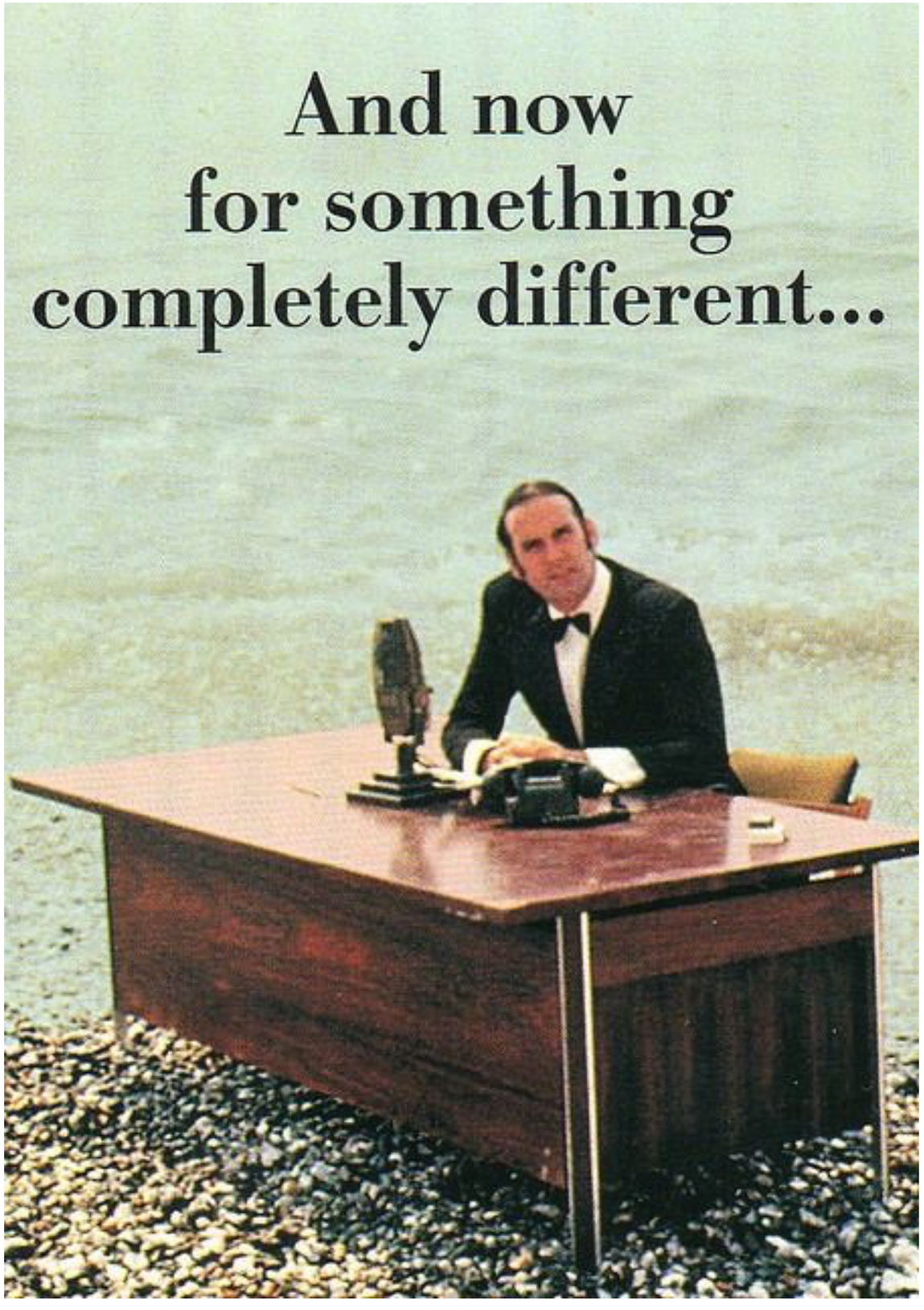
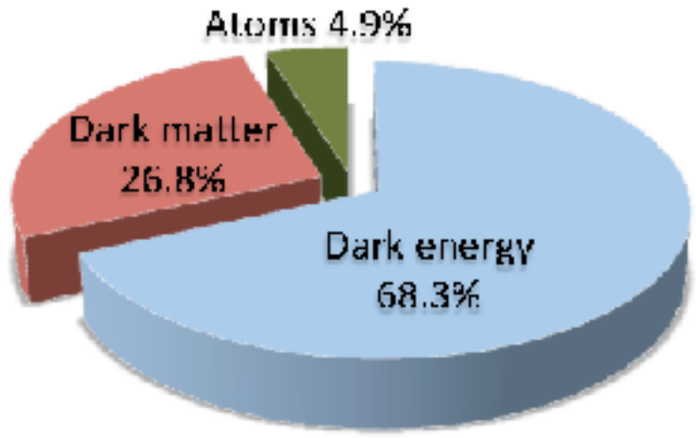
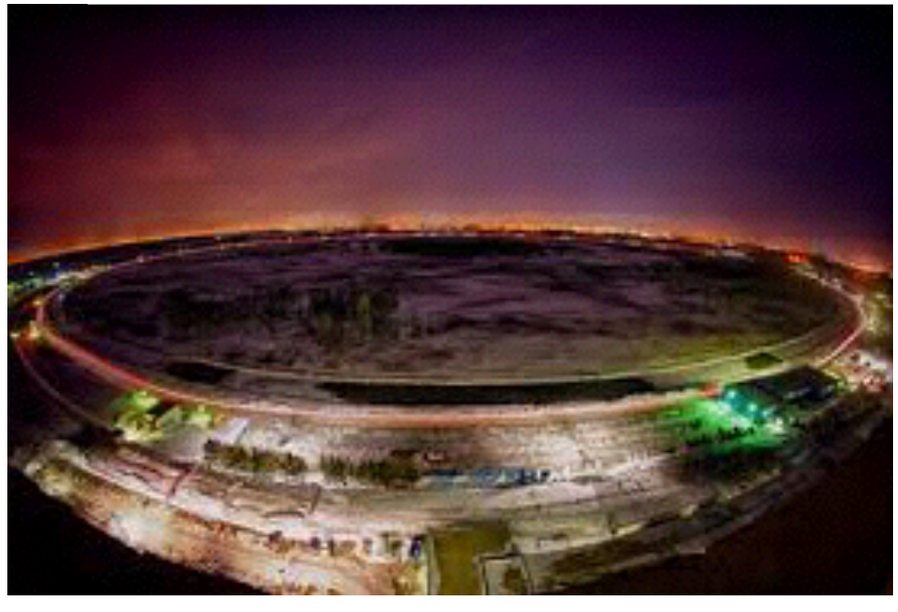
BSM Theory:
The SM and Beyond

Patrick "PaDDy" Fox

Fermilab


And now
for something
completely different...


Atoms 4.9%
Dark matter
26.8%
Dark energy
68.3%



“You spin me right round…”

Fritz Zwicky

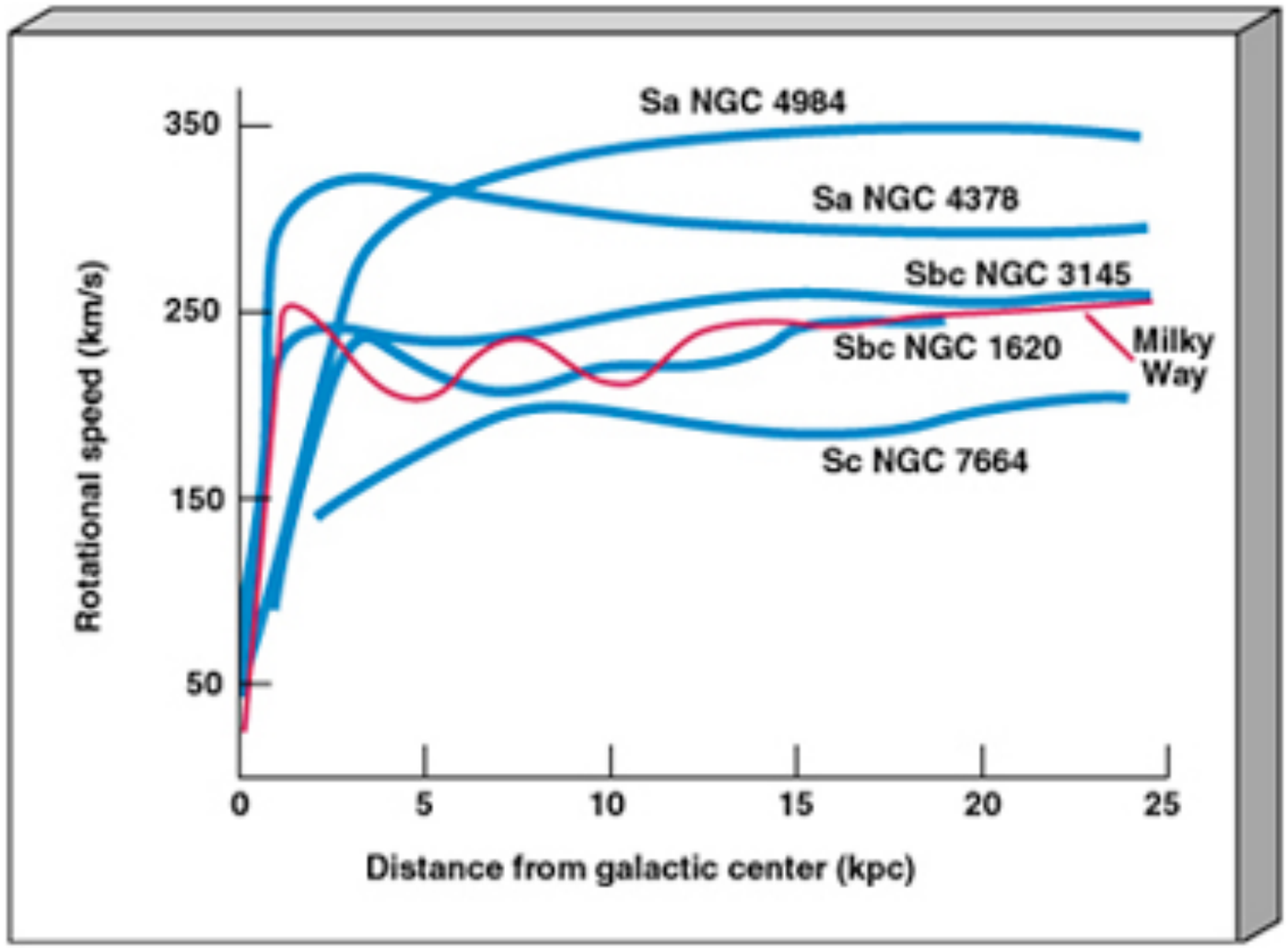
Coma Cluster

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

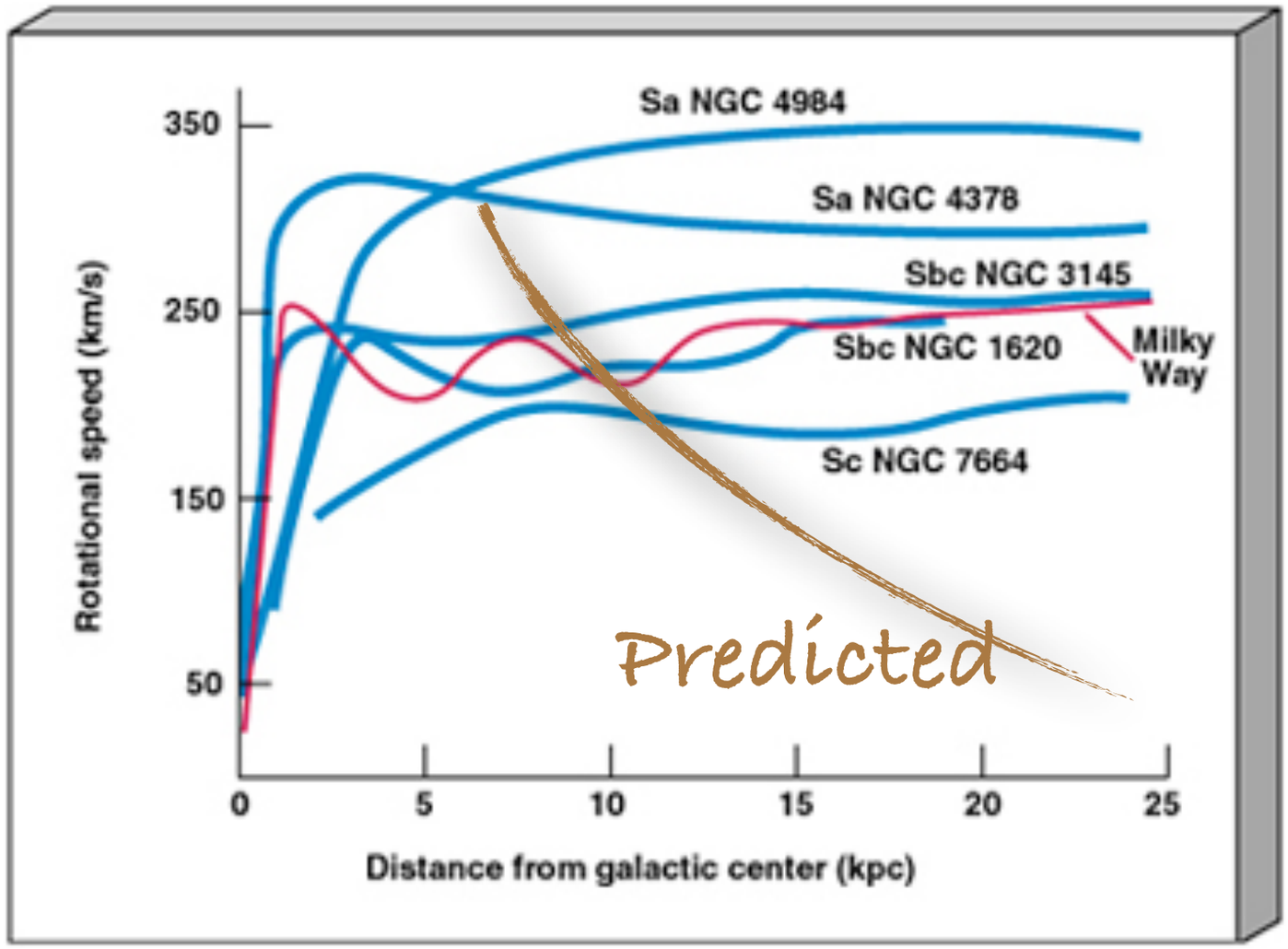
Vera Rubin



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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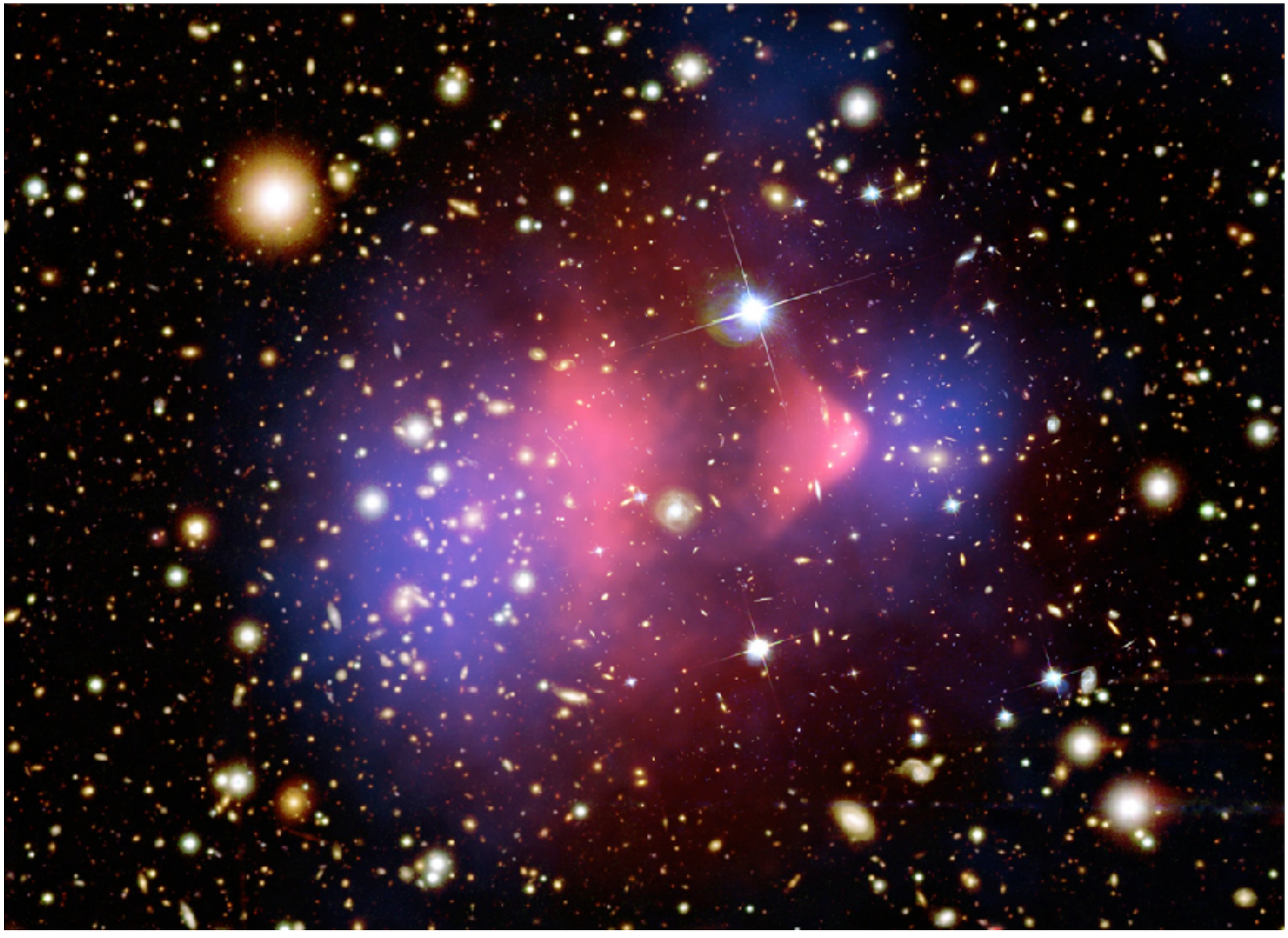
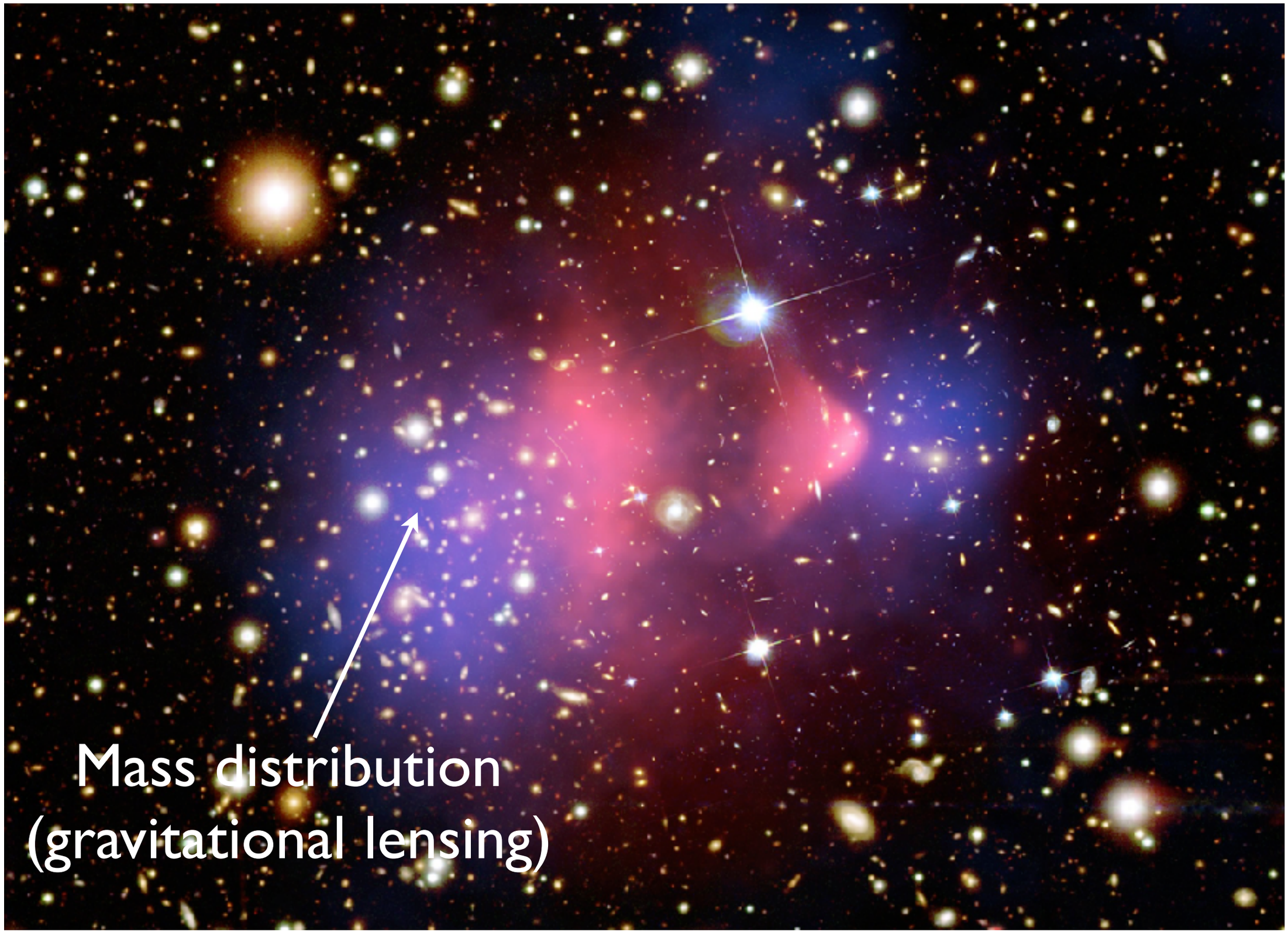
Alway same result: never enough stuff

Evidence for Dark Matter



The Bullet Cluster

Evidence for Dark Matter



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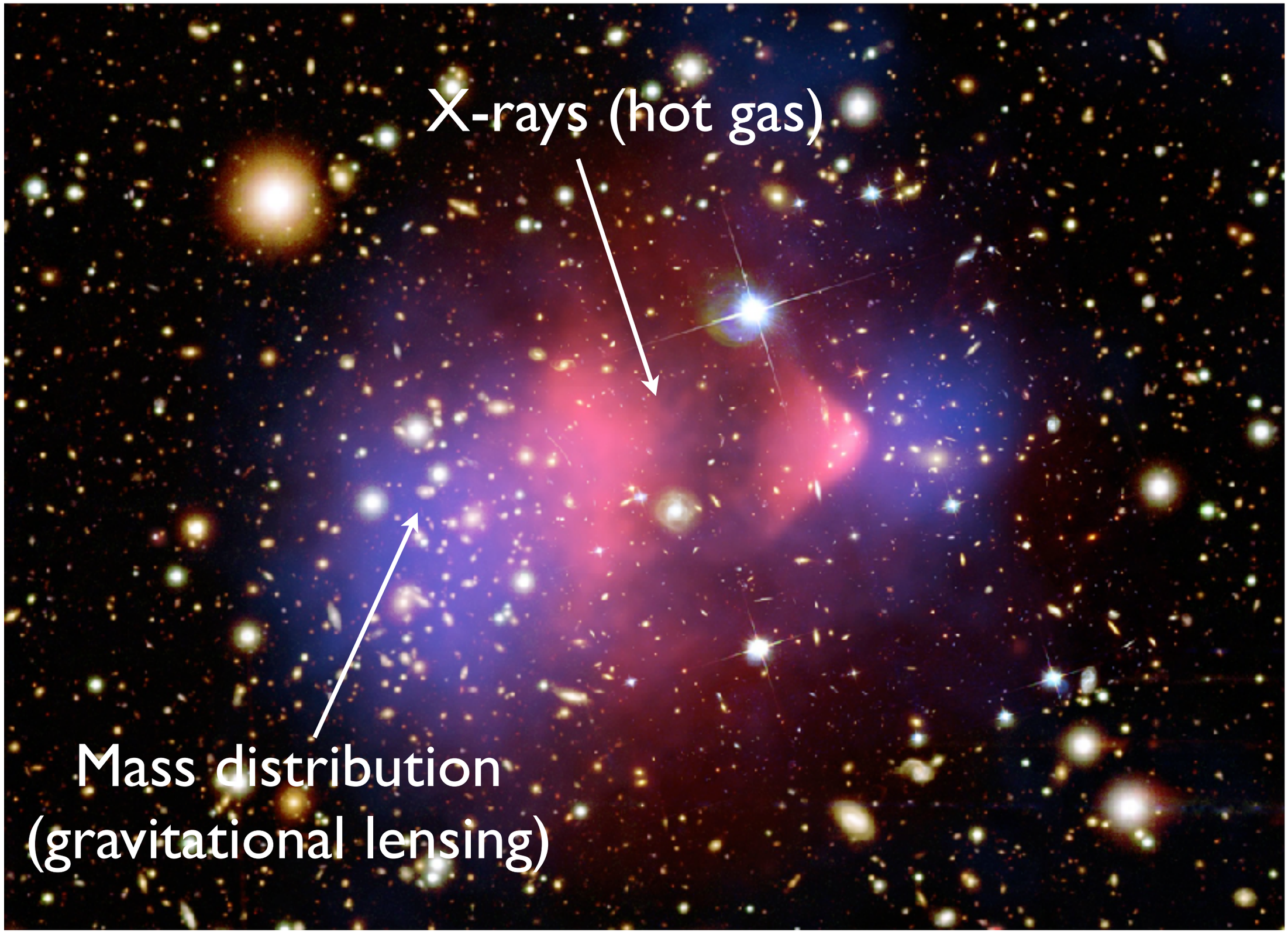

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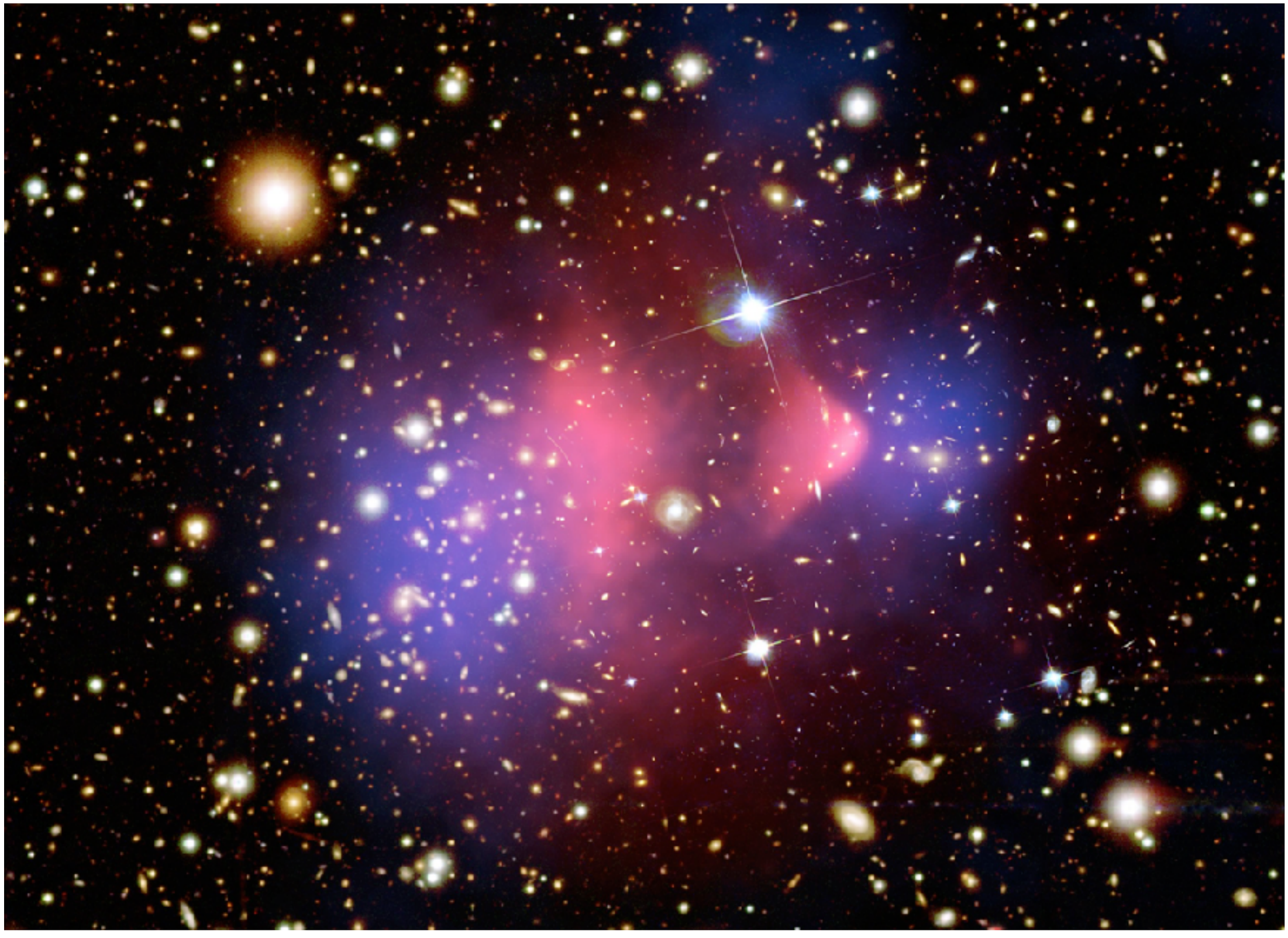

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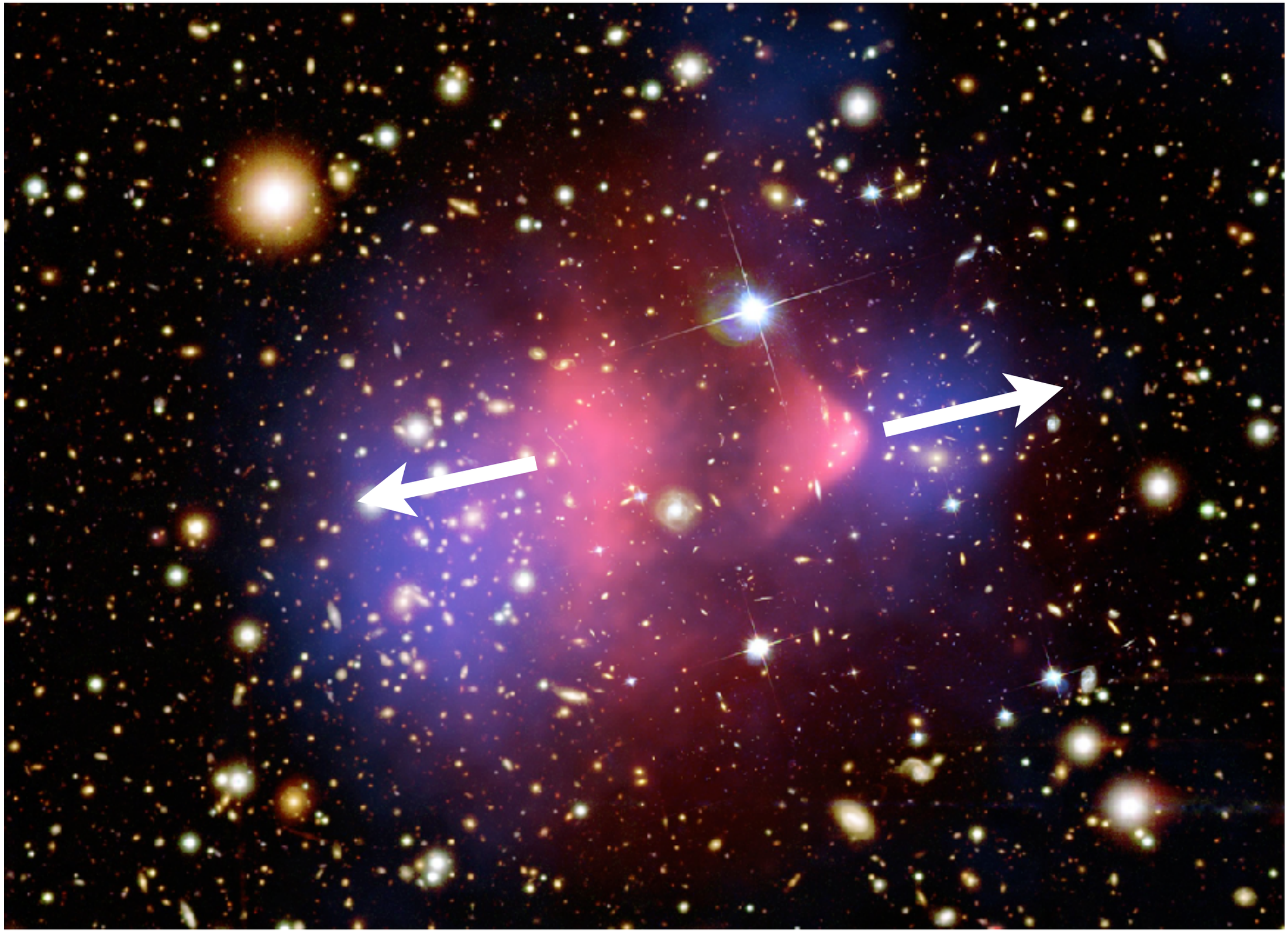

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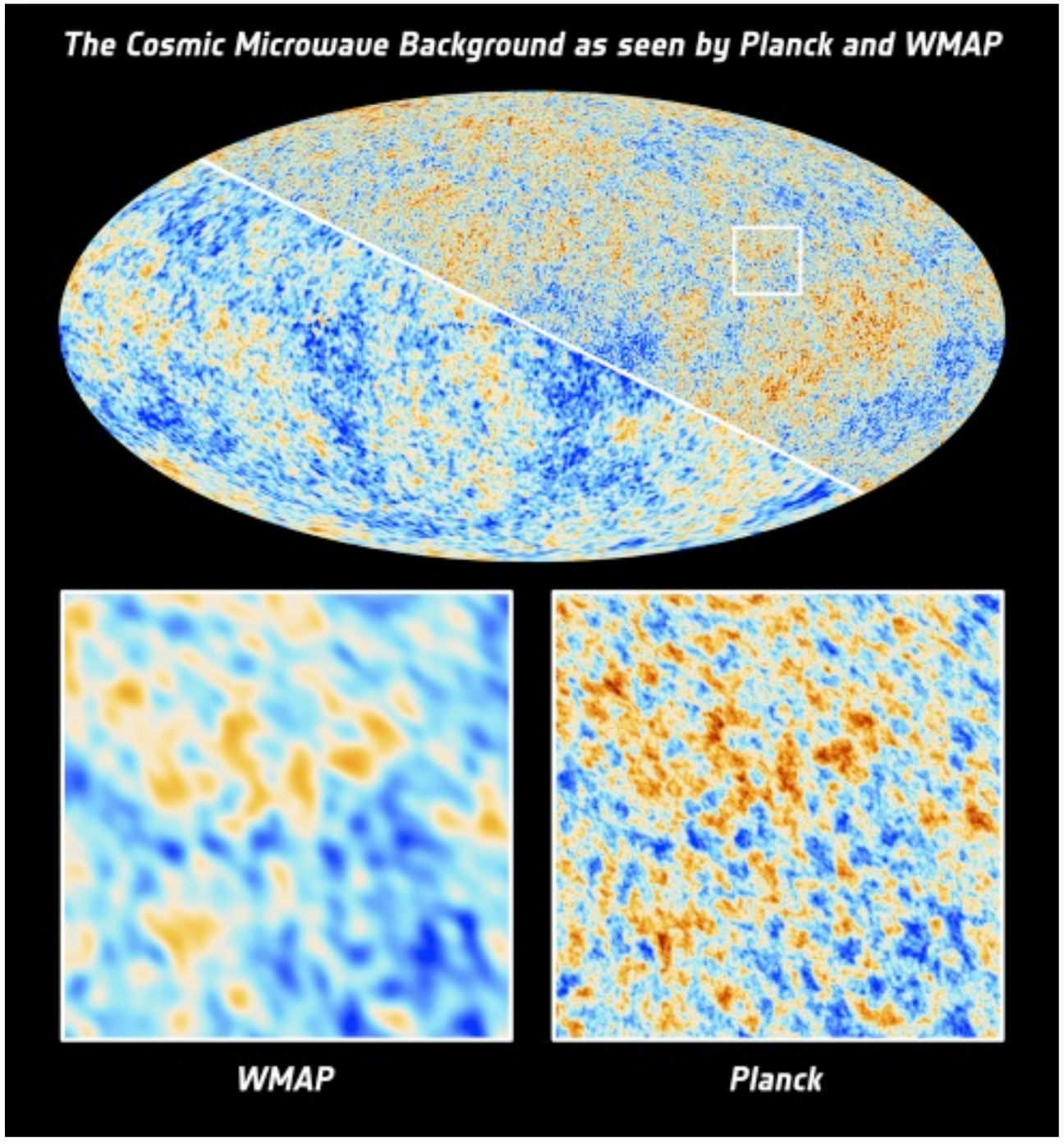
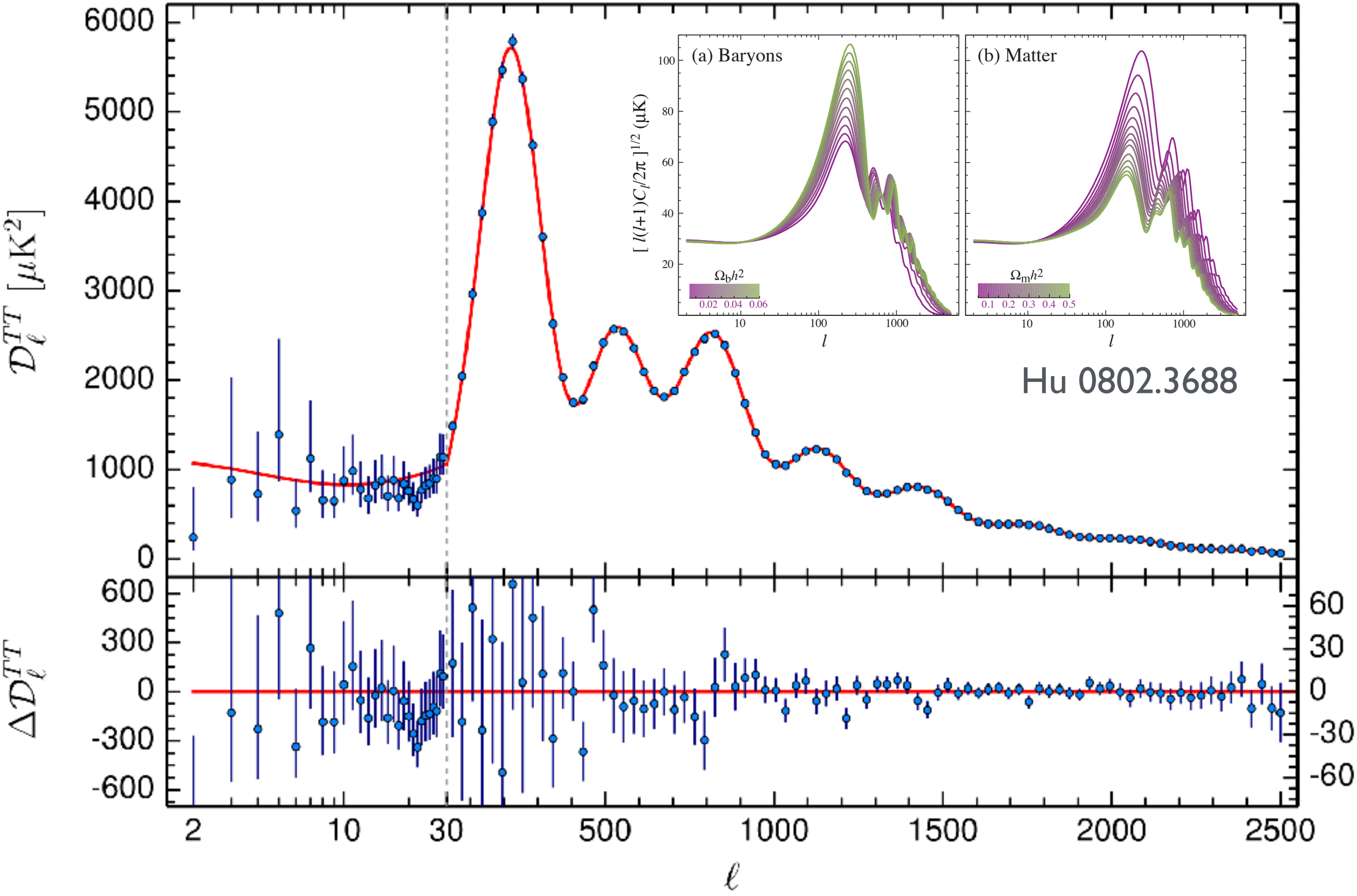


