# Looking for Dark Matter in Novel Ways

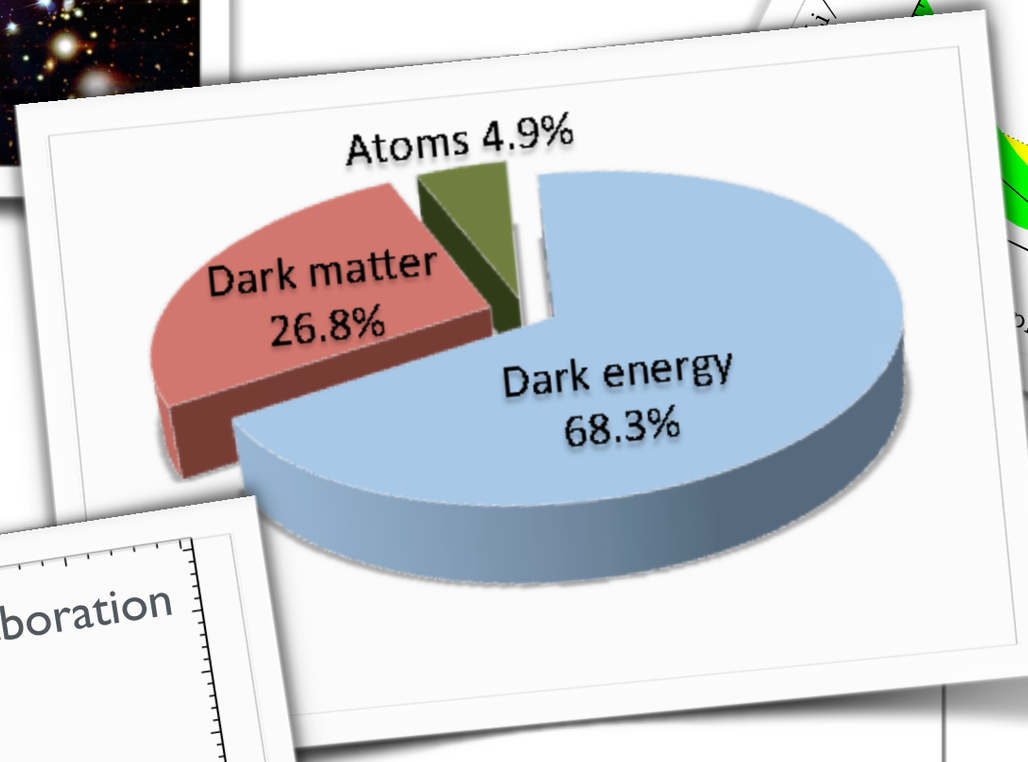
Patrick Fox

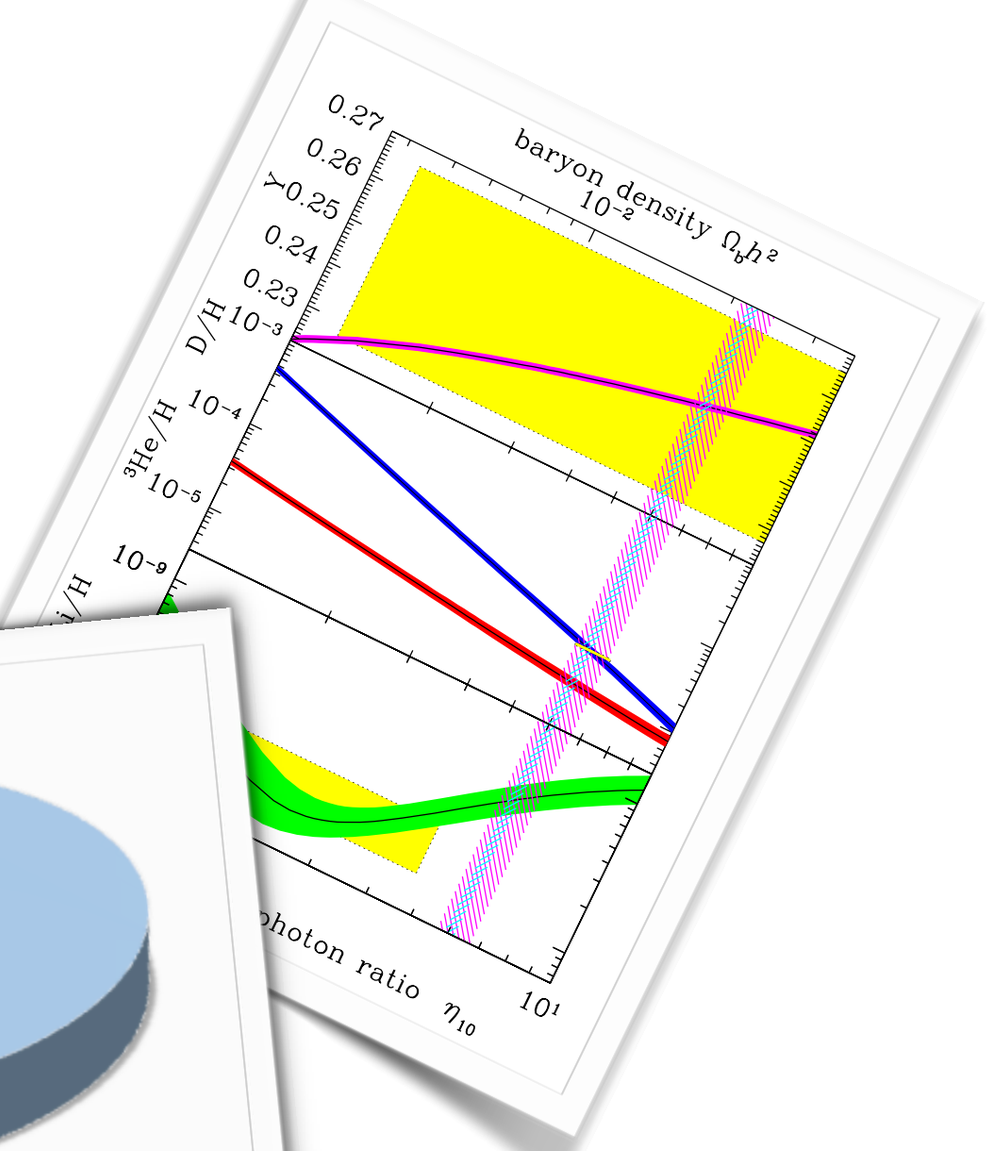
UNIVERSITY OF NOTRE DAME

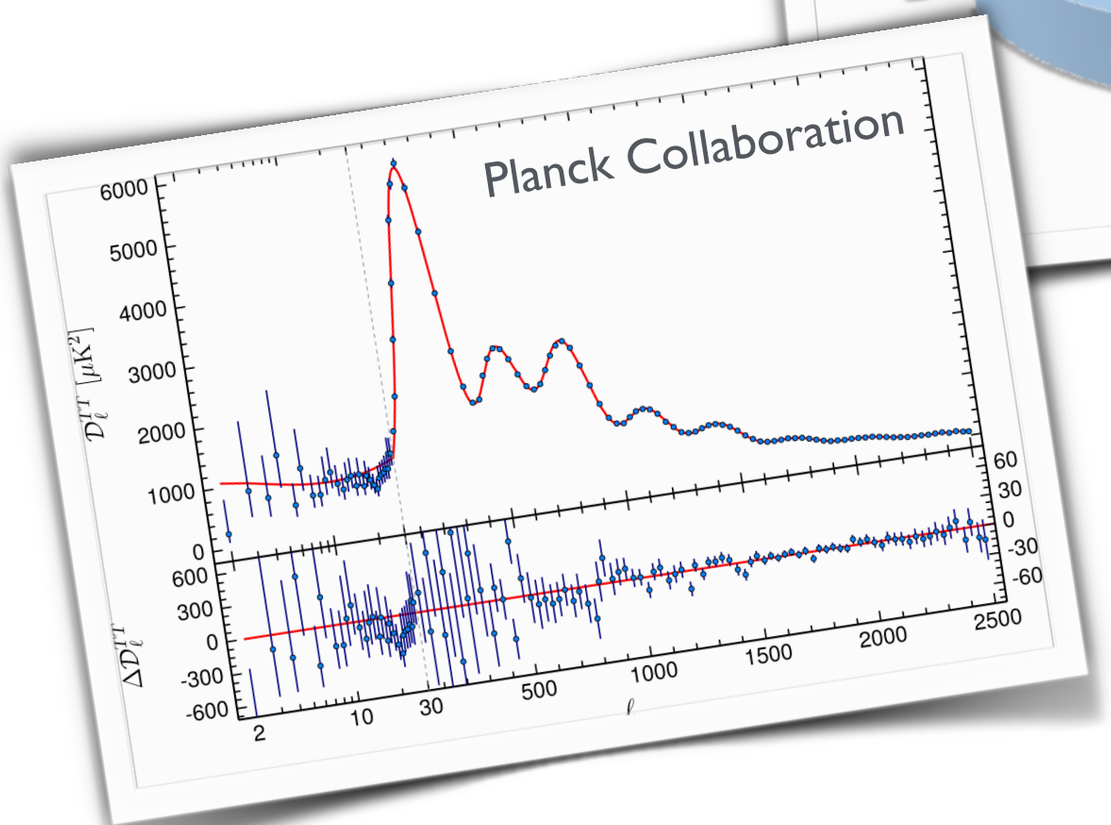
Fermilab

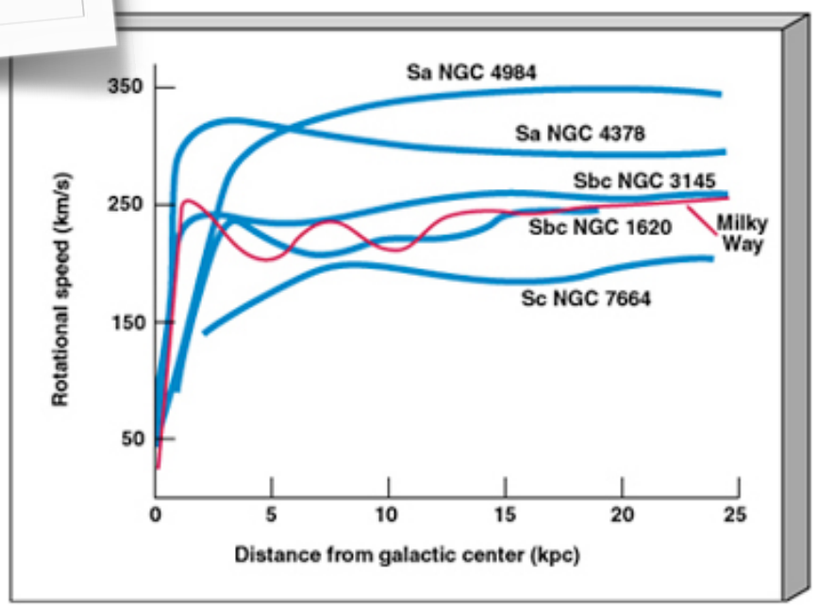
PIKIMO 12

*Phenomenology in Illinois, Kentucky, Indiana, Michigan, and Ohio*


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 $\eta_{10}$
$10^1$

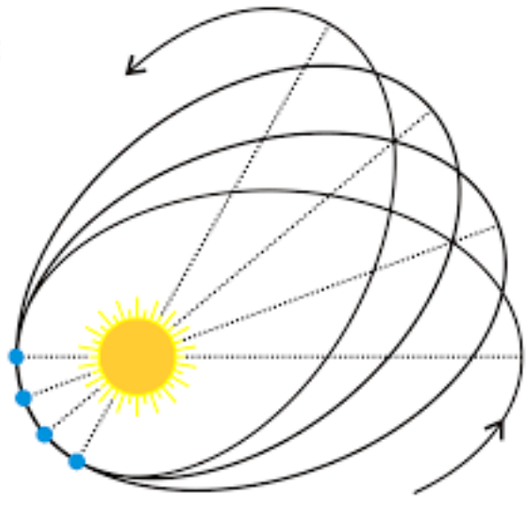

Planck Collaboration
$\mathcal{D}_\ell^{TT}$ [$\mu$K$^2$]
$\Delta\mathcal{D}_\ell^{TT}$
$\ell$


Sa NGC 4984
Sa NGC 4378
Sbc NGC 3145
Sbc NGC 1620
Milky Way
Sc NGC 7664
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!

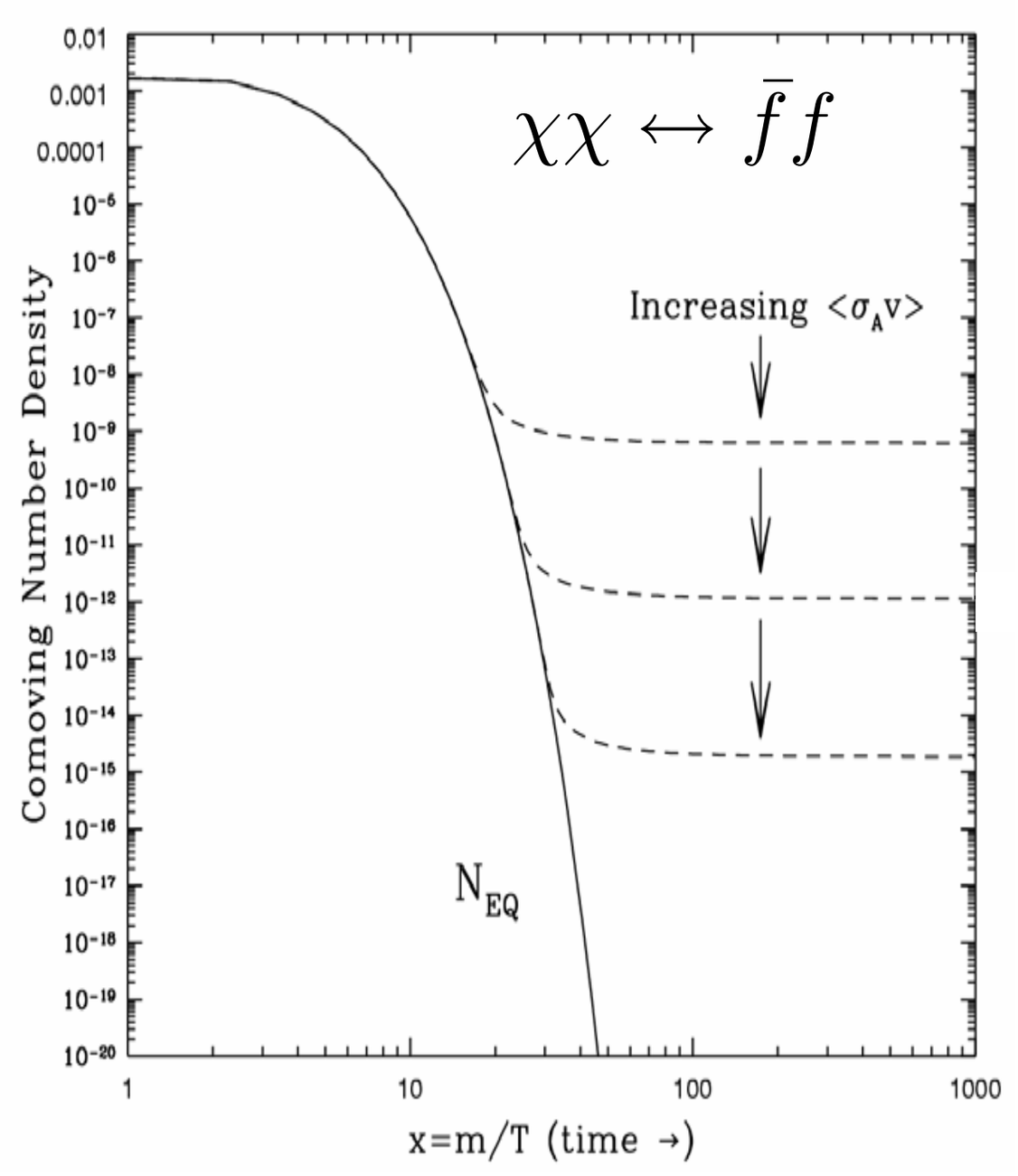

Advance in Perihelion of Mercury needed new physics (general relativity) to explain it. (Originally thought to be planet Vulcan!)




## What about other interactions?

# DM as a thermal relic

"The weak shall inherit the Universe"




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

Amazing (misleading?) fact:

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

WIMP candidates arise in MANY models of BSM physics, often for other reasons eg. SUSY, ex dims

