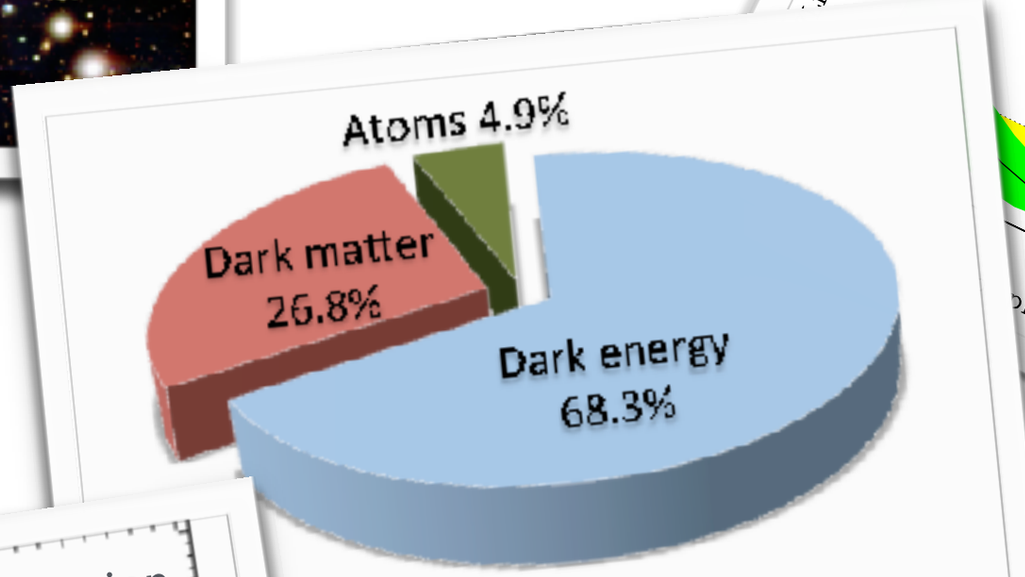
Particle Theories of Dark Matter

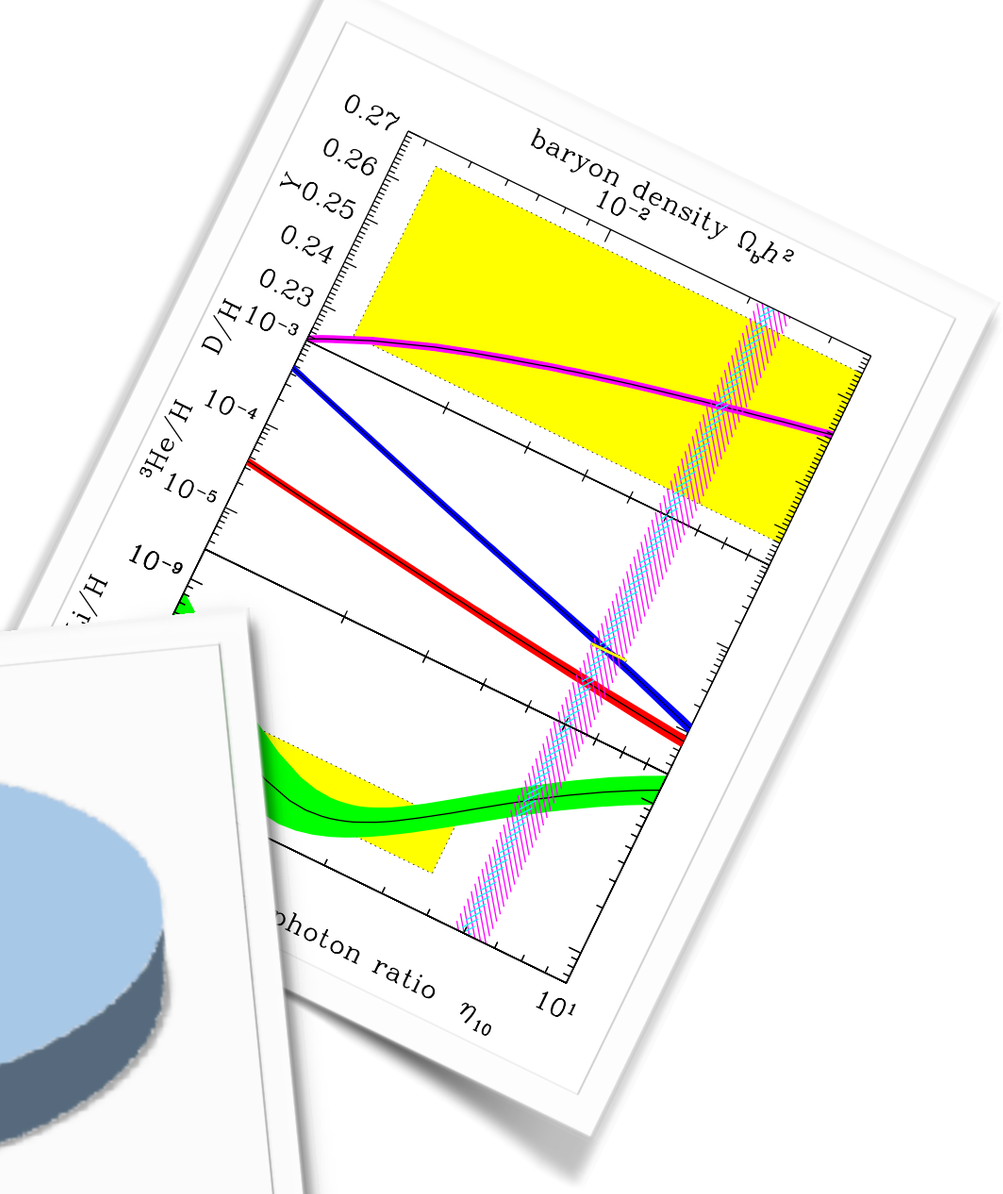
Patrick Fox

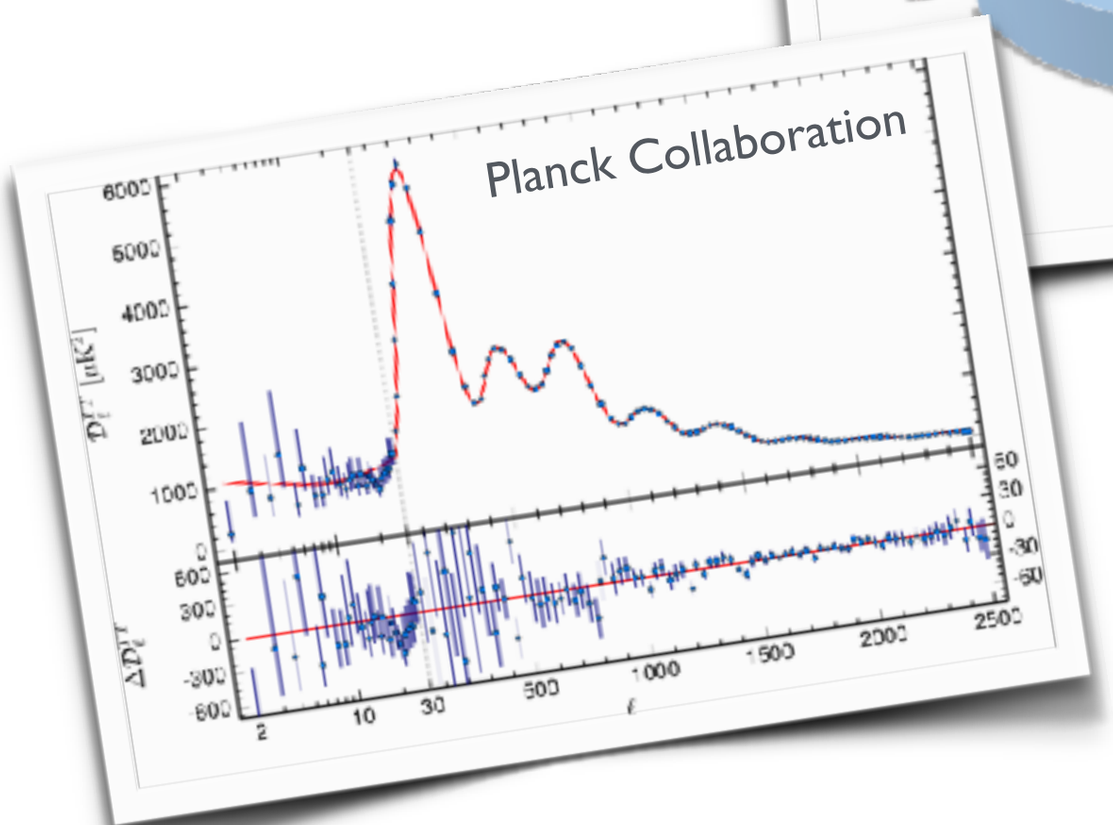


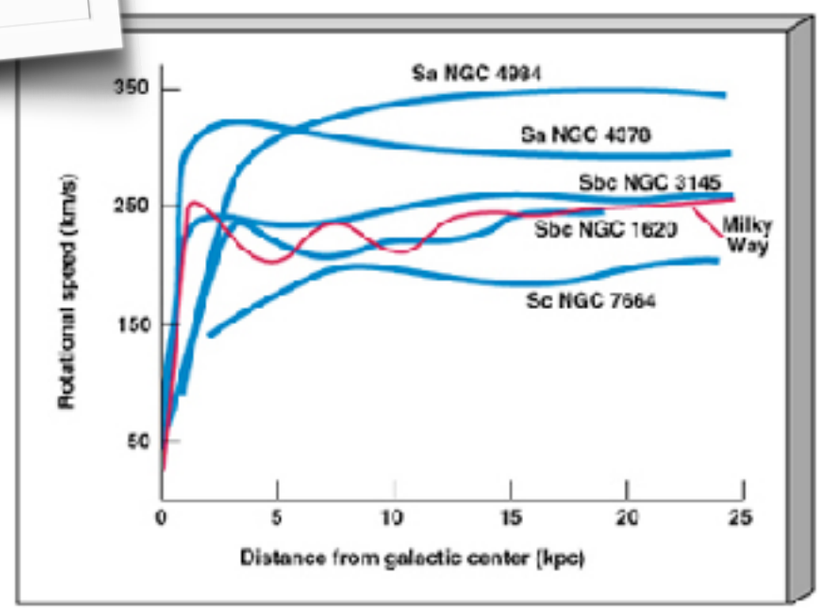
Gordon Research Conferences




Atoms 4.9%
Dark matter
26.8%
Dark energy
68.3%


baryon density $\Omega_b h^2$
10^{-2}
0.27
0.26
Y 0.25
0.24
0.23
D/H 10^{-3}
^{3}He/H 10^{-4}
10^{-5}
10^{-9}
photon ratio η_{10}
10^1


Planck Collaboration
D_ℓ^{TT} [μK^2]
ΔD_ℓ^{TT}
ℓ

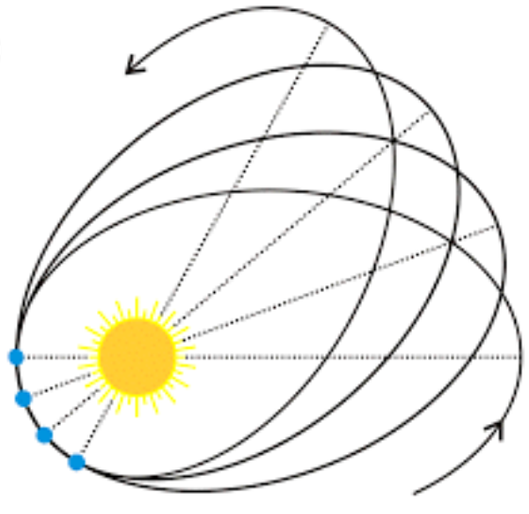

Sa NGC 4594
Sa NGC 4378
Sbc NGC 3145
Sbc NGC 1620
Milky Way
Sc NGC 7564
Rotational speed (km/s)
Distance from galactic center (kpc)

So far all probes have been gravitational in nature

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



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



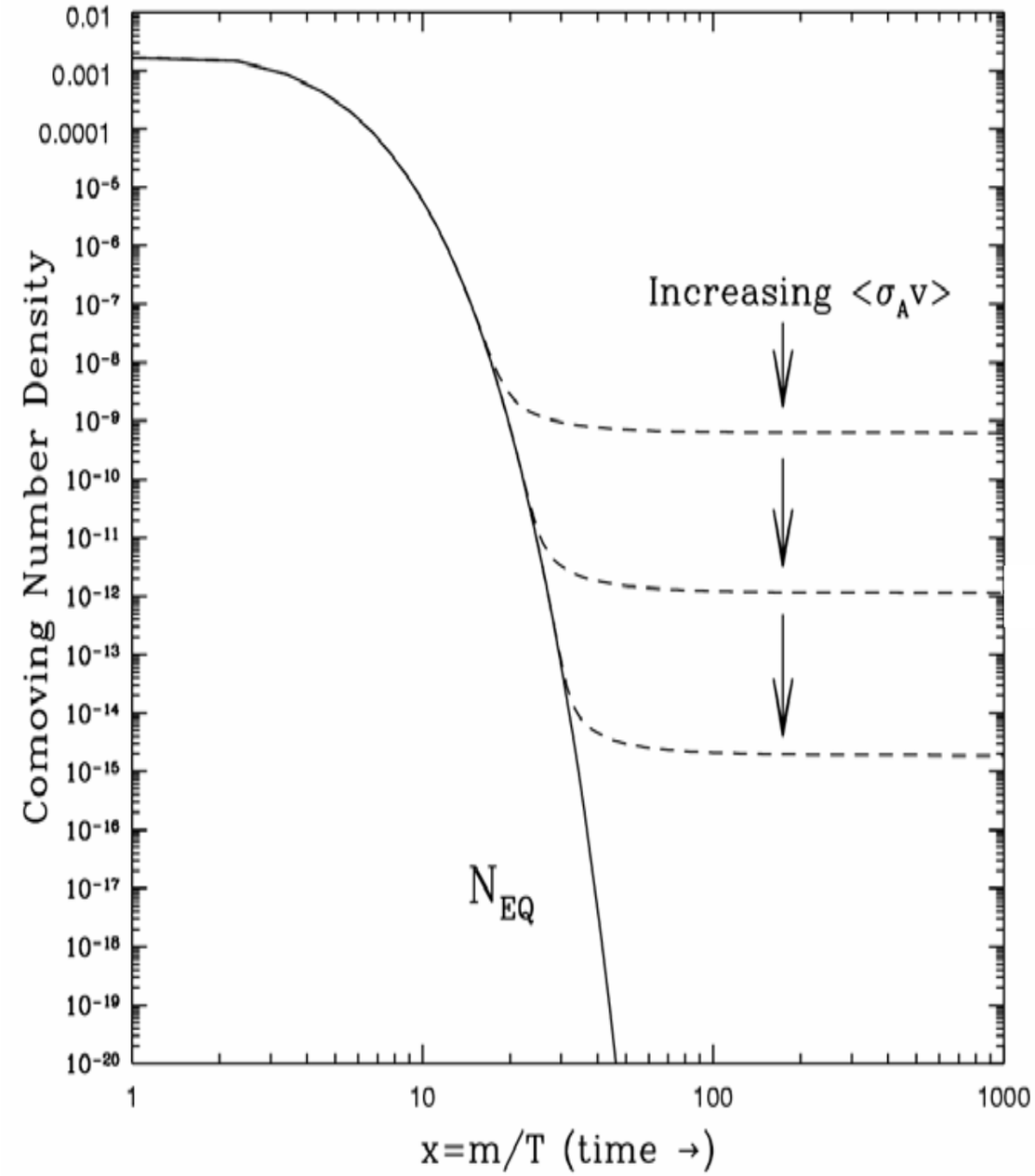


What about other interactions?

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"



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

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

Amazing (misleading?) fact:

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

Dark Matter

Nuclear Matter
quarks, gluons

Leptons
electrons, muons,
taus, neutrinos

Photons,
W, Z, h bosons

Other dark
particles

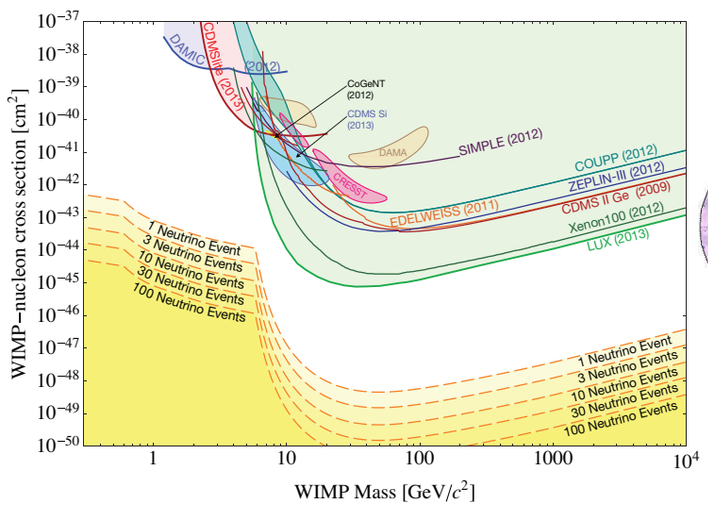
Direct Detection

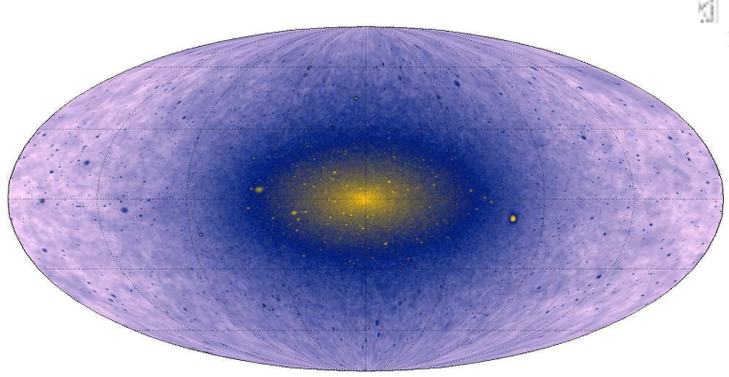
Indirect Detection

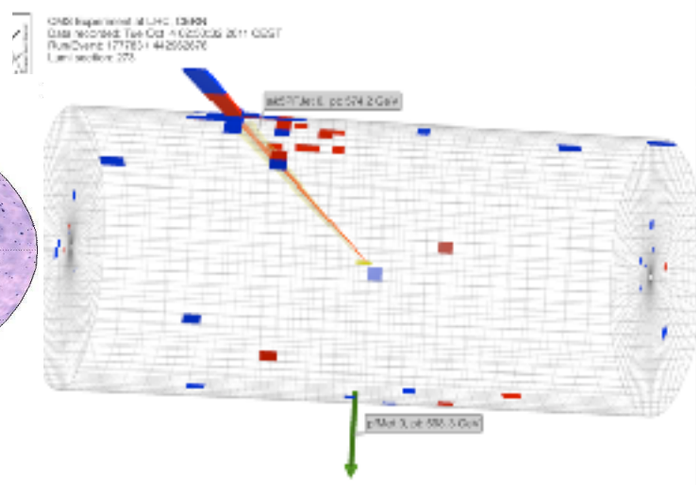


Particle Colliders

Astrophysical Probes









Dark Matter

Leptons

Photons,
W, Z, h bosons

Other dark
particles

Direct
Detection

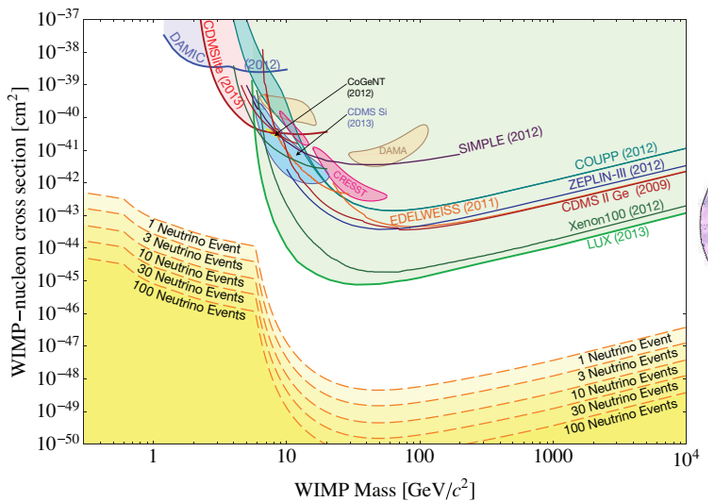
Indirect
Detection

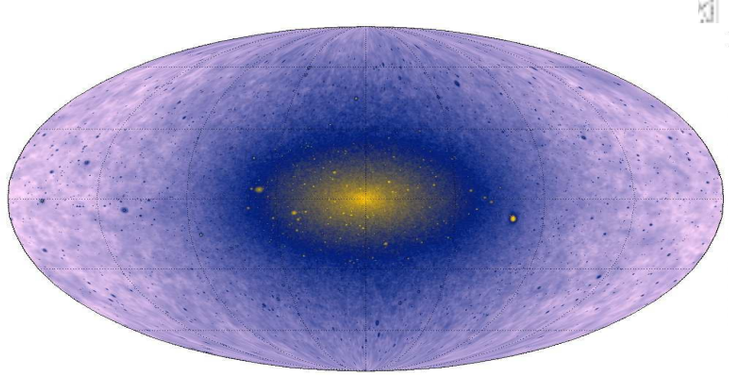
DM

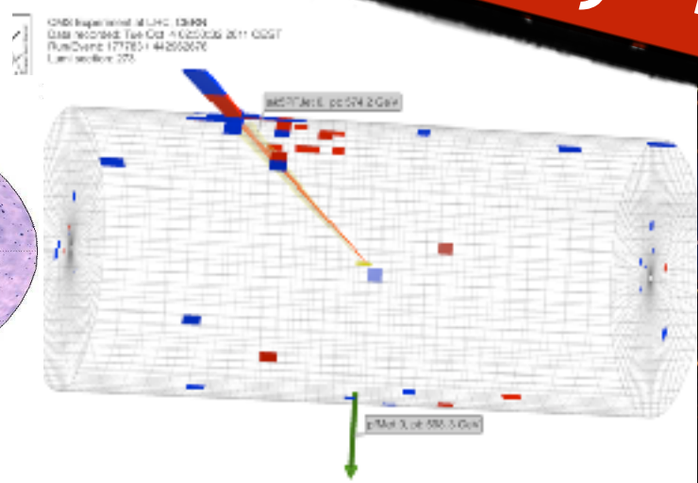
SM

DM

See talks by Rau, Chang, Semertzidis, Zhou, Kazama, Yu,....