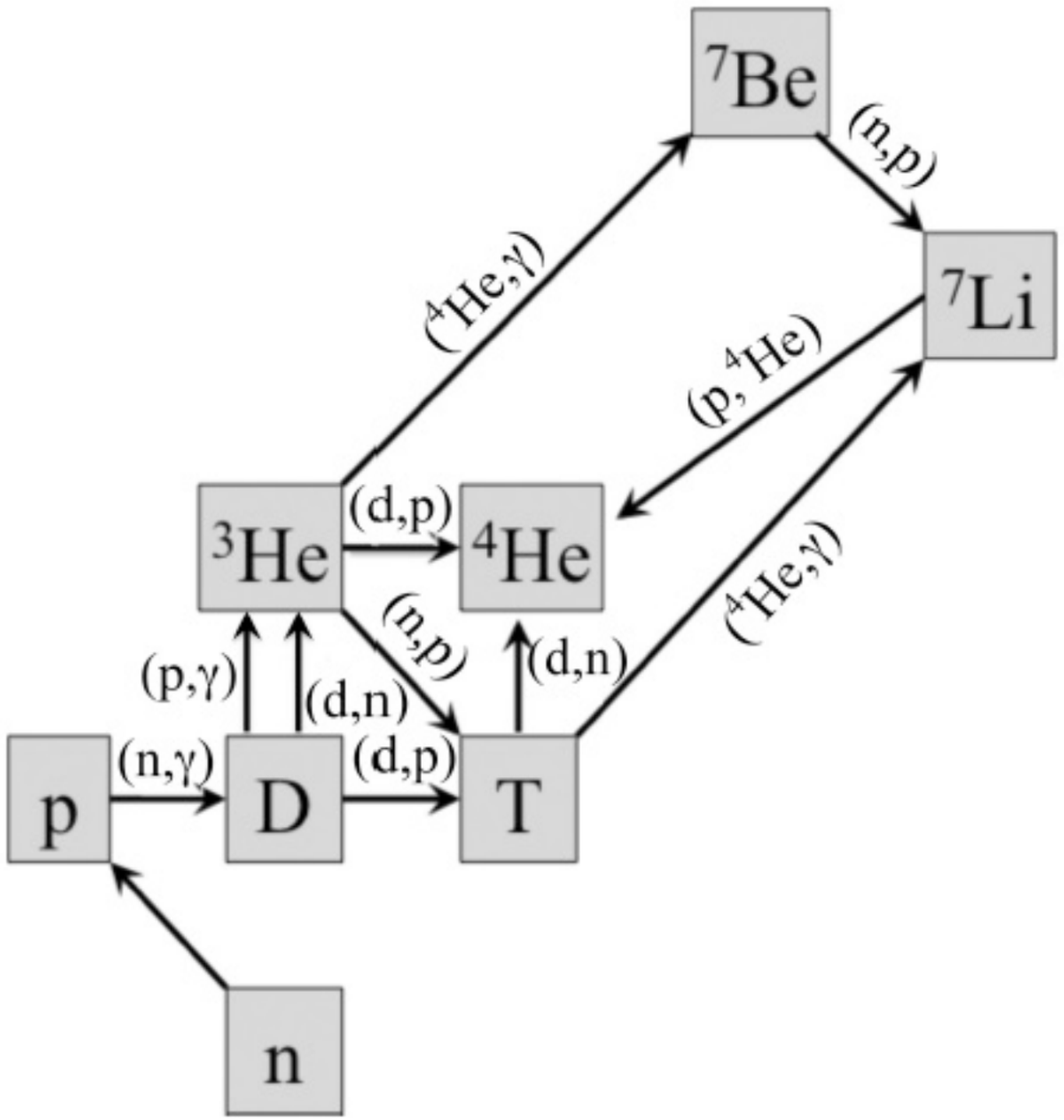
Hot plasma of hydrogen atoms and photons, and DM and cc

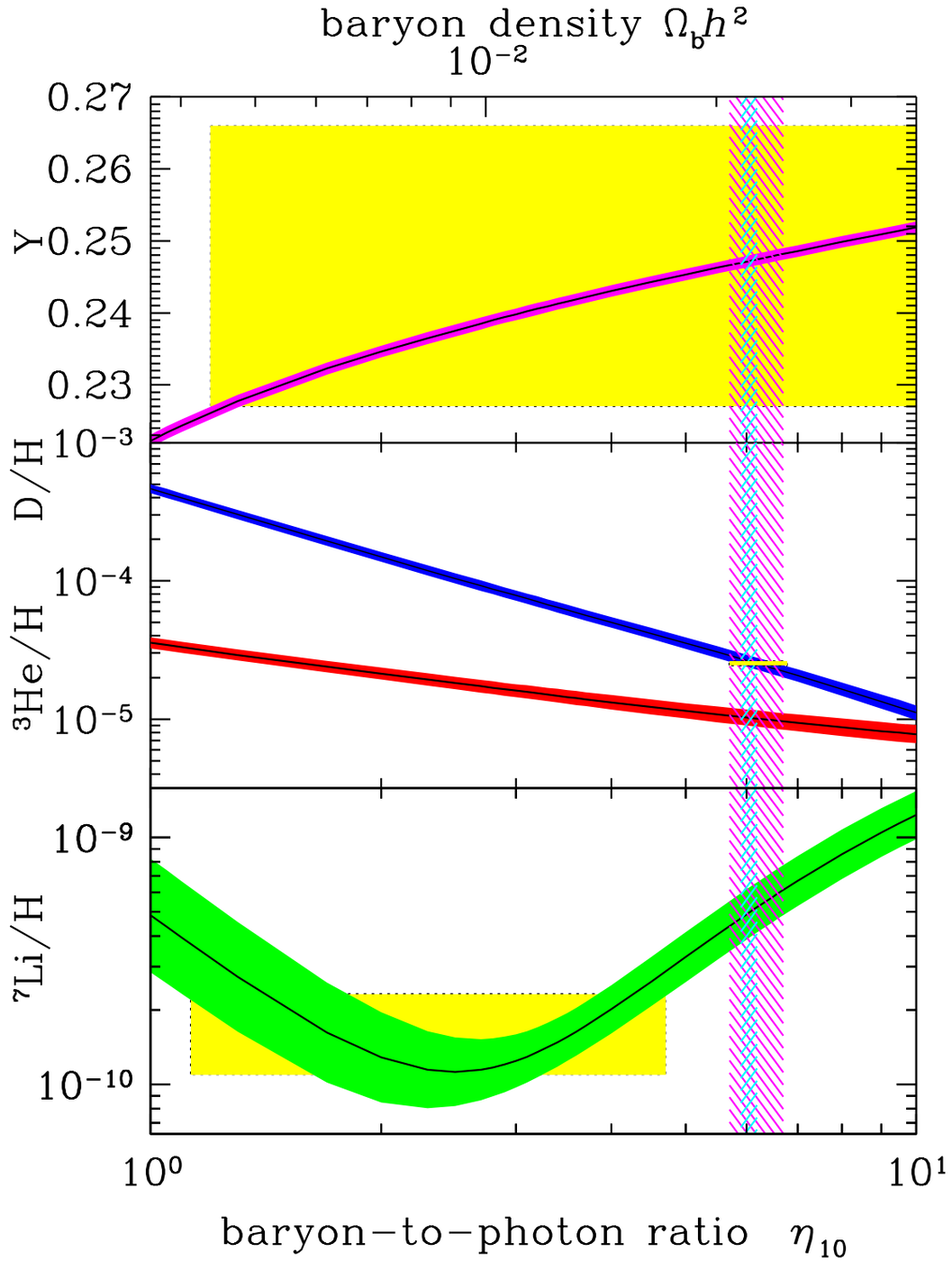
Planck Collaboration



Hu 0802.3688

Big Bang Nucleosynthesis





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

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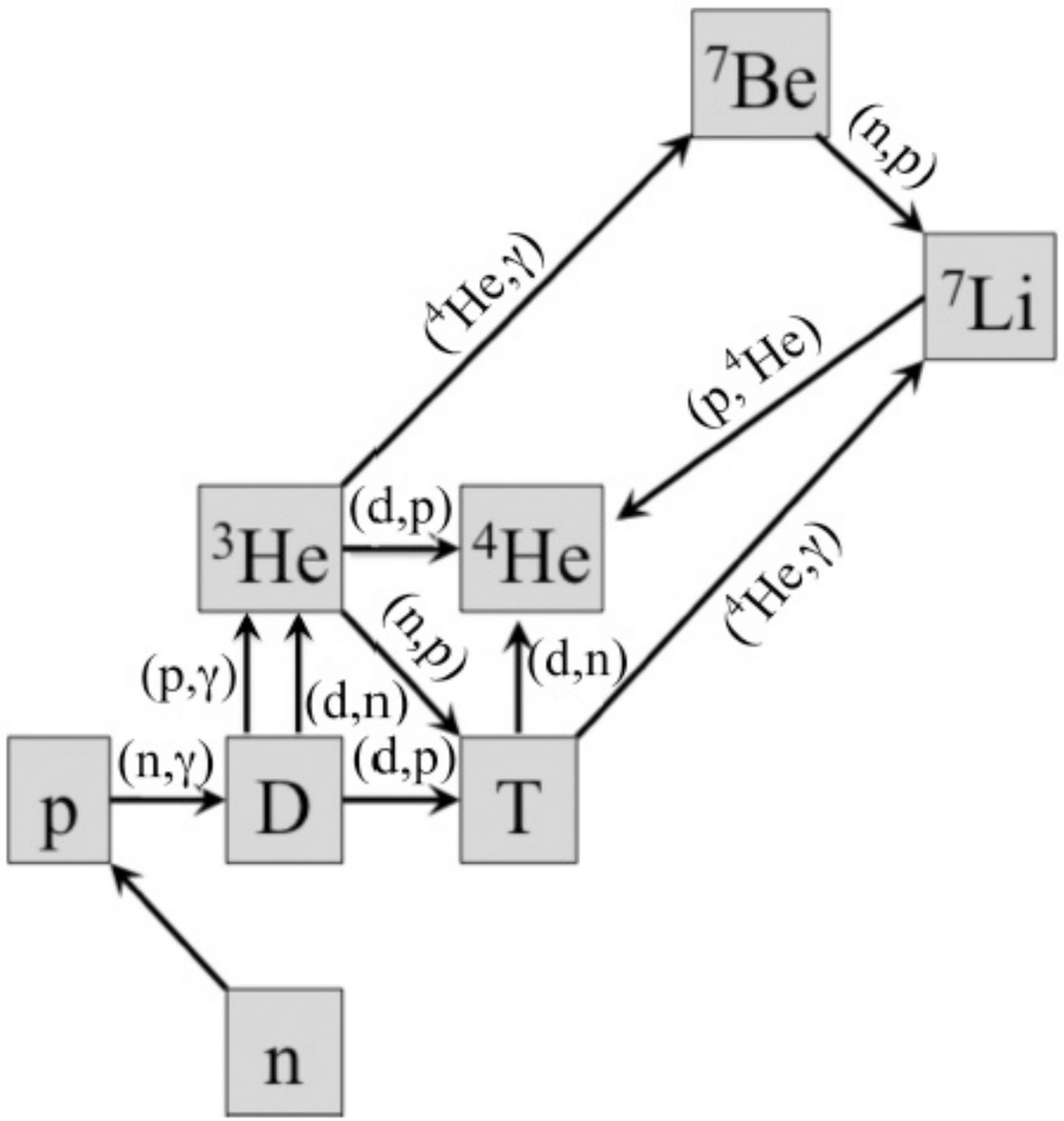

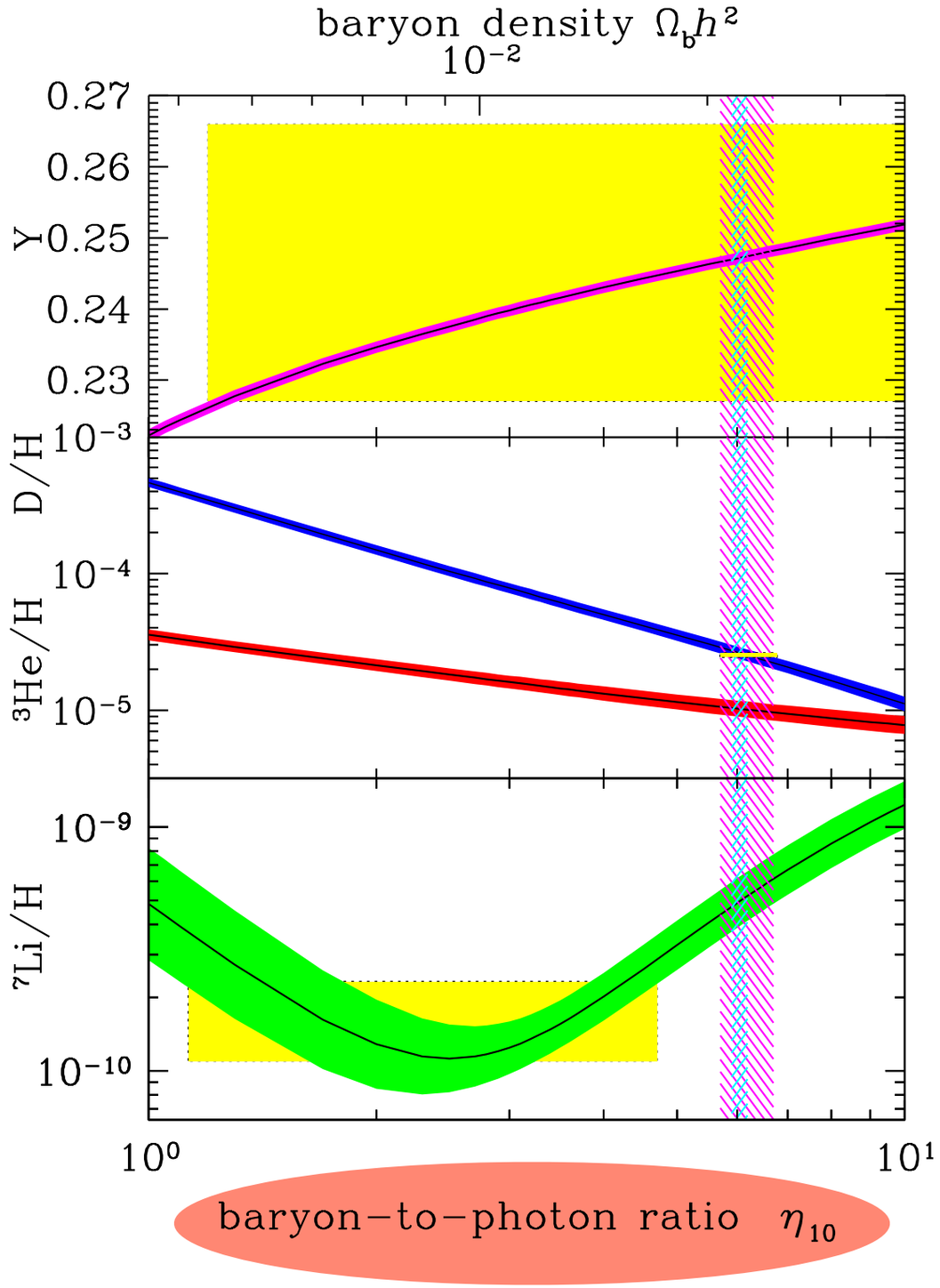

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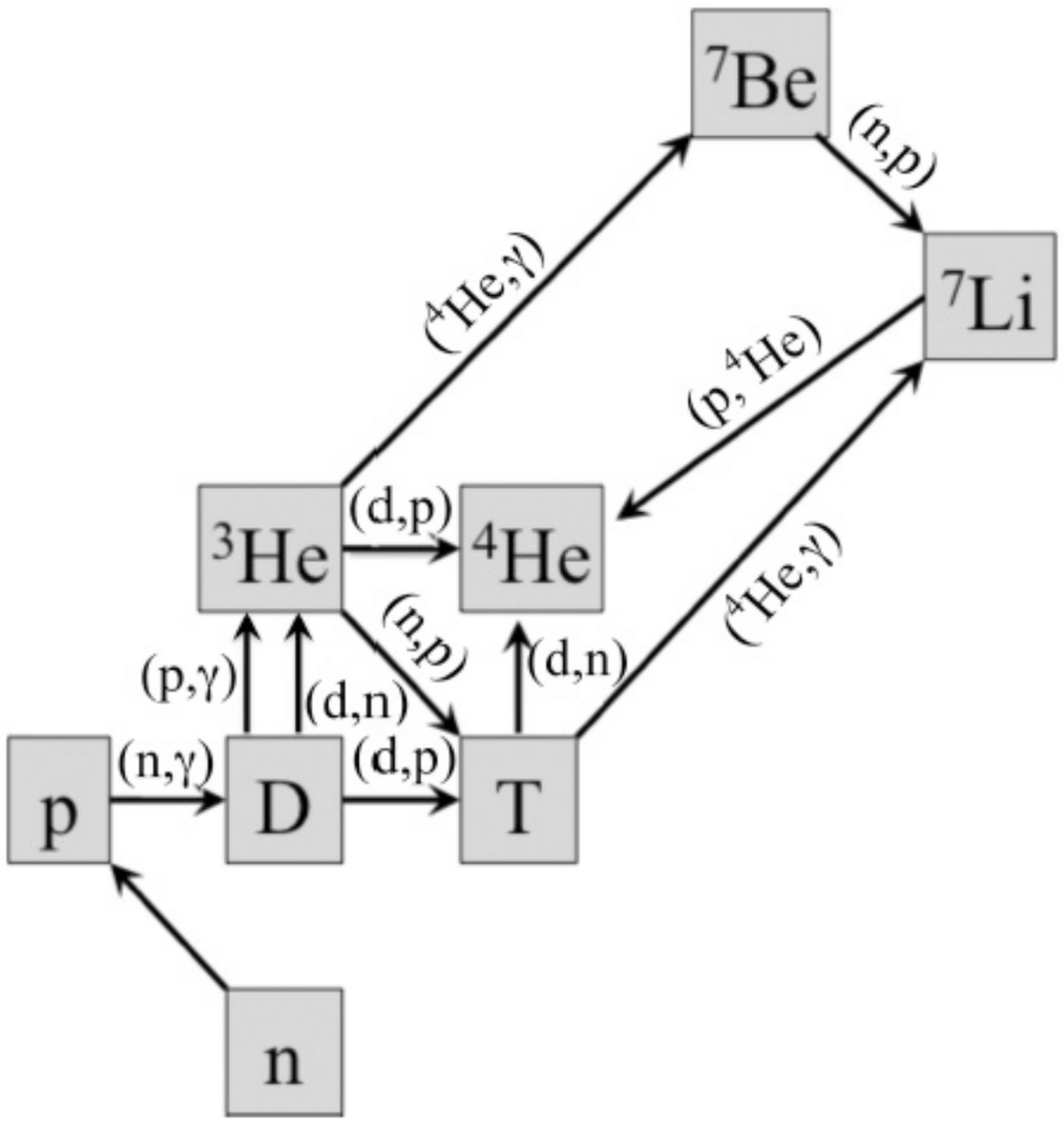
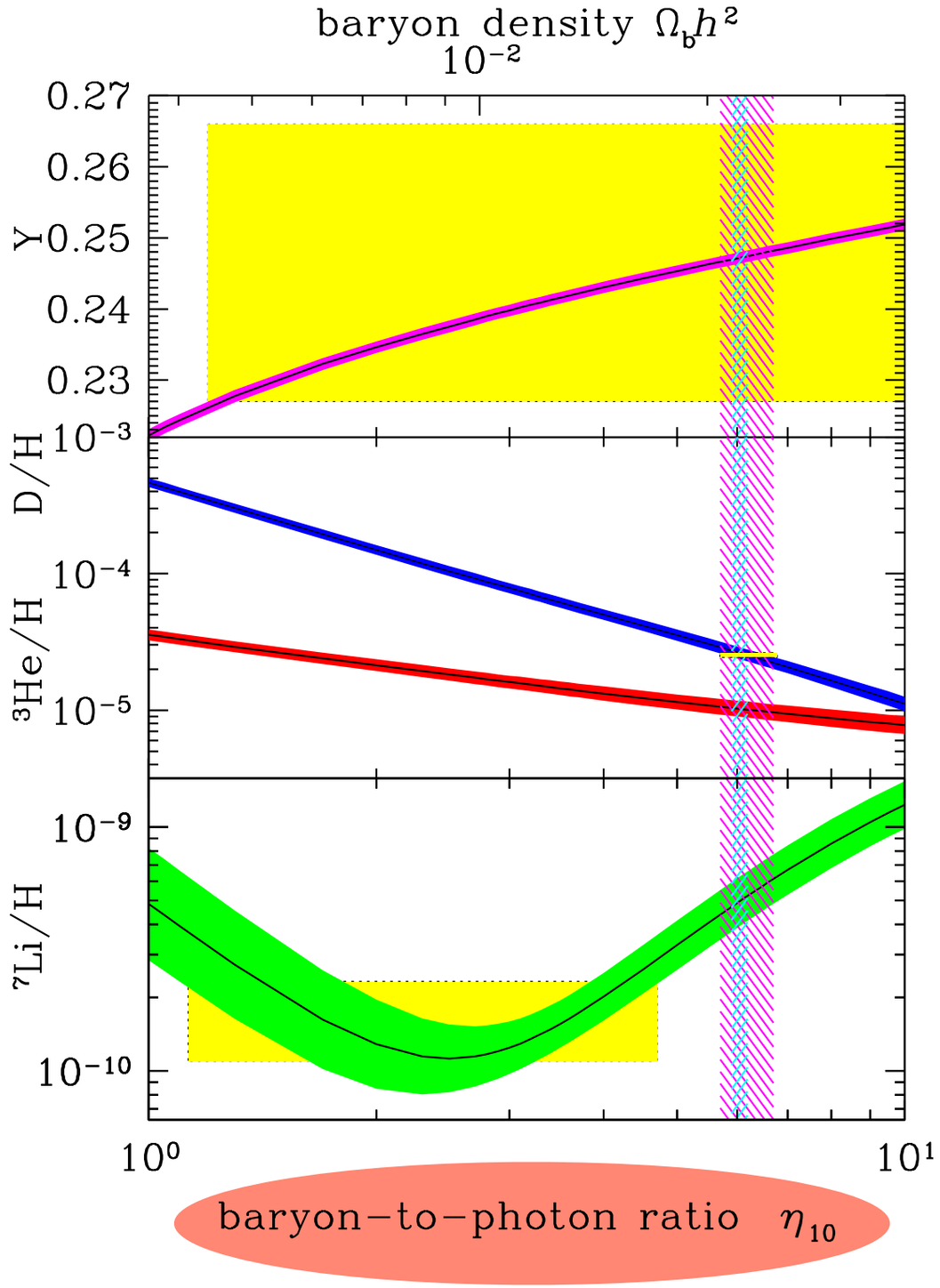




Hot soup of protons and neutrons, can predict light element abundance

~5% in baryons

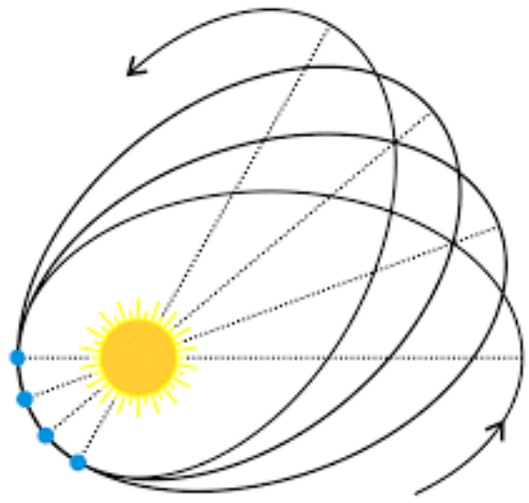
So far all probes have been gravitational in nature

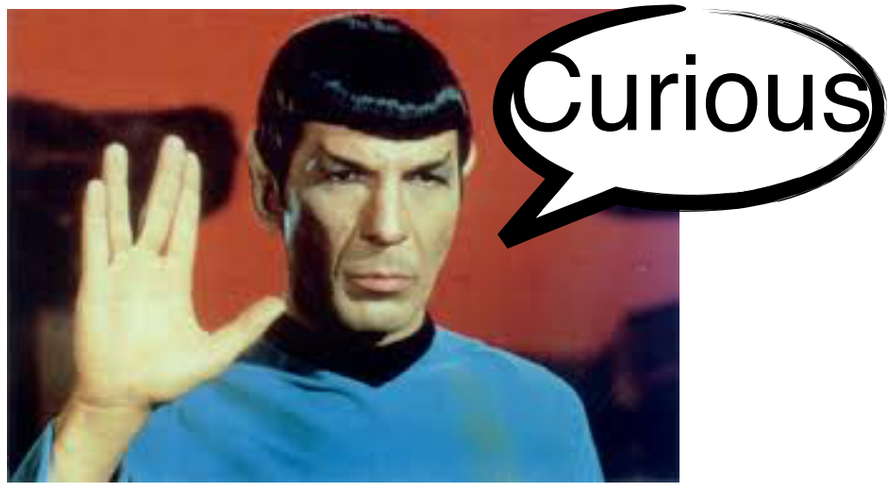
What about other interactions?

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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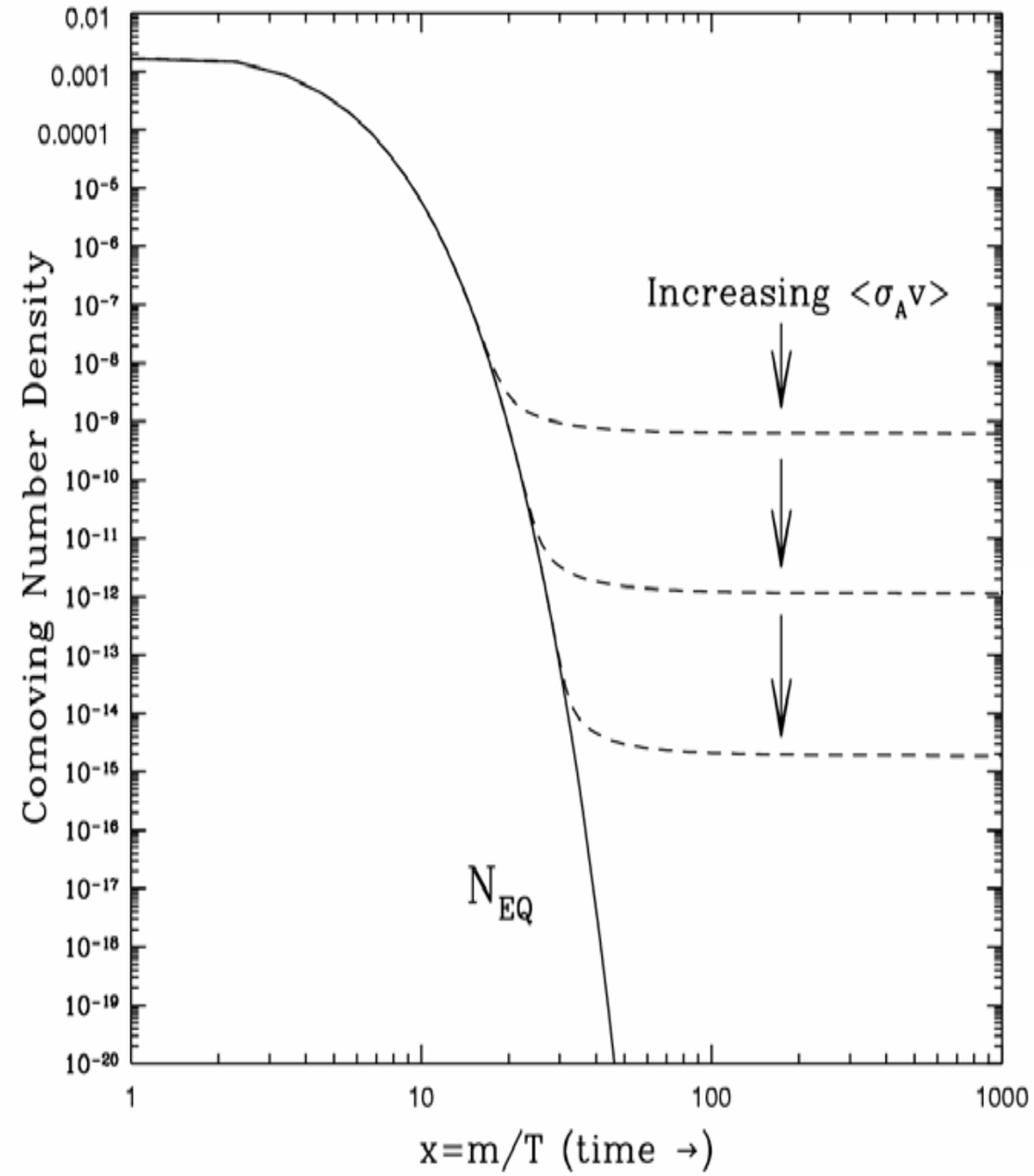

$$\chi\chi \leftrightarrow \bar{f} f$$

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

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

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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

Techni-baryons

Dark Photon

mSUGRA

pMSSM

Gravitino DM

Q-balls

R-parity Conserving

Dirac DM

Asymmetric DM

Light Force Carriers

Extra Dimensions

Dynamical DM

Warm DM

Solitonic DM

UED DM

6d

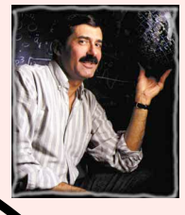
5d

Quark Nuggets

Warped Extra Dimensions

RS DM

Sterile Neutrinos



Axion DM

T-odd DM

Little Higgs

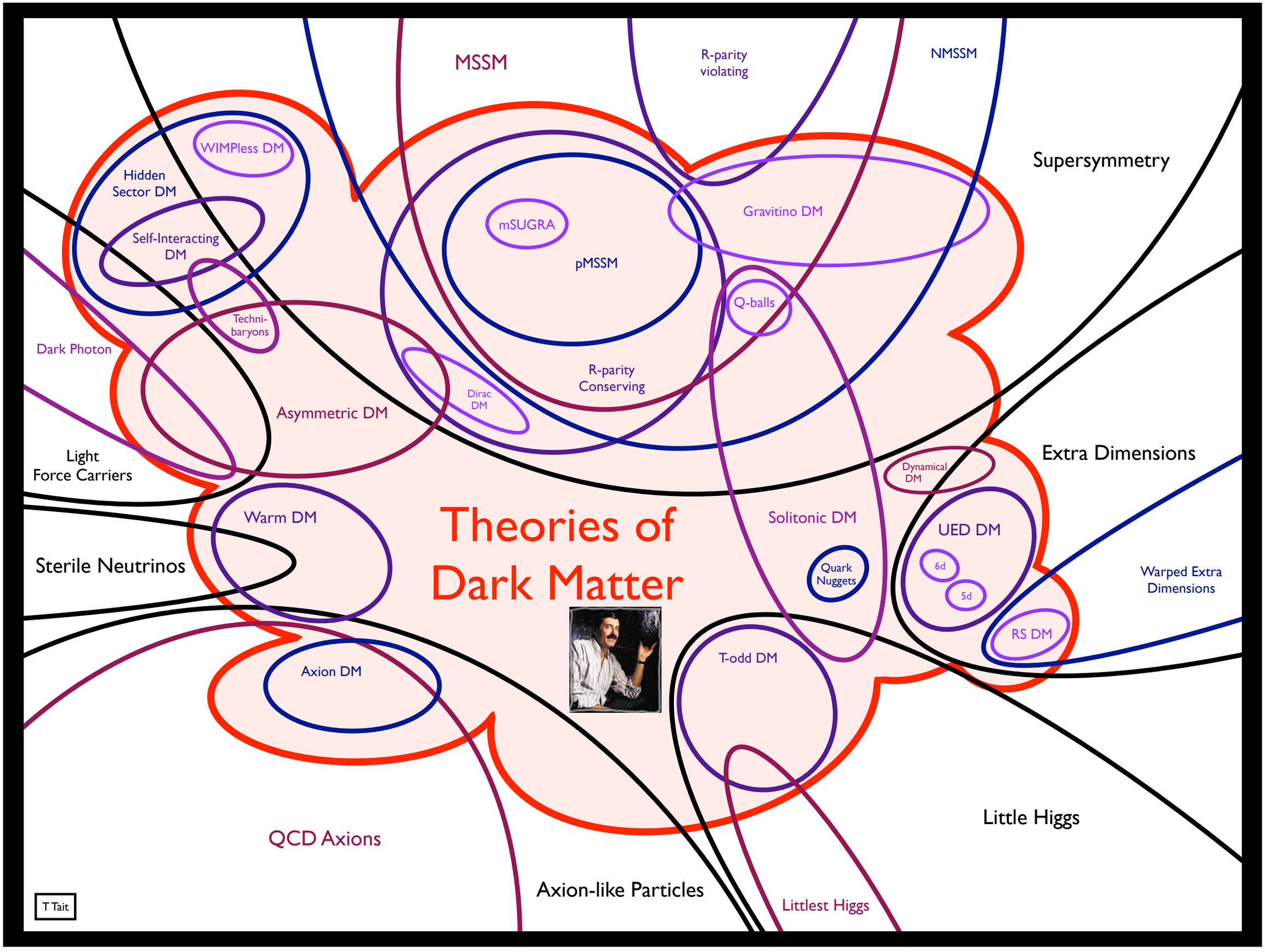
QCD Axions

Axion-like Particles

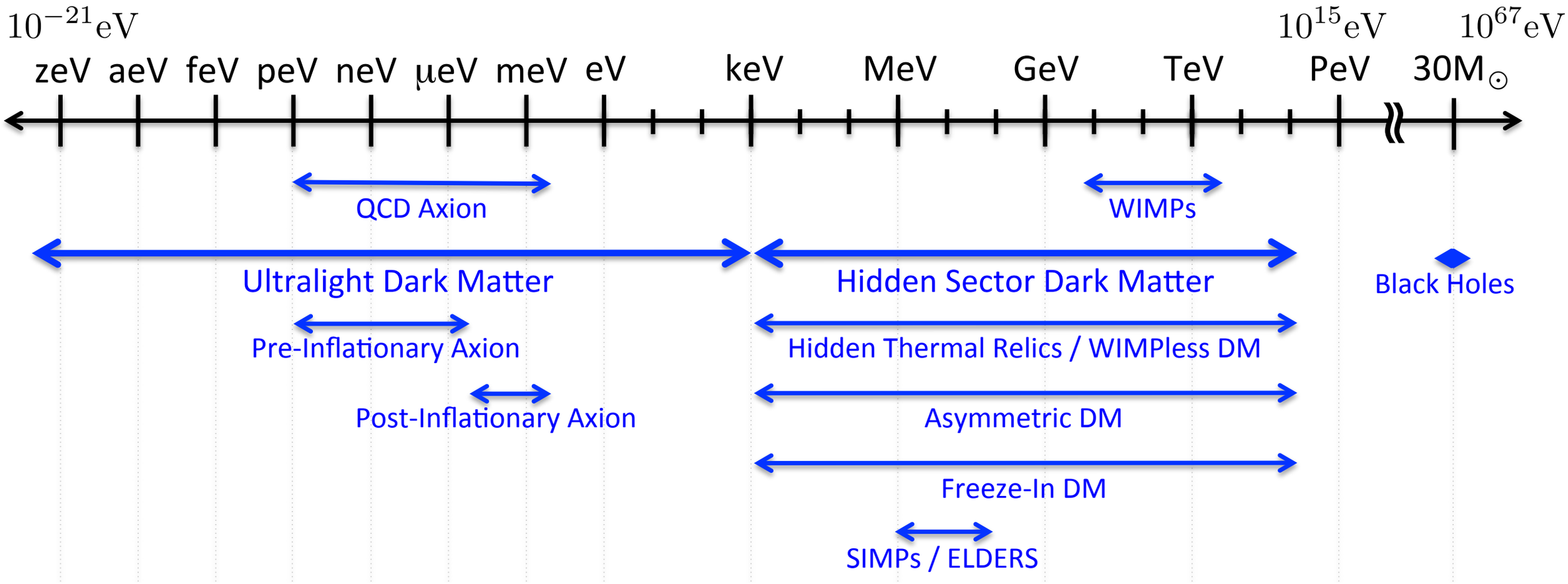
Littlest Higgs

T Tait

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

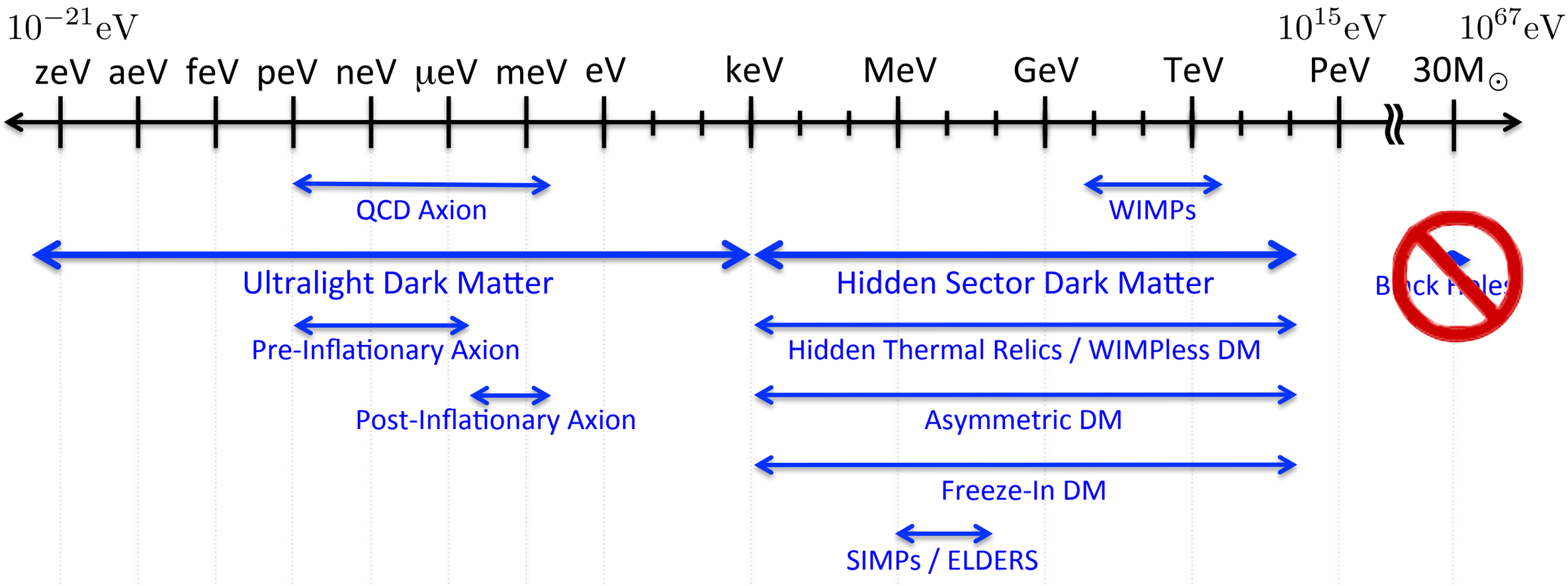


Particle theories



[Feng-US Cosmic Visions White papers]