Dark Matter

Nuclear Matter
quarks, gluons

Leptons
electrons, muons,
taus, neutrinos

Photons,
W, Z, h bosons

Other dark
particles

Direct Detection



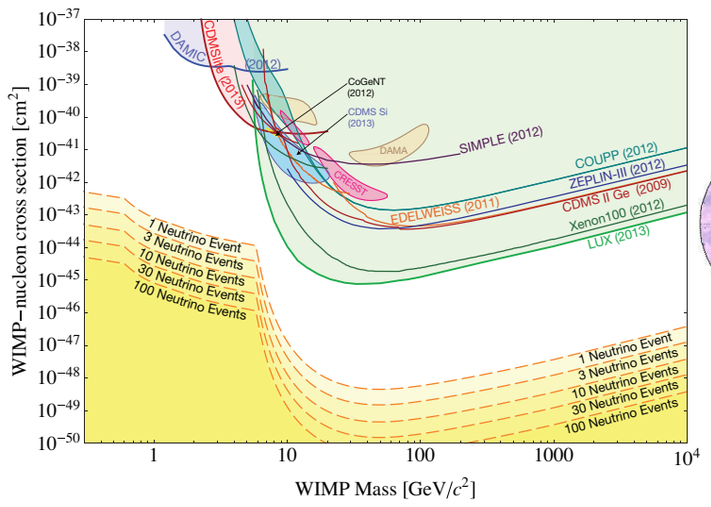

Indirect Detection

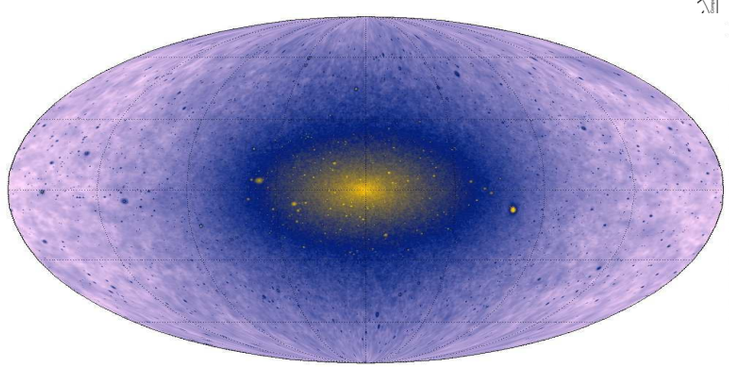

Particle Colliders

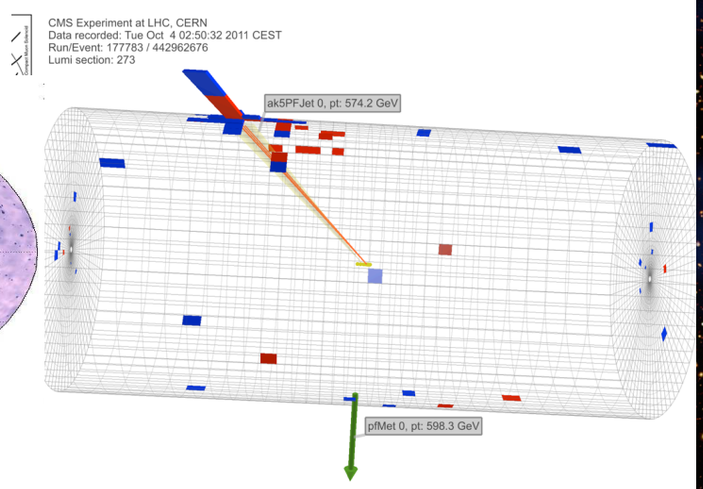


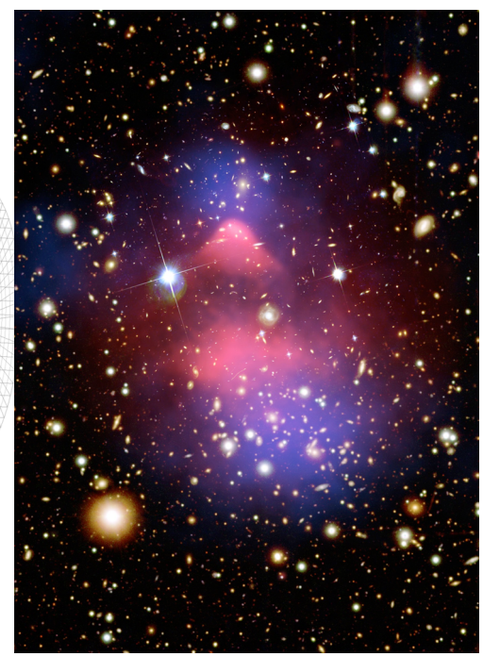

Astrophysical Probes



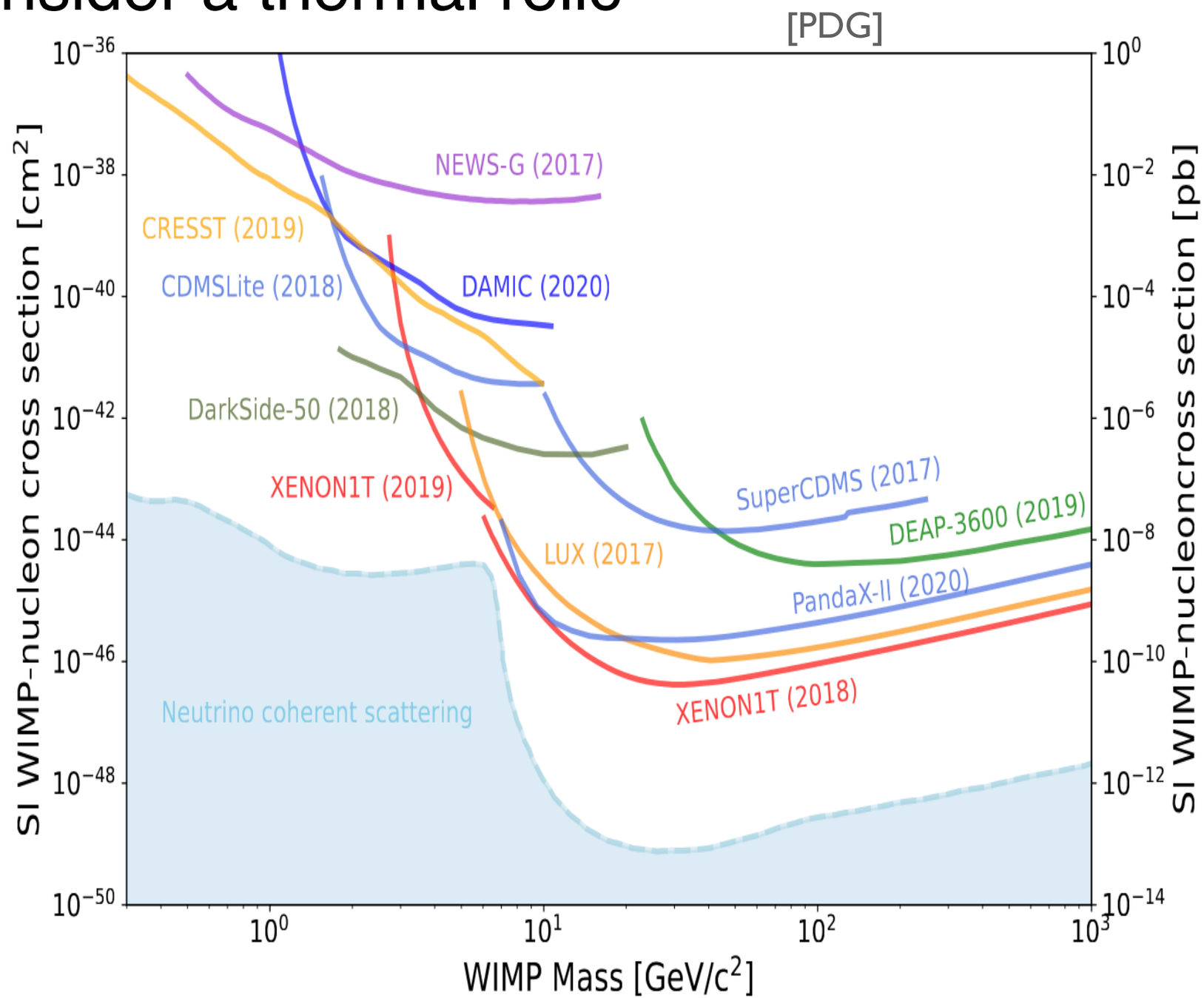





# WIMP

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



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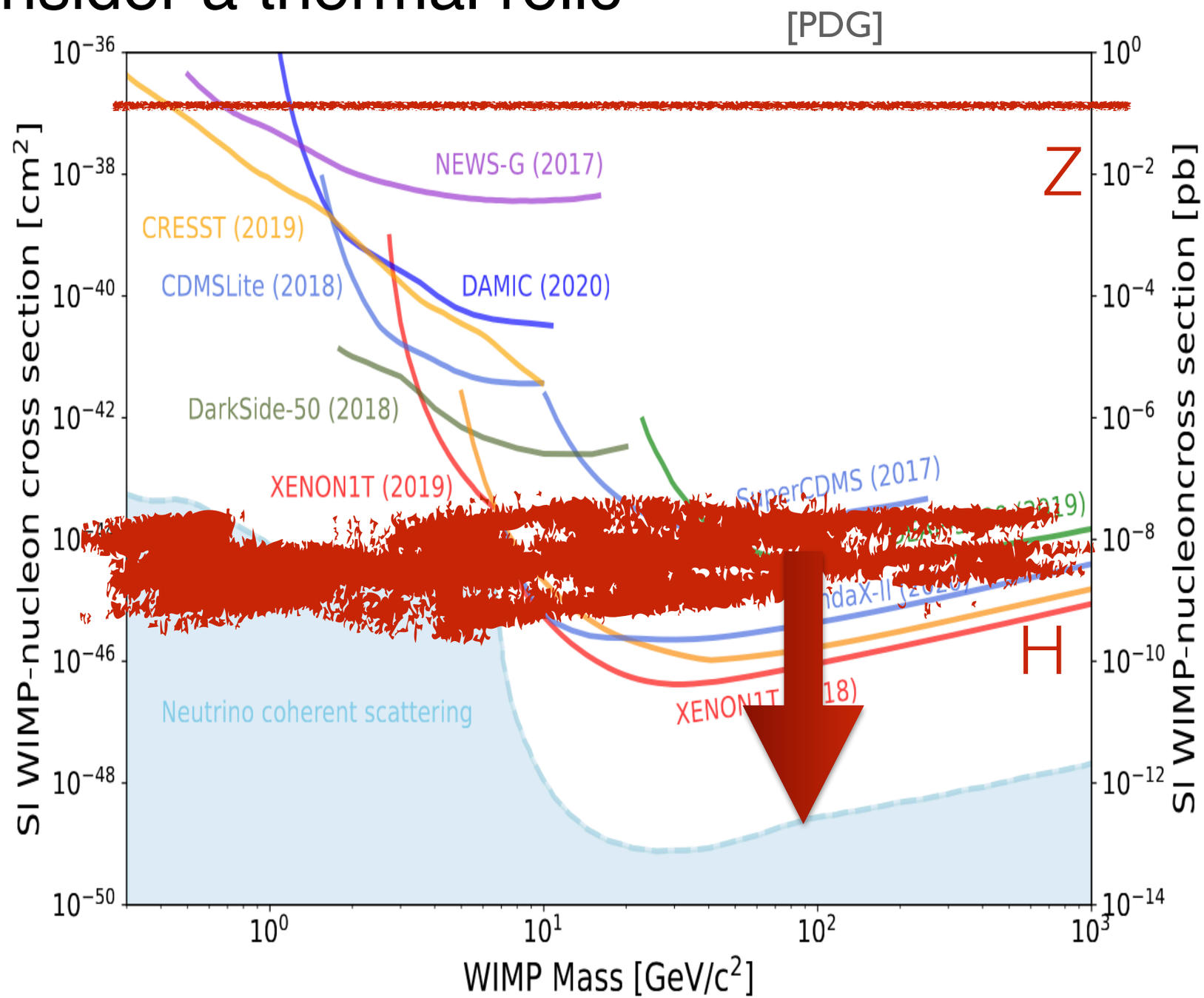
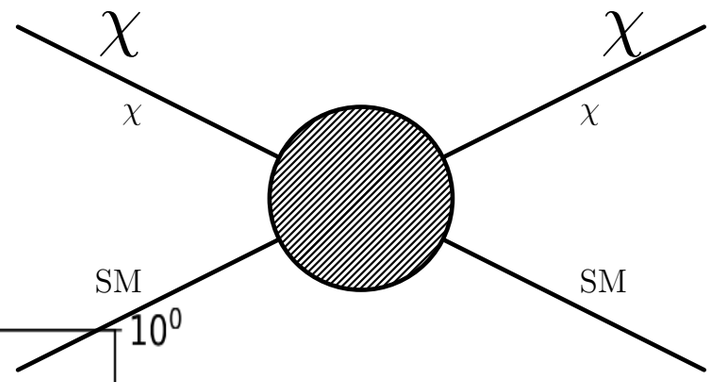
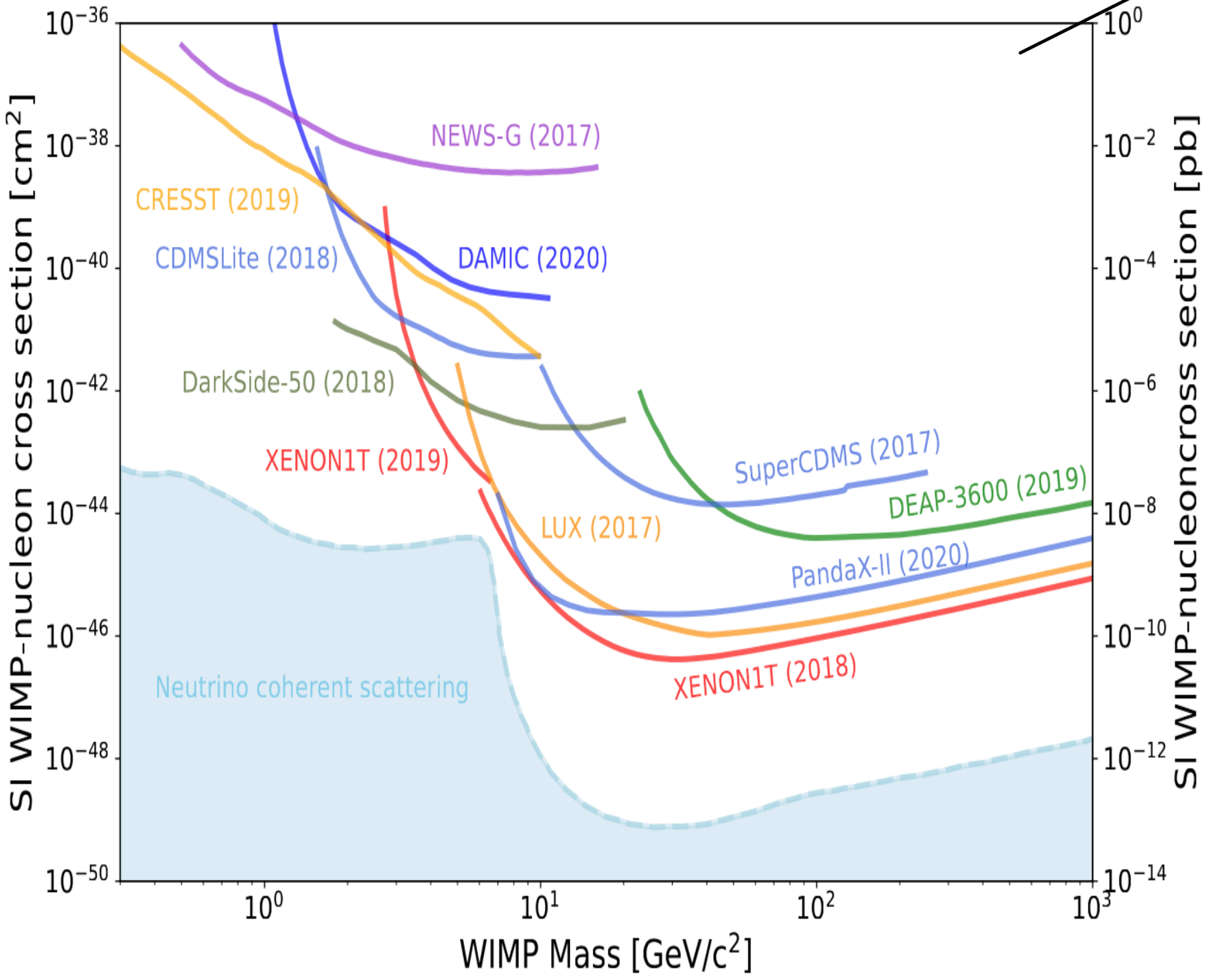


# Status of Direct Detection



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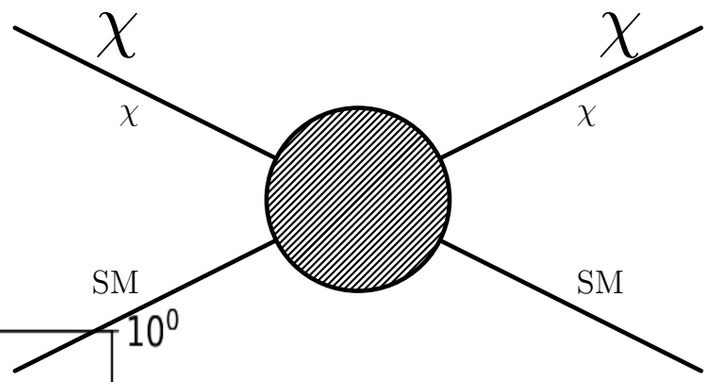
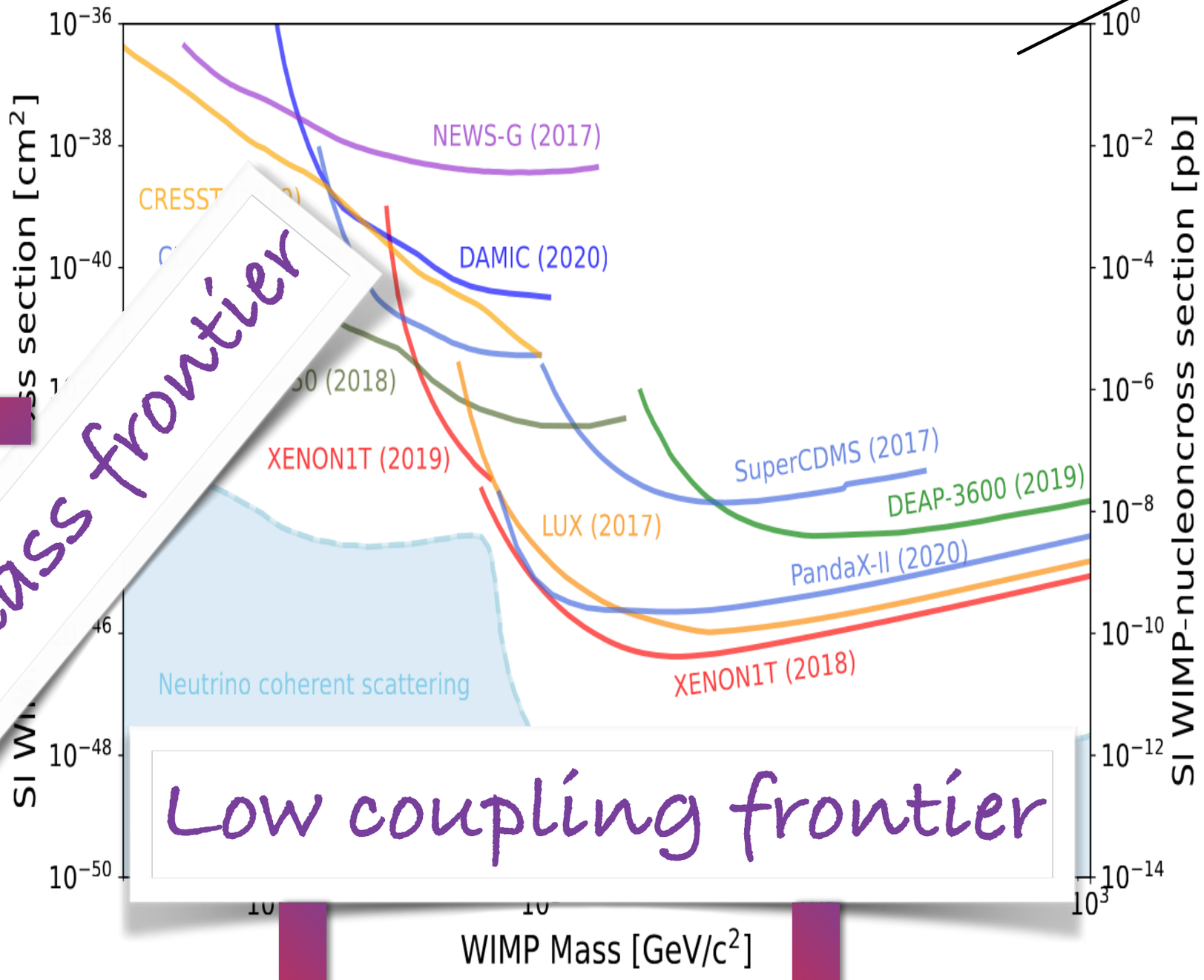
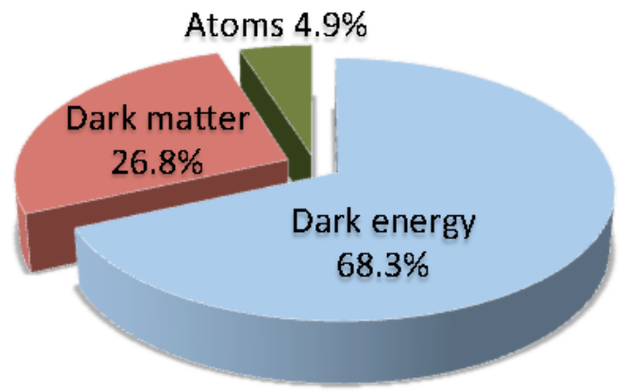



Low mass frontier

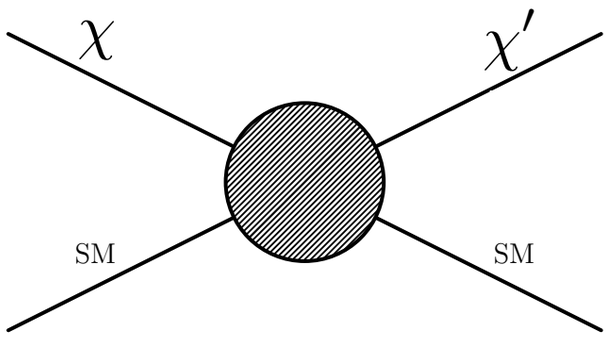
Low coupling frontier

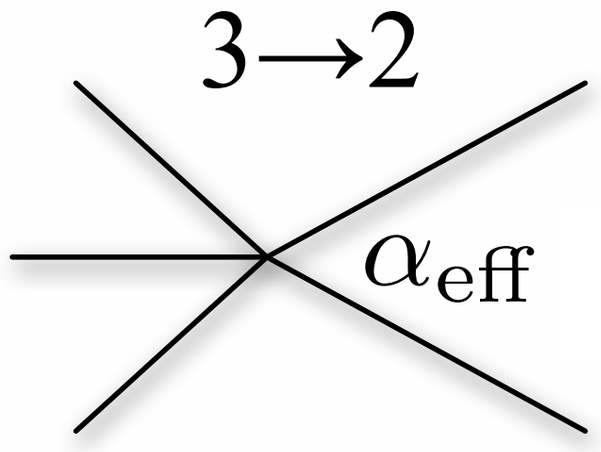



| **SM**<br>**(15% of matter)** | **WIMP**<br>**(85% of matter)** |
|---|---|
| **3 generations of matter**<br>**Mixing, CP violation** | **(Typically) one LPOP** |
| **3 gauge groups**<br>**One confining, one broken, one long range** | **Couples to Z/H** |
| **Composite bound states at many scales** | **Lone state** |

# Hidden sector DM

- DM interacts through *new* mediators
  - "dark photon", U-boson, Z', secluded mediator,….
  - dark Higgs
  - pseudo scalars, ALPs
  - Multiple states involved in DM-SM interactions
- 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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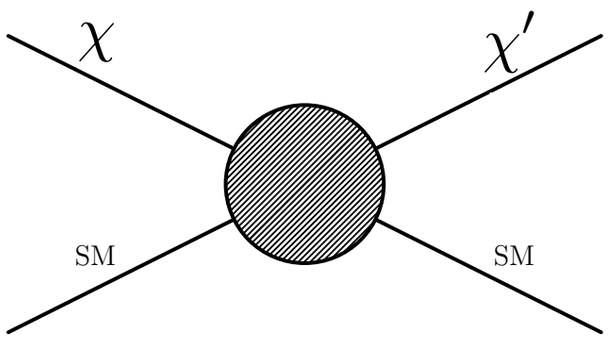


