UC SANTA CRUZ

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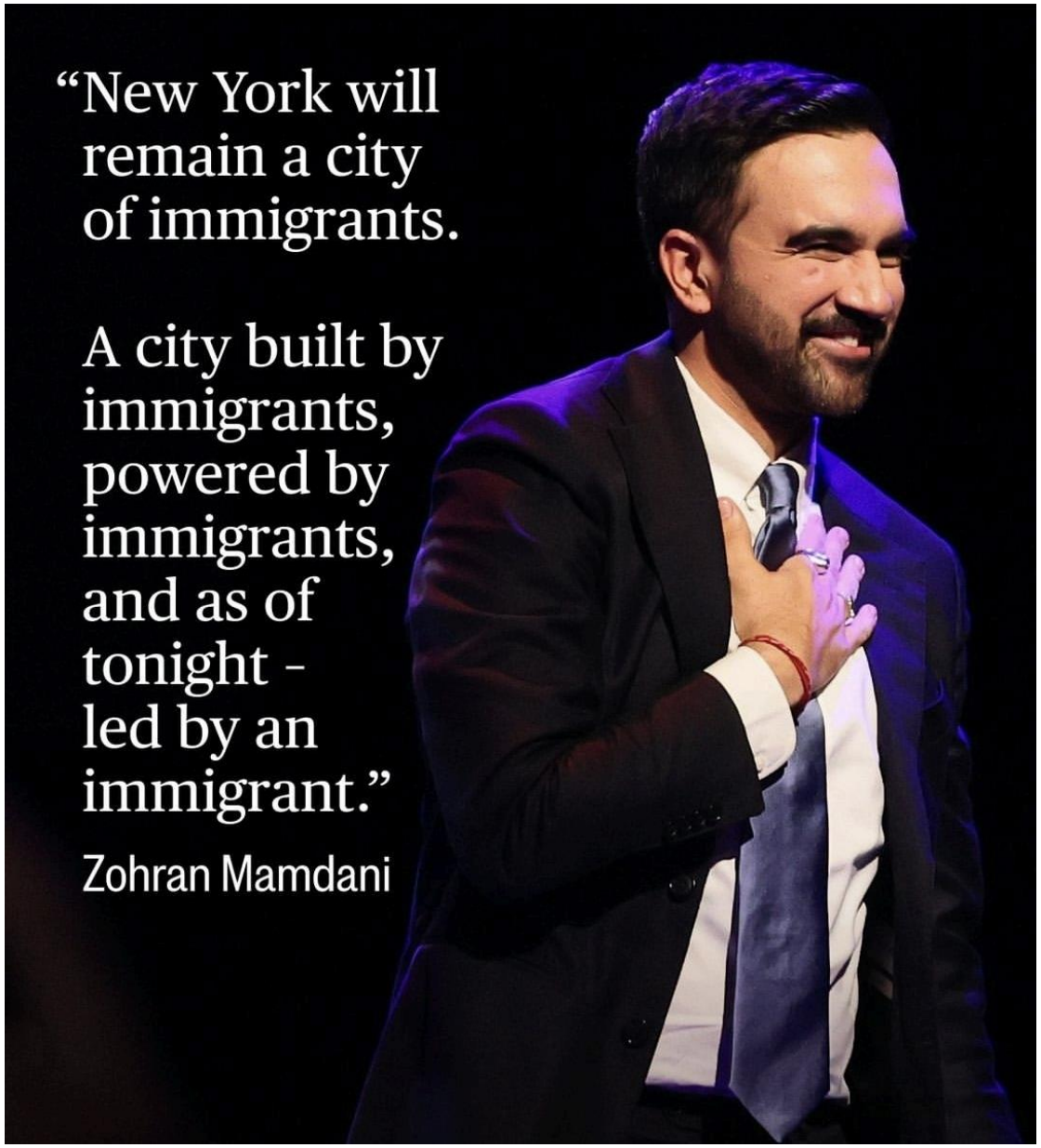
Dark Energy and Dark Matter

Lecture 3

XXVII Special Courses at the Observatório Nacional – Rio de Janeiro, Brazil



"So, if there is any way to terrify a despot, it is by dismantling the very conditions that allowed him to accumulate power. This is not only how we stop Trump, it's how we stop the next one. So, Donald Trump, since I know you're watching, I have four words for you: Turn The Volume Up"

Zohran Mamdani, elected Major of New York

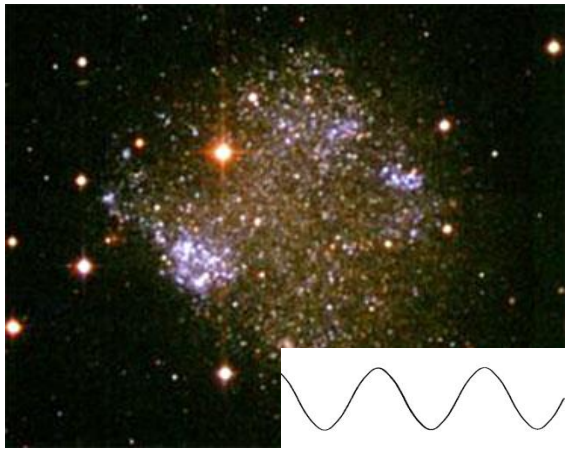
- ***34 year old***
- ***Muslim***

…in the last episode:

- **Cold Relics:** abundance ~ inverse cross section
- **WIMP** miracle
- **Evidences** for **Cold** Dark Matter
- Dark Matter and the **growth of structure**
- Why **modified gravity** doesn't work
- **Smallest** dark matter mass: **quantum mechanics**
- **Largest** dark matter mass: **tidal effects**

10^{-58} kg

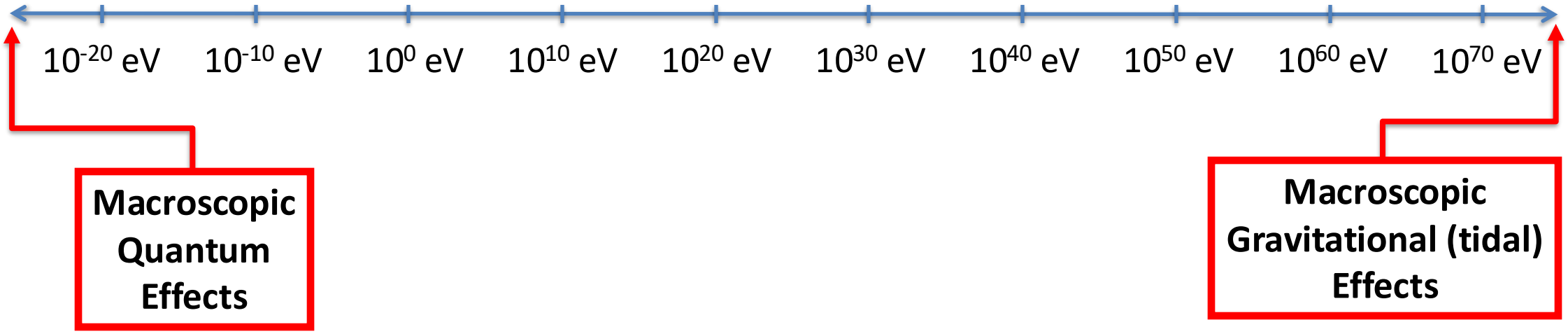
10^{30} times lighter than a proton

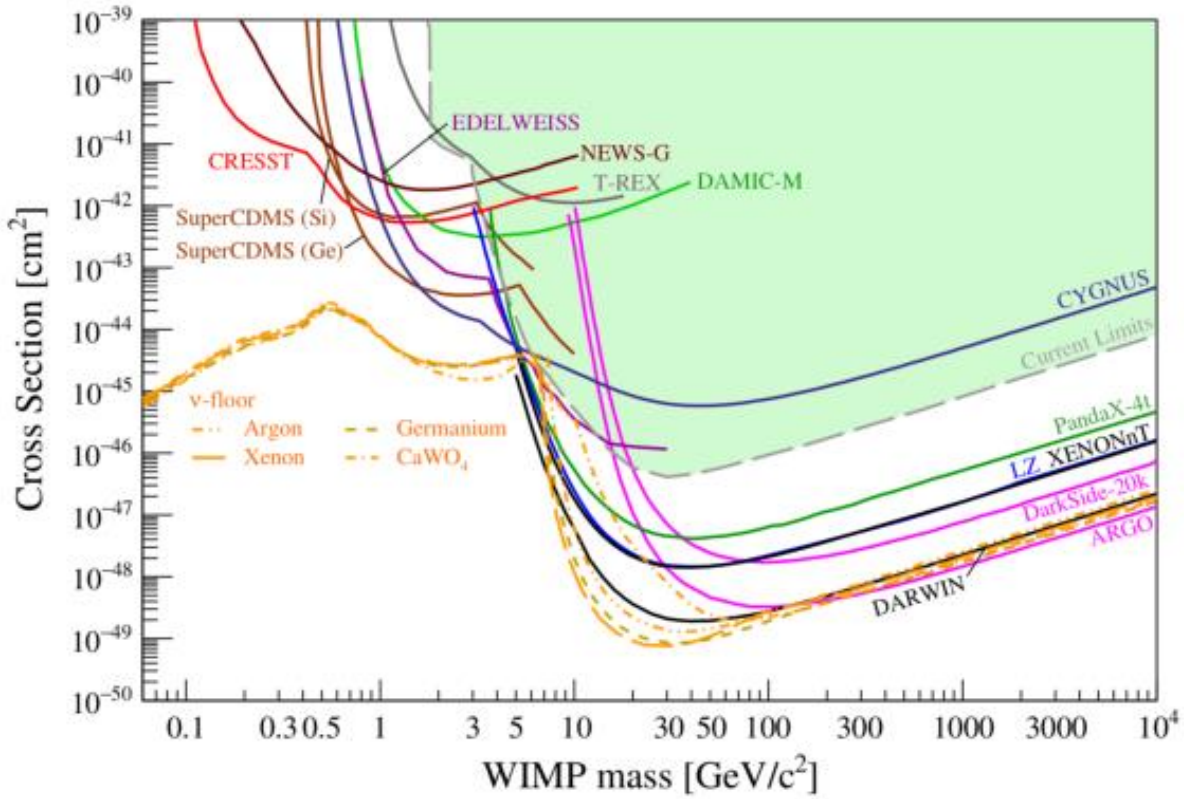


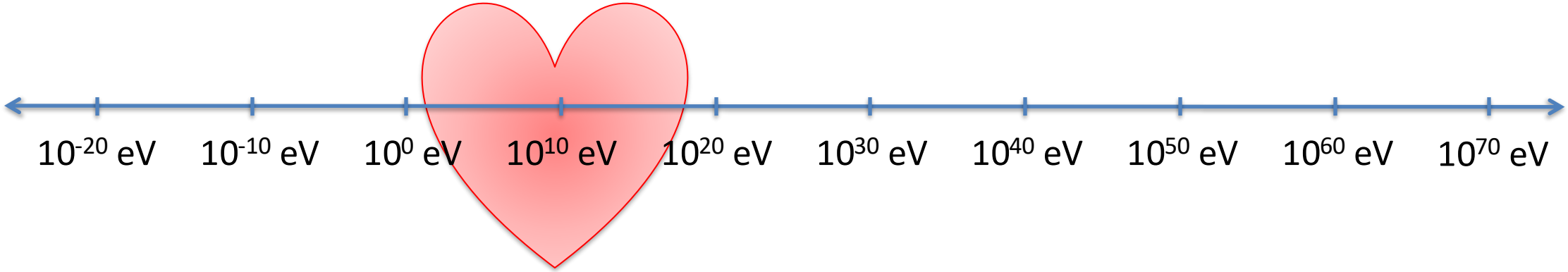
10^{34} kg

10^{3} times heavier than the Sun

[total number of protons in the universe ~10^{82} (Eddington number)]

