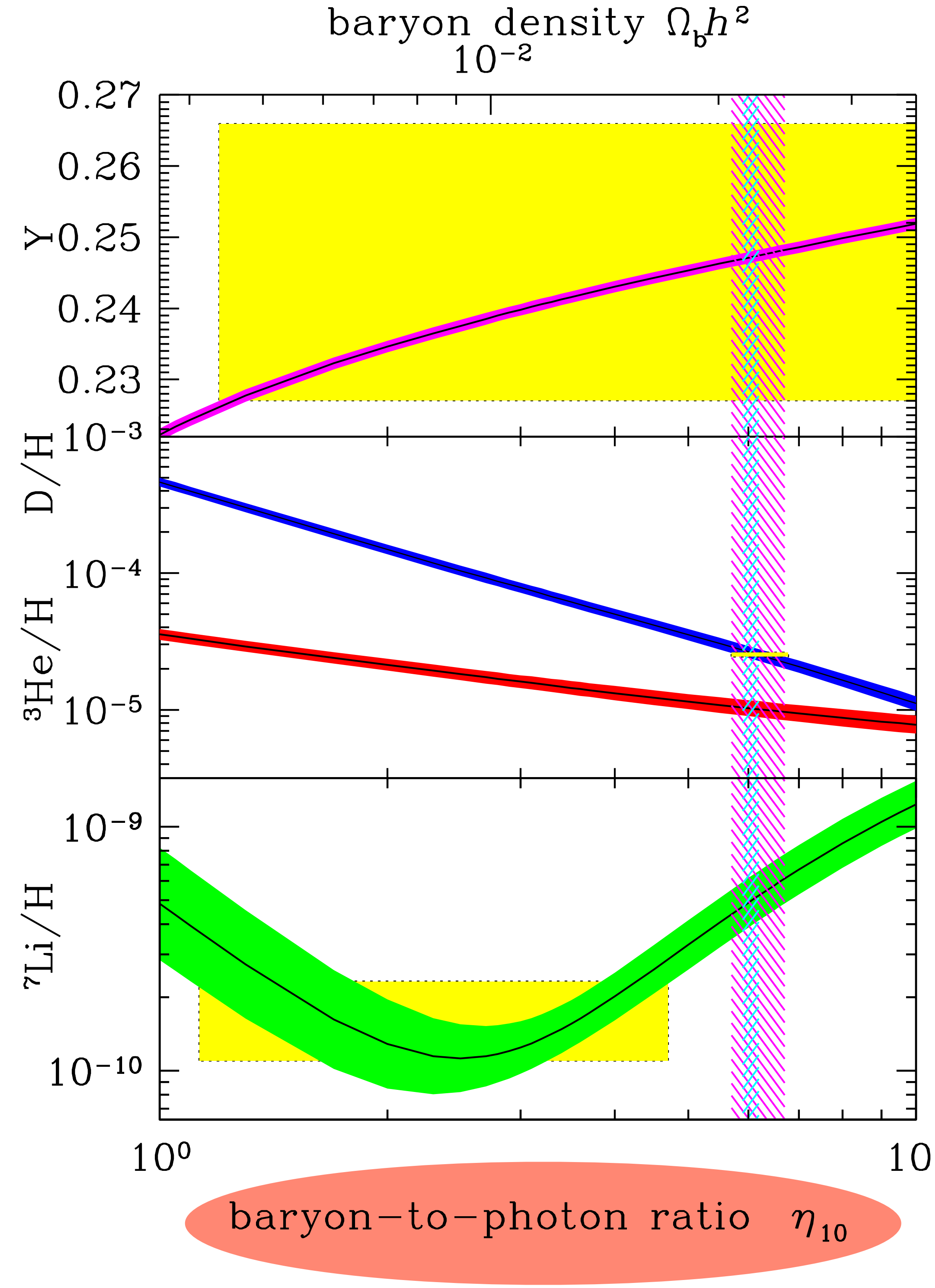




Hot soup of protons and neutrons, can predict light element abundance

Big Bang Nucleosynthesis





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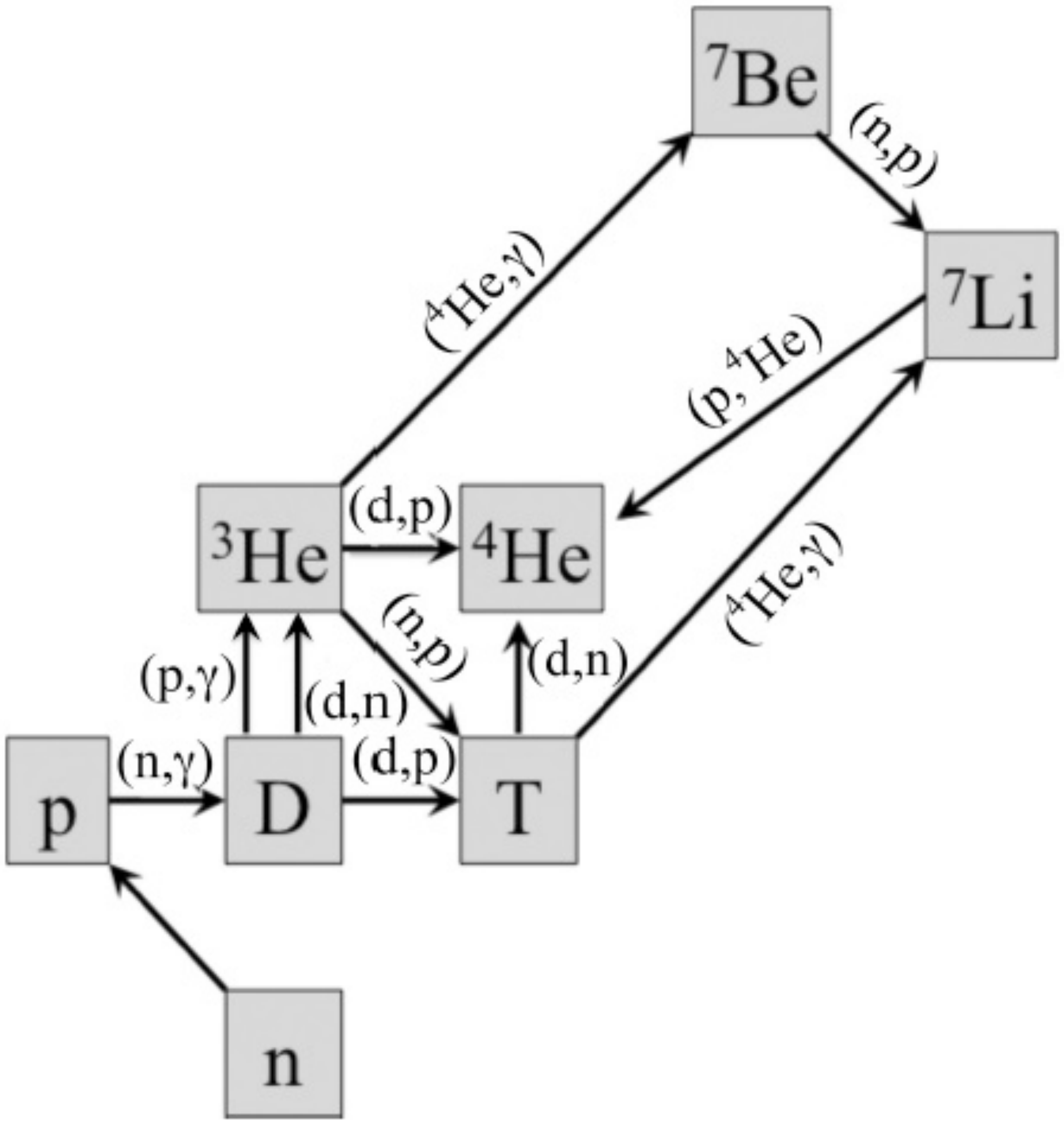
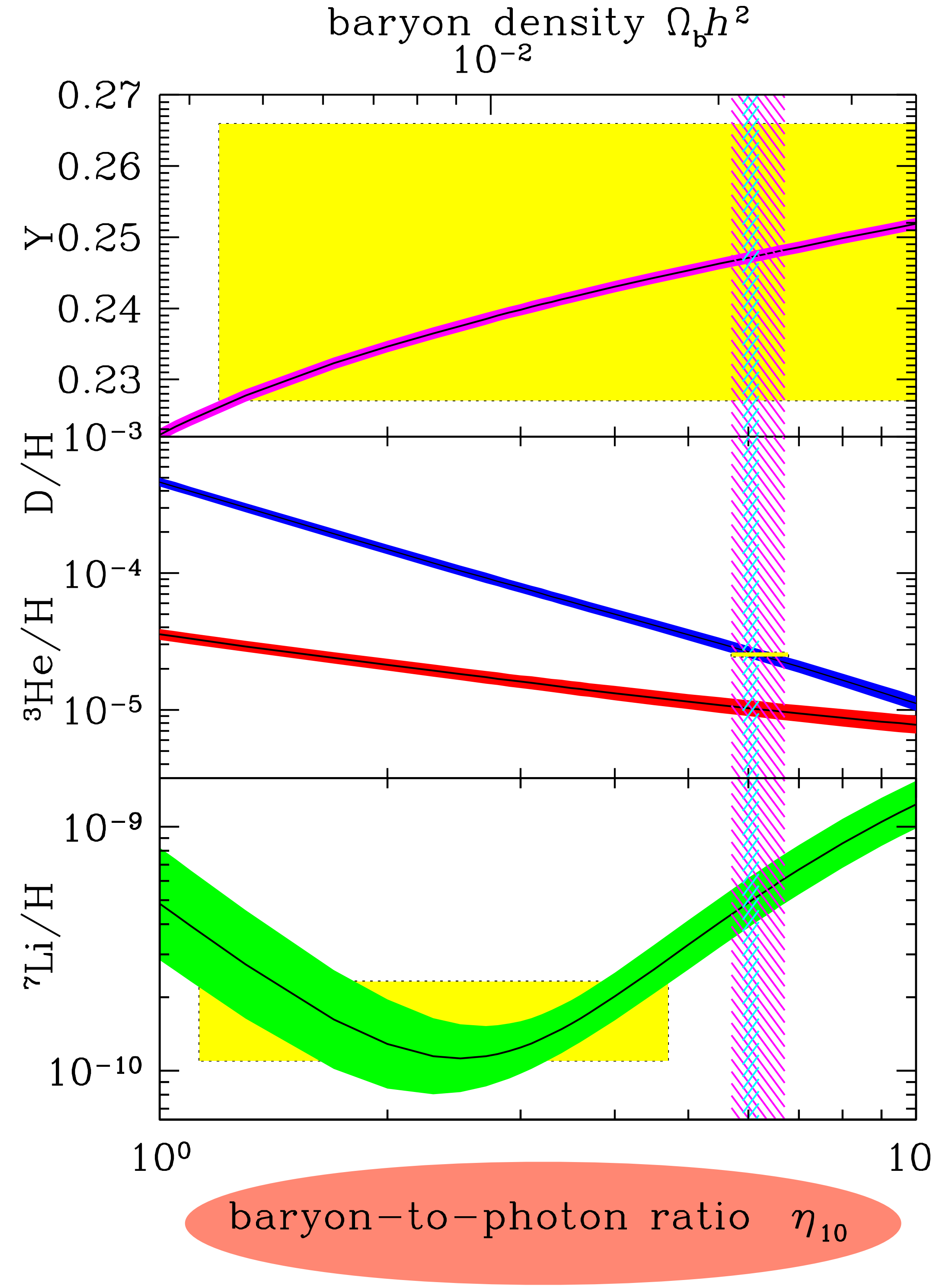




Hot soup of protons and neutrons, can predict light element abundance

~5% in baryons

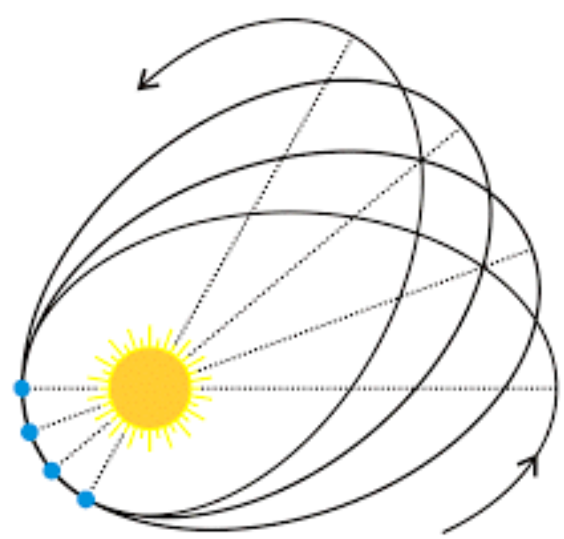
So far all probes have been gravitational in nature

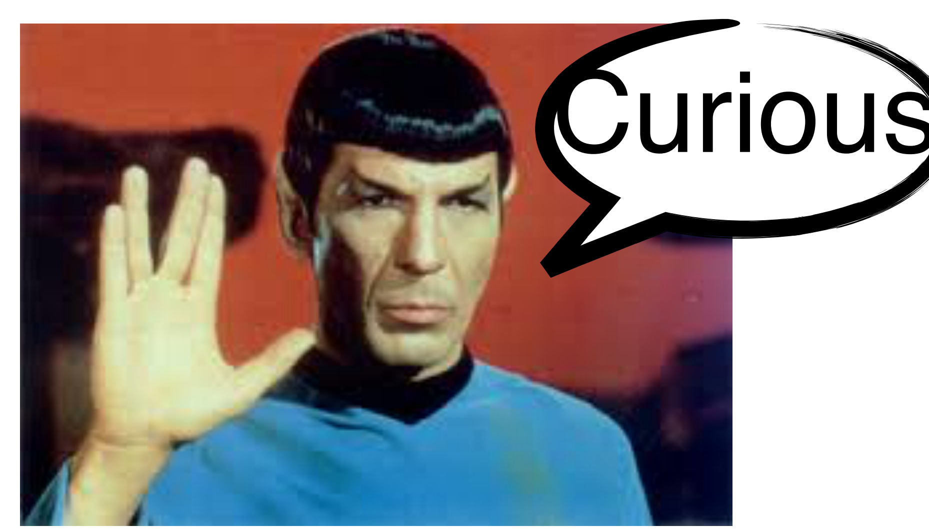
What about other interactions?

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??



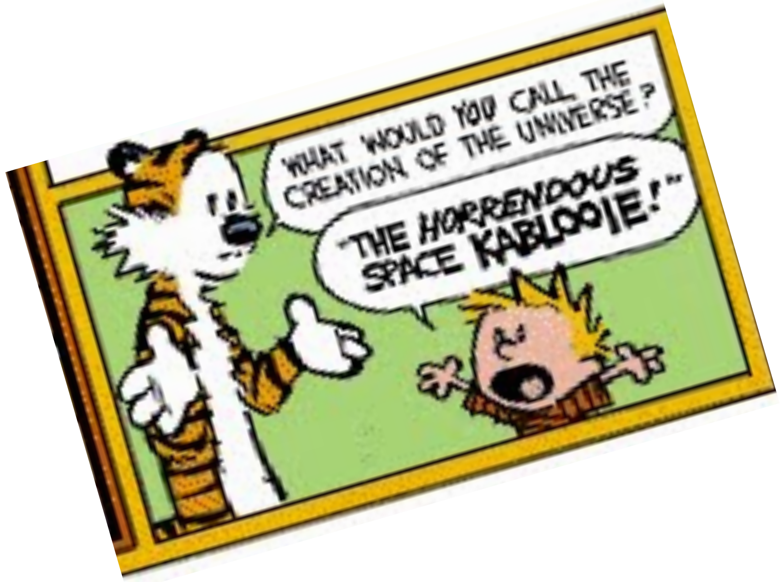


DM as a thermal relic

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

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- At high T production and annihilation in equilibrium
- Once T below mass, annihilation wins. Number drops
- Since universe is expanding, at some point annihilation stops (different from particles in a box)

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

DM as a thermal relic

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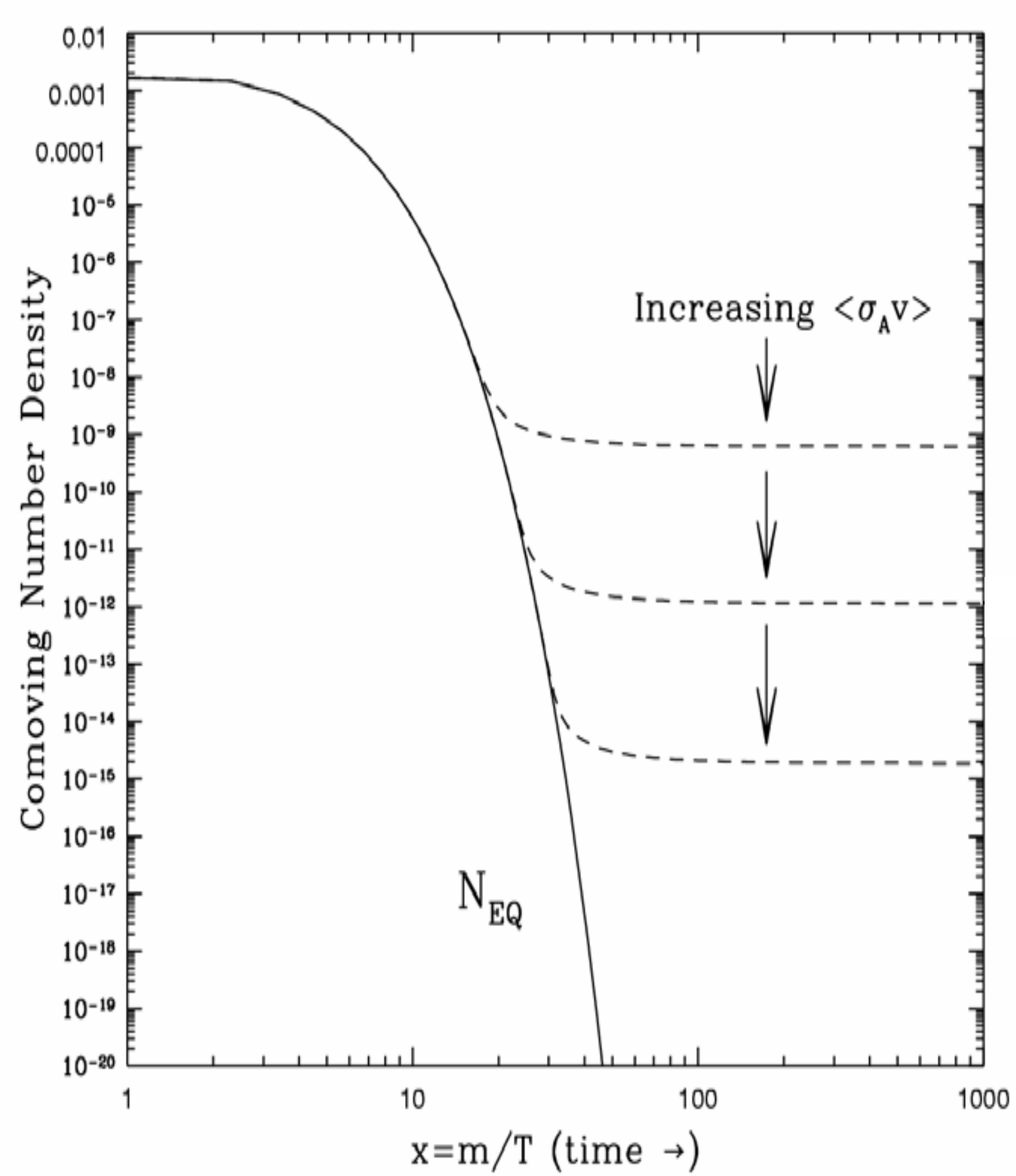

$$\chi\chi \leftrightarrow \bar{f}f$$

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

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 $10\,\mathrm{keV} \lesssim m_\chi \lesssim 70\,\mathrm{TeV}$

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WIMPs

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LPOPs

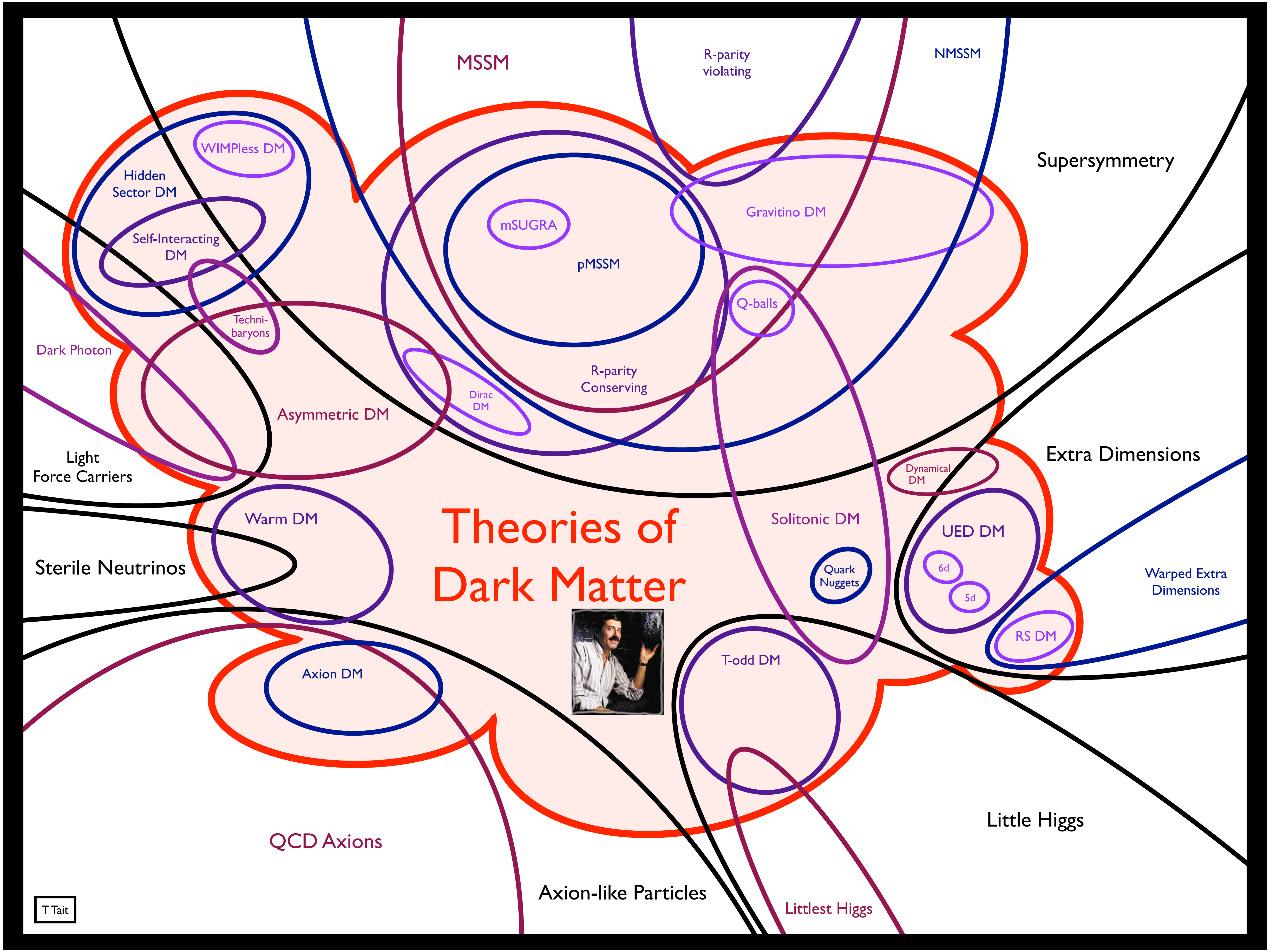
Many models of BSM physics contain a parity

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

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

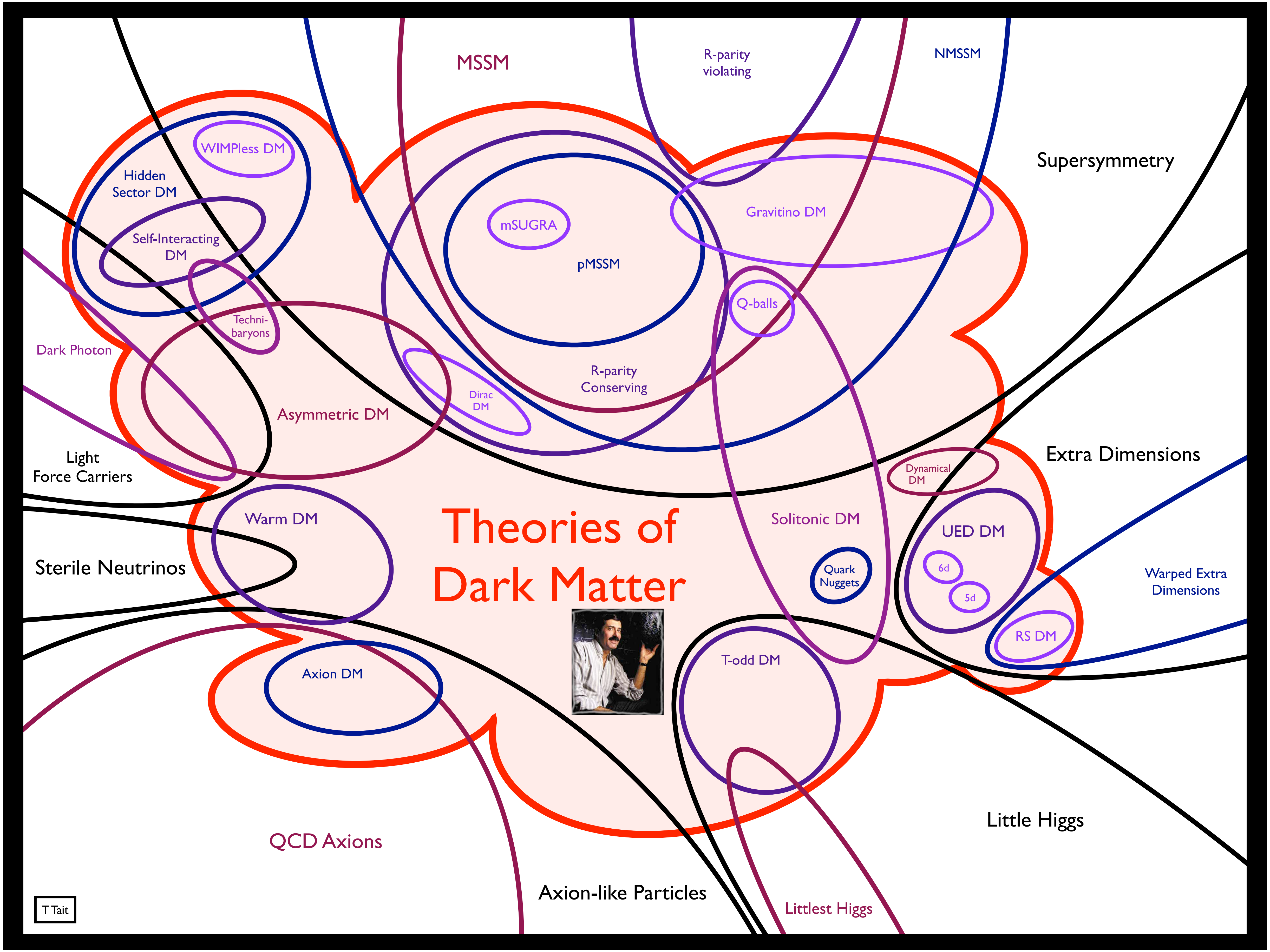
Lightest **P**arity **O**dd **P**article is stable, may be a DM candidate

Always produced in pairs and leaves detector as MET

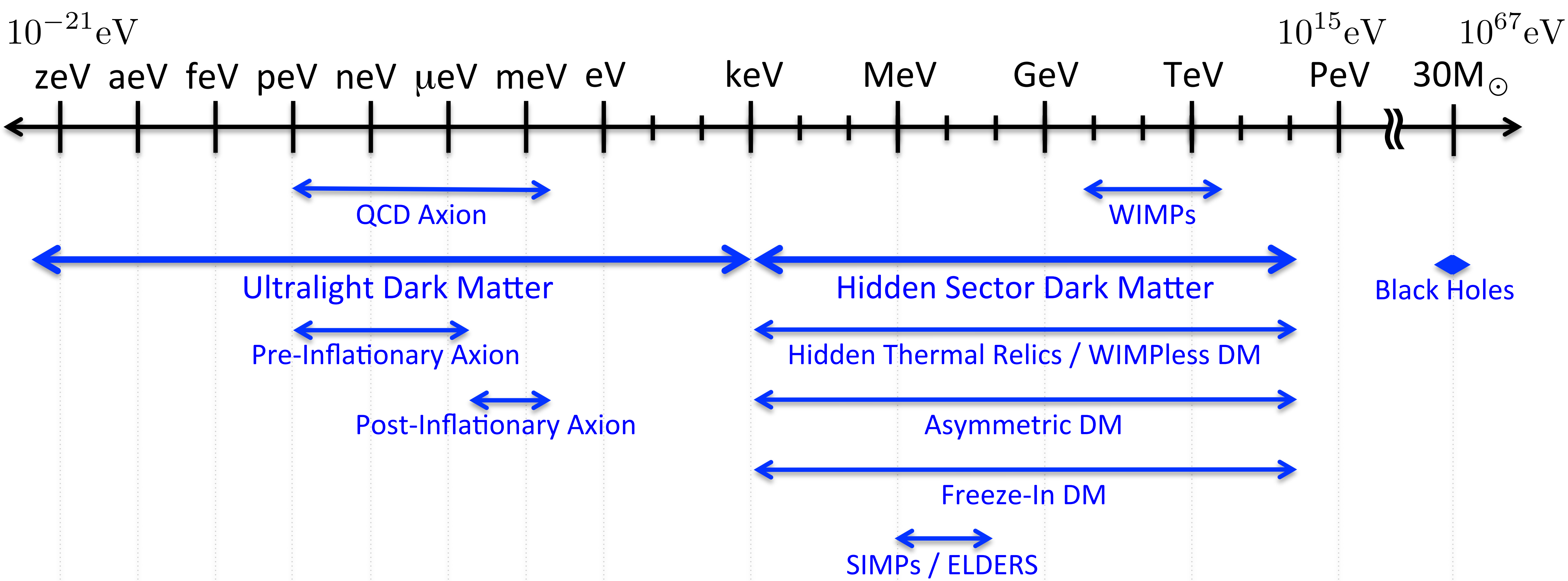


Theories of Dark Matter
MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
mSUGRA
pMSSM
Gravitino DM
Q-balls
Techni-baryons
Dark Photon
R-parity Conserving
Dirac DM
Asymmetric DM
Light Force Carriers
Extra Dimensions
Dynamical DM
Warm DM
Solitonic DM
UED DM
Sterile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

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

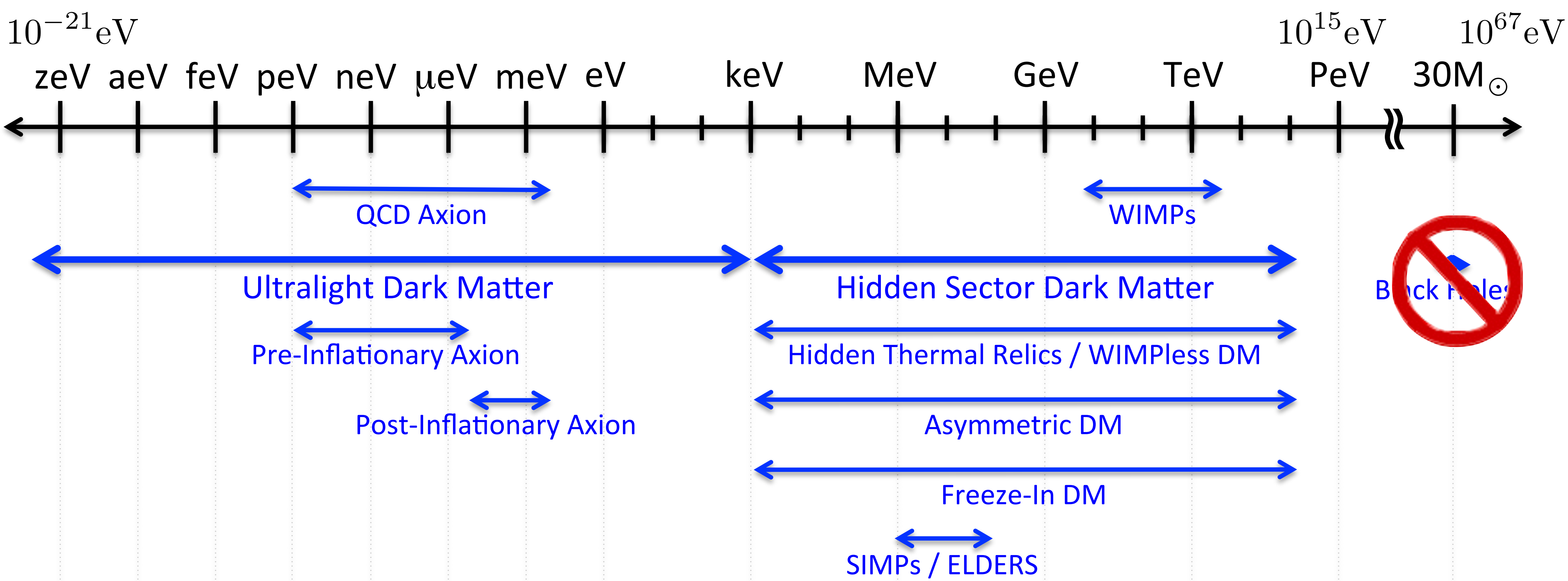


Particle theories



[Feng-US Cosmic Visions White papers]

