Status of Theoretical Candidates of Dark Matter

Patrick Fox

Fermilab

3rd Annual South American Dark Matter Workshop, ICTP-SAIFR, Sao Paulo (via Zoom)

We don't know what we're doing...

We don't know what we're doing…

…but we do know what not to do

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…but we do know what not to do

We don't know what we're doing…

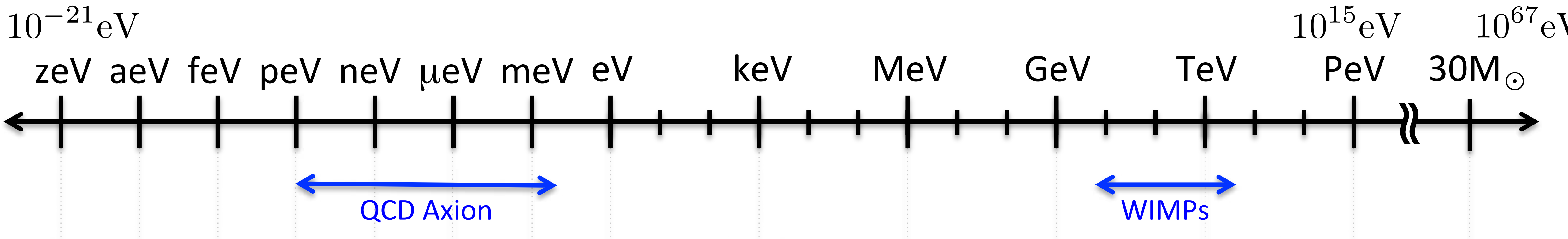
…but we do know what not to do

(No longer just searching for your advisor's dark matter)

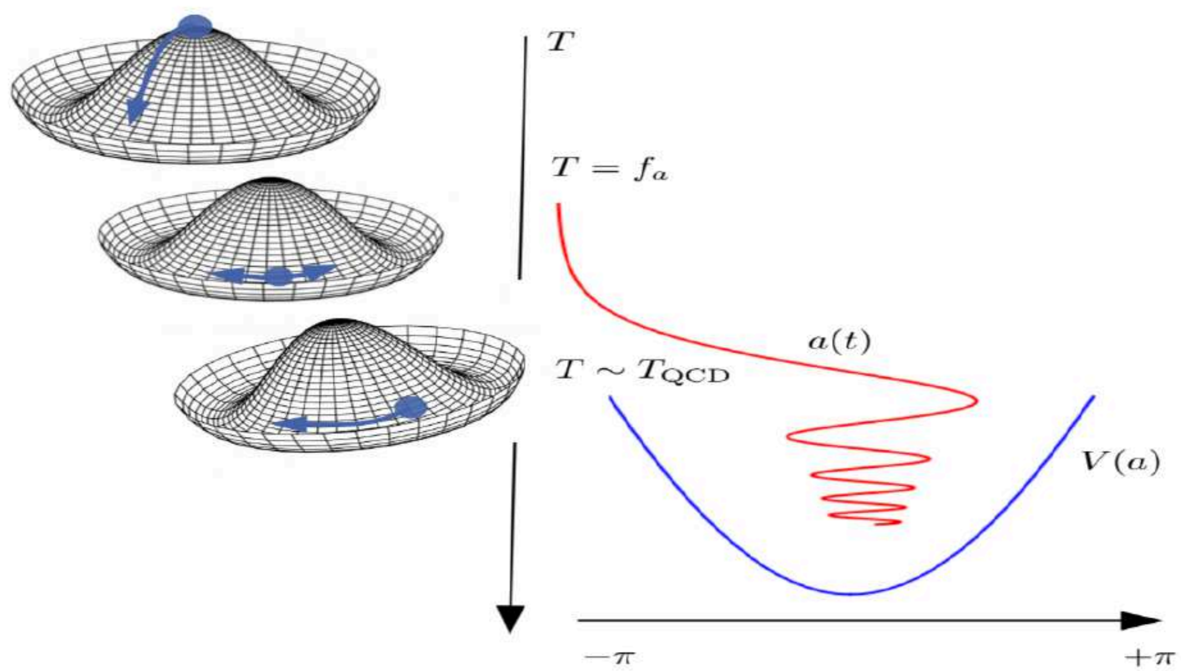
Outline

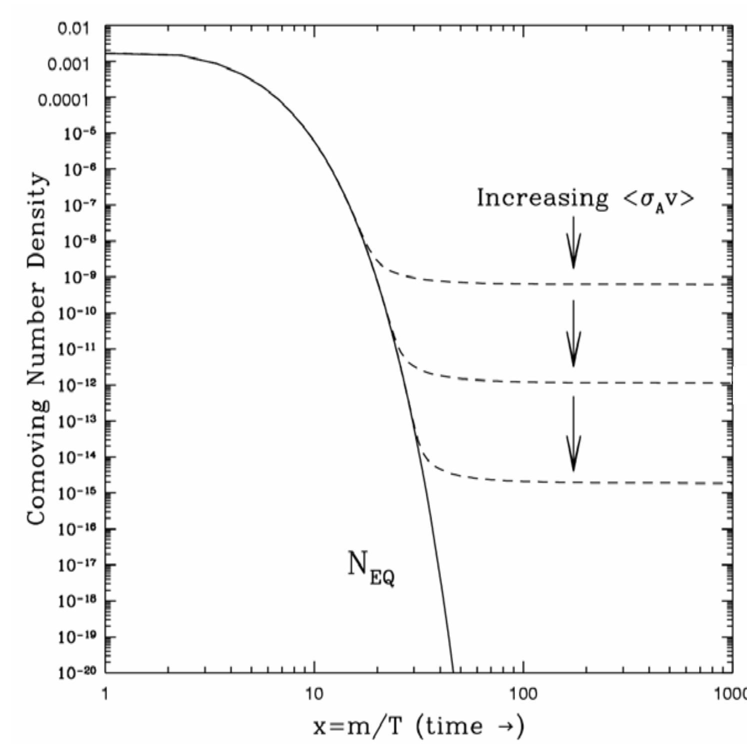
- Some history
- Some recent developments
- Where we are now (abridged)
- (The Inelastic Frontier or The Photon Phrontier)
- Conclusions

Dark Matter circa 2000



(really, SUSY Neutralino
i.e. Wino, Bino, Higgsino)



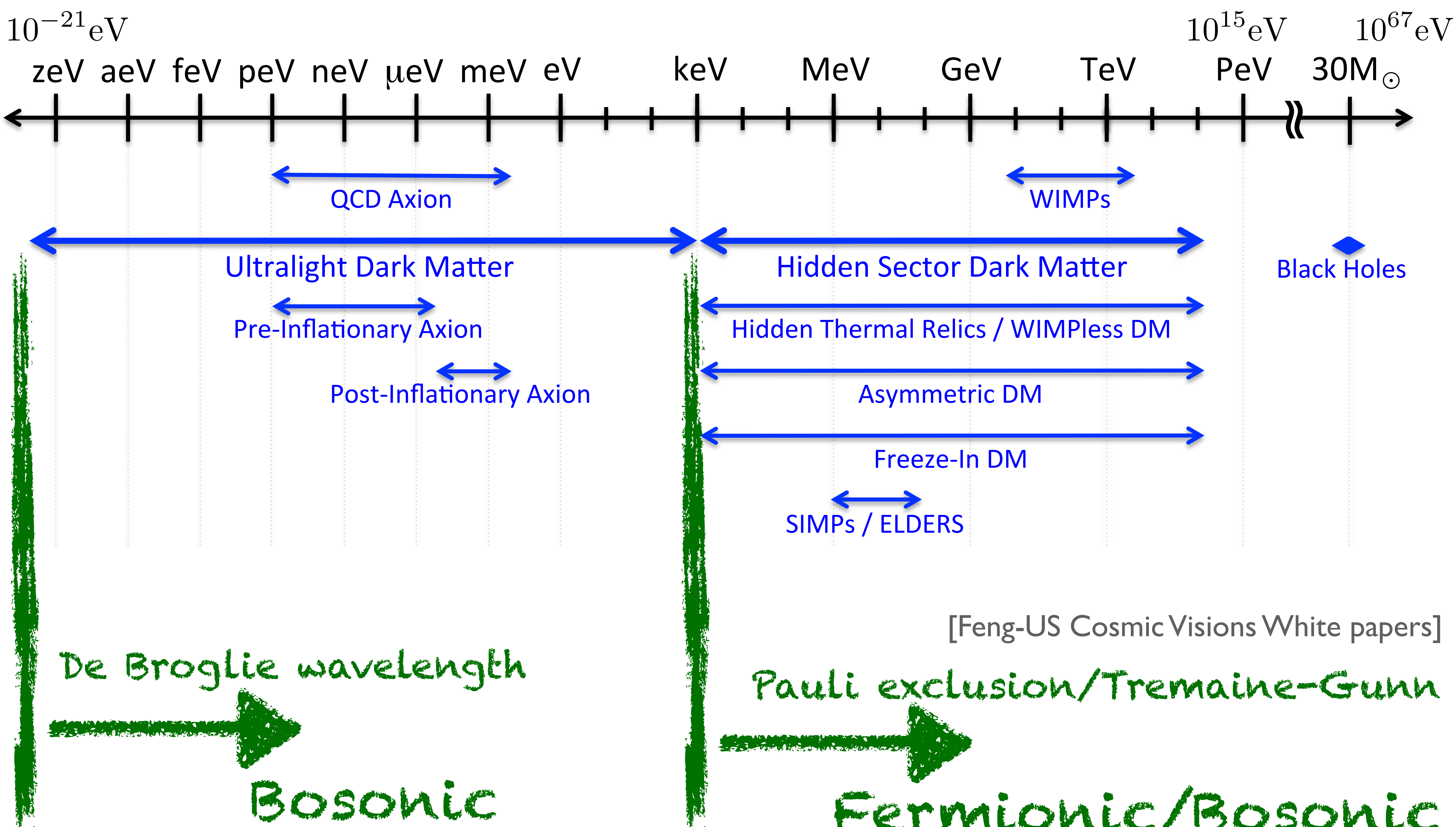


Made through misalignment mechanism or decay of topological objects (strings, domain walls etc)

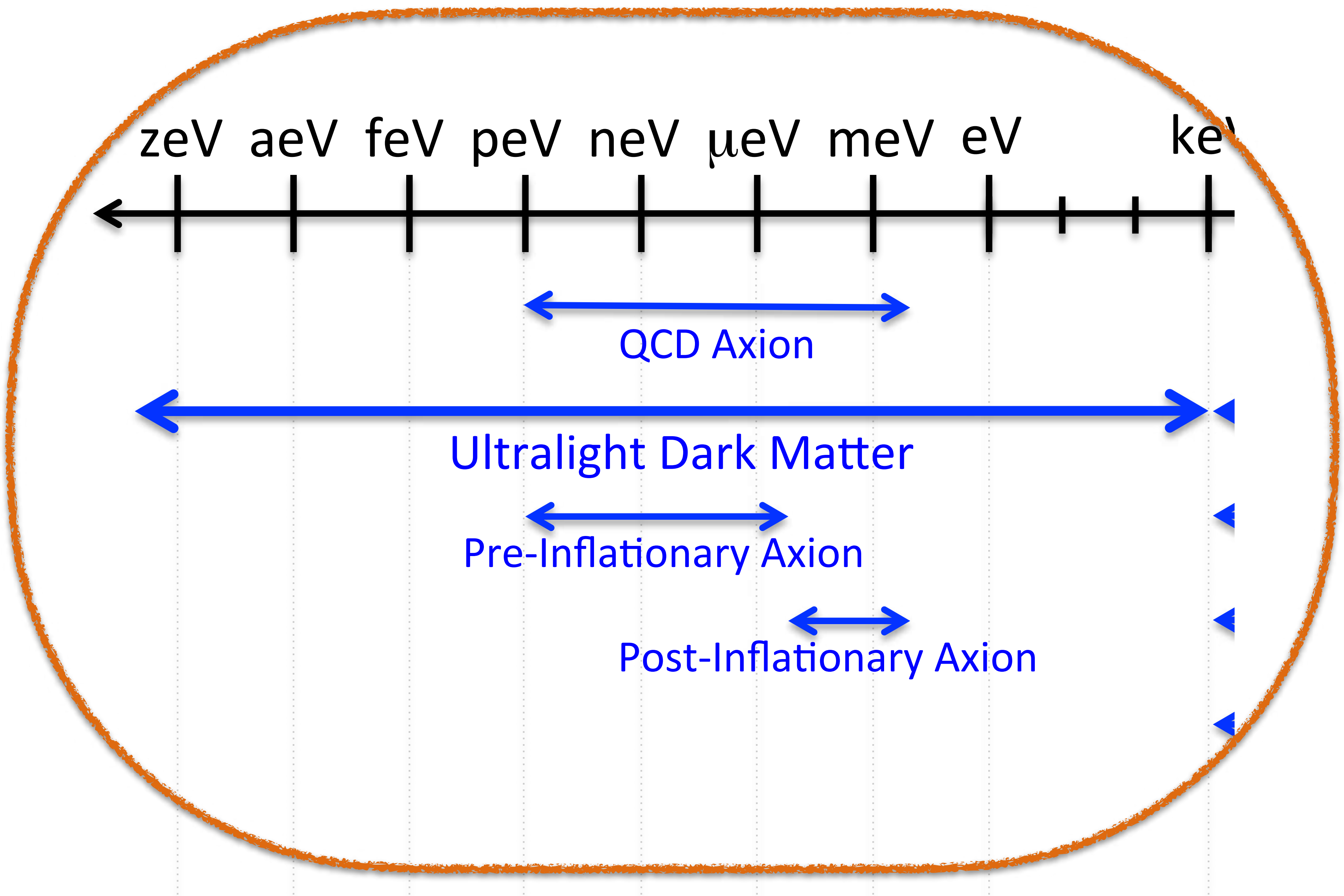
Made through thermal freeze out in the early universe. WIMP “miracle”

DM dynamics approximately determined by one state (see Griest and Seckel `91 for 3 WIMP exceptions)

Dark Matter circa now

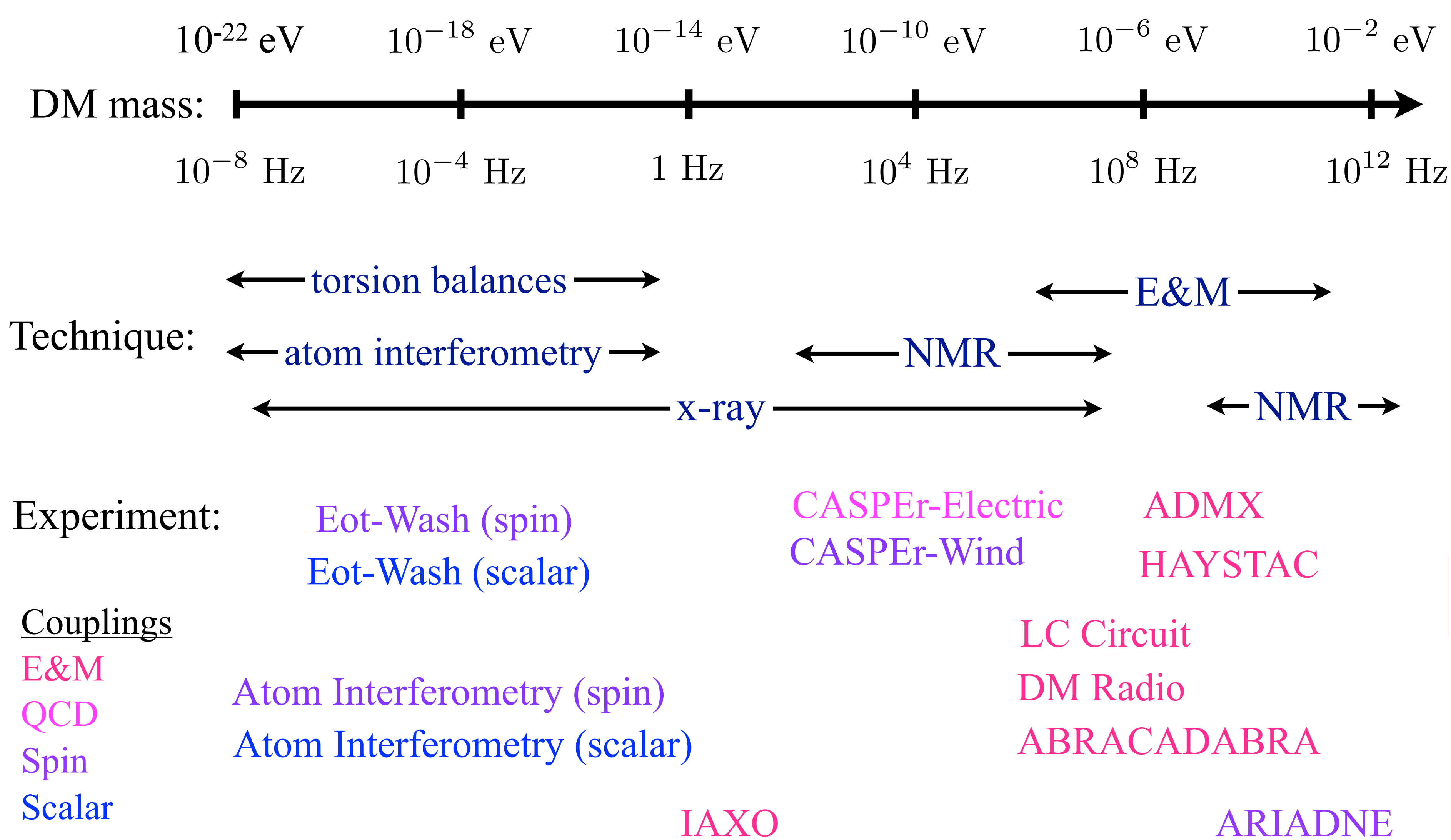


Particle theories

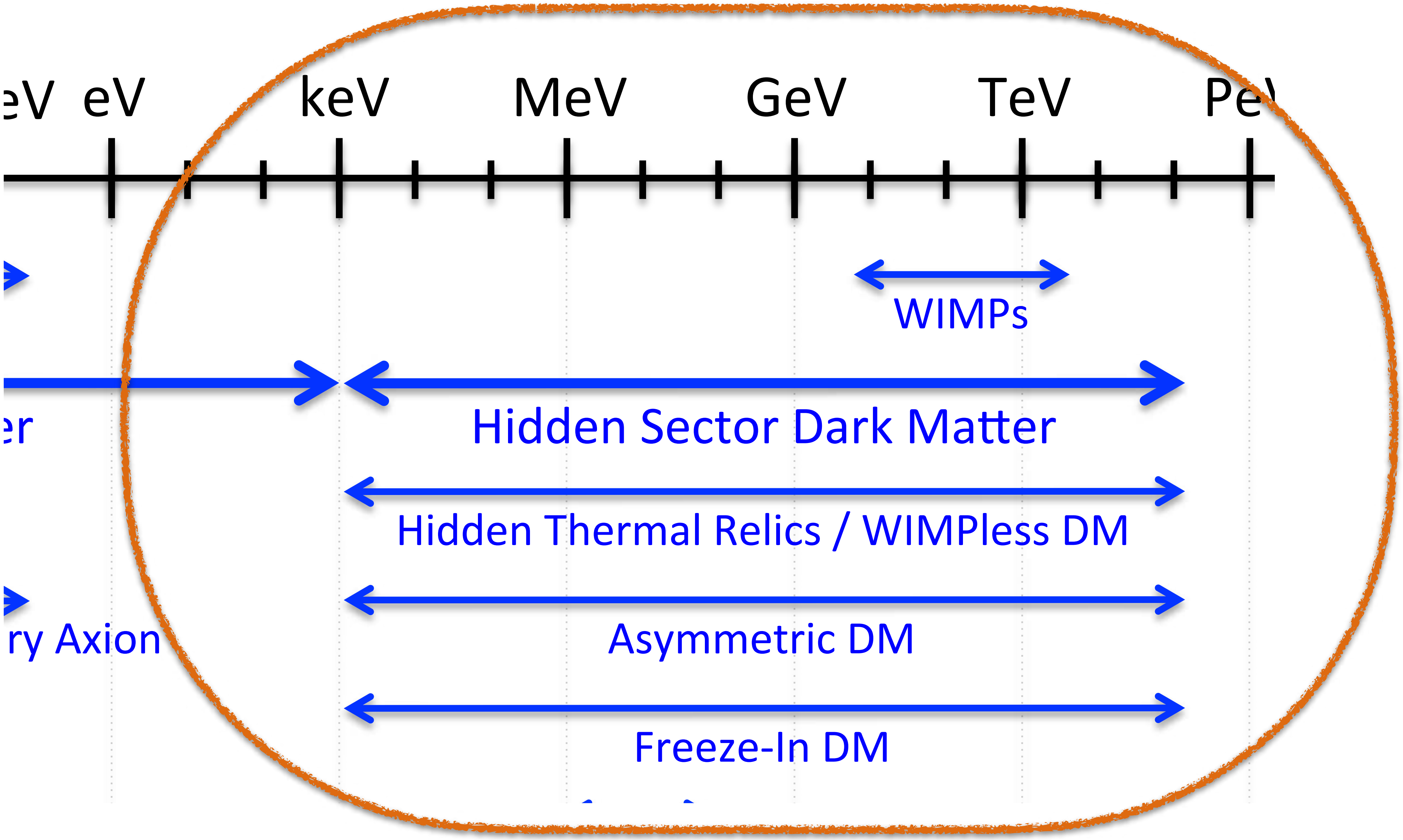


sub-keV DM

- 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]


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

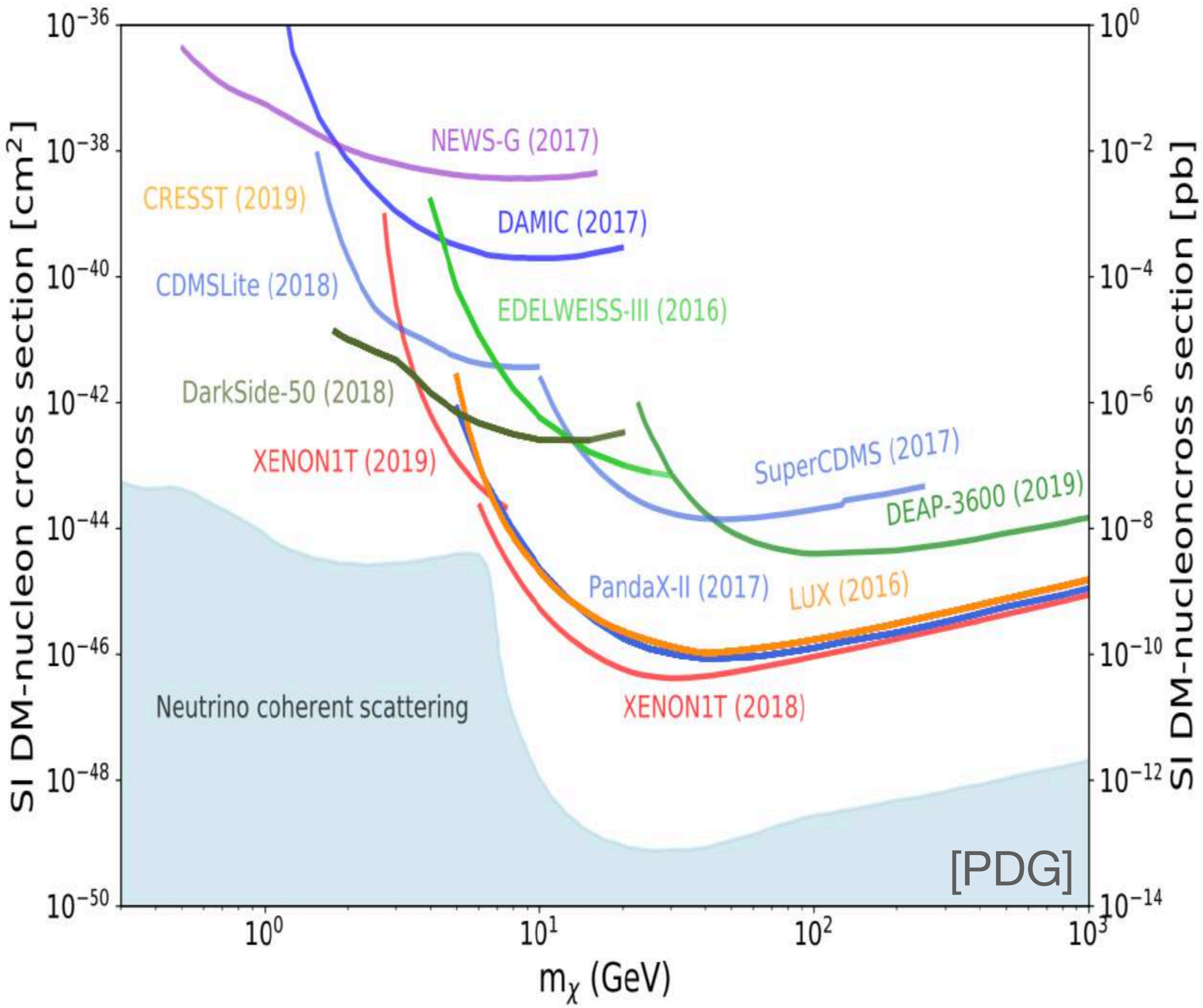
WIMPs (theory)

- DM interacts through weak (or weak scale) couplings
- Lee-Weinberg and Unitarity constrain mass range
  - ~1 GeV —~10 TeV
- LPOPs of a BSM theory e.g. SUSY, Extra dims, Little Higgs (+ T-parity),…
- Usually consider a thermal relic

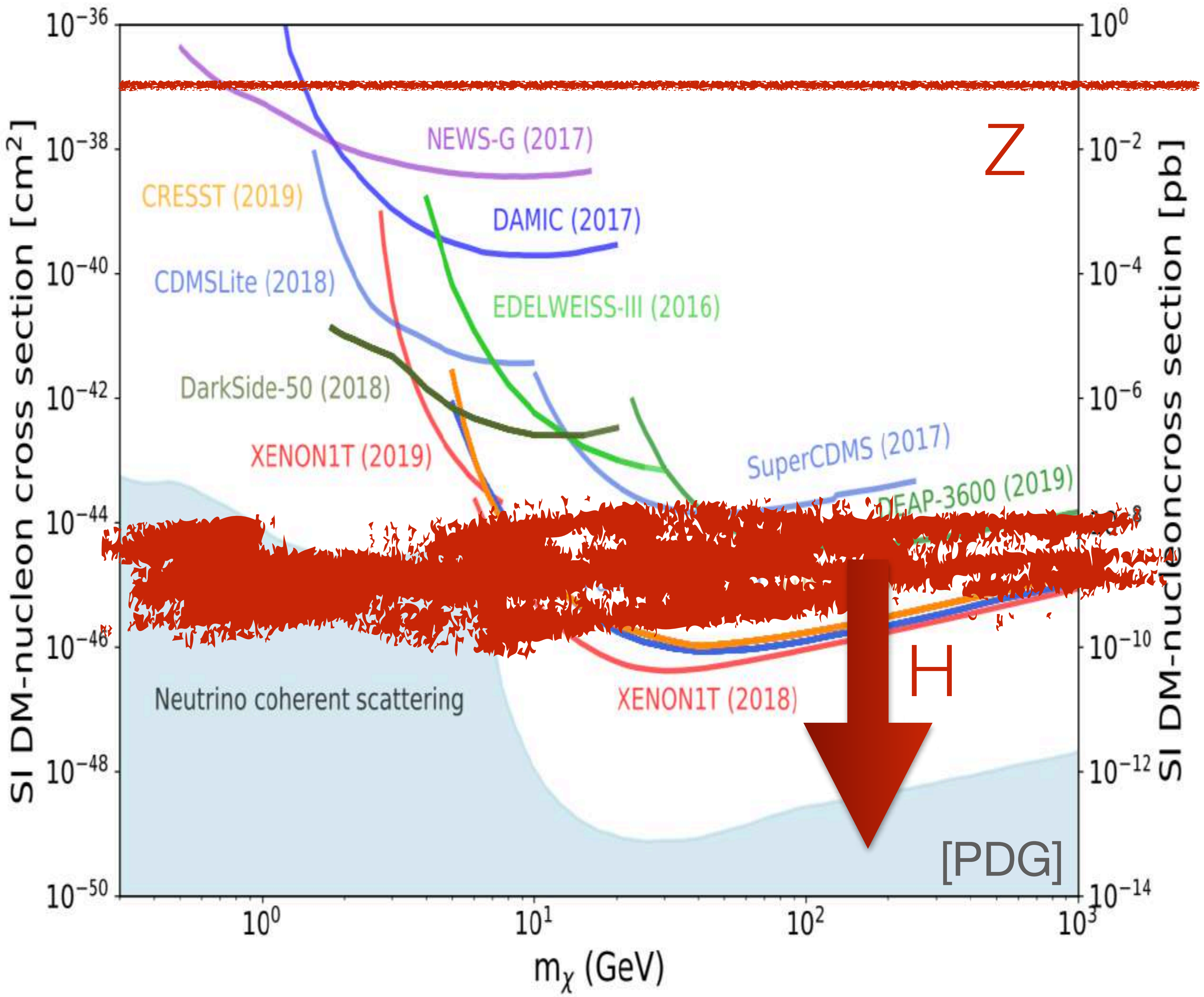
$$\Omega h^2 \approx 0.1 \left(\frac{m/T}{20}\right) \left(\frac{g_*}{80}\right)^{-1} \left(\frac{3 \times 10^{-26}\mathrm{cm}^2\mathrm{s}^{-1}}{\sigma v}\right)$$