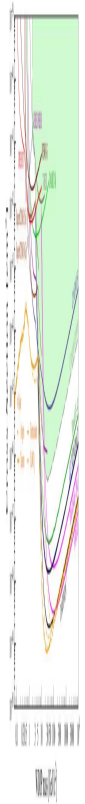


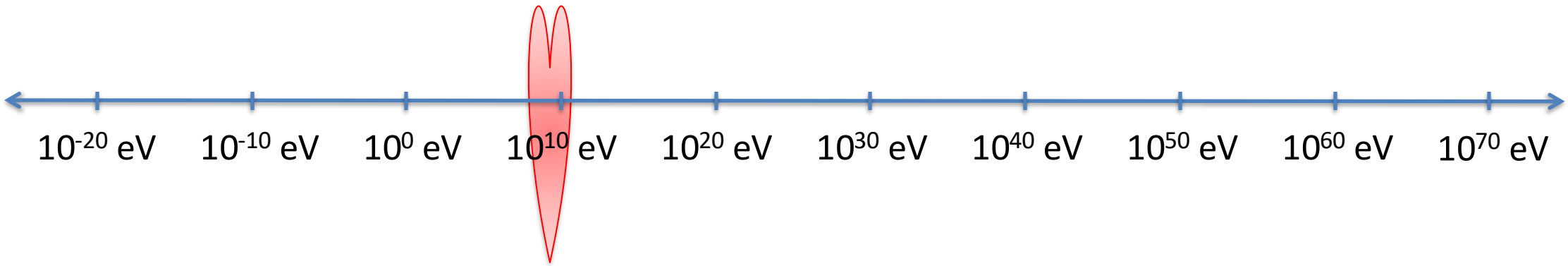




Electroweak scale

Theorists must keep an open attitude, and observers / **experimentalists** must cast a very **wide net**!





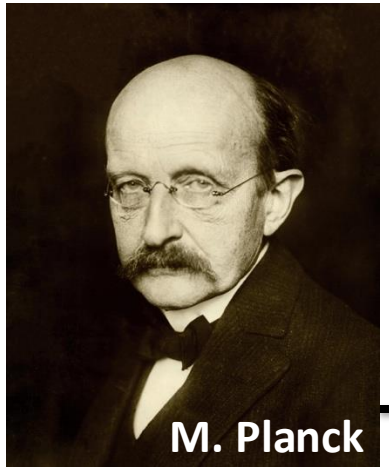
$$G = \frac{hc}{2\pi M_{\rm Pl}^2}$$

$$R_s = \frac{2Gm}{c^2}$$

Schwarzschild radius

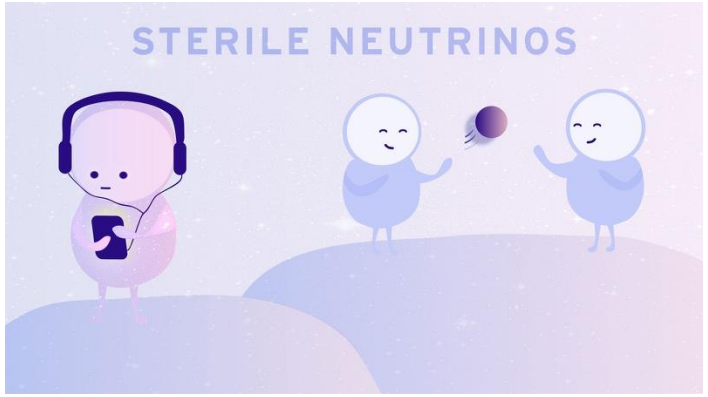
$$\lambda = \frac{h}{mc}$$

Compton wavelength



$$R_s(M_{\rm Pl}) = \frac{2hcM_{\rm Pl}}{2\pi c^2 M_{\rm Pl}^2} = \frac{h}{\pi M_{\rm Pl} c} \sim \lambda(M_{\rm Pl})$$

10^{-20} eV 10^{-10} eV 10^{0} eV 10^{10} eV 10^{20} eV 10^{30} eV 10^{40} eV 10^{50} eV 10^{60} eV 10^{70} eV



Axions
ALPs

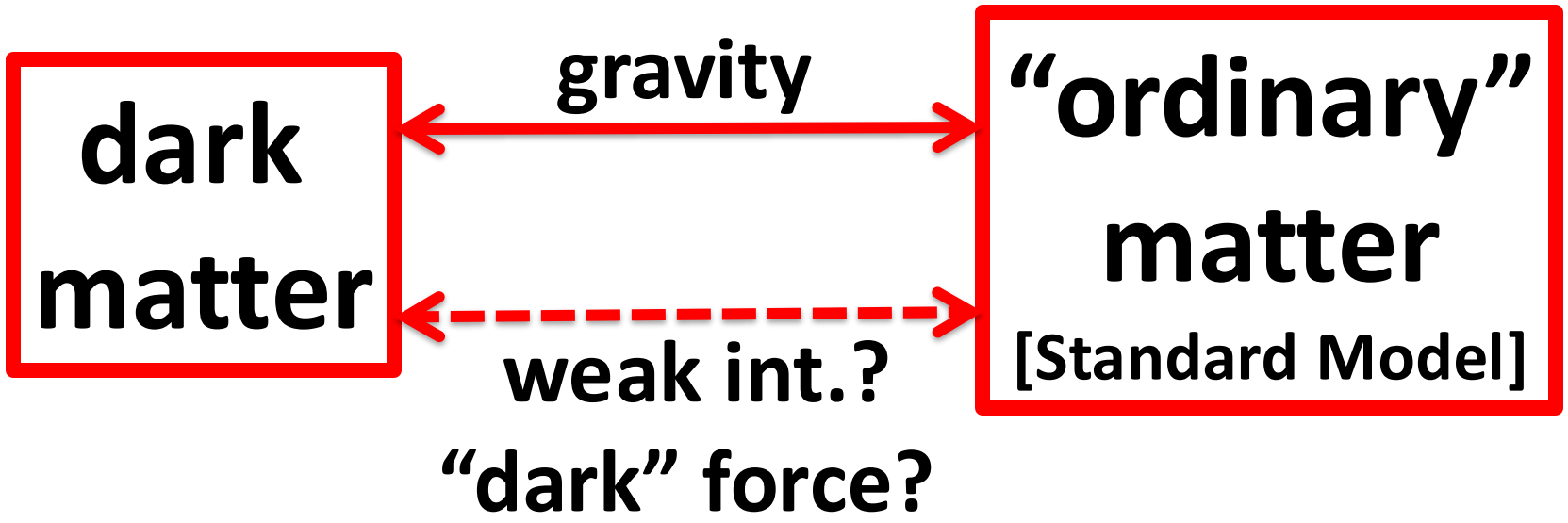
Sterile
Neutrinos

10^{-20} eV 10^{-10} eV 10^{0} eV 10^{20} eV 10^{30} eV 10^{40} eV 10^{50} eV 10^{60} eV 10^{70} eV

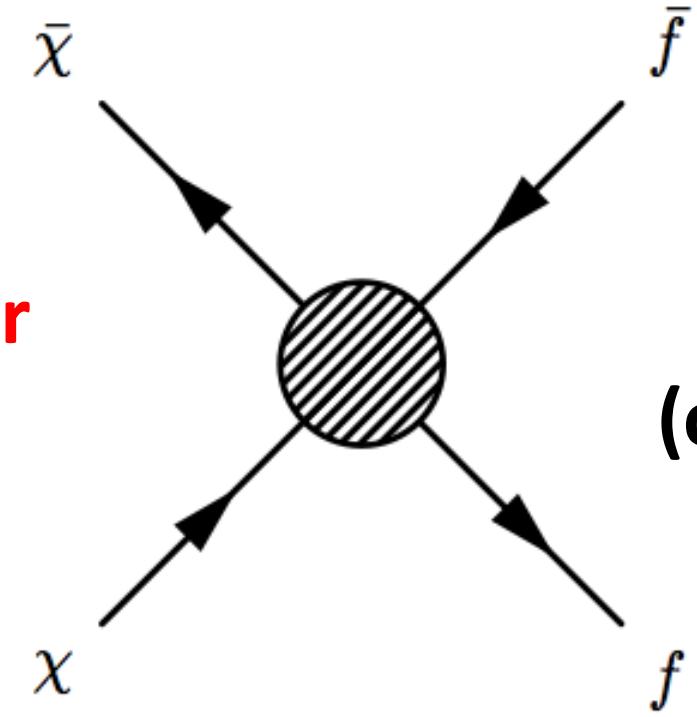
WIMPs

(primordial) black holes

WIMPs

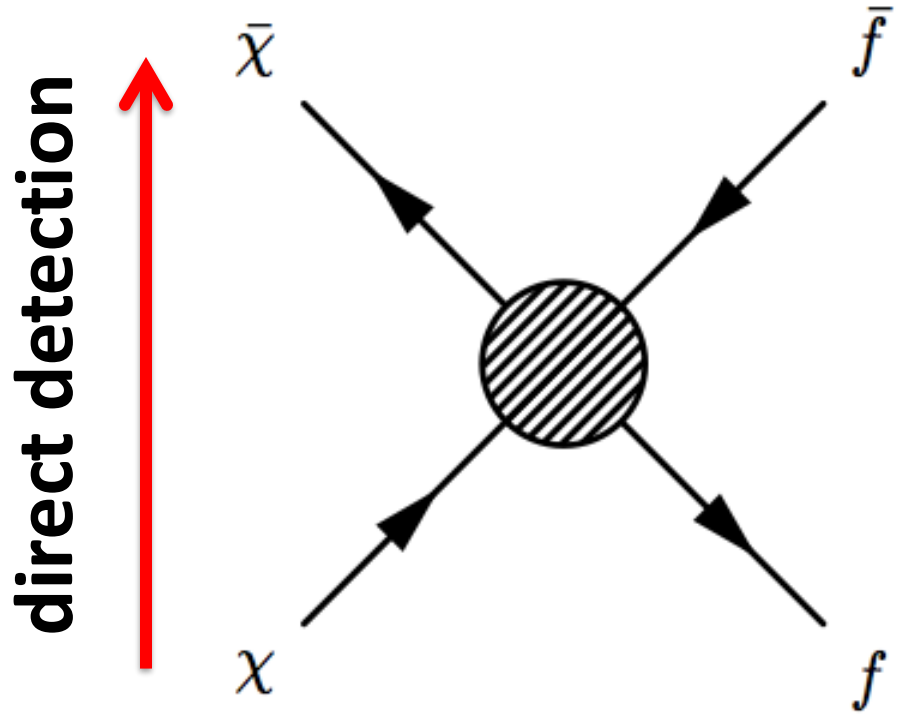

dark matter
gravity
weak int.?
"dark" force?
"ordinary" matter
[Standard Model]

