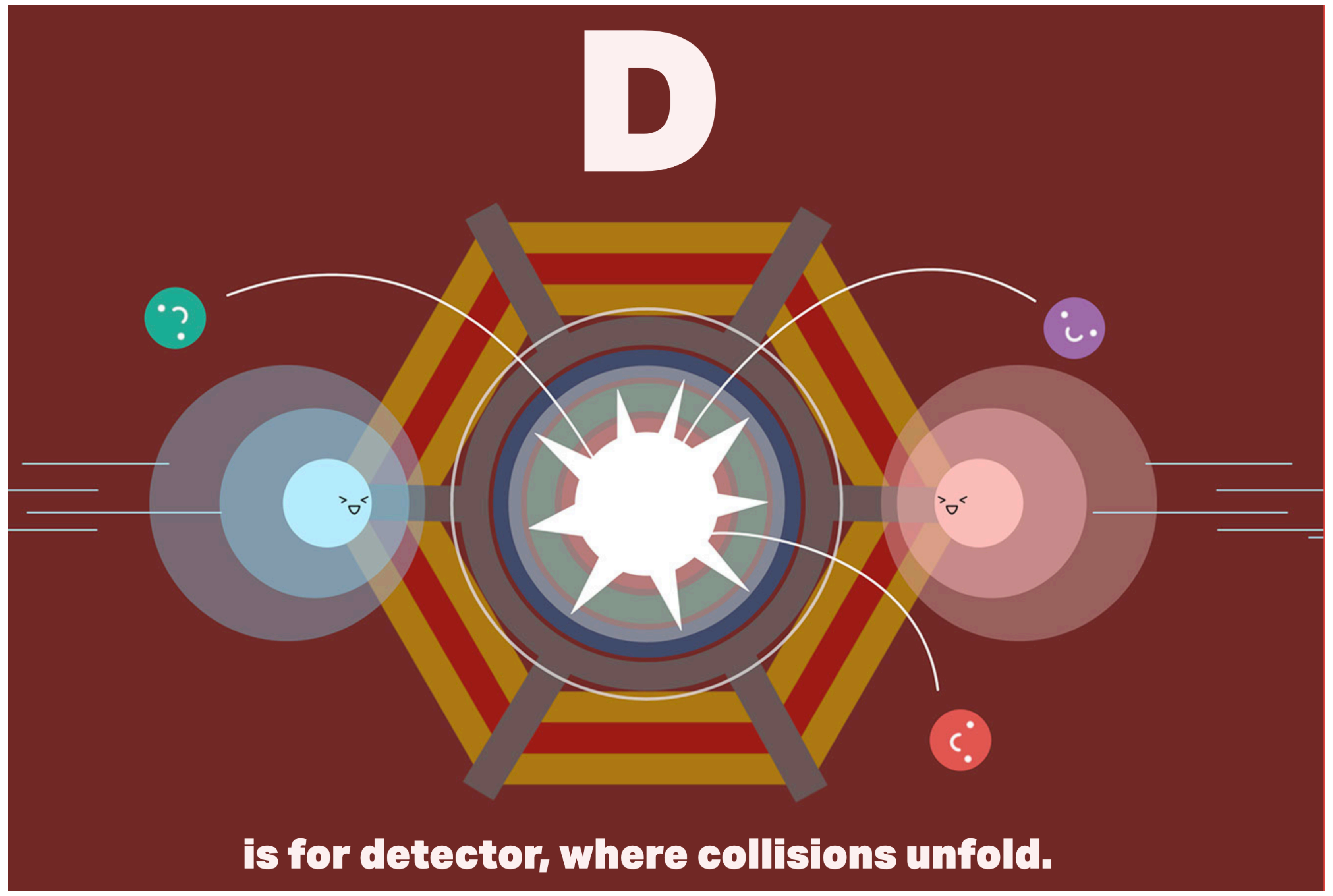


Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

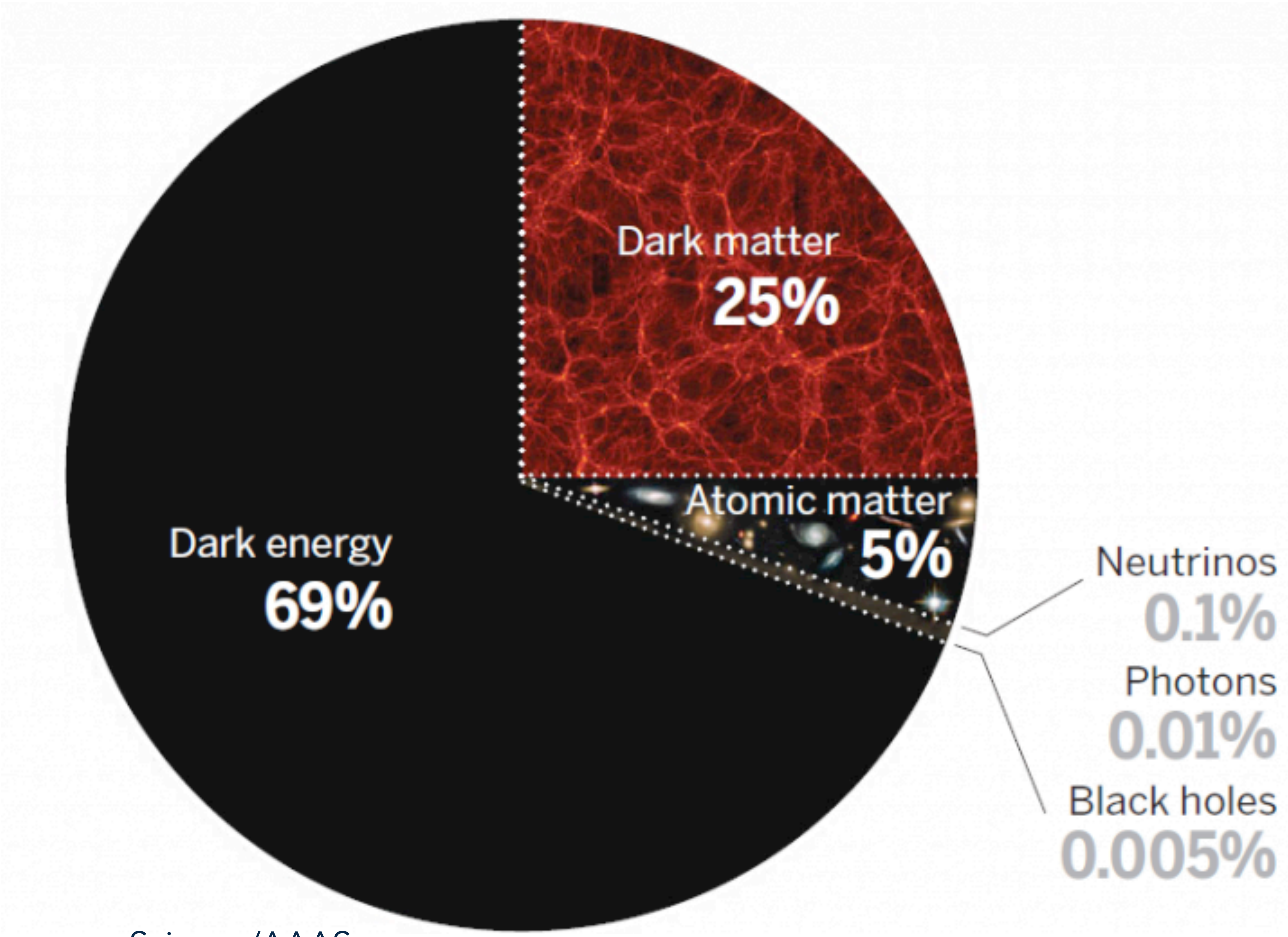
Queen's University

Dark Matter: Direct and Indirect Detection

Summer Particle Astrophysics Workshop 2024

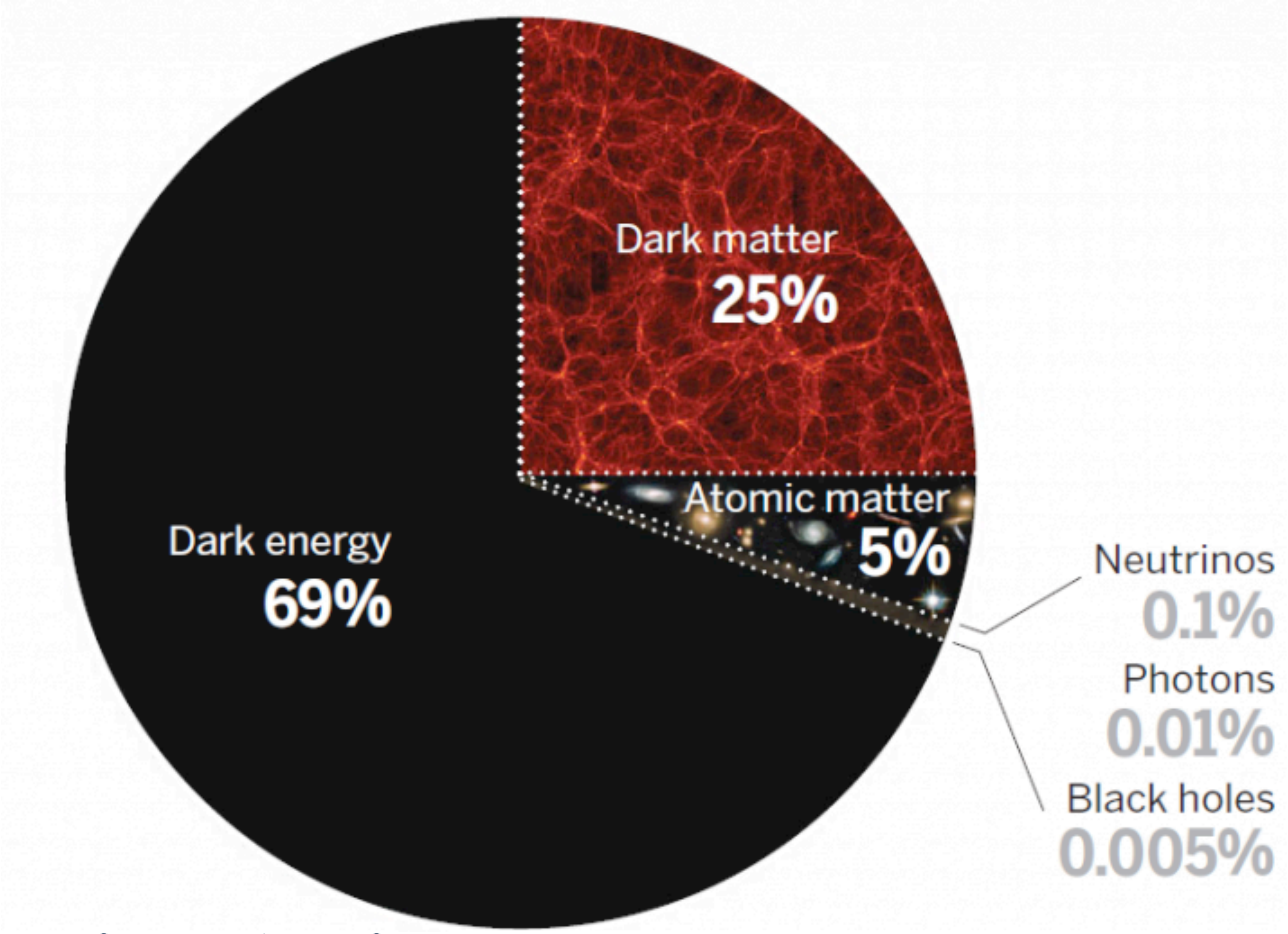
Yilda Boukhtouchen
PhD Candidate, Queen's High-Energy Astroparticle Theory Group

The search for dark matter is well-motivated

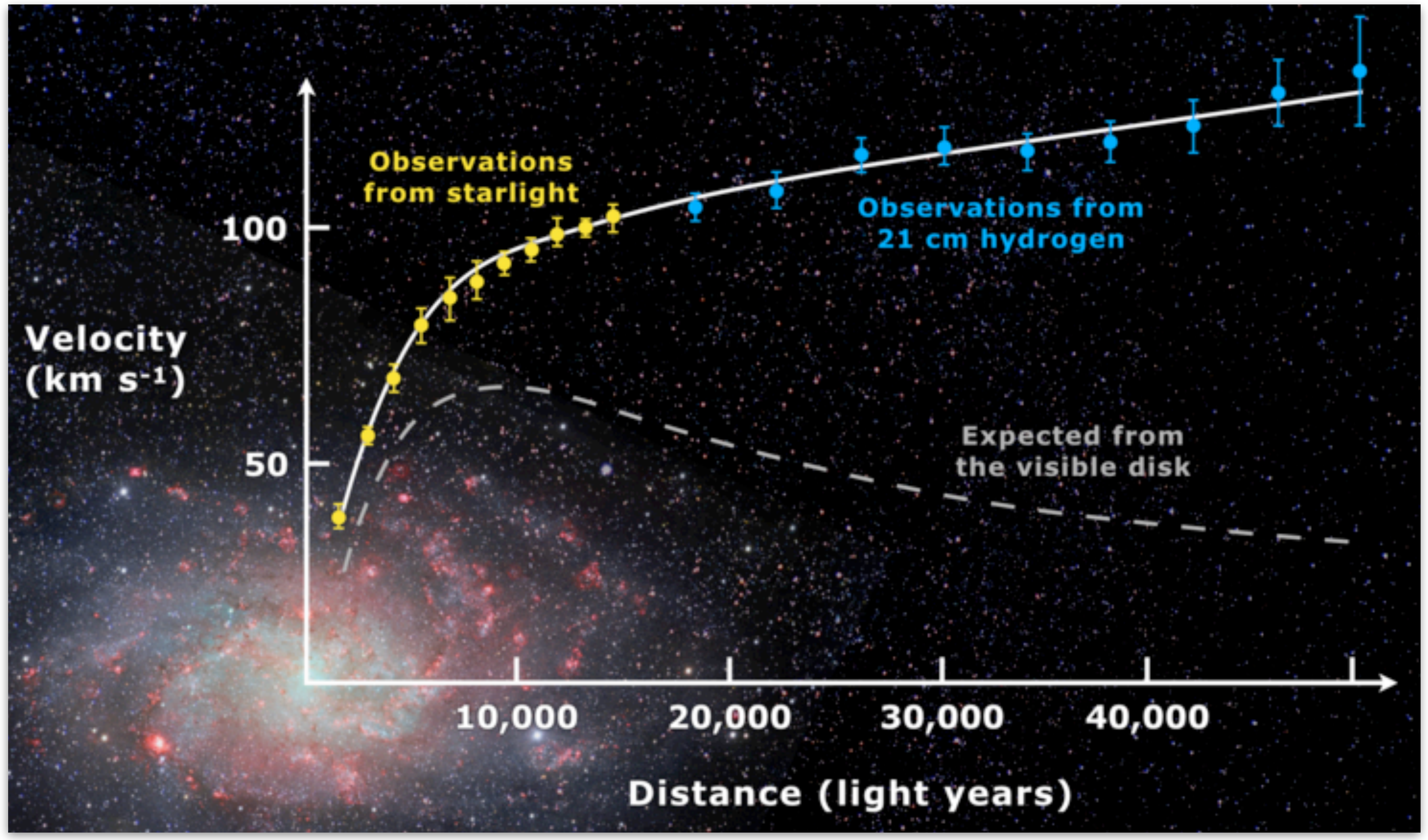


Science/AAAS

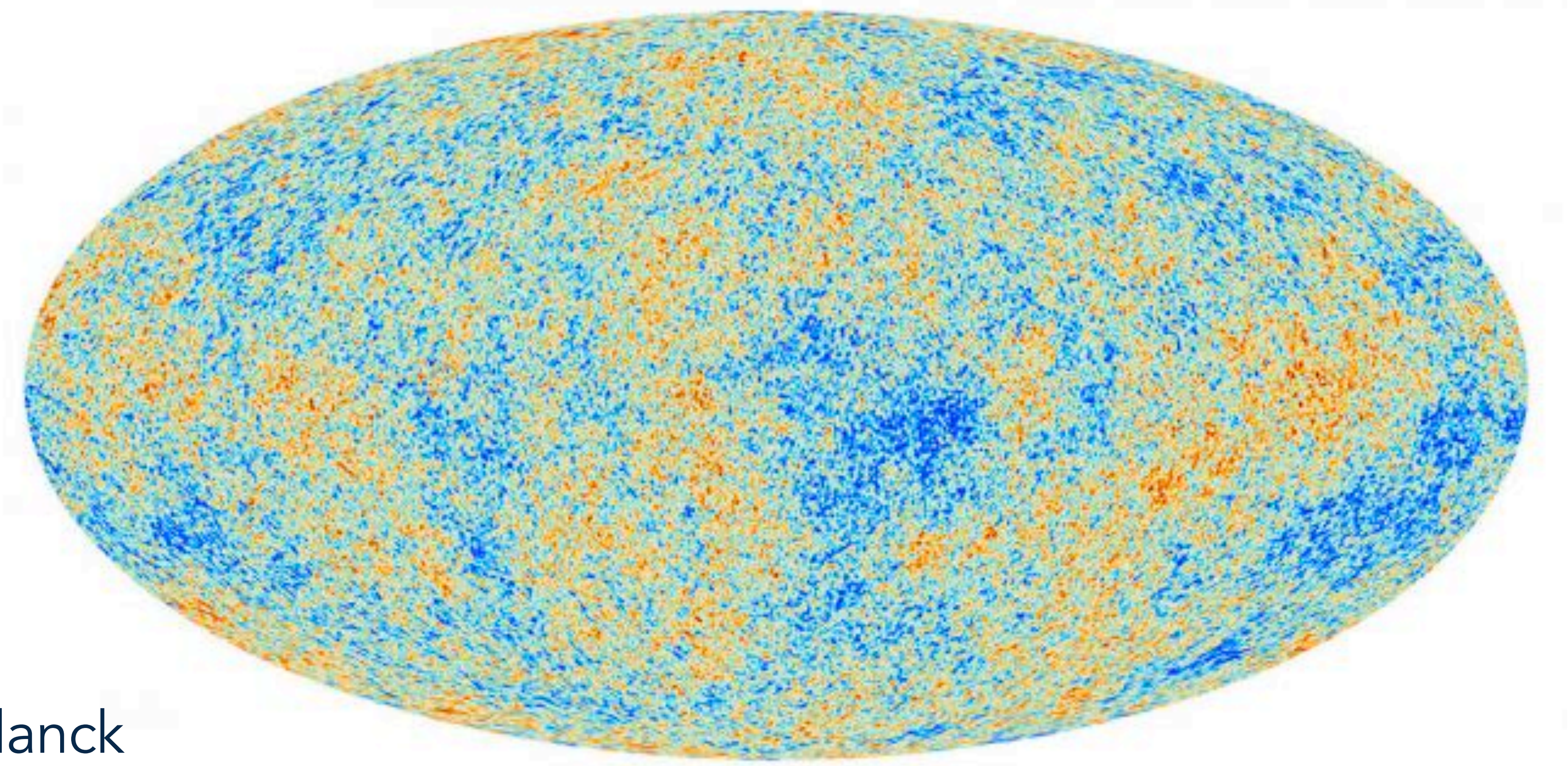
The search for dark matter is well-motivated



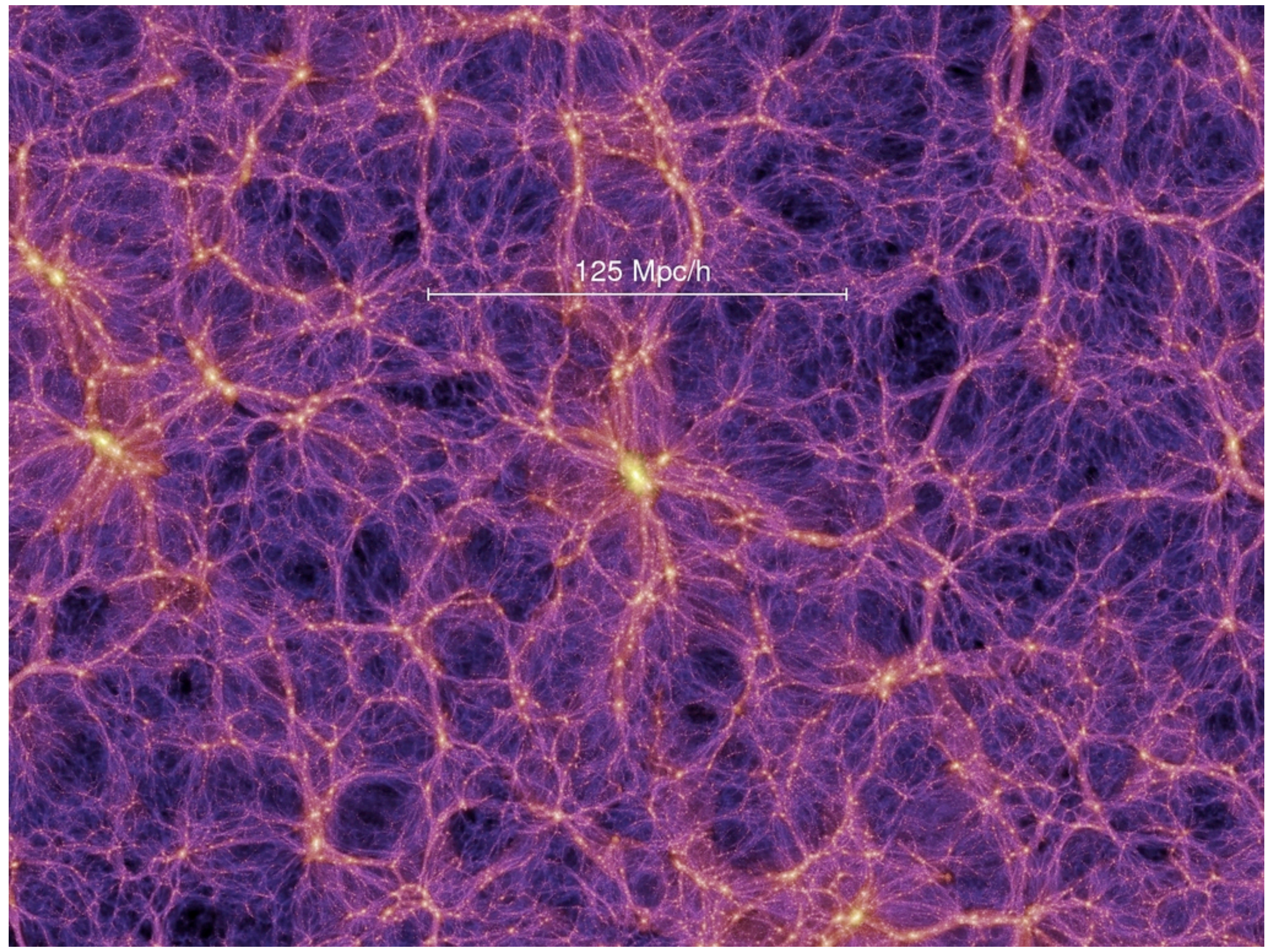
Science/AAAS



De Leon (Infographic)



ESA & Planck



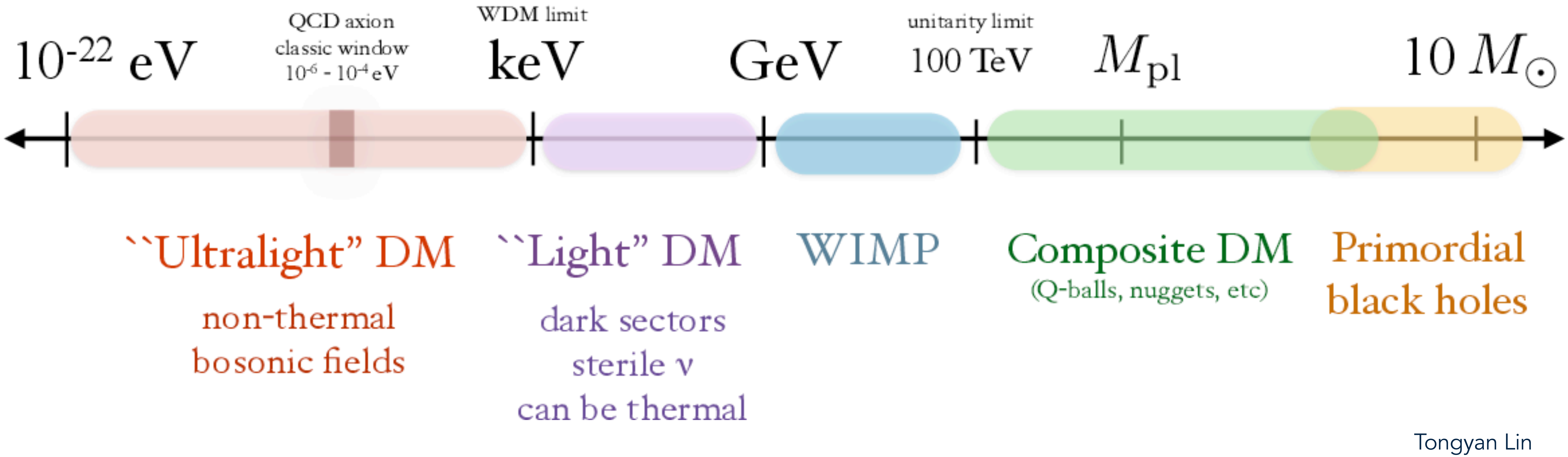
Millenium Simulation

From these, dark matter should…

- Be produced in the early universe, with observed dark matter abundance today
- Be stable ($\tau \gg 10^{10}$ years)
- Cold and collision less

Citation

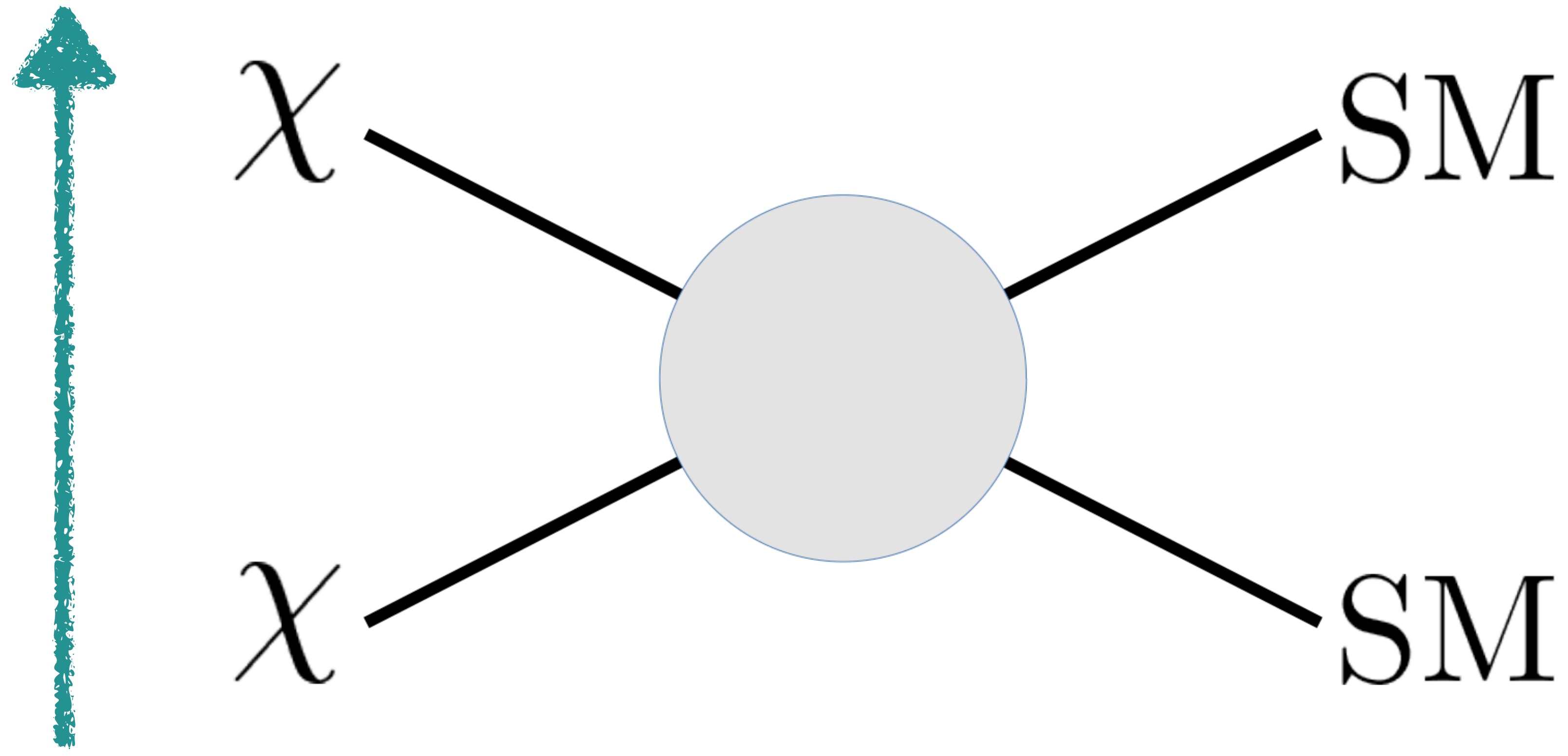
This still leaves lots of possibilities!



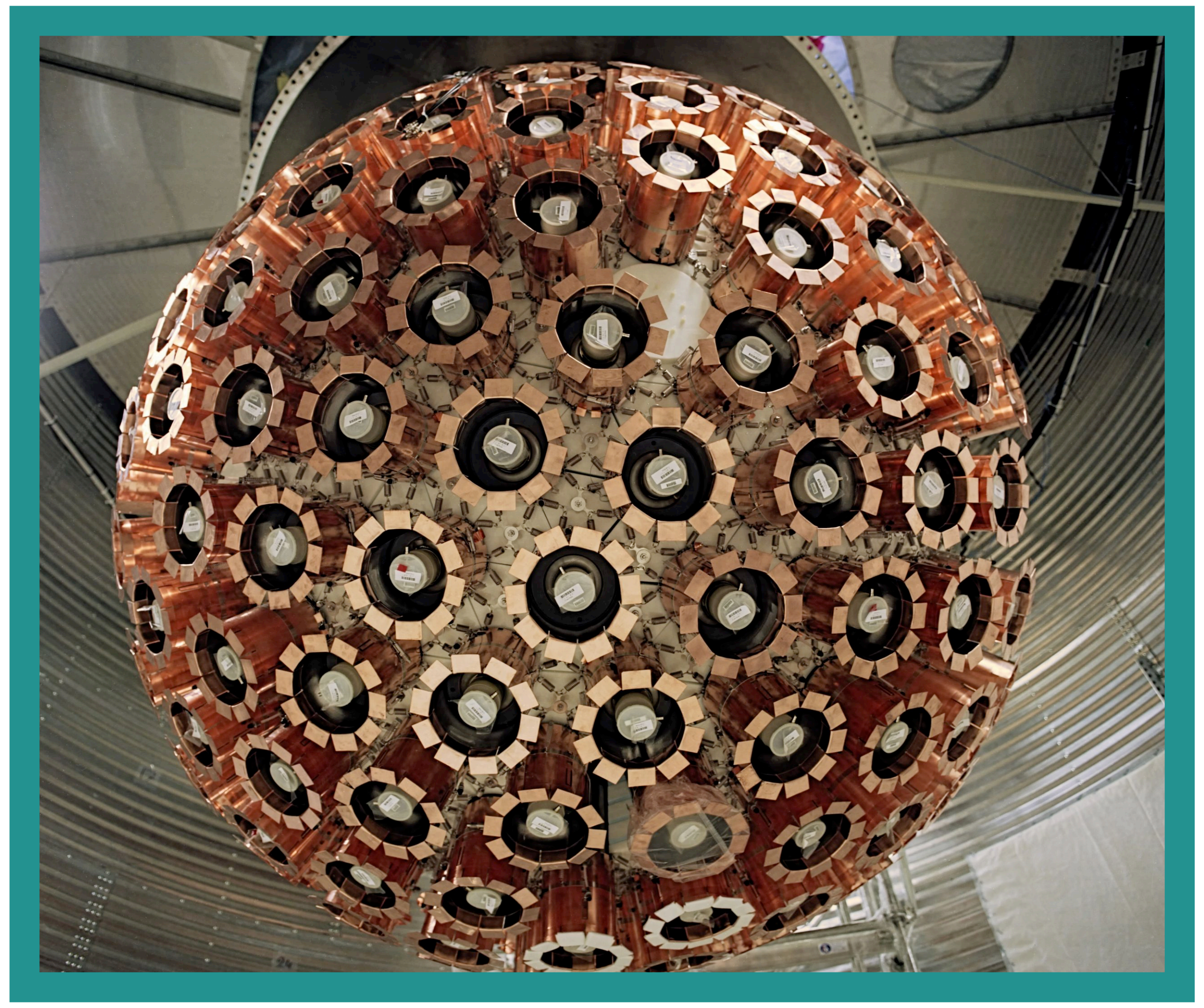
Different models must be targeted with different detection methods.