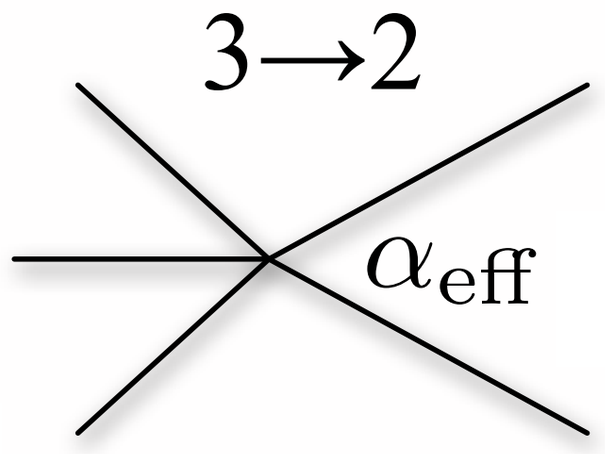

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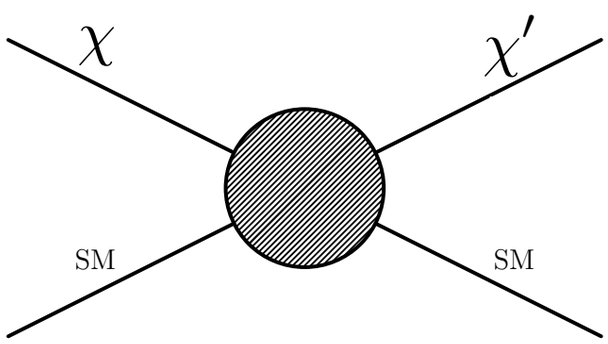
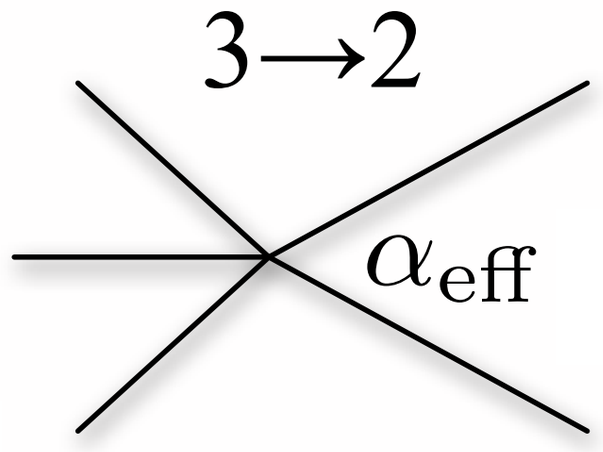
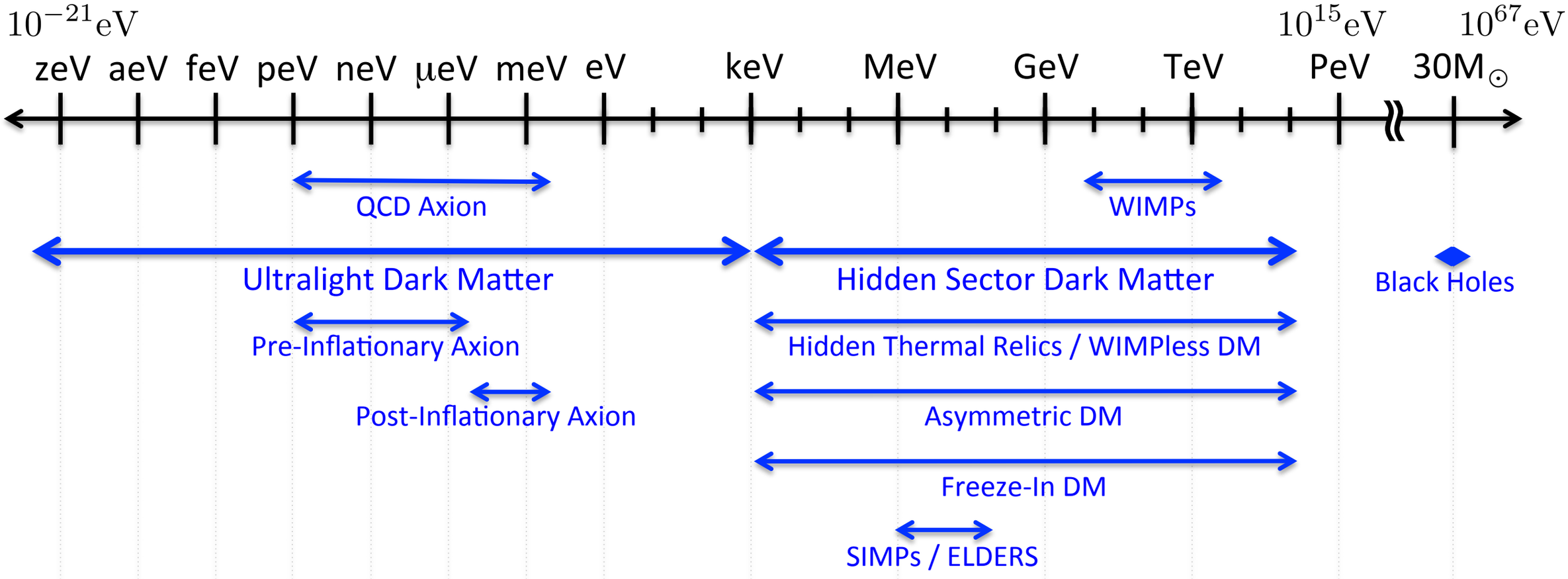


# Spoiled for choice
# or
# We don't know what we are doing?




[Feng-US Cosmic Visions White papers]

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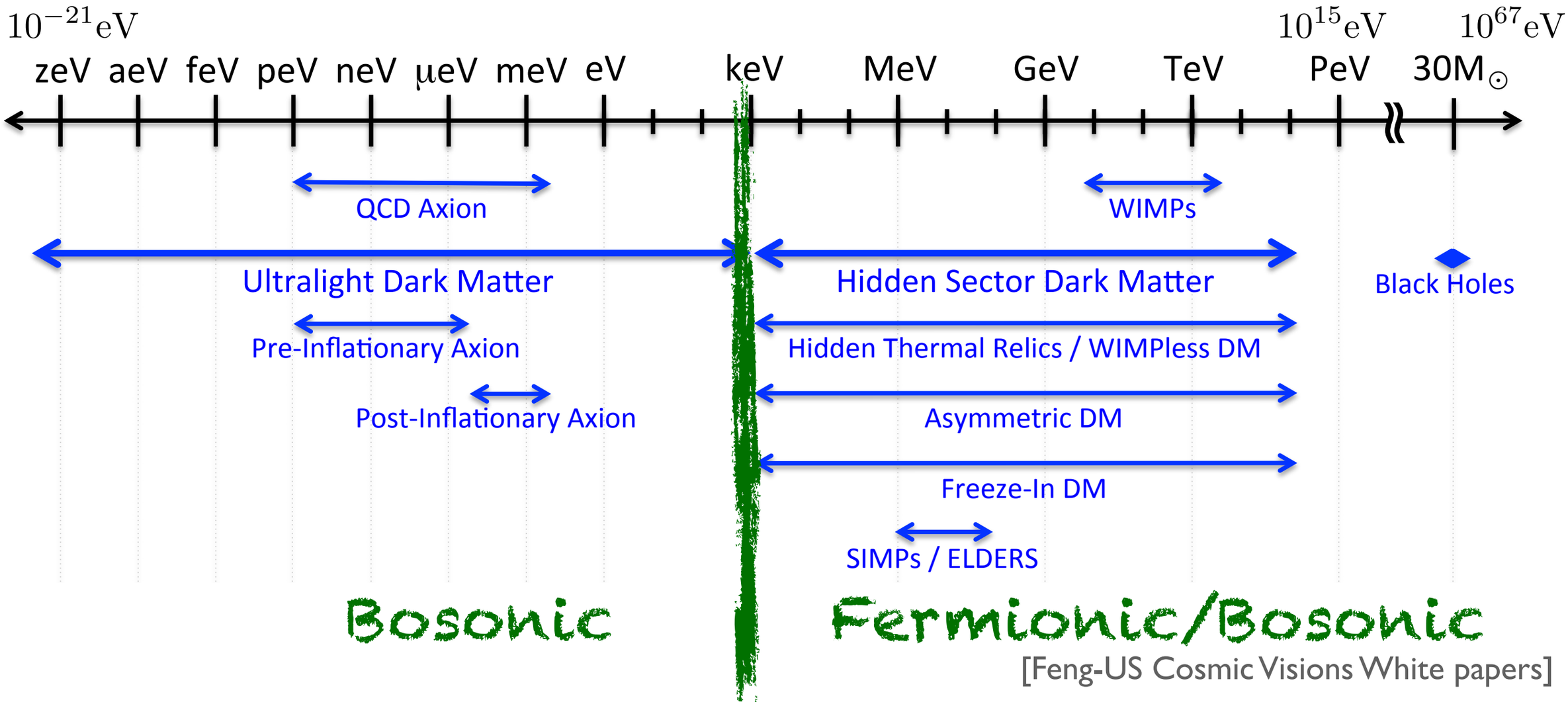
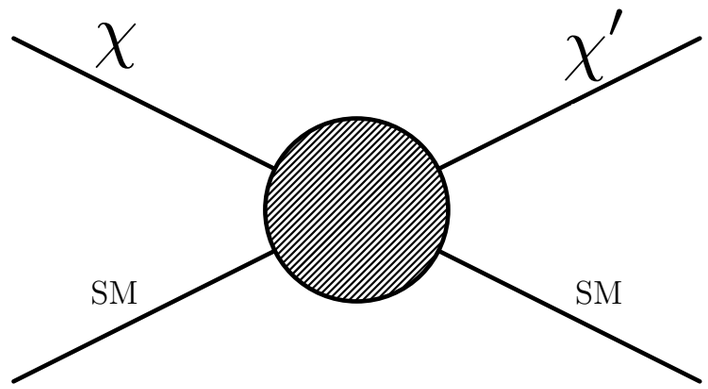
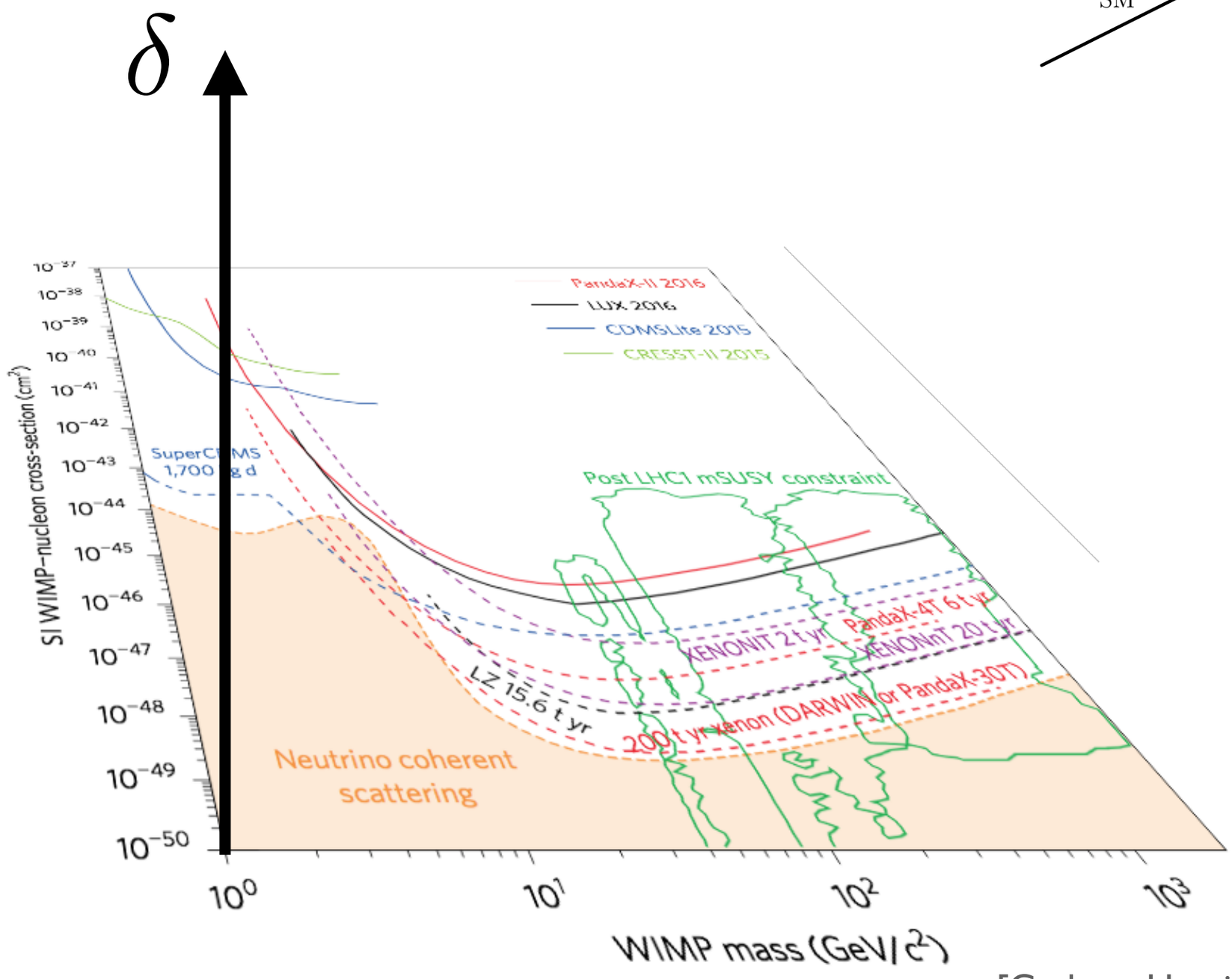



[Feng-US Cosmic Visions White papers]

# Inelastic scattering of DM




[Graham, Harnik, Rajendran, Saraswat]

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

Can be endothermic (iDM) or exothermic

[Tucker-Smith and Weiner]

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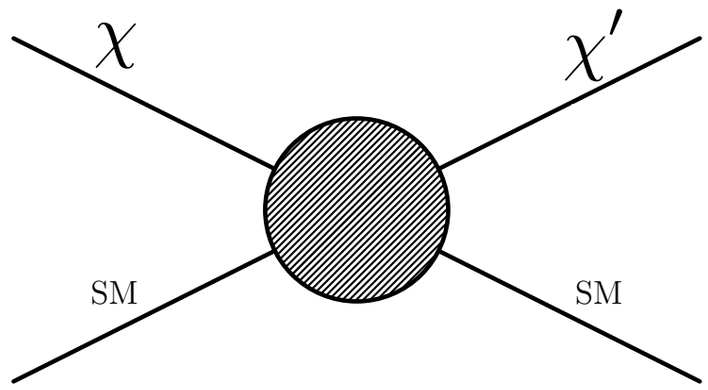
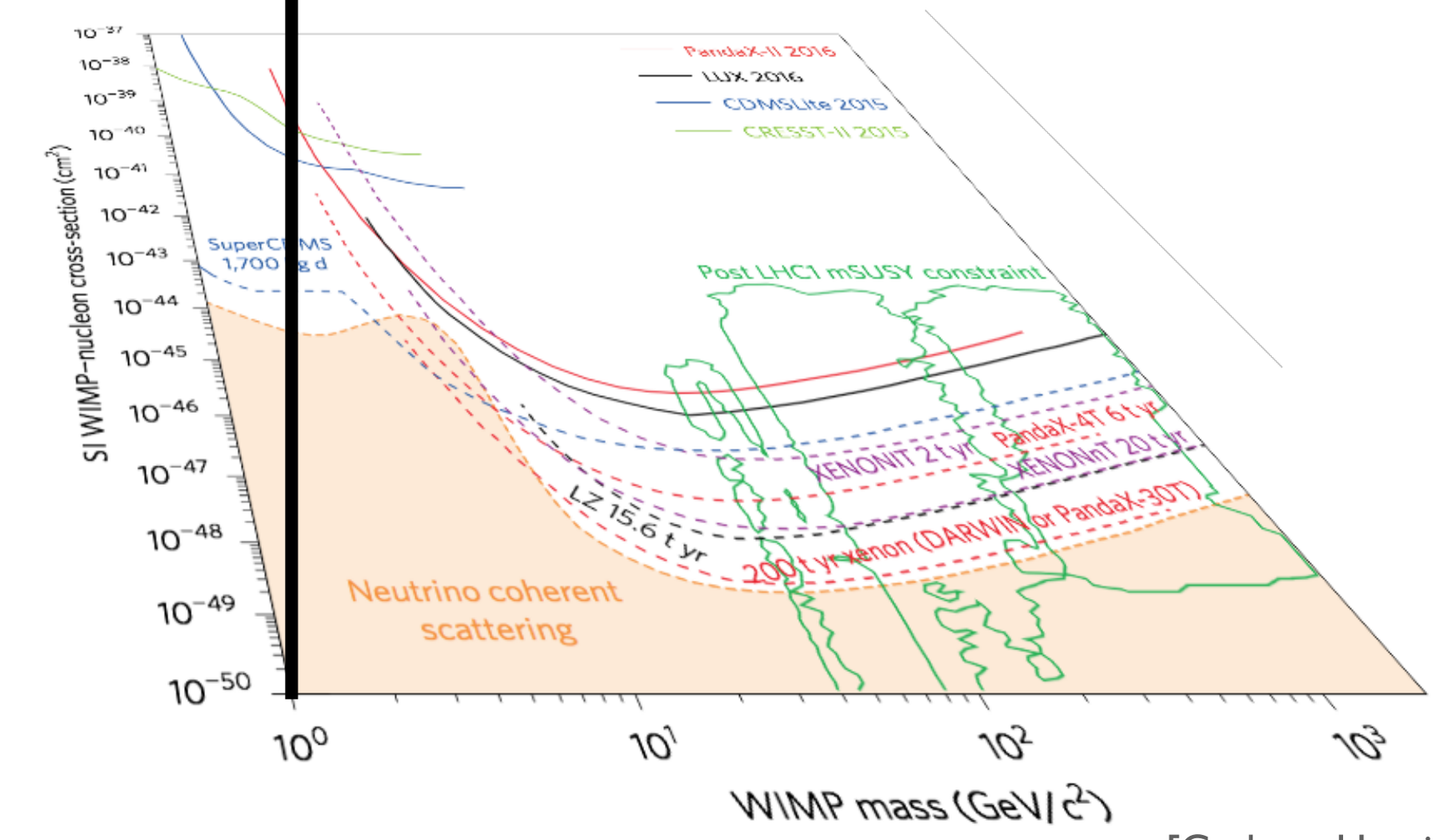



Mass splitting frontier




[Graham, Harnik, Rajendran, Saraswat]

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Can be endothermic (iDM) or exothermic

[Tucker-Smith and Weiner]