Particle theories



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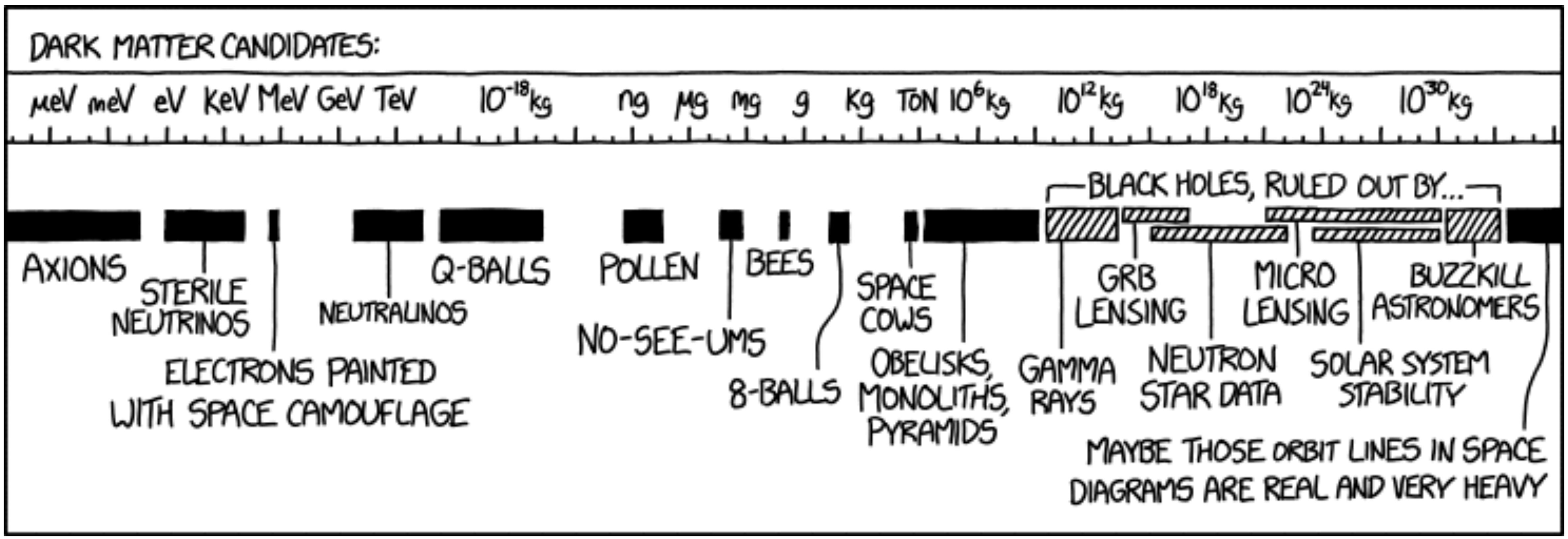
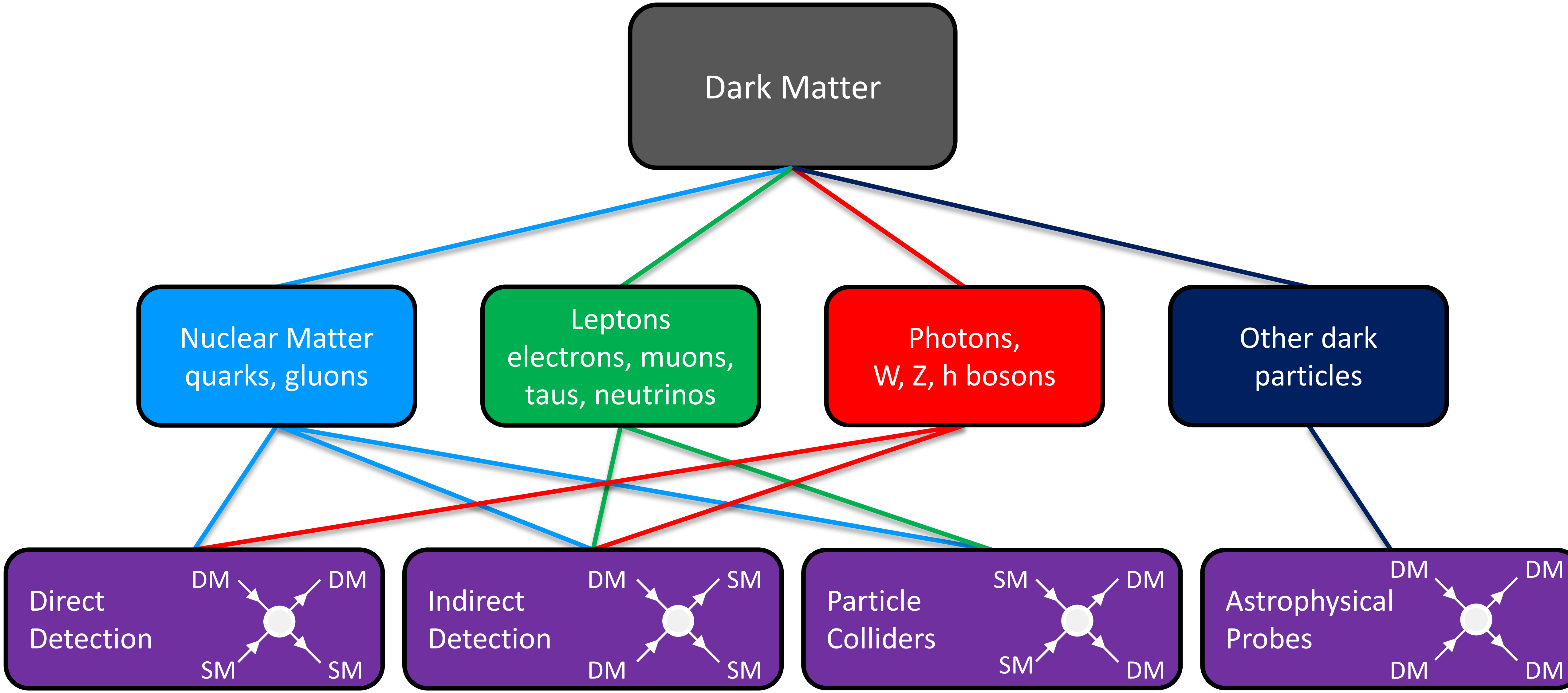
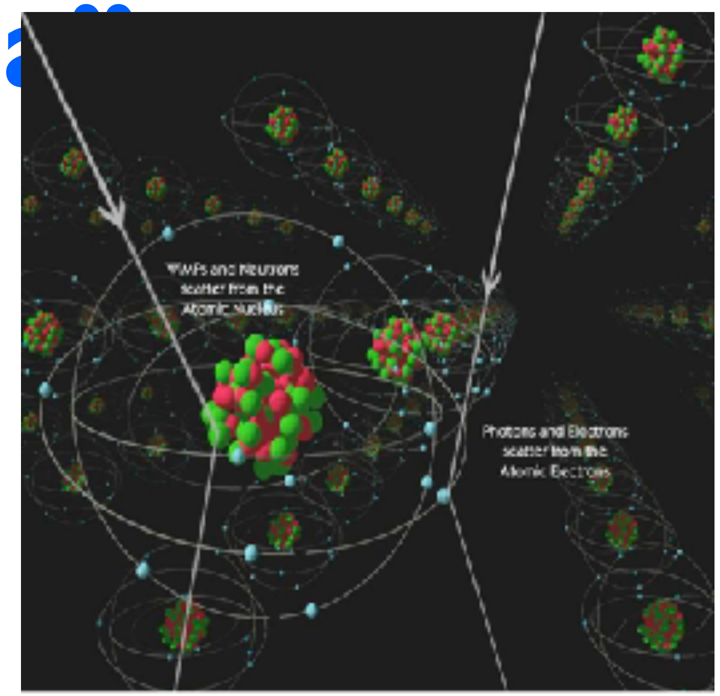

DARK MATTER CANDIDATES:
μeV meV eV KeV MeV GeV TeV 10^-18 kg ng μg mg g Kg TON 10^6 kg 10^12 kg 10^18 kg 10^24 kg 10^30 kg
BLACK HOLES, RULED OUT BY...
AXIONS
STERILE NEUTRINOS
ELECTRONS PAINTED WITH SPACE CAMOUFLAGE
NEUTRALINOS
Q-BALLS
POLLEN
NO-SEE-UMS
BEES
8-BALLS
SPACE COWS
OBELISKS, MONOLITHS, PYRAMIDS
GAMMA RAYS
GRB LENSING
NEUTRON STAR DATA
MICRO LENSING
SOLAR SYSTEM STABILITY
BUZZKILL ASTRONOMERS
MAYBE THOSE ORBIT LINES IN SPACE DIAGRAMS ARE REAL AND VERY HEAVY

xkcd


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

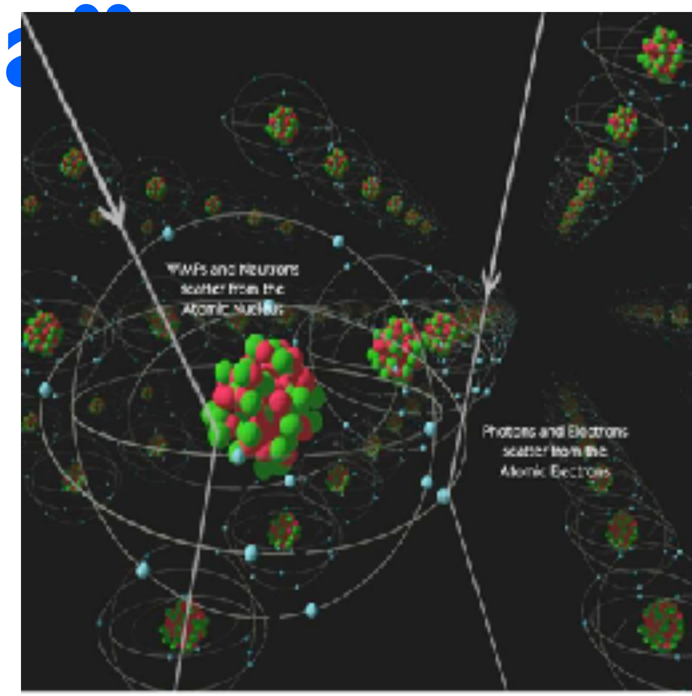
Q: Are these different search strategies separate, redundant, complementary, relatable,….?

rect Detection “Master formula”



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

rect Detection “Master formul



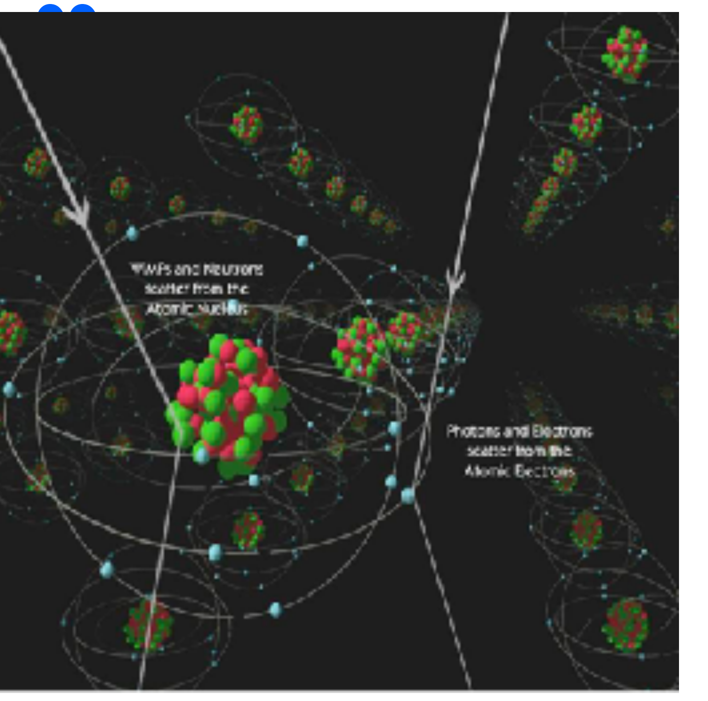
Recoil rate as a function of recoil energy

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

rect Detection "Master formula"



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Number of targets in experiment

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

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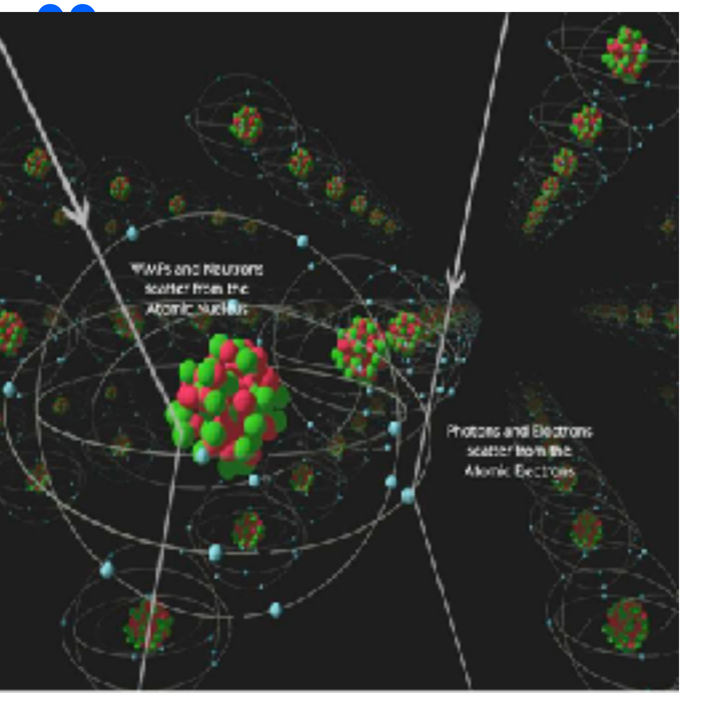

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Number of targets in experiment

...and how it’s moving...

...and how it interacts with nuclei.

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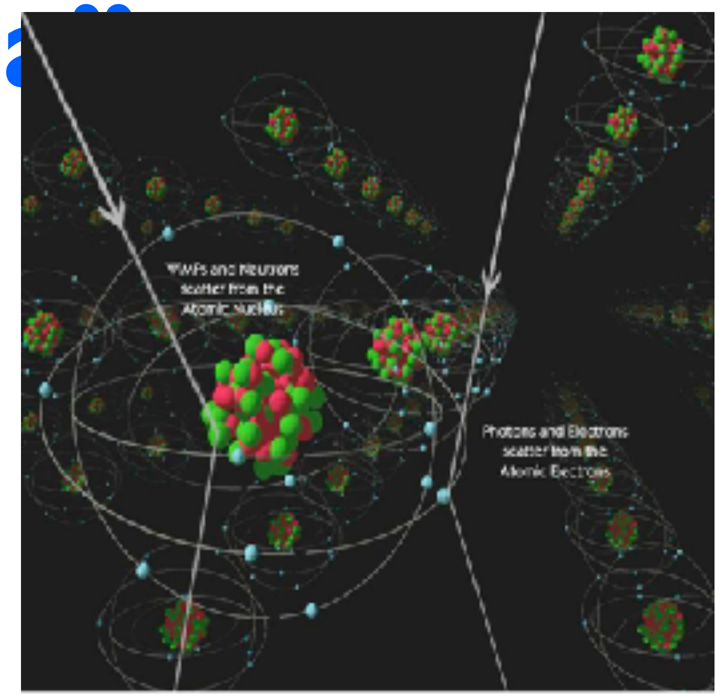

Recoil rate as a function of recoil energy

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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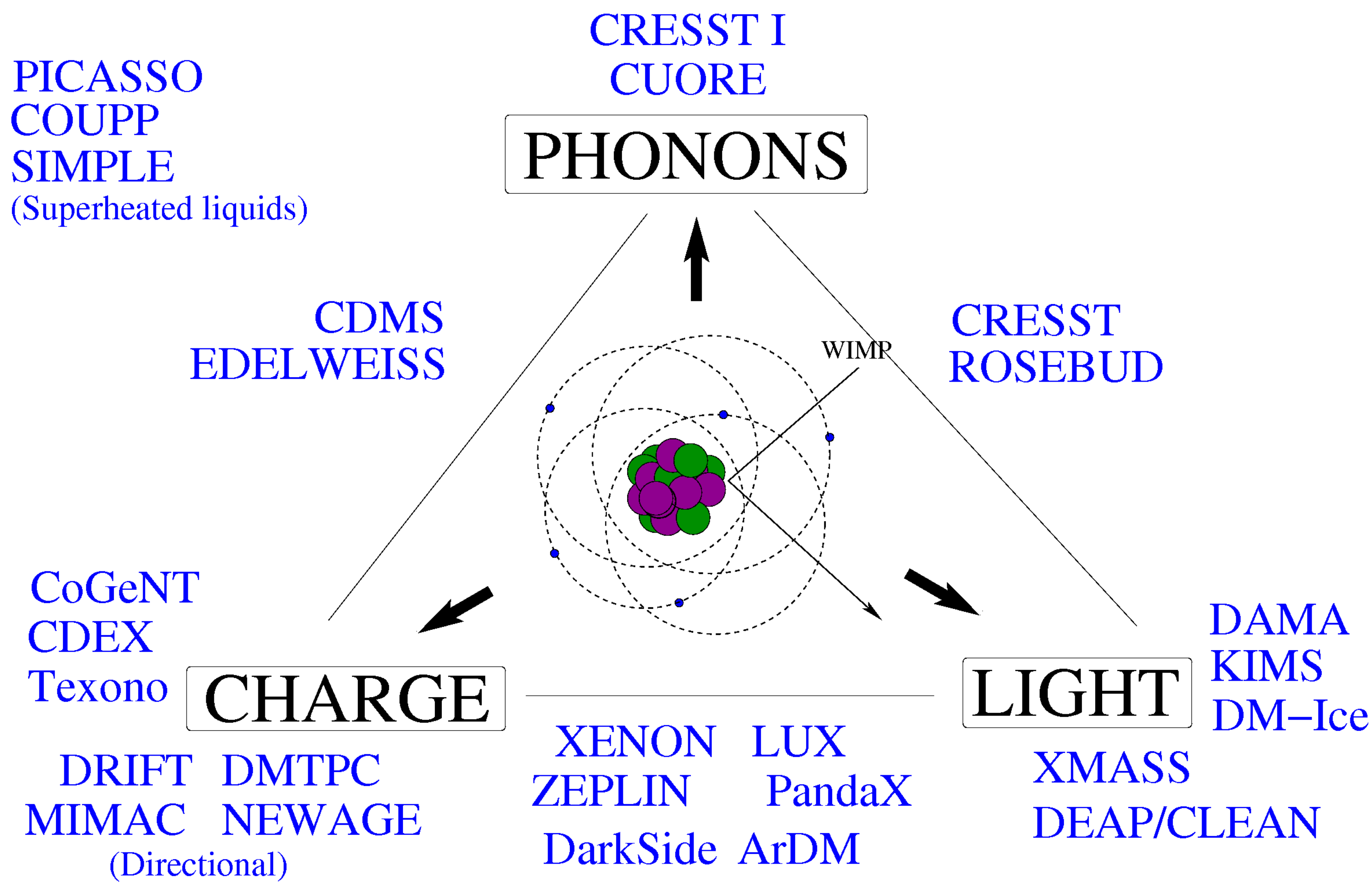
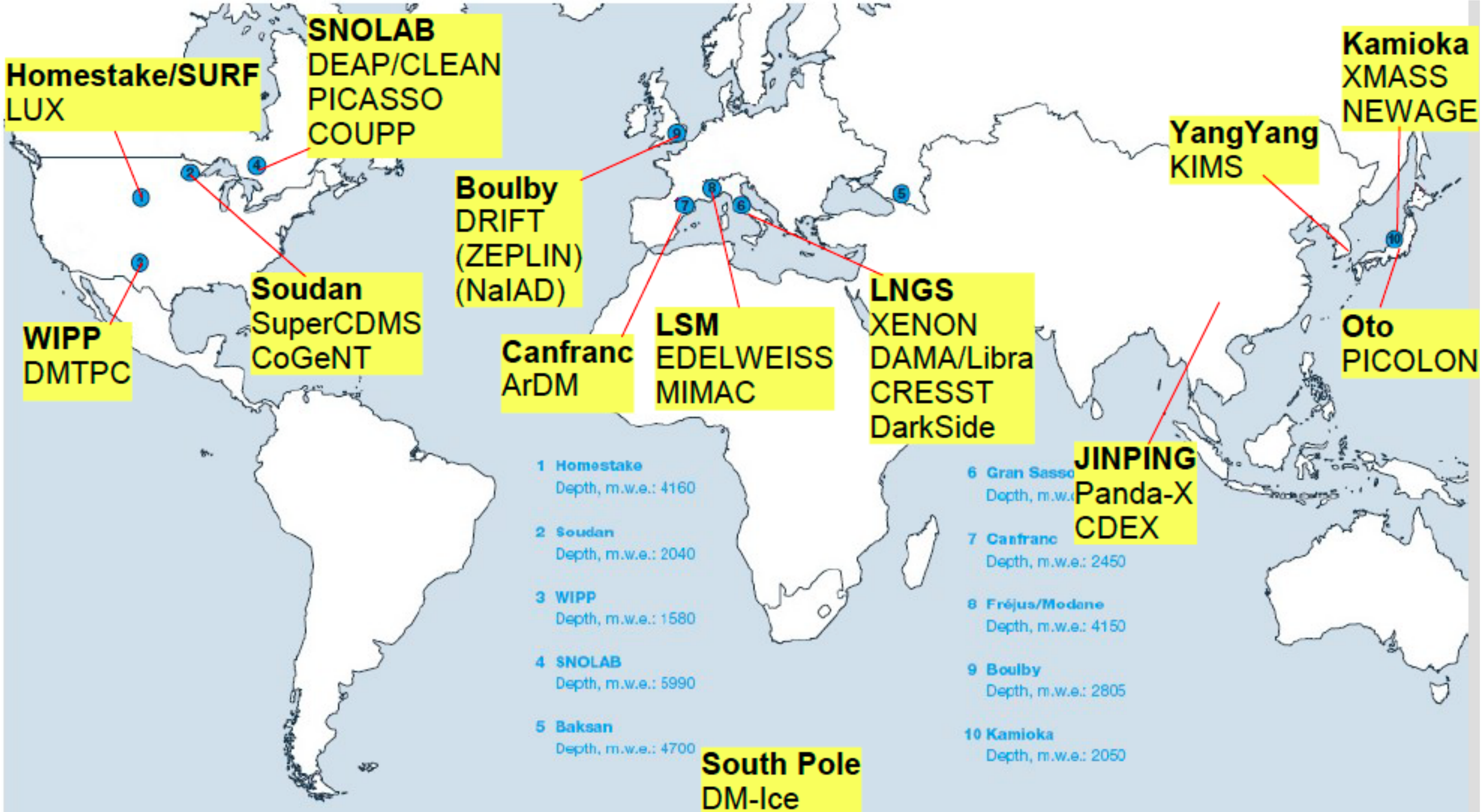
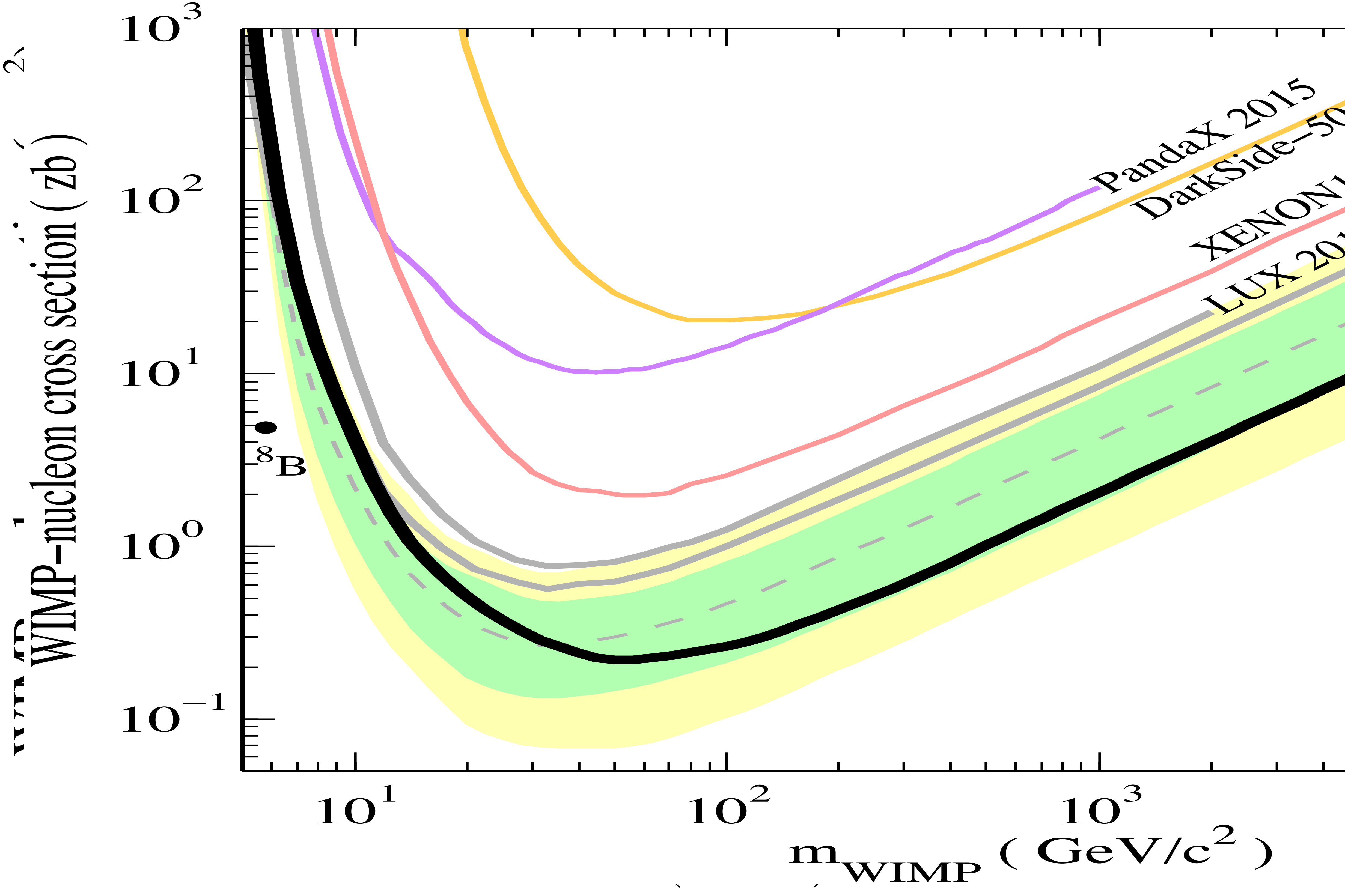


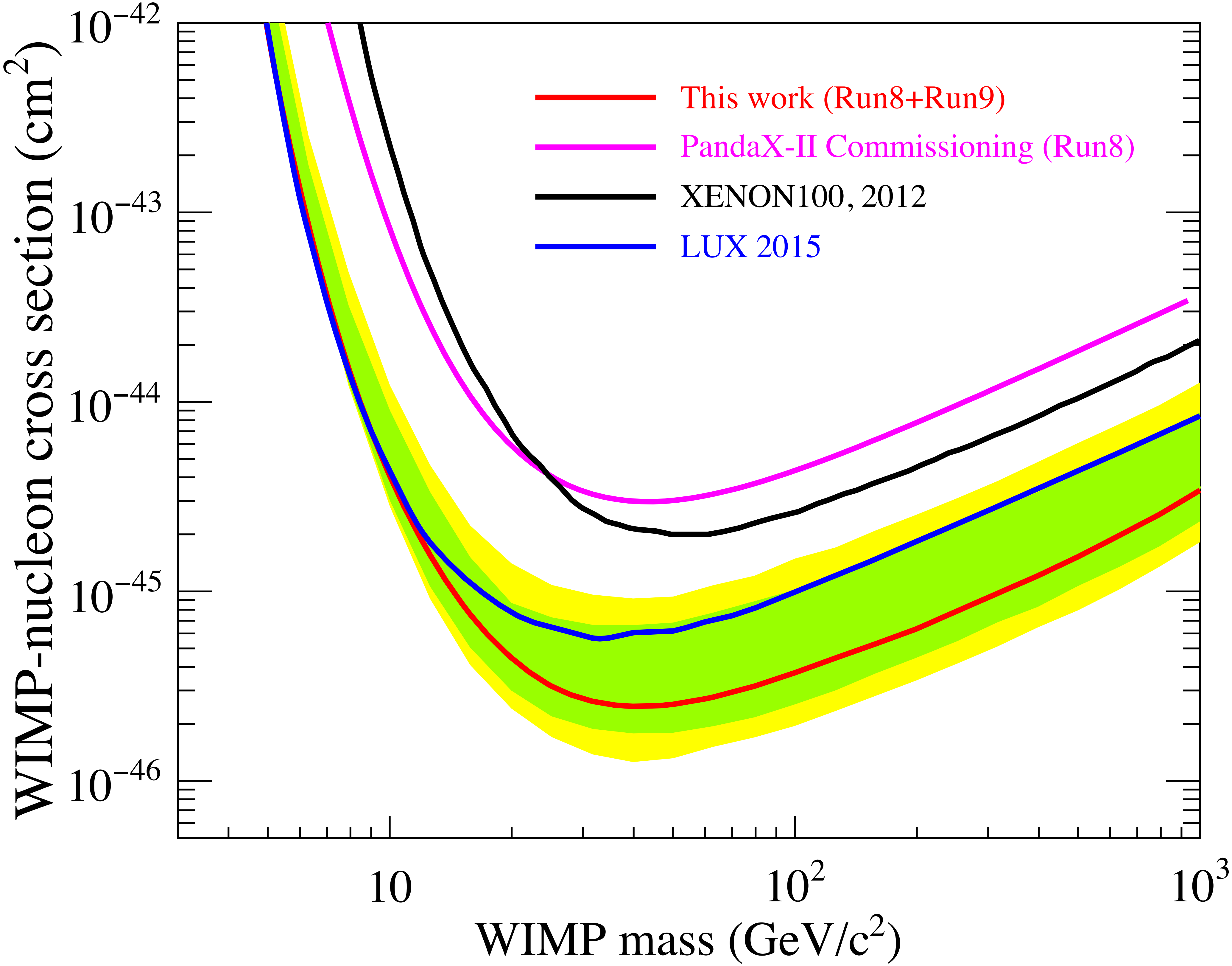
CRESST I
CUORE
PHONONS
PICASSO
COUPP
SIMPLE
(Superheated liquids)
CDMS
EDELWEISS
CRESST
ROSEBUD
WIMP
CoGeNT
CDEX
Texono
CHARGE
LIGHT
DAMA
KIMS
DM–Ice
DRIFT DMTPC
MIMAC NEWAGE
(Directional)
XENON LUX
ZEPLIN PandaX
DarkSide ArDM
XMASS
DEAP/CLEAN