Direct detection vs Indirect Detection

Direct detection

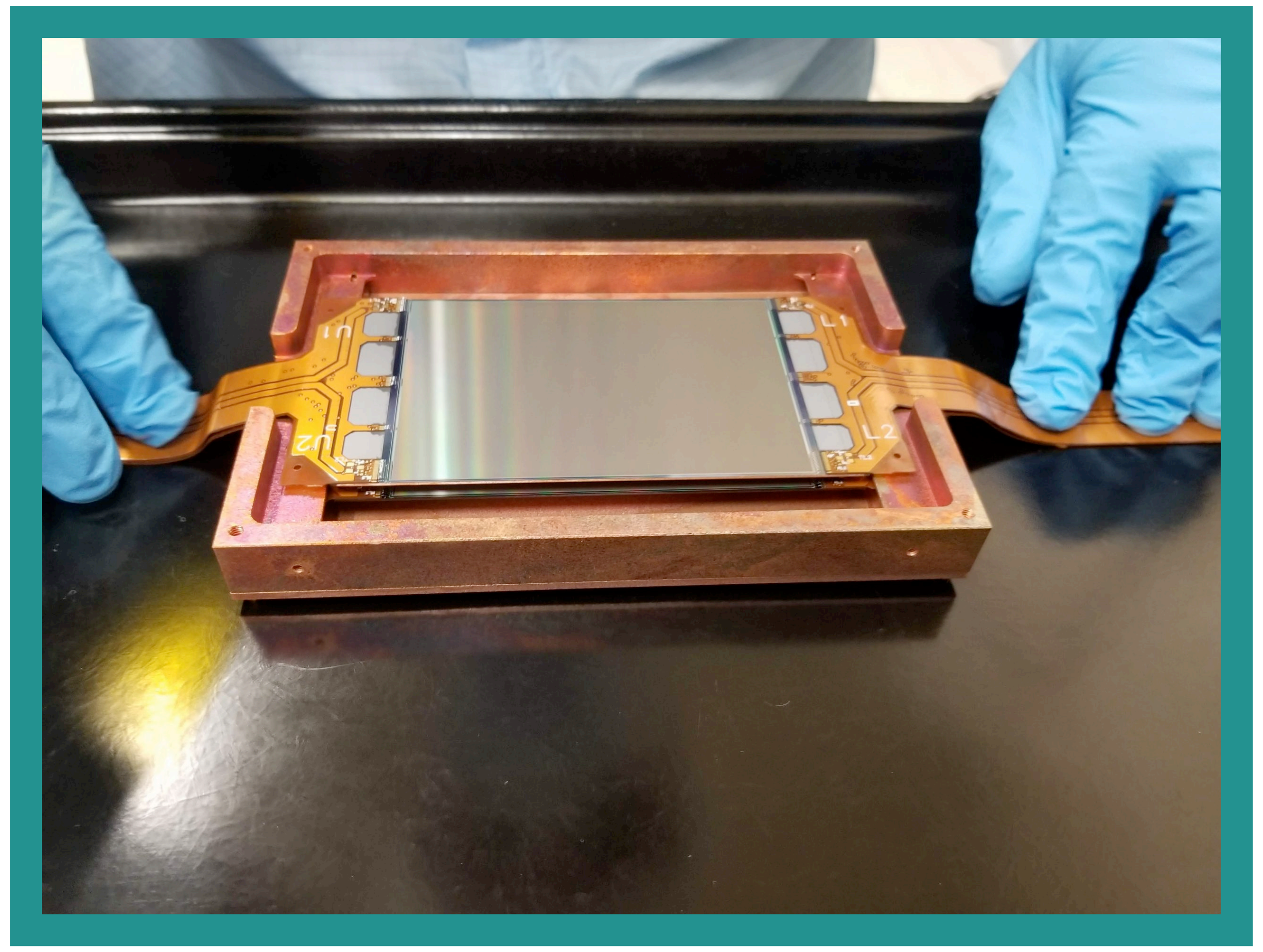


Detecting a dark matter particle colliding with a Standard Model particle



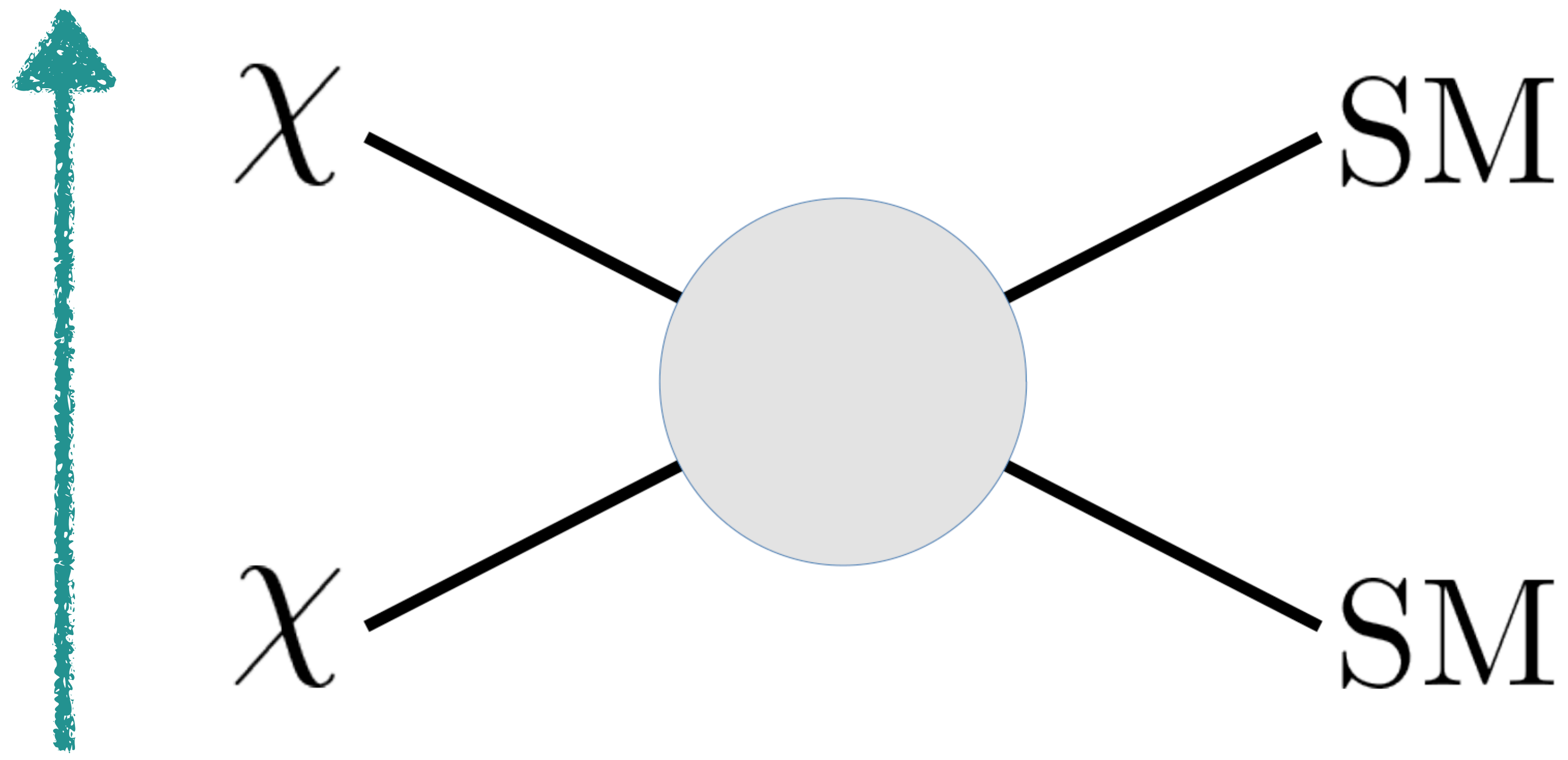
DEAP-3600, SNOLAB

DAMIC, SNOLAB

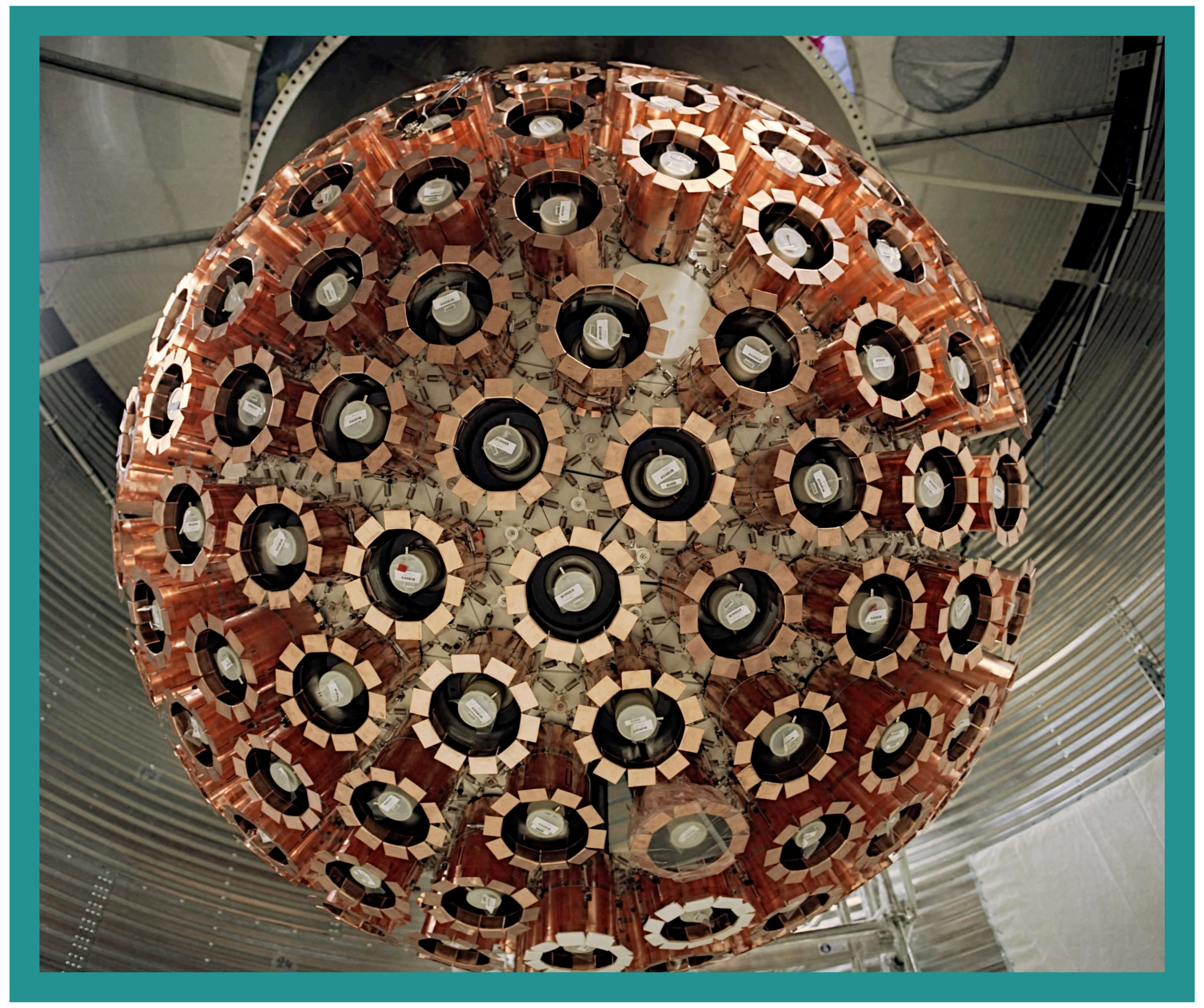


Direct detection vs Indirect Detection

Direct detection

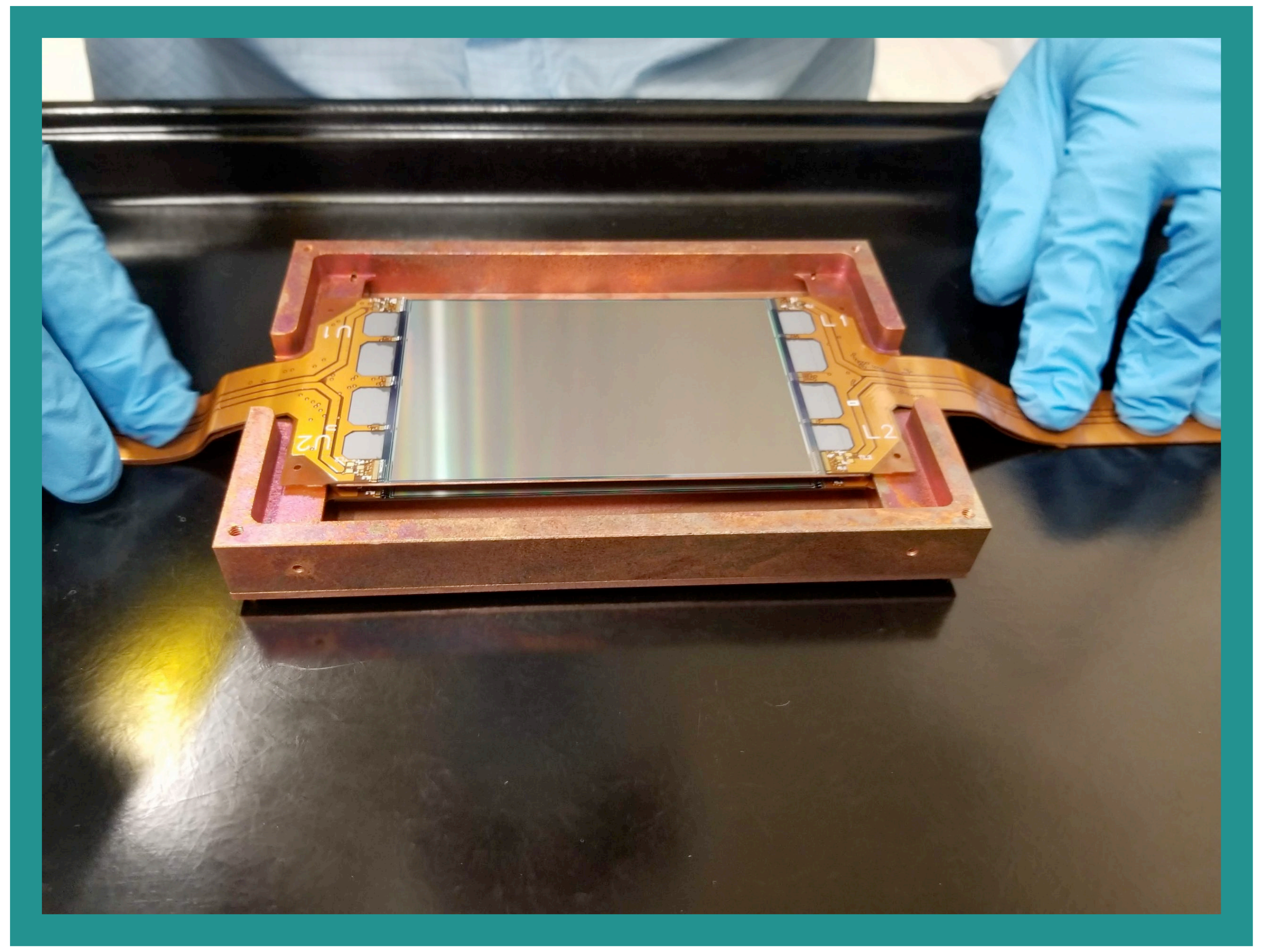


Detecting a dark matter particle colliding with a Standard Model particle



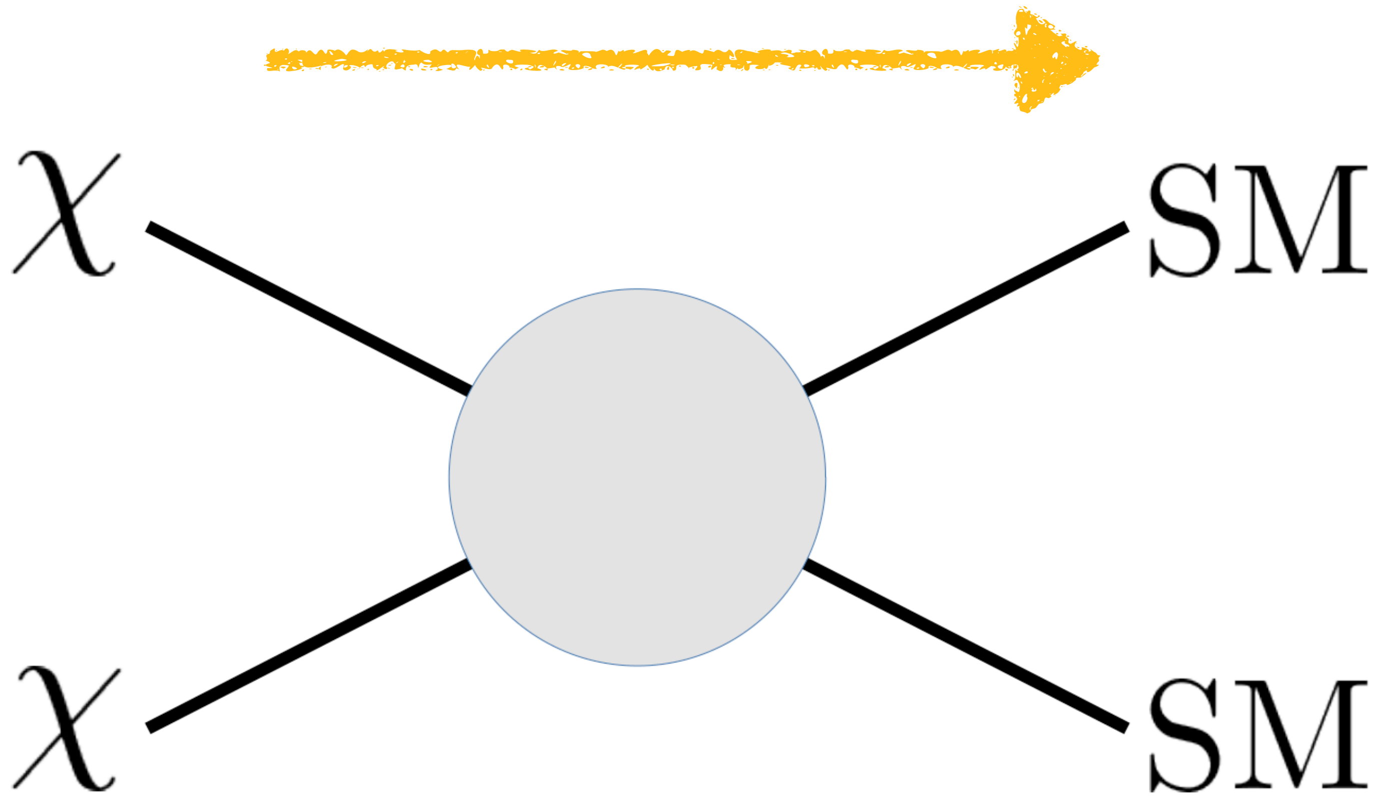
DEAP-3600, SNOLAB

DAMIC, SNOLAB

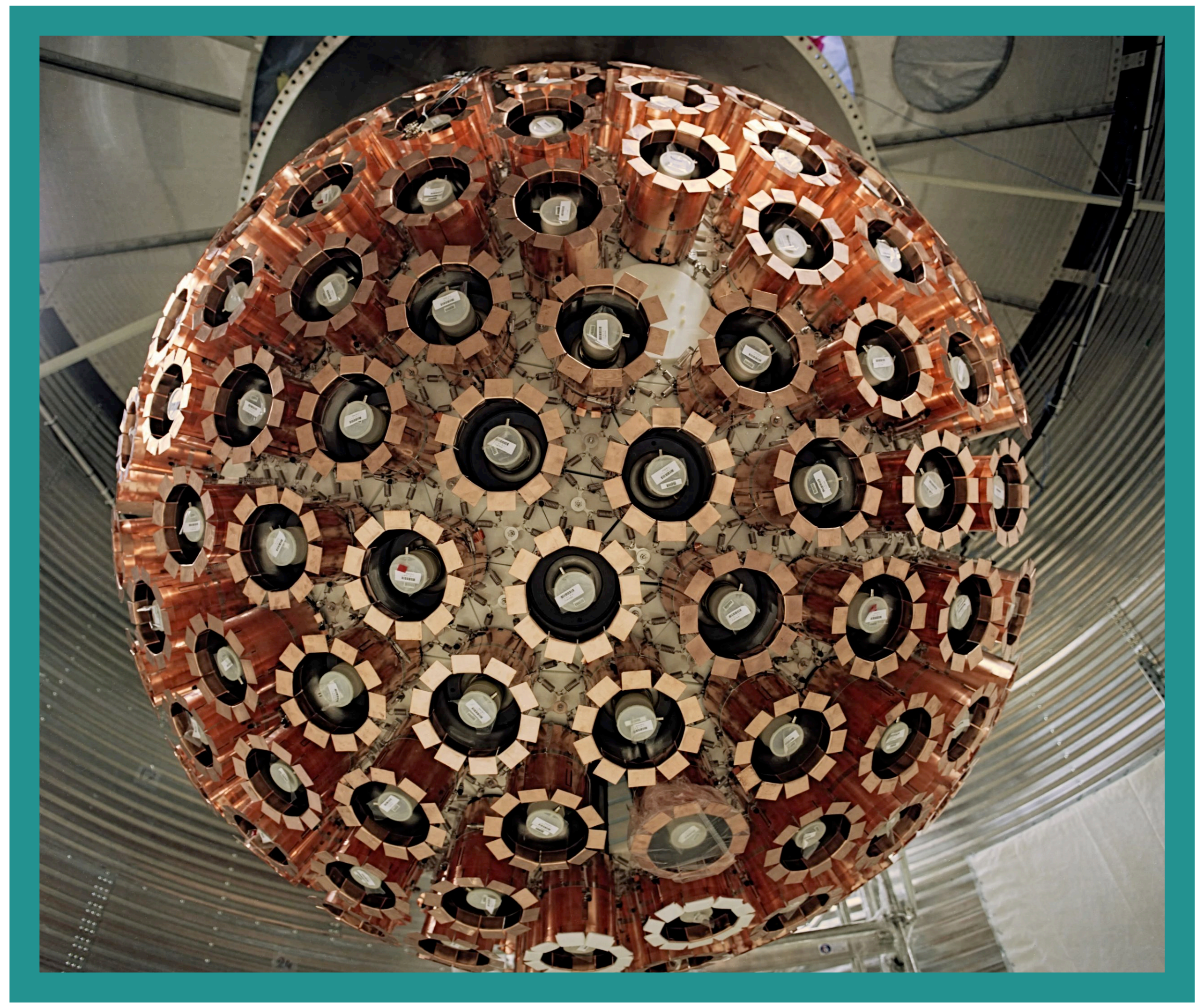


Direct detection vs Indirect Detection

Indirect detection

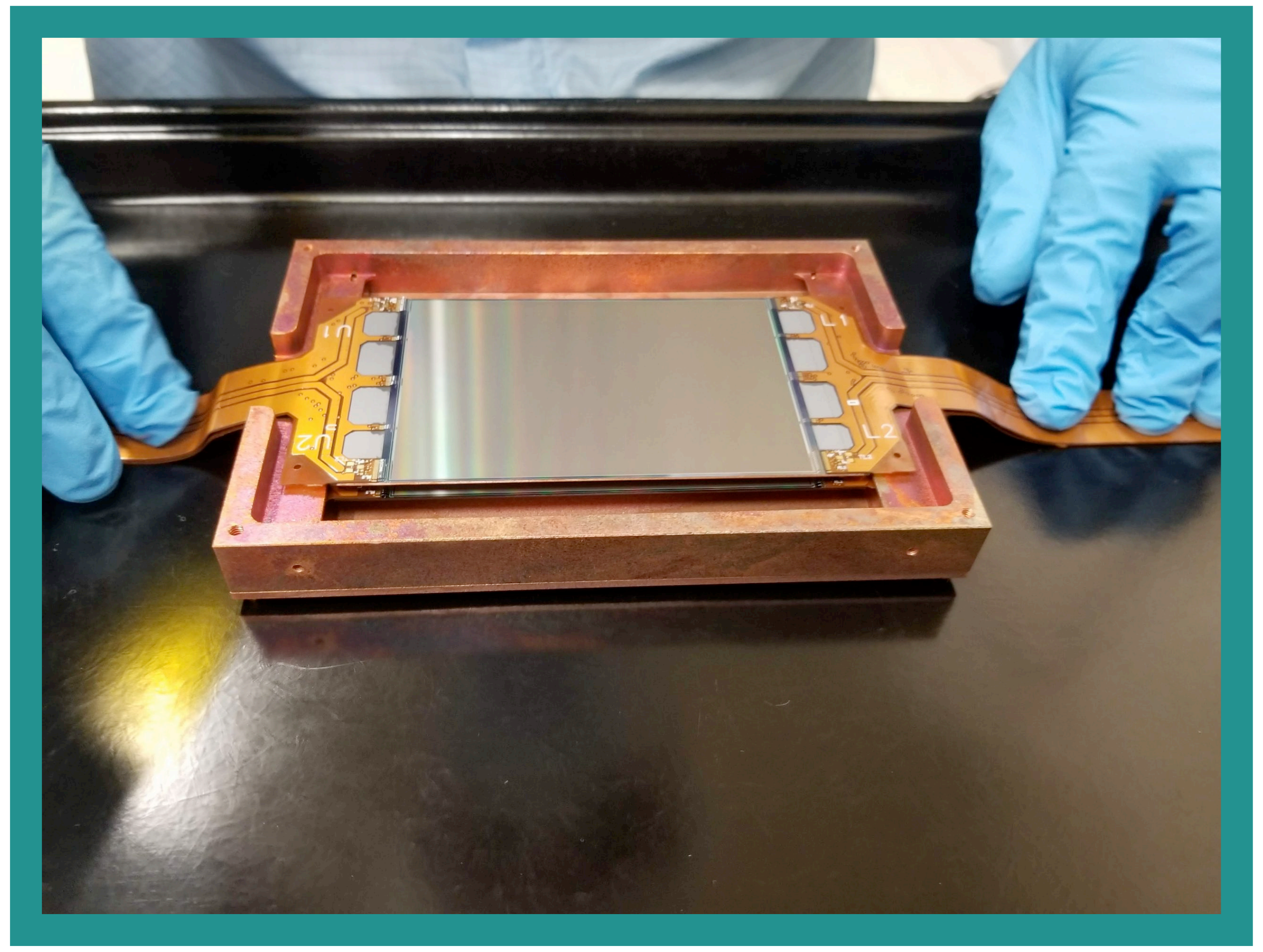


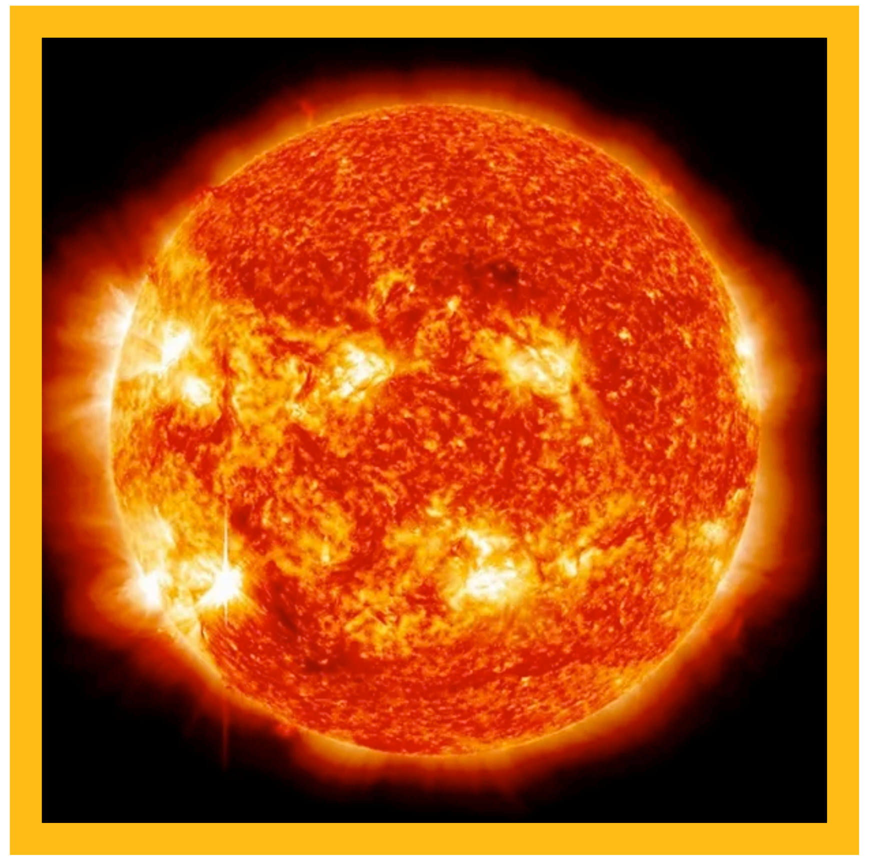
Annihilating or decay to a spectrum of Standard Model particles



DEAP-3600, SNOLAB

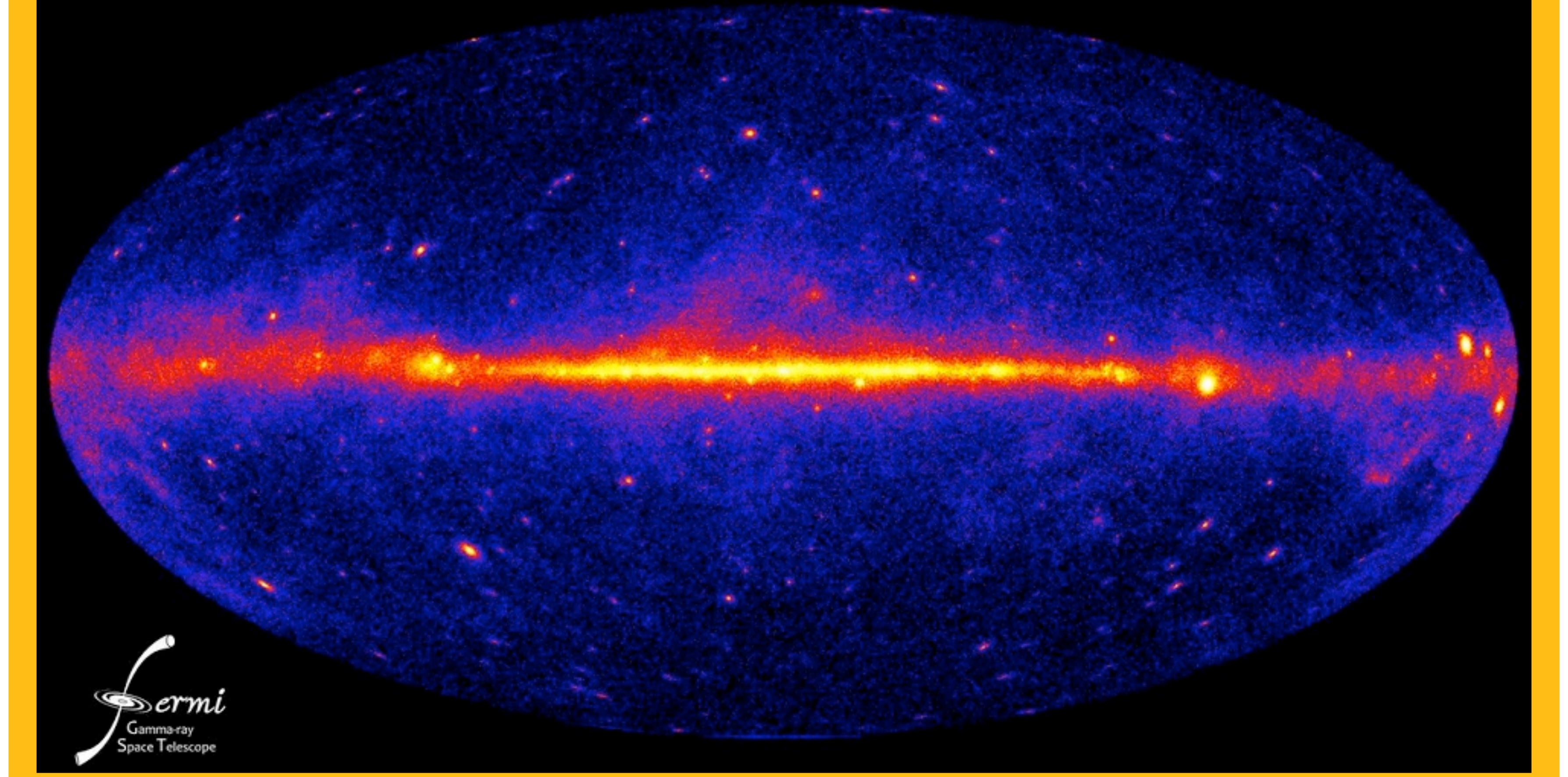
DAMIC, SNOLAB



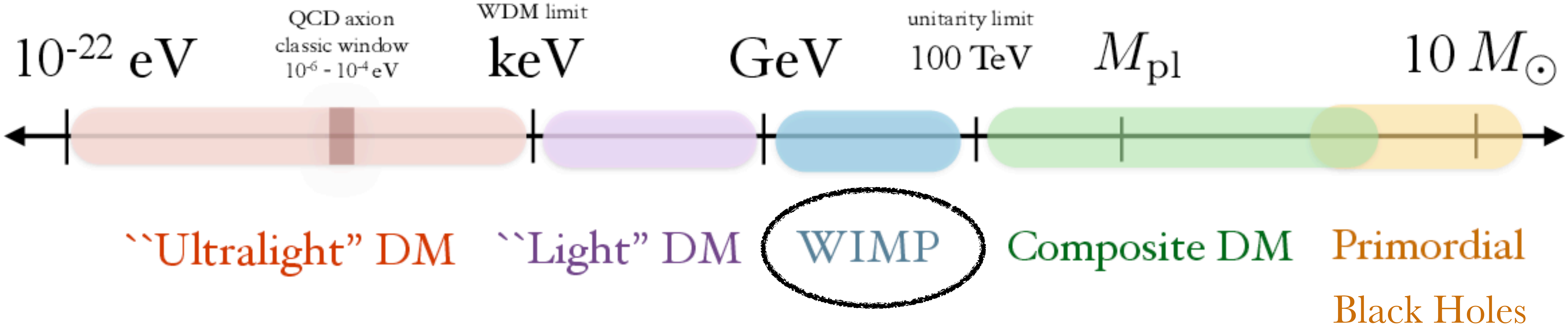


The Sun

Gamma-rays from the Milky Way, FERMI space telescope.



