Dark Sectors and other novel types of particles

Patrick Fox

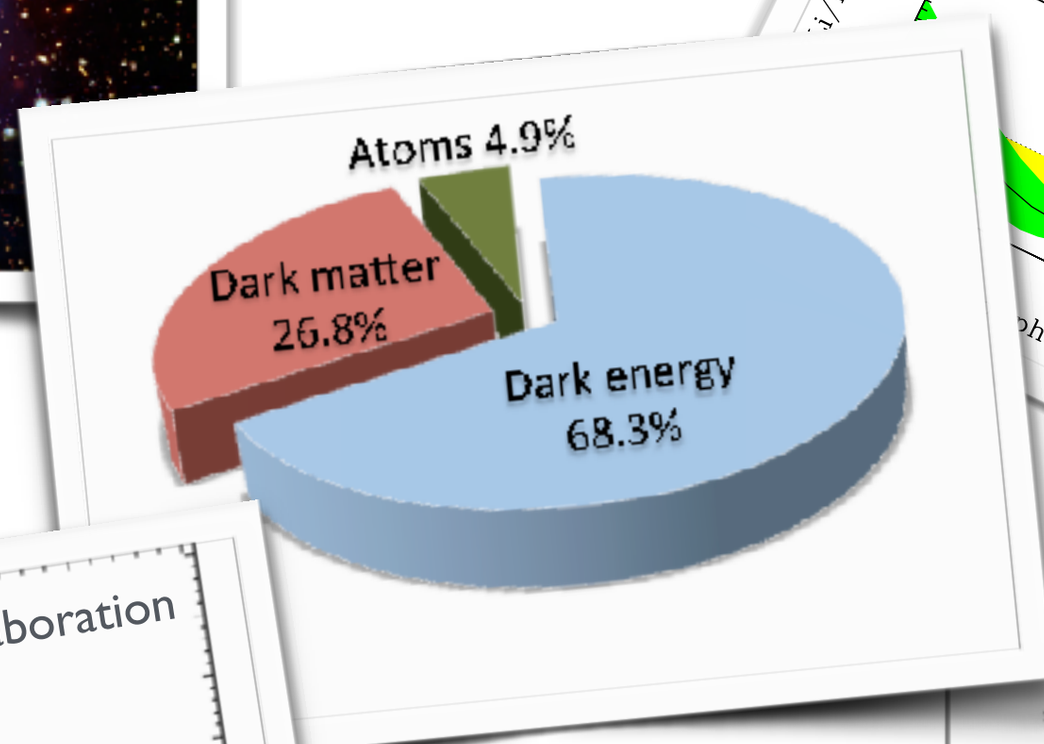
Fermilab

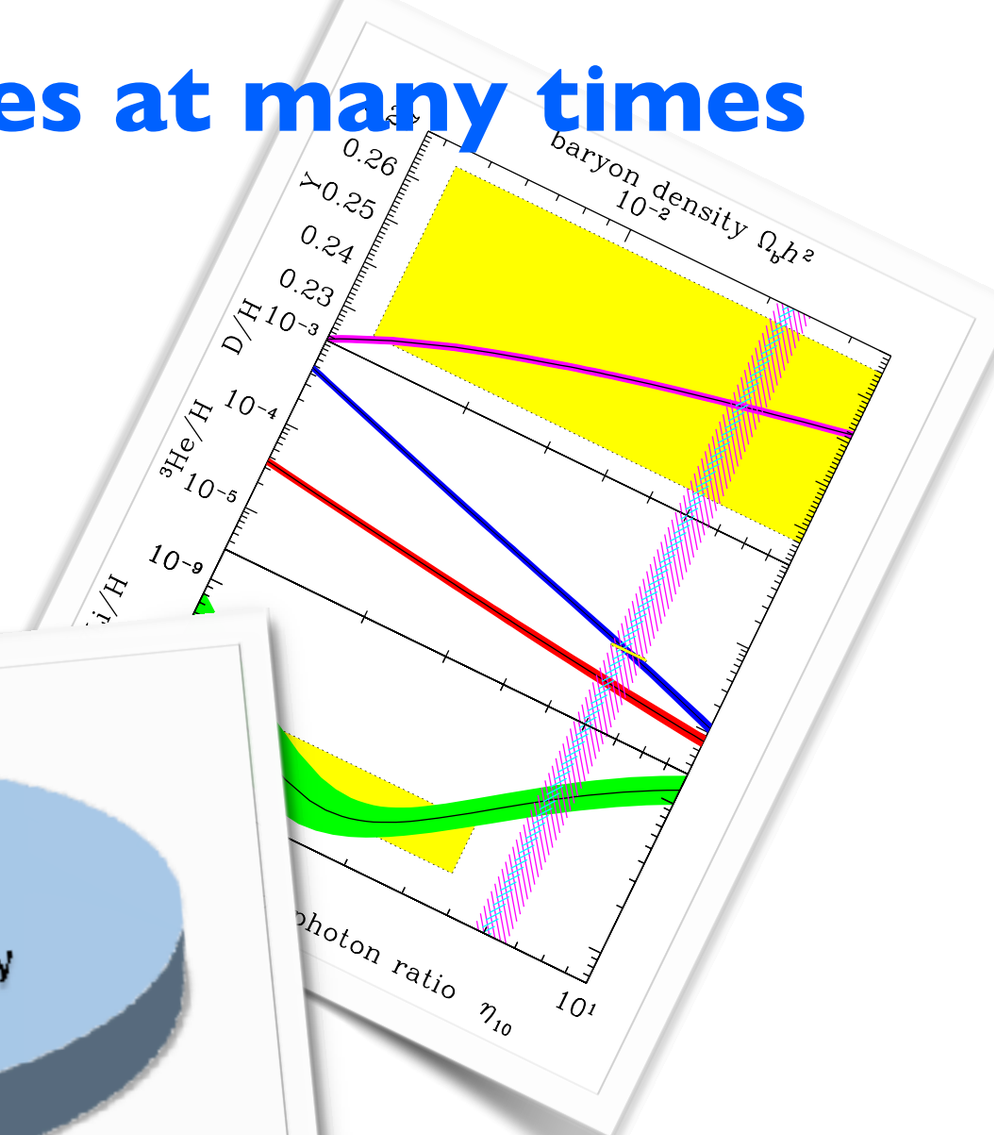
APS | DIVISION OF PARTICLES & FIELDS

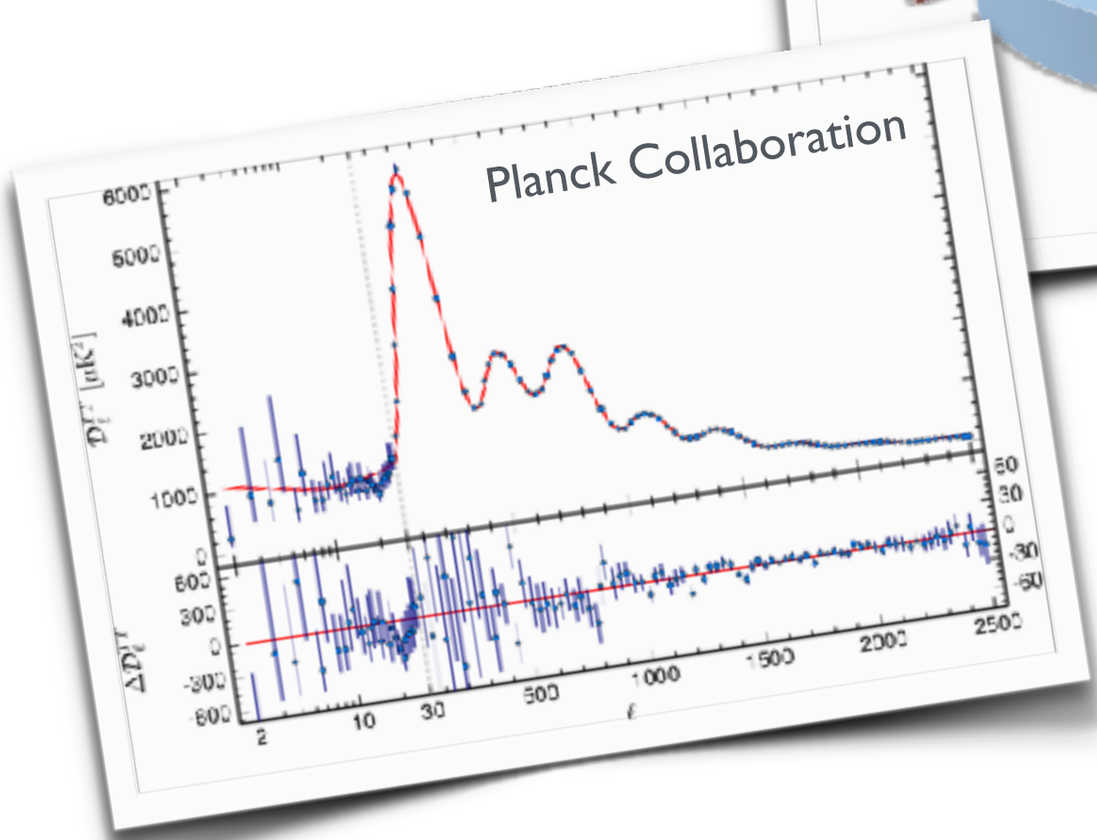
DPF 2017

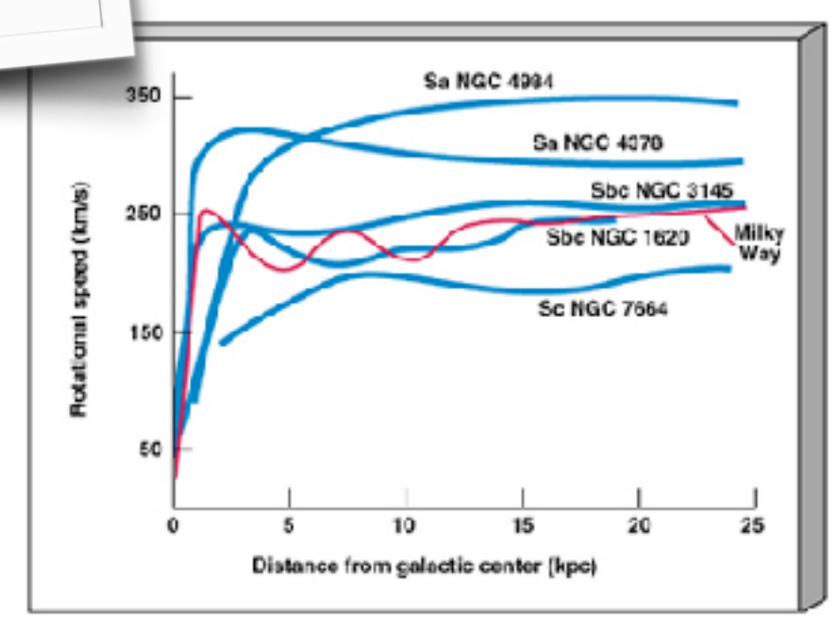
MEETING OF THE AMERICAN PHYSICAL SOCIETY DIVISION OF PARTICLES AND FIELDS

Evidence for DM on many scales at many times





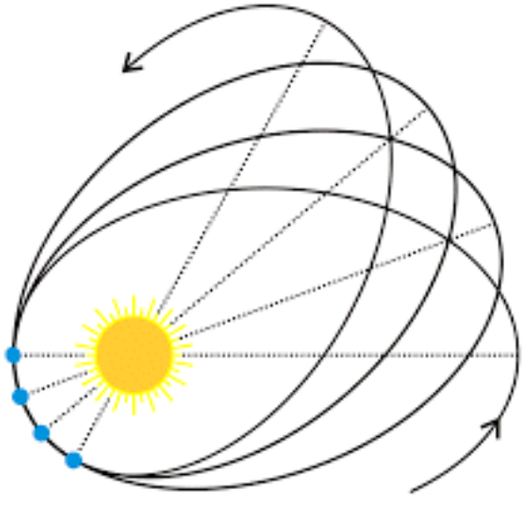


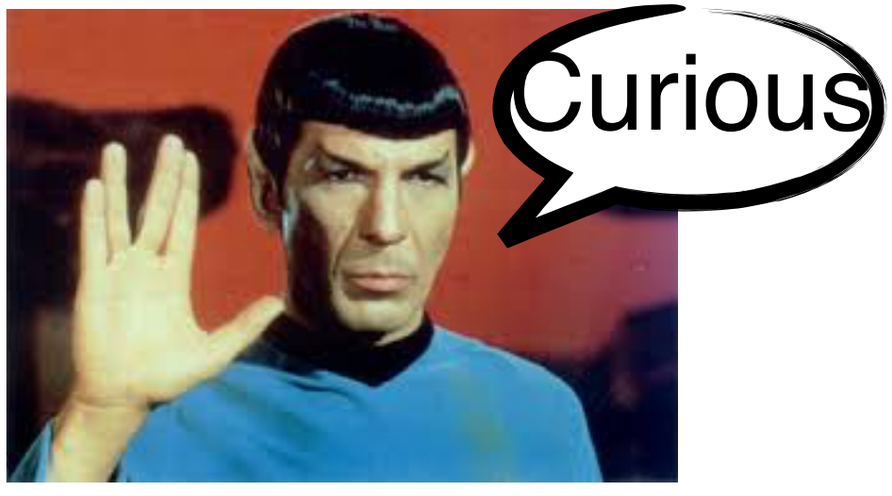


So far all probes have been gravitational in nature

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!)



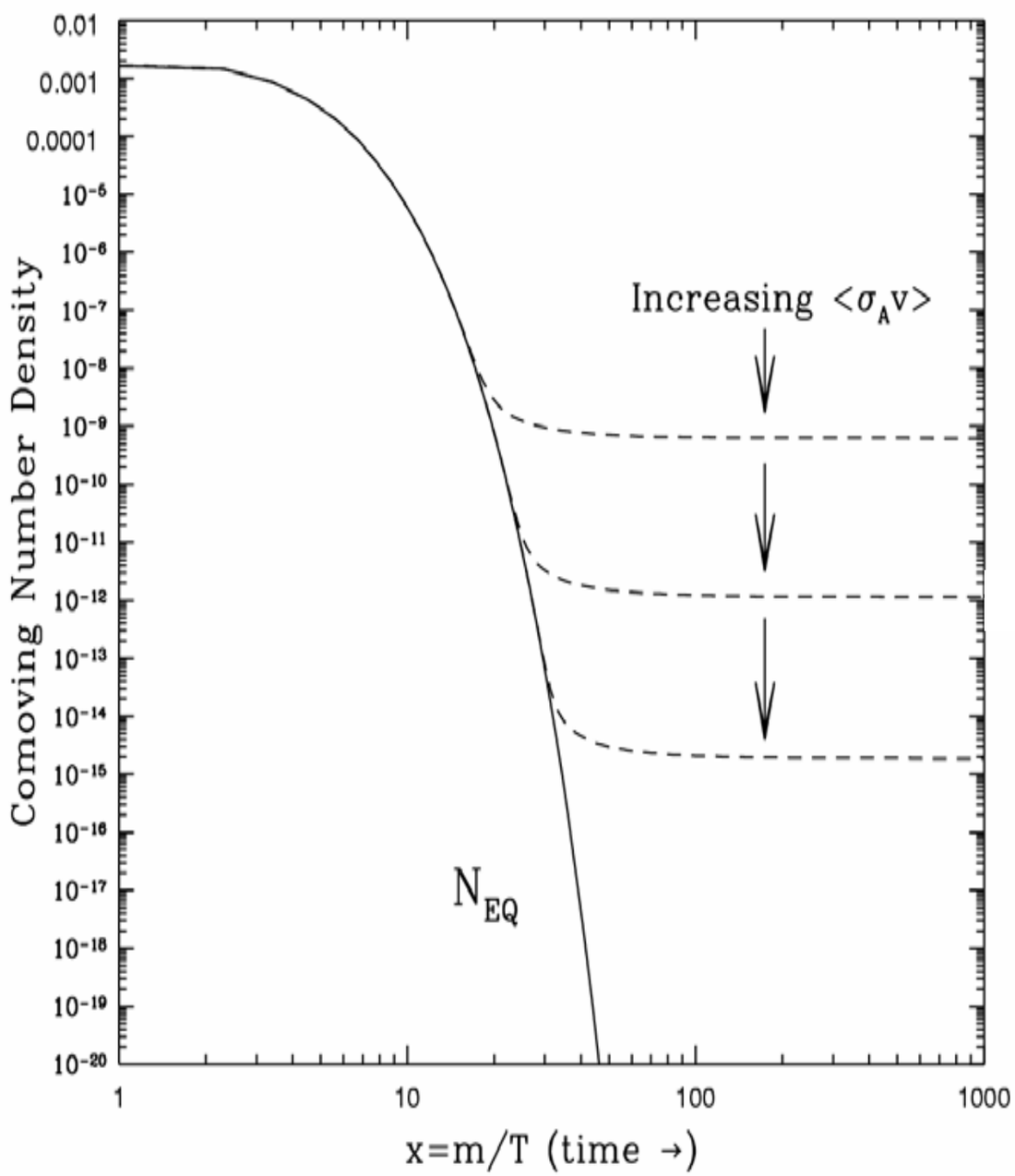


What about other interactions?

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"

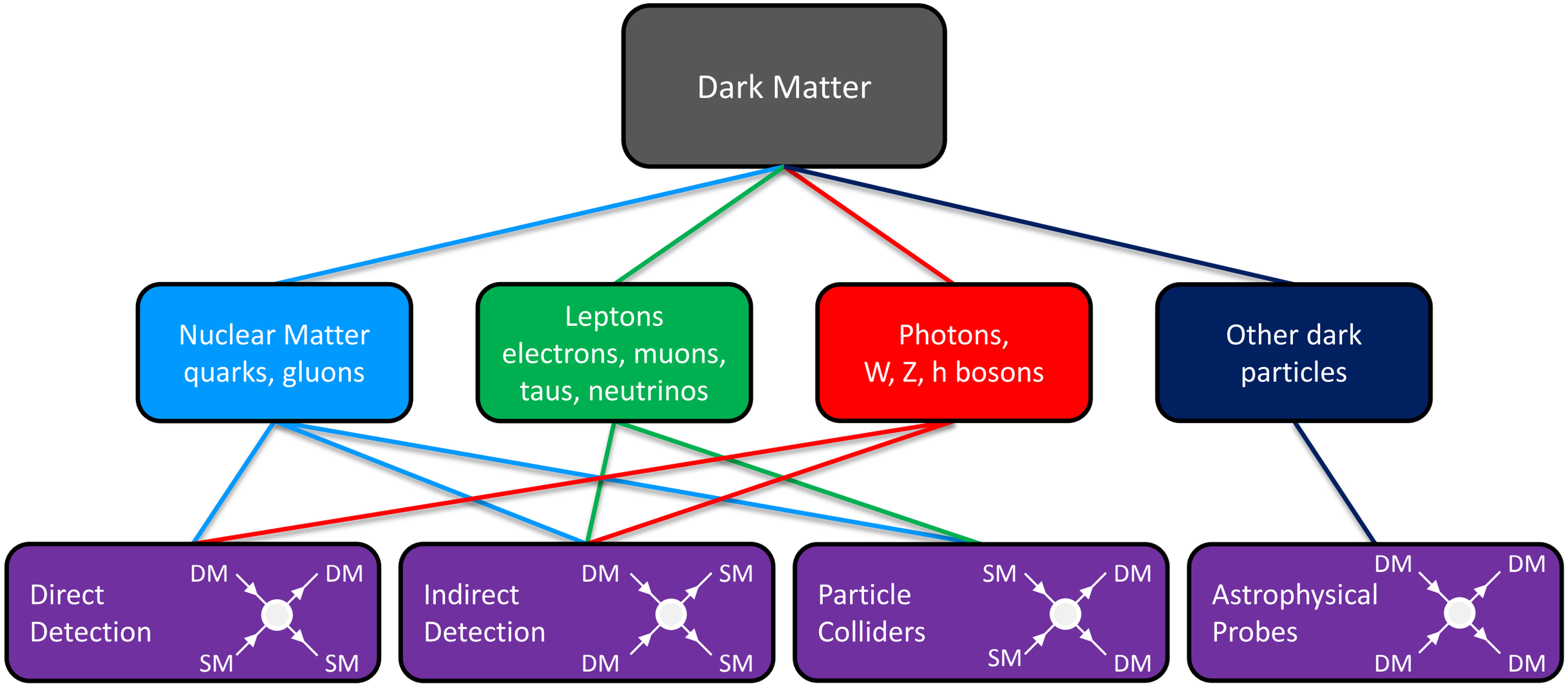


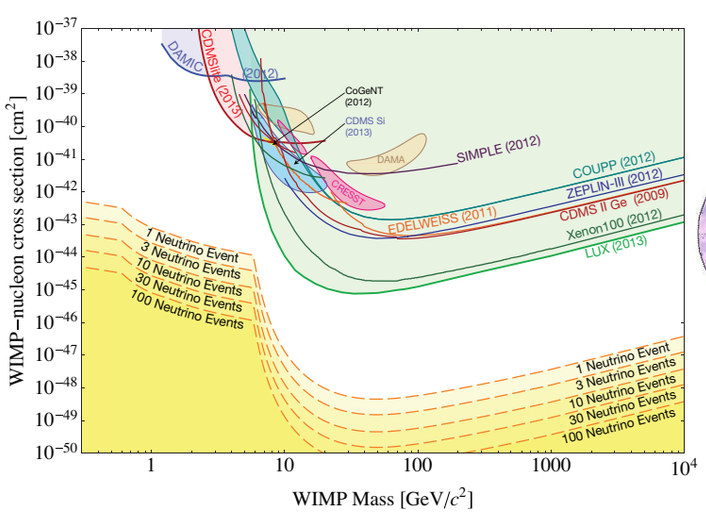
$$\chi\chi \leftrightarrow \bar{f} f$$

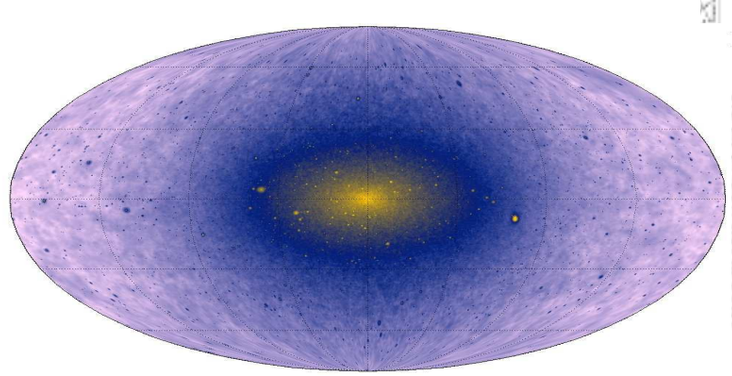
$$\Omega h^2 \approx 0.1 \left(\frac{m/T}{20}\right) \left(\frac{g_*}{80}\right)^{-1} \left(\frac{3 \times 10^{-26} \mathrm{cm}^2 \mathrm{s}^{-1}}{\sigma v}\right)$$

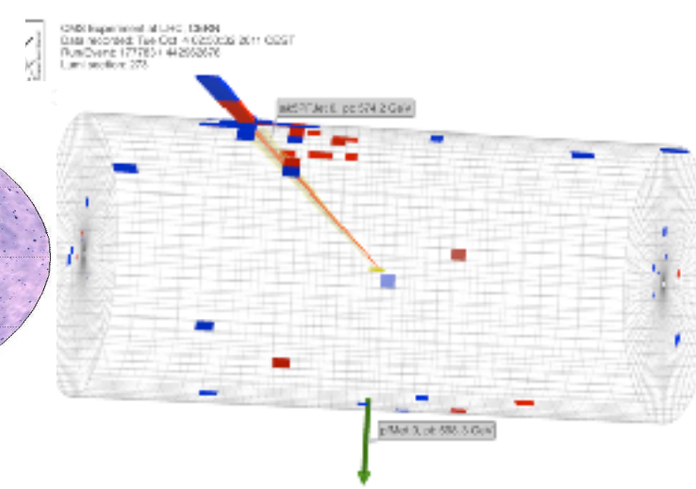
Amazing (misleading?) fact:

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

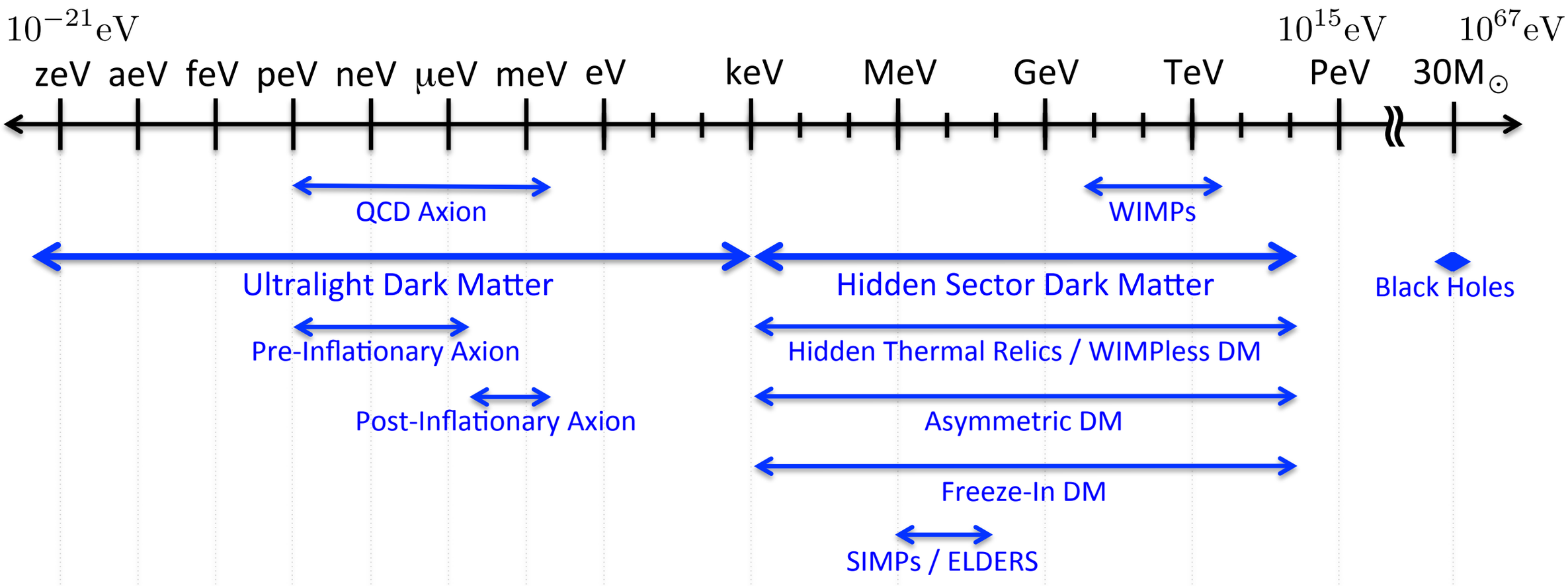

Dark Matter
Nuclear Matter
quarks, gluons
Leptons
electrons, muons,
taus, neutrinos
Photons,
W, Z, h bosons
Other dark
particles
Direct
Detection
DM
DM
SM
SM
Indirect
Detection
DM
SM
DM
SM
Particle
Colliders
SM
DM
SM
DM
Astrophysical
Probes
DM
DM
DM
DM


WIMP–nucleon cross section [cm^2]
WIMP Mass [GeV/c^2]
DAMIC
CDMSlite (2013)
(2012)
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