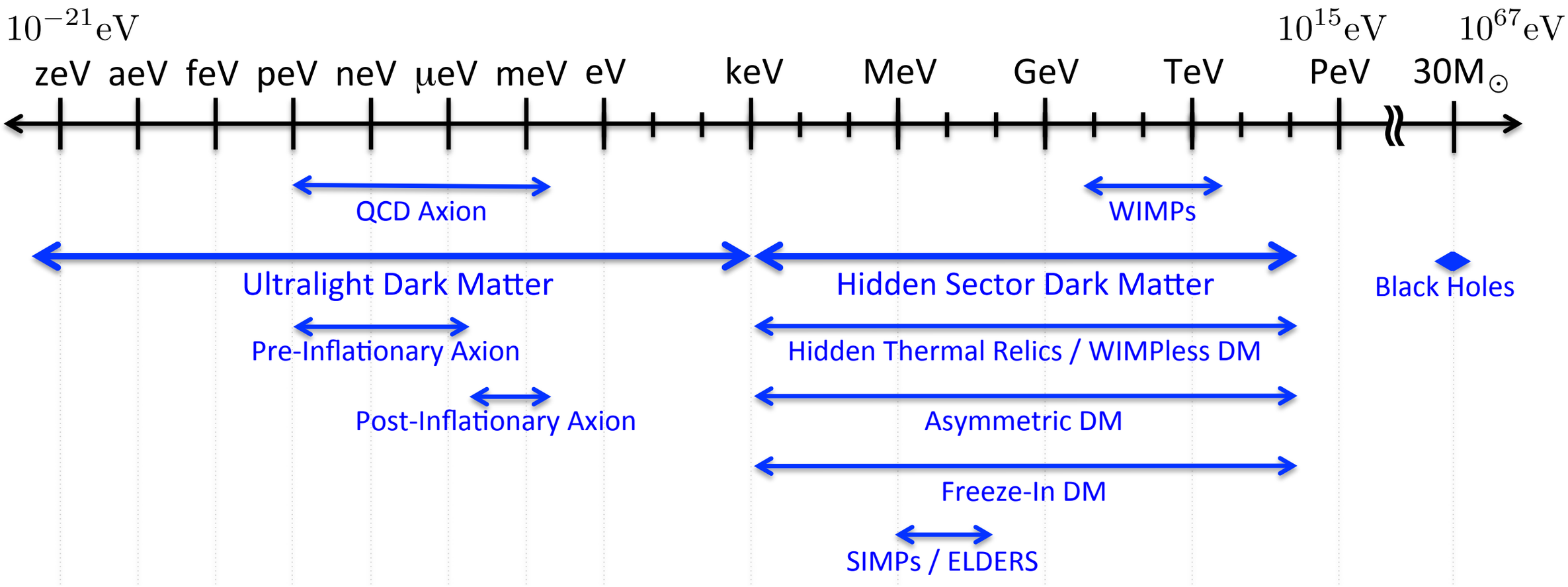






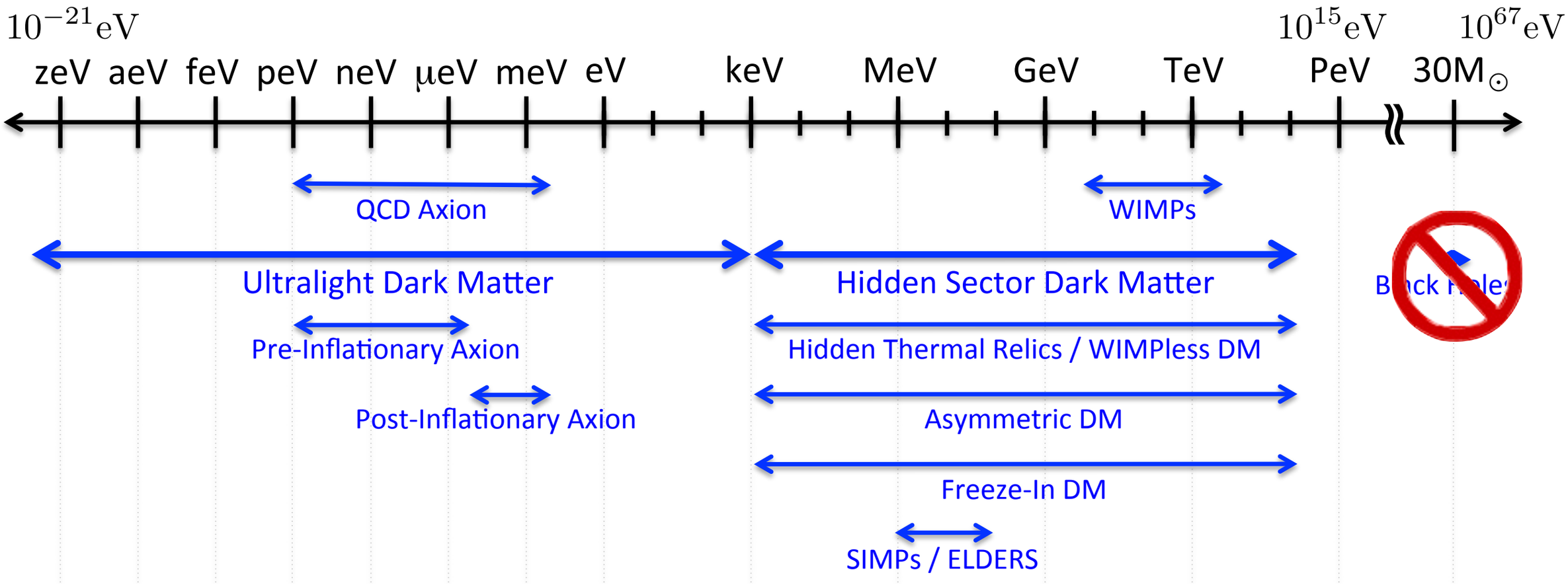


Particle theories



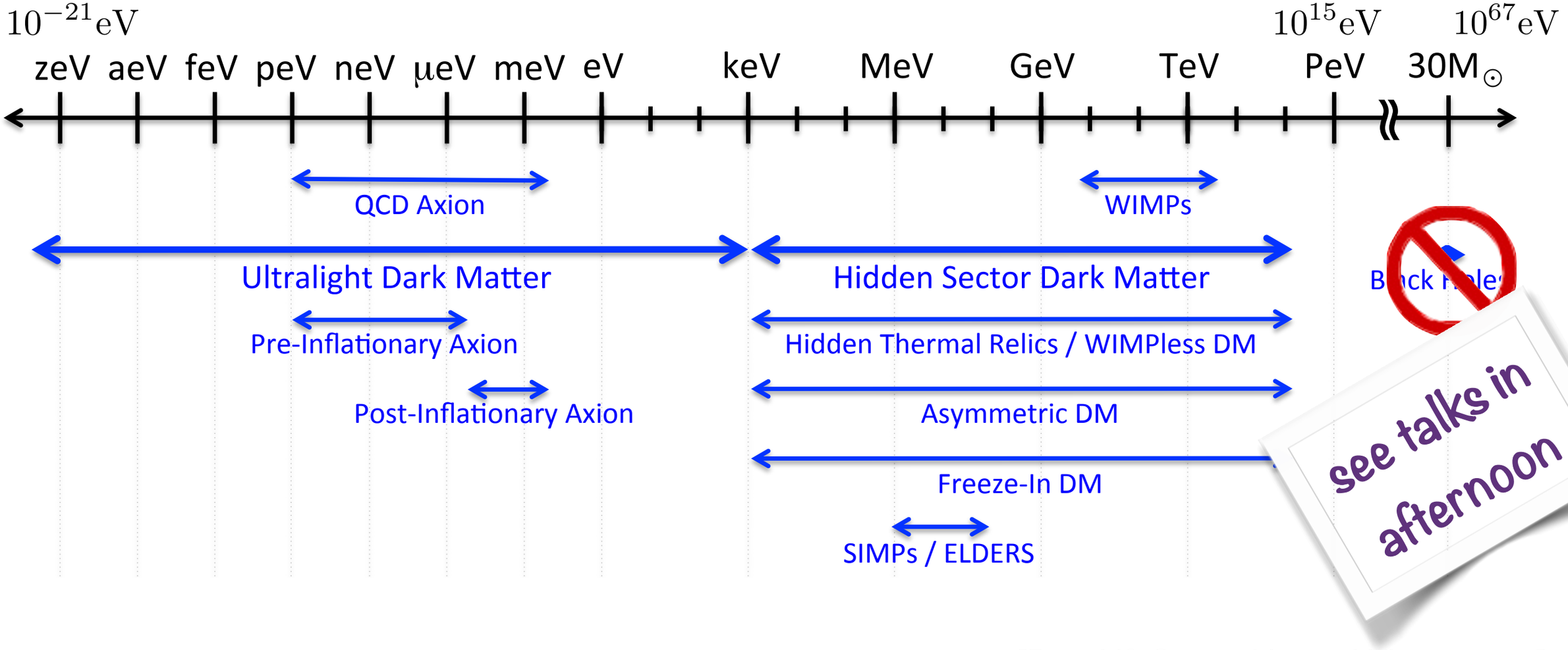
[Feng-US Cosmic Visions White papers]

Particle theories



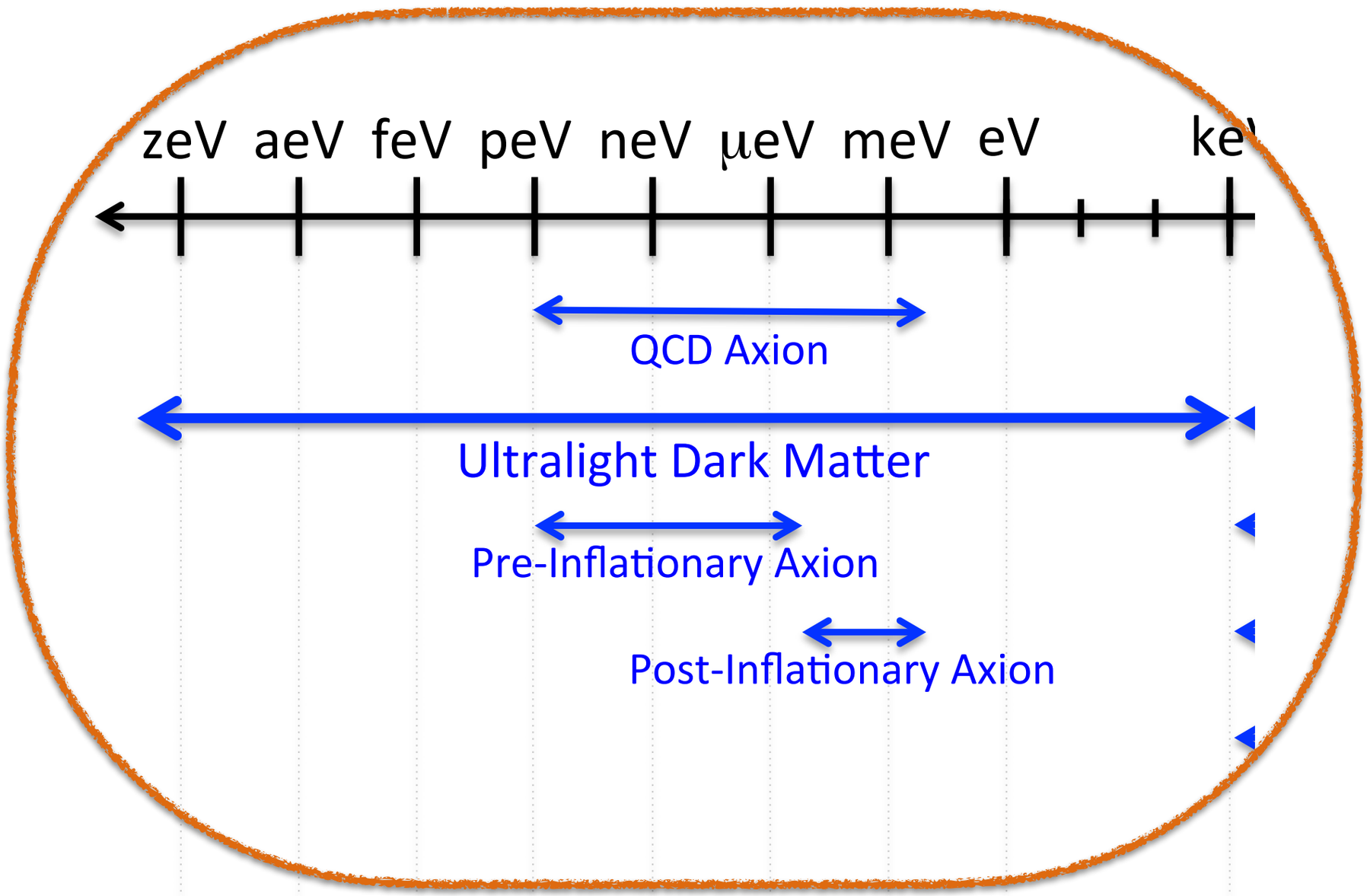
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Particle theories



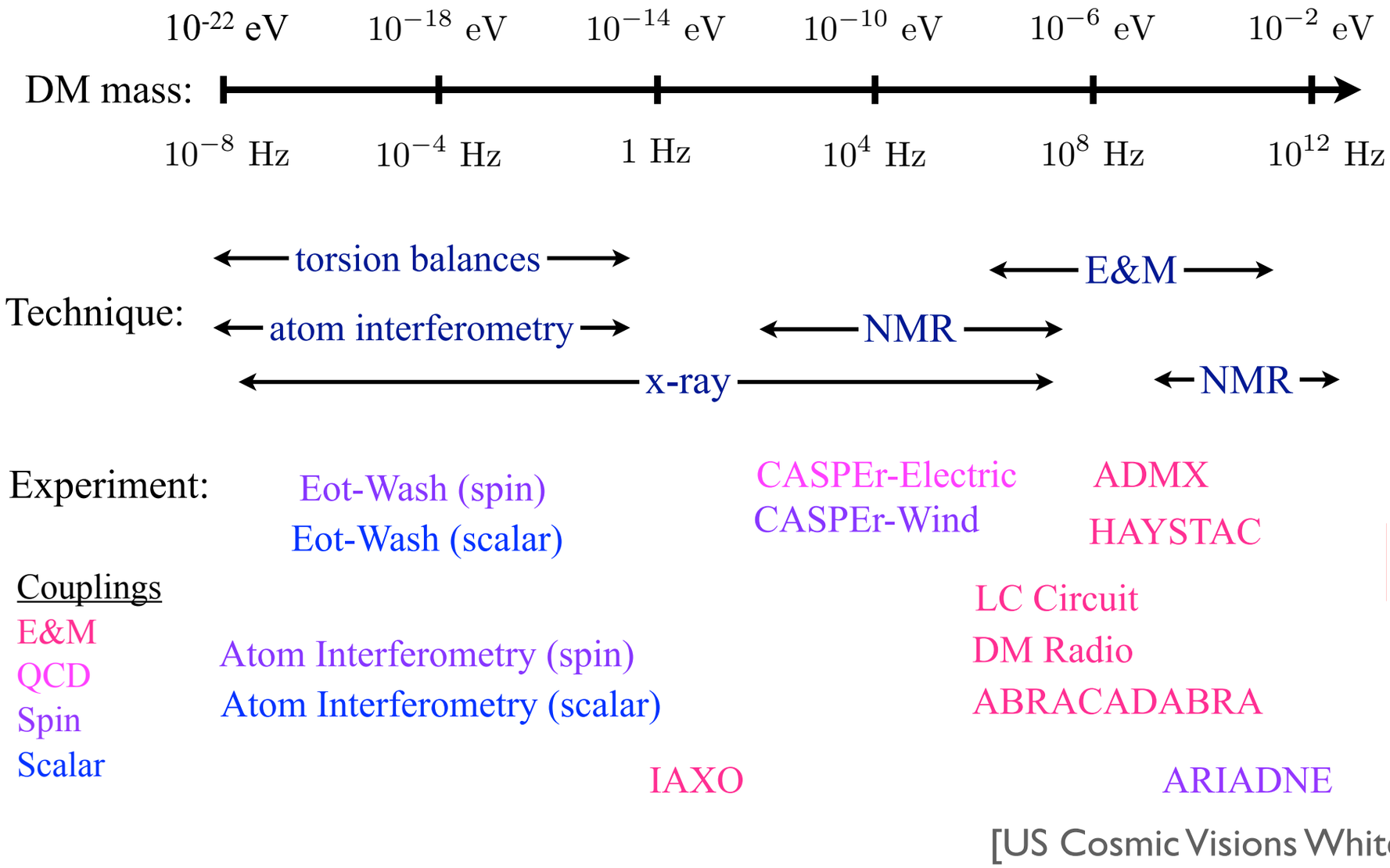
[Feng-US Cosmic Visions White papers]

Particle theories



sub-keV DM

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

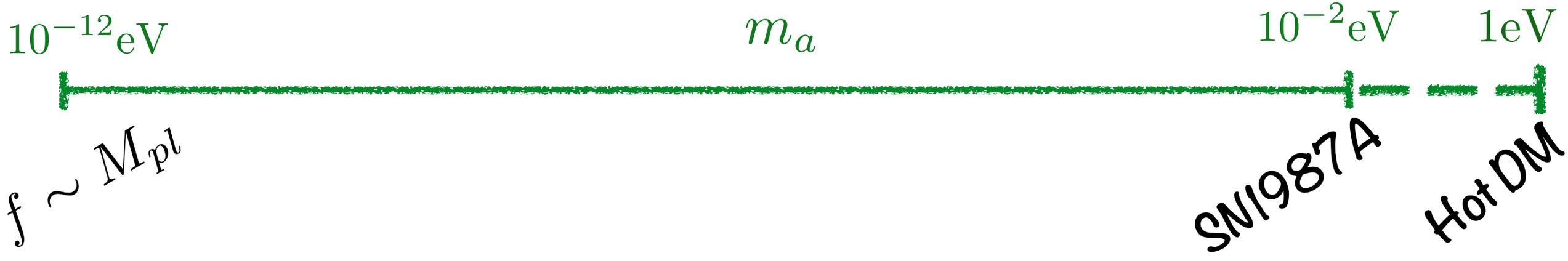


[US Cosmic Visions White papers]

QCD Axion

see talk by Semertzidis

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



PQ broken *after* inflation

Axion starts osc. 10^{-5}eV 1eV

too late, too much DM

PQ broken *before* inflation

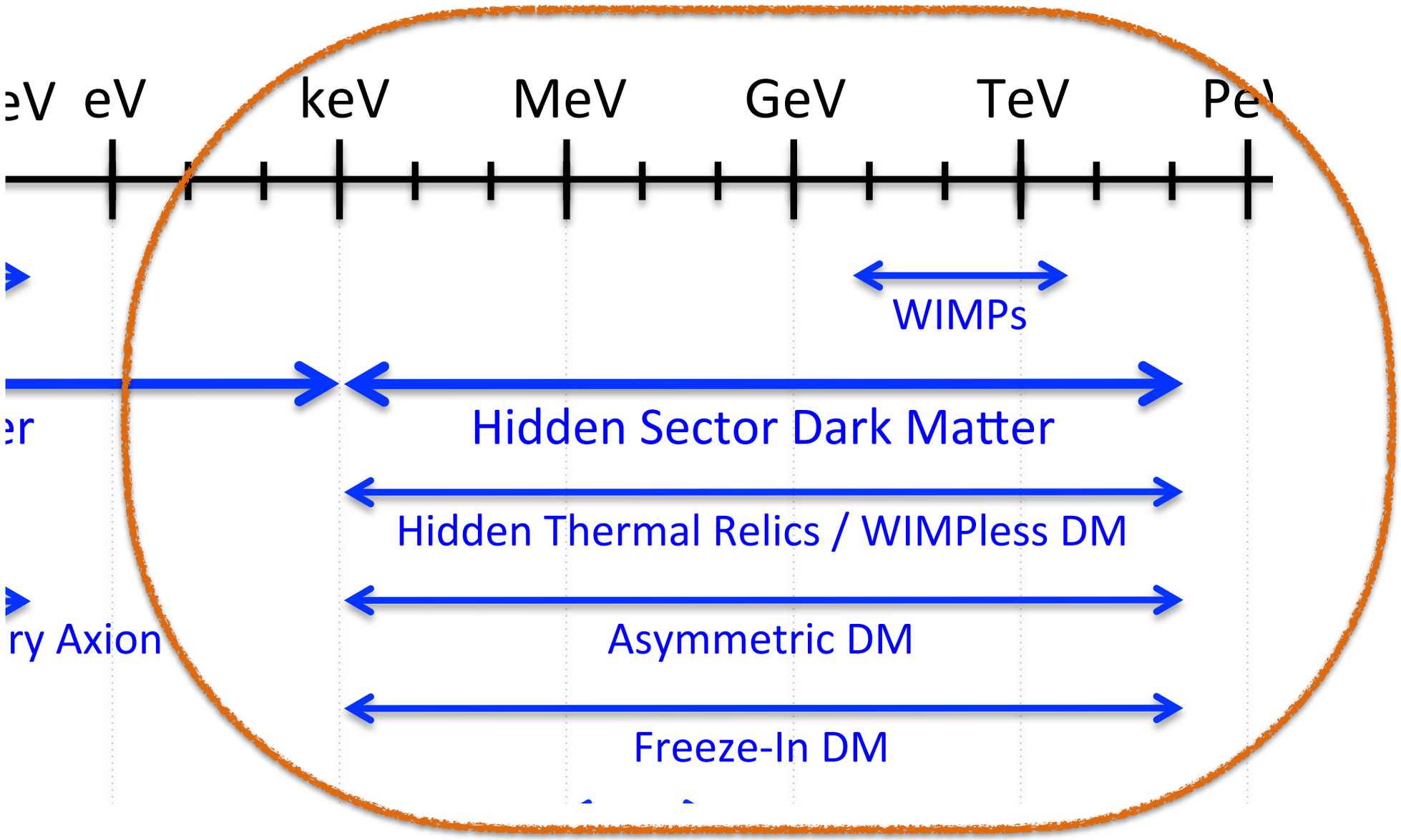
DM abundance requires small θ_{init} Anthropics?