Going back to the dark matter landscape



Citation

The “Standard” Thermal WIMP

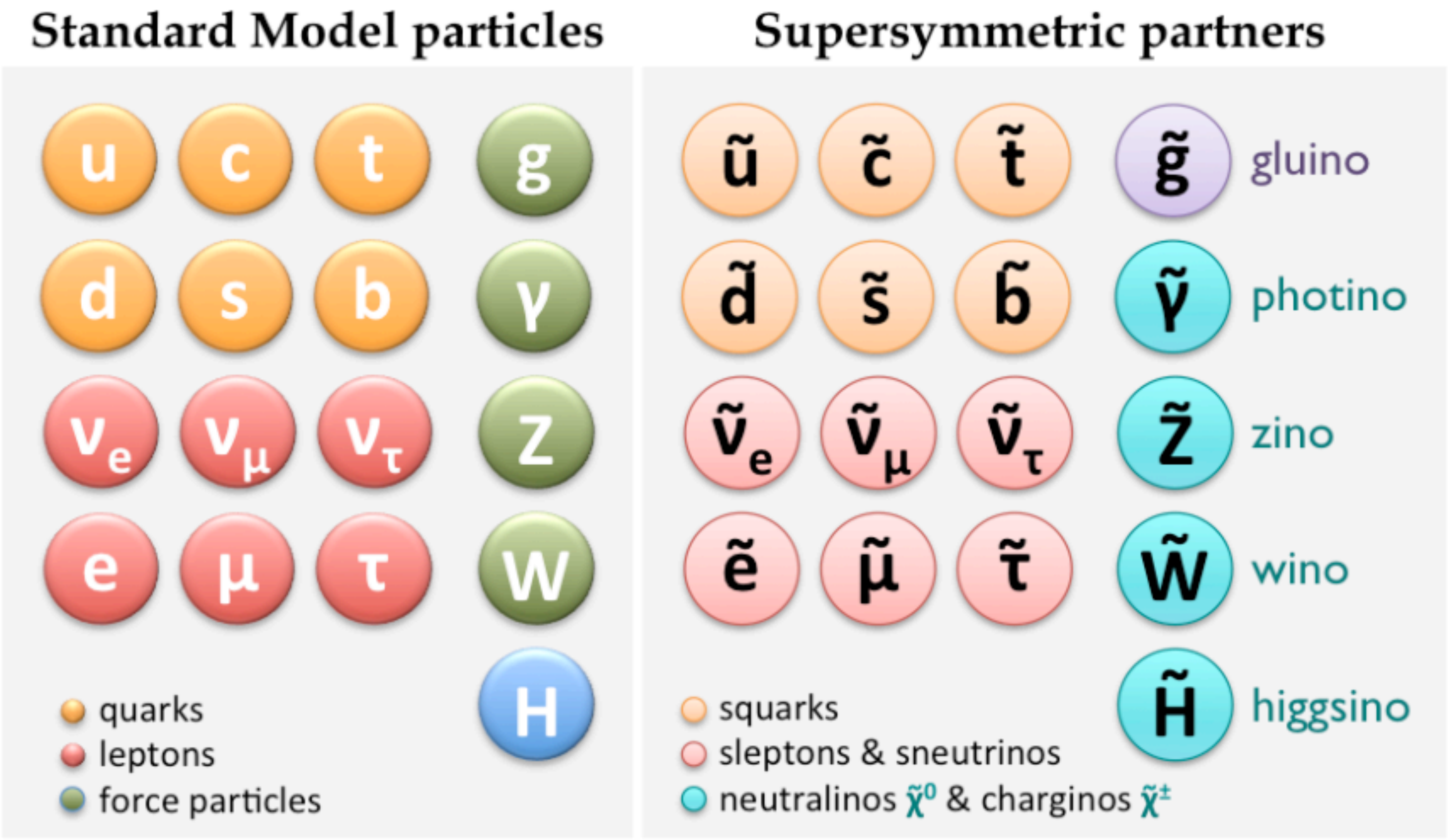
$$m_\chi = 1\ \text{GeV} - 100\ \text{TeV}$$

Weakly-Interacting ⟶ interact with force around the weak scale

Massive Particle ⟶ mass around nucleon / nucleus masses

Theoretical Motivation: e.g. supersymmetry yields stable particle in this mass range

$$\tilde{\chi}^0_1 = N_1\mathbf{B} + N_2\mathbf{W}^3 + N_3\mathrm{H}^0_1 + N_4\mathbf{H}^0_2$$



The “Standard” Thermal WIMP

$m_\chi = 1$ GeV – 100 TeV

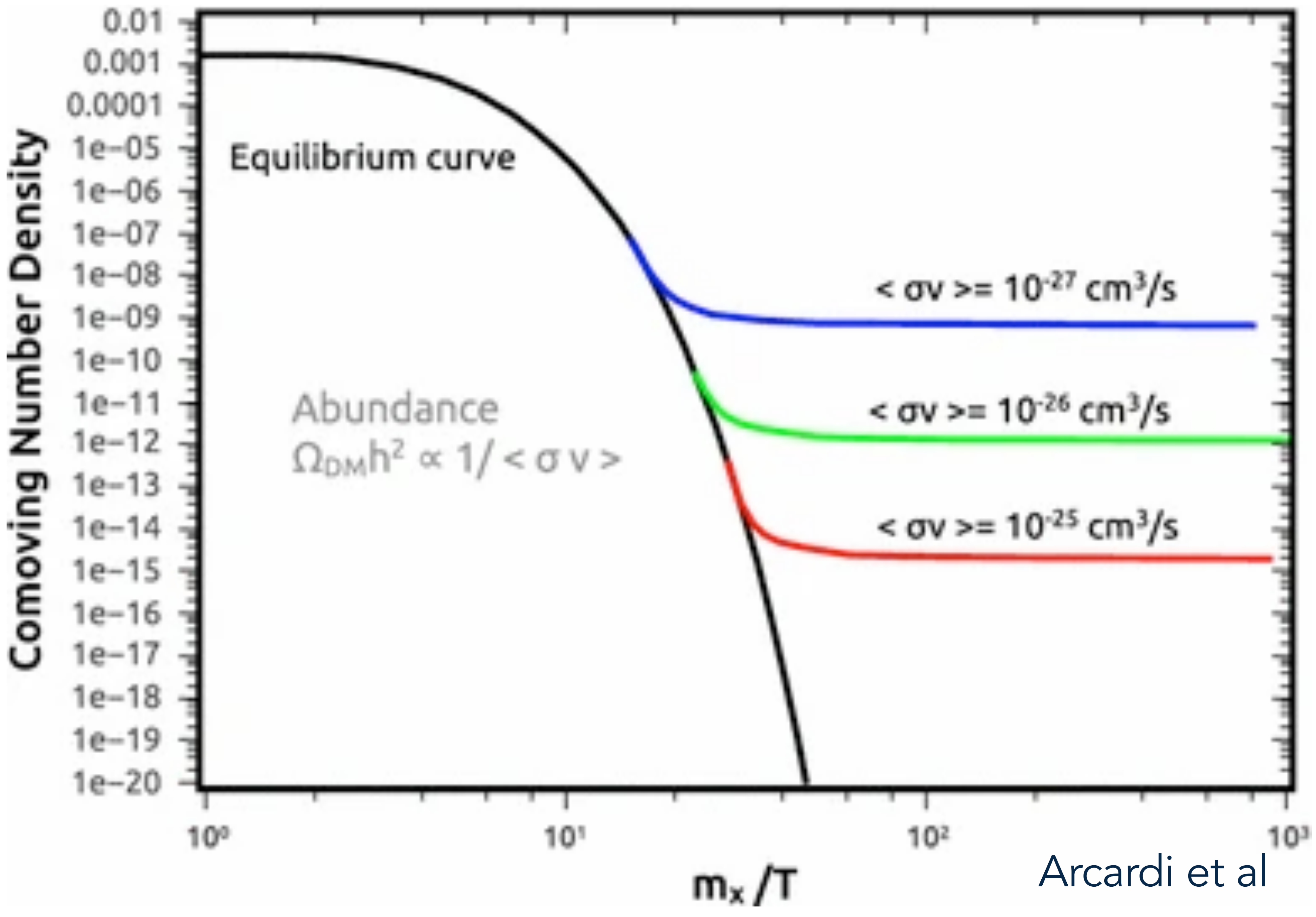
Weakly-Interacting ⟶ interact with force around the weak scale

Massive Particle ⟶ mass around nucleon / nucleus masses

Theoretical Motivation: e.g. supersymmetry yields stable particle in this mass range

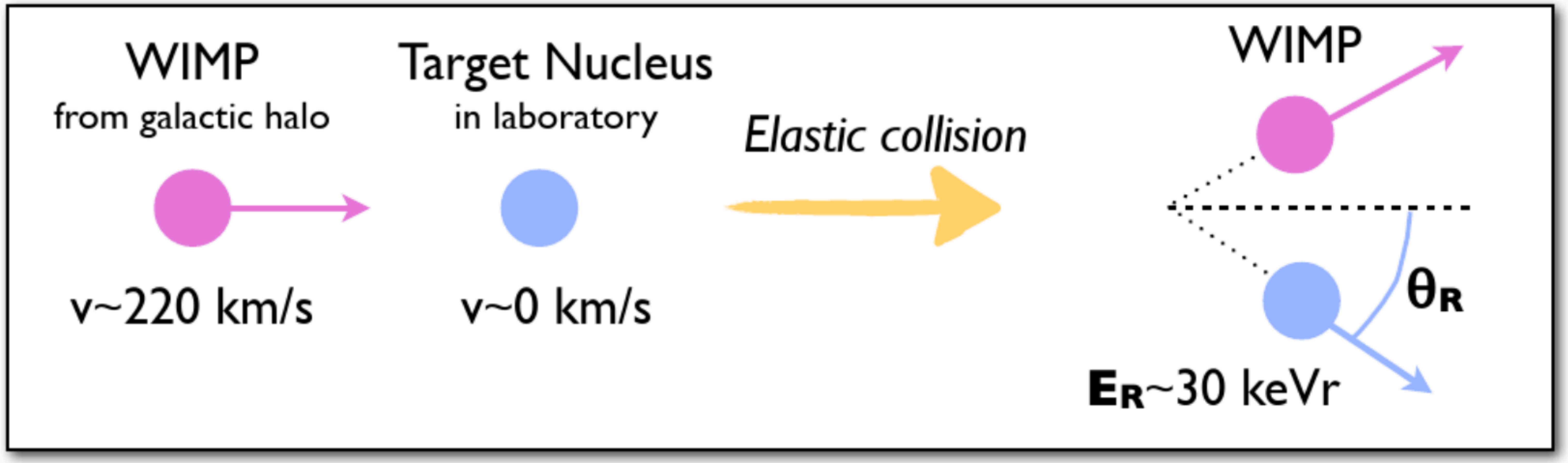
WIMP Miracle: at these masses, thermal freeze-out gives correct DM abundance

Hooray! So much motivation!



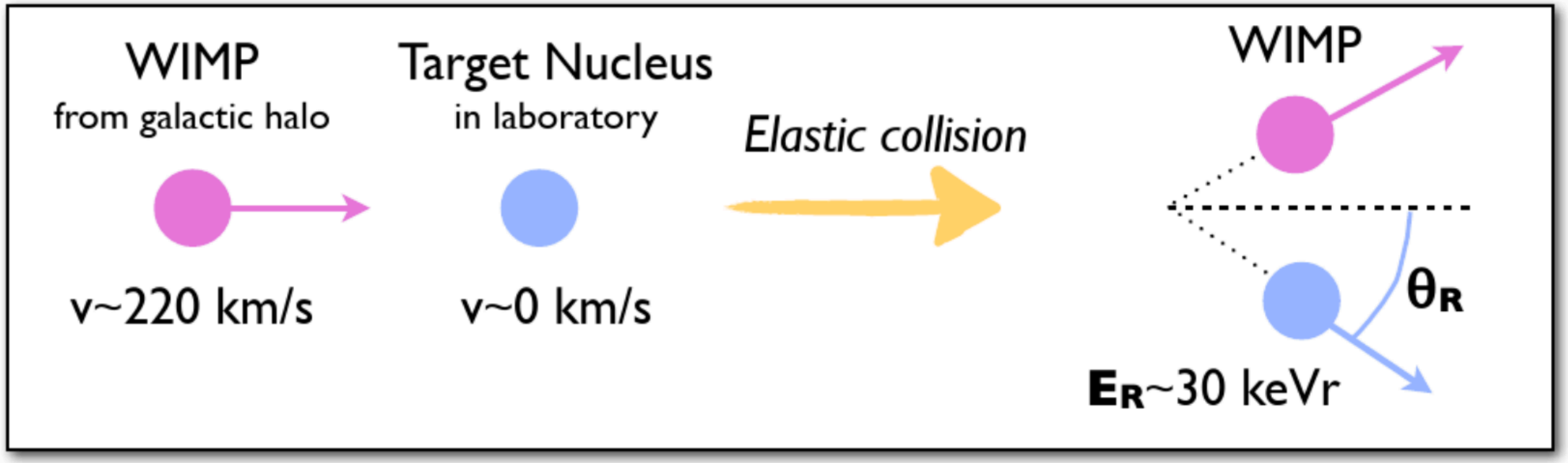
Arcardi et al

Looking for WIMP - Standard Model Scattering



Cooley 2022

Looking for WIMP - Standard Model Scattering



Cooley 2022

In the centre-of-mass frame:

$$q = 2\mu^2 v^2 (1 - \cos\theta_R)$$

$$E_R = \frac{\mu^2 v^2}{m_N}(1 - \cos\theta_R)$$

Scattering Rate in a Detector

$$N = t \cdot N_T \cdot n_\chi \cdot v_\chi \cdot \sigma_{\chi N}$$

Exposure time of detector

Number of target particles

Number density of the DM

Velocity of the DM

DM-target cross-section

Must take into account the recoil energy spectrum: how many scatters are *visible*?

$$\frac{dN}{dE_R} = tN_T n_\chi v_\chi \frac{\sigma_{\chi N}}{dE_R}$$

Citation

Differential Event Rate

Event rate R is the number of scatters per unit time per target mass: $R \equiv N/tM_T$

$$\frac{dR}{dE_R} = \frac{1}{m_N}\frac{\rho_\chi}{m_\chi}\int_{v_{min}}^{\infty} dv\ v\, f(v)\ \frac{d\sigma}{dE_R}$$

Citation

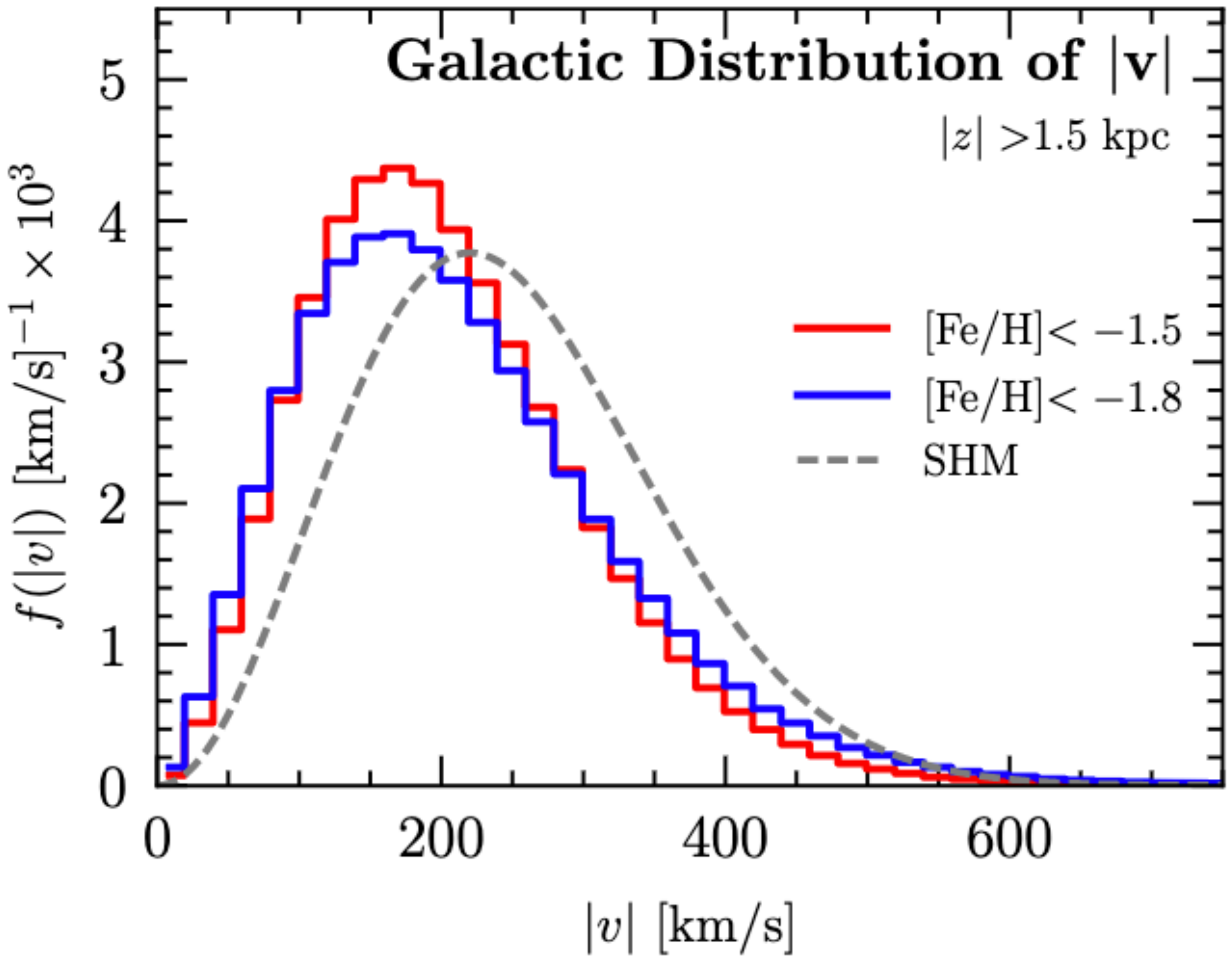
Differential Event Rate

Event rate R is the number of scatters per unit time per target mass: $R \equiv N/tM_T$

$$\frac{dR}{dE_R} = \frac{1}{m_N}\frac{\rho_\chi}{m_\chi}\int_{v_{min}}^{\infty} dv\, v\, f(v)\, \frac{d\sigma}{dE_R}$$

$$E_R = \frac{\mu^2 v^2}{m_N}(1 - \cos\theta_R) \qquad v_{min} = \sqrt{\frac{m_N E_R}{2\mu^2}}$$

Herzog-Arbeitman et al 2017



Differential Event Rate

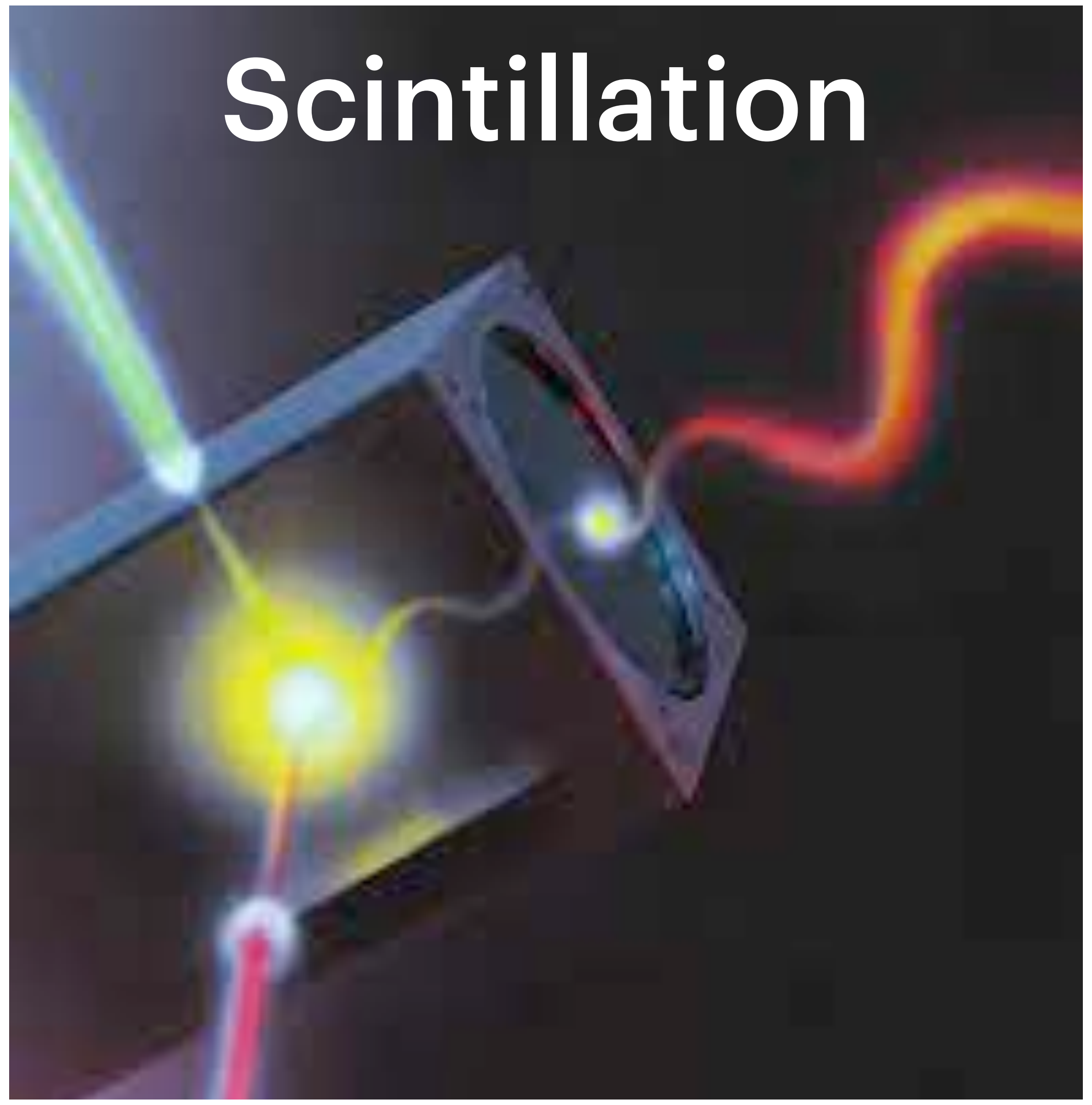
Event rate R is the number of scatters per unit time per target mass: $R \equiv N/tM_T$

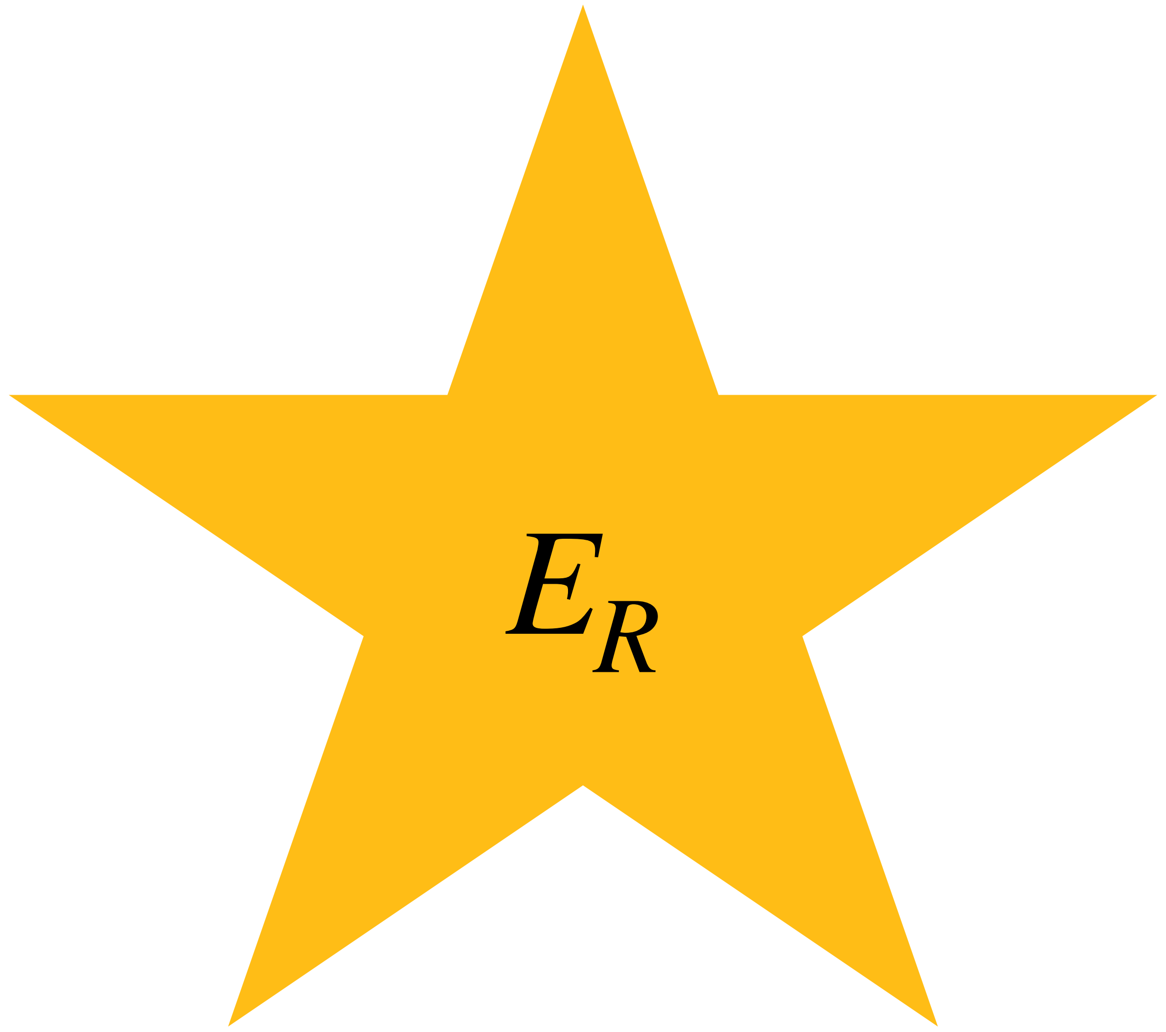
$$\frac{dR}{dE_R} = \frac{1}{m_N}\frac{\rho_\chi}{m_\chi}\int_{v_{min}}^{\infty} dv\ v\ f(v)\frac{d\sigma}{dE_R}$$

differential cross-section

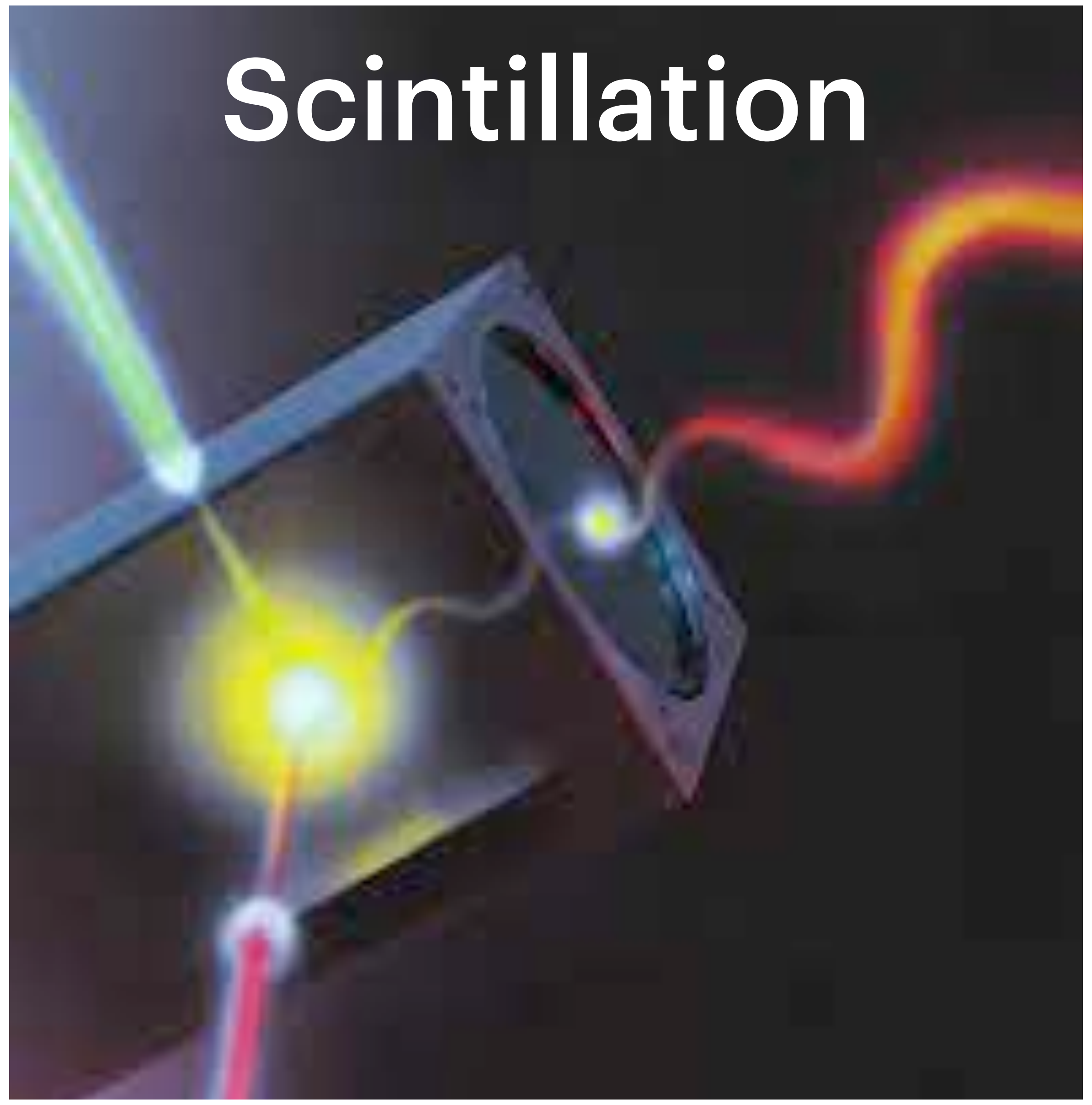
$$\frac{d\sigma}{dE_R} = \frac{m_N}{2\mu^2}\frac{\sigma}{v^2}$$