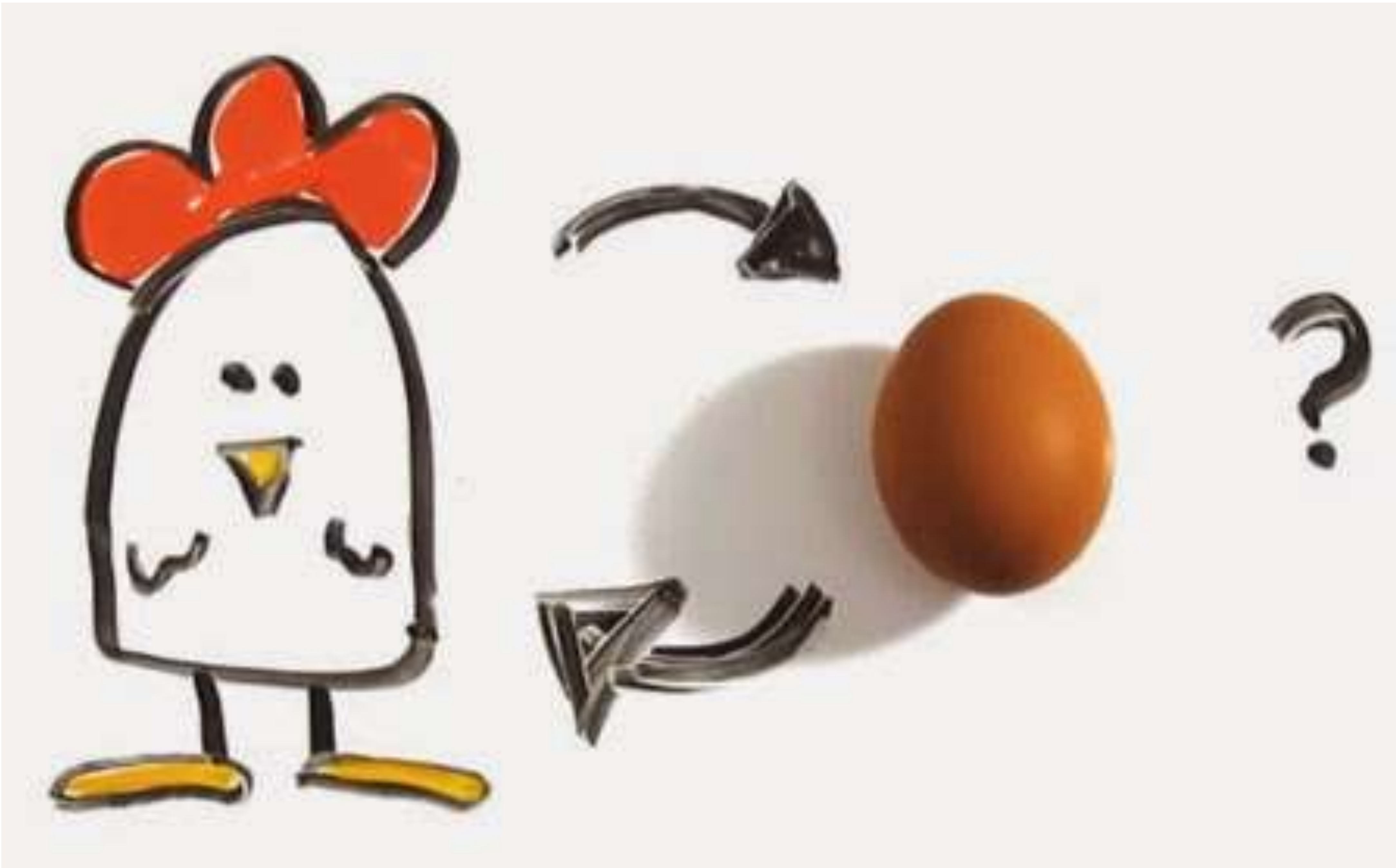
- DM interacts through *new* mediators
  - “dark photon” (U-boson, Z’), dark Higgs, secluded mediator,…
- Thermal relic, annihilate within or through the dark sector
- Allows for lighter DM
  - ~1 keV — ~100 TeV

WIMP (experiment)



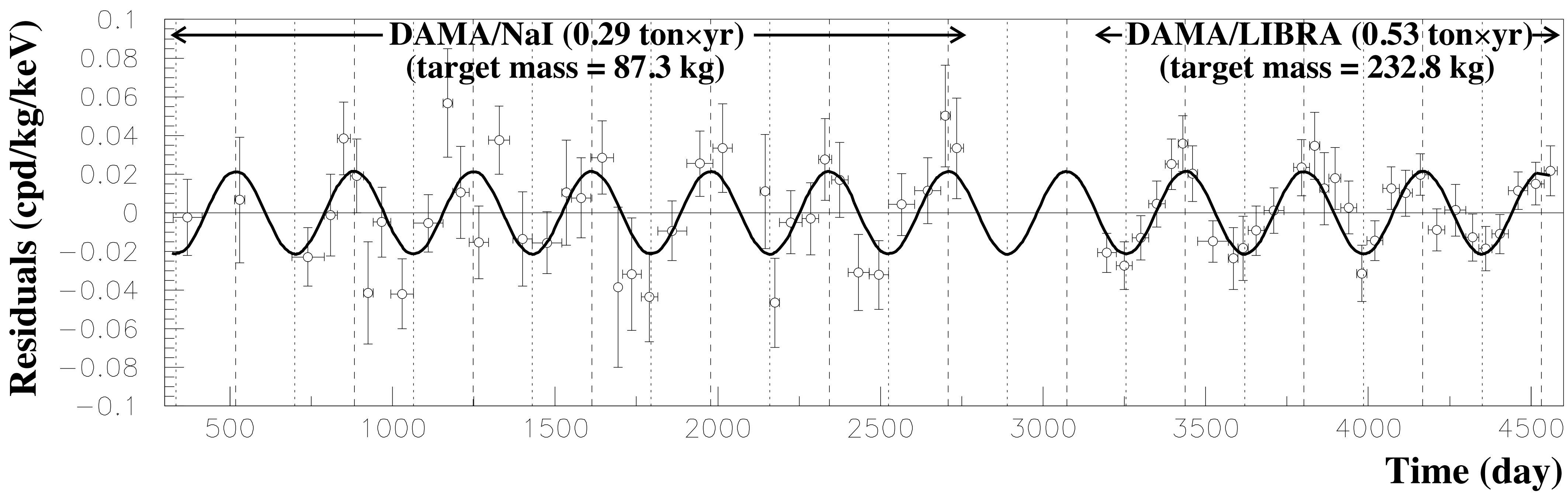
WIMP (experiment)





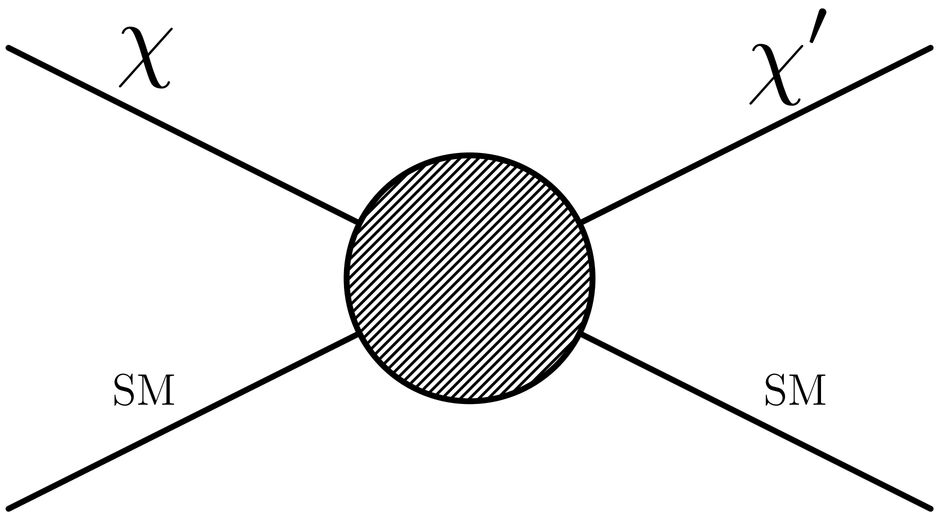

POLICE PUBLIC CALL BOX
POLICE PUBLIC CALL BOX

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]



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

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

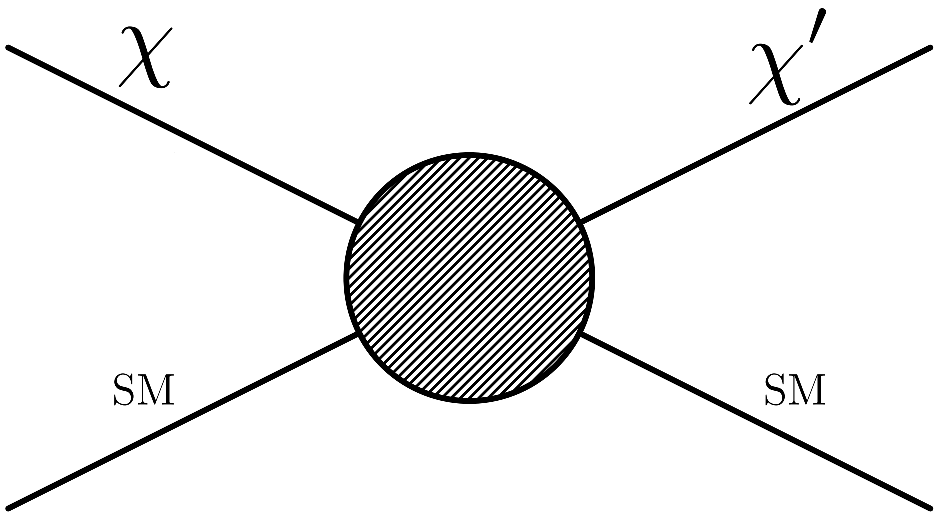
$$m_\chi - m_{\chi'} = \delta \sim 100\,\mathrm{keV}$$

- 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]



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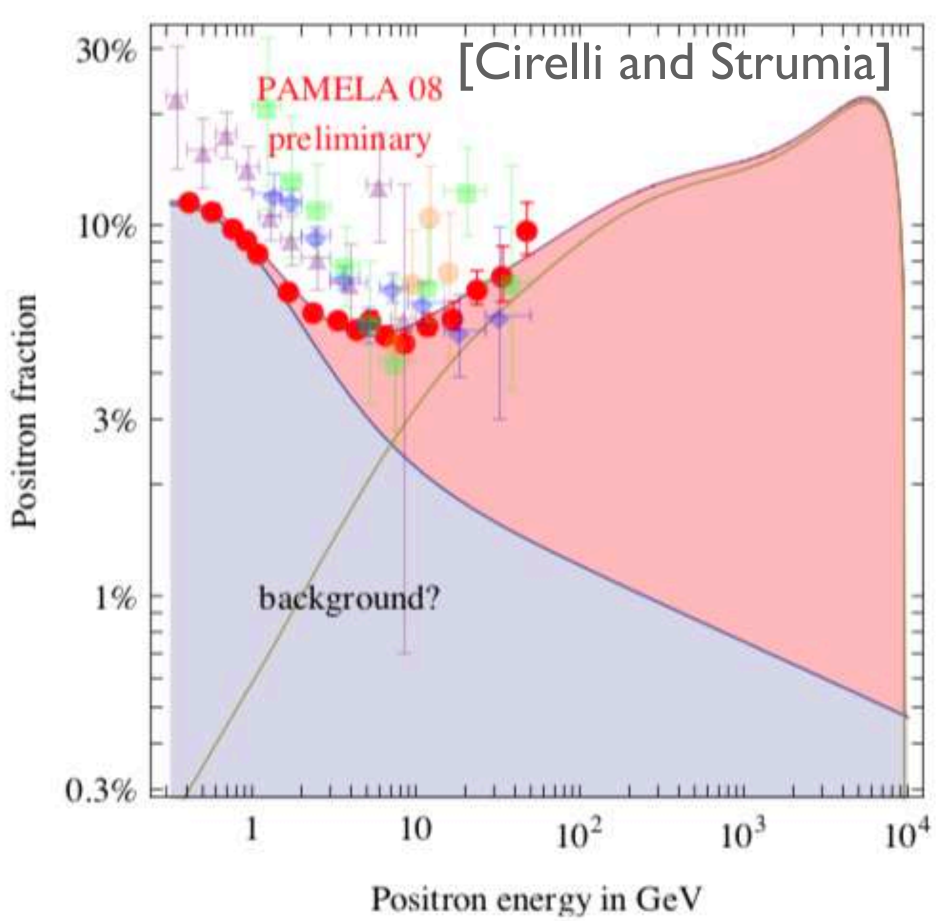
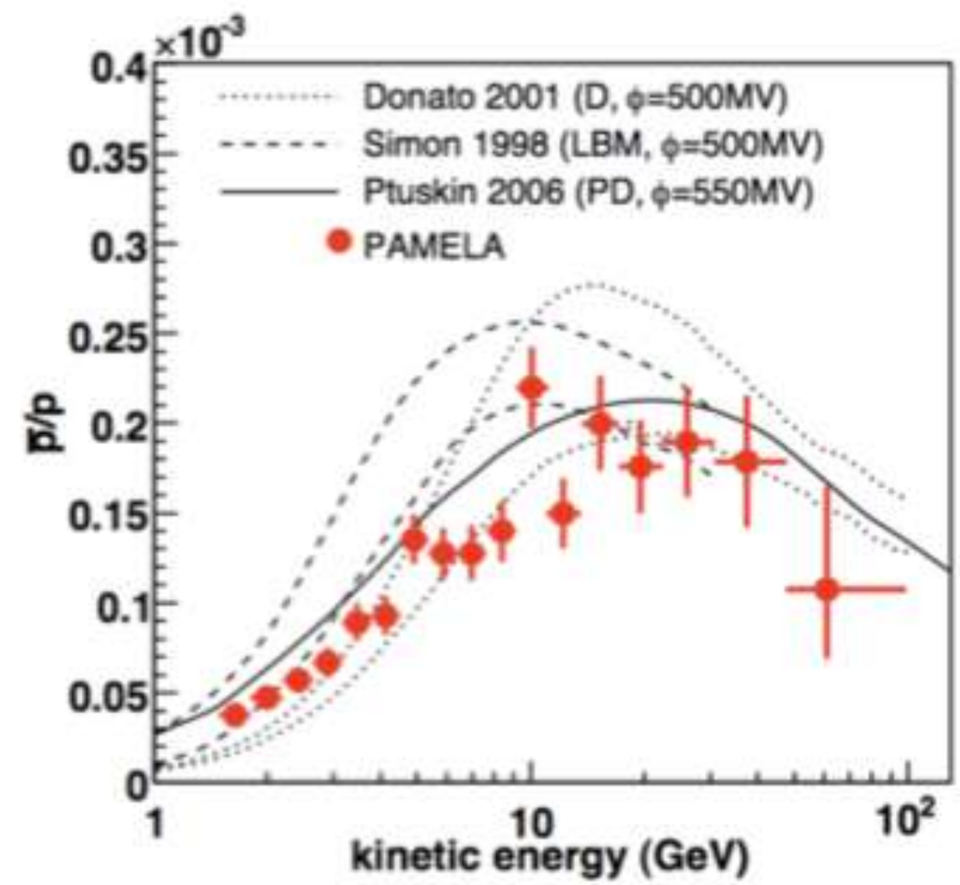
A Theory of Dark Matter

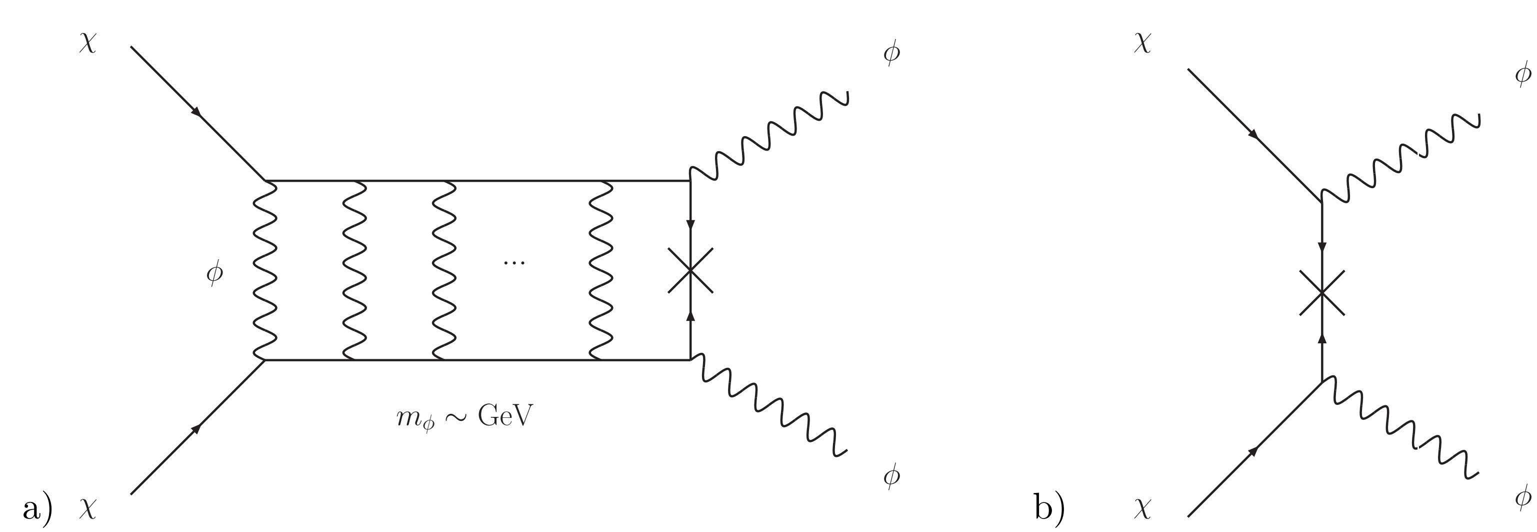
[Arkani-Hamed, Finkbeiner, Slatyer and Weiner; Pospelov and Ritz;….]

PAMELA sees a positron excess, but no anti-proton excess. Rate too large to be vanilla DM annihilation





Light mediators!



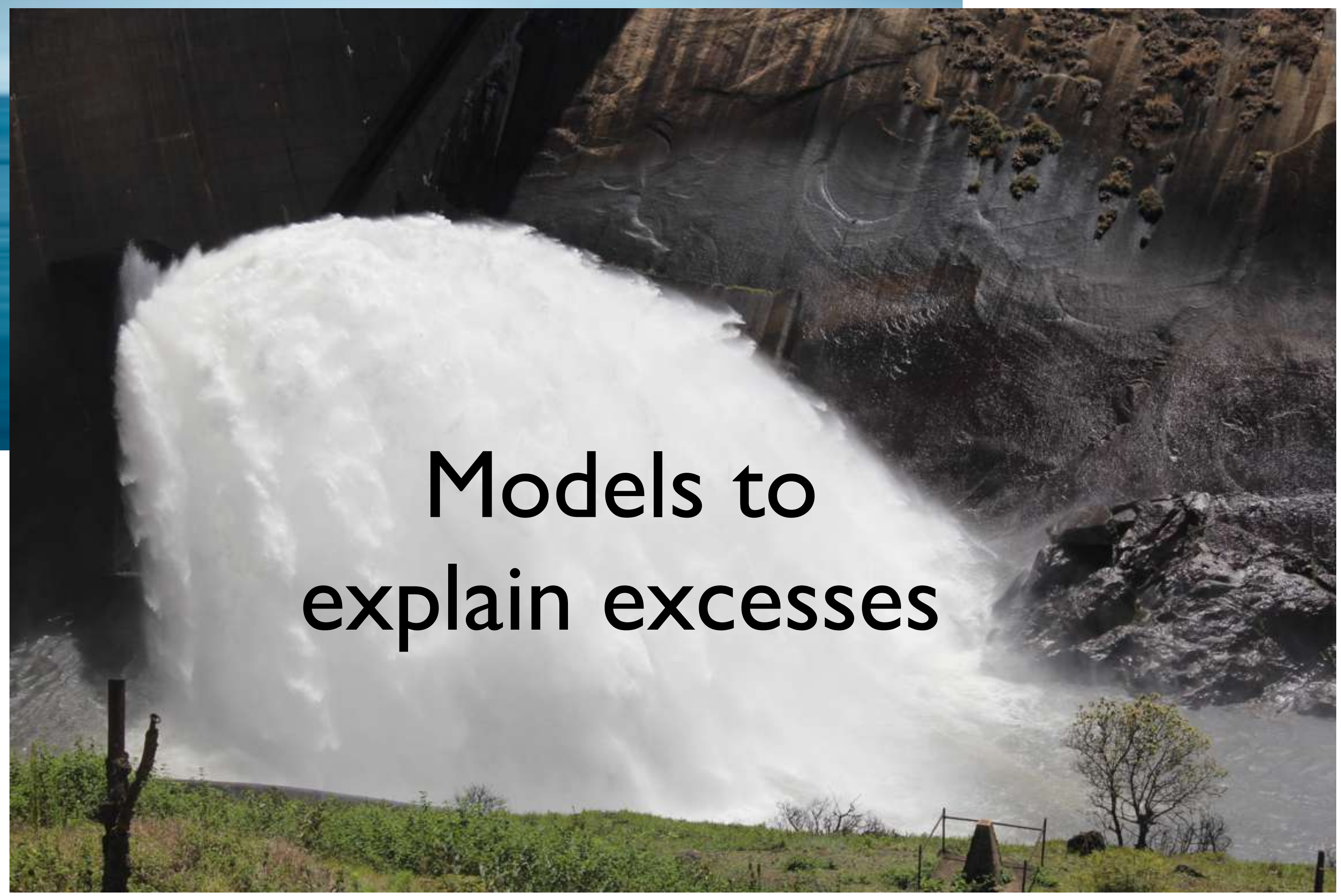
Dark Matter

↓

Dark Sector

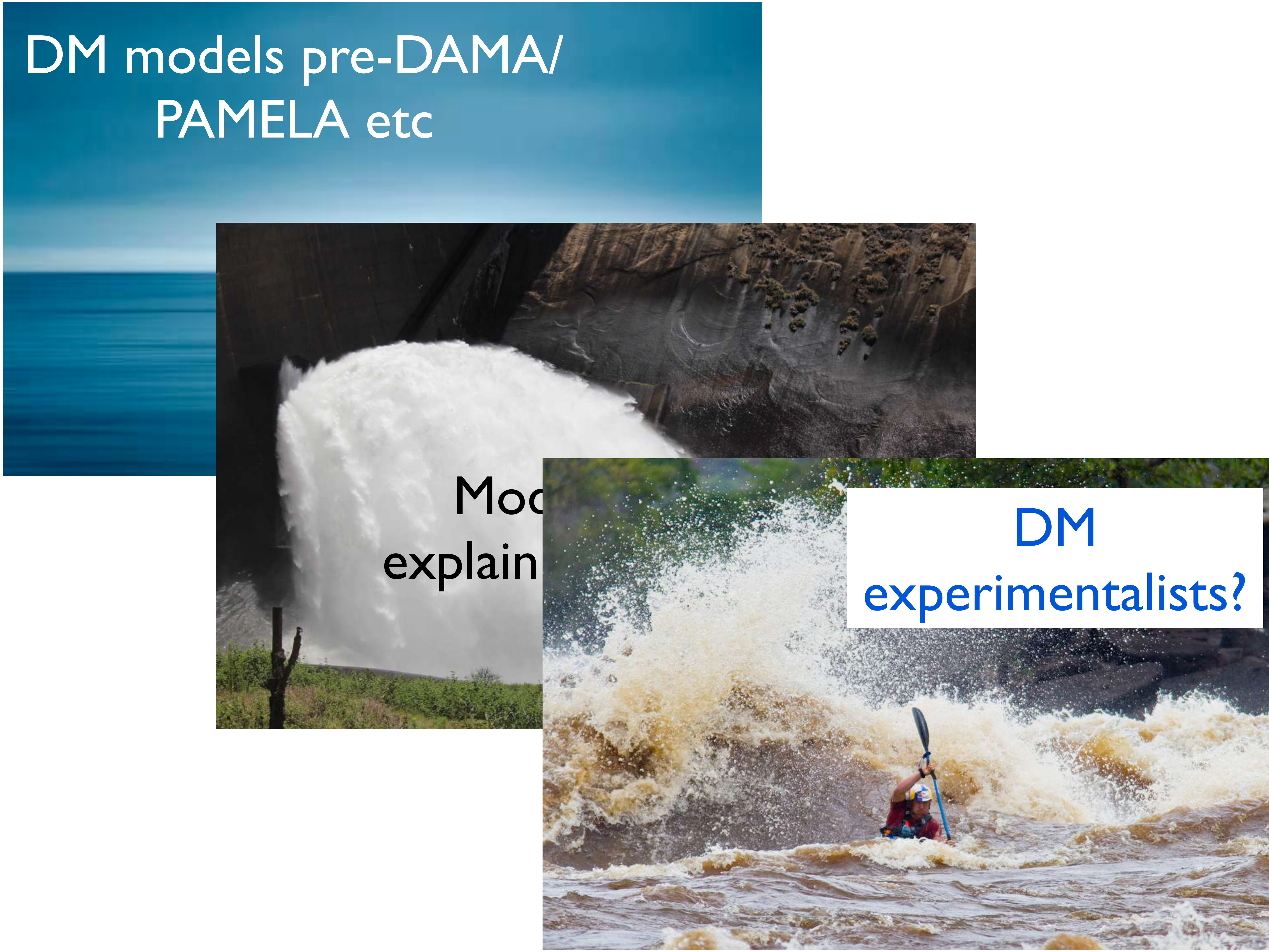

DM models pre-DAMA/
PAMELA etc

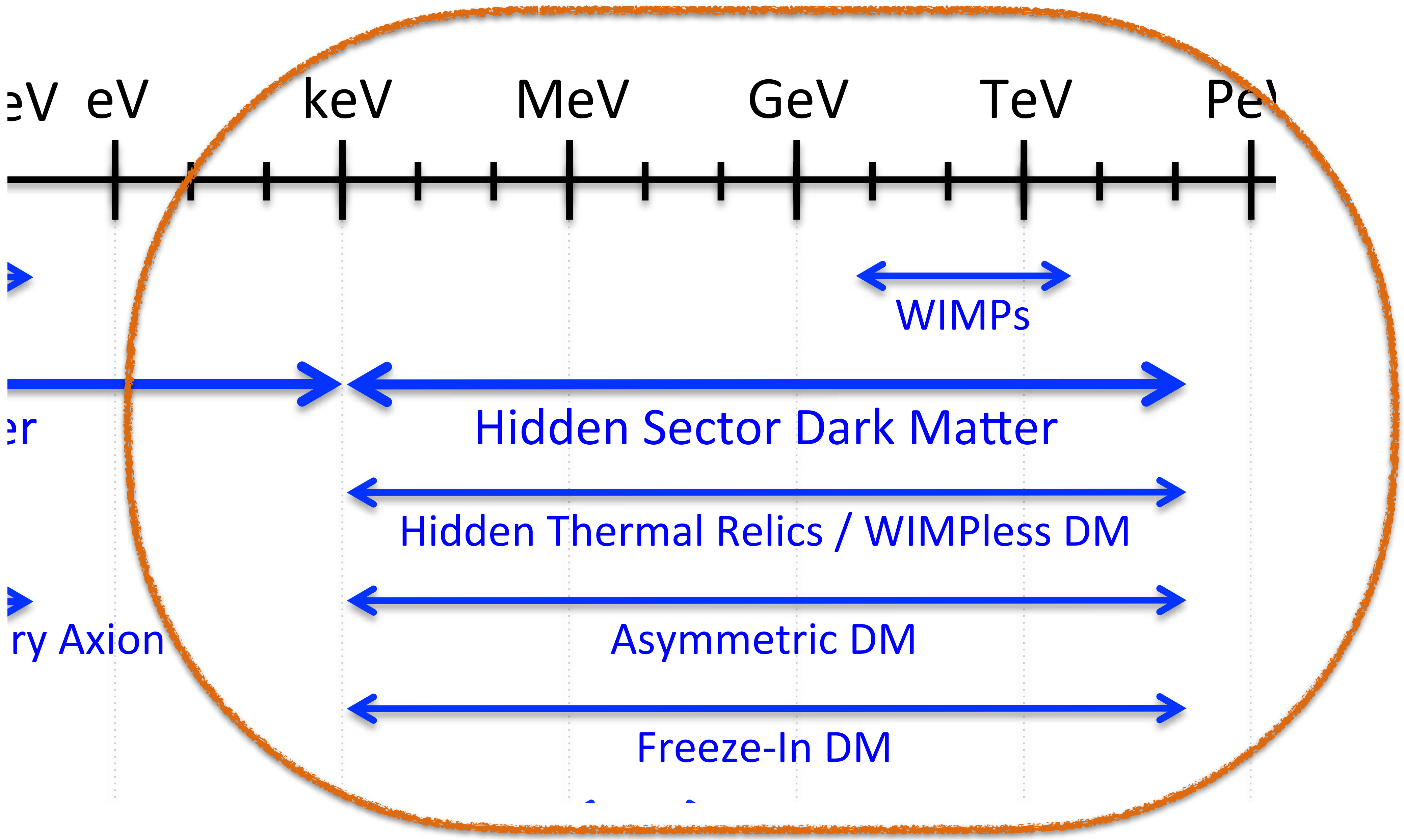

DM models pre-DAMA/
PAMELA etc


Models to
explain excesses


DM models pre-DAMA/
PAMELA etc


Moc
explain


DM models pre-DAMA/
PAMELA etc
DM
experimentalists?