Isocurvature modes $(H_I/f)^2$

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

connections to inflation

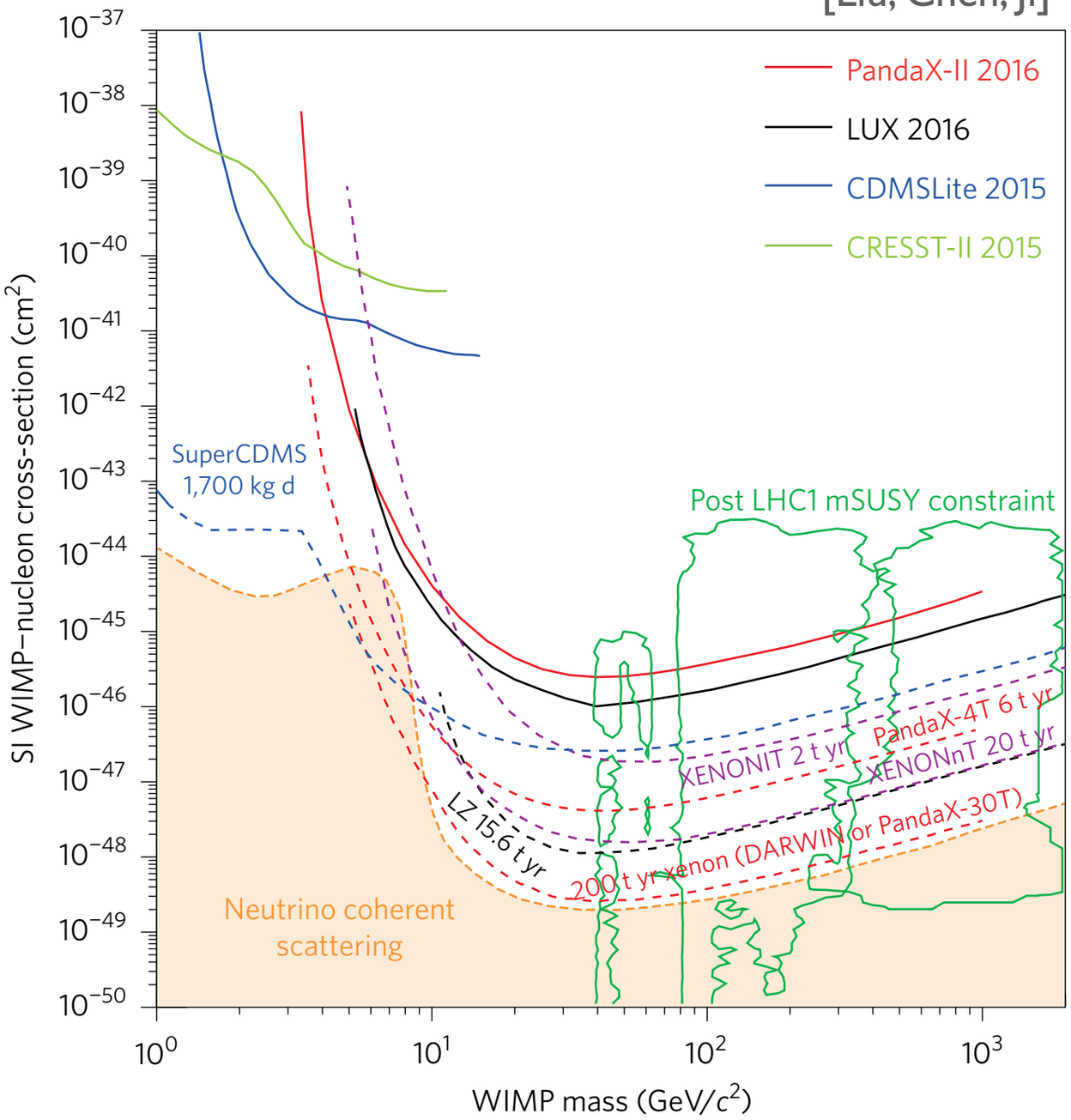
[PF, Pierce, Thomas]


eV
eV
keV
MeV
GeV
TeV
PeV
WIMPs
er
Hidden Sector Dark Matter
Hidden Thermal Relics / WIMPless DM
ry Axion
Asymmetric DM
Freeze-In DM

WIMP

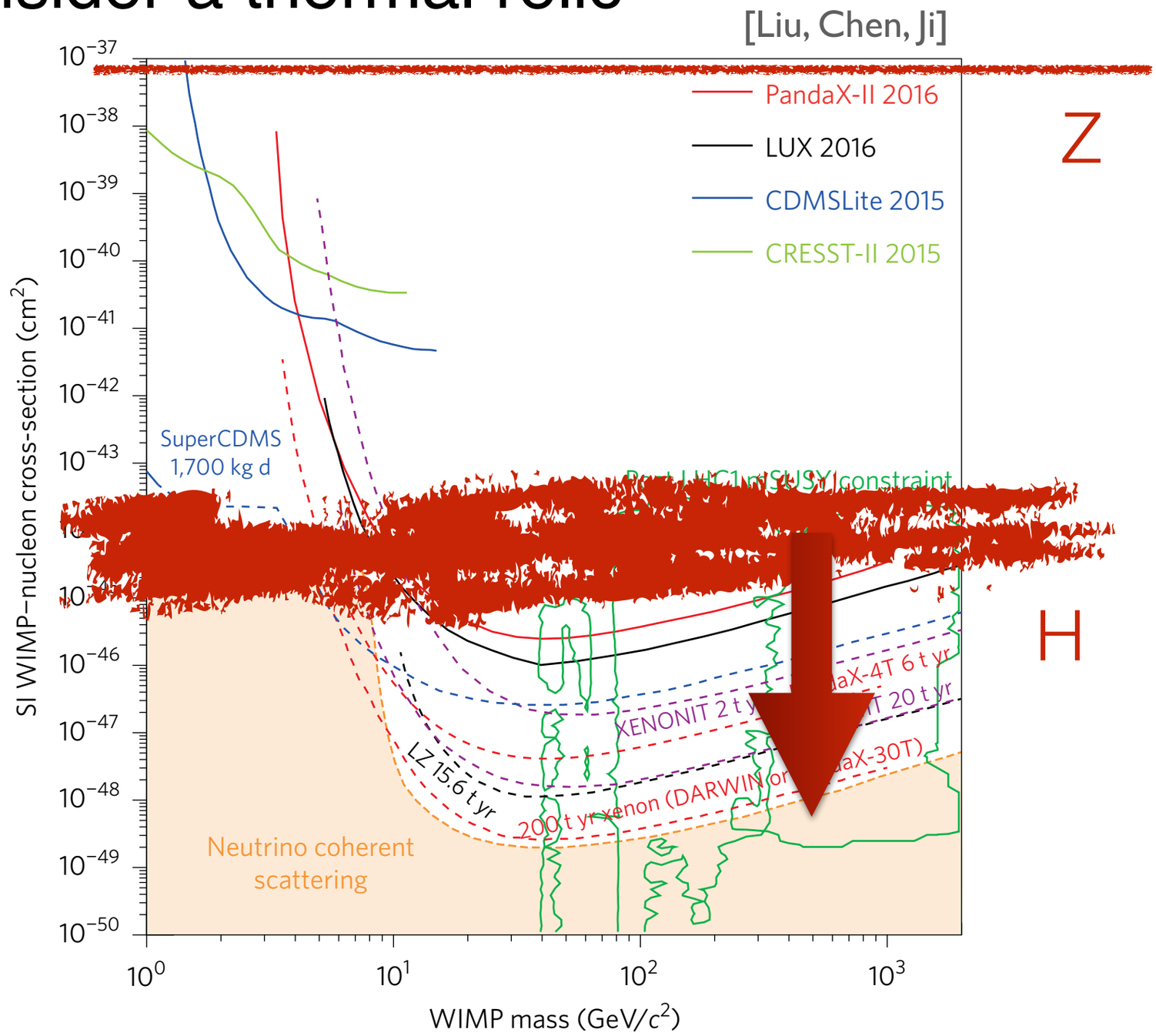
- DM interacts through weak (or weak scale) couplings
- Lee-Weinberg and Unitarity constrain mass range
  - ~1 GeV —~10 TeV
- Usually consider a thermal relic

[Liu, Chen, Ji]



WIMP

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

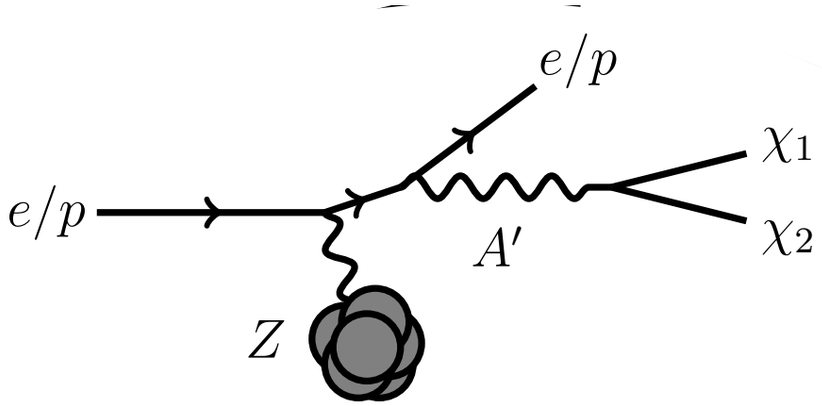
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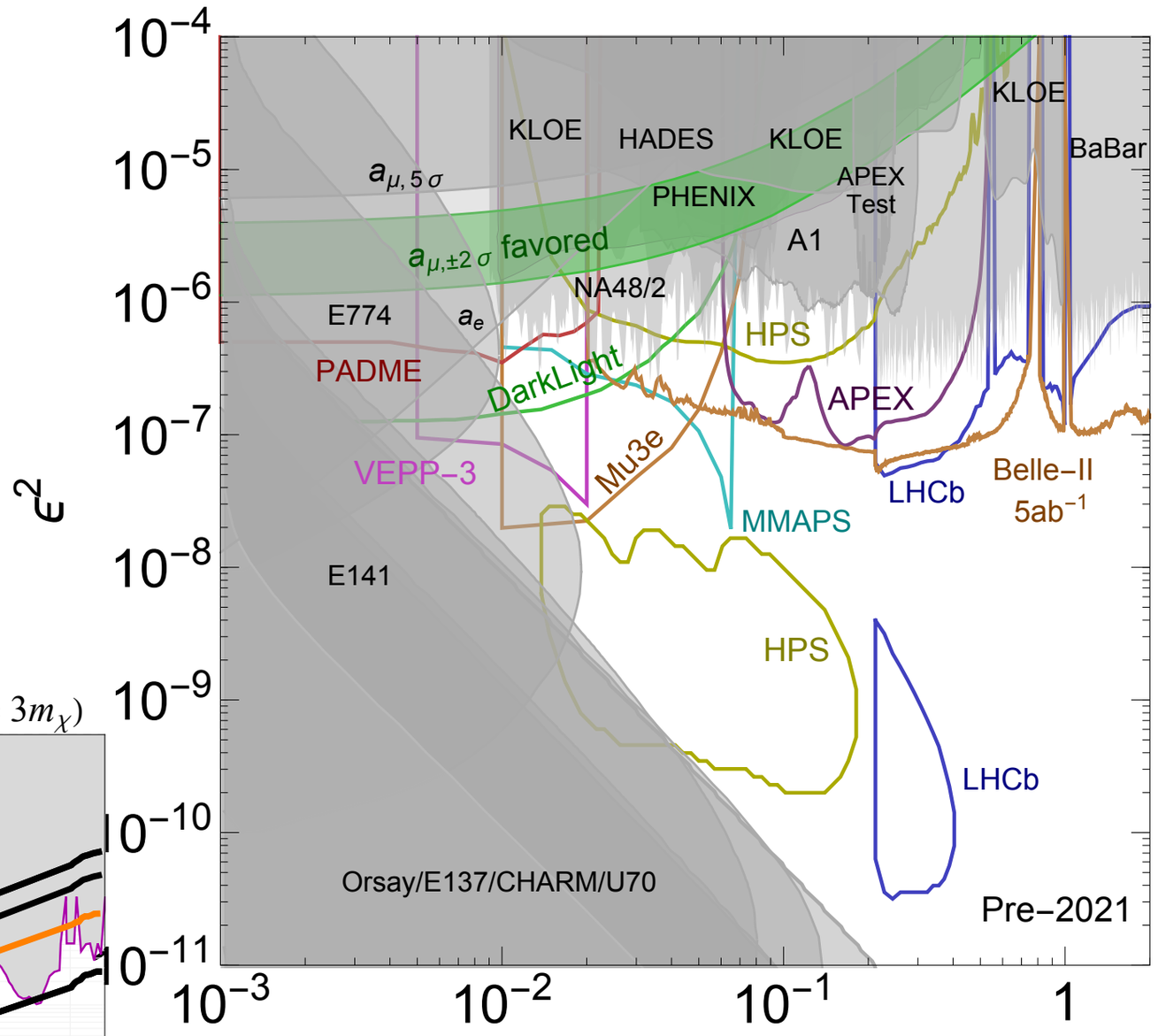
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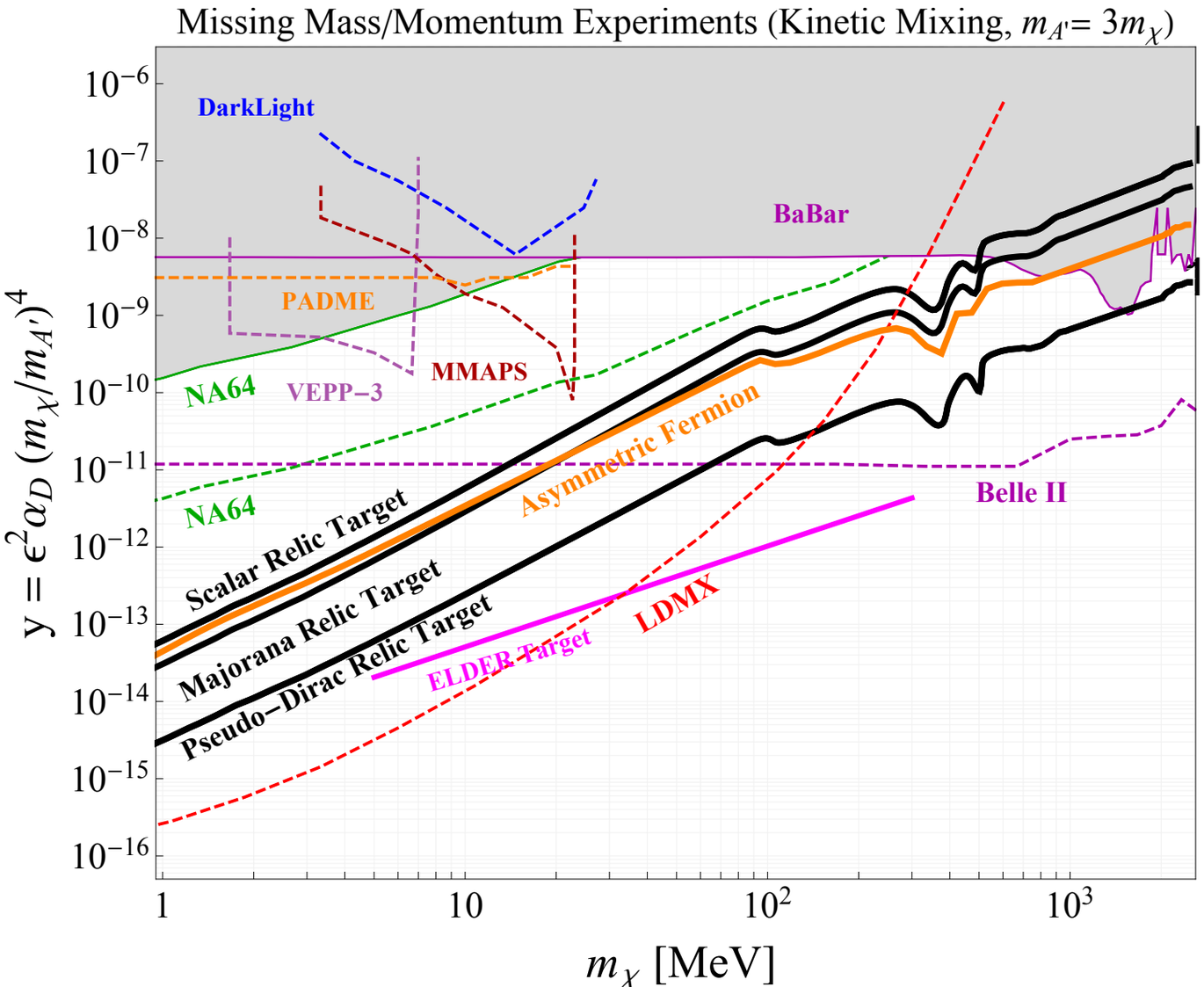
$$\frac{\epsilon}{16\pi^2} F'_{\mu\nu} B_Y^{\mu\nu}$$

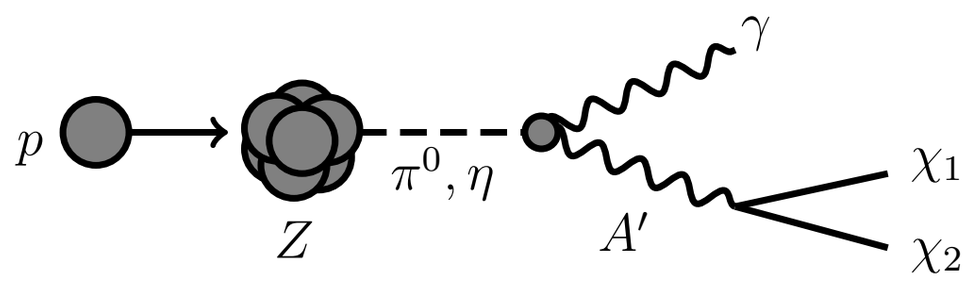
$$\phi|H|^2 + |\phi|^2|H|^2$$





[Dark Sectors WS]