Underground laboratories

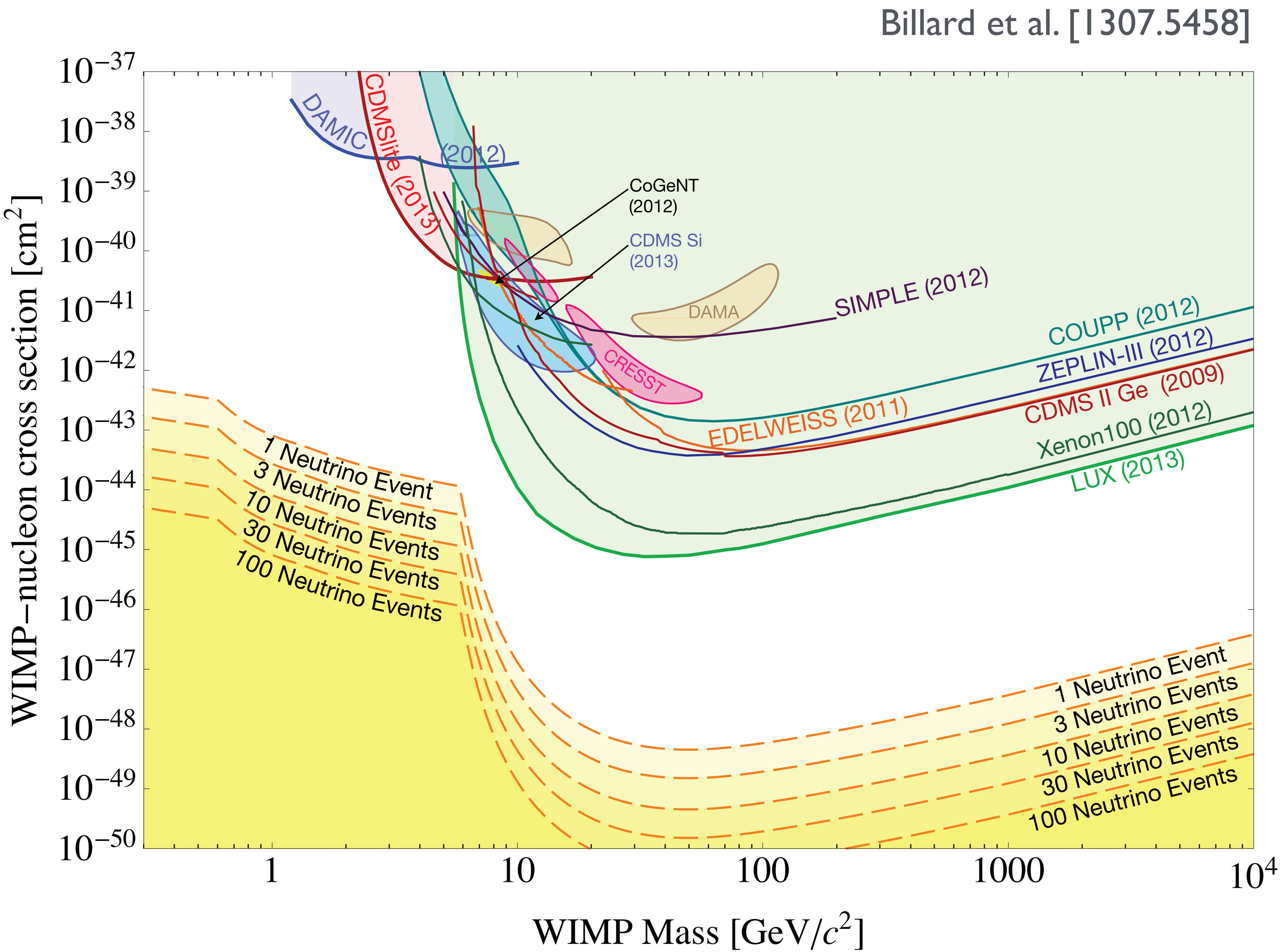




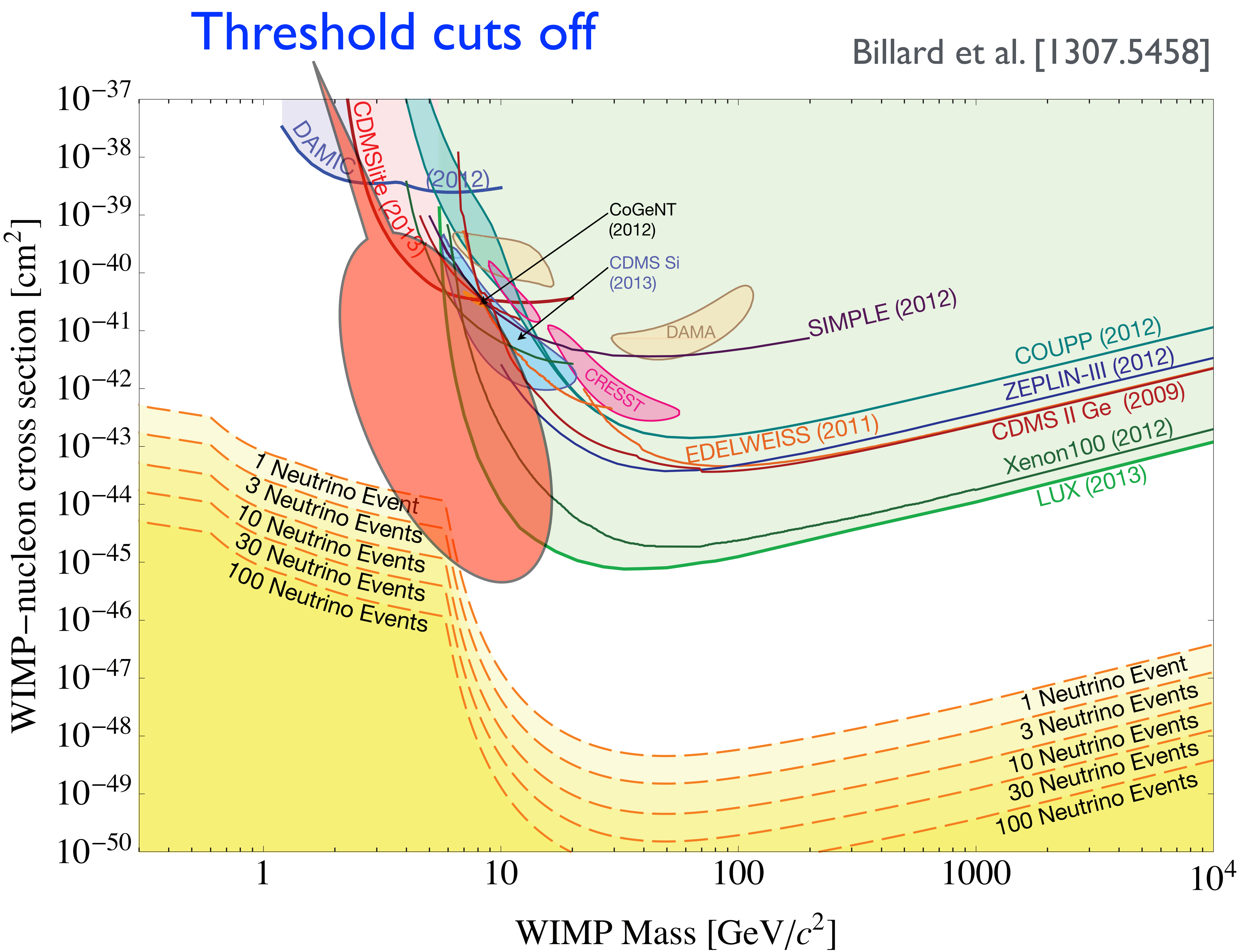
WIMP-nucleon cross section (zb)
10^3
10^2
10^1
10^0
10^{-1}
^8B
PandaX 2015
DarkSide-50
XENON1
LUX 201
10^1
10^2
10^3
m_{WIMP} (GeV/c^2)



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



Billard et al. [1307.5458]
WIMP–nucleon cross section [cm^2]
WIMP Mass [GeV/c^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
DAMIC
(2012)
CDMSlite (2013)
CoGeNT
(2012)
CDMS Si
(2013)
DAMA
SIMPLE (2012)
CRESST
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
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]
WIMP–nucleon cross section [cm^2]
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)
Xenon100 (2012)
LUX (2013)
EDELWEISS (2011)
CRESST
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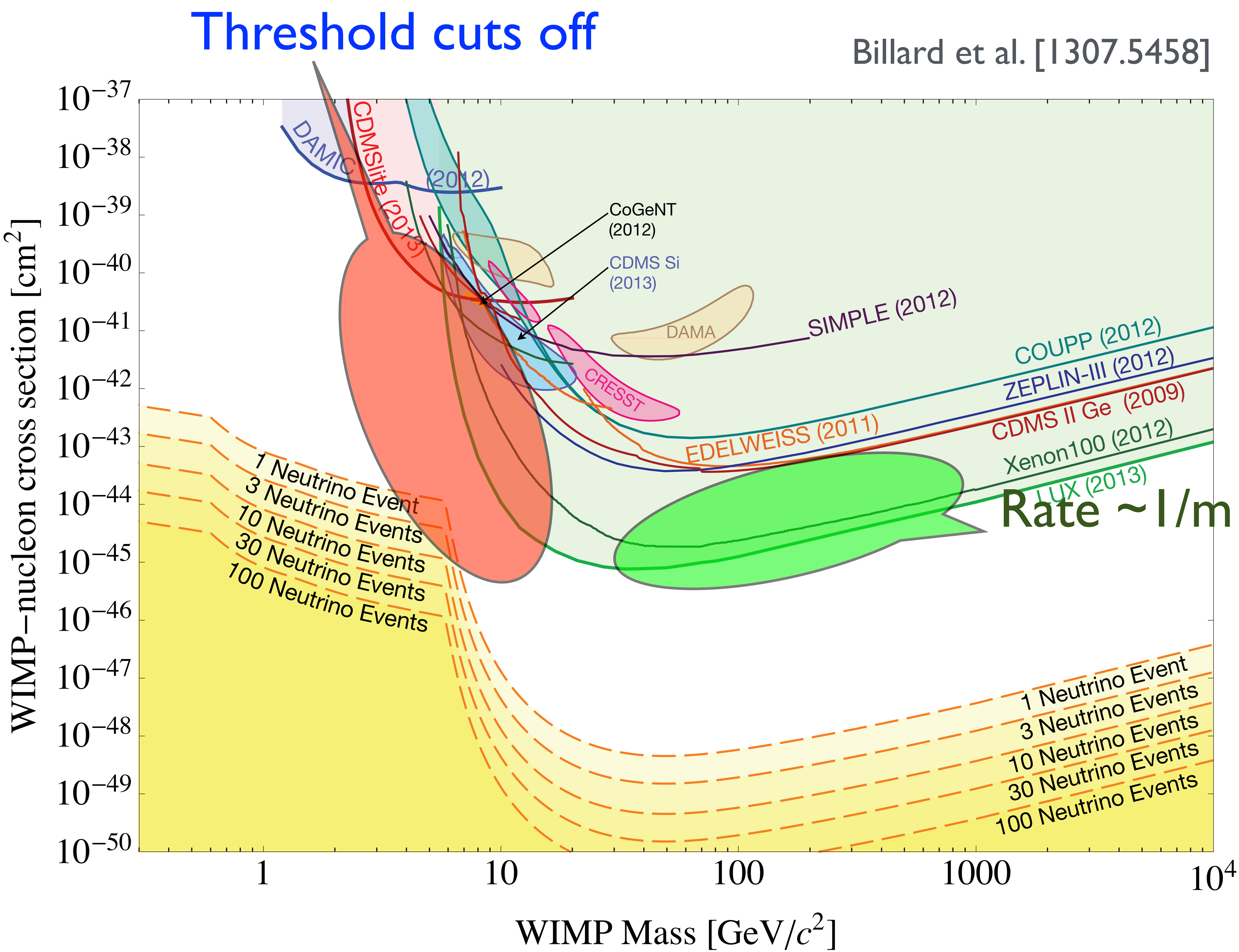
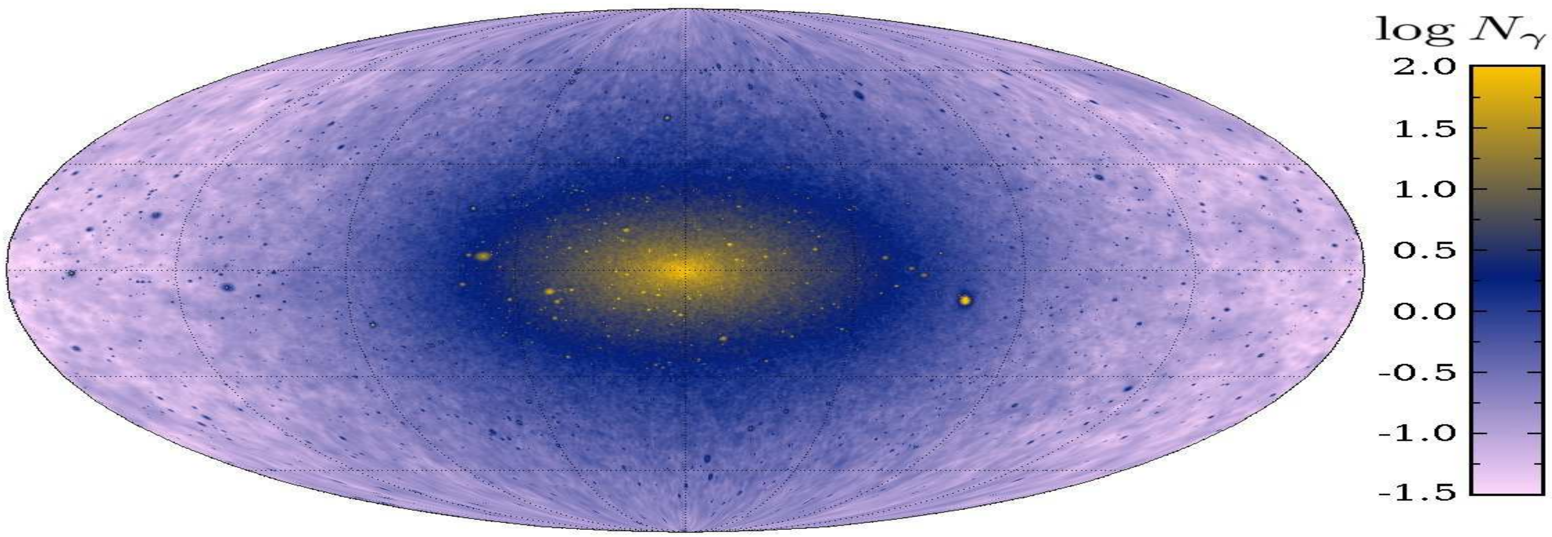
100 Neutrino Events


Threshold cuts off
Billard et al. [1307.5458]
Rate ~1/m
DAMIC
(2012)
CDMSlite (2013)
CoGeNT
(2012)
CDMS Si
(2013)
DAMA
SIMPLE (2012)
CRESST
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
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
WIMP–nucleon cross section [cm^2]
WIMP Mass [GeV/c^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

ndirect 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

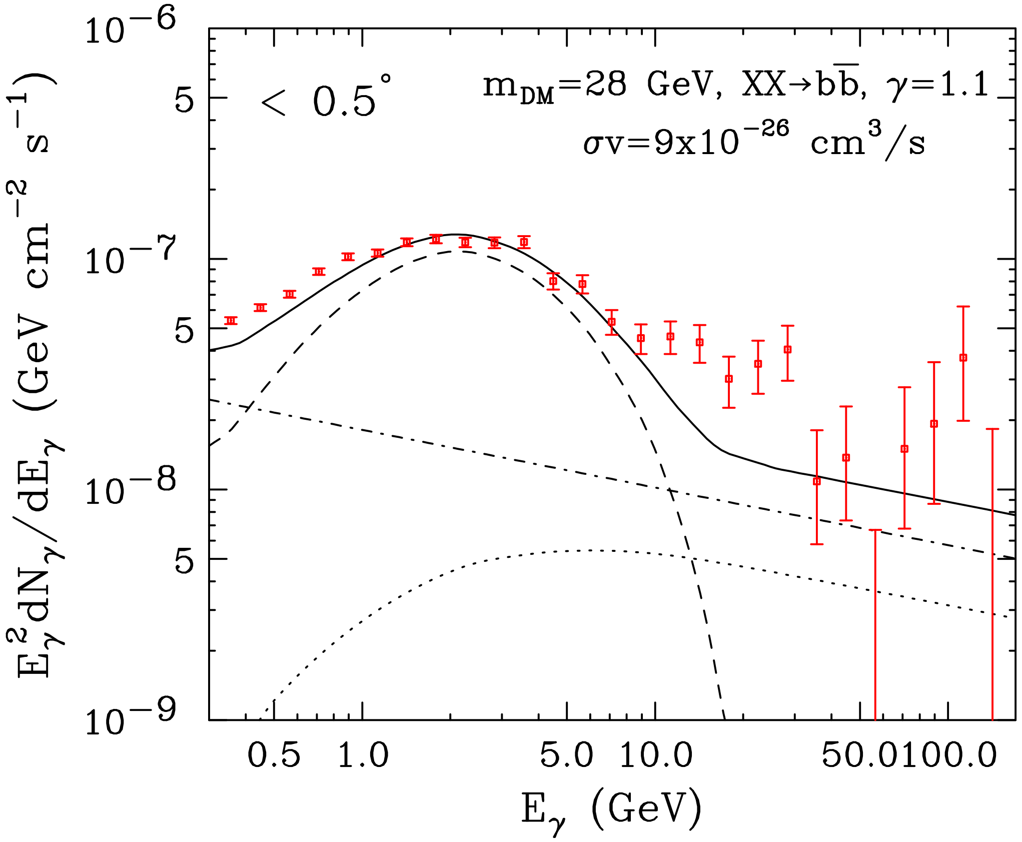
$\chi\chi \to \gamma\gamma$

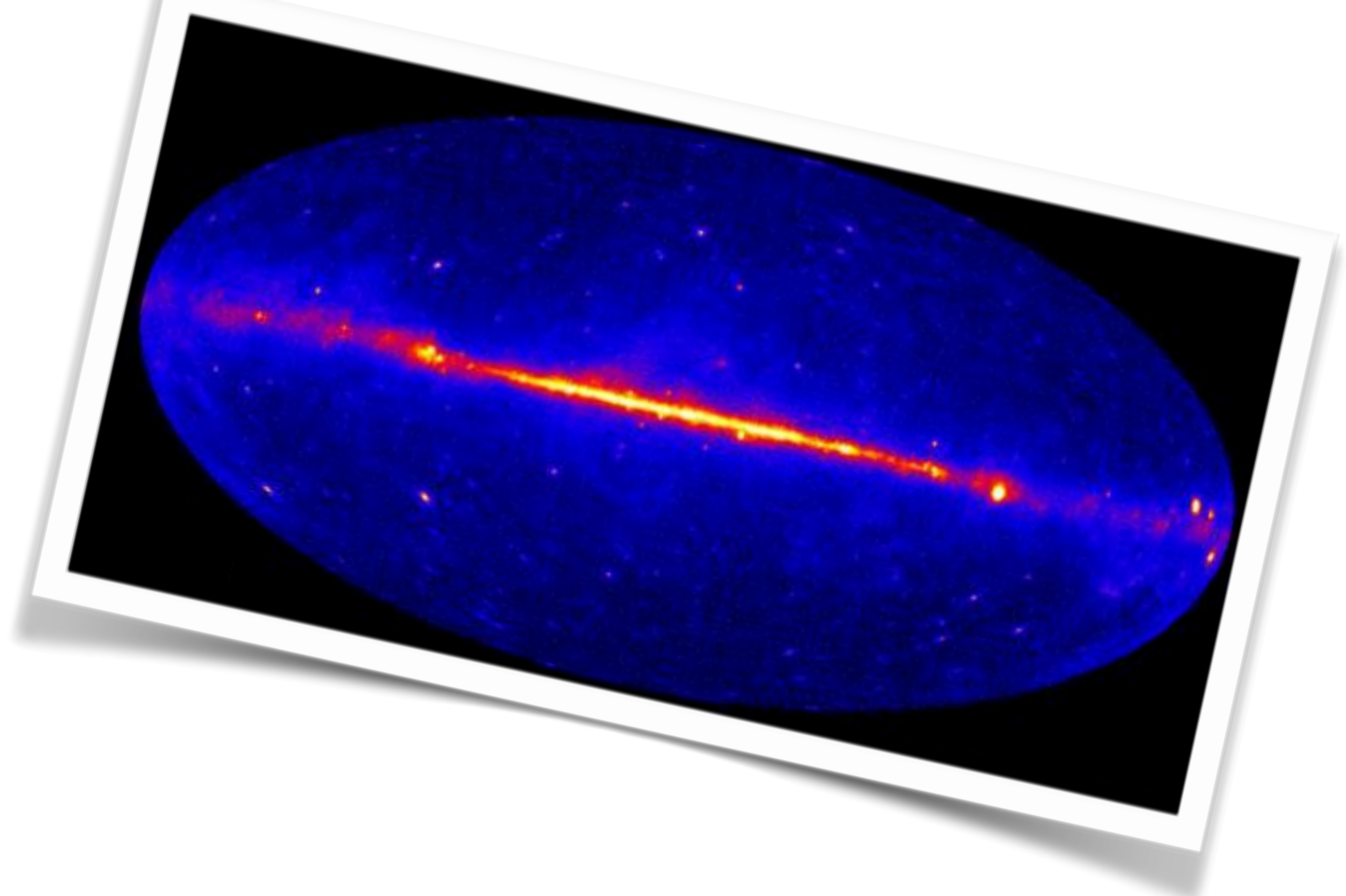
Point back to source, spectral line, low rate
Fermi, HESS

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

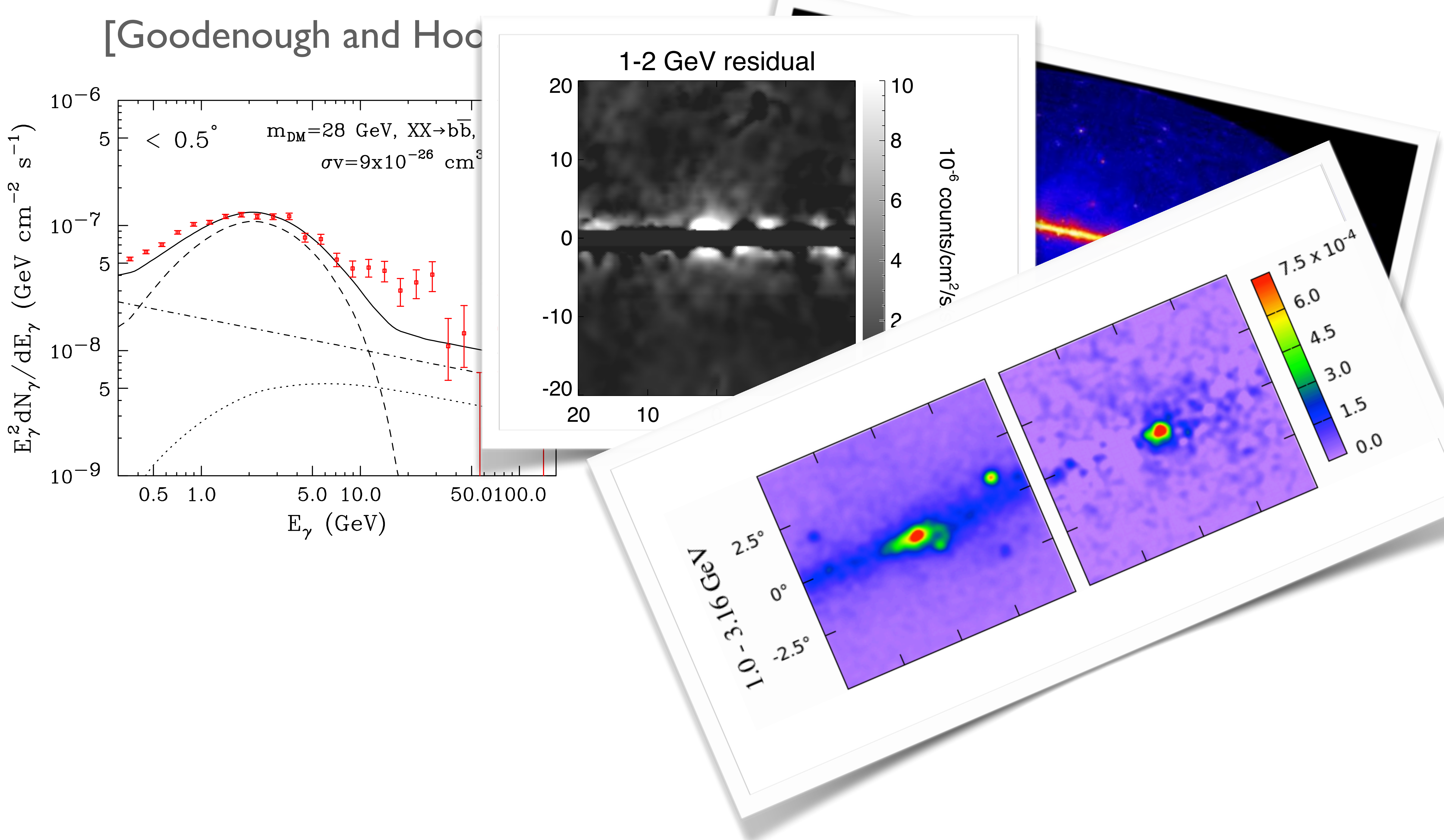
Point back to source, continuum with edge, backgrounds
Fermi, HESS

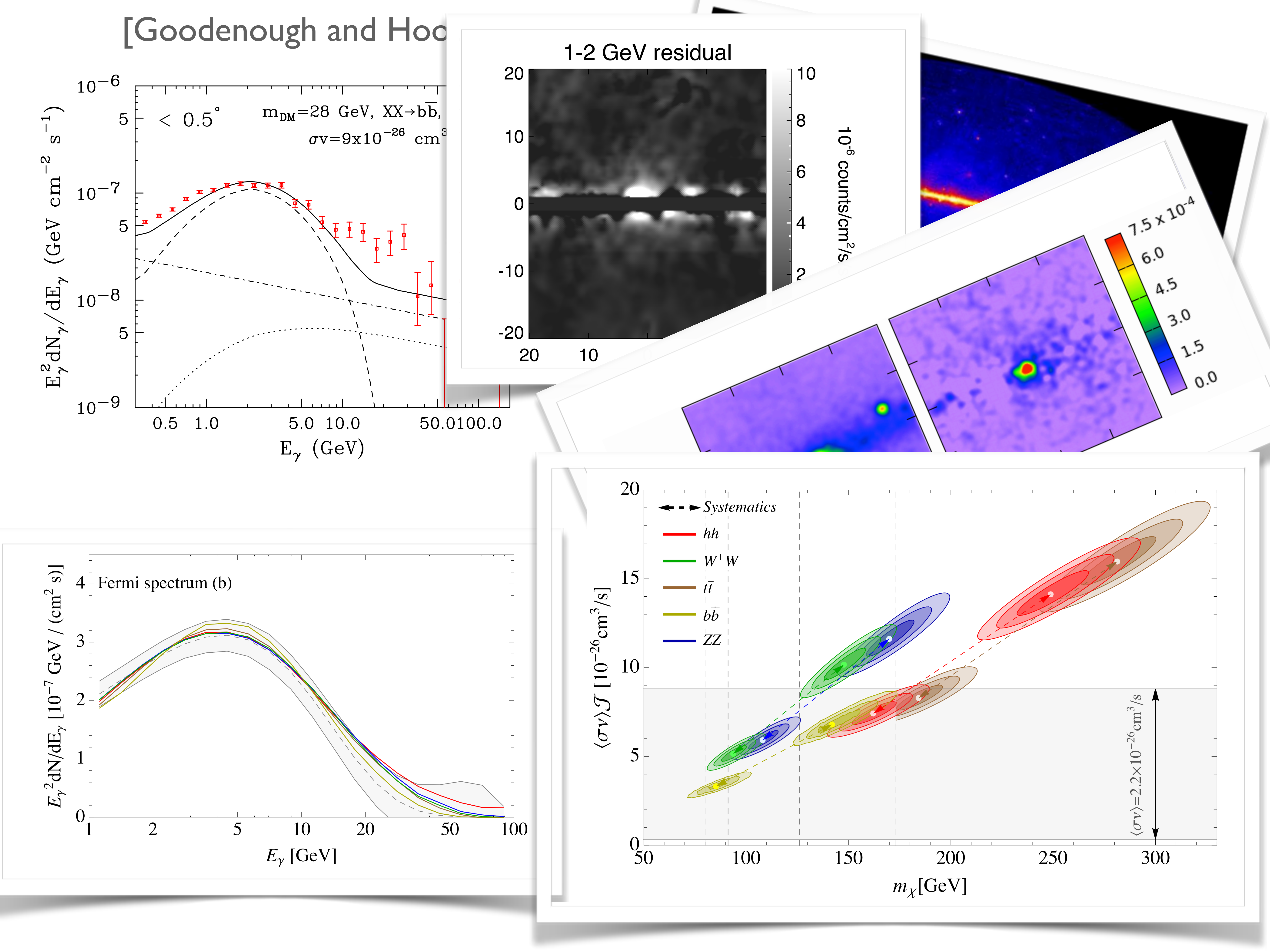
[Goodenough and Hooper, 2009]





[Goodenough and Hoo




[Goodenough and Hoo
< 0.5°
m_DM=28 GeV, XX→bb̄,
σv=9x10^-26 cm^3
E_γ^2 dN_γ/dE_γ (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
Fermi spectrum (b)
E_γ^2 dN/dE_γ [10^-7 GeV / (cm^2 s)]
E_γ [GeV]
Systematics
hh
W^+W^-
tt̄
bb̄
ZZ
⟨σv⟩J [10^-26 cm^3/s]
m_χ [GeV]
⟨σv⟩=2.2×10^-26 cm^3/s

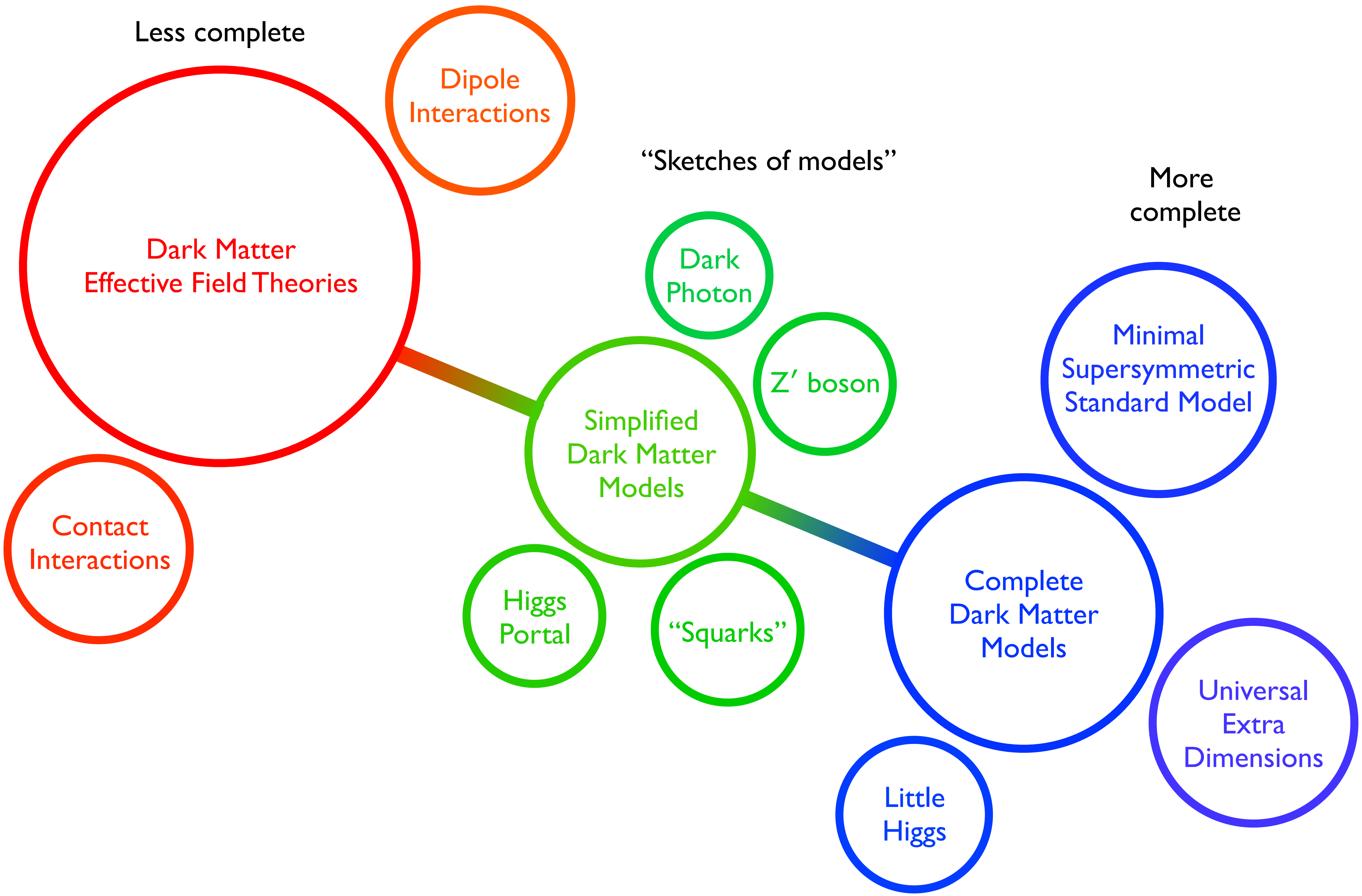
Are the excess photons from the Galactic centre DM?