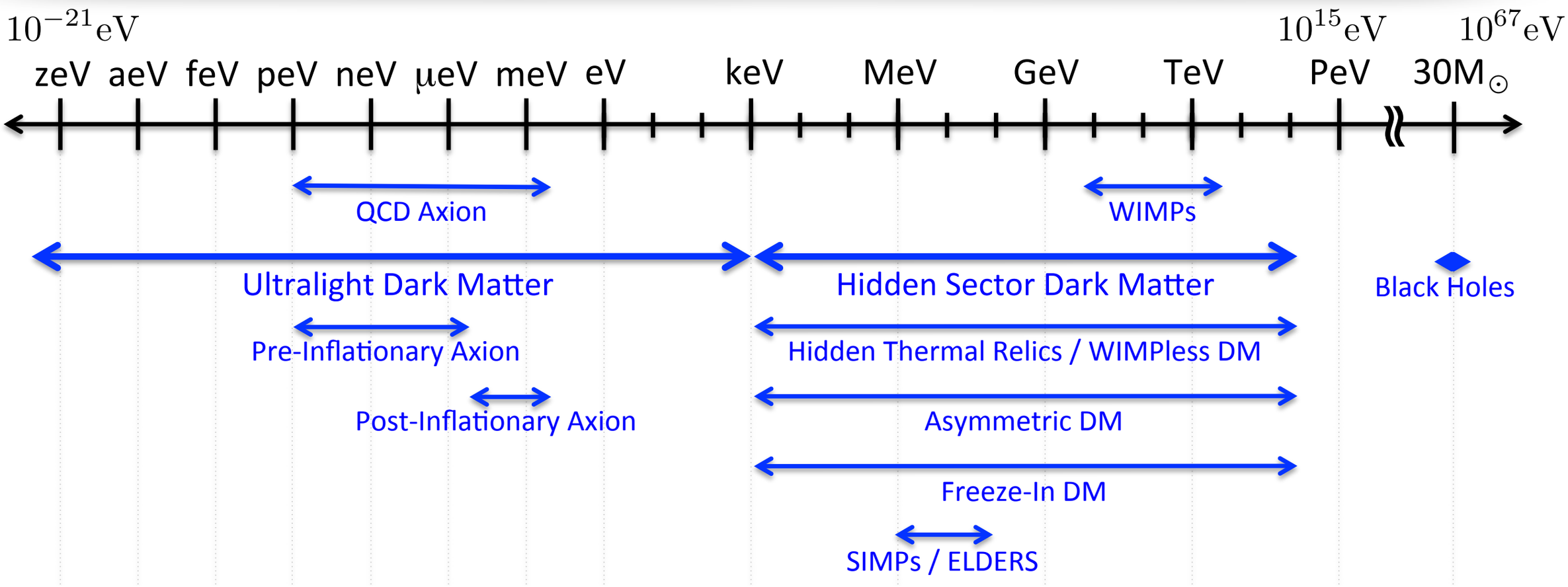
DM candidates



[Feng, US Cosmic Visions White Paper]

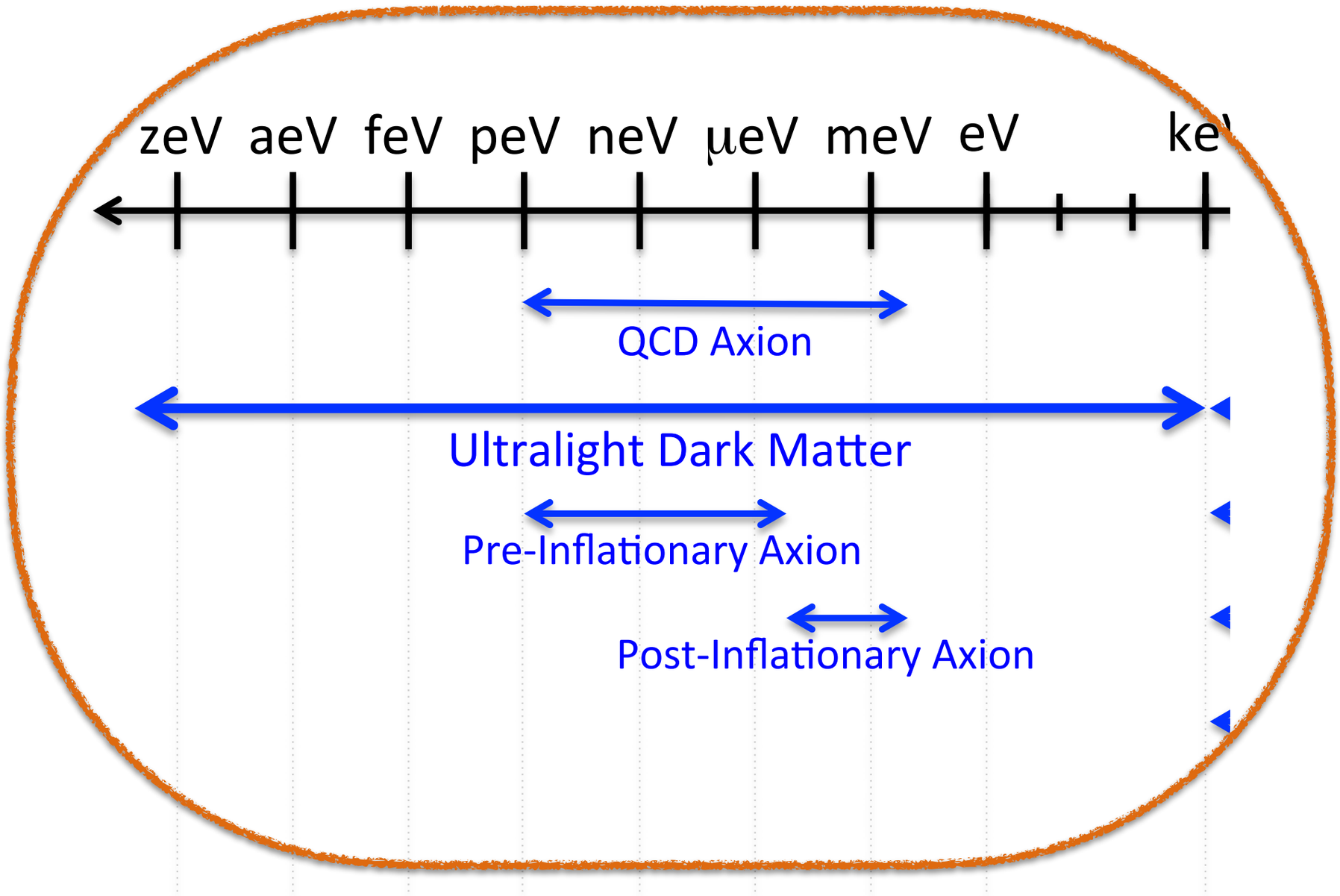
DM candidates

See talks by e.g. Lang and Zurek



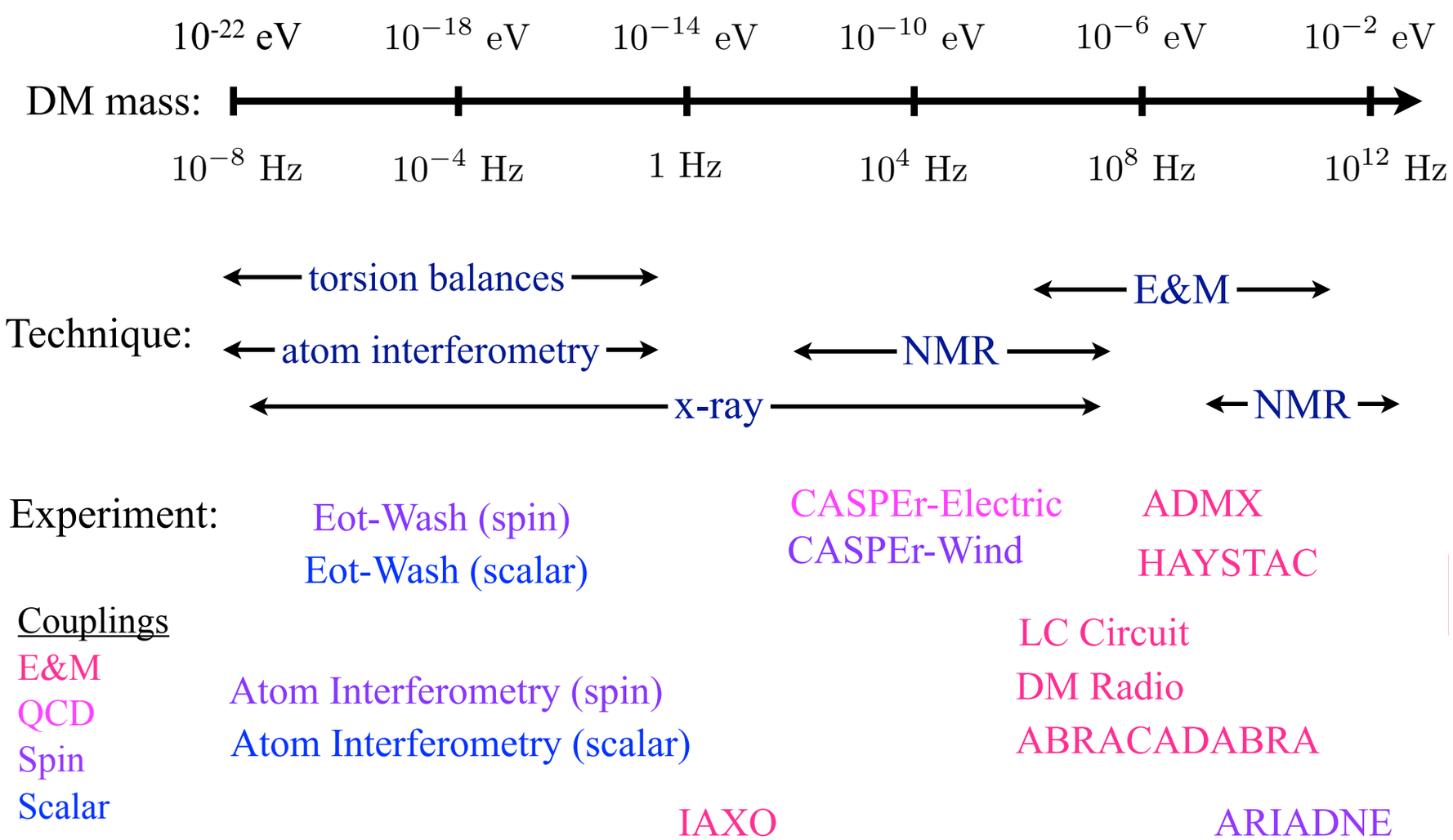
[Feng, US Cosmic Visions White Paper]

“Other novel particles”



sub-keV DM

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



[US Cosmic Visions White papers]

QCD Axion

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

PQ broken *after* inflation

Axion starts osc. too late, too much DM

PQ broken *before* inflation

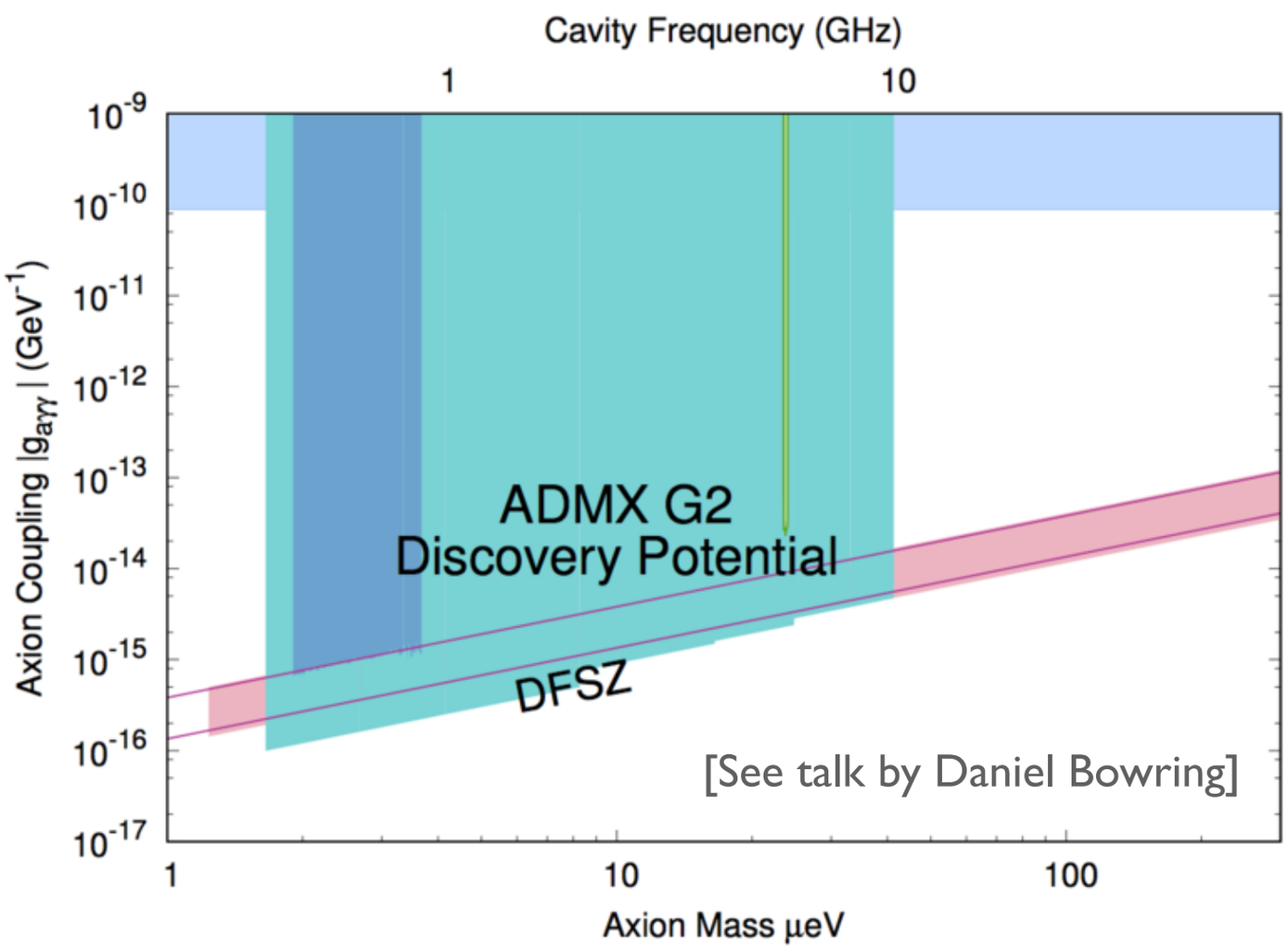
DM abundance requires small θ_{init} Anthropics?

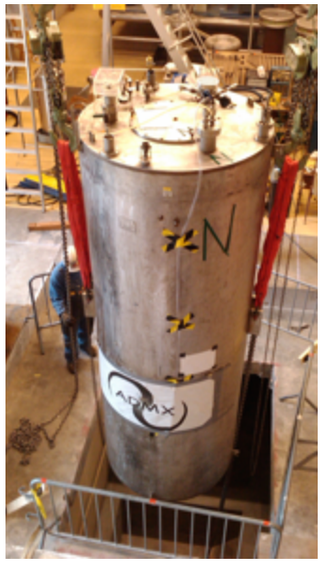
Isocurvature modes $(H_I/f)^2$

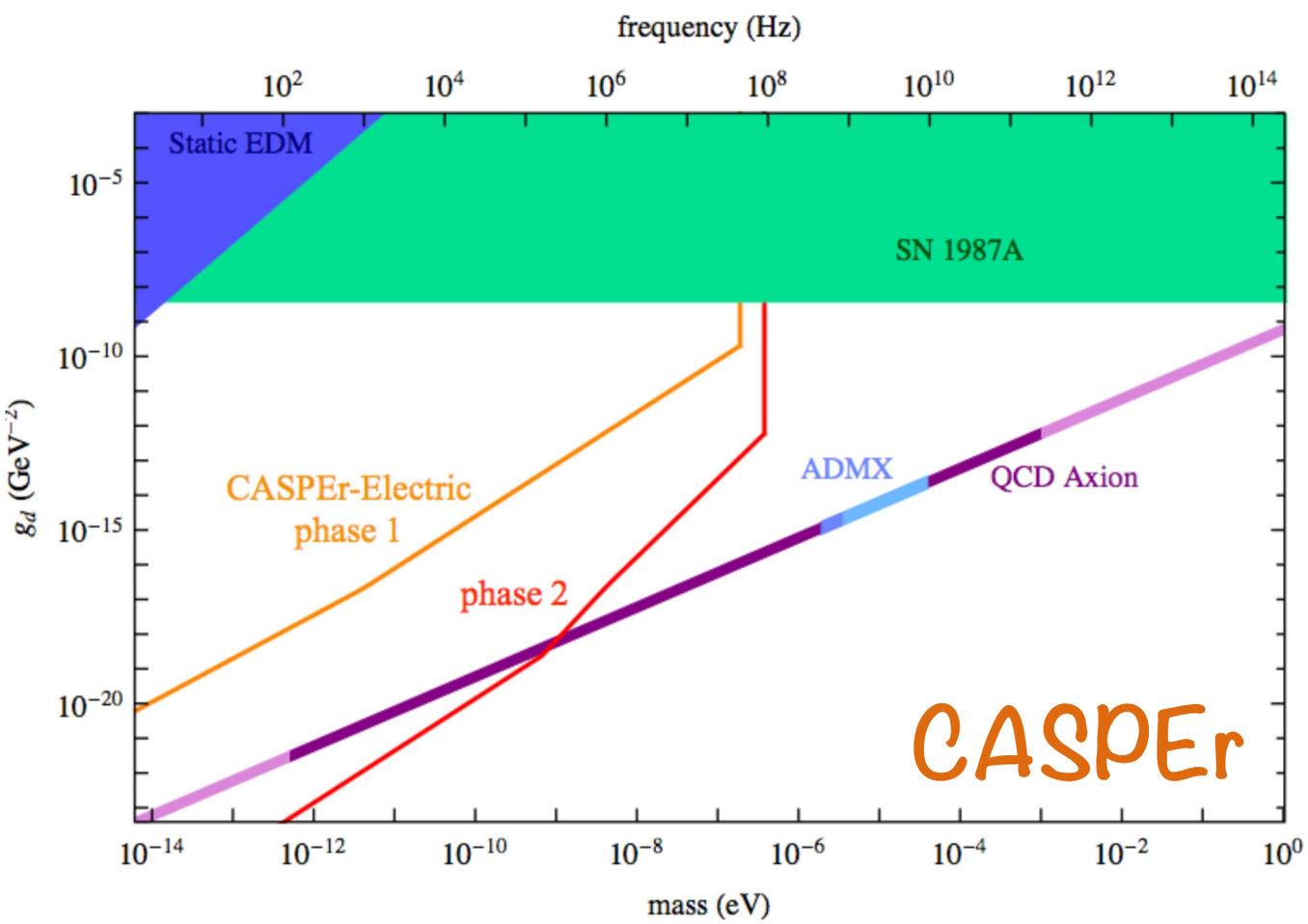
B-modes $(H_I/M_{pl})^2$

connections to inflation

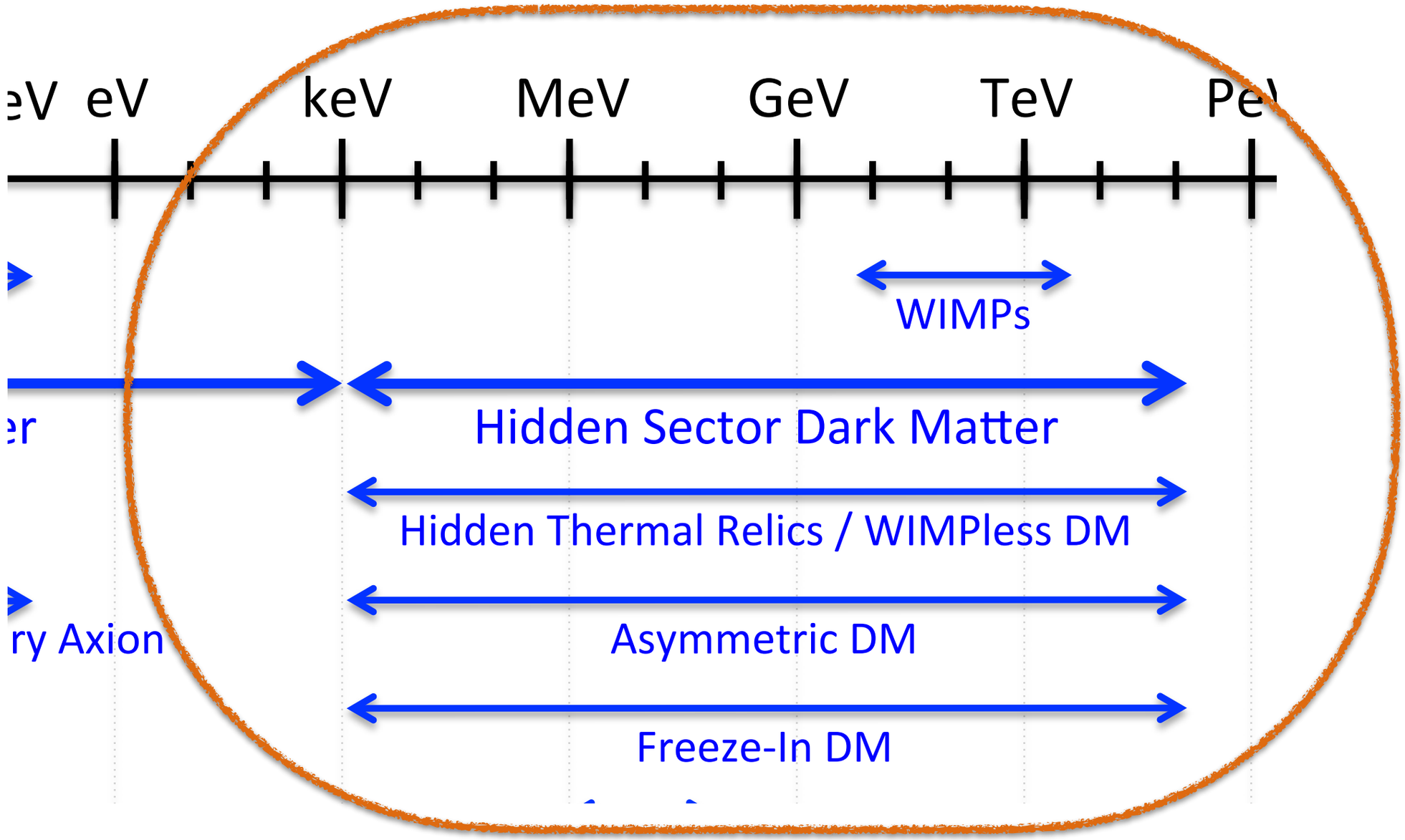
[PF, Pierce, Thomas]


Cavity Frequency (GHz)
1
10
Axion Coupling $|g_{a\gamma\gamma}|$ (GeV^{-1})
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
ADMX G2
Discovery Potential
DFSZ
[See talk by Daniel Bowring]
1
10
100
Axion Mass μeV




frequency (Hz)
10^2
10^4
10^6
10^8
10^{10}
10^{12}
10^{14}
Static EDM
SN 1987A
g_d (GeV^{-2})
10^{-5}
10^{-10}
10^{-15}
10^{-20}
CASPEr-Electric
phase 1
phase 2
ADMX
QCD Axion
CASPEr
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
mass (eV)

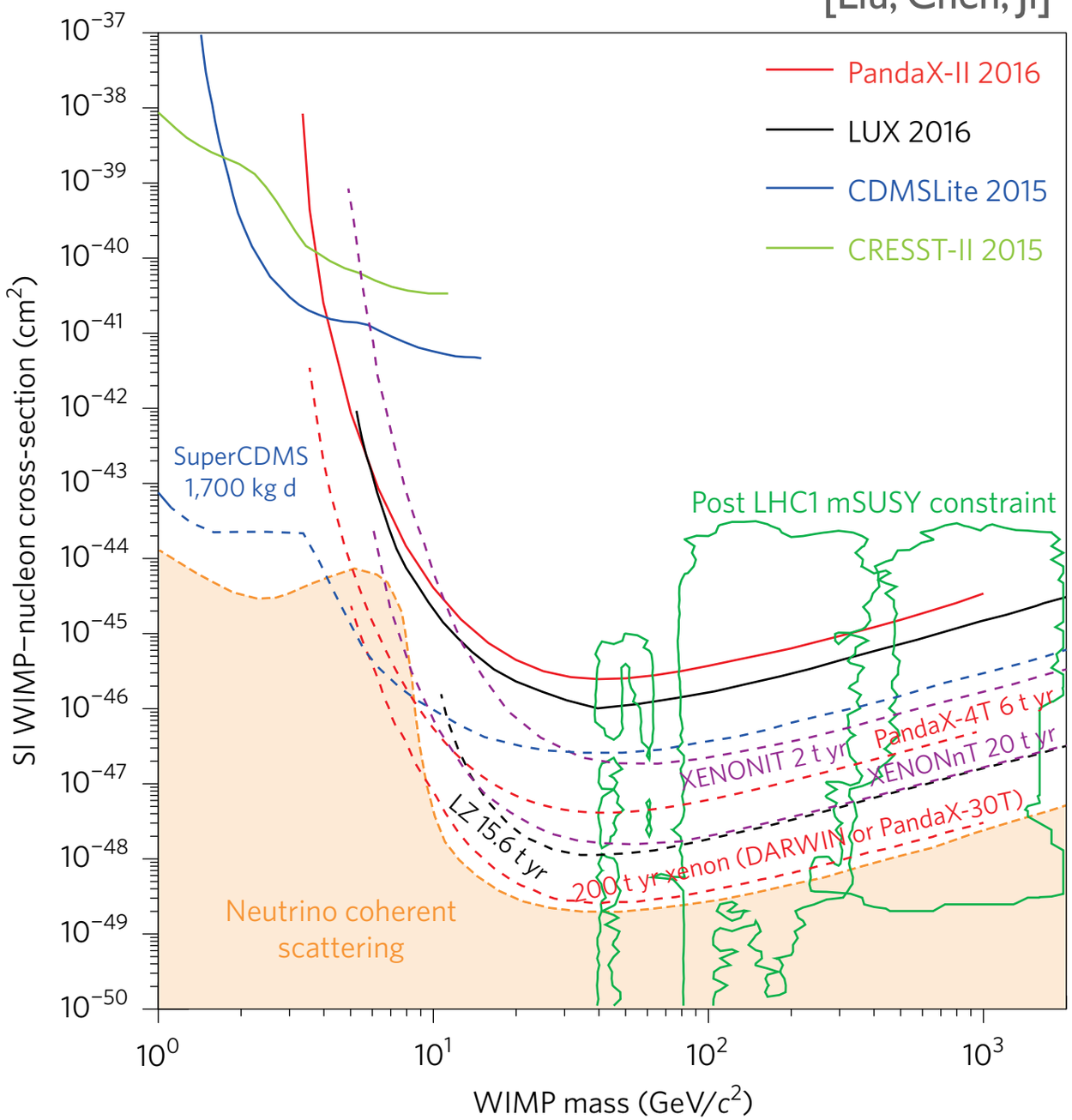
“Dark Sectors”



WIMP

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

[Liu, Chen, Ji]



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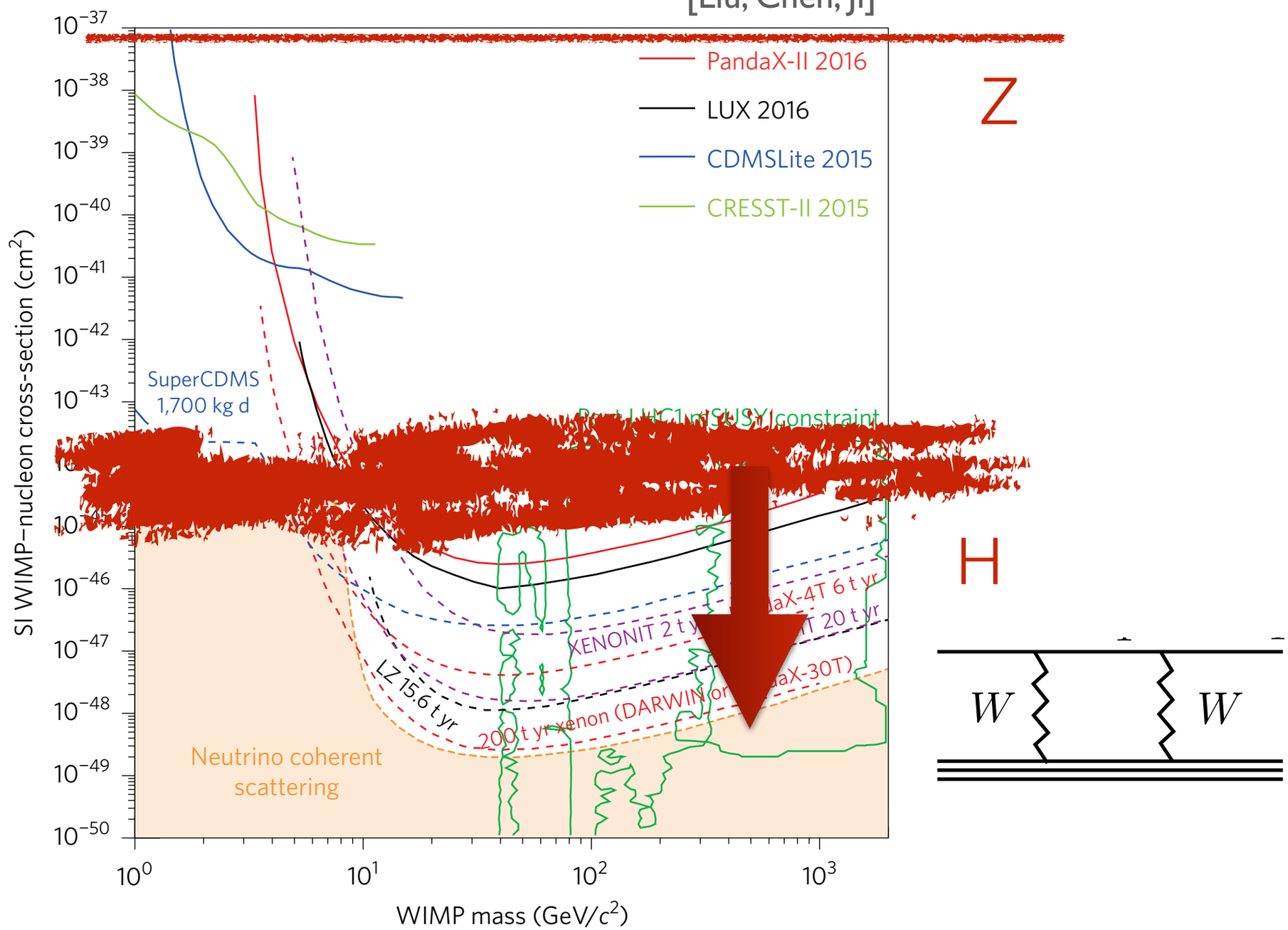

