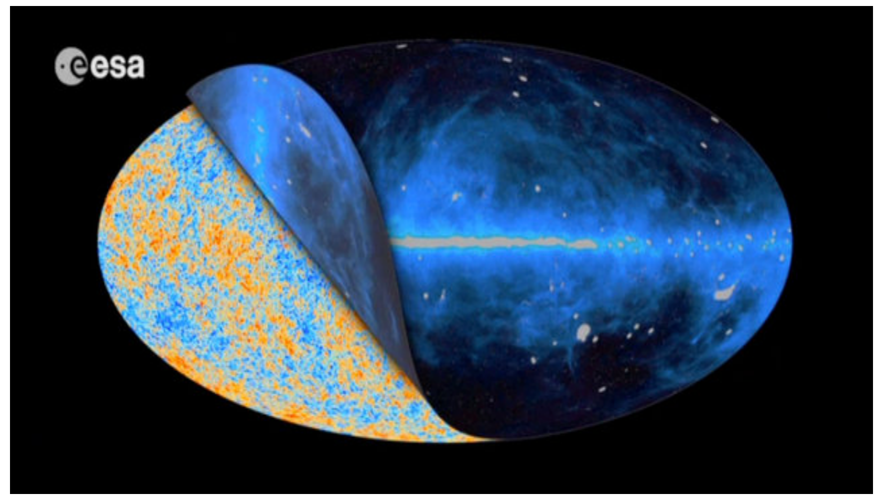
LDMA'25

Cosmological and astrophysical probes of light dark matter

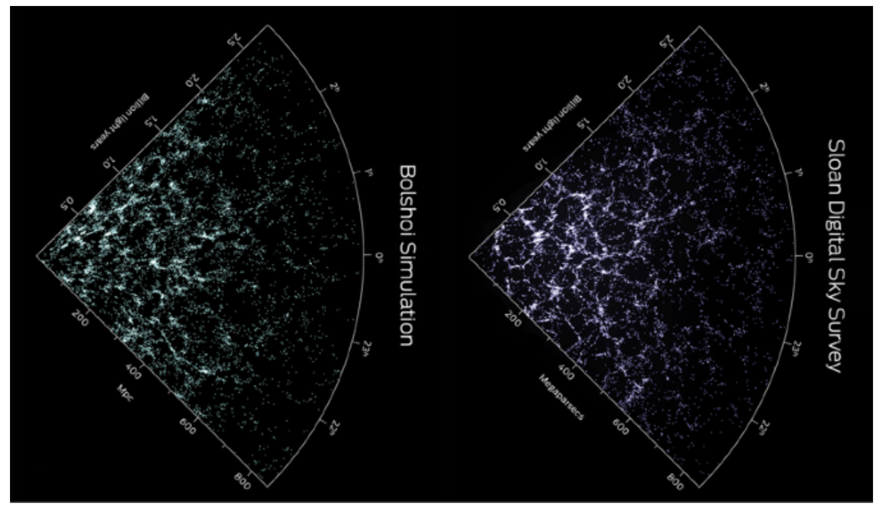
Francesca Calore (CNRS-LAPTh)

Dark matter in the universe

Cosmic microwave background



Large Scale Structures



Galaxy clusters

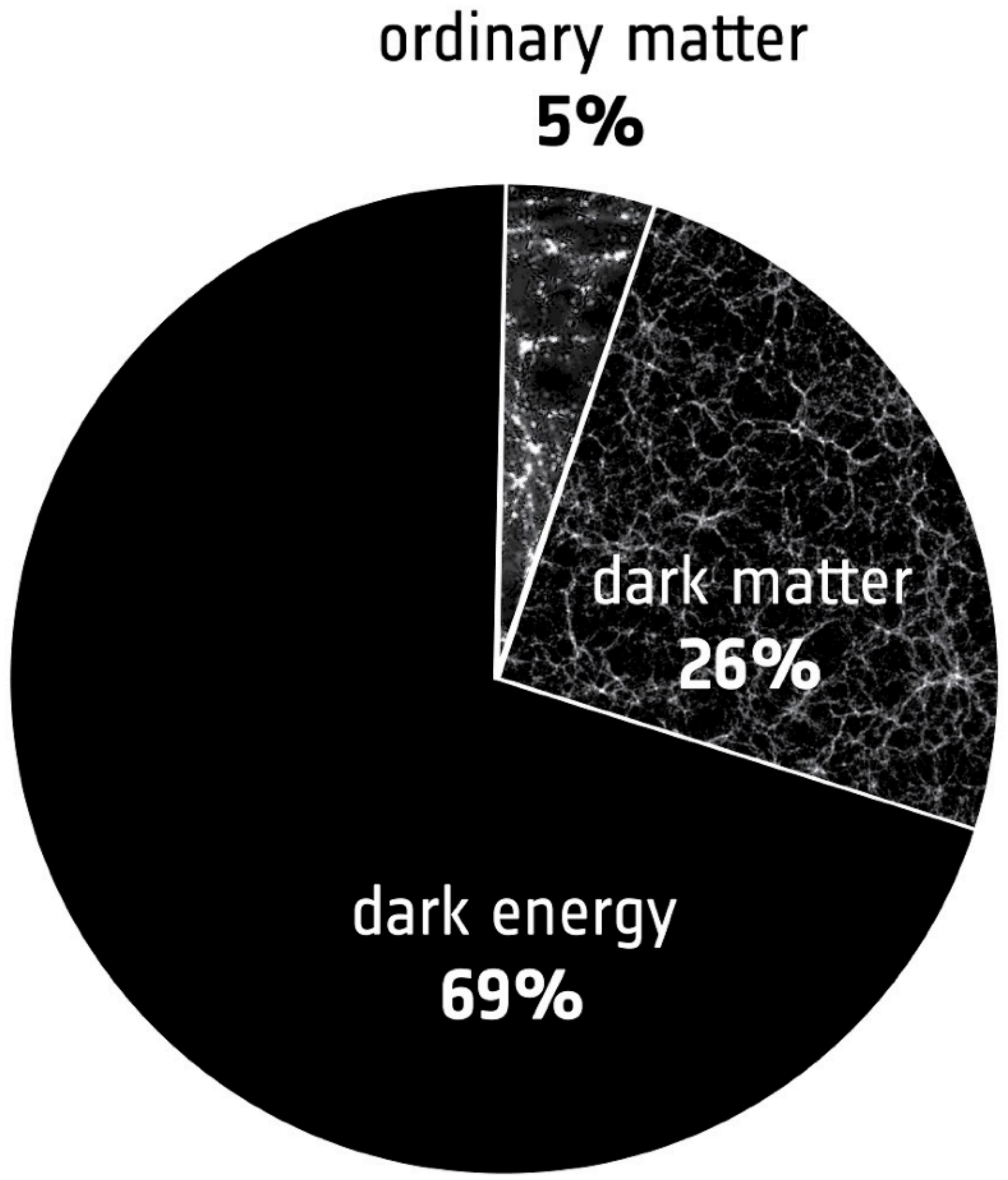
Galaxies

~Gpc

~Mpc

~kpc (10^{19} m)

Mounting evidence suggests that the majority of **pressure-less matter** in the universe is **not baryonic in nature**



Credit: ESA

Despite the dark matter gravitational impact being well measured, its **nature remains a mystery**

Dark matter in the universe

Dark matter must be

- Produced sufficiently non-relativistically, i.e. **cold**
- **Stable** or sufficiently **long-lived** *Audren+ JCAP'14; Poulin+ JCAP'16*
- Smoothly distributed at cosmological scales
- **Sufficiently heavy**, to behave "classically" in astrophysical systems *Tremaine & Gunn PRL 1979*
- Dark and **dissipationless**, i.e. weak e.m. interactions *Wilkinson+ JCAP'14*
- Not very much interacting with other particles, i.e. not very **collisional** *Kaplinghat+ PRL'16*

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Open questions

- Is there cosmic evidence to go beyond the cold and *collisionless paradigm*?
- How is dark matter *produced* in the early universe, and how does this connect to late universe observables?
- Is dark matter a particle and fundamentally *wave-like or particle-like*?
- Is there a *dark sector* containing other new particles and/or forces? Does dark matter have important *self-interactions*?