- 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)

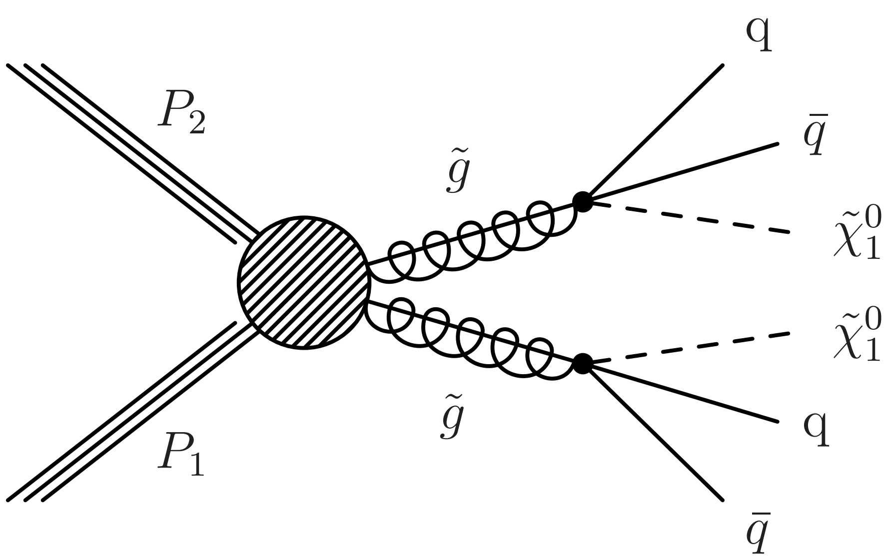
- Look at other DM "bright spots"--dwarf galaxies
- Cosmic ray anti-particles
- Correlated signals, LHC, direct detection
- **Interesting times ahead**

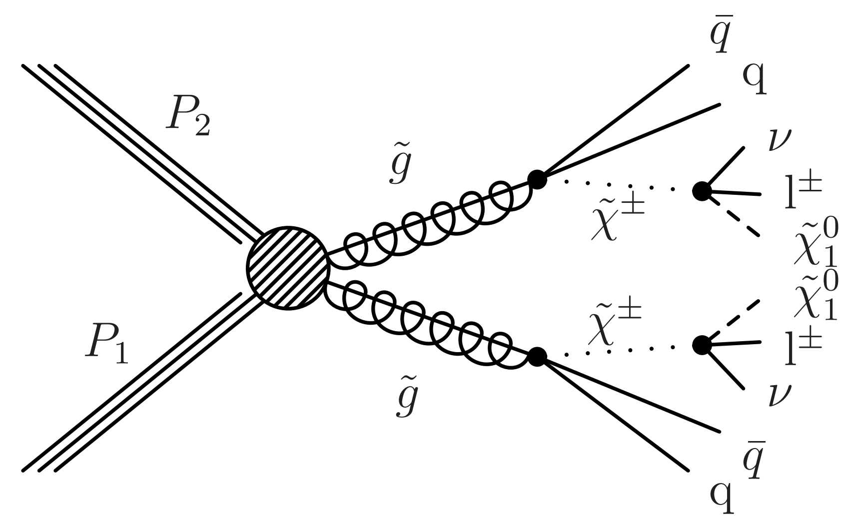
Ways to search for DM at colliders



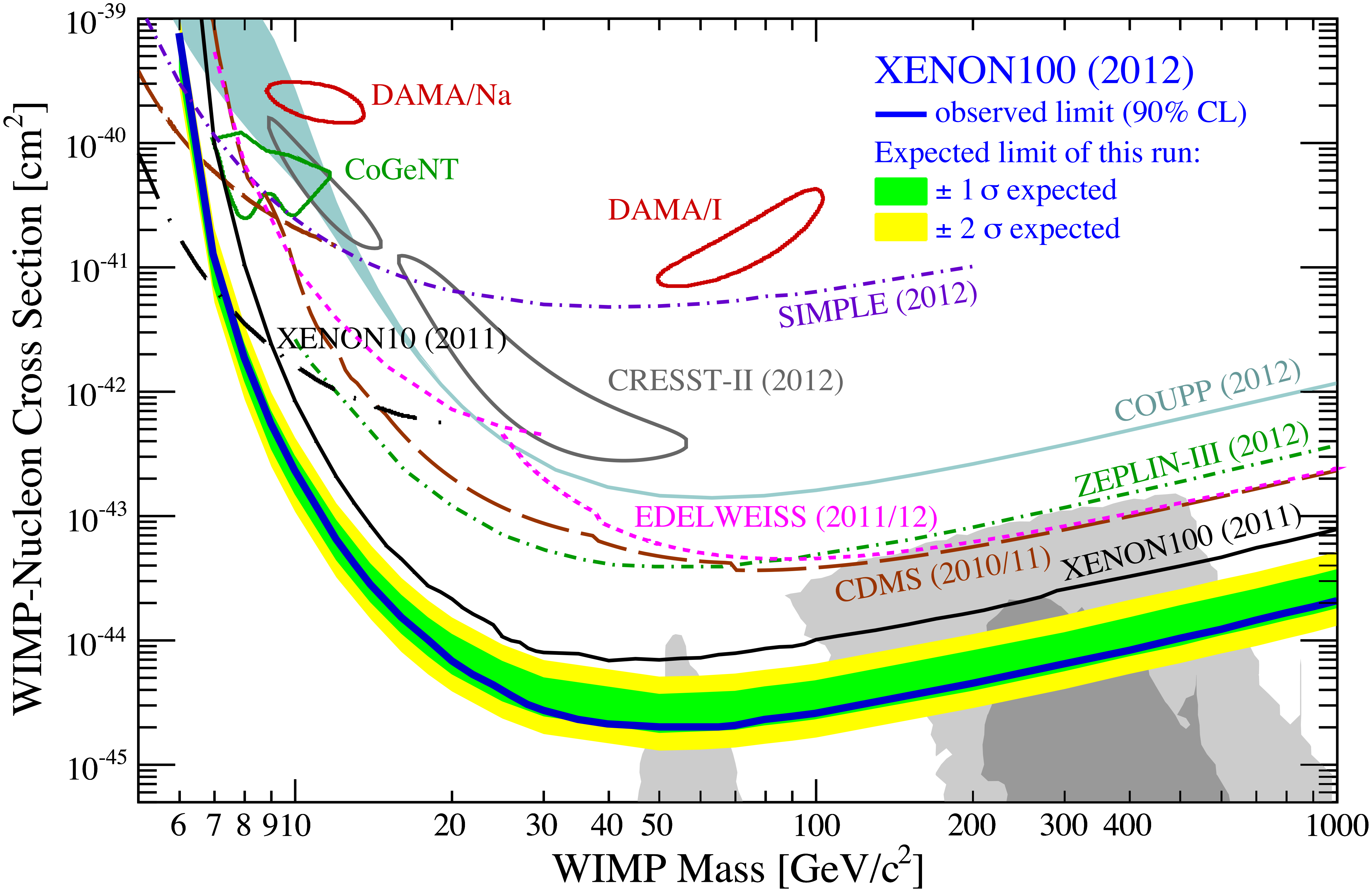
Ways to search for DM at colliders

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

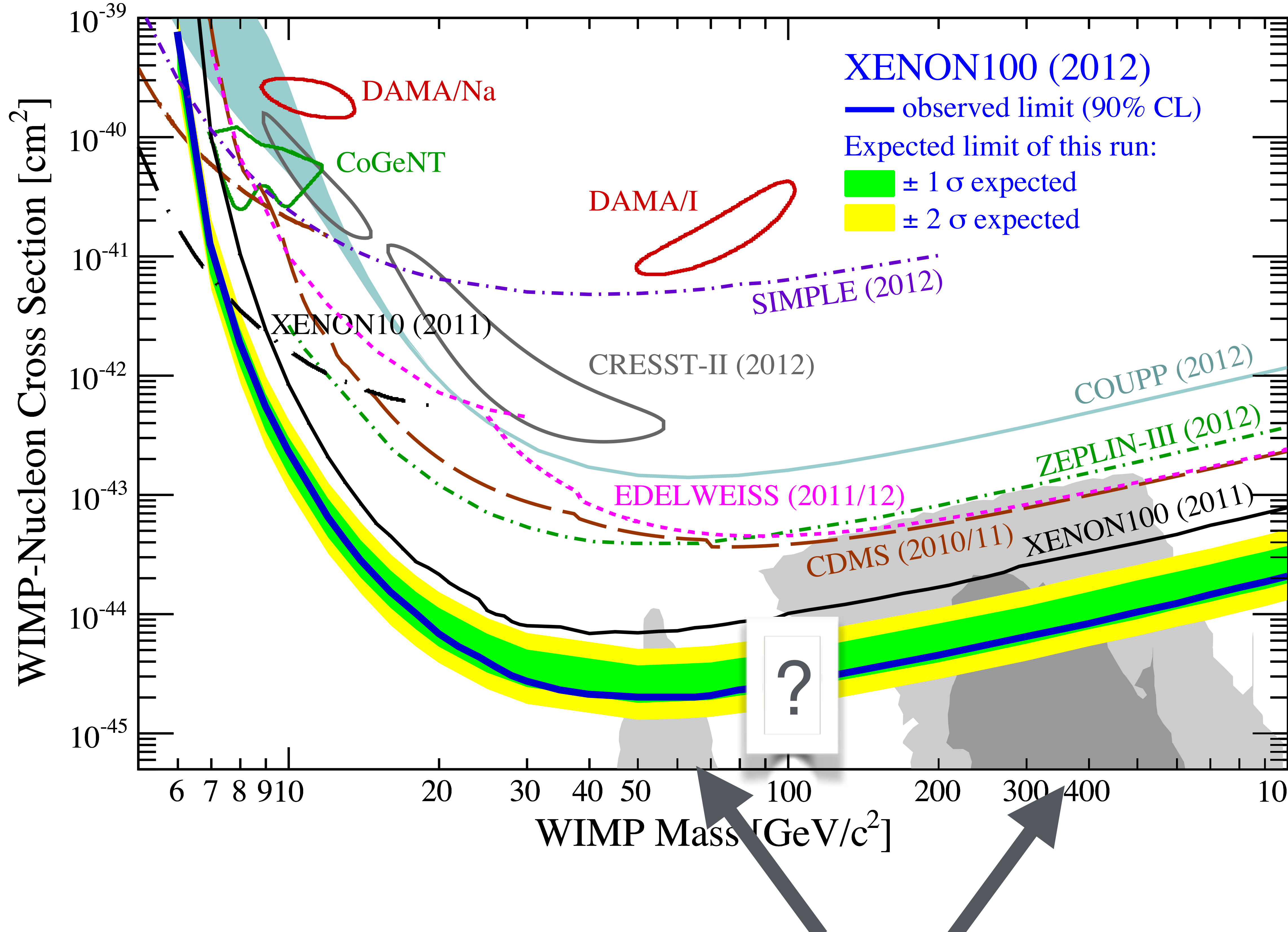




Complicated/interesting final state.
Tuned analyses
No clear relation between different search strategies



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]



SUSY “preferred region”

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

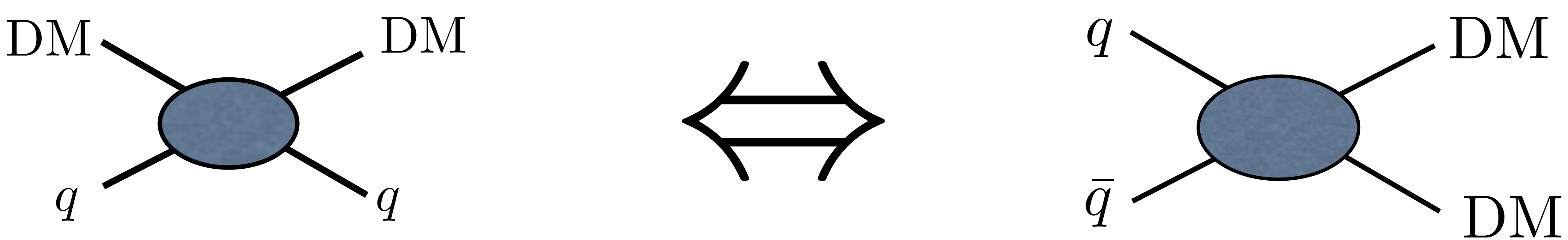
A: traditionally there was no clear way to relate them

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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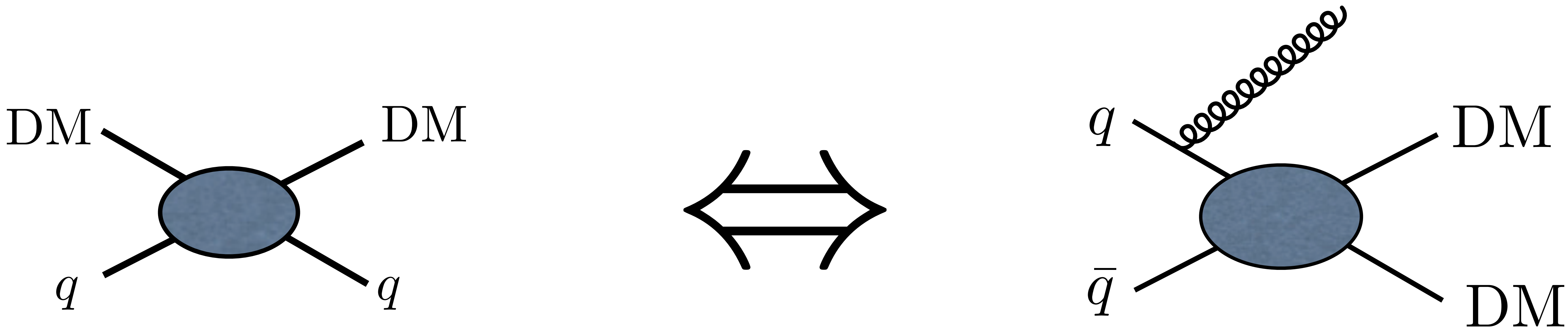
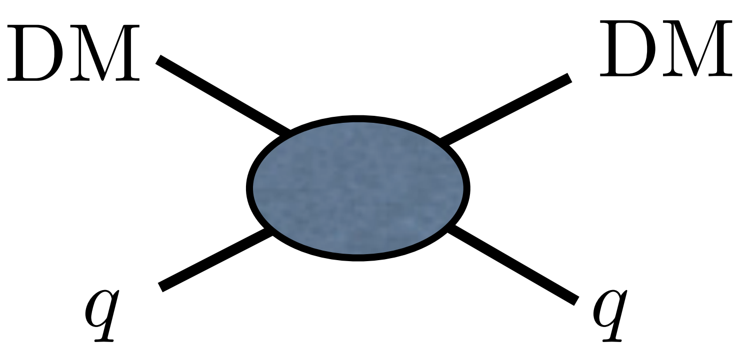


"Monojet", monophoton, mono-top, mono-X,. . . .

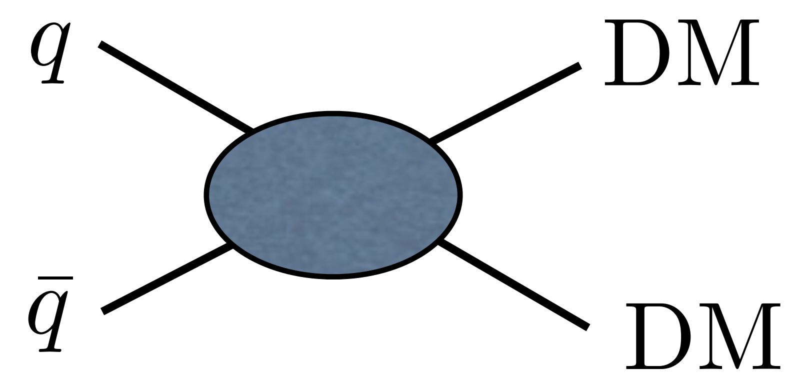
(really up to 2 jets,
with 2 jets not back
to back)

Mono-mania at the LHC

Operators



$\Leftrightarrow$



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

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

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

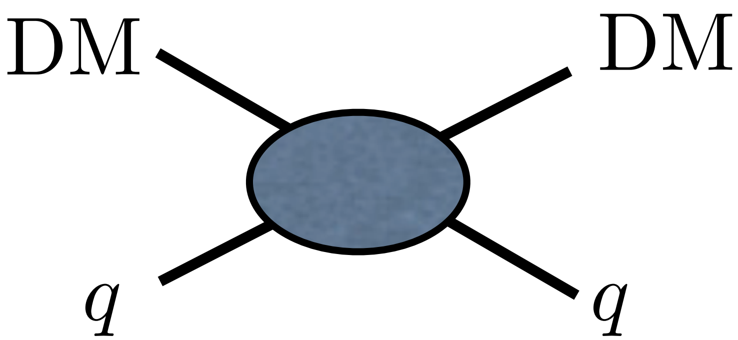
SI, scalar exchange

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

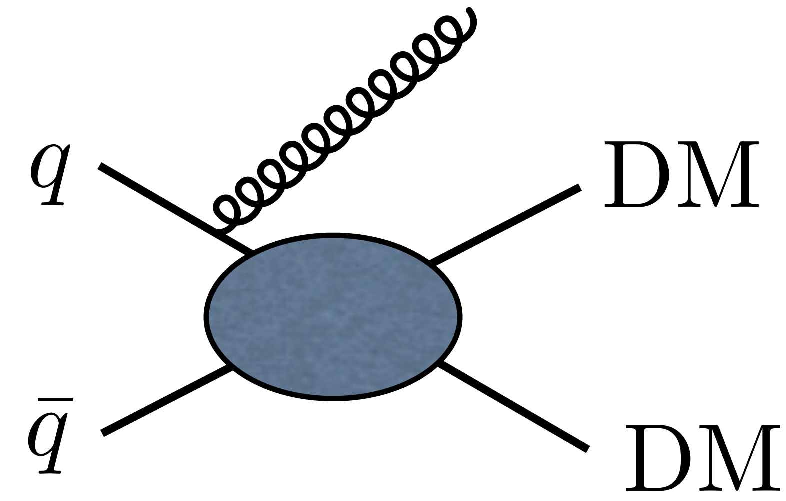
SI, scalar exchange

Typically consider each operator separately

Operators



$\Leftrightarrow$



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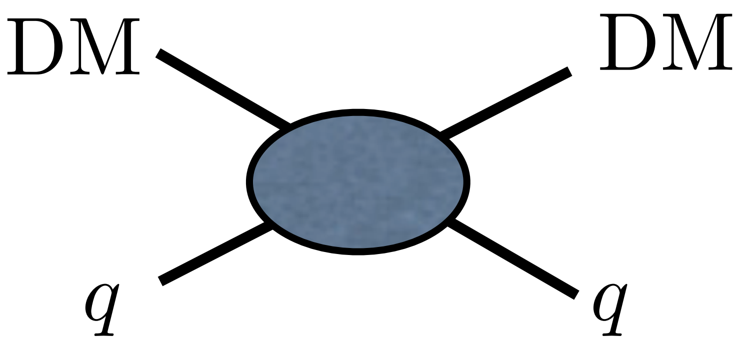
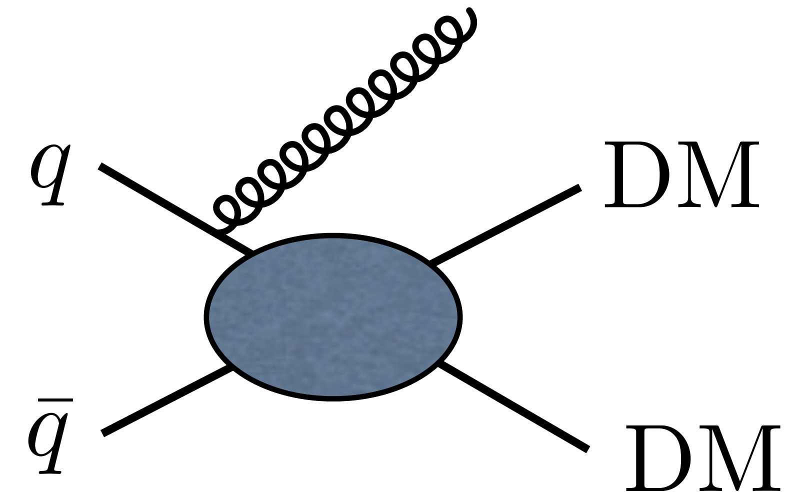


$\Leftrightarrow$



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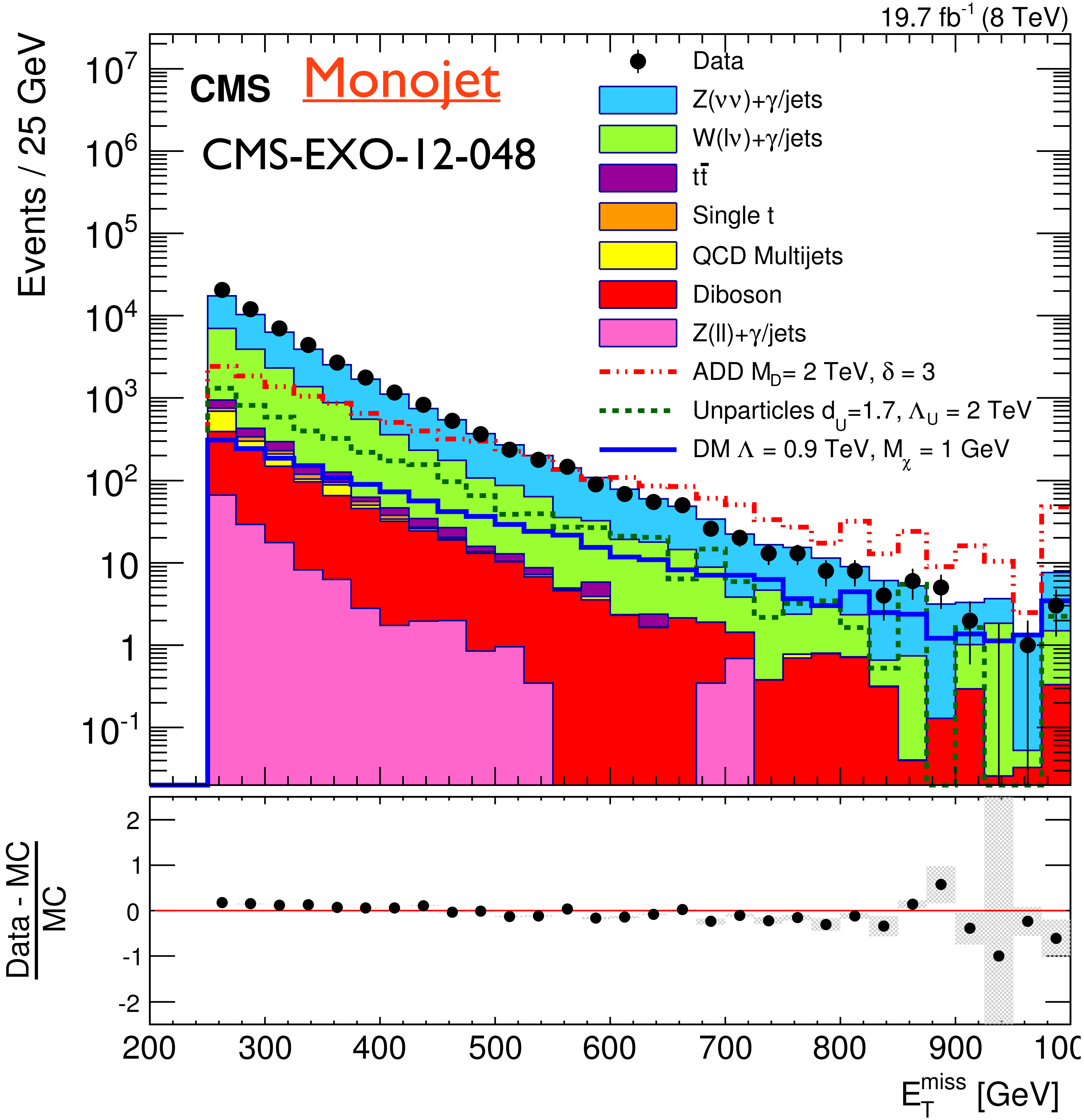
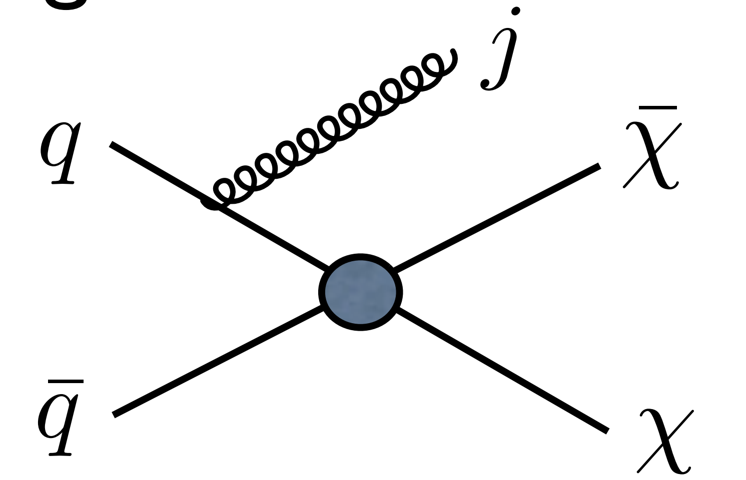
SI, scalar exchange

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

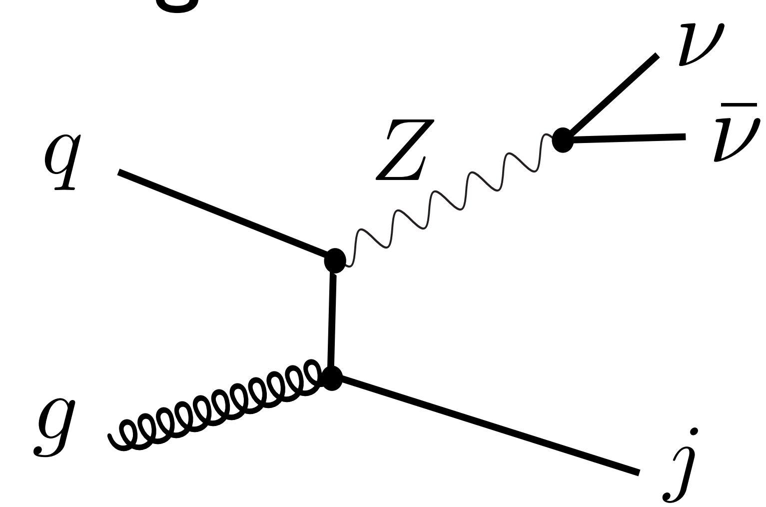
Typically consider each operator separately

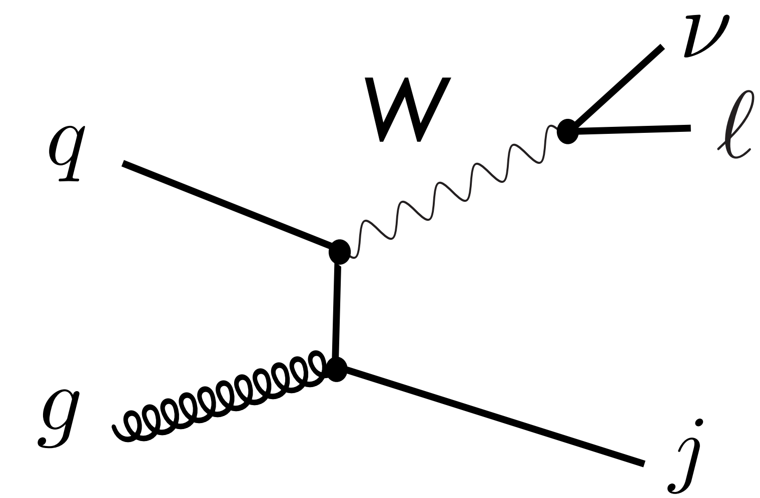


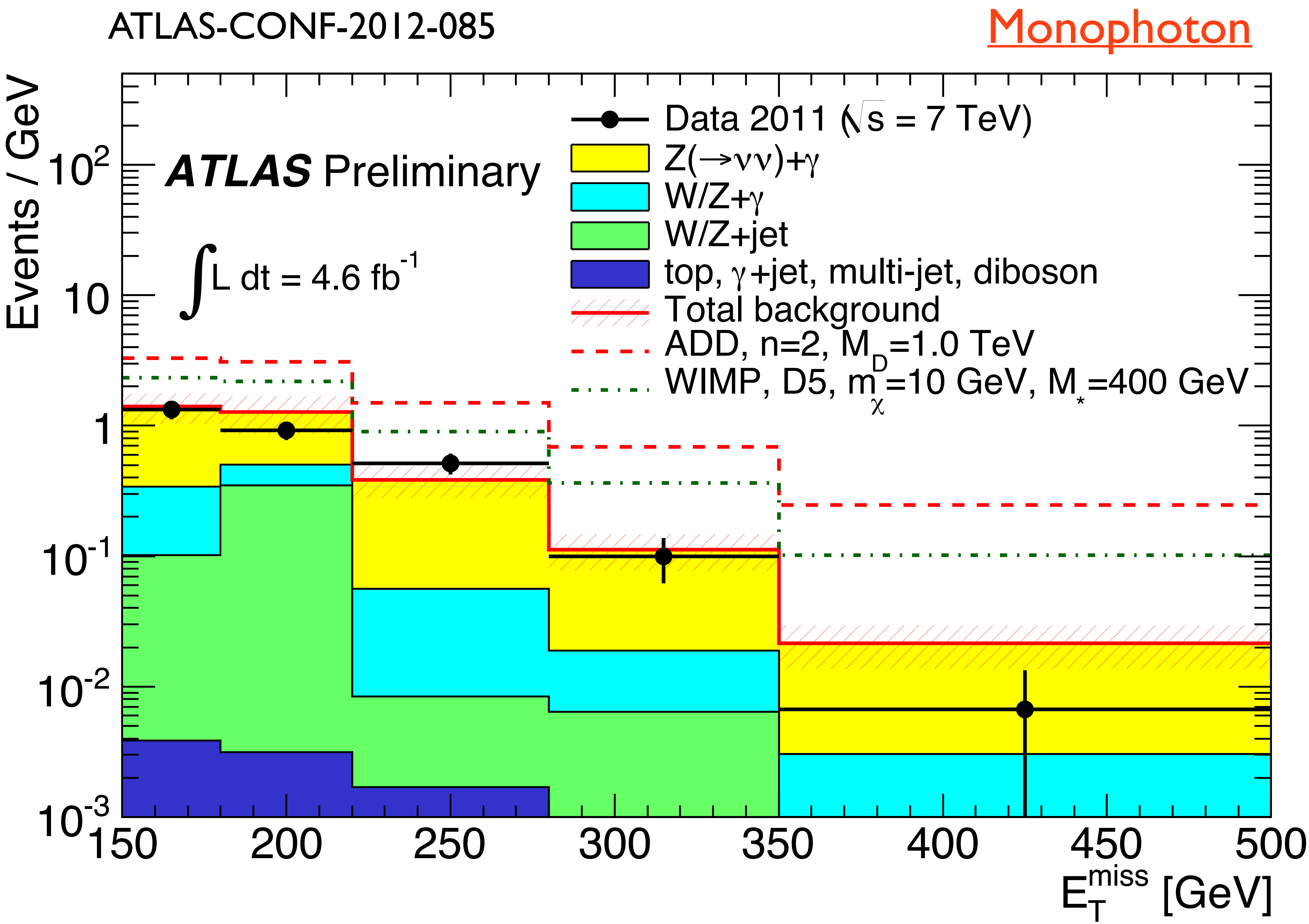
Signal:



(Dominant) Backgrounds:

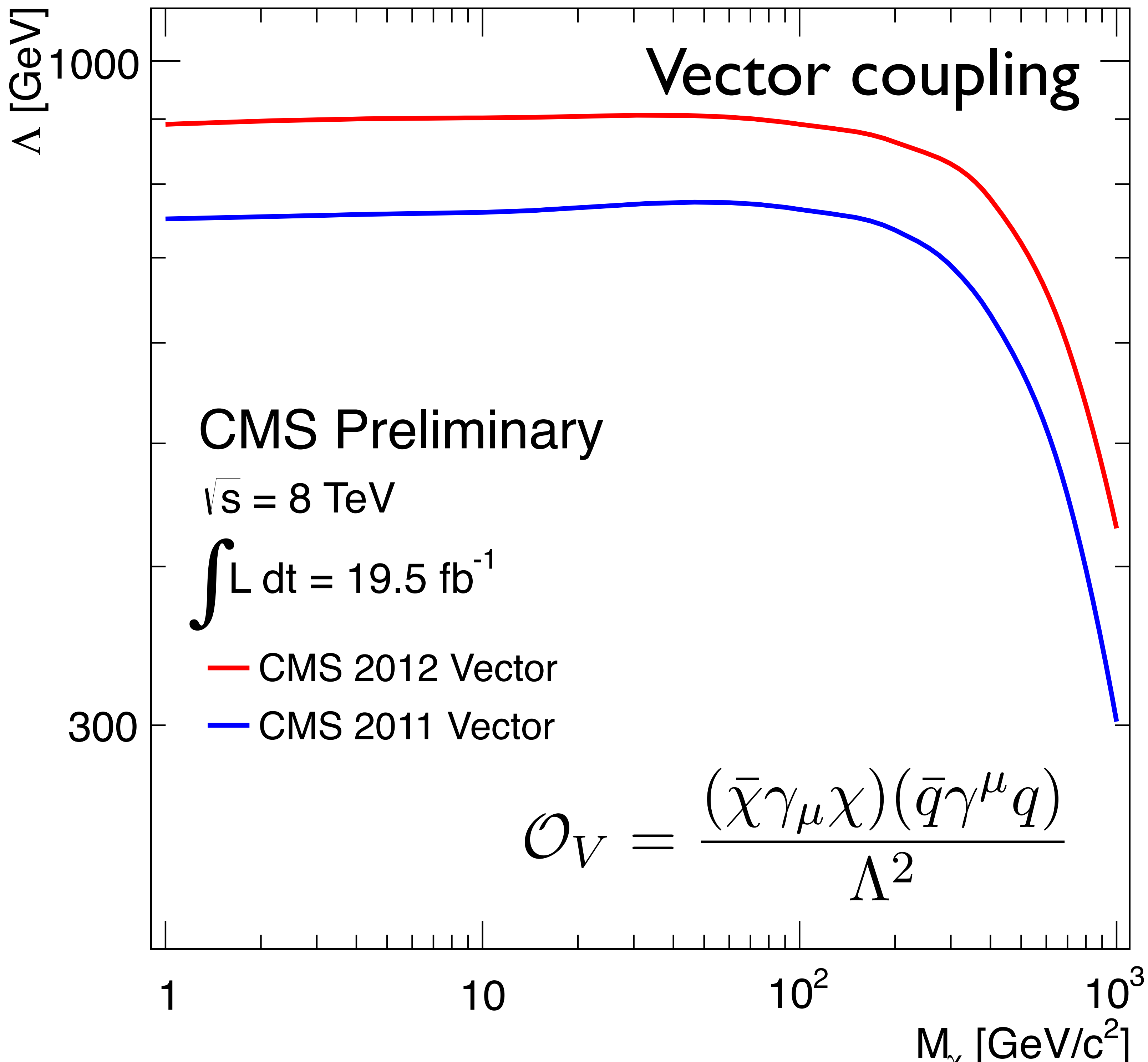


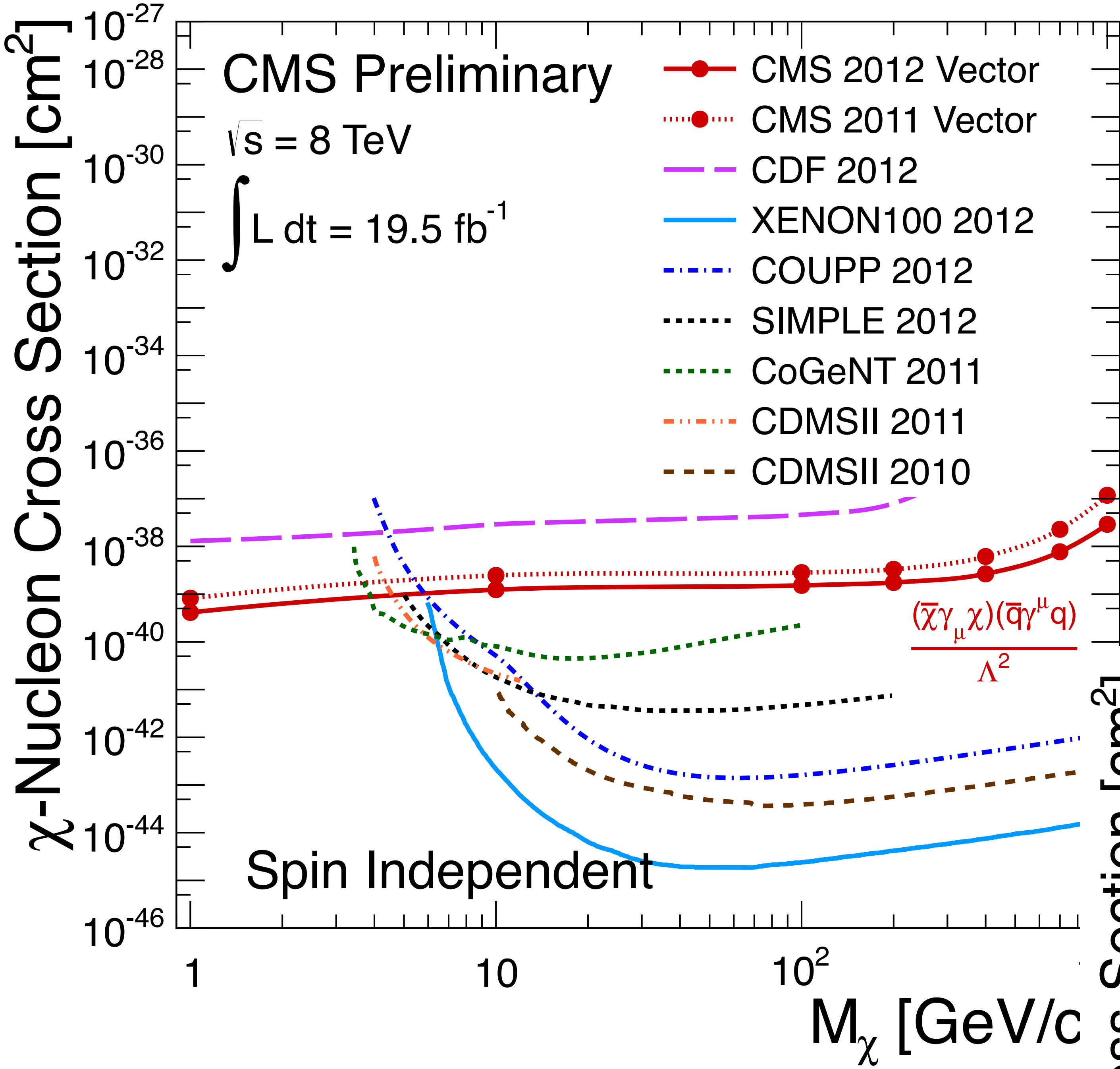


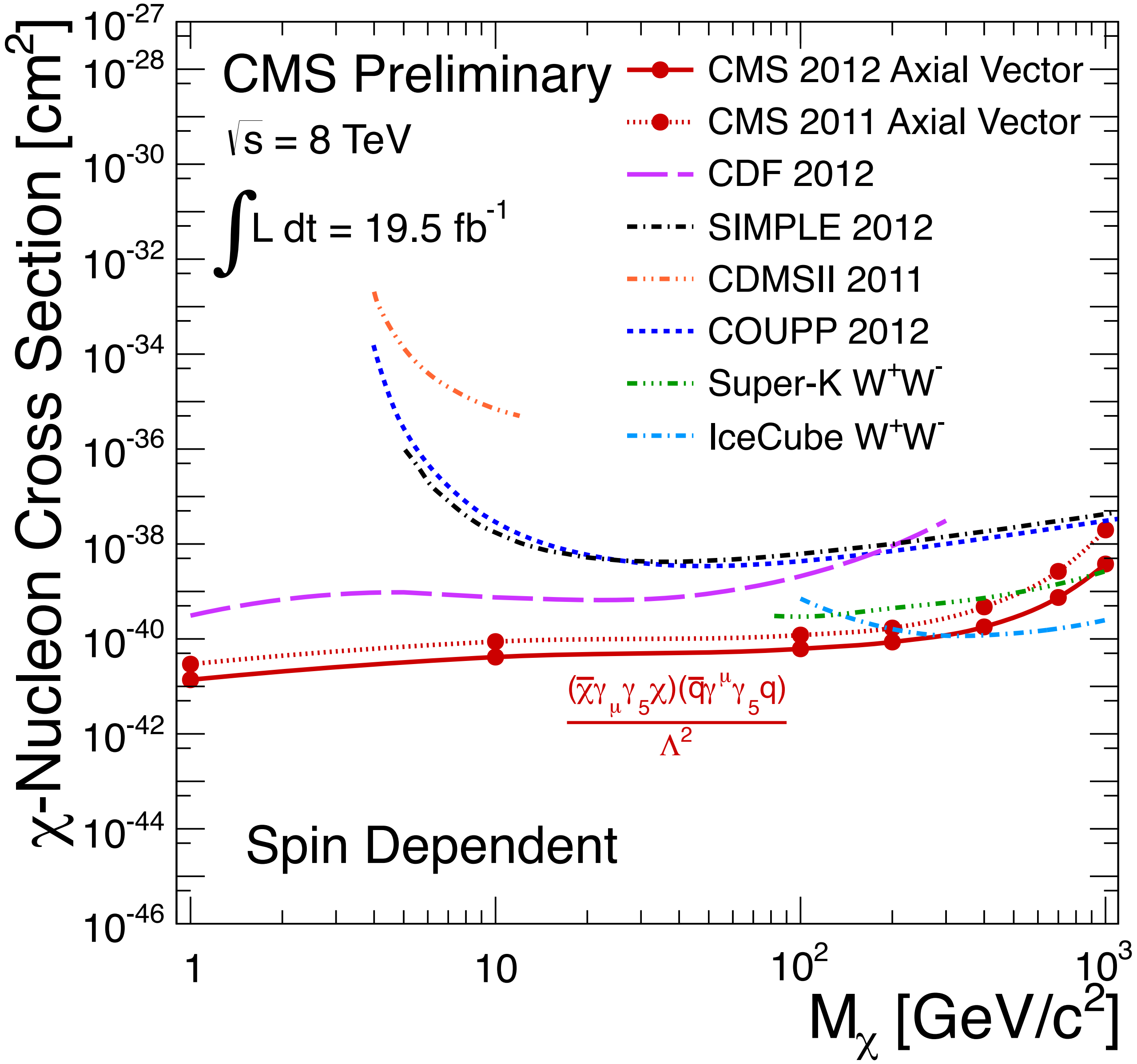


ATLAS-CONF-2012-085
Monophoton
ATLAS Preliminary
∫L dt = 4.6 fb-1
Data 2011 (√s = 7 TeV)
Z(→νν)+γ
W/Z+γ
W/Z+jet
top, γ+jet, multi-jet, diboson
Total background
ADD, n=2, MD=1.0 TeV
WIMP, D5, mχ=10 GeV, M*=400 GeV
Events / GeV
ETmiss [GeV]
10-3
10-2
10-1
1
10
102
150
200
250
300
350
400
450
500

How to quantify nothing?







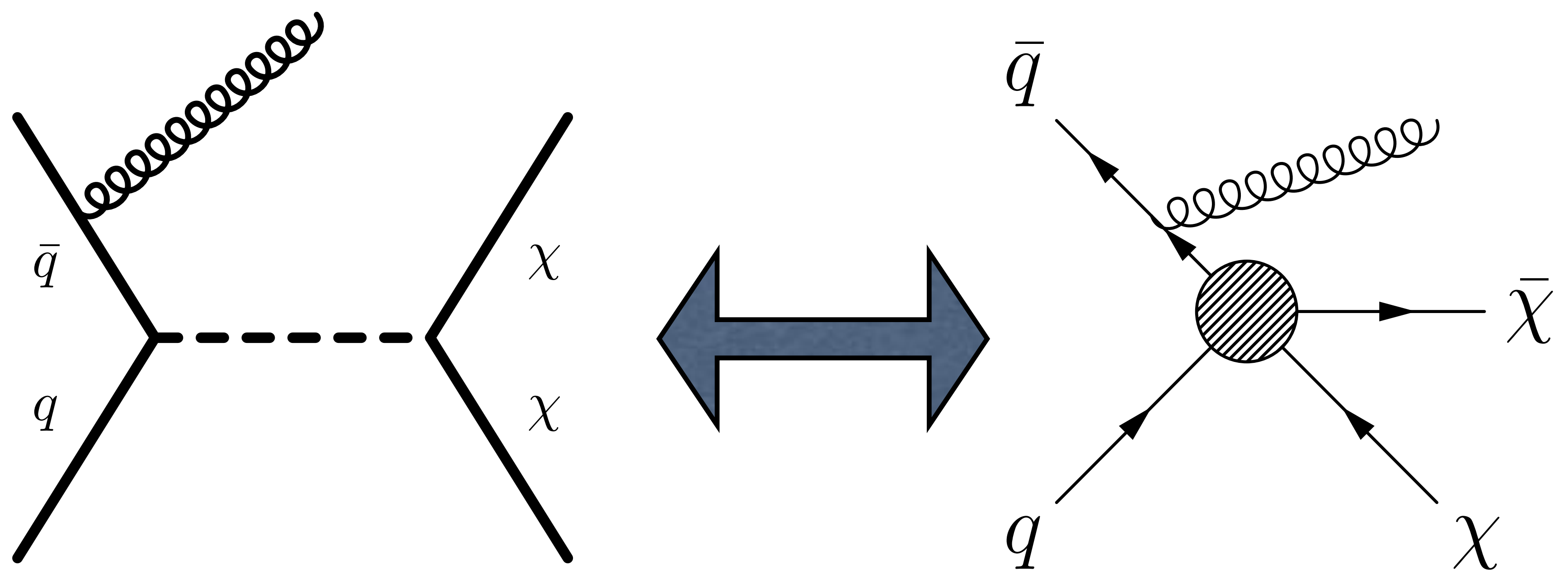
Colliders give complementary constraint at low mass and for SD

Light Mediators

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

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

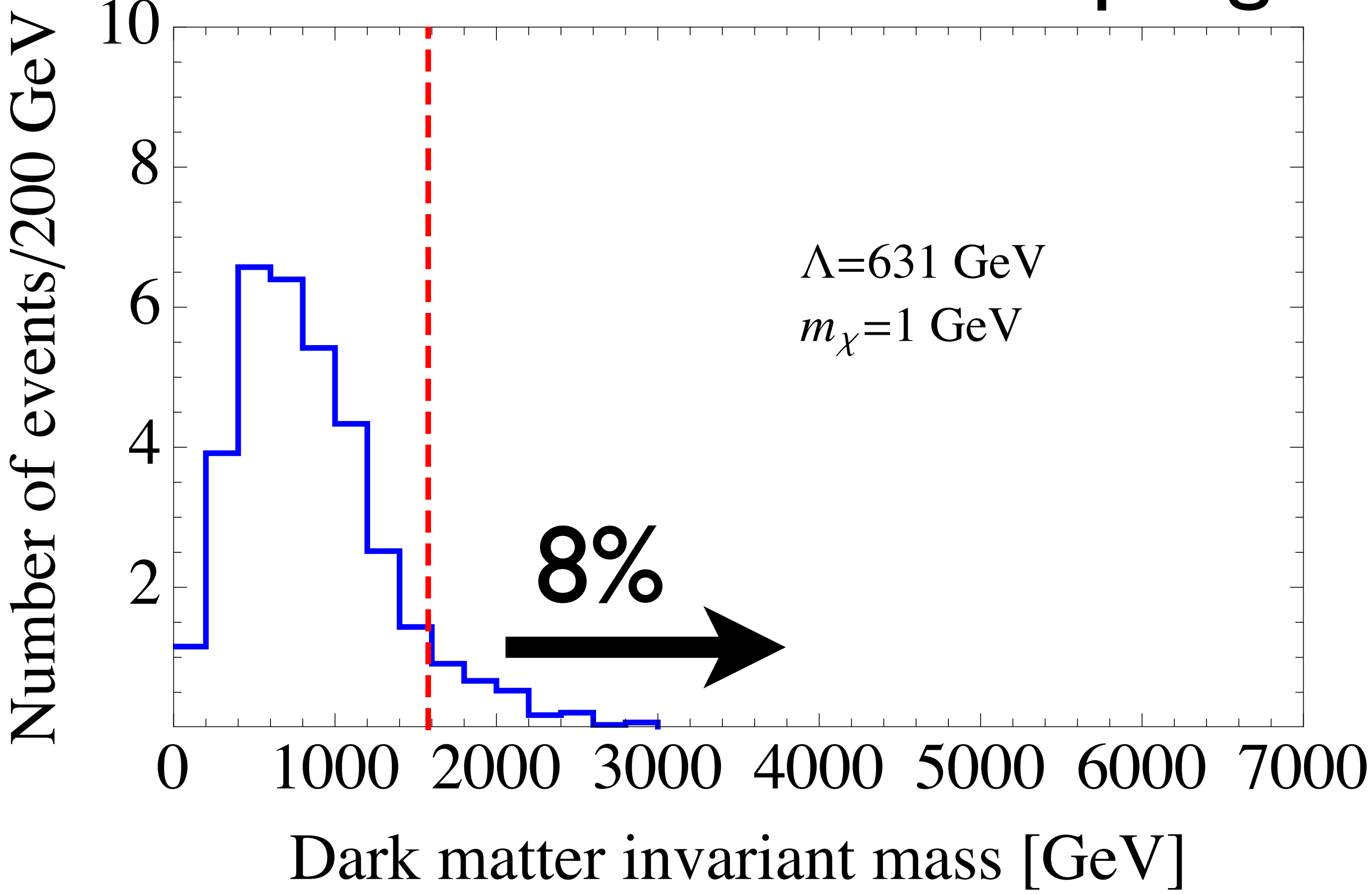
What fraction of collider events have momentum transfers sufficient to probe the UV completion?



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

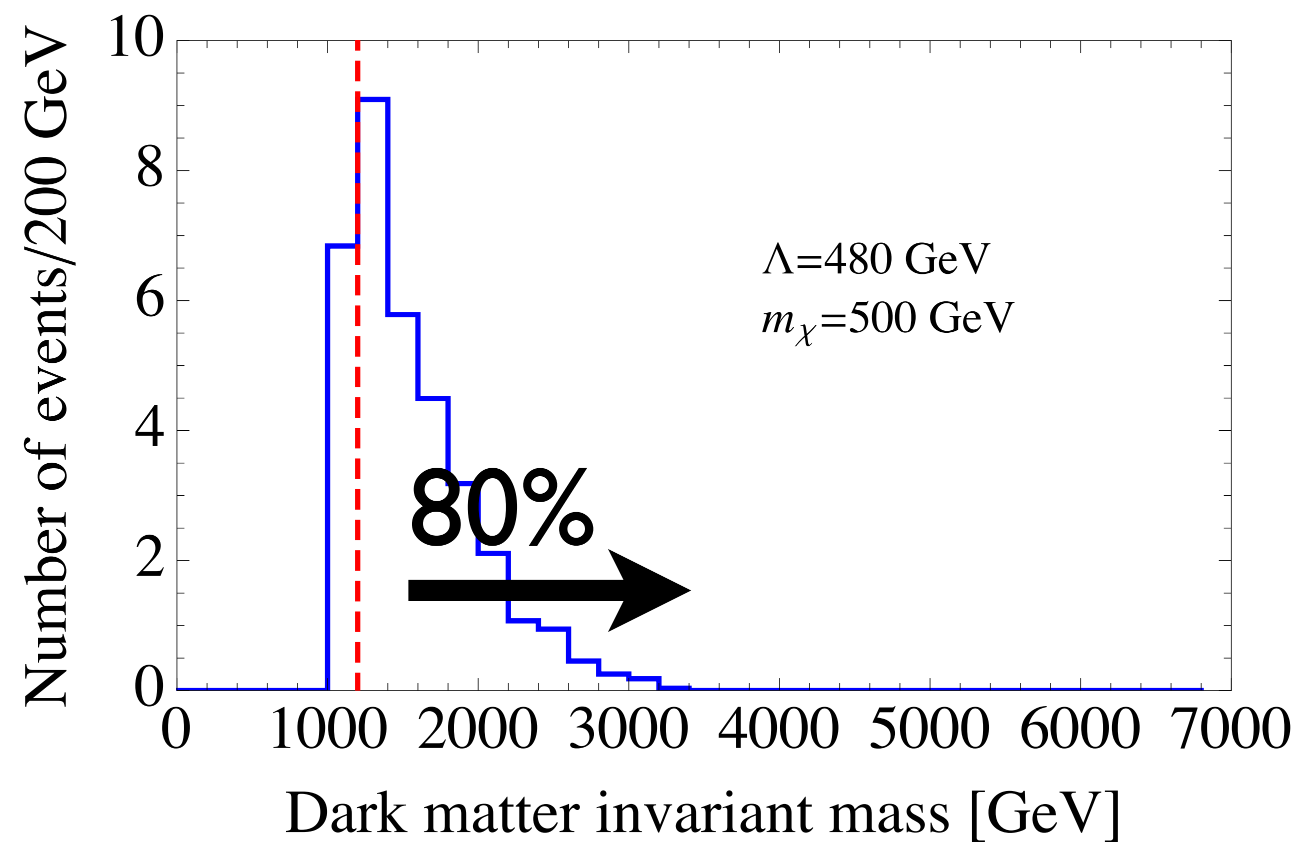
[PJF et al, 1203.1662]

Vector coupling



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

[Shoemaker and Vecchi, 1112.5457]

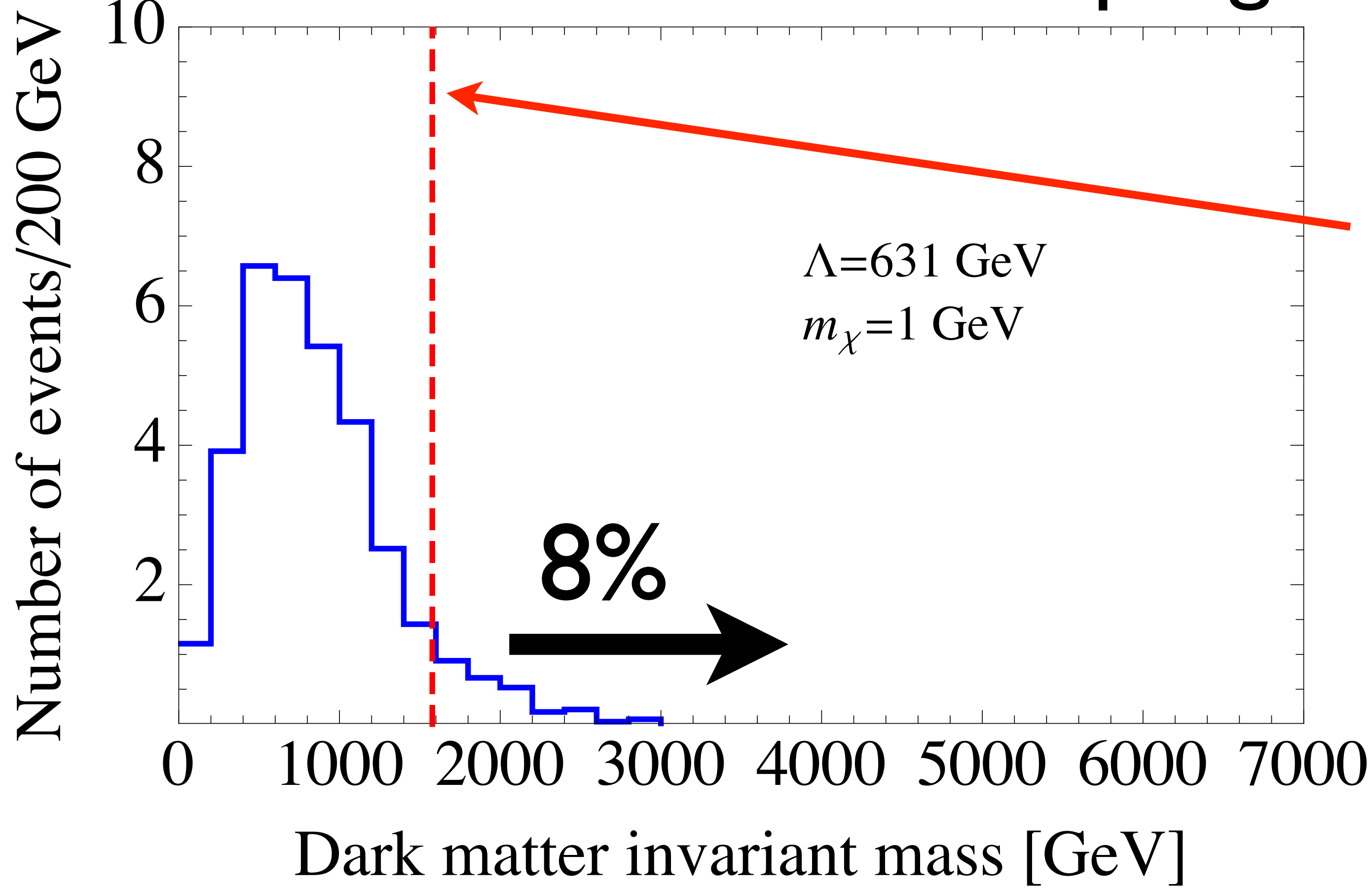


Fraction of events where EFT breaks down may be non-negligible

Depends on DM mass

[PJF et al, 1203.1662]

Vector coupling



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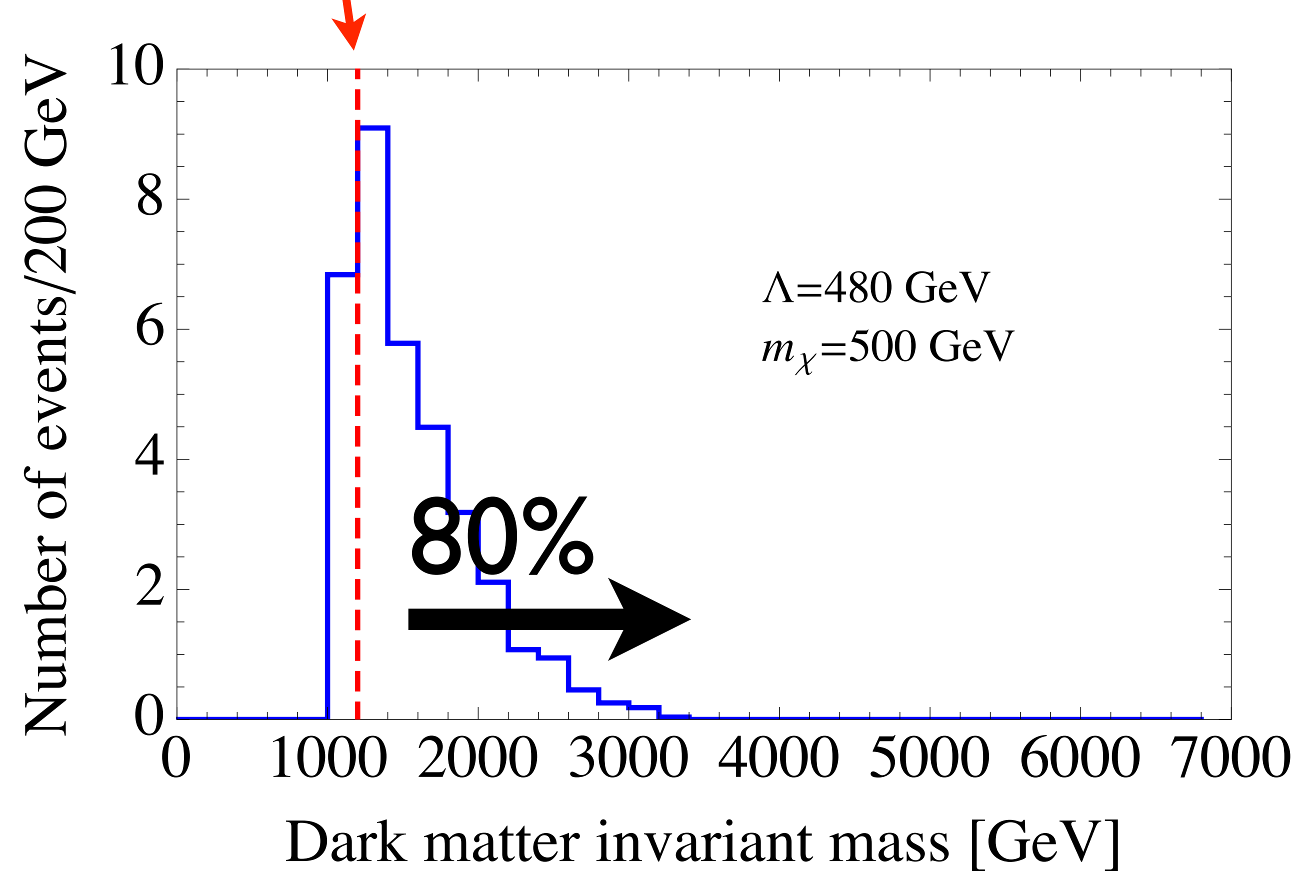