Hidden sector DM

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

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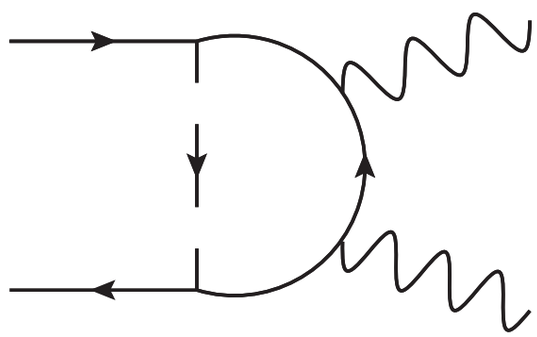
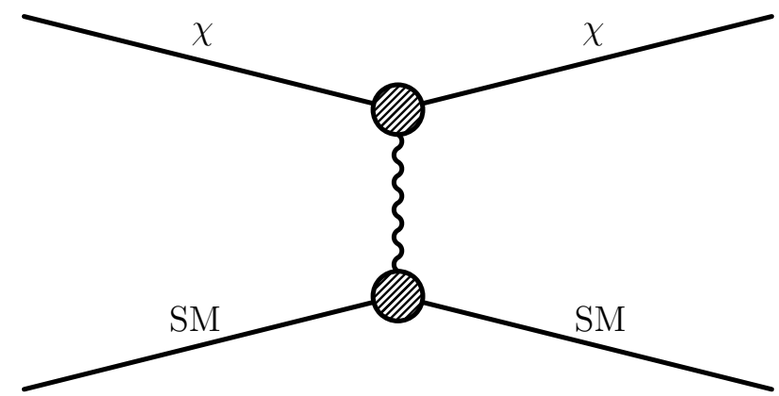
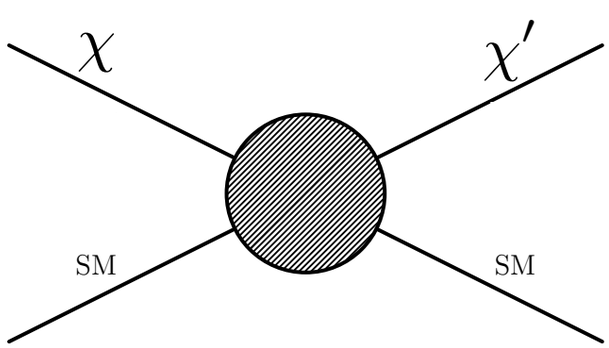
Hidden sector DM—interesting dynamics

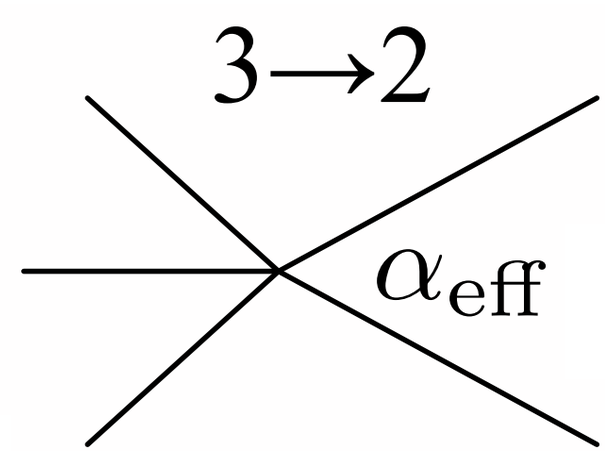
Hidden sector dynamics, new force carriers

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



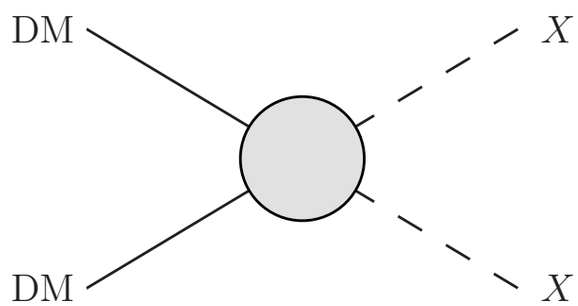


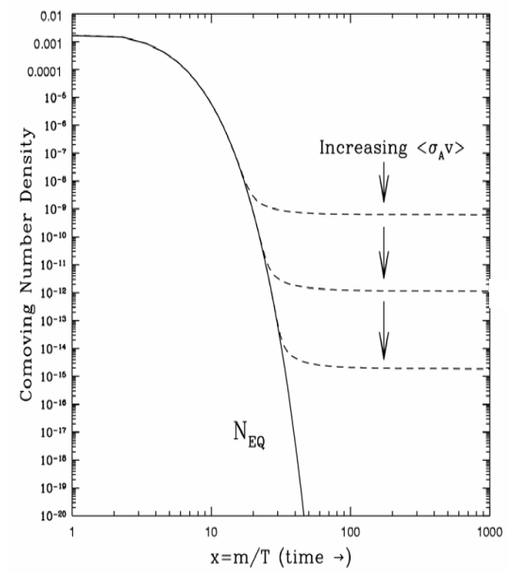


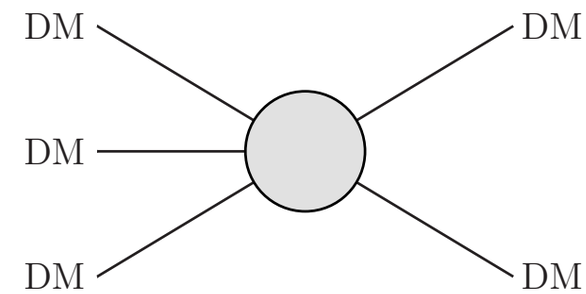


Hidden sector DM—thermal relics

Leads to interesting changes in cosmology



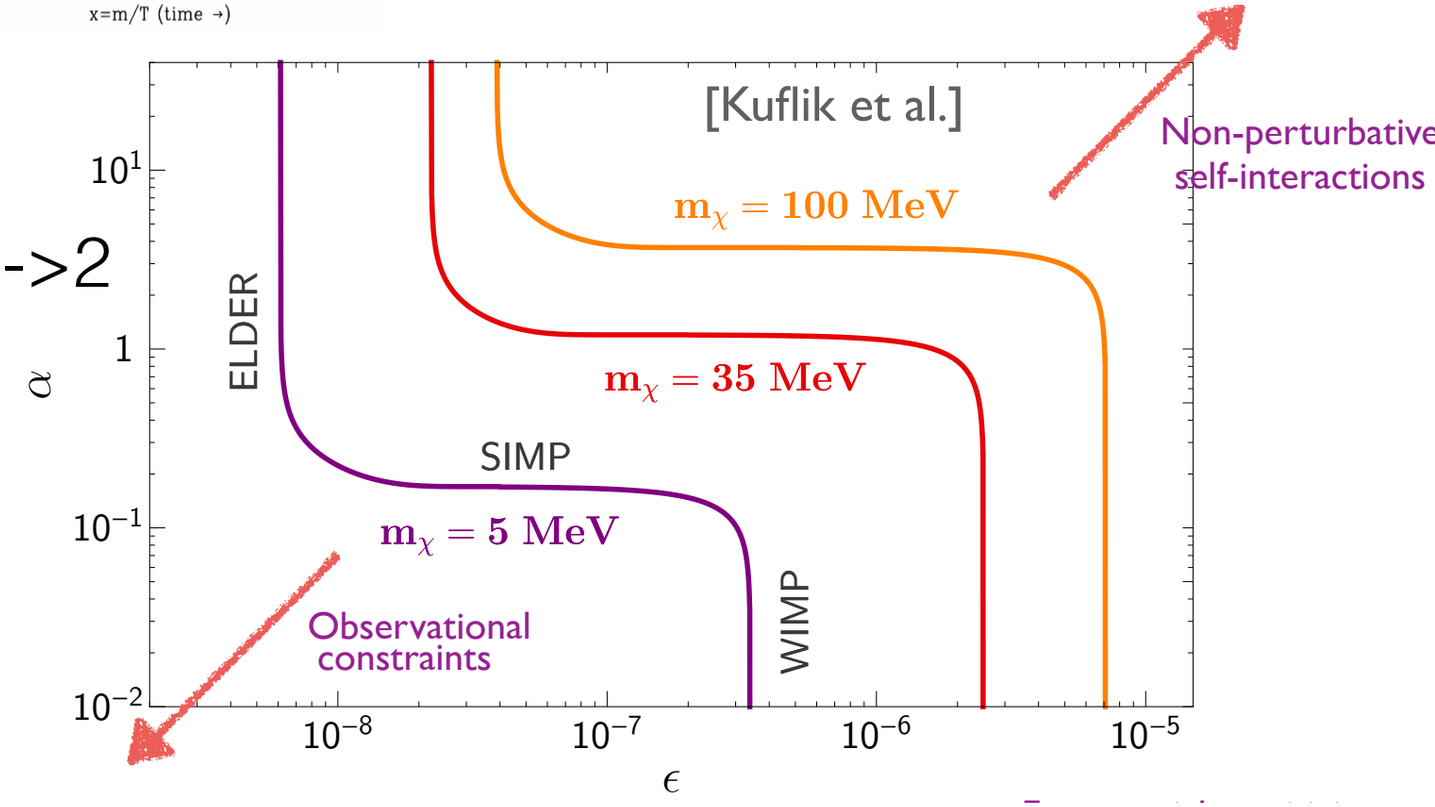




cannibalization

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

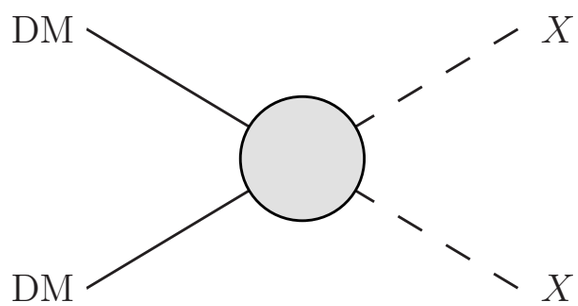
3->2

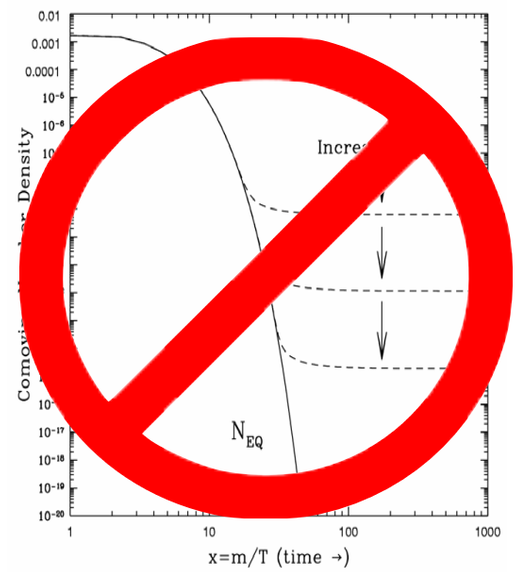


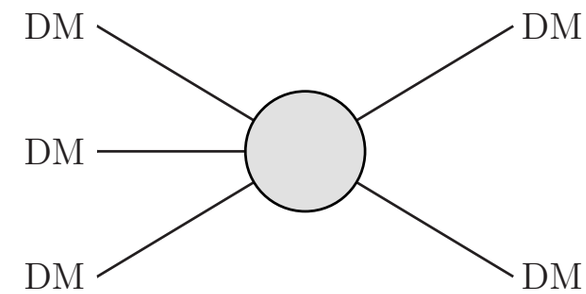
DM-SM elastic scatter

Hidden sector DM—thermal relics

Leads to interesting changes in cosmology







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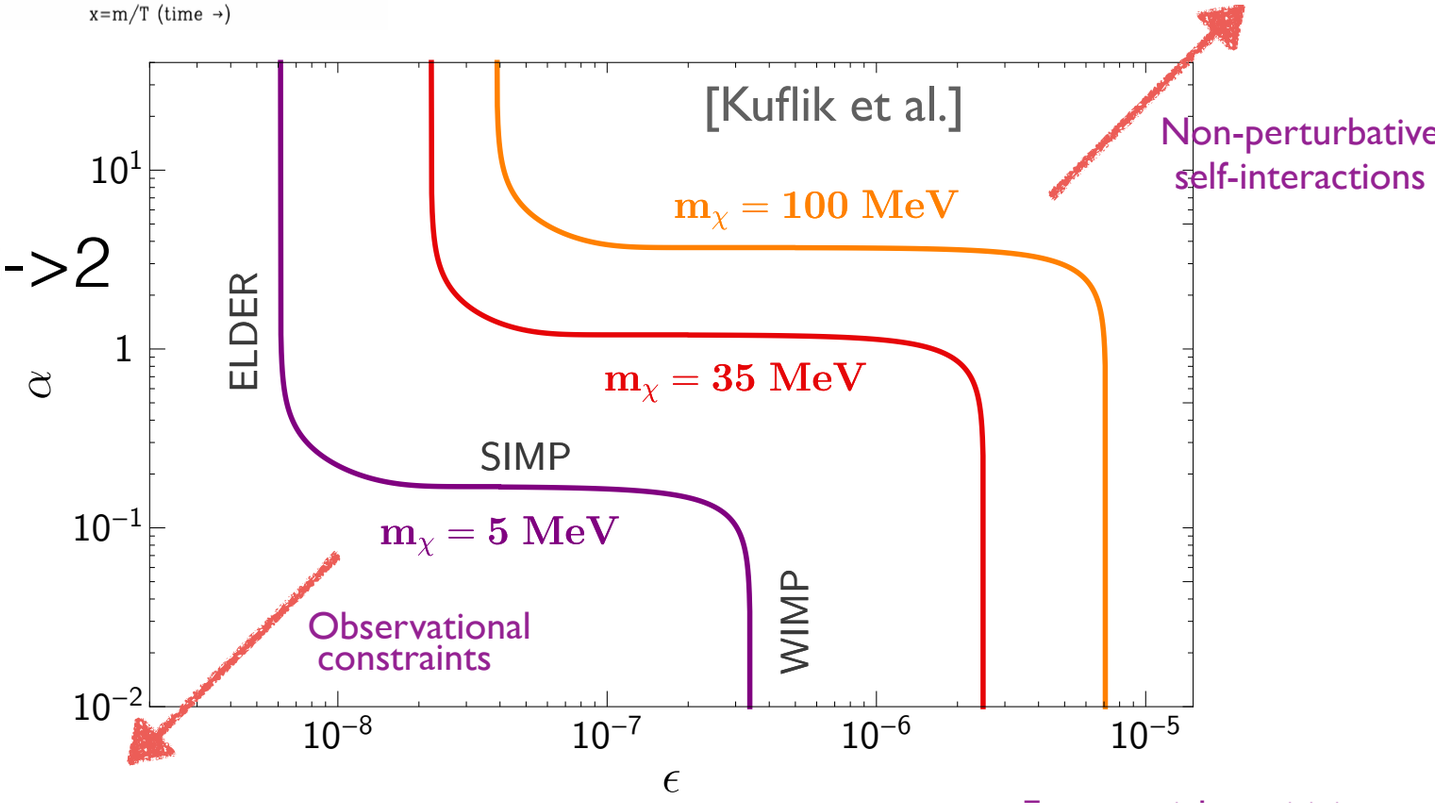
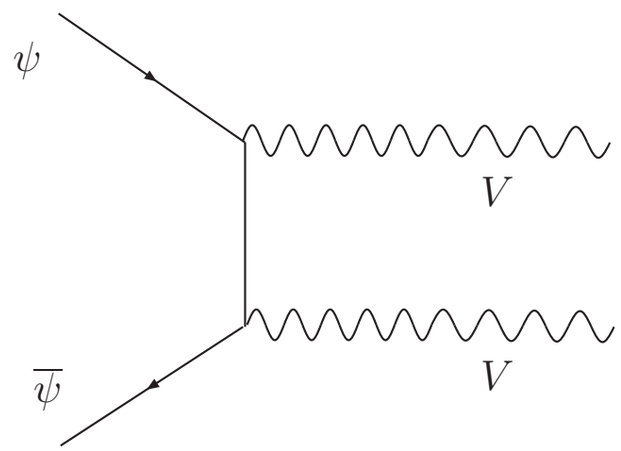


DM-SM elastic scatter

Hidden sector DM—thermal relics

[Pospelov, Ritz, Voloshin]

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

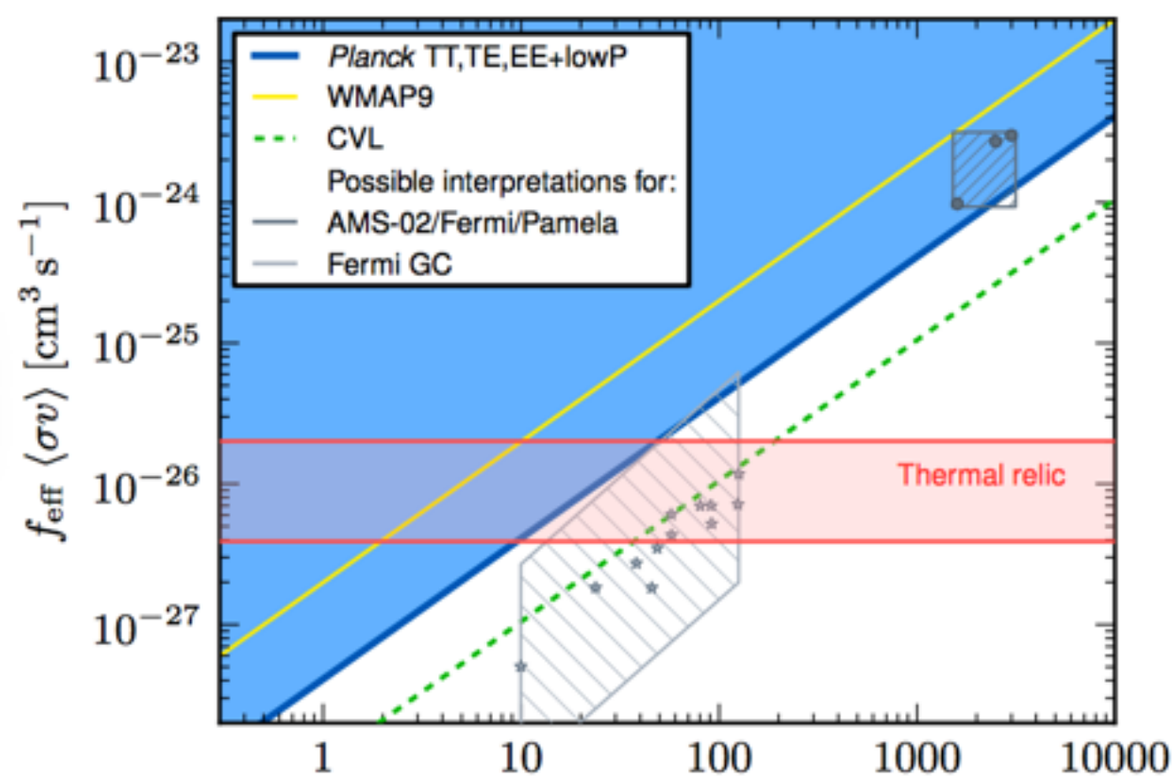


Decouples direct detection from thermal history

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

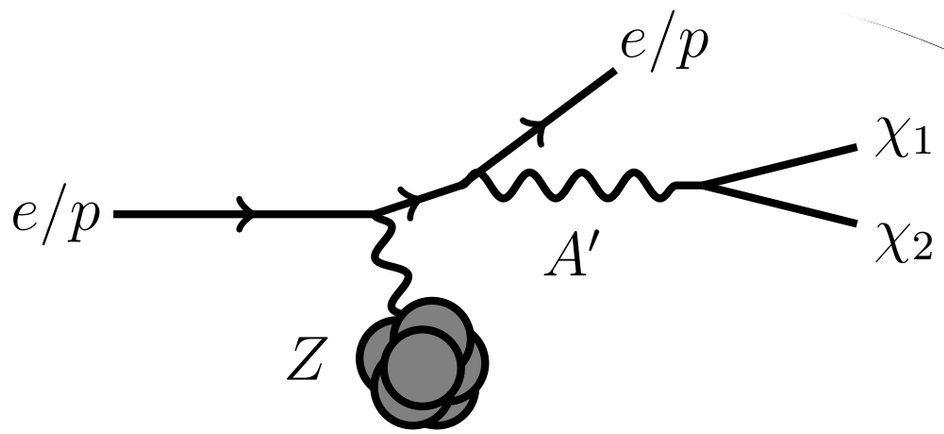
No SM matter directly charged under $U(1)_{\text{dark}}$ use a portal

[Holdom]

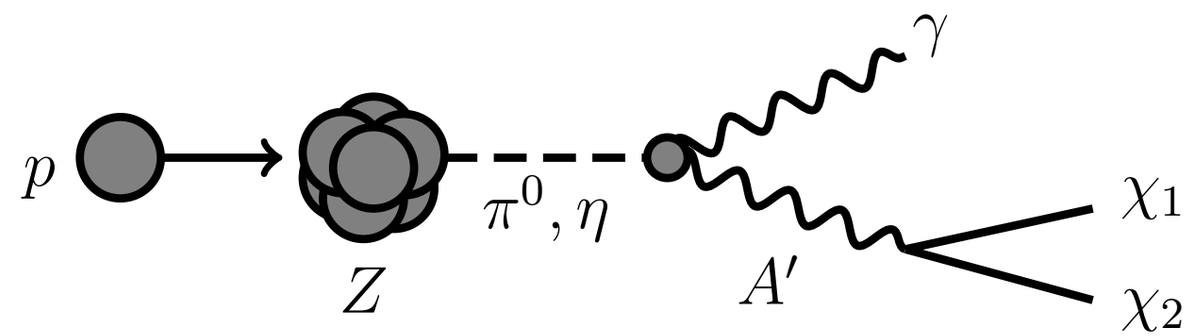
$$\mathcal{L}_{\text{kinetic mixing}} = \epsilon\, F^{\mu\nu} F'_{\mu\nu}$$

SM picks up “dark milli-charge”

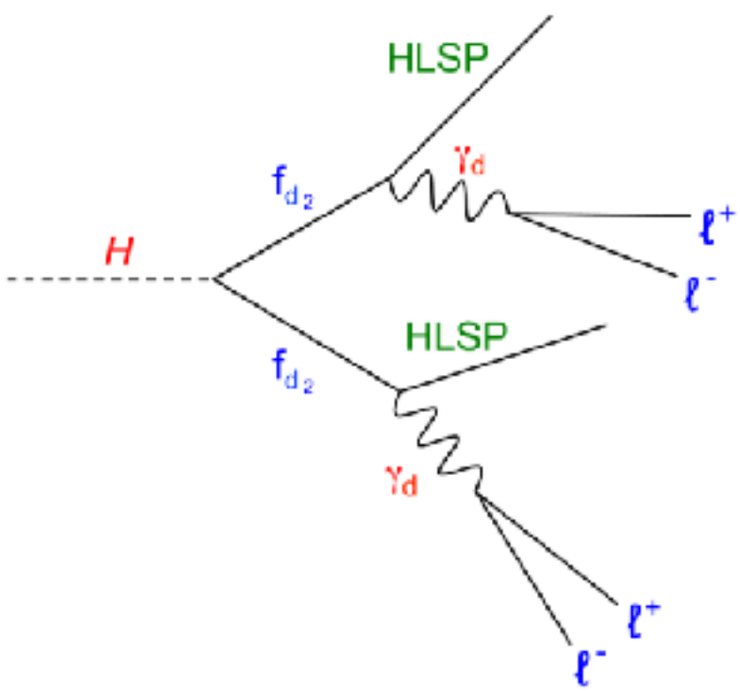
- Small couplings to SM means small production rates
- Visible/invisible decays depending on thresholds
- Possibly long lived—displaced signatures
- Many possible ways to search for DM/dark photon



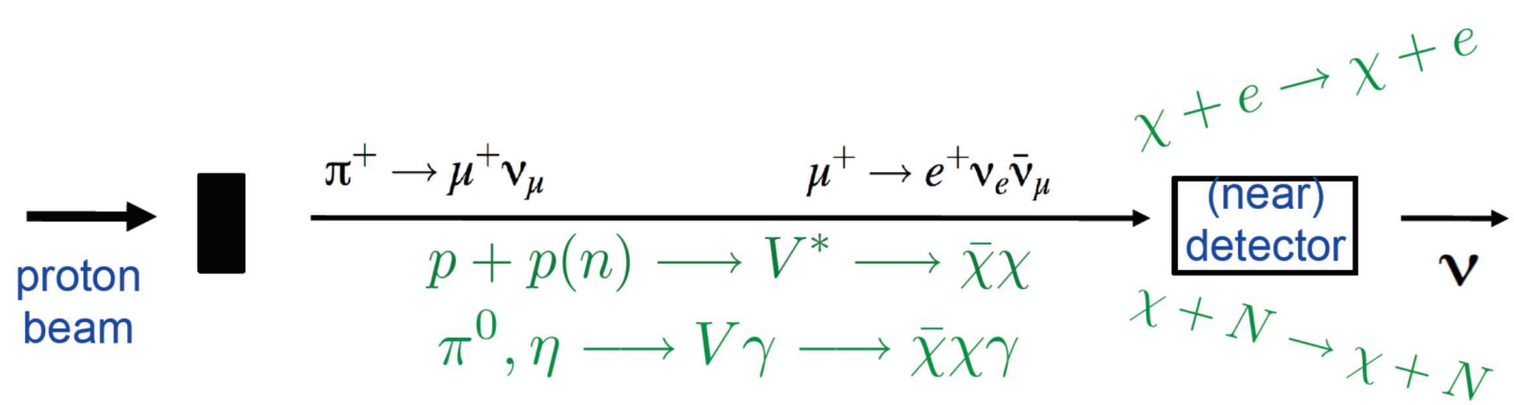
Bremsstrahlung
(LDMX, DarkLight, …)



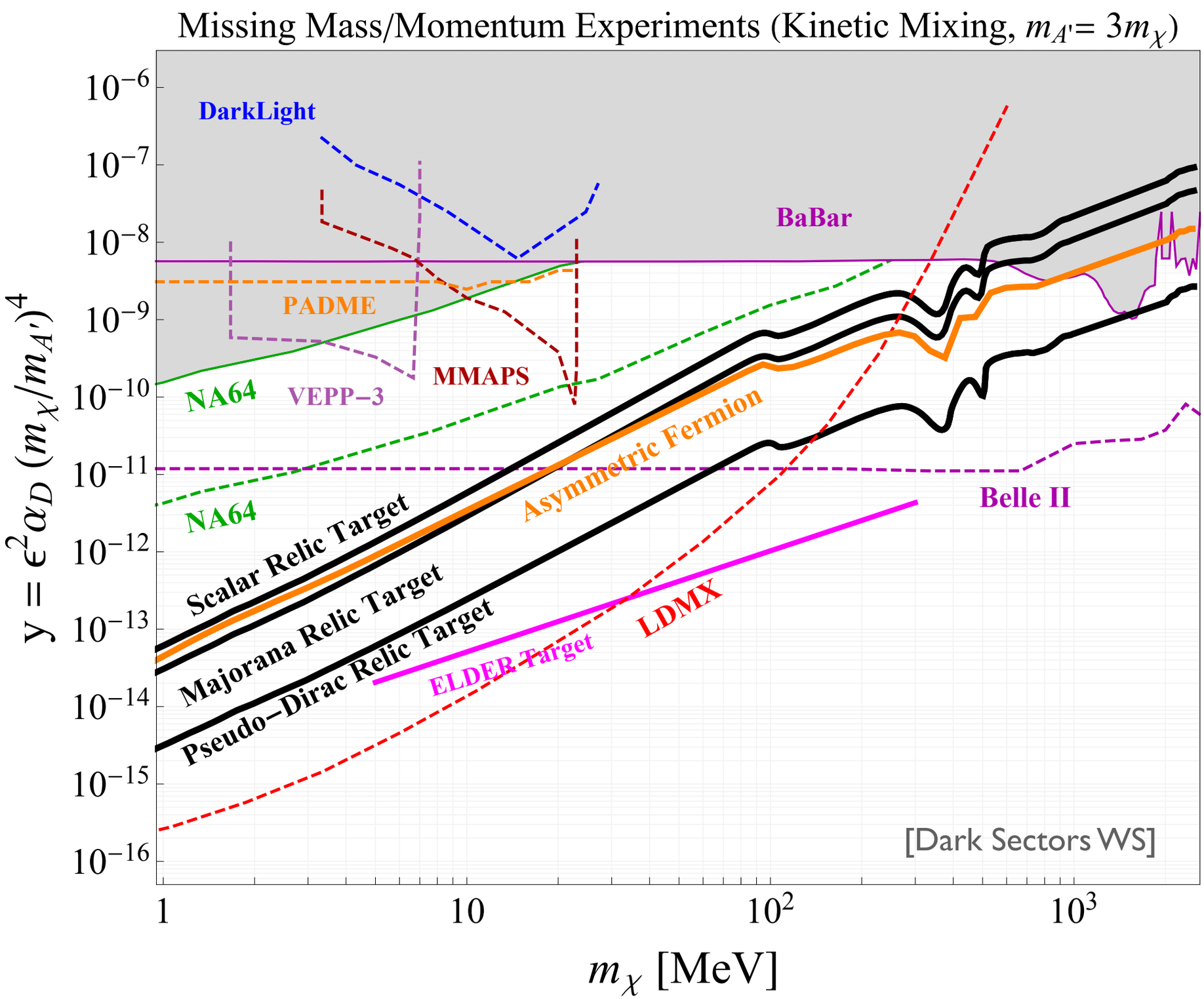
Meson decay
(NA48)