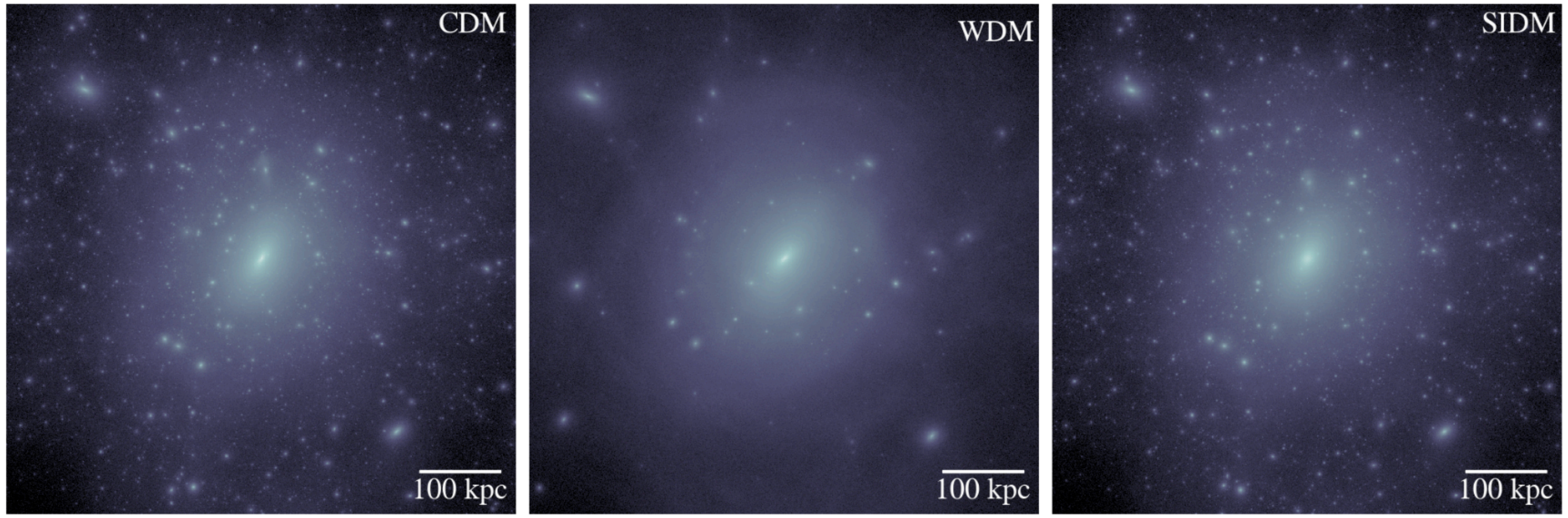
Snowmass Cosmic Frontier; Snowmass Astro&Cosmo Probes of DM; EuCAPT White Paper

What cosmic probes can still tell us?

Simple cosmological model containing stable, non-relativistic, collisionless, **cold dark matter**

Fundamental properties of dark matter can leave an imprint on the macroscopic distribution of dark matter, breaking the CDM paradigm at **small scales**

Bullock & Boylan-Kolchin ARAA'17



What can we learn about DM?

- Warmer (i.e., not non-relativistic) during structure formation
- Not collision-less, i.e. self-interacting
- Wavelike rather than particle-like
- Produced during non-trivial phase transitions in the early universe
- Non-particle nature

Challenge TH: Disentangling dark matter physics from baryon physics ⟶ theoretical/numerical developments required

Snowmass Cosmic Frontier

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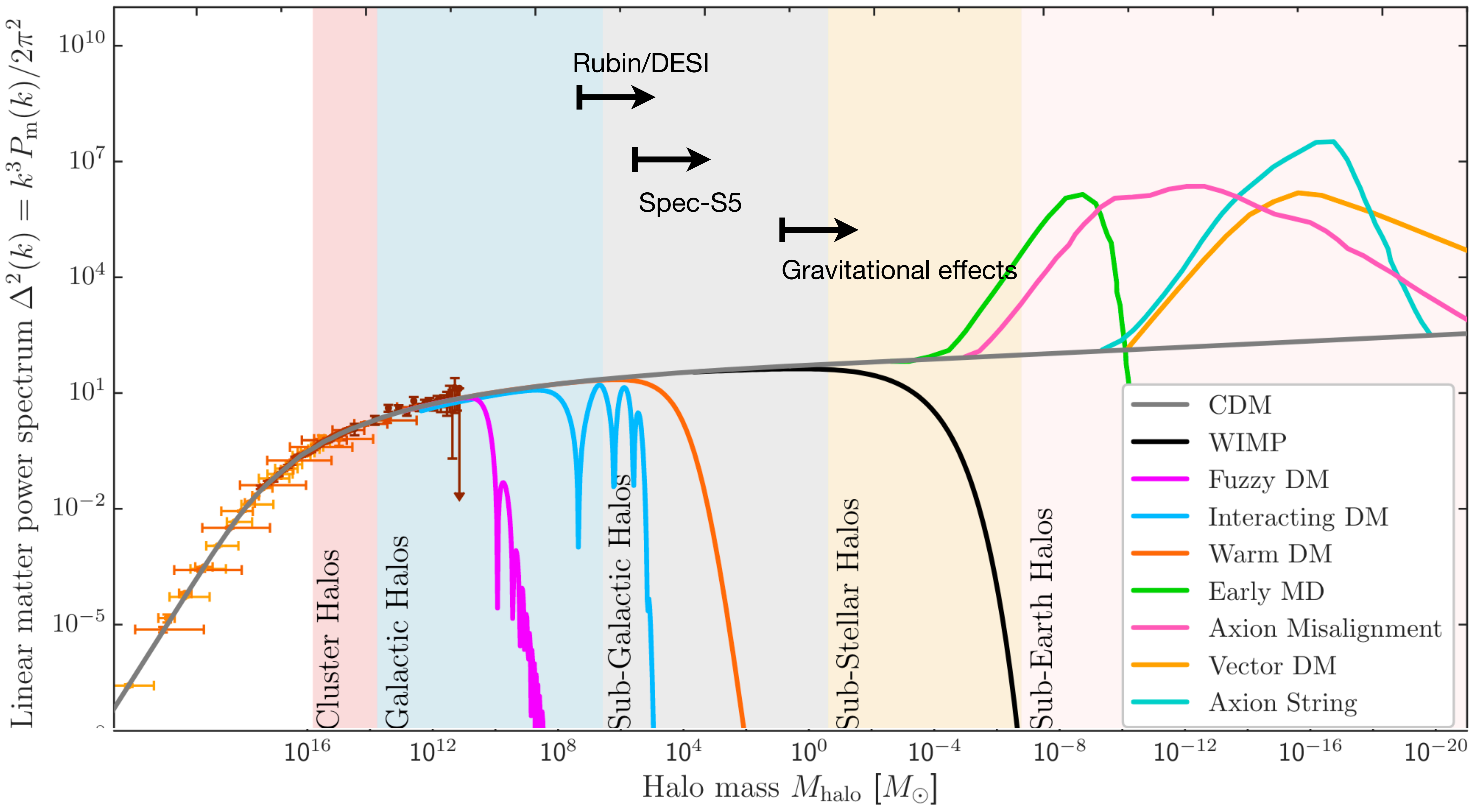


Which observables?

- Matter power spectrum
- Mass spectrum, distribution, and density profiles of dark matter halos
- Abundance of compact objects

Within the reach of up-coming large cosmic surveys (LSST,DESI,Euclid)

Snowmass Cosmic Frontier

Dark matter landscape

Vast parameter space in mass and interaction strength

Dark matter landscape

$10^{-19}\,\mathrm{eV}$ — $\mu\mathrm{eV}$ — $0.1\,\mathrm{eV}$ — keV — MeV — GeV — $10^2\,\mathrm{TeV}$ — $10^{-16}\,M_\odot$ — $10\,M_\odot$ — $10^3\,M_\odot$

Dark matter behaves “classically"