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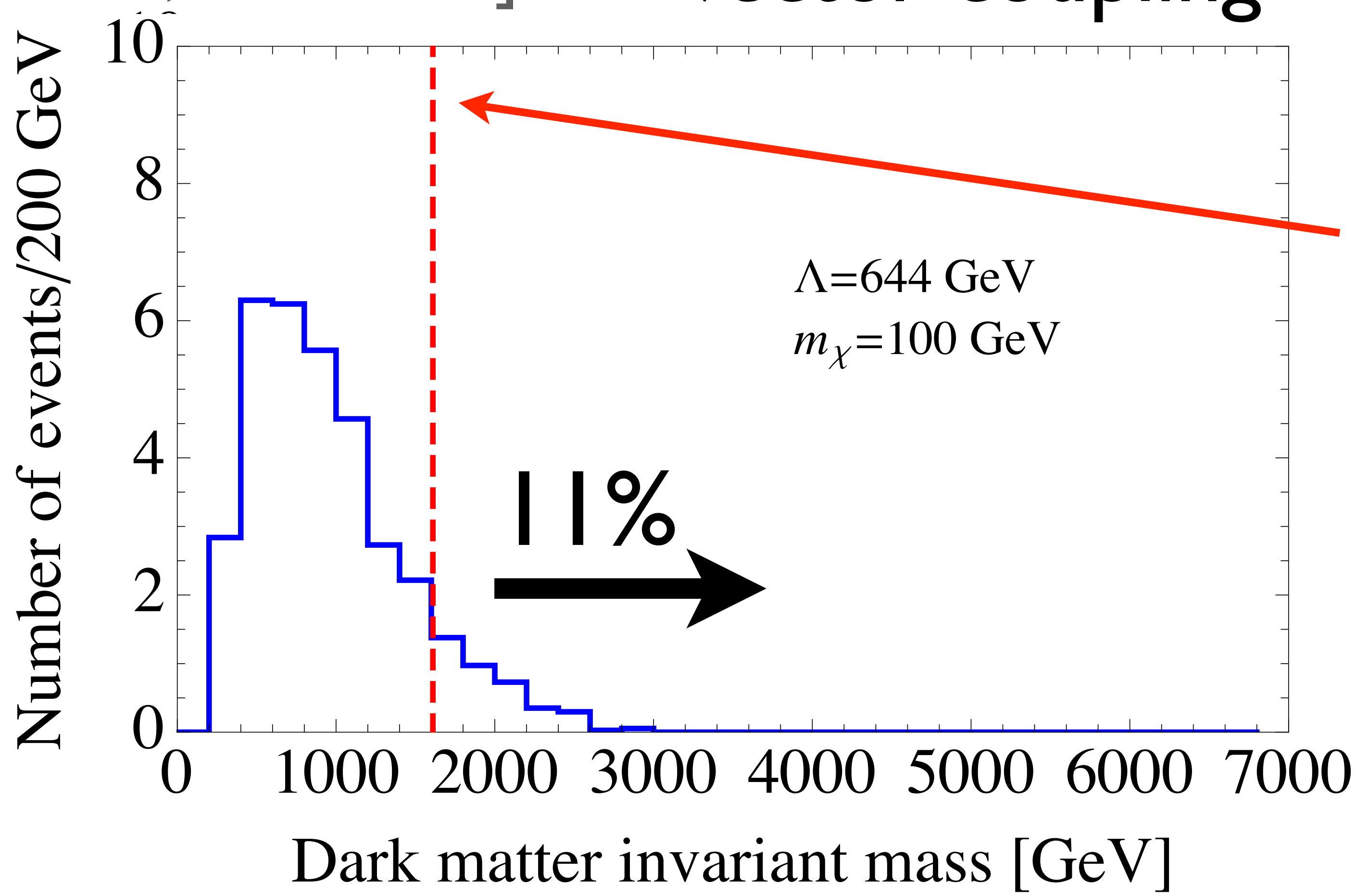

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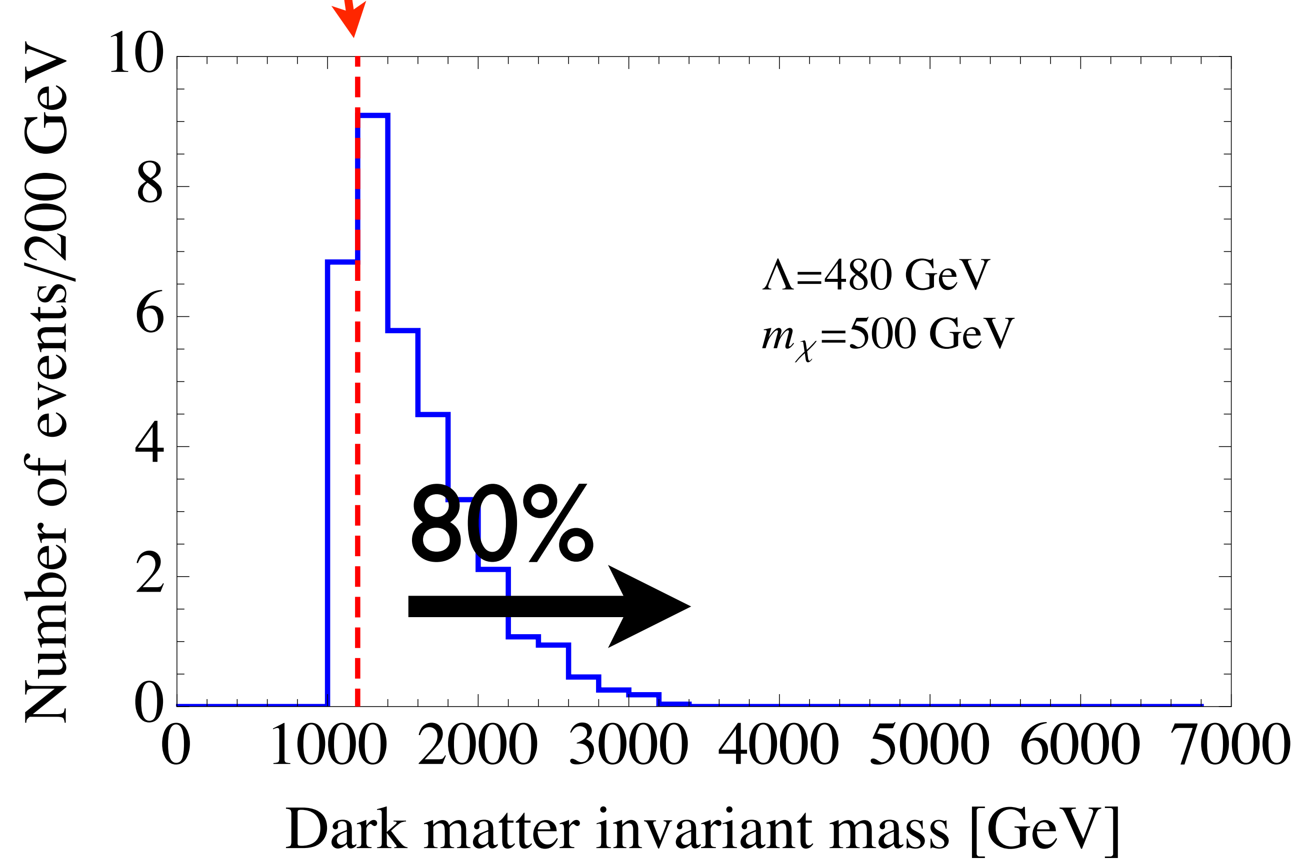

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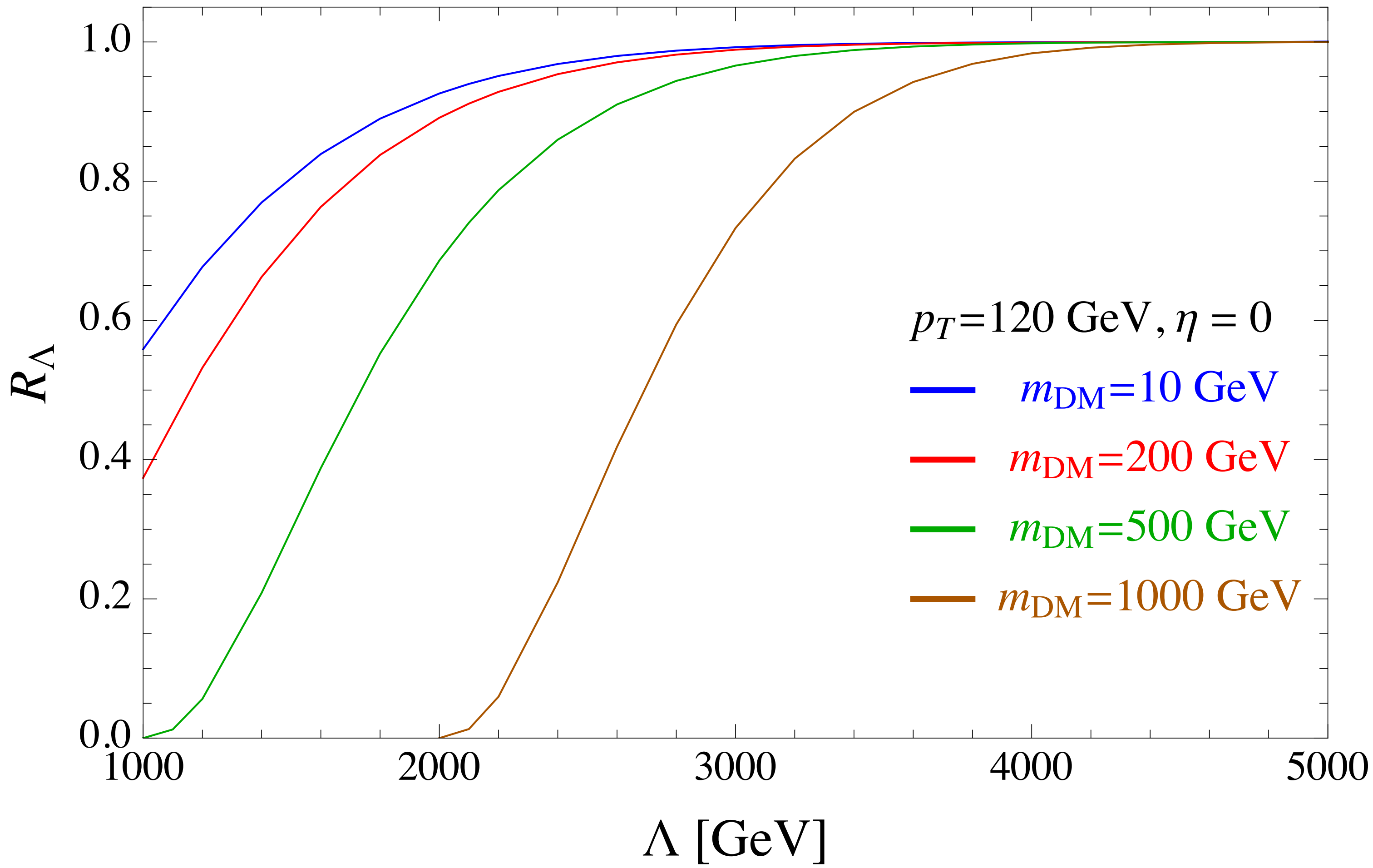
Depends on DM mass

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

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

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



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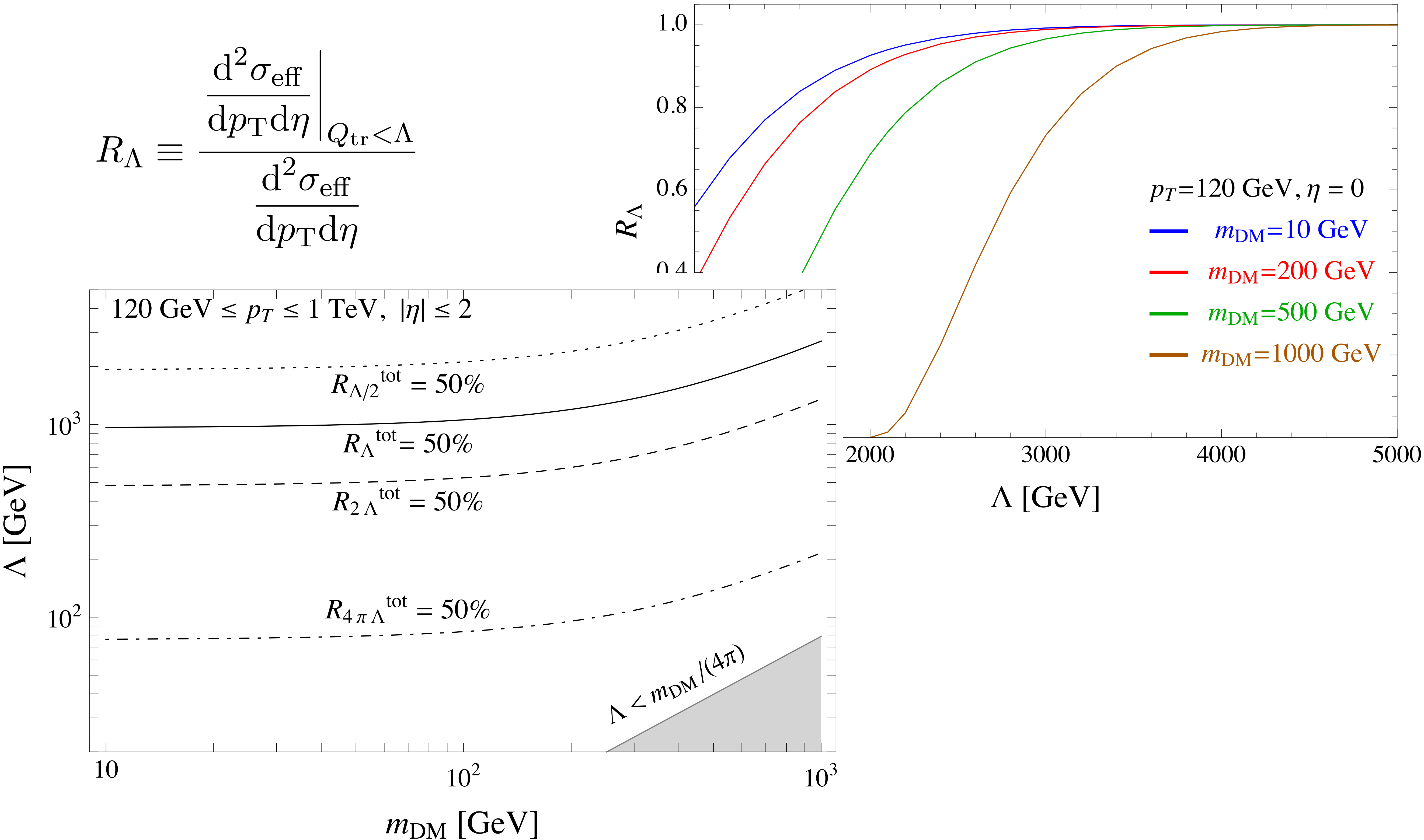
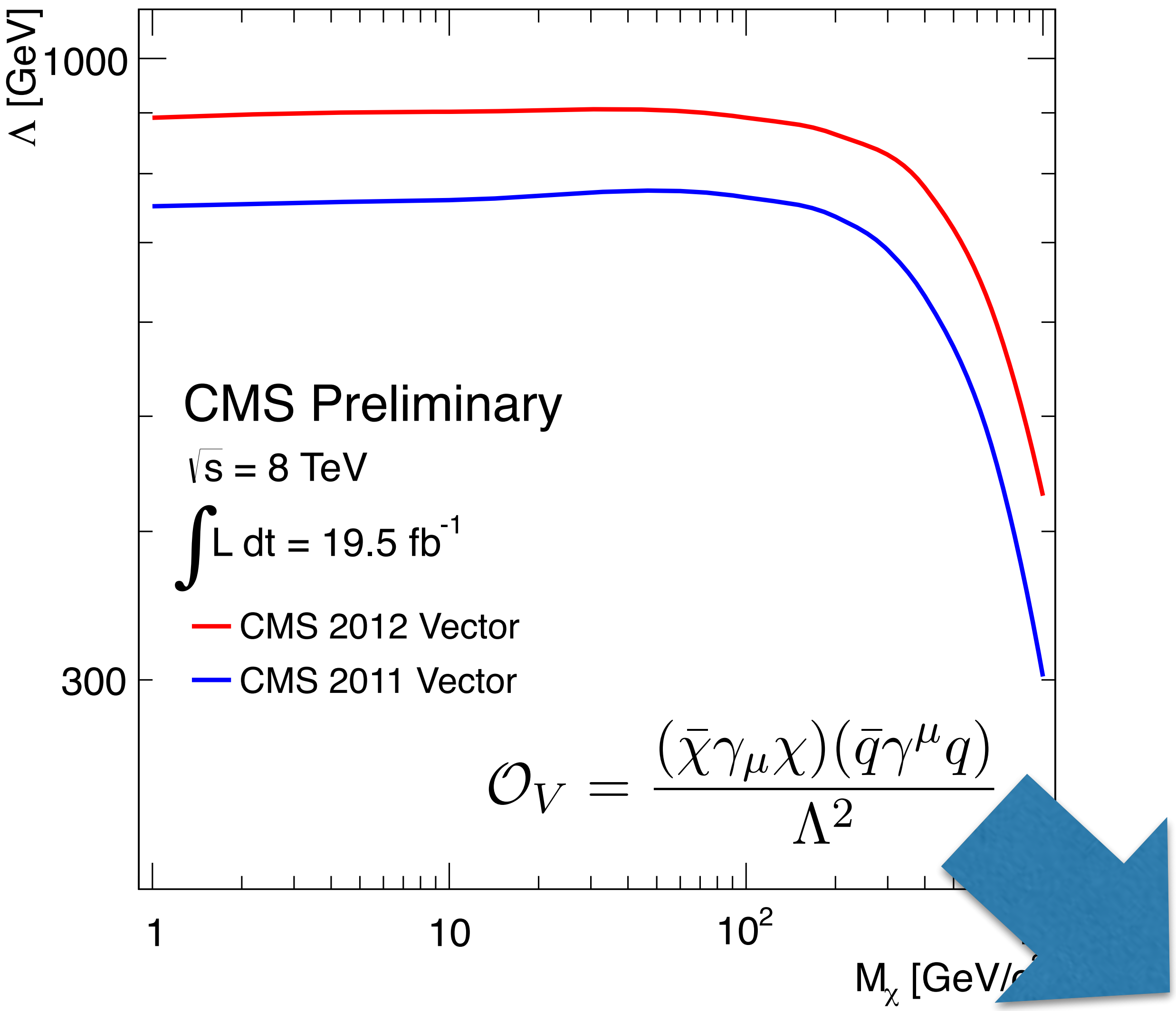
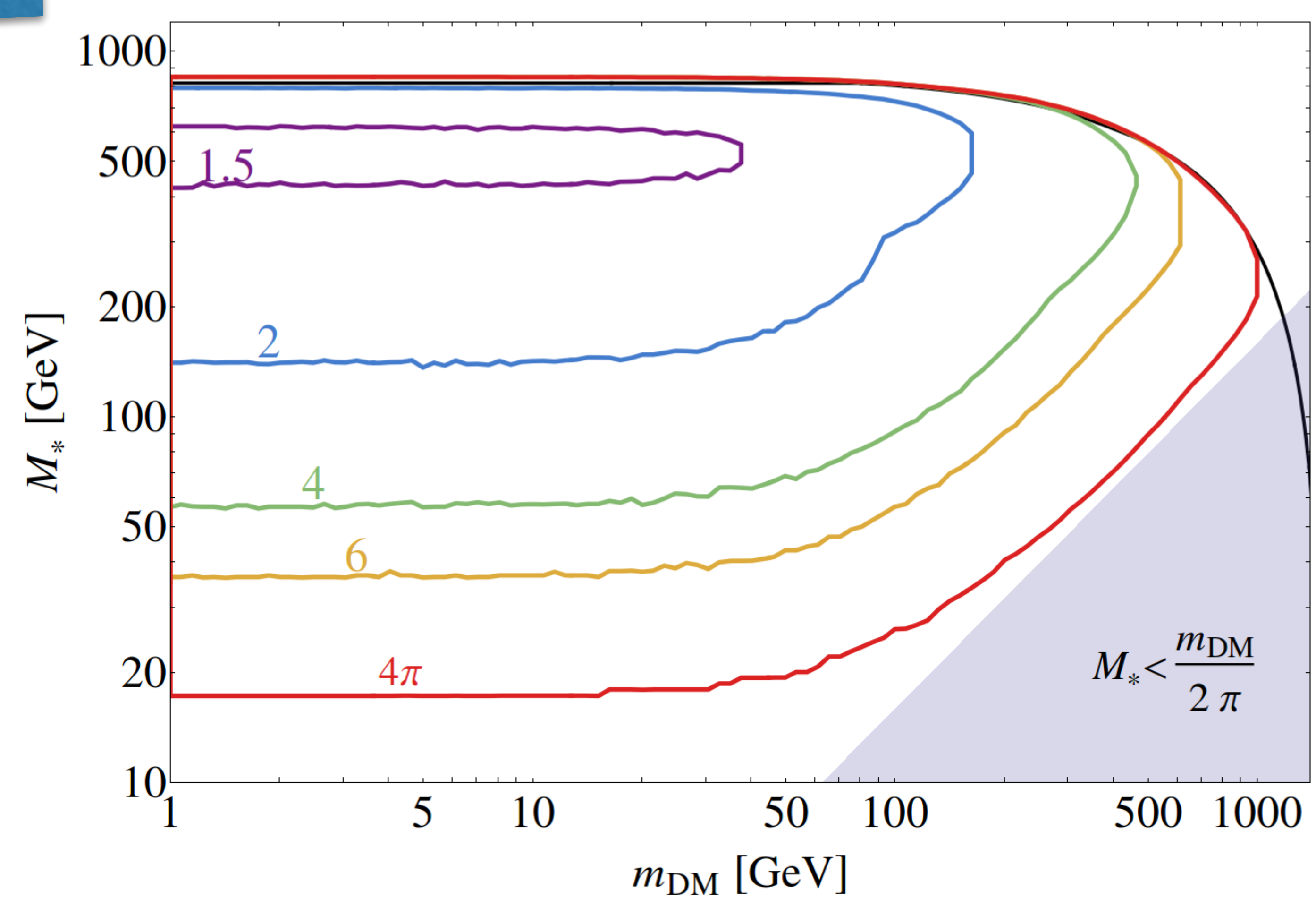




Cutting off theory at the mediator mass scale alters the bounds

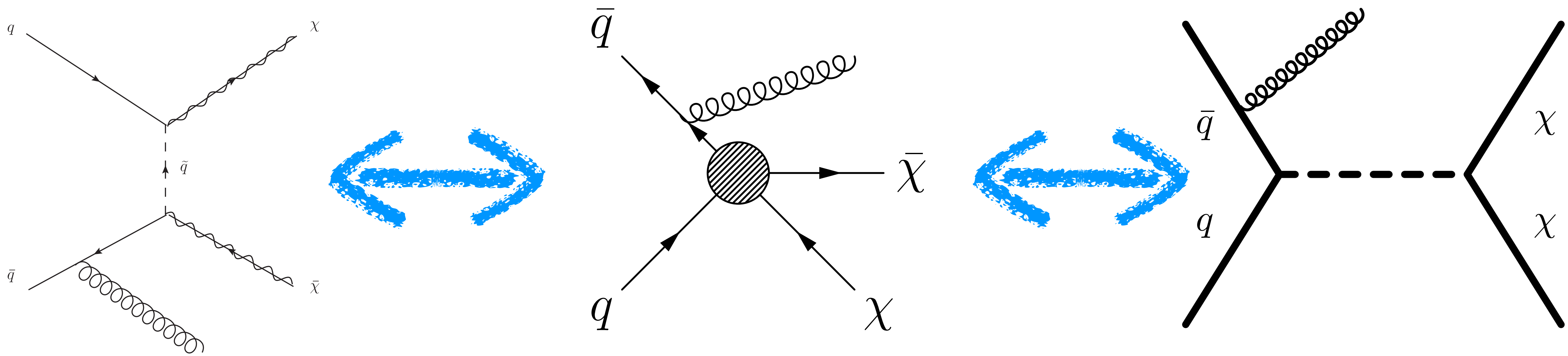
Racco, Wulzer, Zwirner [1502.04701]



Simplified Models

"Integrate in" the mediator

t-channel EFT s-channel

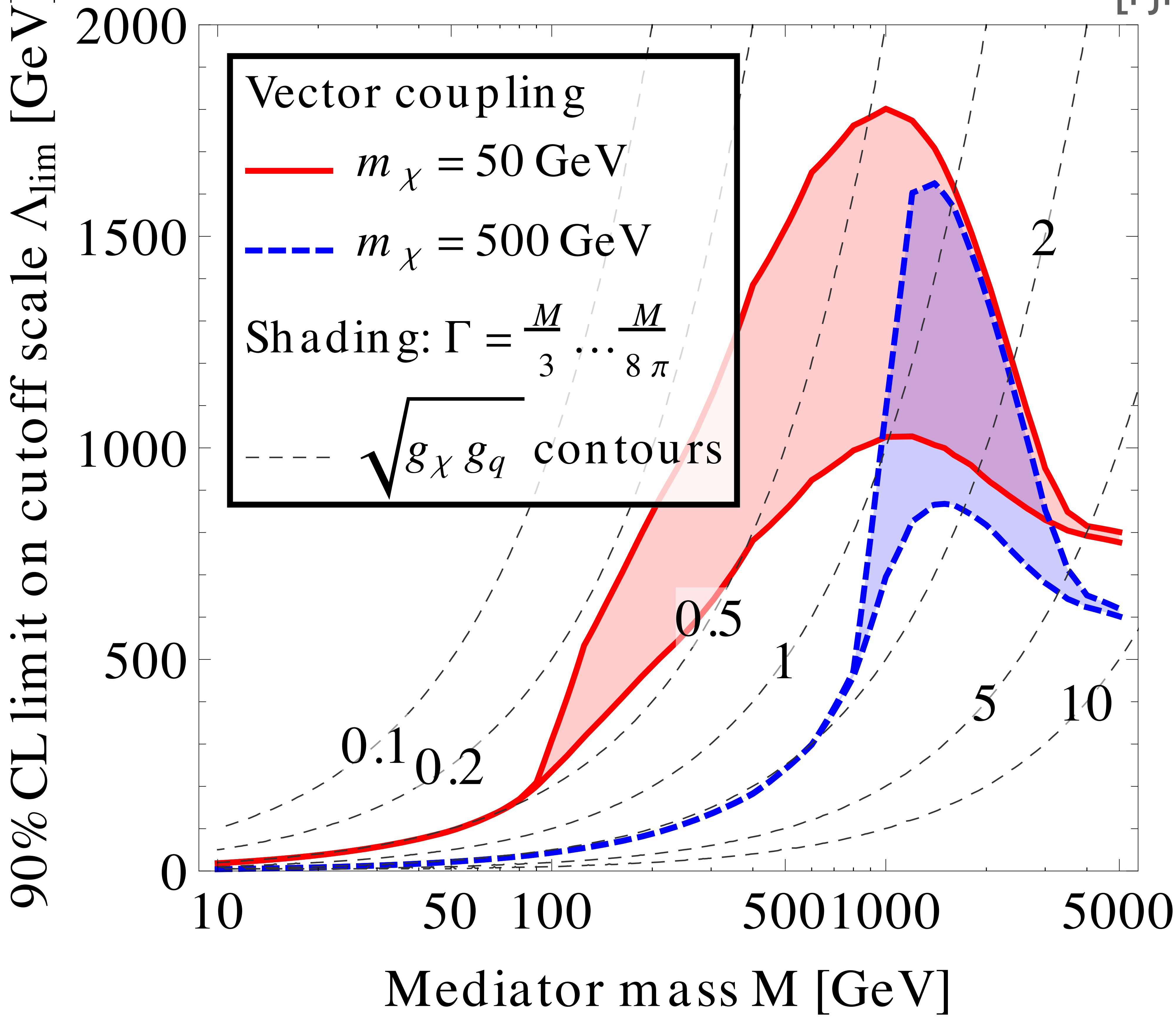


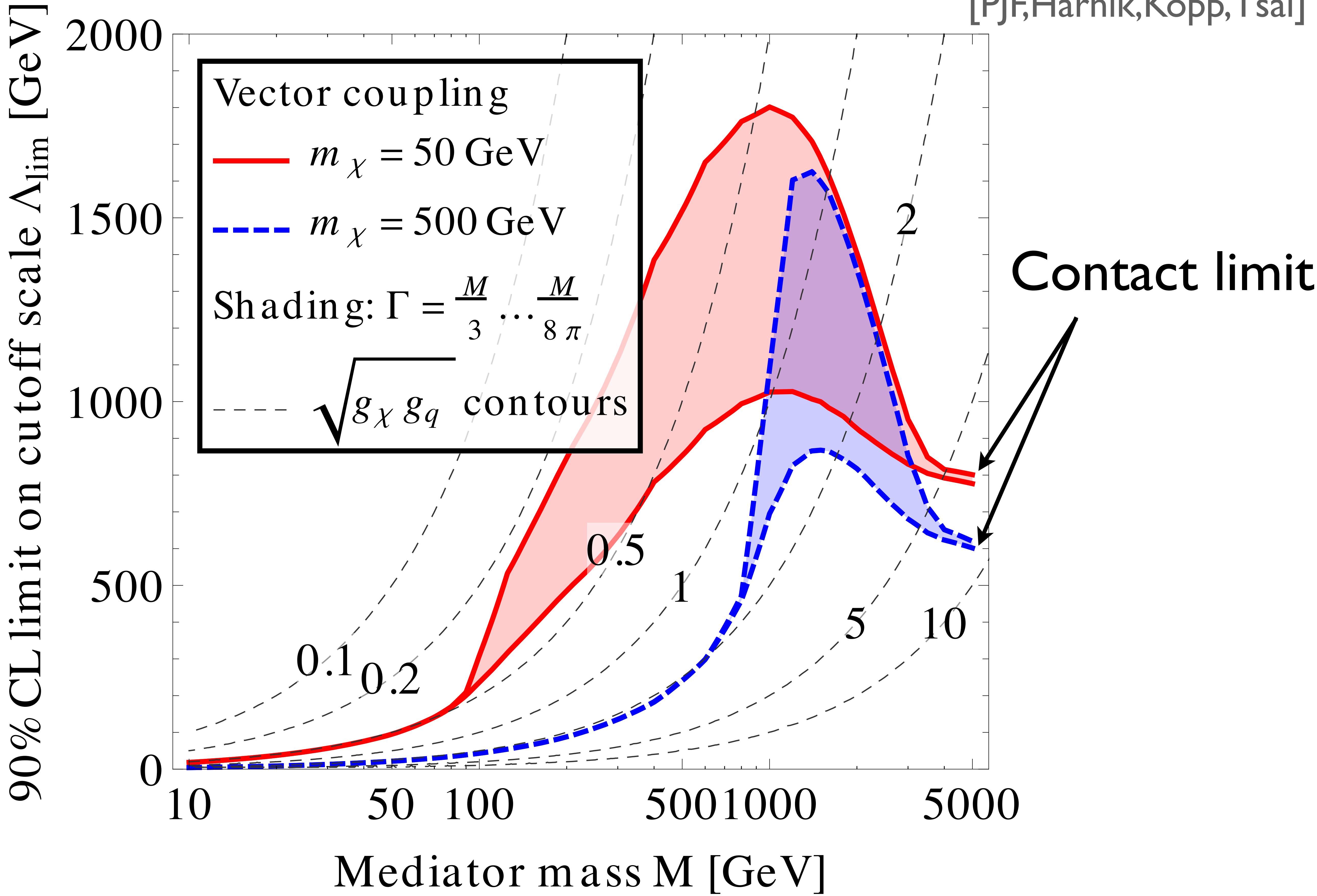
$$\Lambda,\ m_\chi \longrightarrow m_\chi,\ M,\ \Gamma,\ \sqrt{g_q g_\chi}$$

New channels to search for!