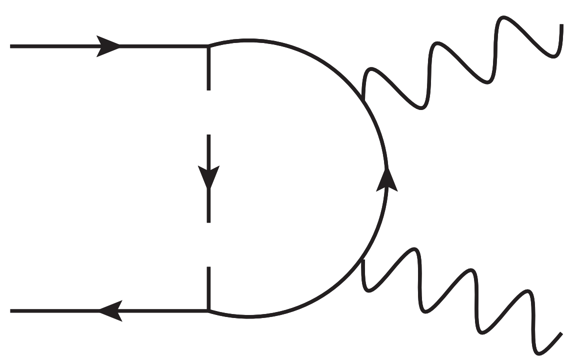


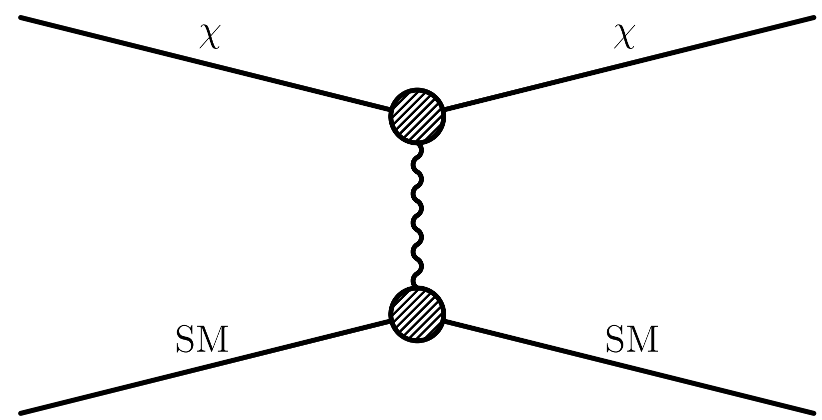
eV
eV
keV
MeV
GeV
TeV
Pe
WIMPs
er
Hidden Sector Dark Matter
Hidden Thermal Relics / WIMPless DM
ry Axion
Asymmetric DM
Freeze-In DM

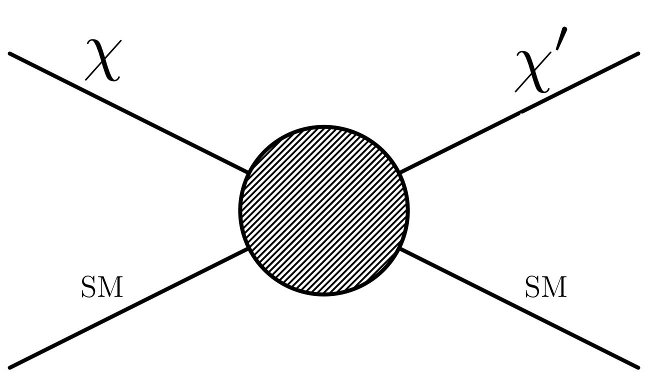
Hidden sector DM—interesting dynamics

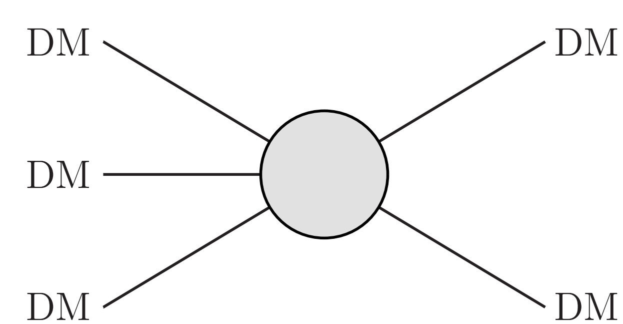
Hidden sector dynamics, new force carriers

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





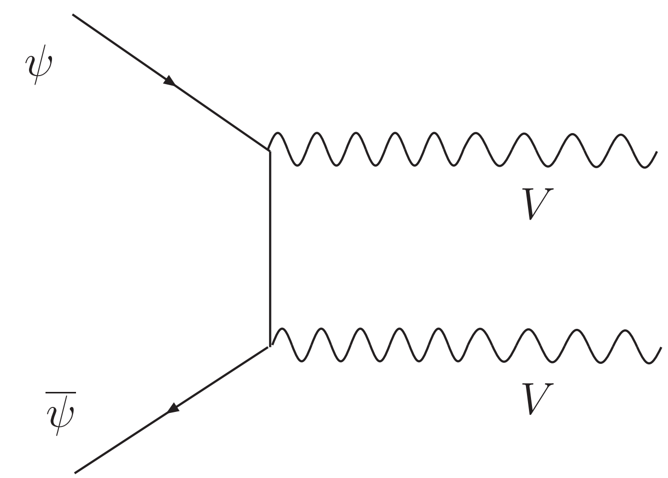




Hidden sector DM—thermal relics

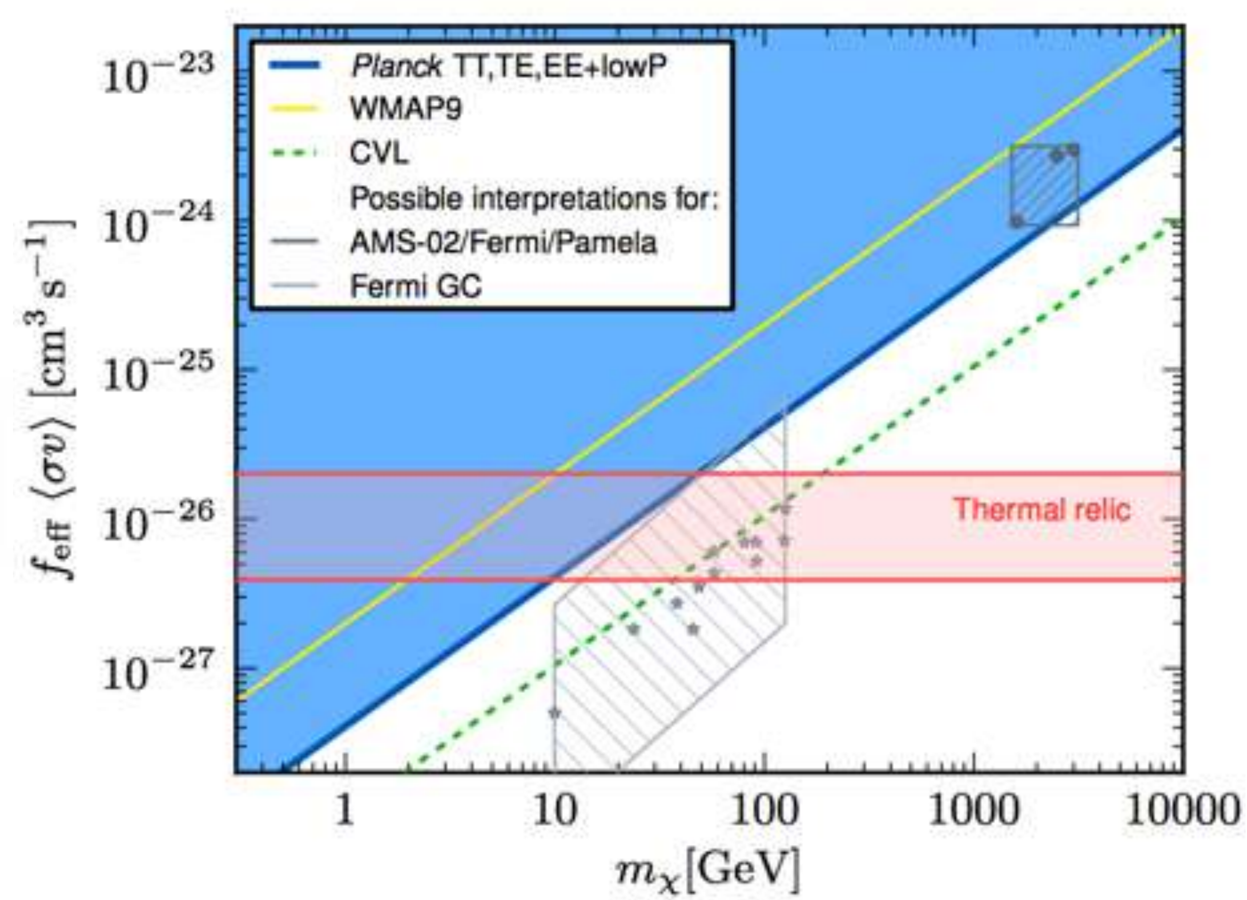
[Pospelov, Ritz, Voloshin]

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



Decouples direct detection from thermal history

[Finkbeiner, Slatyer et al]



Light DM and CMB

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

Portals

New light states allow for new ways to probe the dark sector

$$
\begin{array}{rc}
F^{\mu\nu} F'_{\mu\nu} & \text{Vector Portal, Kinetic Mixing;} \\
V^{\mu} J^{\text{SM}}_{\mu} & \text{Vector Portal, Gauge Coupling;} \\
H^\dagger H\,|S|^2\,, \quad \mu' H^\dagger H S & \text{Scalar Portal;} \\
(LH)\,N & \text{Neutrino Portal.} \\
a F_{\mu\nu} \tilde{F}^{\mu\nu} & \text{Axion Portal}
\end{array}
$$

Hidden sector U(1) — dark photon

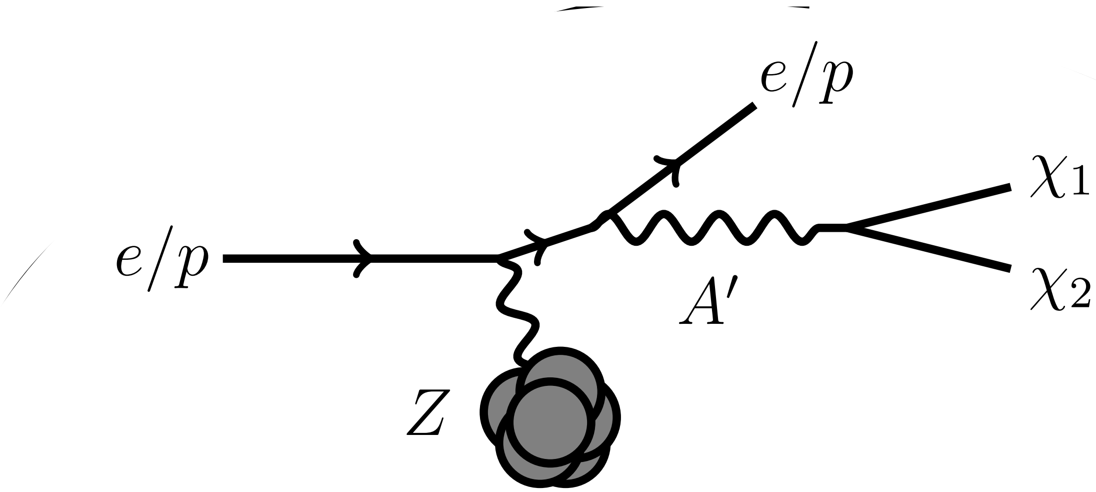
No SM matter directly charged under $U(1)_{\text{dark}}$ use a portal

[Holdom]

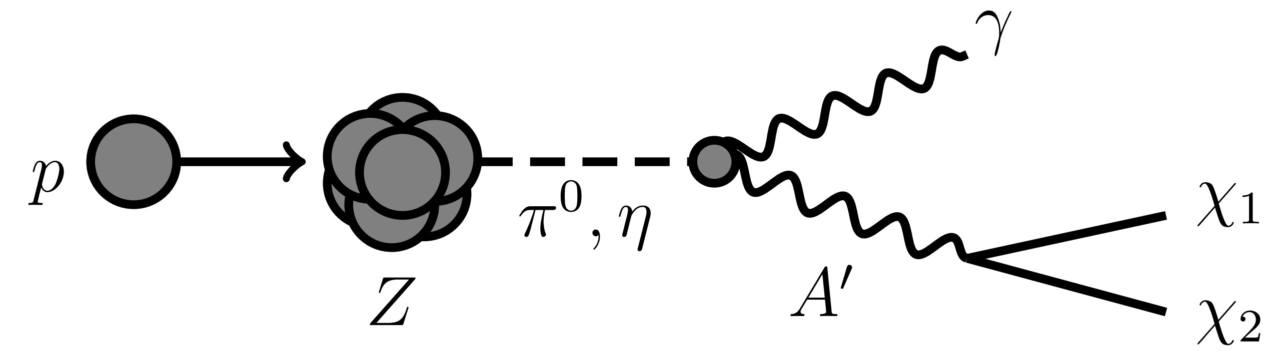
$$\mathcal{L}_{\text{kinetic mixing}} = \epsilon\, F^{\mu\nu} F'_{\mu\nu}$$

SM picks up "dark milli-charge"

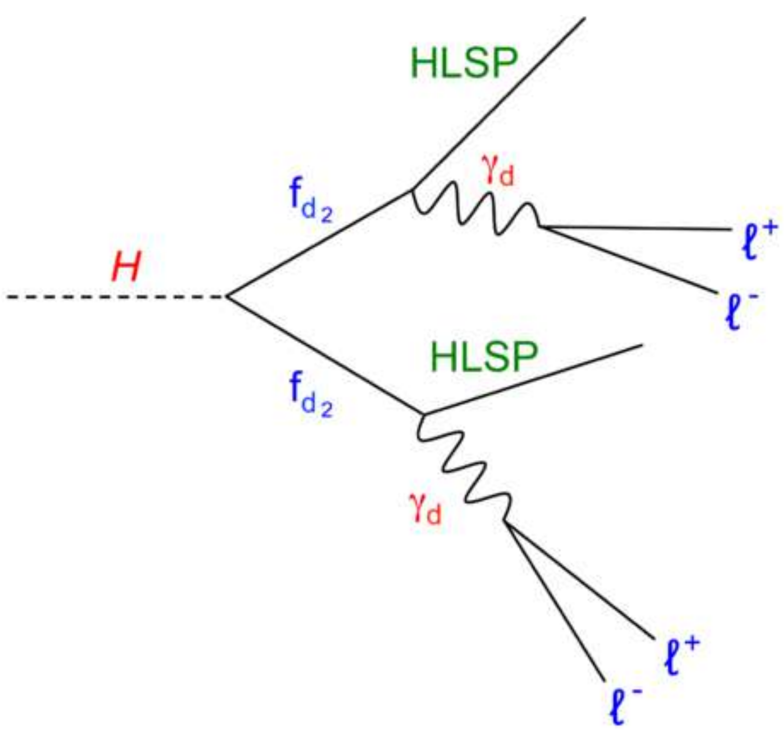
- Small couplings to SM means small production rates
- Visible/invisible decays depending on thresholds
- Possibly long lived—displaced signatures
- Many possible ways to search for DM/dark photon



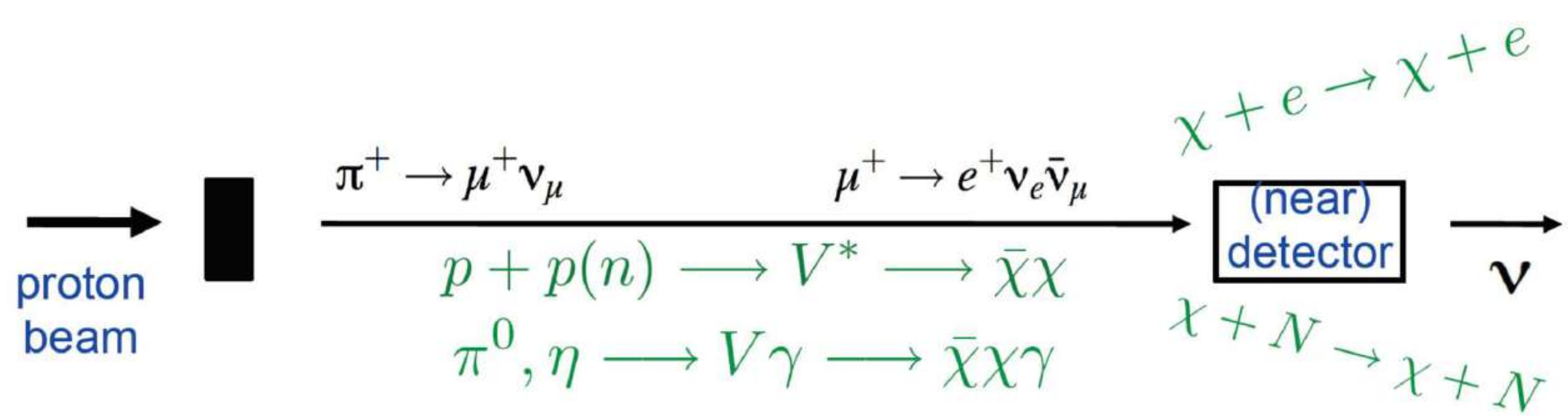
Bremsstrahlung
(LDMX, DarkLight, …)



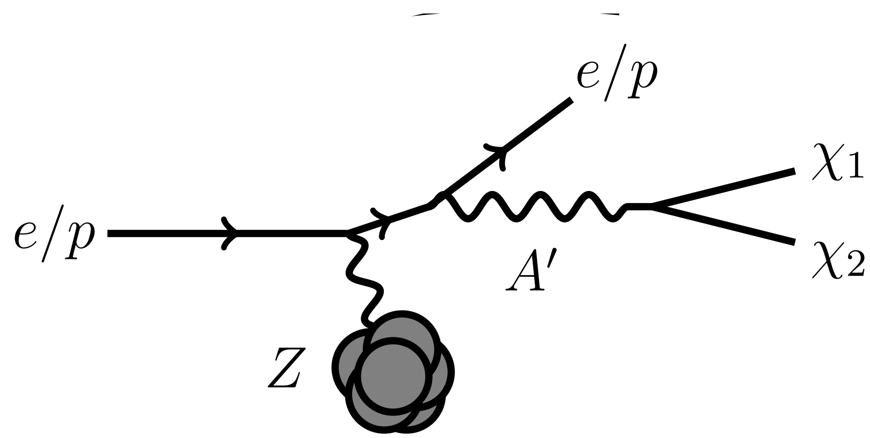
Meson decay
(NA48)



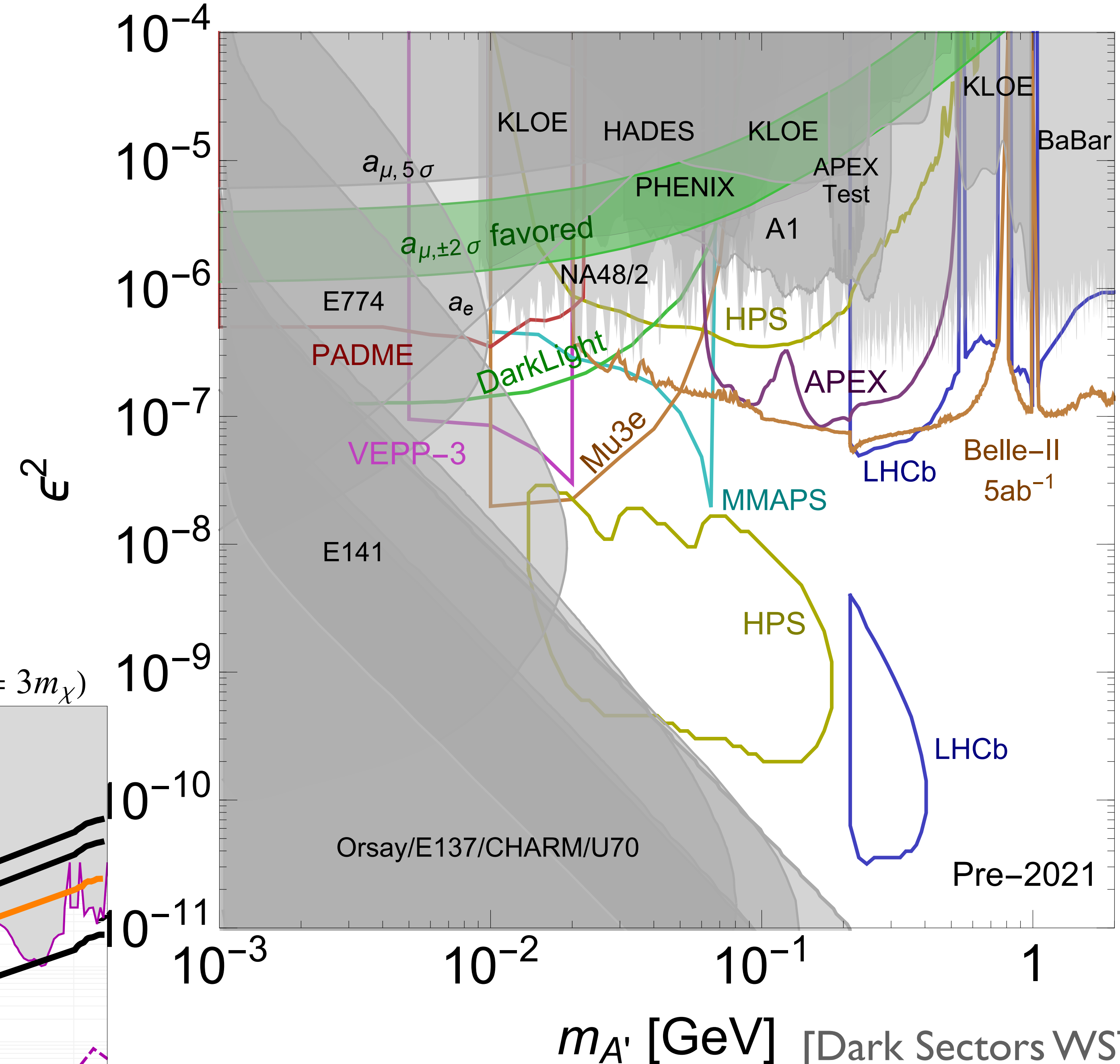
Lepton jets, Emerging tracks
(LHC)



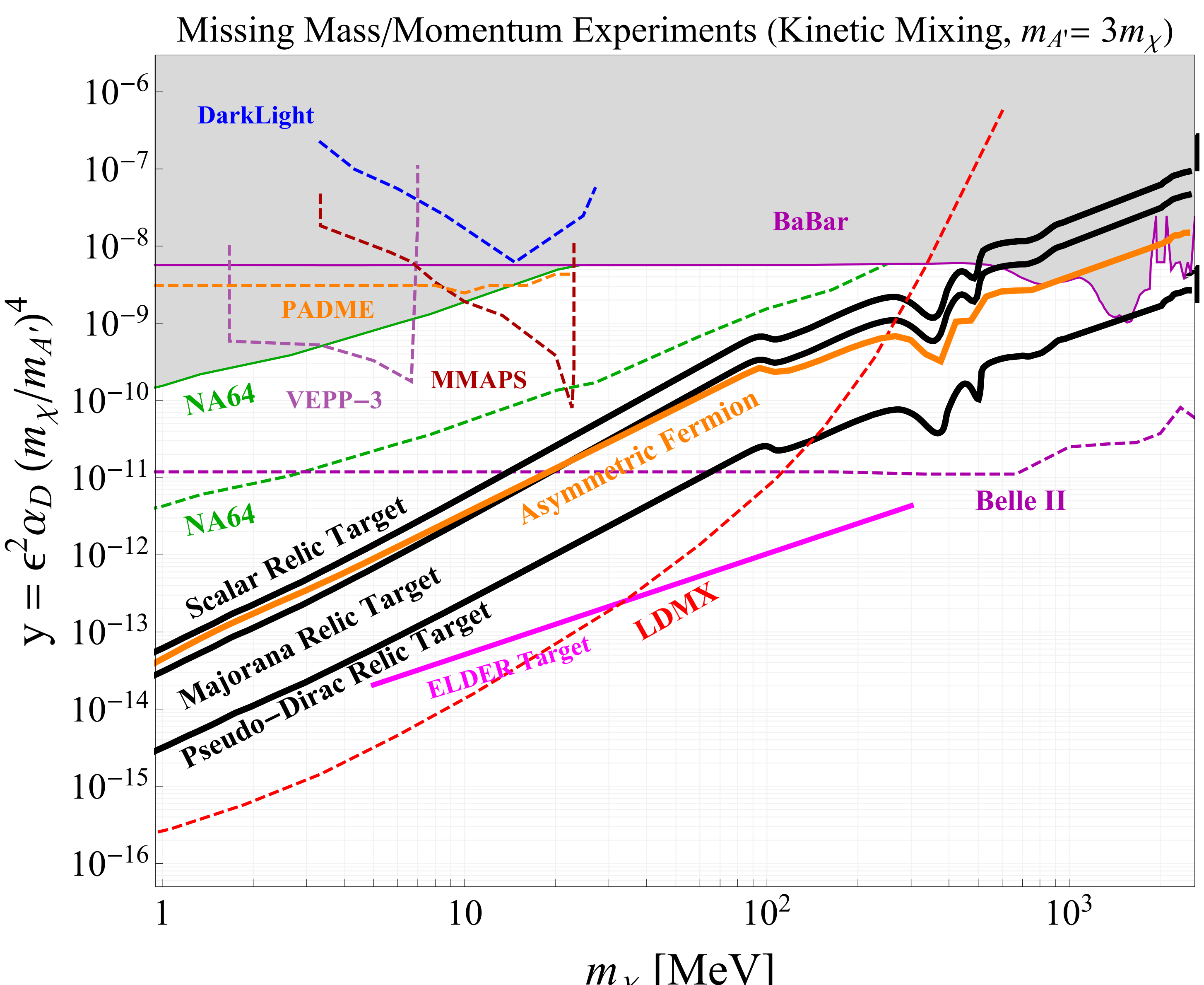
Production and scattering
(MiniBooNE, DUNE, SHiP,…)