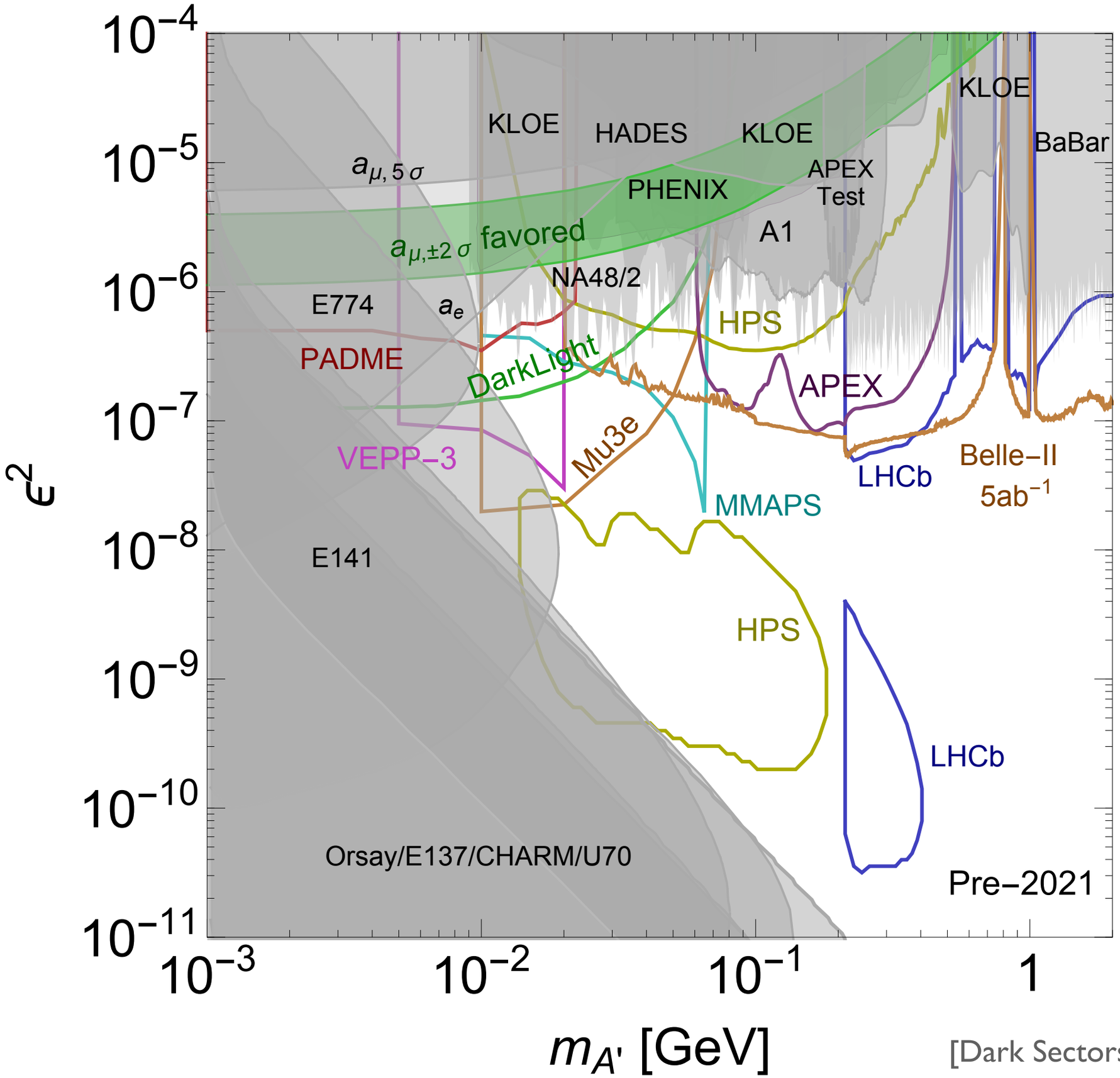


Lepton jets, Emerging tracks
(LHC)



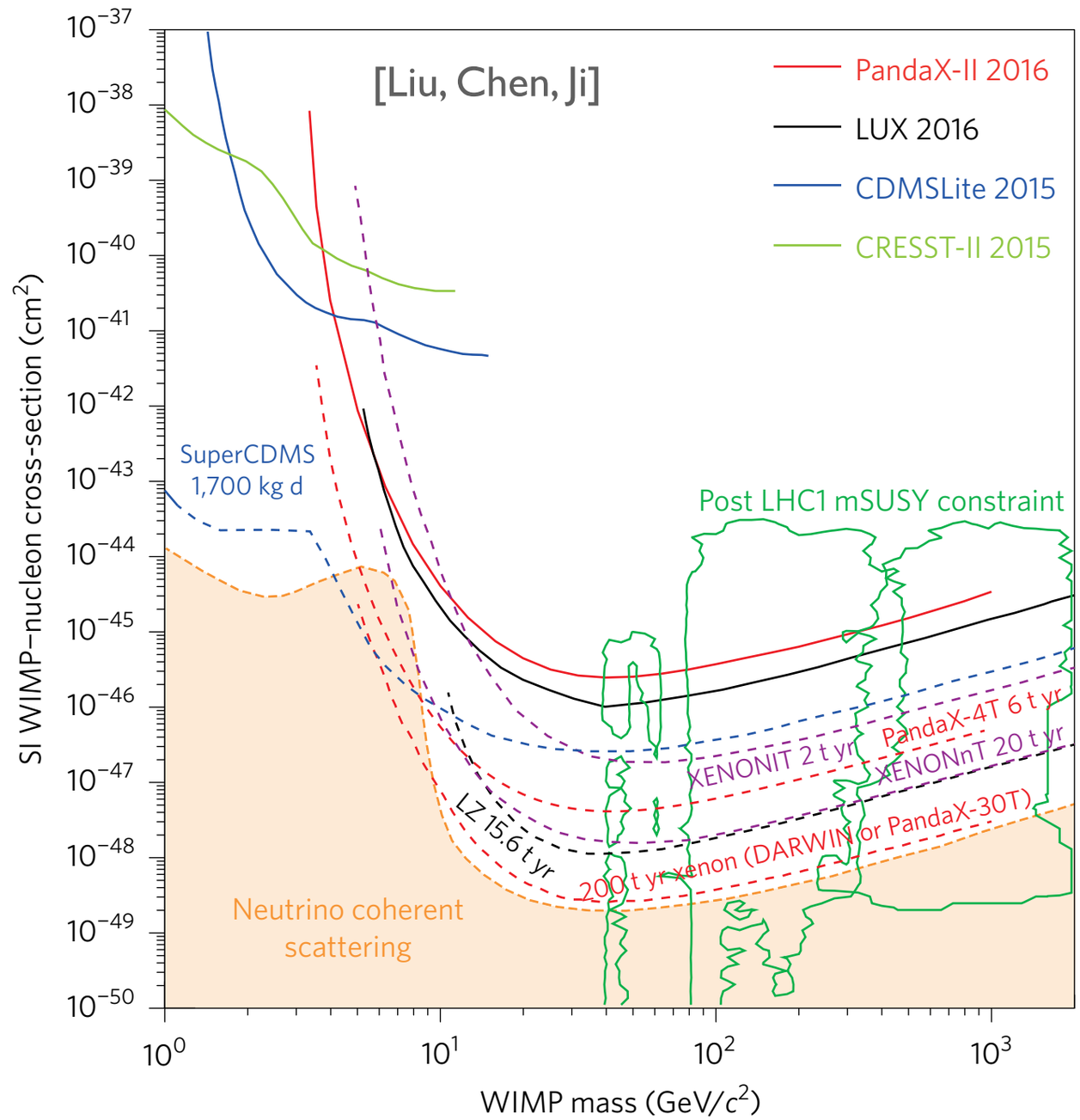
Production and scattering
(MiniBooNE, SHiP,…)


Missing Mass/Momentum Experiments (Kinetic Mixing, $m_{A'} = 3m_\chi$)
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]
$y = \epsilon^2 \alpha_D (m_\chi/m_{A'})^4$
m_χ [MeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
1
10
10^2
10^3



[Dark Sectors WS]

Dark sectors and direct detection



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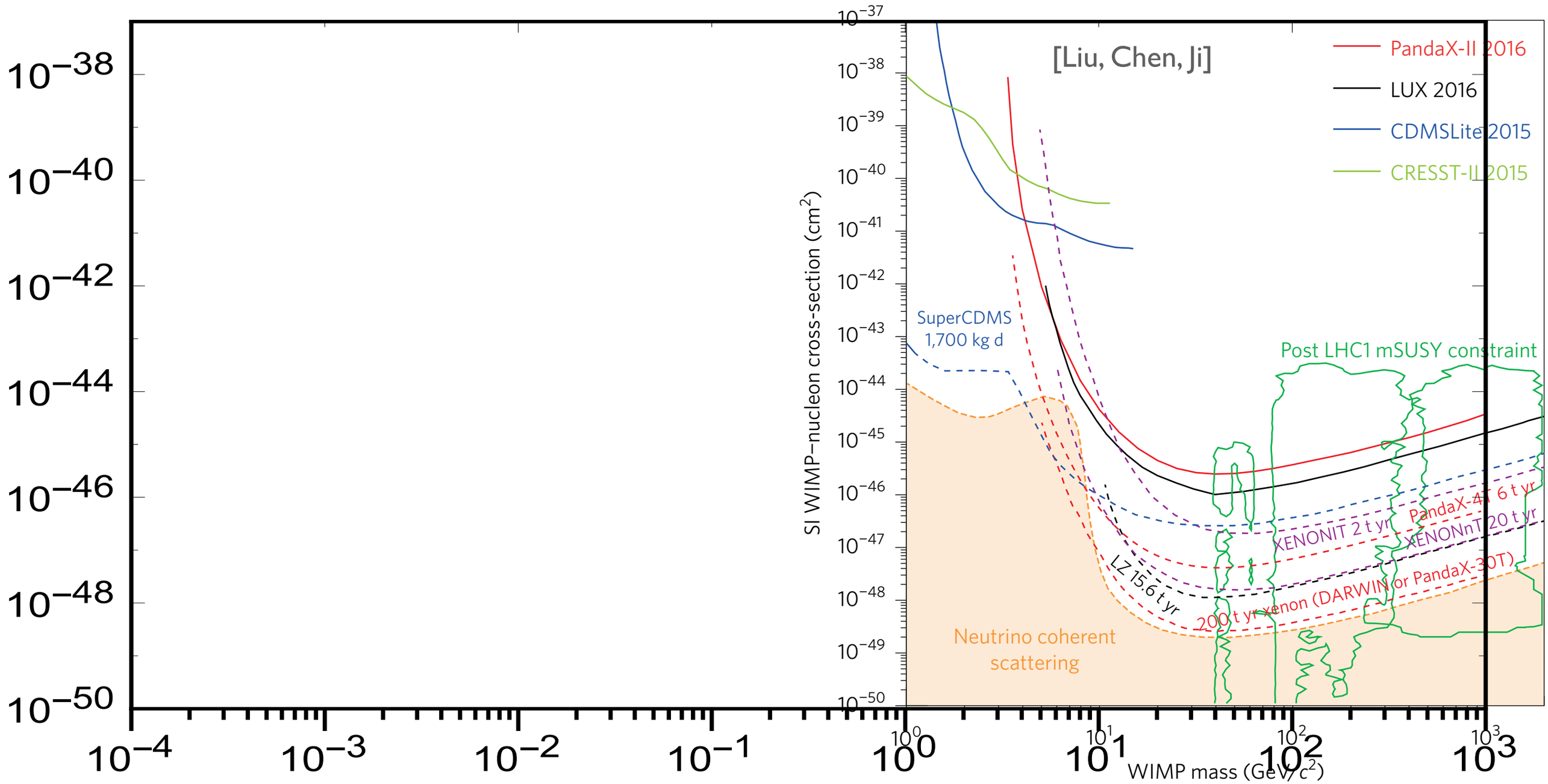
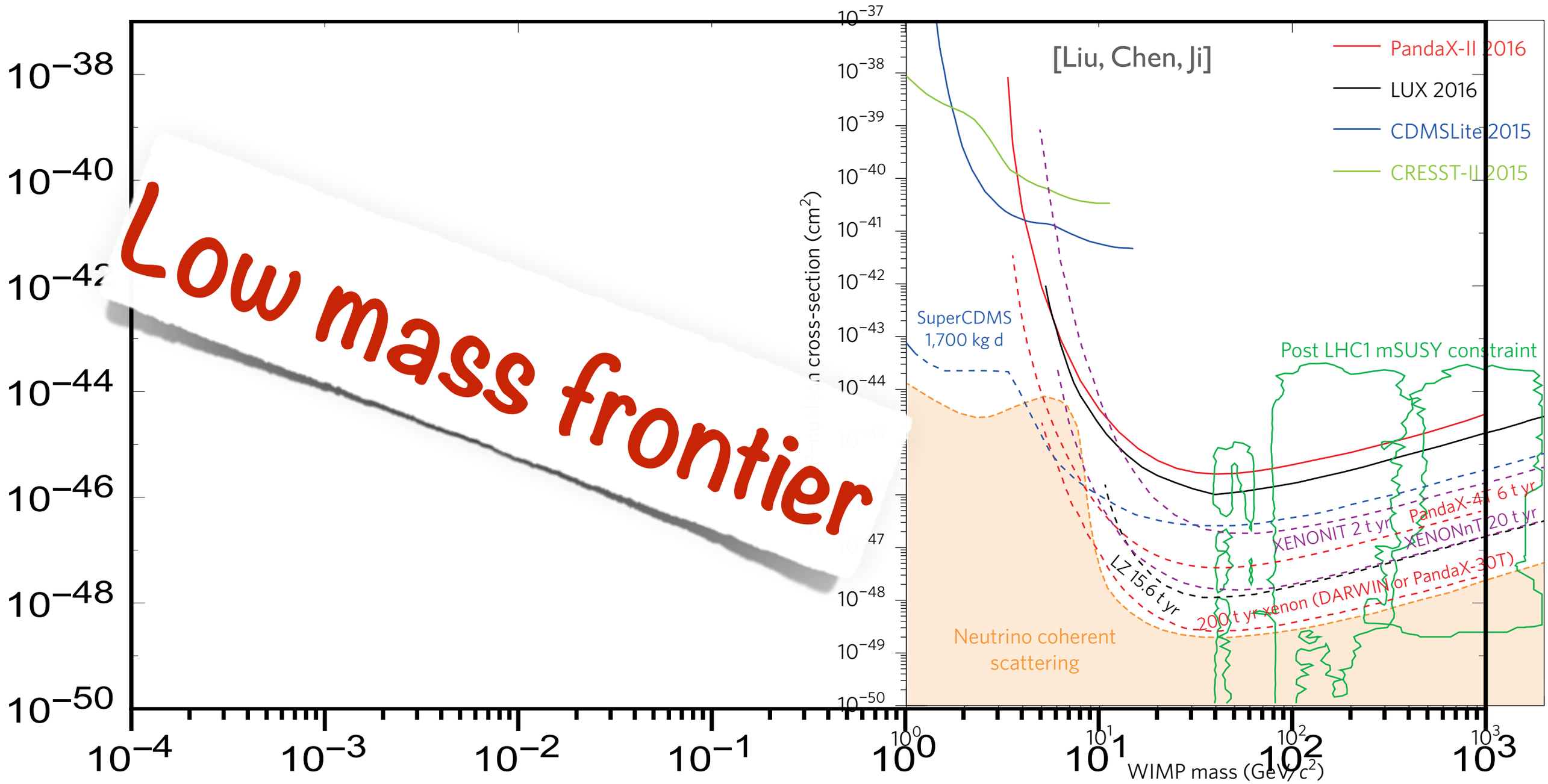
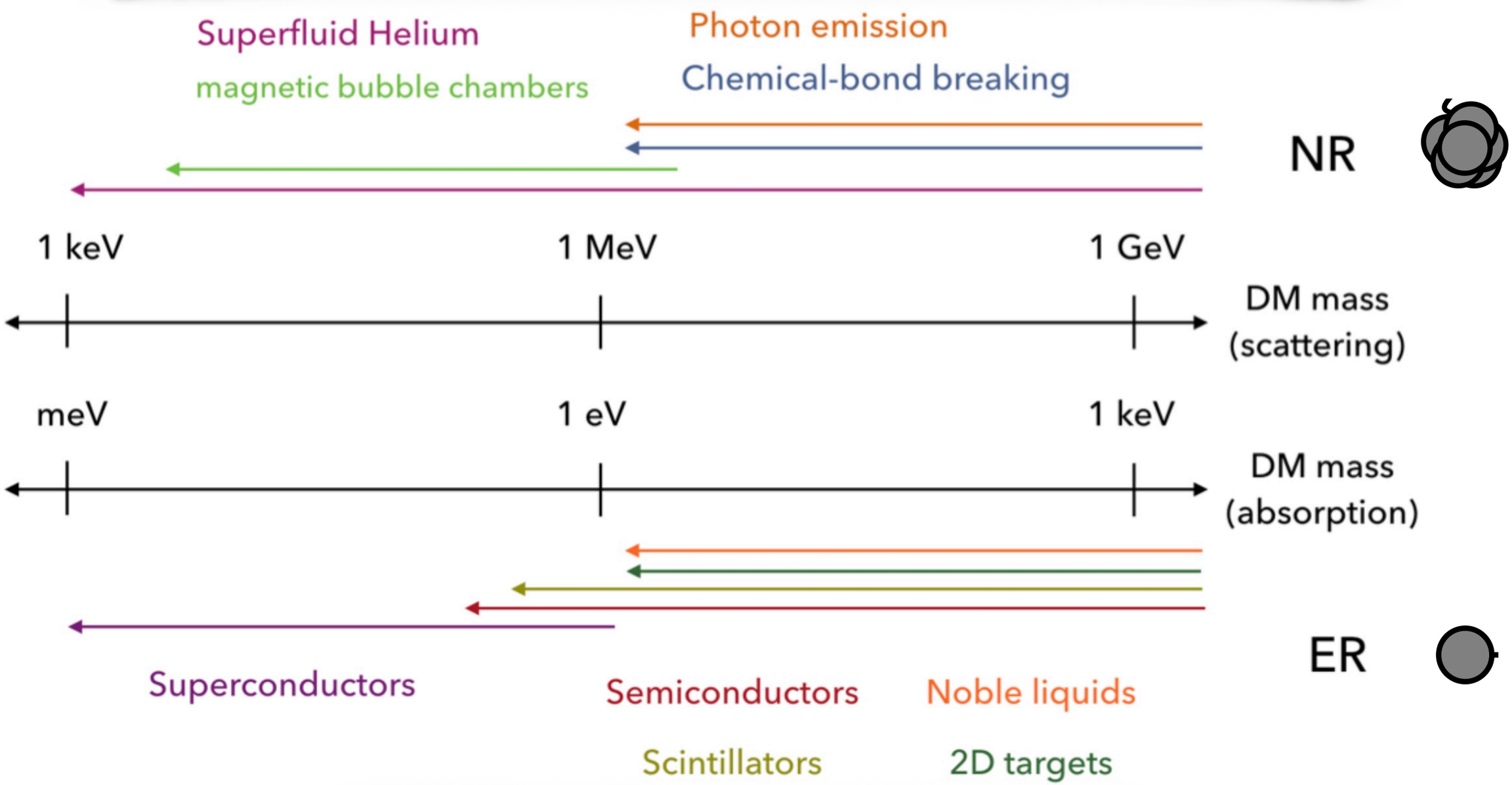


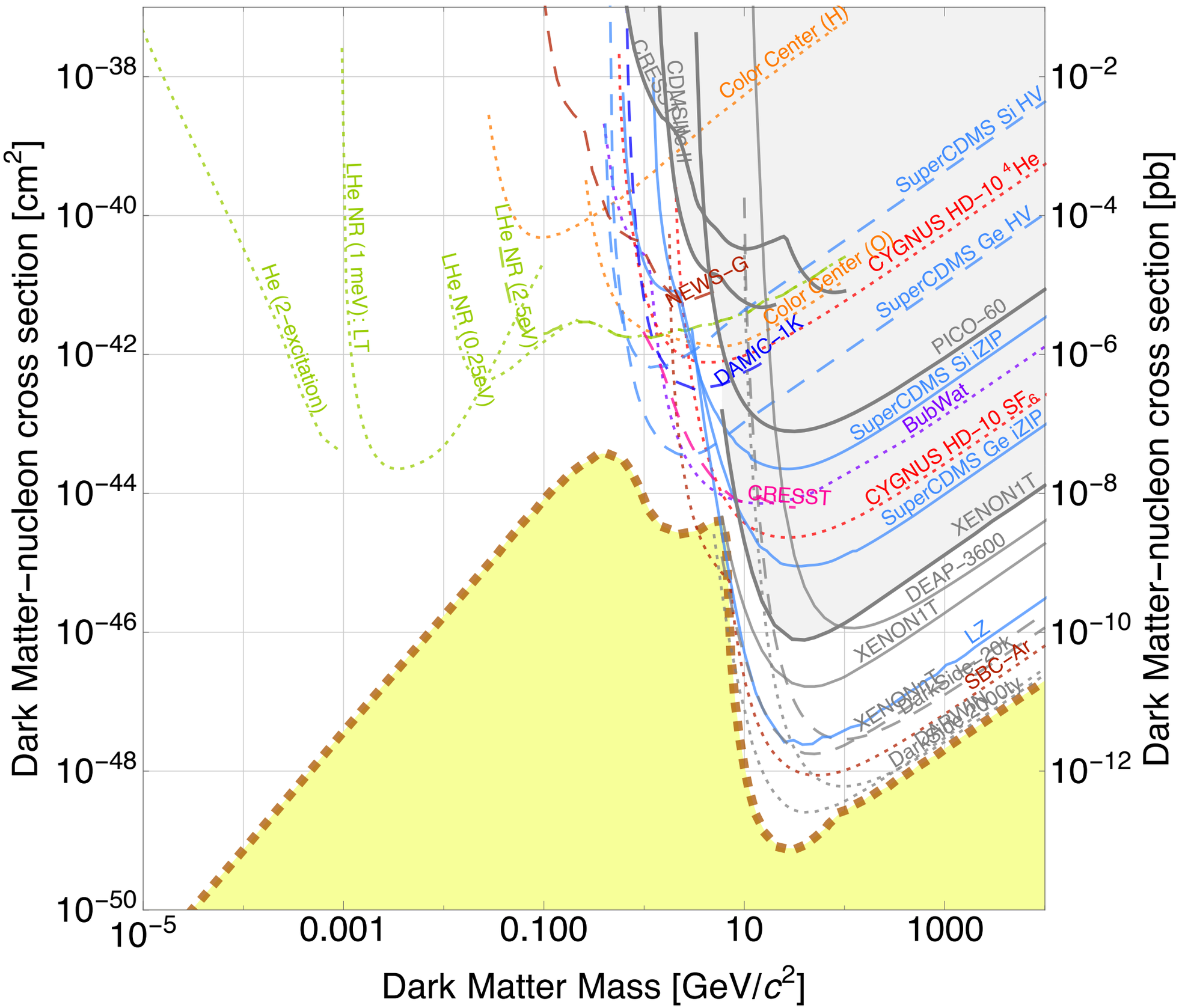
Dark sectors and direct detection

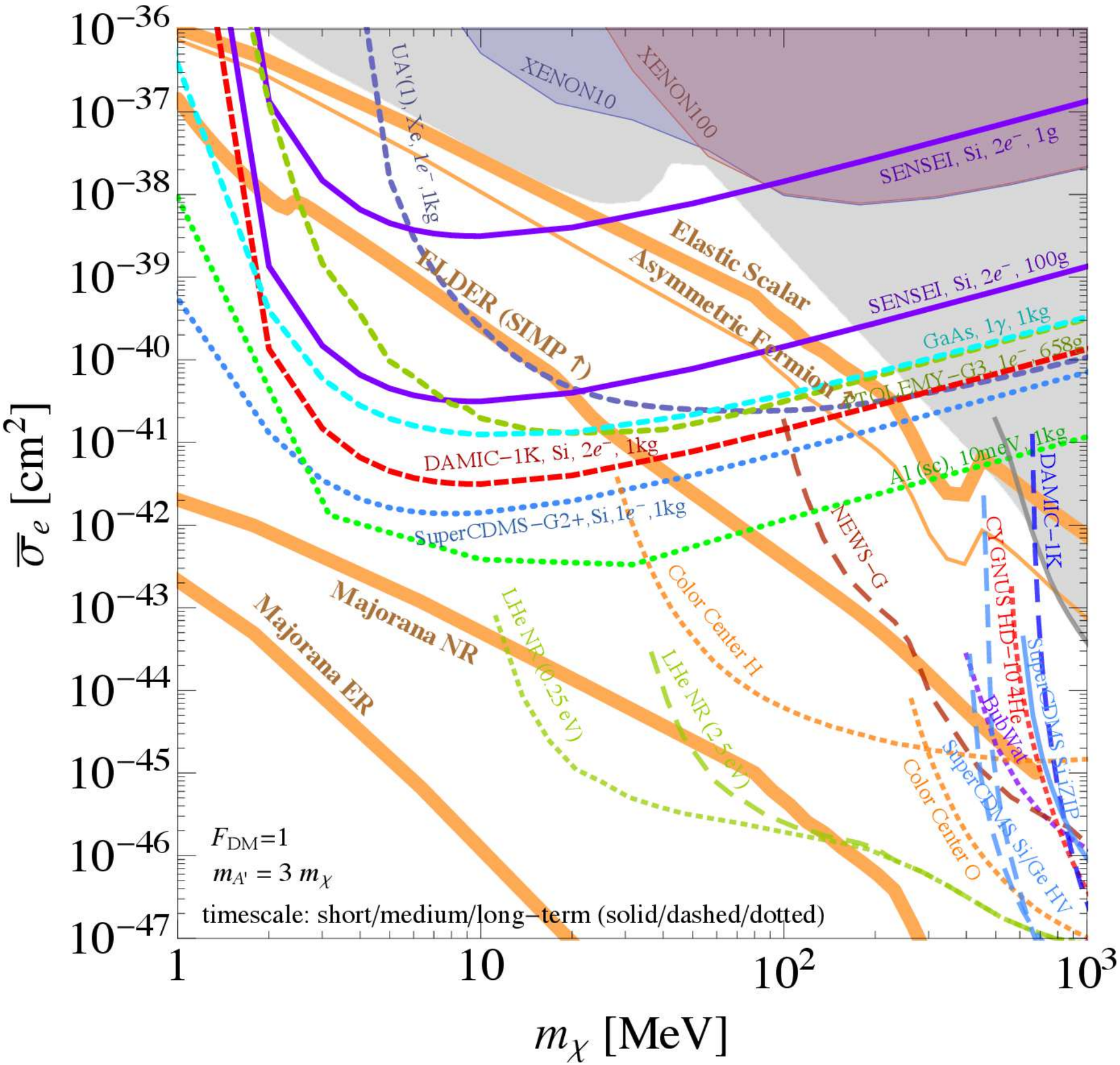


$$E_{\rm NR} = \frac{q^2}{2m_N} \leq \frac{2\mu_{\chi N}^2 v_\chi^2}{m_N} \lesssim 190\ {\rm eV} \times \left(\frac{m_\chi}{500\ {\rm MeV}}\right)^2 \left(\frac{16\ {\rm GeV}}{m_N}\right)$$