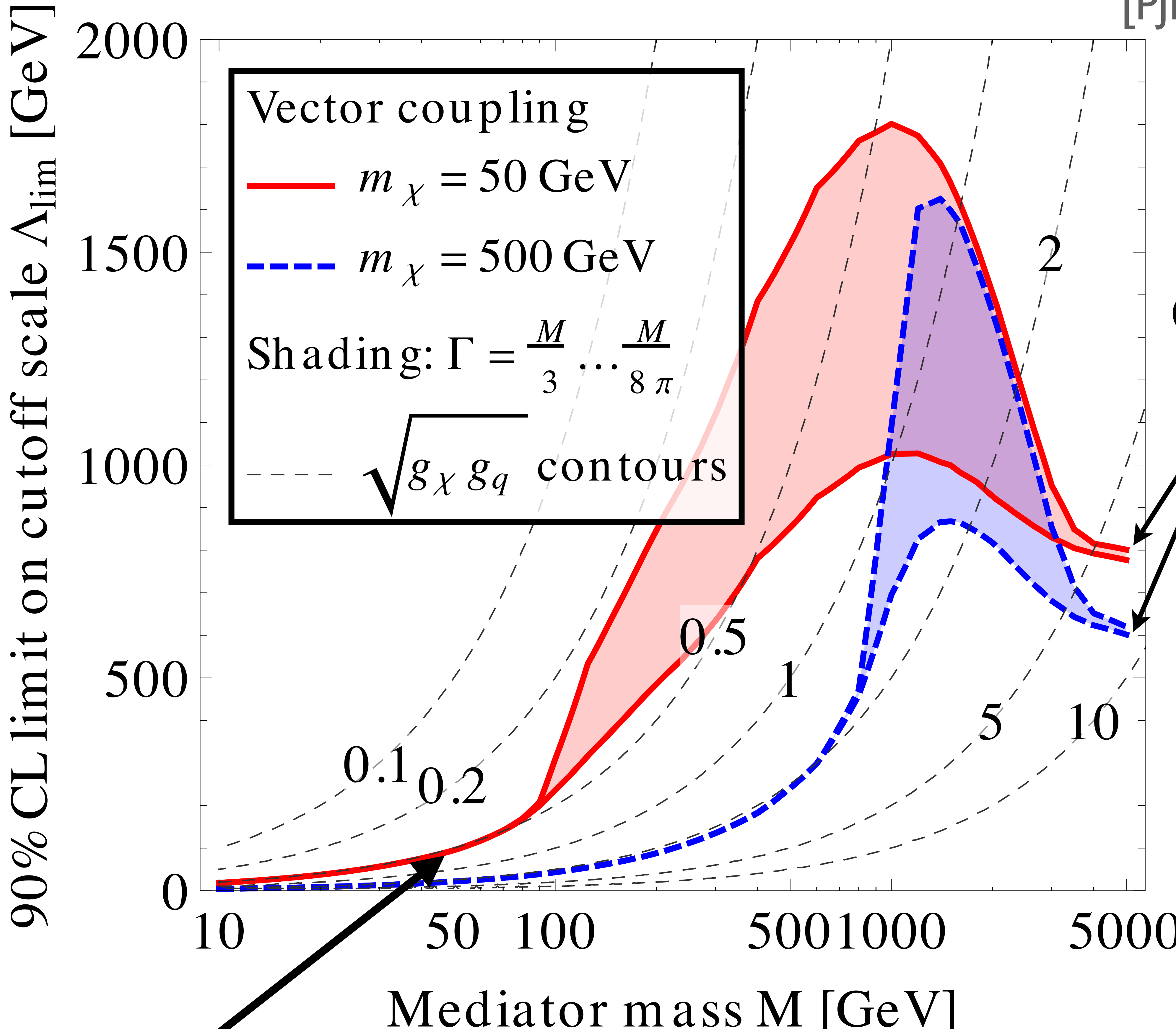
Collider only sensitive to all 4 parameters over a narrow range

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


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
90% CL limit on cutoff scale Λ_{lim} [GeV]
0
500
1000
1500
2000
Mediator mass M [GeV]
10
50
100
500
1000
5000


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

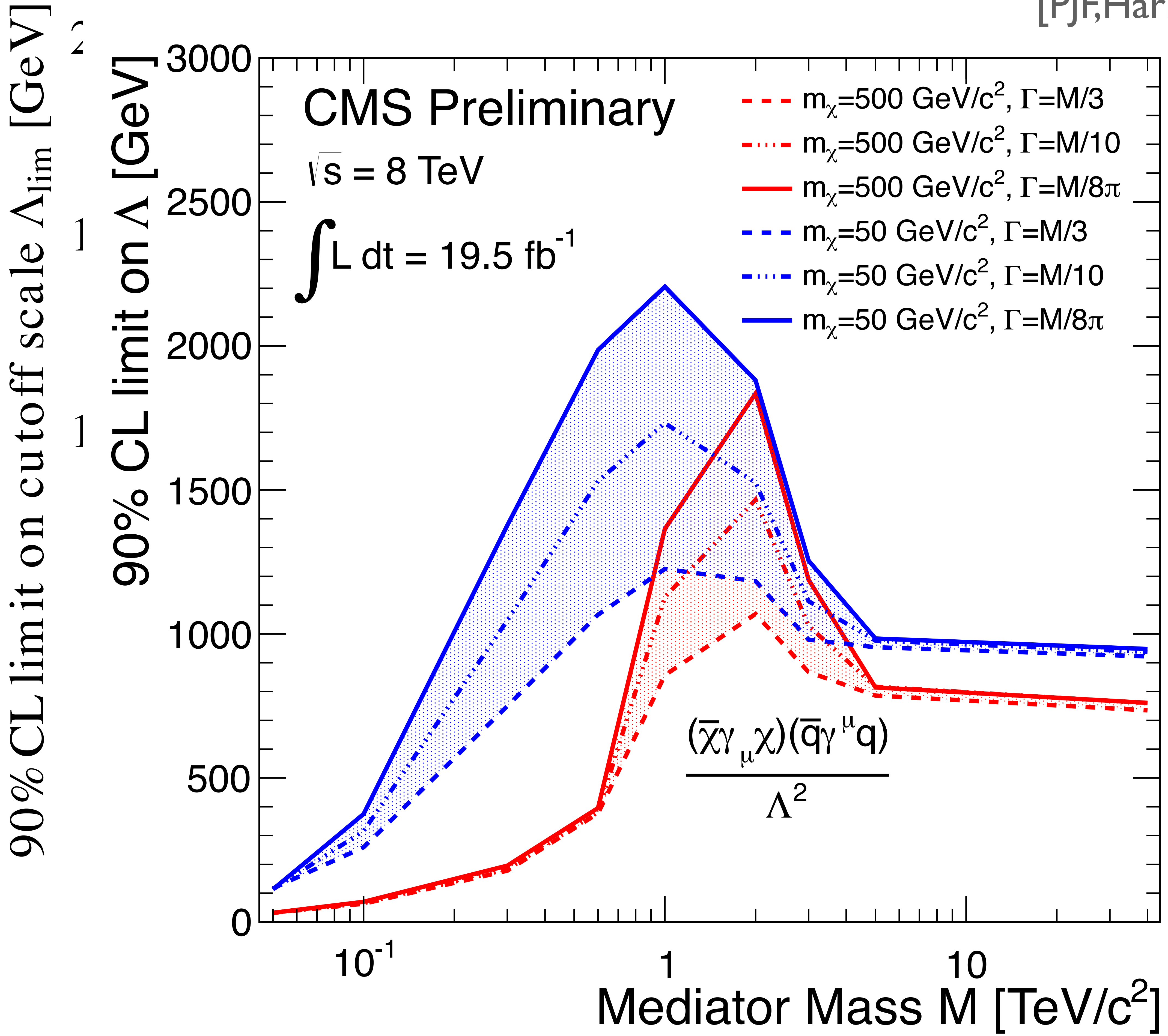
[PJF,Harnik,Kopp,Tsai]



Contact limit

Light mediator severely weakens limit

[PJF,Harnik,Kopp,Tsai]



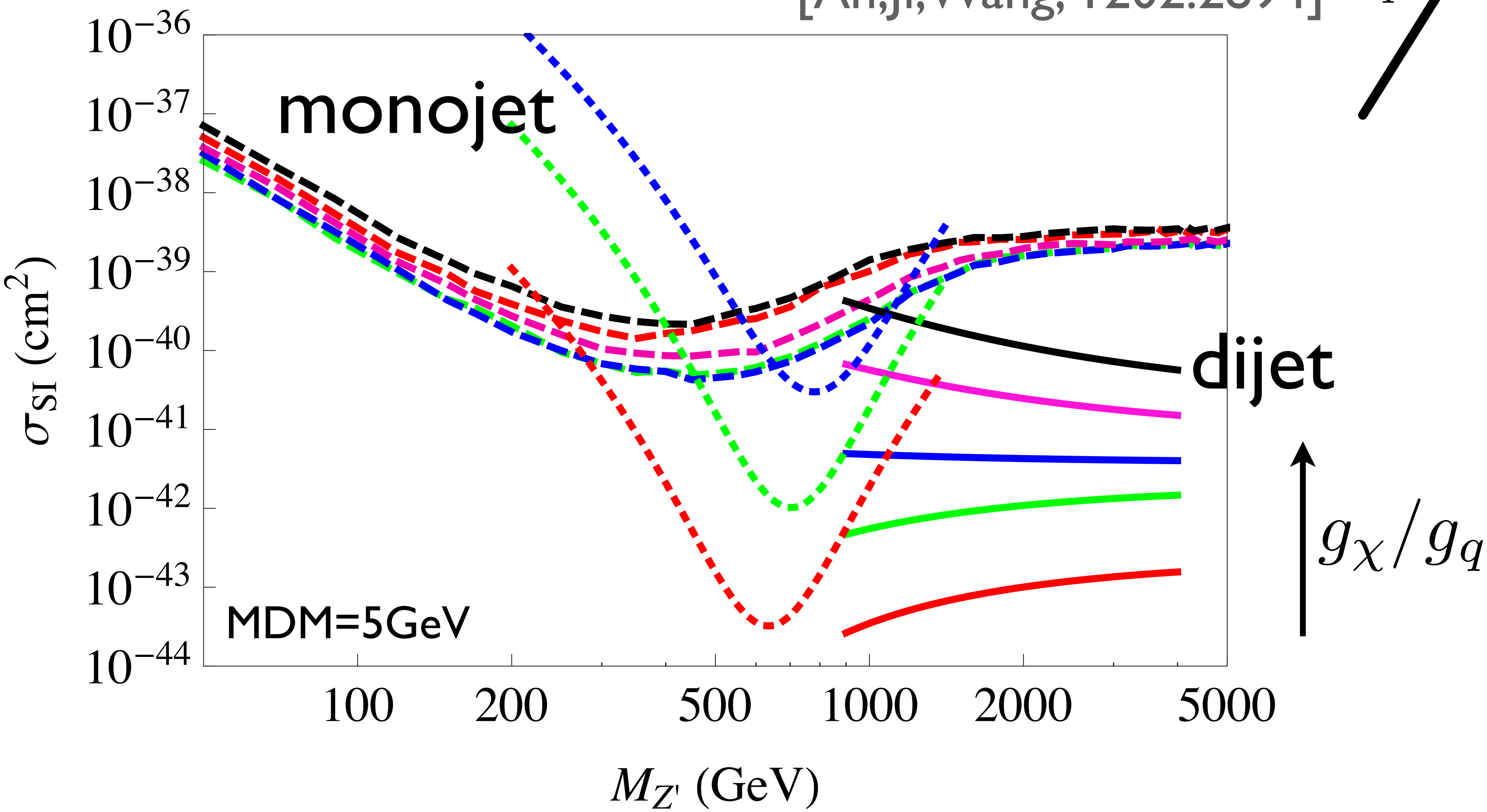
tact limit

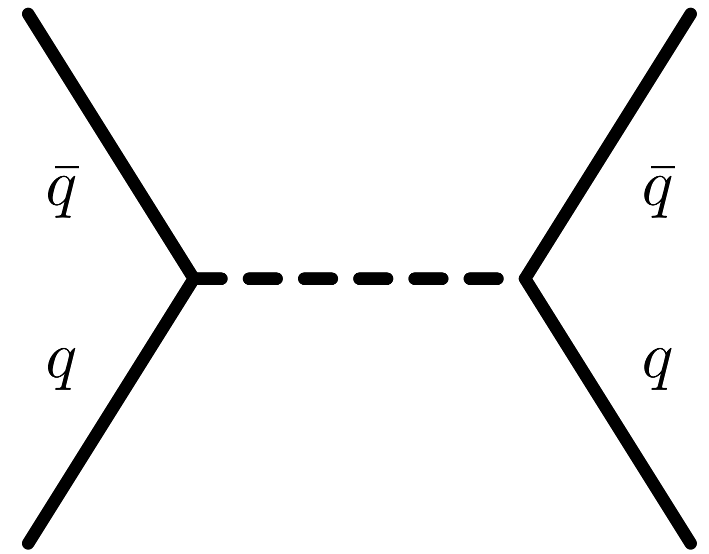
Light Mediators

[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]





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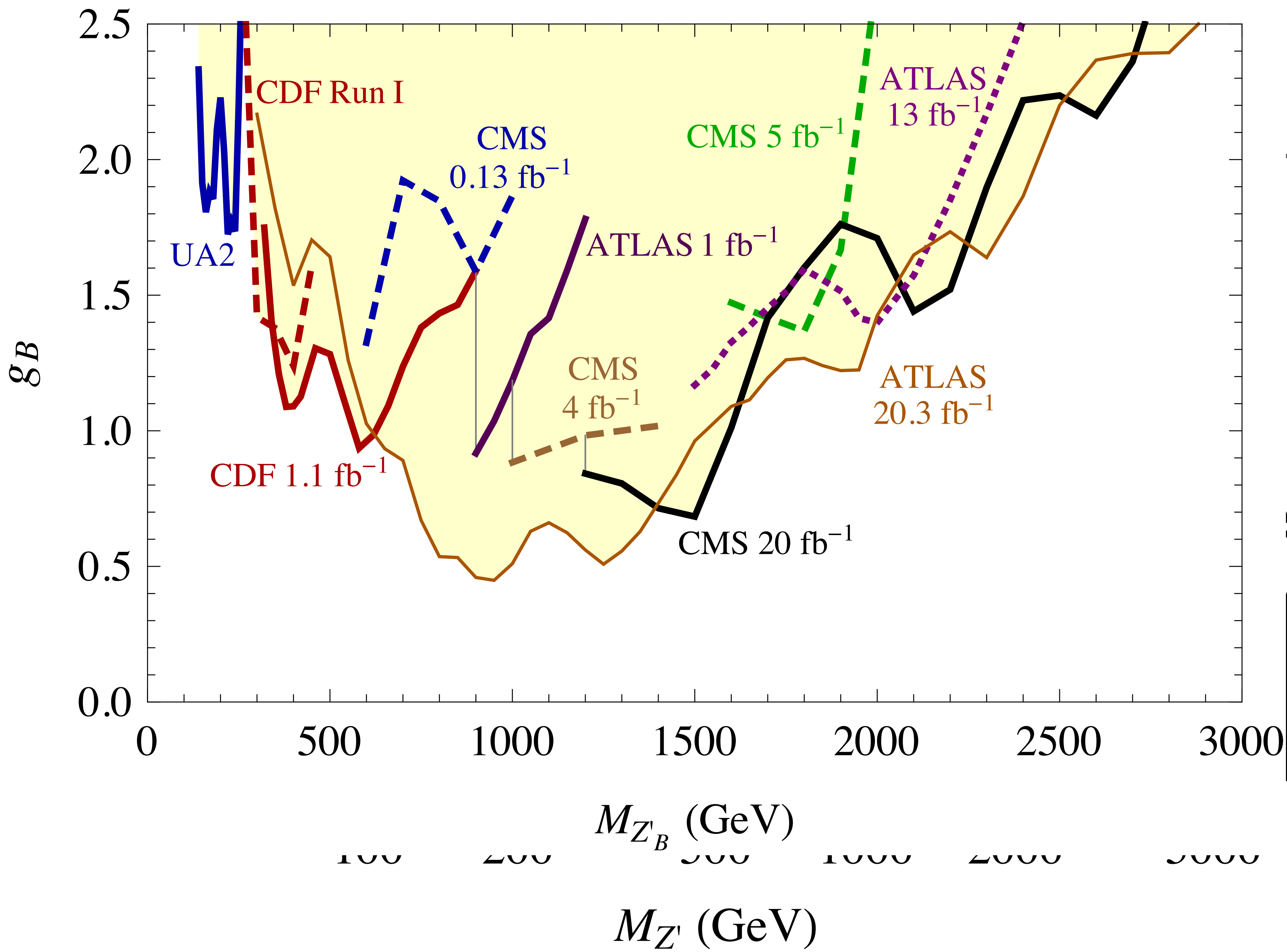

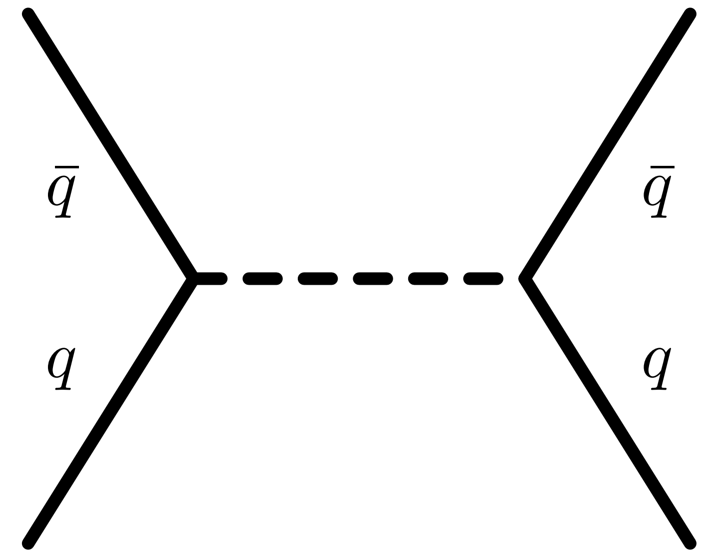

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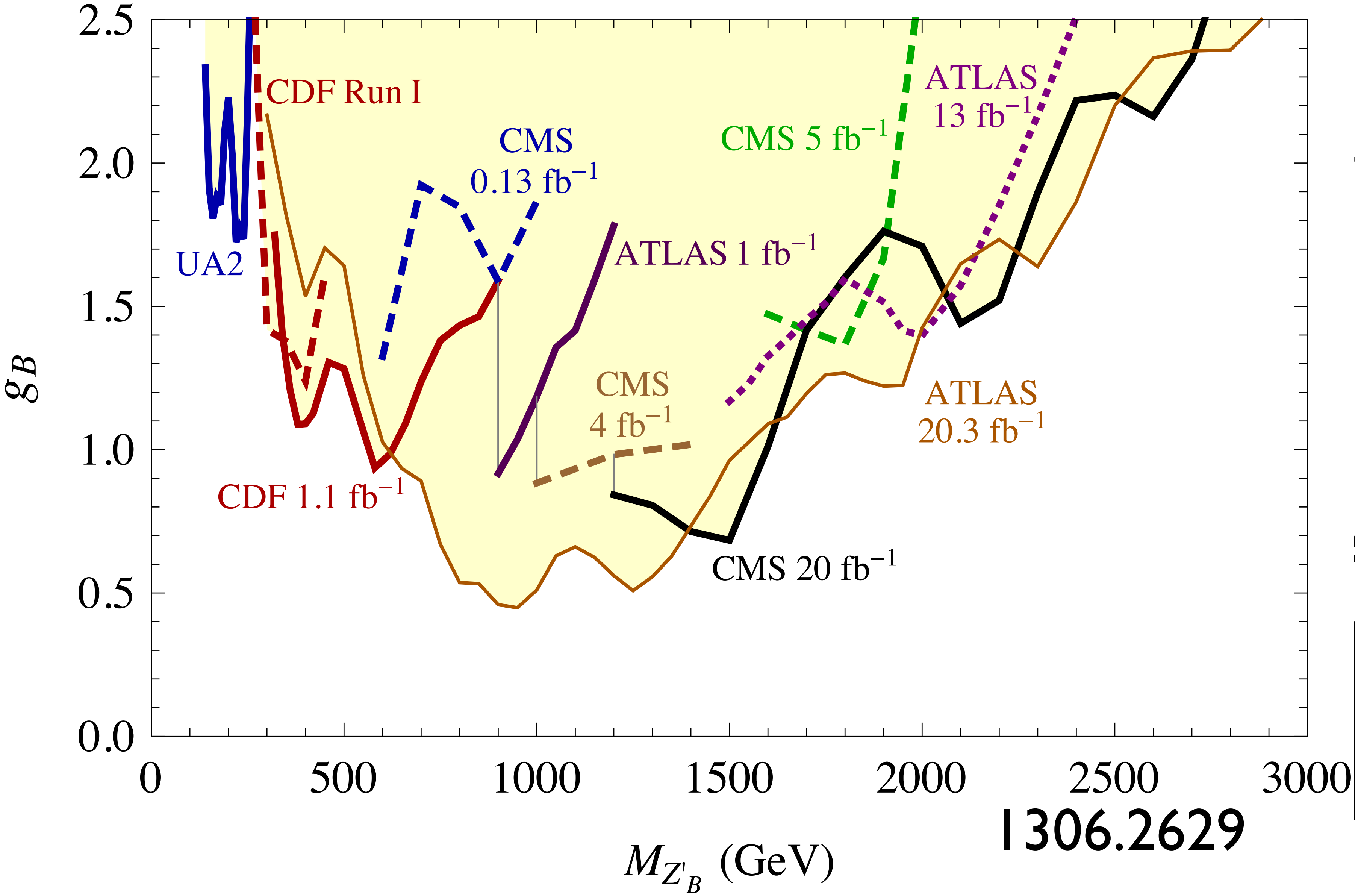
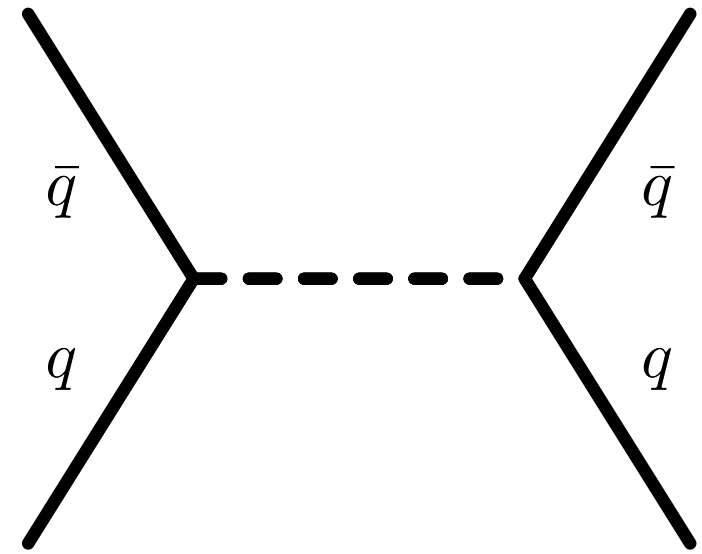




g_χ / g_q

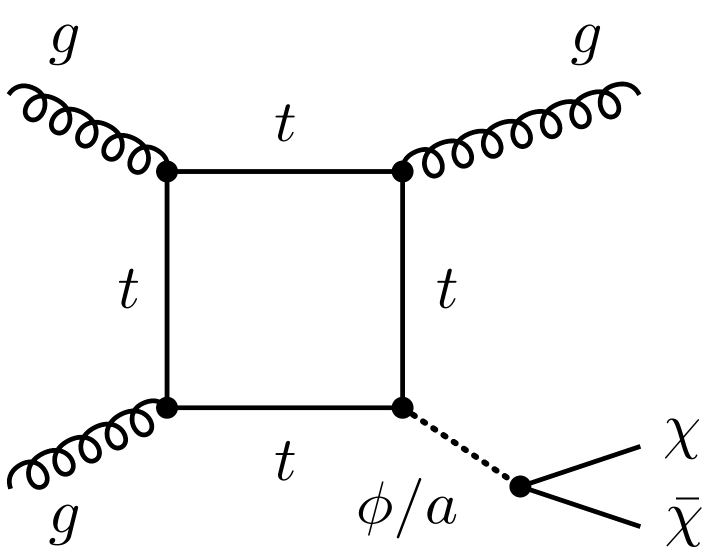
1306.2629

$M_{Z'}$ (GeV)

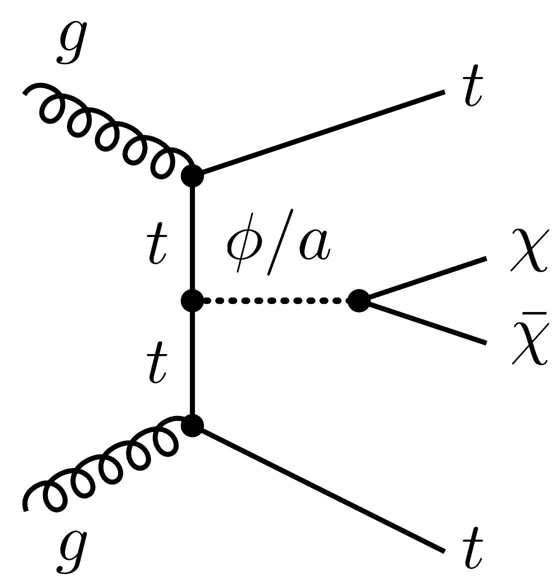
Types of Simplified models

-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

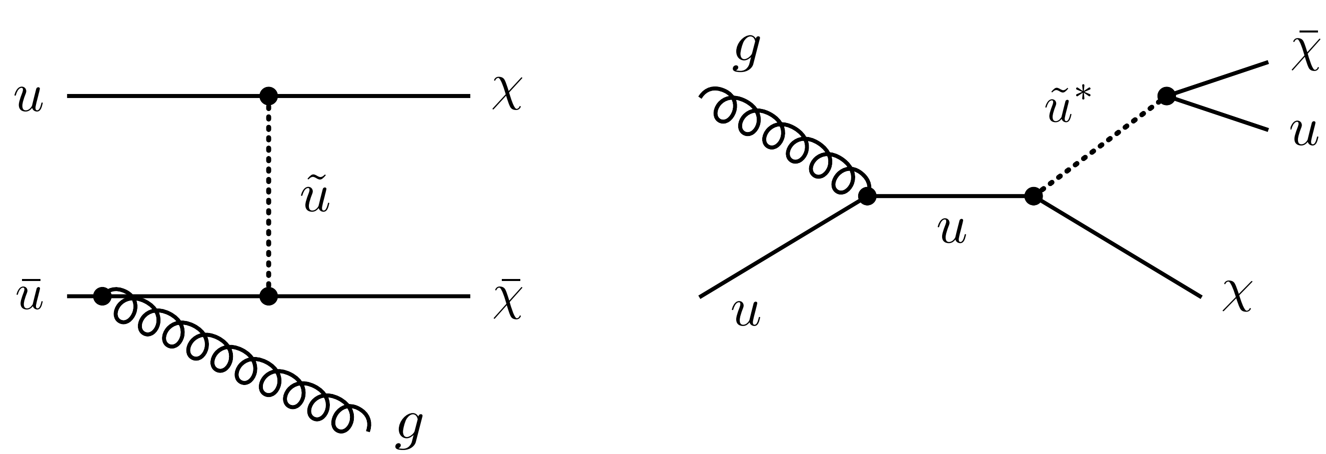
- Scalars have helicity suppressed annihilation, and SI DD
- Pseudo scalars do not, and have SD momentum suppressed DD

Types of Simplified models

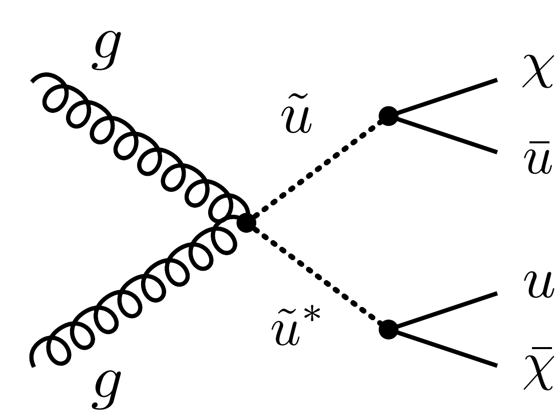
-channel scalar/psuedo-scalar

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

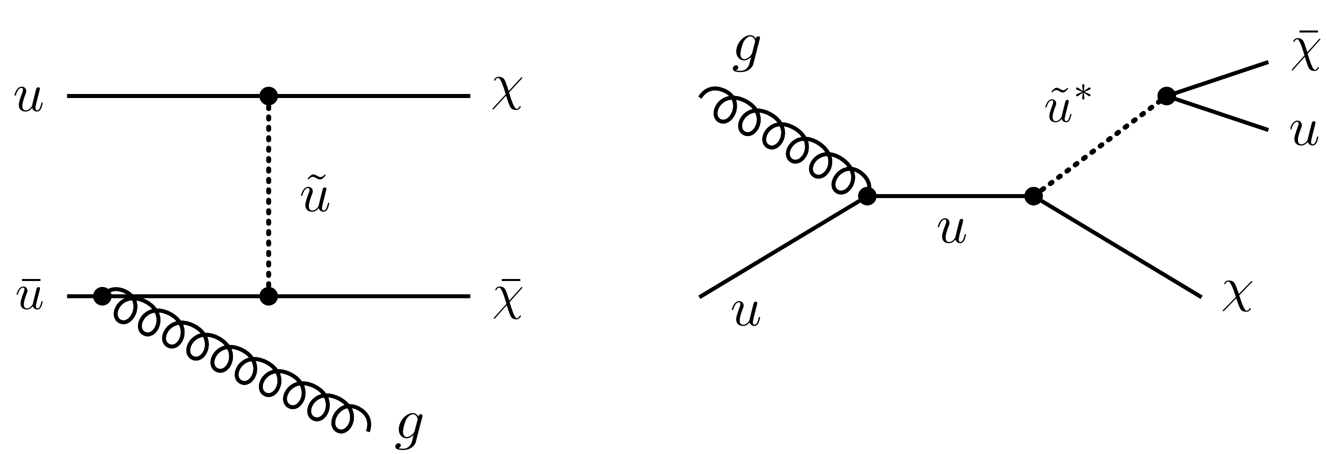
Types of Simplified models

-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.)