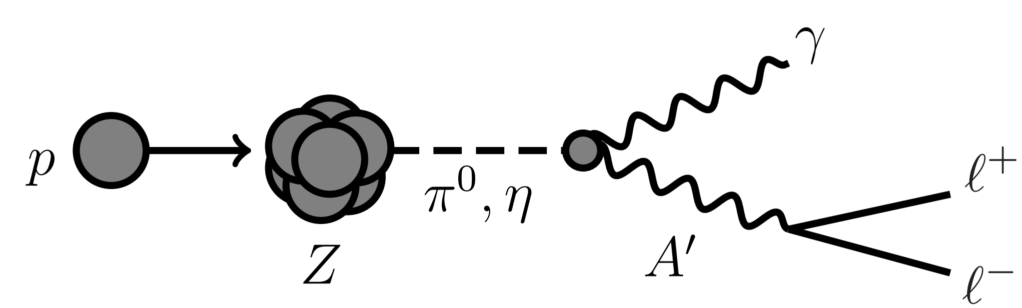
e/p
e/p
χ_1
χ_2
A'
Z



ϵ^2
$m_{A'}$ [GeV]
[Dark Sectors WS]
Pre–2021
KLOE
HADES
KLOE
KLOE
BaBar
APEX
Test
PHENIX
A1
$a_{\mu,5\sigma}$
$a_{\mu,\pm 2\sigma}$ favored
NA48/2
E774
a_e
PADME
DarkLight
HPS
APEX
Mu3e
VEPP–3
LHCb
Belle–II
$5ab^{-1}$
MMAPS
E141
HPS
LHCb
Orsay/E137/CHARM/U70

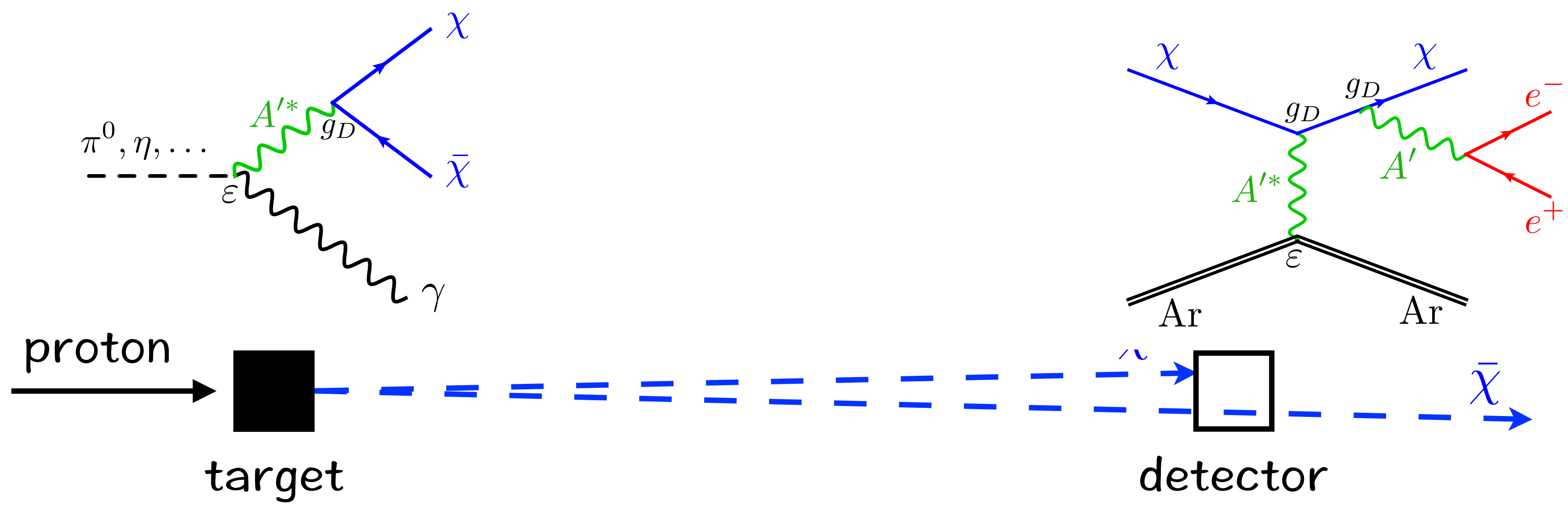


Missing Mass/Momentum Experiments (Kinetic Mixing, $m_{A'} = 3m_\chi$)
$y = \epsilon^2 \alpha_D (m_\chi/m_{A'})^4$
m_χ [MeV]
DarkLight
BaBar
PADME
MMAPS
NA64
VEPP–3
Asymmetric Fermion
Belle II
NA64
Scalar Relic Target
Majorana Relic Target
Pseudo–Dirac Relic Target
ELDER Target
LDMX

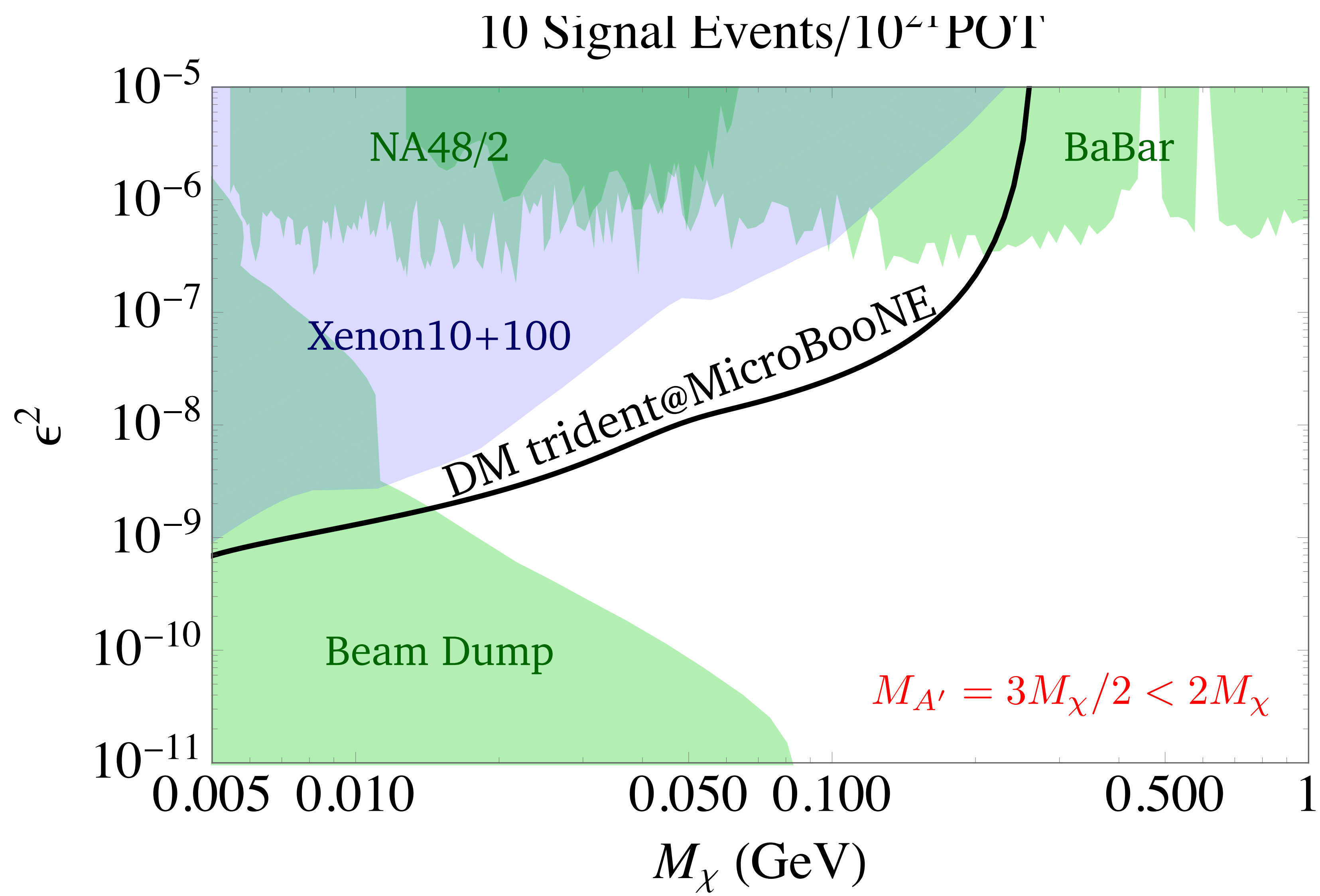


p
Z
π^0, η
A'
γ
ℓ^+
ℓ^-

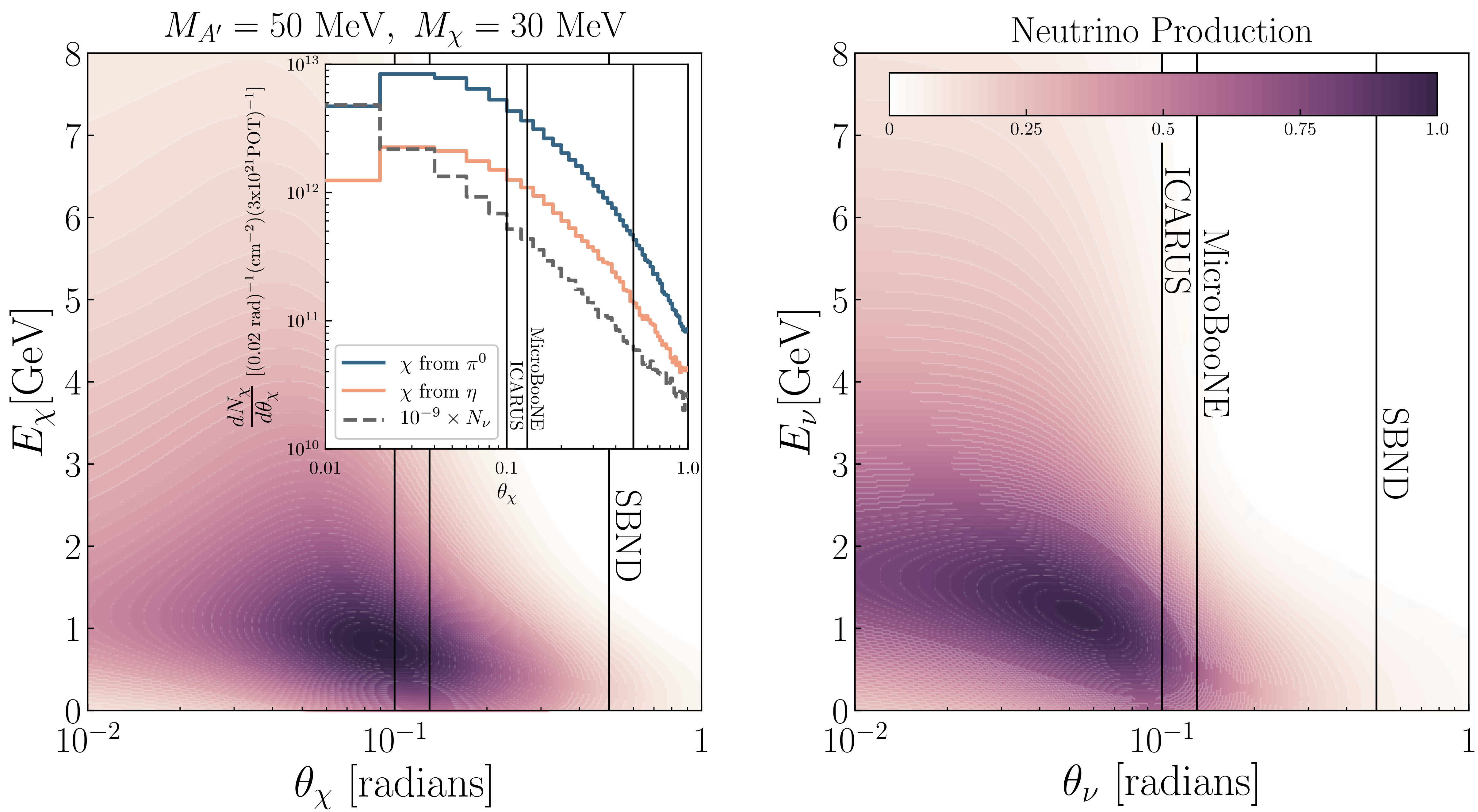
$m_V < 2m_\chi$



[de Gouvea, PF, Harnik, Kelly, Yang]

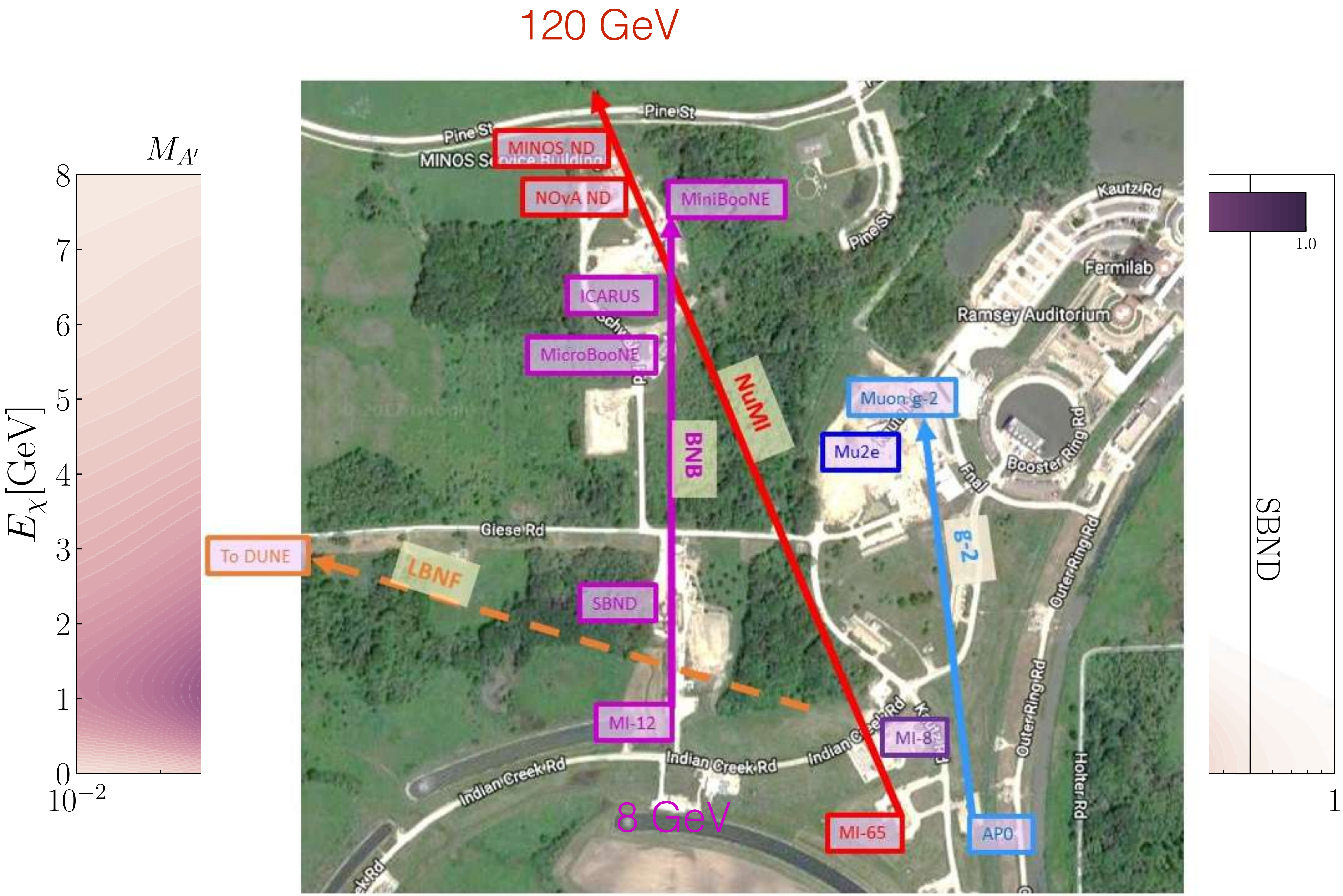


Useful to look off axis



Other places with detectors near (but not on) beam lines?
e.g. protoDUNE/LHC

Useful to look off axis



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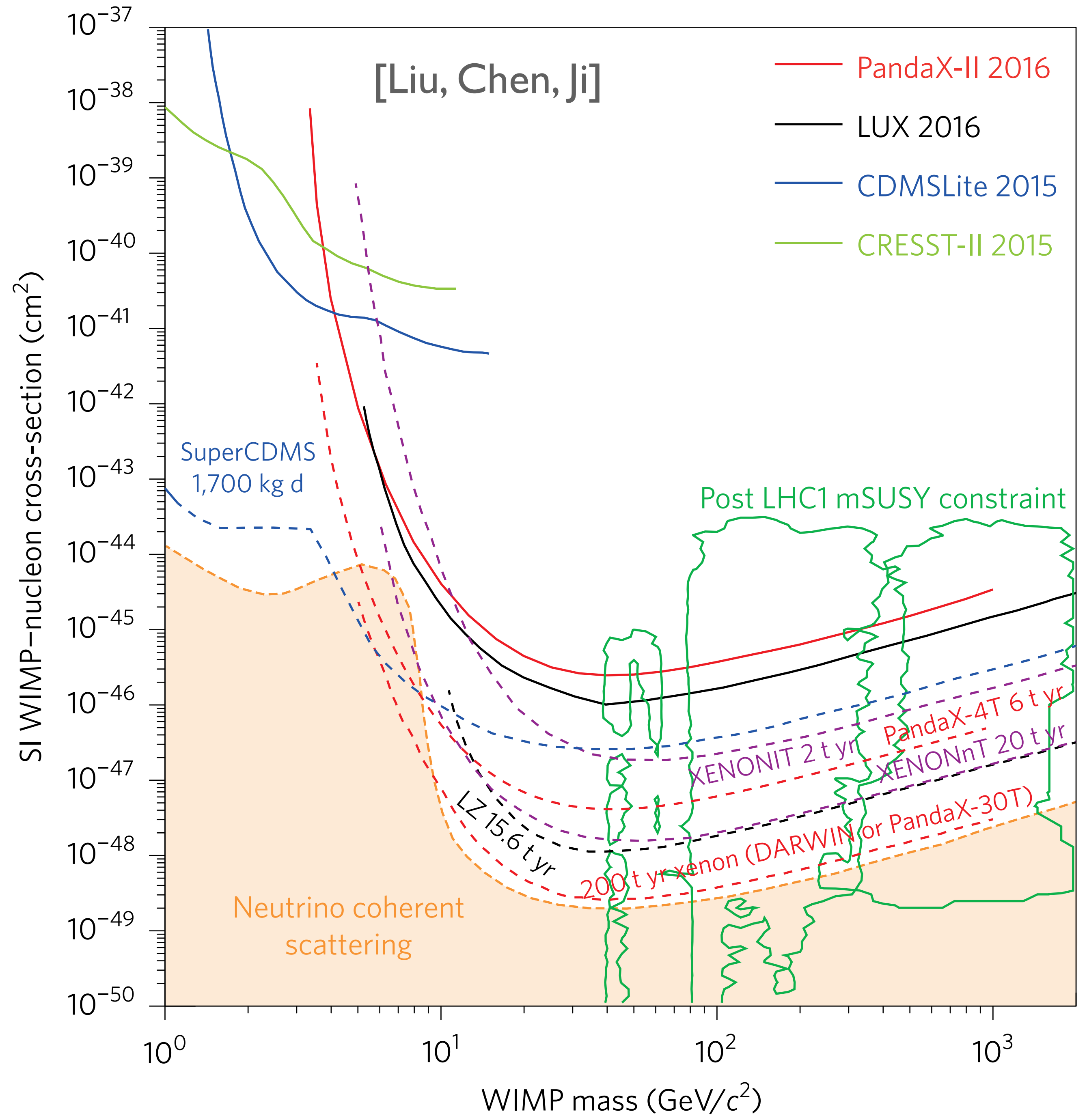
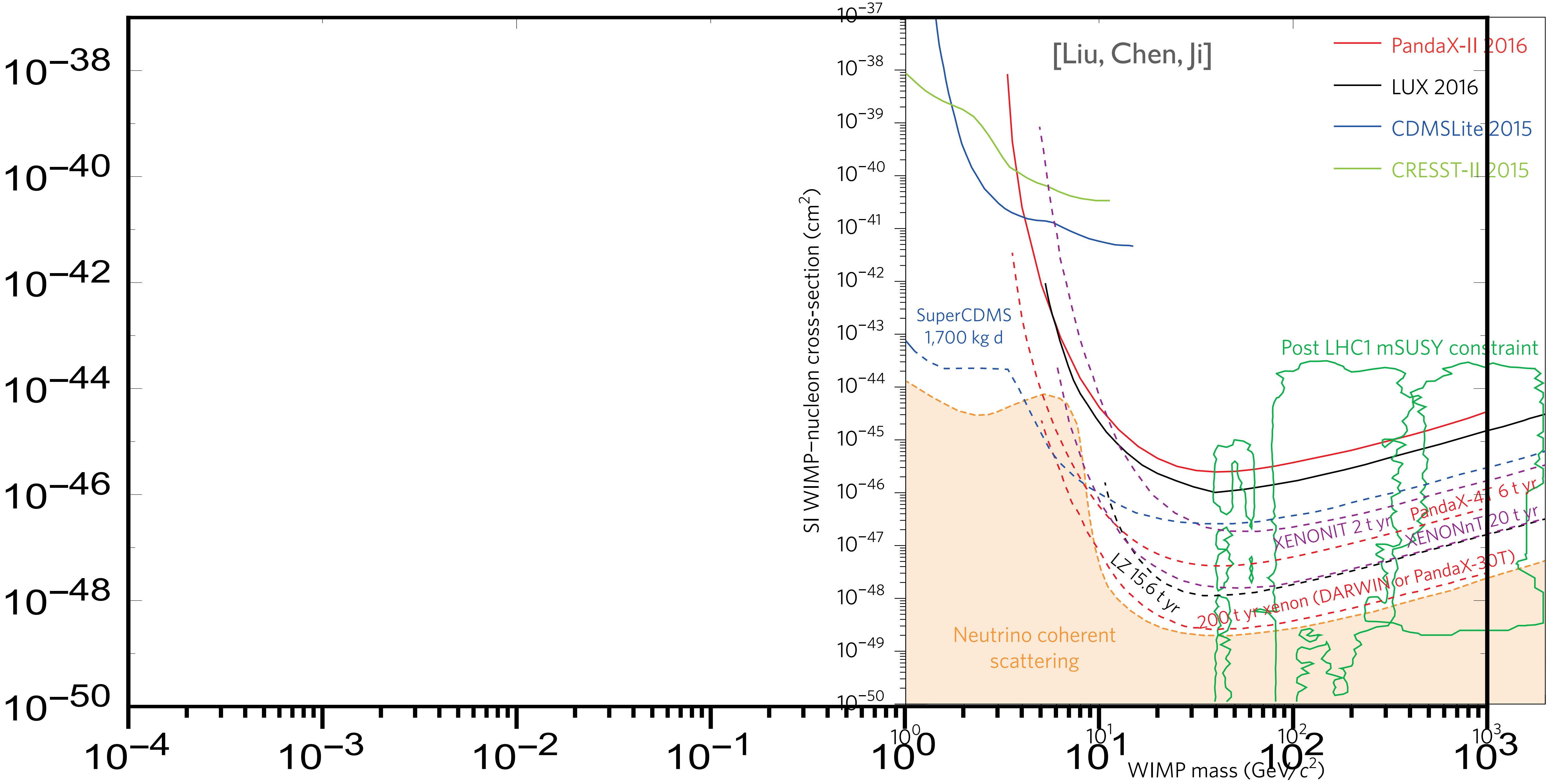
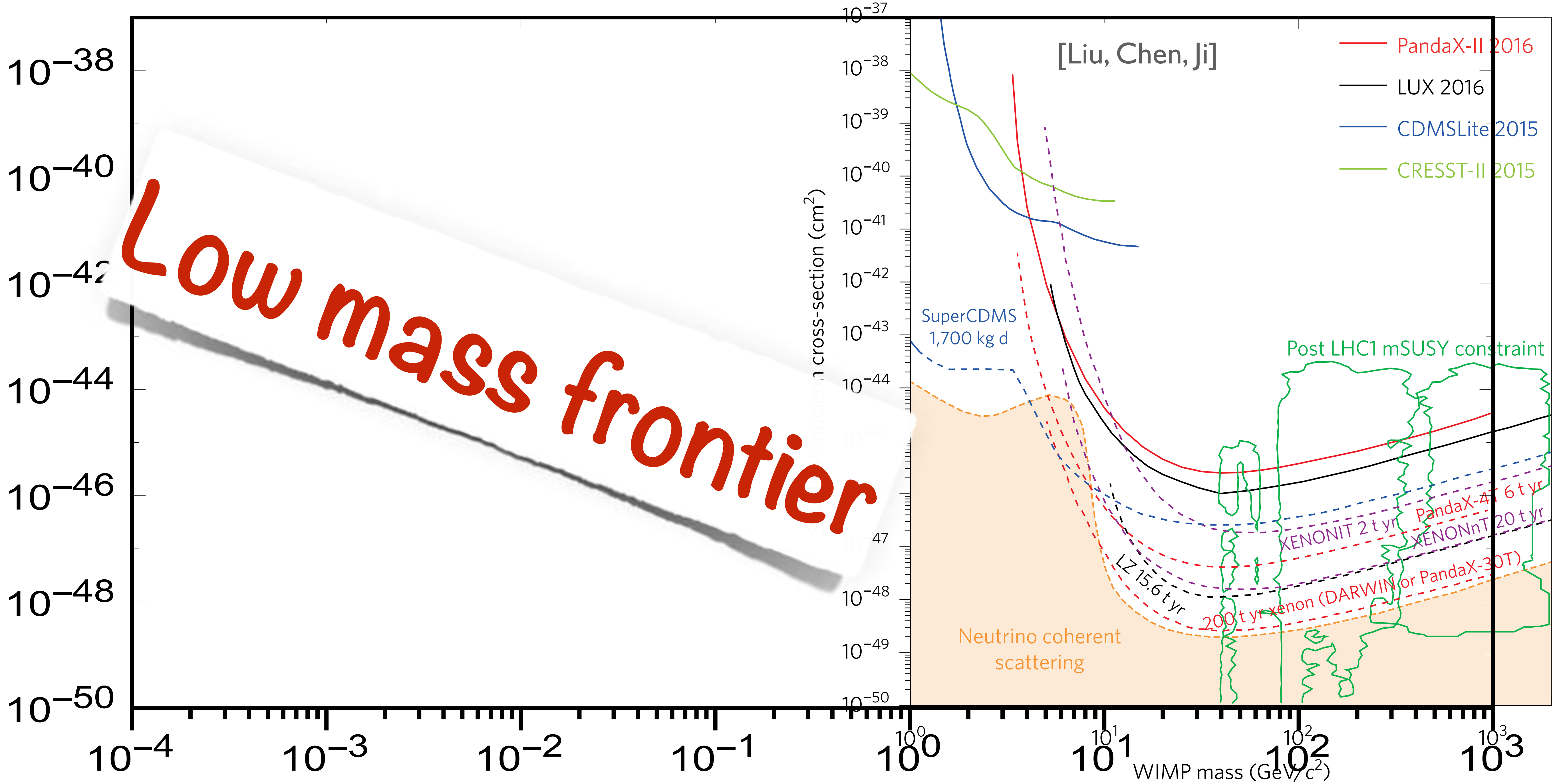
Dark sectors and direct detection