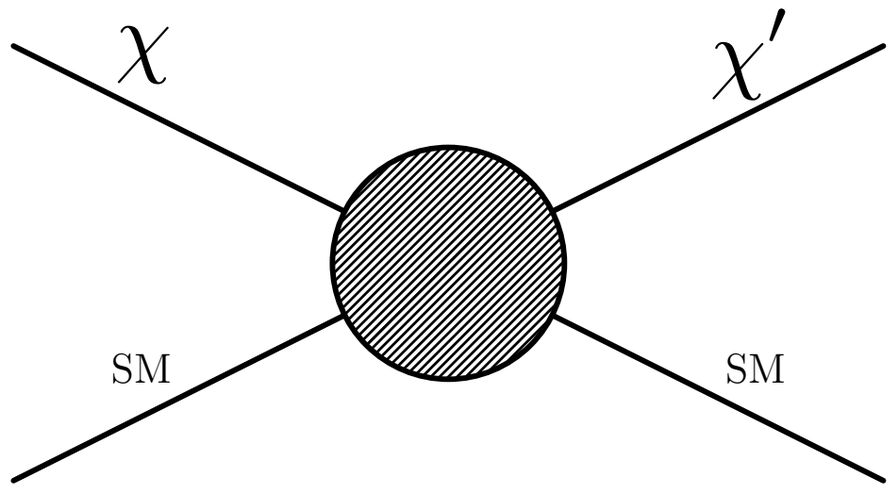
$$E_e \leq \frac{1}{2} m_\chi v_\chi^2 \lesssim 3\ {\rm eV} \left(\frac{m_\chi}{\rm MeV}\right)$$


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
Color Center (H)
CRESST
CDMSLite H
SuperCDMS Si HV
CYGNUS HD-10 ^{4}He
SuperCDMS Ge HV
Color Center (O)
NEWS-G
DAMIC-1K
PICO-60
SuperCDMS Si iZIP
BubWat
CYGNUS HD-10 SF$_6$
SuperCDMS Ge iZIP
CRESST
XENON1T
DEAP-3600
XENON1T
LZ
DarkSide-20k
SBC-Ar
XENON1T
DarkSide-200
DAMIC-1000ty
LHe NR (1 meV): LT
He (2-excitation)
LHe NR (2.5eV)
LHe NR (0.25eV)


$\overline{\sigma}_e$ [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
PTOLEMY−G3, $1e^-$, 658g
DAMIC−1K, Si, $2e^-$, 1kg
Al (sc), 10meV, 1kg
DAMIC−1K
SuperCDMS−G2+, Si, $1e^-$, 1kg
NEWS−G
CYGNUS HD−10 4He
BubWat
SuperCDMS SiZIP
SuperCDMS Si/Ge HV
Color Center H
Color Center O
Majorana NR
Majorana ER
LHe NR (0.25 eV)
LHe NR (2.5 eV)
$F_{\rm DM}$=1
$m_{A'} = 3\, m_\chi$
timescale: short/medium/long−term (solid/dashed/dotted)

Inelastic Dark Matter (iDM)

[Weiner and Tucker-Smith]



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

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

Dirac fermion coupled to vector, with small Majorana masses

$$V_\mu \left(\chi_1^\dagger \bar{\sigma}^\mu \chi_1 - \chi_2^\dagger \bar{\sigma}^\mu \chi_2 \right) + m_D \left(\chi_1 \chi_2 + \text{h.c.} \right)$$
$$+ \delta_1 \left(\chi_1 \chi_1 + \text{h.c.} \right) + \delta_2 \left(\chi_2 \chi_2 + \text{h.c.} \right)$$

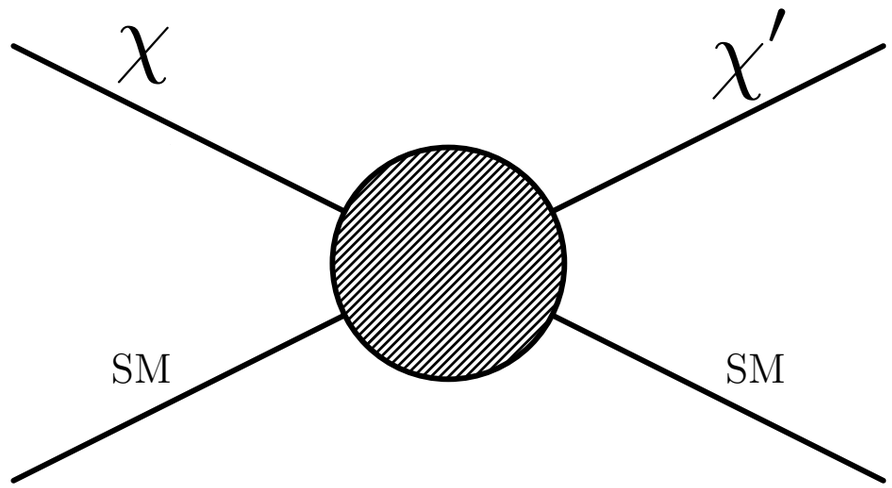
Mass eigenstates only have off-diagonal couplings
e.g. (almost) pure Higgsinos

DM couples to the Z
(a WIMP!)

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

Inelastic Dark Matter (iDM)

[Weiner and Tucker-Smith]



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

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

Dirac fermion coupled to vector, with small Majorana masses

$$V_\mu \left(\chi_1^\dagger \bar{\sigma}^\mu \chi_1 - \chi_2^\dagger \bar{\sigma}^\mu \chi_2 \right) + m_D \left(\chi_1 \chi_2 + \text{h.c.} \right)$$
$$+ \delta_1 \left(\chi_1 \chi_1 + \text{h.c.} \right) + \delta_2 \left(\chi_2 \chi_2 + \text{h.c.} \right)$$

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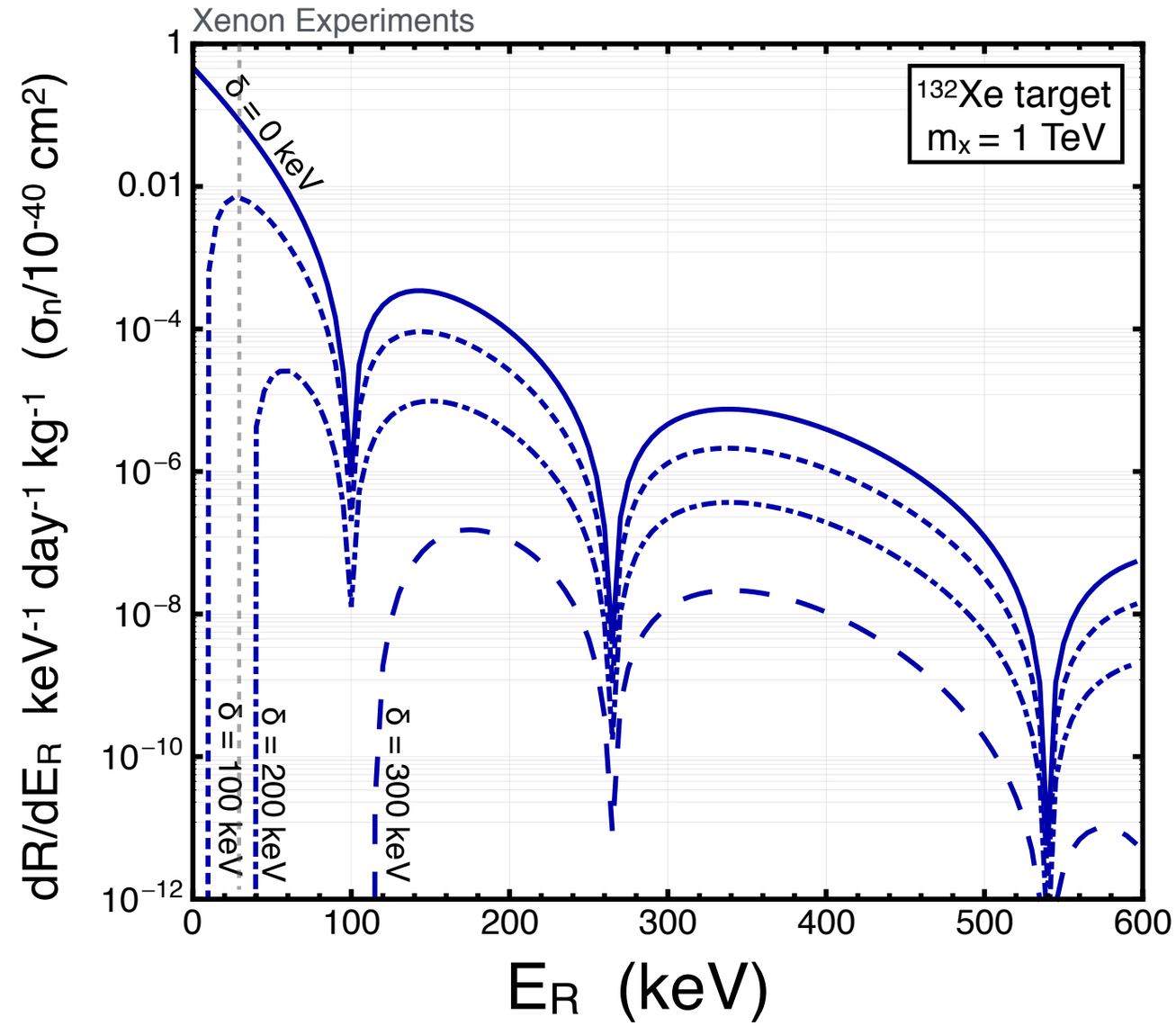
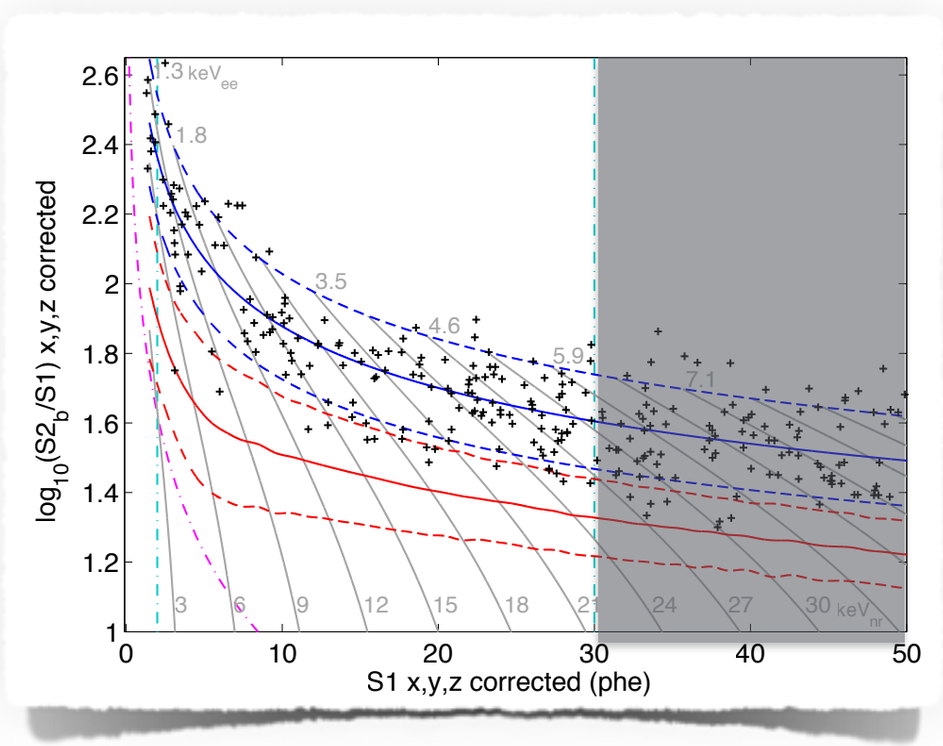
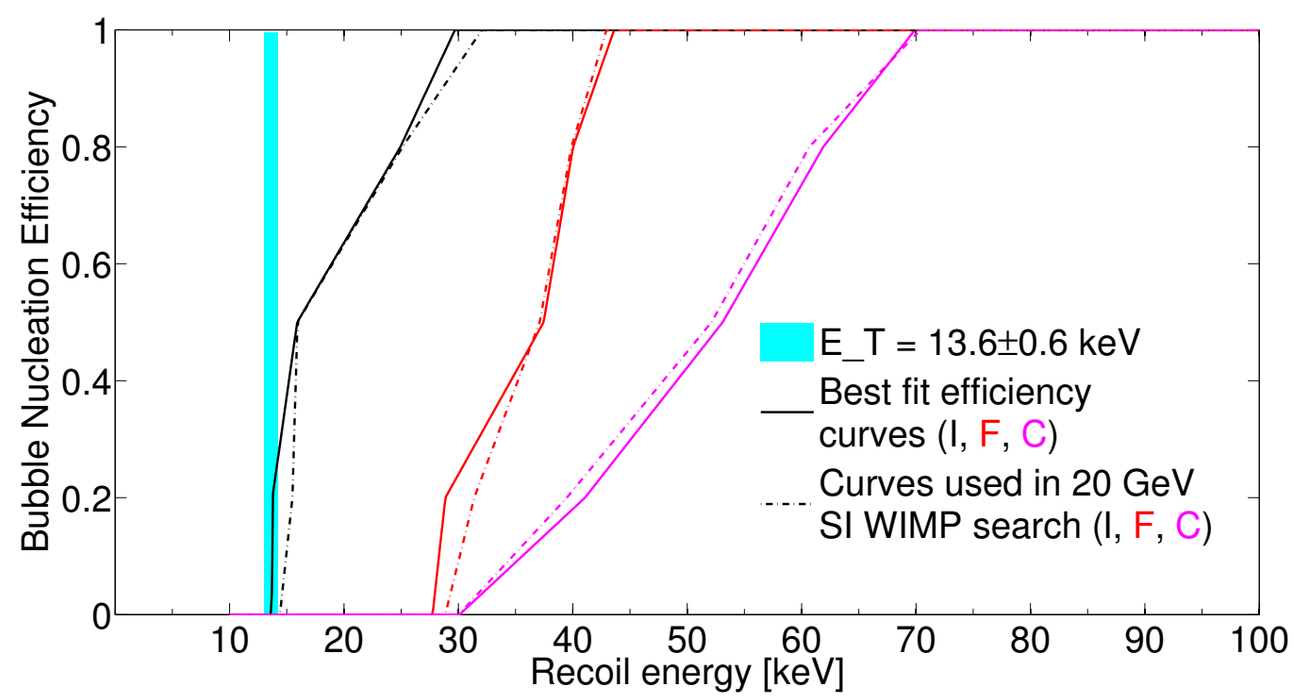
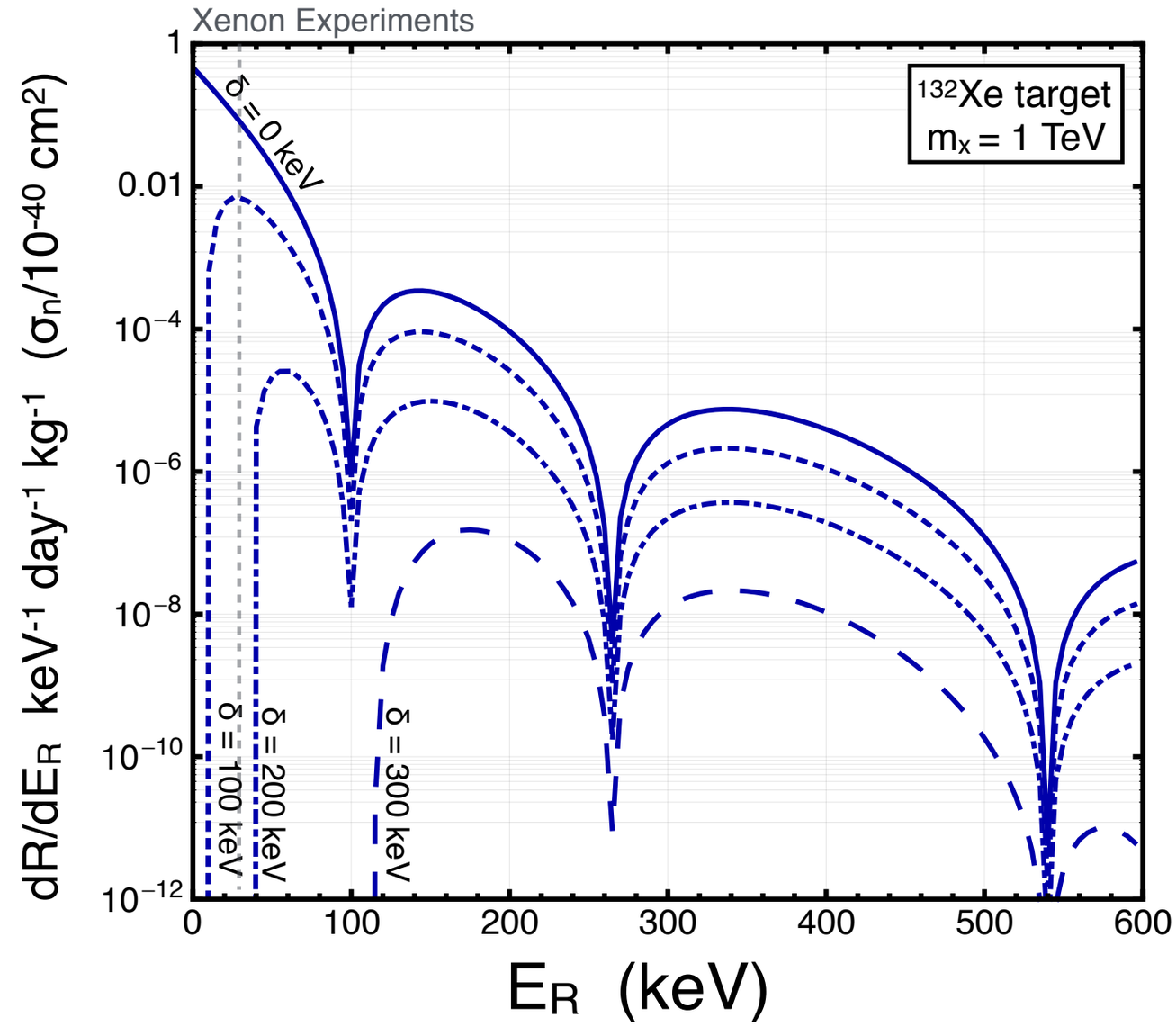
Some experiments “blind” to iDM with splittings above ~200 keV

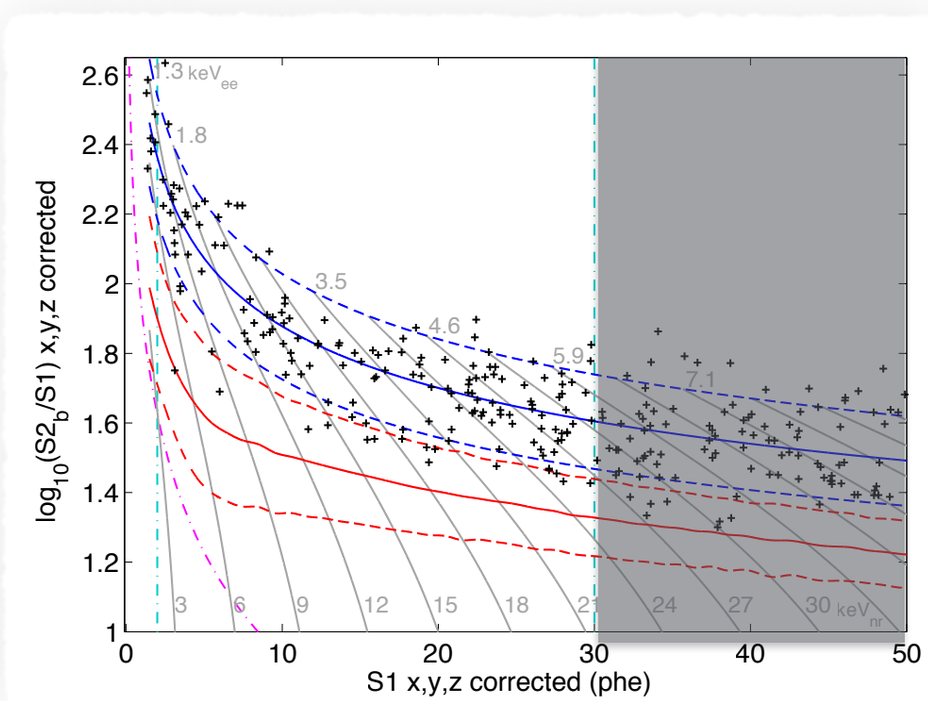


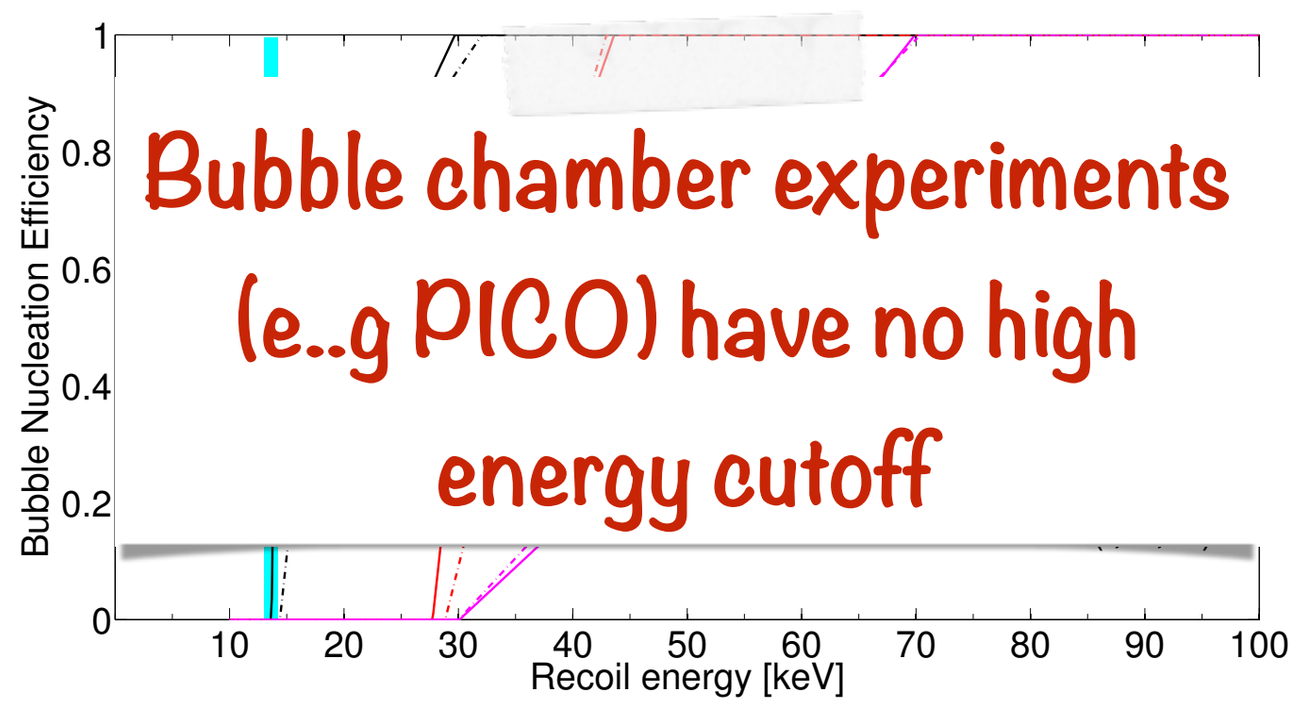




Some experiments “blind” to iDM with splittings above ~200 keV





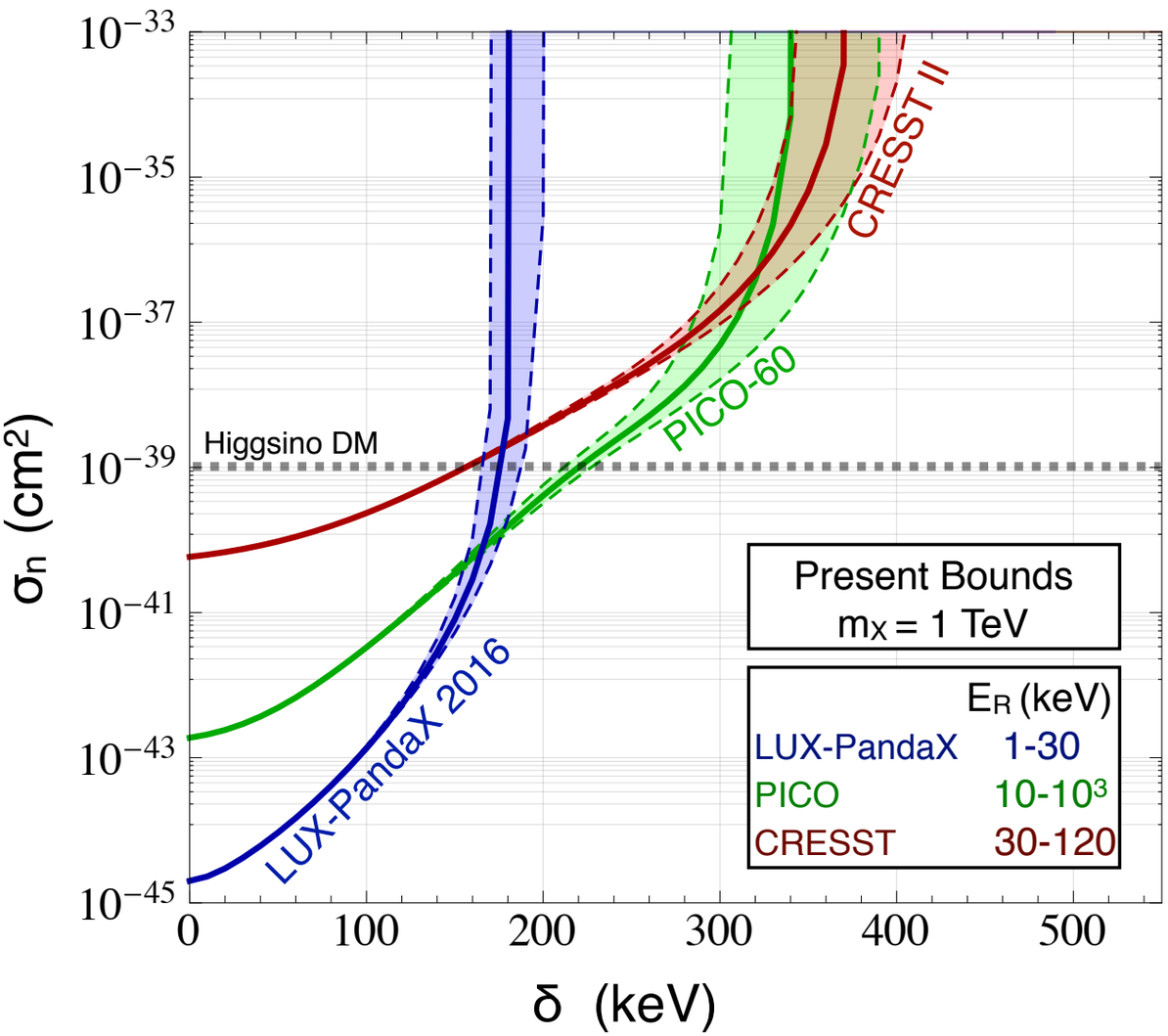


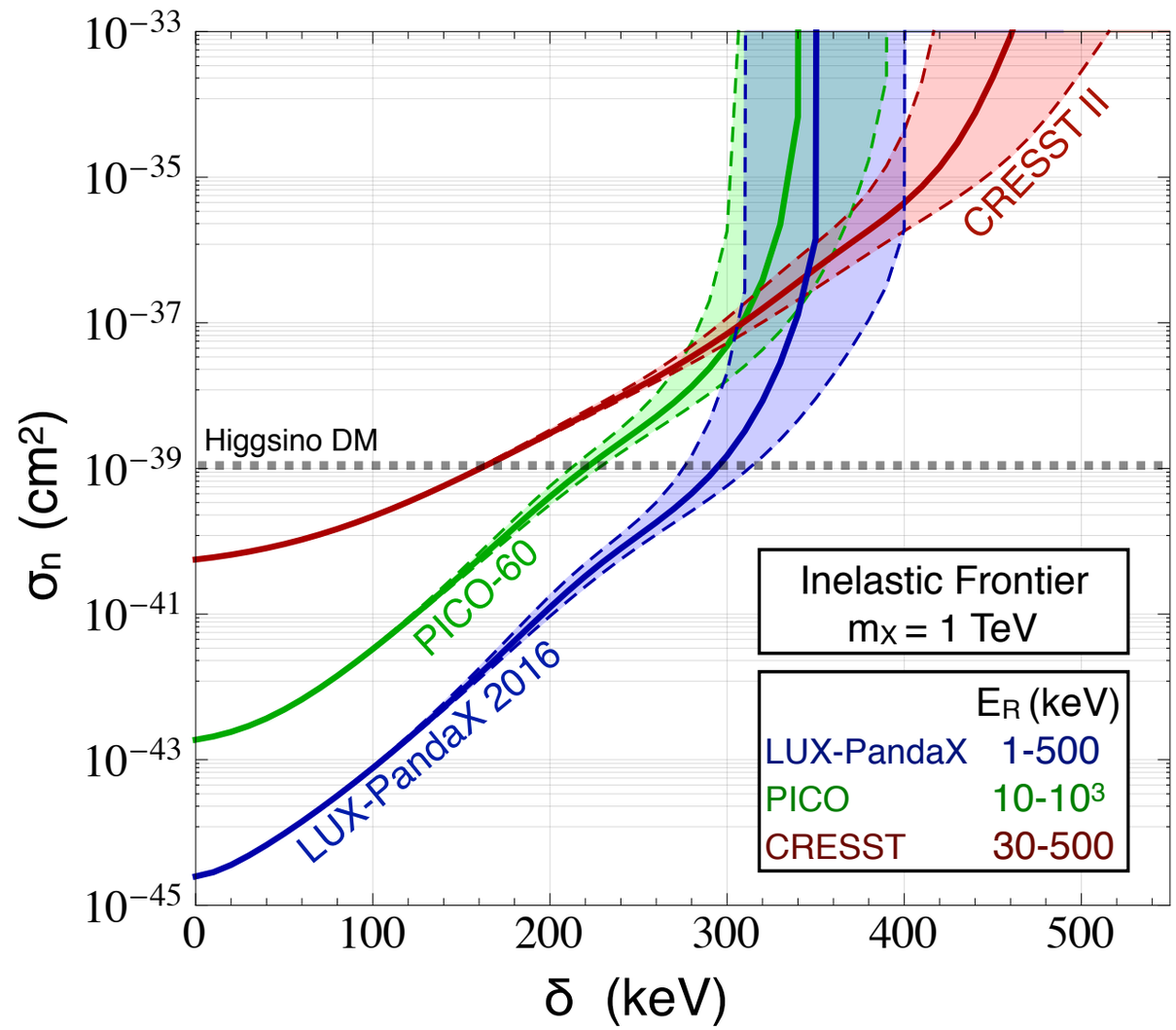
Bubble chamber experiments (e..g PICO) have no high energy cutoff