Dark Matter
Particles



Standard Model
(ordinary) Particles

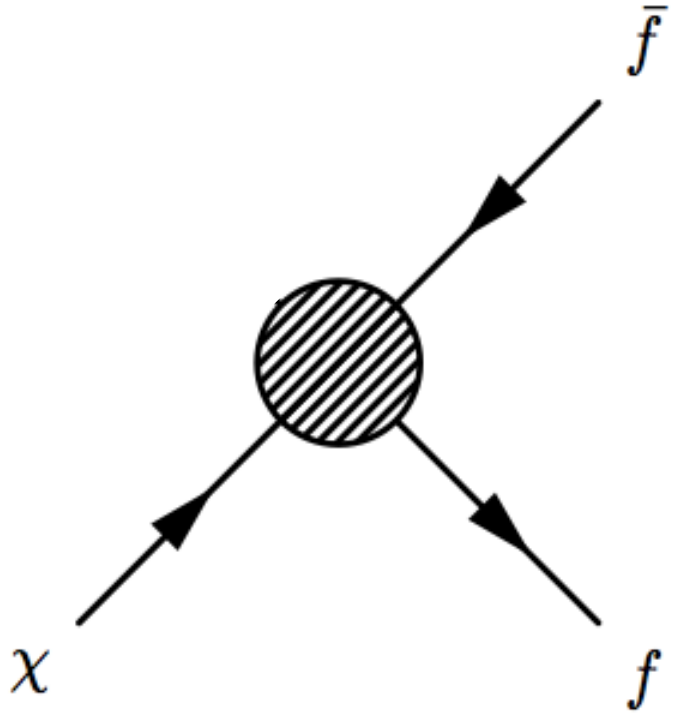
collider production



direct detection

thermal equilibrium ?

[pair annihilation]



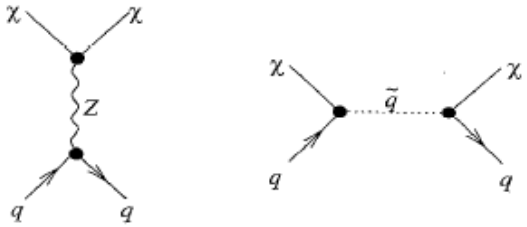
long-lived, but metastable

Given a **microscopic** theory of dark matter,

how does one get to the **DM-nucleus cross section**?

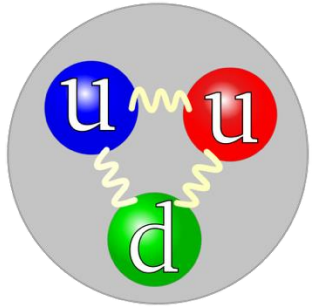
An interesting **multi-layered** problem in **effective field theory**!

(1) Low-energy EFT **Dark Matter-quark**



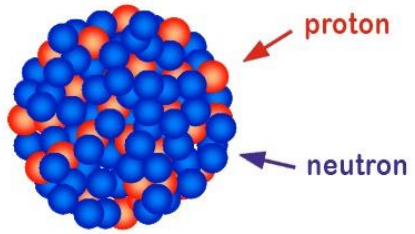
(2) Nucleon matrix elements

Dark Matter-nucleon



(3) Form factors

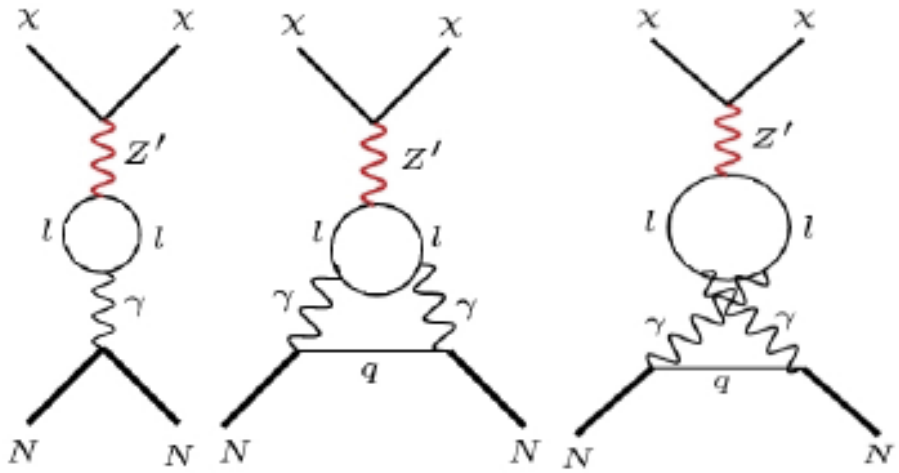
Dark Matter-nucleus

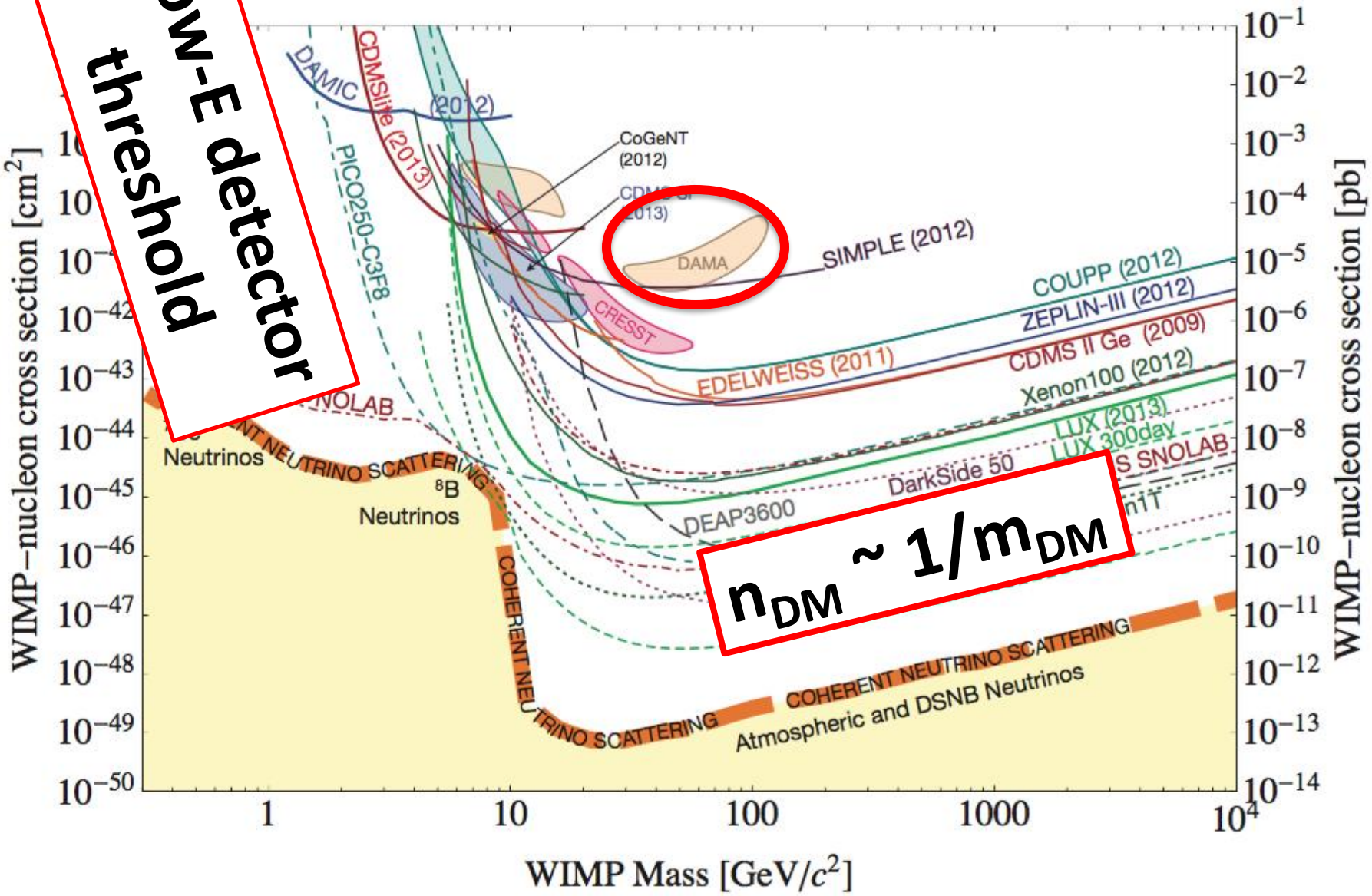


Sometimes life is simpler, e.g. if DM is (**milli**-electric-)**charged**

$$\sigma_N = \frac{16\pi\alpha^2\varepsilon^2 Z^2 \mu_N^2}{q^4}$$

Sometimes life is nastier, e.g. if DM is **lepto-philic**




Low-E detector threshold
WIMP–nucleon cross section [cm^2]
WIMP–nucleon cross section [pb]
WIMP Mass [GeV/c^2]
DAMIC
CDMSlite (2013)
(2012)
PICO250-C3F8
CoGeNT (2012)
DAMA
SIMPLE (2012)
CRESST
EDELWEISS (2011)
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
Xenon100 (2012)
LUX (2013)
LUX 300day
DarkSide 50
DEAP3600
SNOLAB
Neutrinos
^{8}B
Neutrinos
COHERENT NEUTRINO SCATTERING
COHERENT NEUTRINO SCATTERING
Atmospheric and DSNB Neutrinos
$n_{DM} \sim 1/m_{DM}$

Now off to **indirect** dark matter detection

Idea: use the **debris** of DM **pair-annihilation**
(likely large if thermal relic) or **decay**

$$\Gamma_{\mathrm{SM,\ ann}} \sim \left(\int_V \frac{\rho_{\mathrm{DM}}^2}{m_\chi^2} \mathrm{d}V\right) \times (\sigma v) \times (N_{\mathrm{SM,\ ann}}),$$

What do we know about these **rates**?

σv from **thermal production**

Annihilation (or decay) of DM can be **detected**
or **constrained** in a variety of ways

Here's one possible **classification**:

1. **Very Indirect**: effects on **astrophysical objects** or on **cosmology**

2. **Pretty Indirect**: probes that don't "trace back": **charged cosmic rays**

3. **Not-so-indirect**: **neutrinos** and **gamma rays** (travel in ~ **straight lines**)

Very indirect probes include e.g.