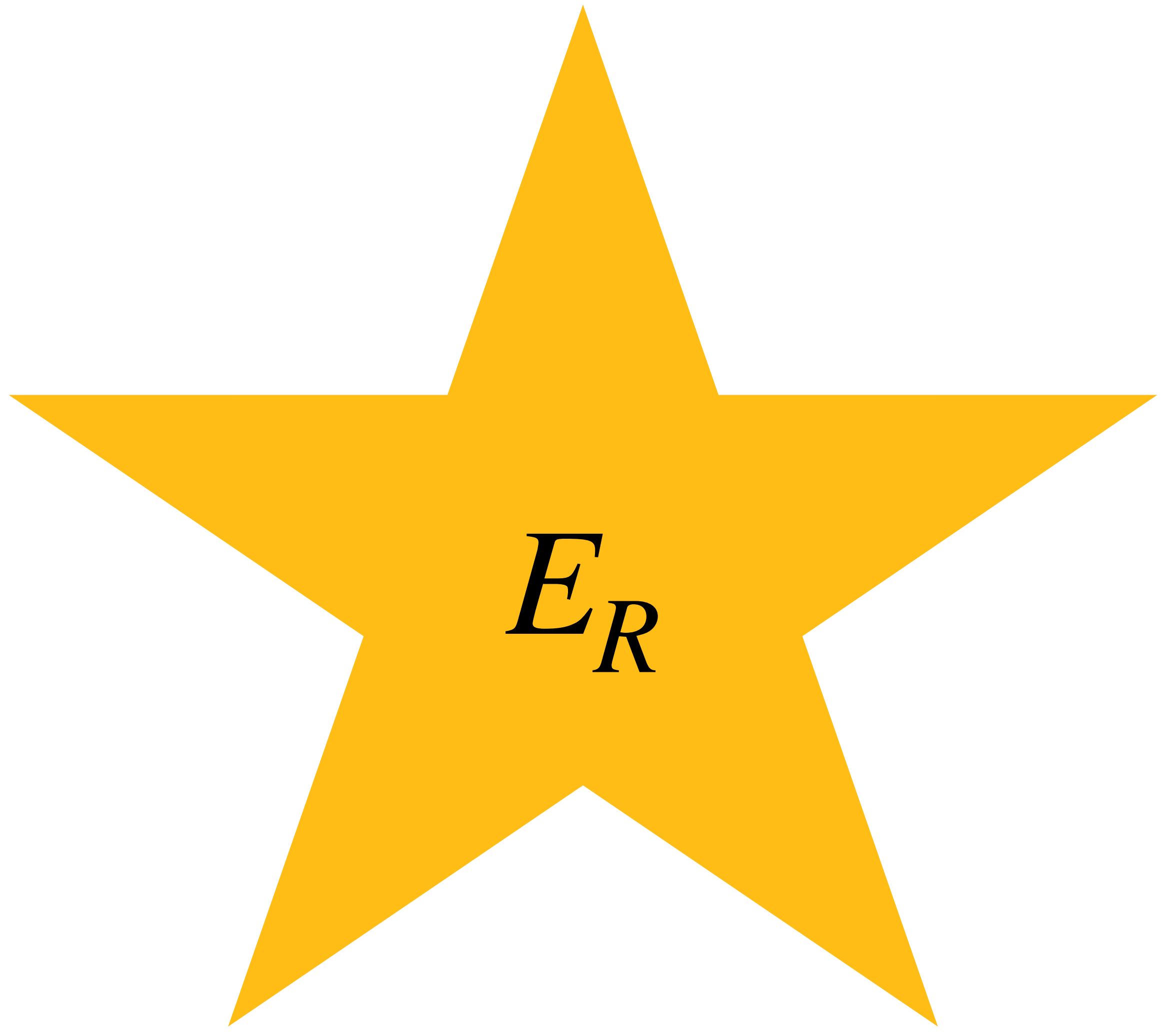
What signal?



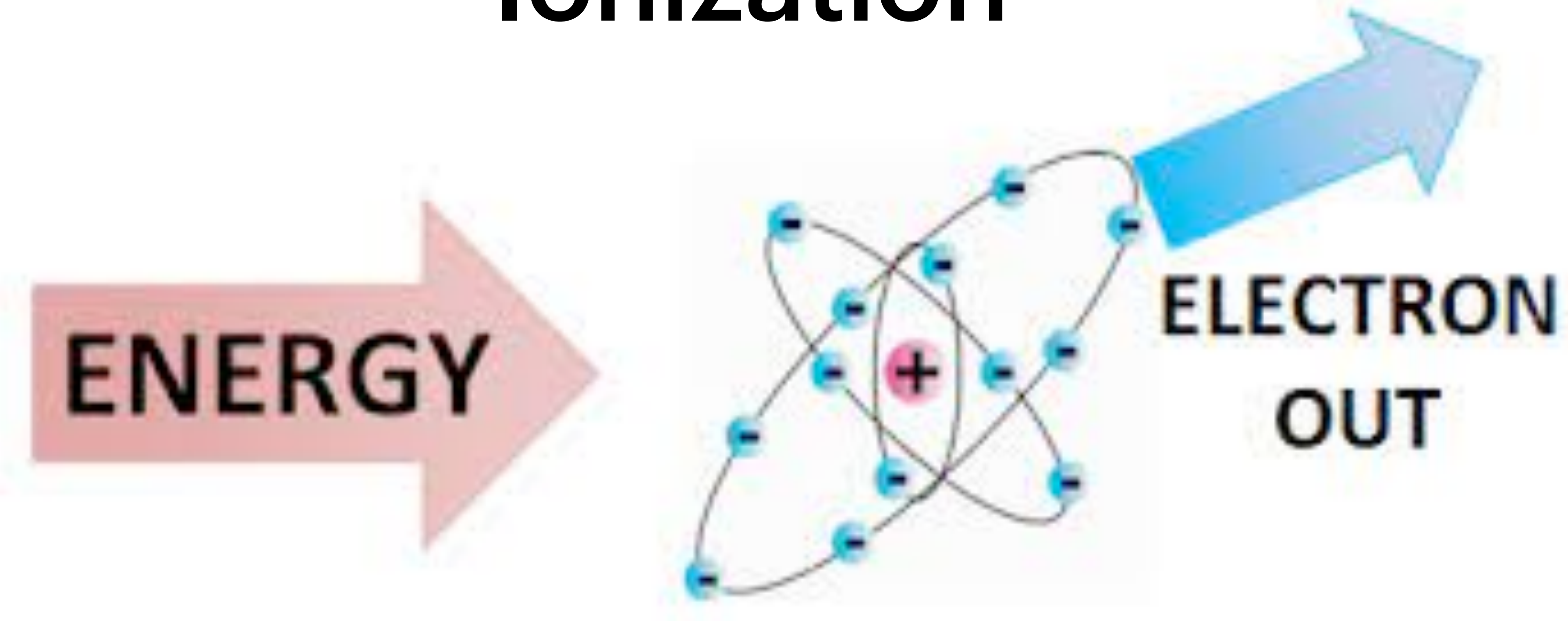


What signal?

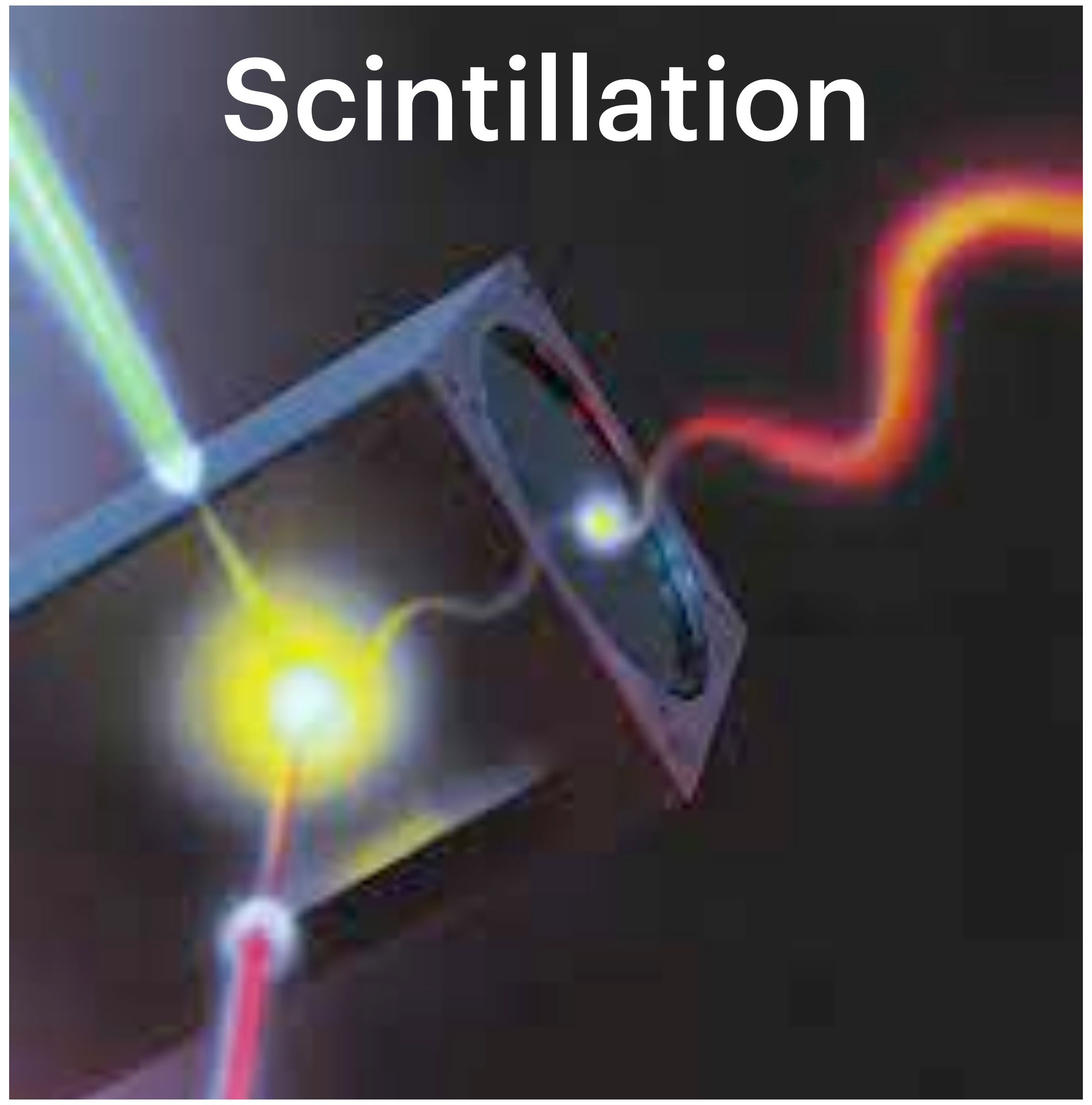




Ionization

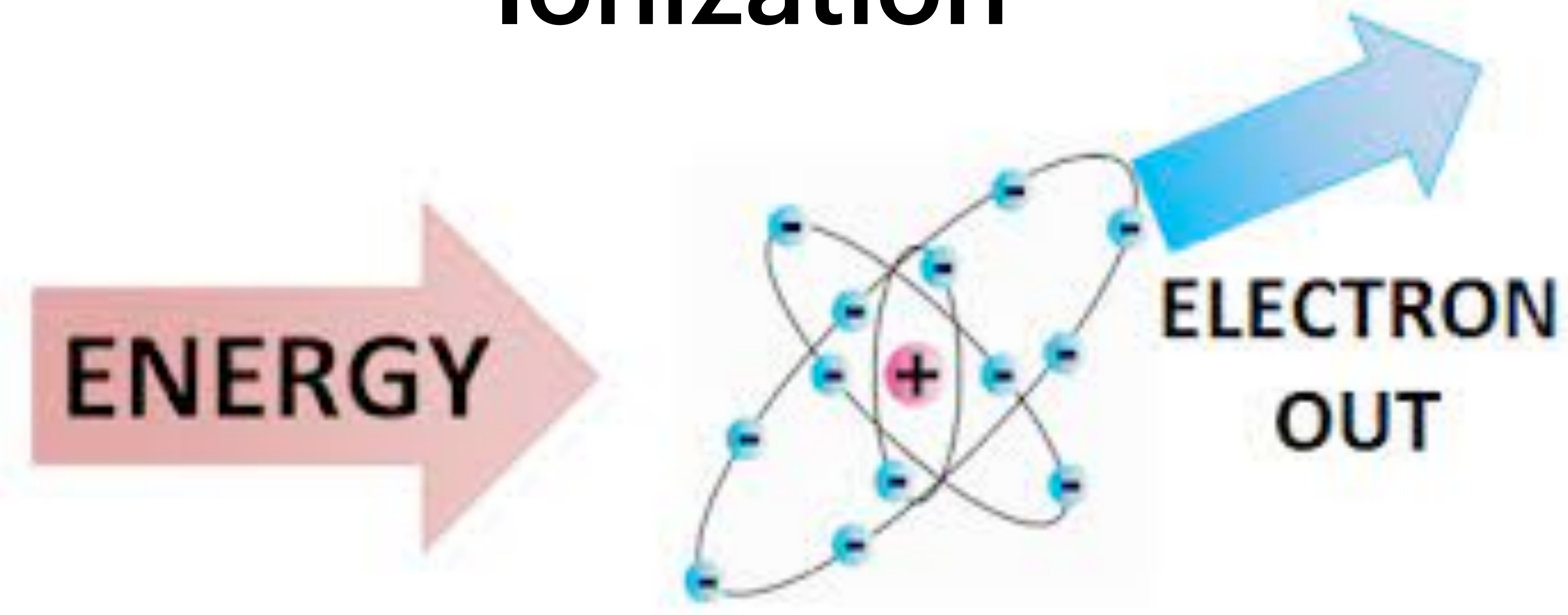


What signal?

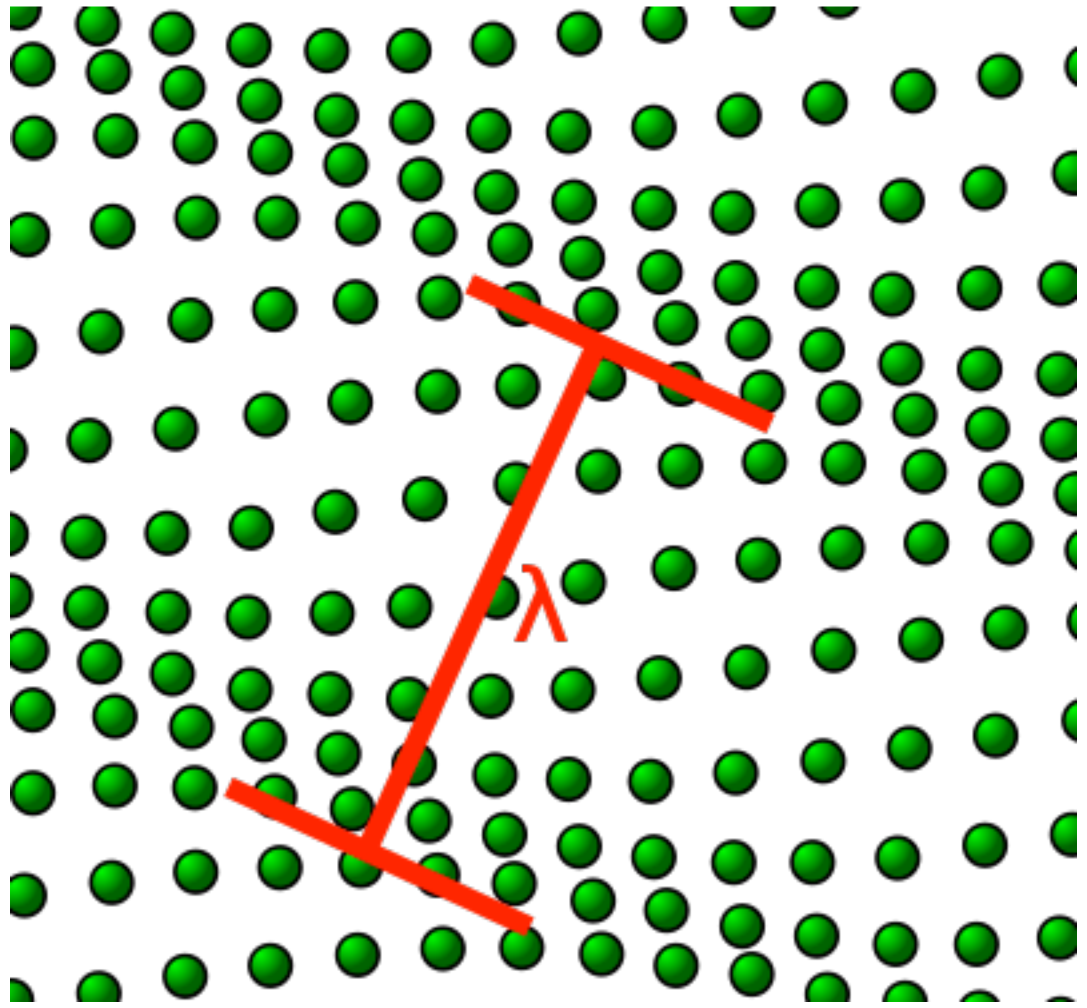


E_R

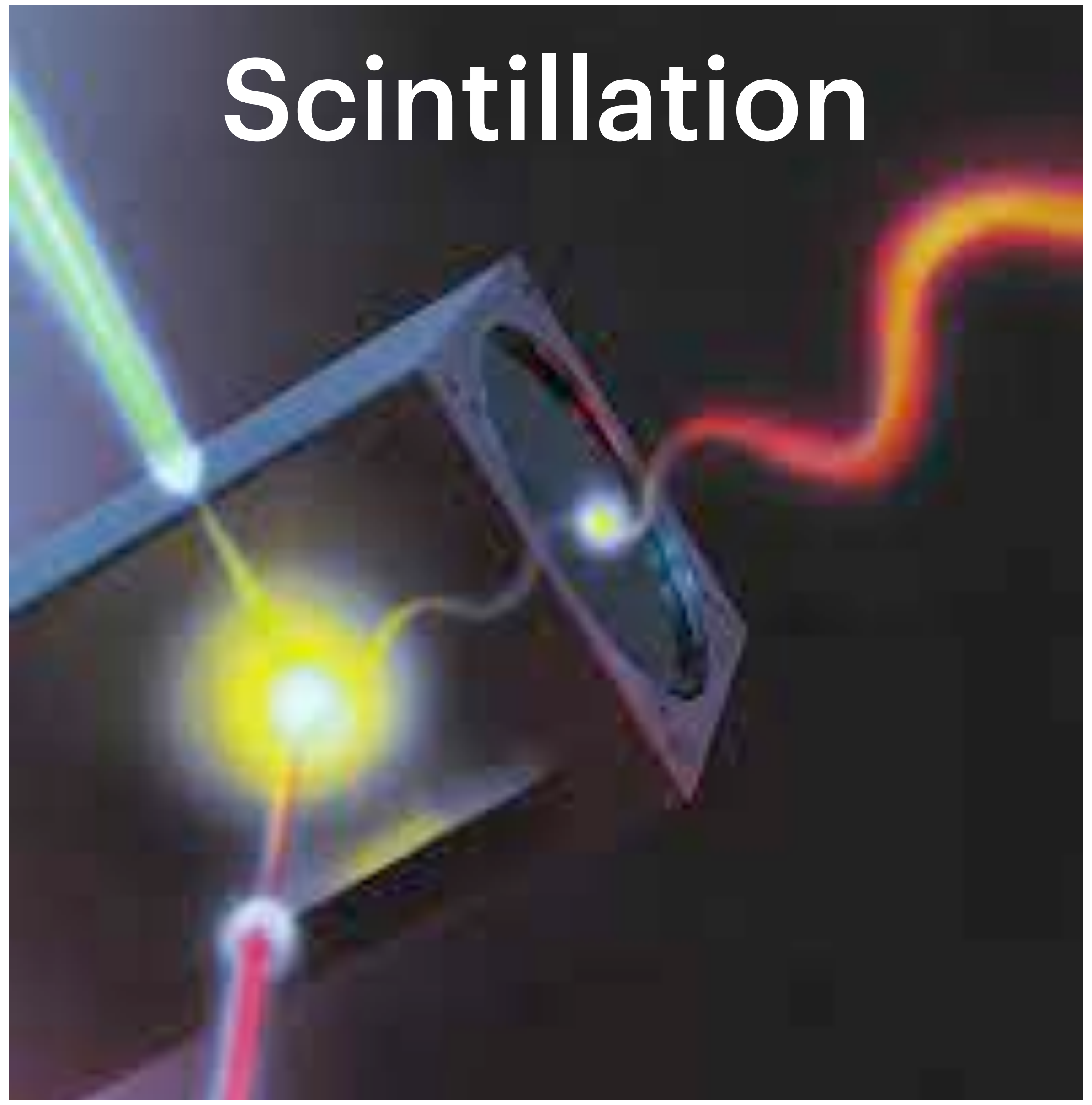
Ionization



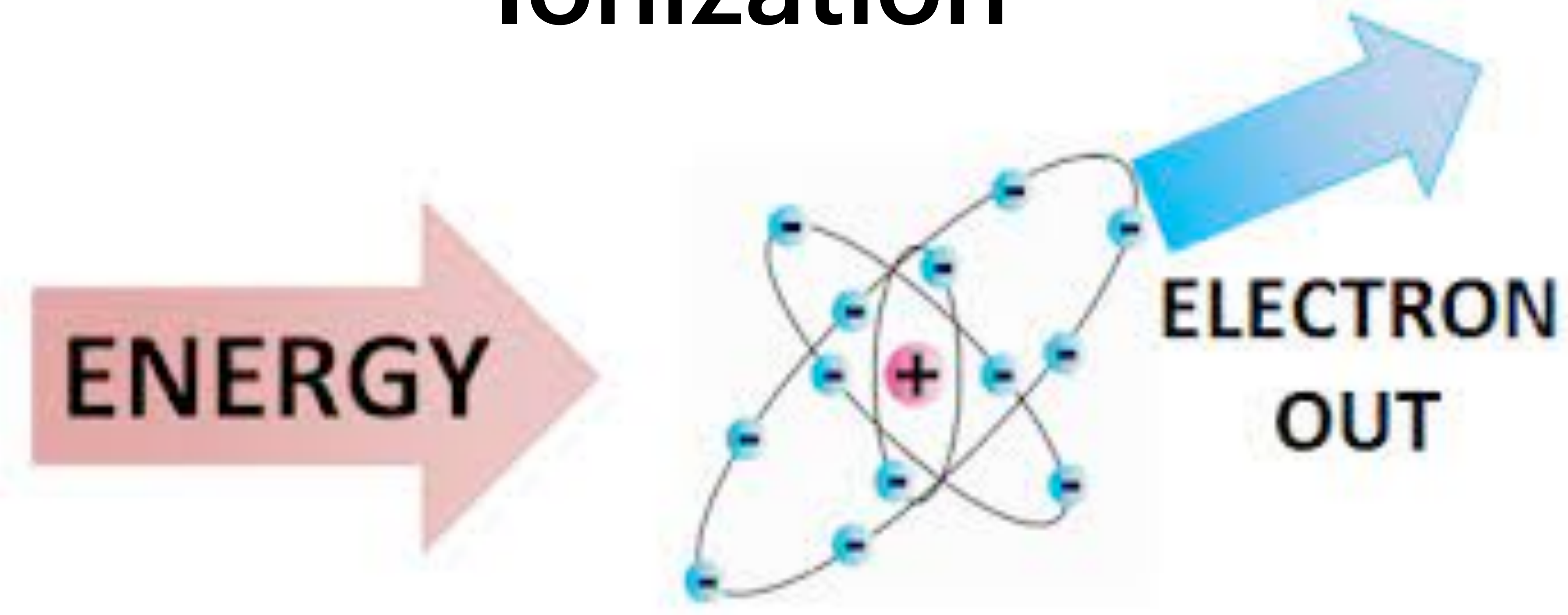
Phonons



What signal?