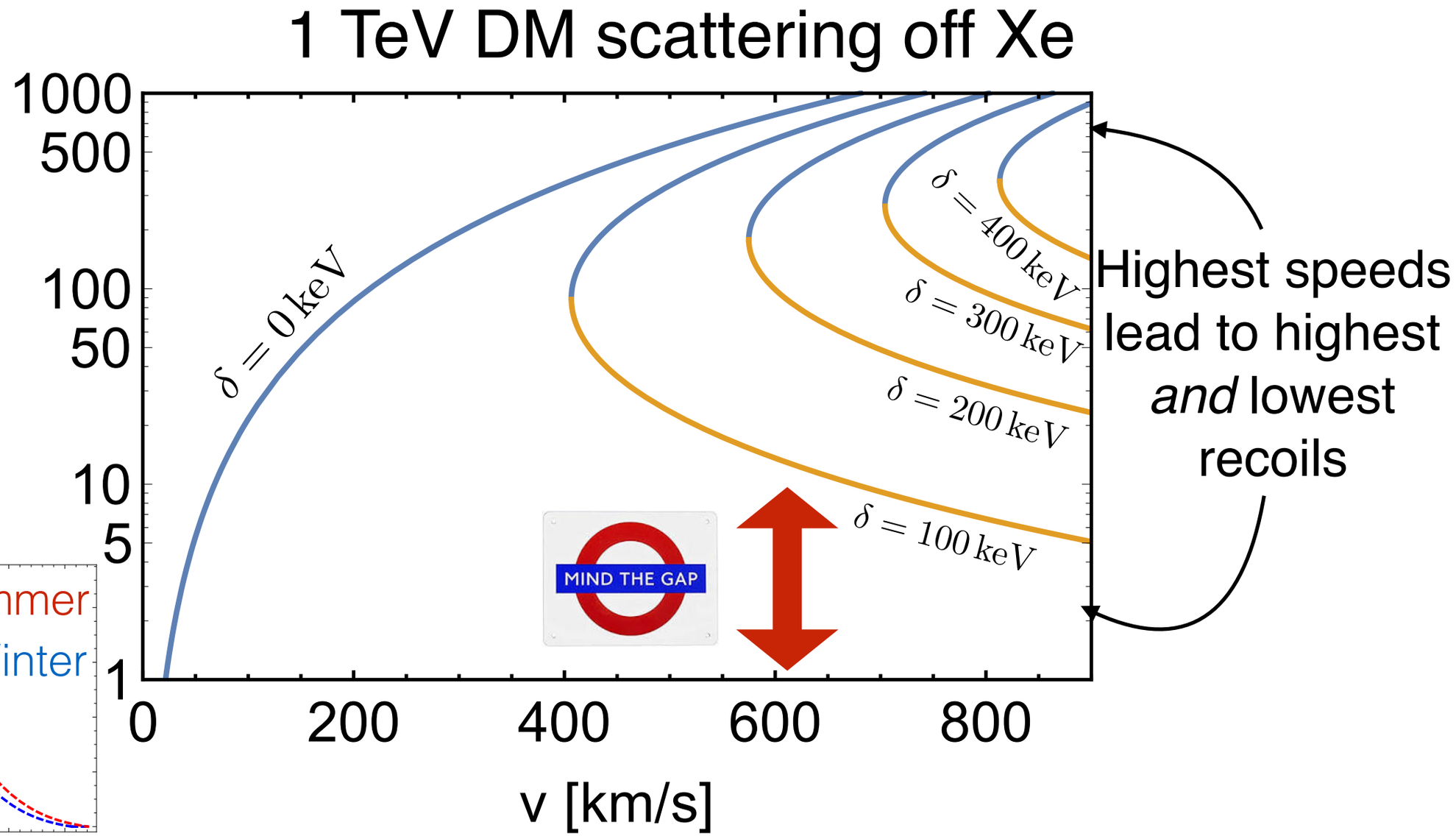
# Inelastic kinematics

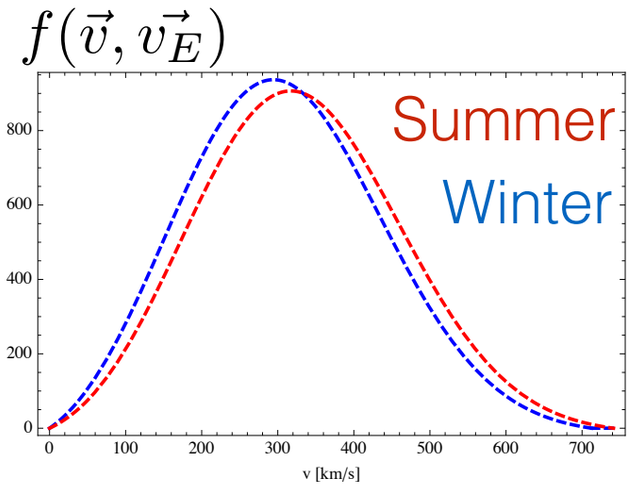
Nuclear recoil energy

Lab scattering angle

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

DM speed in lab frame

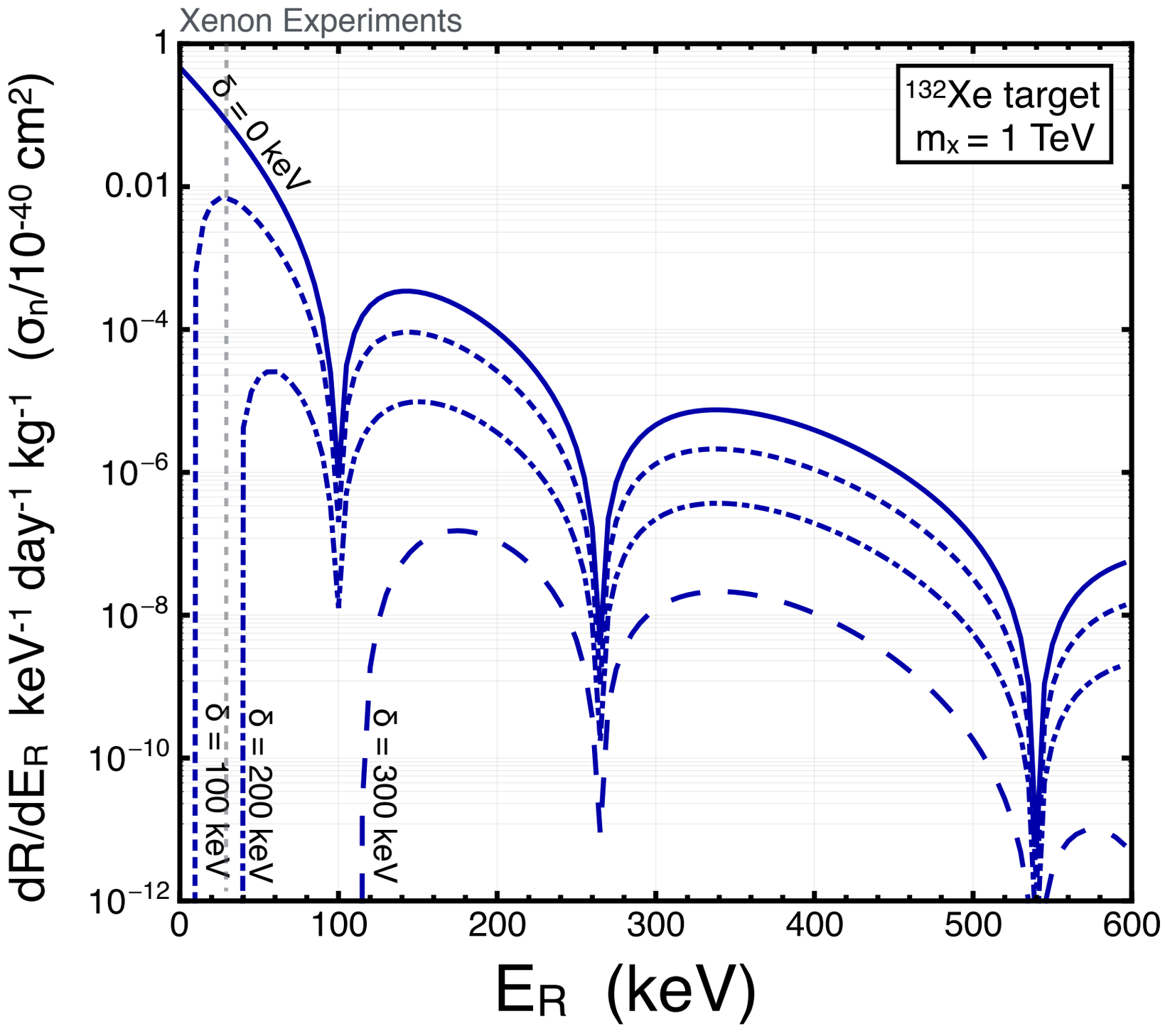


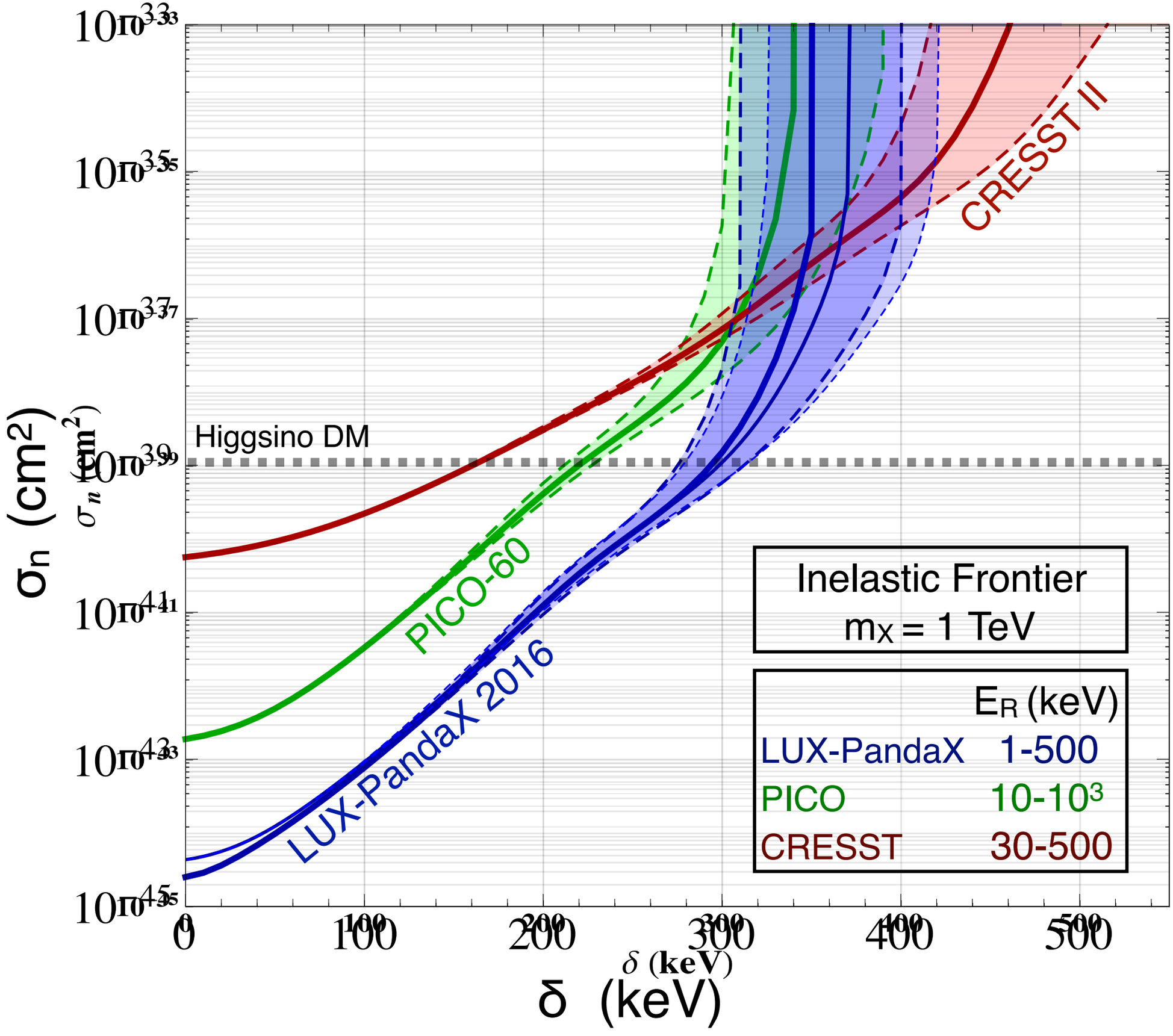
# Inelastic Dark Matter (iDM)

- Requires "large" momentum exchange to upscatter
- Favours high velocity tail of phase space distribution
- Increased modulation
- Prefers heavy targets e.g. iodine, xenon, tungsten,..
- Recoil spectrum has a peak
- Sensitivity increased by going to *higher* recoil

# High Recoil Energy Frontier



[Bramante, PF, Kribs, Martin]

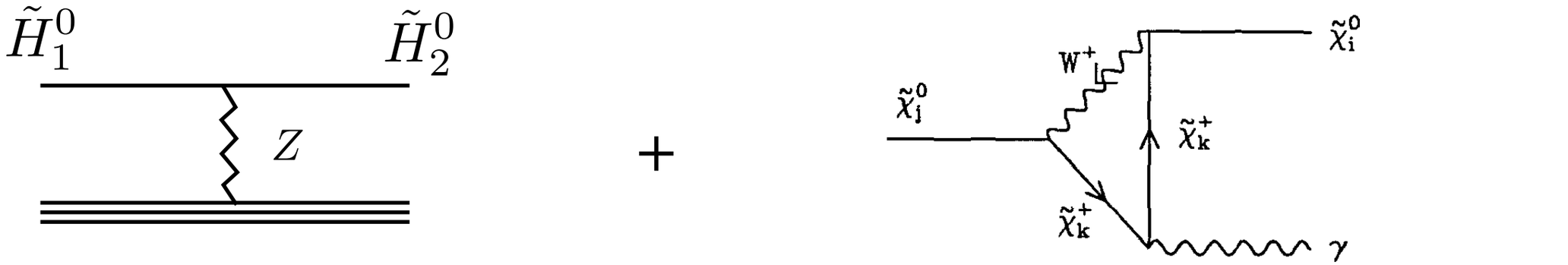


# Photon Phrontier

## Upscatter + Visible Decay

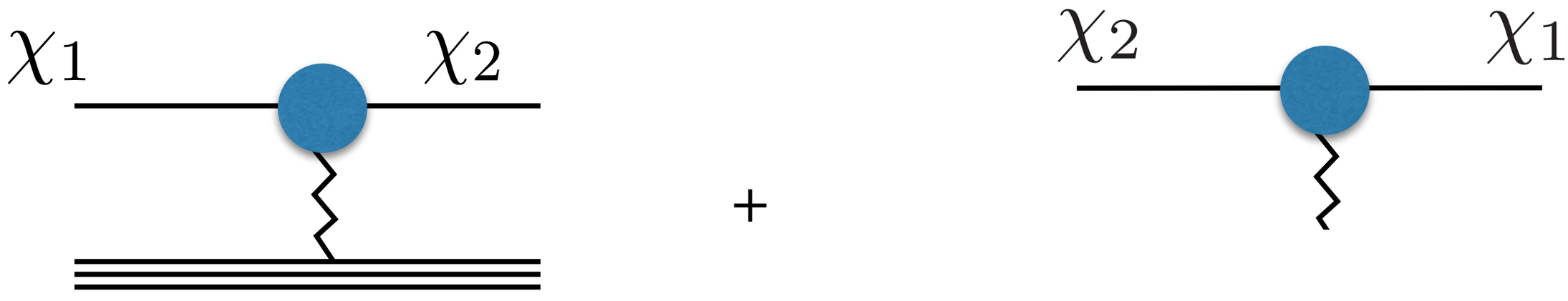
### Almost pure Higgsino

[Haber and Wyler]



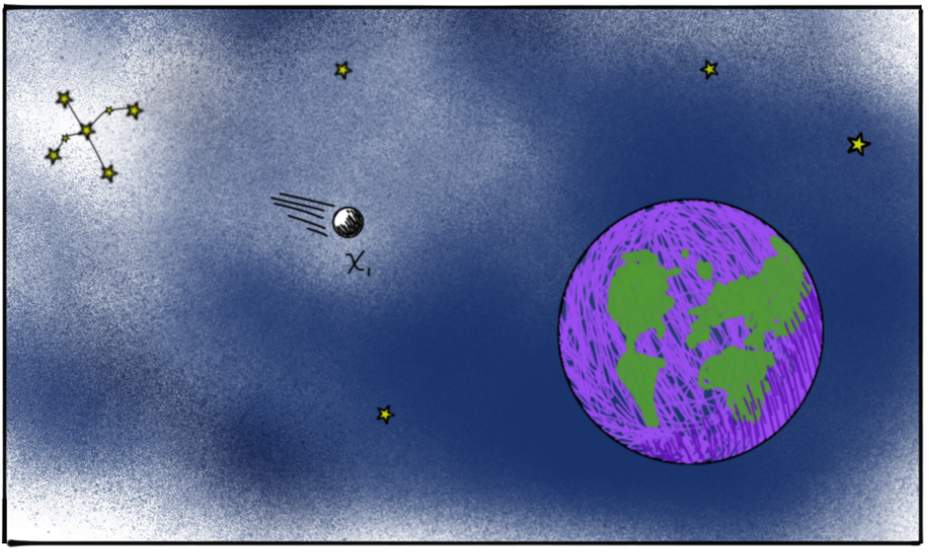

### Magnetic inelastic DM

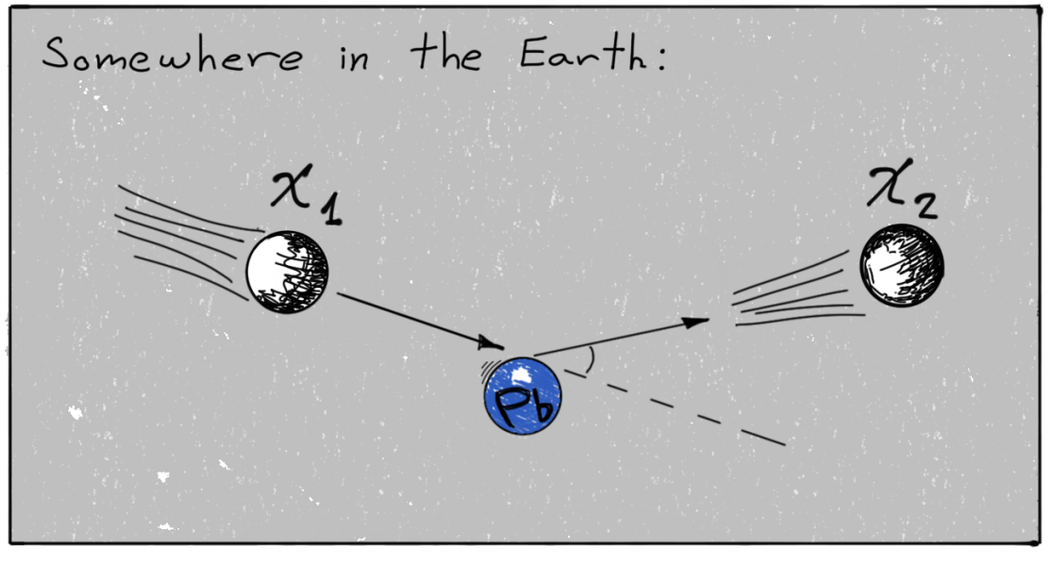
[Chang, Weiner, Yavin]

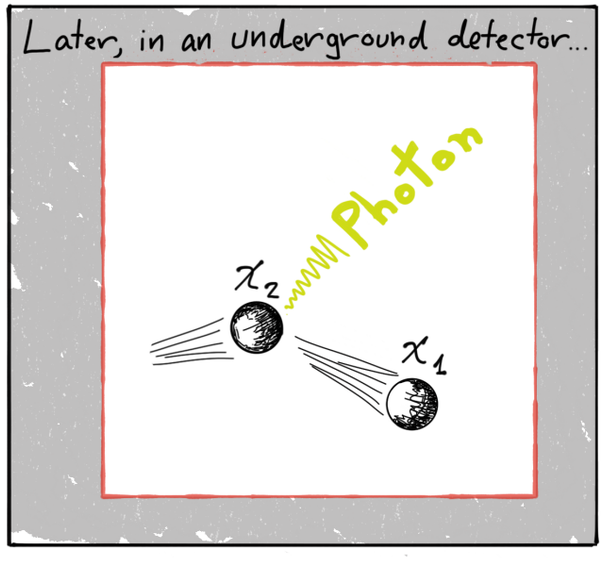


# Illuminating the Inelastic Frontier

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



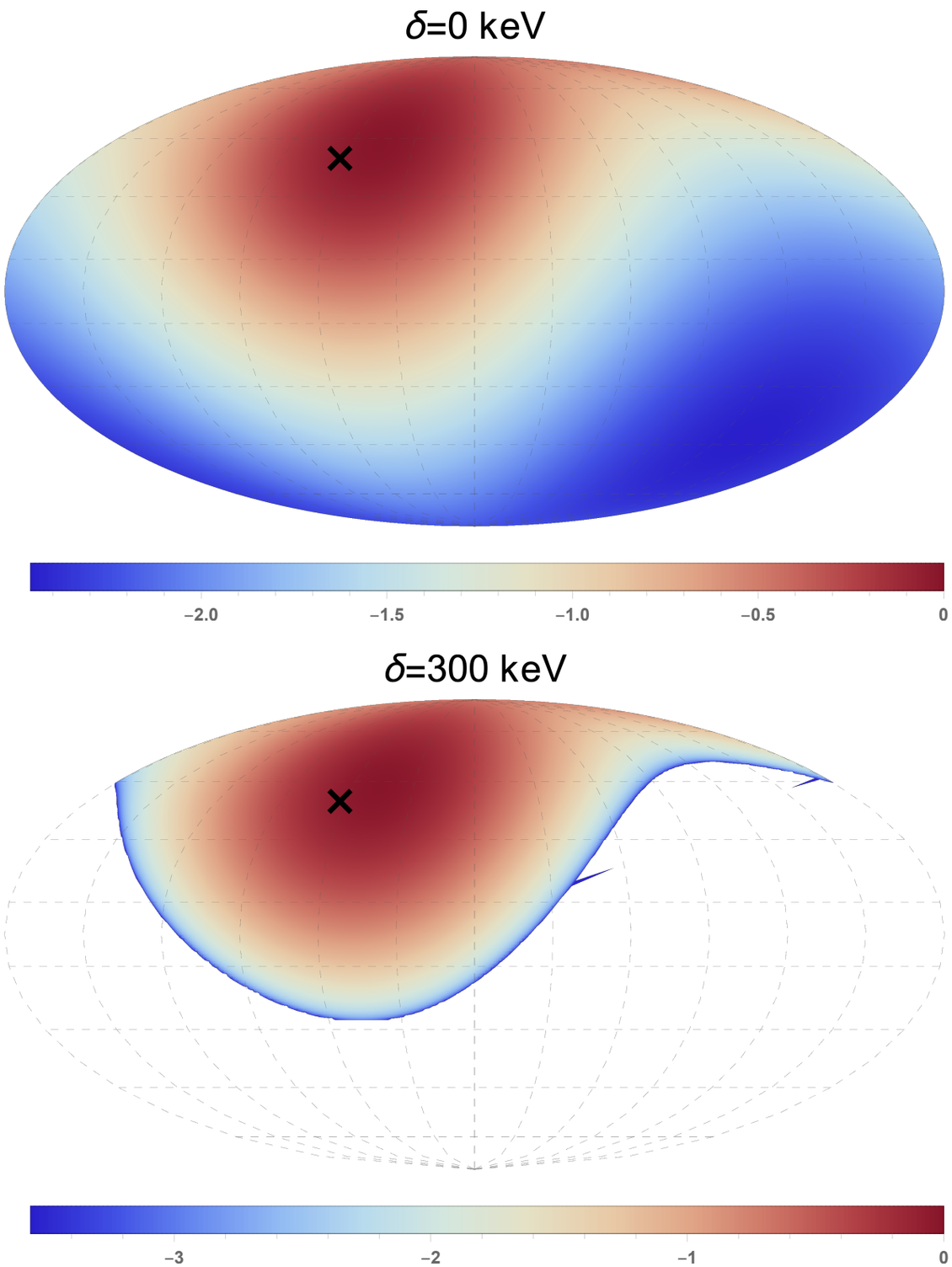



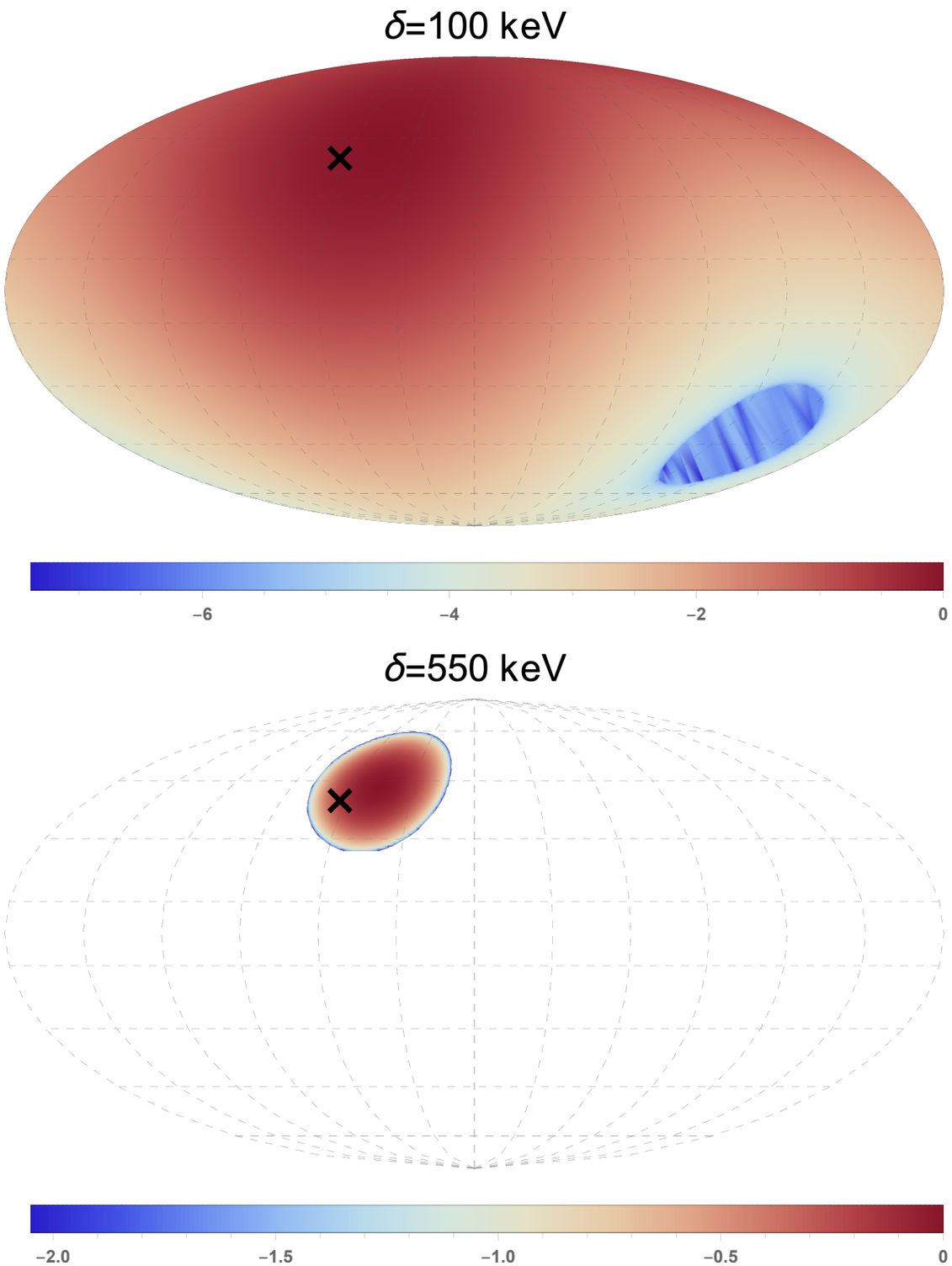

[Eby,PF, Harnik,Kribs]