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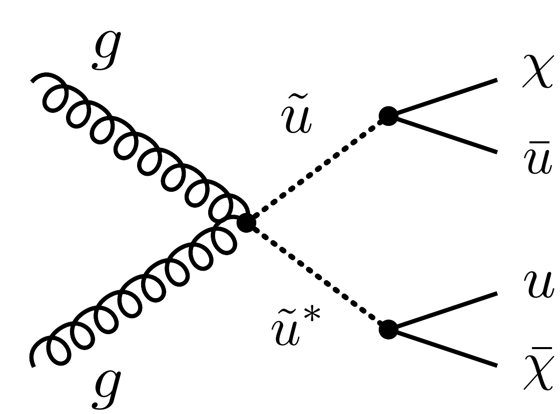

jets+MET

Majorana has only SD, Dirac has both
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Types of Simplified models

s-channel vector/axial-scalar

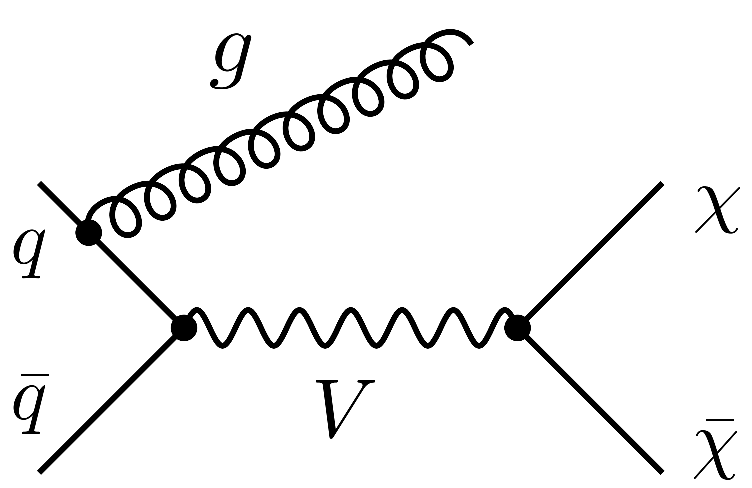
Spontaneously broken $U(1)'$

(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'



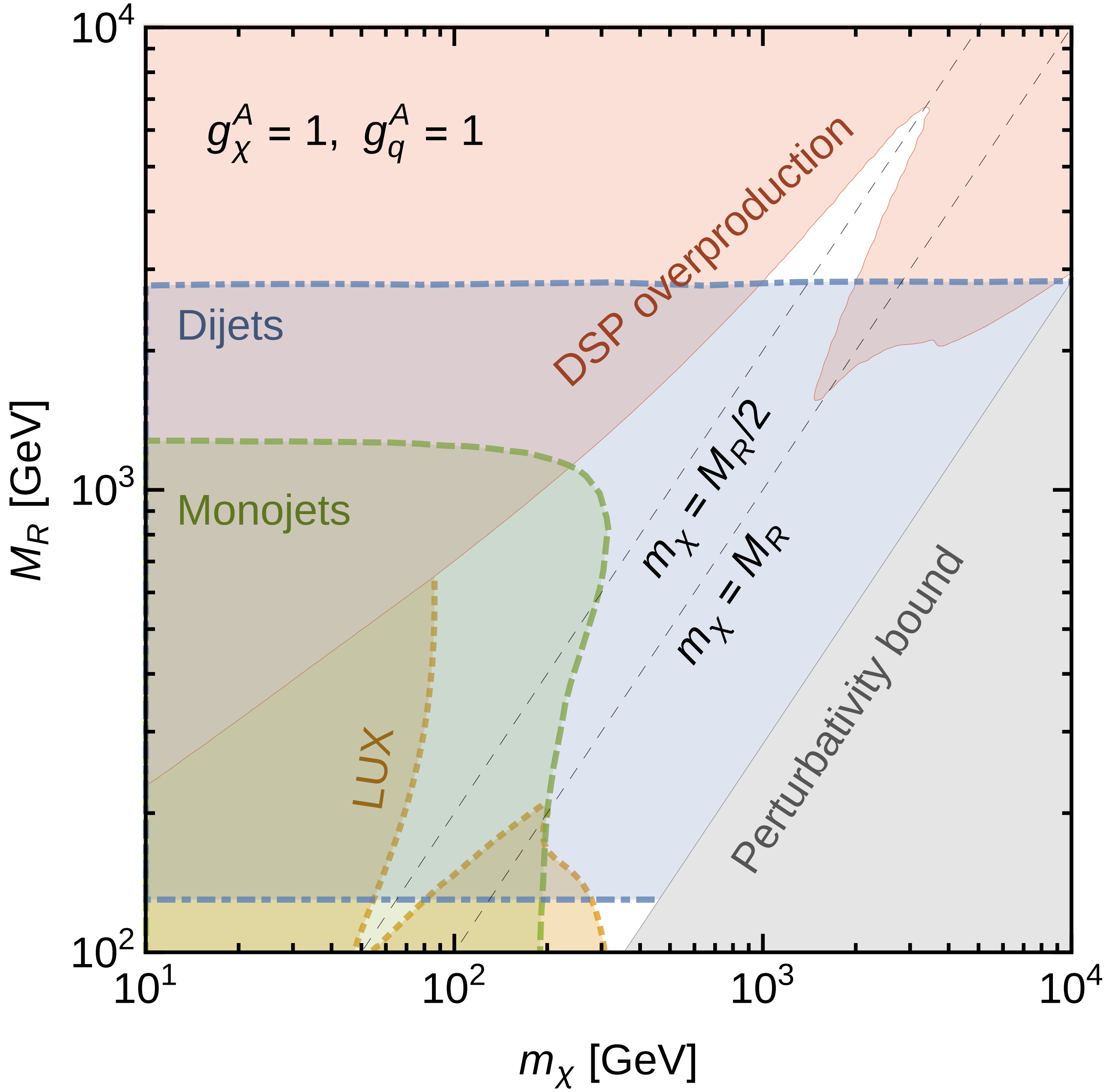
monojet

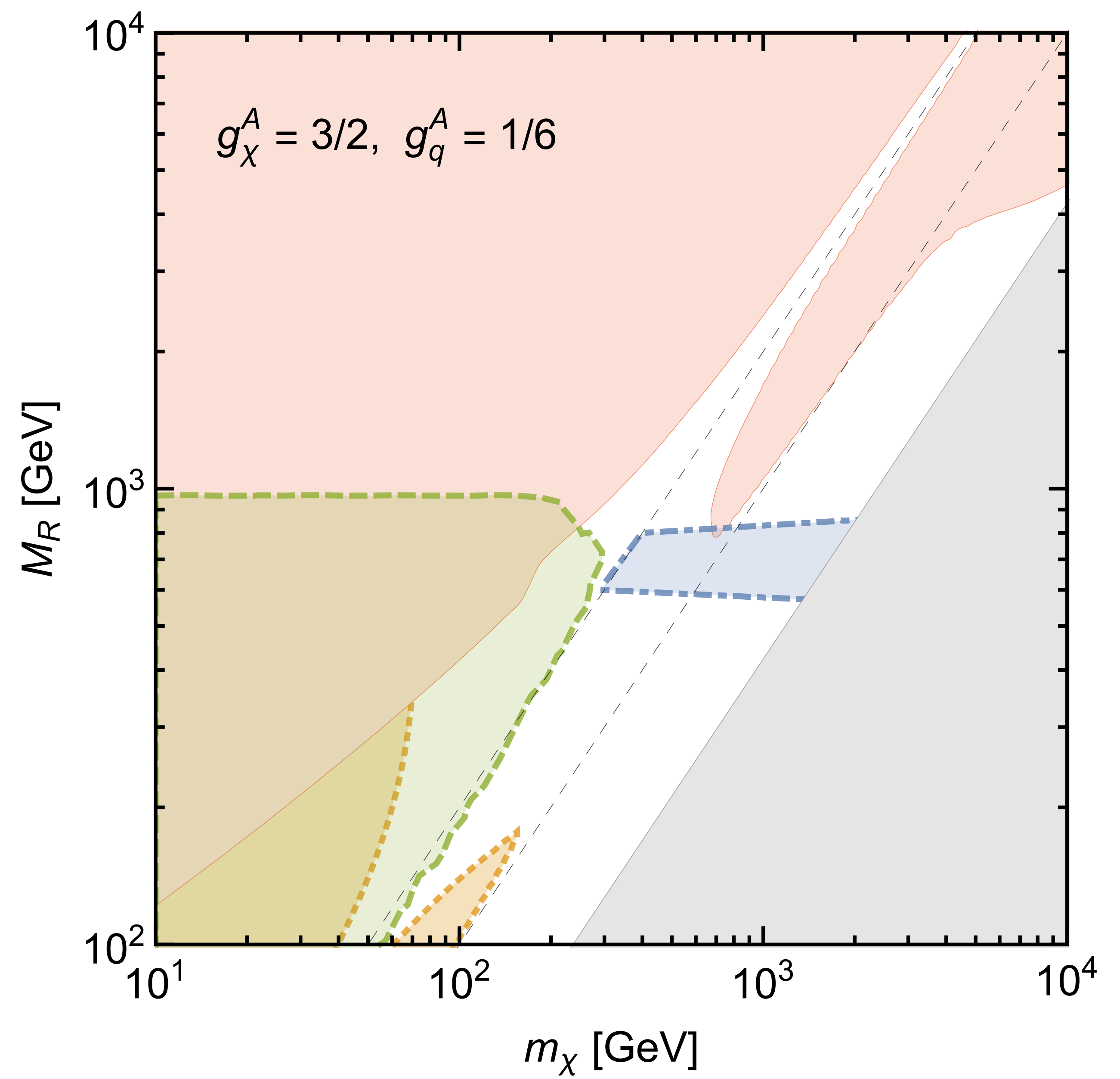
- Vectors are SI
- Axial vectors SD
- If thermal often underproduced

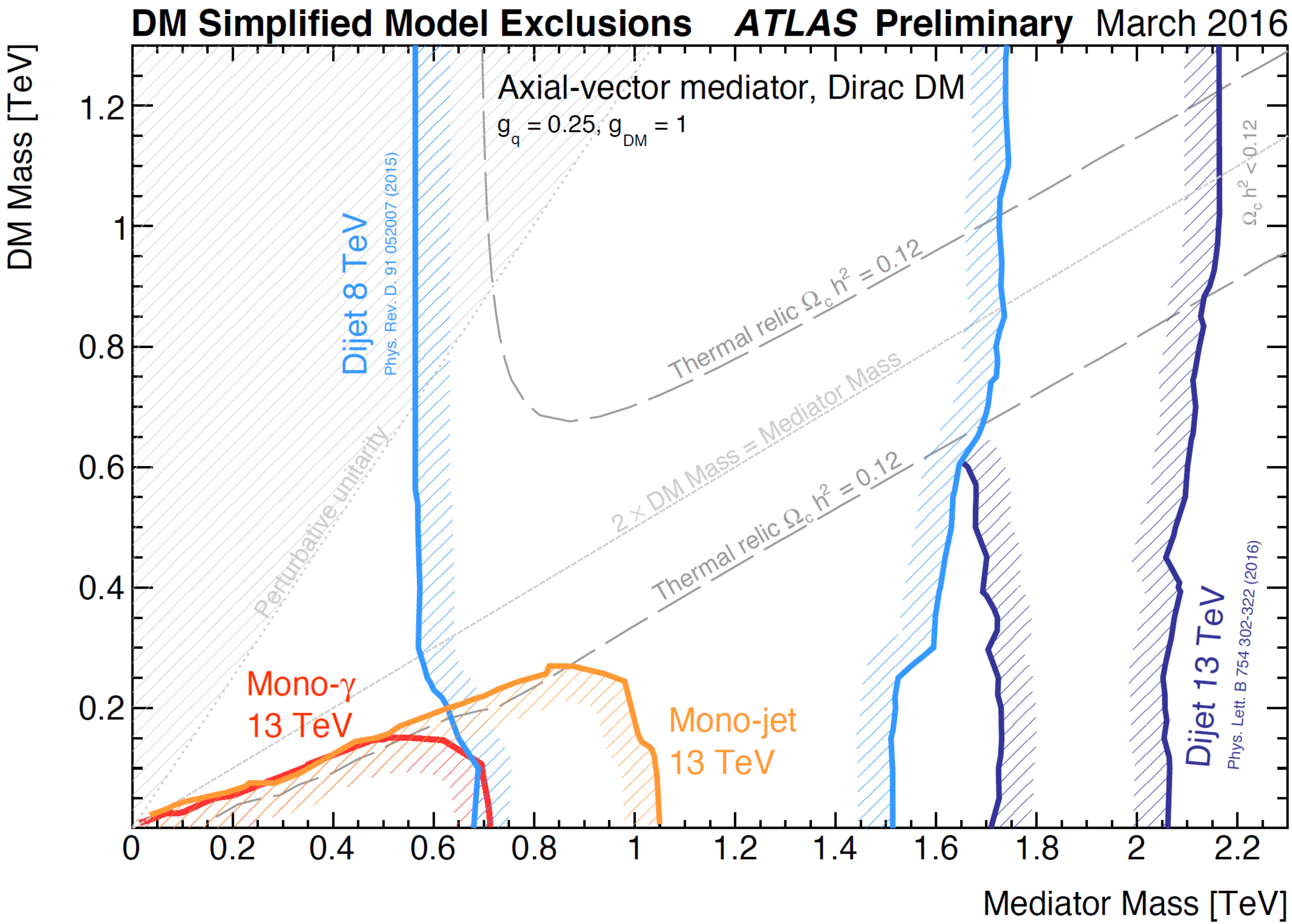
Types of Simplified models

- 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]



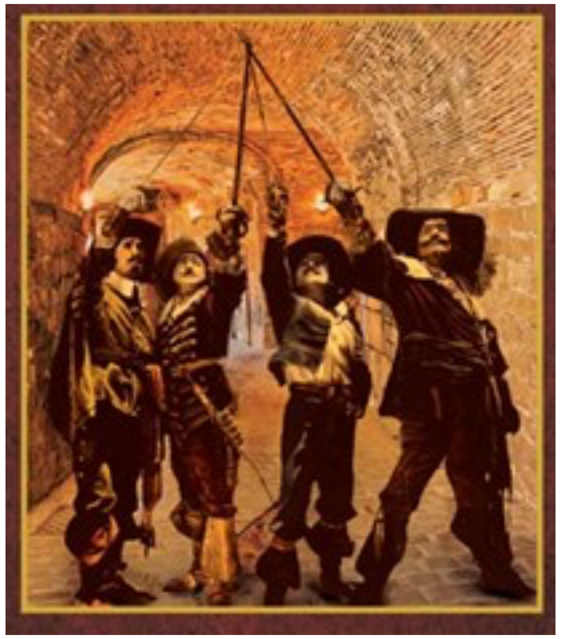



DM Simplified Model Exclusions
ATLAS Preliminary
March 2016
Axial-vector mediator, Dirac DM
g_q = 0.25, g_DM = 1
DM Mass [TeV]
Mediator Mass [TeV]
Dijet 8 TeV
Phys. Rev. D. 91 052007 (2015)
Dijet 13 TeV
Phys. Lett. B 754 302-322 (2016)
Mono-γ
13 TeV
Mono-jet
13 TeV
Thermal relic Ω_c h² = 0.12
Thermal relic Ω_c h² = 0.12
2 × DM Mass = Mediator Mass
Perturbative unitarity
Ω_c h² < 0.12
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
0.2
0.4
0.6
0.8
1
1.2

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
- Indirect detection very sensitive to astrophysics
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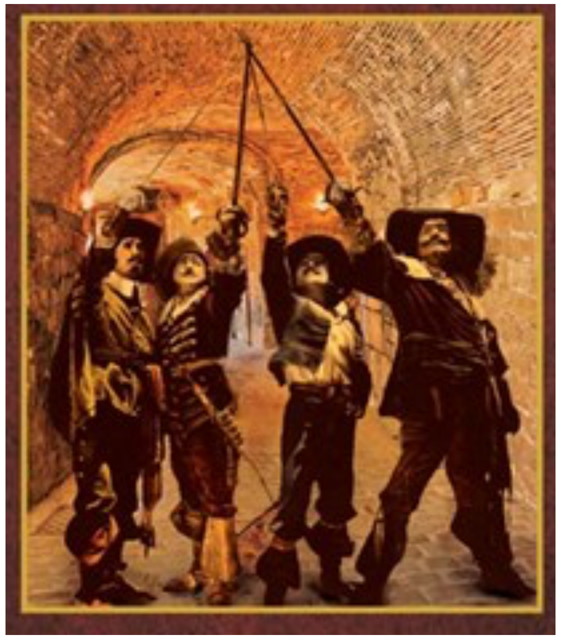

"If you like laws and sausages, you should never watch either one being made"

Otto von Bismark

Why model builders build models...

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Clever field theory idea, cute new symmetry, deep new underlying principle

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or

Why model builders build models...

Clever field theory idea, cute new symmetry, deep new underlying principle

or

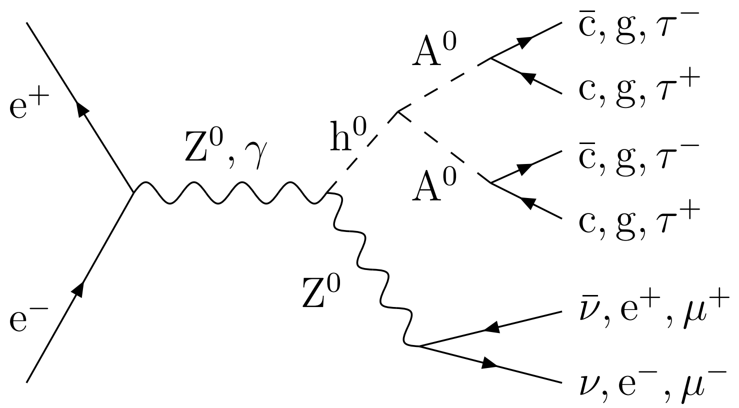
New data needs explaining, signal not being searched for

“Top down”

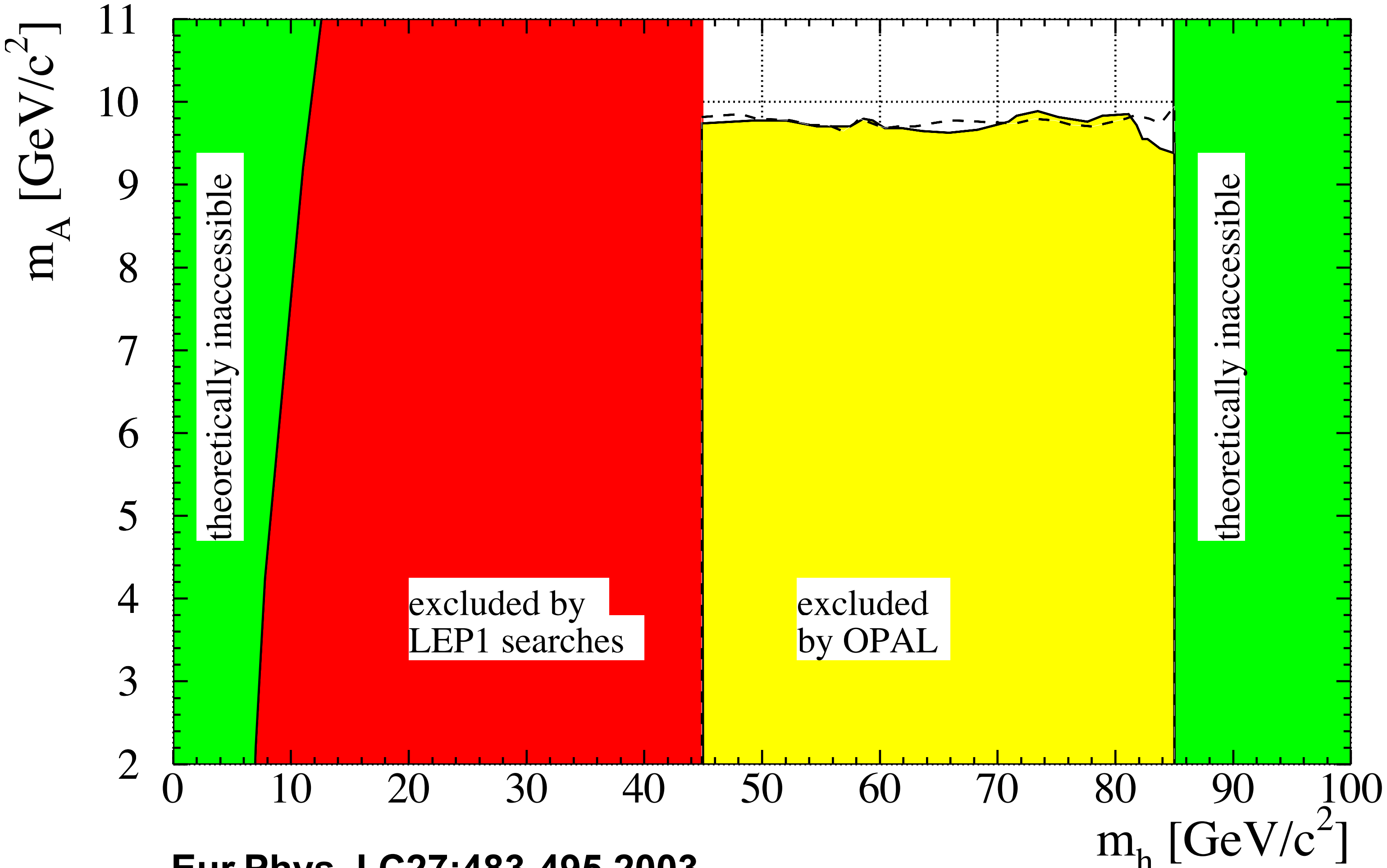
- Identify “grand problem” e.g. weak hierarchy, cosmological constant, flavour
- Introduce “grand principle” e.g. extra dimensions, supersymmetry, new strong dynamics
- Define new theory obeying principle that has SM as long energy limit

Outcome: theoretically very appealing model, often highly correlated signals, complicated parameter space

A cautionary tale

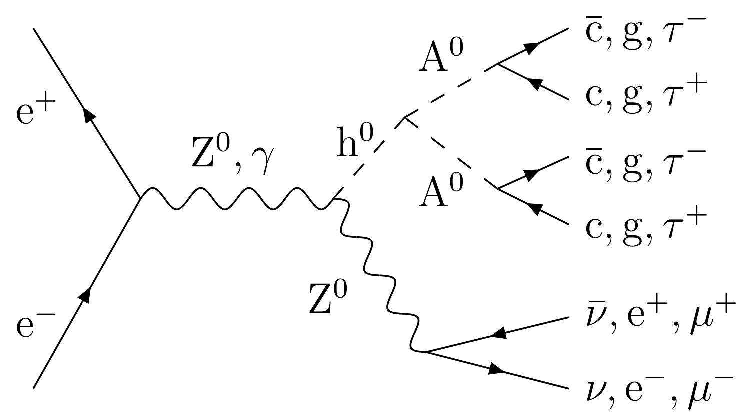


OPAL Higgs search



Eur.Phys.J.C27:483-495,2003.

A cautionary tale



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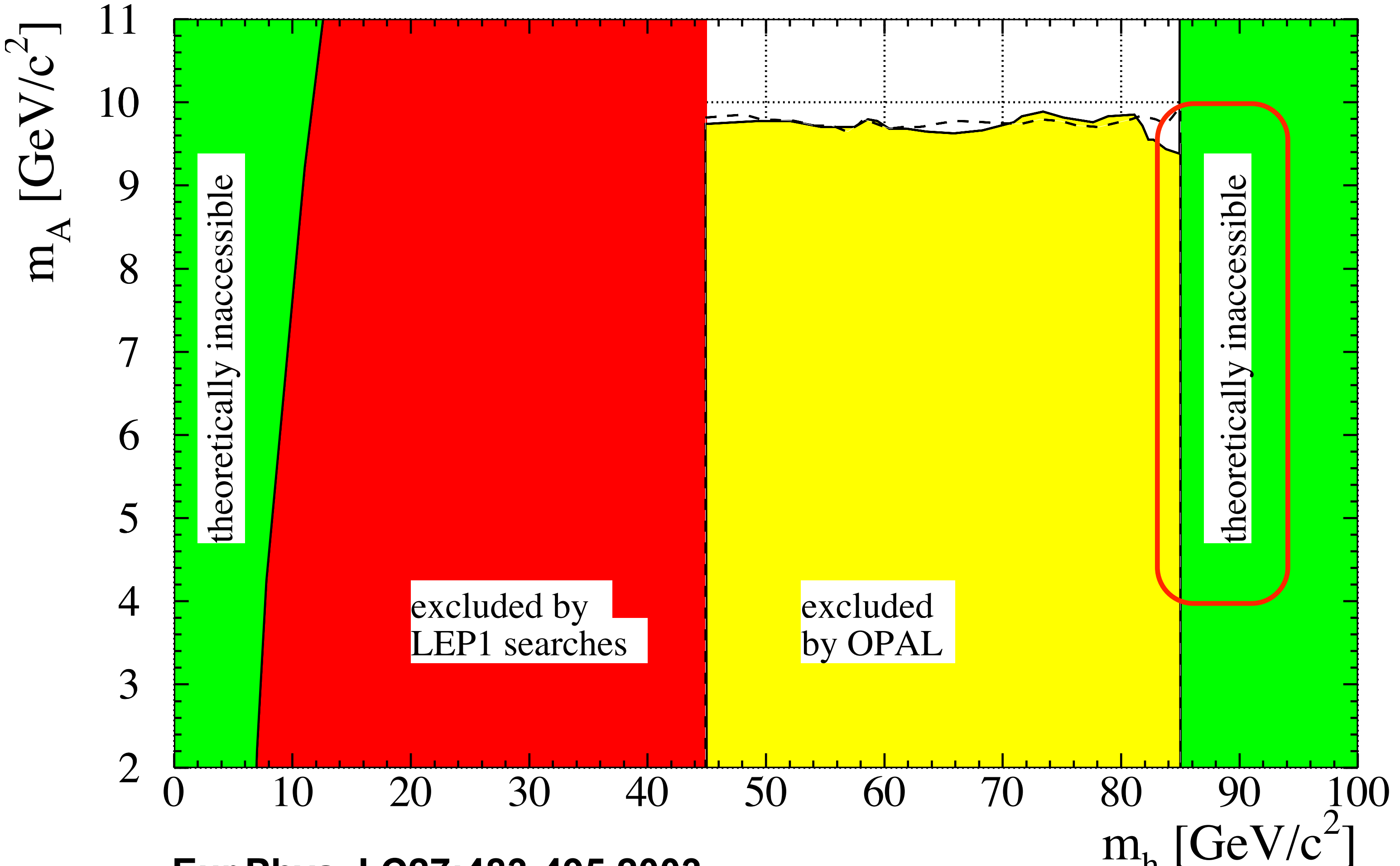

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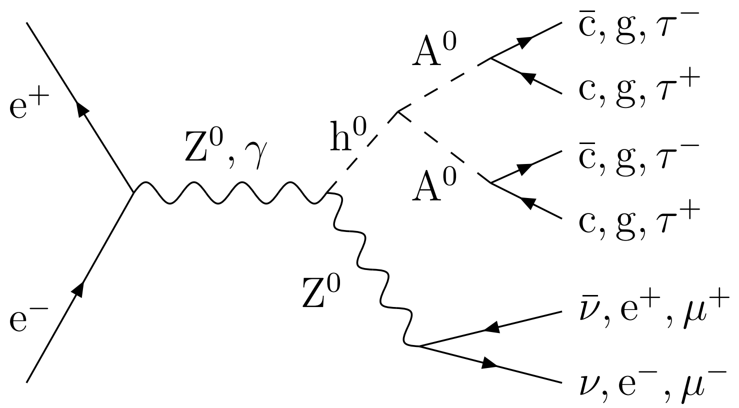
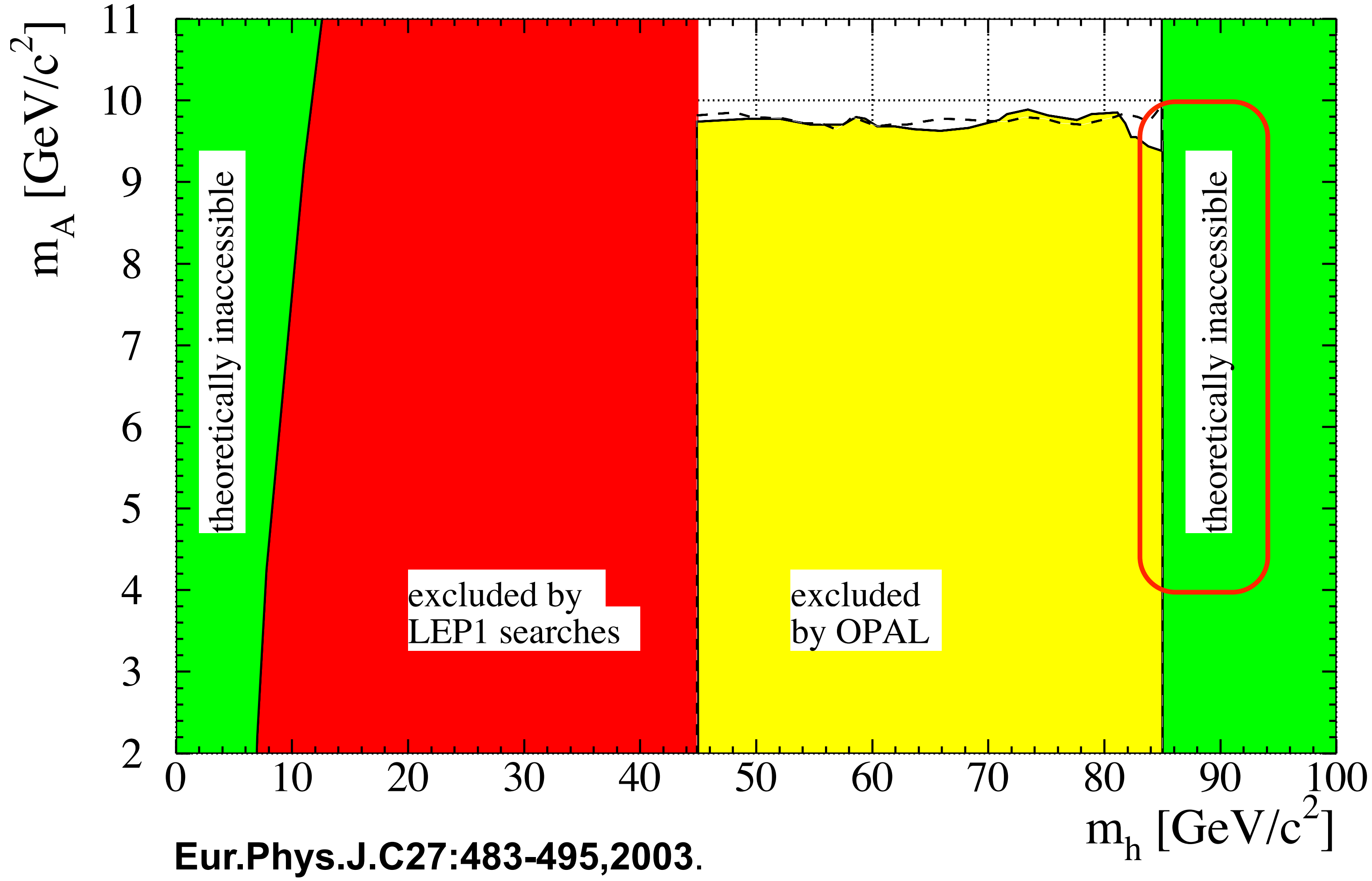


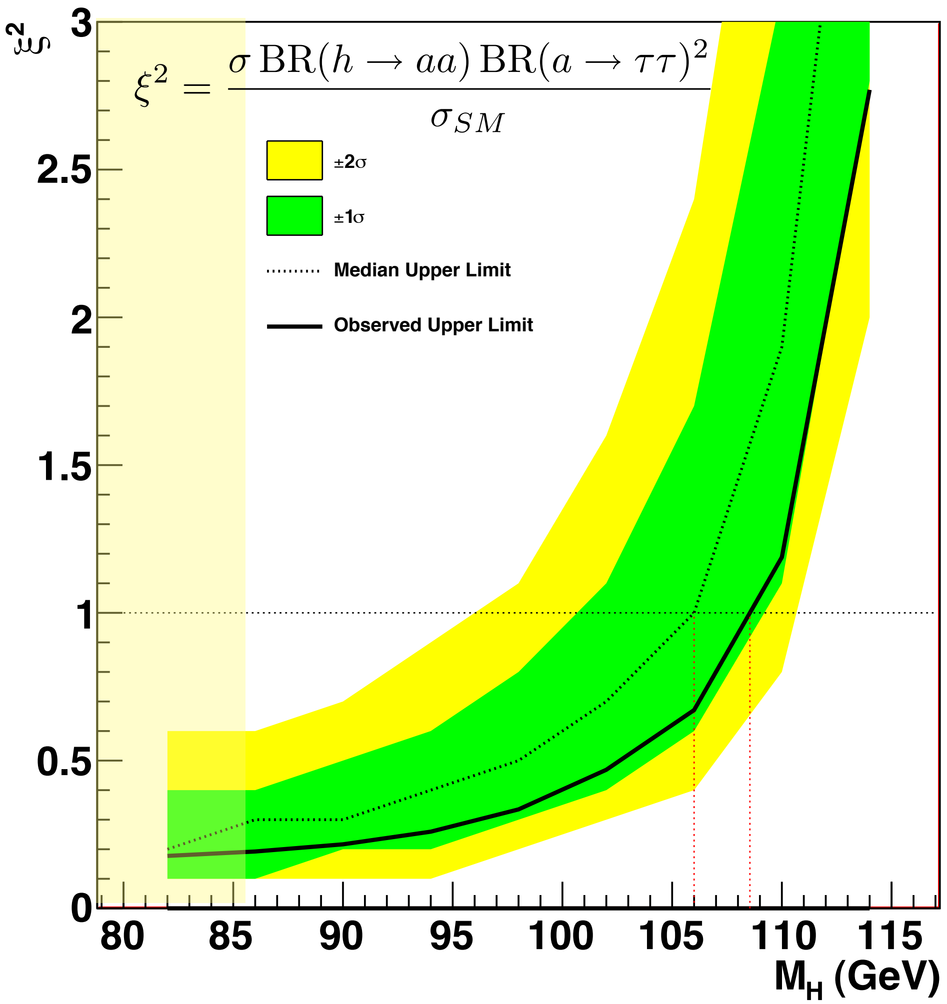
OPAL Higgs search



Eur.Phys.J.C27:483-495,2003.

New ALEPH search

expected limit for $m_a = 10$ GeV



Cranmer, Yavin, Beacham, Spagnolo

“Bottom up”

- Data disagrees with SM in some channel(s)
- Add new states and couplings to SM to explain deviations
- Must have some concept of minimality: degrees of freedom, parameters

Outcome: build up the new physics piece by piece, correlations may not be apparent initially, simple parameter space

Easy for us to talk...exchange MadGraph/SHERPA model files that contain a few dials

“Bottom up”.... without anomaly

Bottom up without excess = “signal building”

- Build simple modules that contain interesting new signatures not necessarily contained in other models
- Motivate new analyses
- Again allows simple communication

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“Top down” $\xrightarrow{\text{data}}$ “Bottom up”

Rules of model building

- "First do no harm"
  - FCNC's, PEWT, LEP, B-physics, proton decay, existing searches,.. (often reason for new parity...DM)
- Describe physics with a local, Lorentz invariant, unitary field theory, causal
- Preserve gauge invariance, anomaly free
- Prefer renormalizable field theories
- Occam's razor? cf. Hickam's Dictum
- Perturbativity
- Running of gauge couplings, unification