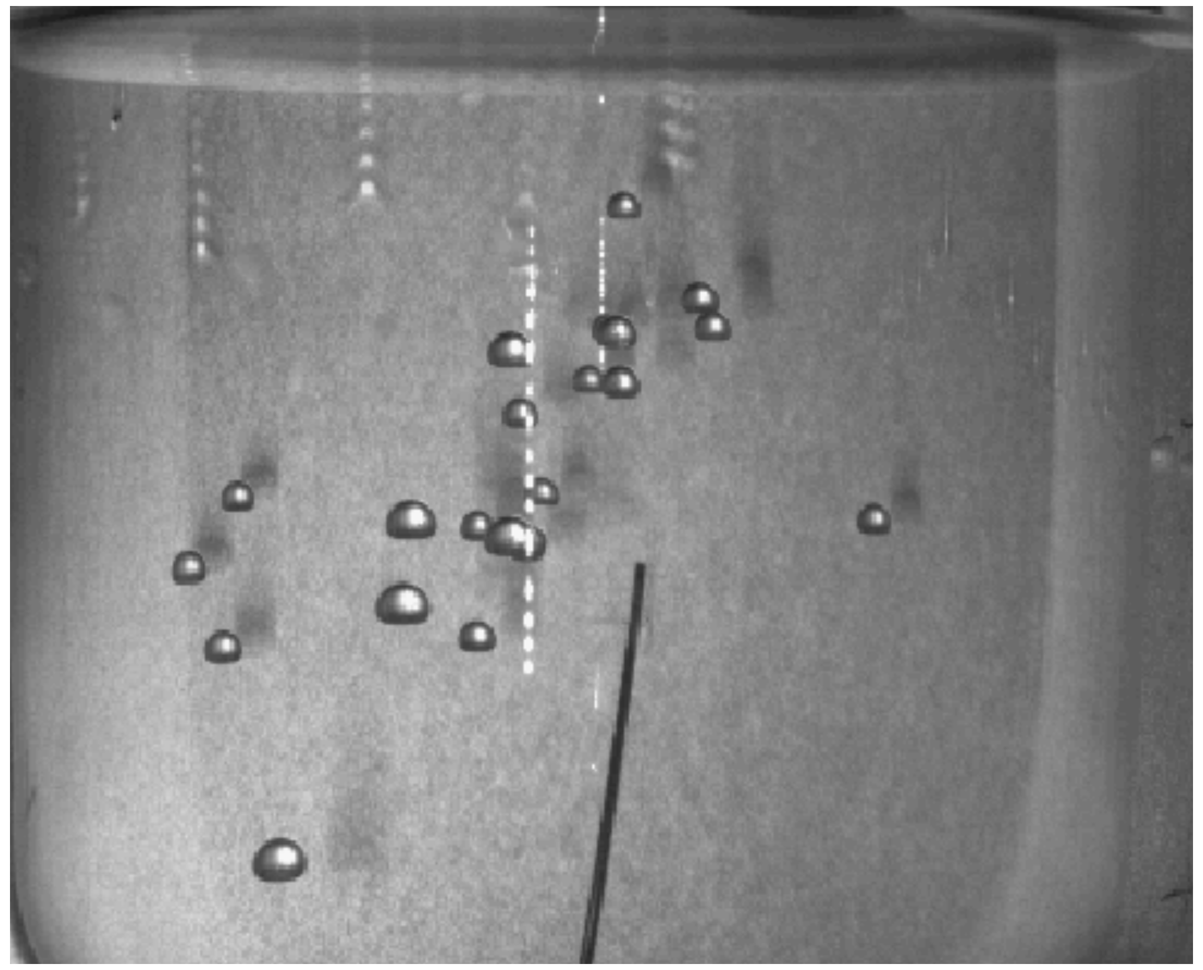


Ionization



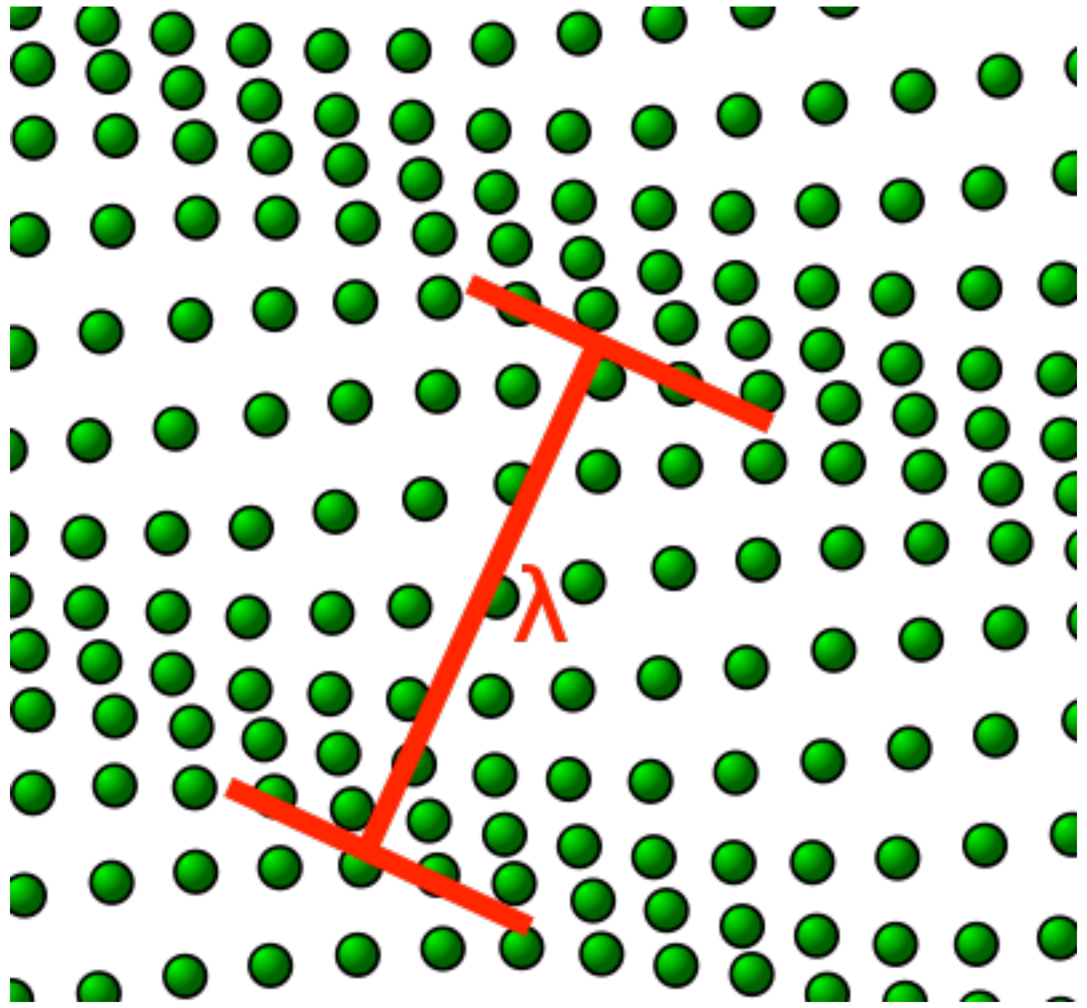
E_R

Phase transition

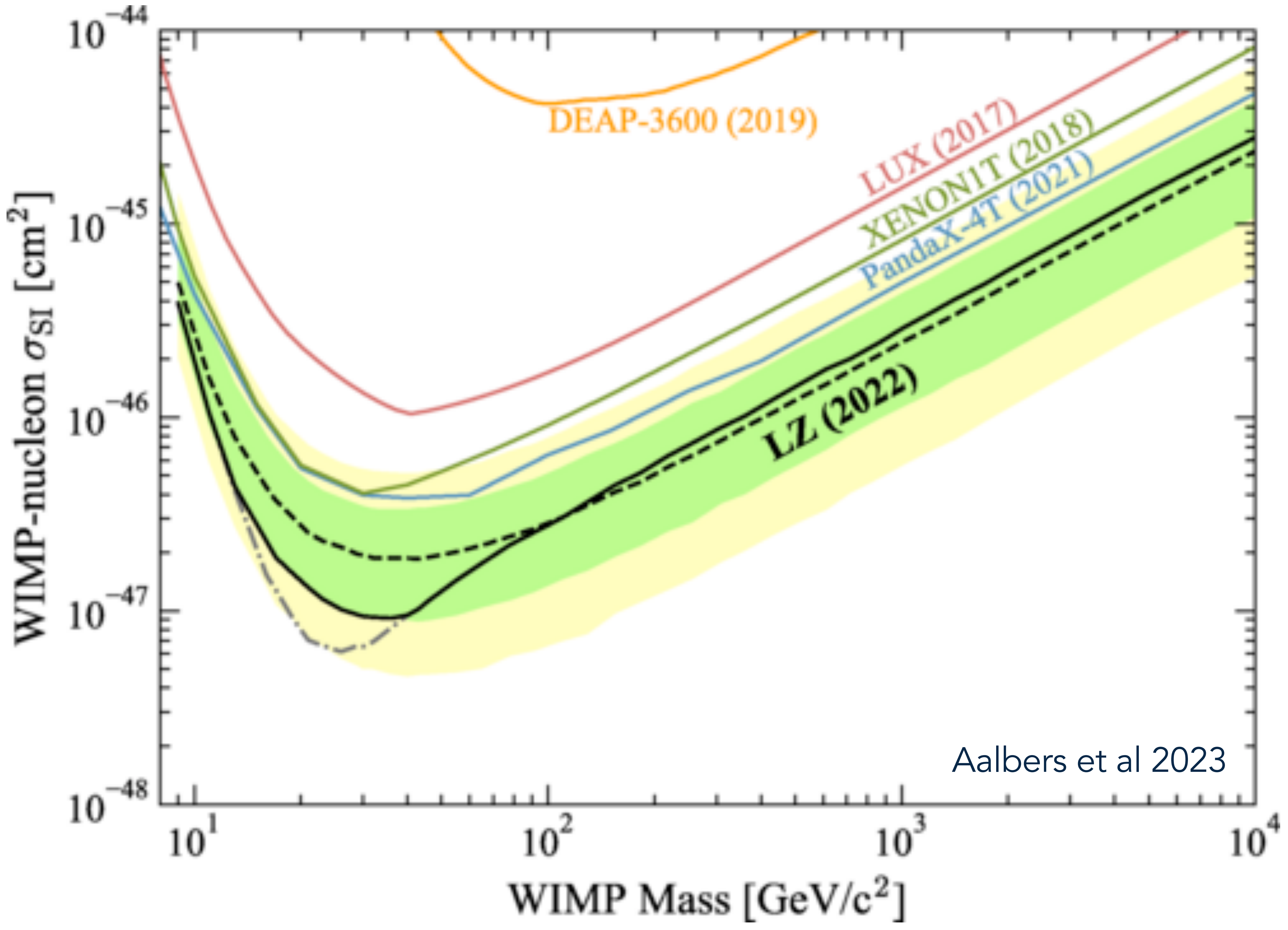


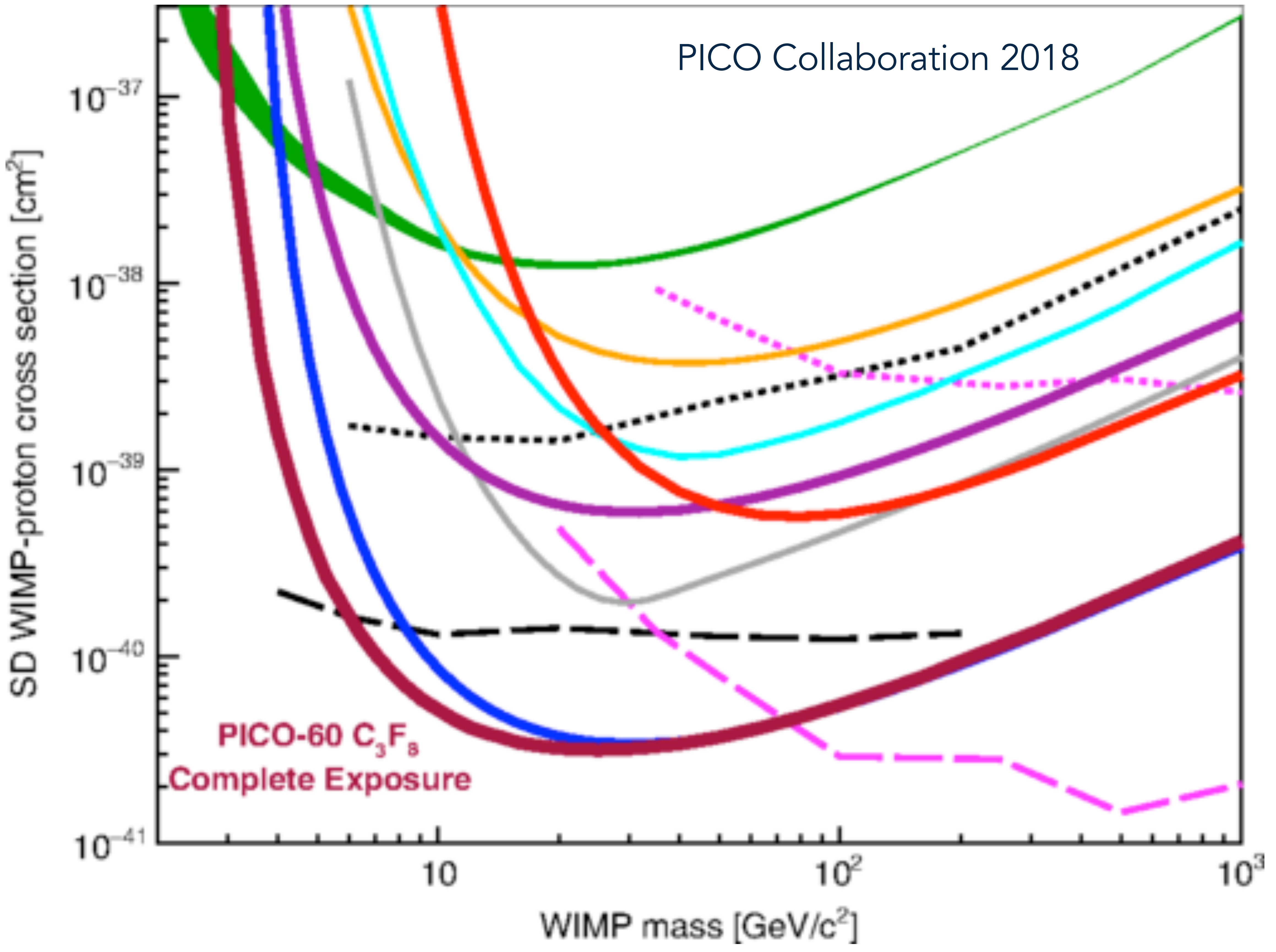
Bubbles in PICO-2L

Phonons



Placing Limits on WIMP Cross-Section





Spin-Independent vs Spin-Dependent Scattering

Spin-Independent

Interaction does not depend on the spin of the particles involved

$$\sigma_{NX}^{SI} \propto (Zf_p + (A-Z)f_n)^2$$

"effective couplings"

Citation

Spin-Independent vs Spin-Dependent Scattering

Spin-Independent

Interaction does not depend on the spin of the particles involved

$$\sigma_{NX}^{SI} \propto (Zf_p + (A-Z)f_n)^2$$

"effective couplings"

Spin-Dependent

Interaction does depend on spin: effectively couples to the *net* particle spin

angular momentum of atom

$$\sigma_{NX}^{SD} \propto \frac{J+1}{J}[a_p\langle S_p\rangle + a_n\langle S_n\rangle]^2$$

average nucleon spins

Citation

Spin-Independent vs Spin-Dependent Scattering

Spin-Independent

Interaction does not depend on the spin of the particles involved

$$\sigma_{NX}^{SI} \propto (Zf_p + (A - Z)f_n)^2$$

Spin-Dependent

Interaction does depend on spin: effectively couples to the *net* particle spin

$$\sigma_{NX}^{SD} \propto \frac{J+1}{J}[a_p\langle S_p\rangle + a_n\langle S_n\rangle]^2$$

Different experiments have different target nuclei: report DM-*nucleon* cross-section instead

$$\sigma_{NX}^{SI} = A^2\sigma_{nX}$$

$$\sigma_{(p,n)X} \propto |a_{p,n}|^2$$

Citation

Spin-Independent vs Spin-Dependent Scattering

Spin-Independent

Interaction does not depend on the spin of the particles involved

$$\sigma_{NX}^{SI} \propto (Zf_p + (A - Z)f_n)^2$$

Spin-Dependent

Interaction does depend on spin: effectively couples to the *net* particle spin

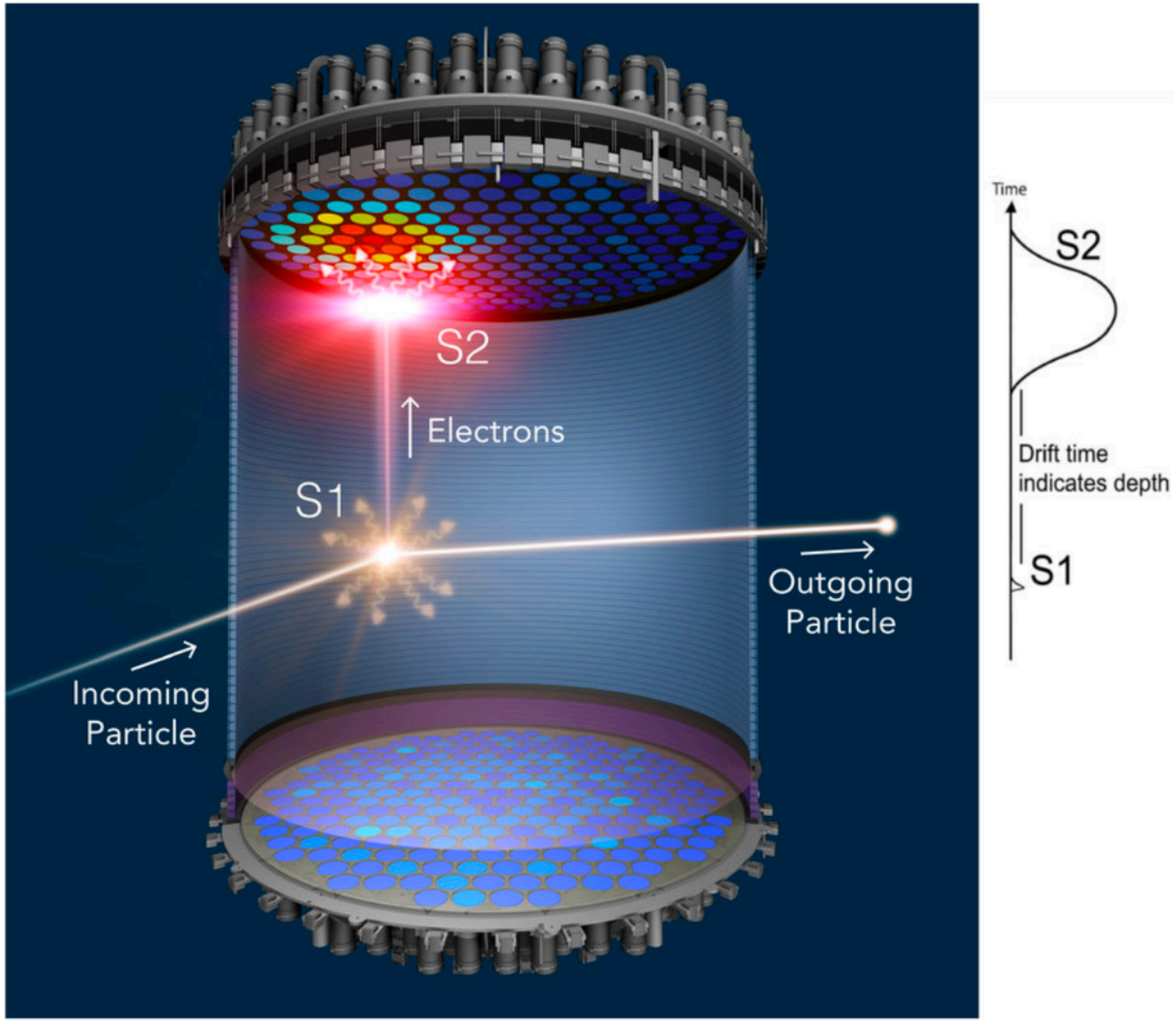
$$\sigma_{NX}^{SD} \propto \frac{J+1}{J}[a_p\langle S_p\rangle + a_n\langle S_n\rangle]^2 S^2(q)$$

Different experiments have different target nuclei: report DM-*nucleon* cross-section instead

$$\sigma_{NX}^{SI} = A^2\sigma_{nX}F^2(q)$$

Form factors take into account the structure of the nucleus: these are not free particles

SI: Dual-Phase Time-Projection Chamber (TPC)



Noble liquids:

Xenon (LZ, XENONnT), Argon (DarkSide)

→ avoid radioactive isotopes

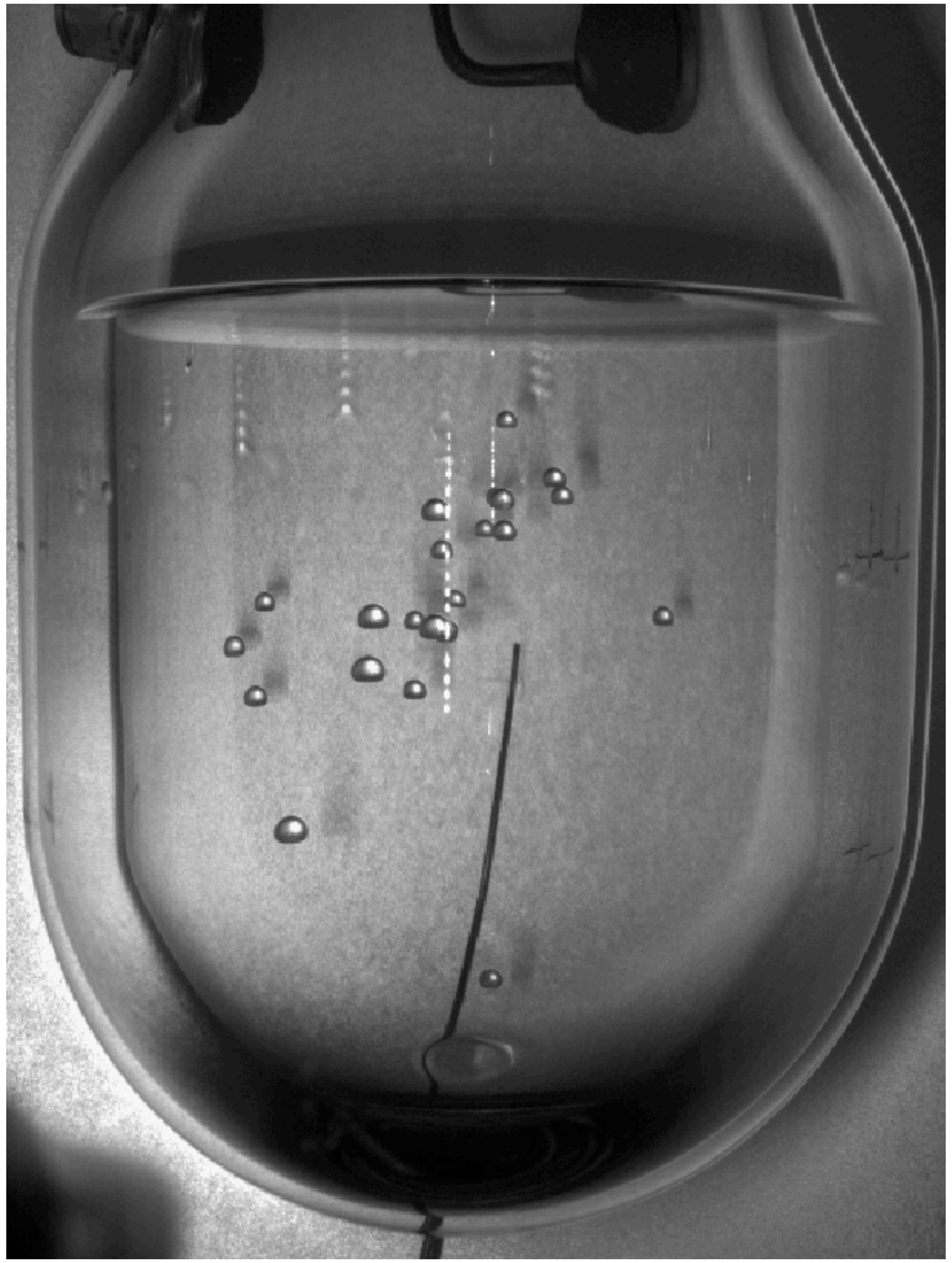
→ $\sigma_{NX}^{SI} = A^2 \sigma_{nX}$ — use a large nucleus!

→ Good scintillator

→ Ask the experimental talks why they chose their target!

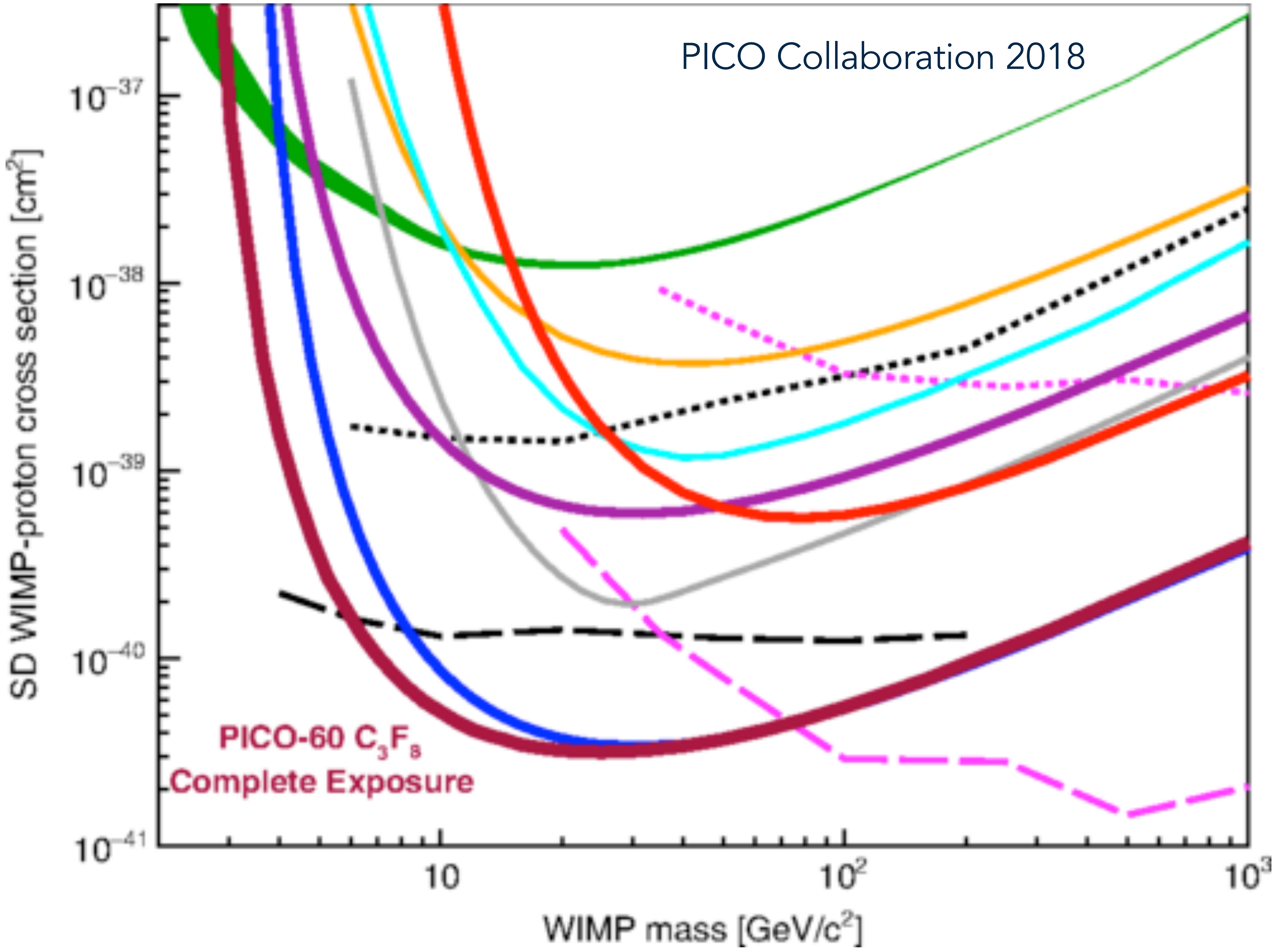
Citation

SD: Superheated C3F8

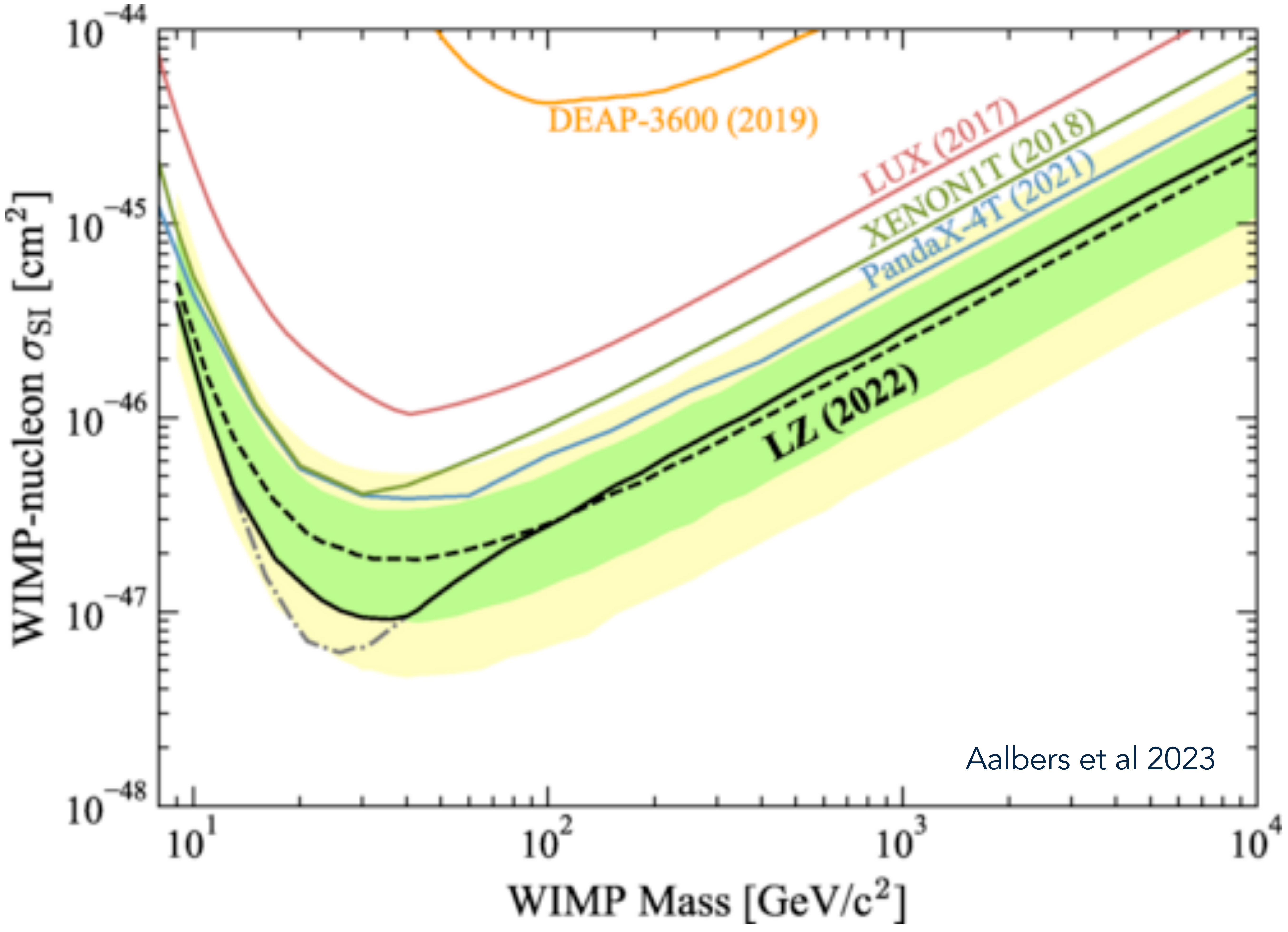


Bubbles in PICO-2L, SNOLAB Science Program 2016

Fluorine's unpaired proton & spin characteristics make it a good target for spin-dependent interactions

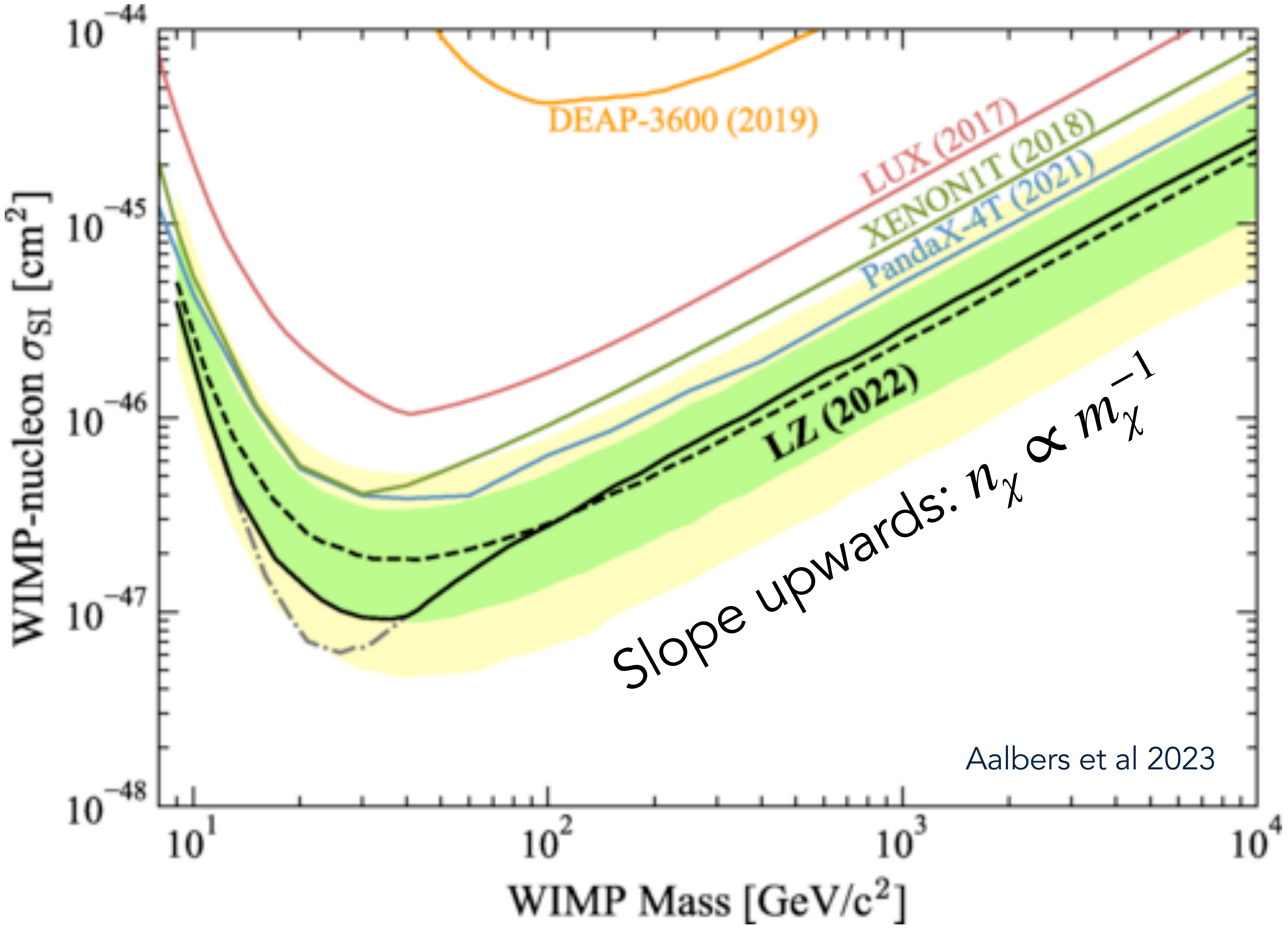


Reading a DM Exclusion Plot



Anything above each line is excluded to 95% confidence by that experiment

Reading a DM Exclusion Plot

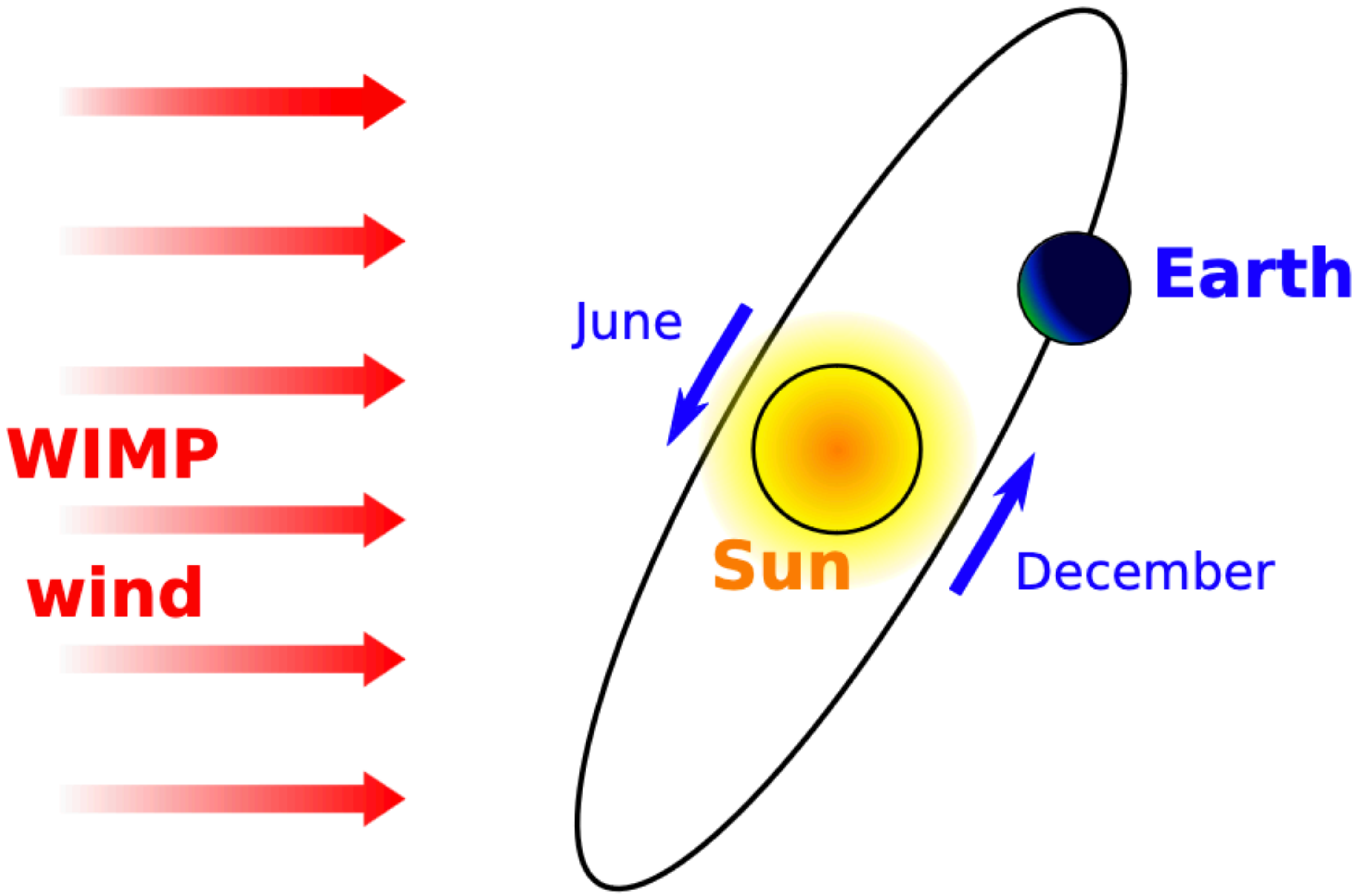


Anything above each line is excluded to 95% confidence by that experiment

Limited at low masses by E_{th}: recoil is small

Limited at the bottom by exposure (and E_{th})