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

# The Cygnus “gun”

Upscatter needs high speeds, which comes from Cygnus



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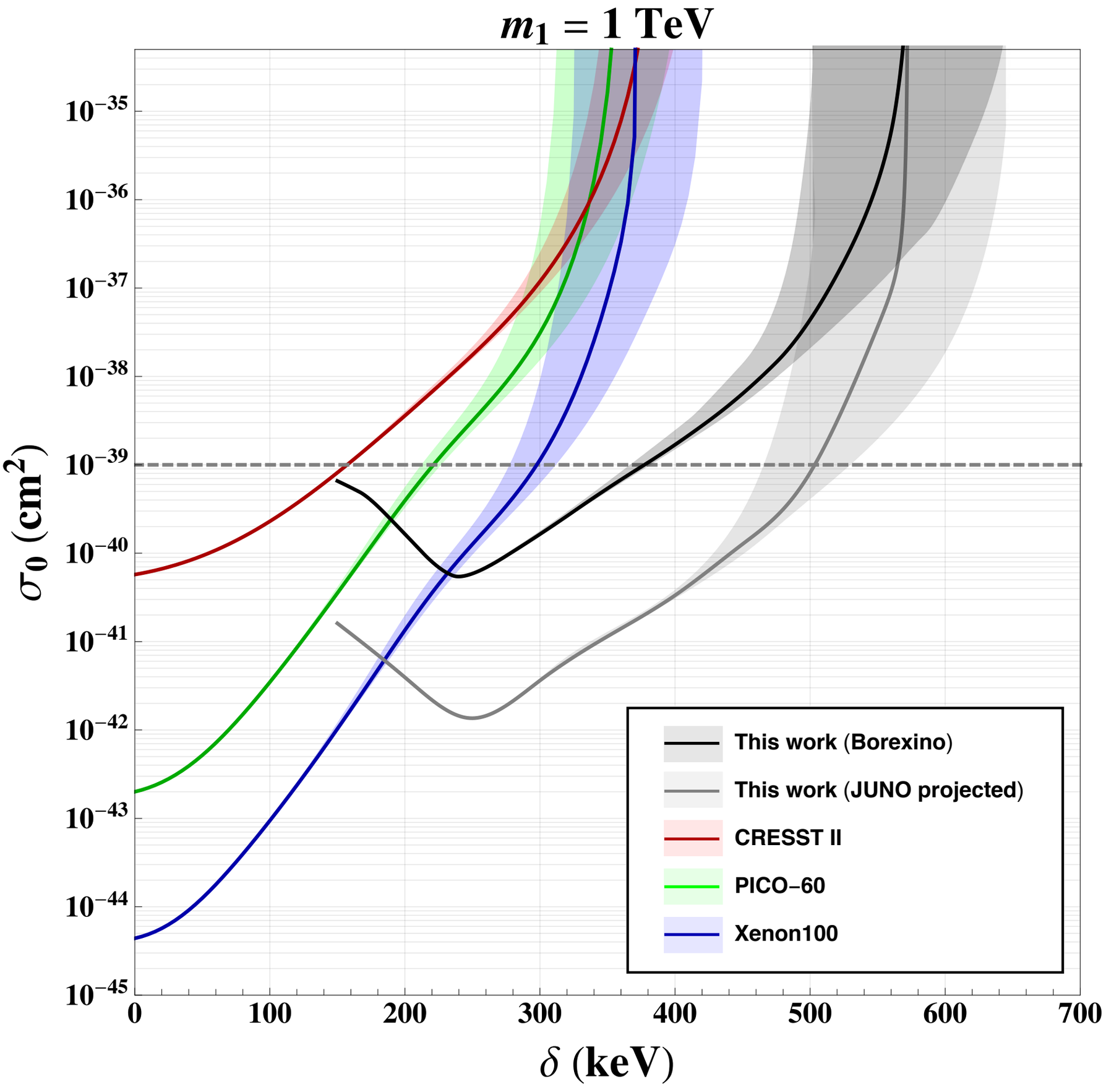
# Illuminating the Inelastic Frontier

[Eby, PF, Harnik,Kribs]



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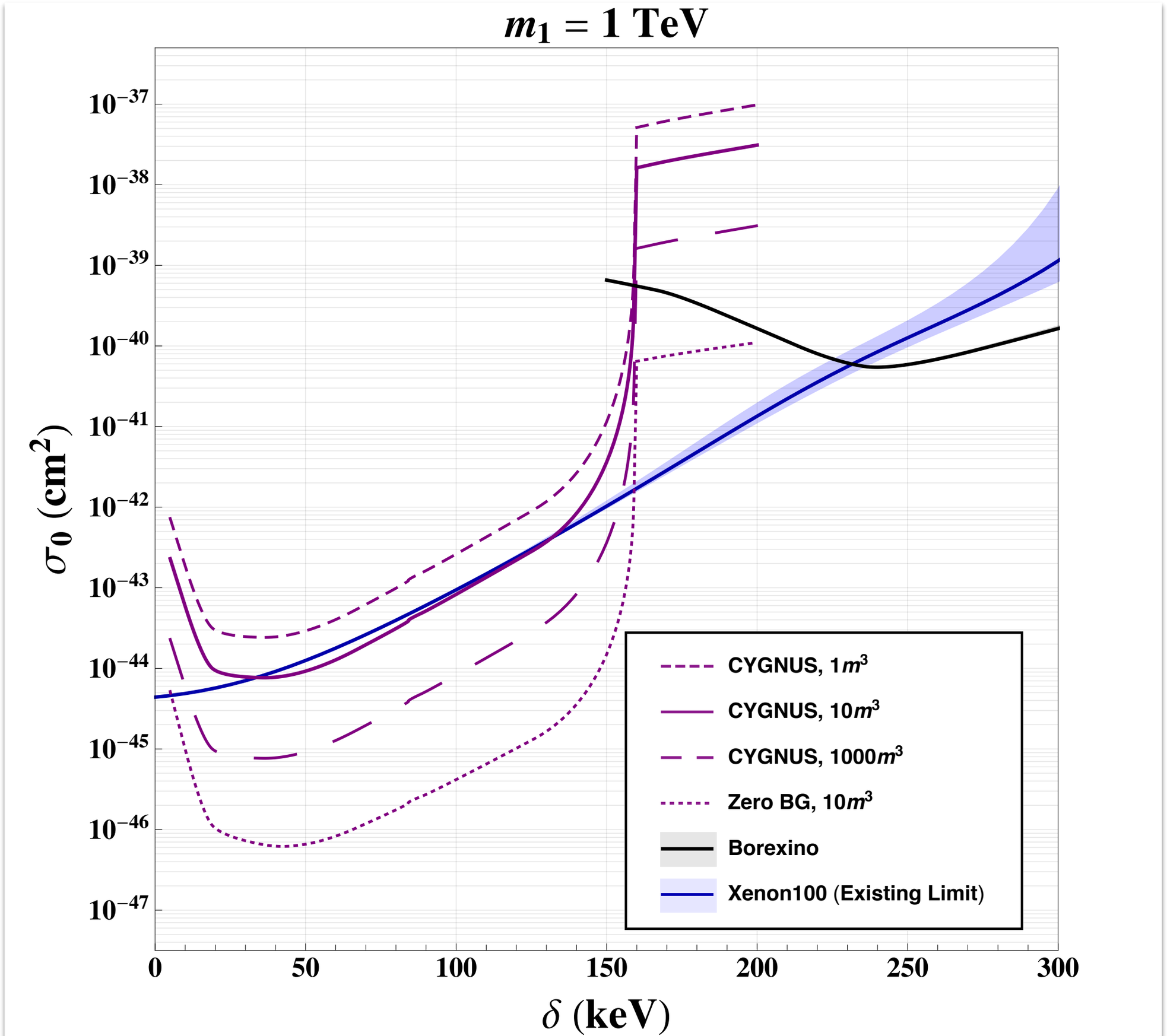
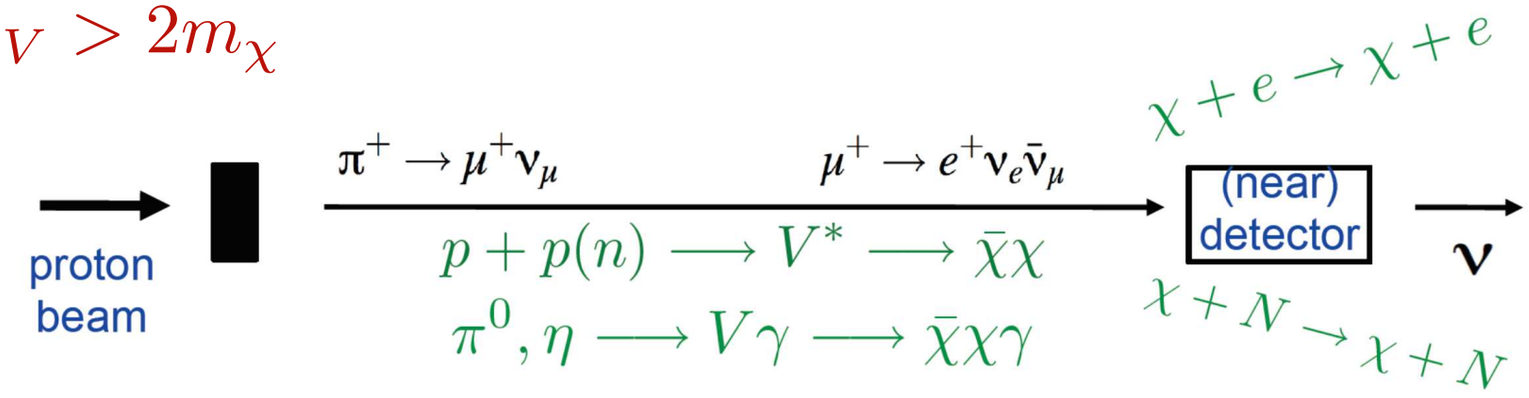


# DM @ neutrino detectors

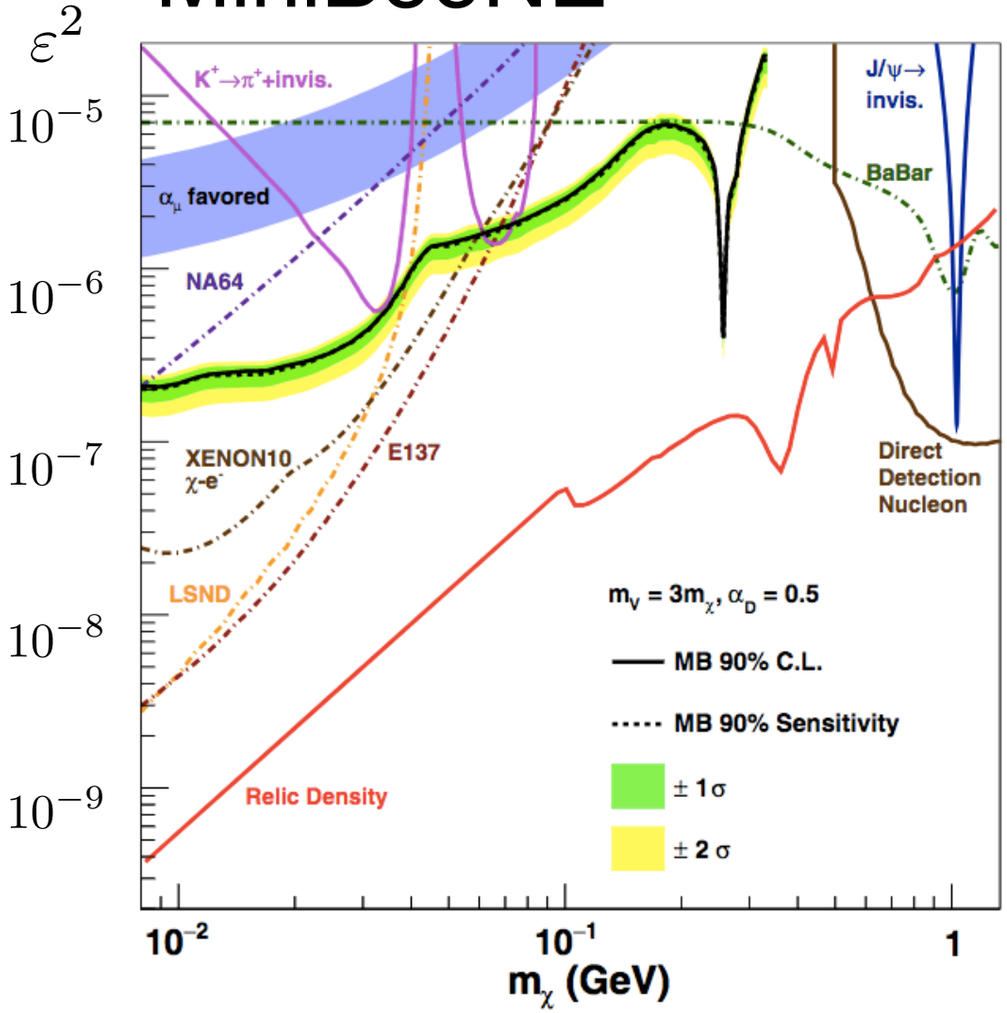
- Beam produced DM/dark sector states in near detectors

$m_V > 2m_\chi$

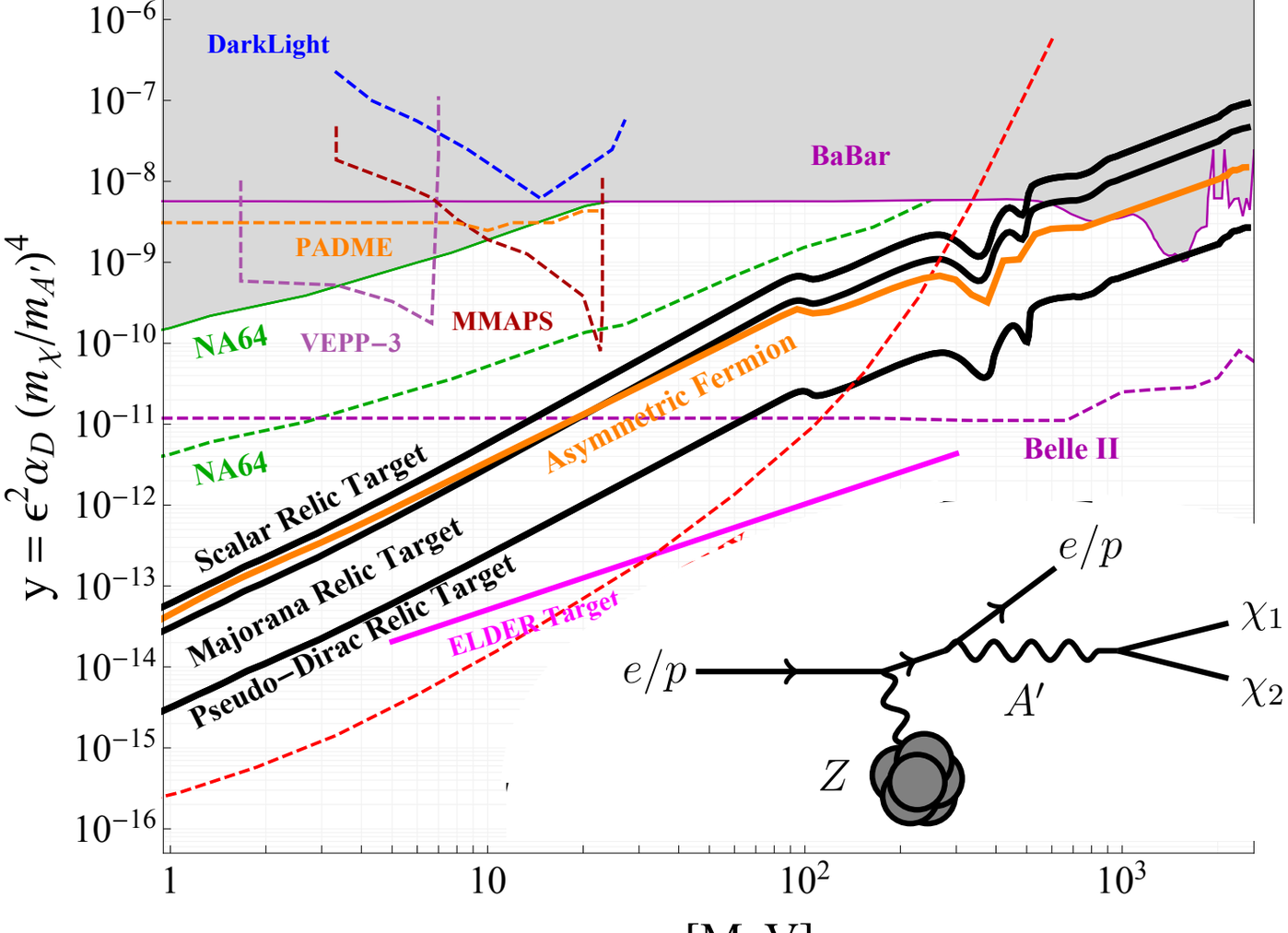



[e.g. Batell, Pospelov, Ritz]

MiniBooNE




Missing Mass/Momentum Experiments (Kinetic Mixing, $m_{A'} = 3m_\chi$)