$$m \gtrsim 10^{-22}\,\mathrm{eV}$$

If bosonic, from confinement in dwarf galaxies

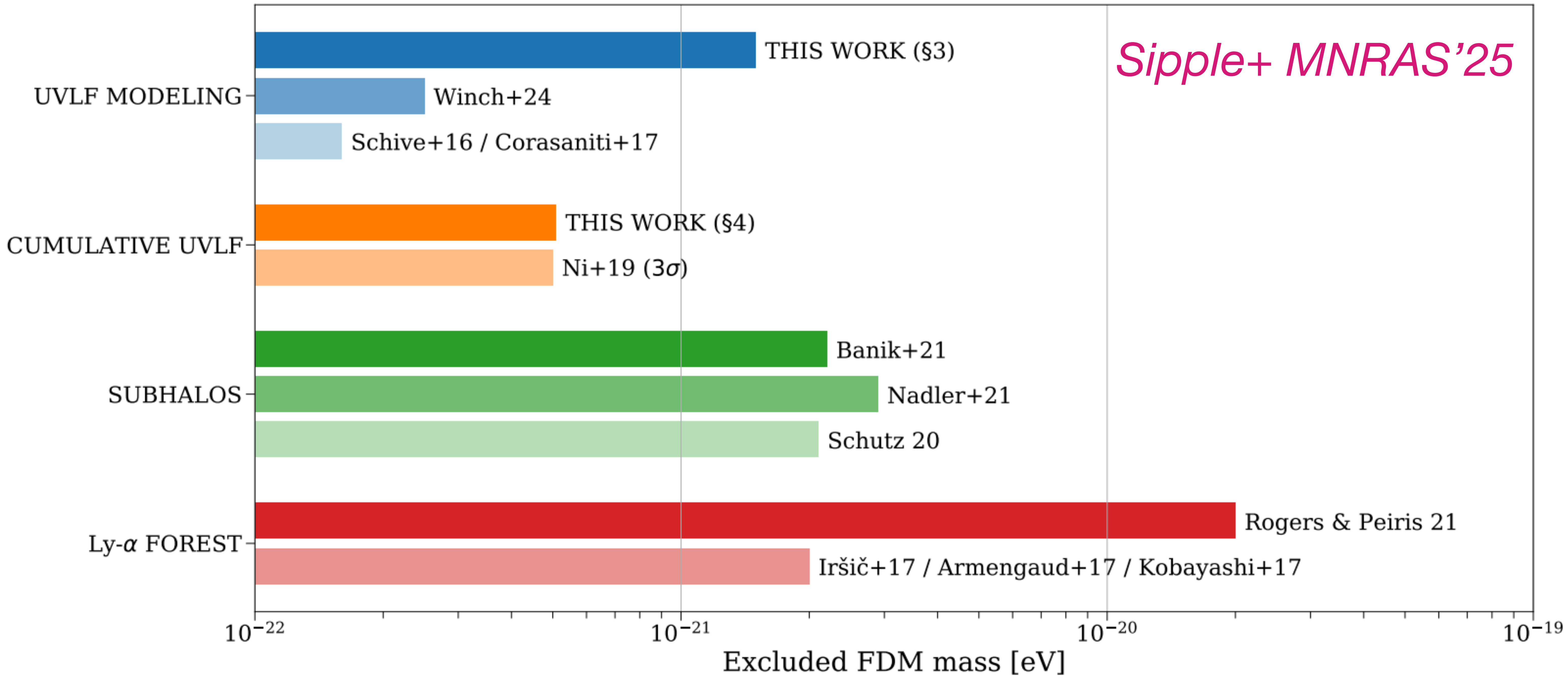
Dark matter “lighter” than halo mass

Vast parameter space in mass and interaction strength

How light can dark matter be?

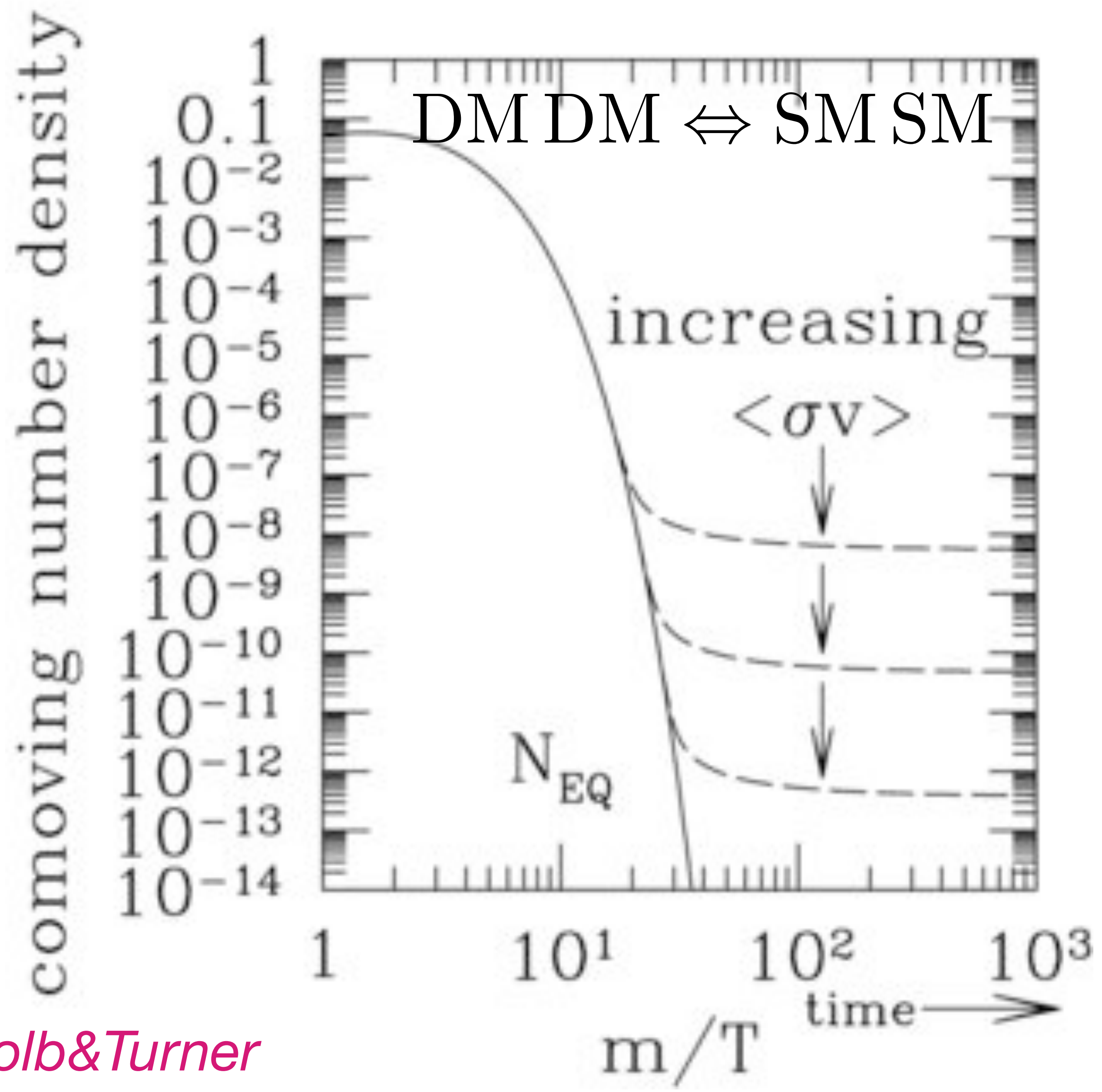
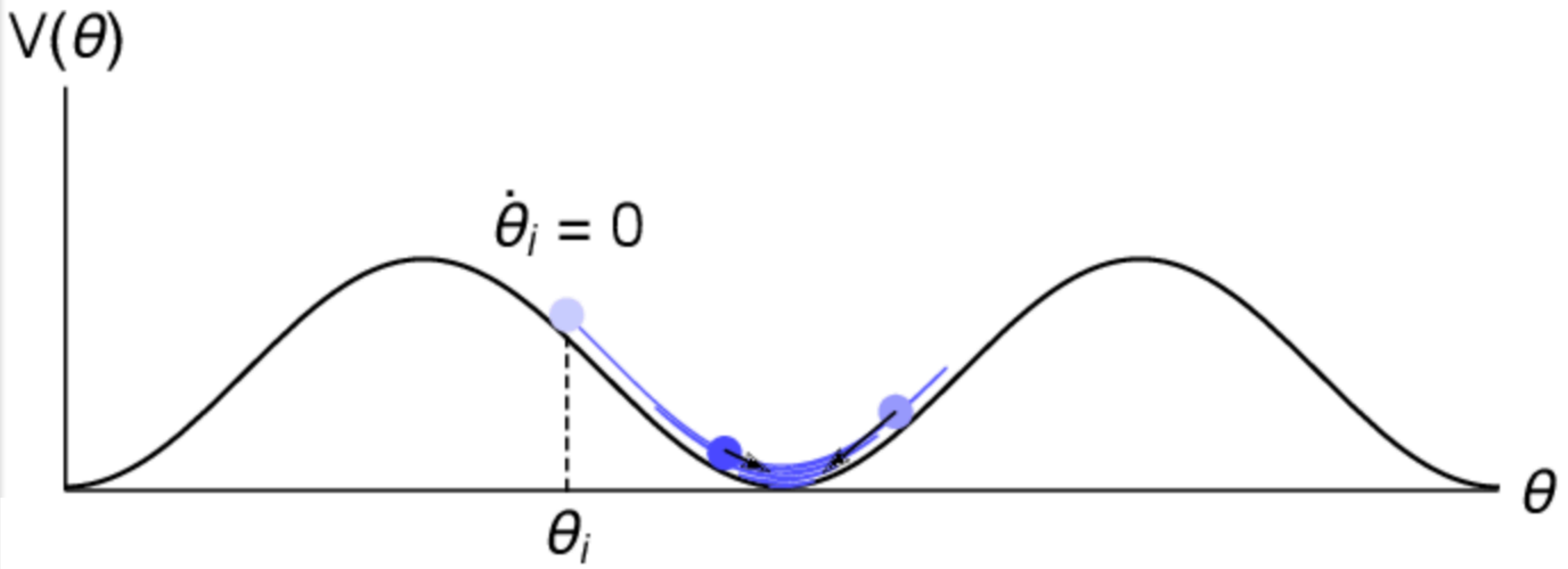
- If sufficiently light, dark matter can have a wavelength large enough to modify observed sub-galactic structure - “fuzzy dark matter"
- The minimum dark matter mass is controlled by the smallest scale structures we can observe
- Multiple approaches to mapping the smallest halos:
    - Lyman-alpha forest (probes matter clumpiness at z ~2-6) [e.g. *Armengaud+ 17, Irsic+’17, Nori+ ’19*]
    - Fluctuations in linear density of stellar streams (perturbed by DM sub-halos) [e.g. *Banik+ ’19*]
    - Strong gravitational lensing of quasars [e.g. *Hsueh+ ’19, Gilman+’19*]
    - Observation of faint Milky Way satellites [e.g. *Nadler+ ’19*]