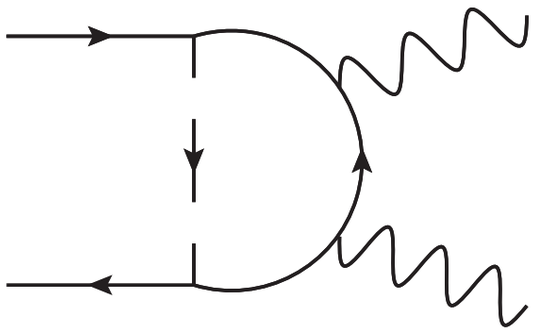


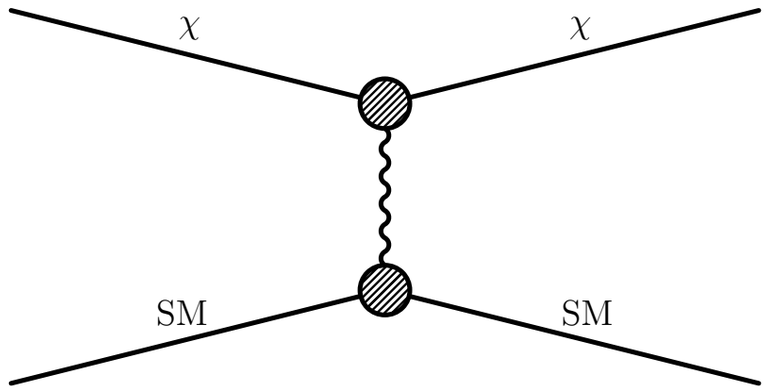


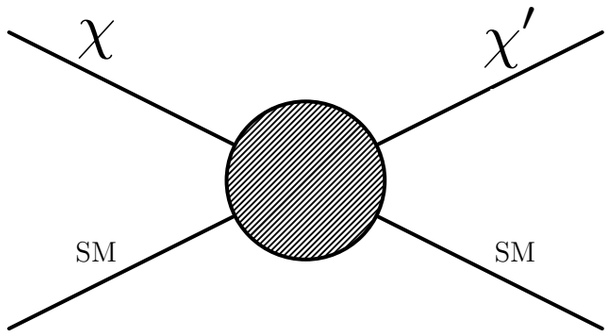
Hidden sector DM—interesting dynamics

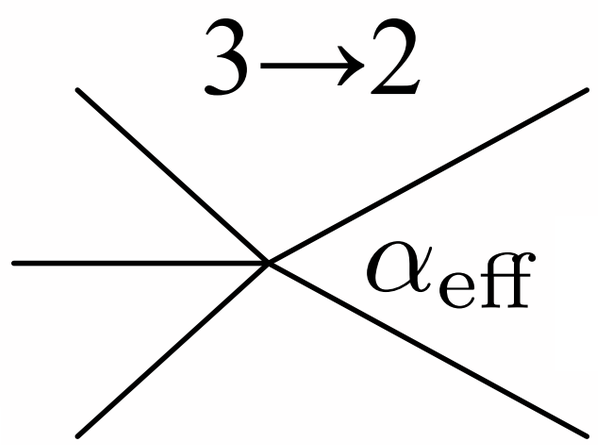
Hidden sector dynamics, new force carriers

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





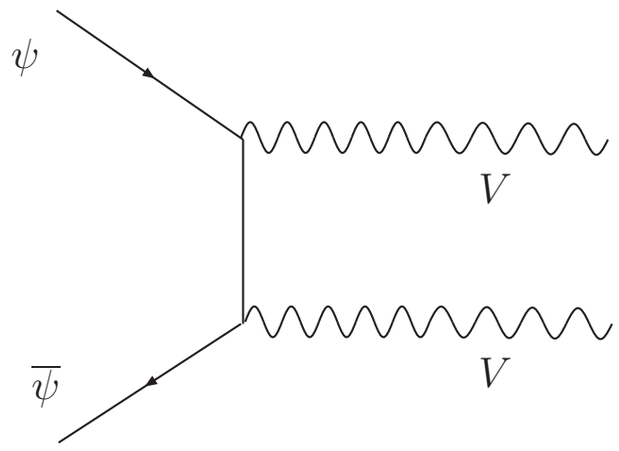




Hidden sector DM—thermal relics

[Pospelov, Ritz, Voloshin]

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



Decouples direct detection from thermal history

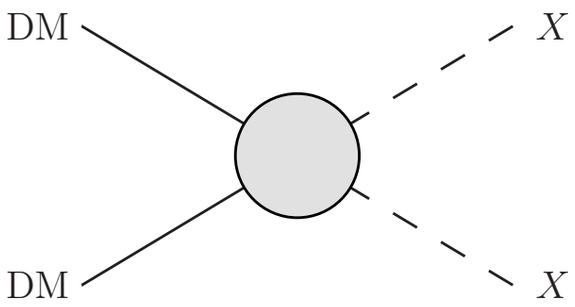
Light DM and CMB

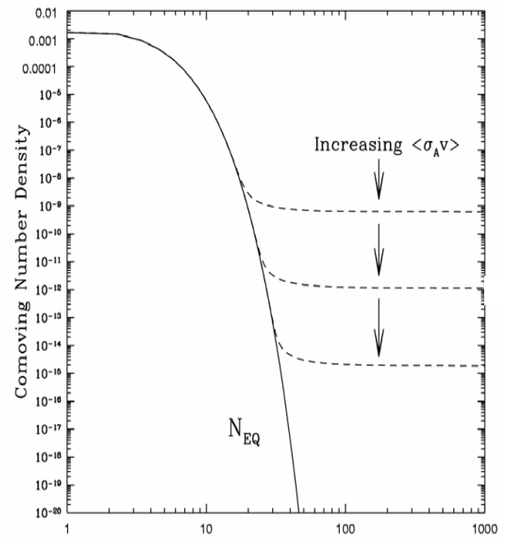
$$p_{CMB} = f_{off}\frac{\langle\sigma v\rangle_{T\sim eV}}{m_\chi} < 3.5\times 10^{-11}\mathrm{GeV}^{-3}$$

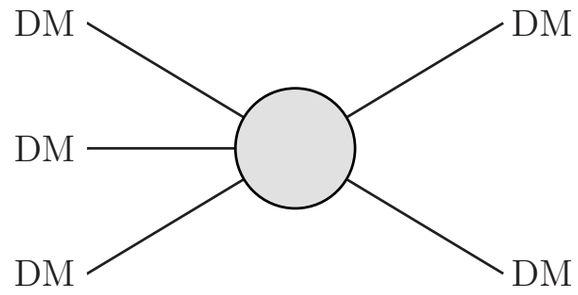
P-wave (Majorana fermions), asymmetric, co-annihilation w/ suppressed species

Hidden sector DM—thermal relics

Leads to interesting changes in cosmology

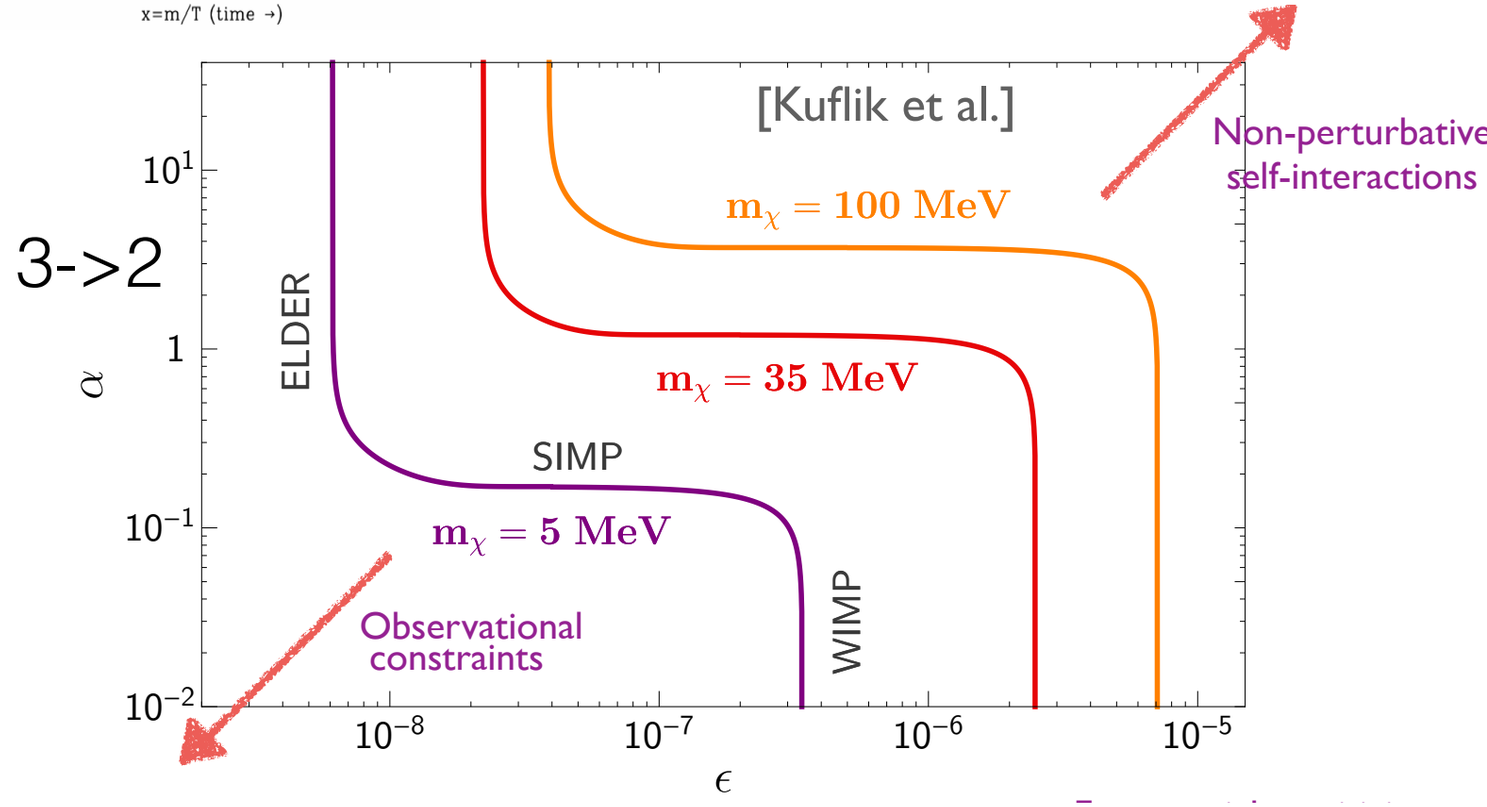






cannibalization

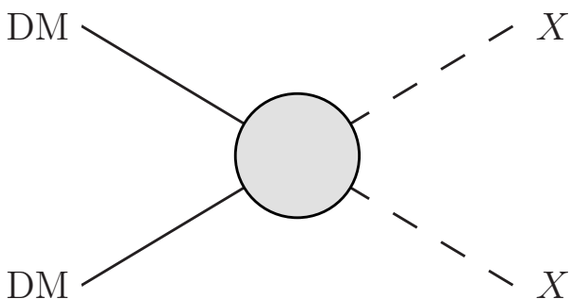
WIMPless-miracle
(1-100 MeV scale)
SIMP-miracle
ELDER…
all smoothly connected
in parameter space

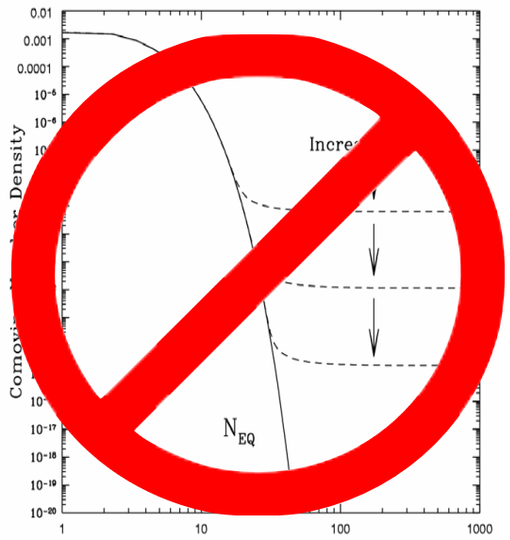


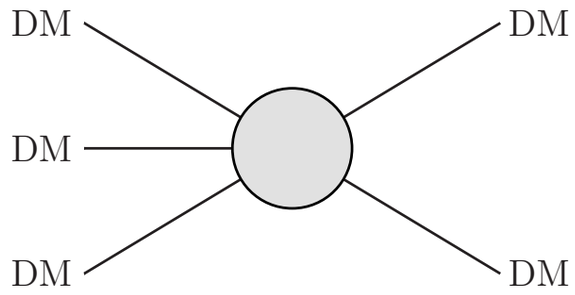
DM-SM elastic scatter

Hidden sector DM—thermal relics

Leads to interesting changes in cosmology

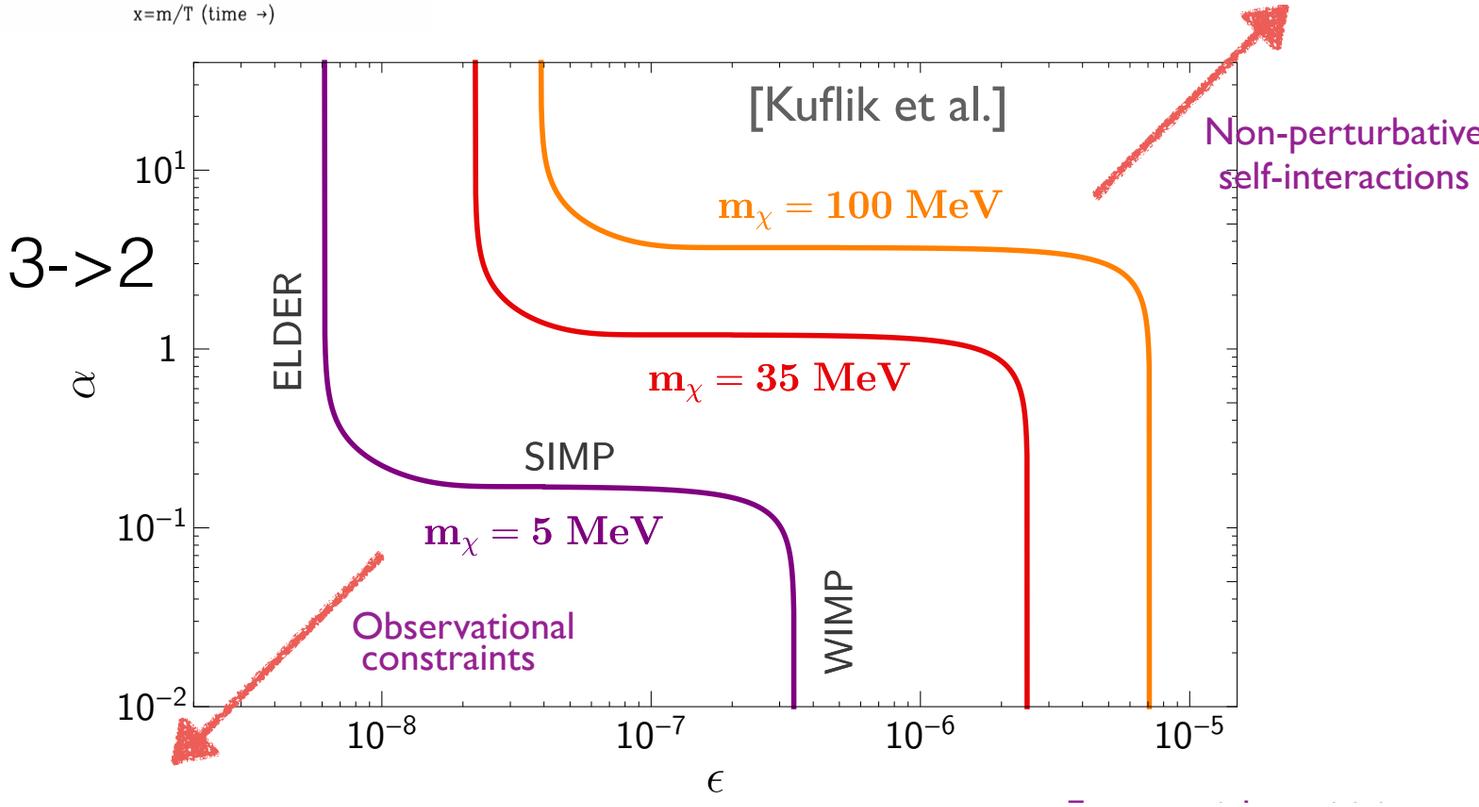




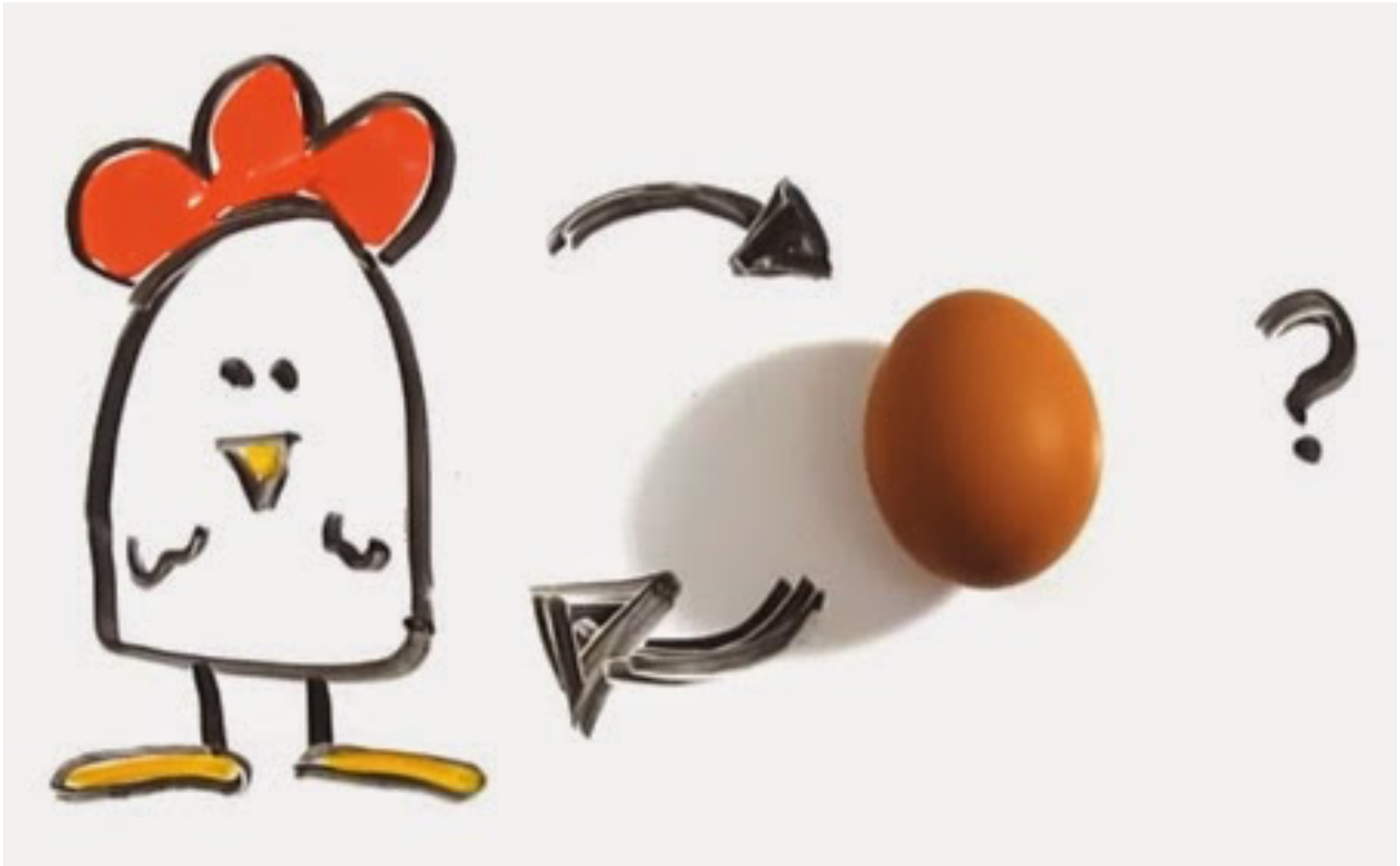


cannibalization

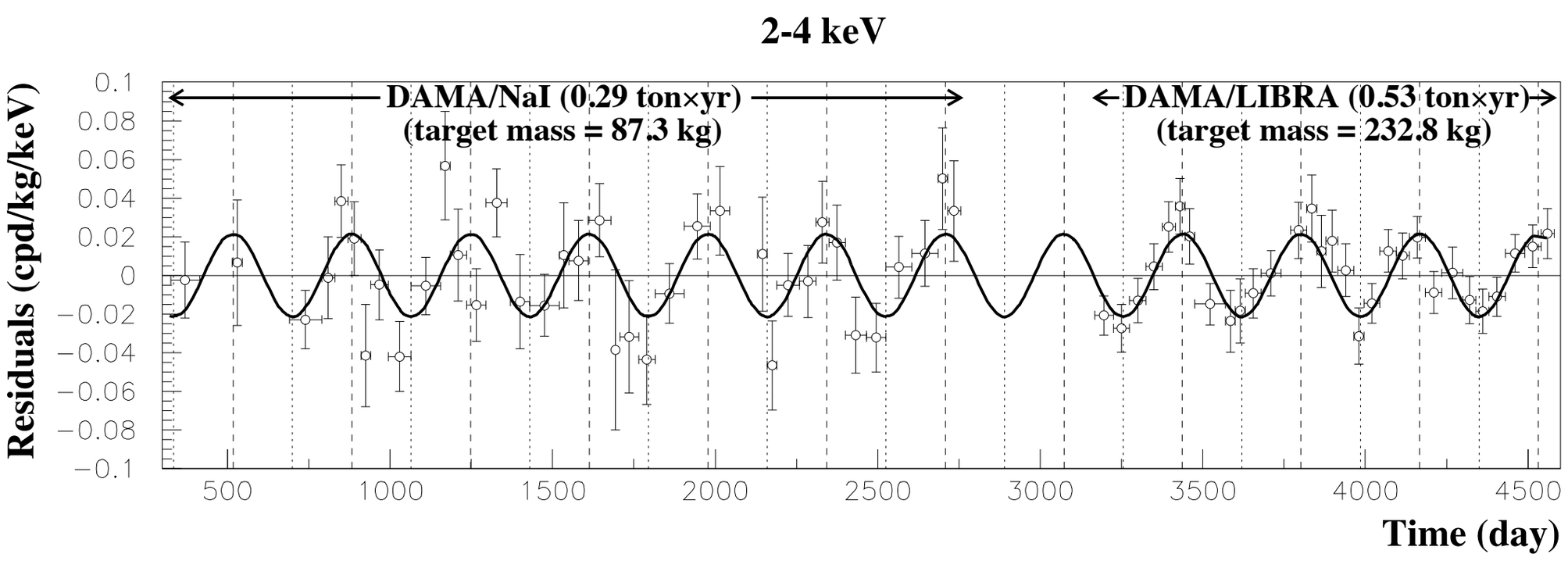
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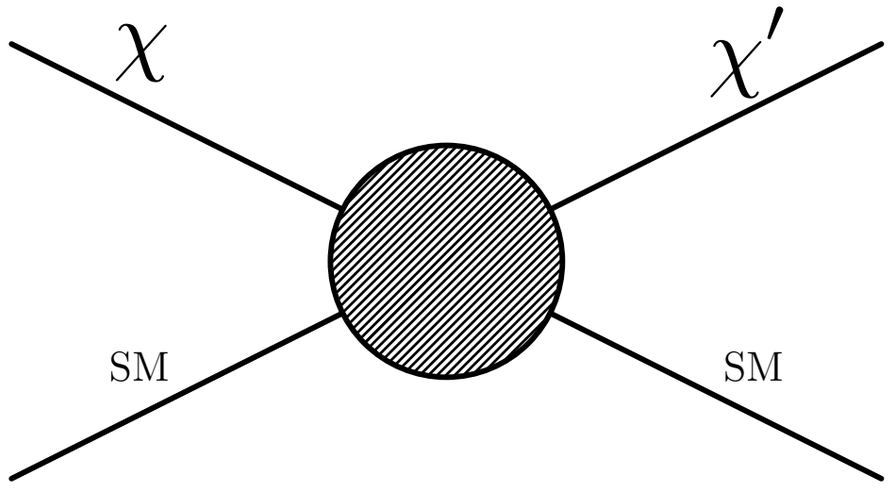