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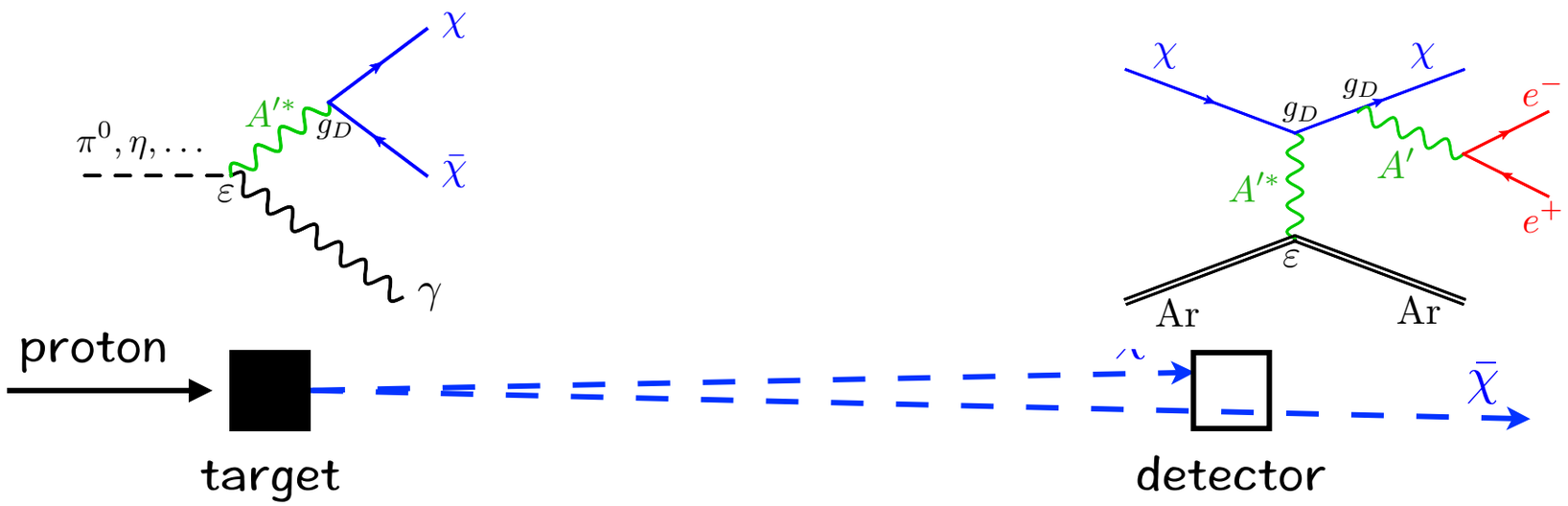
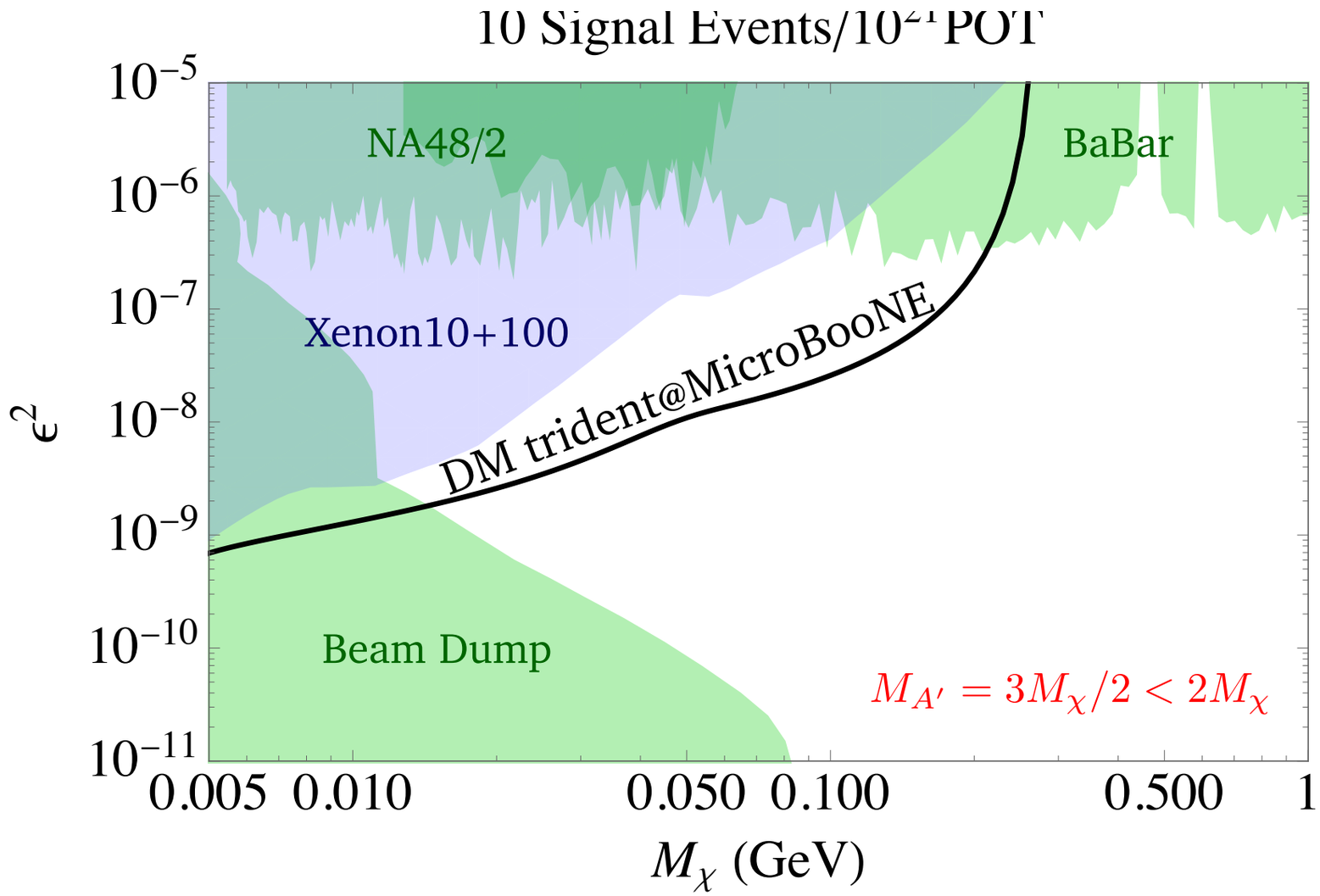
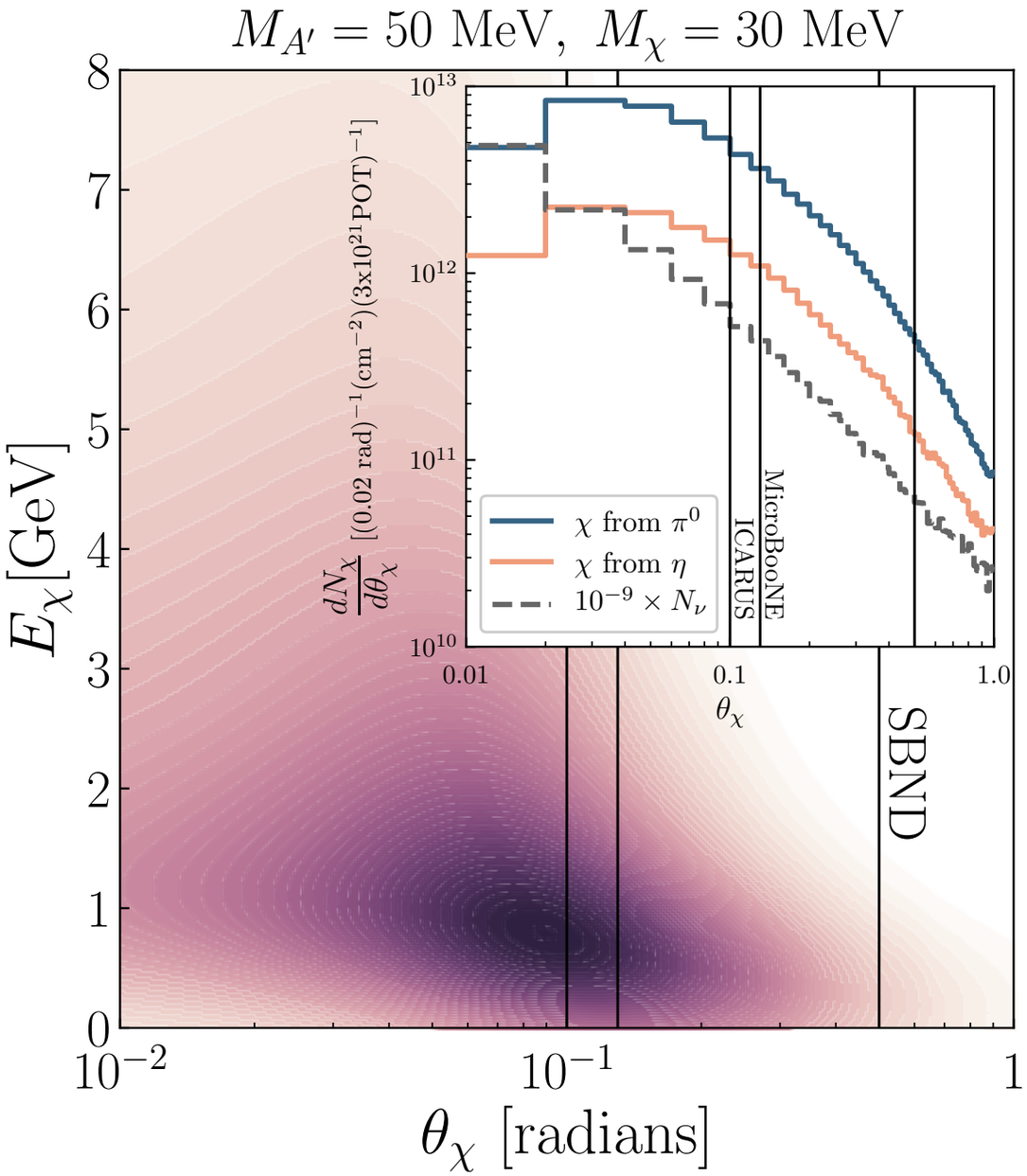
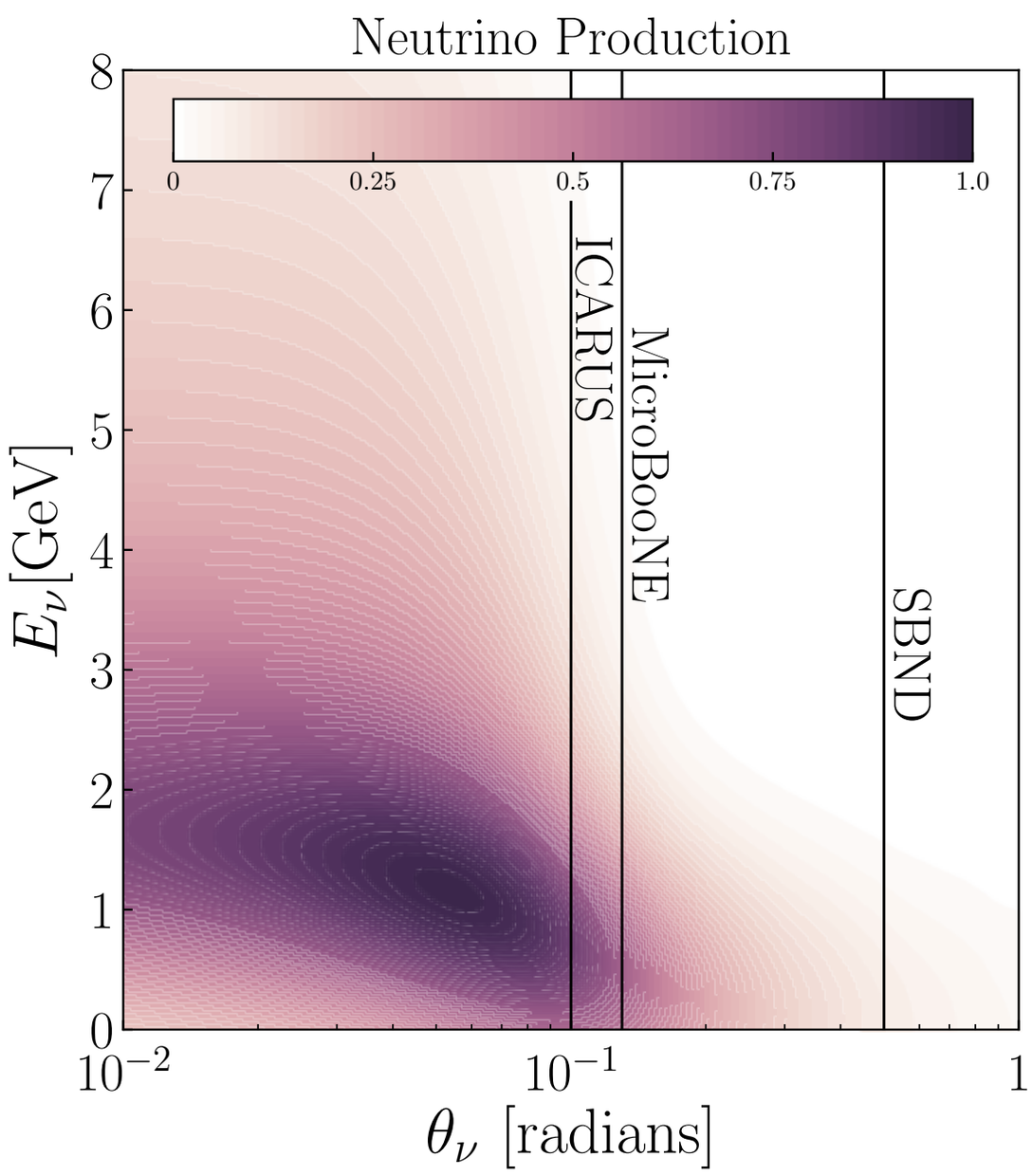



[e.g. de Gouvea, PF, Harnik, Kelly, Yang]



# Useful to look off axis

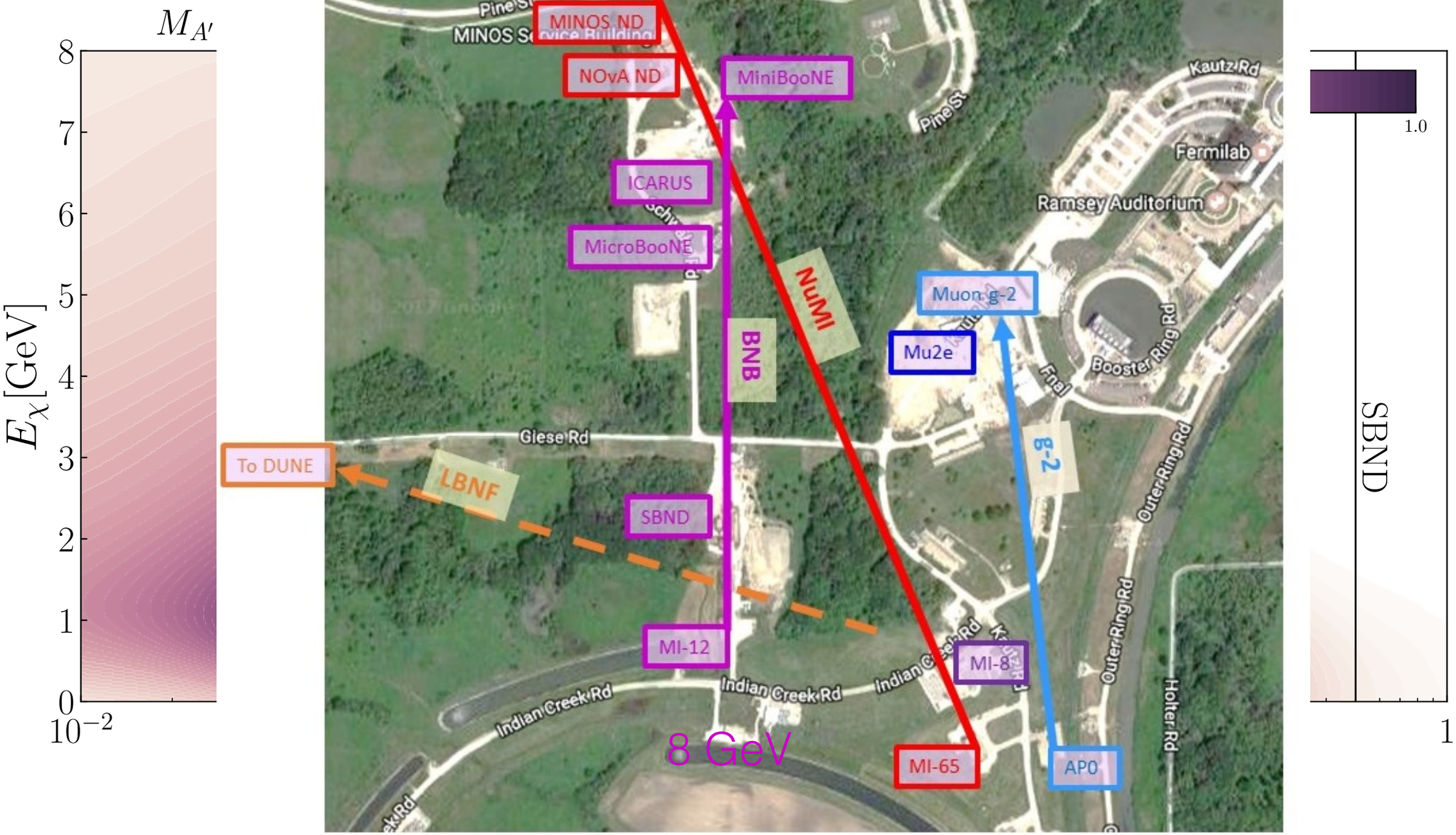



Other places with detectors near (but not on) beam lines?
e.g. protoDUNE/LHC

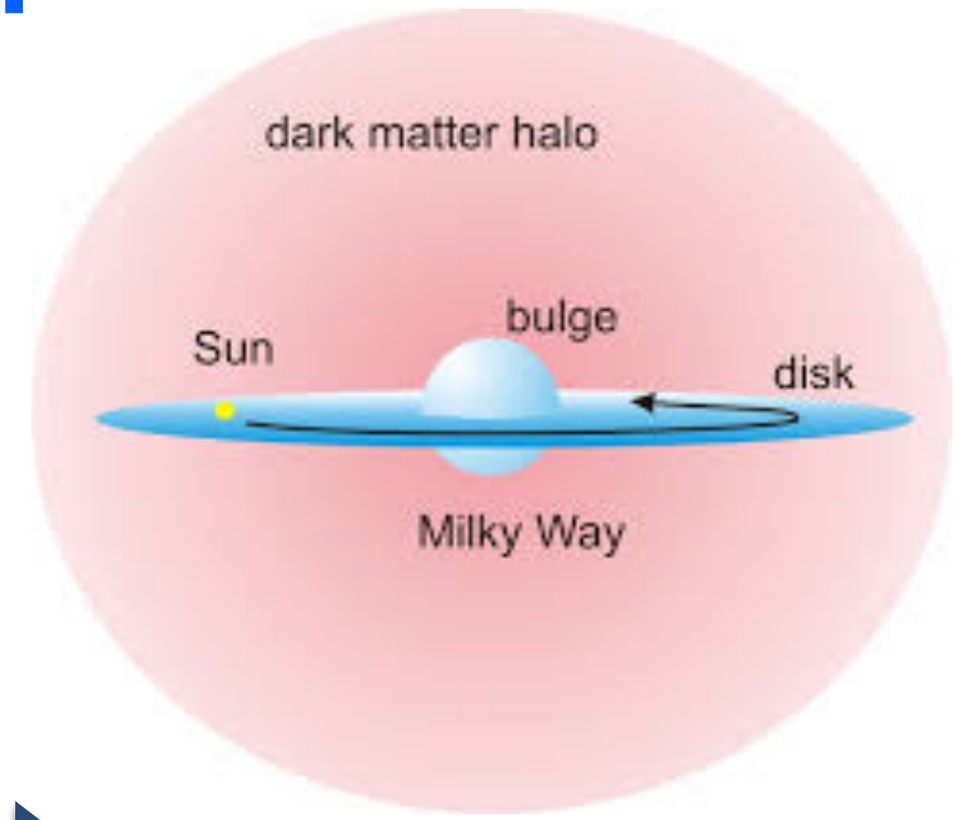
# Useful to look off axis

120 GeV




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

# DM — one lump or two?

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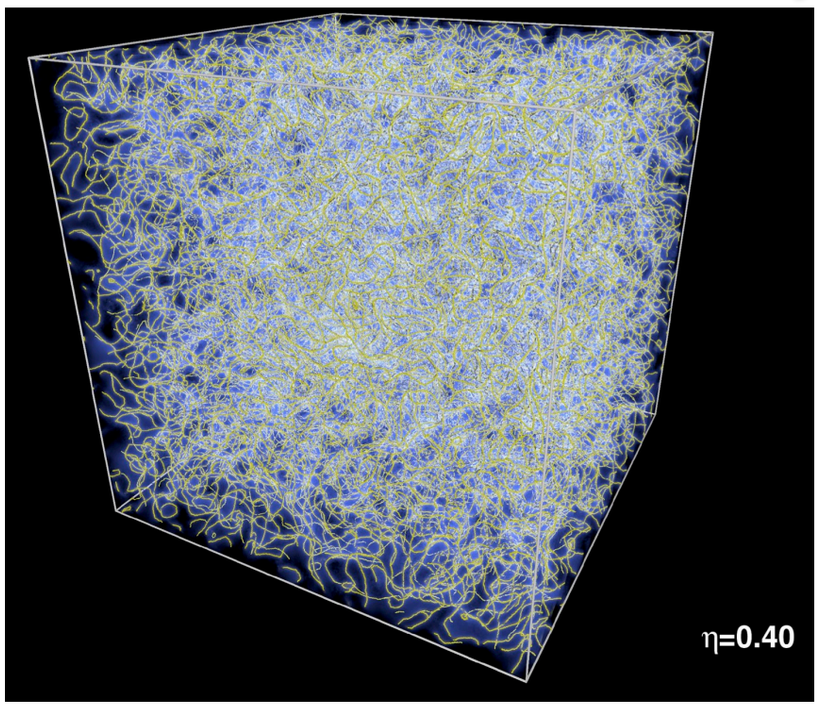
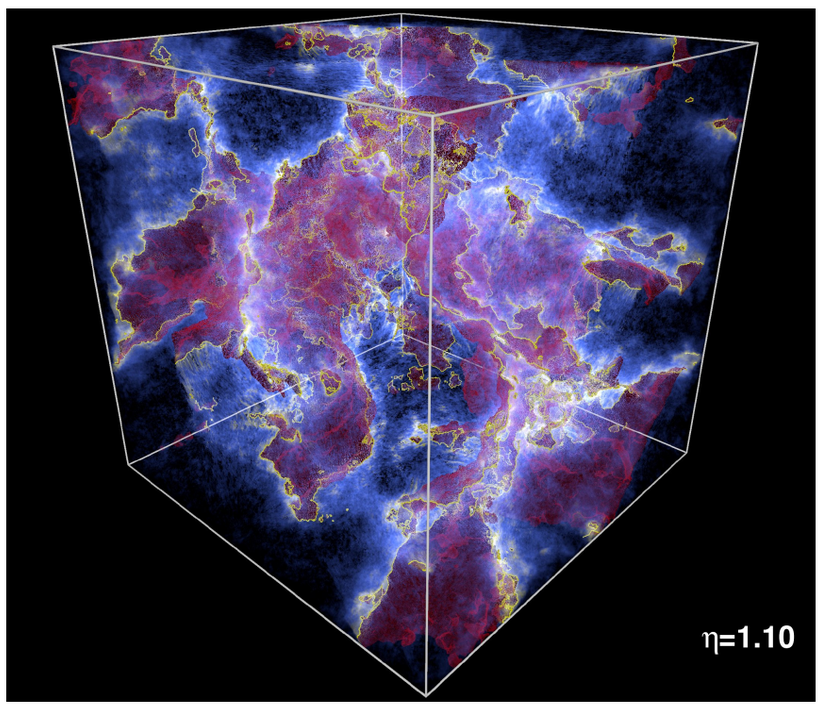
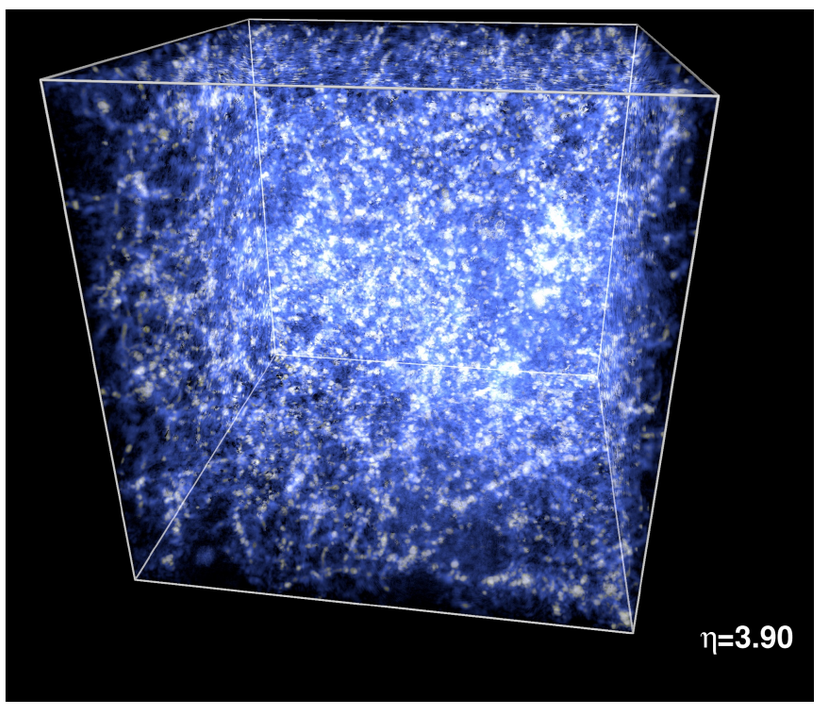