Latest limits on fuzzy dark matter



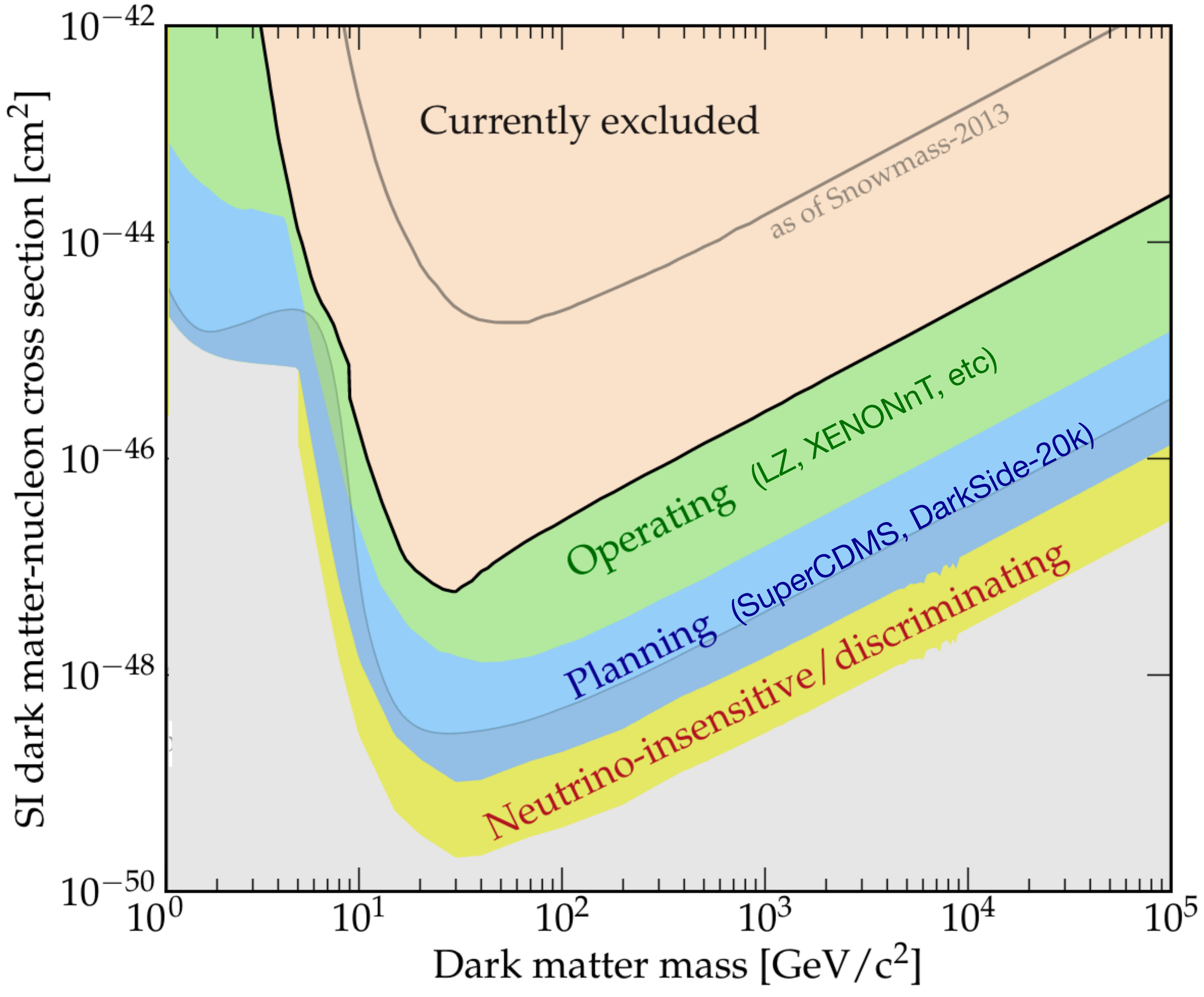
Dark matter production in the early universe

Two very plausible scenarios for how the dark matter could be produced in the early universe

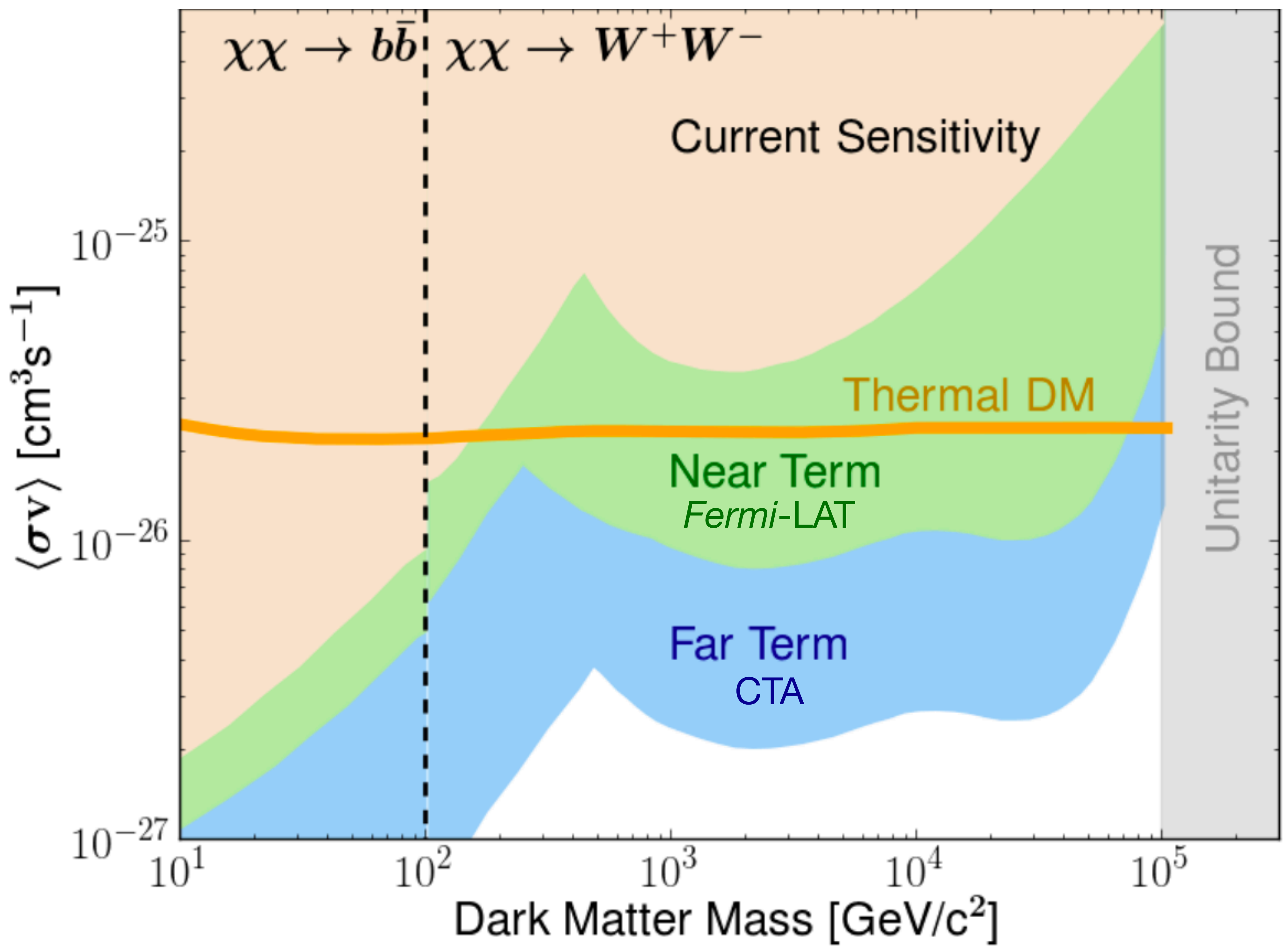
Production	**Thermal freeze-out**	**Mis-alignment**
	 Kolb&Turner	 Preskill+ PLB'83
DM candidate	**Weakly interacting massive particles (WIMPs)**	**QCD axion**
Further TH motivation	Solution to the electroweak hierarchy problem	Solution to the strong CP-problem

Weakly interacting massive particles

Quick ID: 1 GeV — 100 TeV, electroweak coupling with SM bosons (Z, H)



Snowmass Cosmic Frontier



Delve deep with terrestrial and astroparticle experiments

Excluding Z-mediated and almost H mediated couplings, but still viable parameter space