Particle theories



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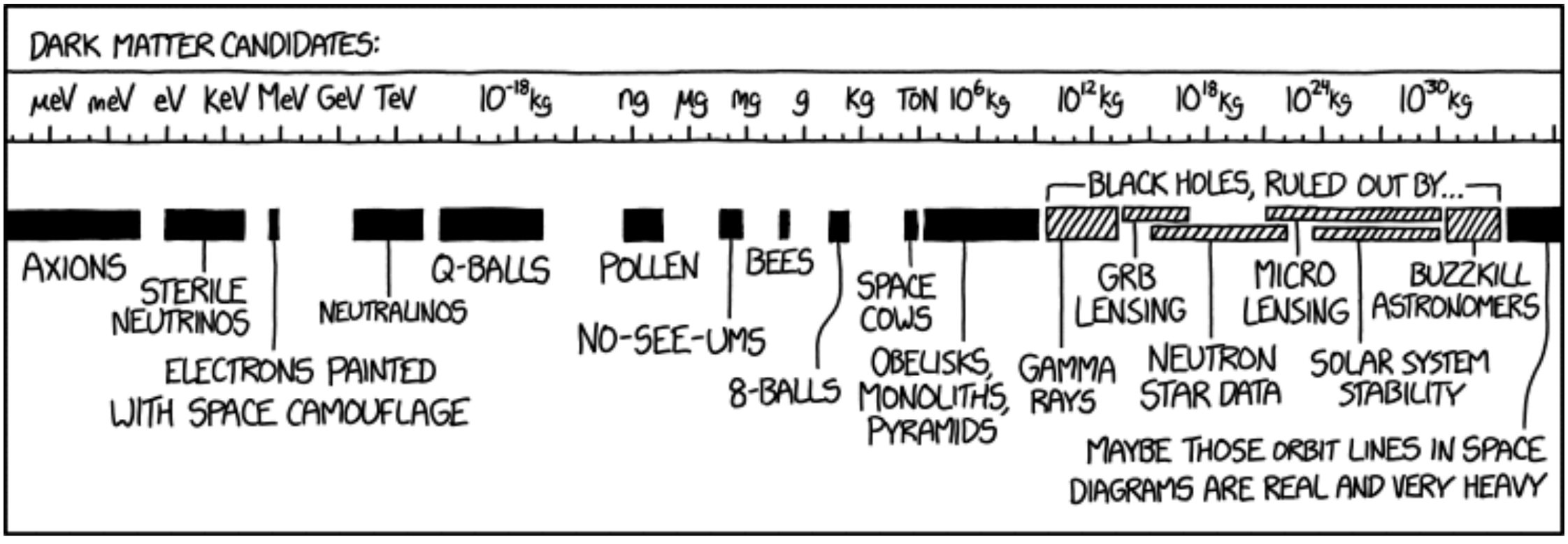
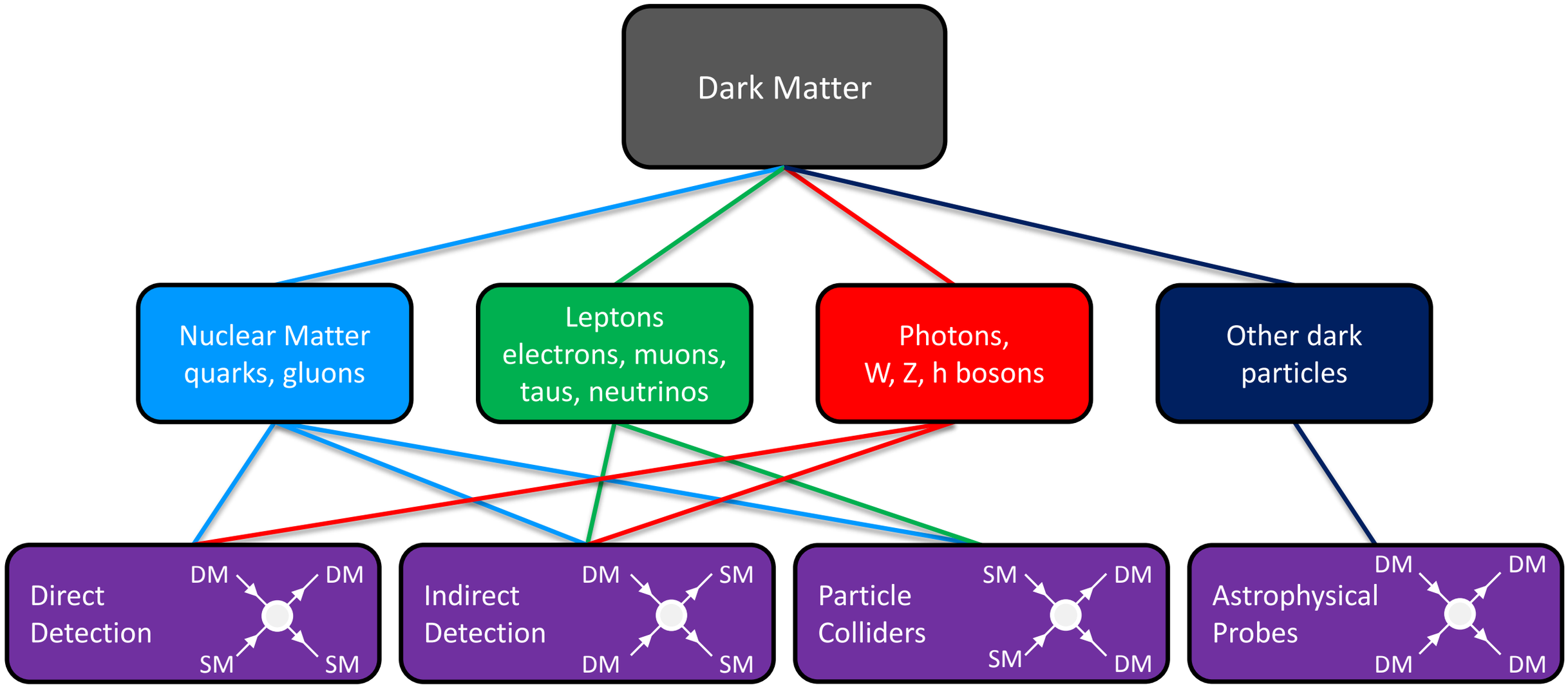
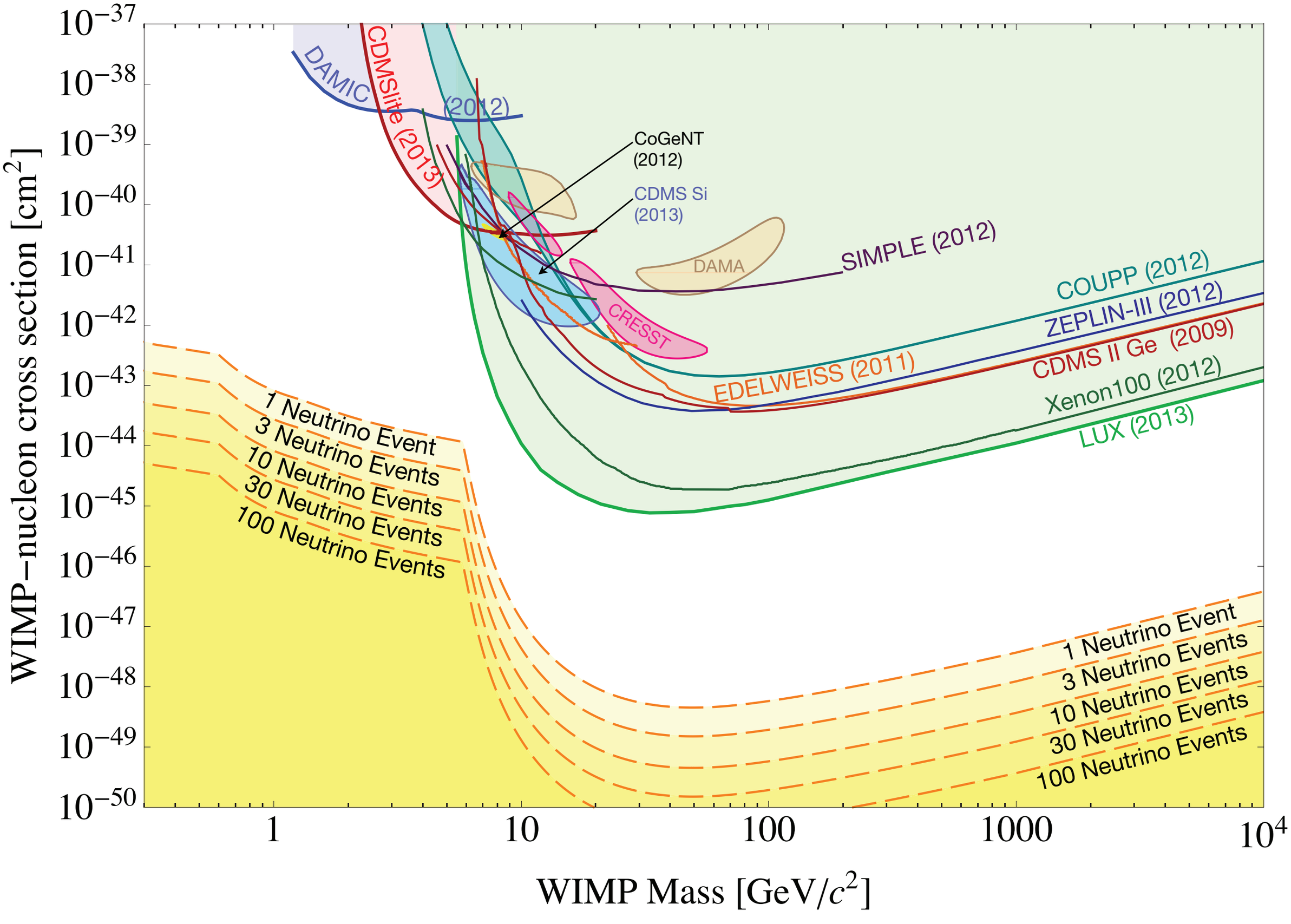

DARK MATTER CANDIDATES:
μeV meV eV KeV MeV GeV TeV
10^-18 kg
ng μg mg g Kg TON 10^6 kg
10^12 kg
10^18 kg
10^24 kg
10^30 kg
BLACK HOLES, RULED OUT BY...
AXIONS
STERILE NEUTRINOS
ELECTRONS PAINTED WITH SPACE CAMOUFLAGE
NEUTRALINOS
Q-BALLS
POLLEN
NO-SEE-UMS
BEES
8-BALLS
SPACE COWS
OBELISKS, MONOLITHS, PYRAMIDS
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

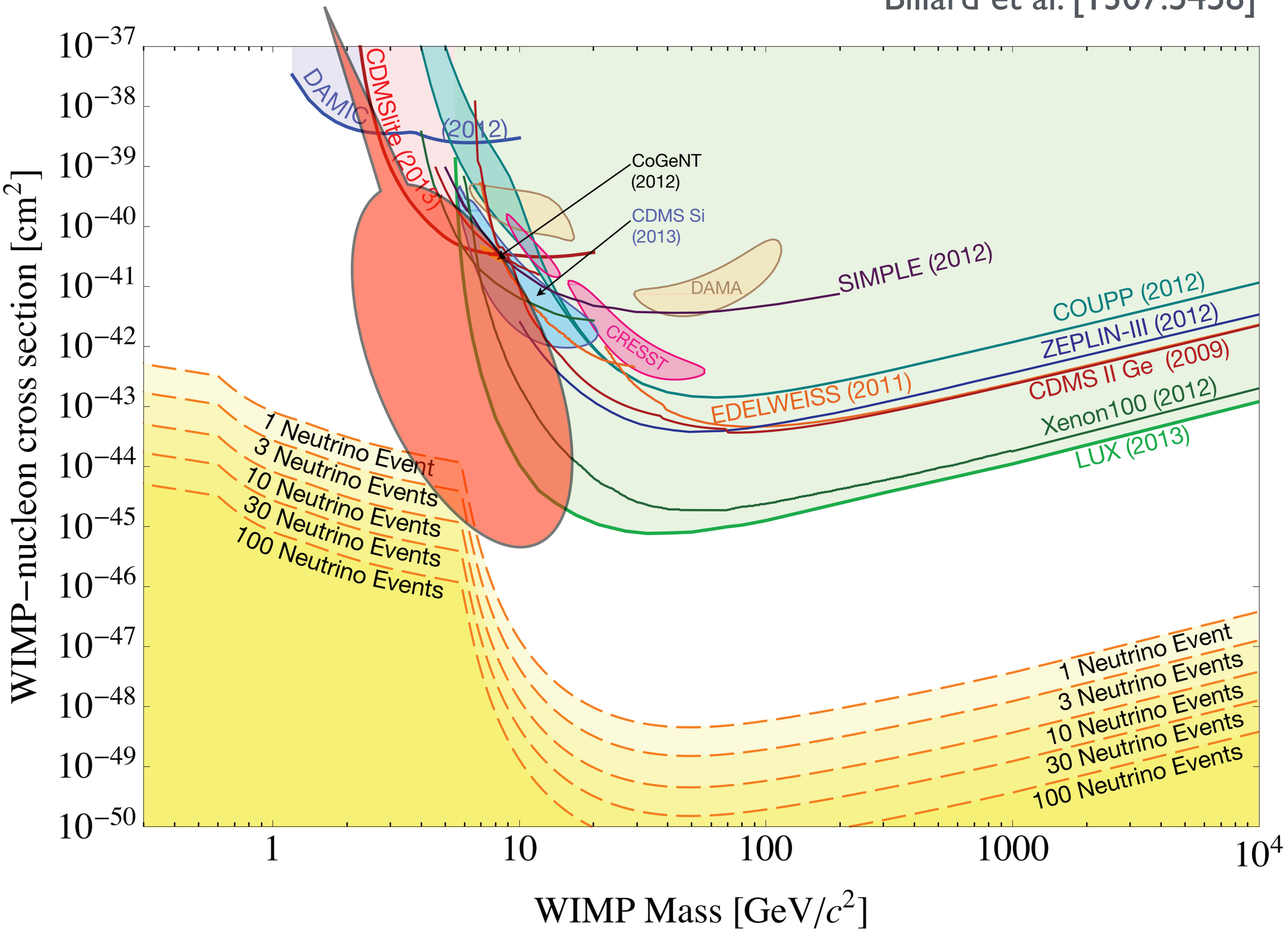

Dark Matter
Nuclear Matter
quarks, gluons
Leptons
electrons, muons,
taus, neutrinos
Photons,
W, Z, h bosons
Other dark
particles
Direct
Detection
DM
DM
SM
SM
Indirect
Detection
DM
SM
DM
SM
Particle
Colliders
SM
DM
SM
DM
Astrophysical
Probes
DM
DM
DM
DM

Billard et al. [1307.5458]



Threshold cuts off

Billard et al. [1307.5458]



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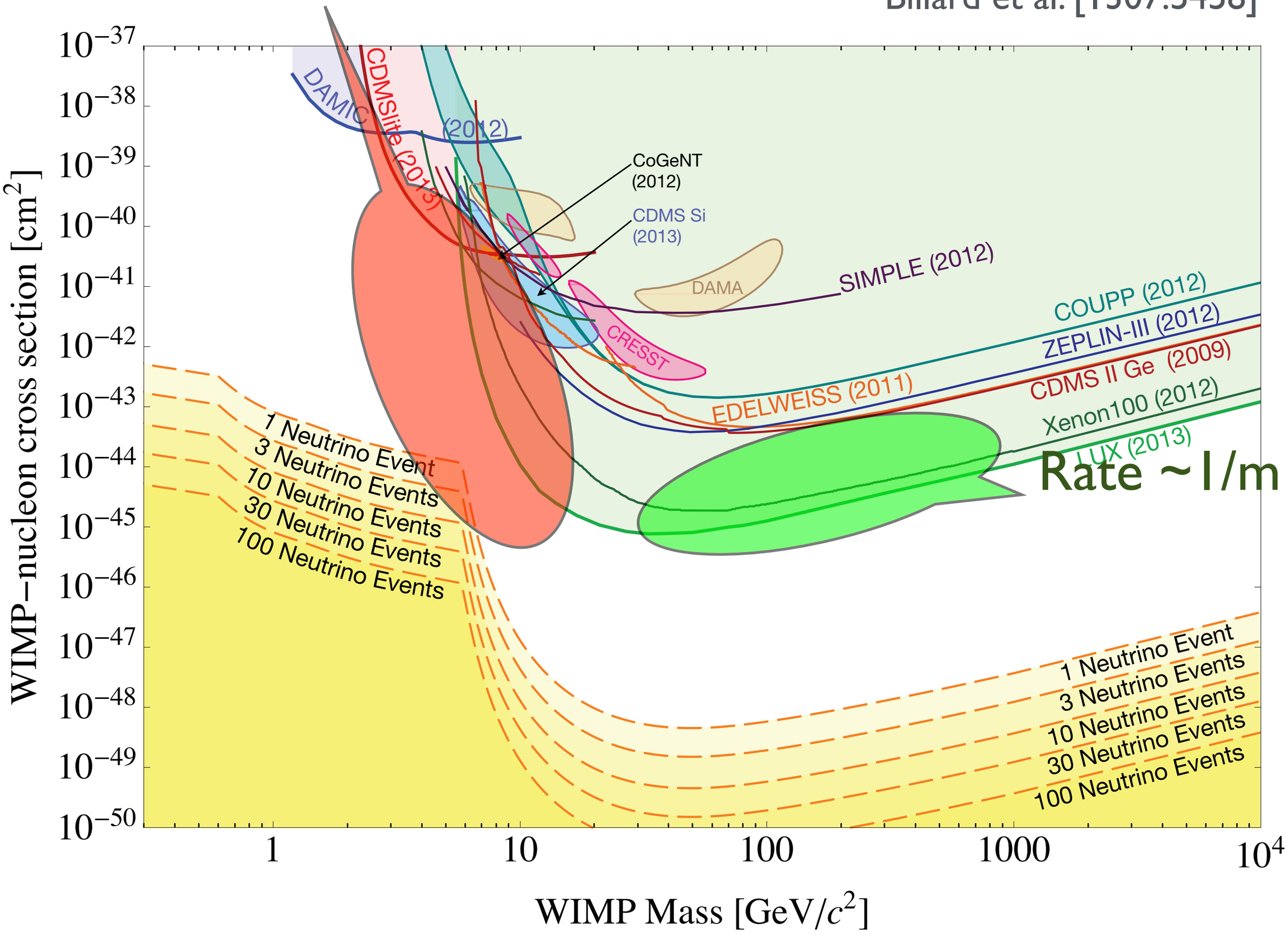
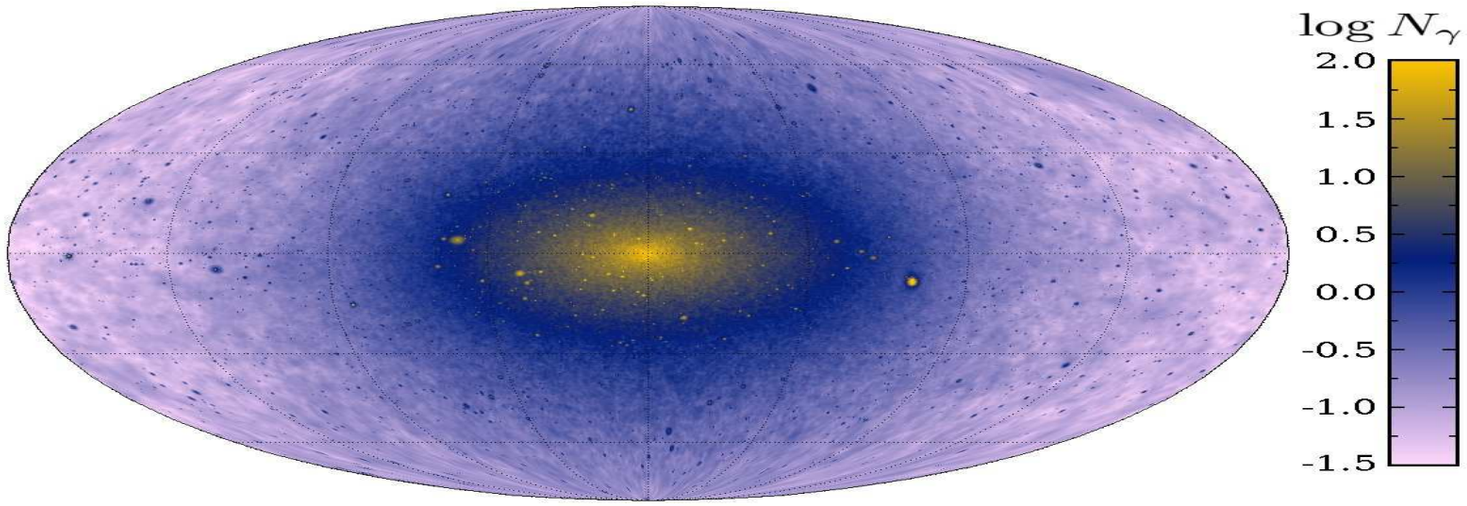


Indirect Detection "Master formula"



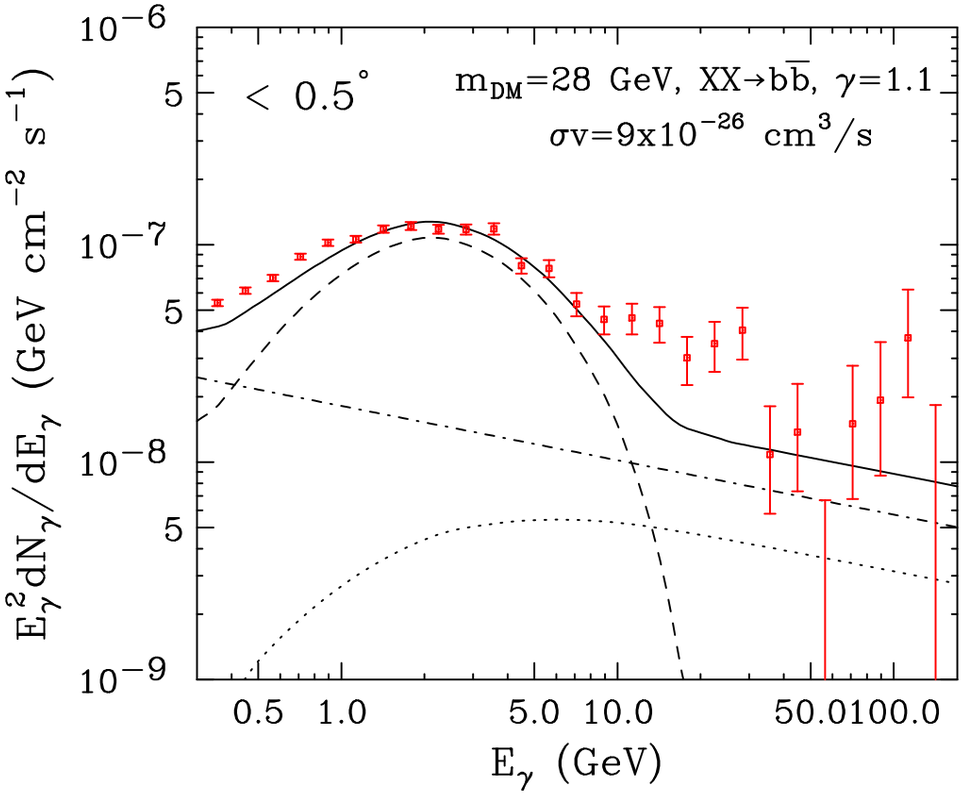
$$\frac{dN}{d\Omega dE}(\psi) = \frac{1}{4\pi\eta}\frac{f_\chi^2 J(\psi)}{m_\chi^2}\sum_i \langle\sigma v\rangle_i \frac{dN^i}{dE_\gamma}$$

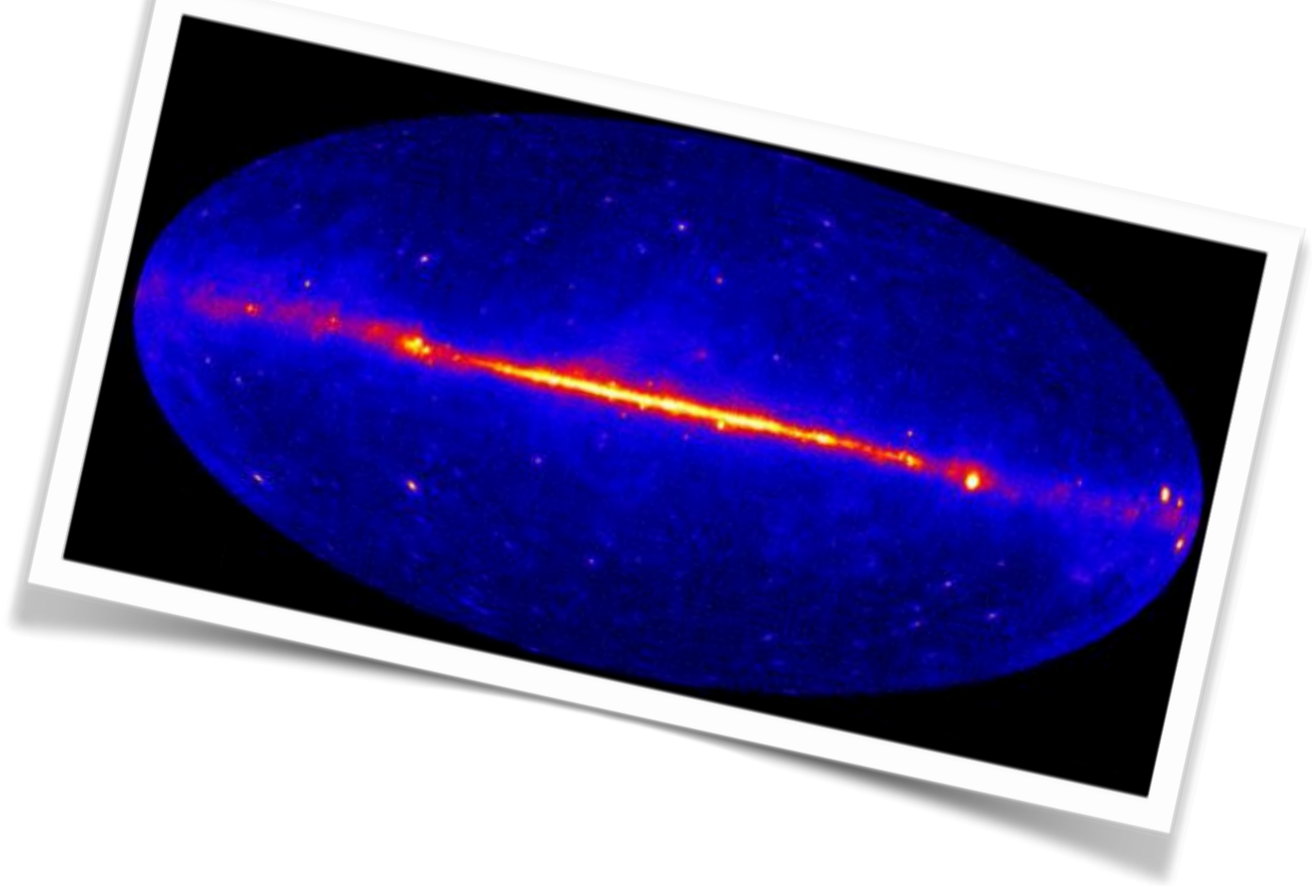
Spectrum of particles in final state

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

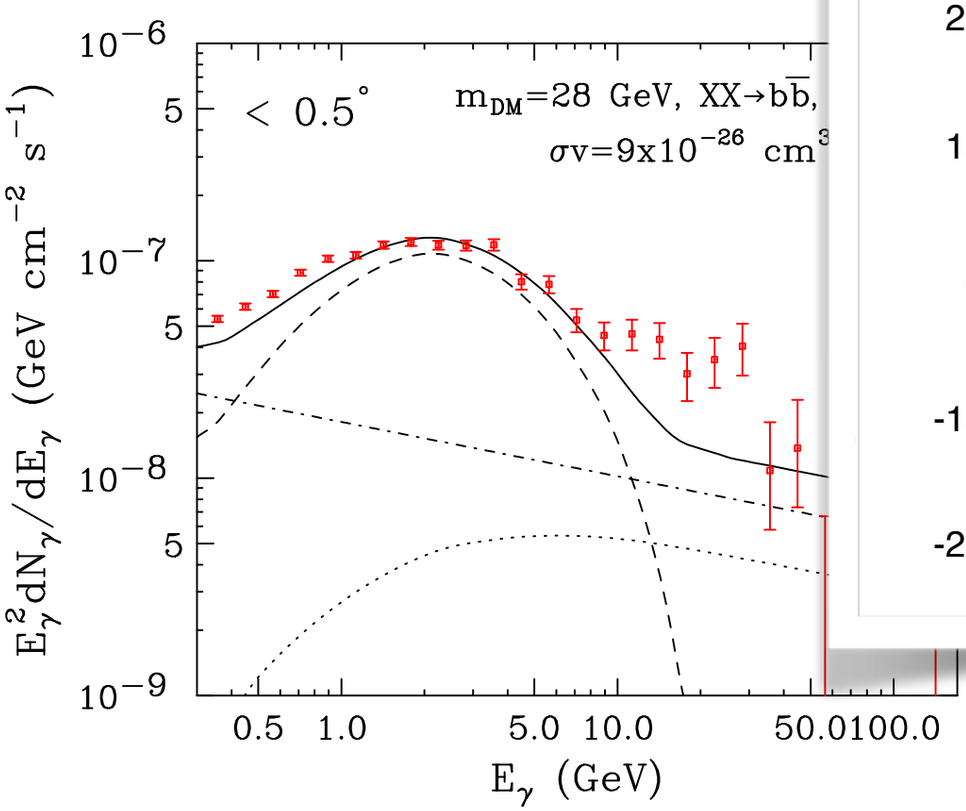
Line of sight integral

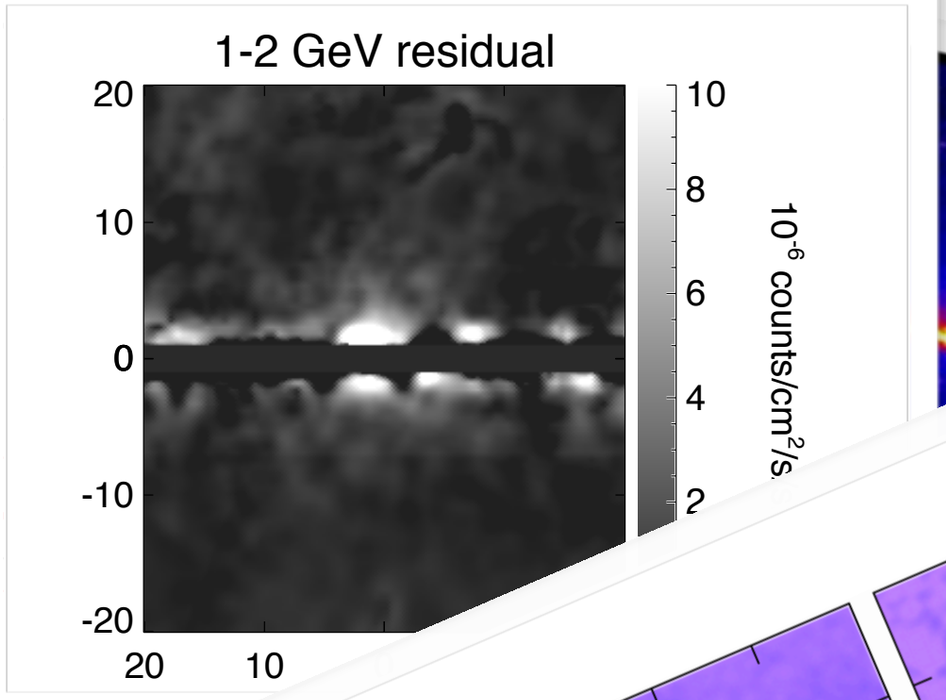
[Goodenough and Hooper, 2009]