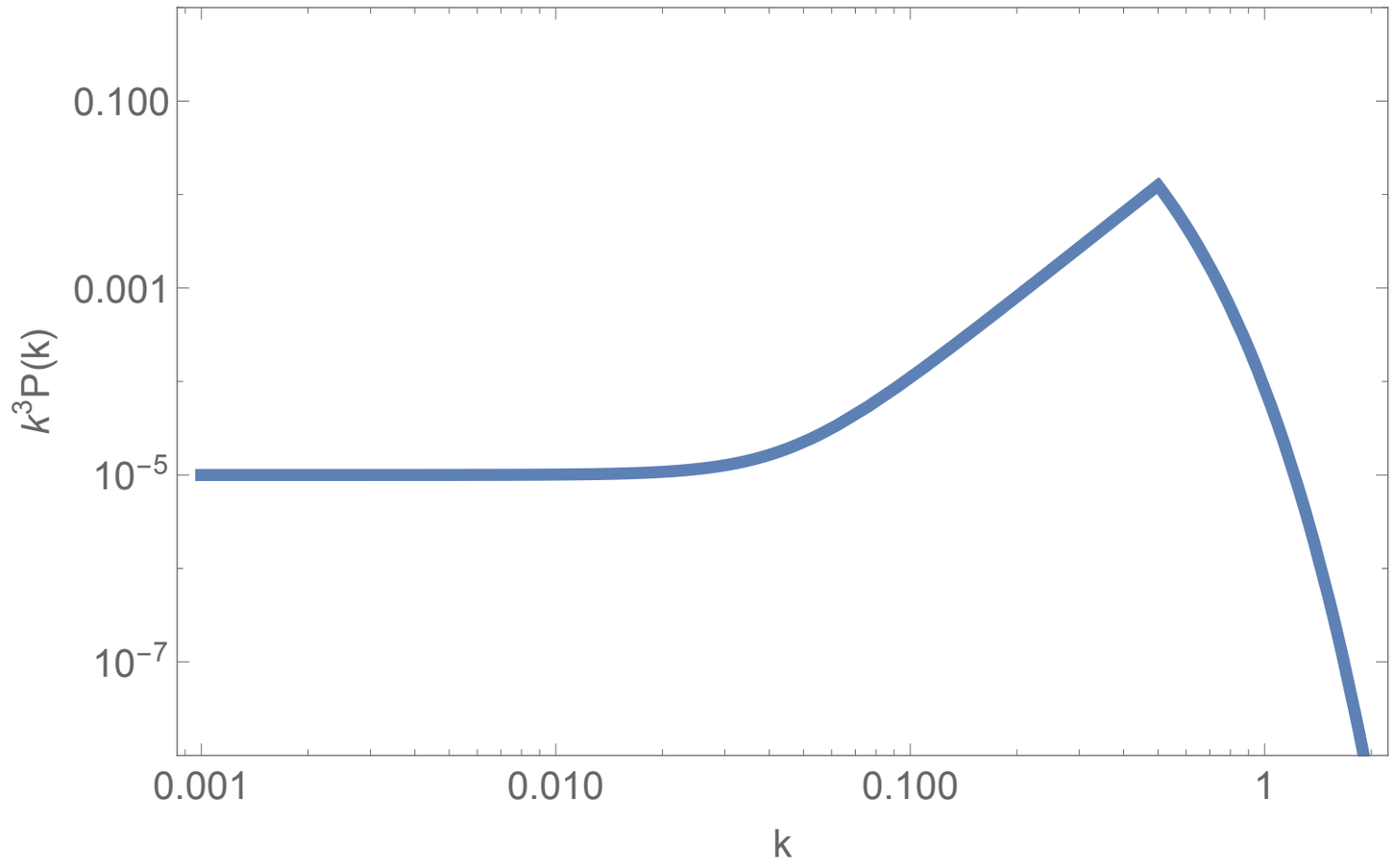




[Buschmann, Foster, Safdi]

# DM — one lump or two?

O(1) white noise isocurvature fluctuations at small scales

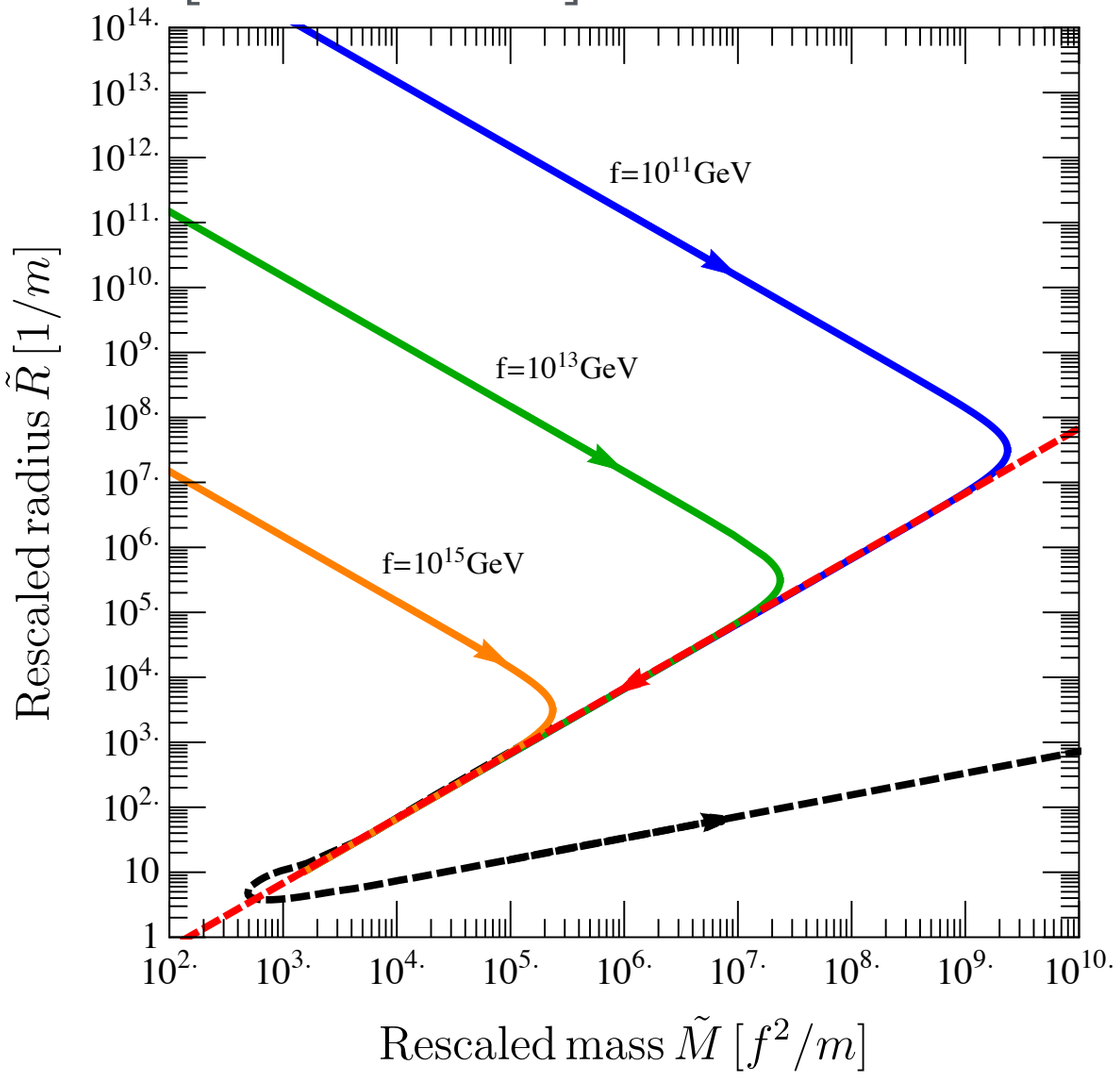



Axion miniclusters quickly form after matter-radiation equality

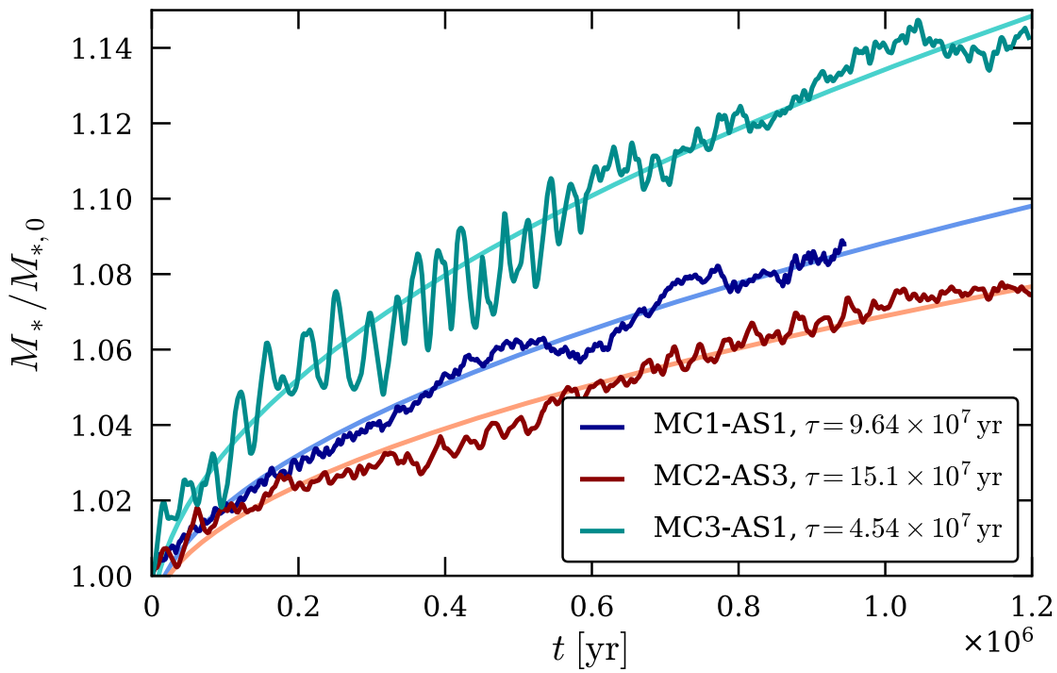
# Axion “stars”

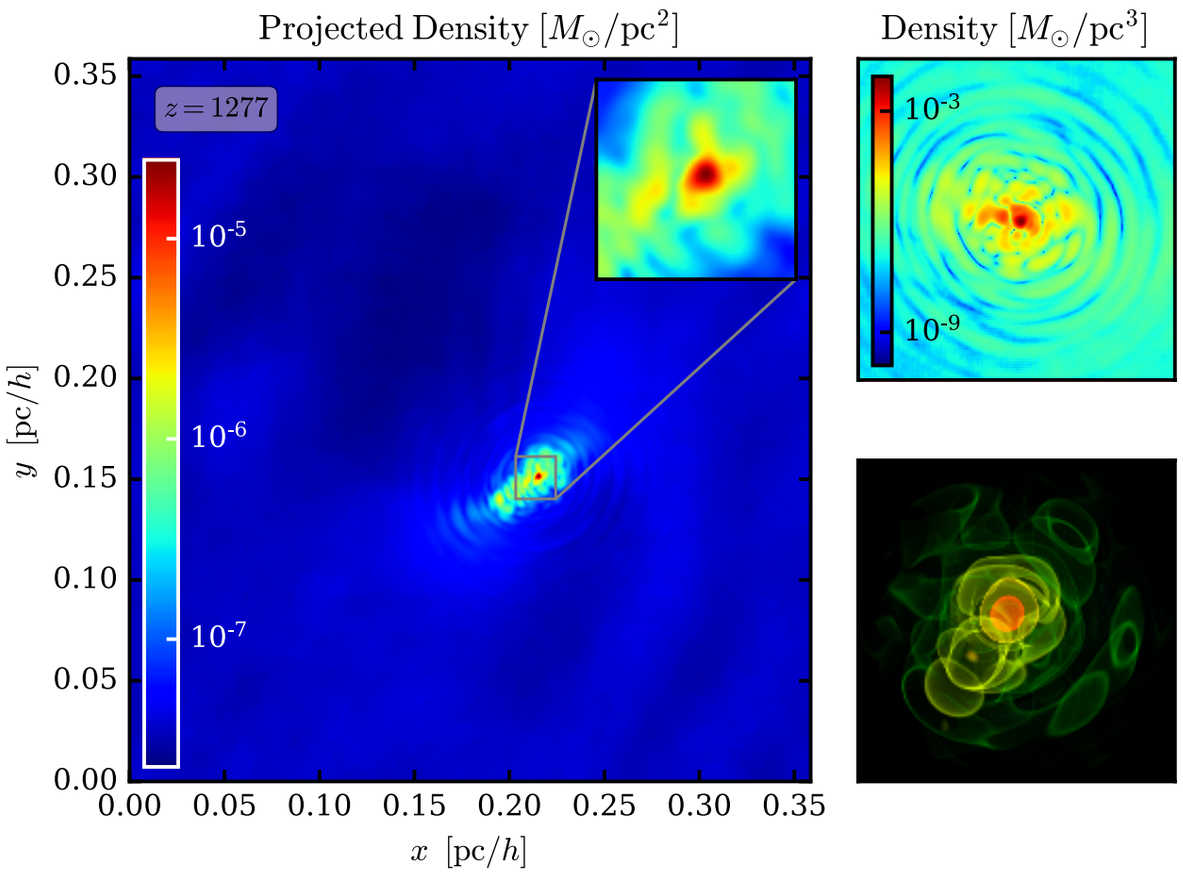
Stable solutions: gravity/self-interaction vs gradient energy (“Heisenberg pressure”)

[Visinelli et al]



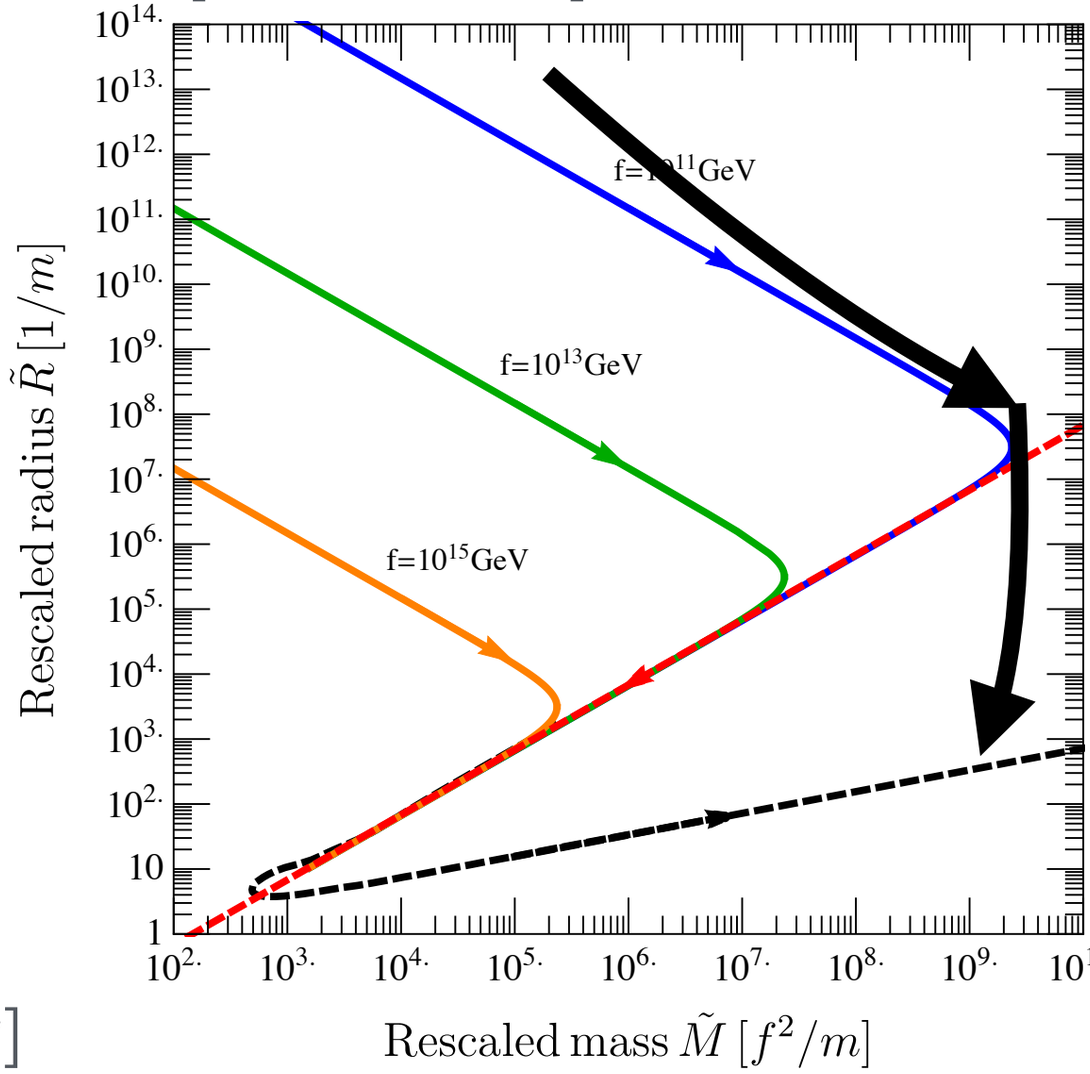

[Eggemeier and Niemeyer]



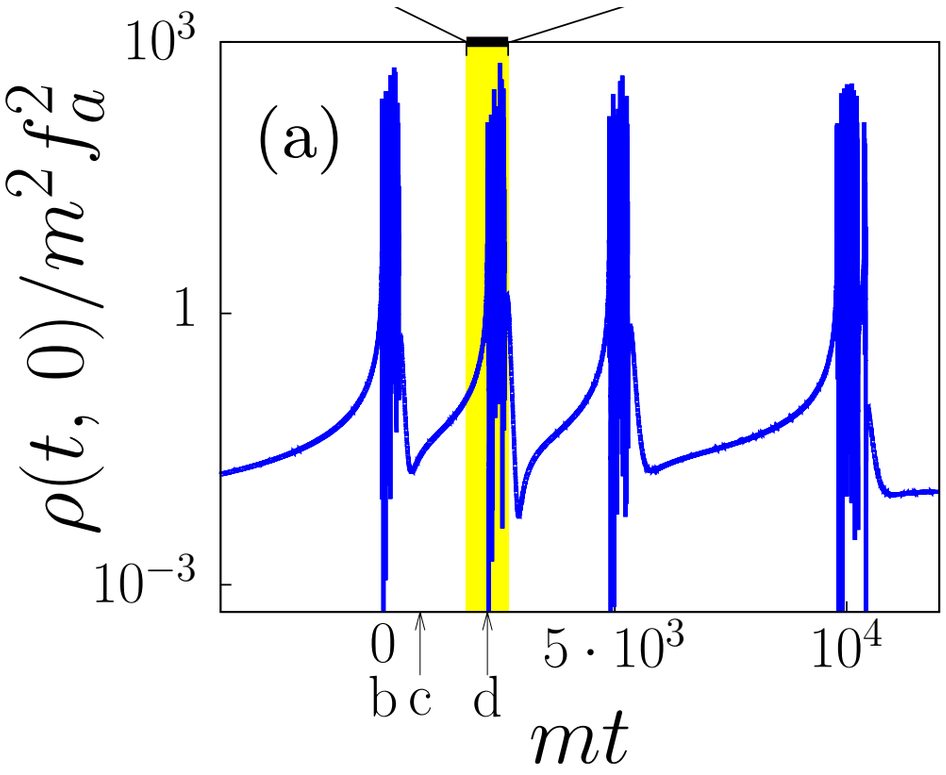



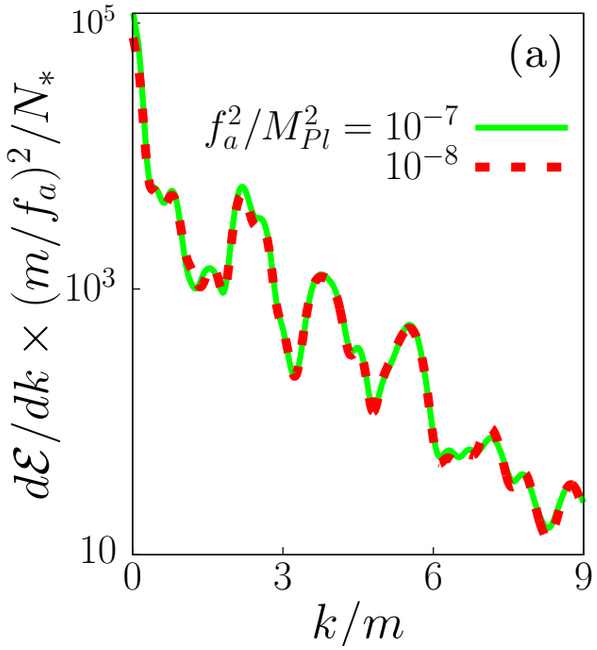
Star reaches critical mass and then explodes