POLICE BOX
POLICE BOX


2-4 keV
DAMA/NaI (0.29 ton×yr)
(target mass = 87.3 kg)
DAMA/LIBRA (0.53 ton×yr)
(target mass = 232.8 kg)
Residuals (cpd/kg/keV)
0.1
0.08
0.06
0.04
0.02
0
−0.02
−0.04
−0.06
−0.08
−0.1
500
1000
1500
2000
2500
3000
3500
4000
4500
Time (day)

Inelastic Dark Matter (iDM)

[Weiner and Tucker-Smith]



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

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

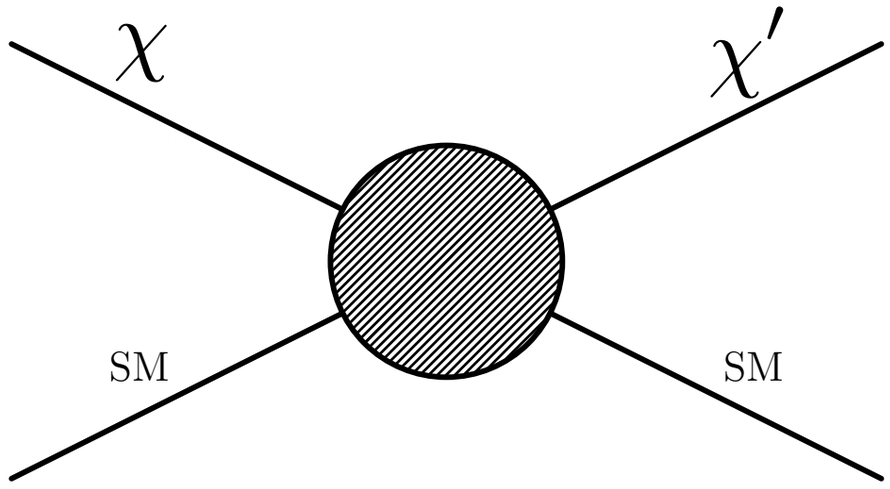
$$m_\chi - m_{\chi'} = \delta \sim 100\,\mathrm{keV}$$

- Requires "large" momentum exchange to upscatter
- Favours high velocity tail of MB distribution
- Increased modulation
- Prefers heavy targets e.g. iodine, xenon, tungsten,..
- Recoil spectrum has a peak

All of the above helped to make DAMA consistent with CDMS, *predicts events at other heavy element detectors*

Inelastic Dark Matter (iDM)

[Weiner and Tucker-Smith]



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

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

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

- Requires "large" momentum exchange to upscatter
- Favours high velocity tail of MB distribution
- Increased modulation
- Prefers heavy targets e.g. iodine, xenon, tungsten,..
- Recoil spectrum has a peak

All of the above helped to make DAMA consistent with CDMS, *predicts events at other heavy element detectors*

iDM—example model

Dirac fermion coupled to vector, with small Majorana masses

$$V_\mu \left(\chi_1^\dagger \bar{\sigma}^\mu \chi_1 - \chi_2^\dagger \bar{\sigma}^\mu \chi_2\right) + m_D \left(\chi_1 \chi_2 + \text{h.c.}\right)$$

$$+\delta_1 \left(\chi_1 \chi_1 + \text{h.c.}\right) + \delta_2 \left(\chi_2 \chi_2 + \text{h.c.}\right)$$

Mass eigenstates only have off-diagonal couplings

e.g. (almost) pure Higgsinos

$$\delta_{\tilde{\text{H}}} \simeq m_Z^2 \left(\frac{\sin^2\theta_W}{M_1} + \frac{\cos^2\theta_W}{M_2}\right) + \mathcal{O}\left(\frac{1}{M_{1,2}^2}\right)$$

DM couples to the Z (a WIMP!)

$$\sigma_{\text{n}}^{\tilde{H}} \sim \frac{\pi\, m_n^2\, \alpha_W^2}{8\, m_W^4} \times (\text{velocity factor}) \sim 10^{-39}\ \text{cm}^2 \times (\text{velocity factor})$$

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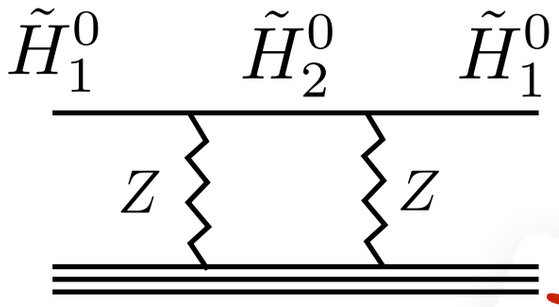
$$\delta_{\tilde{\text{H}}} \simeq m_Z^2 \left(\frac{\sin^2\theta_W}{M_1} + \frac{\cos^2\theta_W}{M_2}\right) + \mathcal{O}\left(\frac{1}{M_{1,2}^2}\right) = \begin{cases} 192\,\text{keV}\left(\frac{10^7\,\text{GeV}}{M_1}\right) & M_2 \gg M_1 \gg \mu \\ 640\,\text{keV}\left(\frac{10^7\,\text{GeV}}{M_2}\right) & M_1 \gg M_2 \gg \mu \end{cases}$$

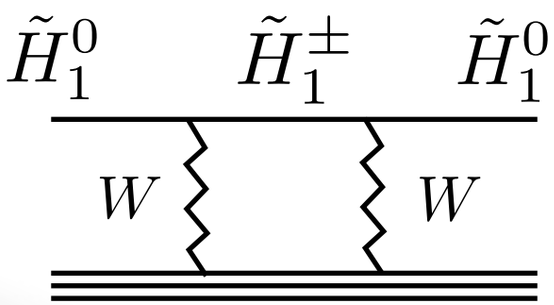
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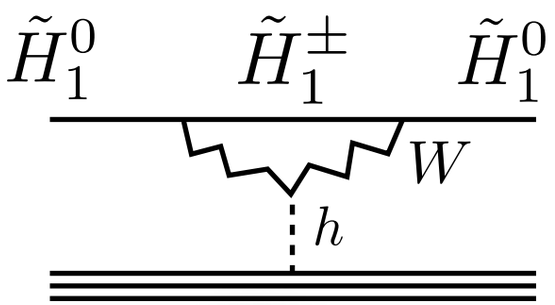
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iDM—loop level elastic rate

[Hisano et al.; Hill and Solon]





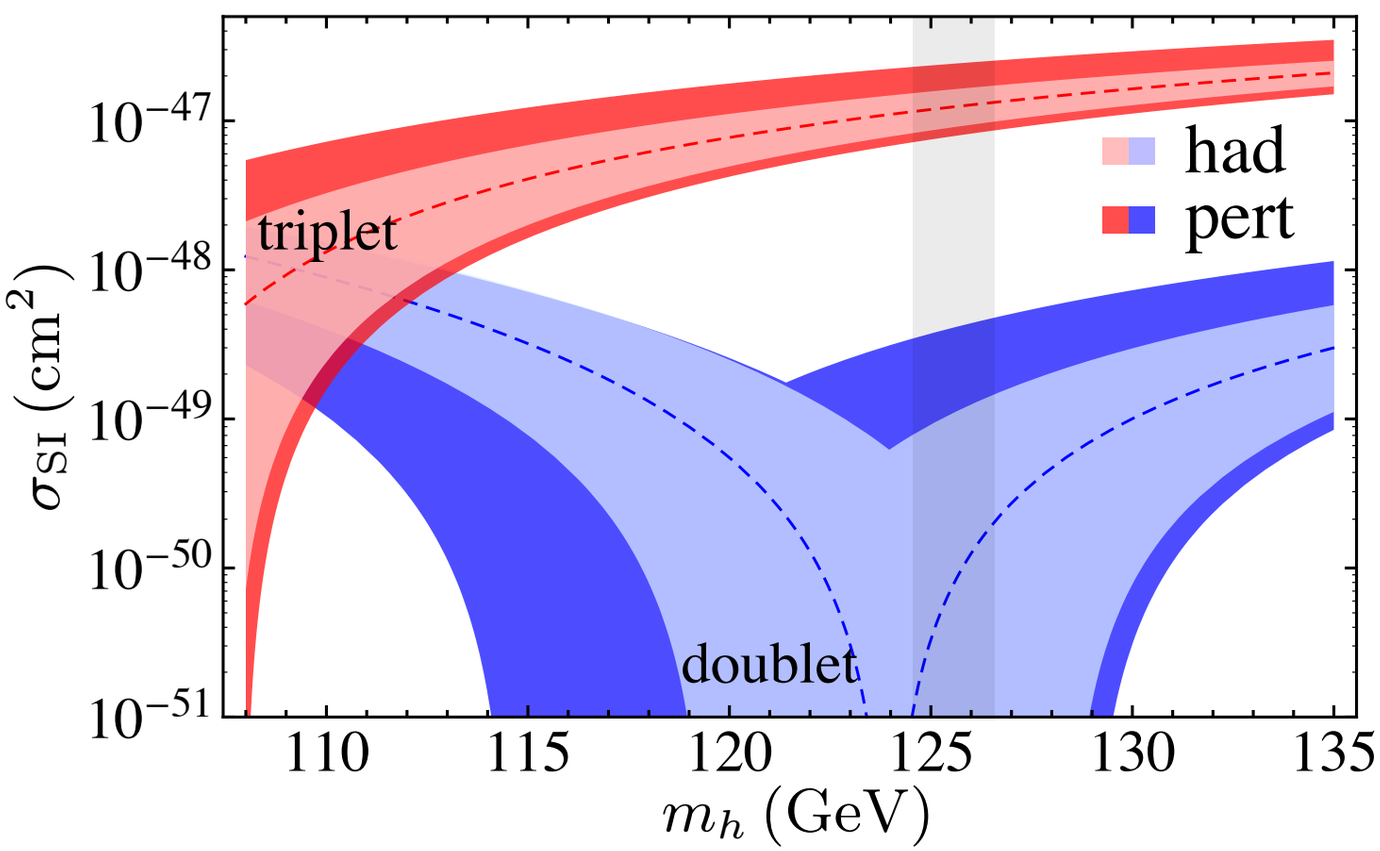


Twist-2

Twist-0

$$\sigma^{\tilde{H}}_{\rm n,loop} \sim \frac{m_n^4 \alpha_W^4}{\pi\, m_W^6} f_q^2 \sim 10^{-47}\ {\rm cm}^2$$

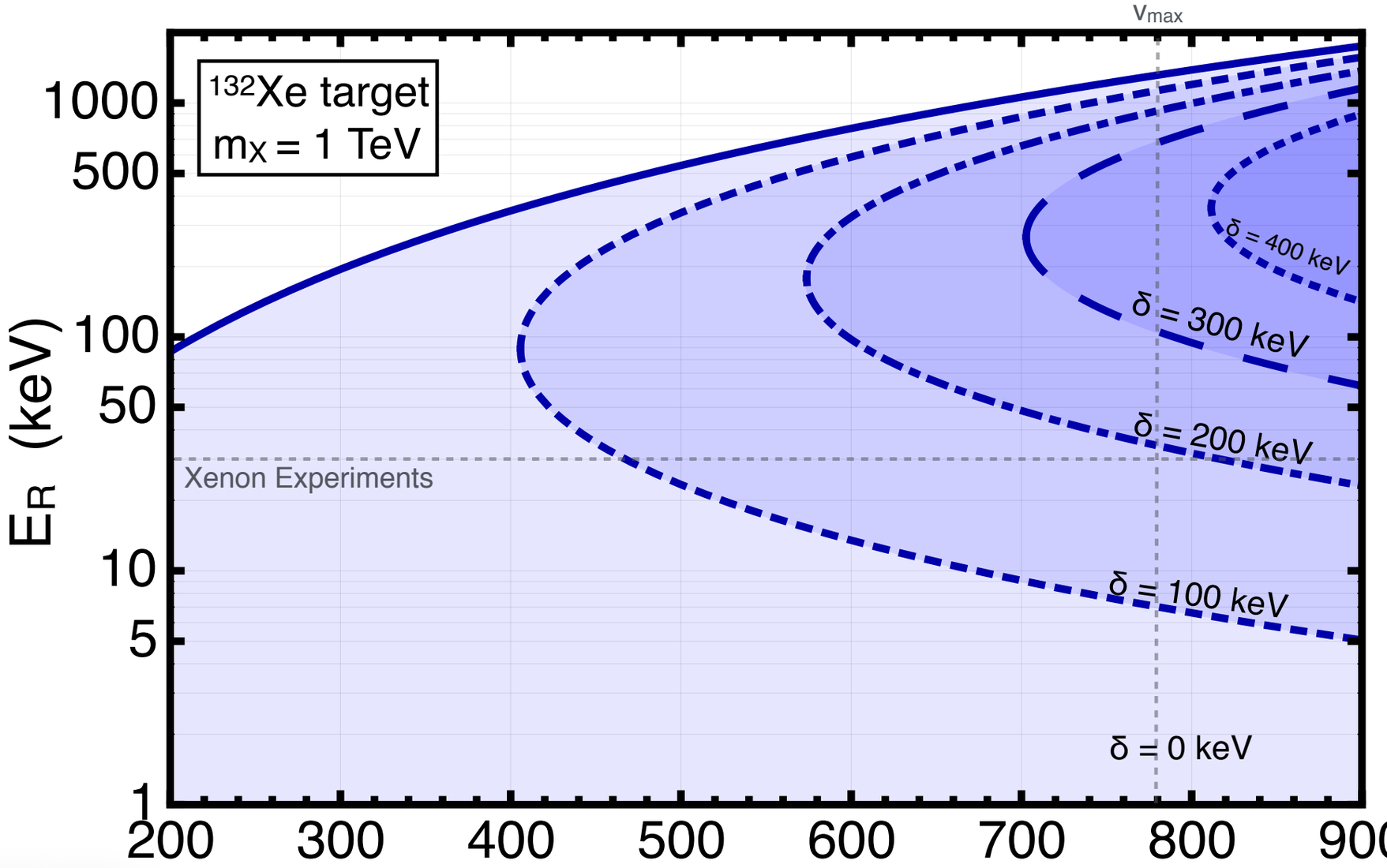
[Hill and Solon]

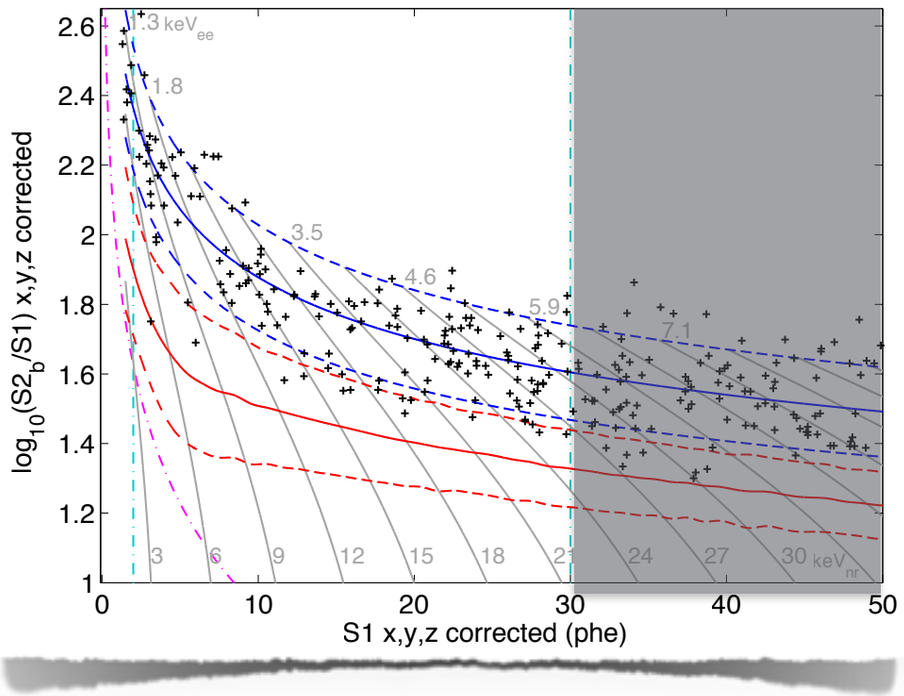


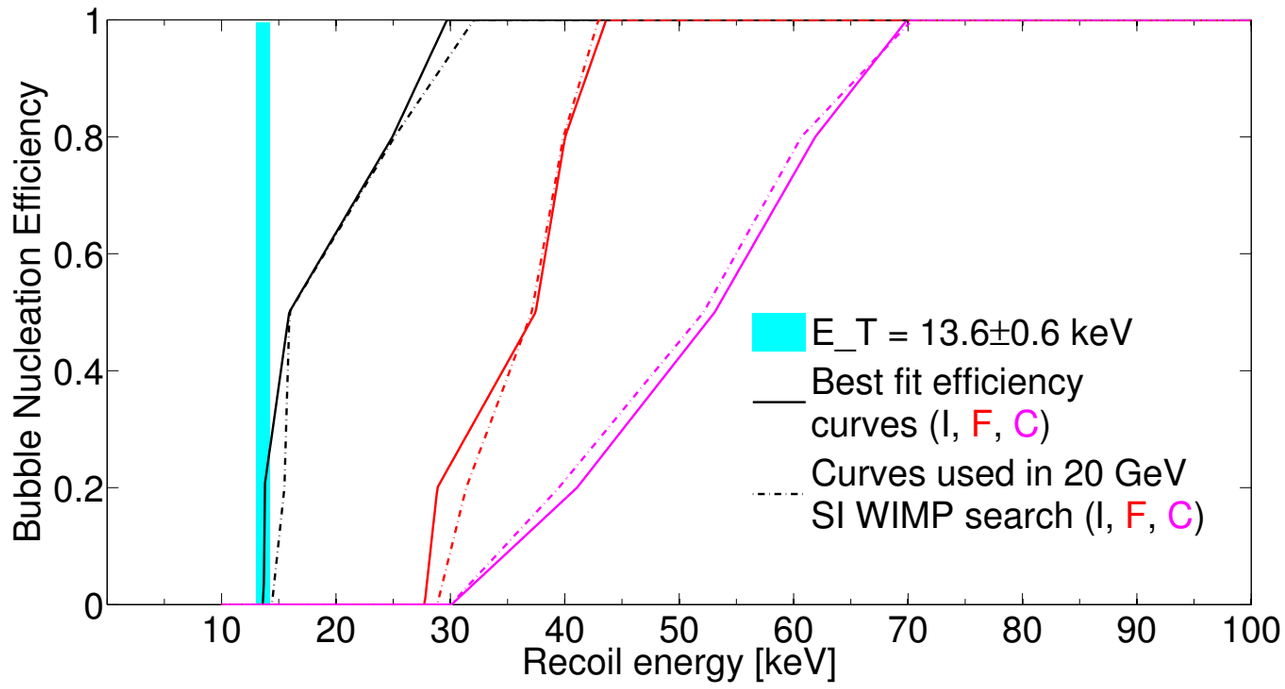
$$\sigma^{\tilde{H}}_{\rm n,loop} \lesssim 10^{-48}\ {\rm cm}^2$$

accidental cancellation

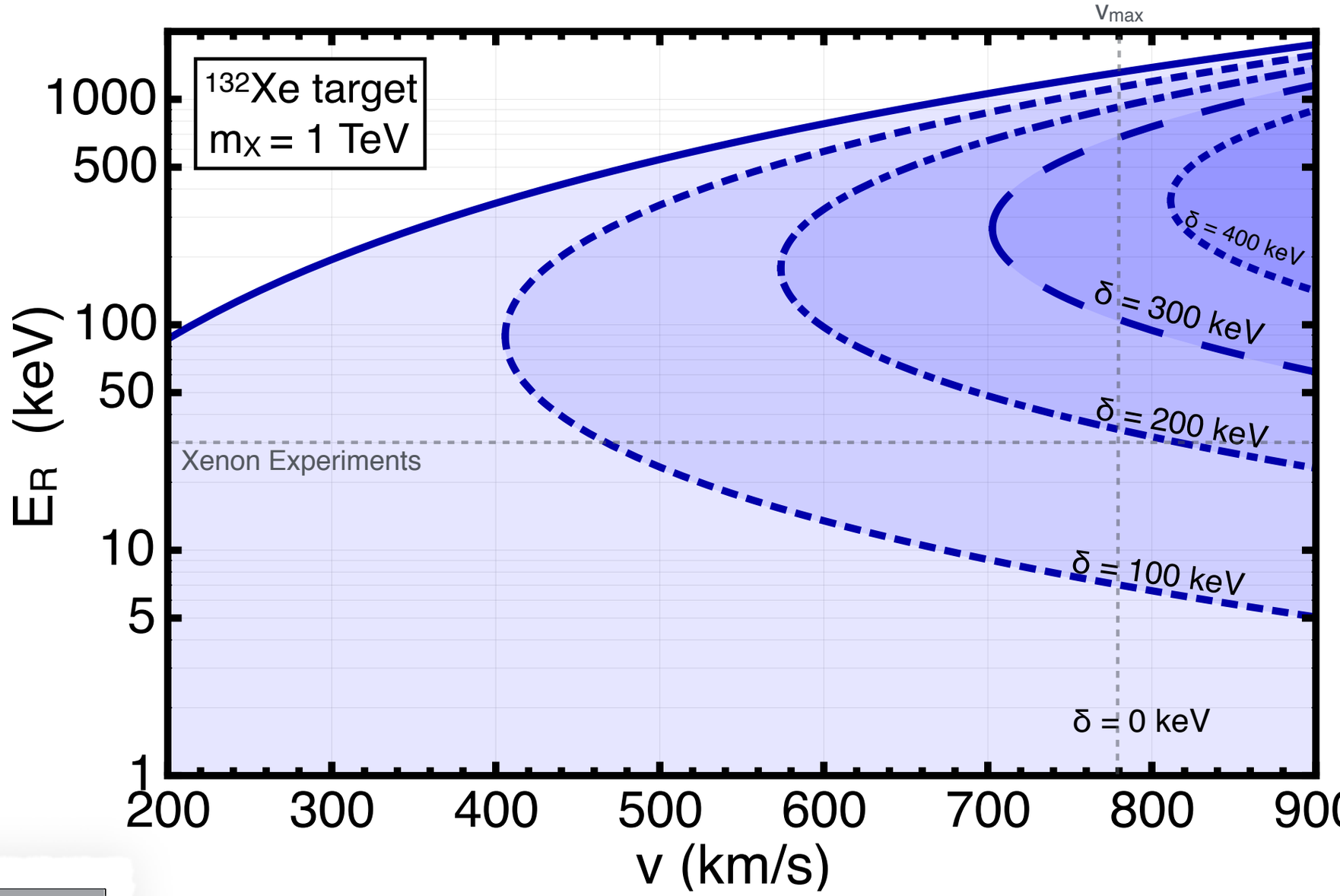
LUX(and others) “blind” to iDM with splittings above ~200 keV