[Goodenough and Hoo





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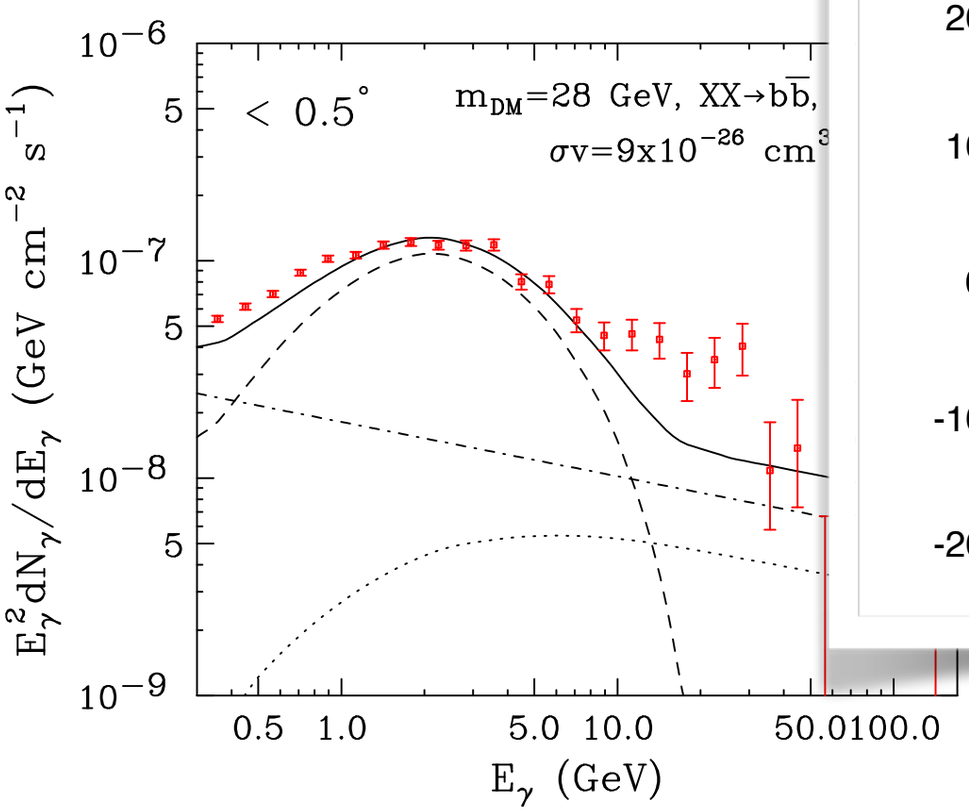
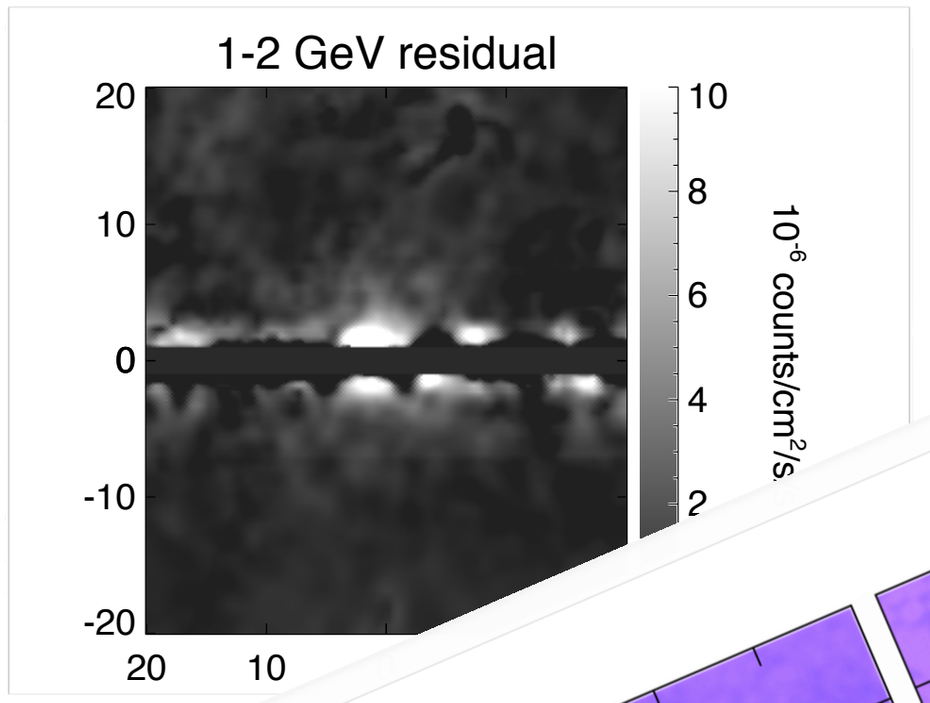
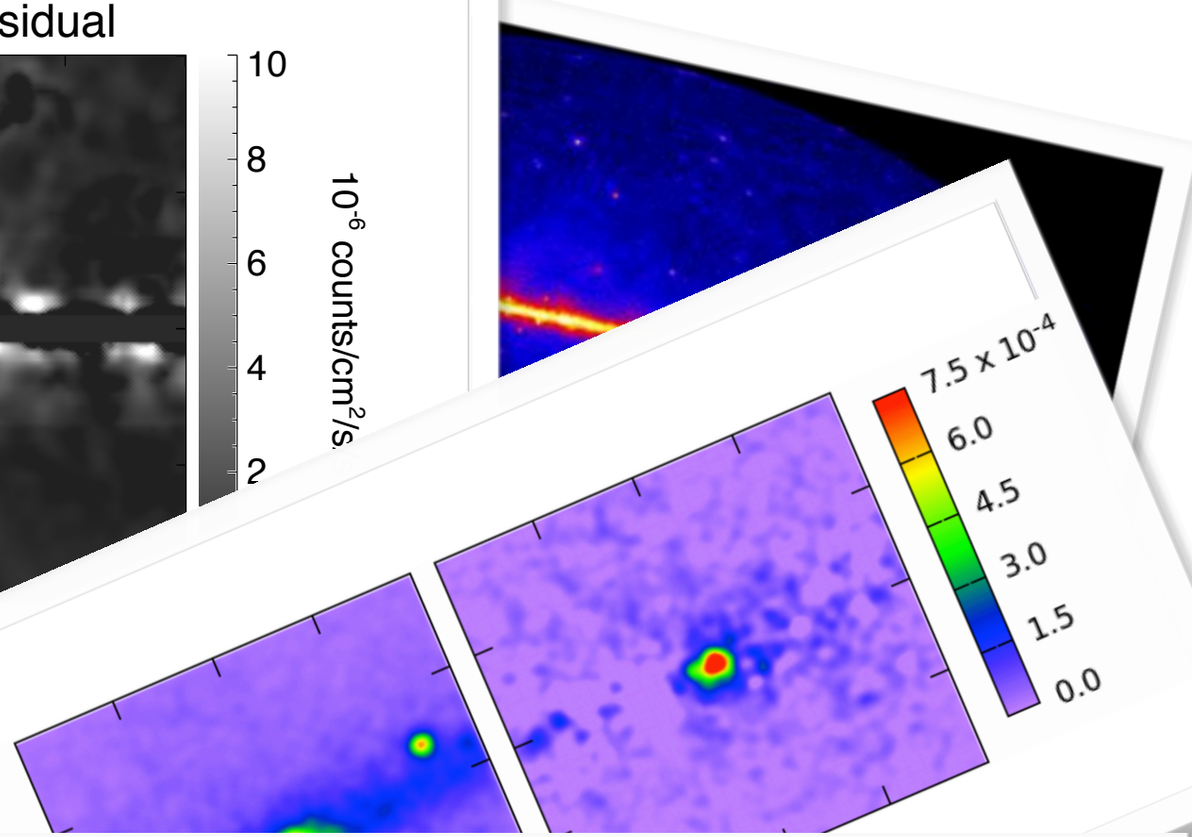
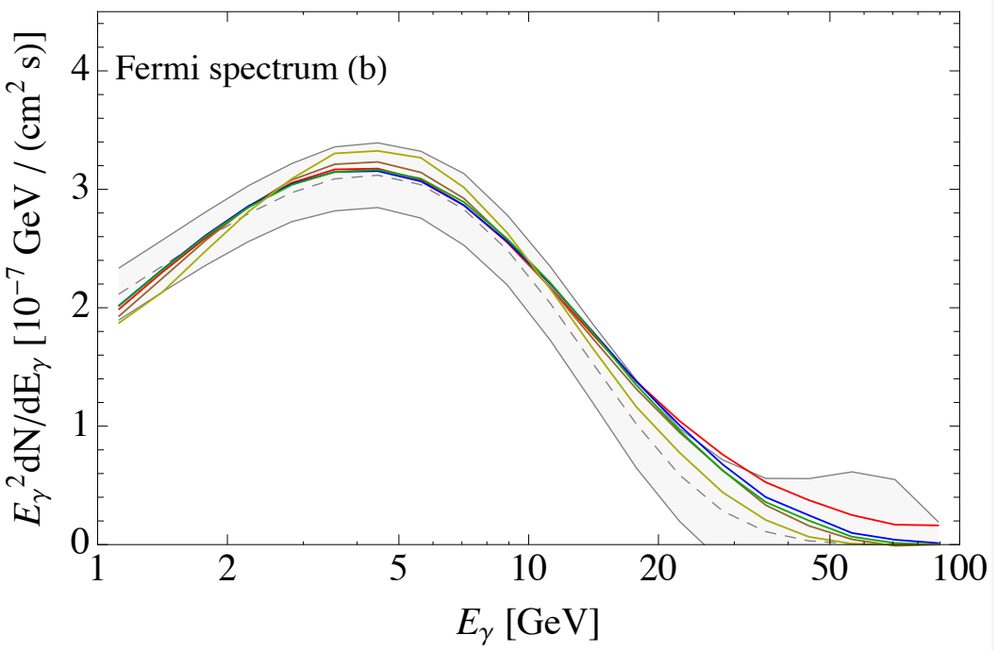
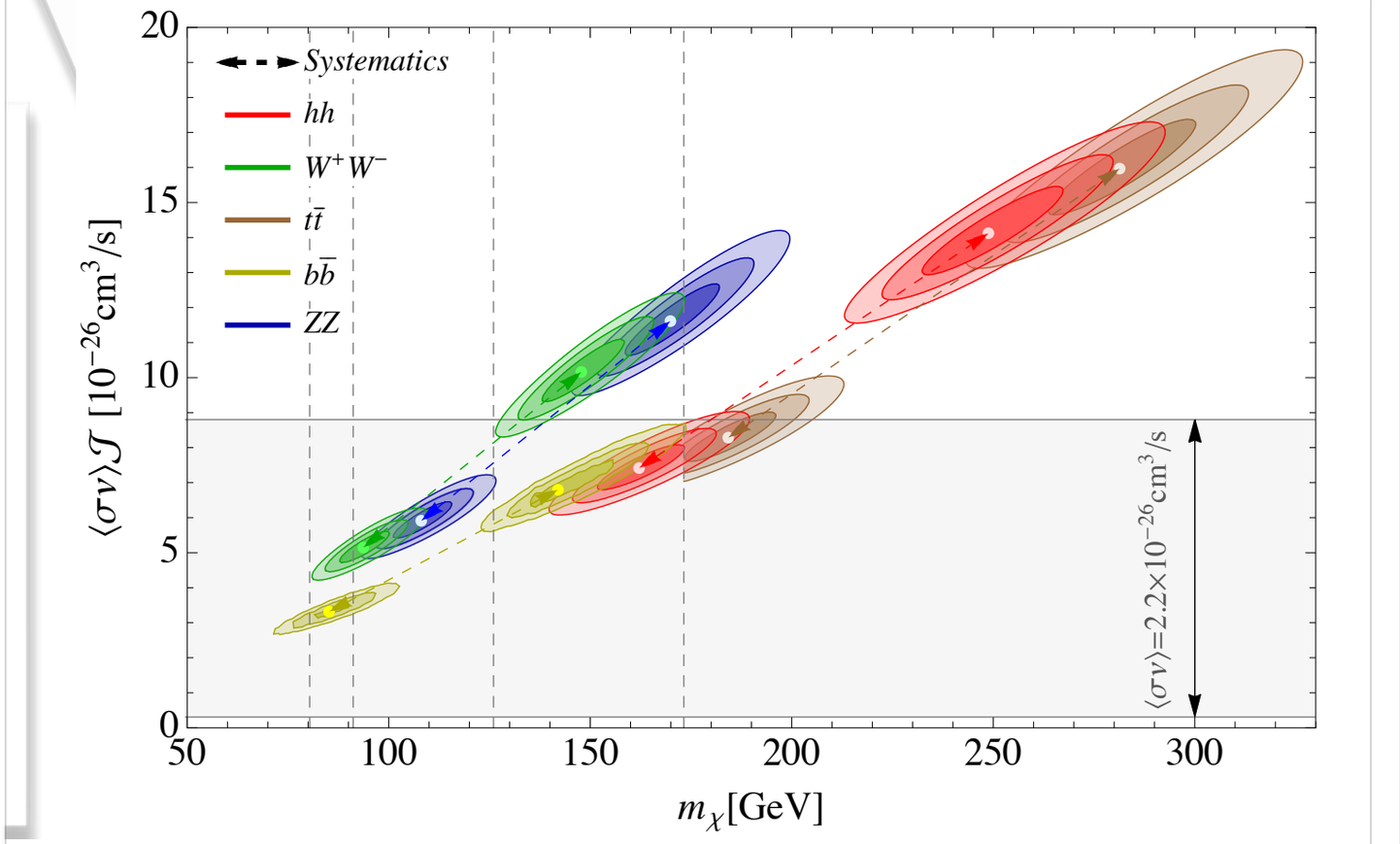


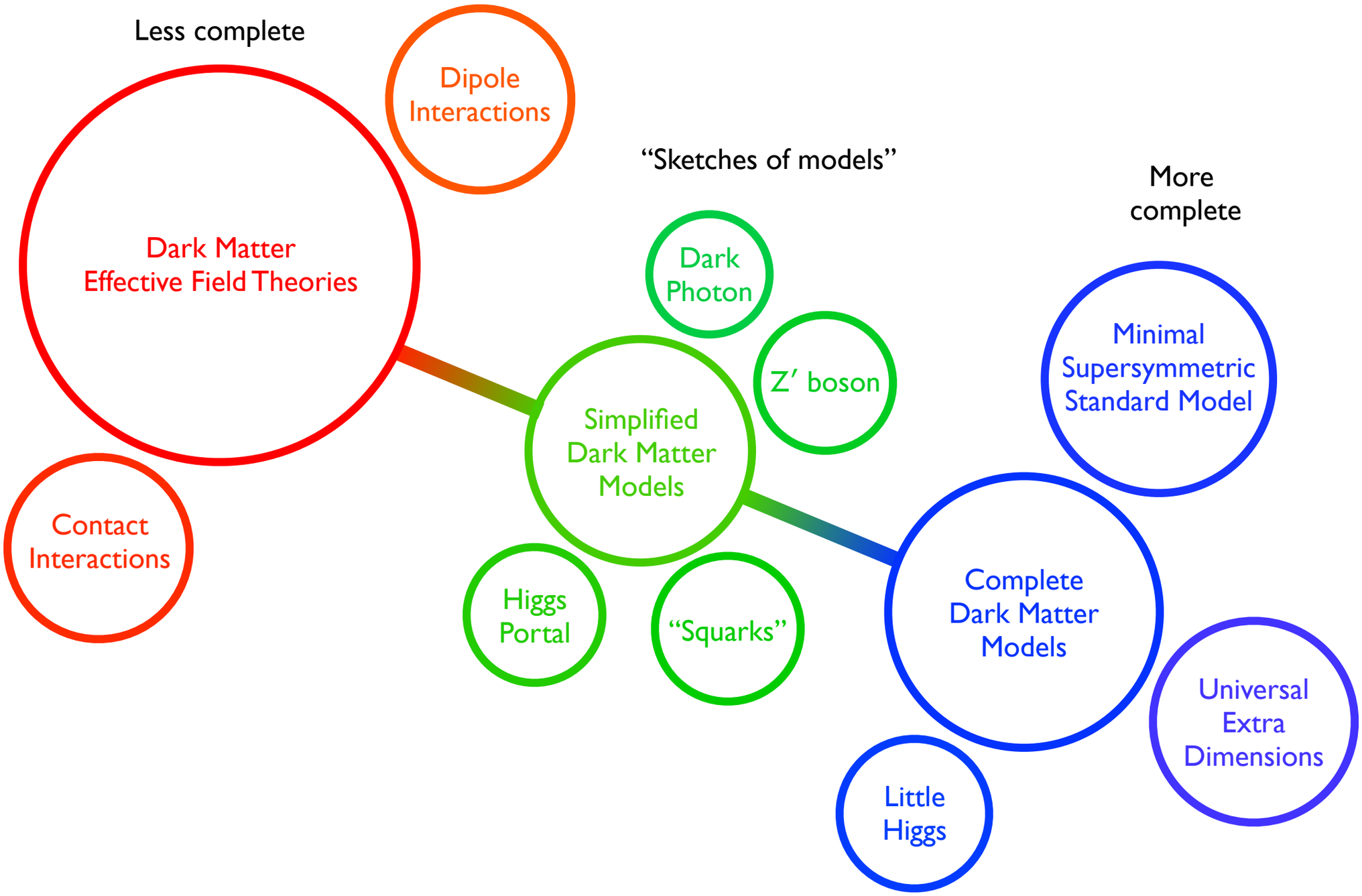






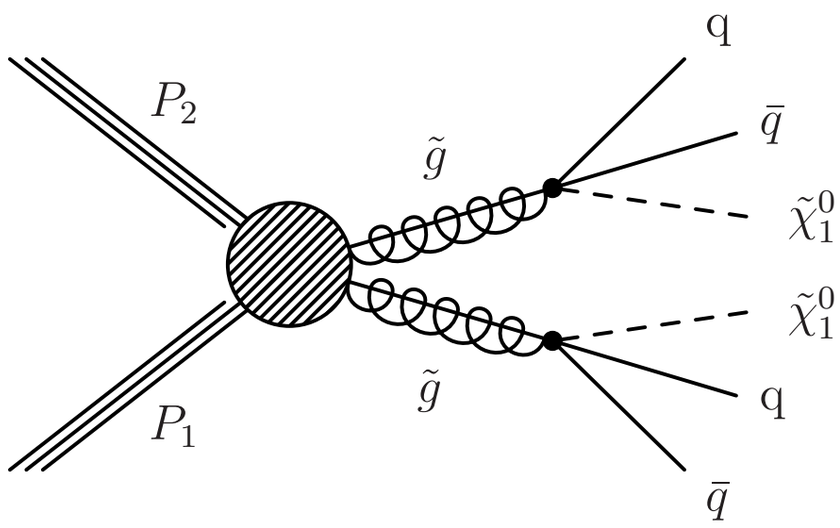


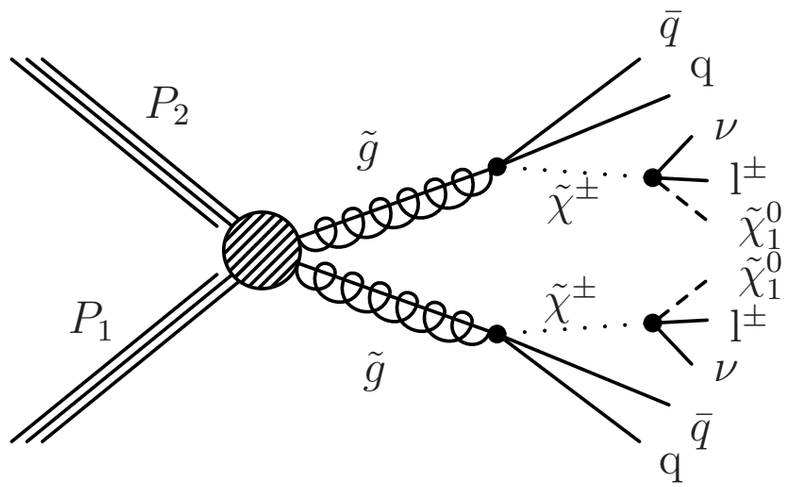
Ways to search for DM at colliders



Ways to search for DM at colliders

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





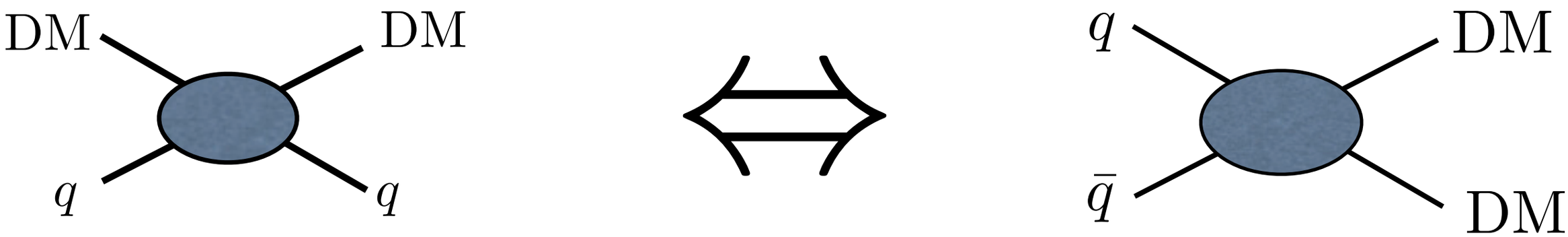
Complicated/interesting final state.
Tuned analyses
No clear relation between different search strategies

Ways to search for DM at colliders

Beltran et al. [1002.4137]

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

Straightforward relationship between DD and collider



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

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

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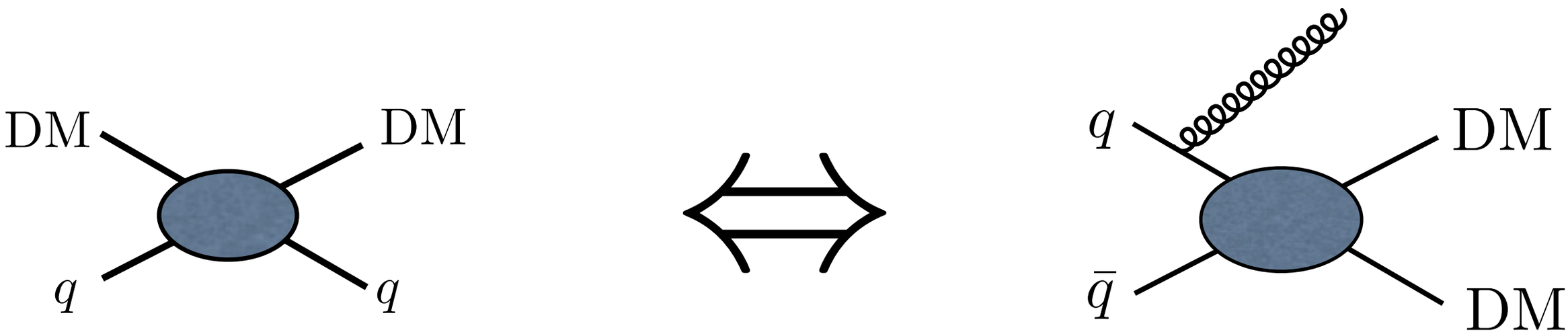

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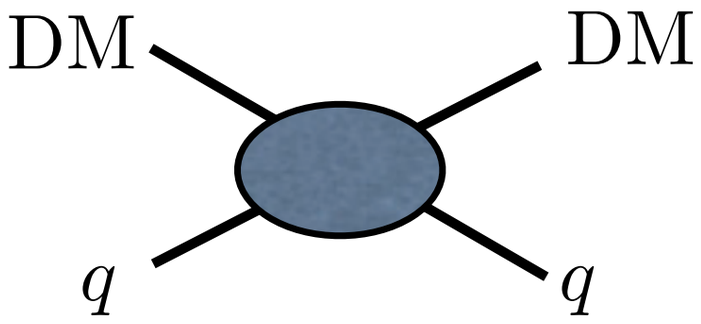
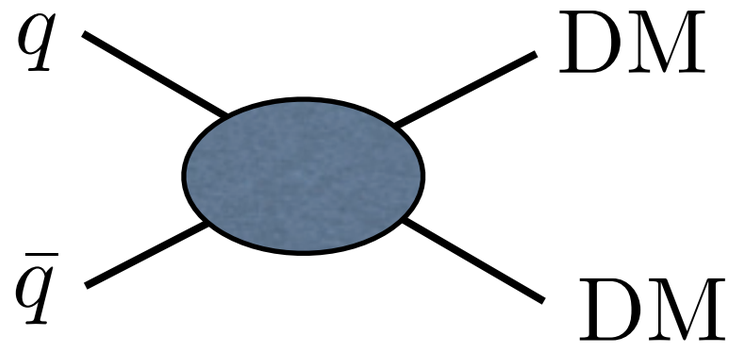
Mono-mania at the LHC

Operators



$\Leftrightarrow$



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

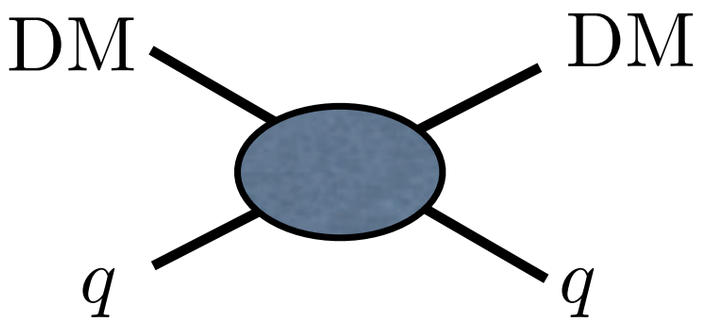
$$\mathcal{O}_A = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2}\,,$$ SD, axial-vector exchange

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

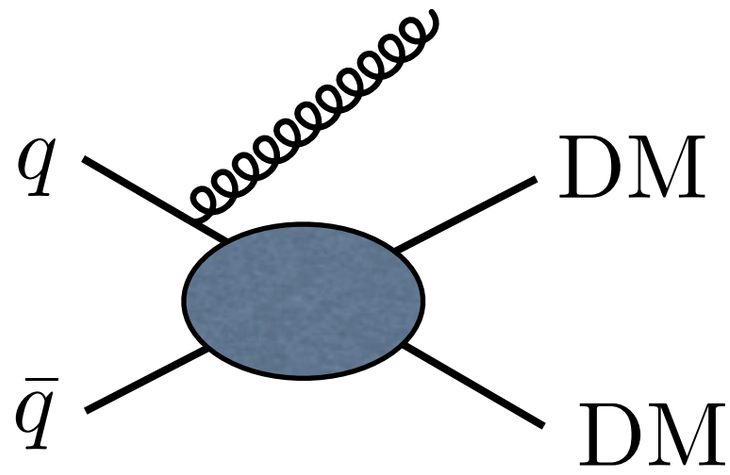
$$\mathcal{O}_g = \alpha_s \frac{(\bar{\chi}\chi)\,(G^a_{\mu\nu}G^{a\mu\nu})}{\Lambda^3}$$ SI, scalar exchange

Typically consider each operator separately

Operators



$\Longleftrightarrow$



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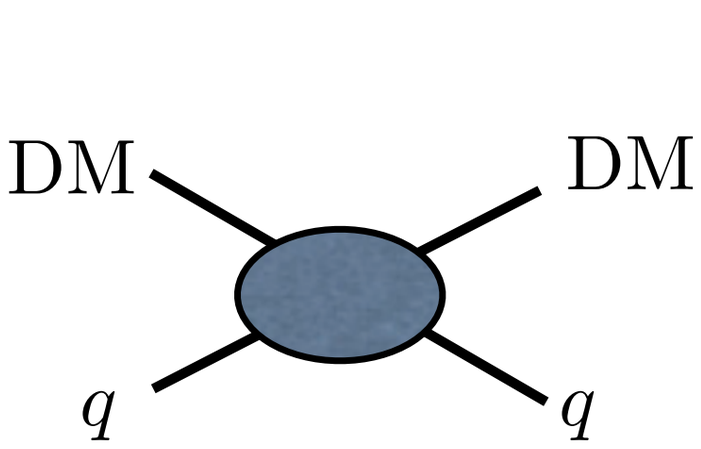

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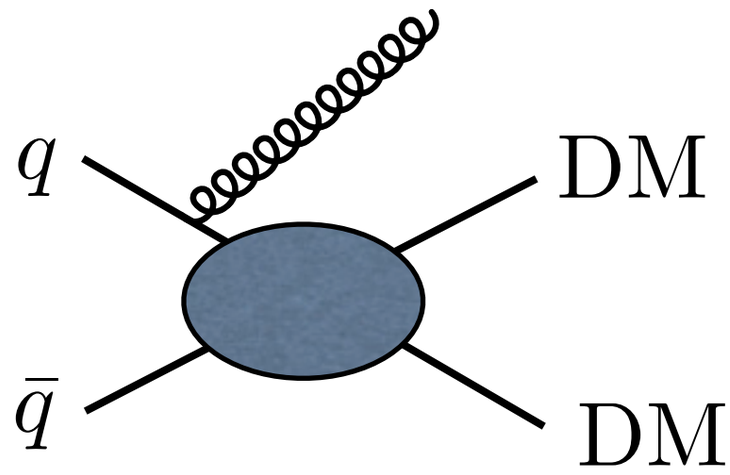

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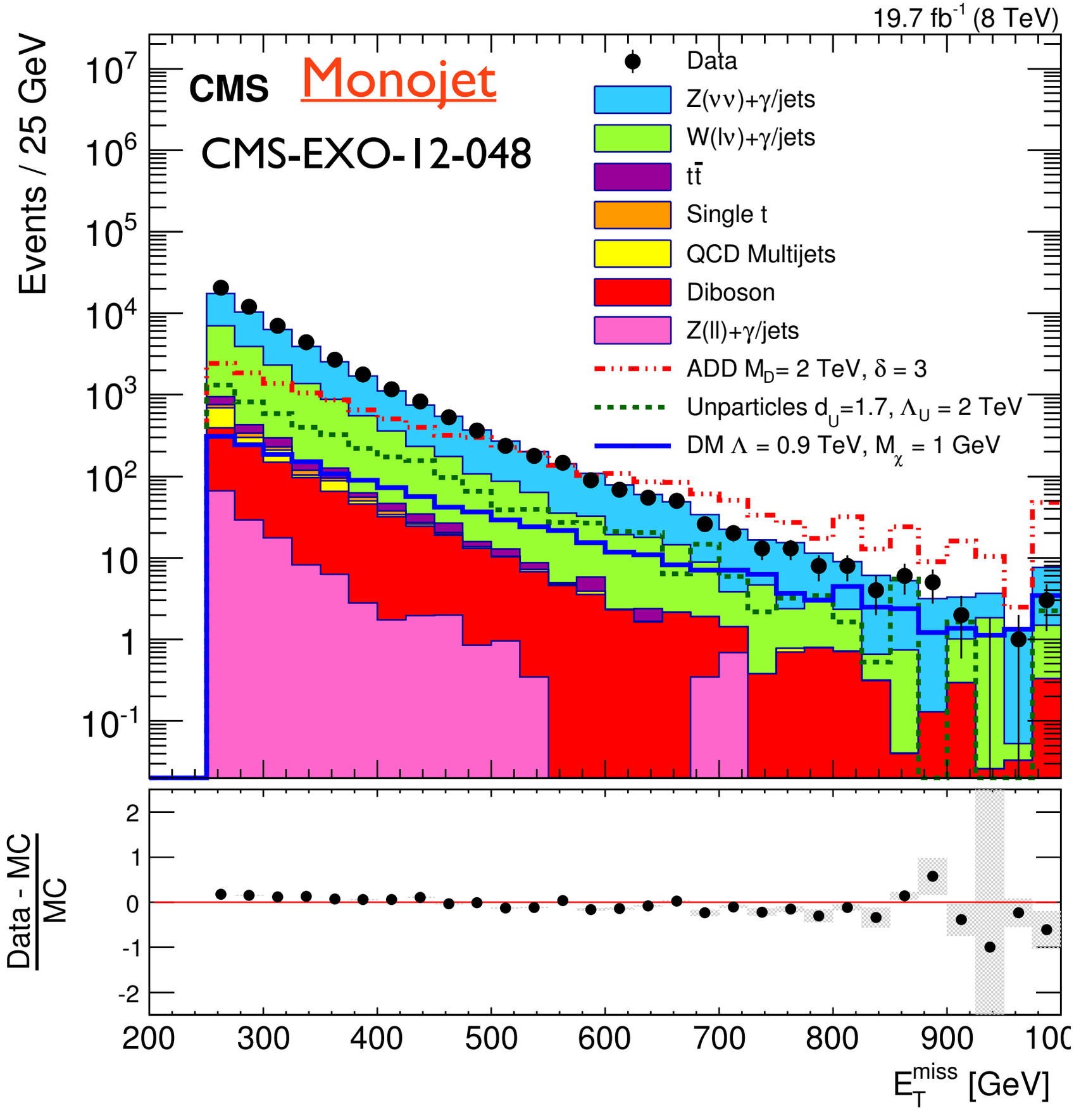
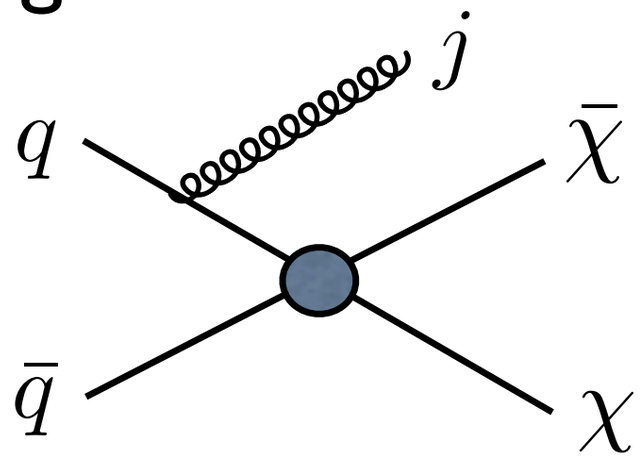
SI, scalar exchange

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

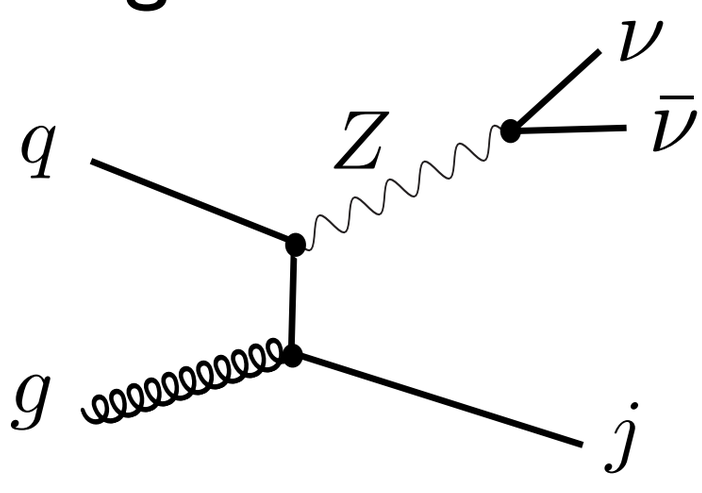
Typically consider each operator separately

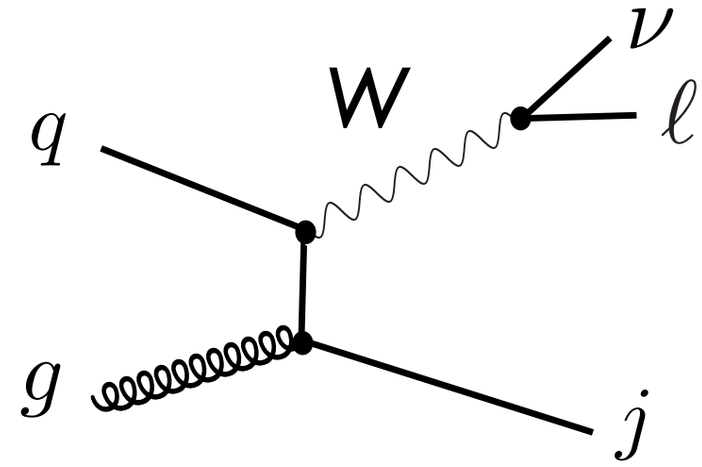


Signal:



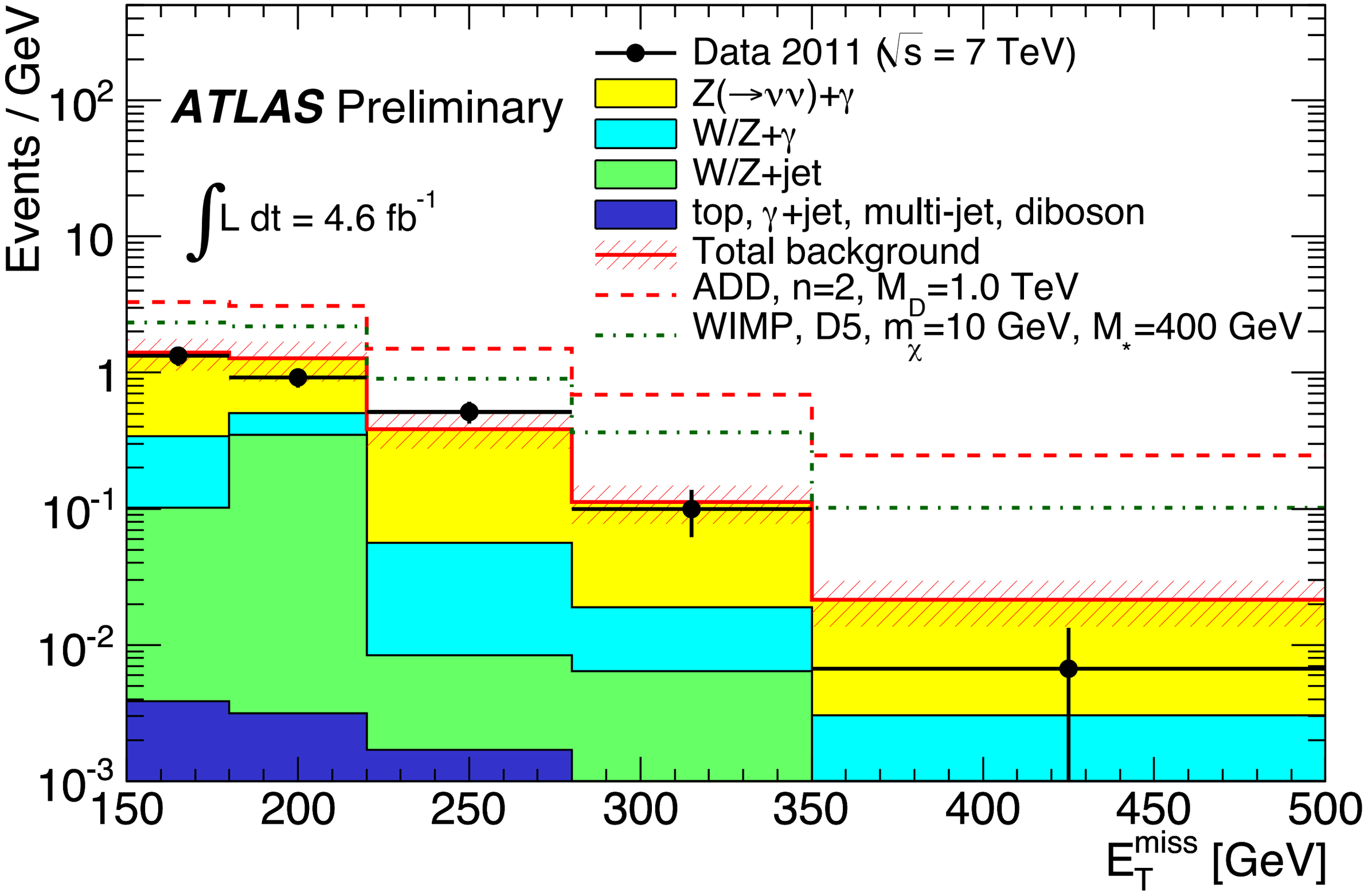
(Dominant) Backgrounds:



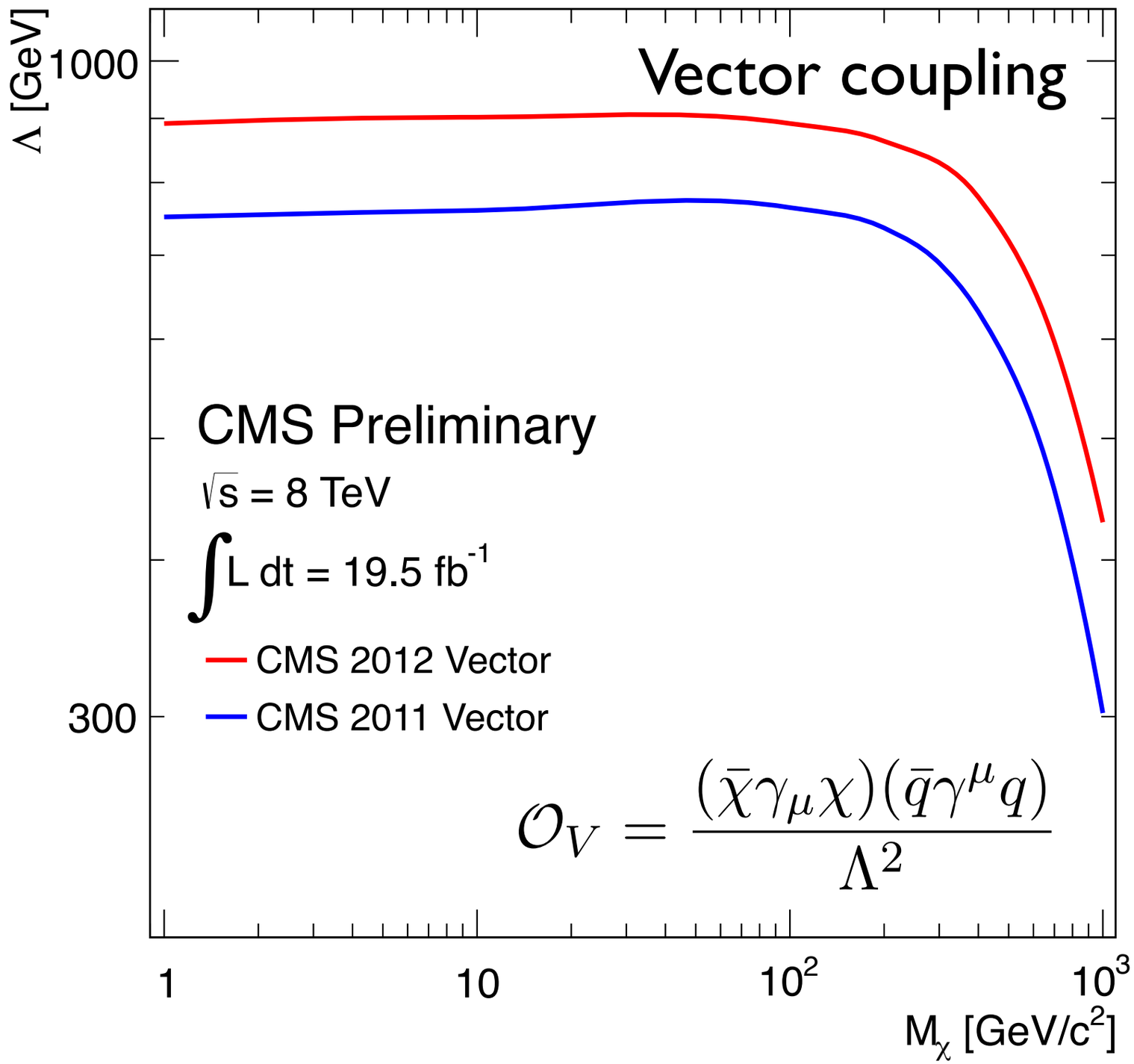


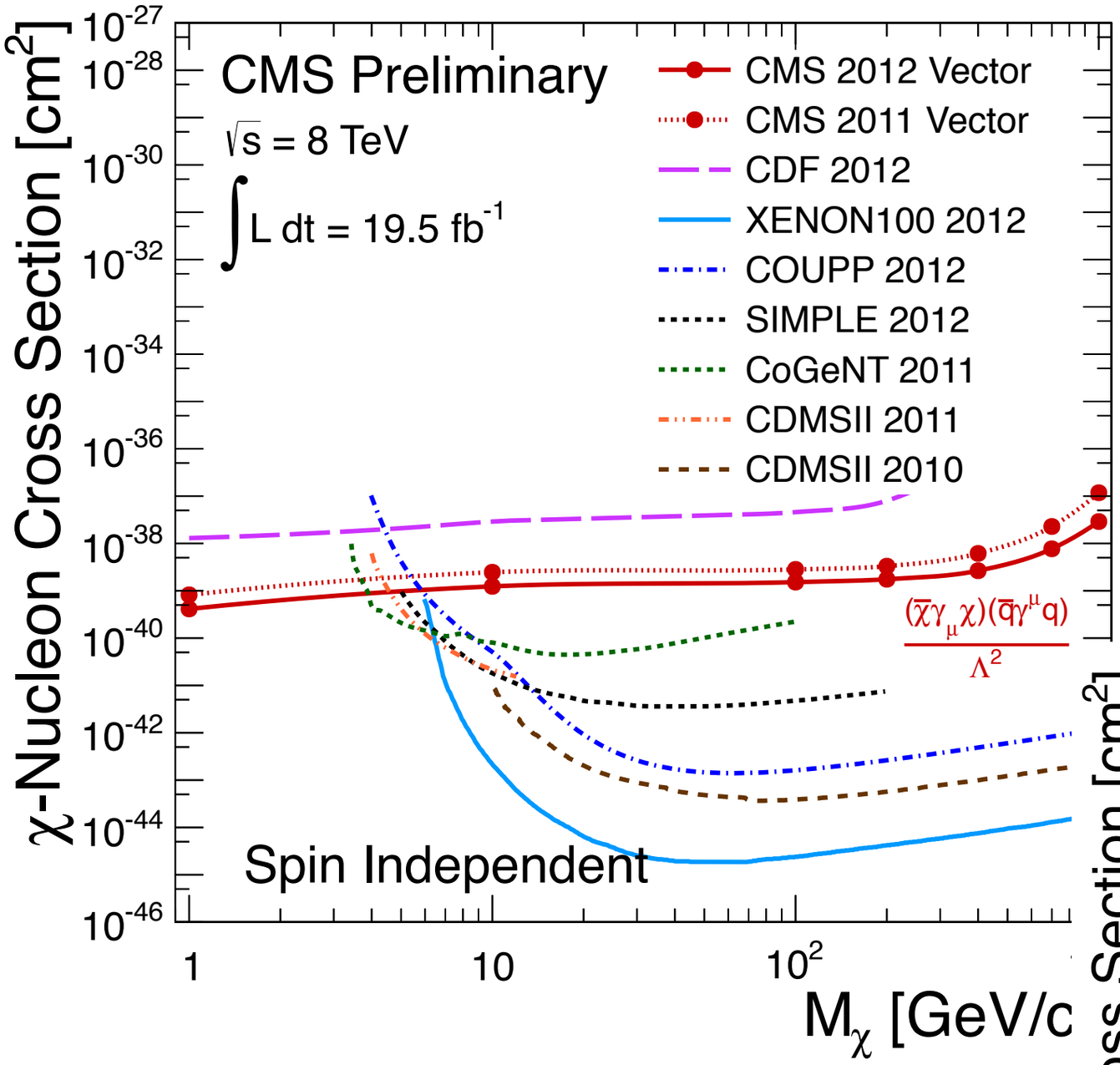
ATLAS-CONF-2012-085

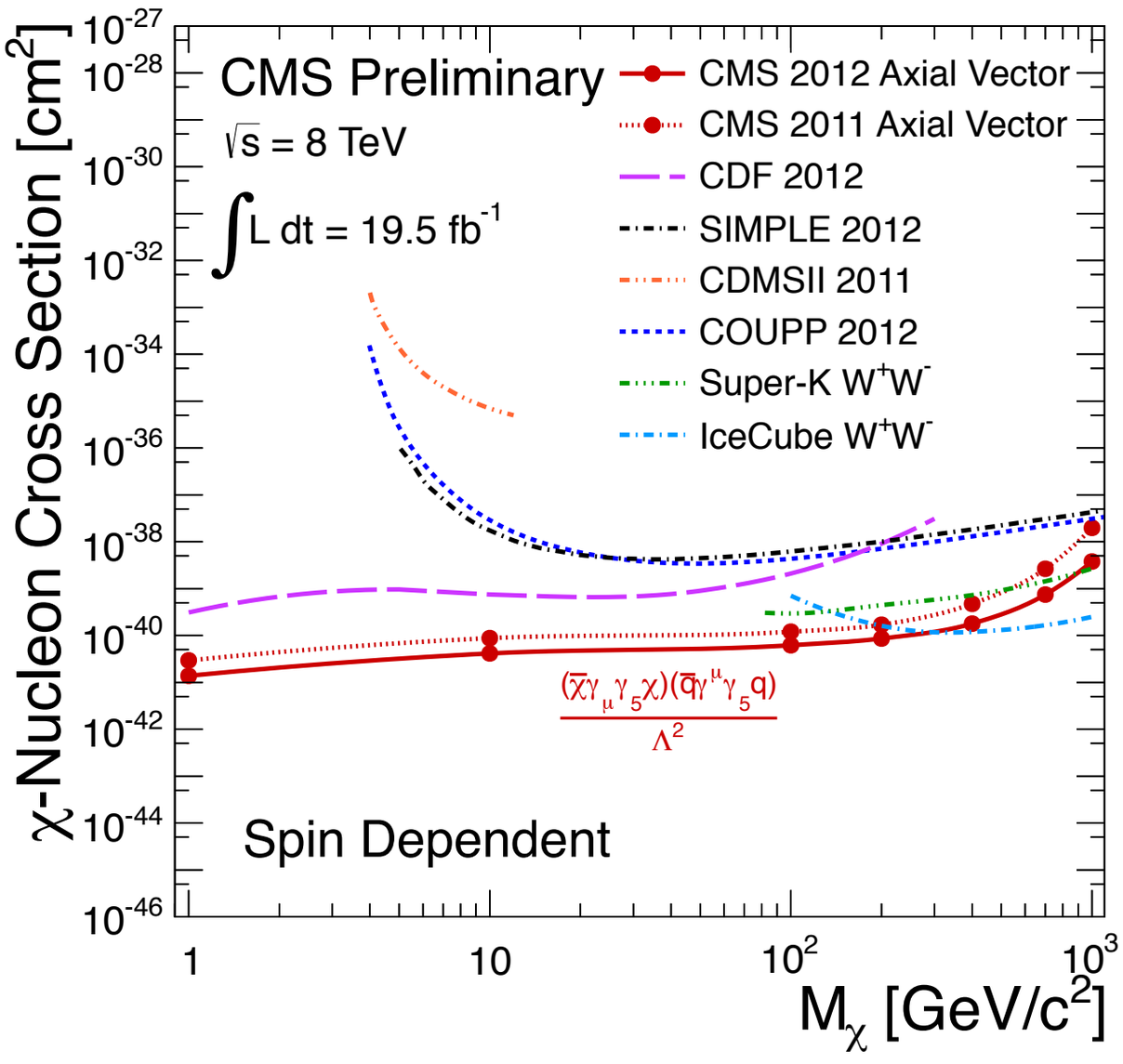
Monophoton



How to quantify nothing?