A Distinctive Signature: Annual Modulation



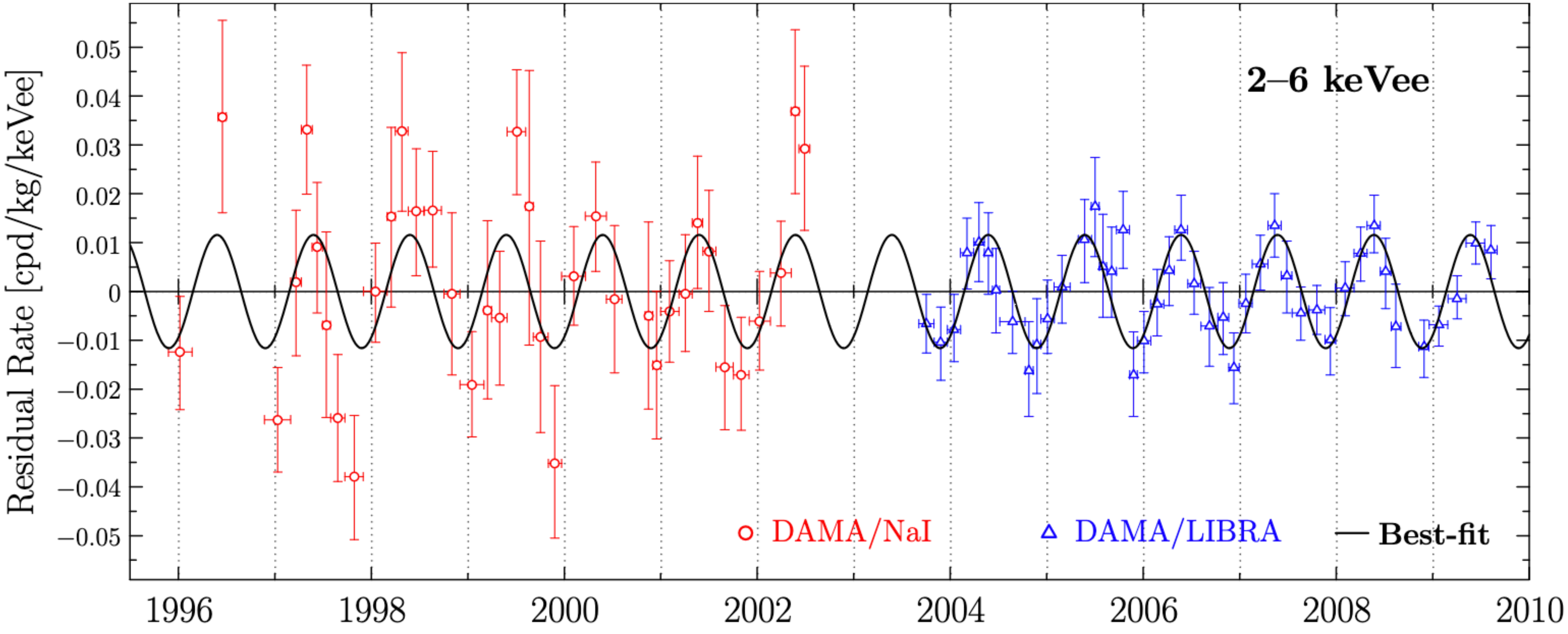
Freese et al 2013

The galactic disk rotates while the DM halo is non-rotating

Change in relative velocity because of Earth's rotation around Sun

DM rates should have some modulation, whereas backgrounds would not

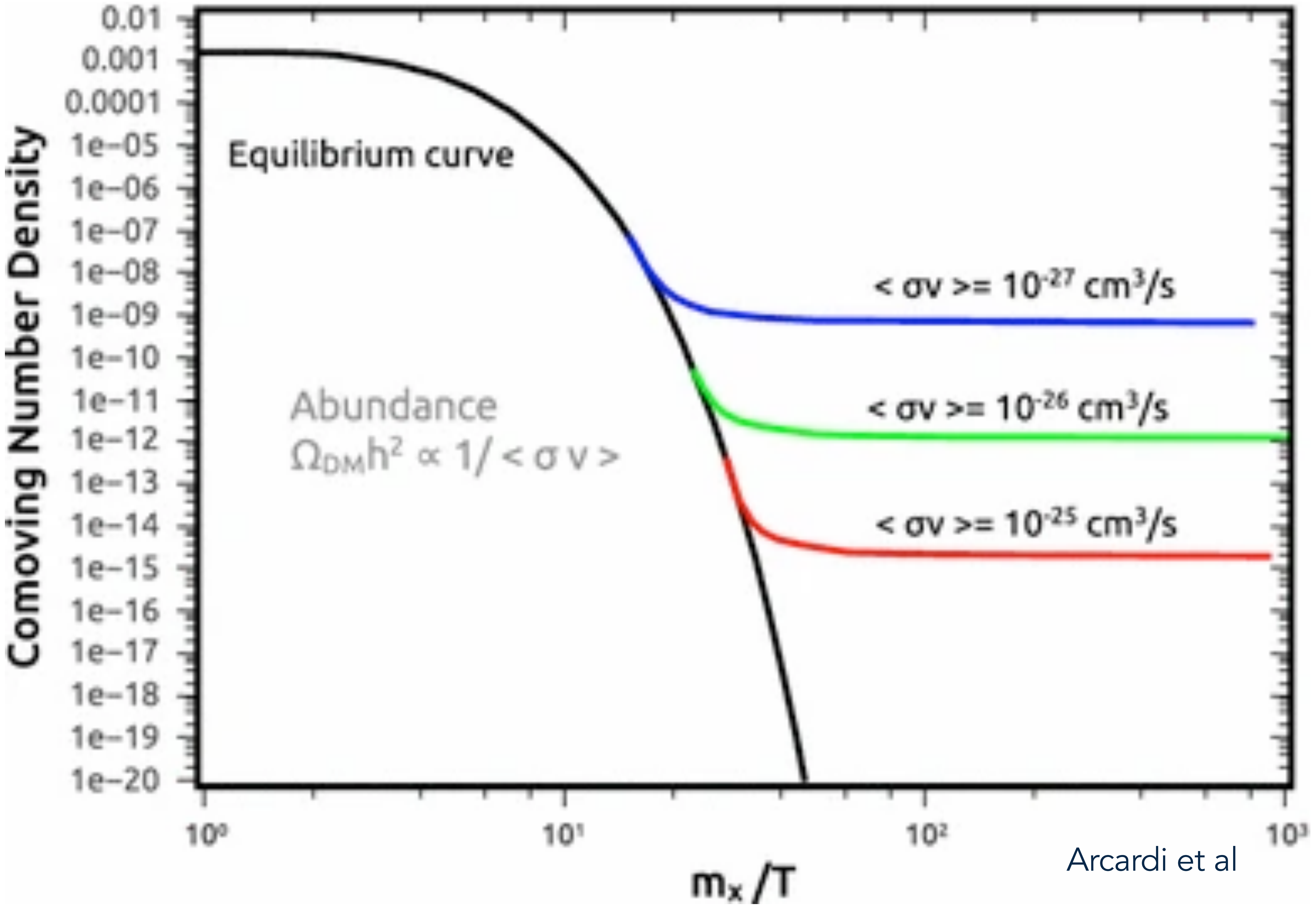
DAMA(-LIBRA)



DAMA-LIBRA

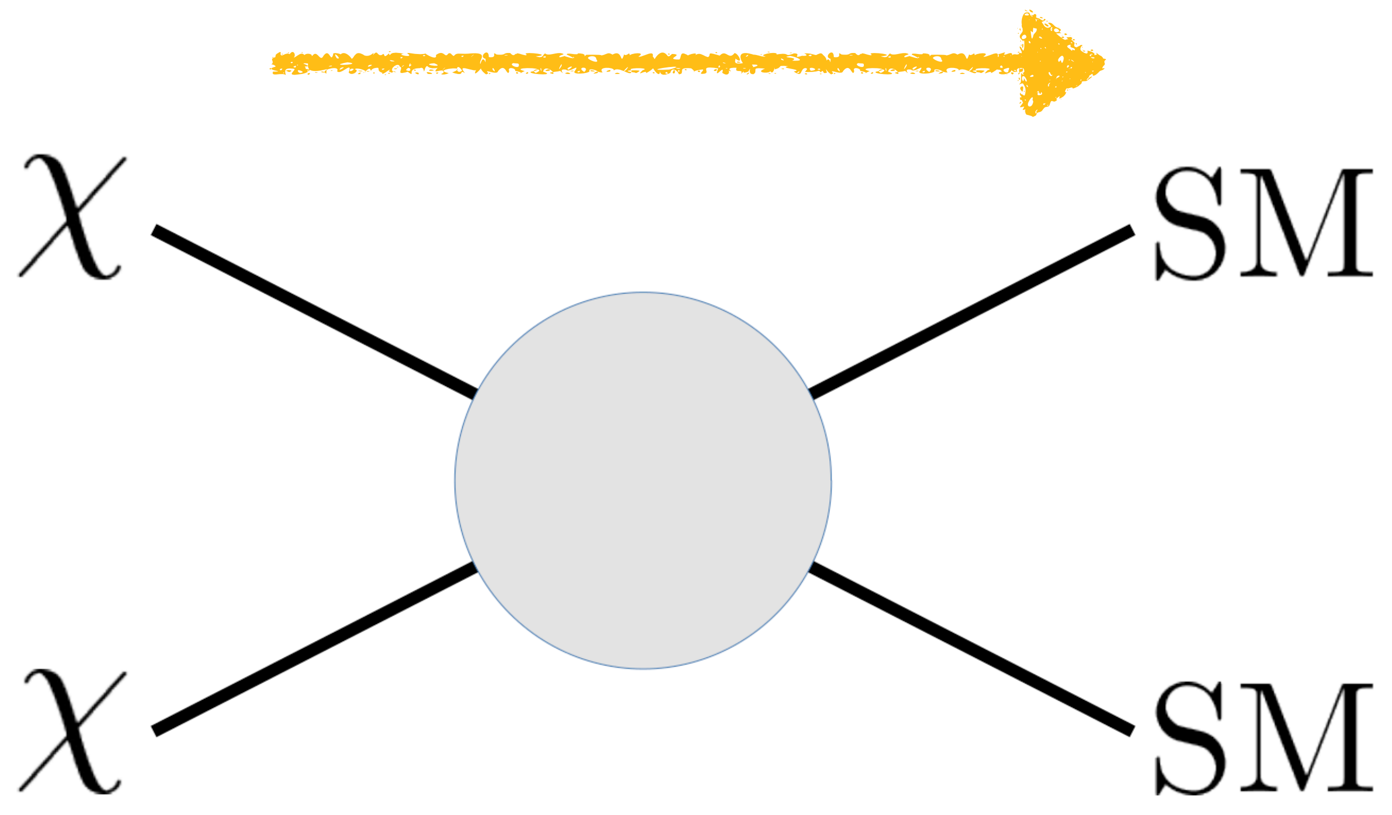
Before we move to indirect detection of WIMPs: any questions?

Thermal WIMP abundance was due to annihilations



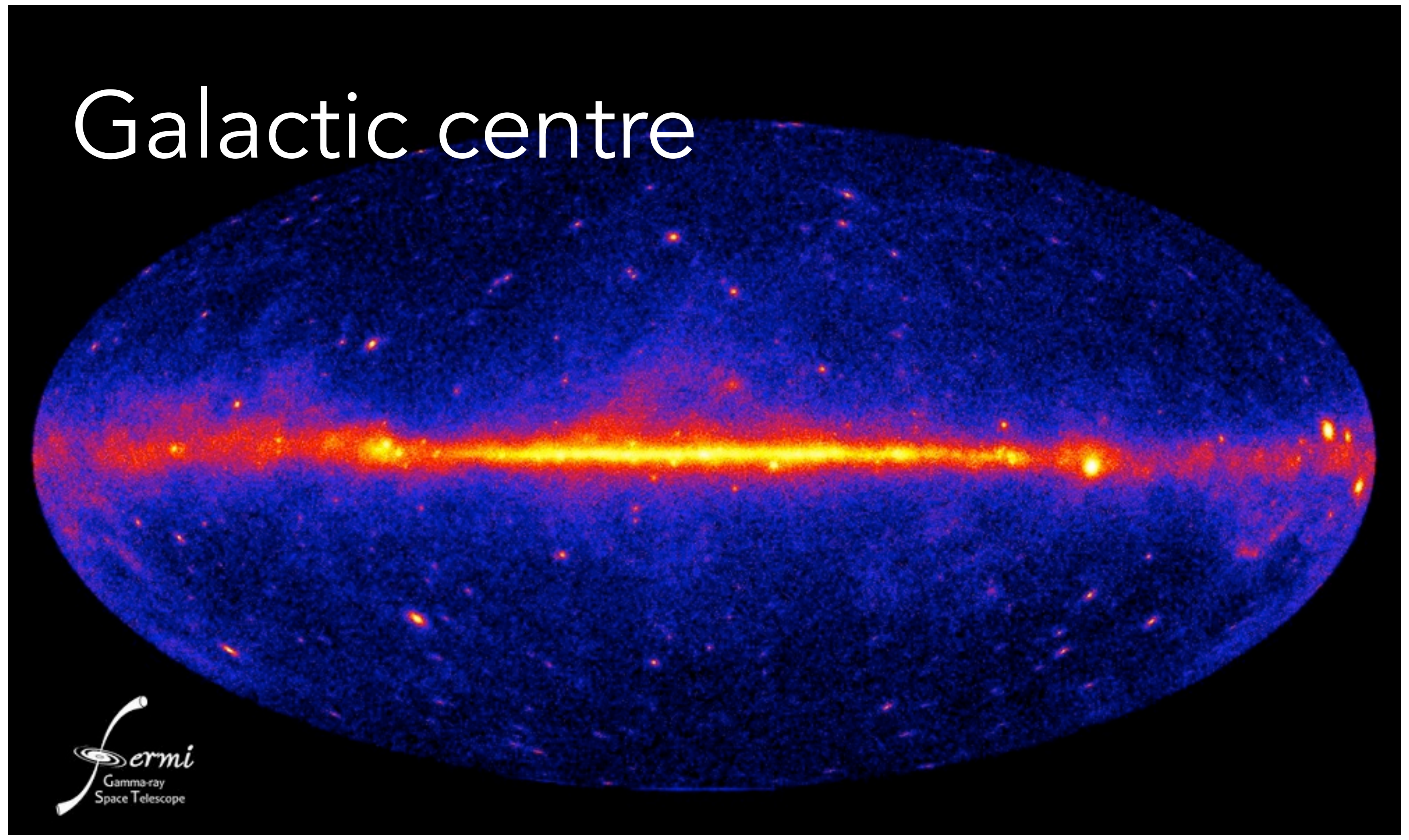
Arcardi et al

Indirect detection

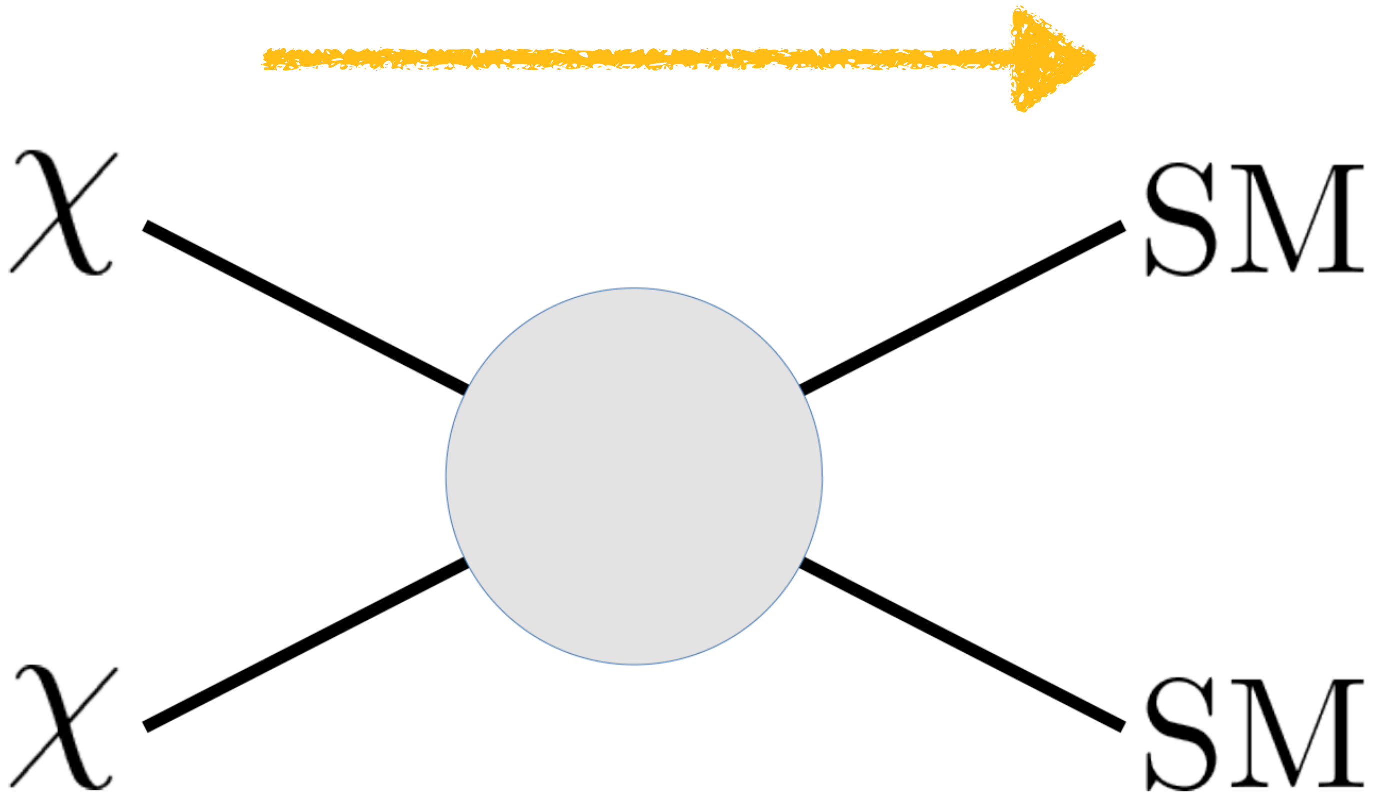


Citation

Thermal WIMP abundance was due to annihilations



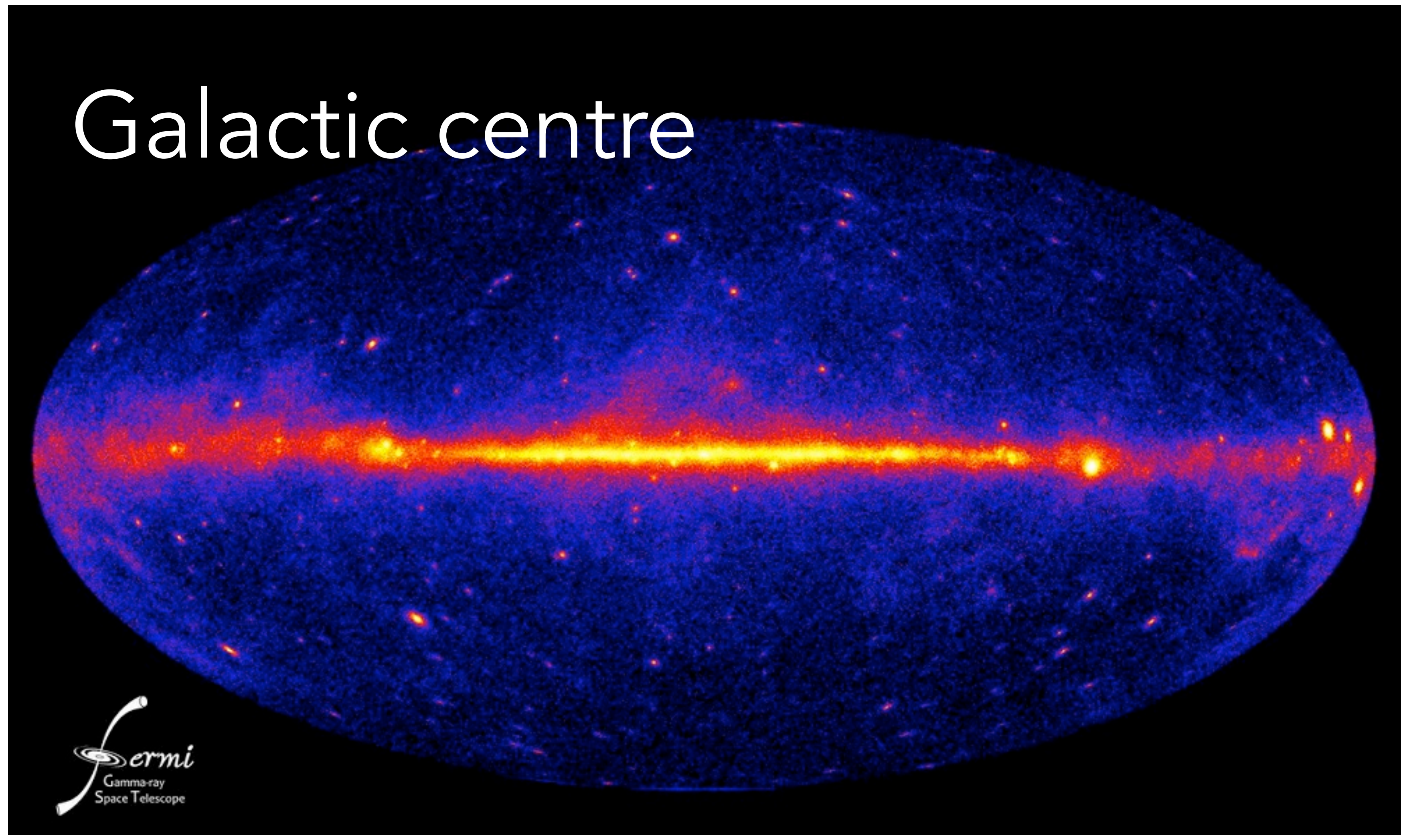
Indirect detection



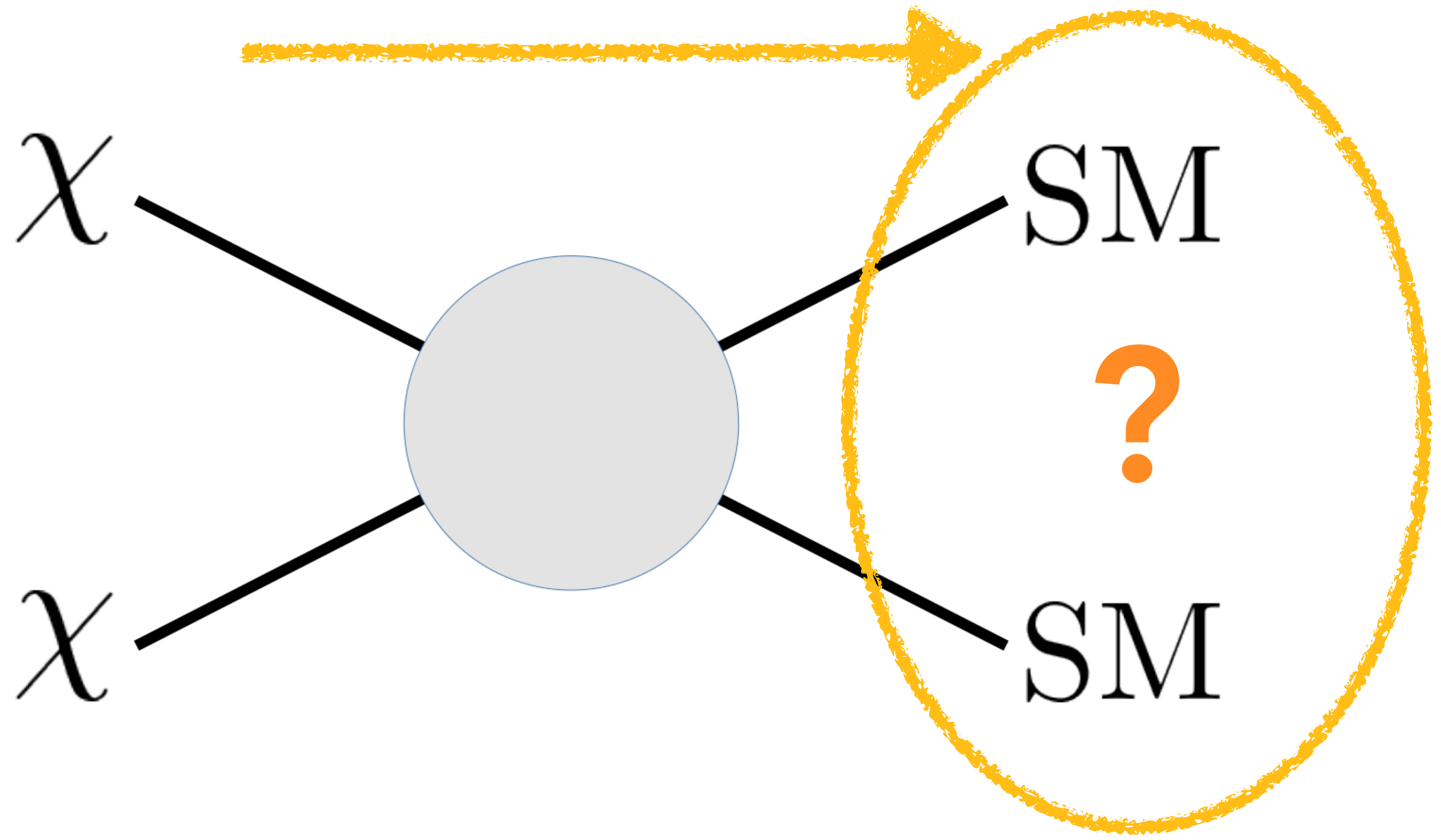
A small amount of annihilation is still possible, in regions with a large density of DM

Citation

Thermal WIMP abundance was due to annihilations



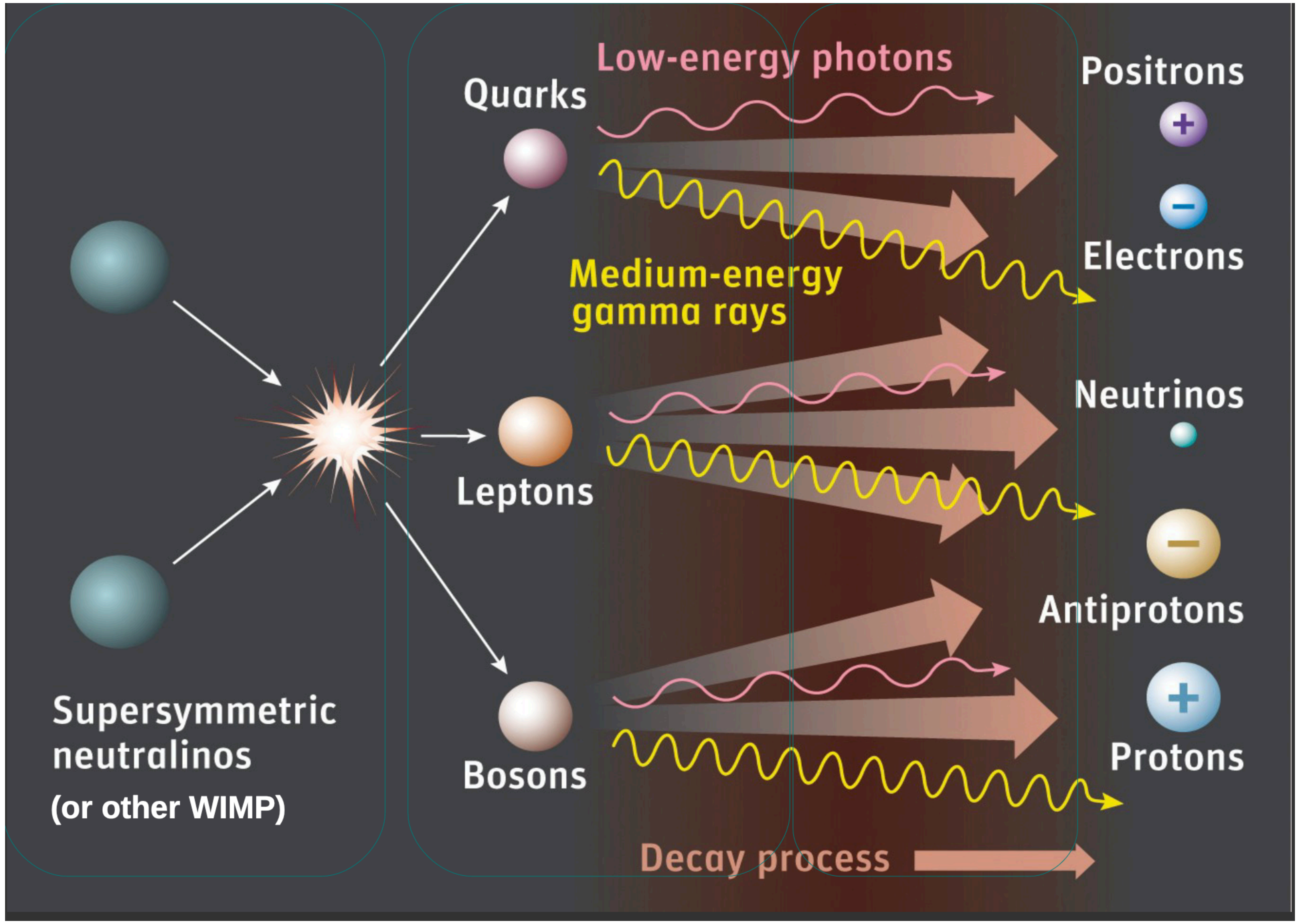
Indirect detection



Eventually…

Photons? Protons? Electrons? Neutrinos?