- **Solar Physics** (dark matter can affect the Sun's core temperature, the sound speed inside the Sun,...)
- **Neutron Star Capture**, possibly leading to the formation of black holes (notably e.g. in the context of asymmetric dark matter)
- **Supernova** and **Star** cooling
- **Protostars** (e.g. WIMP-fueled population-III stars)
- **Planets warming**
- **Big Bang Nucleosynthesis**, on the **cosmic microwave background**, on **reionization**, on **structure formation**…

Pretty Indirect Probes: **charged cosmic rays**

Good idea is to use **rare** cosmic rays, such as **anti-matter**

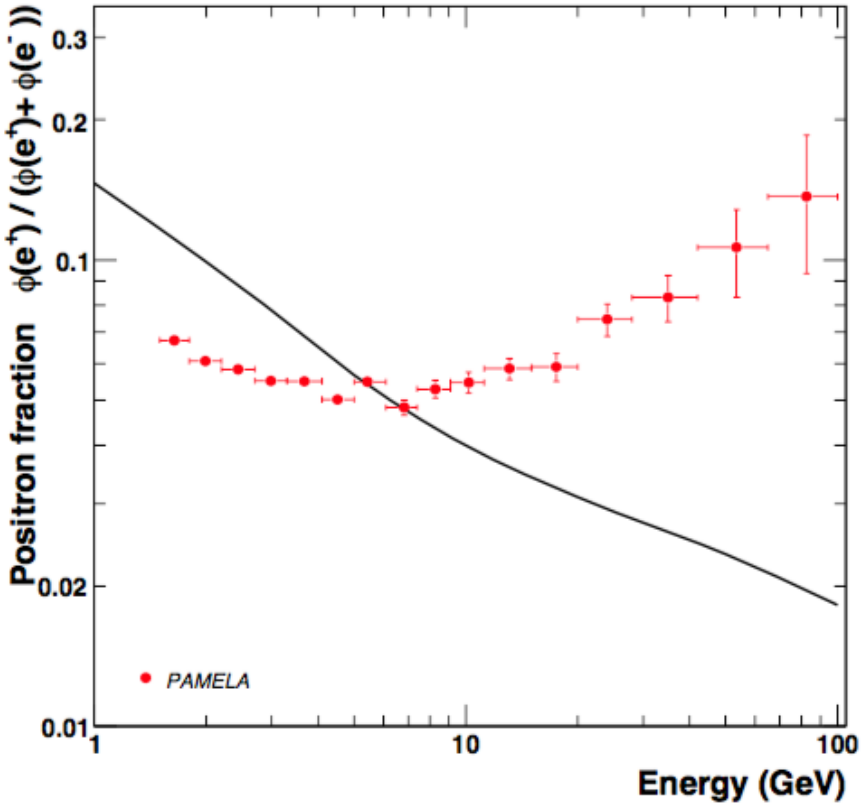
antiprotons, **positrons** relatively abundant
(mostly from inelastic processes CR p on ISM p)

Interesting probe: **antideuterons** (or even **anti-^{3}He** !!)

$$\bar{D}: \quad p + p \to p + p + \bar{p} + p + \bar{n} + n$$

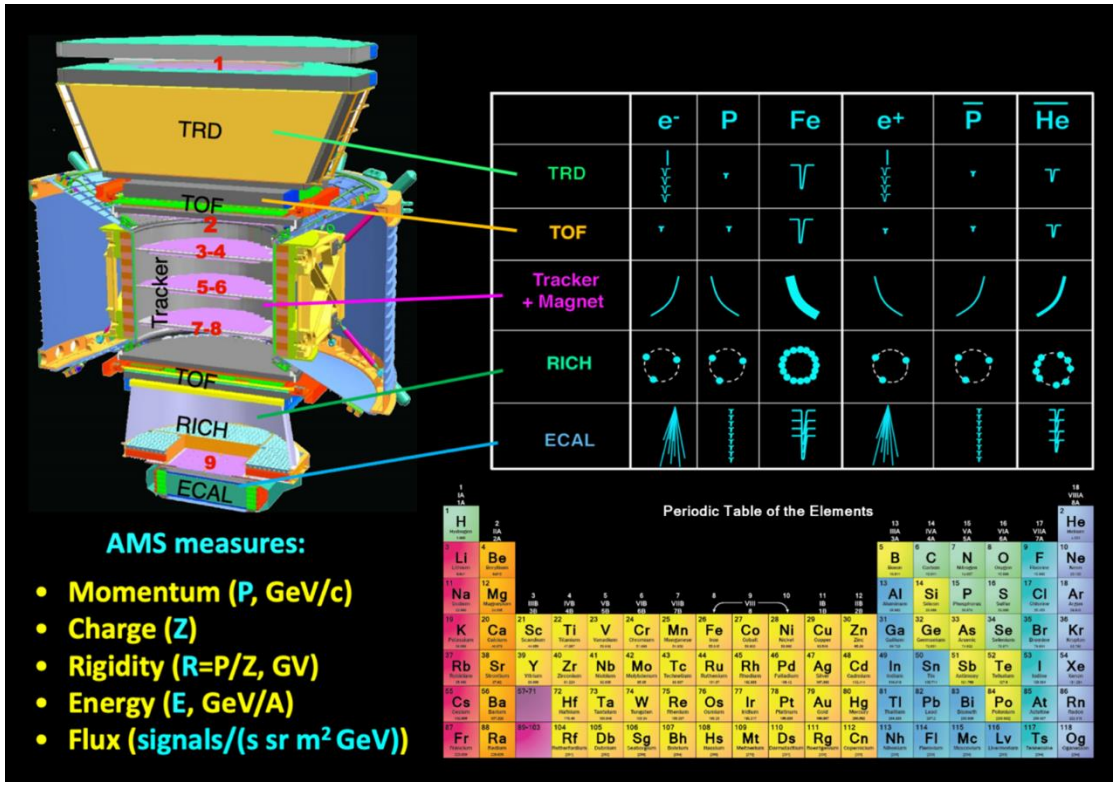
large energy **threshold** (~17 GeV), so typically large momentum, while from DM produced at very low momentum! Select **low-energy antideuterons**

positrons (and in part antiprotons) have attracted attention because of "**anomalies**" reported by PAMELA, AMS-02, DAMPE



Very problematic to explain with **dark matter** annihilation
Local **Pulsar** magnetosphere is a natural explanation

Excess of anti-^{3}He?



- …unclear if **antiprotons** can be confused as 3He
- Very suspicious that **no antideuterons** have been detected
- Also very suspicious that **no clear antiproton signal** was detected

Not-so-indirect DM detection: **neutrinos**!

Hard (but not impossible) to detect particles

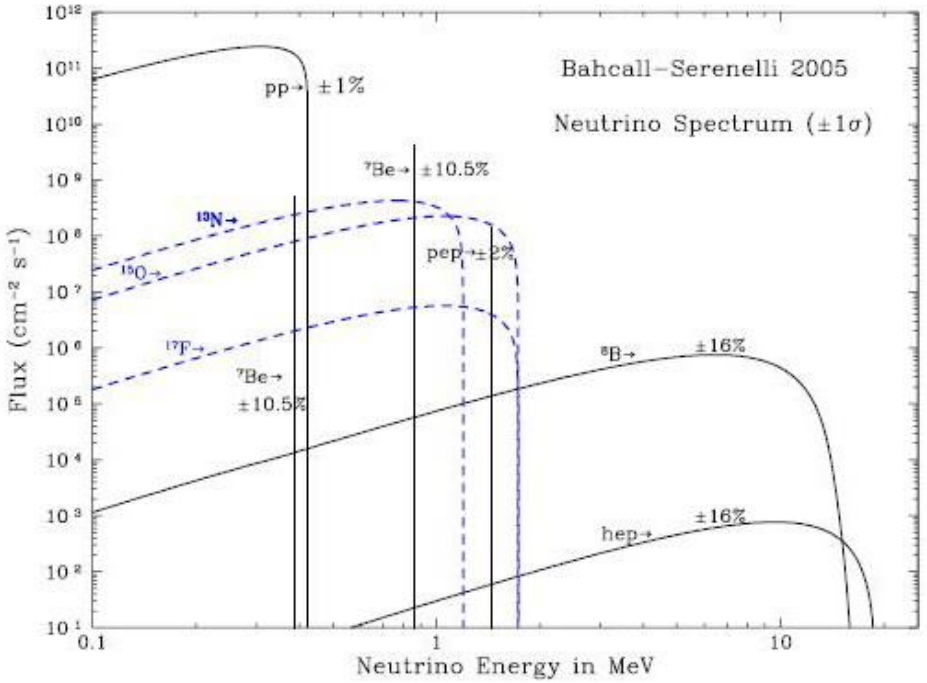
flip side: neutrinos have very **long mean free paths** in matter!

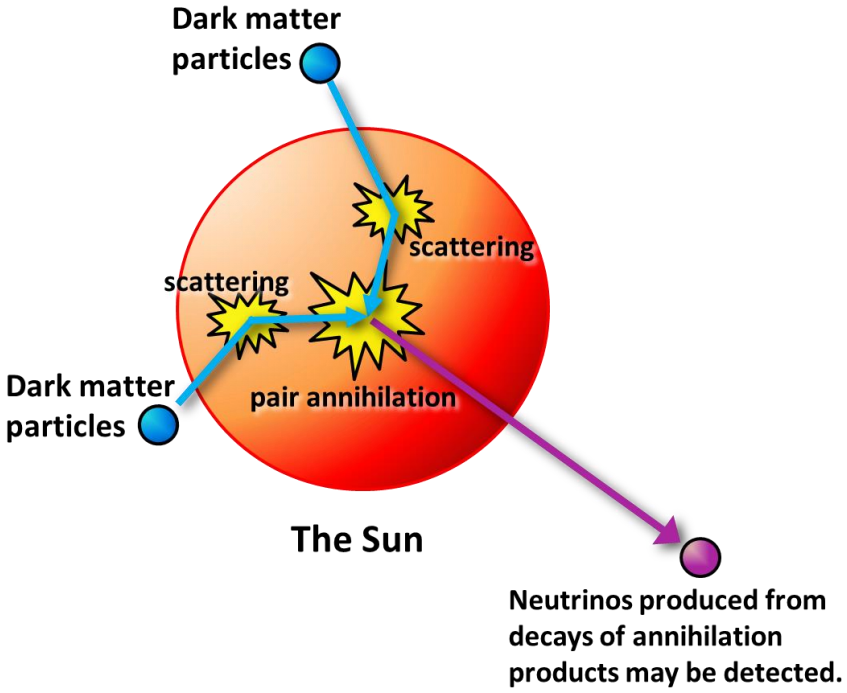
idea: DM can be **captured** in celestial bodies, **accrete** in sizable densities, start pair-annihilating

if the process of capture and annihilation is in **equilibrium**, large **fluxes** of neutrino can escape