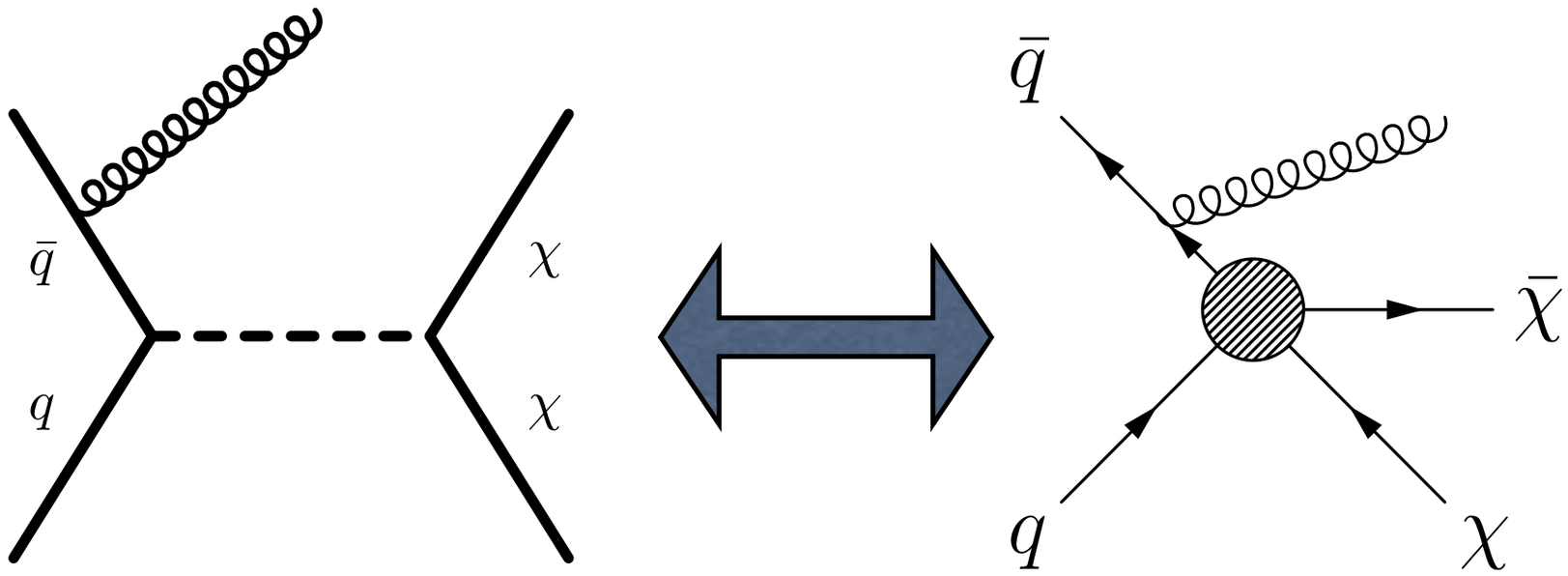
Colliders give complementary constraint at low mass and for SD

Light Mediators

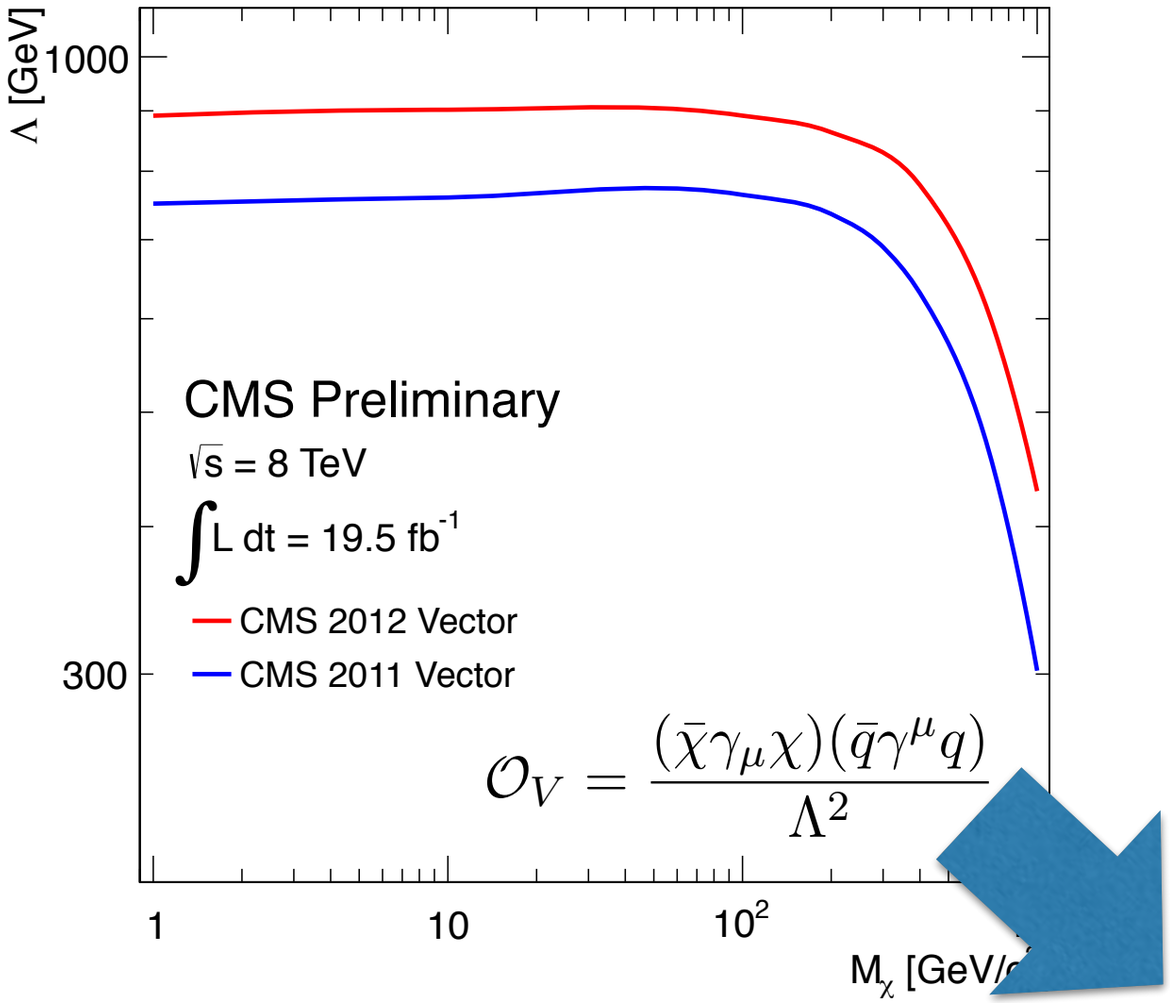
For all but the lightest mediators EFT is good for direct detection

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

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

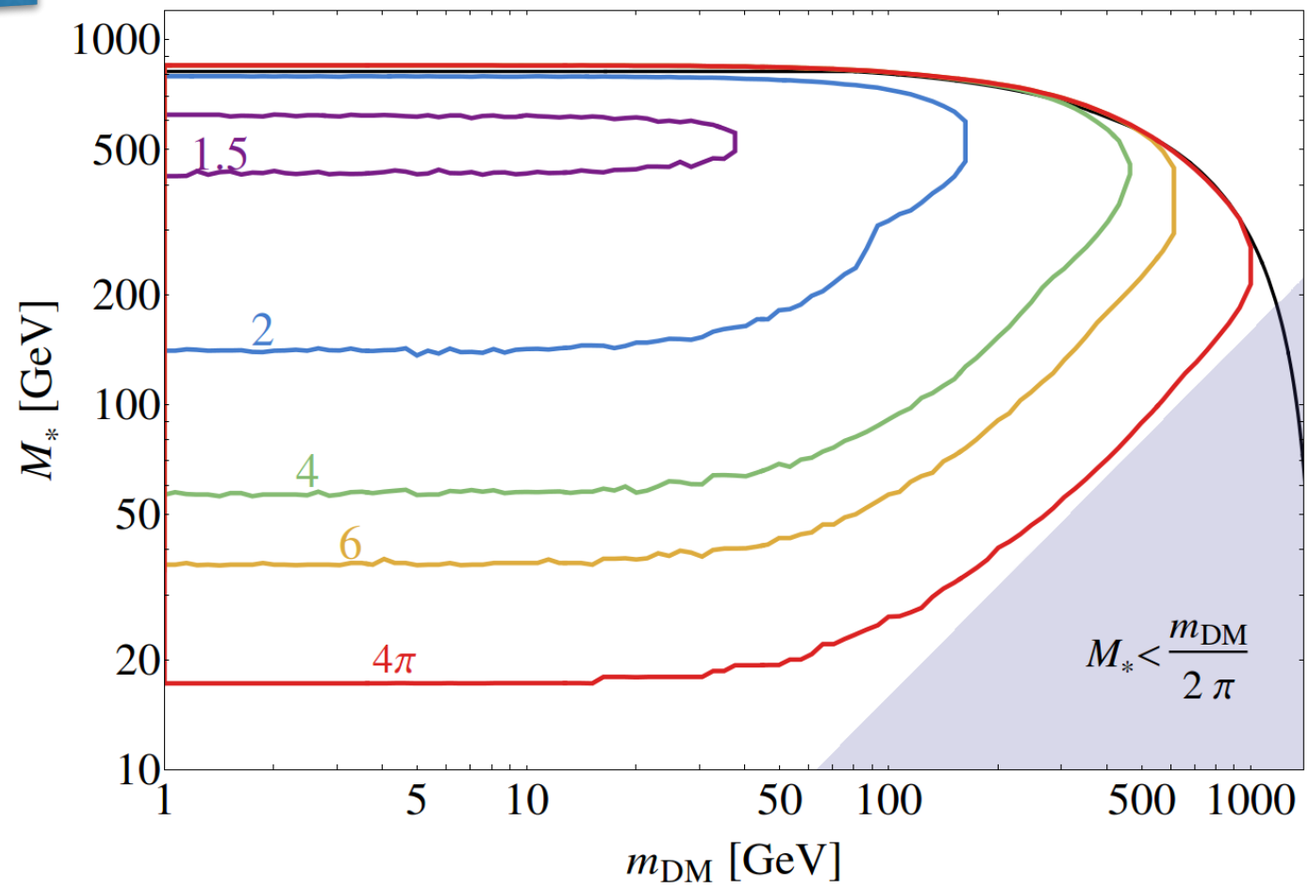


$$\frac{g_q g_\chi}{q^2 - M^2} \xrightarrow{q^2 \ll M^2} \frac{1}{\Lambda^2} \qquad \Lambda^2 = \frac{M^2}{g_q g_\chi}$$



Cutting off theory at the mediator mass scale alters the bounds

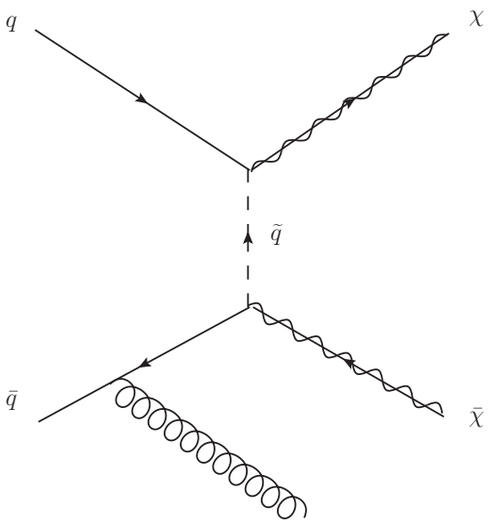
Racco, Wulzer, Zwirner [1502.04701]



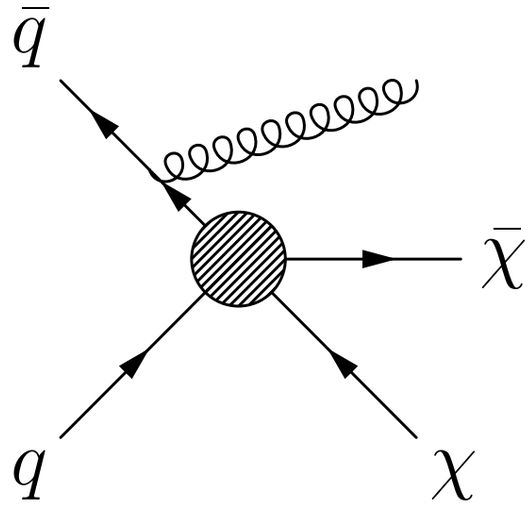
Simplified Models

"Integrate in" the mediator

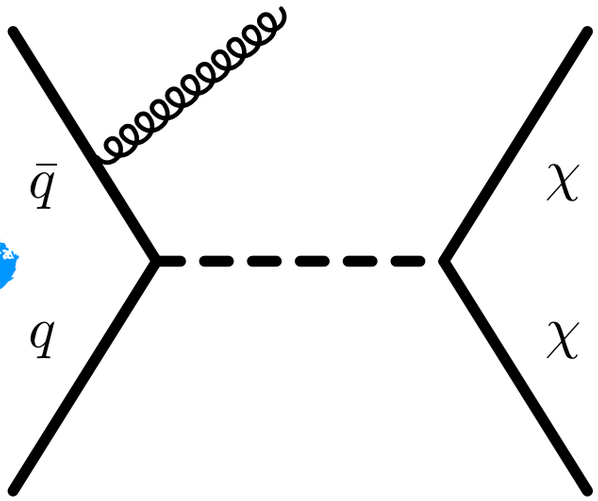
t-channel



EFT



s-channel



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

New channels to search for!

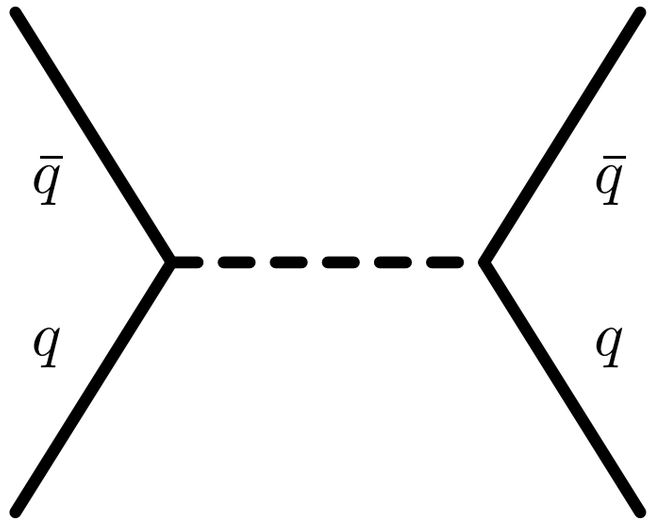
Collider only sensitive to all 4 parameters over a narrow range

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

Light Mediators

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

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



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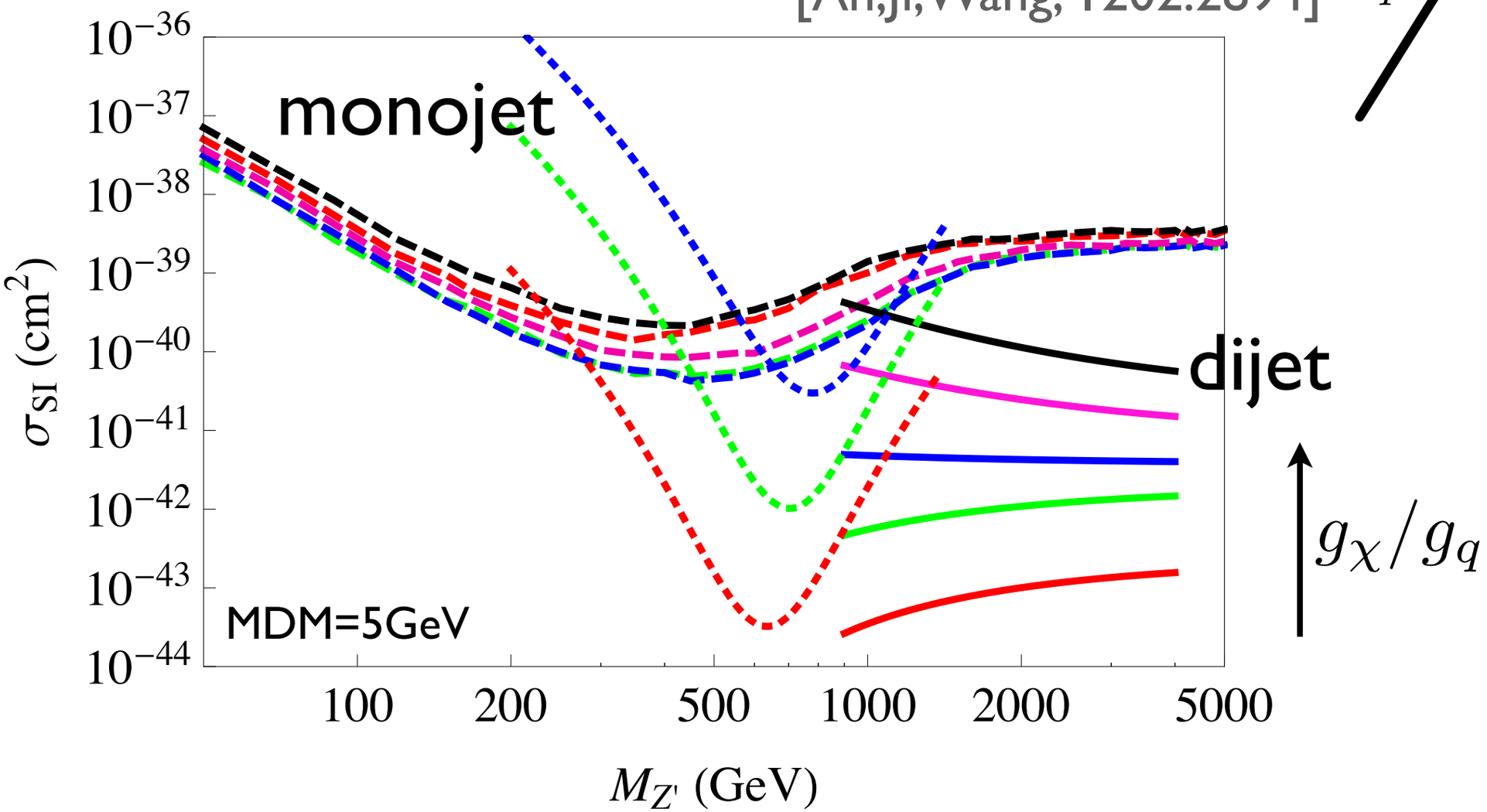

g_χ / g_q

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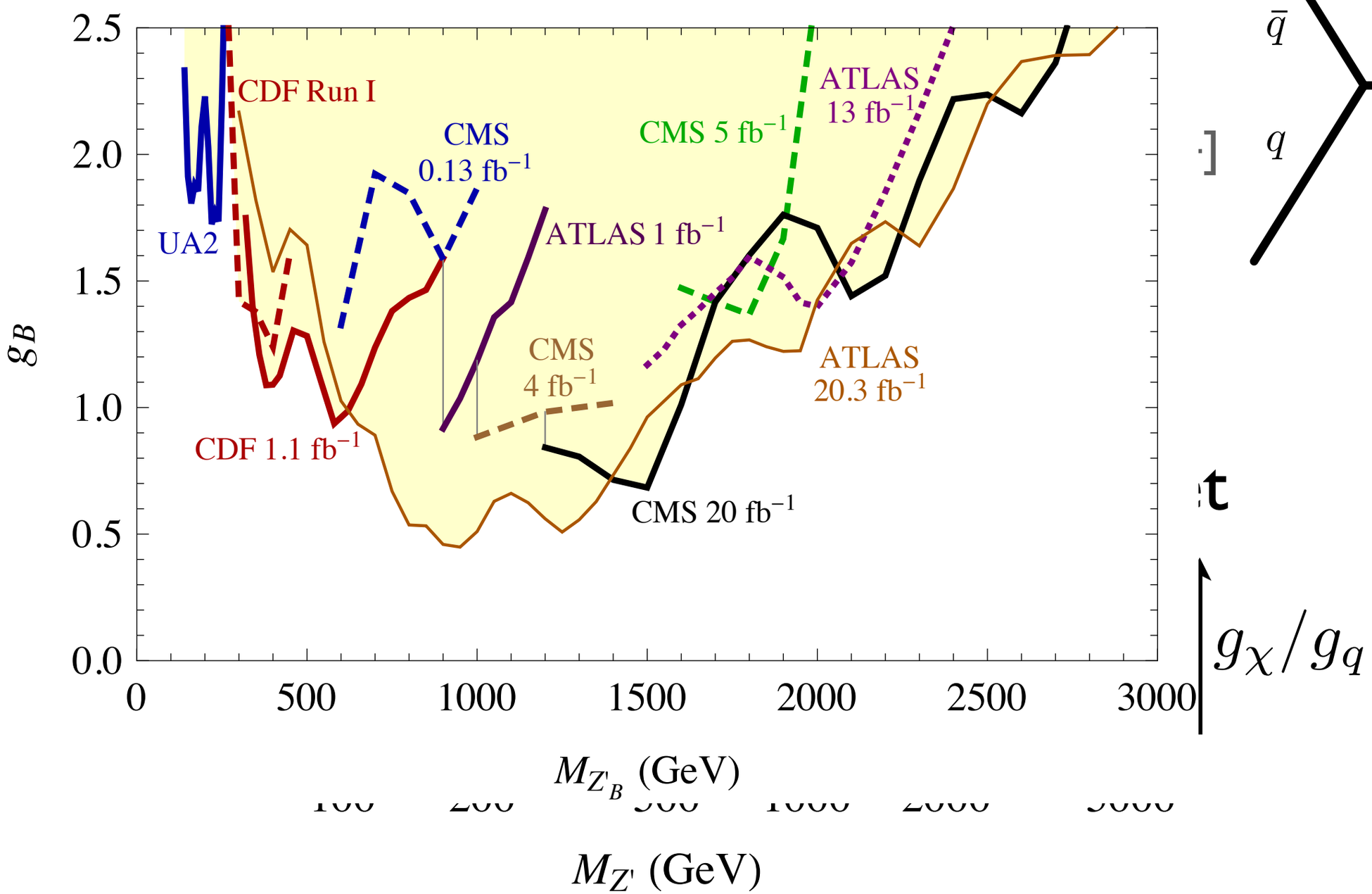

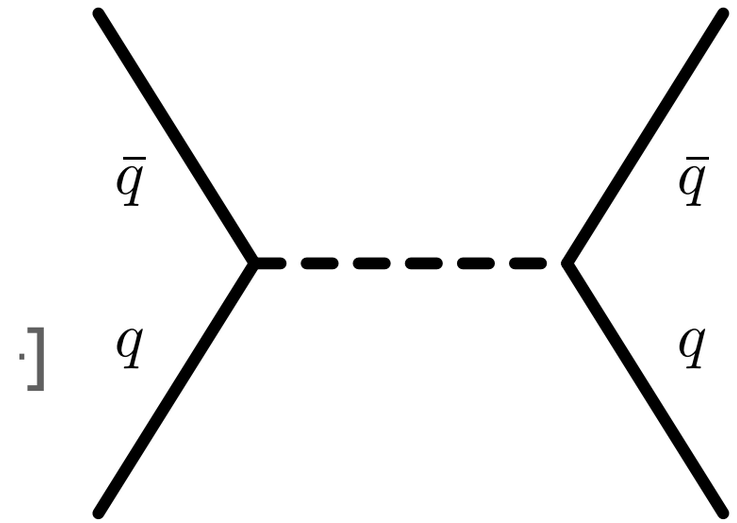

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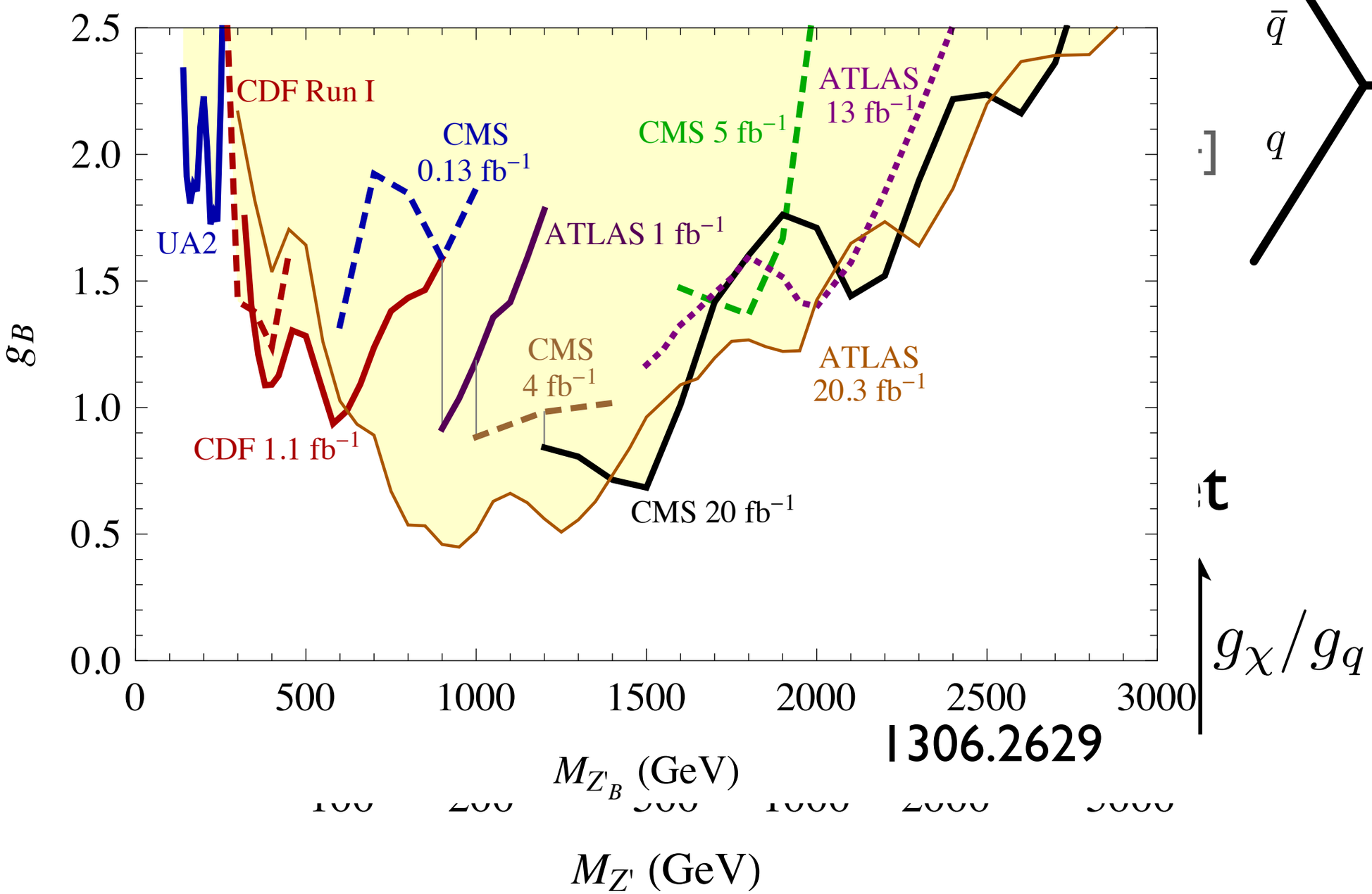
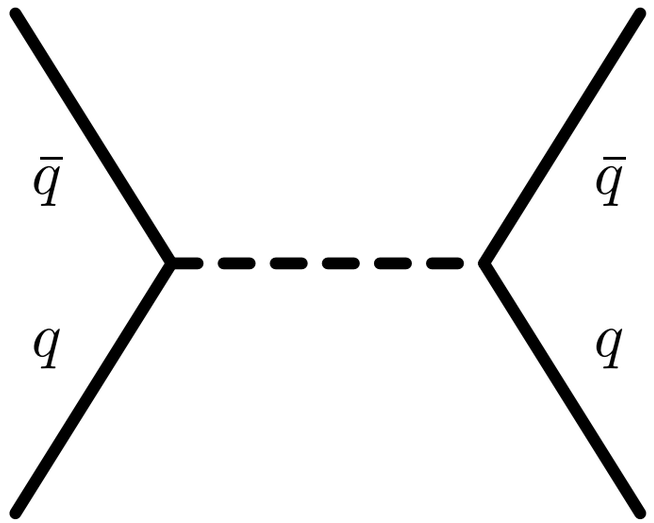


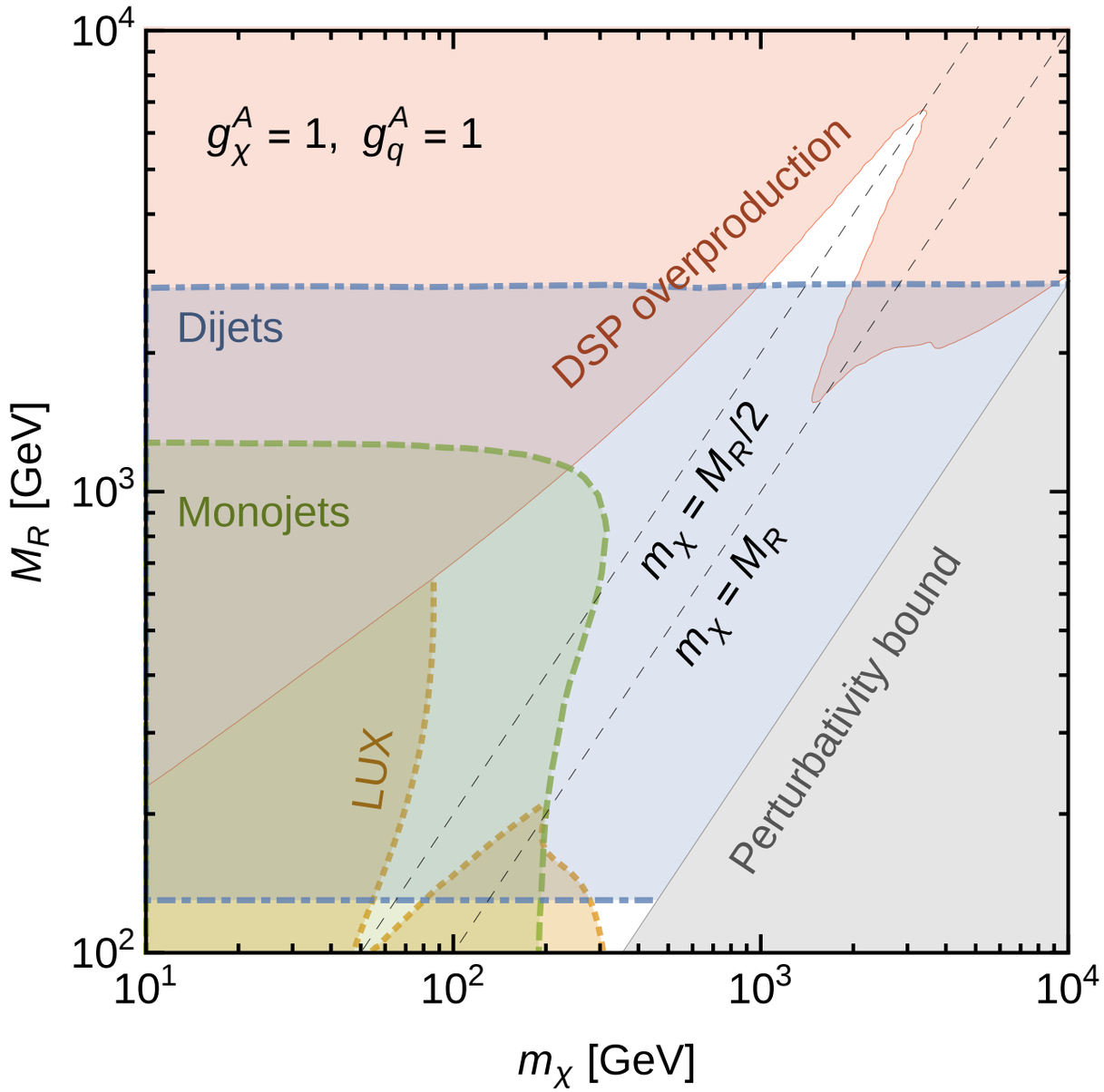


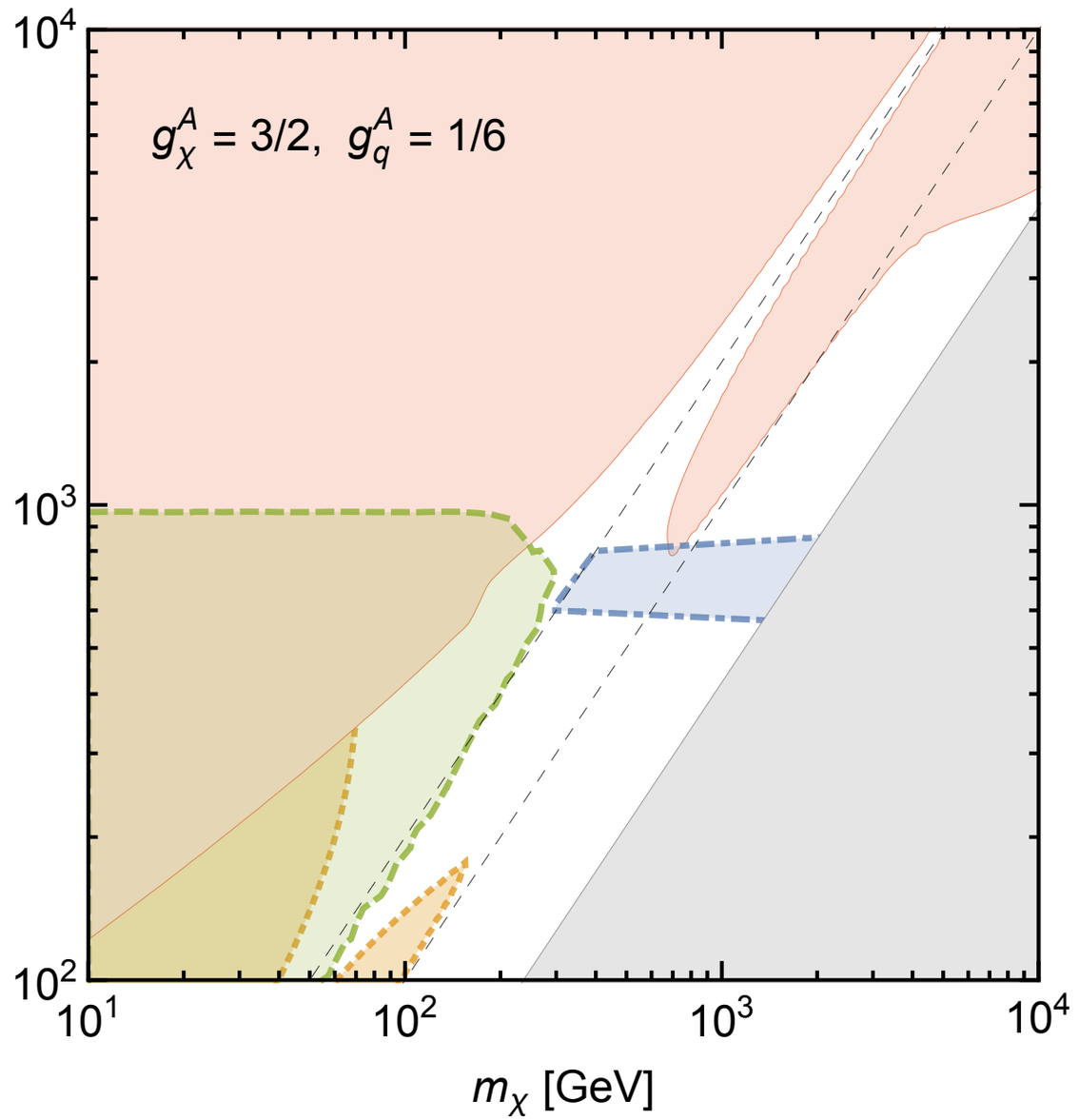
t

g_χ / g_q

1306.2629

[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)