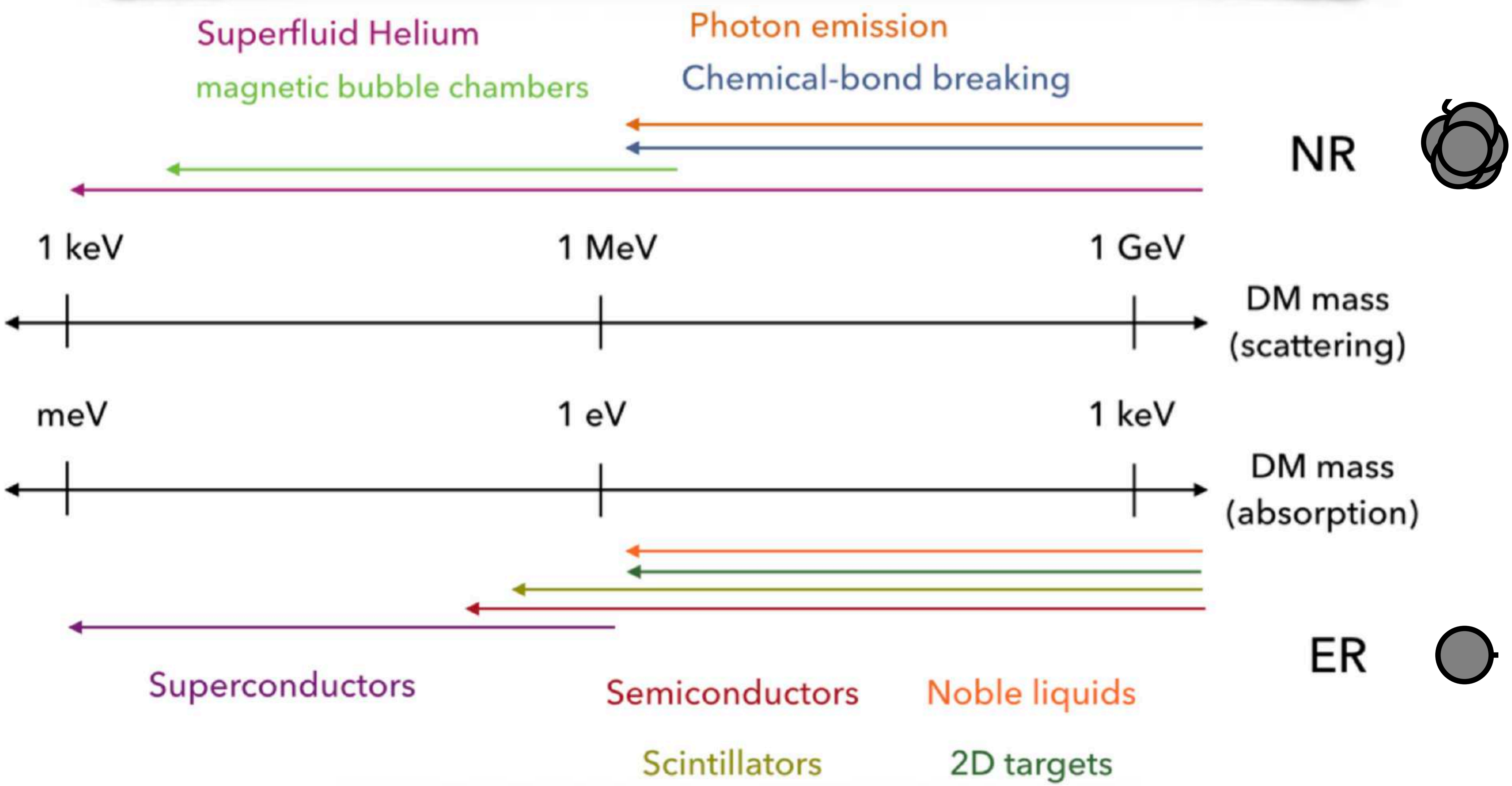
Dark sectors and direct detection



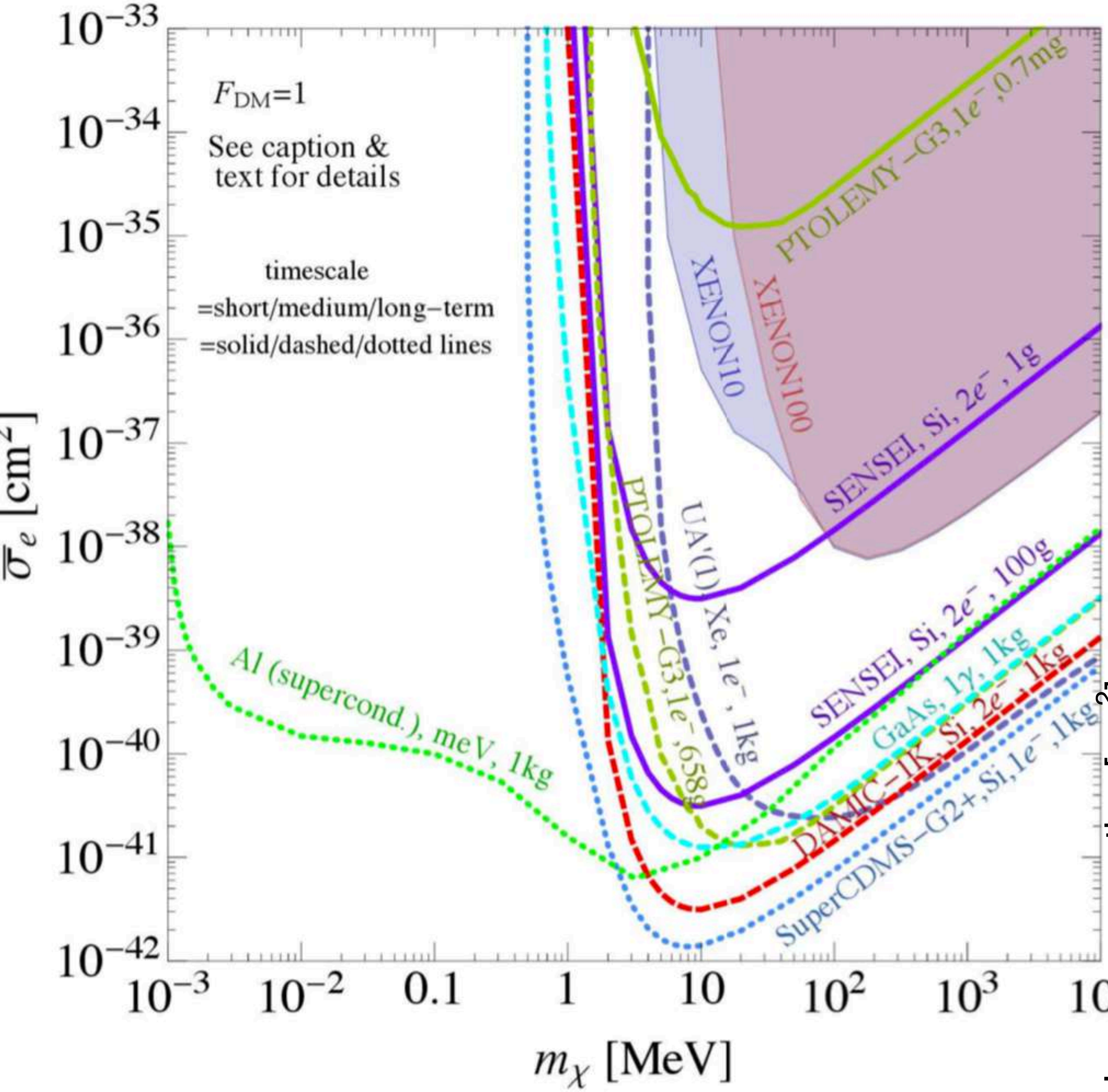
Dark sectors and direct detection

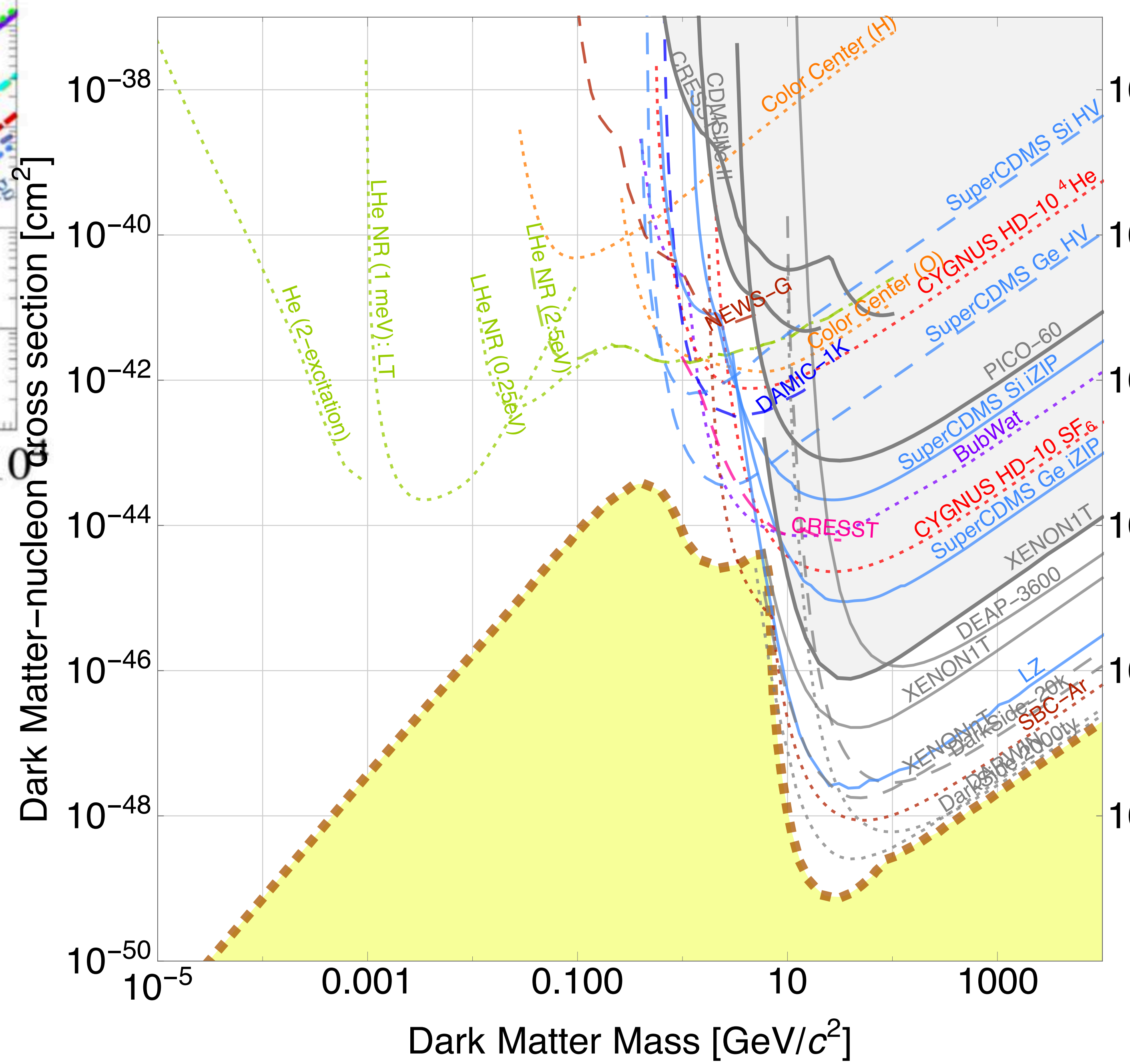


$$E_{\rm NR} = \frac{q^2}{2m_N} \leq \frac{2\mu_{\chi N}^2 v_\chi^2}{m_N} \lesssim 190 \text{ eV} \times \left(\frac{m_\chi}{500 \text{ MeV}}\right)^2 \left(\frac{16 \text{ GeV}}{m_N}\right)$$

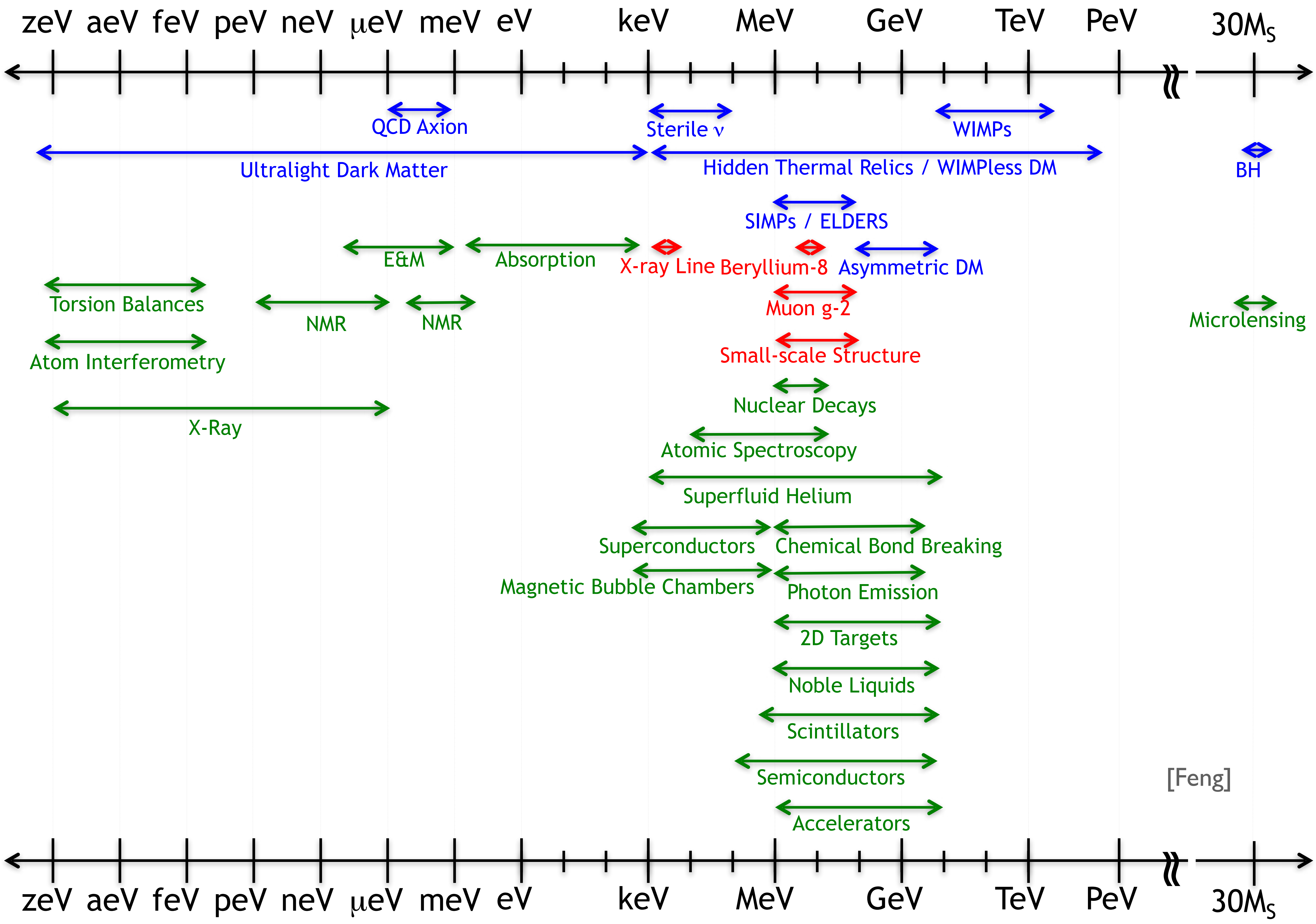


$$E_e \leq \frac{1}{2} m_\chi v_\chi^2 \lesssim 3 \text{ eV} \left(\frac{m_\chi}{\text{MeV}}\right)$$


$F_{\rm DM}$=1
See caption & text for details
timescale =short/medium/long−term =solid/dashed/dotted lines
PTOLEMY−G3,1e⁻,0.7mg
XENON10
XENON100
SENSEI, Si, 2e⁻, 1g
UA'(1) Xe, 1e⁻, 1kg
PTOLEMY−G3,1e⁻,658g
SENSEI, Si, 2e⁻, 100g
GaAs, 1γ, 1kg
DAMIC−1K,Si, 2e⁻, 1kg
SuperCDMS−G2+,Si,1e⁻,1kg
Al (supercond.), meV, 1kg
$\overline{\sigma}_e$ [cm²]
m_χ [MeV]


Dark Matter−nucleon cross section [cm²]
Dark Matter Mass [GeV/c²]
He (2-excitation)
LHe NR (1 meV): LT
LHe NR (0.25eV)
LHe NR (2.5eV)
CRESST
CDMSlite II
Color Center (H)
Color Center (O)
SuperCDMS Si HV
CYGNUS HD−10 ⁴He
SuperCDMS Ge HV
NEWS−G
DAMIC−1K
PICO−60
SuperCDMS Si iZIP
BubWat
CYGNUS HD−10 SF₆
SuperCDMS Ge iZIP
CRESST
XENON1T
DEAP−3600
XENON1T
LZ
SBC−Ar

Dark Sector Candidates, Anomalies, and Search Techniques



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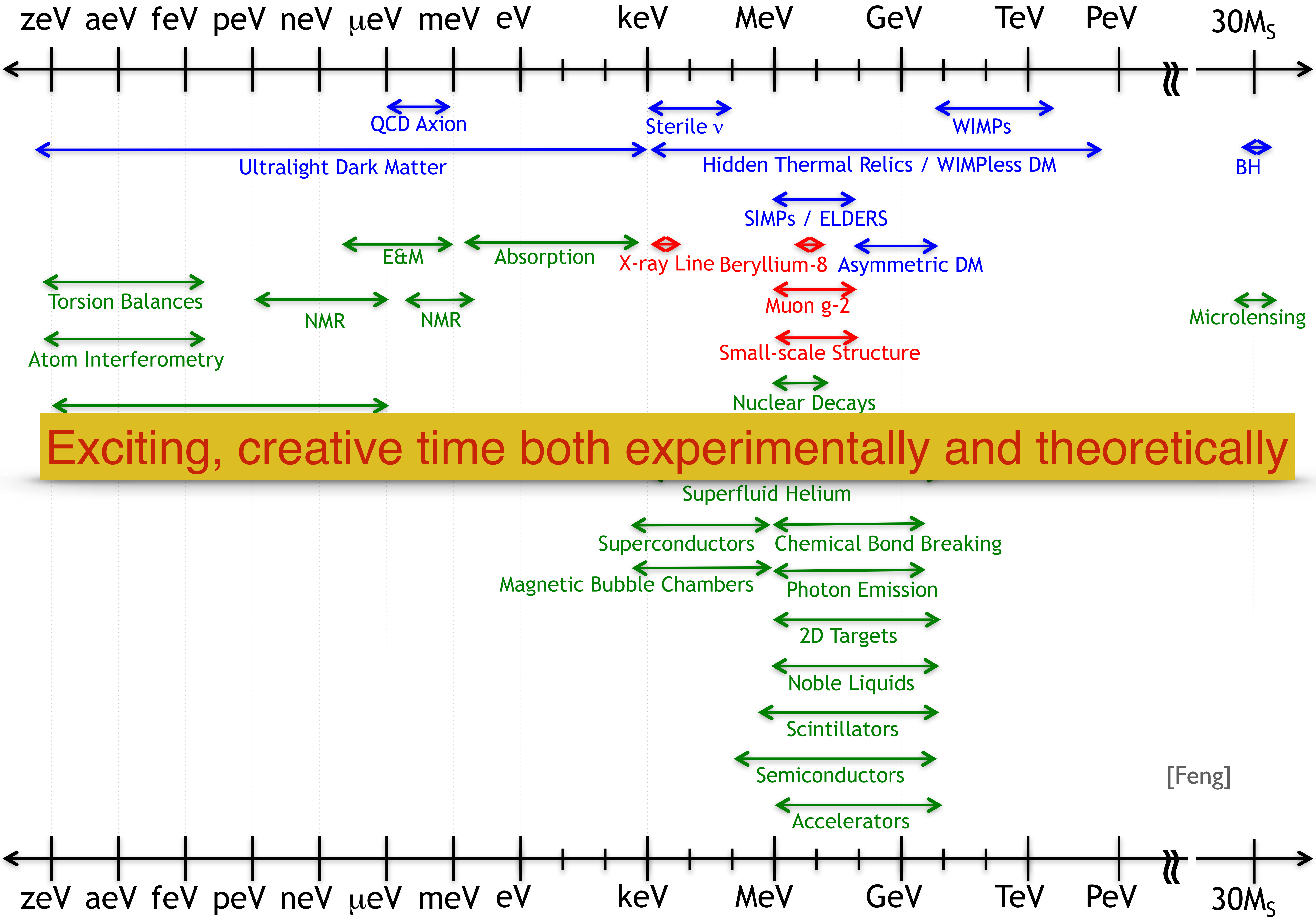
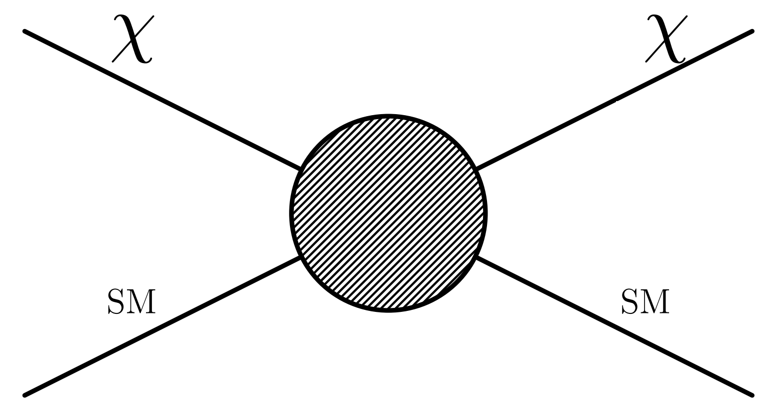
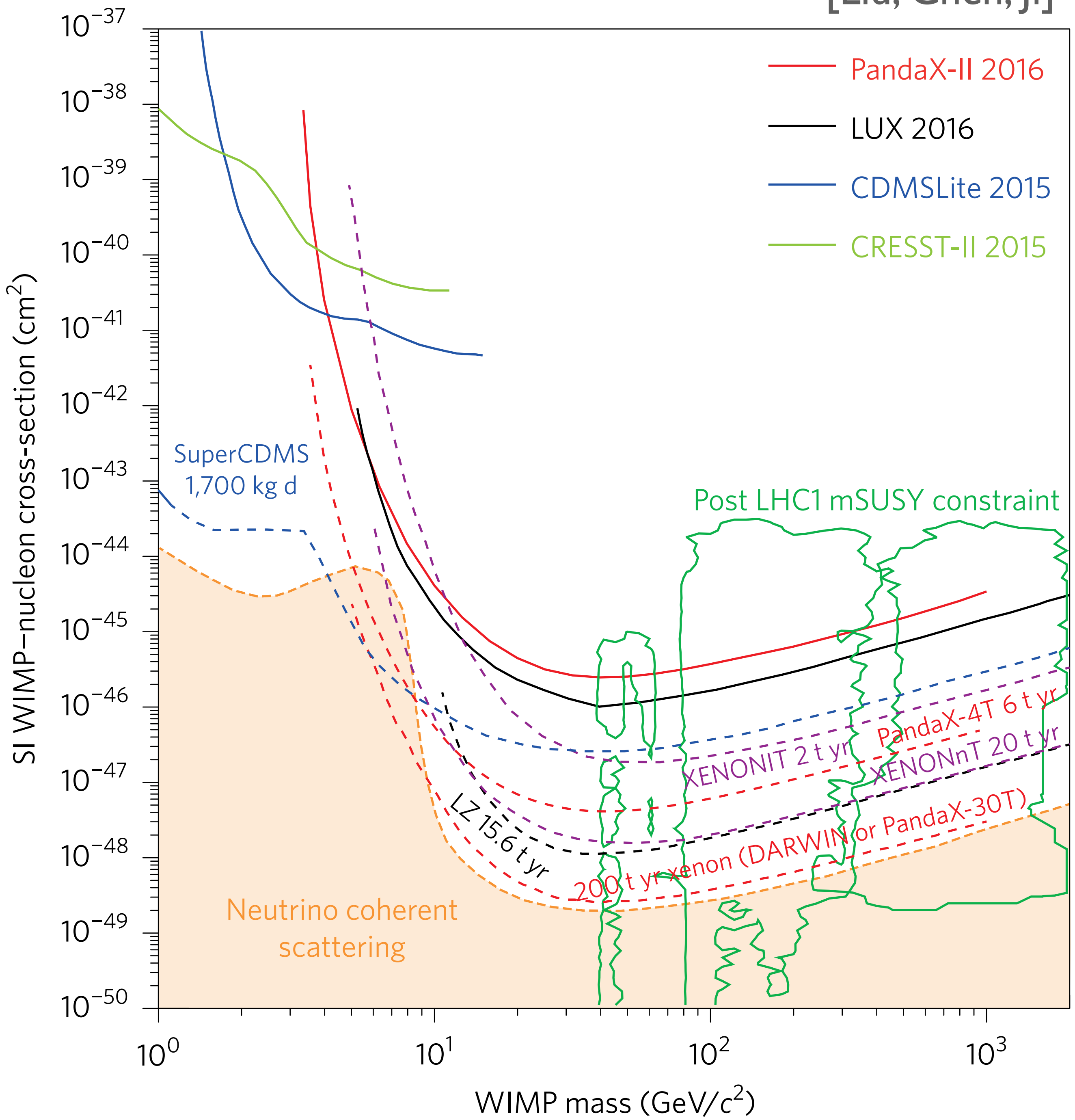