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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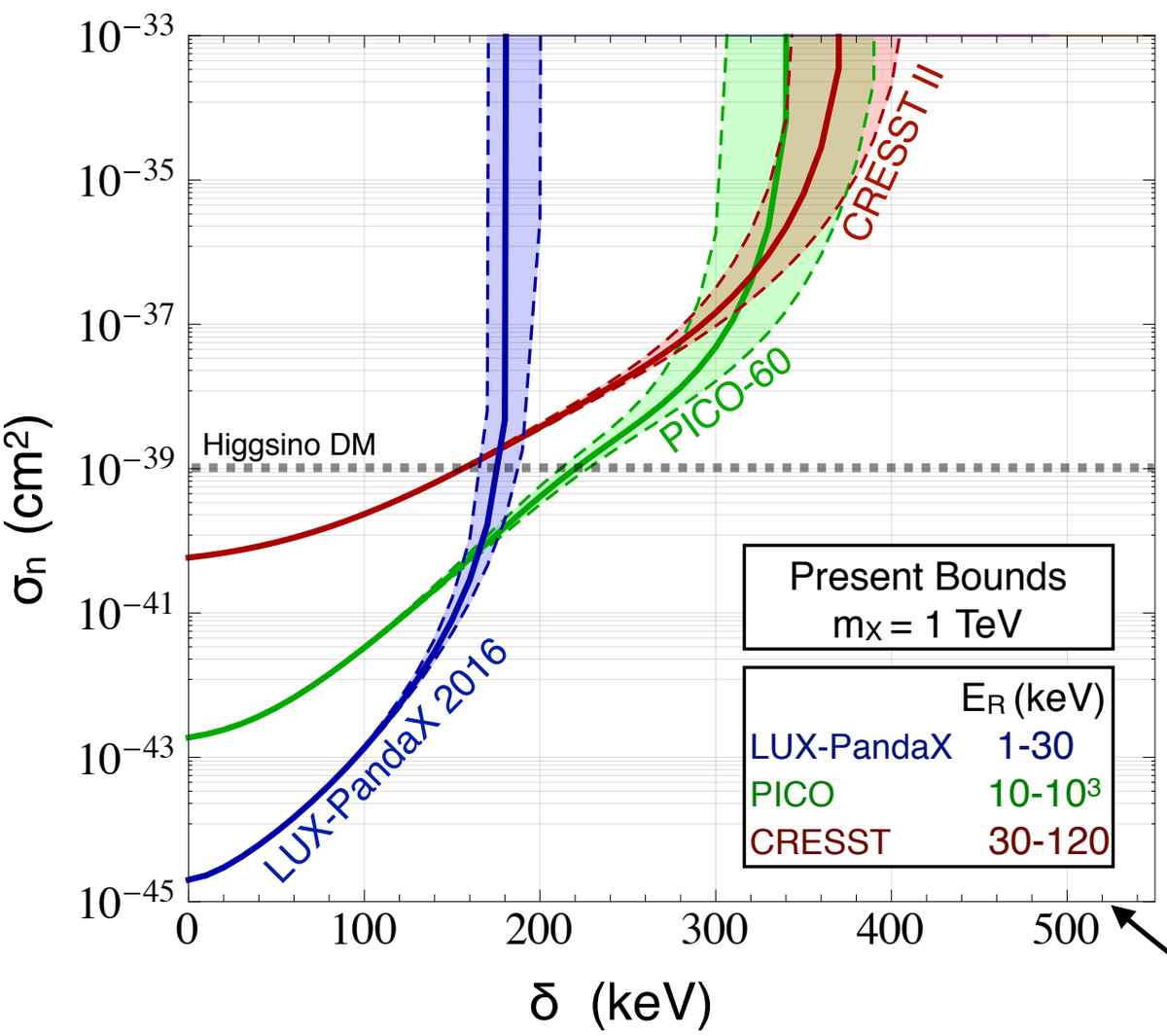
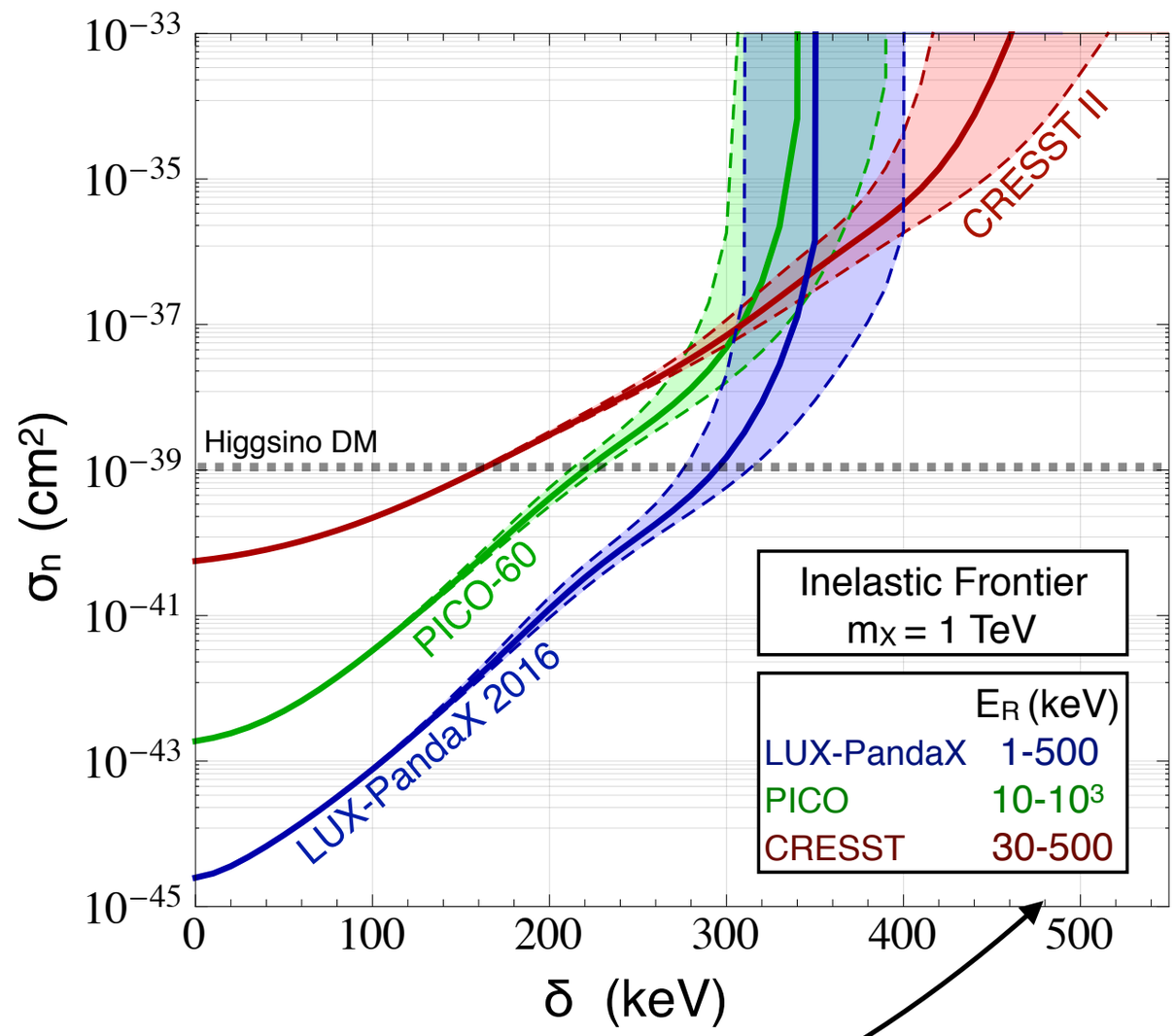
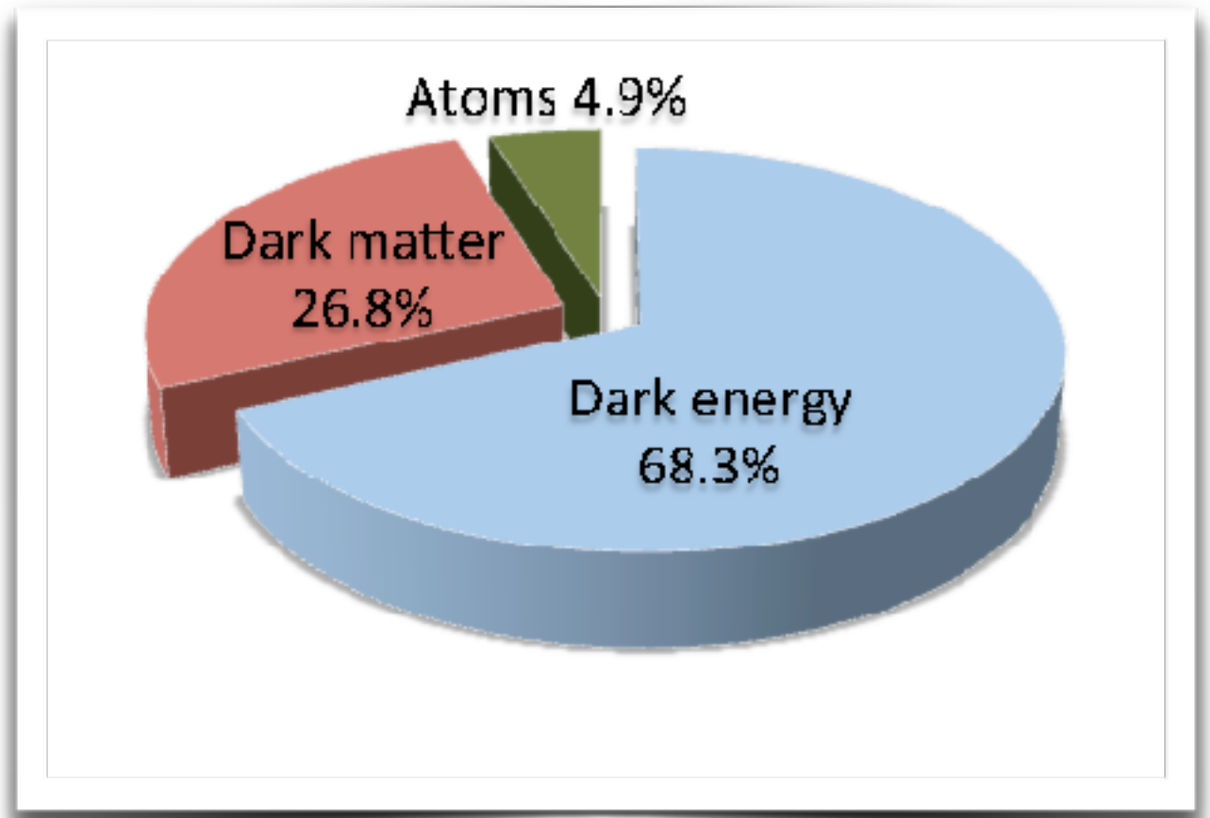




Outlook

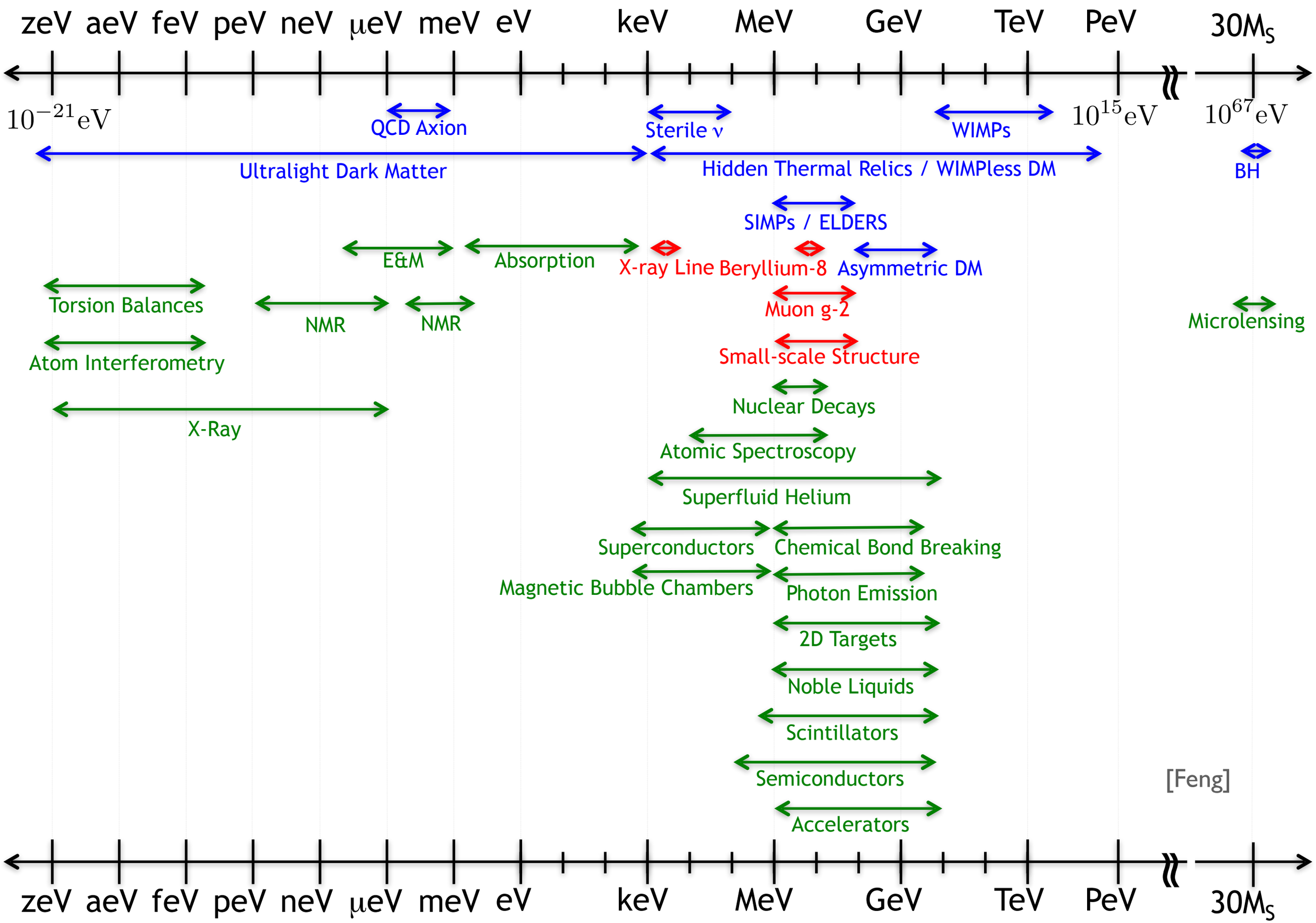
- Models of DM have come a long way in 20 years
- Result of vibrant experiment-theory interface
- Entering a new era in Dark Matter research, crossing all HEP frontiers (as well as nuclear, cond. matt. and atomic)
- Many possibilities, many search opportunities
- Many topics not discussed e.g. GCE, small scale structure, and other anomalies

Dark sector—possibly (likely?) with its own non-trivial dynamics

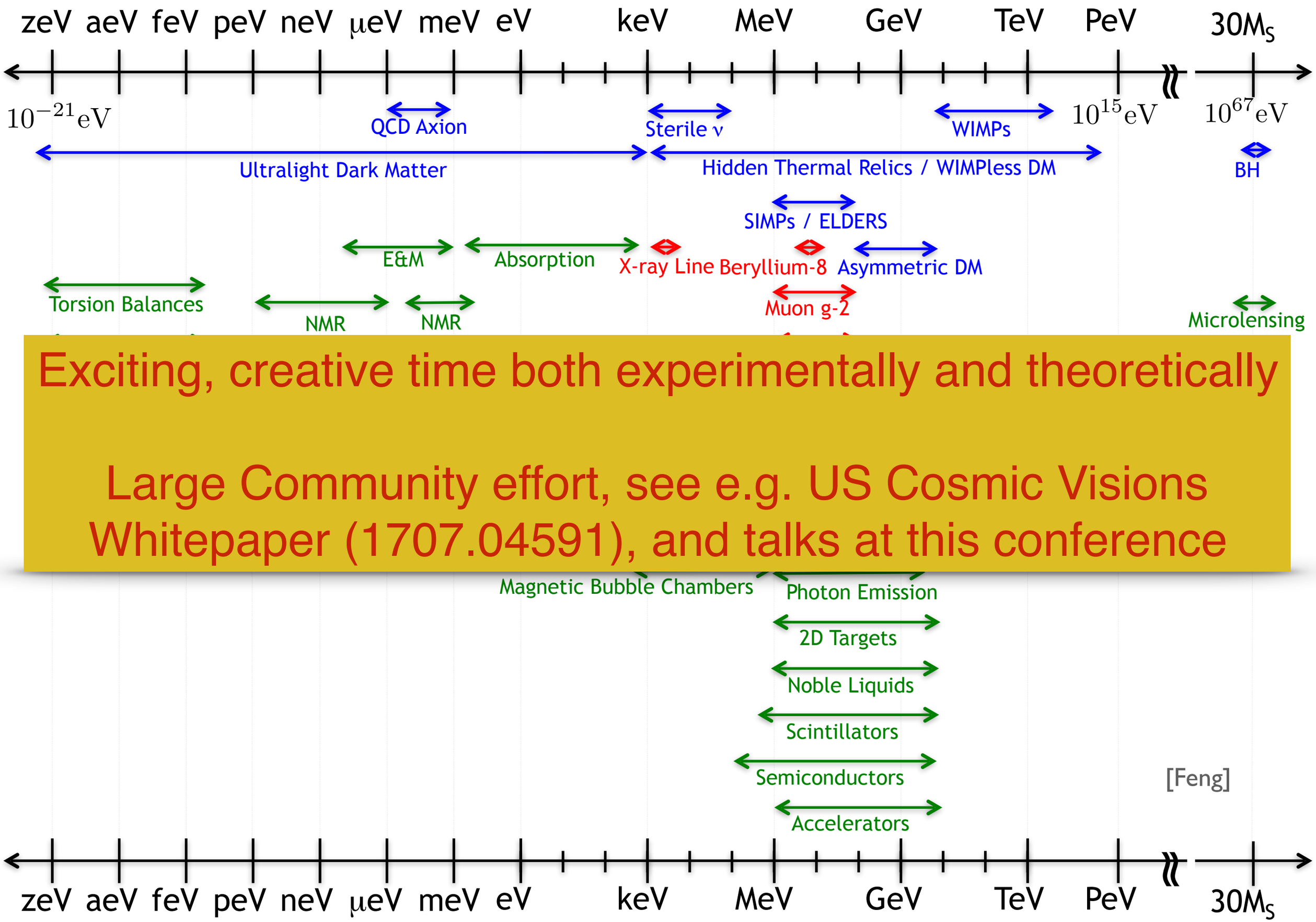


3 generations, gauge groups in 3 different phases, CPV, lots of interesting dynamics and emergent phenomena

Dark Sector Candidates, Anomalies, and Search Techniques



Dark Sector Candidates, Anomalies, and Search Techniques

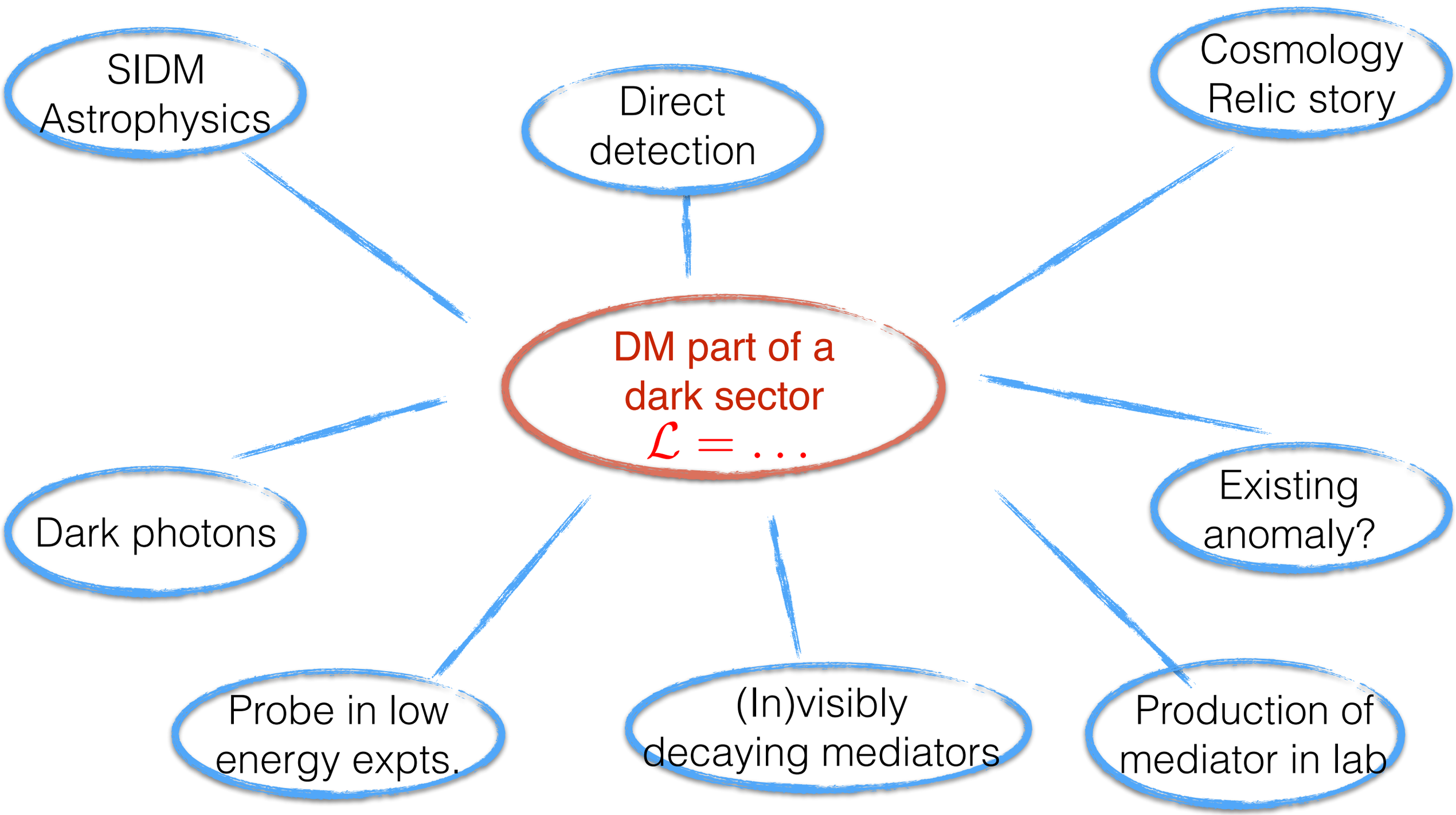


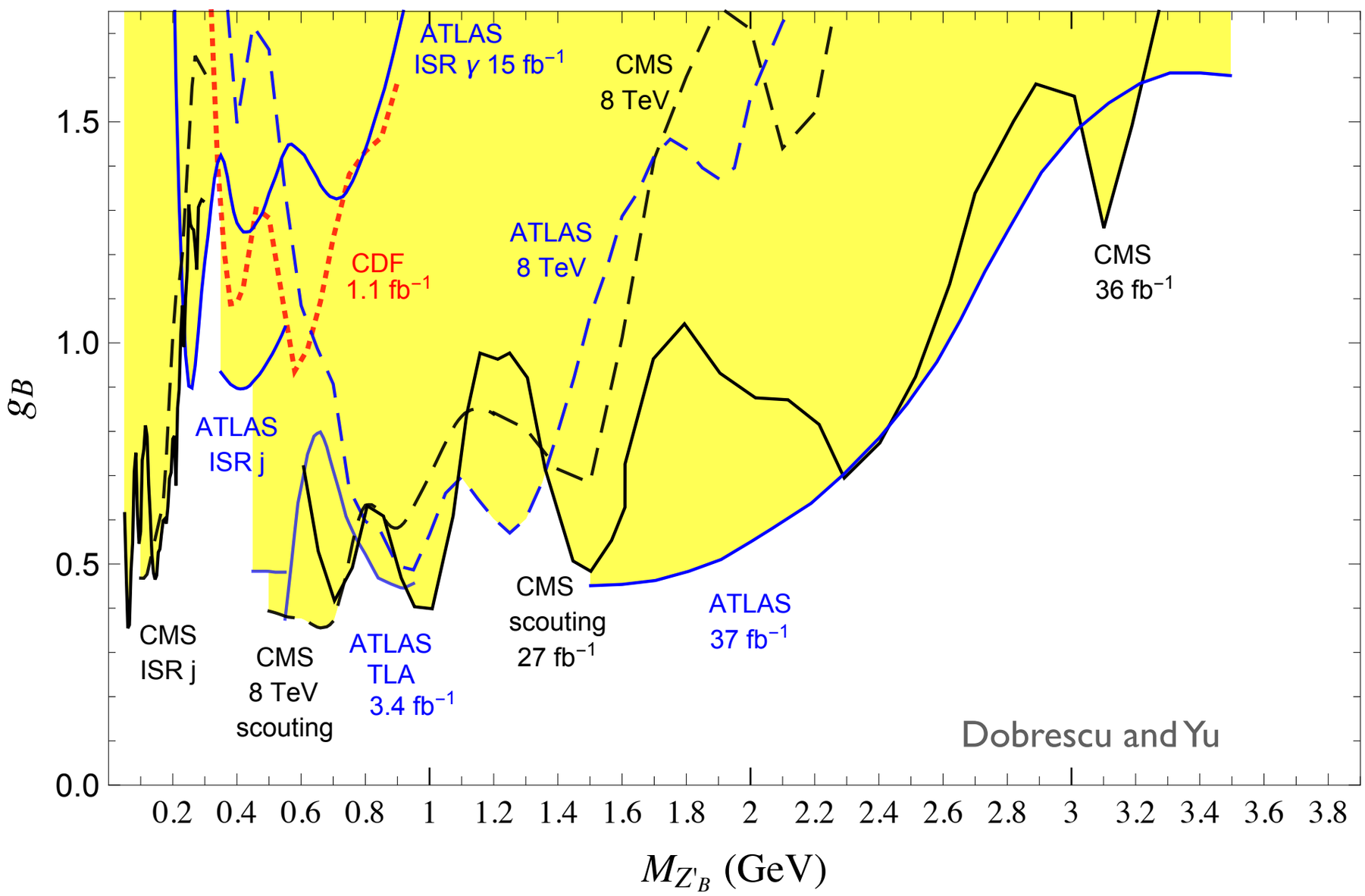
Exciting, creative time both experimentally and theoretically