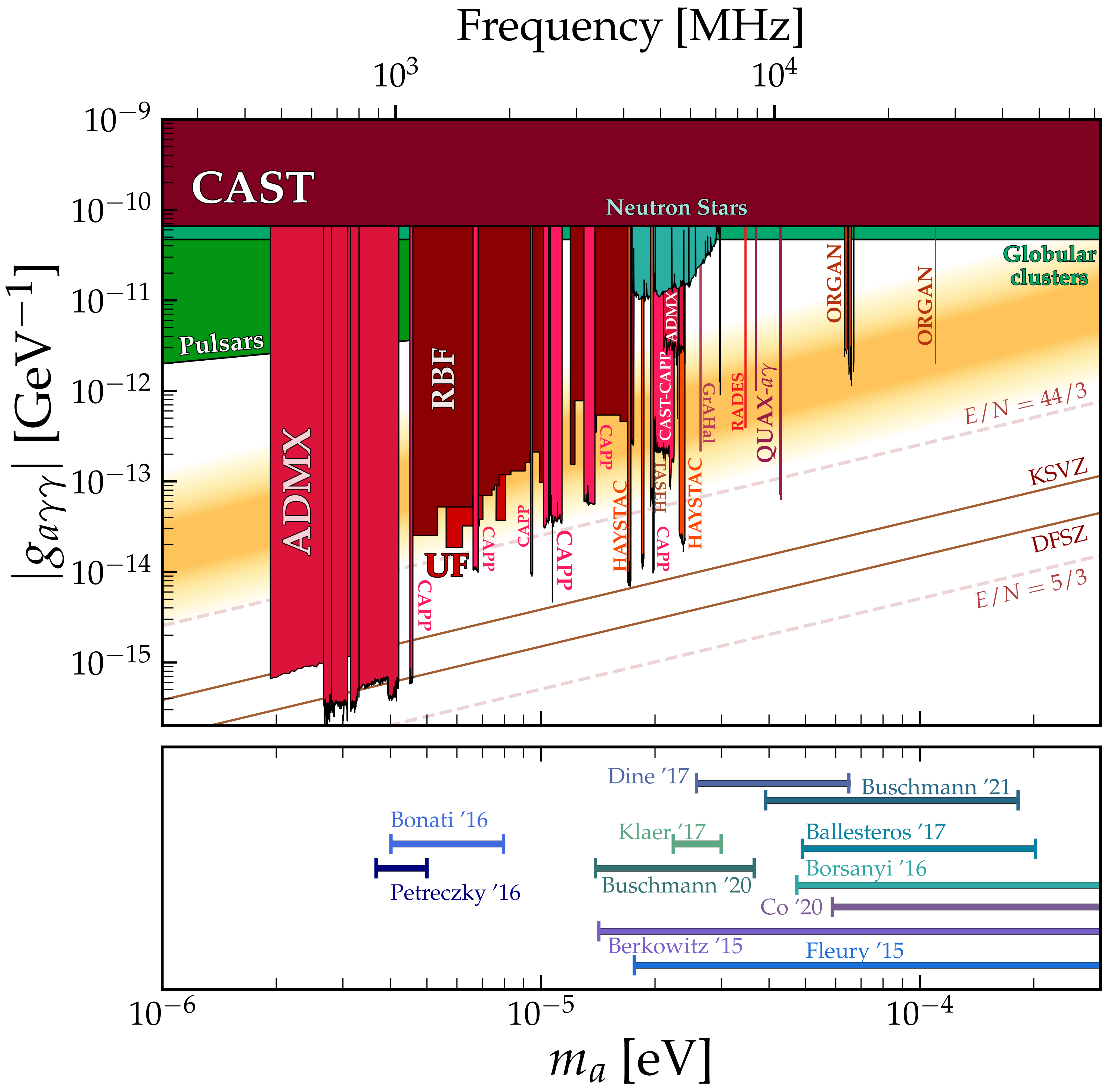
Leane+ PRD'18; Akerib+ 2203.08084

[Similar searches for SD cross-section + strong complementarity w/ HE astro neutrino searches]

The QCD axion

Quick ID: 10^{-12} — 0.01 eV, minimal coupling with photons

$$\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a = g_{a\gamma} \mathbf{E} \cdot \mathbf{B} a$$



https://github.com/cajohare/AxionLimits

Axion CDM: $f_a \approx 10^{10}\,\mathrm{GeV}\left(\frac{0.6\mathrm{meV}}{m_a}\right)$

A diversified search program:

- **Haloscopes**: DM axion conversion in B field (ADMX, HAYSTAC, DMRadio, etc) $\sim g_{a\gamma}^2 \rho_{\rm DM}$
- **Helioscopes**: Solar axion conversion in B field (CAST, IAXO) $\sim g_{a\gamma}^4$
- **Pulsars**: DM axion conversion in pulsar magnetosphere (Green Bank Telescope)

Foster+ PRL'22

Several detection methods are systematically probing axion DM scenarios

Broadening the landscape

Dark sectors: theory motivation

Extended **theoretical exploration** to define the boundaries of what models are consistent with observations

Development of **new experimental opportunities** to provide sensitivity to the new theory-space

⟶ **Portal dark matter models**: Hidden dark sector weakly interacting with the Standard Model sector through specific messenger particles

	Vector	Scalar or pseudo-scalar
Messenger	**Massive dark photon**	**Dark Higgs**
Connection to SM	**Kinetic mixing** with the hypercharge field strength portal	**Mixing** with the SM Higgs mass portal

Dark matter particles and therefore the dark sectors must satisfy the relic density measurement and cosmological bounds!

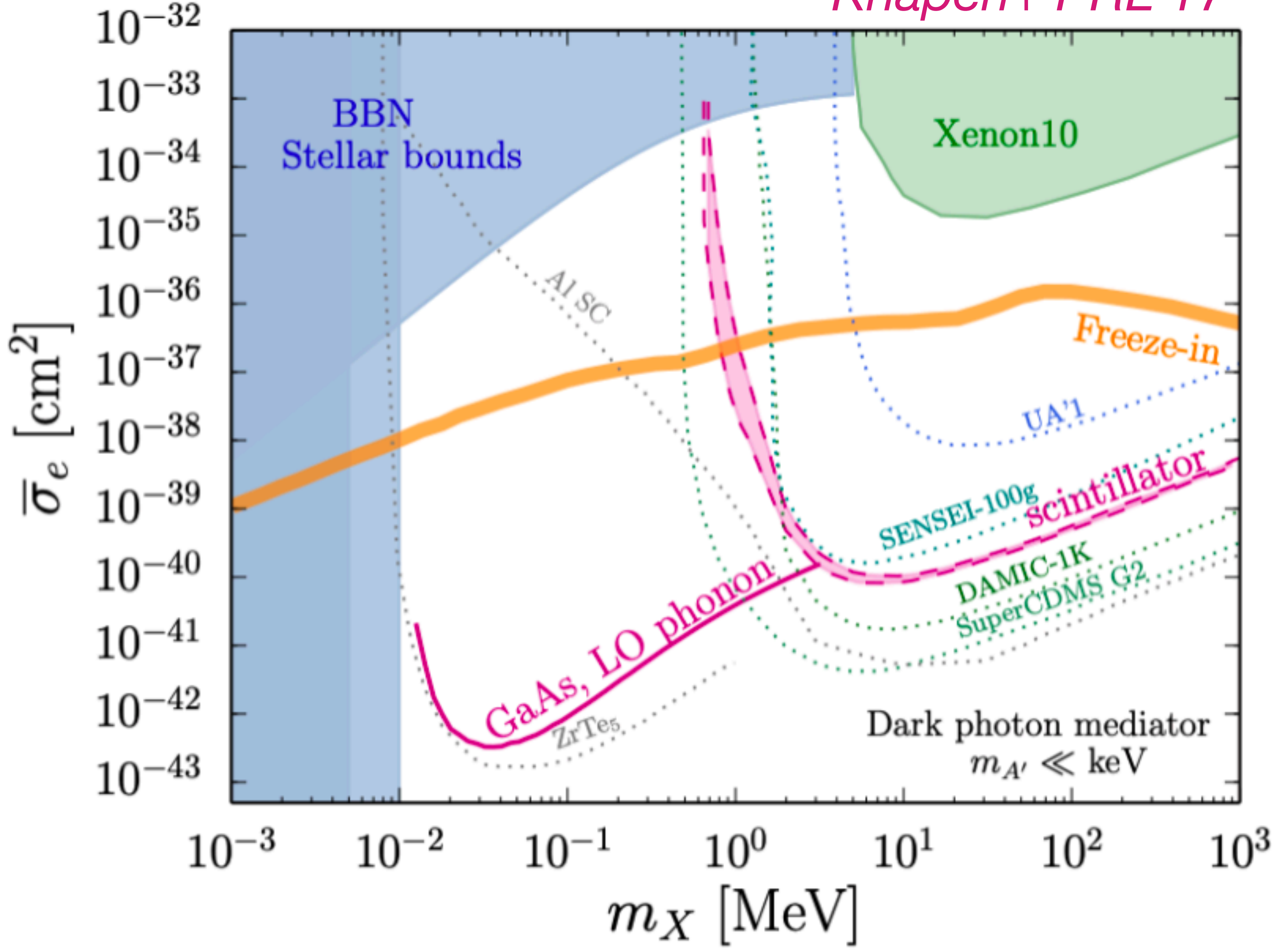
[In the keV mass range, let's not forget **sterile neutrino** dark matter *Boyarsky+ PrPNP'19*]