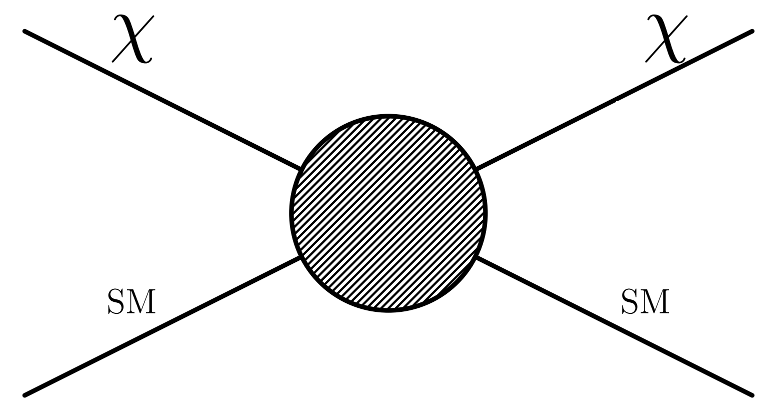
Status of Direct Detection

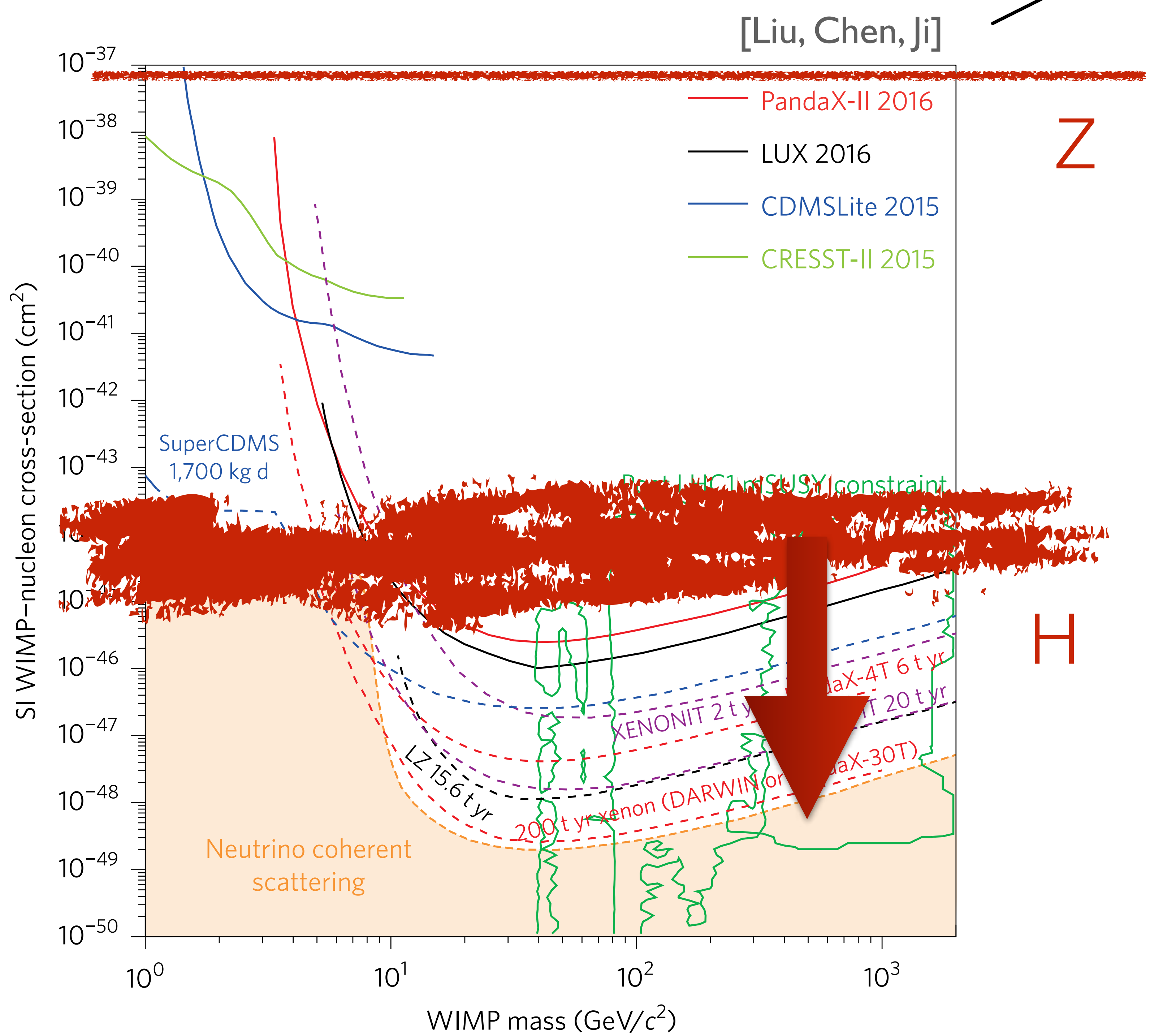


[Liu, Chen, Ji]

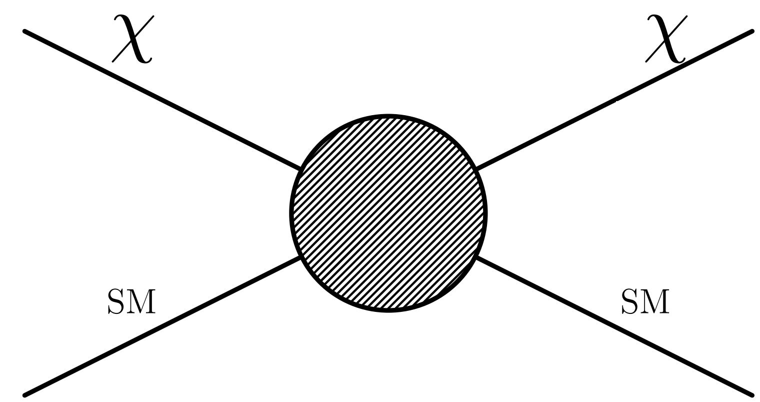


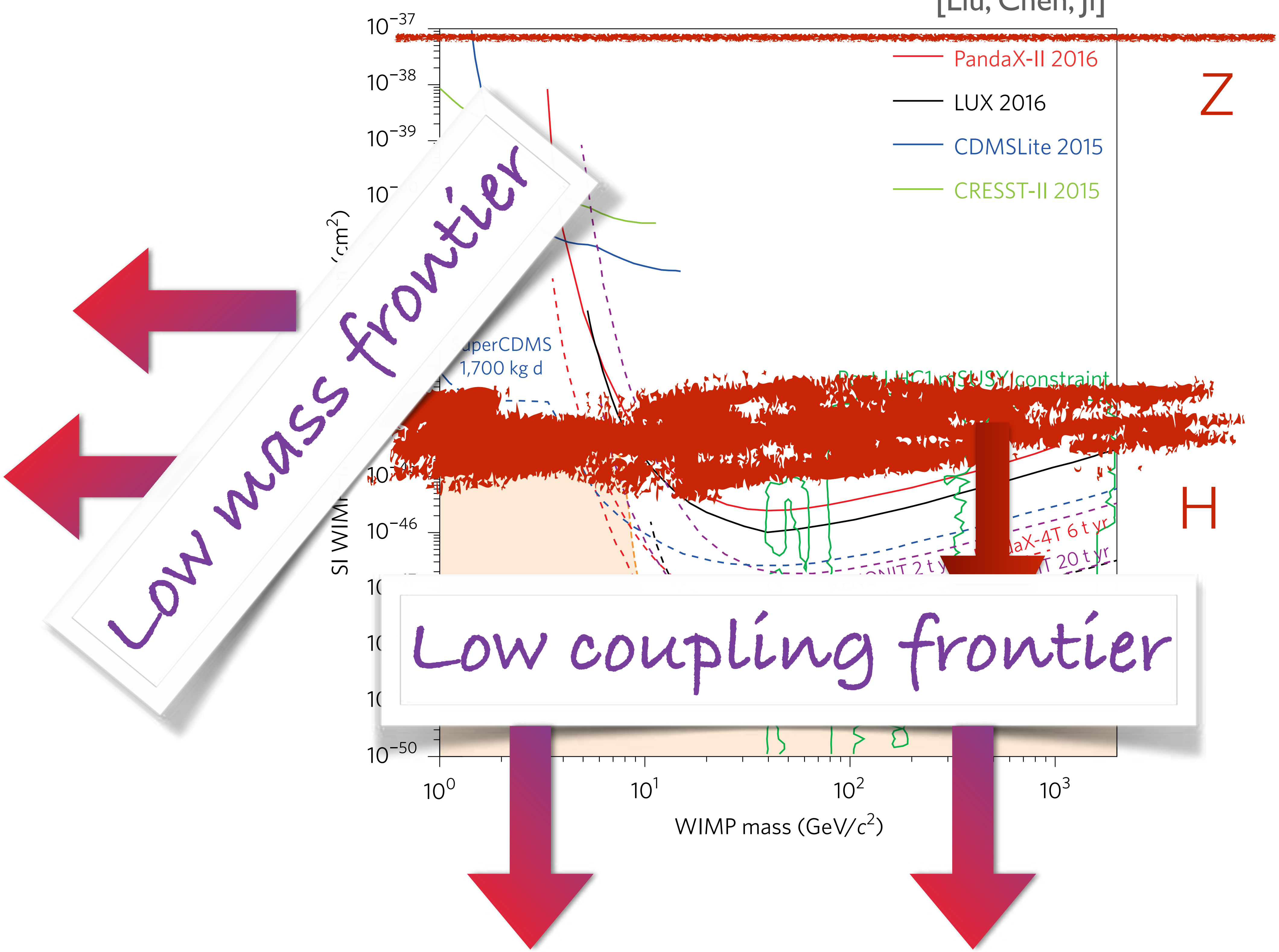
Status of Direct Detection



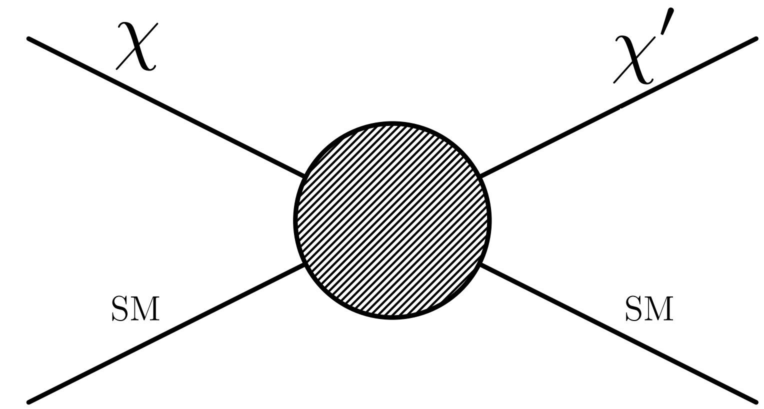


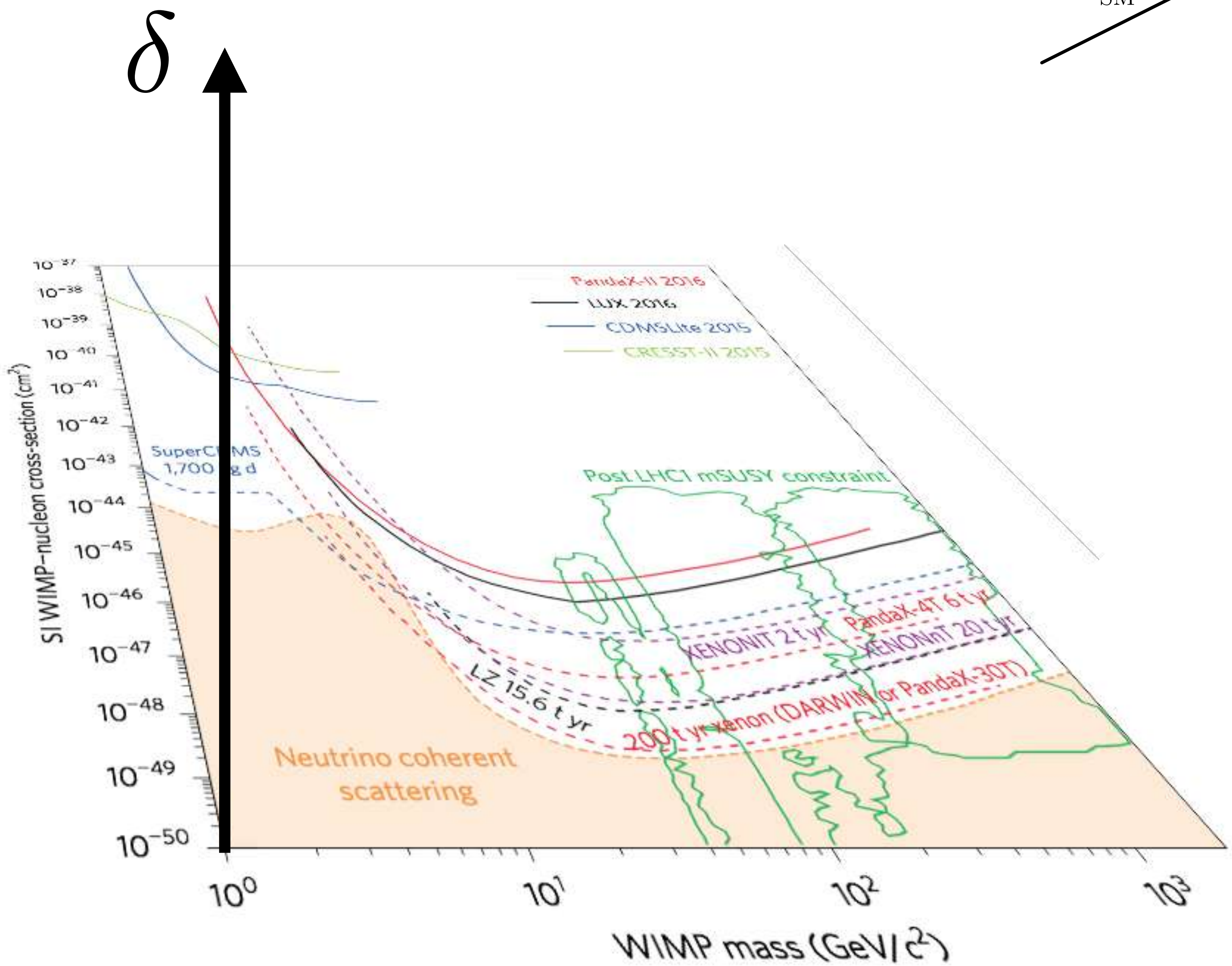
Status of Direct Detection





Inelastic scattering of DM





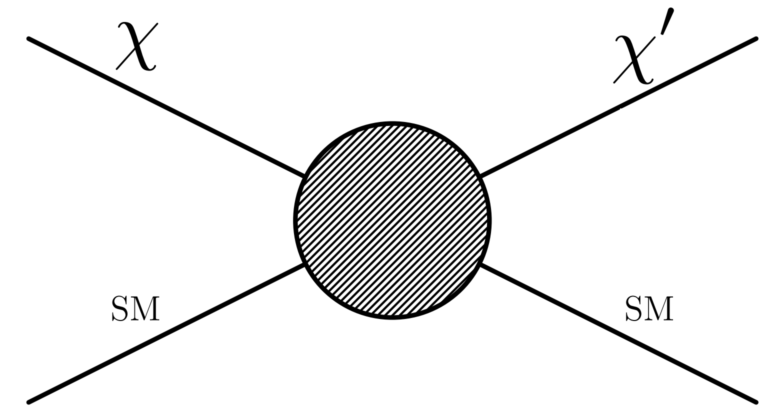
[Graham, Harnik, Rajendran, Saraswat]

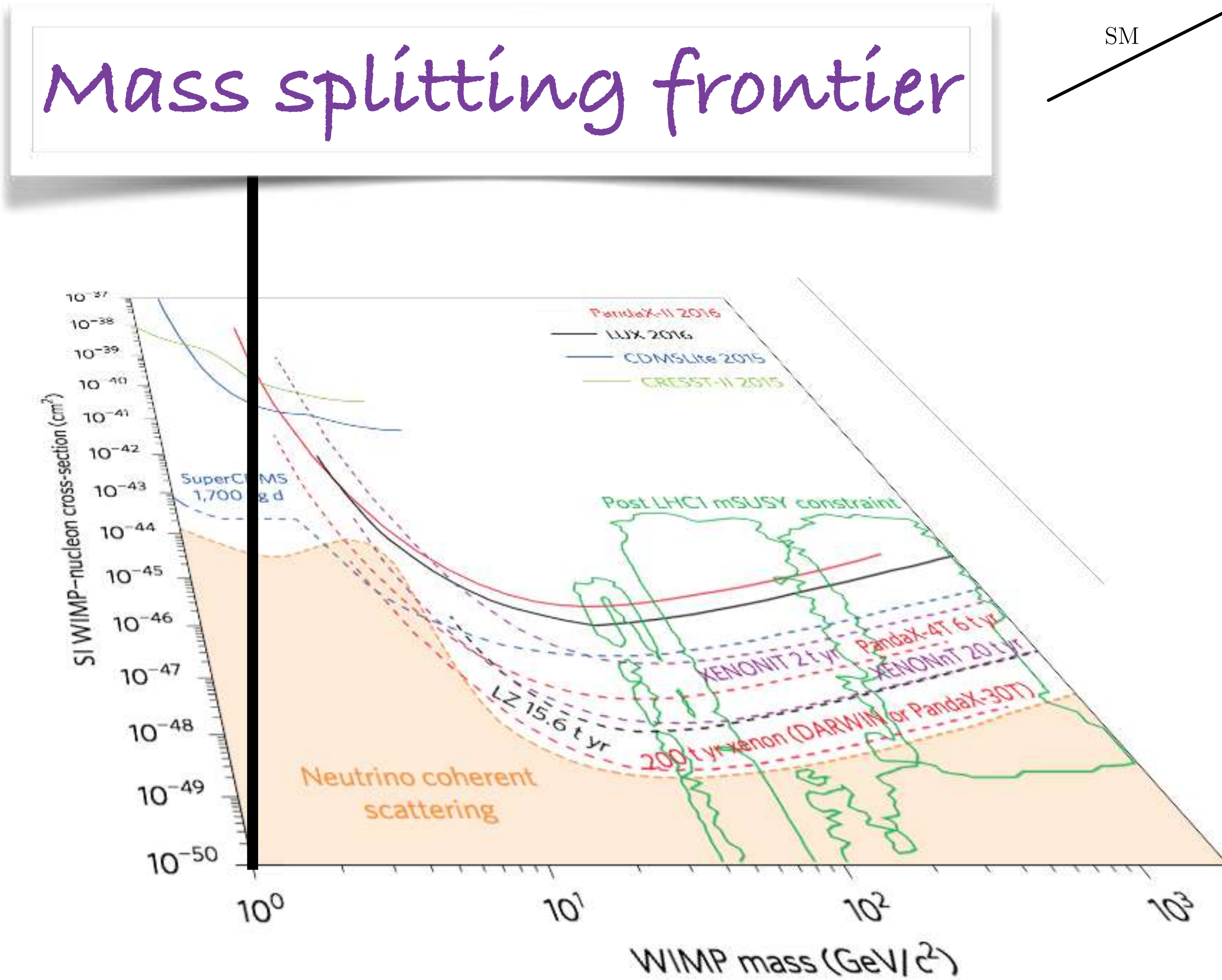
$\delta \equiv m_{\chi'} - m_{\chi}$

Can be endothermic (iDM) or exothermic

[Tucker-Smith and Weiner]

Inelastic scattering of DM





[Graham, Harnik, Rajendran, Saraswat]

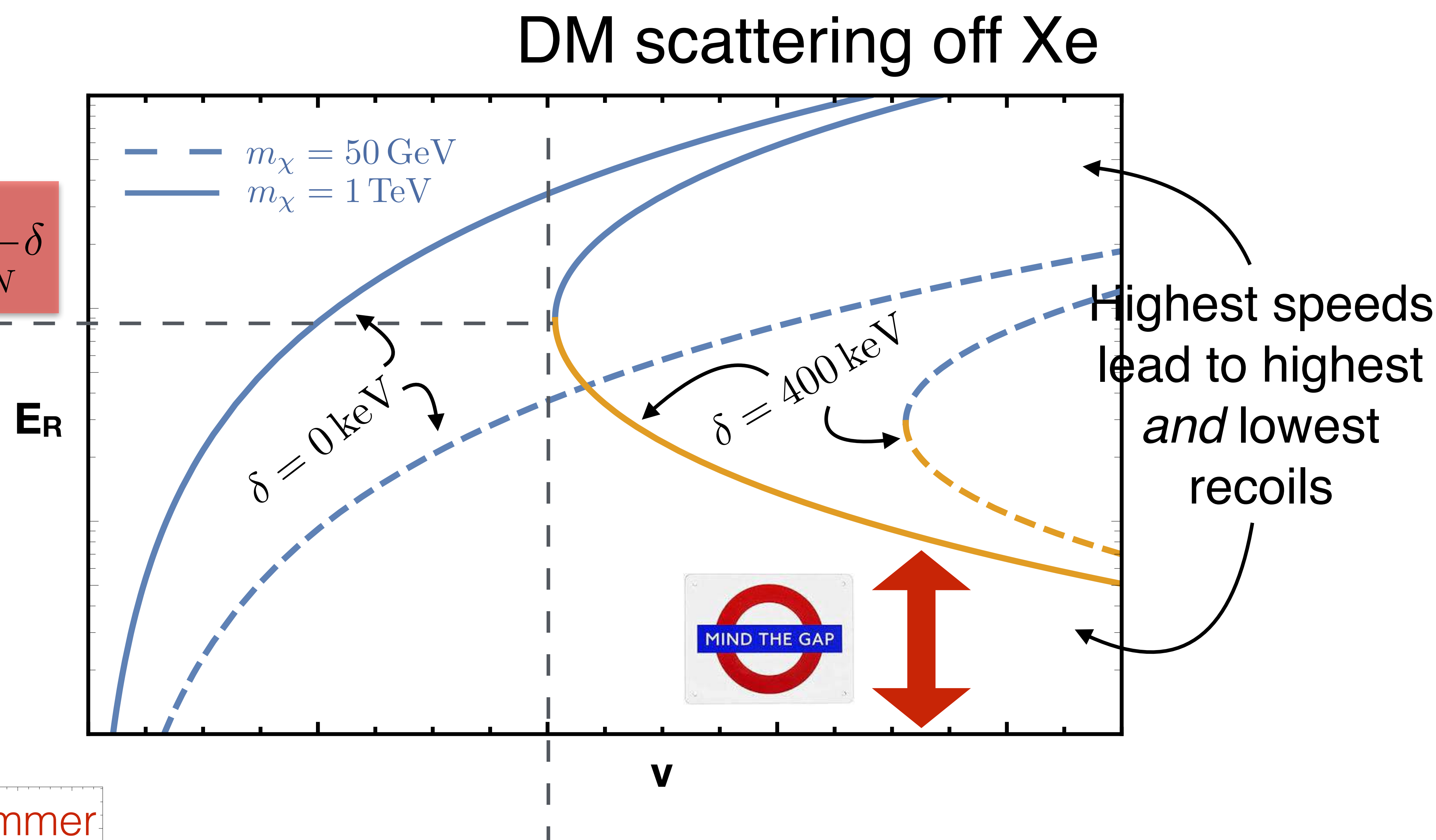
$$\delta \equiv m_{\chi'} - m_\chi$$

Can be endothermic (iDM) or exothermic

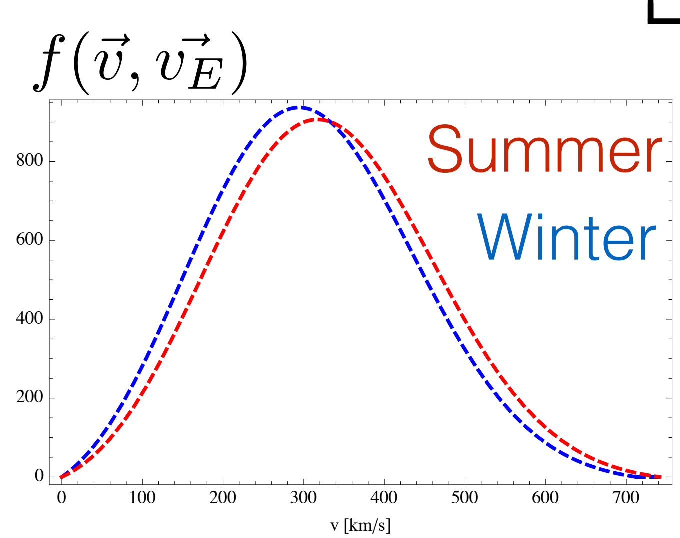
[Tucker-Smith and Weiner]

Inelastic kinematics

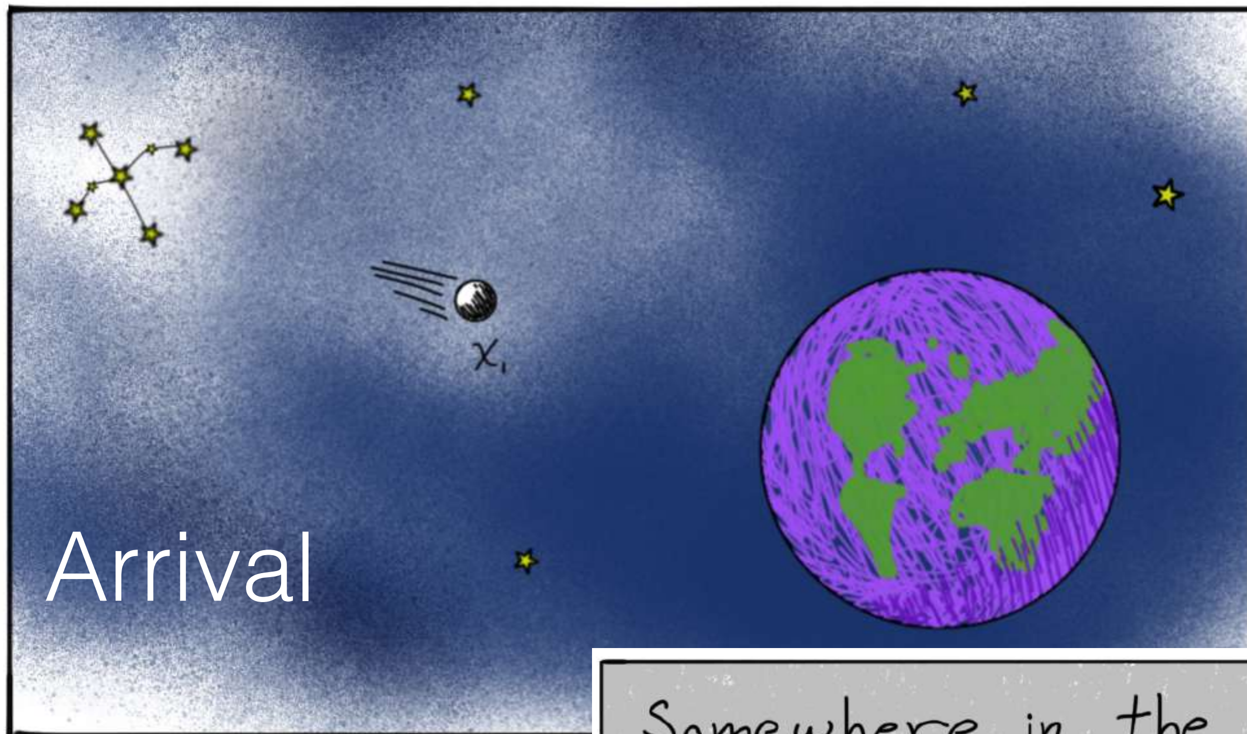
$$E_R(v_{\min}^{\text{apex}}) \quad = \quad \frac{\mu}{m_N}\delta$$