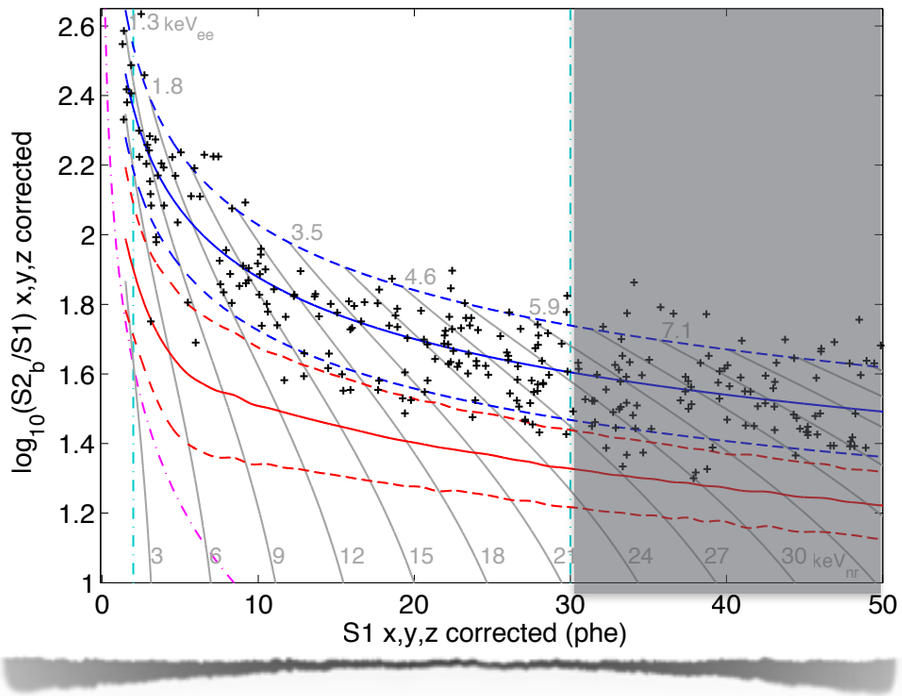


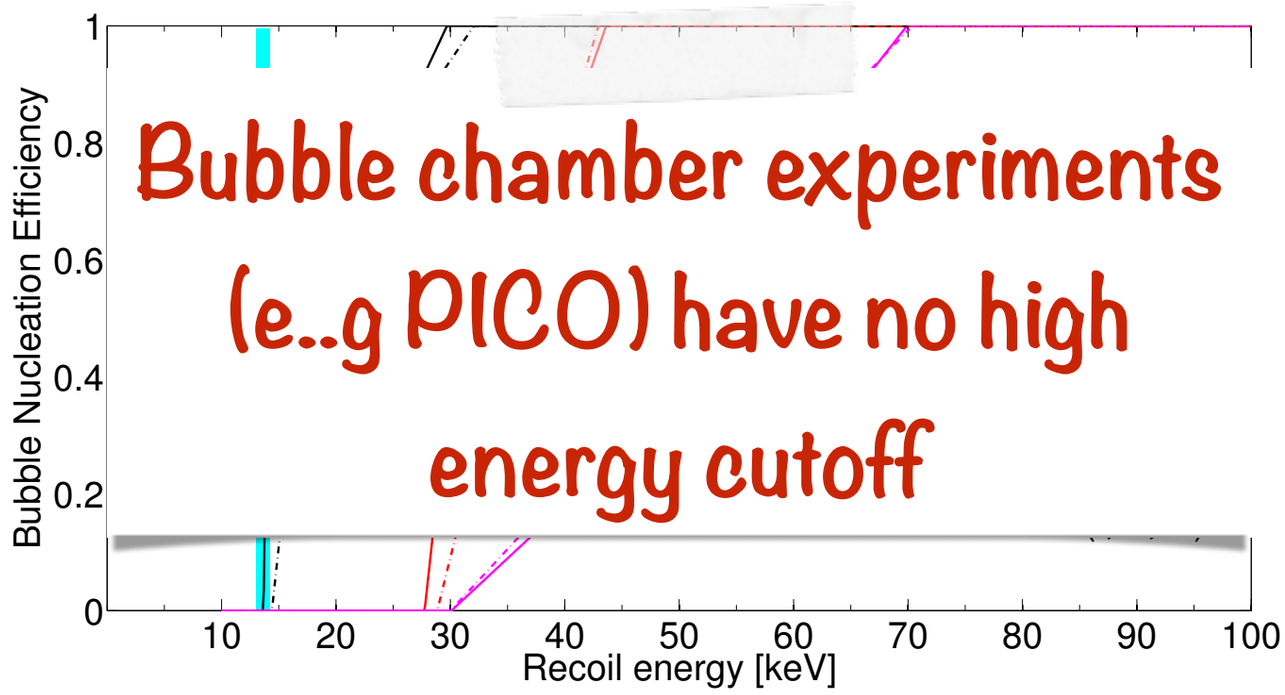




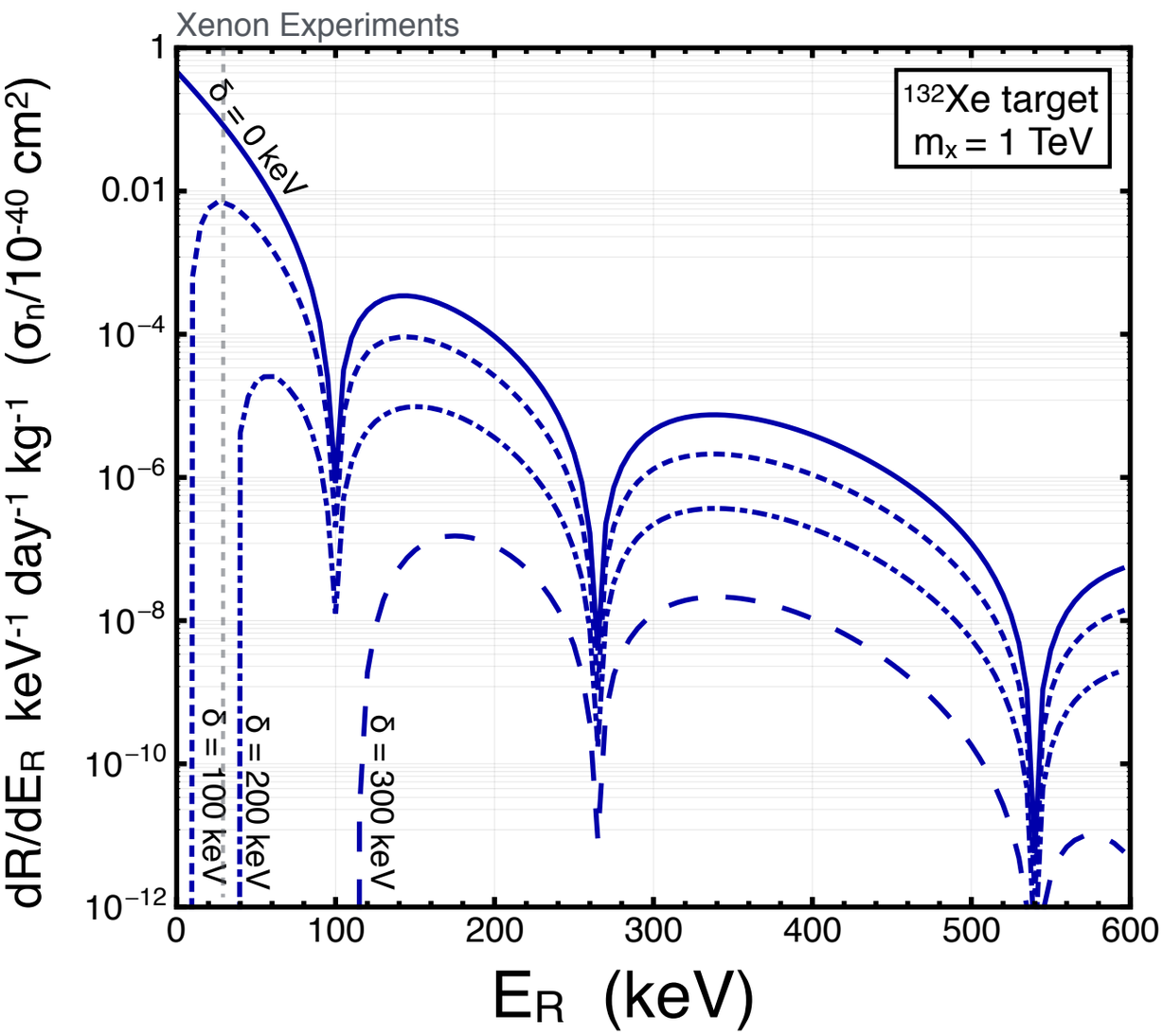
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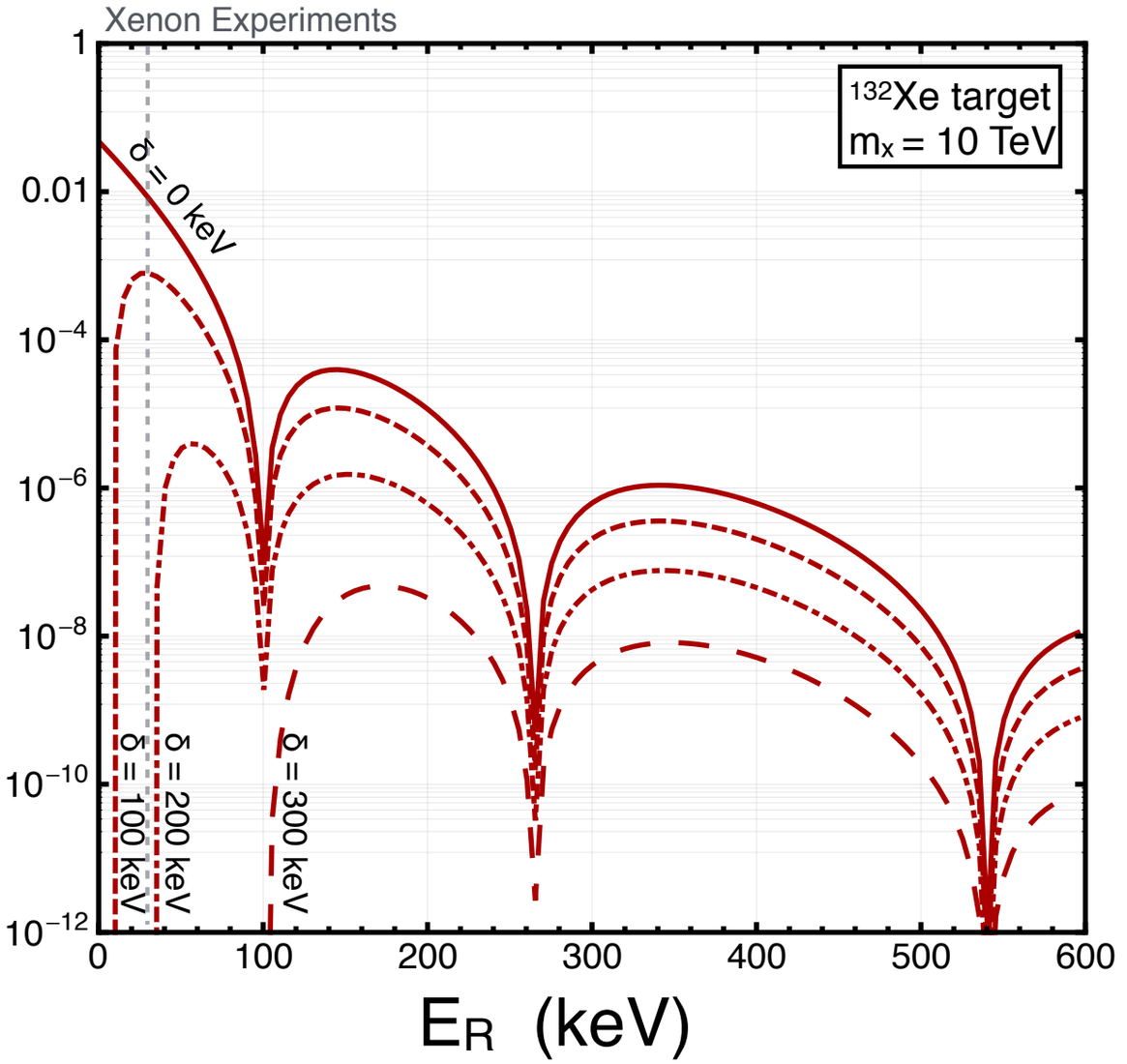






Bubble chamber experiments (e..g PICO) have no high energy cutoff





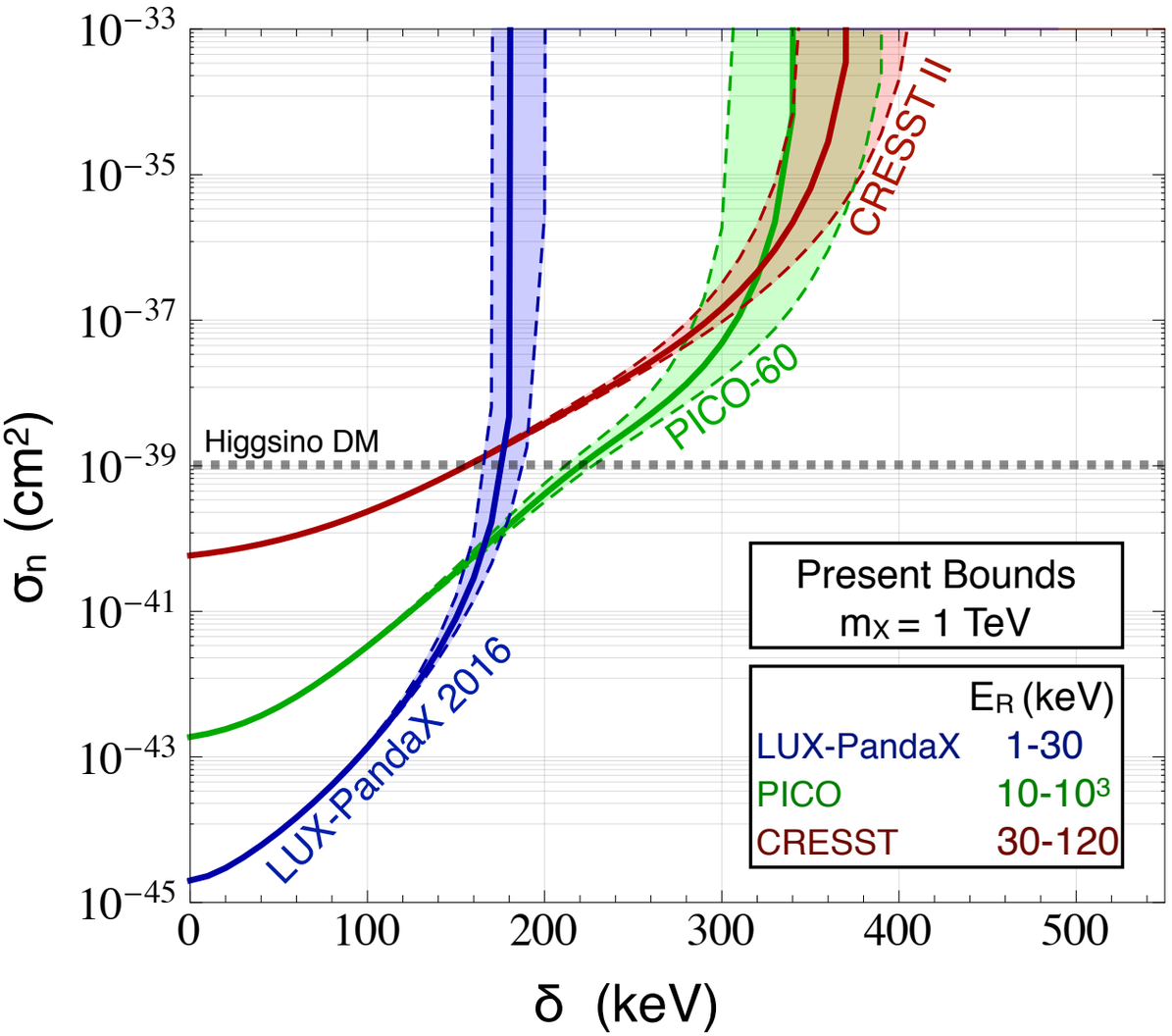
$$\frac{dR}{dE_{\rm R}} = n_X N_{\rm T} \int_{v_{\rm min}}^{v_{\rm max}} v\ f(\vec{v}, \vec{v}_{\rm e})\ \frac{d\sigma}{dE_{\rm R}}\ d^3v$$