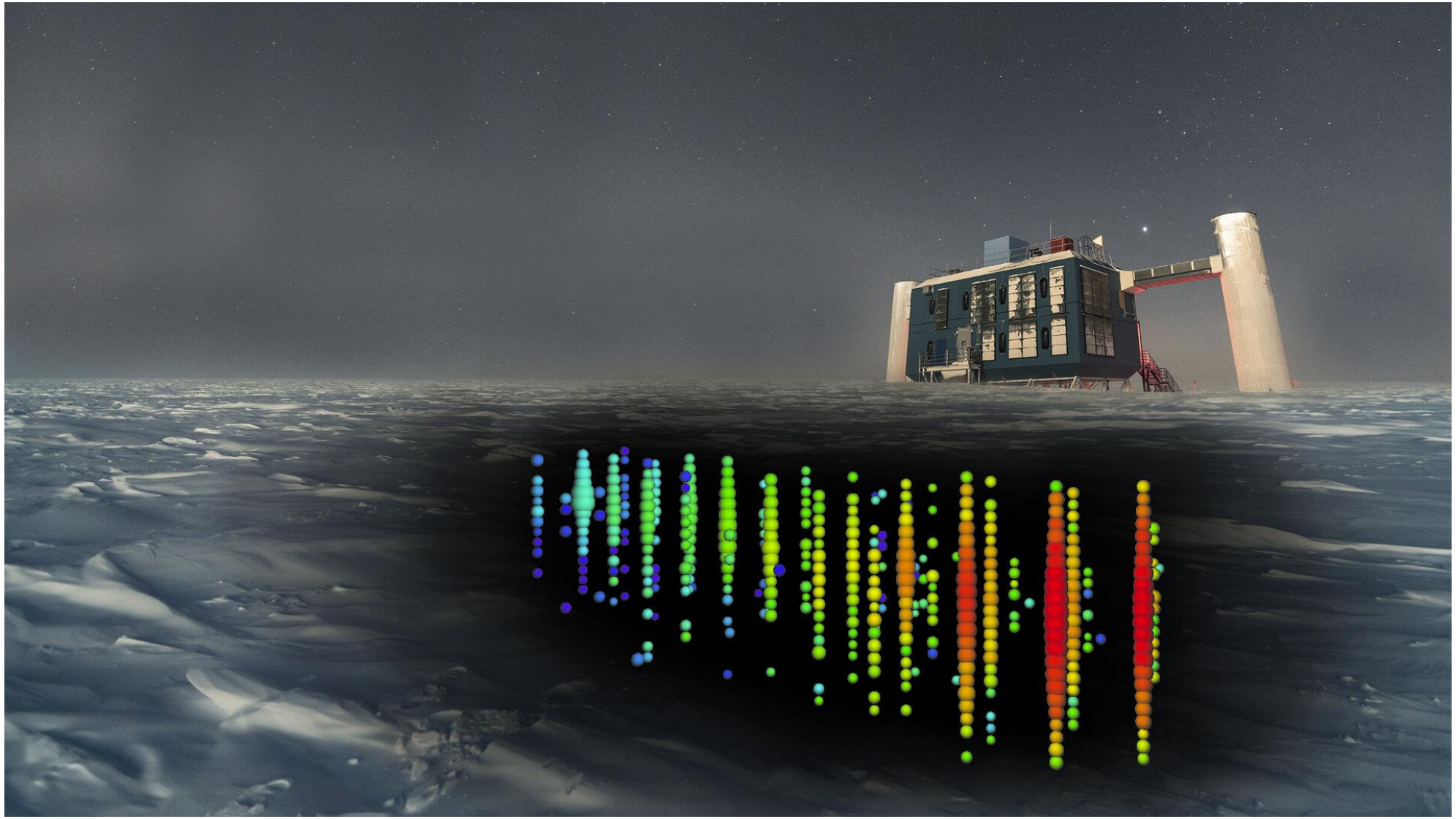
Not-so-indirect DM detection: **neutrinos**!

best target: **Sun**! Large, **nearby**, **low-E** neutrino emission

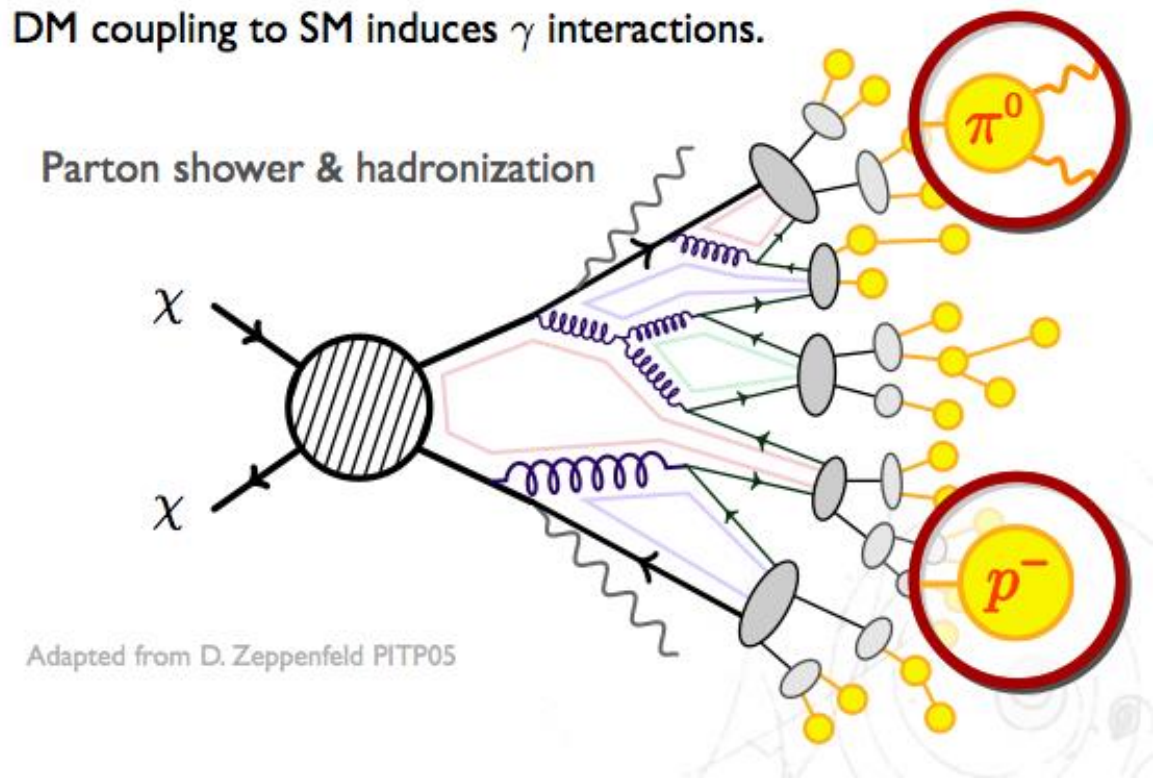




Not-so-indirect DM detection: **neutrinos**!



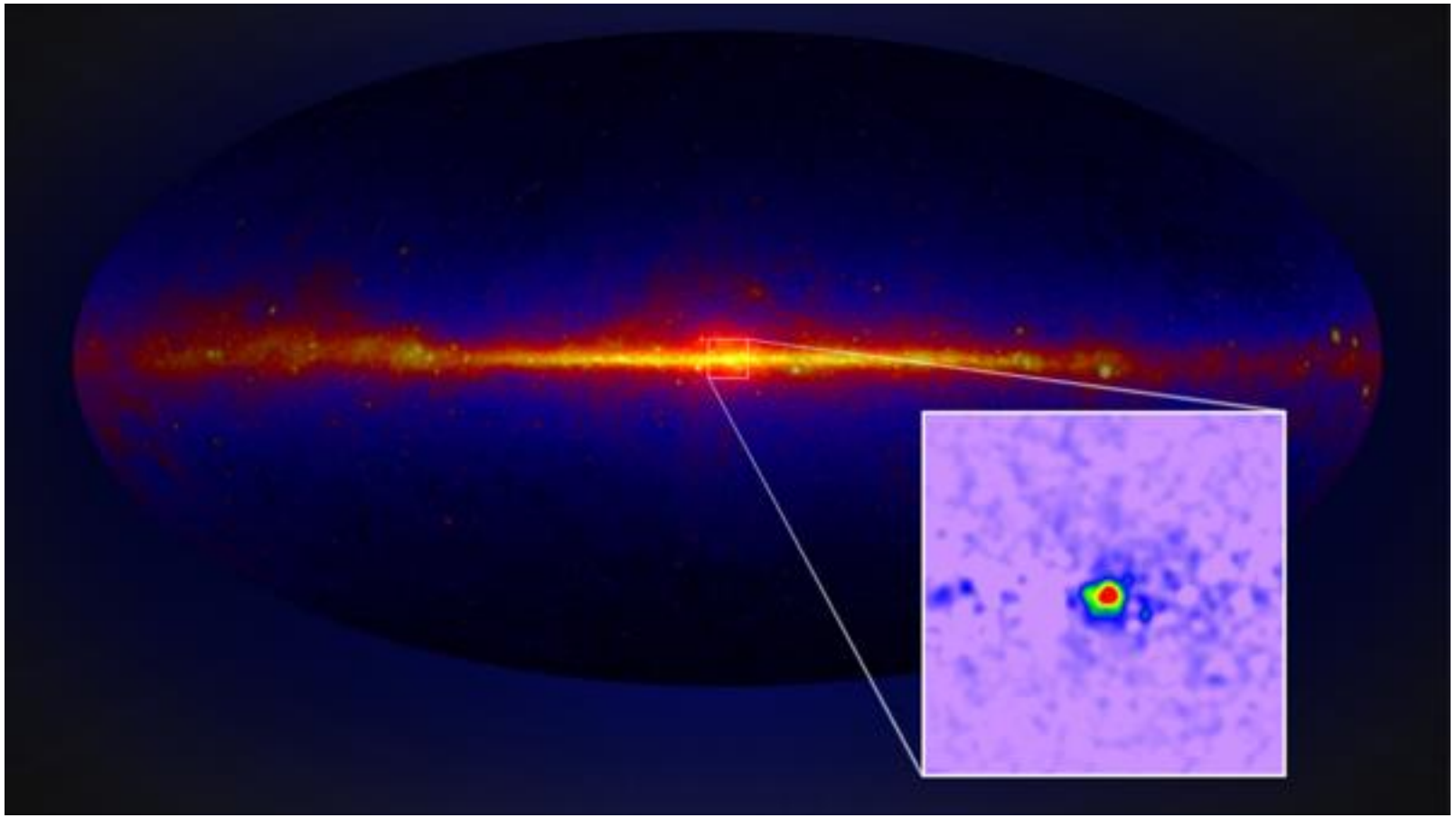
Light from **dark matter**!