Perturbative unitarity

Thermal relic $\Omega_c h^2 = 0.12$

2 × 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)

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

- Direct detection limits
- Mass probed, learn about DM in cosmos
- Indirect detection very sensitive to astrophysics
- Halo shapes can probe DM-DM interactions
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Many exciting new ideas for probing light DM e.g. scattering off electrons in semi/super conductors

Complementary taken together provide complete picture

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Hidden sector DM

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

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

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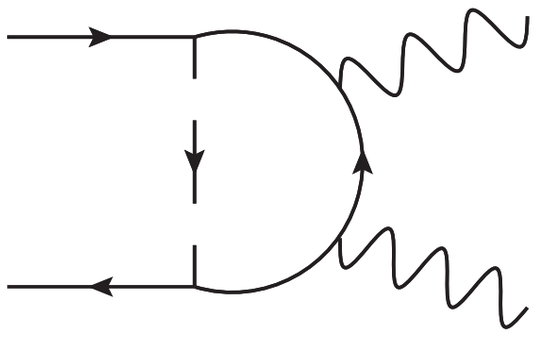
$$\frac{\epsilon}{16\pi^2} F'_{\mu\nu} B_Y^{\mu\nu}$$

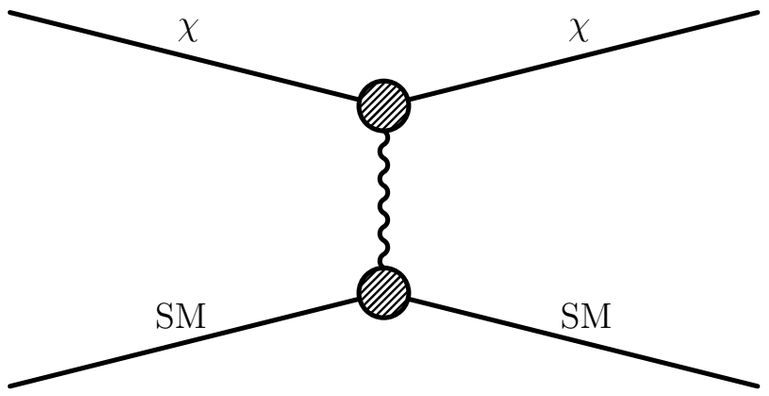
$$\phi|H|^2 + |\phi|^2|H|^2$$

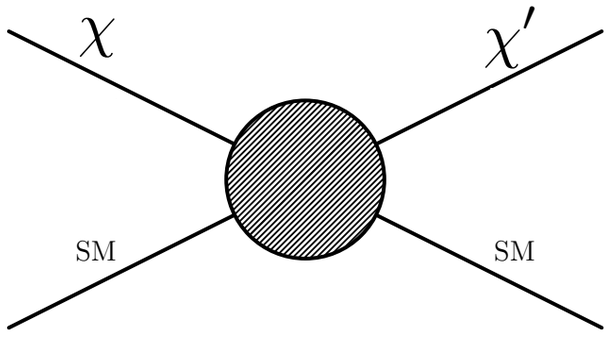
Hidden sector DM—interesting dynamics

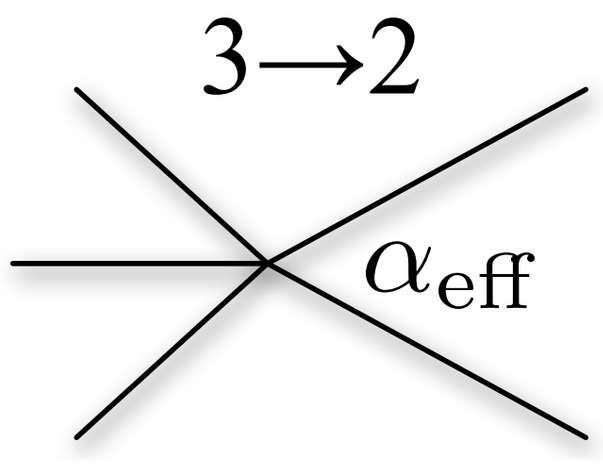
Hidden sector dynamics, new force carriers

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



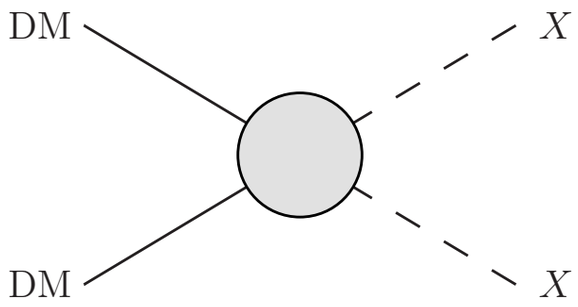


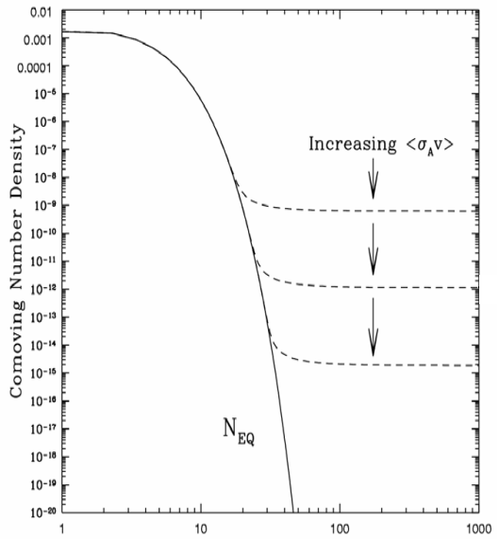


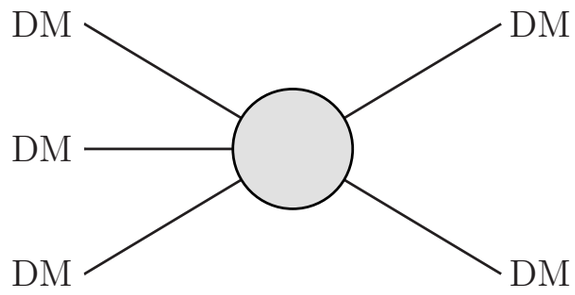


Hidden sector DM—thermal relics

Leads to interesting changes in cosmology

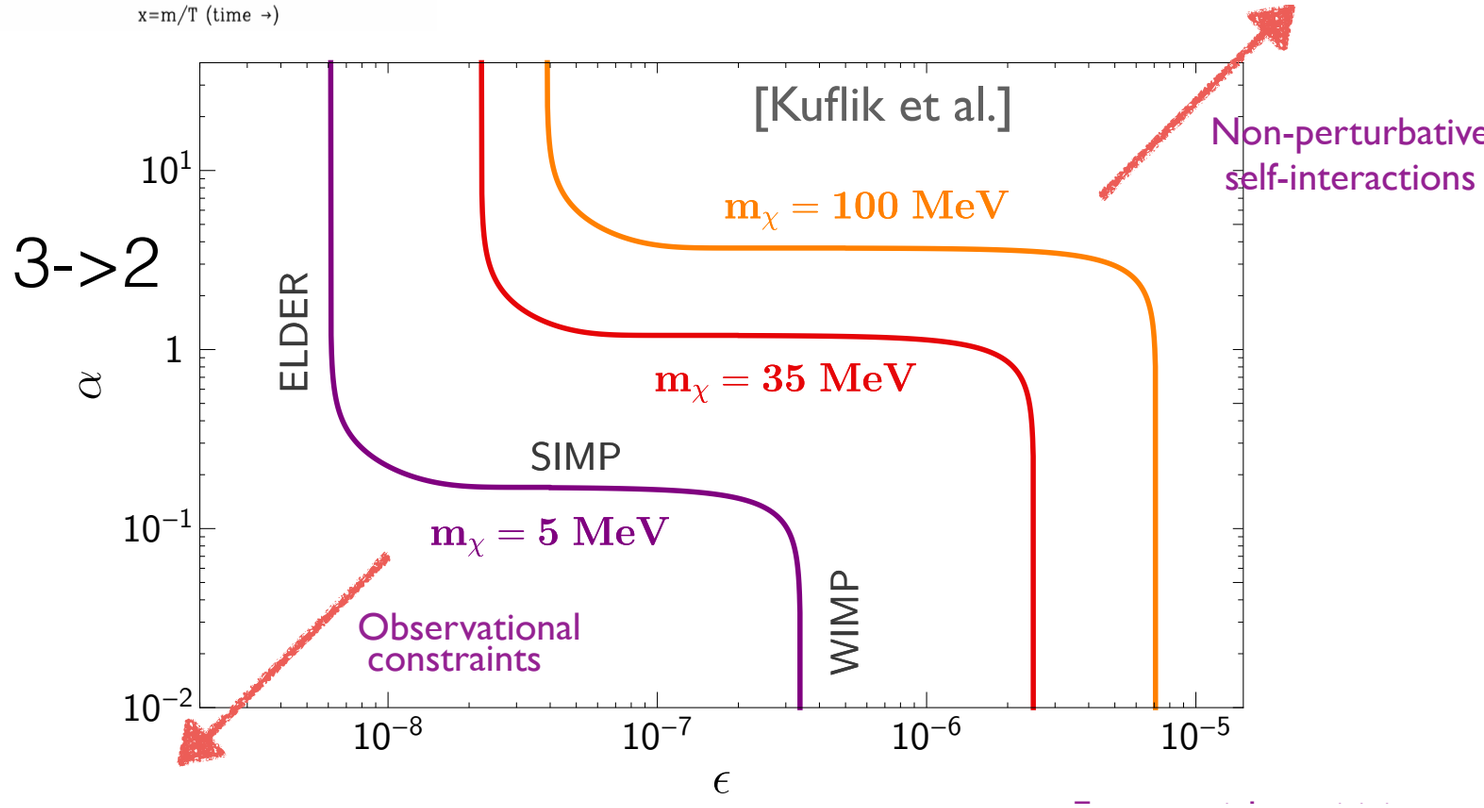






cannibalization

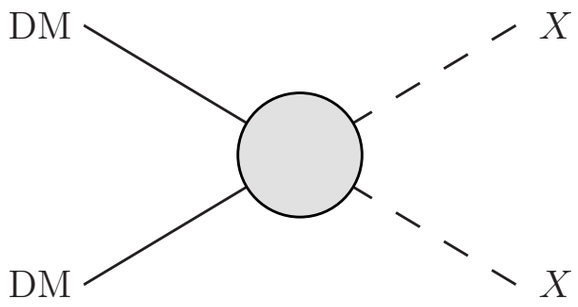
WIMPless-miracle
SIMP-miracle
ELDER…
all smoothly connected
in parameter space

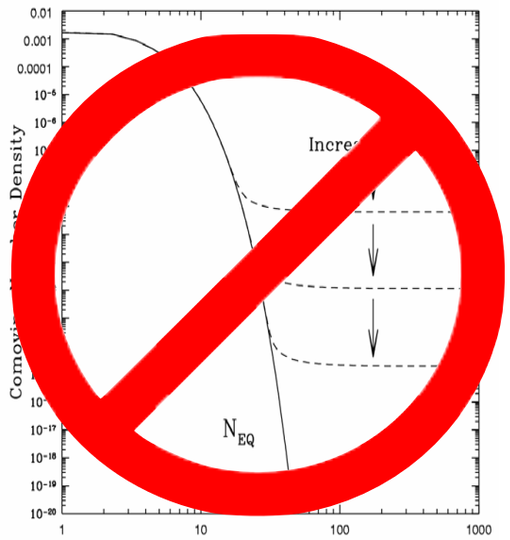


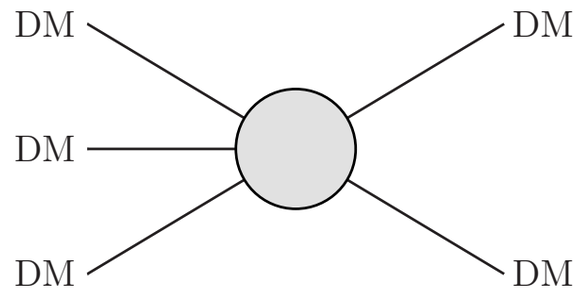
DM-SM elastic scatter

Hidden sector DM—thermal relics

Leads to interesting changes in cosmology







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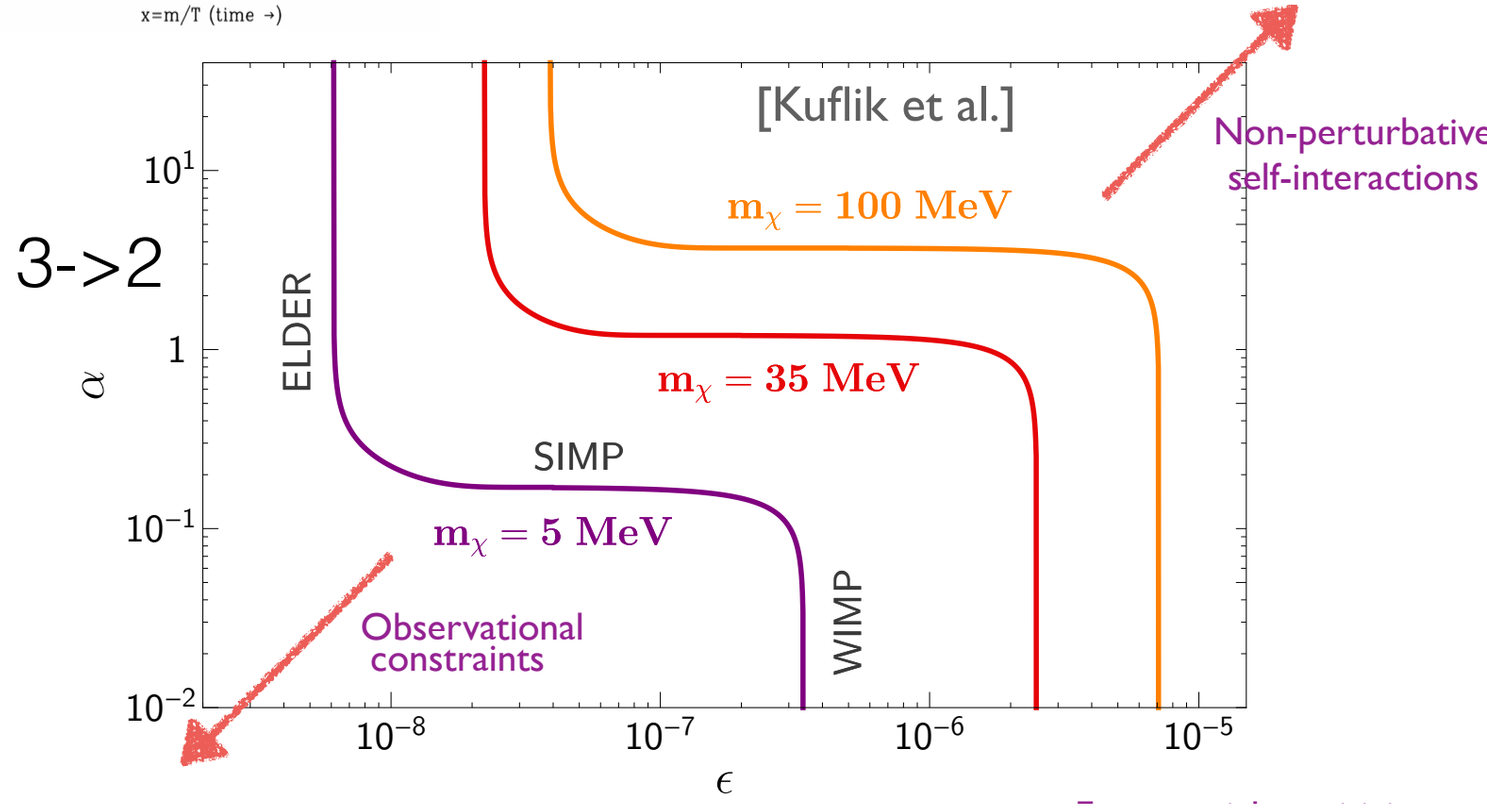
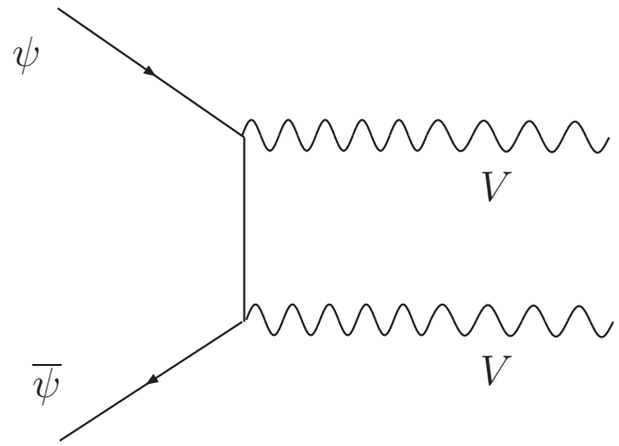


DM-SM elastic scatter

Hidden sector DM—thermal relics

[Pospelov, Ritz, Voloshin]

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

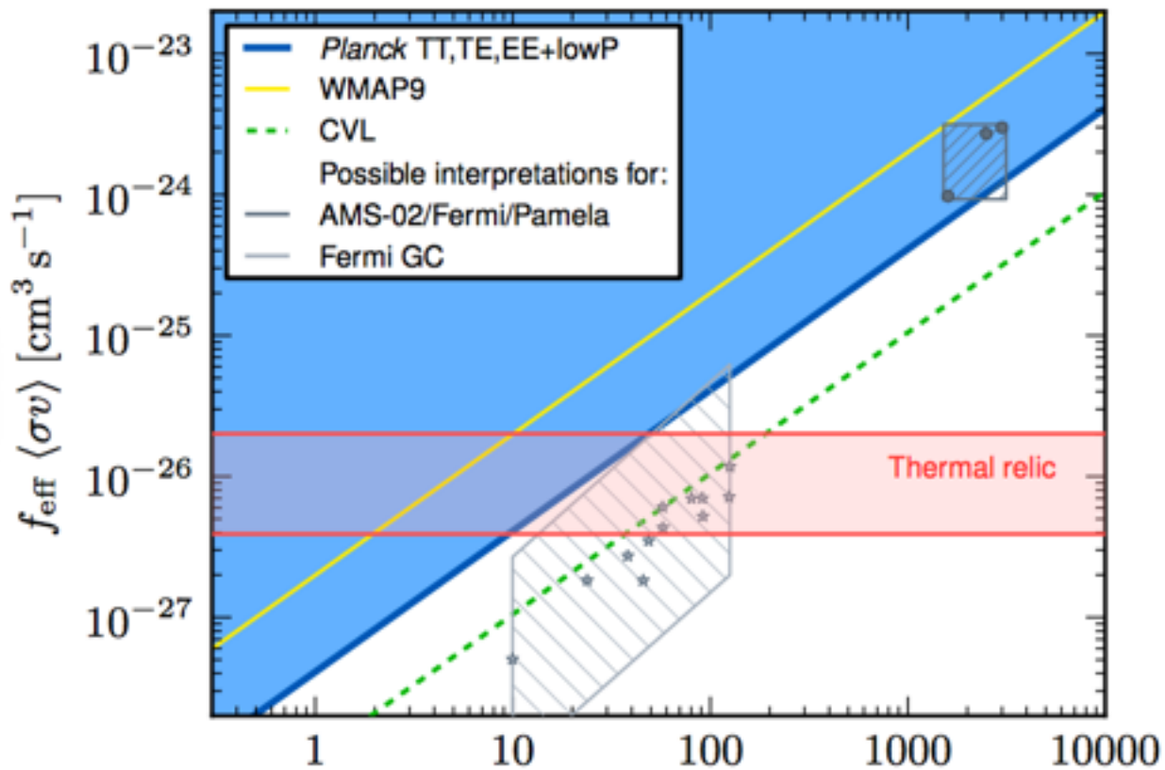


Decouples direct detection from thermal history

Light DM and CMB

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

[Finkbeiner, Slatyer et al]



Hidden sector U(1) — dark photon

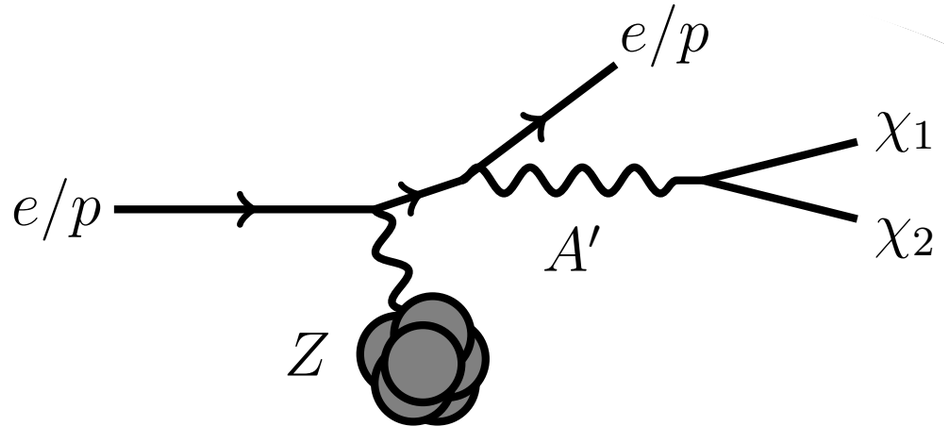
No SM matter directly charged under $U(1)_{dark}$ use a portal

[Holdom]

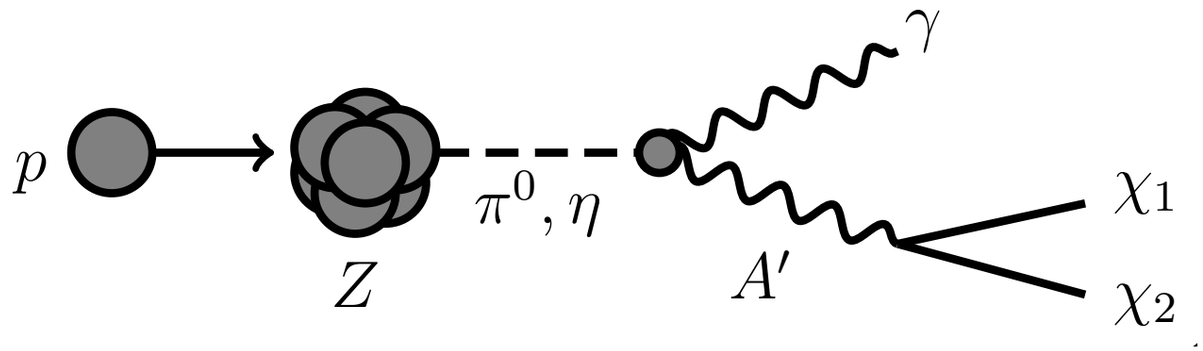
$$\mathcal{L}_{\text{kinetic mixing}} = \epsilon F^{\mu\nu} F'_{\mu\nu}$$

SM picks up “dark milli-charge”

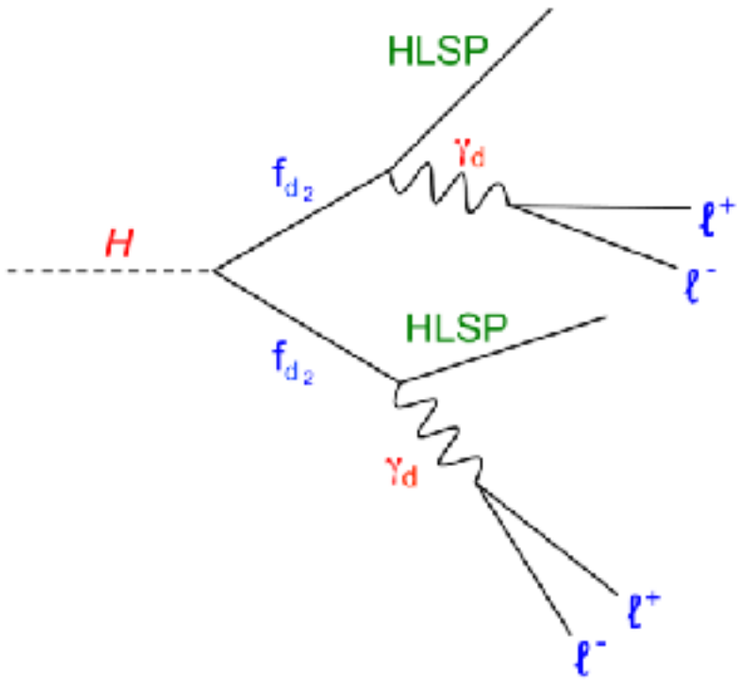
- Small couplings to SM means small production rates
- Visible/invisible decays depending on thresholds
- Possibly long lived—displaced signatures
- Many possible ways to search for DM/dark photon



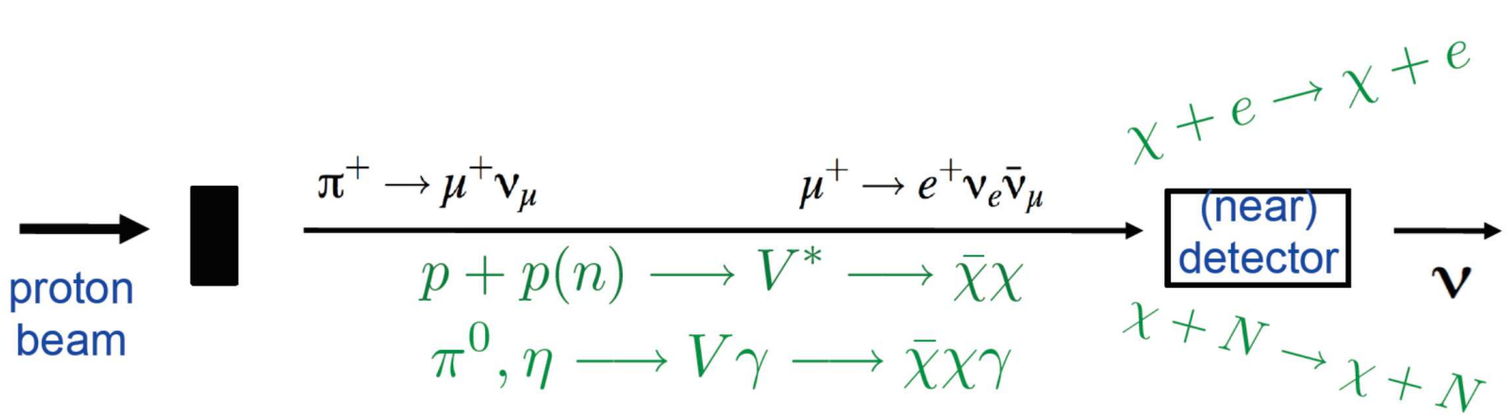
Bremsstrahlung
(LDMX, DarkLight, …)



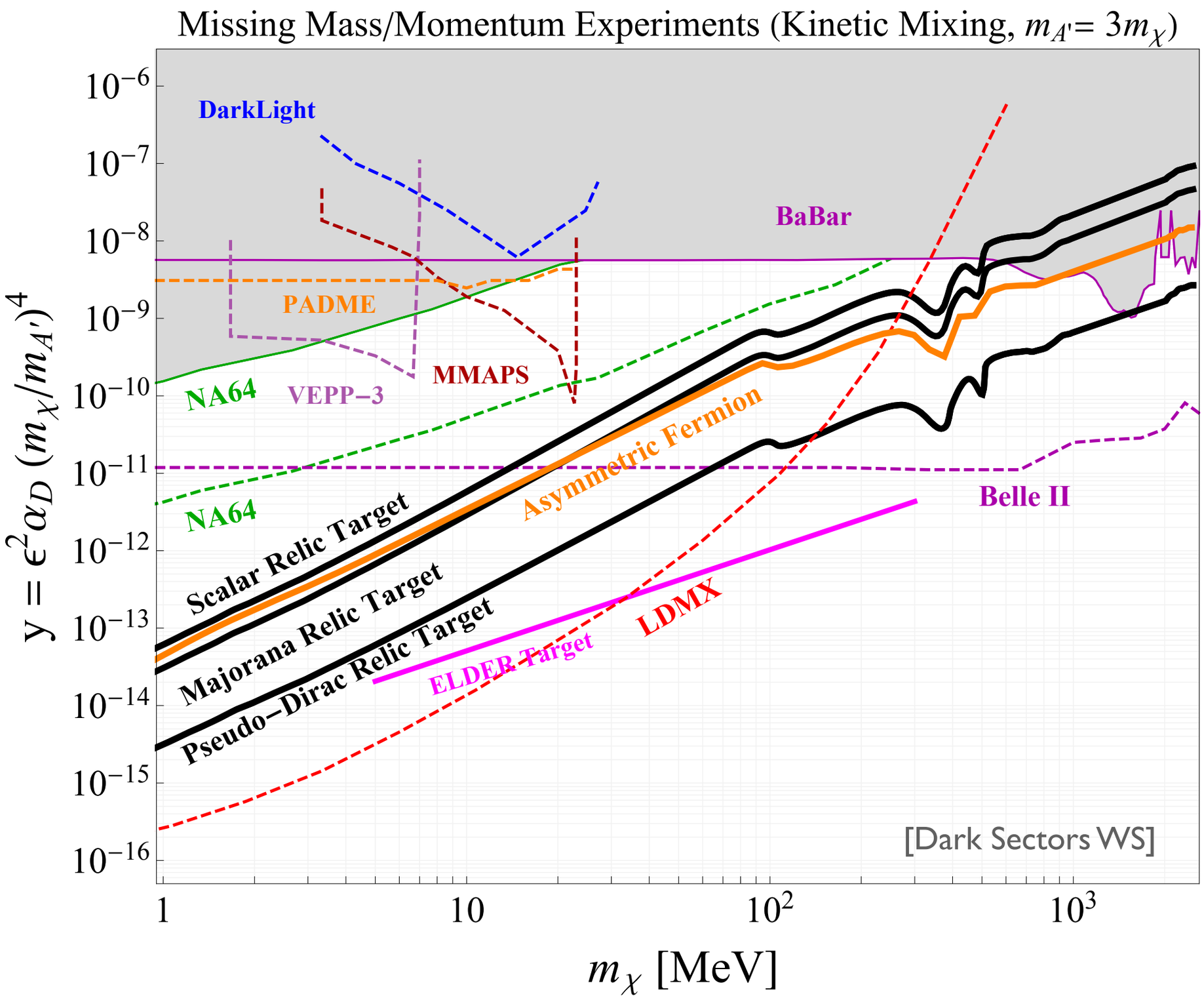
Meson decay
(NA48)

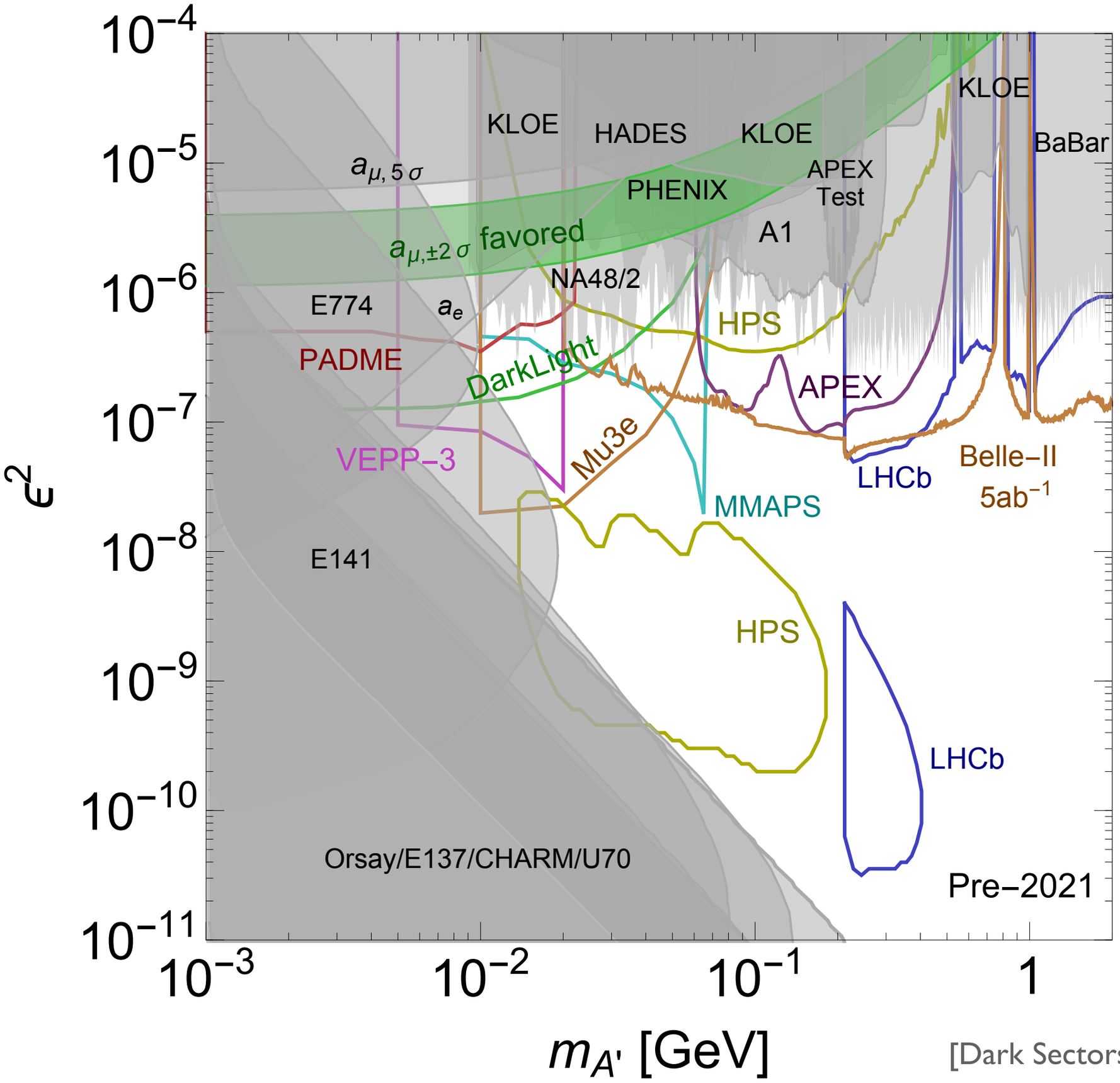


Lepton jets, Emerging tracks
(LHC)



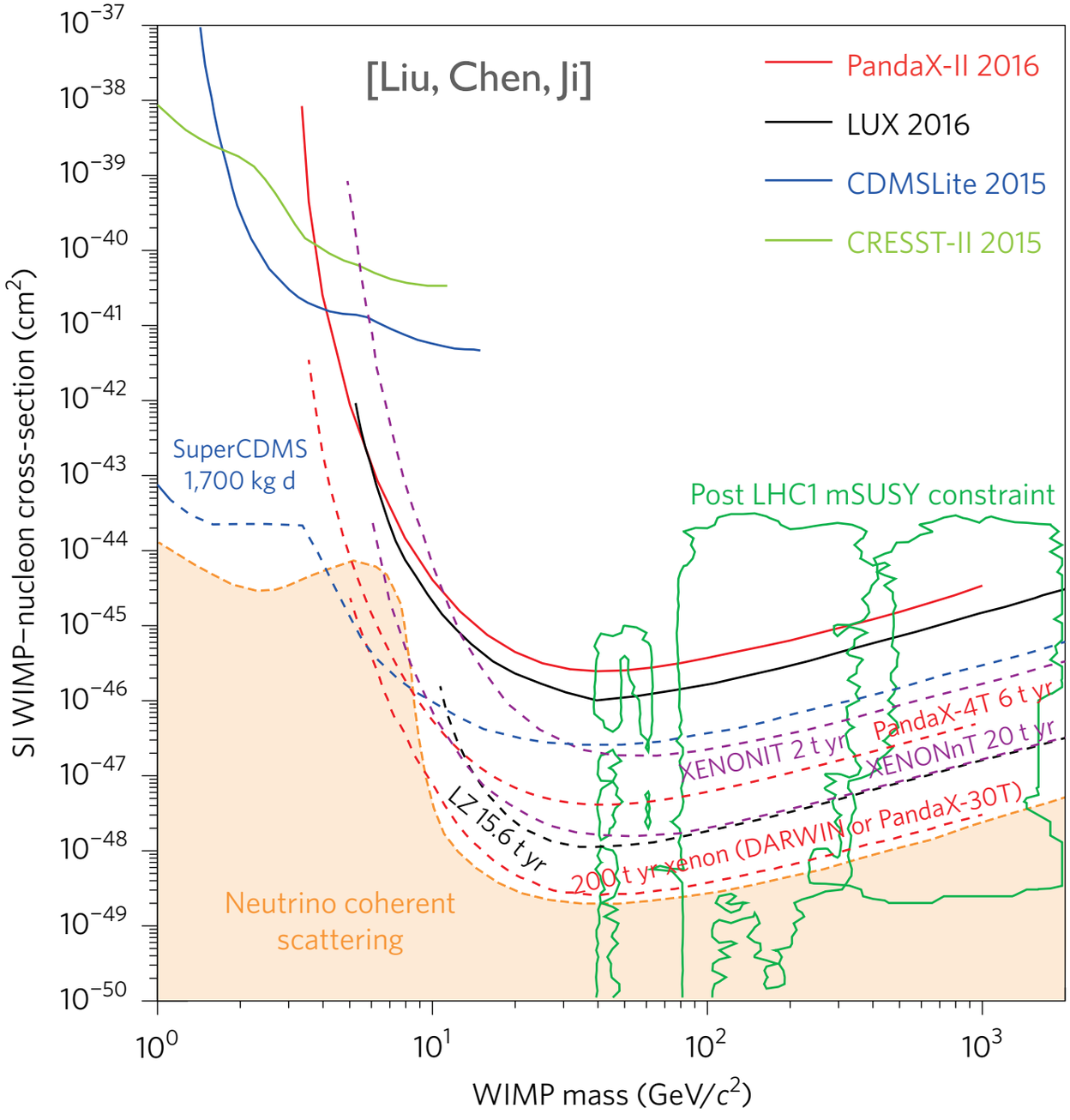
Production and scattering
(MiniBooNE, SHiP,…)