Why would DM annihilate (or decay) to photons?



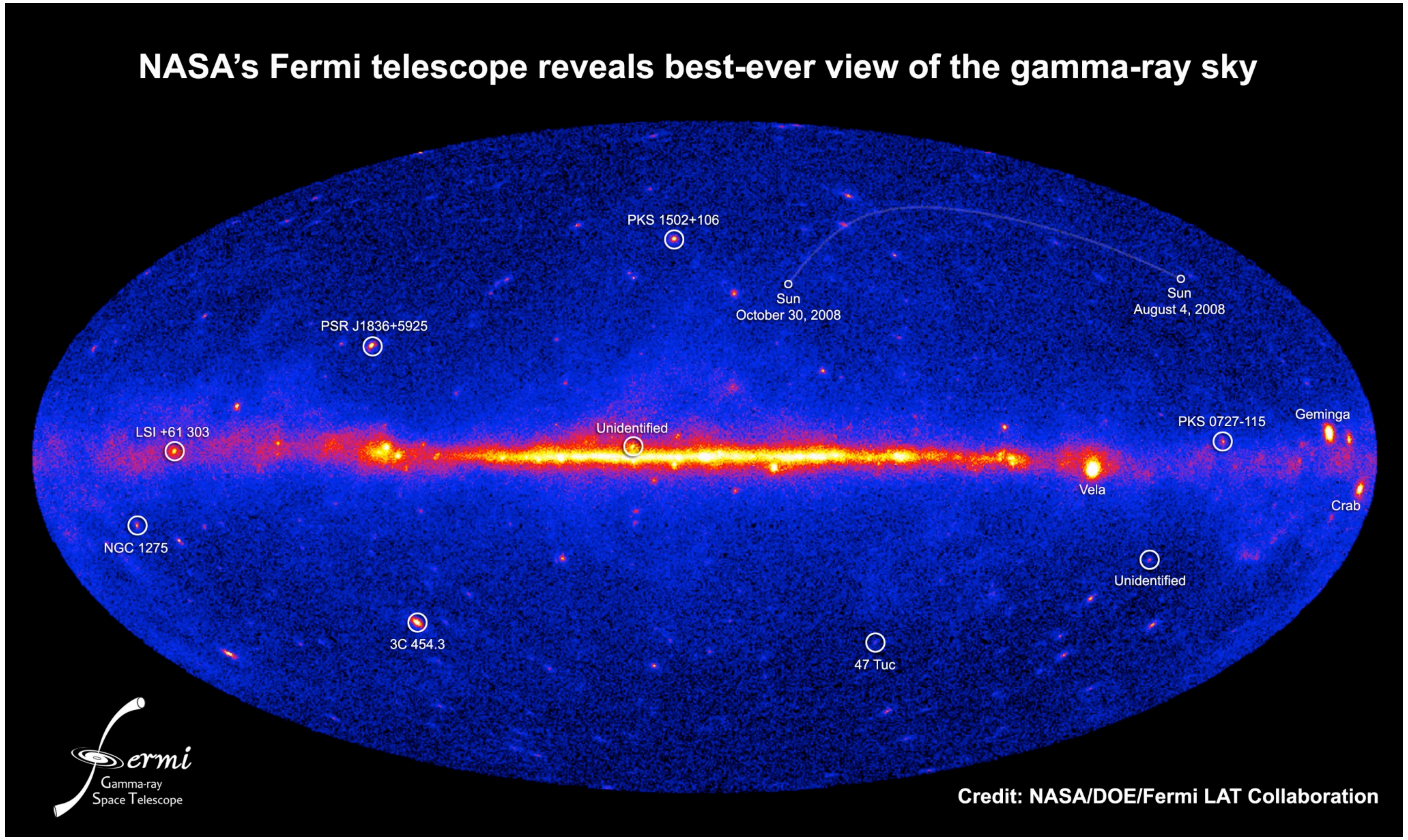
The SM products eventually themselves decay/annihilate

Decays of heavy products produce gamma rays, and e.g. pions, which decay to gamma rays, neutrinos, muons

Annihilation produces radiation

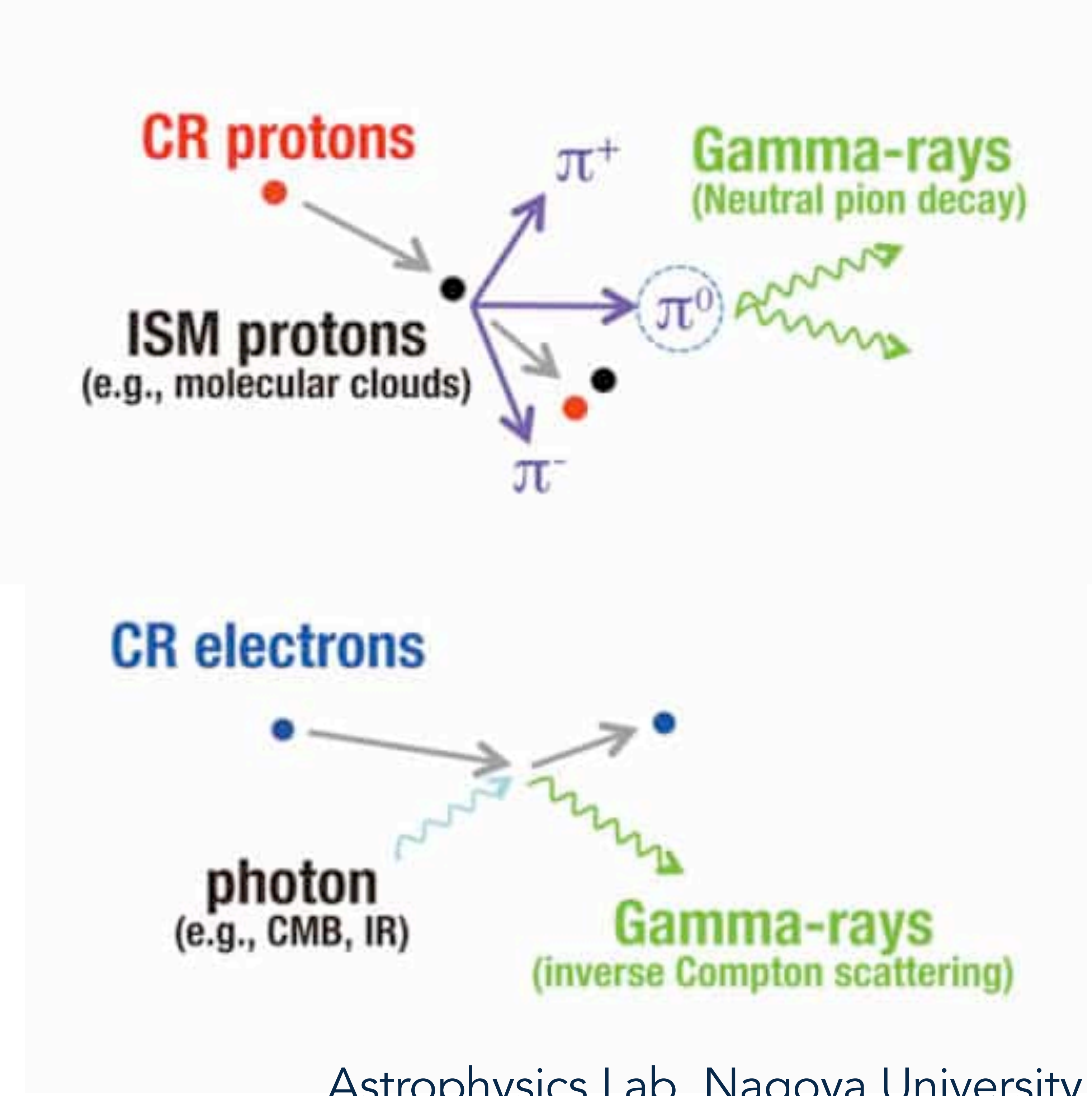
Citation

The Galactic-Centre Gamma Ray Excess



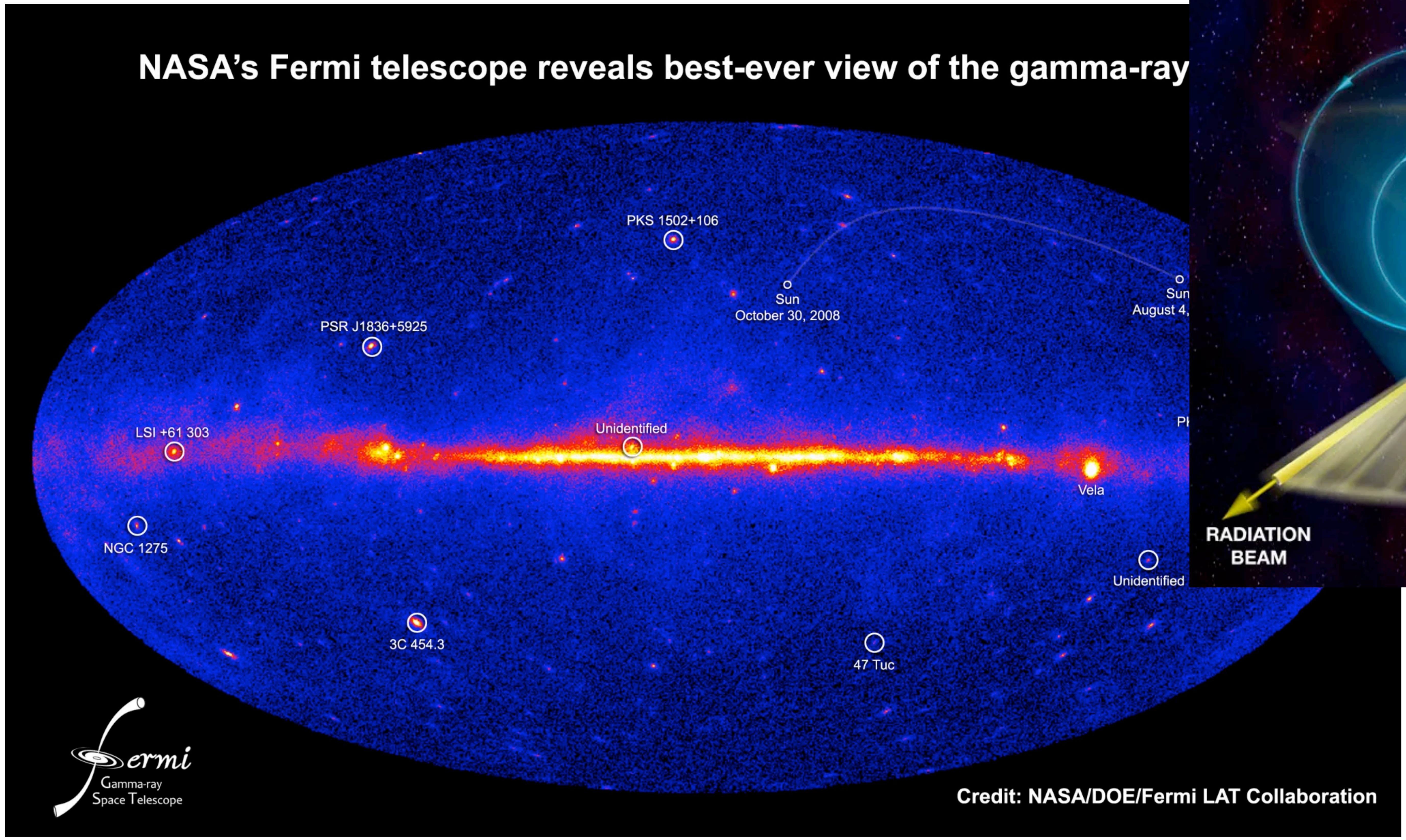
So bright!

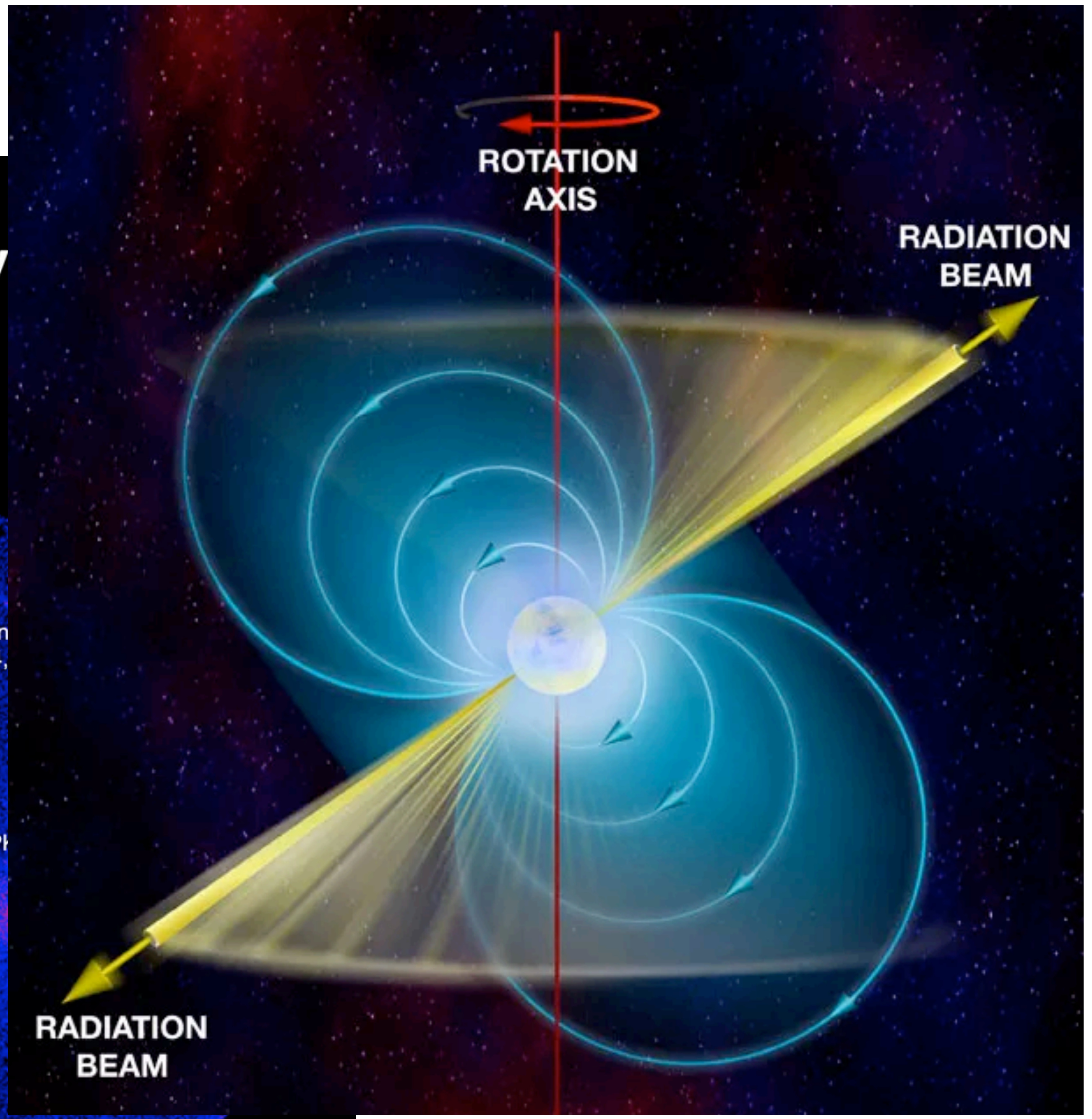
Much gas, much cosmic rays



Astrophysics Lab, Nagoya University

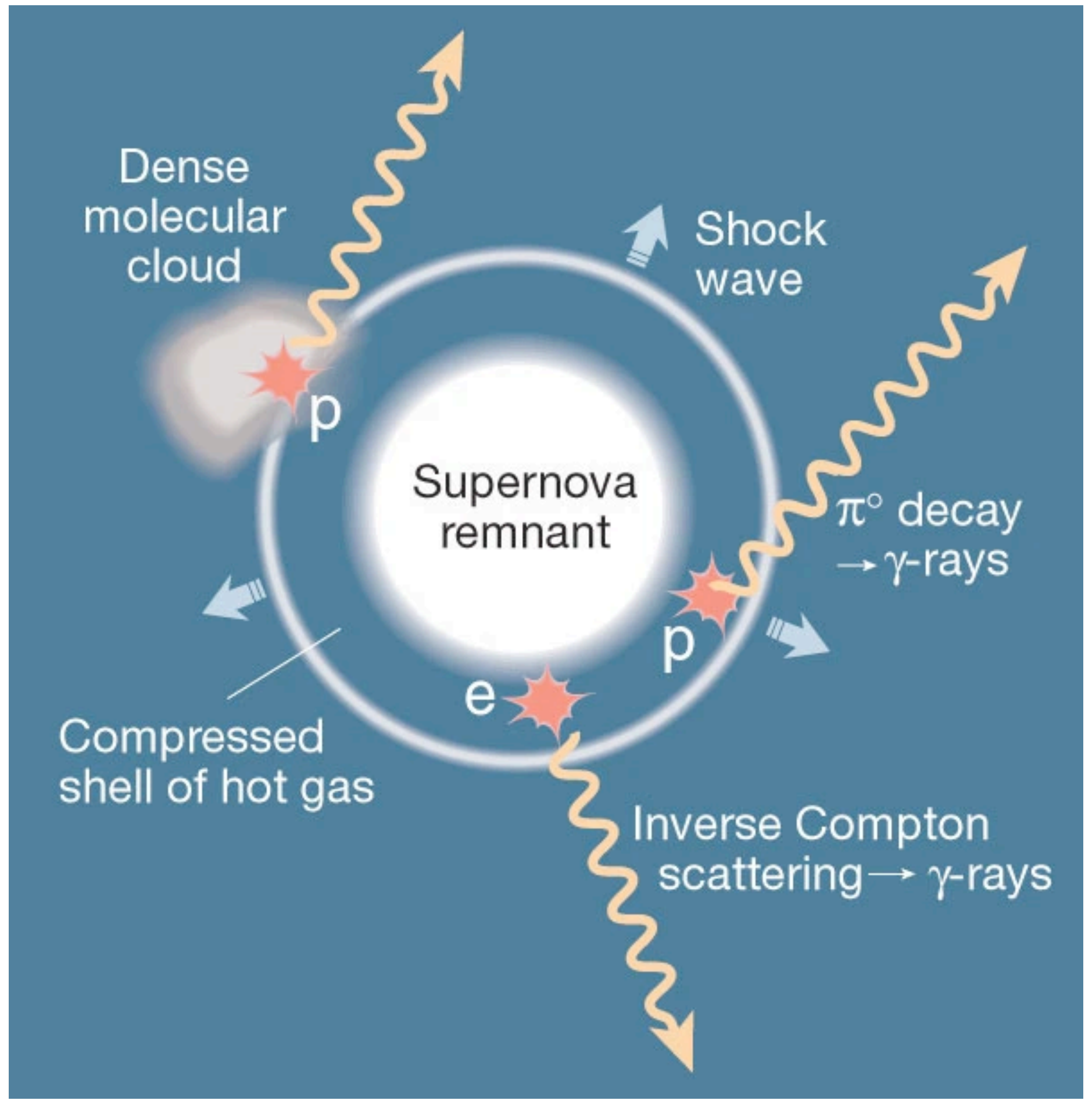
The Galactic-Centre Gamma Ray Excess





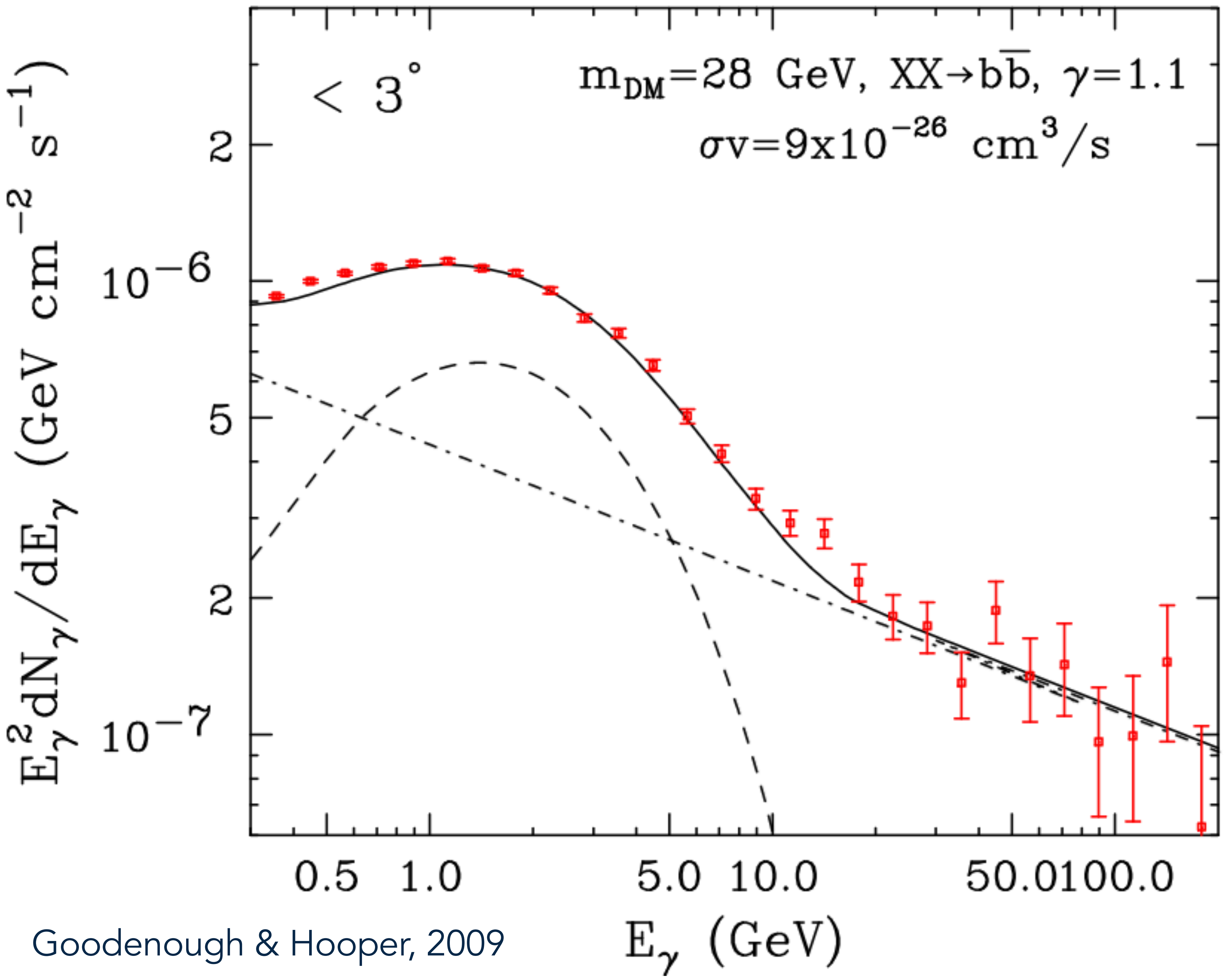
Pulsars accelerating CRs

Shock waves from SNR

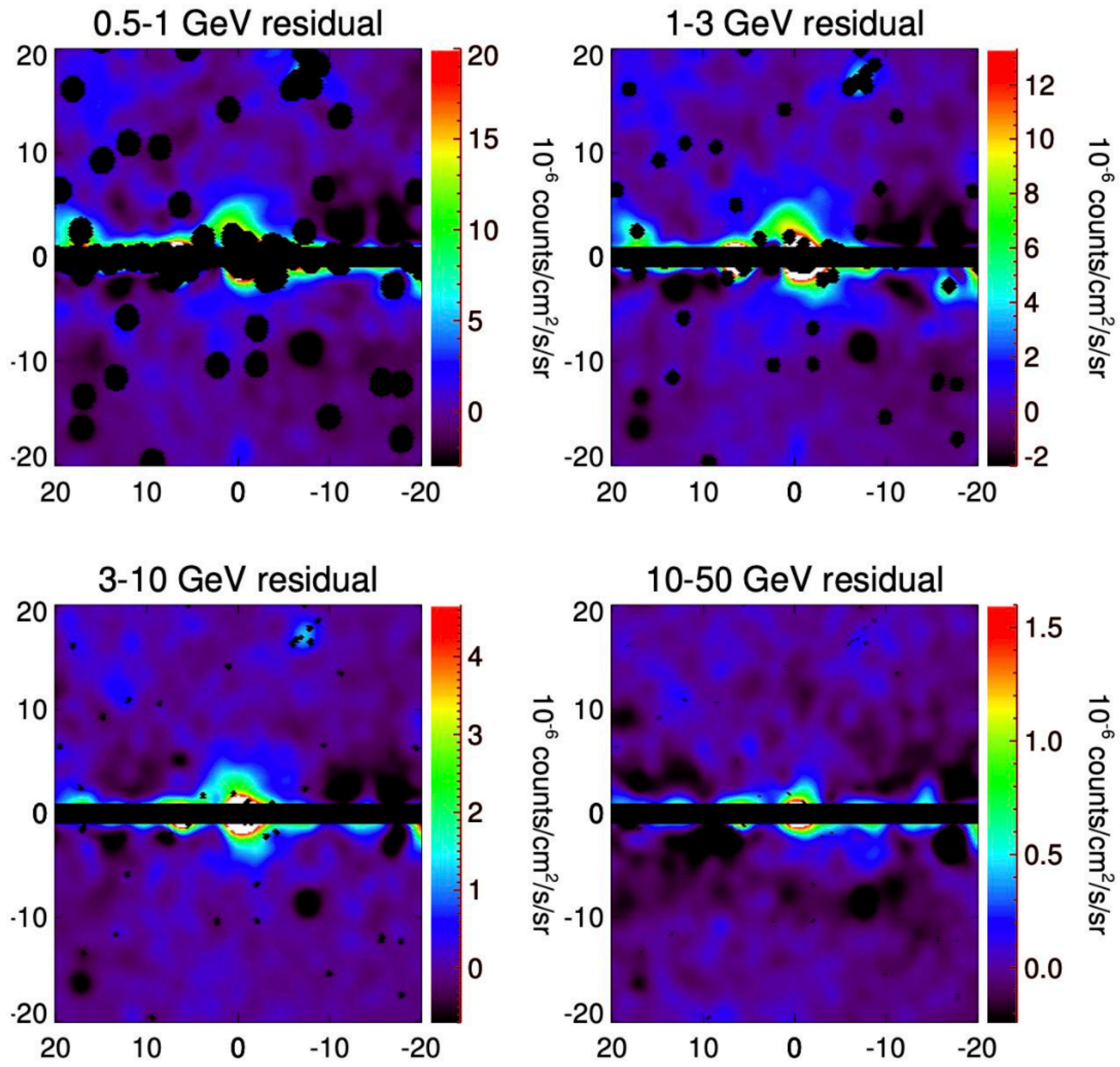


Nature

An excess of gamma rays?