Large Community effort, see e.g. US Cosmic Visions Whitepaper (1707.04591), and talks at this conference

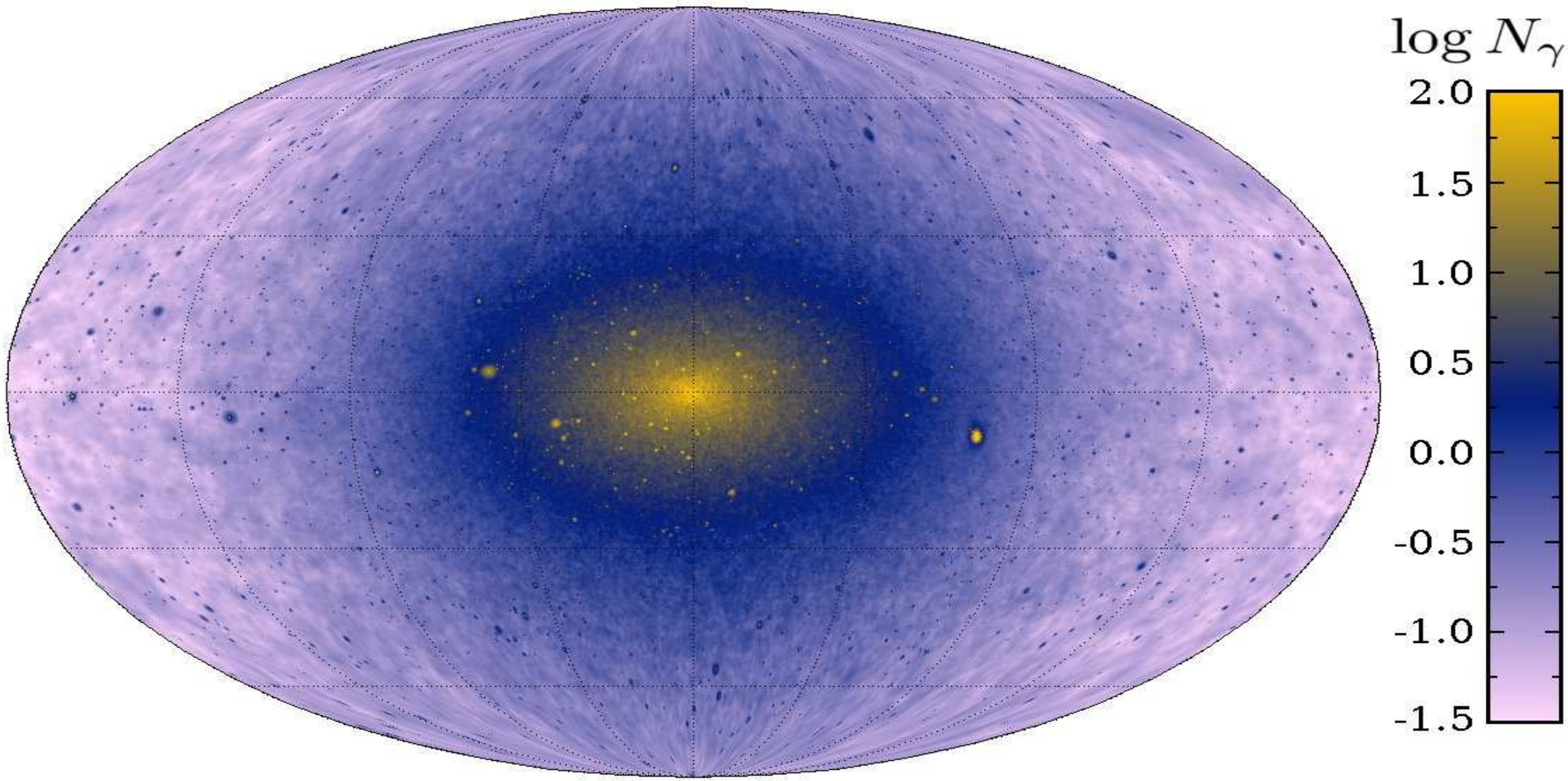
BACKUP SLIDES

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

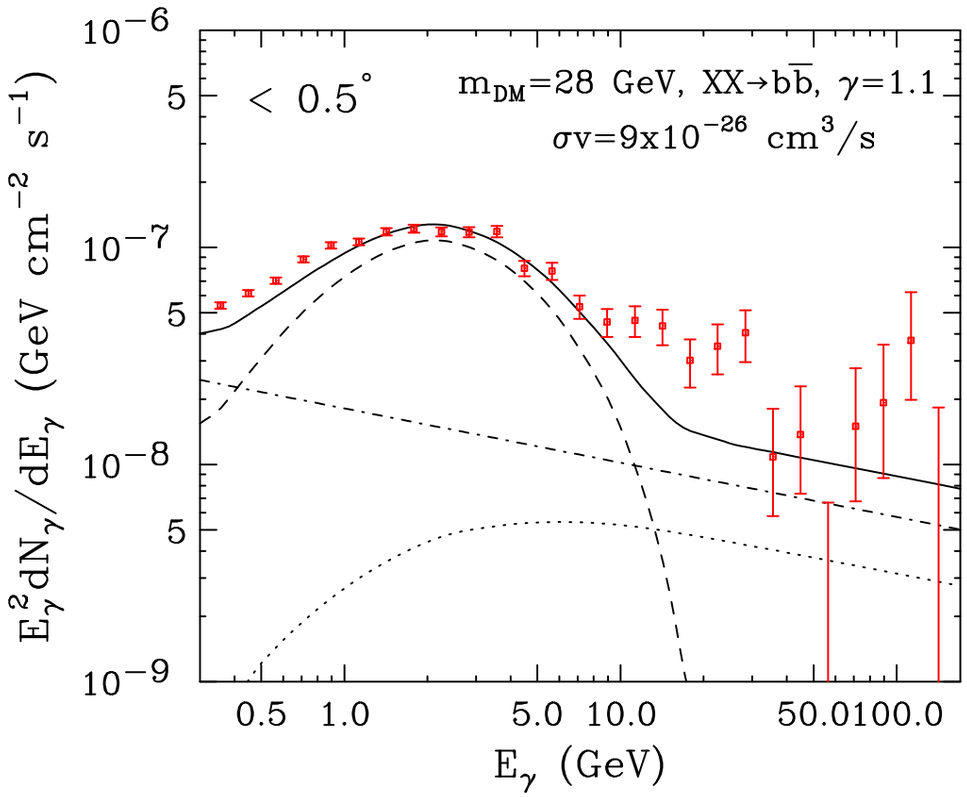


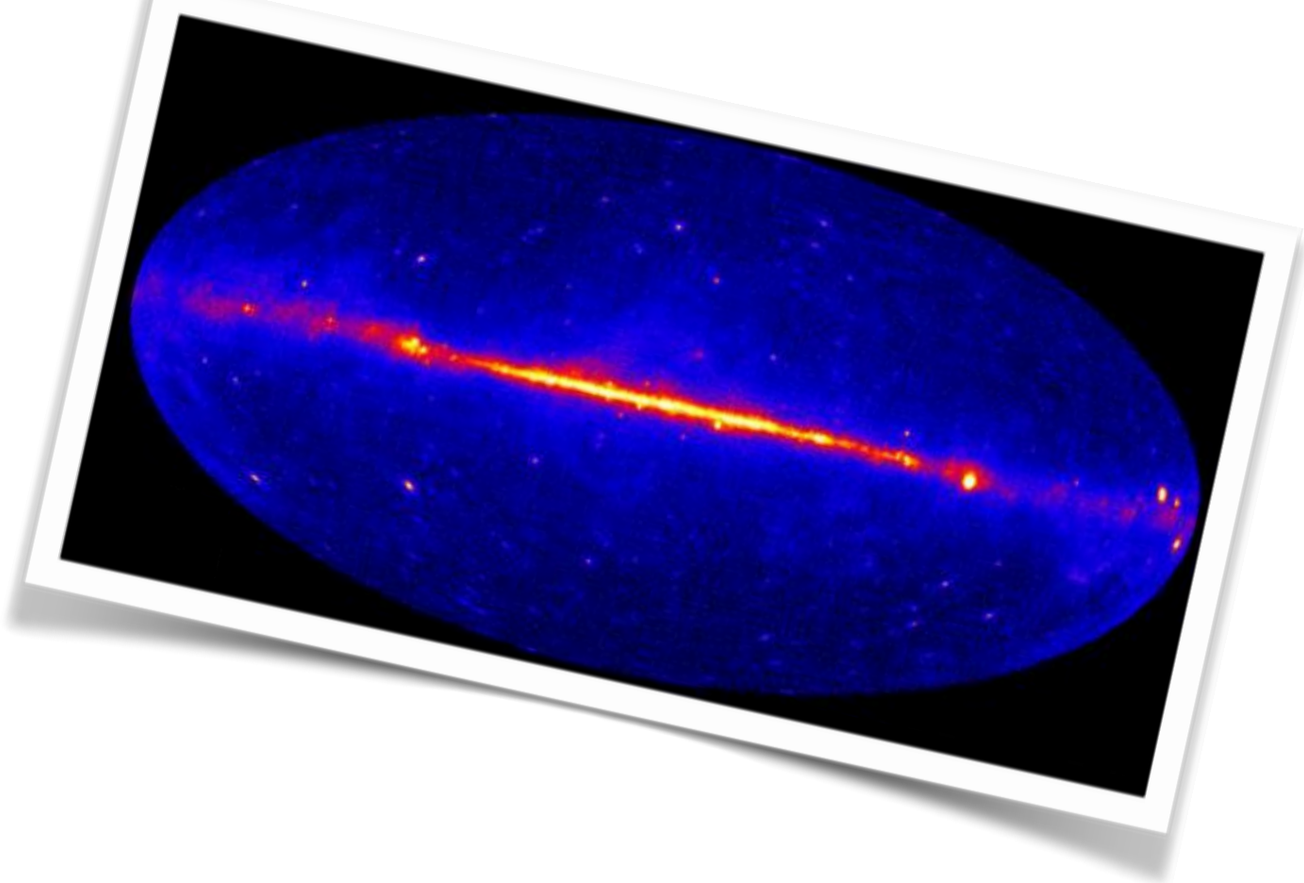

ATLAS
ISR γ 15 fb⁻¹
CMS
8 TeV
ATLAS
8 TeV
CDF
1.1 fb⁻¹
CMS
36 fb⁻¹
ATLAS
ISR j
CMS
ISR j
CMS
8 TeV
scouting
ATLAS
TLA
3.4 fb⁻¹
CMS
scouting
27 fb⁻¹
ATLAS
37 fb⁻¹
Dobrescu and Yu
g_B
$M_{Z'_B}$ (GeV)
0.0
0.5
1.0
1.5
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
3
3.2
3.4
3.6
3.8

Simulation of DM photon signal in our galaxy

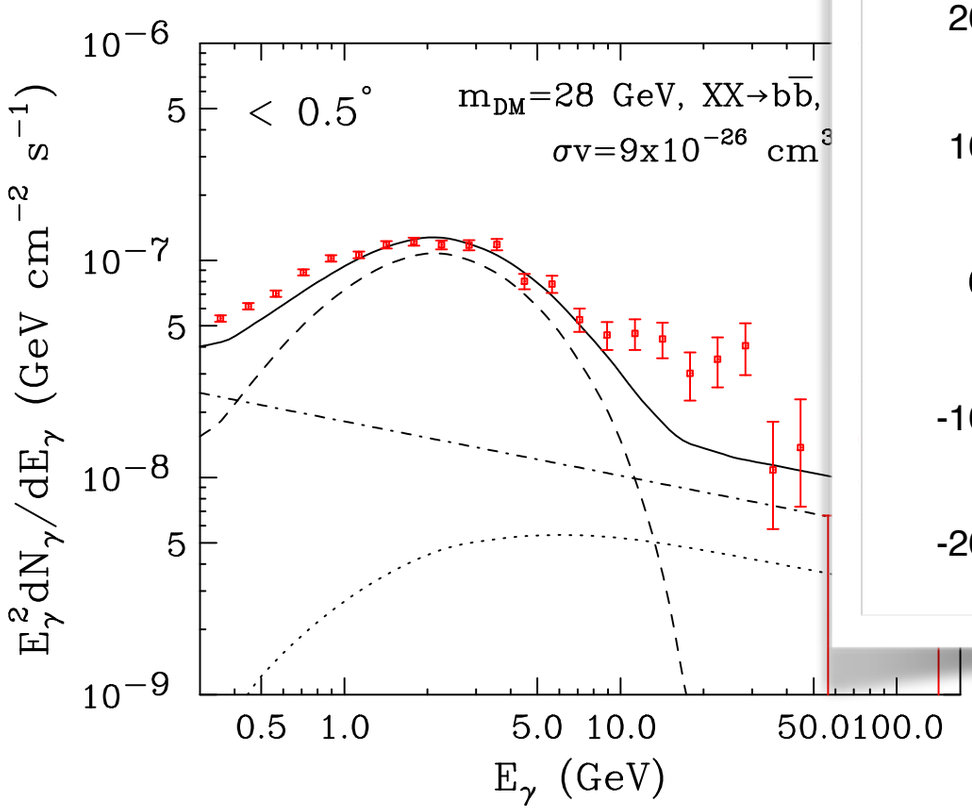


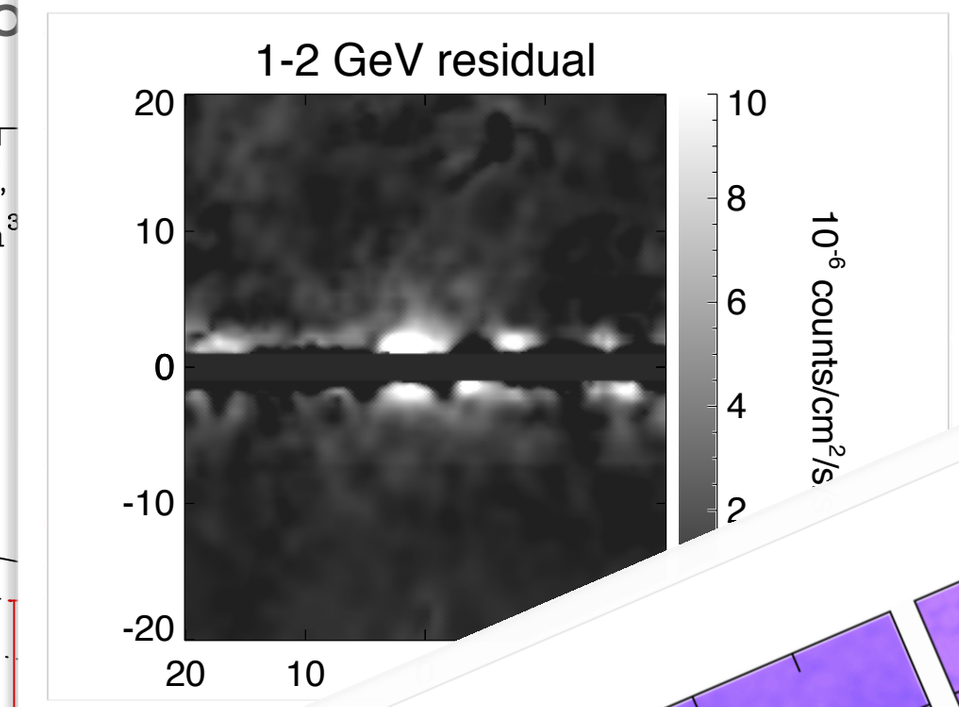
[Goodenough and Hooper, 2009]