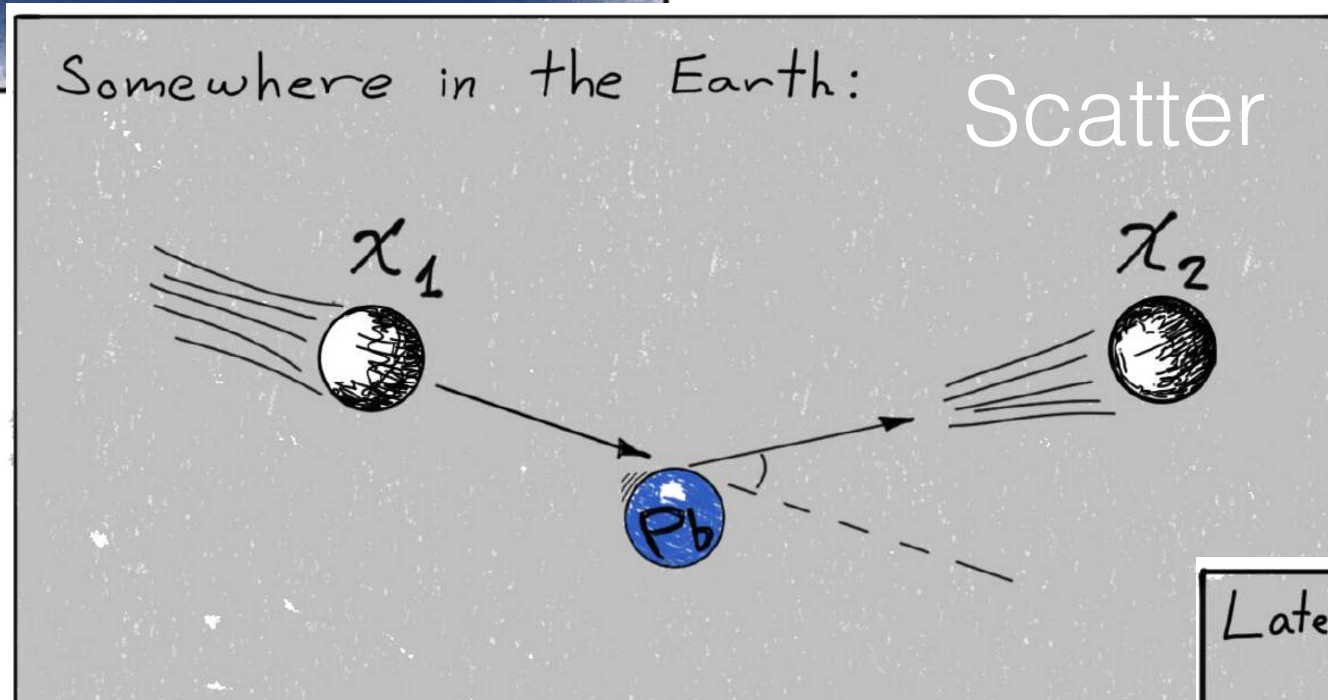


$$v_{\min}^{\text{apex}} \quad = \quad \sqrt{\frac{2\delta}{\mu}}$$

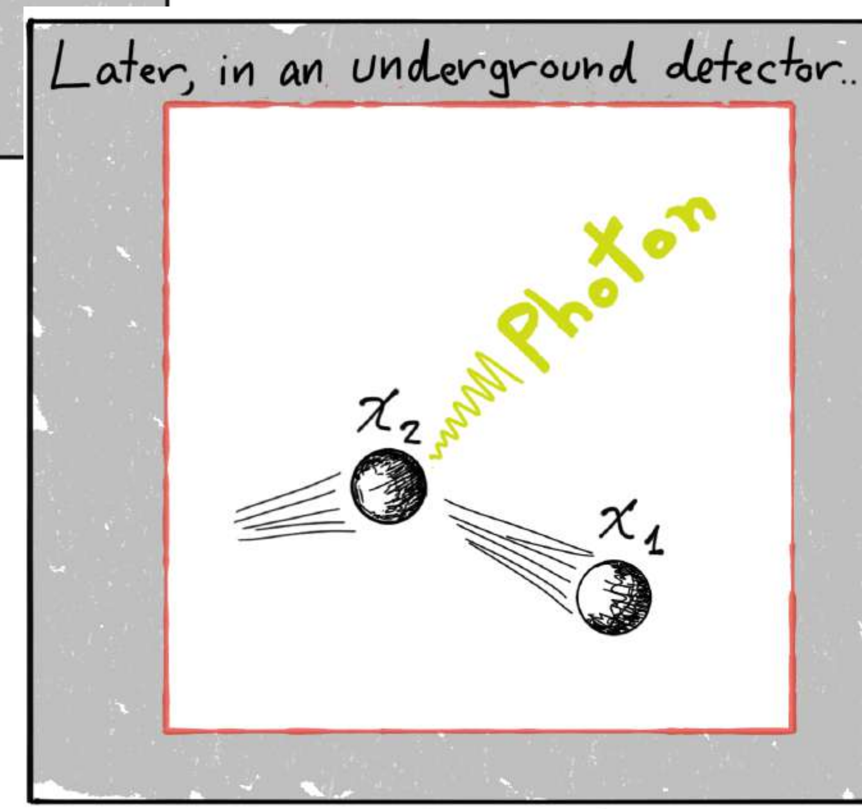


A day in the life of luminous iDM





Detection



Illuminating the Inelastic Frontier

See also "Luminous DM" [Feldstein, Graham, Rajendran] and "DM in 2 Easy Steps" [Pospelov, Weiner, Yavin]

Higgsino DM scatters inelastically off nucleus through Z
Travels for 10-1000 km
Decays to mono energetic photon

- Abundant heavy target
- Large volume, low threshold detector

Detector	Xenon 1T	Borexino	SNO	DUNE	IceCube
Mass (ton)	1	300	10^3	3×10^4	10^7
Threshold (MeV)	10^{-3}	0.15	1	$1-10$	10^4

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Higgsino DM scatters inelastically off nucleus through Z
Travels for 10-1000 km
Decays to mono energetic photon

- Abundant heavy target — Pb
- Large volume, low threshold detector — Borexino

Detector	Xenon 1T	Borexino	SNO	DUNE	IceCube
Mass (ton)	1	300	10^3	3×10^4	10^7
Threshold (MeV)	10^{-3}	0.15	1	$1-10$	10^4

Luminous Rate

$$\mathrm{Rate} \sim n_T\, n_\chi\, \sigma\, v\, V.$$

Complicated 6d integral, sensitive to lifetime, speed, position etc…

Solid angle

Prob. to decay in det.

$$\Gamma = \sum_{\pm} \int d^3r_s\, d^3v_\chi \left\{ n_T(r_s)\, \frac{\rho_\chi}{m_{\chi_1^0}} \left[\frac{R_D}{|\vec{r}_s - \vec{r}_D|\, \theta^{lab}_{max}} \right]^2 P_0(|\vec{r}_s - \vec{r}_D|, v^{lab}_{f,\pm}) \right.$$

$$\left. \times\, f(v_\chi)\, |F(q_\pm)|^2 \left[\frac{d\sigma}{d\cos\theta^{lab}} \right]_\pm v_{tot} \right\}$$

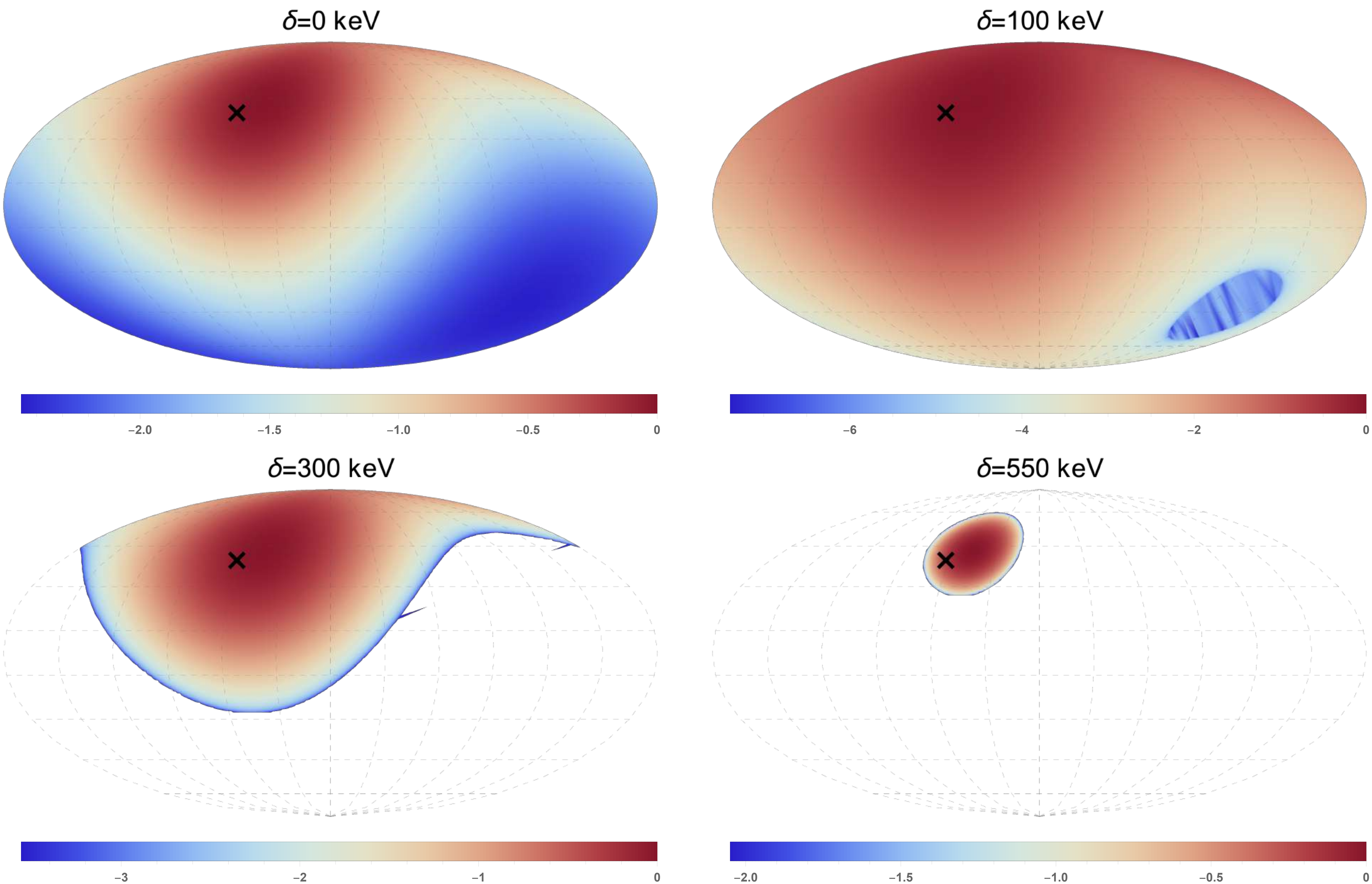
2 c.o.m.
scattering angles

X-sec isotropic in c.o.m. frame

$$P_0(|\vec{r}_s - \vec{r}_D|, v_f) = 2\, e^{-|\vec{r}_s - \vec{r}_D|/v_f \tau} \sinh \frac{L_D}{2 v_f \tau}$$

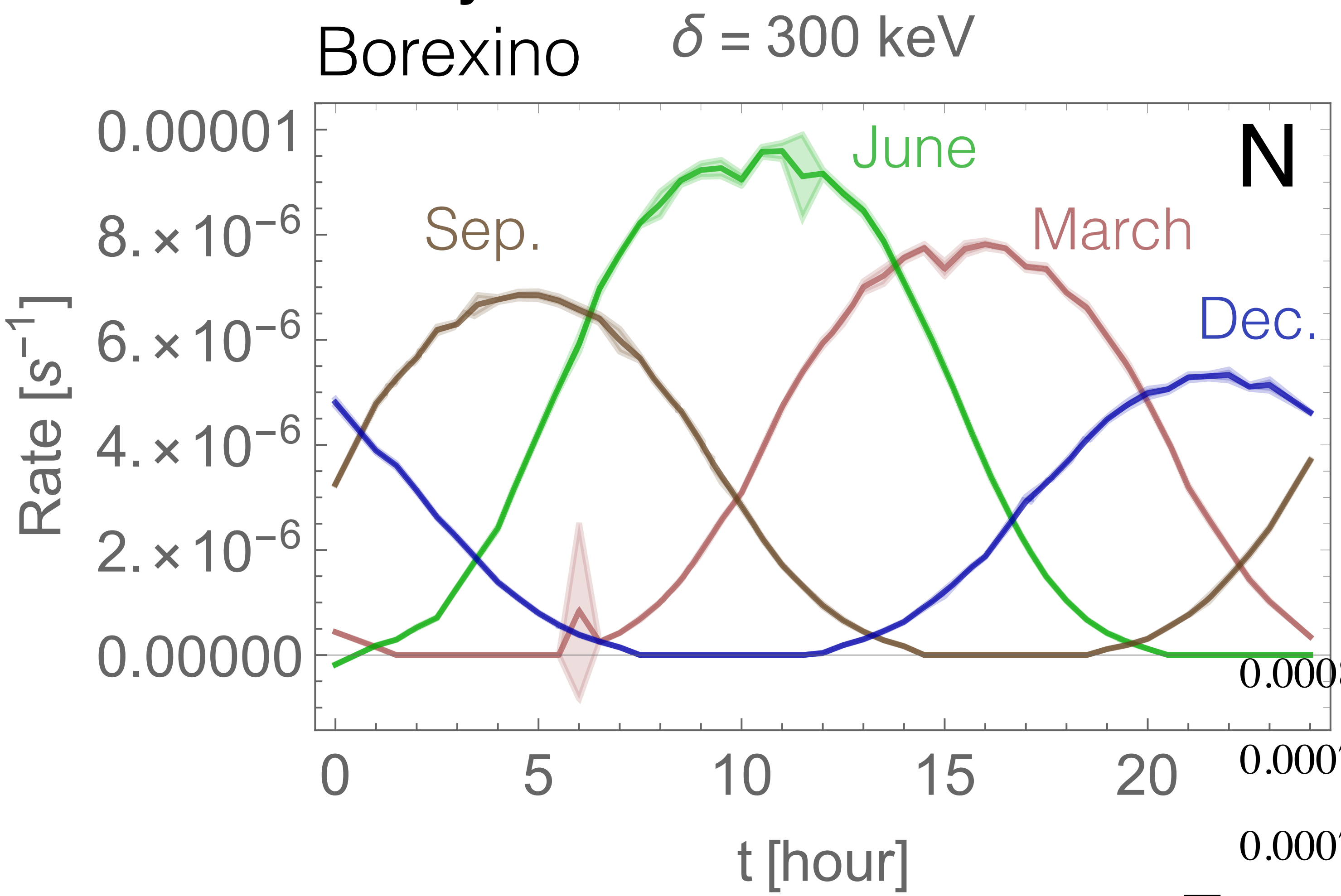
The Cygnus "gun"

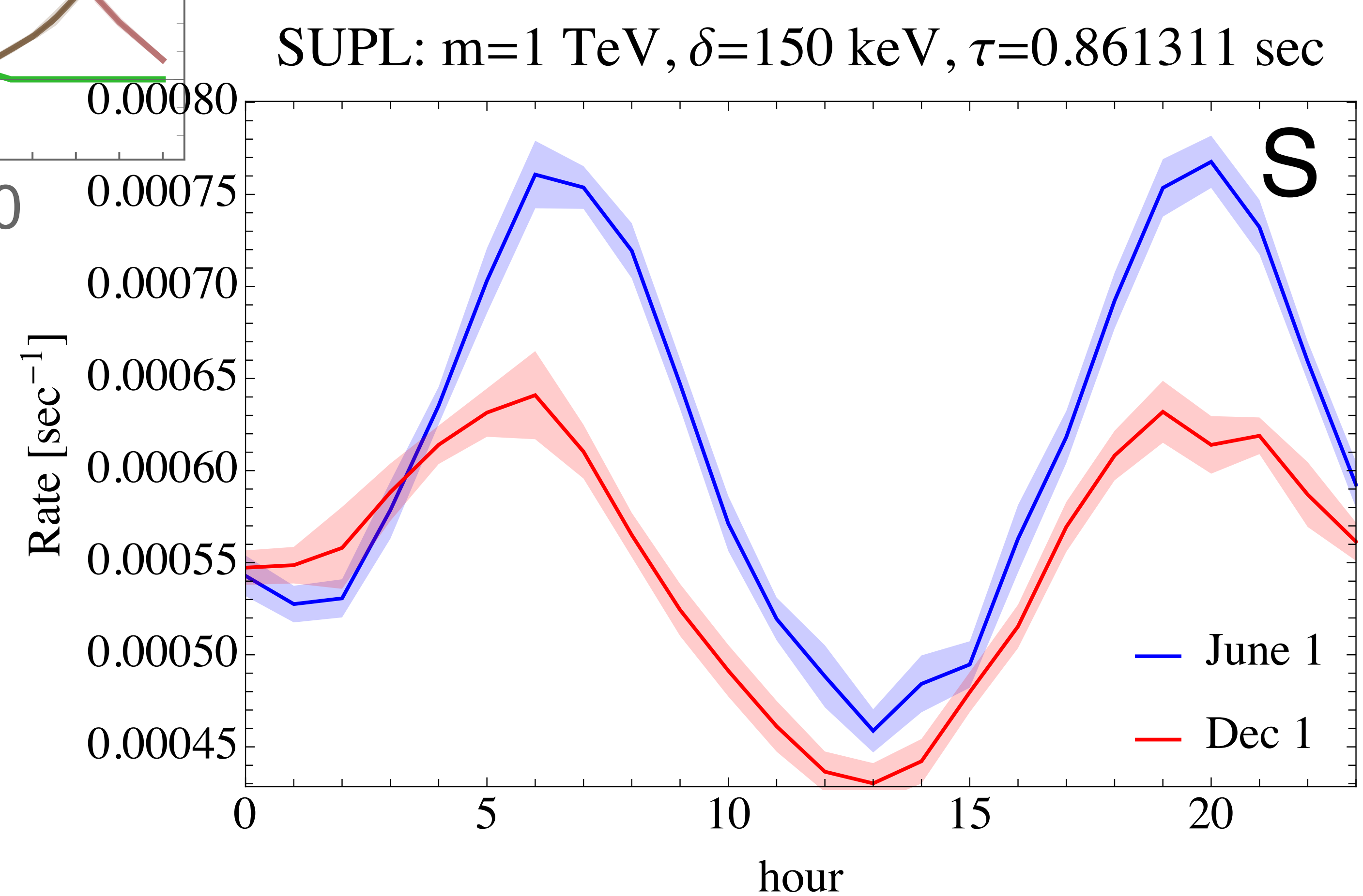
Upscatter needs high speeds, which comes from Cygnus



Modulation

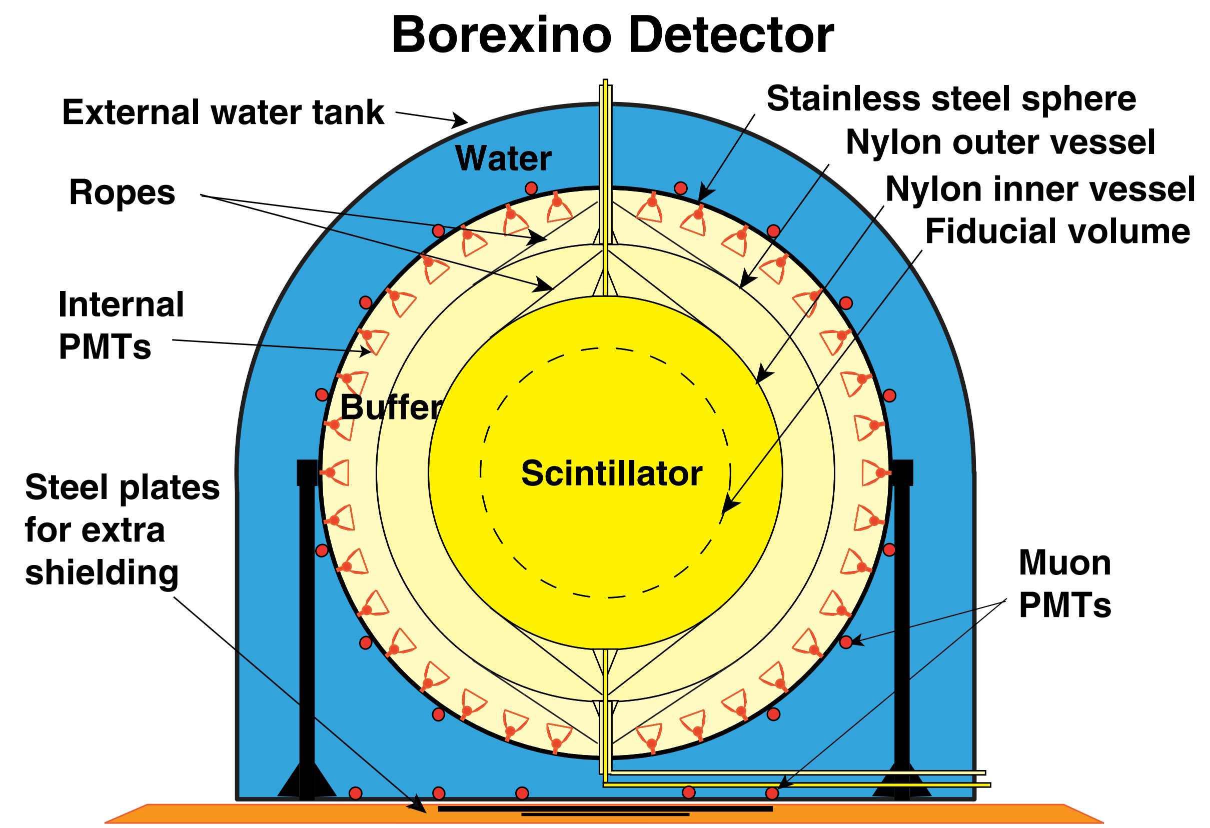
Lead overburden depends on position of Cygnus *not* the Sun.
1 sidereal day = 23 hours 56 minutes 4 seconds





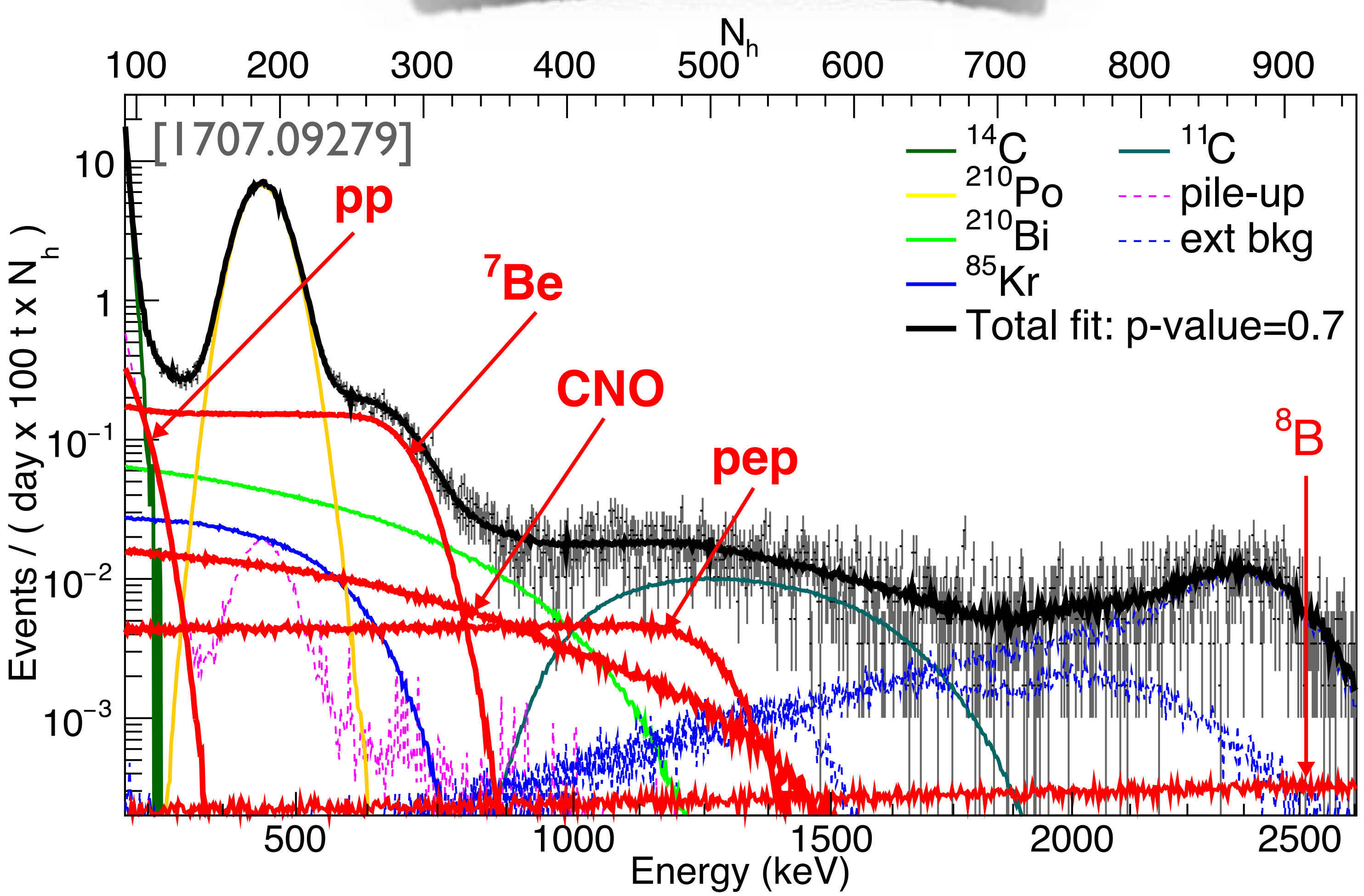
Borexino

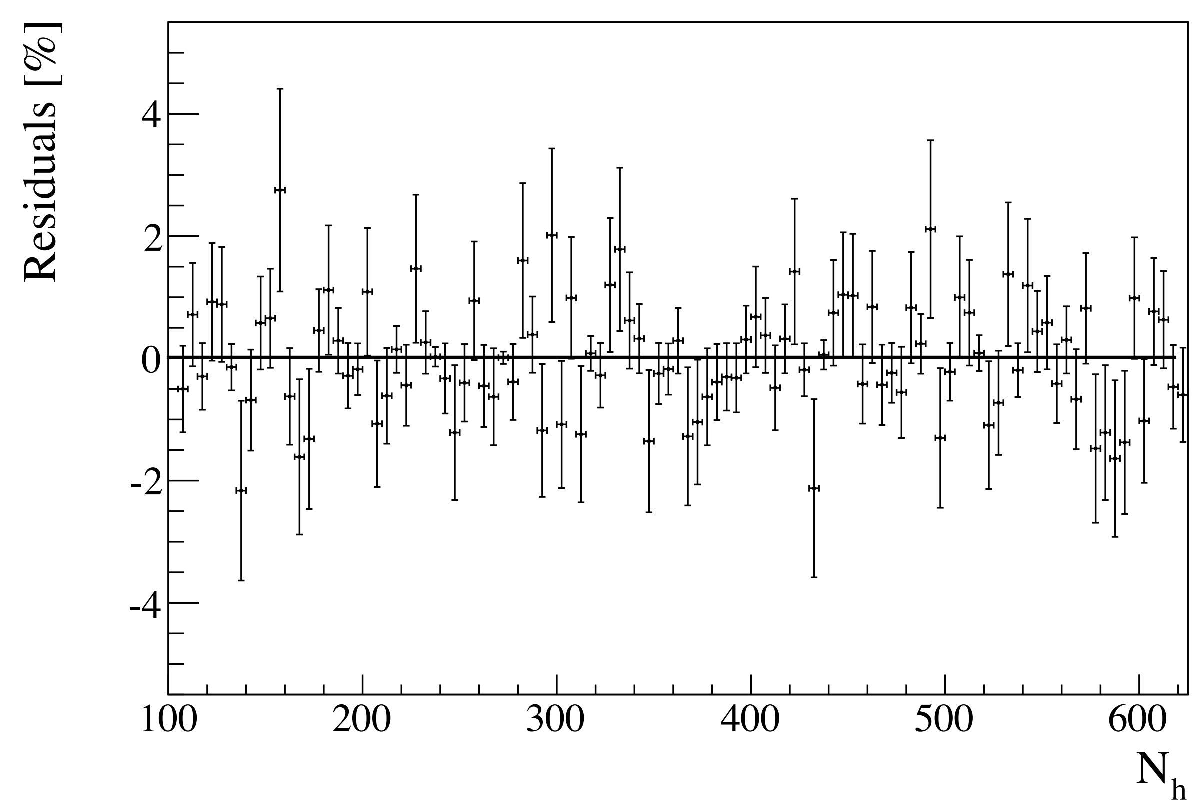
- 278 tons of scintillator, ~5m radius
- ~1300 days of data
- ~150 keV threshold, maybe lower?
- Good energy resolution