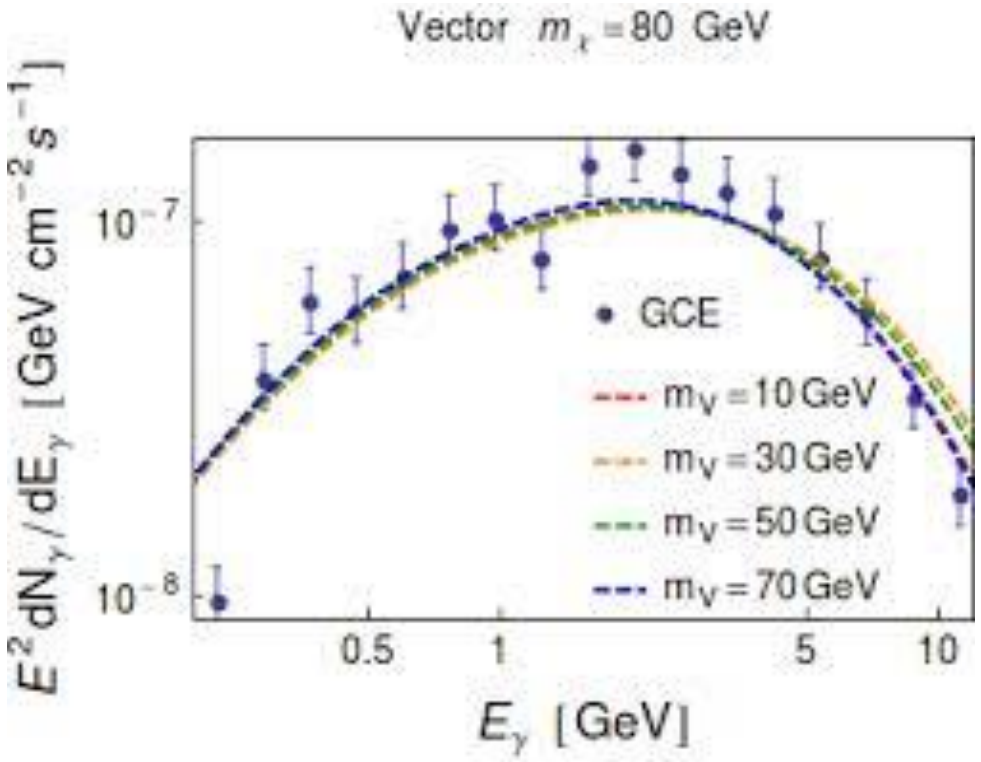
Primary photons: prompt, or internal brems; just run Pythia (if you can!)

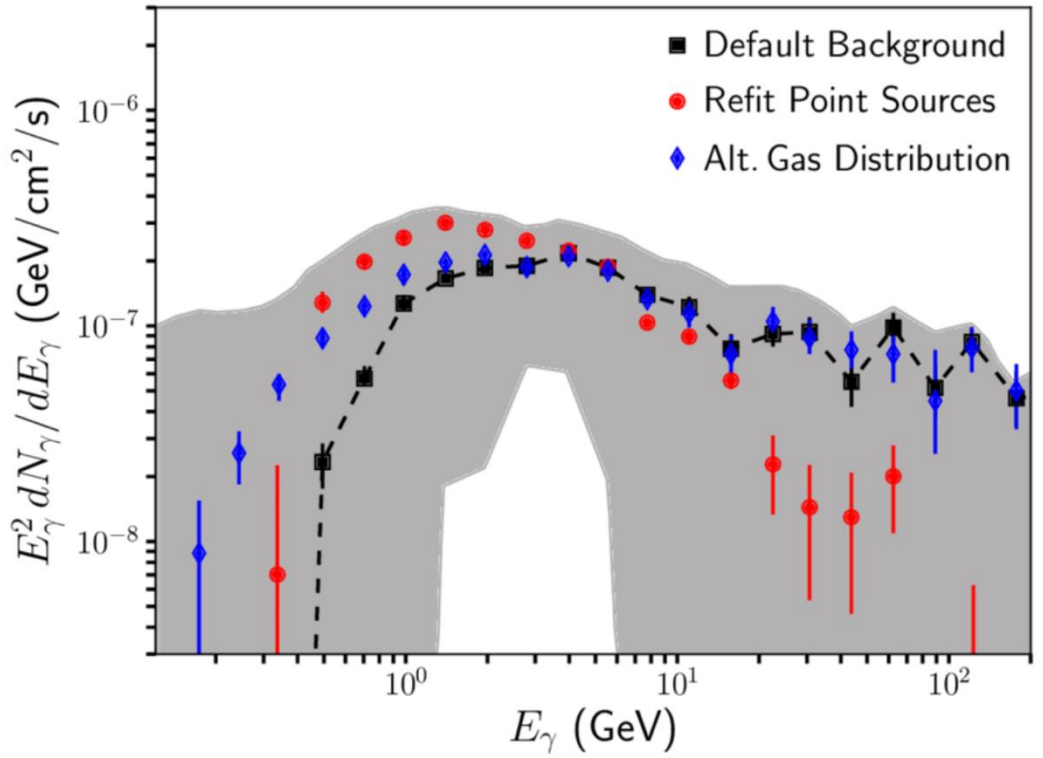
Secondary photons: Inverse Compton, synchrotron

Light from **dark matter**!

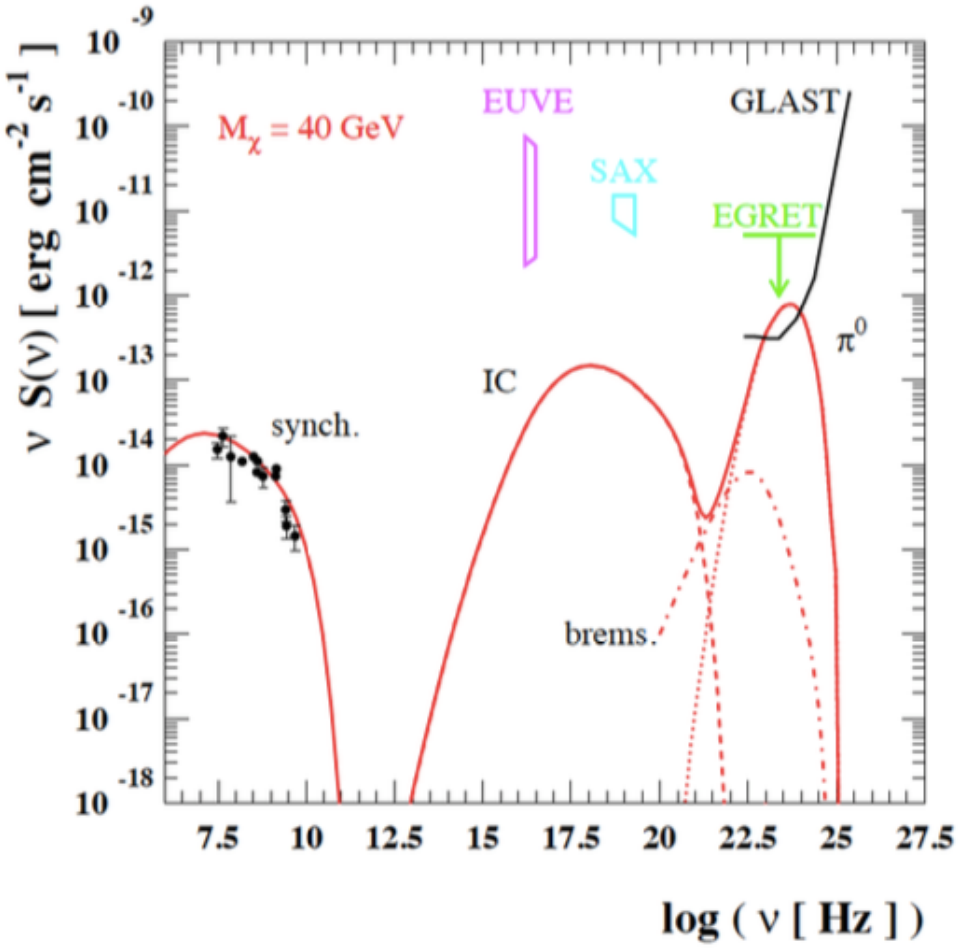


Light from **dark matter**!





Light from **dark matter**!



Overall **emission** looks like this, e.g. in a **cluster** of galaxies


AXION
EL VERDADERO ARRANCAGRASA
Antibacterial
AXION
EL VERDADERO ARRANCAGRASA
Limón
AXION
EL VERDADERO ARRANCAGRASA
BICARBONATO
AXION
EL VERDADERO ARRANCAGRASA
OXY Plus
BICARBONATO
AXION
EL VERDADERO ARRANCAGRASA
Lima

Axion and ALPs

- **Axions** were originally proposed as a solution to the **strong CP problem** in QCD (why the QCD θ-angle is so small)
- They arise as **pseudo-Nambu–Goldstone bosons** of a spontaneously broken global U(1) symmetry: the **Peccei–Quinn (PQ) symmetry**
- **Axion-like particles (ALPs)** generalize the idea to other pseudo-scalars **not necessarily tied to QCD**, often arising in string theory or other extensions of the Standard Model (SM).