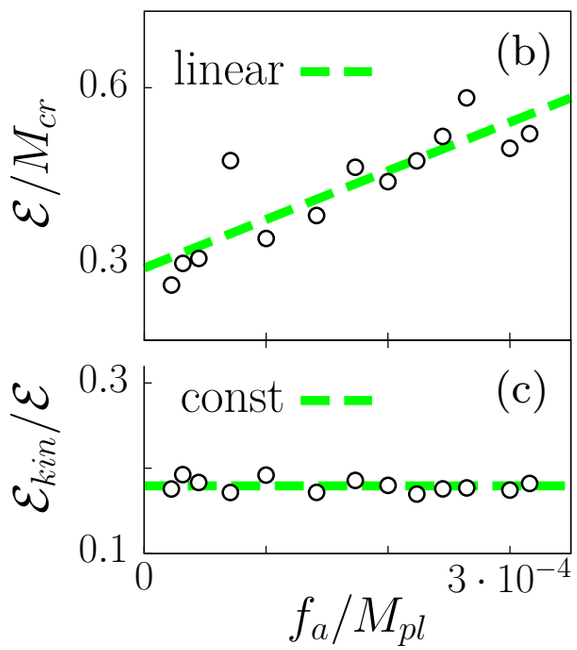
[Visinelli et al]




[Levkov, Panin, Tkachev]



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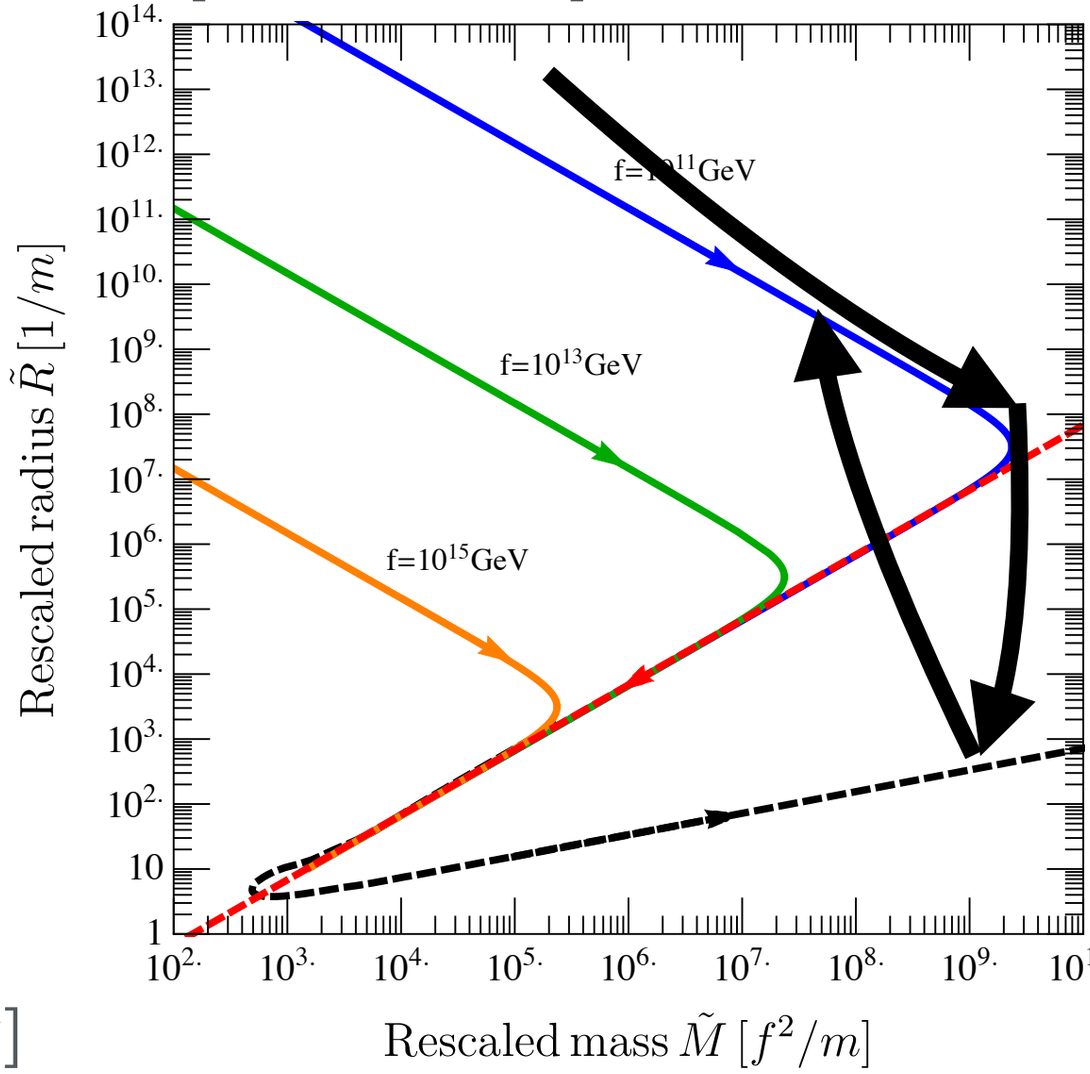
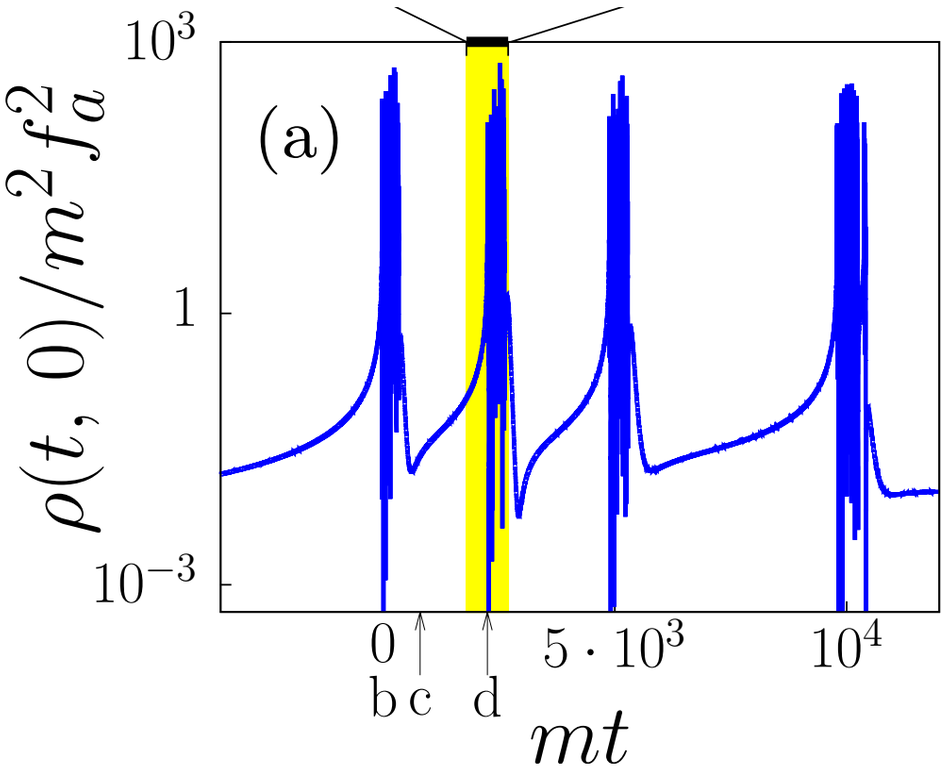
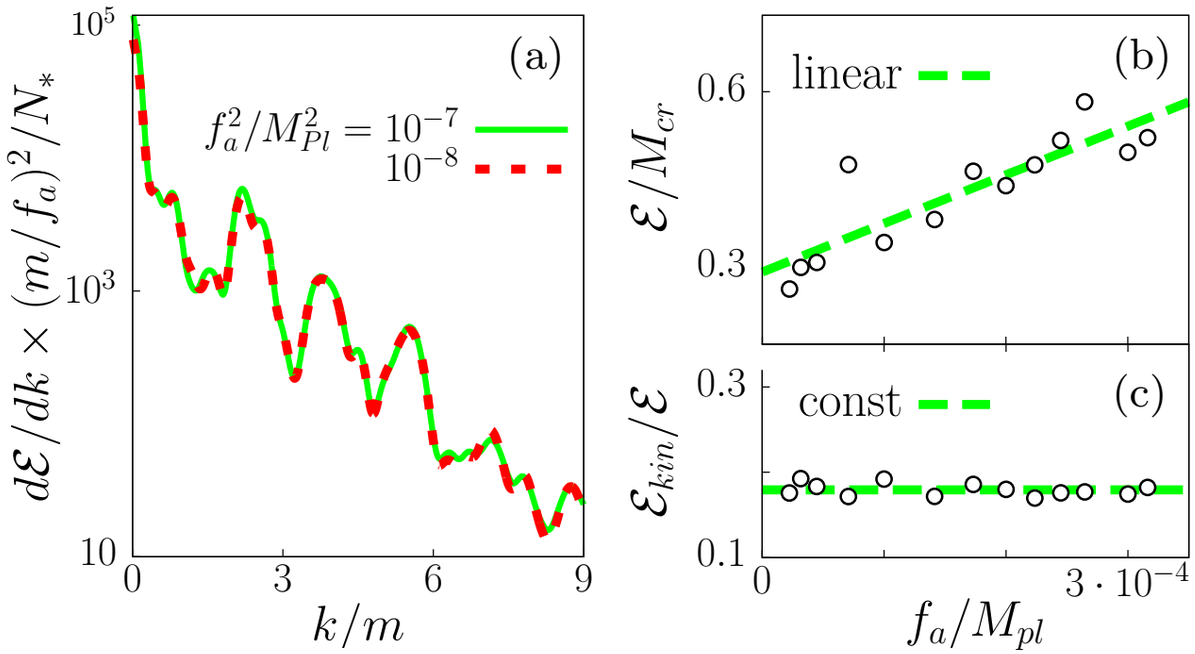


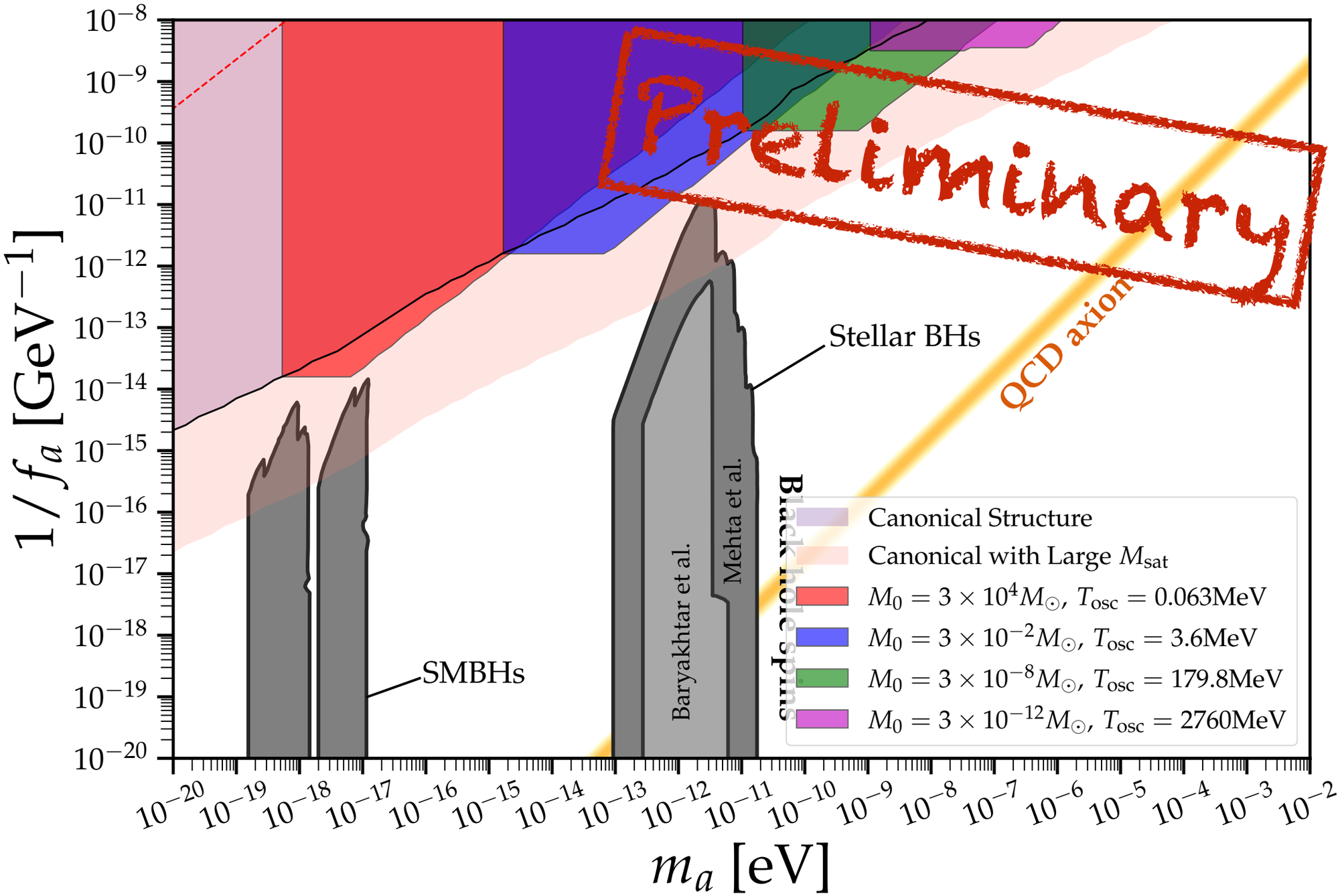

[Levkov, Panin, Tkachev]



# “Recurrent axinova” ~ late decaying dark matter

[PF, Weiner, Xiao]



# No Conclusions...yet

DM exists!  We need to find and measure it

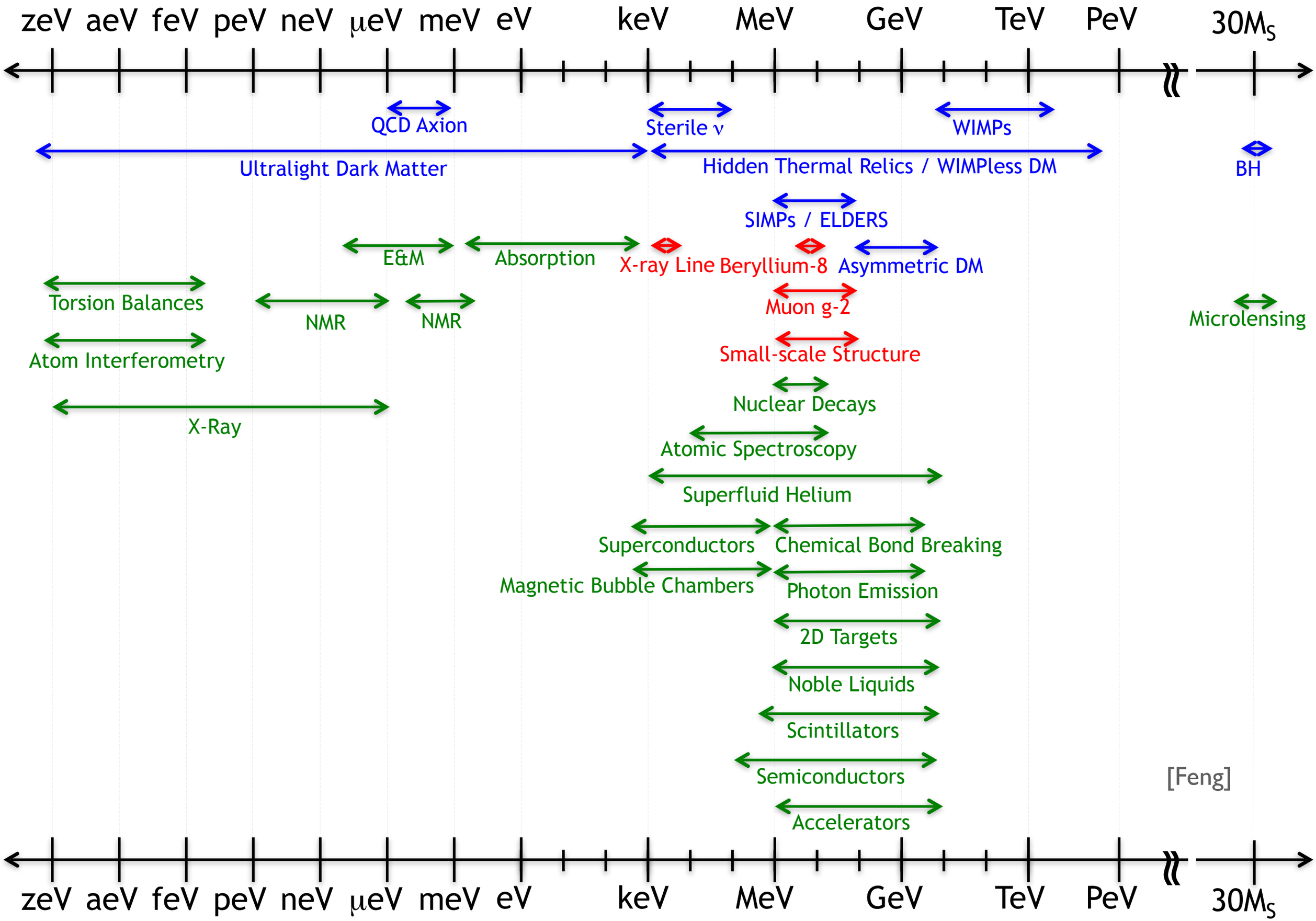
DM is *probably* not your advisors model

Dark matter may sit in a larger dark sector
(why does SM get to have all the fun?)

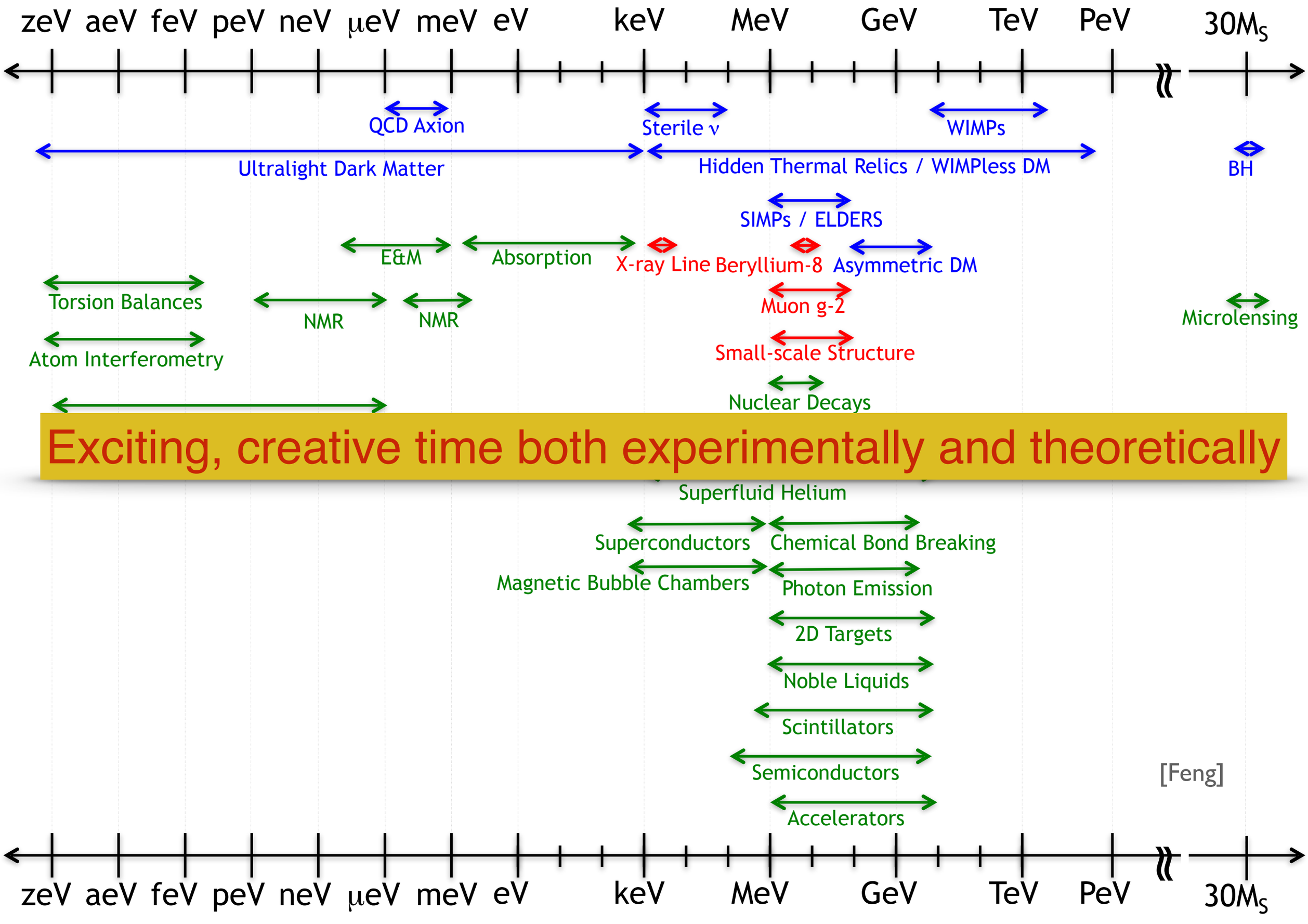
Finding it requires all the tools we have — TH and EXP

*"Stupidity is coming to a conclusion"*

# Dark Sector Candidates, Anomalies, and Search Techniques



# Dark Sector Candidates, Anomalies, and Search Techniques




Thank you