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

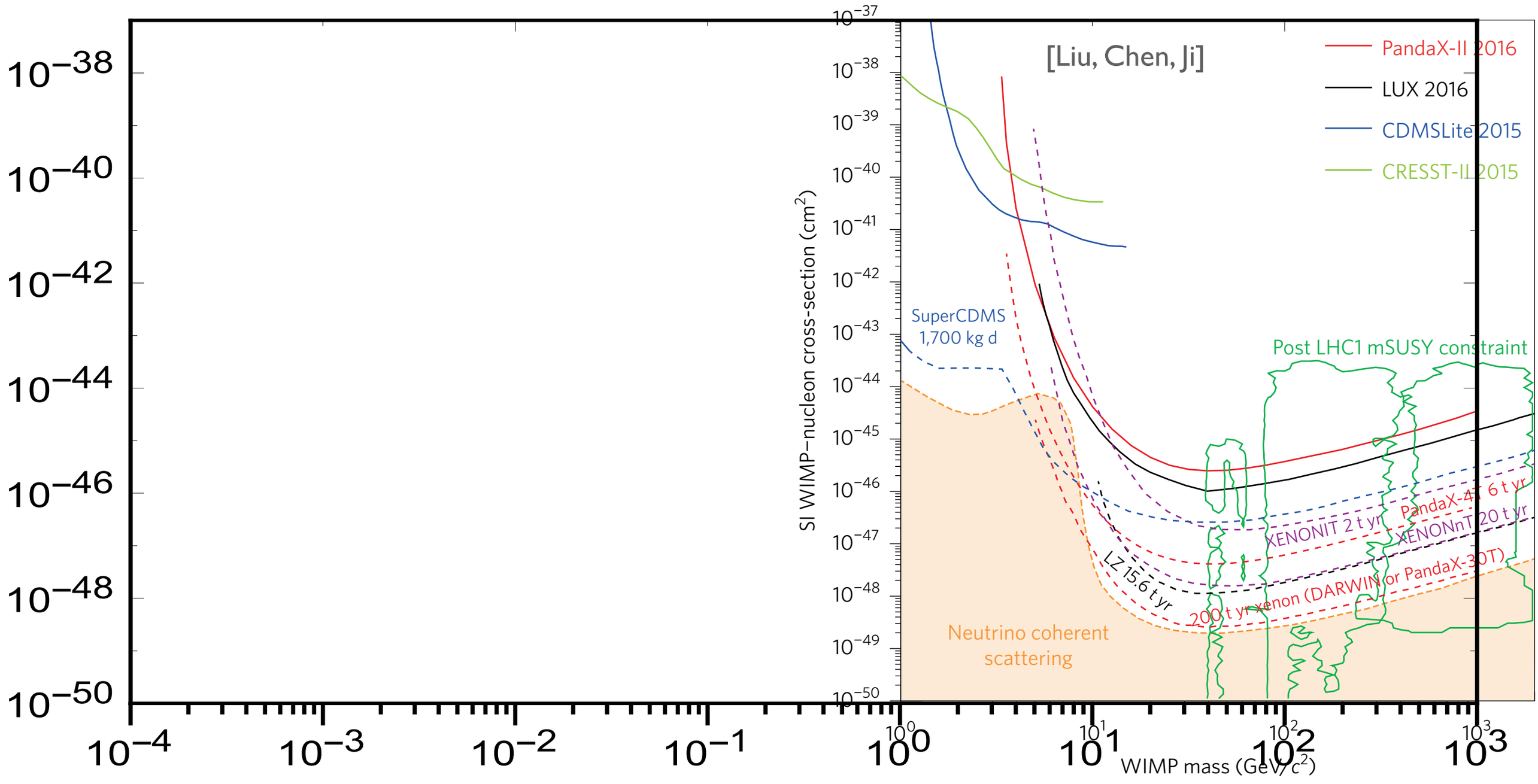


[Dark Sectors WS]

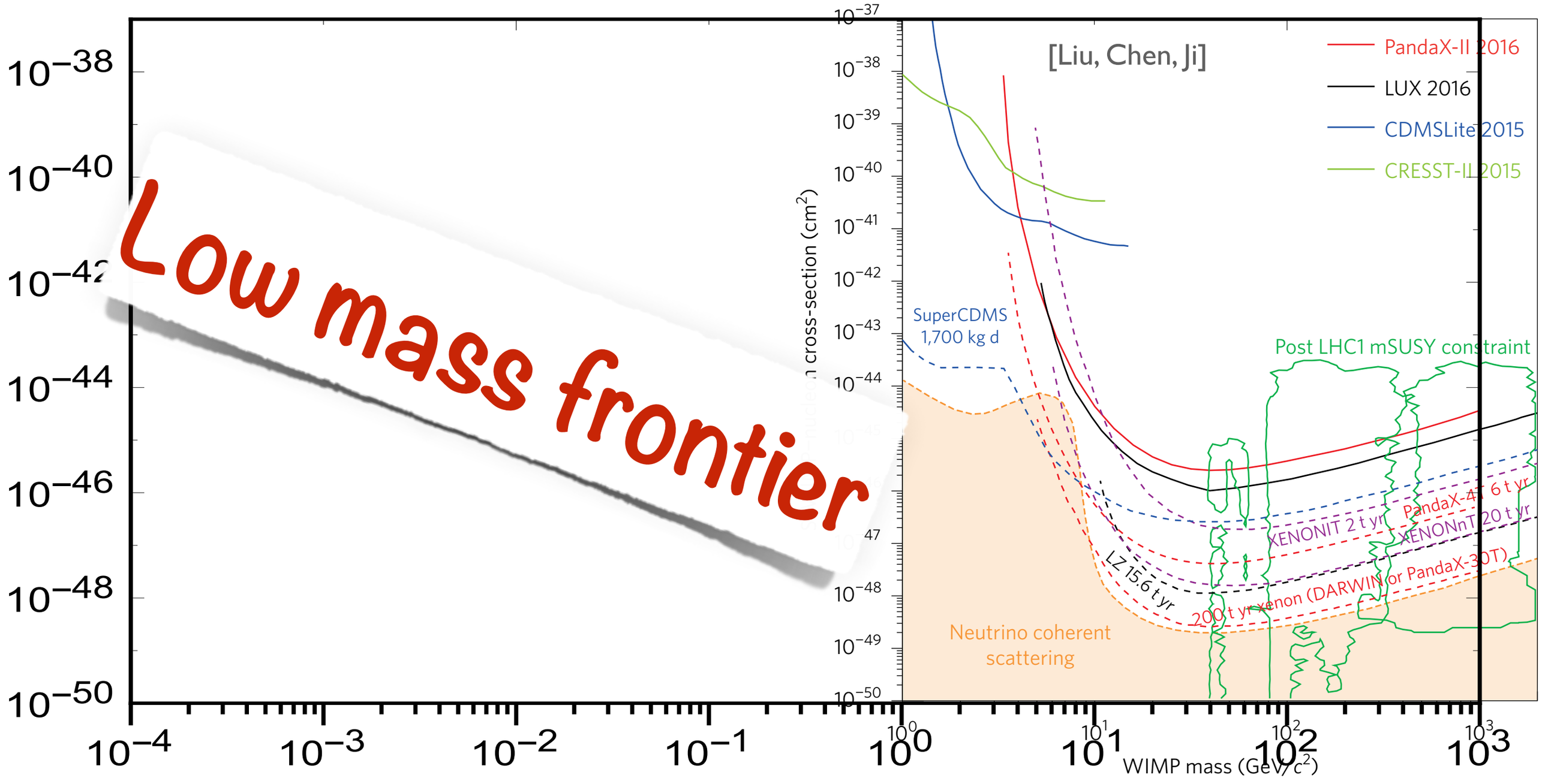
Dark sectors and direct detection



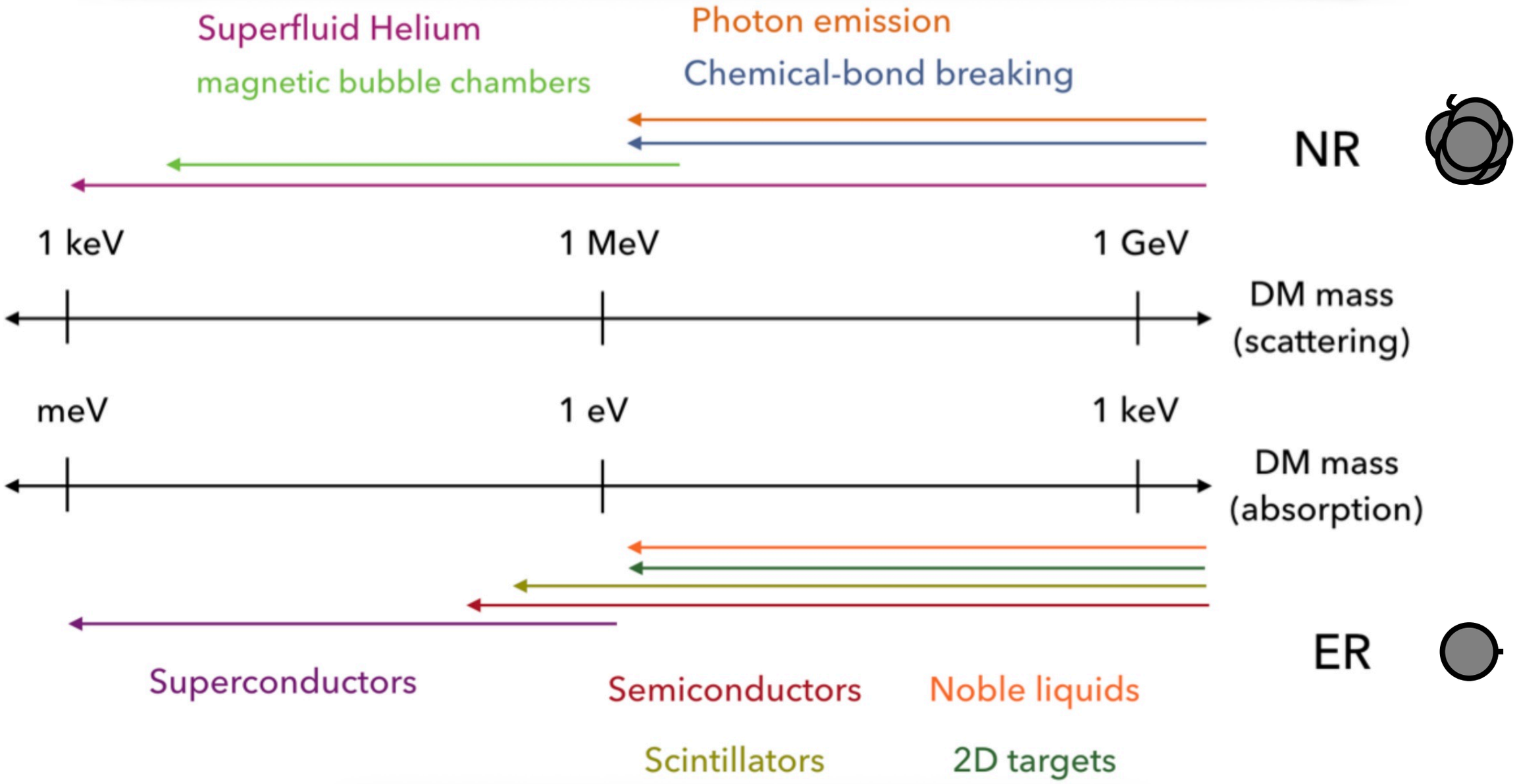
Dark sectors and direct detection



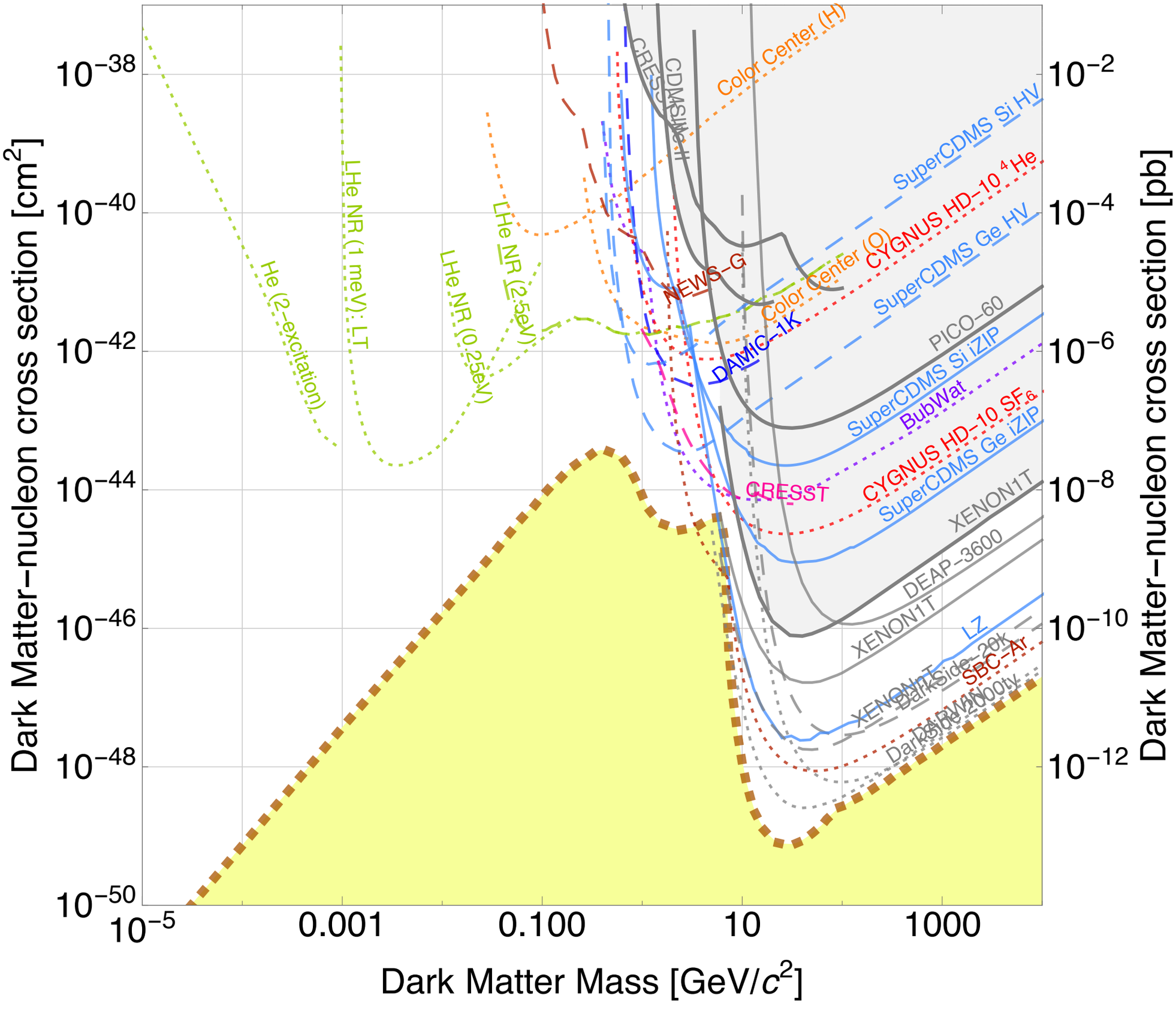
Dark sectors and direct detection

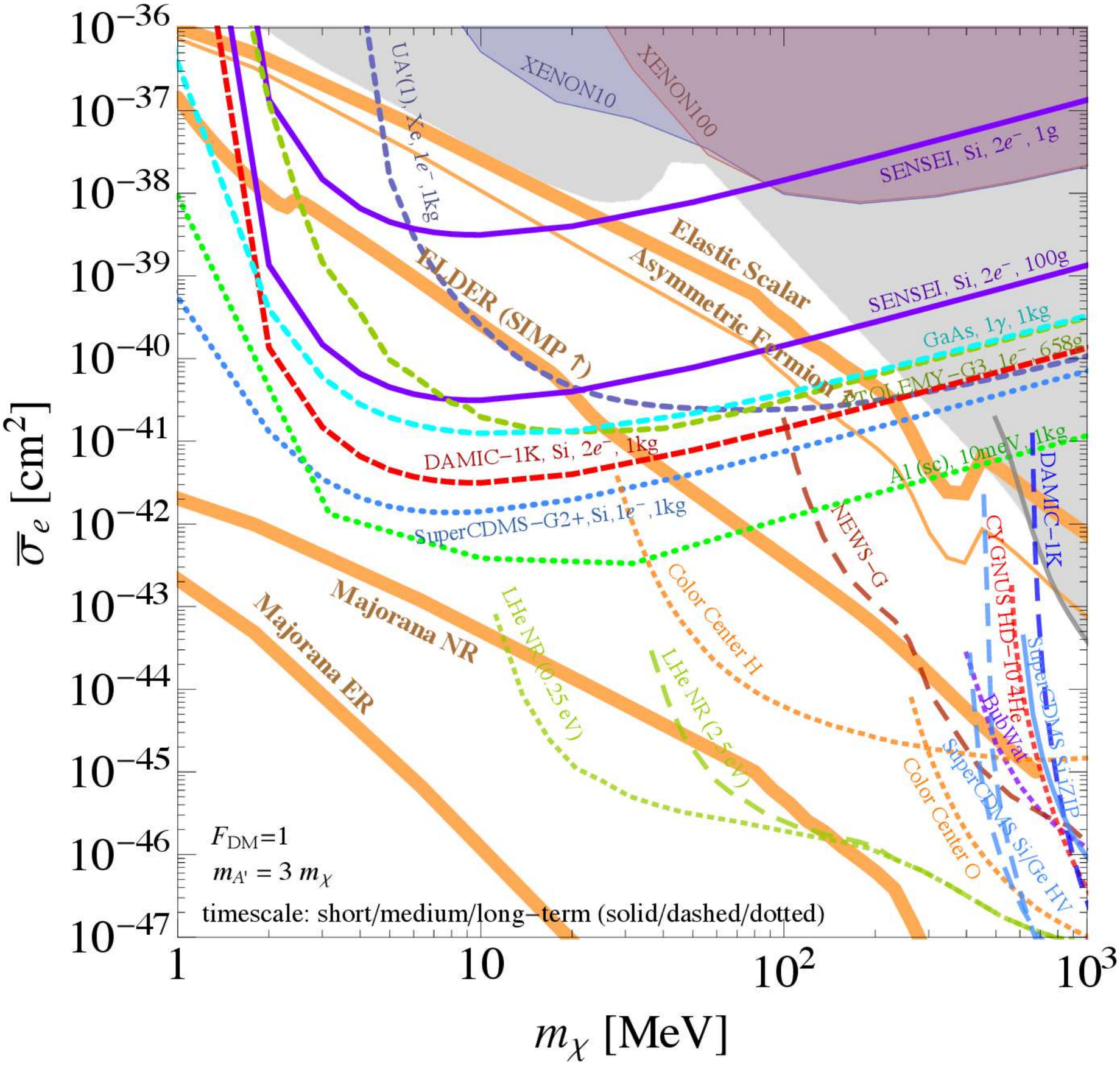


$$E_{\rm NR} = \frac{q^2}{2m_N} \leq \frac{2\mu_{\chi N}^2 v_\chi^2}{m_N} \lesssim 190\ {\rm eV} \times \left(\frac{m_\chi}{500\ {\rm MeV}}\right)^2 \left(\frac{16\ {\rm GeV}}{m_N}\right)$$



$$E_e \leq \frac{1}{2} m_\chi v_\chi^2 \lesssim 3\ {\rm eV} \left(\frac{m_\chi}{\rm MeV}\right)$$


Dark Matter–nucleon cross section [cm^2]
Dark Matter–nucleon cross section [pb]
Dark Matter Mass [GeV/c^2]
10^{-38}
10^{-40}
10^{-42}
10^{-44}
10^{-46}
10^{-48}
10^{-50}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-5}
0.001
0.100
10
1000
He (2–excitation)
LHe NR (1 meV): LT
LHe NR (0.25eV)
LHe NR (2.5eV)
Color Center (H)
Color Center (O)
CRESST-SiMic-H
NEWS–G
DAMIC–1K
CYGNUS HD–10 ^{4}He
SuperCDMS Si HV
SuperCDMS Ge HV
PICO–60
SuperCDMS Si iZIP
BubWat
CYGNUS HD–10 SF_6
CRESST
SuperCDMS Ge iZIP
XENON1T
DEAP–3600
XENON1T
LZ
DarkSide–20k
XENONnT
SBC–Ar
DARWIN 200ty
DarkSide–20k


$\overline{\sigma}_e$ [cm^2]
m_χ [MeV]
10^{-36}
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
1
10
10^2
10^3
XENON10
XENON100
UA'(1), Xe, $1e^-$, 1kg
SENSEI, Si, $2e^-$, 1g
SENSEI, Si, $2e^-$, 100g
Elastic Scalar
Asymmetric Fermion
ELDER (SIMP ↑)
GaAs, 1γ, 1kg
TOLEMY−G3, $1e^-$, 658g
DAMIC−1K, Si, $2e^-$, 1kg
SuperCDMS−G2+,Si,$1e^-$,1kg
Al (sc), 10meV, 1kg
NEWS−G
CYGNUS HD−TO 4He
DAMIC−1K
SuperCDMS SNOLAB HVeV
SuperCDMS SNOLAB iZIP
BubWat
SuperCDMS Si/Ge HV
Color Center H
Color Center O
LHe NR (0.25 eV)
LHe NR (2.5 eV)
Majorana NR
Majorana ER
$F_{\rm DM}$=1
$m_{A'} = 3\, m_\chi$
timescale: short/medium/long−term (solid/dashed/dotted)

“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

Why model builders build models...

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

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

Rules of model building

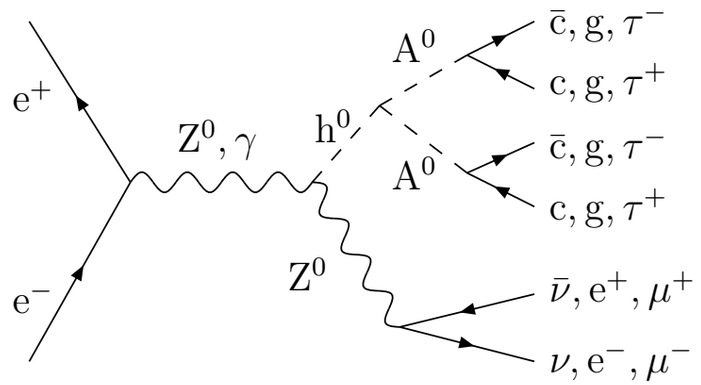
- "First do no harm"
  - FCNC's, PEWT, LEP, B-physics, proton decay, existing searches,.. (often reason for new parity...DM)
- Describe physics with a local, Lorentz invariant, unitary field theory, causal
- Preserve gauge invariance, anomaly free
- Prefer renormalizable field theories
- Occam's razor?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

"Top down"

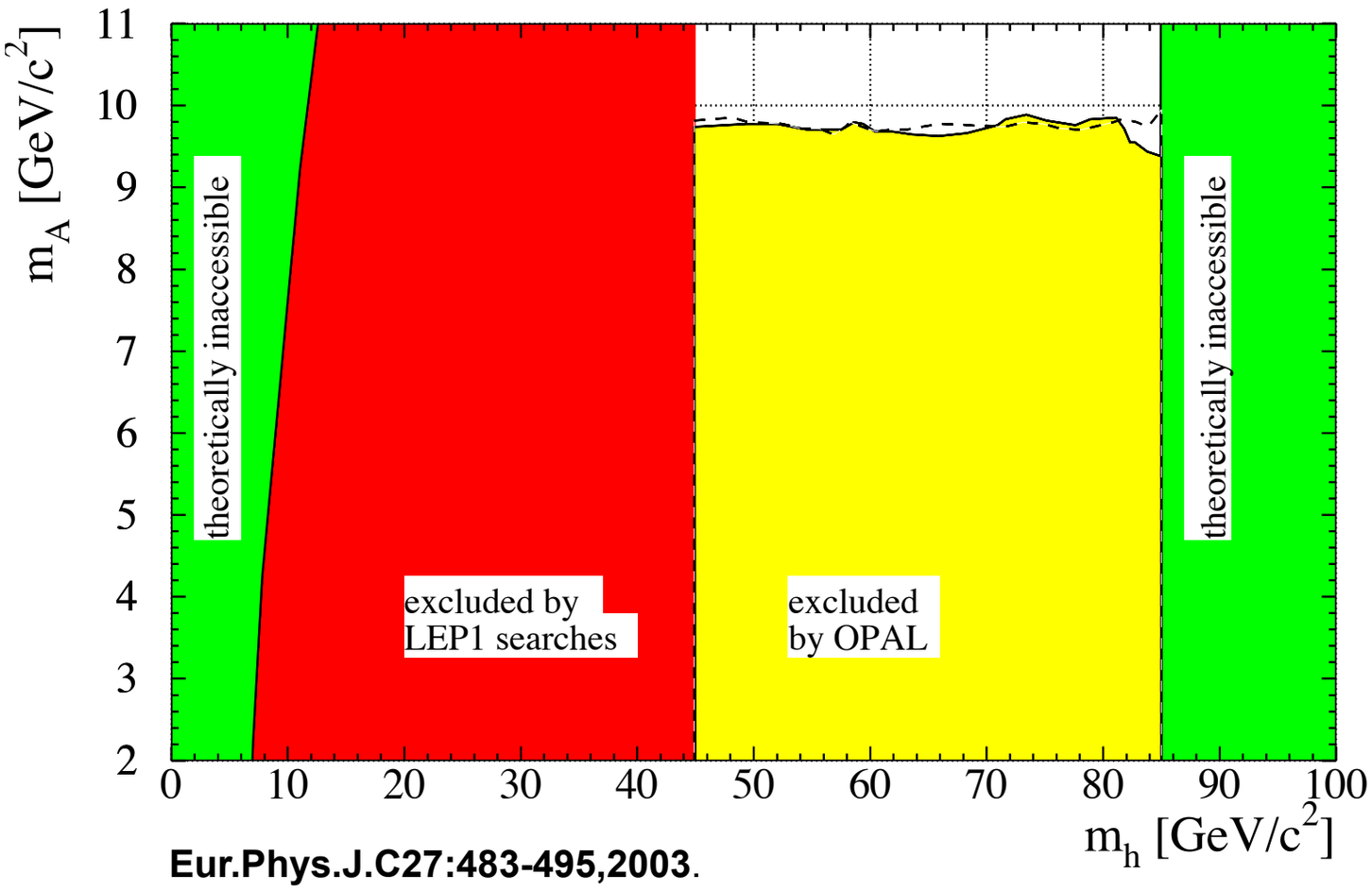
- Identify "grand problem" e.g. weak hierarchy, cosmological constant, flavour
- Introduce "grand principle" e.g. extra dimensions, supersymmetry, new strong dynamics
- Define new theory obeying principle that has SM as long energy limit

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

A cautionary tale

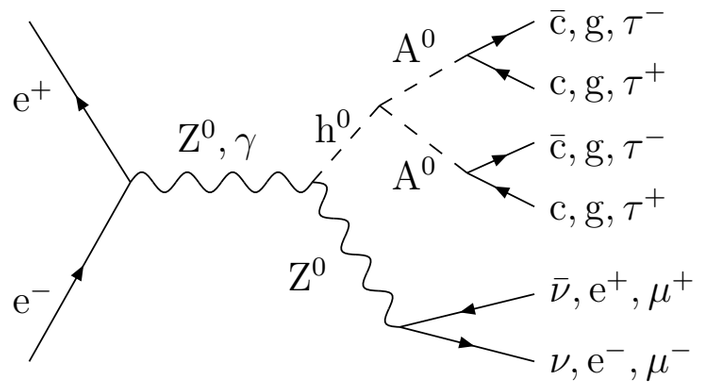


OPAL Higgs search

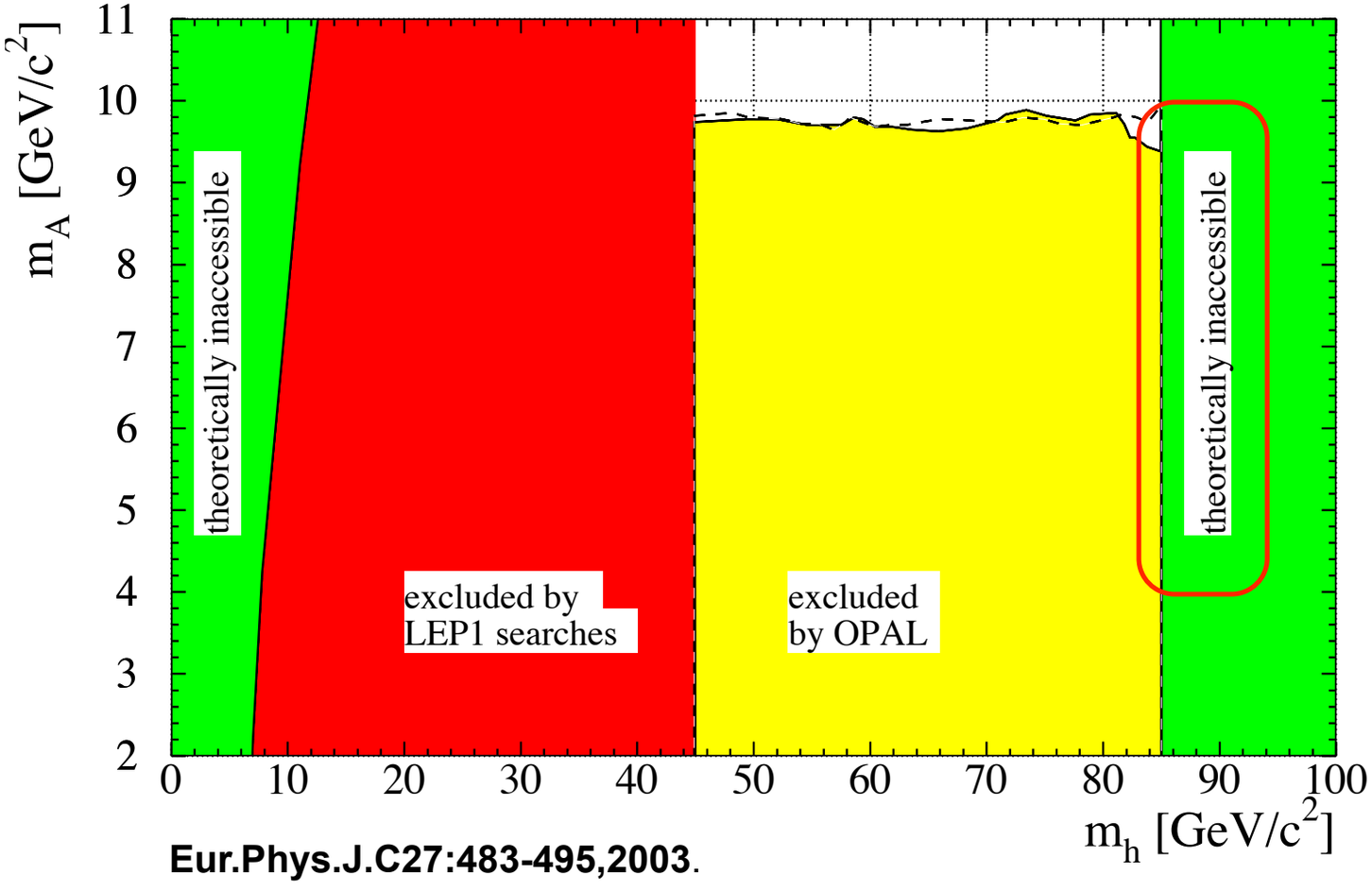


Eur.Phys.J.C27:483-495,2003.

A cautionary tale



OPAL Higgs search



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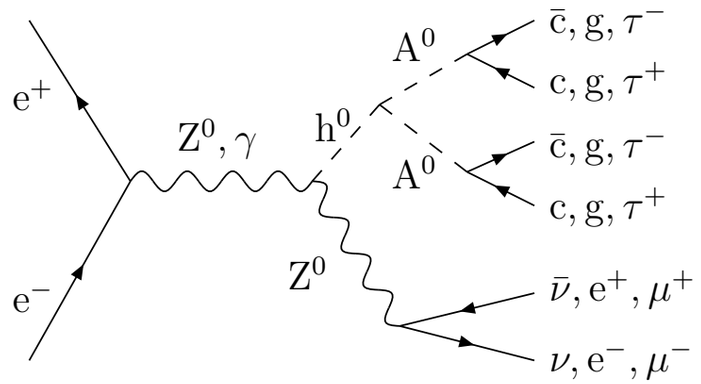

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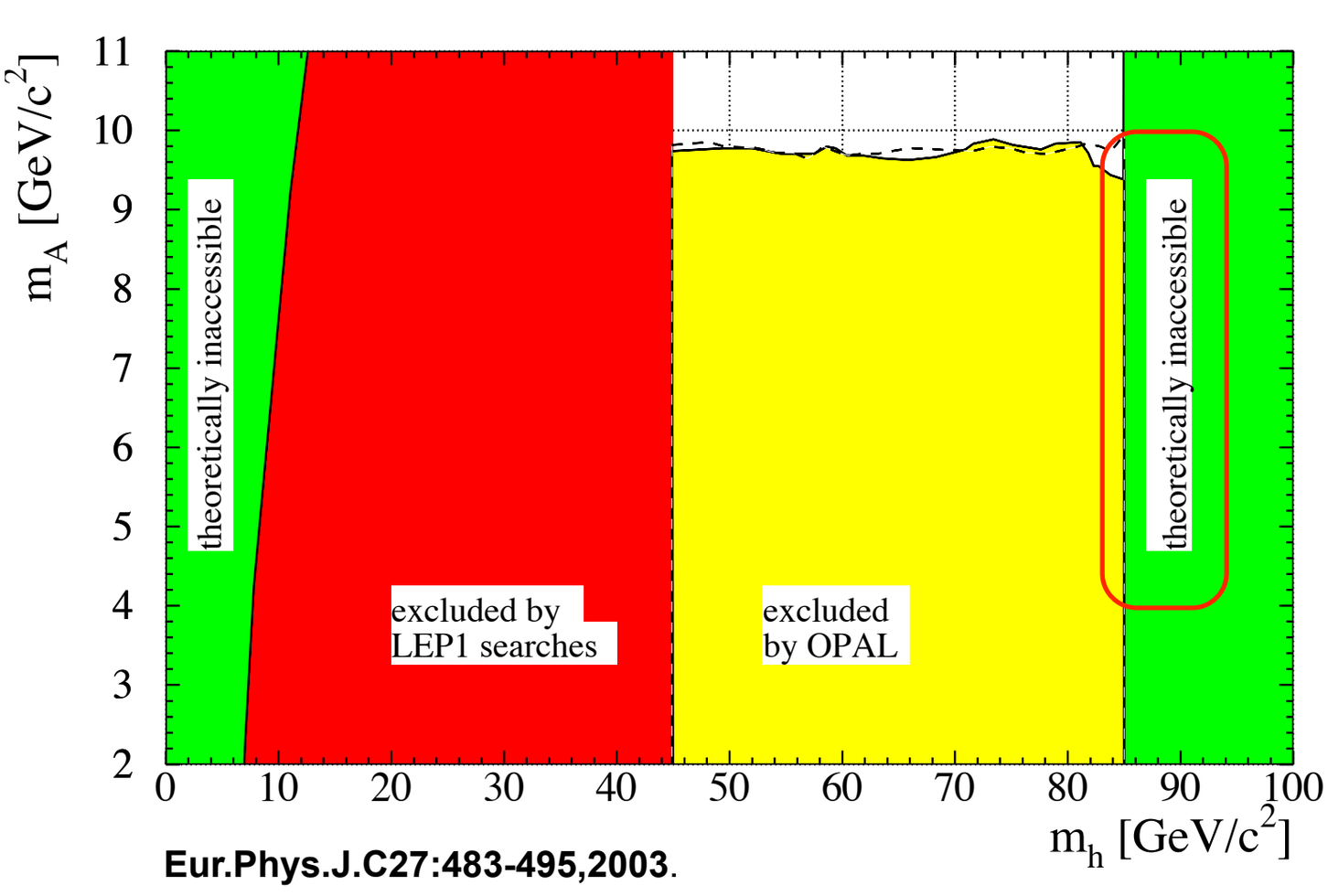
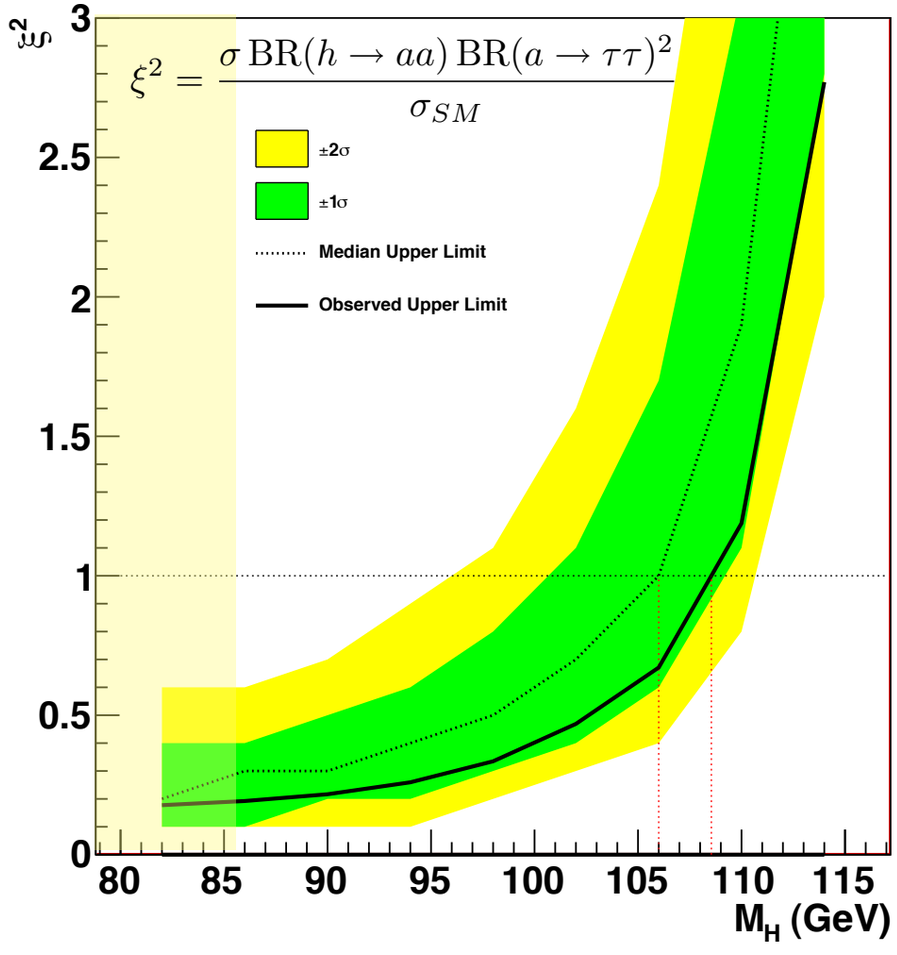


Eur.Phys.J.C27:483-495,2003.

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

“Bottom up”.... without anomaly

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“Top down” —data→ **“Bottom up”**

Conclusions

BSM physics creates lamppost

Interesting searches being done, keep being creative

A return to the “historical norm”? Expt. in the driver’s seat

No guaranteed discovery (unlike W, top, EWSB)

This should not stop us doing our best!!!