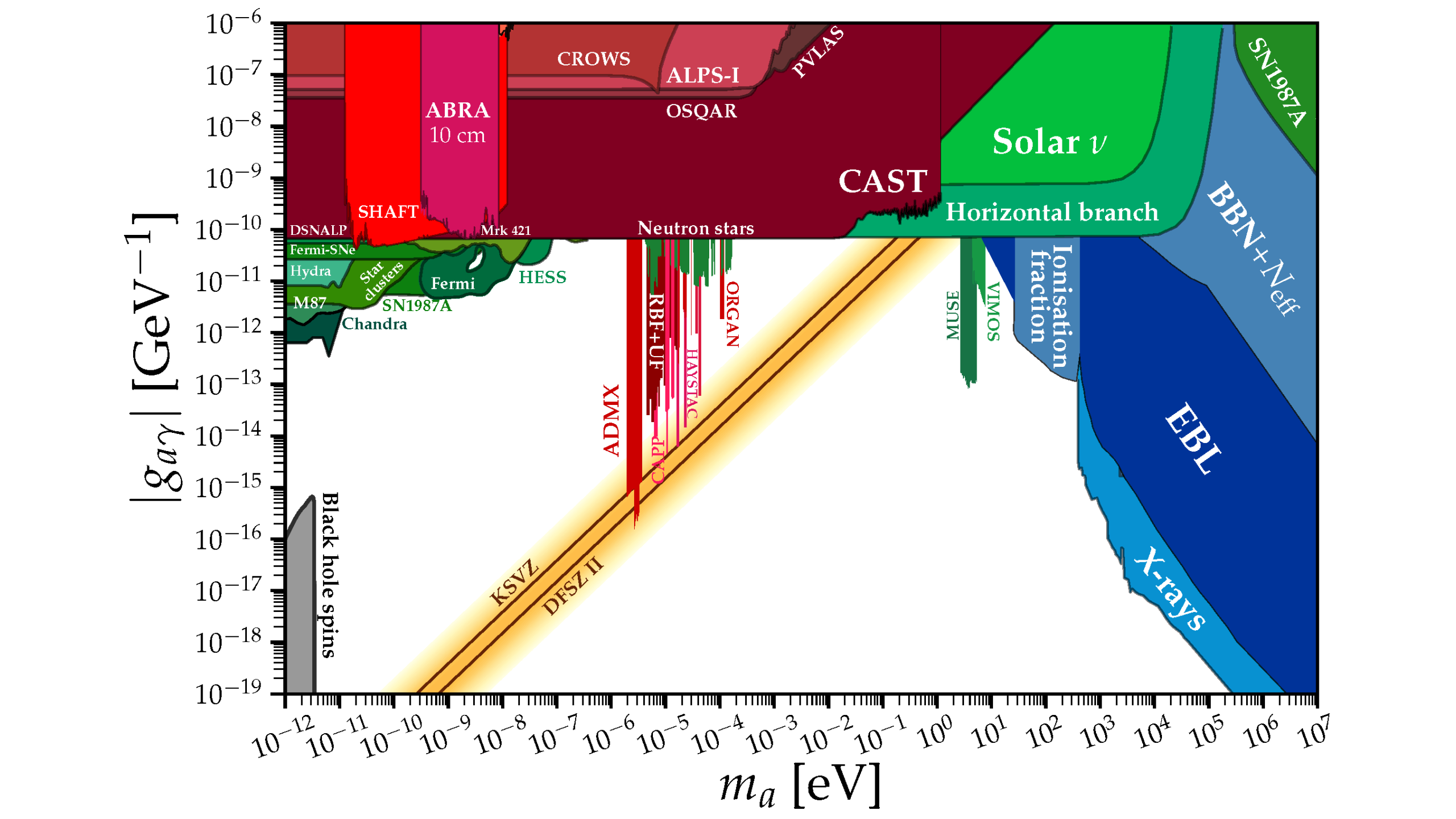
Production Mechanisms

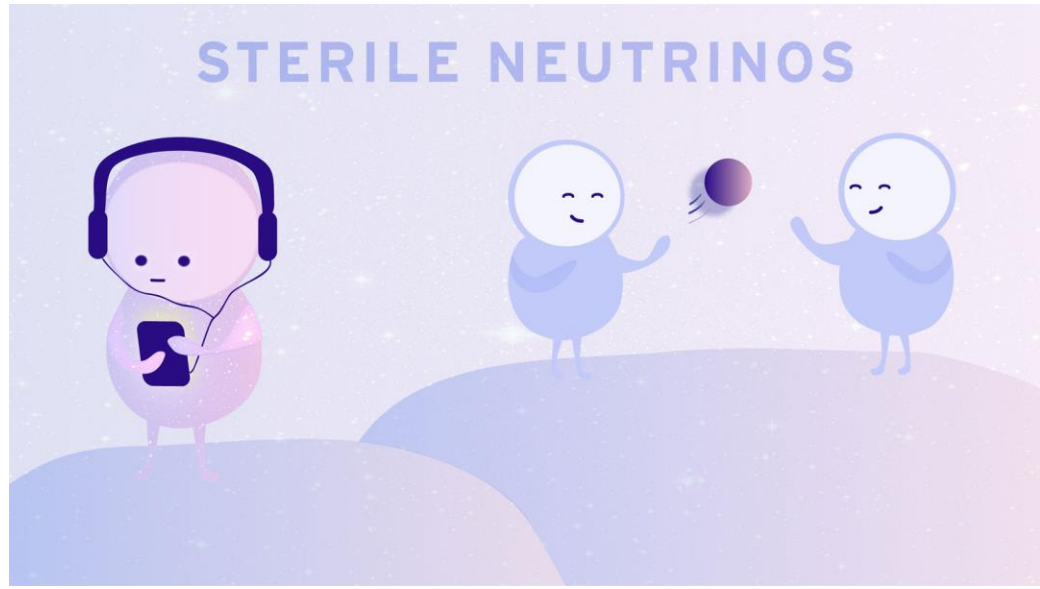
Mechanism	Description	Key Regime
Misalignment	Coherent field starts displaced from minimum; begins oscillating when $H \sim m_a$	$f_a \lesssim 10^{17}\,\mathrm{GeV}$
Topological defects	Decay of strings or domain walls	Depends on symmetry-breaking history
Thermal production	Interactions with plasma	Generally yields hot or warm DM unless decouples early

Detection Strategies

Category	Concept	Target	Sensitivity Range
Haloscopes	Axion DM converts to photons in strong magnetic field in a resonant cavity (e.g., ADMX, HAYSTAC)	Galactic axion DM	$\mu\text{eV} \sim 10^{-6}\,\text{eV}$
Broadband Haloscopes	Non-resonant or tunable systems (e.g., DMRadio, ABRACADABRA)	Lower-mass axions ($10^{-12} - 10^{-6}\,\text{eV}$)	$f_a \sim 10^{13} - 10^{17}\,\text{GeV}$
DM Radio	LC-circuit coupled to a pickup coil sensing oscillating axion-induced magnetic fields	Ultralight axions $m_a \sim 10^{-12} - 10^{-7}\,\text{eV}$	High f_a, low $g_{a\gamma\gamma}$
ABRACADABRA	Axion-induced magnetic flux in toroidal magnets	Very low-mass ALPs	$m_a \lesssim 10^{-9}\,\text{eV}$
CASPEr (NMR-based)	Axion–nucleon coupling causes time-varying spin precession	g_{aNN}, not just $g_{a\gamma\gamma}$	$10^{-22} - 10^{-7}\,\text{eV}$
Helioscopes (CAST, IAXO)	Detect solar axions via conversion in magnetic field	Solar ALPs	$g_{a\gamma\gamma} \gtrsim 10^{-11}\,\text{GeV}^{-1}$
Light-Shining-Through-Walls	Laser photons convert to ALPs in B-field, traverse wall, reconvert	Purely lab-based, model-independent	$g_{a\gamma\gamma} \lesssim 10^{-7}\,\text{GeV}^{-1}$
Atomic Interferometry / Precision Spectroscopy	Oscillating fundamental constants or forces from ALP DM	Ultralight ALPs $m_a \lesssim 10^{-15}\,\text{eV}$	Scalar/axion DM
Dielectric Haloscopes (e.g., MADMAX)	Stack of dielectric layers to enhance photon conversion	Intermediate mass axions	$m_a \sim 10^{-5} - 10^{-3}\,\text{eV}$
Astrophysical Observations	Cooling rates, SN1987A, galaxy birefringence, pulsar timing	Stellar ALPs, ultralight ALPs	Wide mass range

~ GHz


CROWS
ALPS-I
PVLAS
OSQAR
ABRA
10 cm
CAST
Solar ν
SN1987A
Horizontal branch
BBN+Neff
SHAFT
DSNALP
Mrk 421
Neutron stars
Fermi-SNe
Hydra
Star clusters
Fermi
HESS
M87
SN1987A
Chandra
RBF+UF
ORGAN
HAYSTAC
CAPP
ADMX
MUSE
VIMOS
Ionisation fraction
EBL
X-rays
Black hole spins
KSVZ
DFSZ II
$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]


STERILE NEUTRINOS

SM Neutrinos are strictly **massless**;
however, they are not observed to be!

Simplest addition: set of ***n*** singlet fermions N_a, gauge singlets

$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\bar{N}_a \partial\!\!\!/ N_a - y_{\alpha a} H^\dagger \bar{L}_\alpha N_a - \frac{M_a}{2} \bar{N}_a^c N_a$$

$$M^{(n+3)} = \begin{pmatrix} 0 & y_{\alpha a}\langle H\rangle \\ y_{\alpha a}\langle H\rangle & \mathrm{diag}(M_1, ..., M_n) \end{pmatrix}$$

Sterile neutrinos mix via explicit (but possibly very small) **mixing** with ordinary neutrinos

...as such, they **decay** (into 3 SM neutrinos)
…but to be the dark matter, they must be sufficiently **long-lived**

$$\Gamma \sim \theta^2 G_F^2 m^5 \sim \theta^2 \left(\frac{m}{\mathrm{keV}}\right)^5 \; 10^{-40}\,\mathrm{GeV} \Rightarrow \tau \sim 10^{16}\mathrm{s}\,\theta^{-2}\left(\frac{m}{\mathrm{keV}}\right)^{-5}$$

$$\theta^{-2}\left(\frac{m}{\mathrm{keV}}\right)^{-5} \gg 1$$

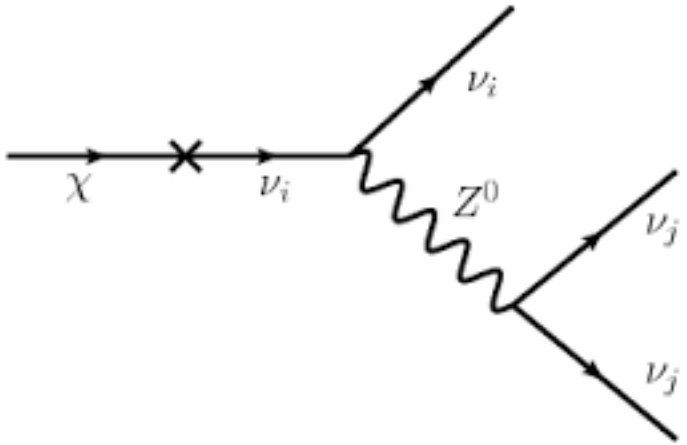
Being fermions, ***m > 30 eV*** (e.g. Tremaine-Gunn)

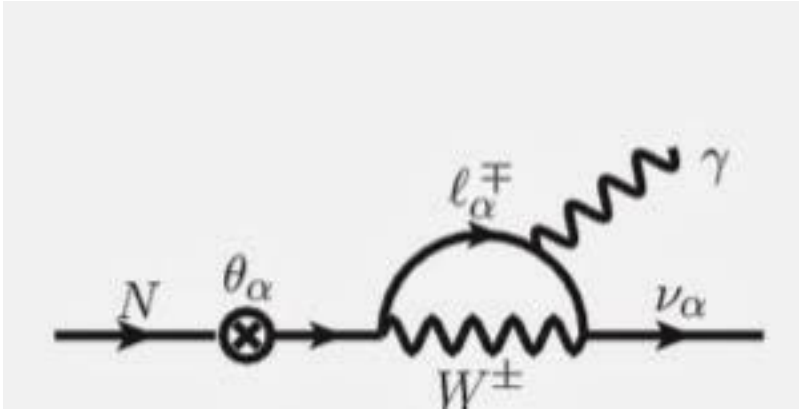
How can sterile neutrinos be **produced**?