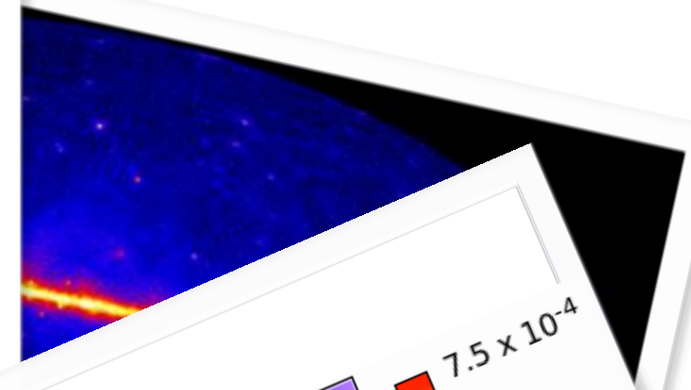


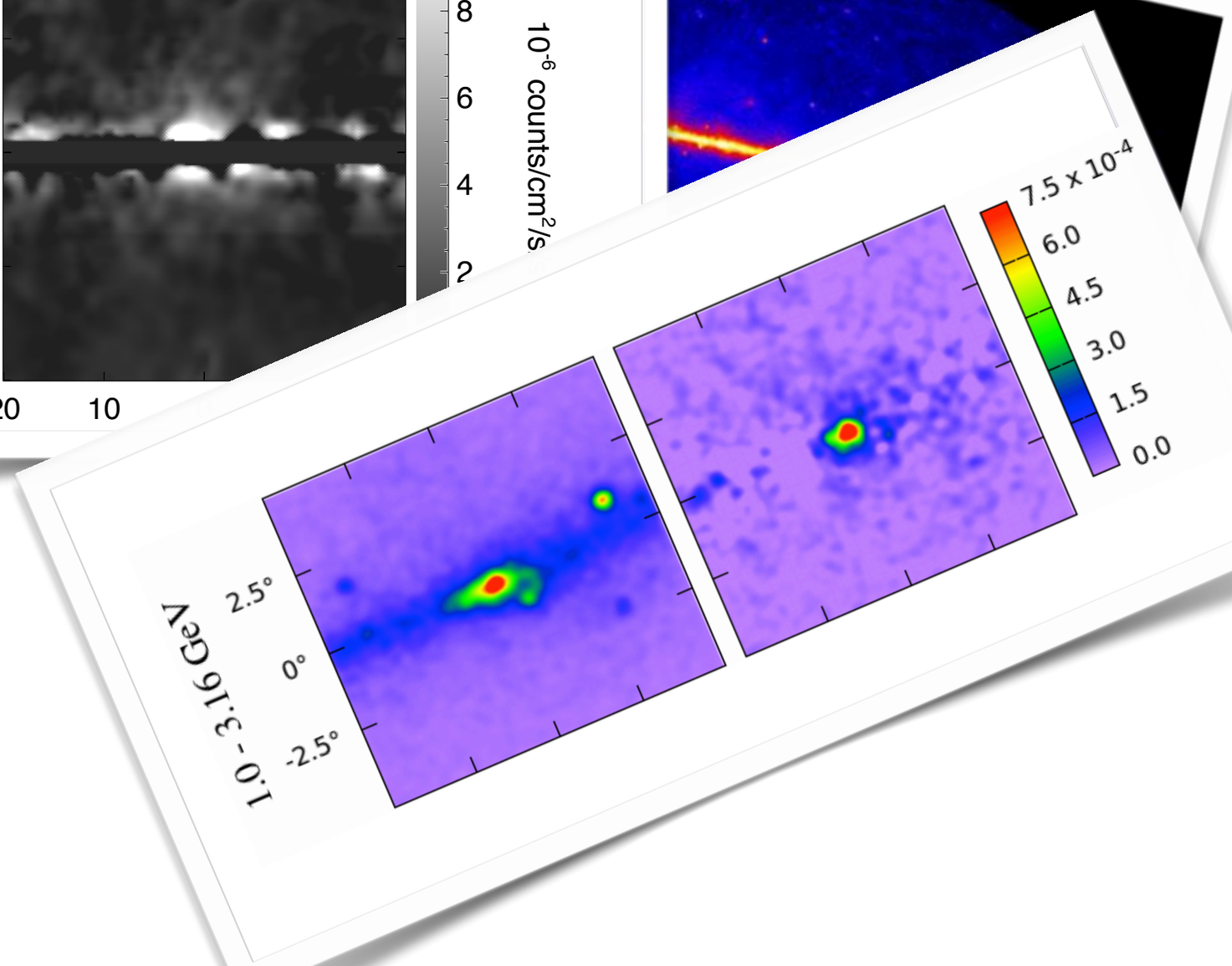


[Goodenough and Hoo

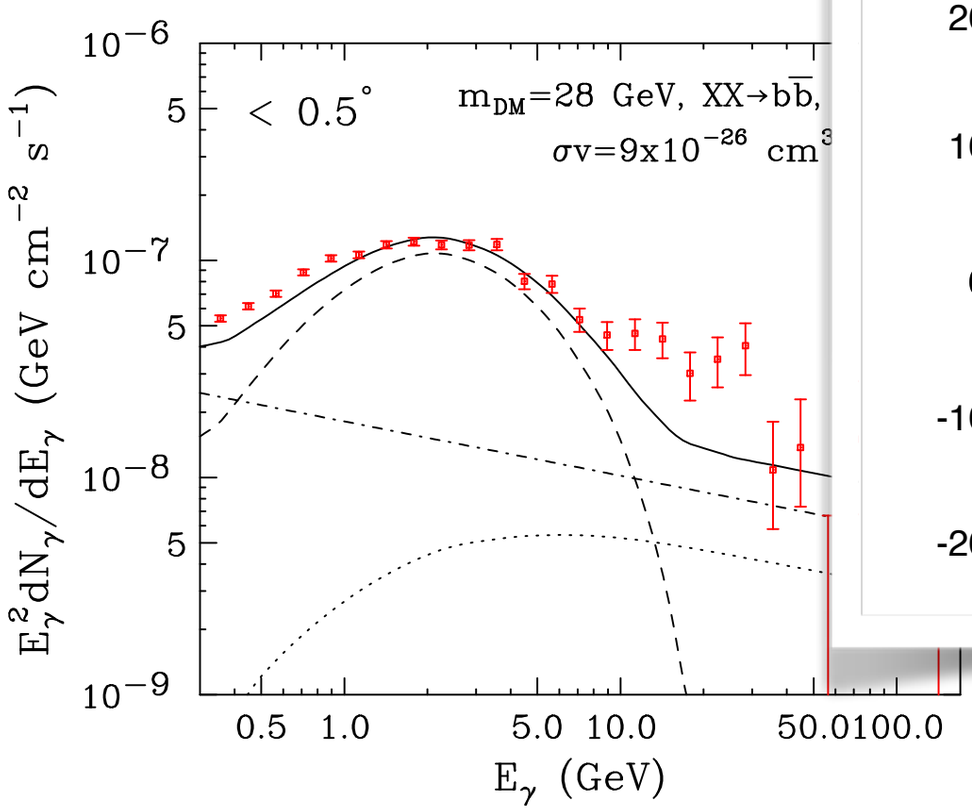


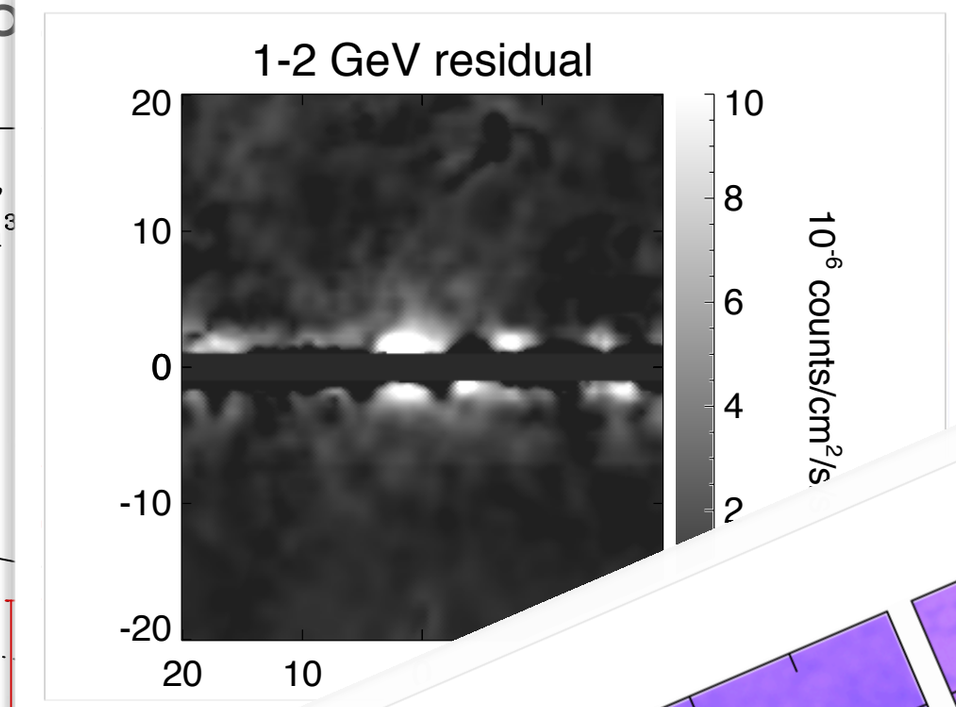


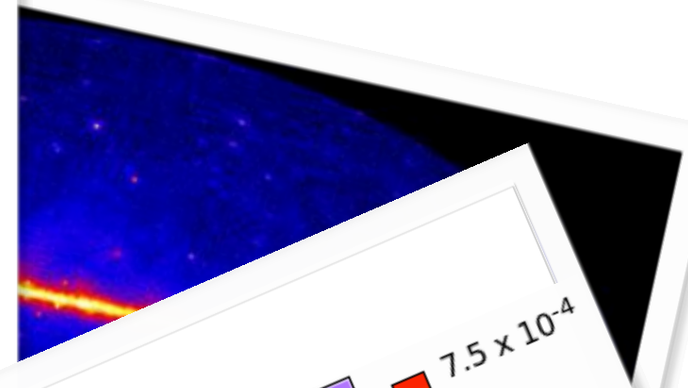


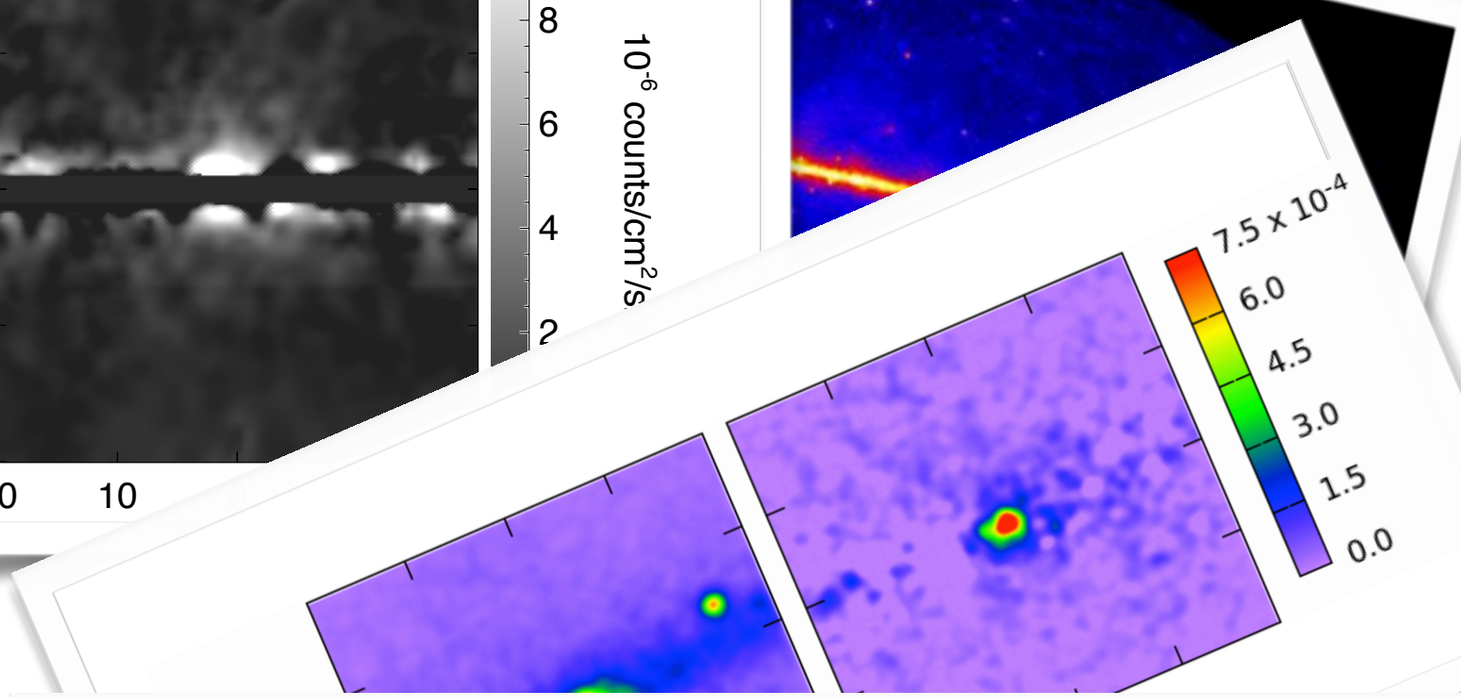


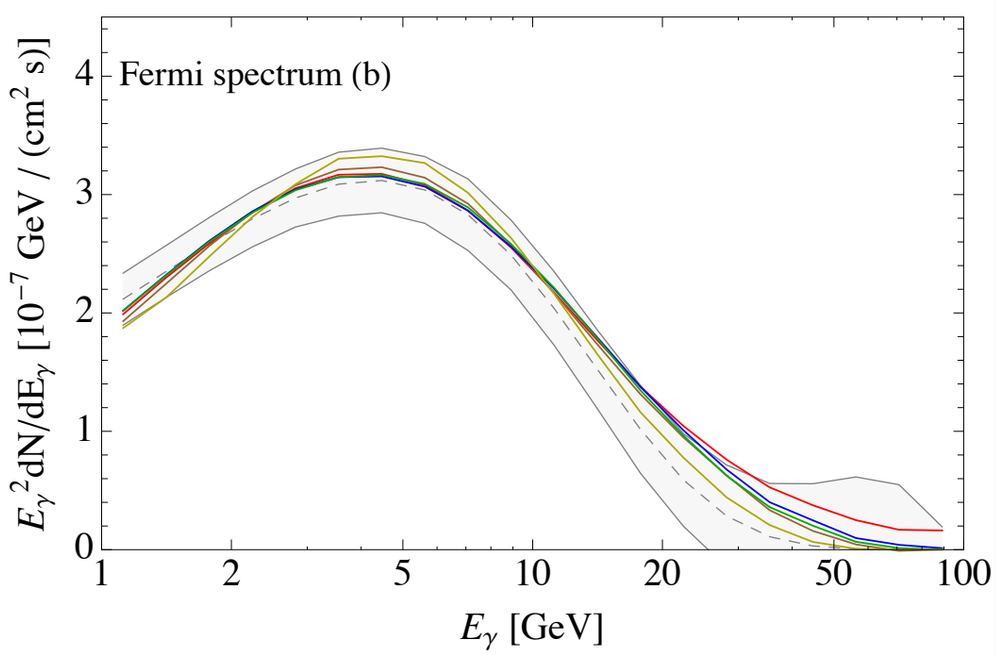
[Goodenough and Hoo

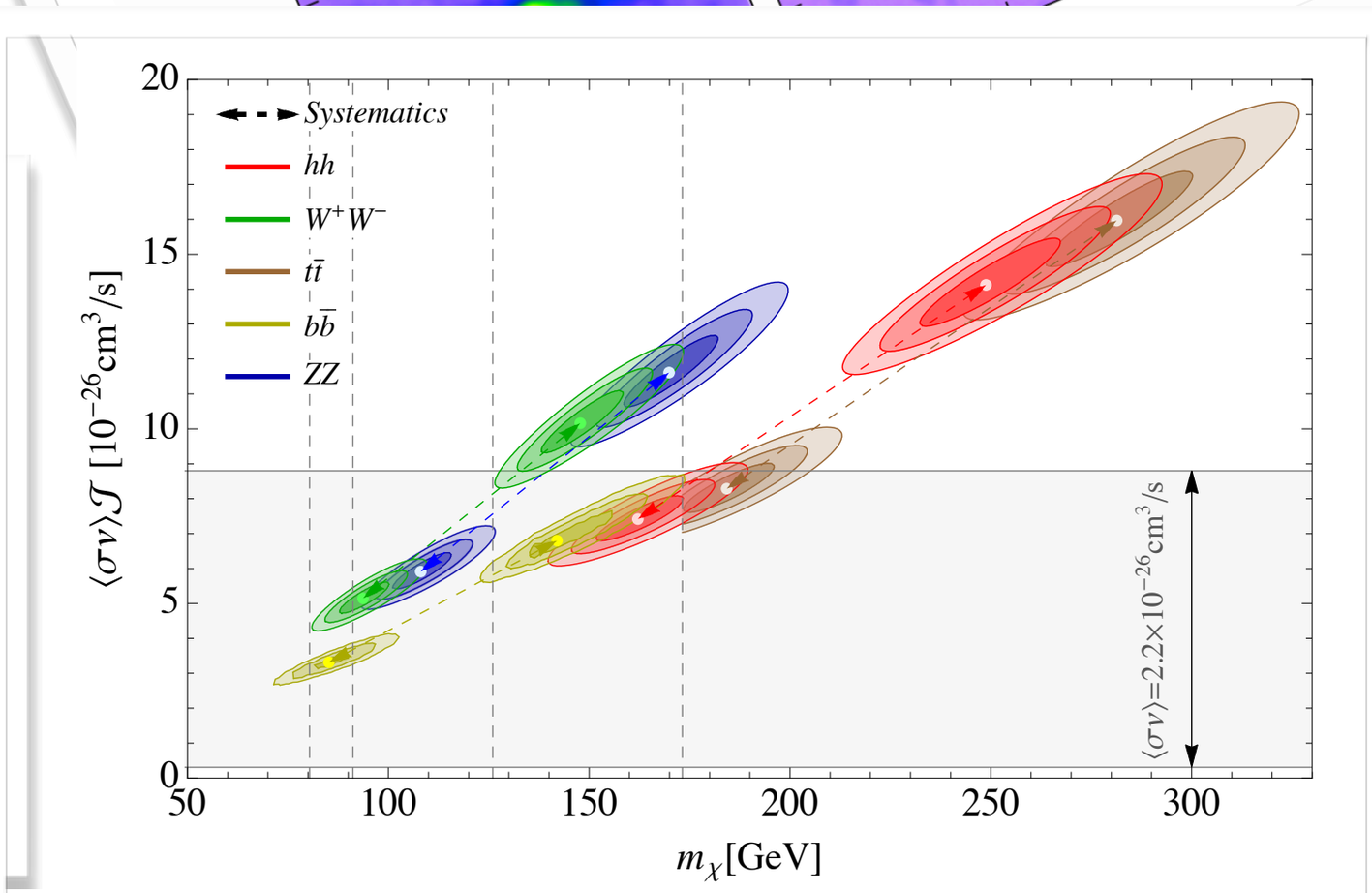








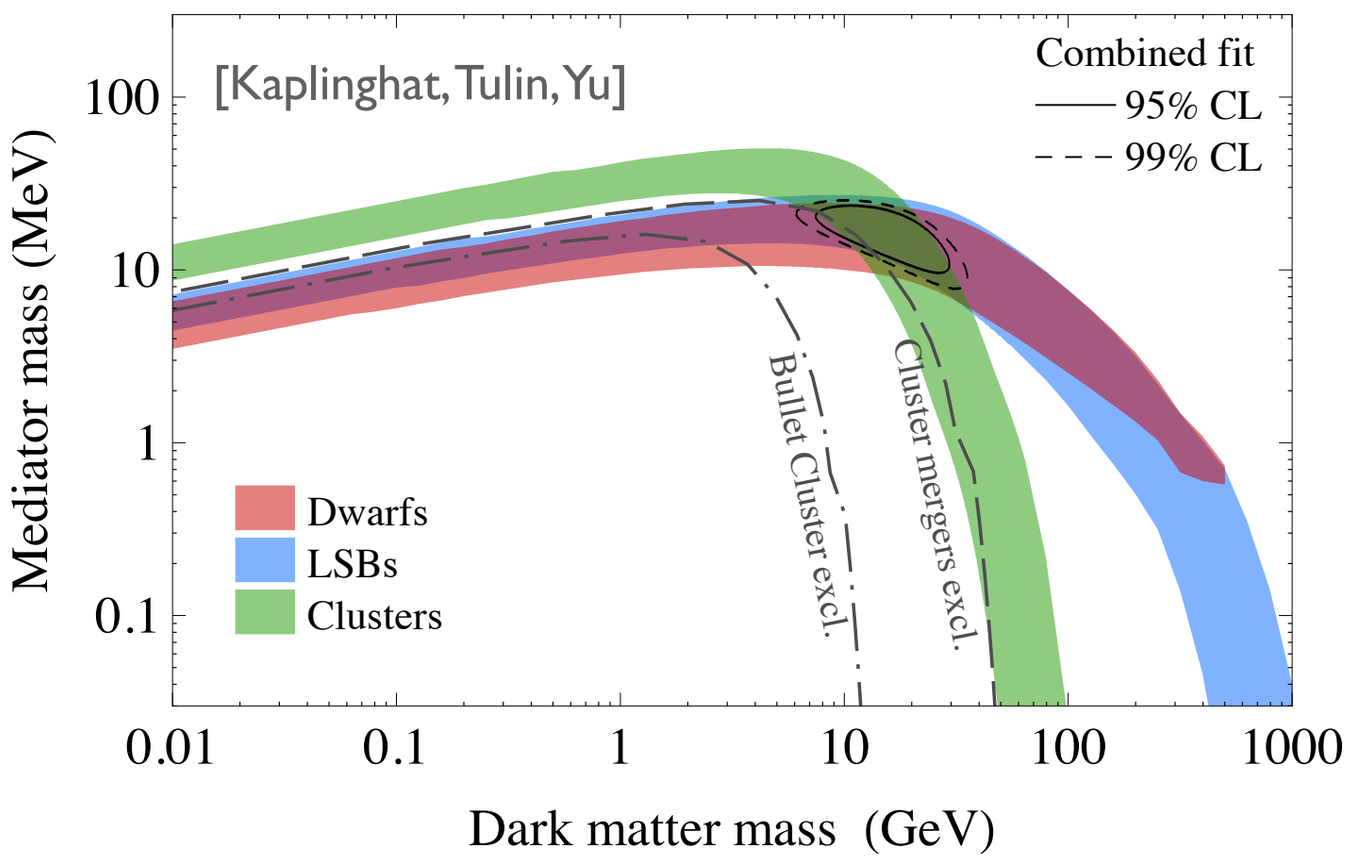




Small scale structure and dark sectors

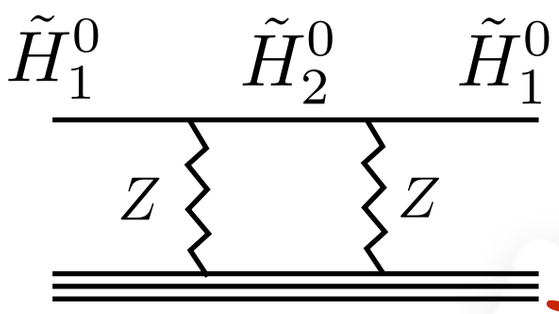
Small-scale structure problems: core-cusp, missing satellites and too-big-to-fail

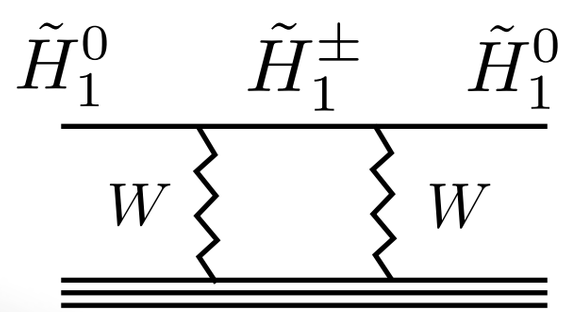
Alleviated by DM self-interactions via light mediator (100 MeV)

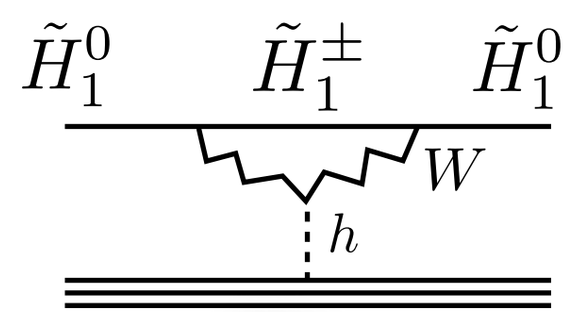


iDM—loop level elastic rate

[Hisano et al.; Hill and Solon]





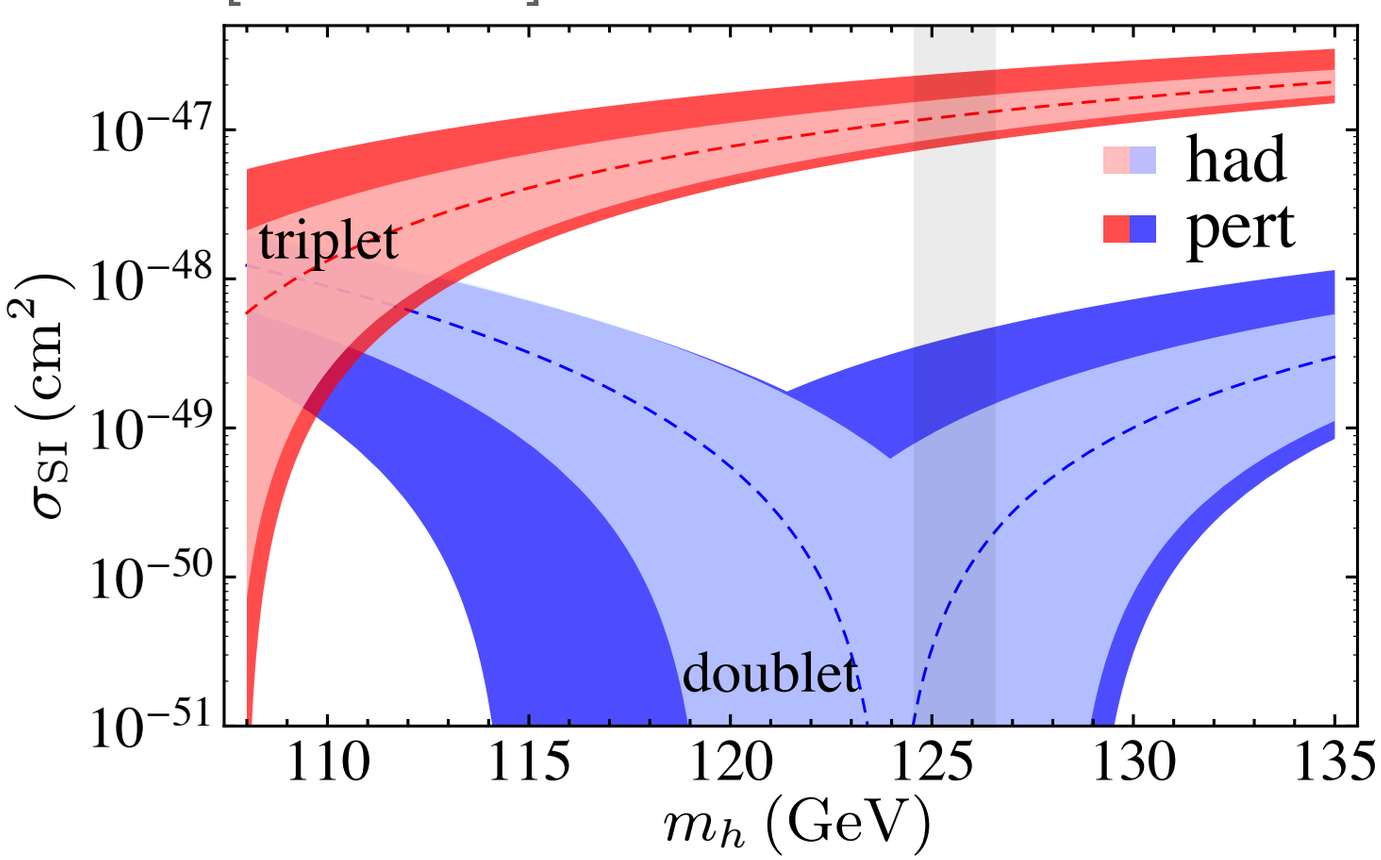


Twist-2

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]

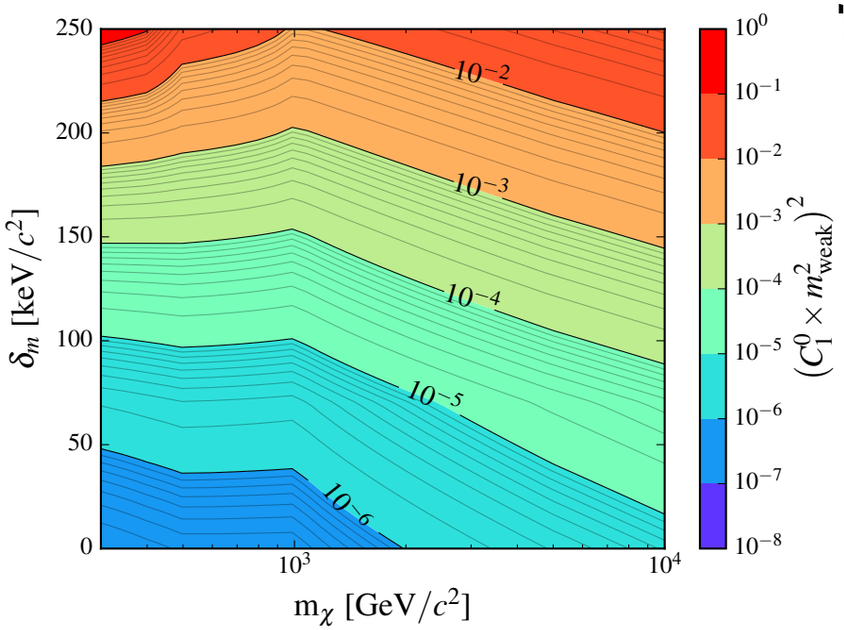


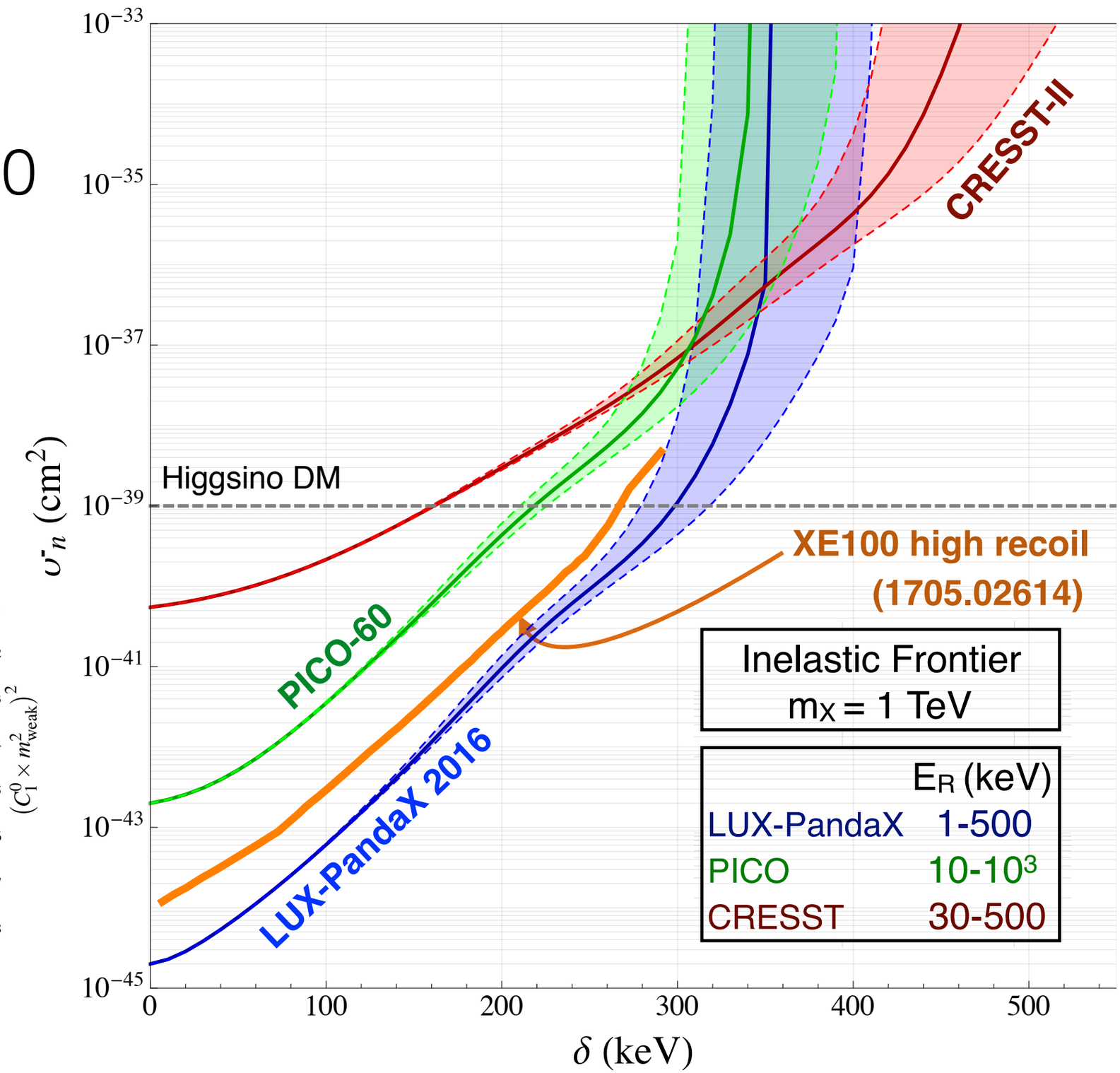
$$\sigma^{\tilde{H}}_{\rm n,loop} \lesssim 10^{-48}\ {\rm cm}^2$$

accidental cancellation

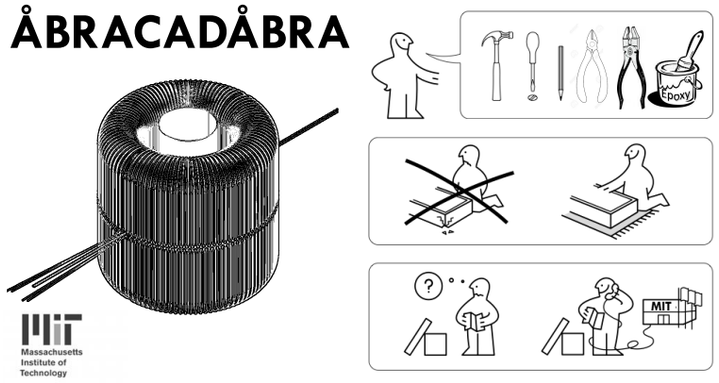
Crossing the Inelastic Frontier—Xenon100

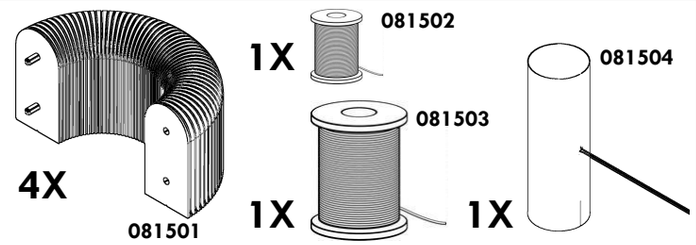
Reanalysis
7.6 ton-days, Xe100
6.6-240 keVnr
Inelastic analysis





ÅBRACADÅBRA





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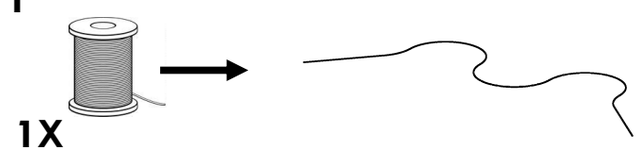

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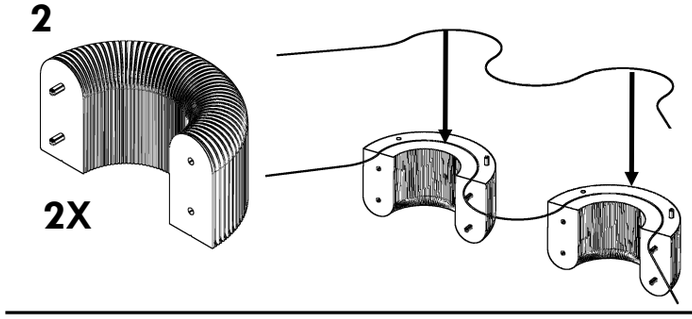

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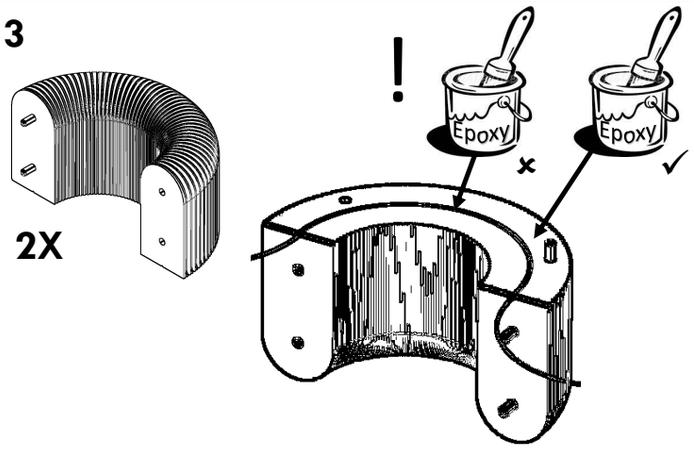

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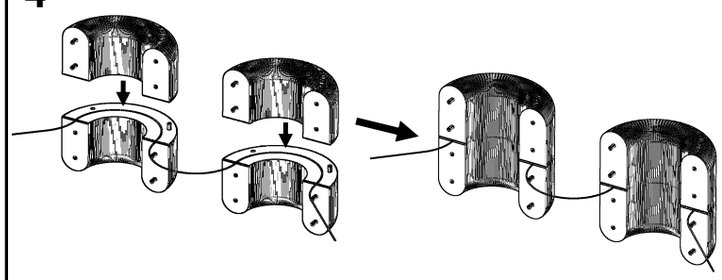

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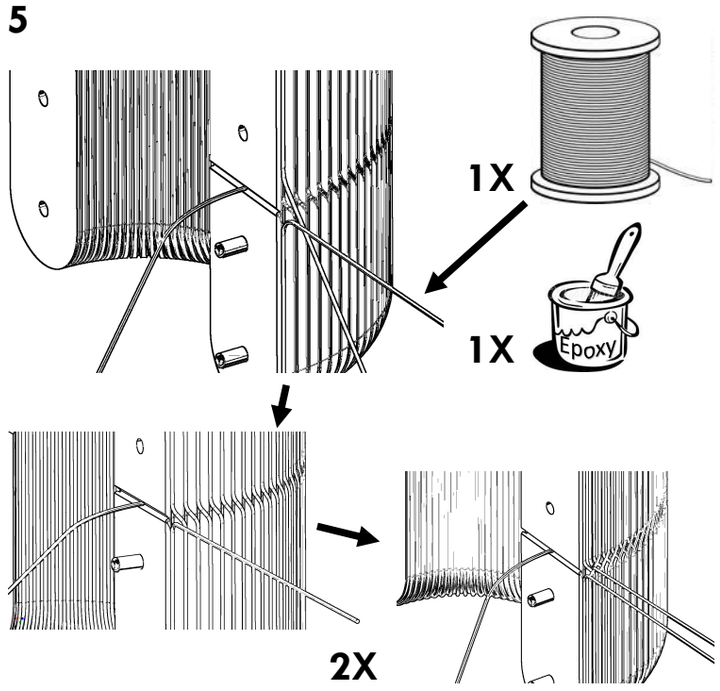

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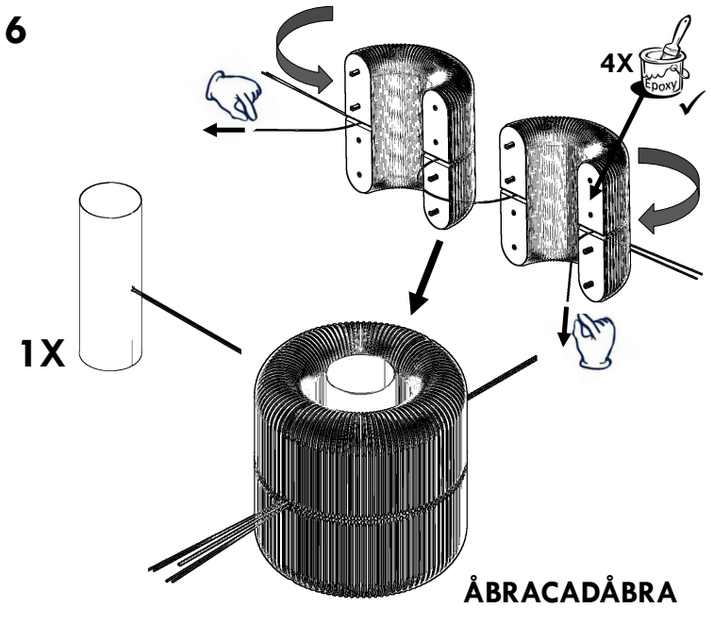

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