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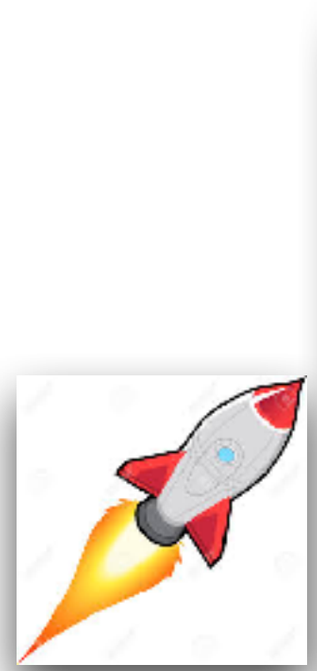
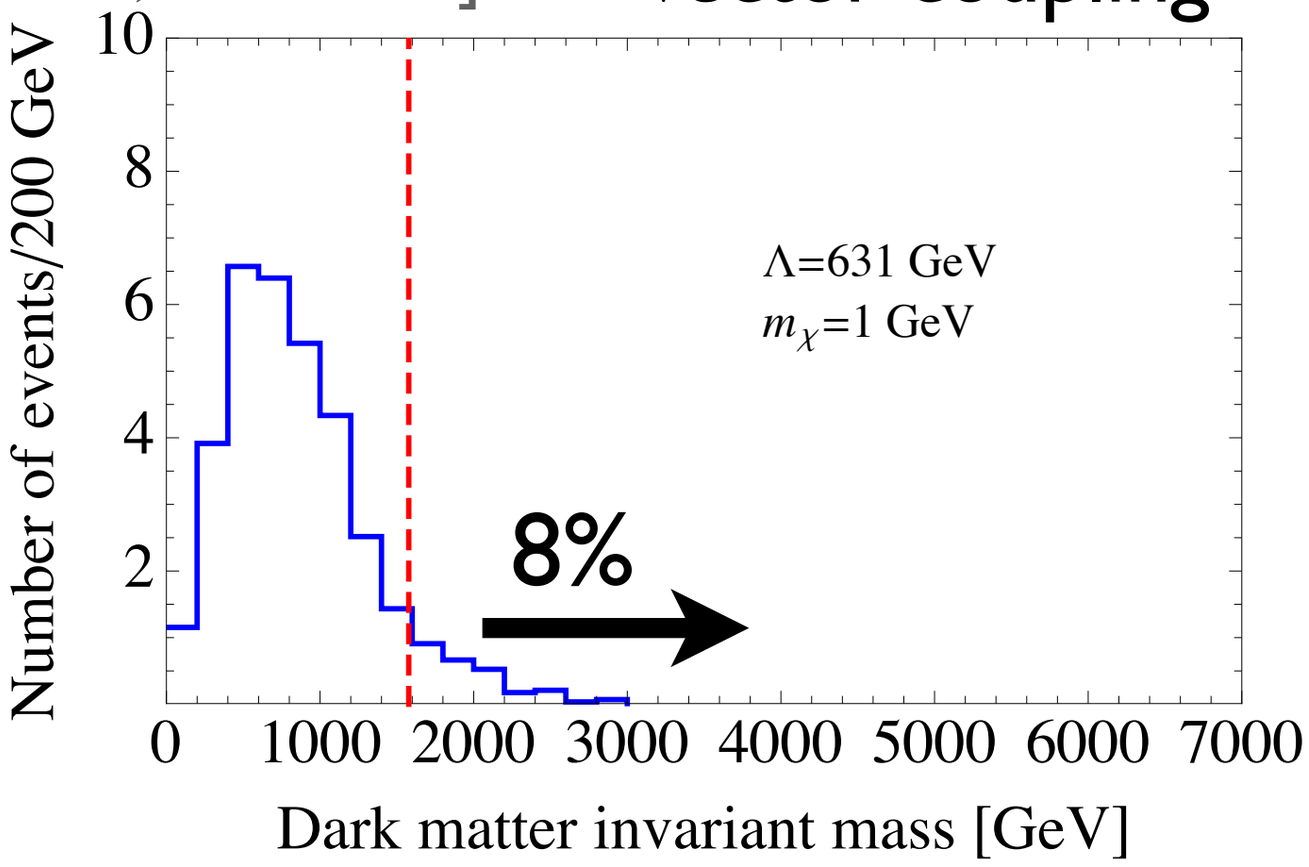


Extras

[PJF et al, 1203.1662]

Vector coupling

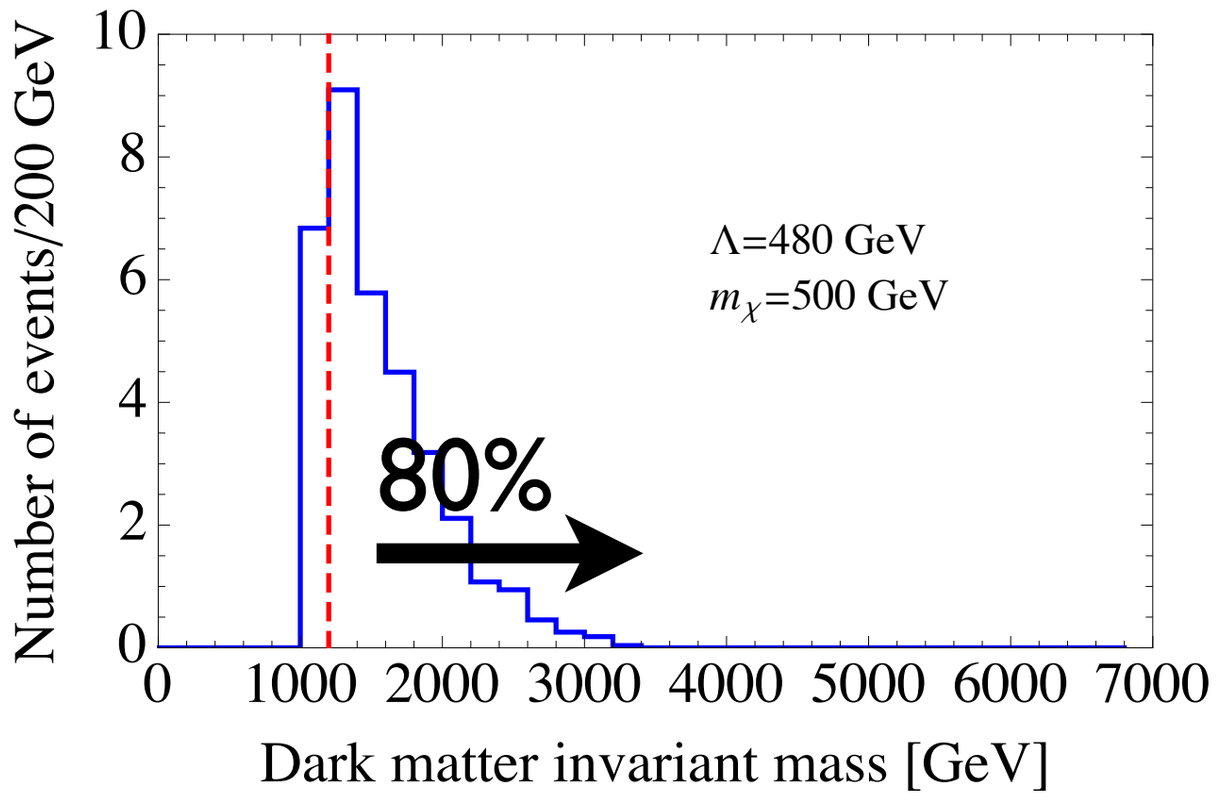


Unitarity bound $m_{\chi\chi} < \frac{\Lambda}{0.4}$

[Shoemaker and Vecchi, 1112.5457]

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

Depends on DM mass



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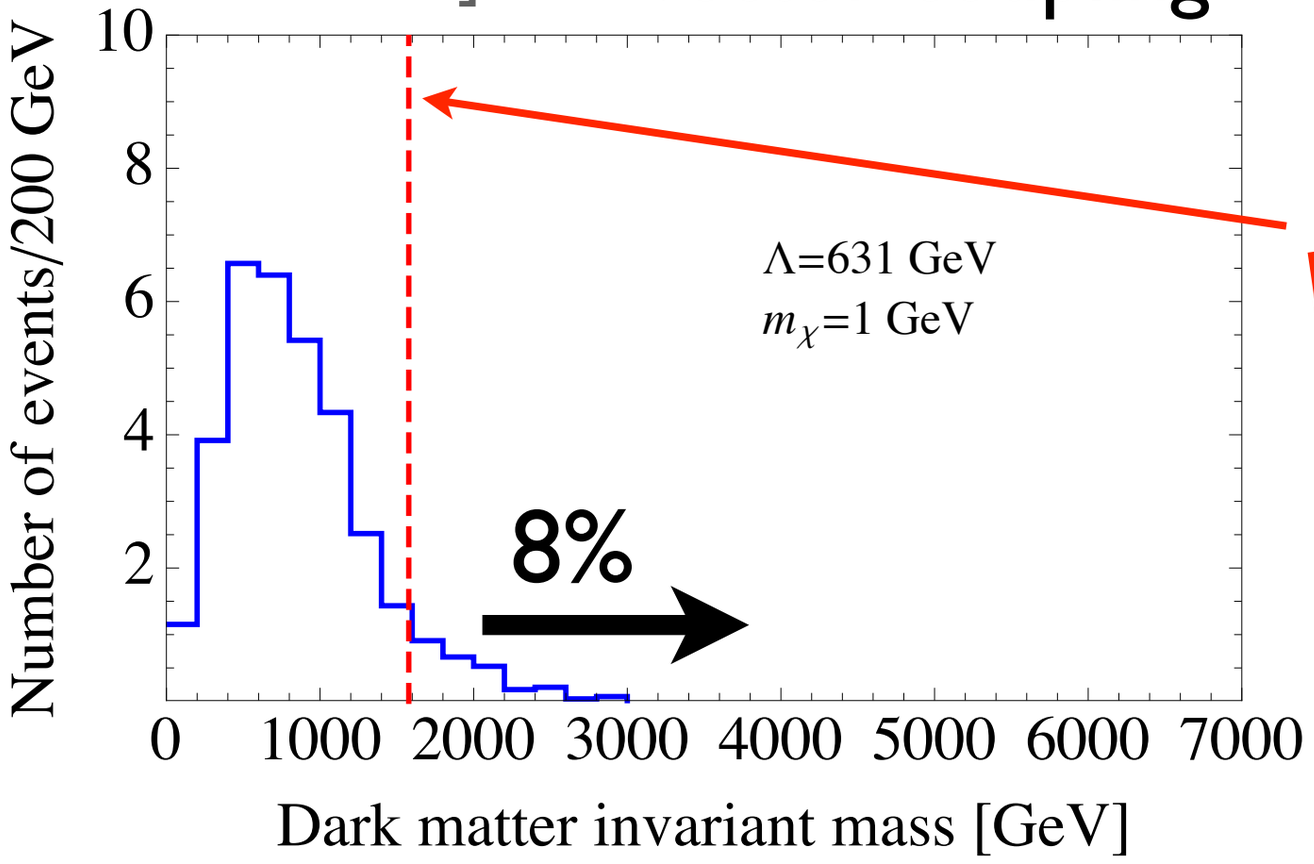

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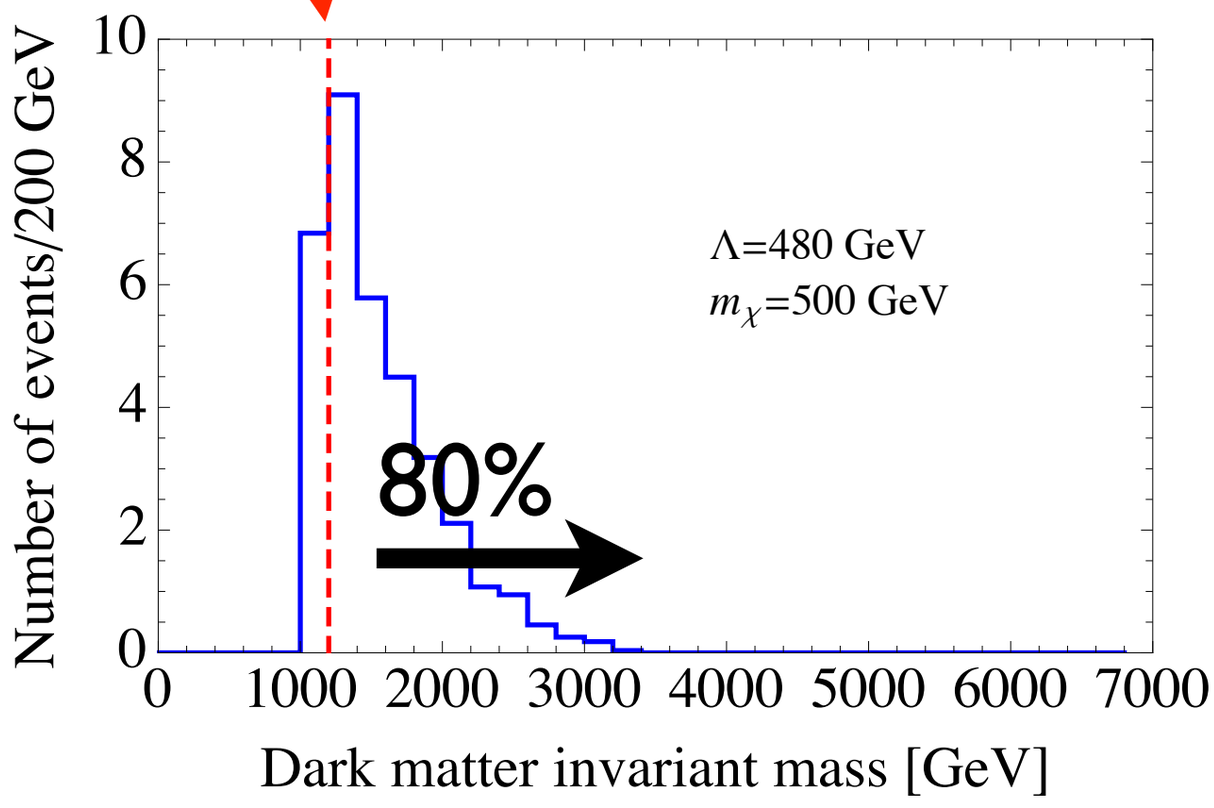

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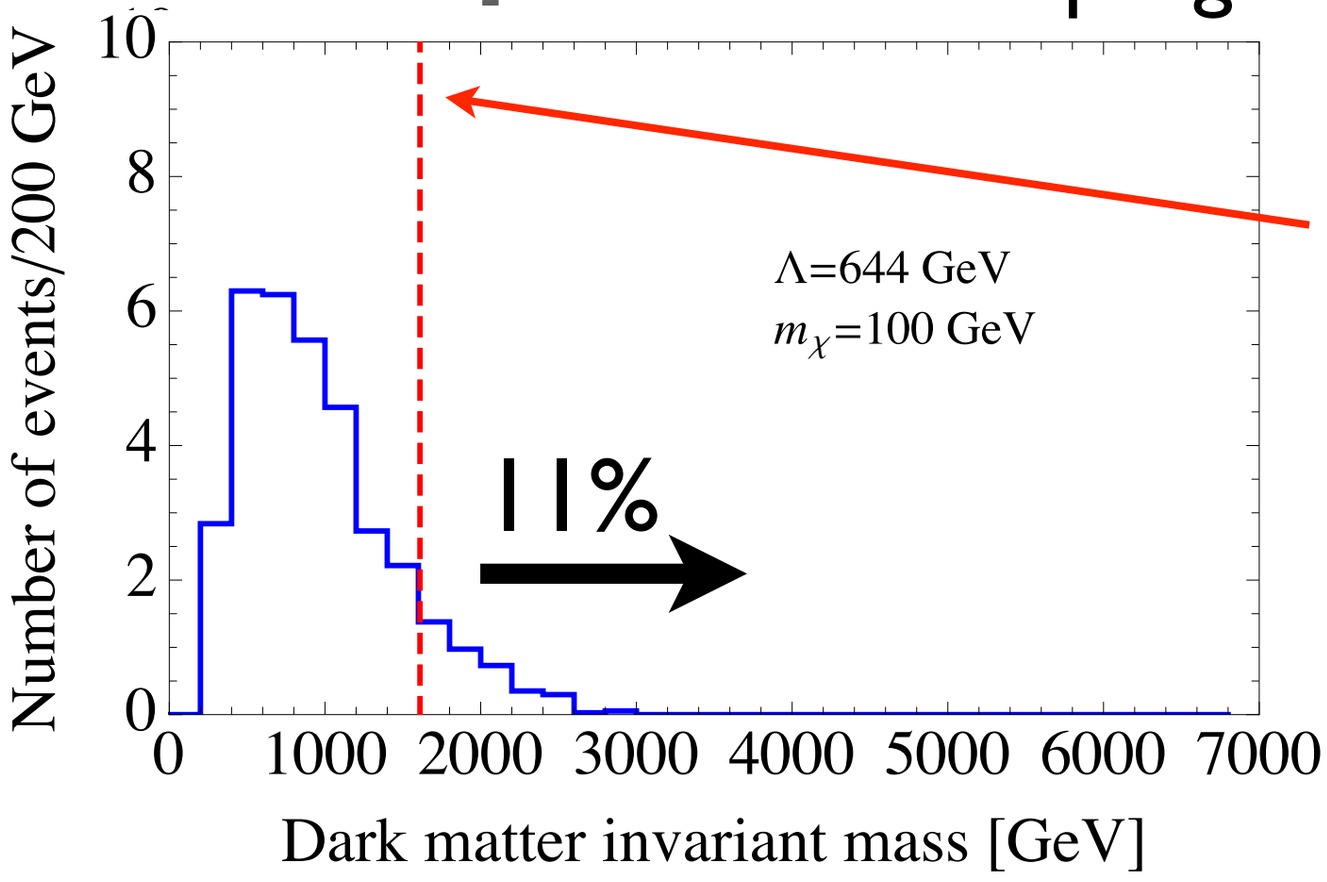

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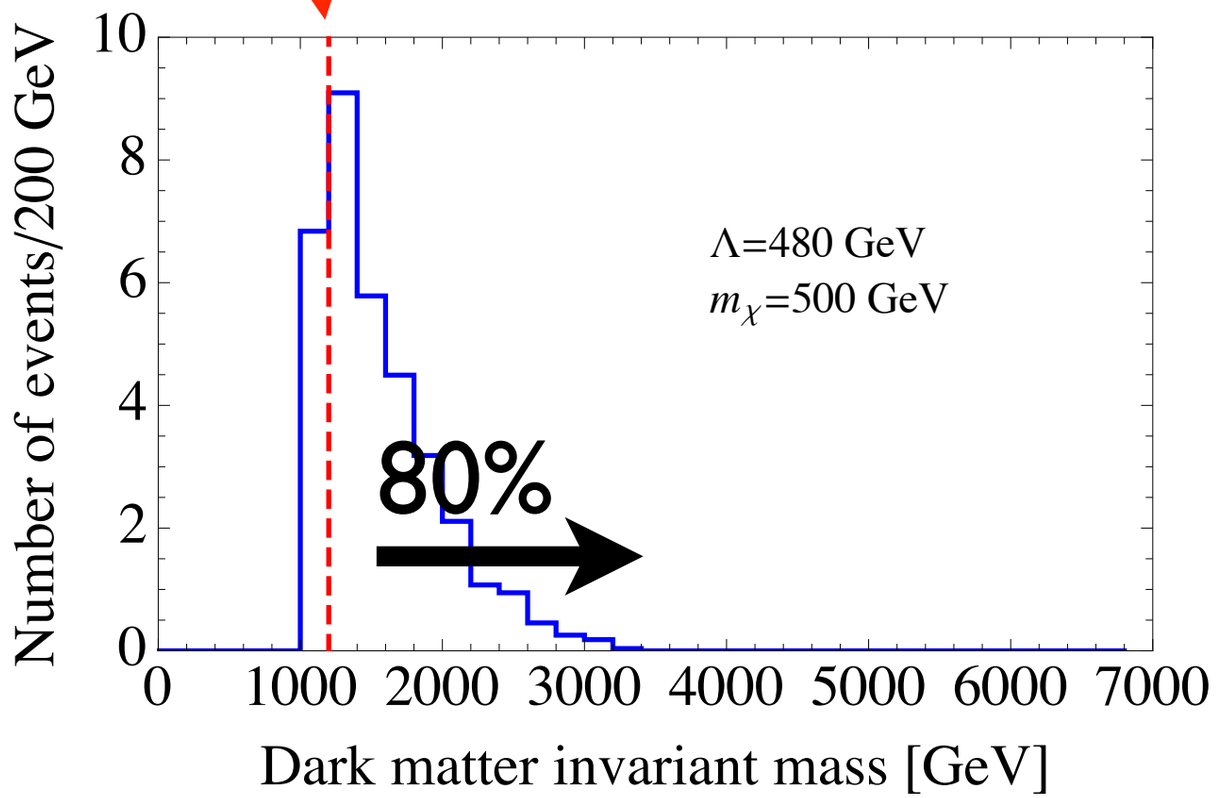
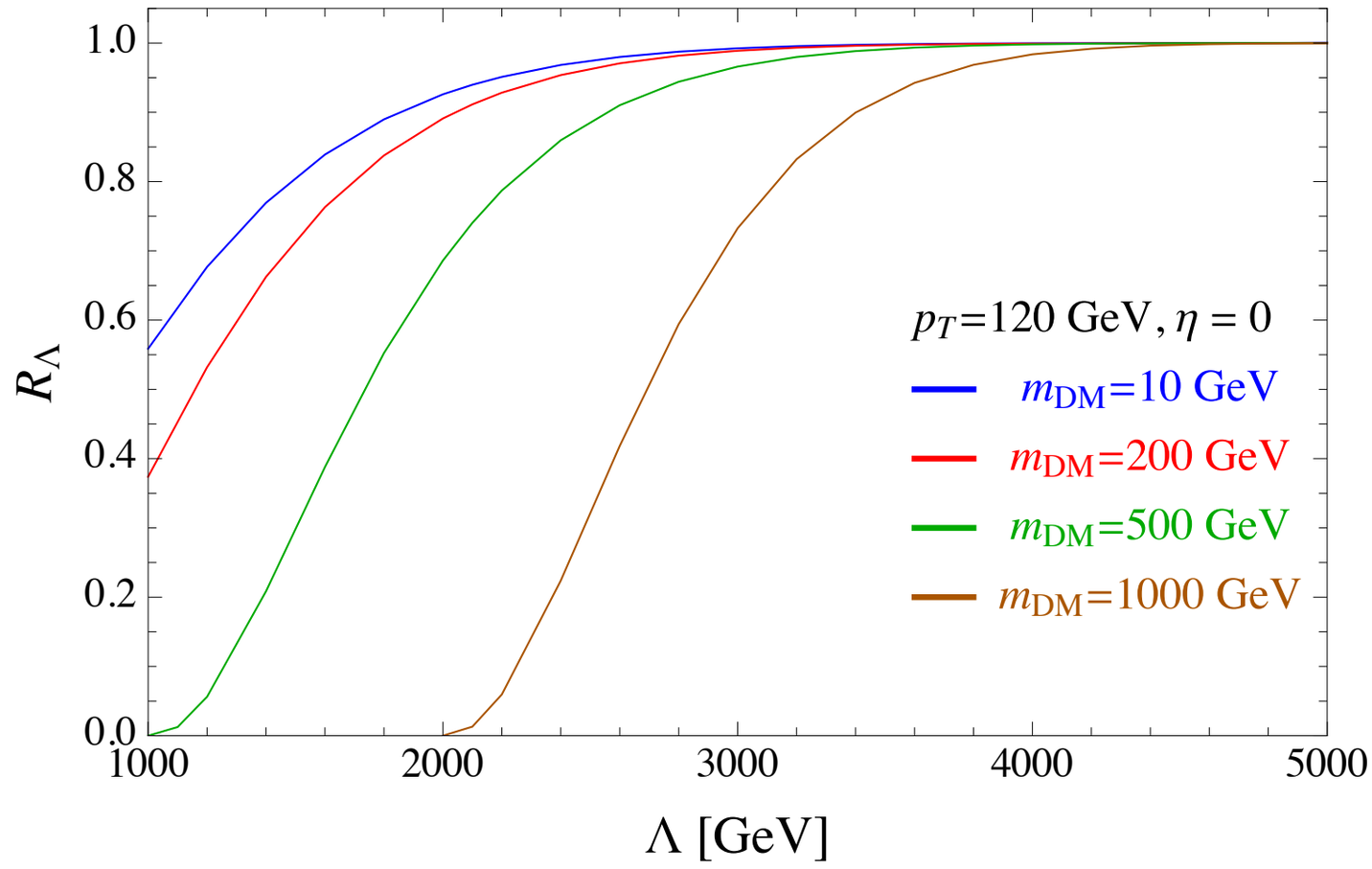


What fraction of events have momentum transfers sufficient to probe the UV completion?

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

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



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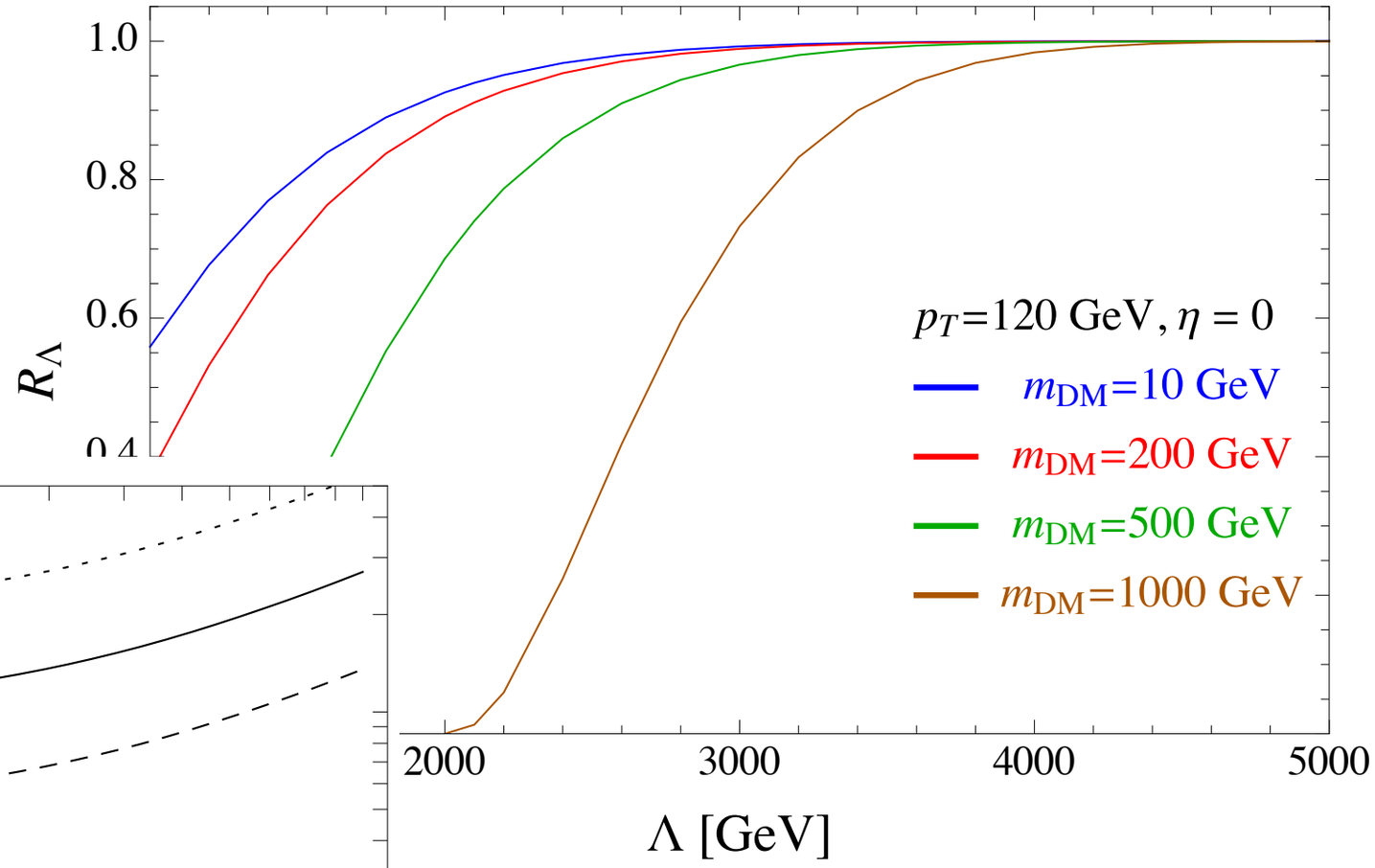
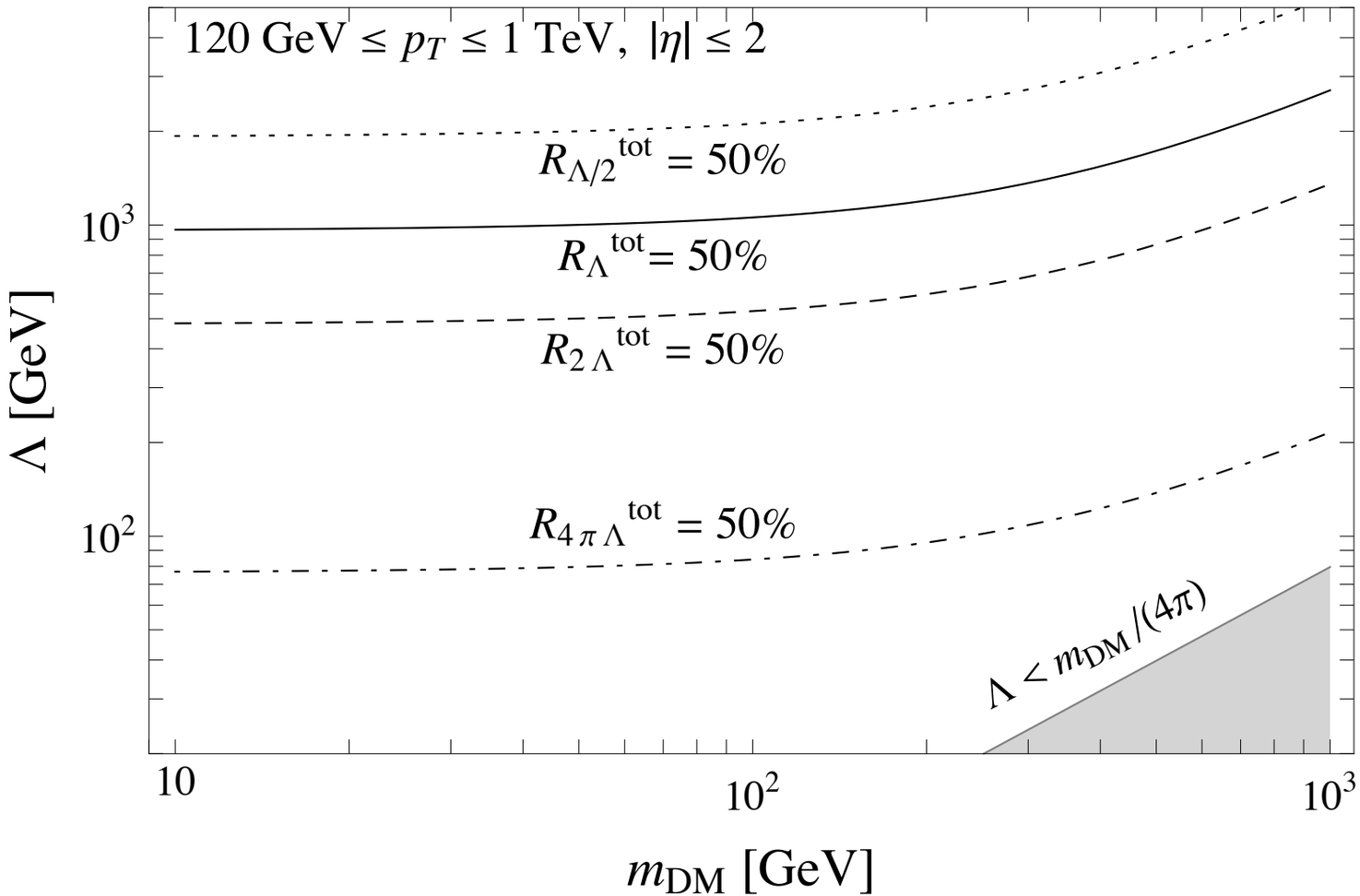


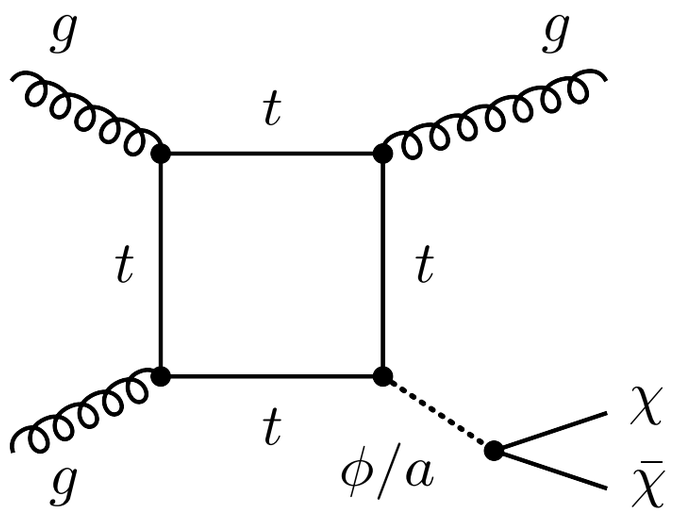


Types of Simplified models

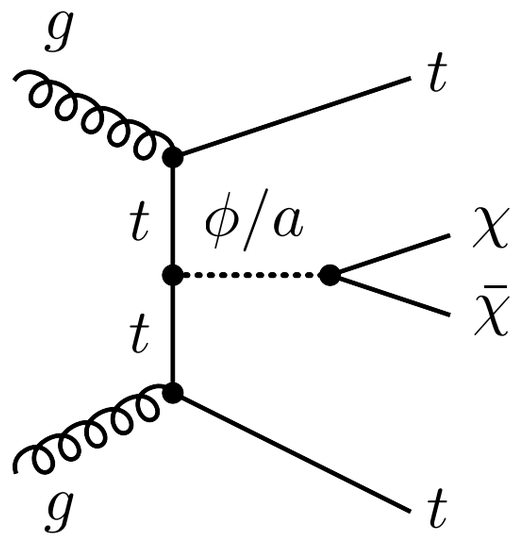
s-channel scalar/psuedo-scalar

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

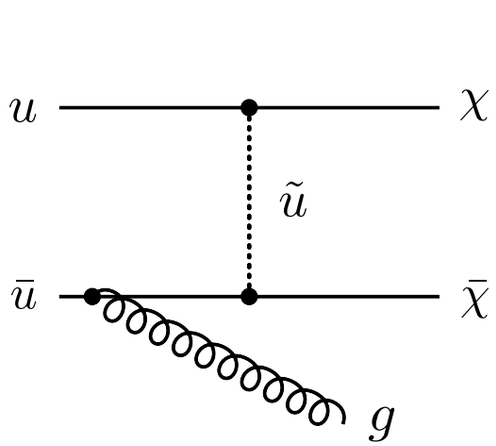
- Scalars have helicity suppressed annihilation, and SI DD
- Pseudo scalars do not, and have SD momentum suppressed DD

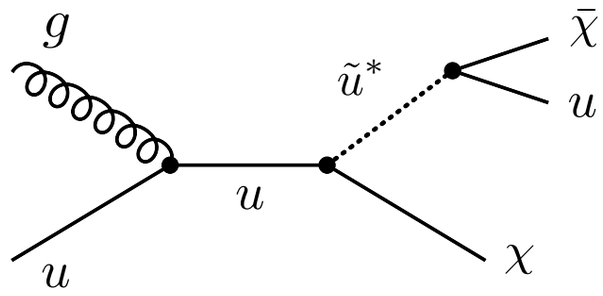
Types of Simplified models

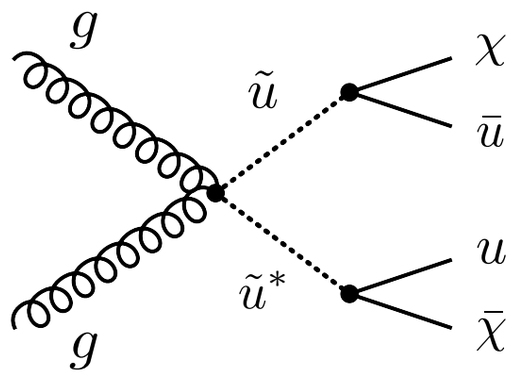
t-channel scalar/psuedo-scalar

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

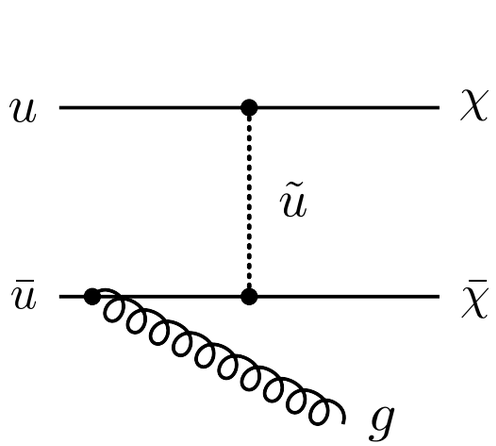
Types of Simplified models

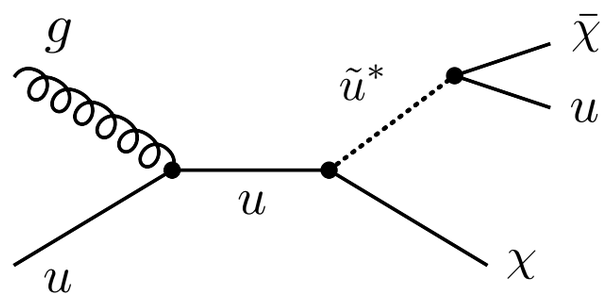
t-channel scalar/psuedo-scalar

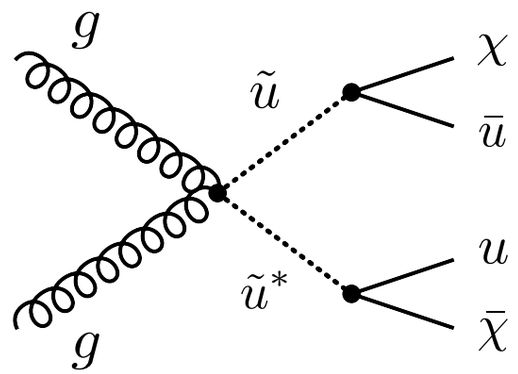
"squarks" w/o SUSY prior

MFV requires DM or mediator to c[illegible] 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

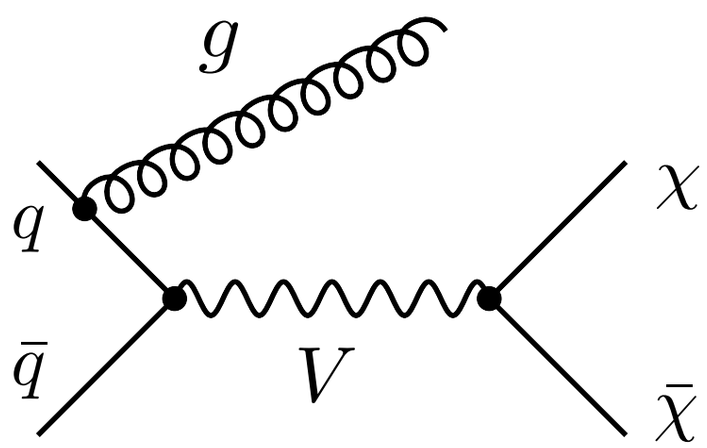
s-channel vector/axial-scalar

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