Broadening the landscape

Dark sectors: Production mechanisms

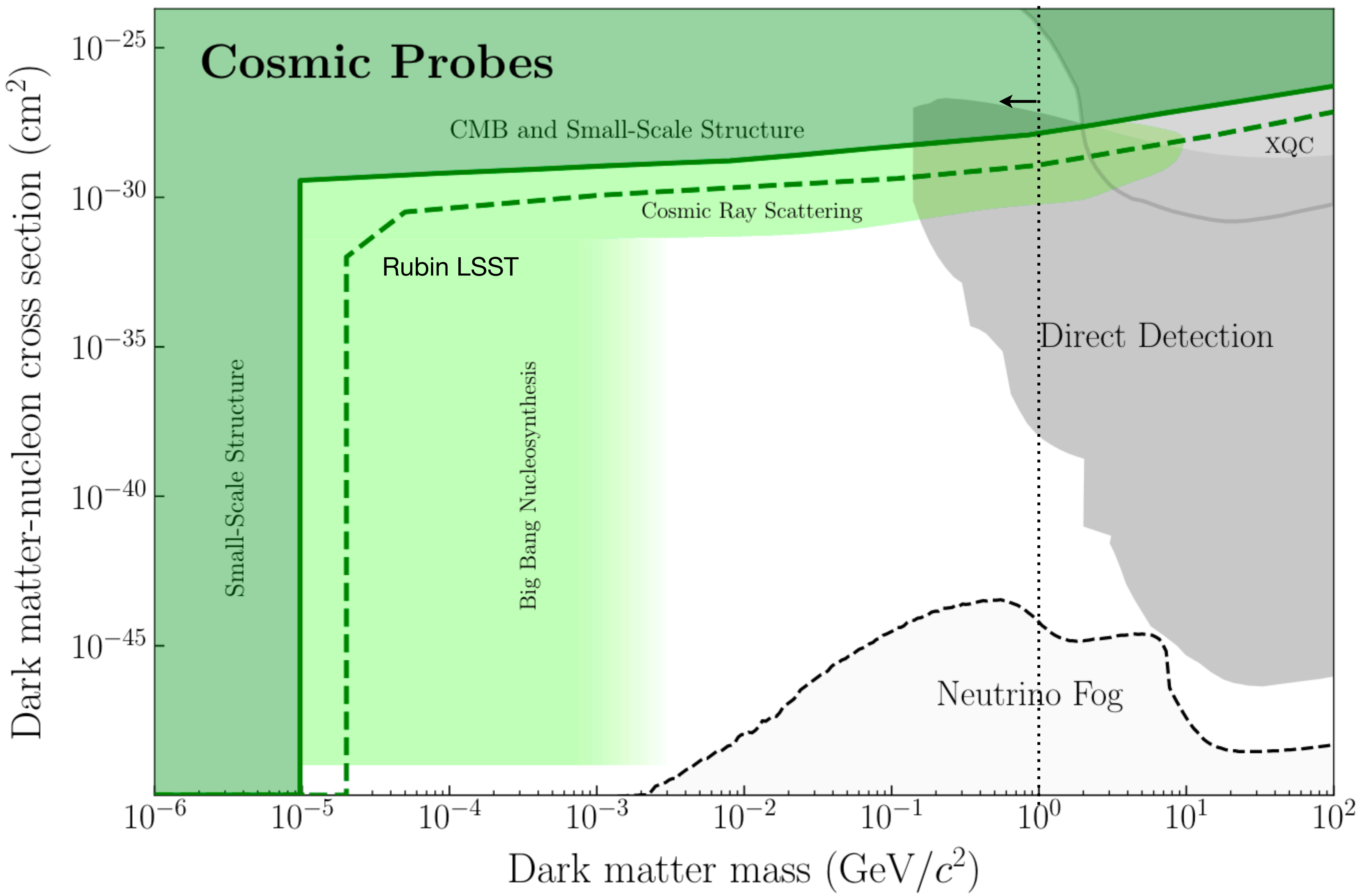
- In dark sectors, the relic abundance is set by interactions with the SM
- **Thermal production** possible from eV up to GeV masses
- **Below 1 MeV**, light DM modifies predictions for light-element abundances during BBN and it is therefore strongly constrained [e.g. *Sabti+ JCAP'20, '21*]
- **Above 1 MeV** (up to ~10 GeV), velocity-independent freeze-out models (*s-wave*) are severely constrained by CMB and indirect detection probes
- The mediator mass should be smaller than the dark matter mass
- One needs to rely on alternative production mechanisms:
    - Thermal production with v-dependent interactions (e.g. vector portals)
    - Freeze-in at low re-heating temperatures
    - Dark phase transitions at low temperatures

Knapen+ PRL'17

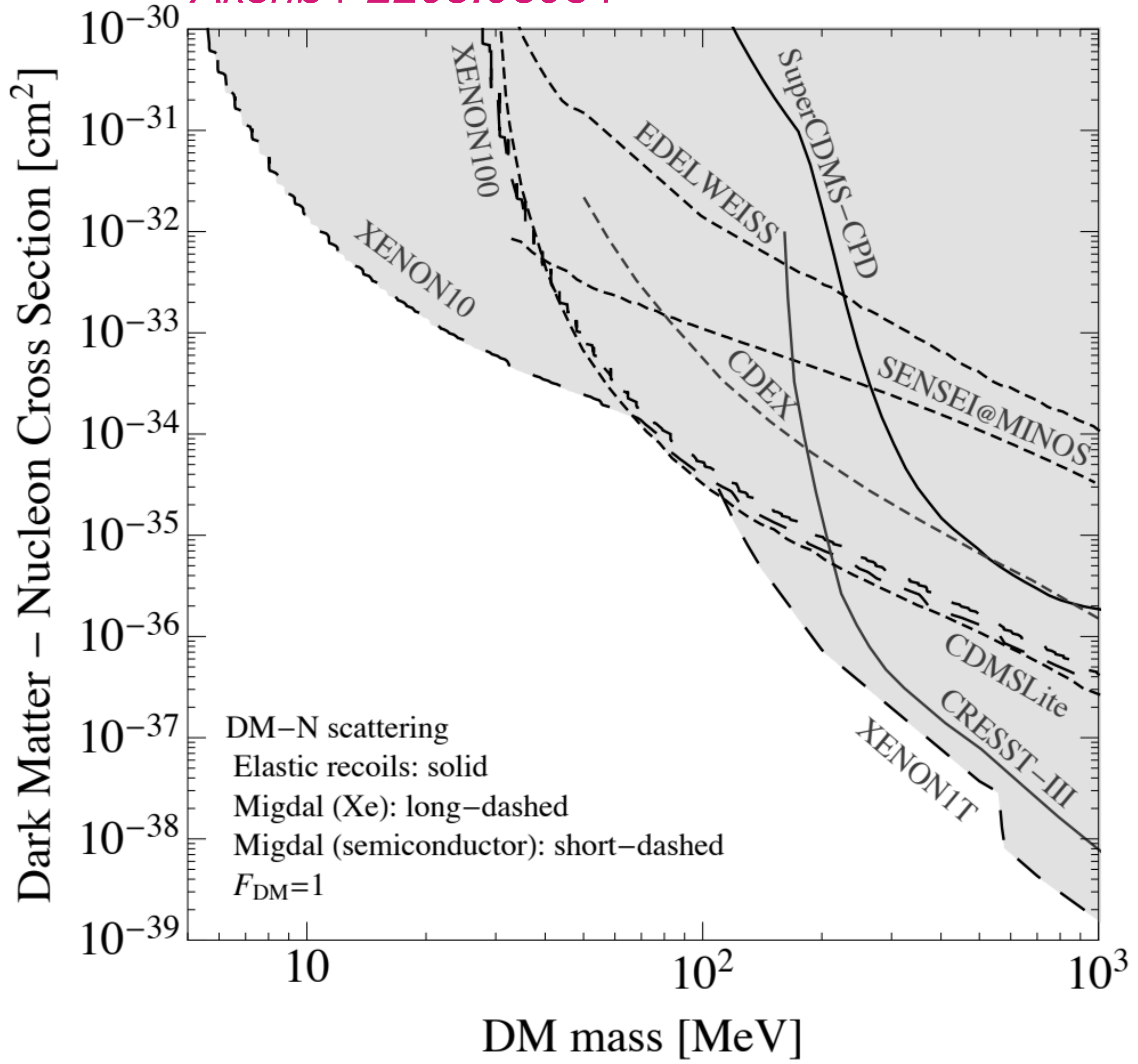


Broadening the landscape
Dark sectors and light dark matter: constraints

Snowmass Cosmic Probes of DM



Akerib+ 2203.08084



Challenge DD: Calorimetric detectors sensitive to recoil energies in the range μeV – keV