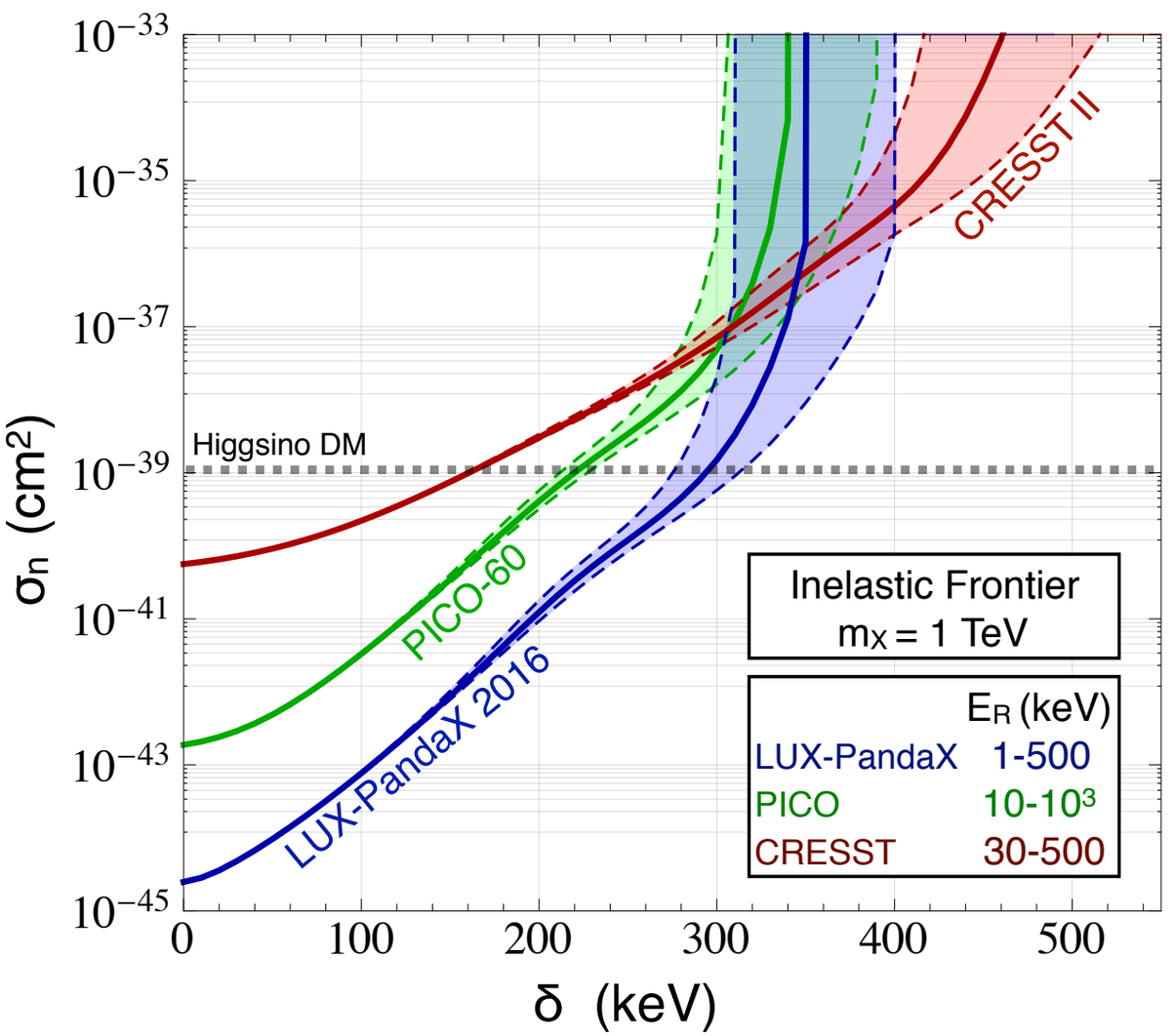
$$\frac{d\sigma}{dE_{\rm R}} = \frac{\sigma_{\rm n}}{v^2} \frac{m_{\rm N}}{2\mu_{\rm n}^2} \frac{\left[Z f_p + (A-Z) f_n\right]^2}{f_n^2} F^2(E_{\rm R})$$

The Inelastic Frontier

Analyze existing data out to 500 keV recoil energies, assume no new events above background

[Bramante, PJF, Kribs, Martin]

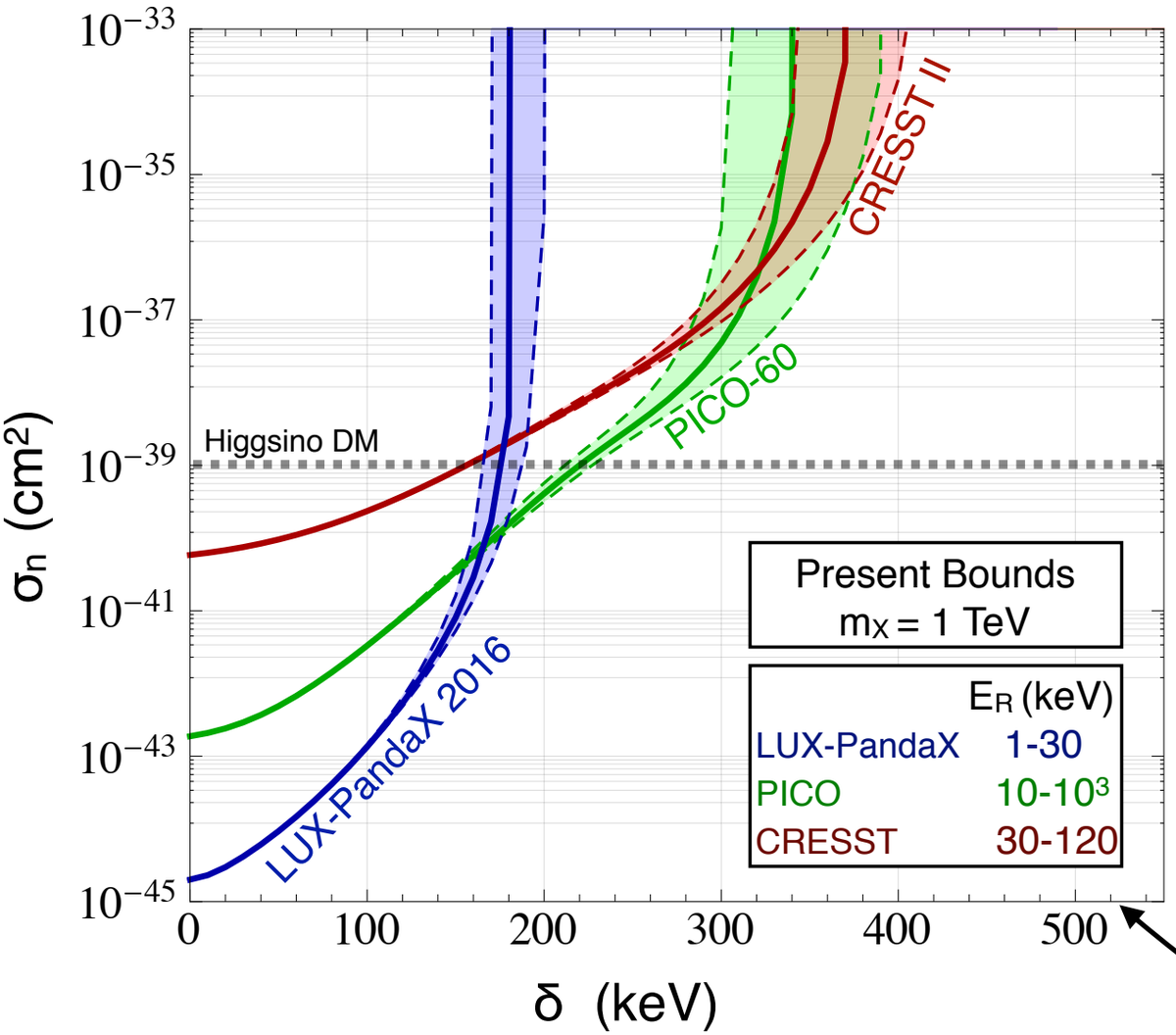


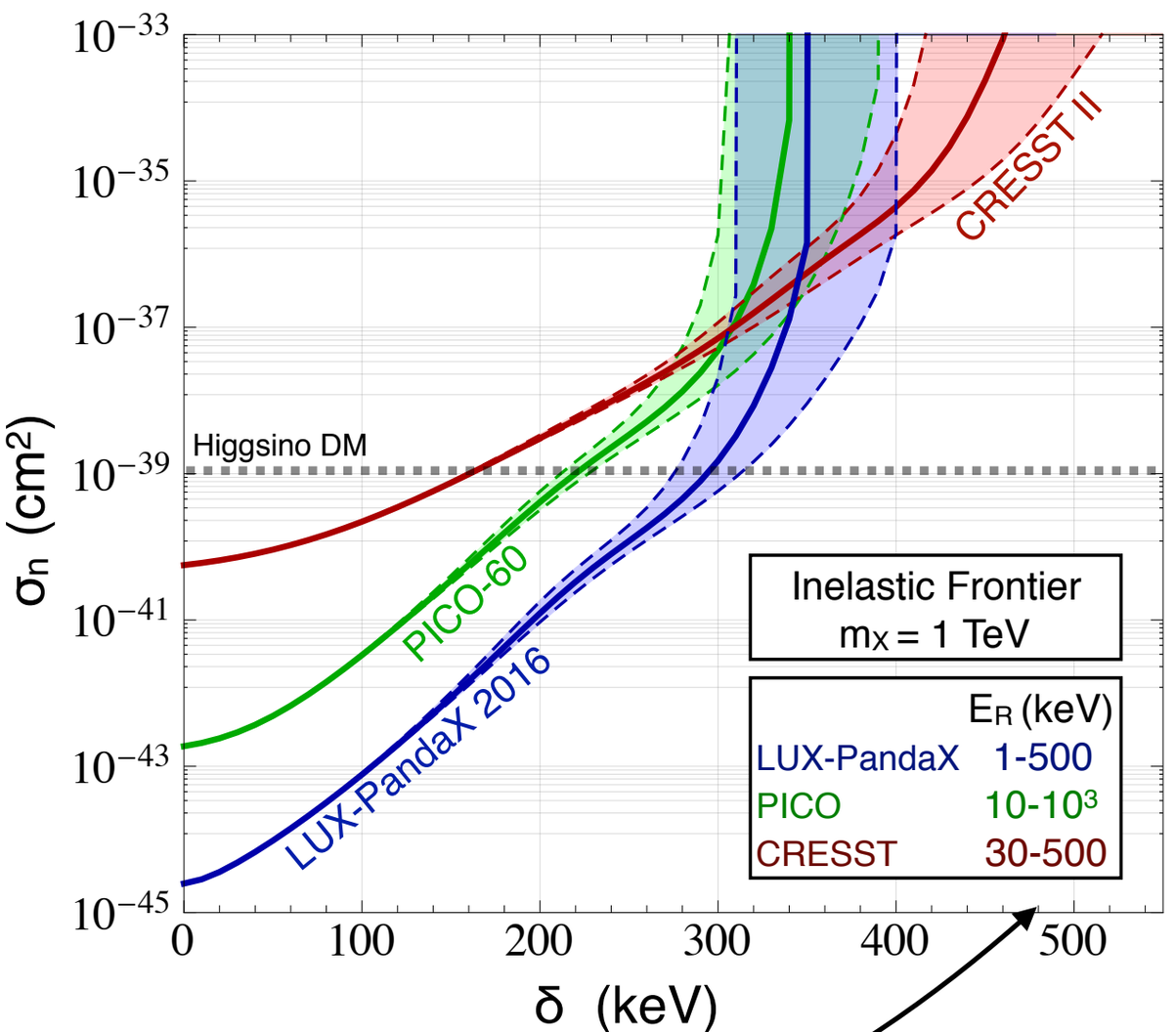


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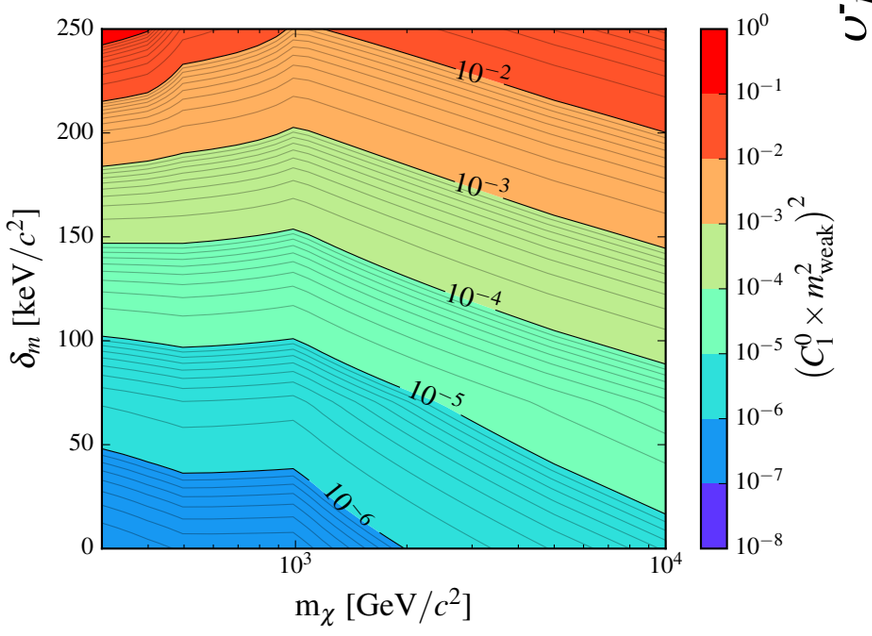
[Bramante, PJF, Kribs, Martin]

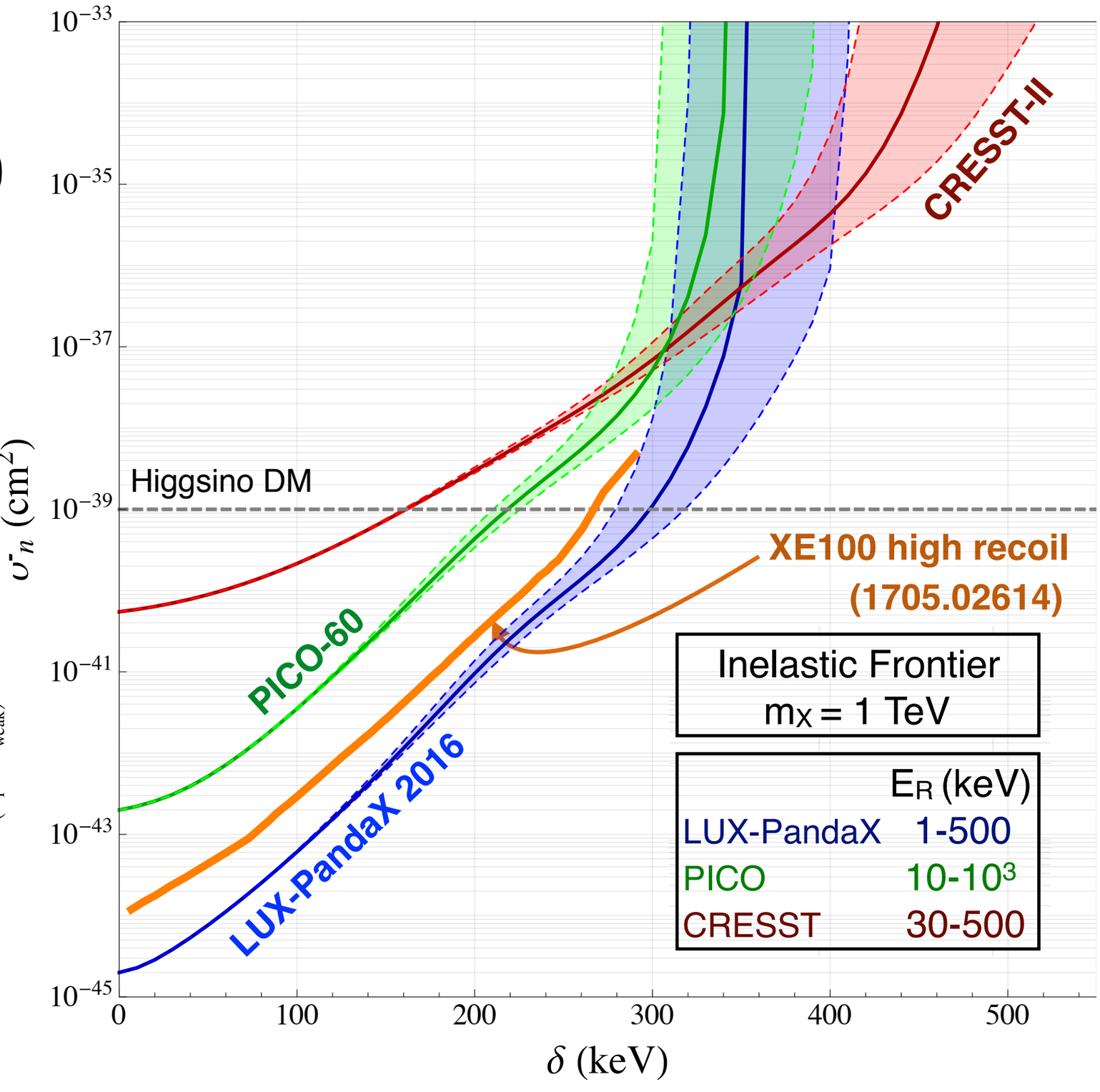




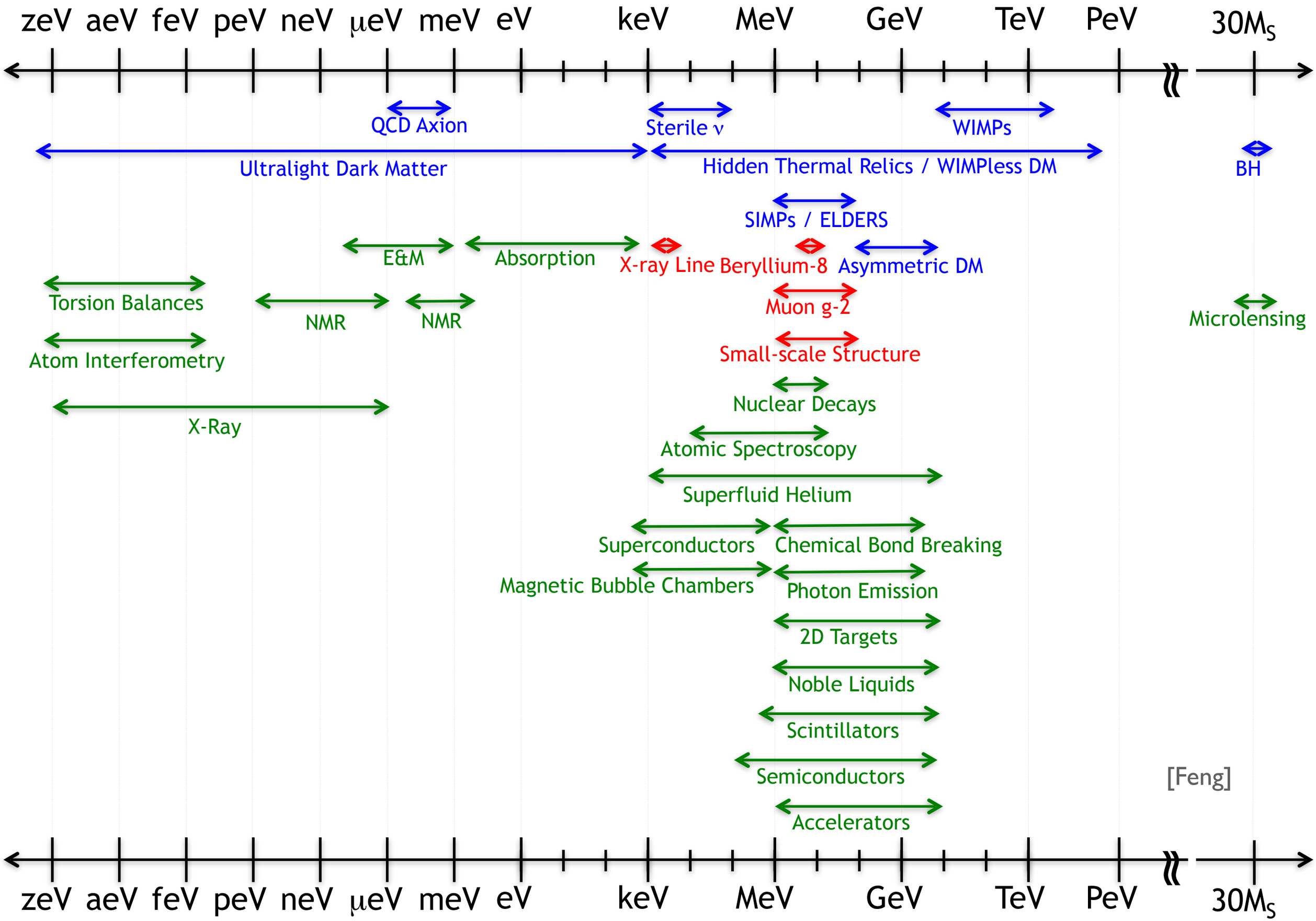
Crossing the Inelastic Frontier—Xenon100

Reanalysis
7.6 ton-days, Xe100
6.6-240 keVnr
Inelastic analysis





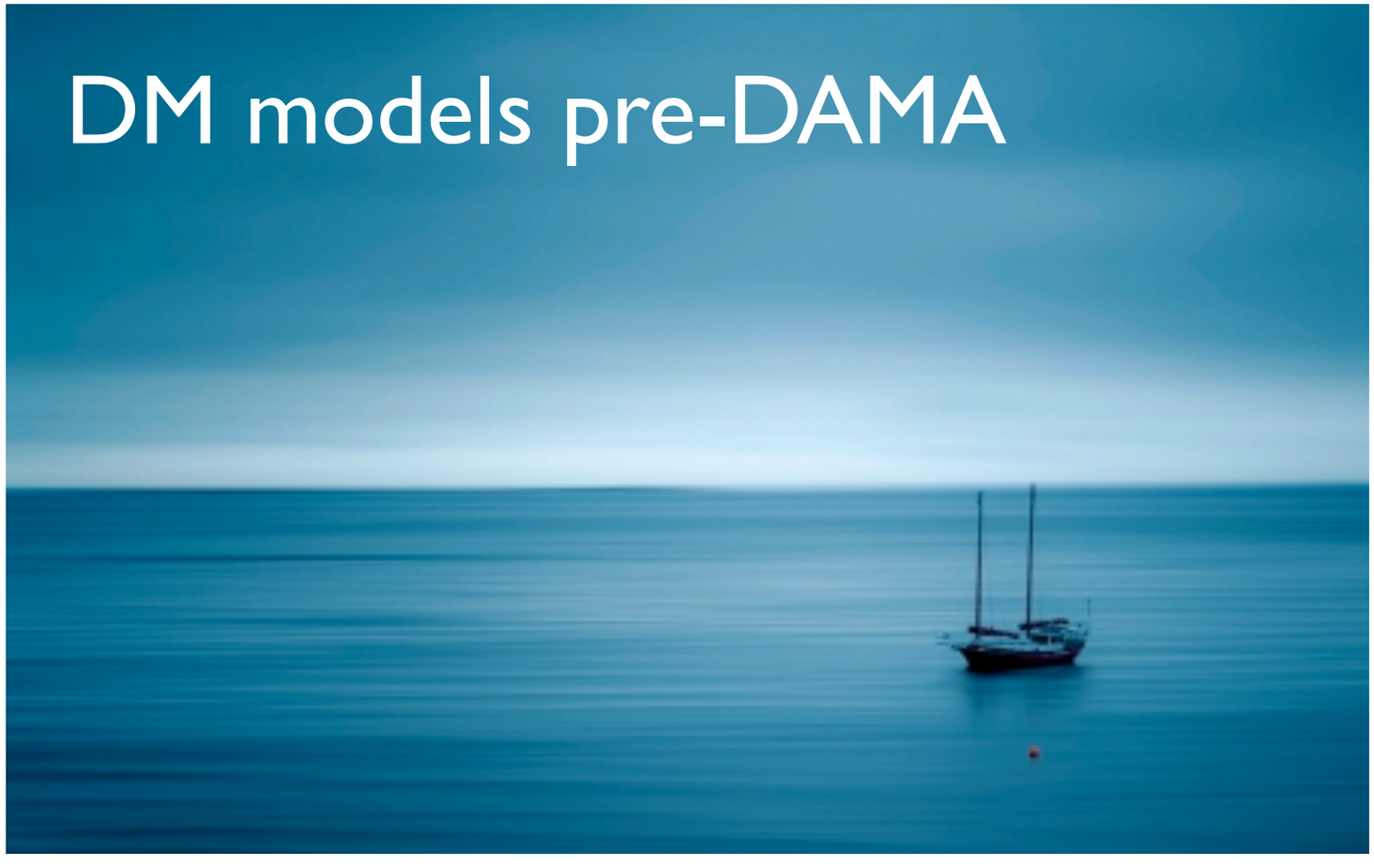
Dark Sector Candidates, Anomalies, and Search Techniques