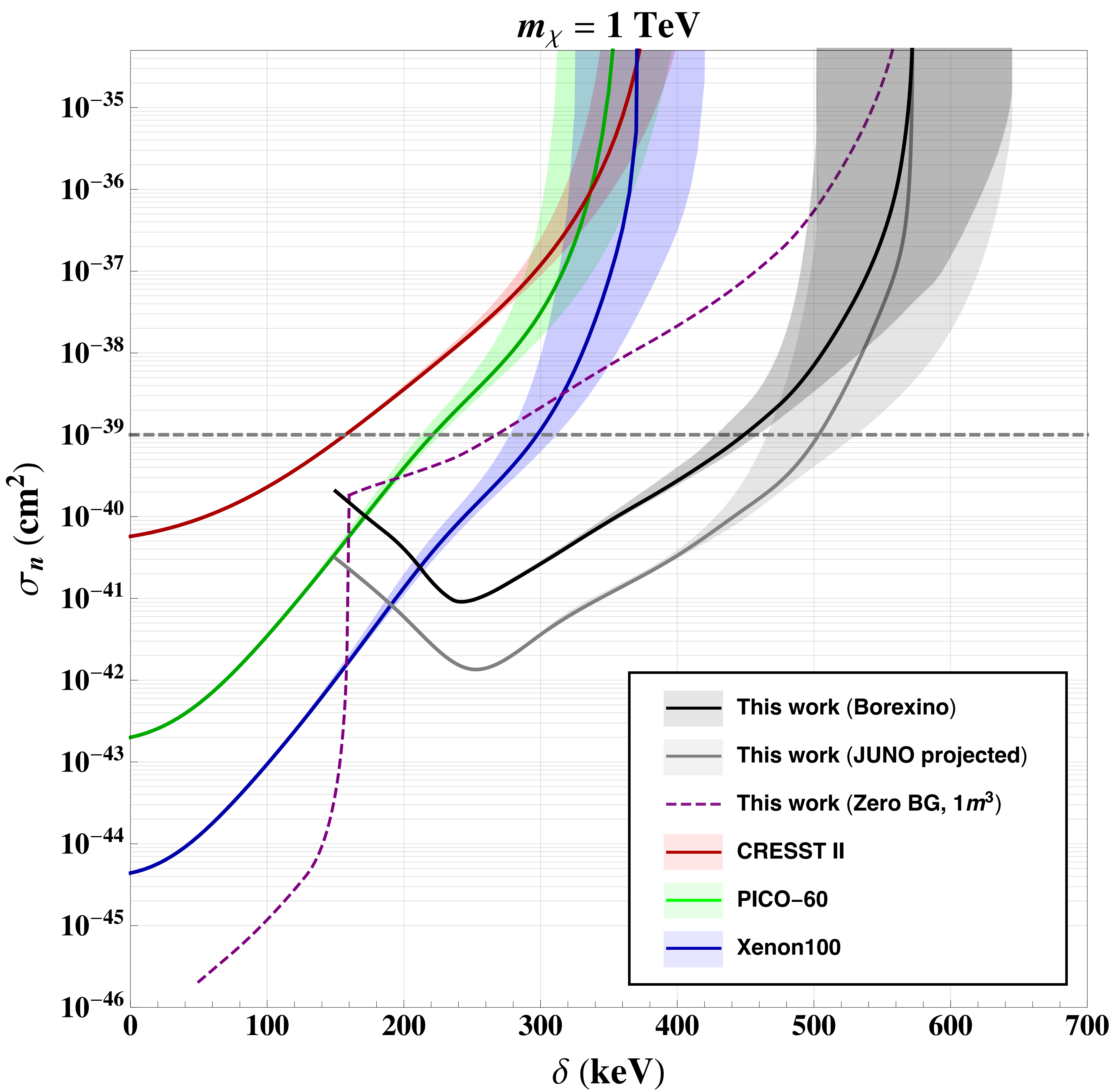
PHYSICAL REVIEW D **89,** 112007 (2014)

Event rate~5/day





Illuminating the Inelastic Frontier



Things not covered, a partial list

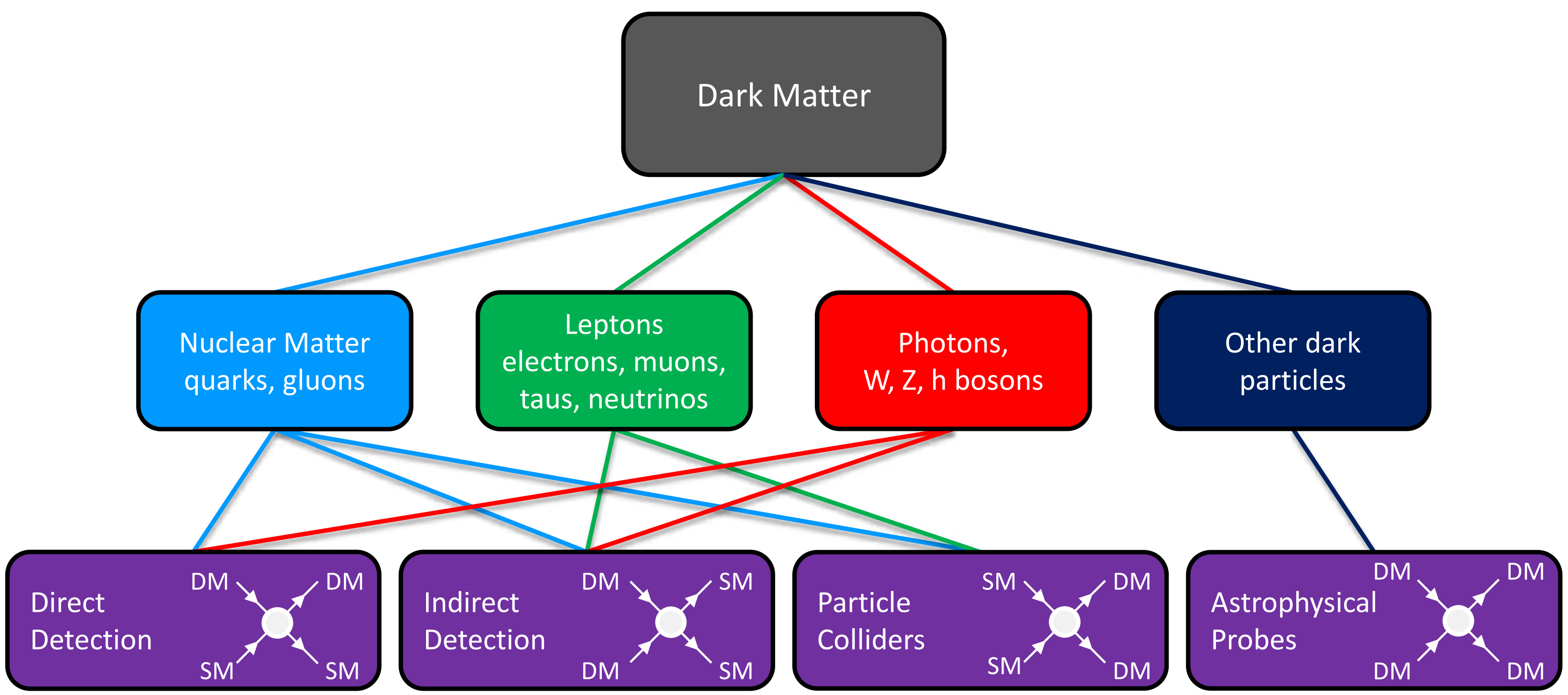
- DM@LHC
- Asymmetric DM
- The Galactic Center Excess
- GAIA data
- Primordial Black Holes
- Composite Dark Matter
- DM Nuggets
- Boosted DM
- Self-interactions, velocity dependence, small scale structure
- ….

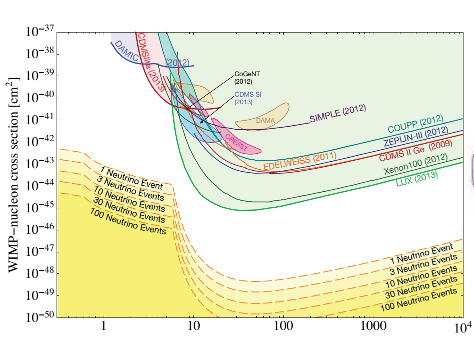
Conclusions

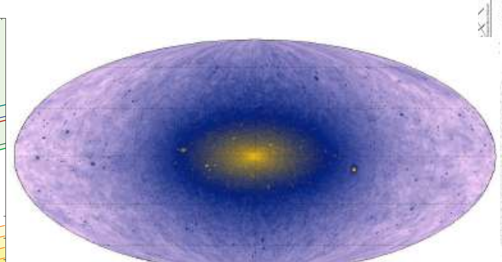
The theory landscape is rich and getting richer

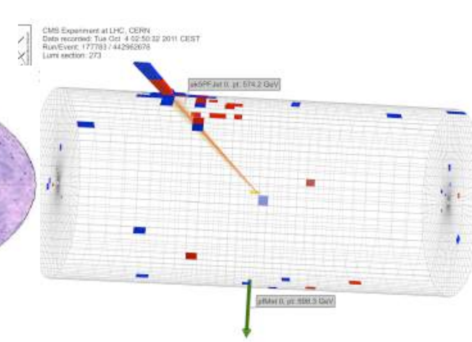
New technologies adding to experimental searches

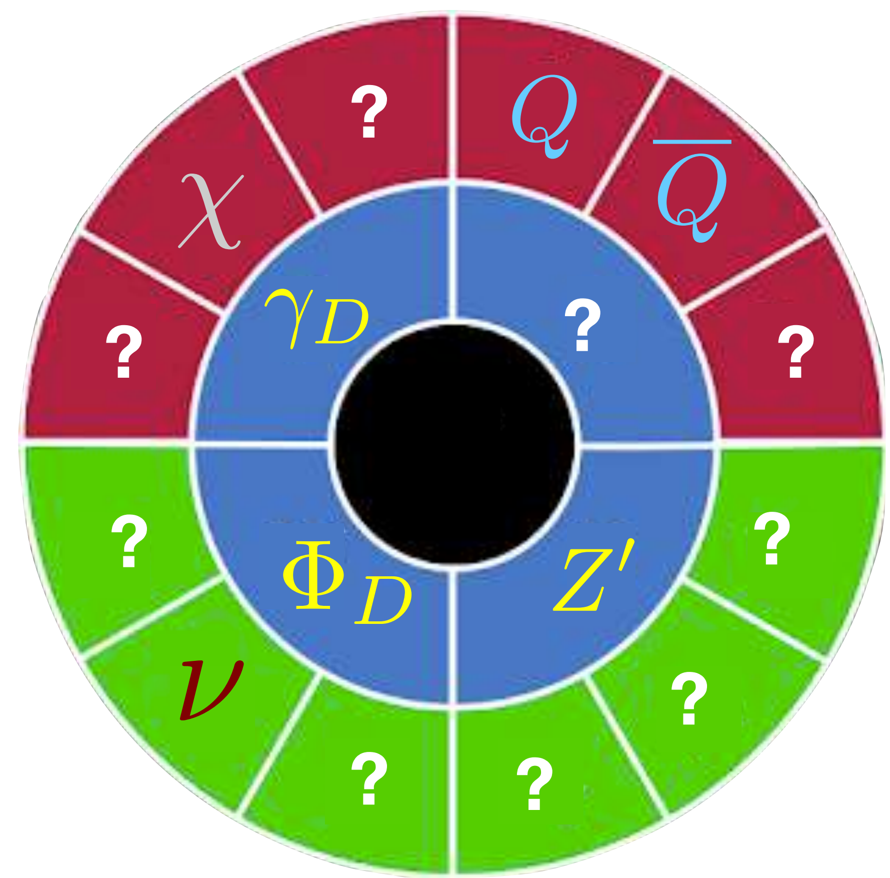
Exciting, vibrant, and creative time to be working on Dark Matter!











EXTRA SLIDES

QCD Axion

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

10^{-12}eV m_a 10^{-2}eV 1eV

$f \sim M_{pl}$ SN1987A Hot DM

PQ broken
after inflation

Axion starts osc.
too late, too much DM

10^{-5}eV 1eV

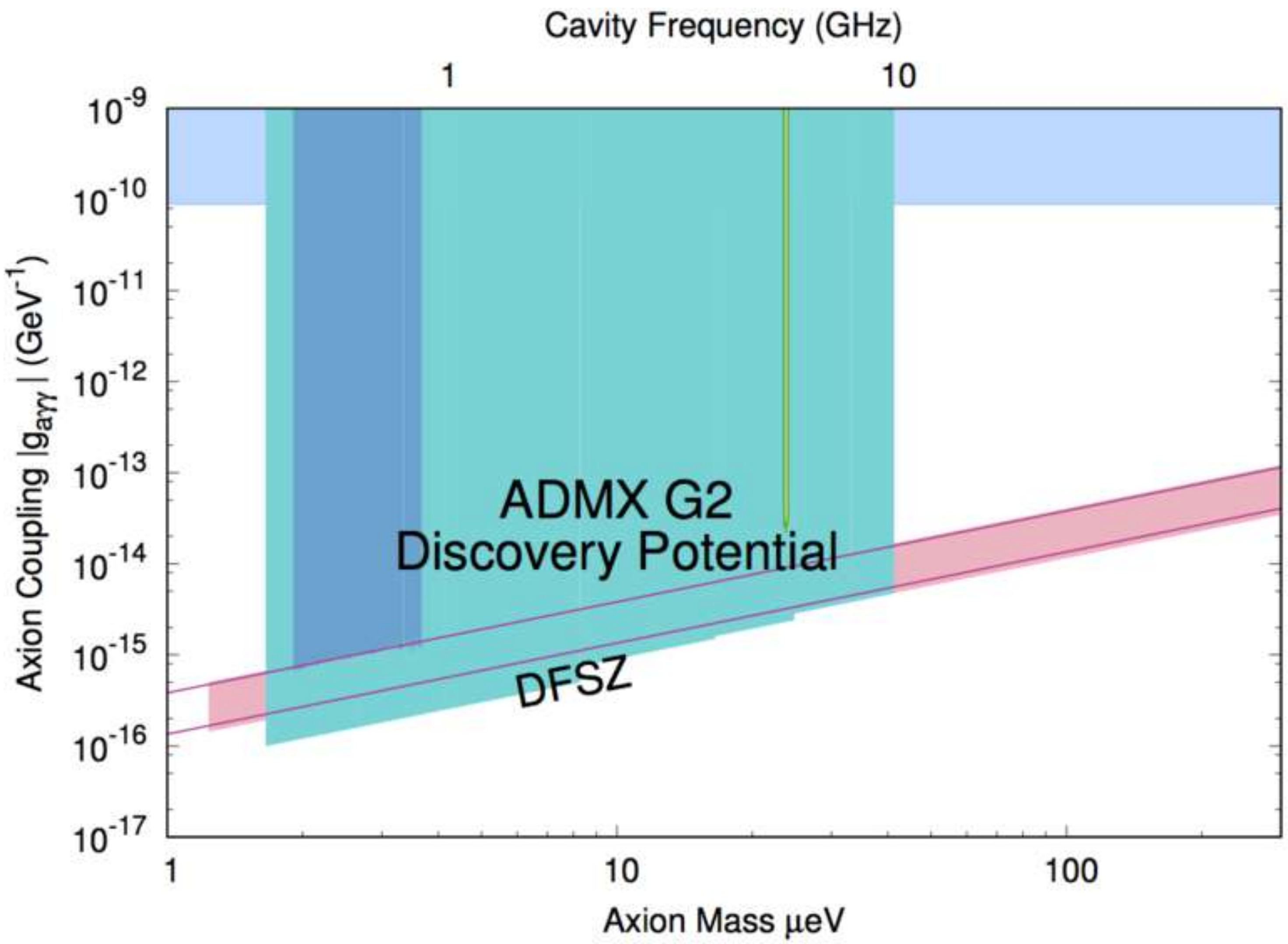
PQ broken
before inflation

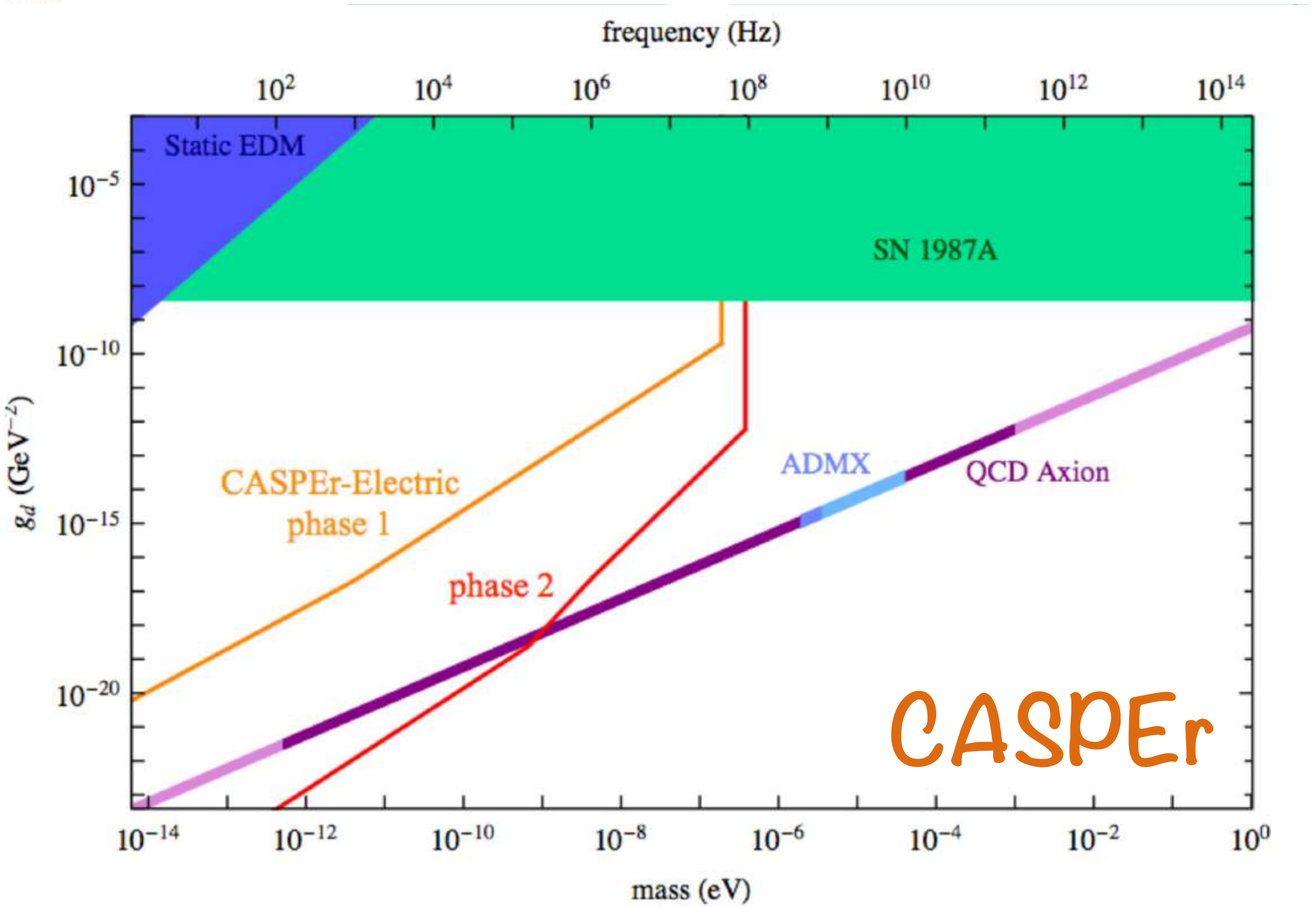
DM abundance requires small θ_{init} Anthropics?

Isocurvature modes $(H_I/f)^2$

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

connections to inflation
[PF, Pierce, Thomas]


Cavity Frequency (GHz)
1
10
ADMX G2
Discovery Potential
DFSZ
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}
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
CASPEr-Electric
phase 1
phase 2
ADMX
QCD Axion
g_d (GeV^{-2})
10^{-5}
10^{-10}
10^{-15}
10^{-20}
10^{-14} 10^{-12} 10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 10^{0}
mass (eV)
CASPEr

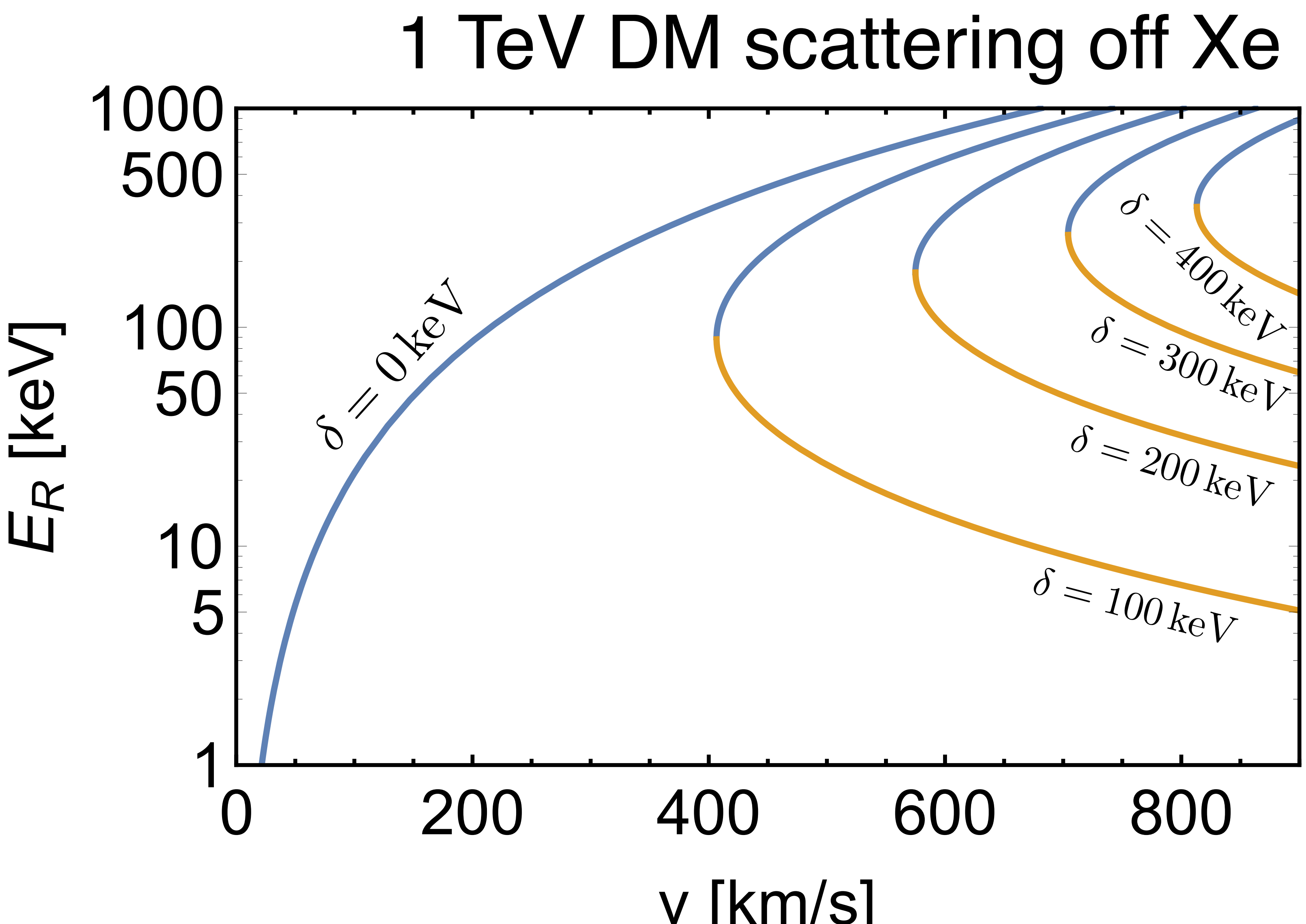
Inelastic kinematics

Lab scattering angle

Nuclear recoil energy

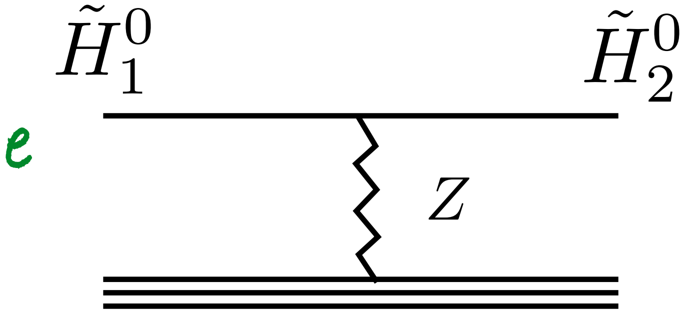
$$E_R = \frac{\mu}{m_N}\left[\left(\mu v^2\cos^2\theta_{\rm lab}-\delta\right)\pm\left(\mu v^2\cos^2\theta_{\rm lab}\right)^{1/2}\left(\mu v^2\cos^2\theta_{\rm lab}-2\delta\right)^{1/2}\right]$$

DM speed in lab frame



iDM—Higgsino model

DM couples to the Z (a WIMP!)



Dirac fermion coupled to vector, with small Majorana masses

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

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

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

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

iDM—Higgsino model

Couples to Z, makes definitive predictions

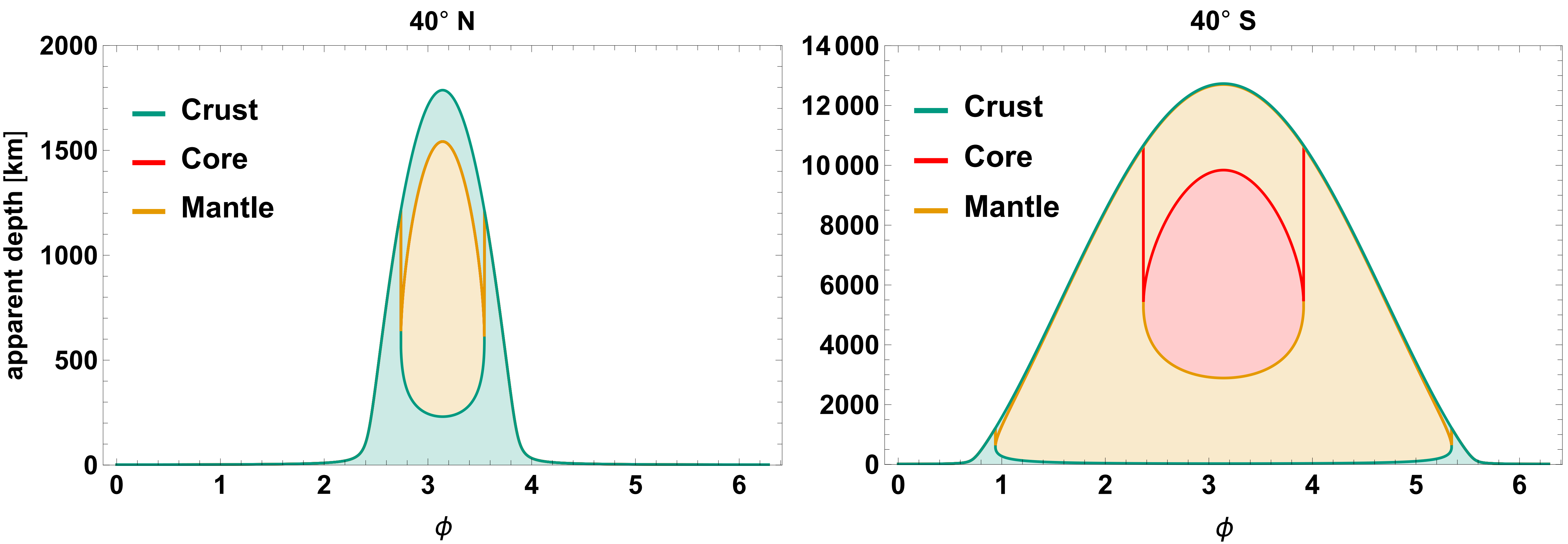
Relic abundance: $\Omega h^2 = 0.10 \left(\frac{\mu}{1\ \mathrm{TeV}}\right)^2$ (all χ_1)

Direct detection:

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

The Cygnus “gun”

Overburden proxy



-	n_{Fe} [km^{-3}]	n_{Pb} [km^{-3}]	Outer Radius [km]
Core	1.1×10^{38}	1.3×10^{31}	3483
Mantle	3.1×10^{36}	2.4×10^{30}	6341
Crust	2.0×10^{36}	8.4×10^{31}	6371

$$\Gamma = \sum_{\pm} \int d^3 r_s \, d^3 v_\chi \left\{ n_T(r_s) \, \frac{\rho_\chi}{m_{\chi_1^0}} \left[\frac{R_D}{|\vec{r}_s - \vec{r}_D| \, \theta_{max}^{lab}} \right]^2 P_0(|\vec{r}_s - \vec{r}_D|, v_{f,\pm}^{lab}) \right.$$
$$\left. \times \; f(v_\chi) \; |F(q_\pm)|^2 \; \left[\frac{d\sigma}{d\cos\theta^{lab}} \right]_\pm \, v_{tot} \right\}$$