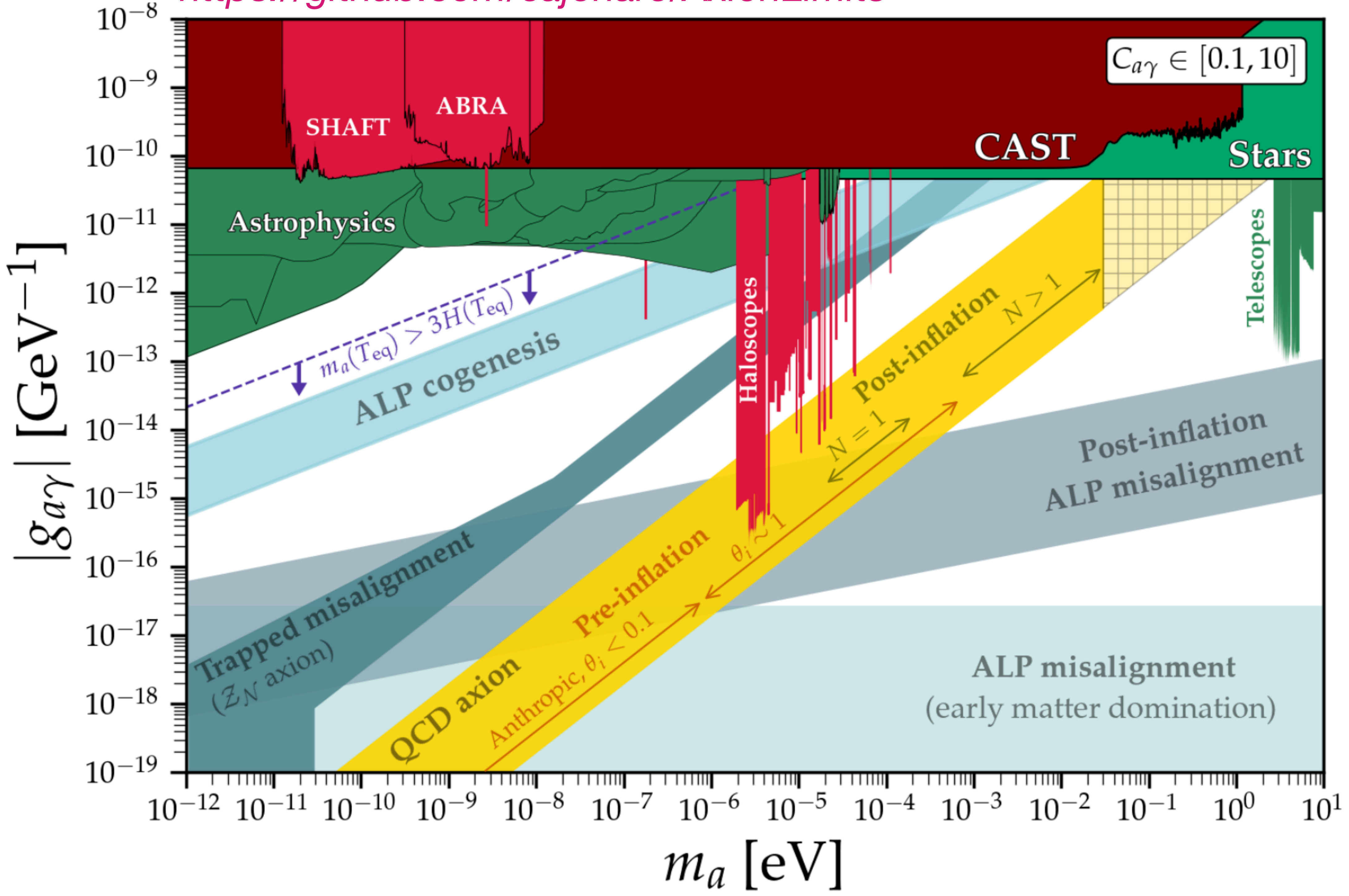
Broadening the landscape

Axion-like particles: theory motivation

Axion-like particles: (pseudo-)scalar particles, masses as low as ZeV, very weak couplings with SM, coupled with photons as QCD axions

Chang+ PRD 2000; Turok PRL 1996; Arvanitaki+ PRD'10

https://github.com/cajohare/AxionLimits



Quick ID:

- **Common** in many **extensions of the SM** from the spontaneous breaking of approximate global symmetries
- **Mass** is **not determined** by QCD effects
- They do **not solve** the **strong CP problem**

[Wave-like DM is even broader: more generally, light scalars or vectors]