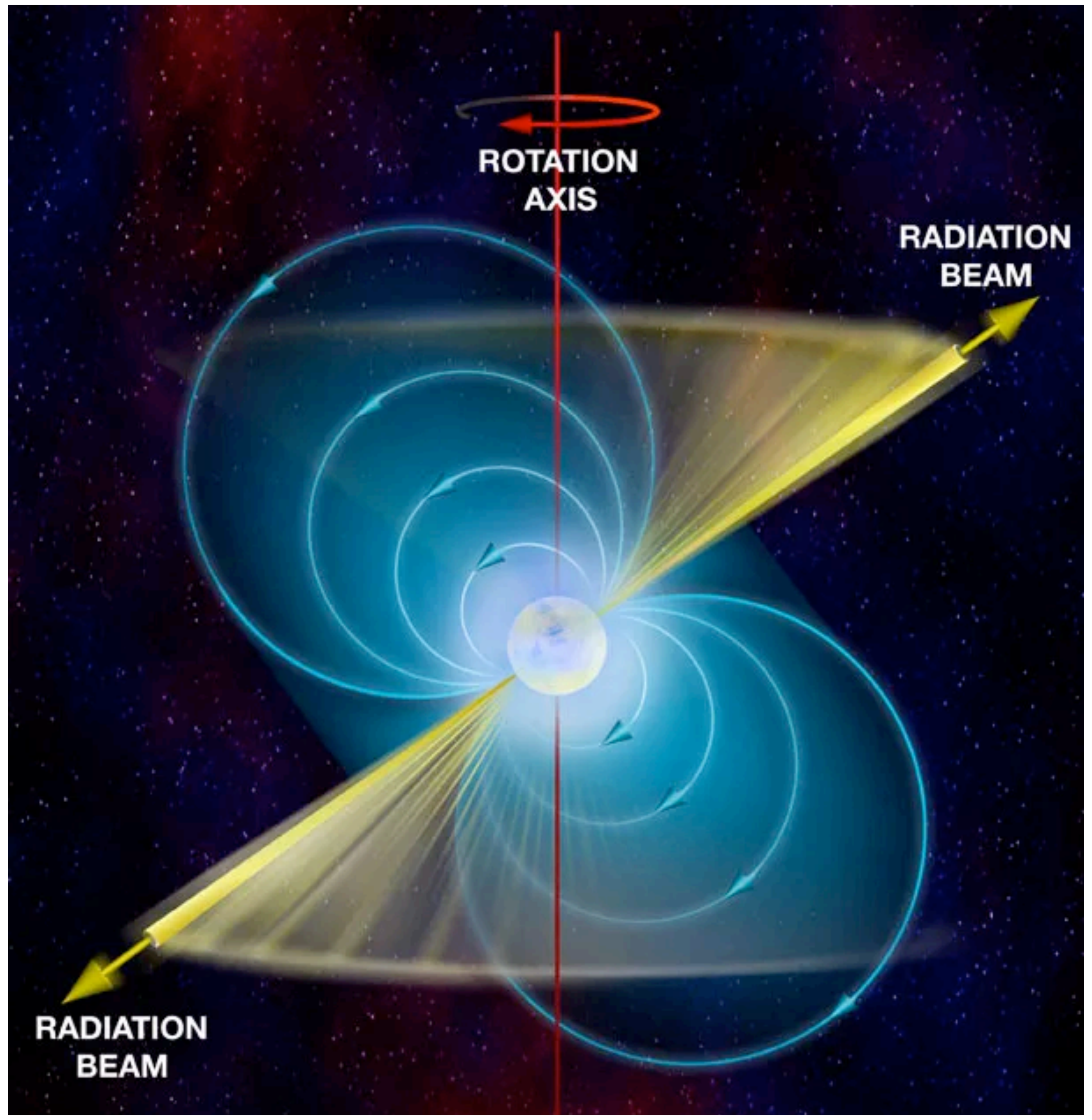
Goodenough & Hooper, 2009

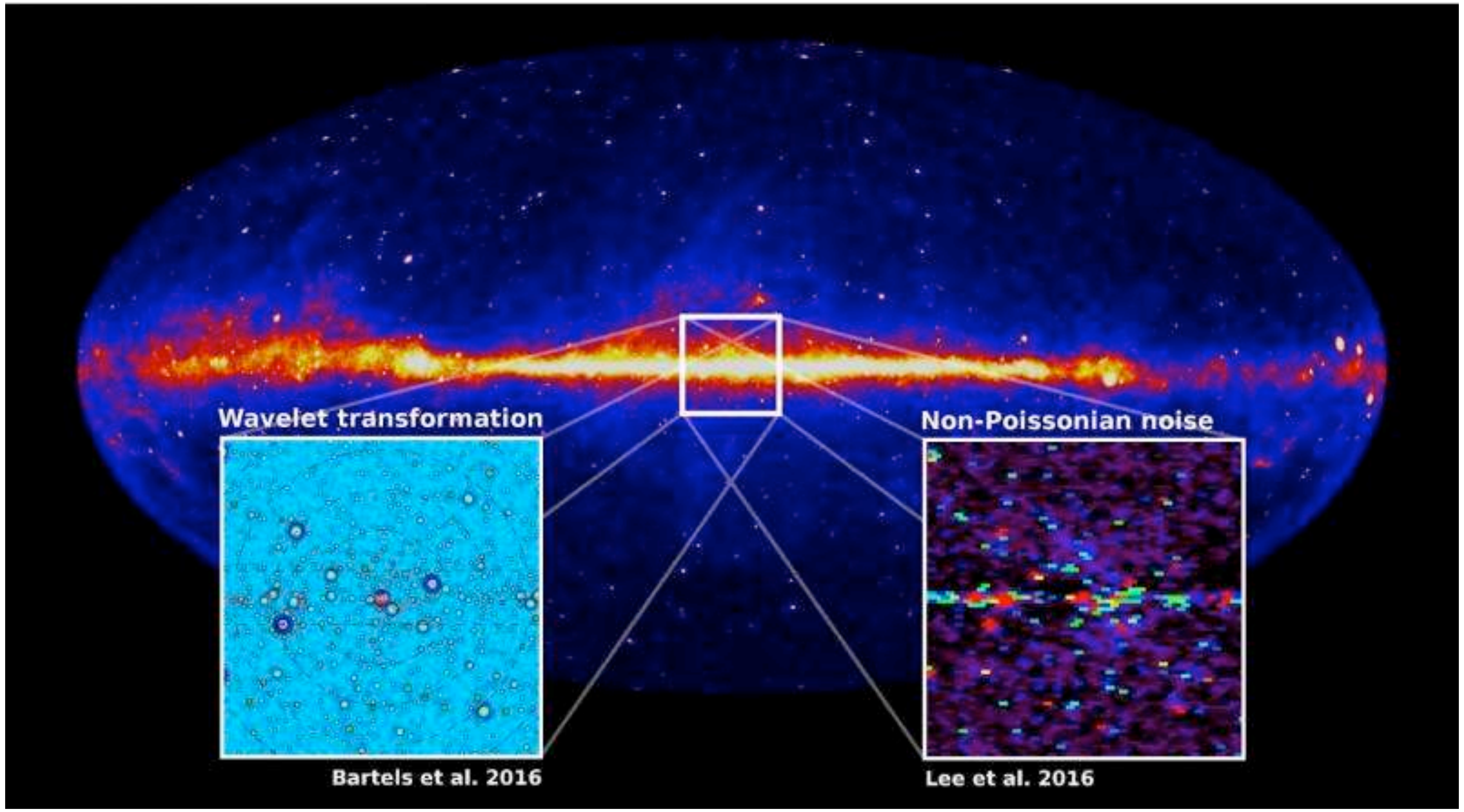


Daylen et al 2016

Or not?

A population of millisecond pulsars that hasn't yet been observed?





Princeton

Complementary search: dwarf galaxies

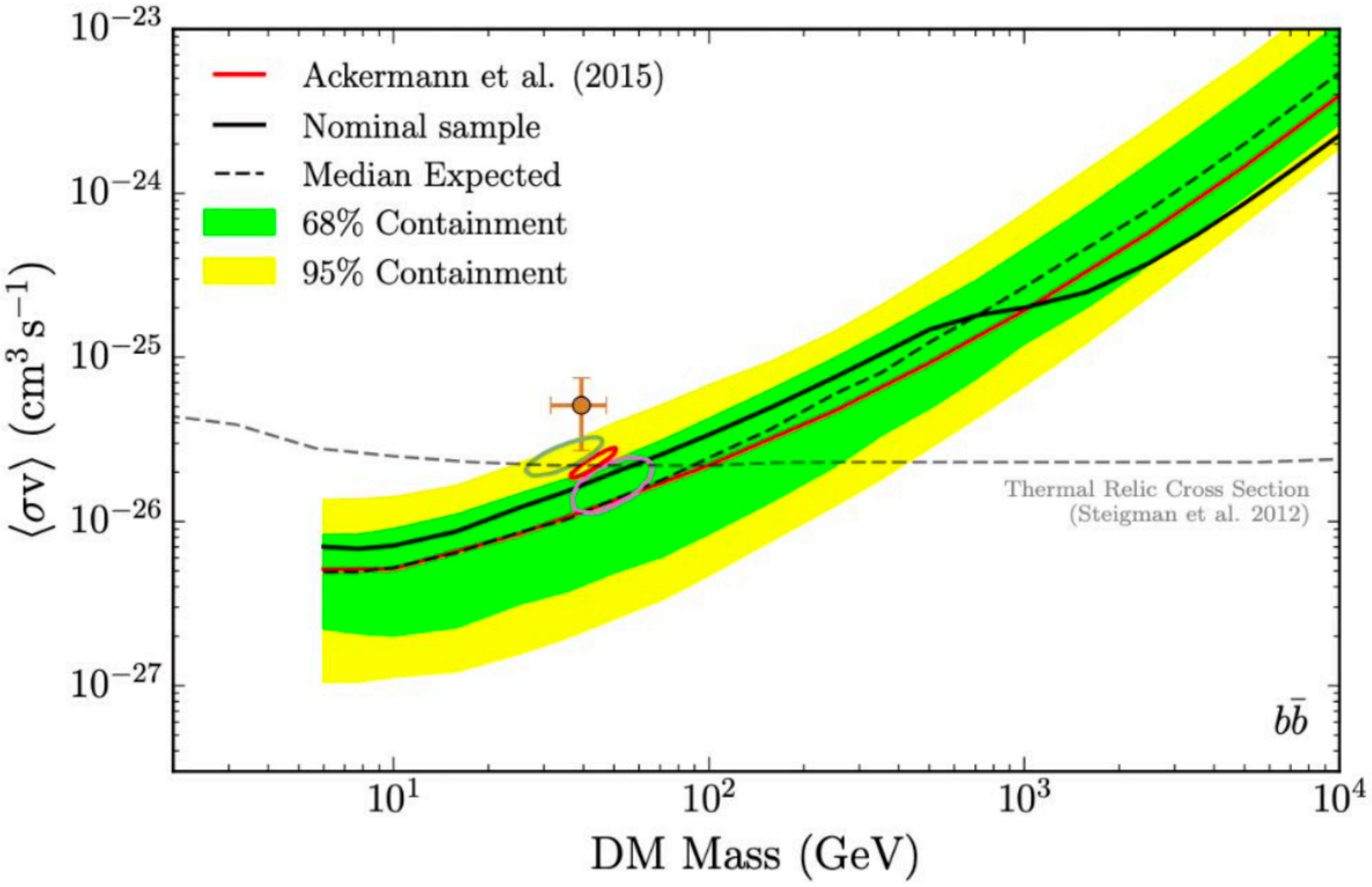
Lots of dark matter, not a lot of gas

Much smaller than Milky Way, but a lot less background

Many Milky Way satellites

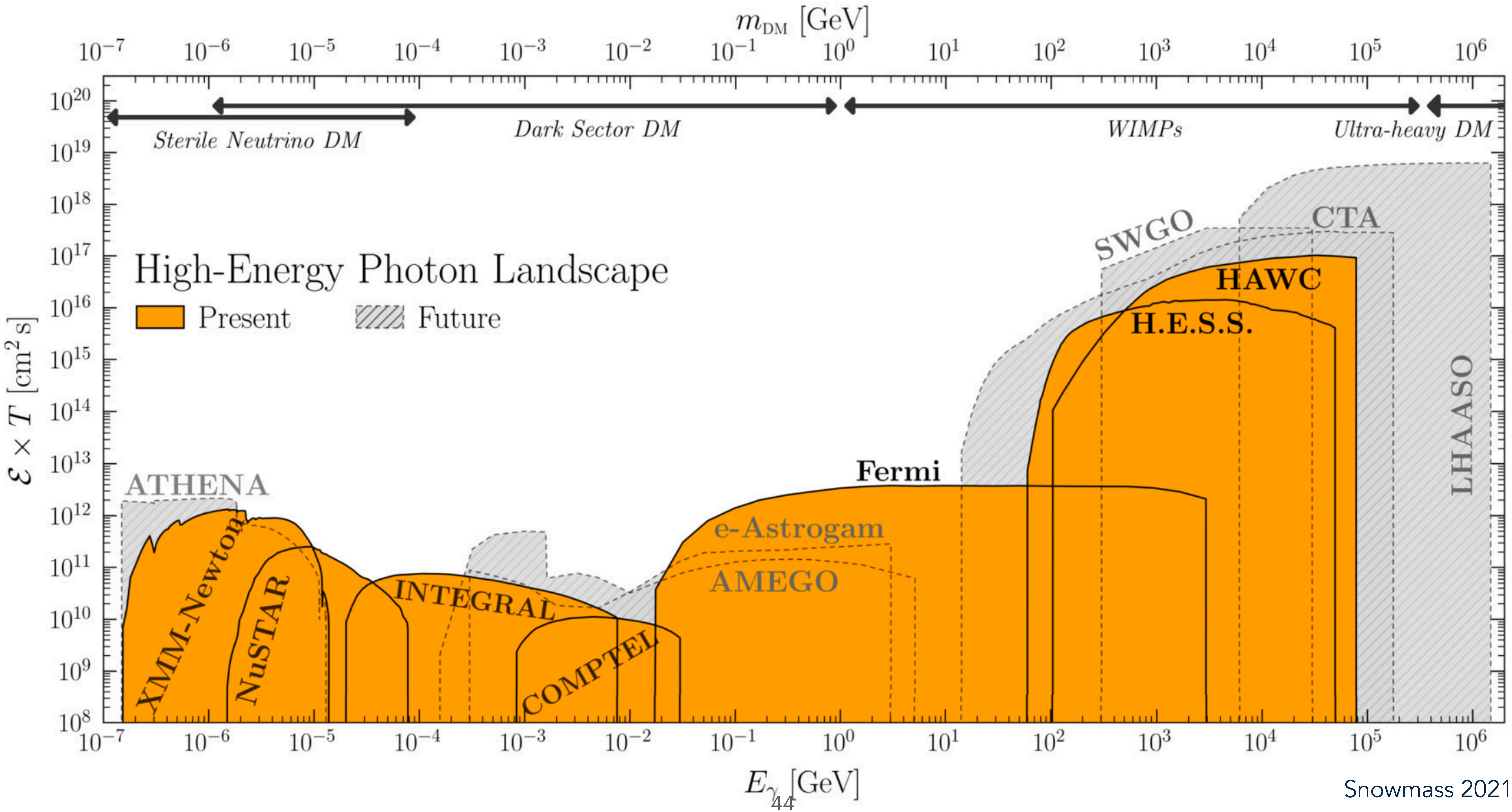
Complementary search: dwarf galaxies

Dwarf Spheroidal Galaxy, Fornax. ESO



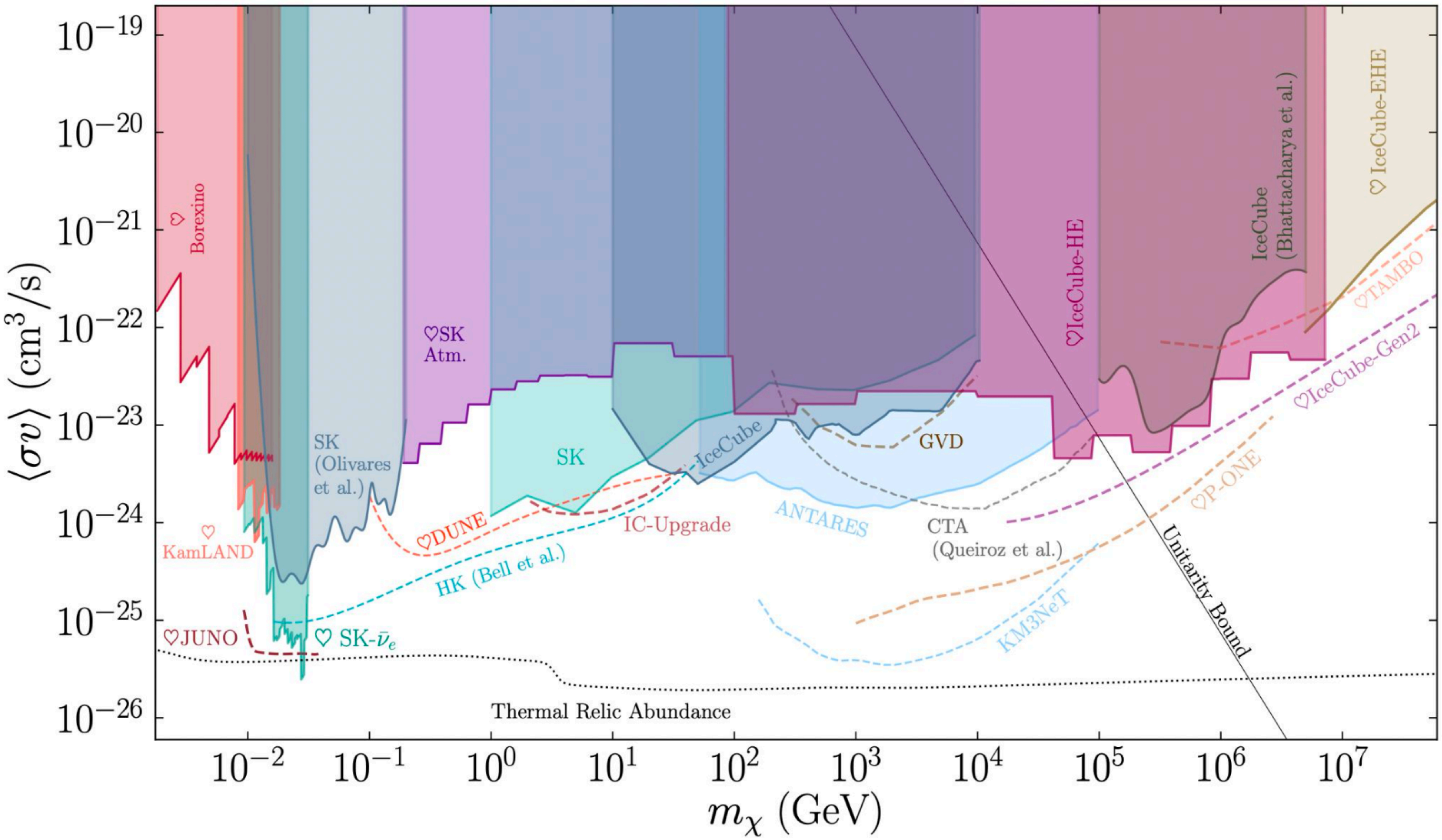
Albert et al 2017

Detecting Gamma Rays



Snowmass 2021

Annihilation to Neutrinos

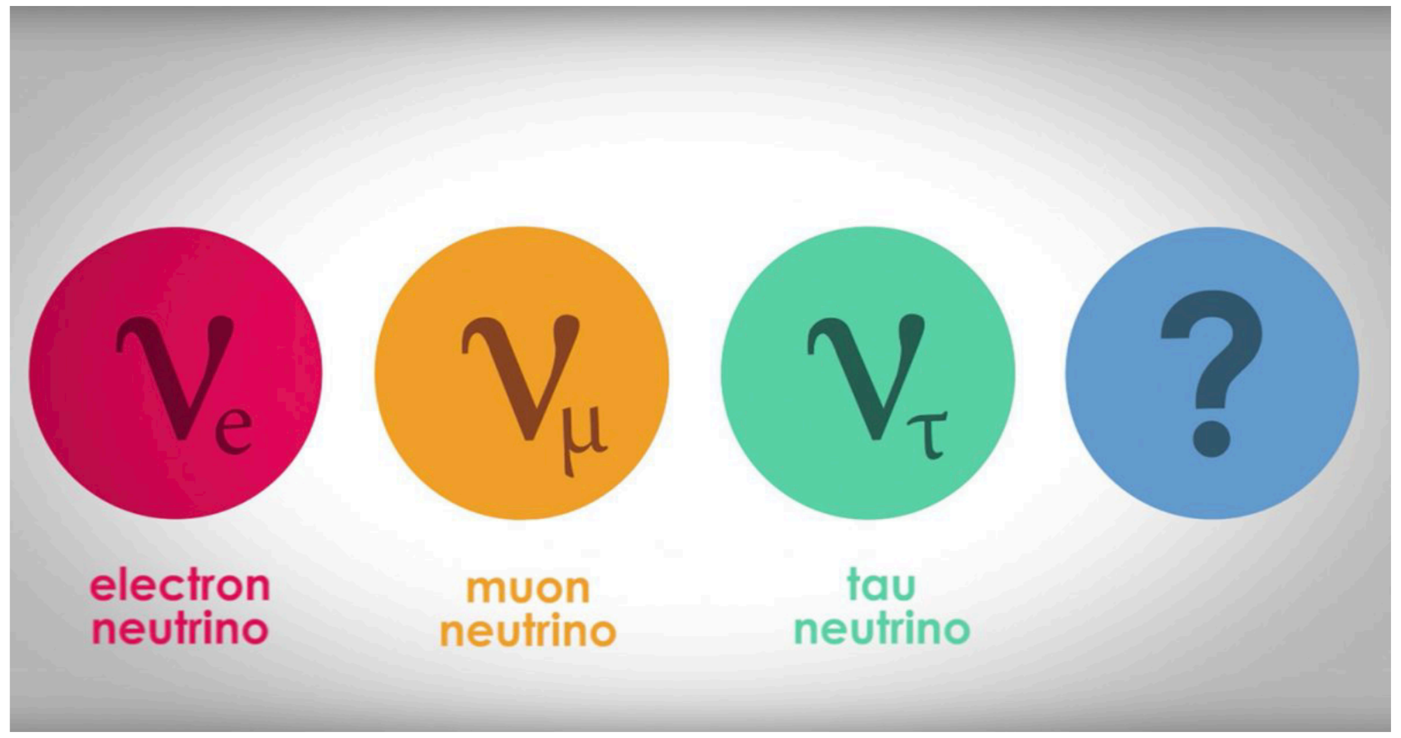


Arguelles et al 2022

Any questions?

What about light dark matter?

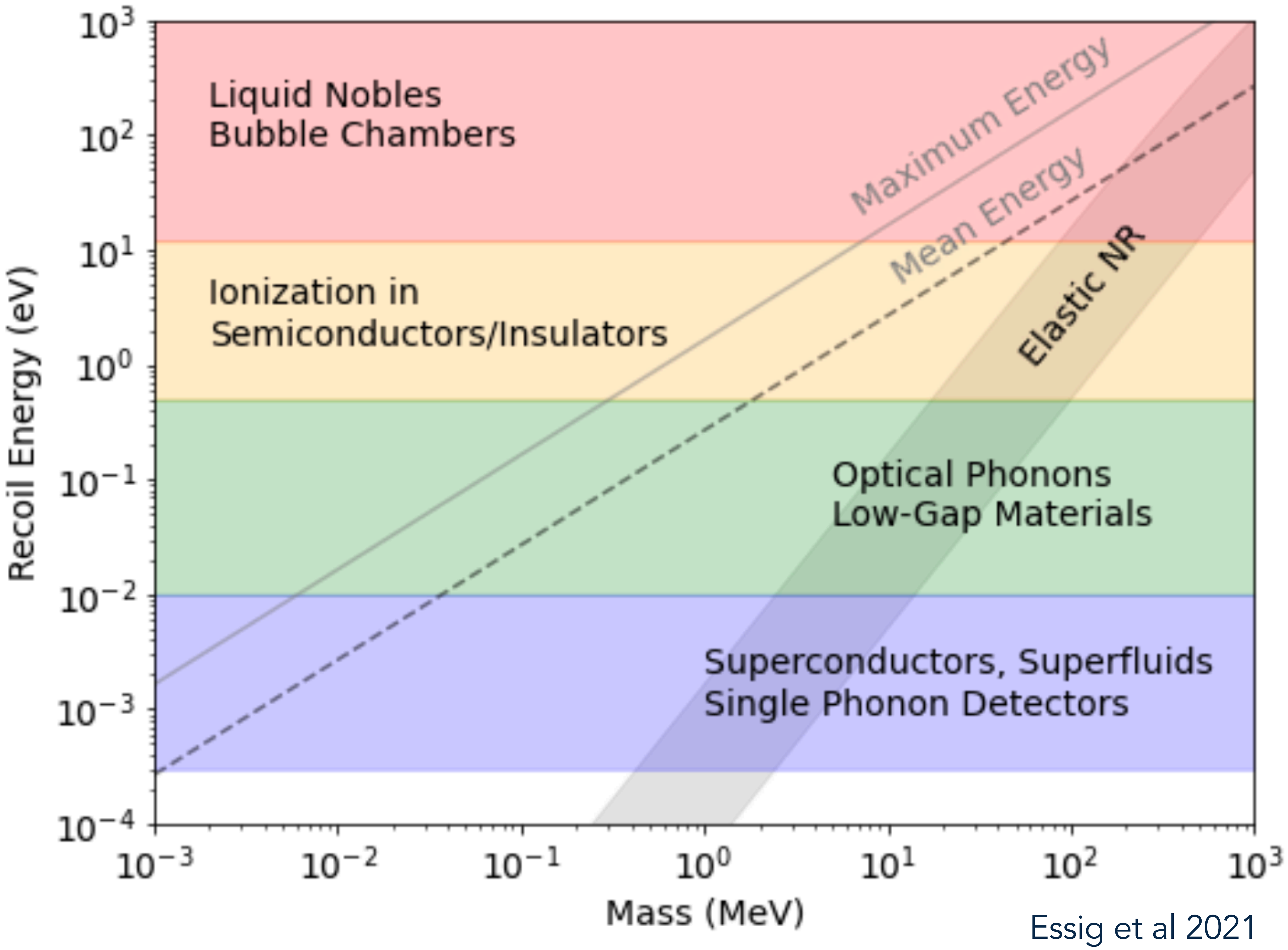
$m_\chi = 1\ \mathrm{keV} - 1\ \mathrm{GeV}$



De Gouvea

Model example: the sterile neutrino

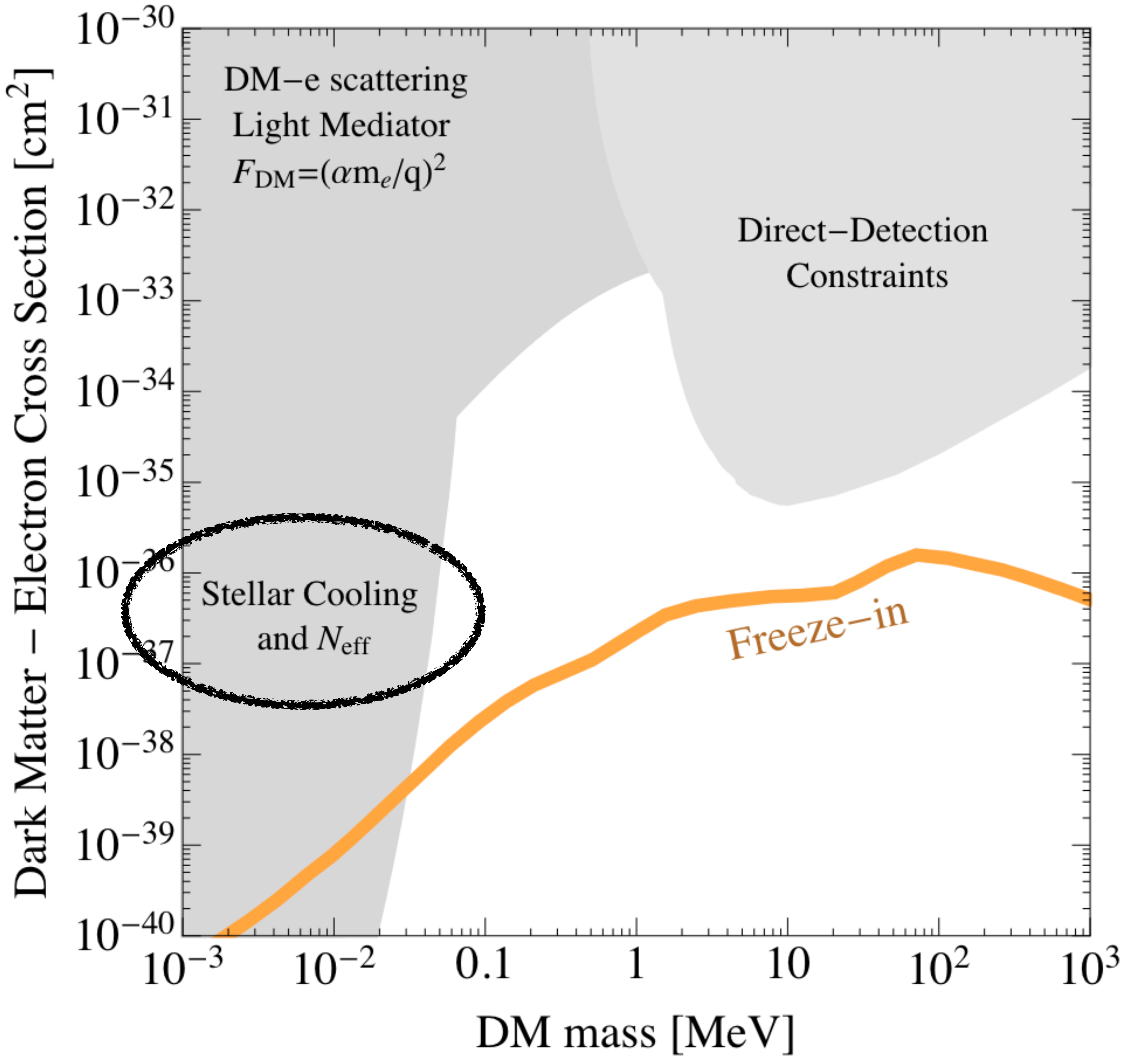
Or, DM with a light mediator

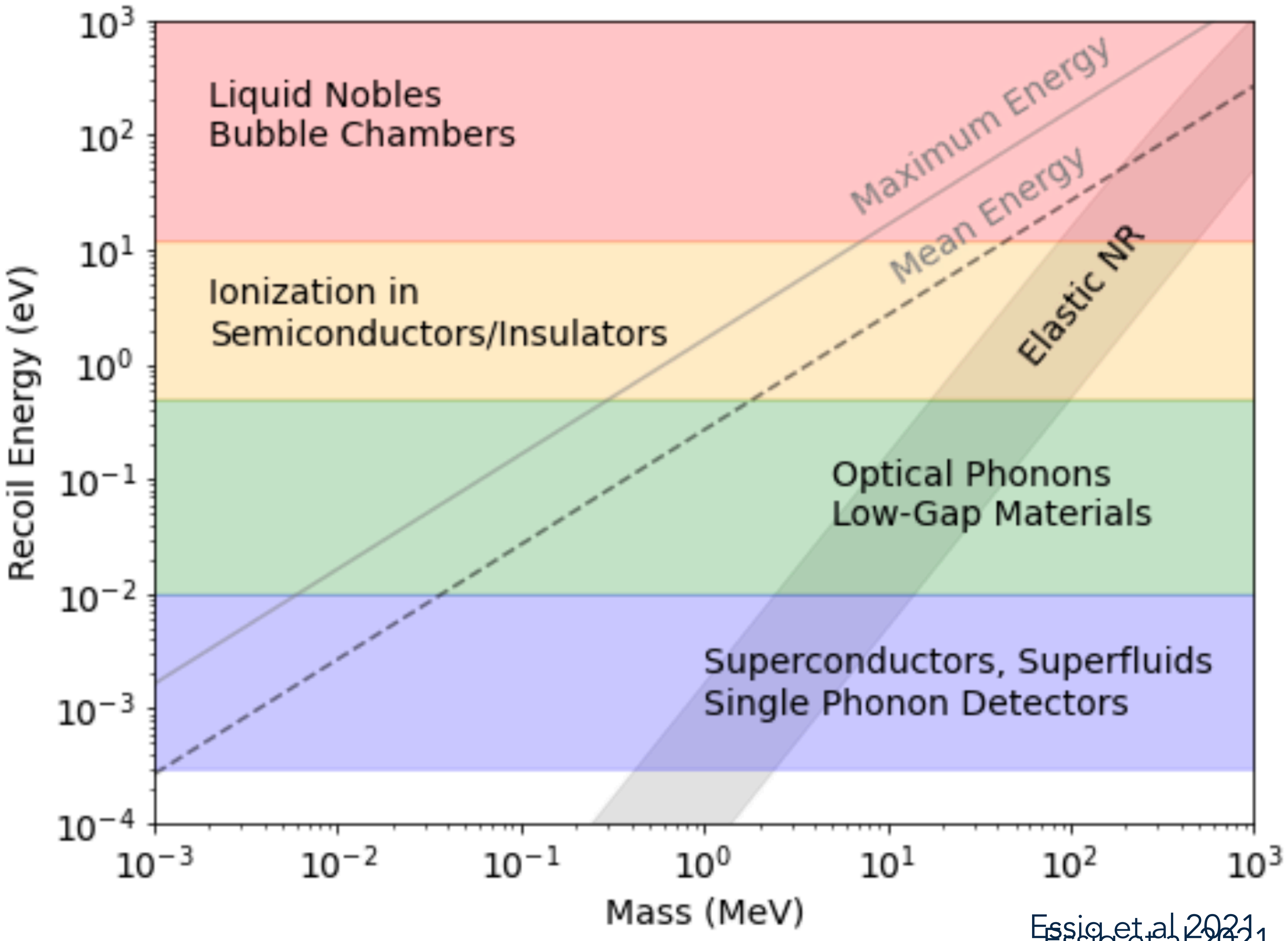


Essig et al 2021

What about light dark matter?

m_χ = 1 keV – 1 GeV





Essig et al 2021

Essig et al 2021

Useful References & Review Papers

Which I used to make these slides
(among others)

Dark Matter, a Brief Review, Annika Peter, https://arxiv.org/abs/1201.3942

Dark Matter Direct Detection of Classical WIMPs, Jodi Cooley https://scipost.org/10.21468/SciPostPhysLectNotes.55

TASI Lectures on Indirect Detection of DM, Tracy Slater arxiv.org/abs/1710.05137

Les Houches Summer School Lectures on Dark Matter (many topics), https://scipost.org/series/collection/2021_07_dark_matter/