Thank you

BACKUP

DM models pre-DAMA



DM models pre-DAMA



DM models pre-DAMA



DAN



DM models pre-DAMA



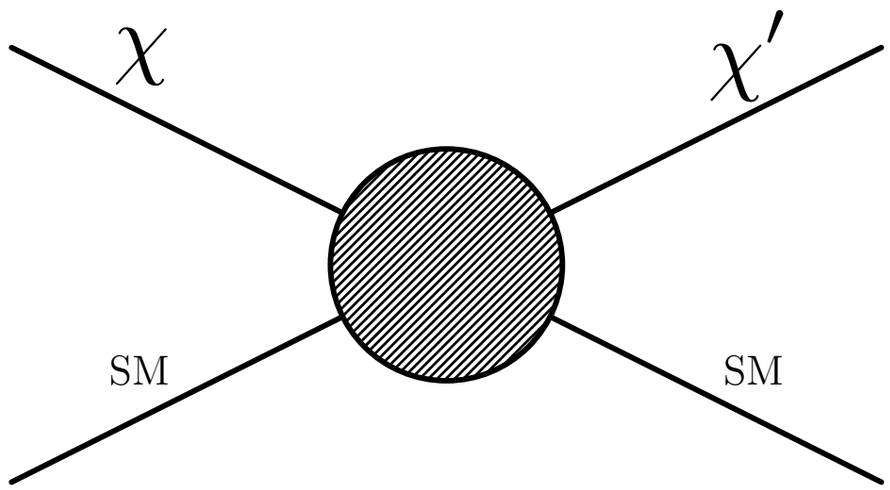
DAN



direct detection experimentalist?

Exothermic DM (exoDM)

[Graham, Harnik, Rajendran, Saraswat]

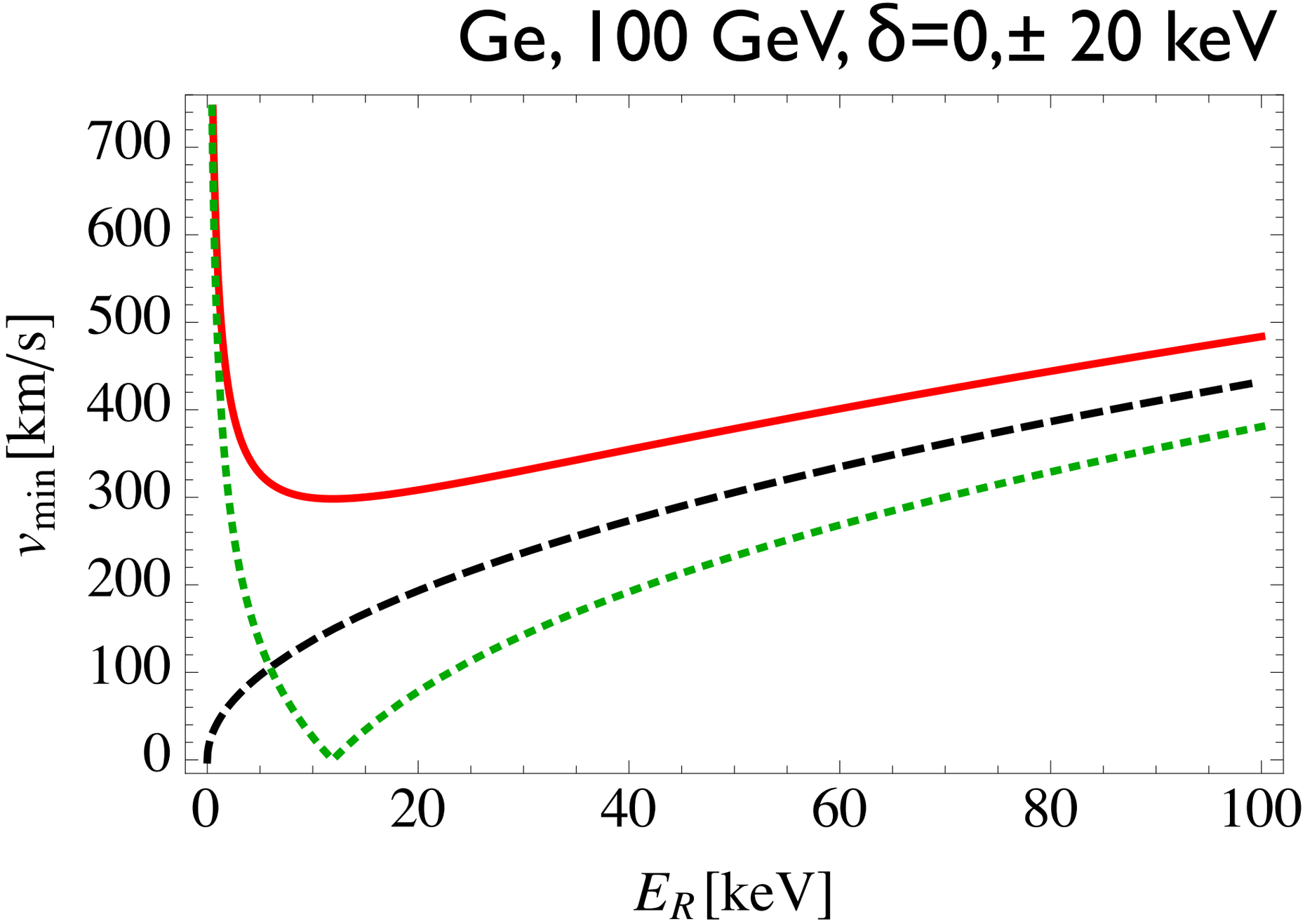


$$m_\chi - m_{\chi'} = \delta \sim -10\,\mathrm{keV}$$

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

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

e/i/exo-DM


Ge, 100 GeV, δ=0,± 20 keV
v_{min} [km/s]
700
600
500
400
300
200
100
0
0
20
40
60
80
100
E_R [keV]

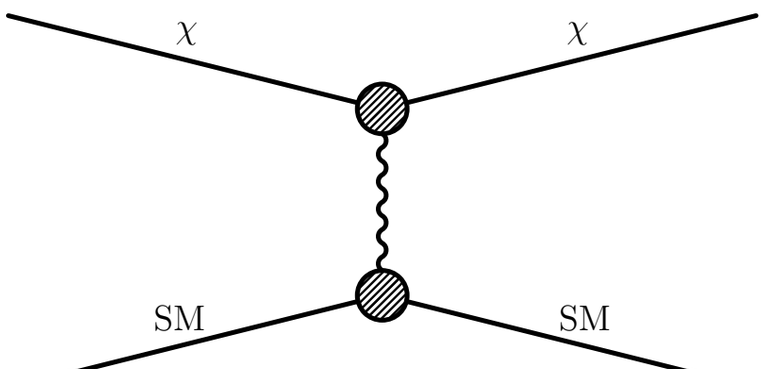
Form Factor DM

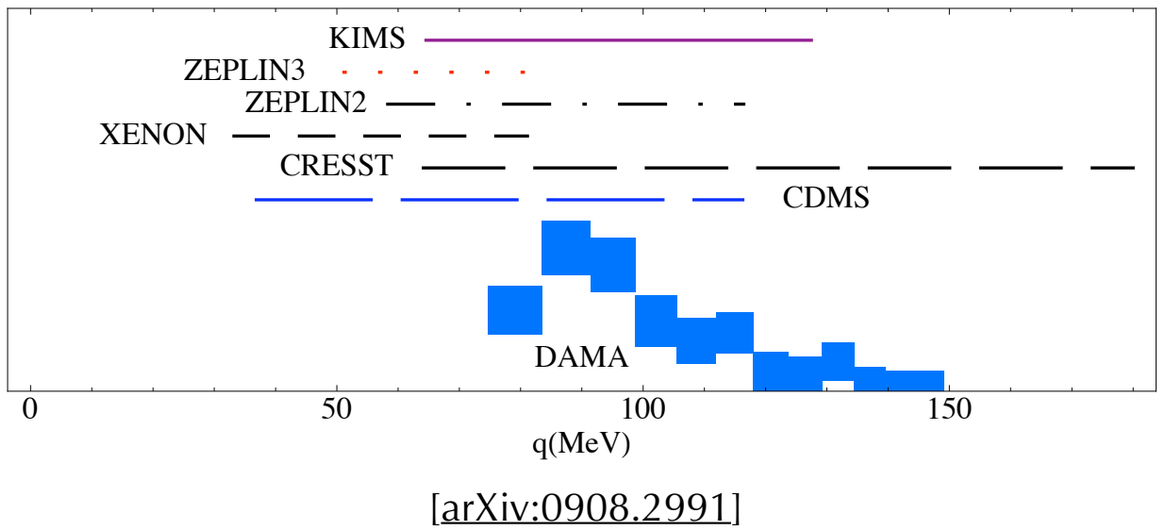
[Chang, Weiner, Pierce and Feldstein, Fitzpatrick, Katz]

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

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





[arXiv:0908.2991]

- Form factors suppress certain ranges of recoil energy
- Works best with SD couplings, or non-standard velocity distributions e.g. via Lactea
- Although suppresses events at other detectors still expect some signal
- Peak in spectrum at non-zero recoil energy

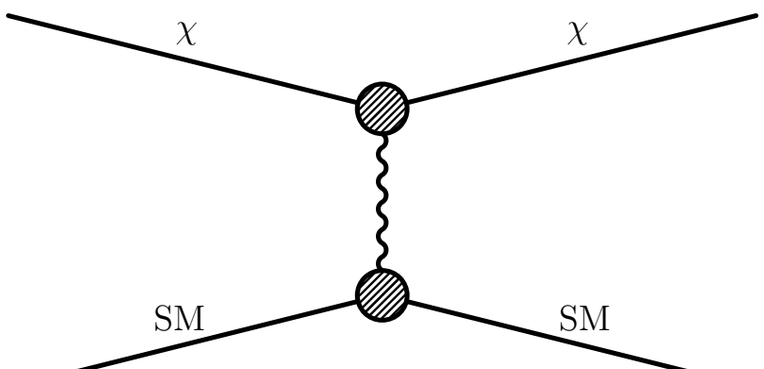
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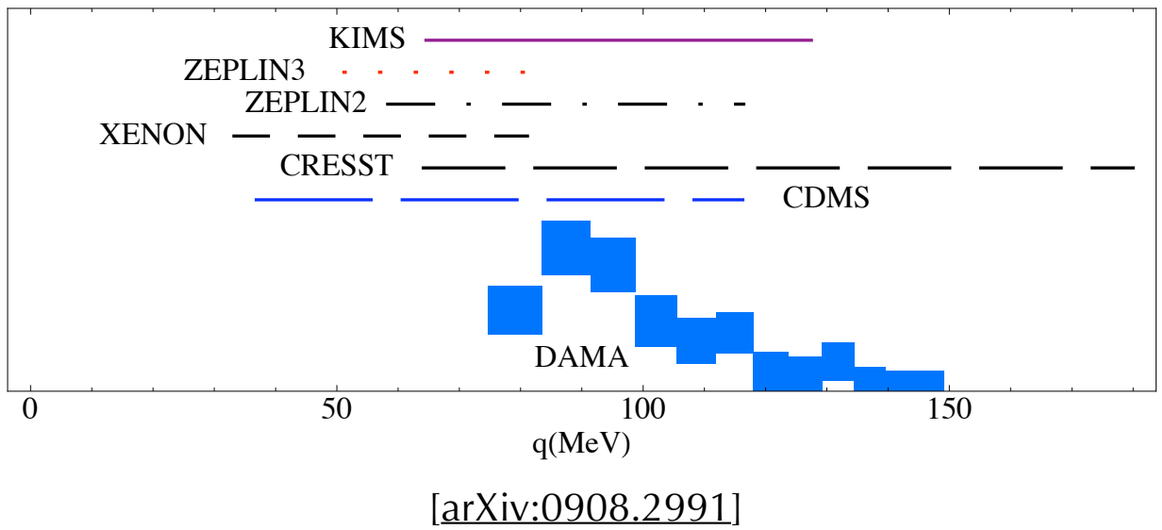
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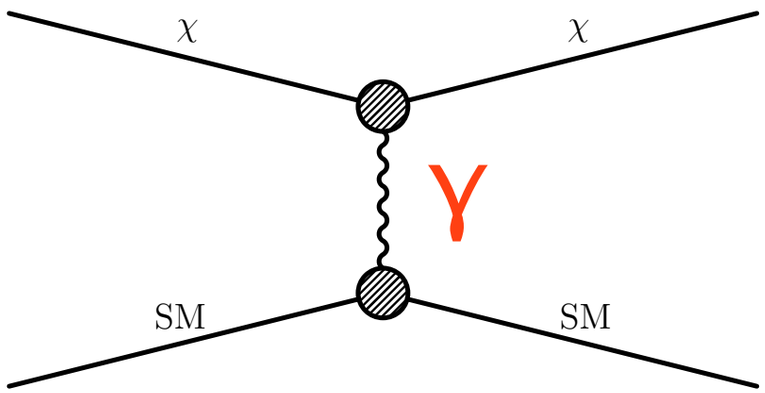


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A moment with the photon

[Pospelov and ter Veldhuis]



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

DM couples to nucleus through photon exchange

Leads to interesting momentum dependence e.g.

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

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

Typically assume fn~fp
But different elements have different ratios of p/n
Can remove some of the strongest constraints if

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

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

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

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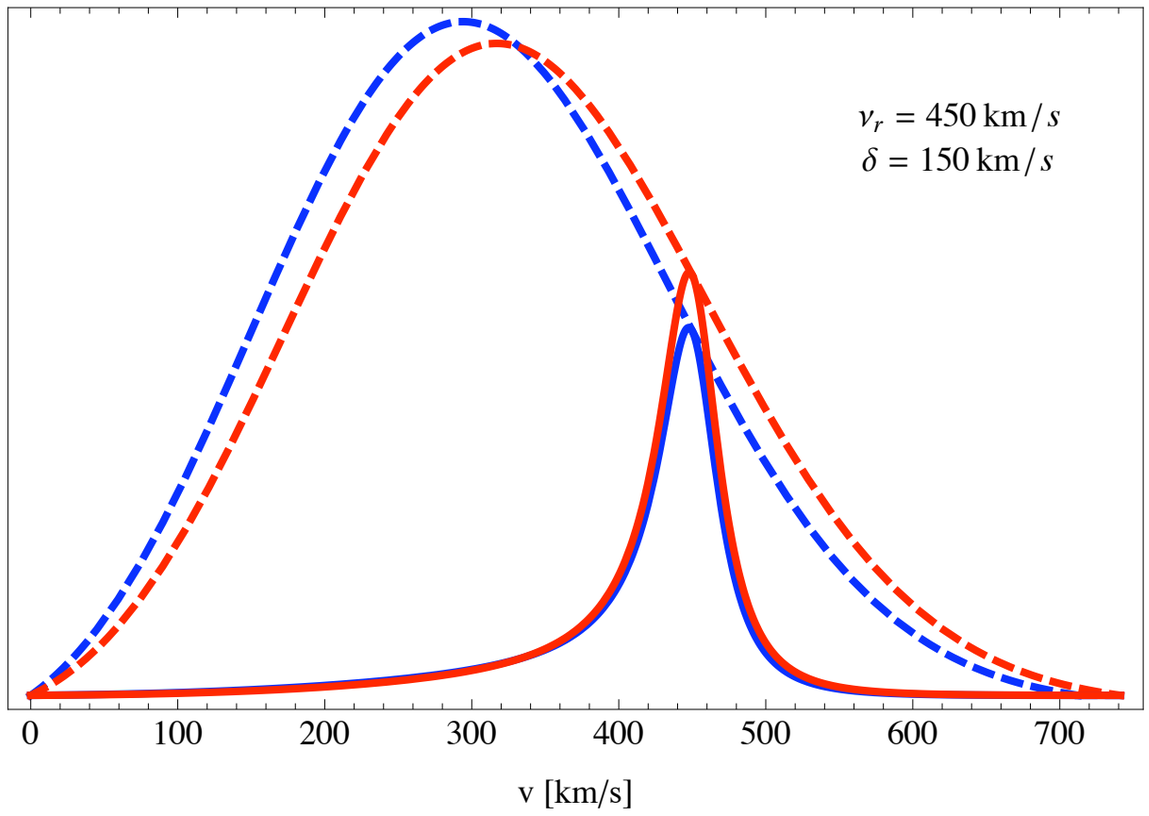
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Resonant Dark Matter (rDM) [Bai and PJF]

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

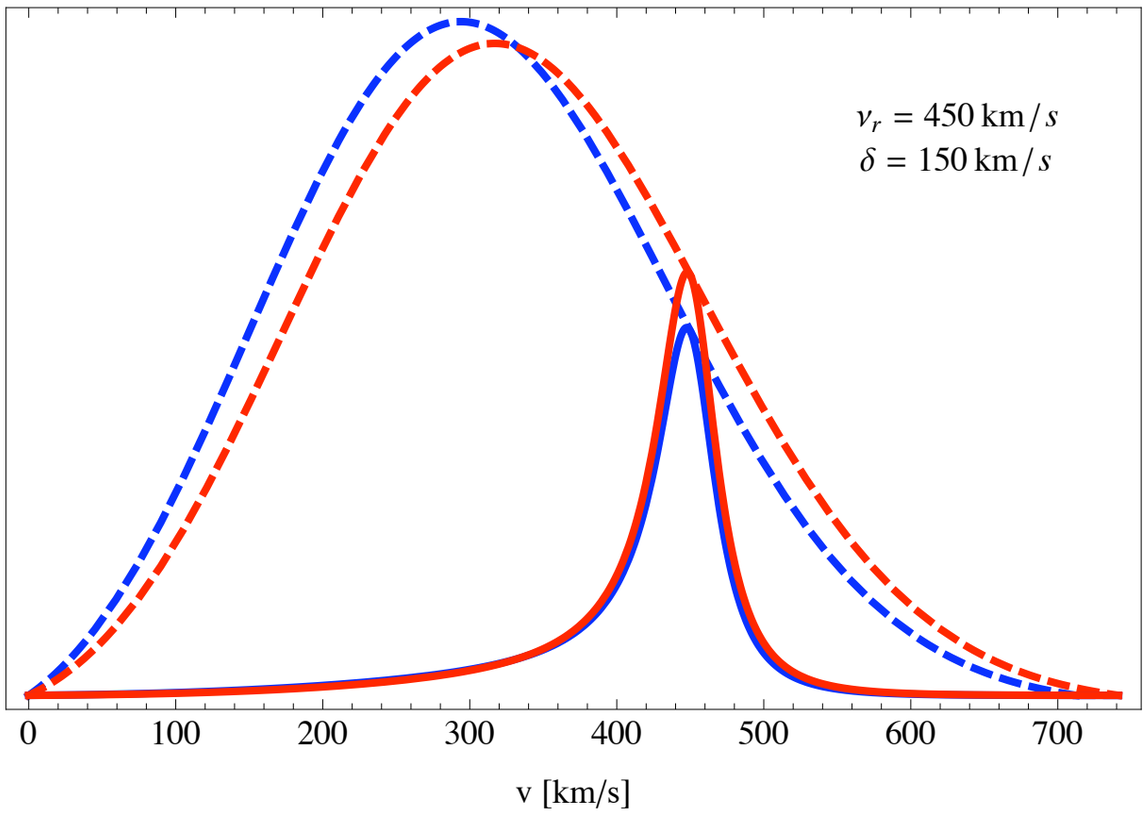


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Theory motivates new models and regions of parameter space, suggests new search methods, and draws connections between disparate phenomena.