Basically, **freeze-in**: dump out-of-equilibrium sterile ν's through the universe history

$$\Gamma_{\nu_s} \sim (G_F^2 T^5)\theta^2(T)$$

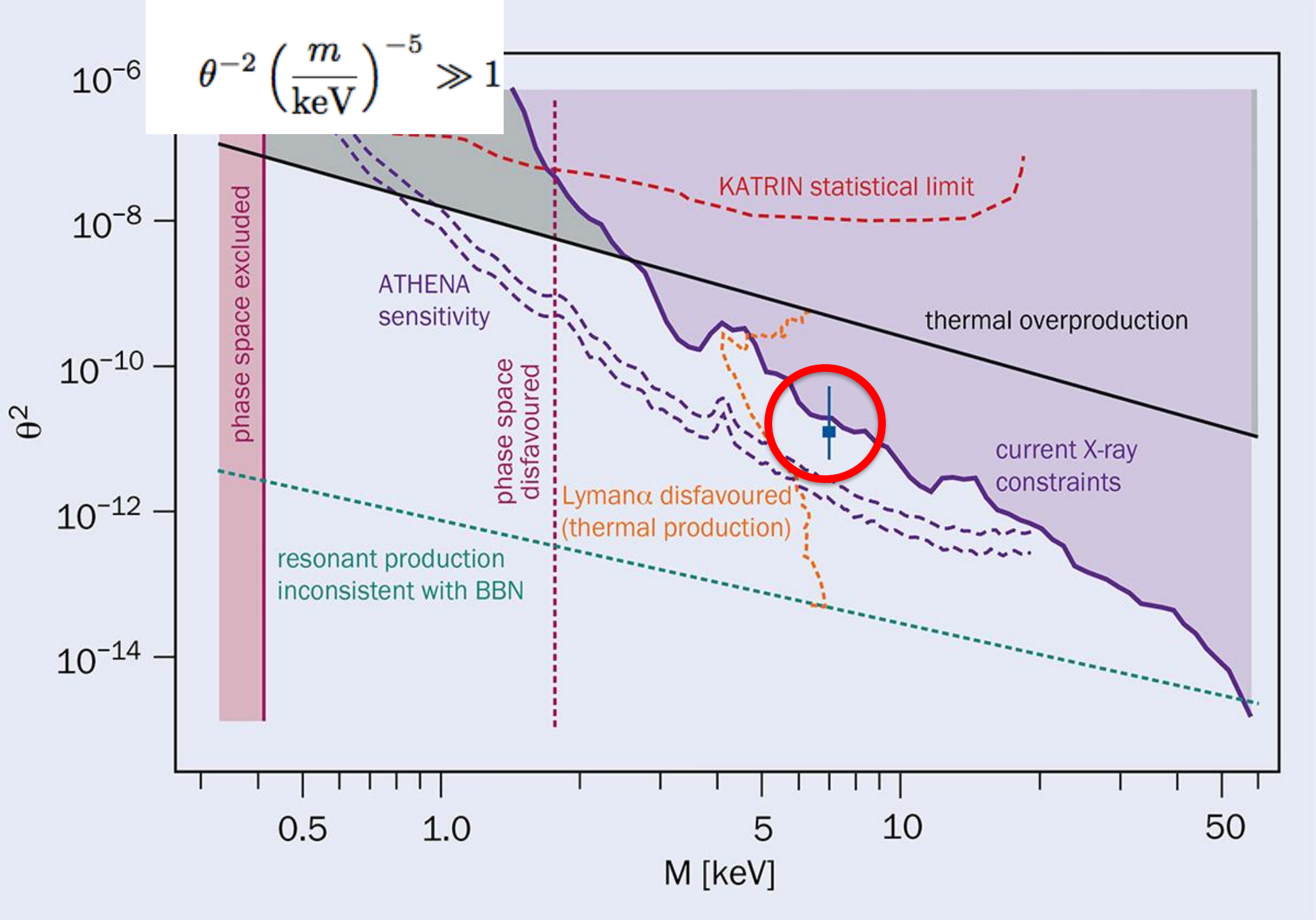
Subtlety is **matter effects**, inducing ***T*-dependence** in the mixing angle

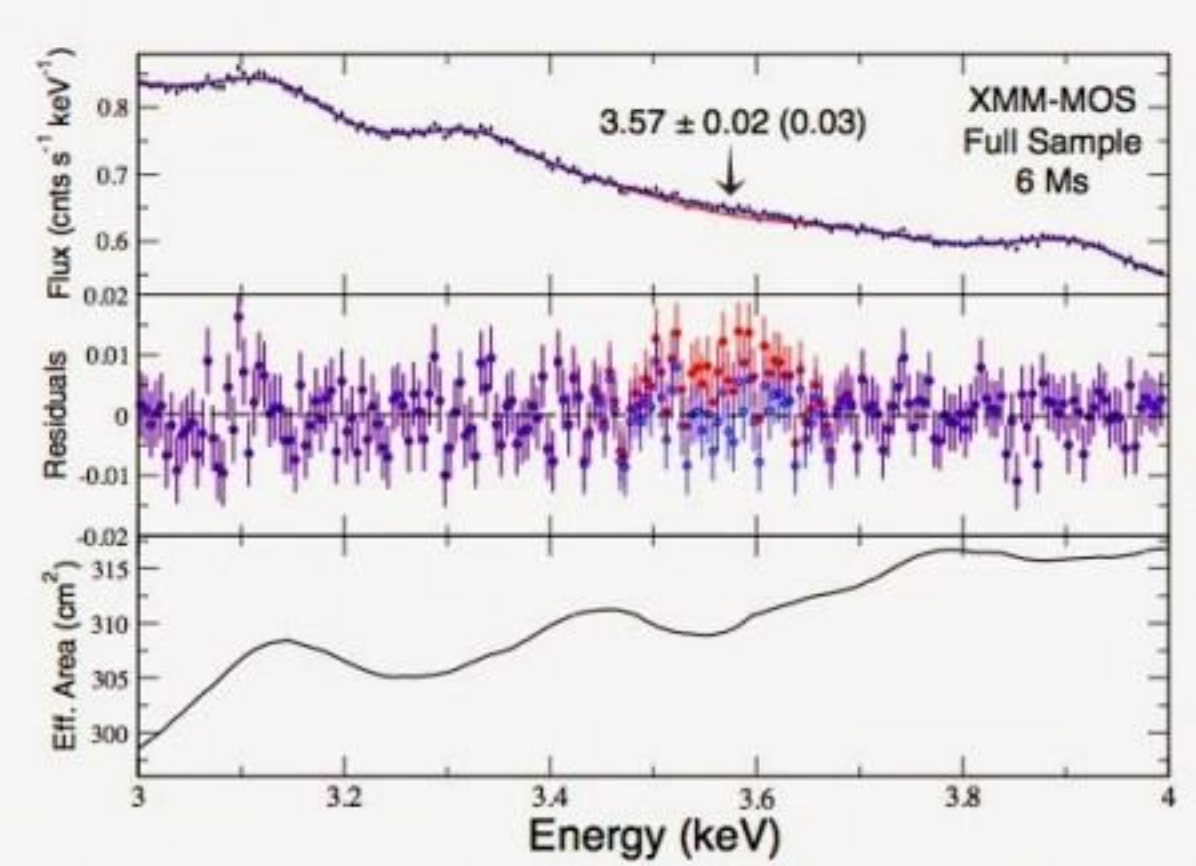




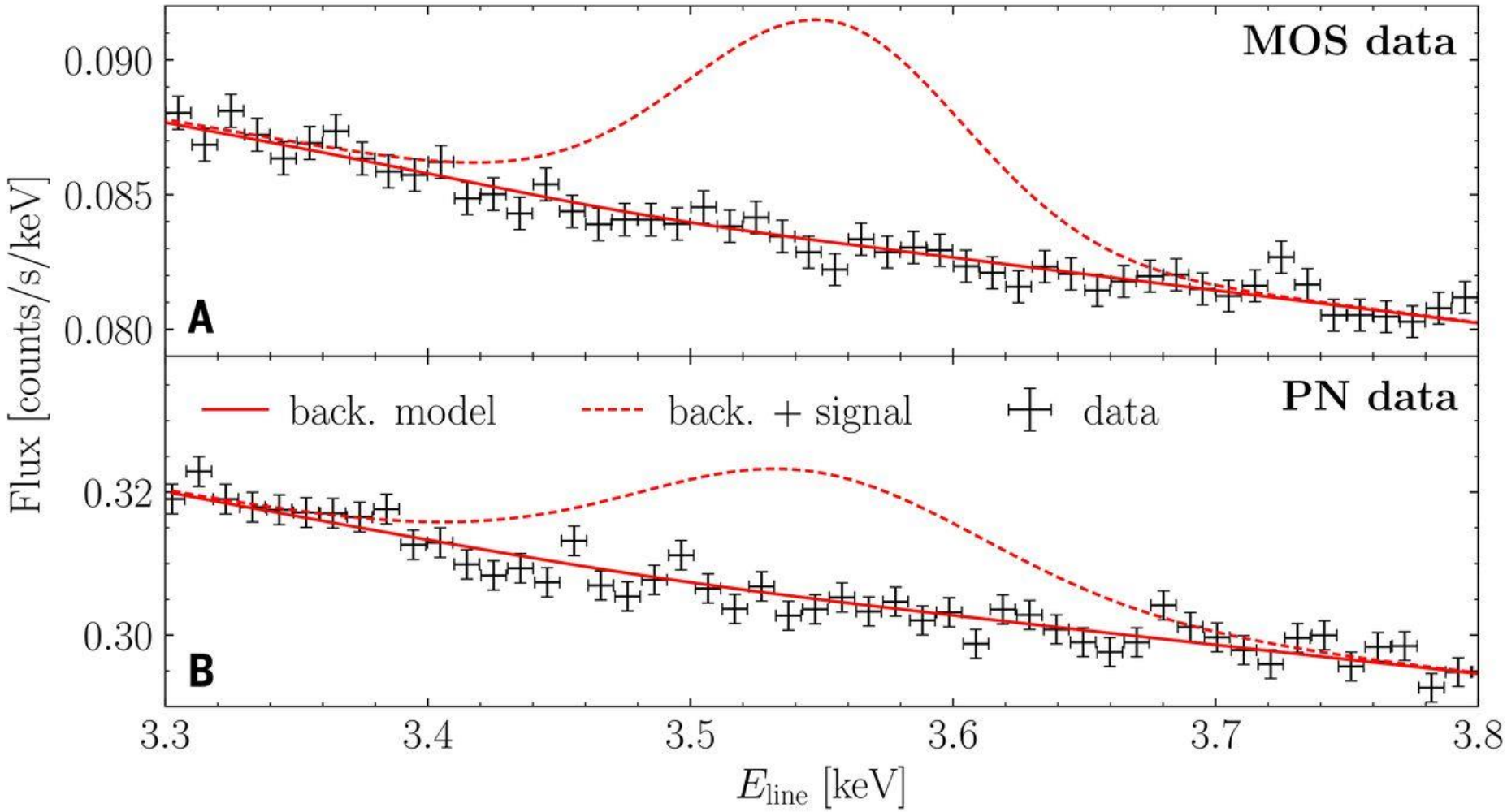
…being a two-body decay of a (cold, non-relativistic) particle, photon is **monochromatic** with energy, $E_\gamma = m_\nu/2$

$$\Gamma_{\nu_s \to \gamma \nu_a} \approx \frac{\alpha}{16\pi^2} \theta^2 G_F^2 m^5$$


$\theta^{-2}\left(\frac{m}{\mathrm{keV}}\right)^{-5} \gg 1$
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
θ^2
phase space excluded
KATRIN statistical limit
ATHENA
sensitivity
thermal overproduction
phase space
disfavoured
current X-ray
constraints
Lymanα disfavoured
(thermal production)
resonant production
inconsistent with BBN
0.5
1.0
5
10
50
M [keV]



- Positive **detection** claimed from galaxy clusters (2014, Bulbul+, Boyarsky+)
- **dSph observations** showed signal could not originate from sterile neutrino decay (Jeltema+Profumo, 2016)
- further **conclusive evidence** from blank sky data (Dessert+ 2019), and **XRISM**


MOS data
PN data
A
B
back. model
back. + signal
data
0.090
0.085
0.080
0.32
0.30
3.3
3.4
3.5
3.6
3.7
3.8
Flux [counts/s/keV]
$E_{\rm line}$ [keV]