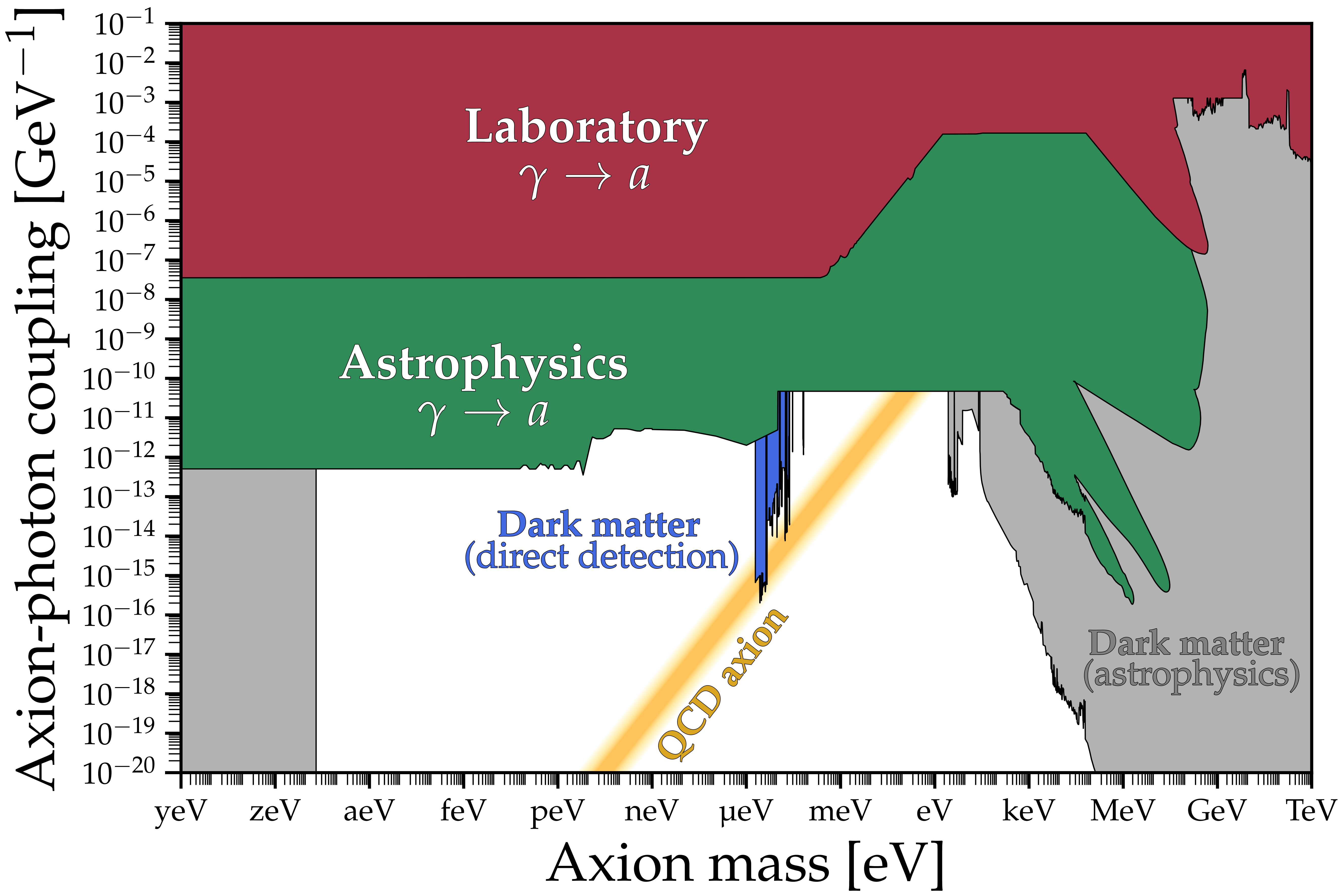
Broadening the landscape

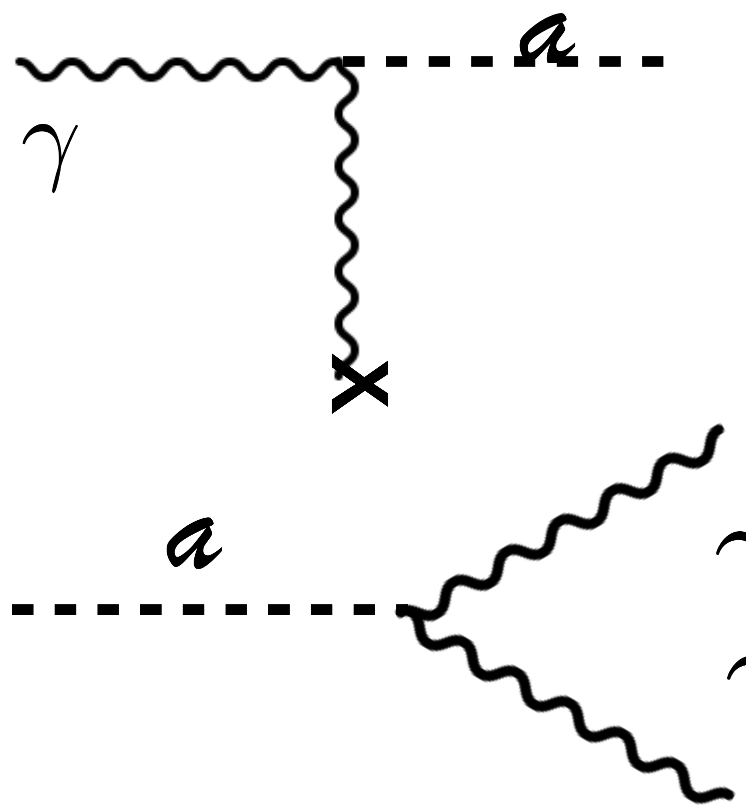
Axion-like particles: wider searches

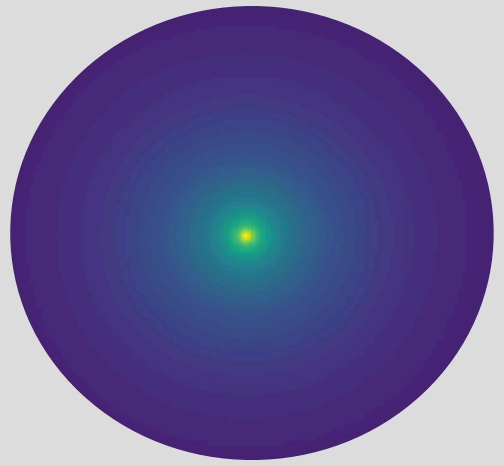
$$\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a = g_{a\gamma} \mathbf{E} \cdot \mathbf{B} a$$

cc-SNe Primakoff

Photons in source B field





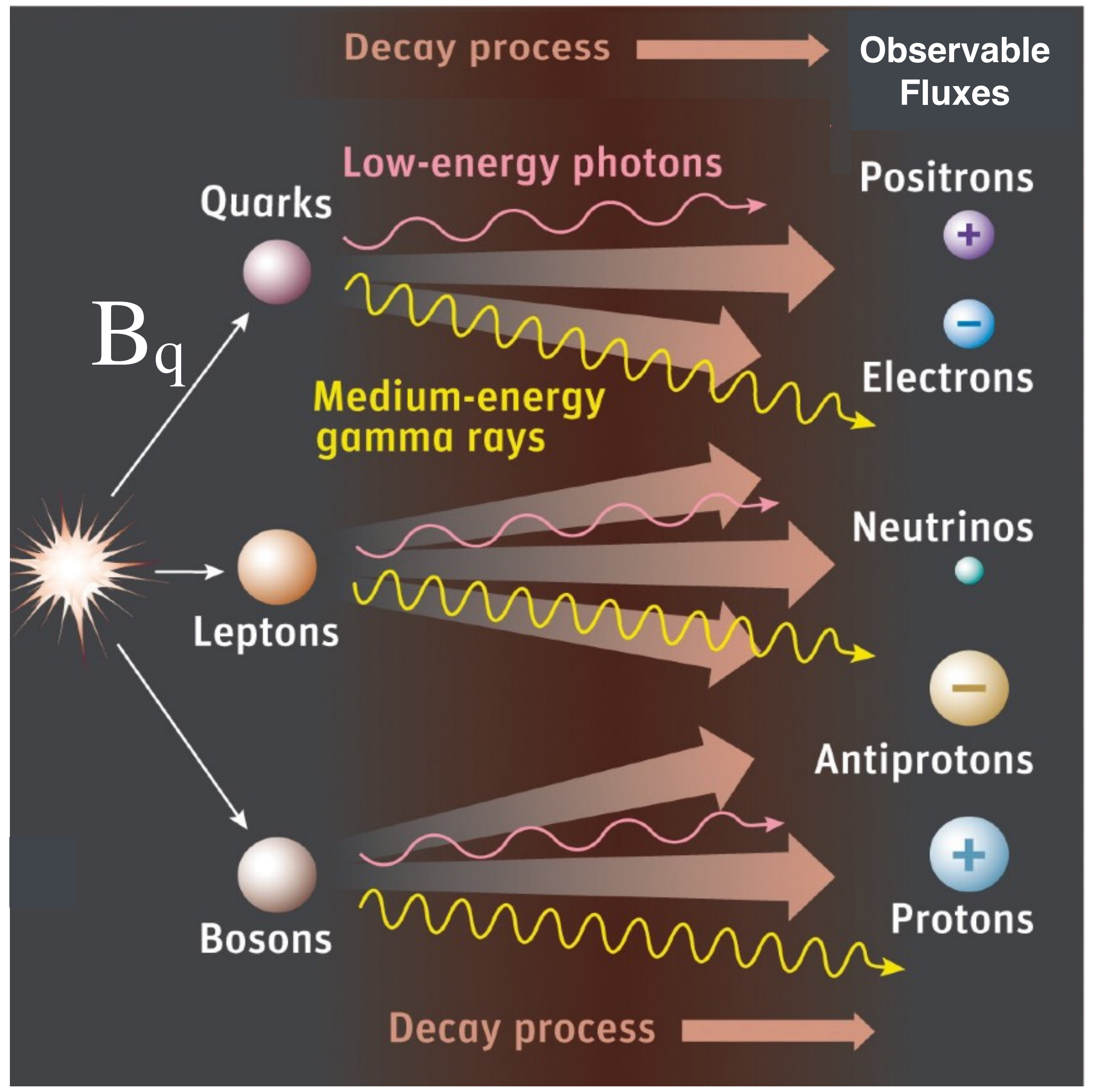


Dark matter

https://github.com/cajohare/AxionLimits

Particle dark matter emission

DM annihilation/decay



$$(DM)\, DM \to SM\, SM$$

$$E_{\rm CM} = N\, m_{\rm DM}\,, \qquad N = 1\ ({\rm decay}),\ 2\ ({\rm annih})$$

Centre of mass energy $\simeq$ Signal energy

$m_{\rm DM} \lesssim {\rm MeV}$

$$E_\gamma = \frac{N m_{\rm DM}}{2}$$

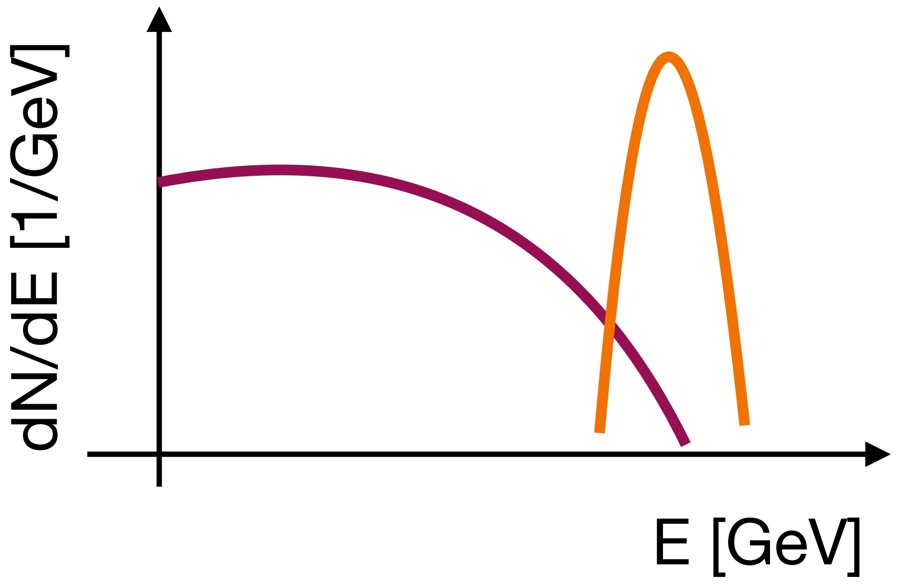
Narrow line signal

$$\frac{dN_\gamma}{dE} = 2\delta\left(E - \frac{N m_{\rm DM}}{2}\right)$$

$m_{\rm DM} \gtrsim {\rm MeV}$

Broader energy distribution

$$\frac{dN_\gamma}{dE} = \left(\frac{dN_\gamma}{dE}\right)_{\gamma\gamma} + \left(\frac{dN_\gamma}{dE}\right)_{\rm sec} + \left(\frac{dN_\gamma}{dE}\right)_{\rm FSR}$$



Particle dark matter emission

$$(DM)\, DM \to SM\, SM$$

$$E_{\rm CM} = N\, m_{\rm DM}\,, \qquad N = 1 \text{ (decay)},\ 2 \text{ (annih)}$$

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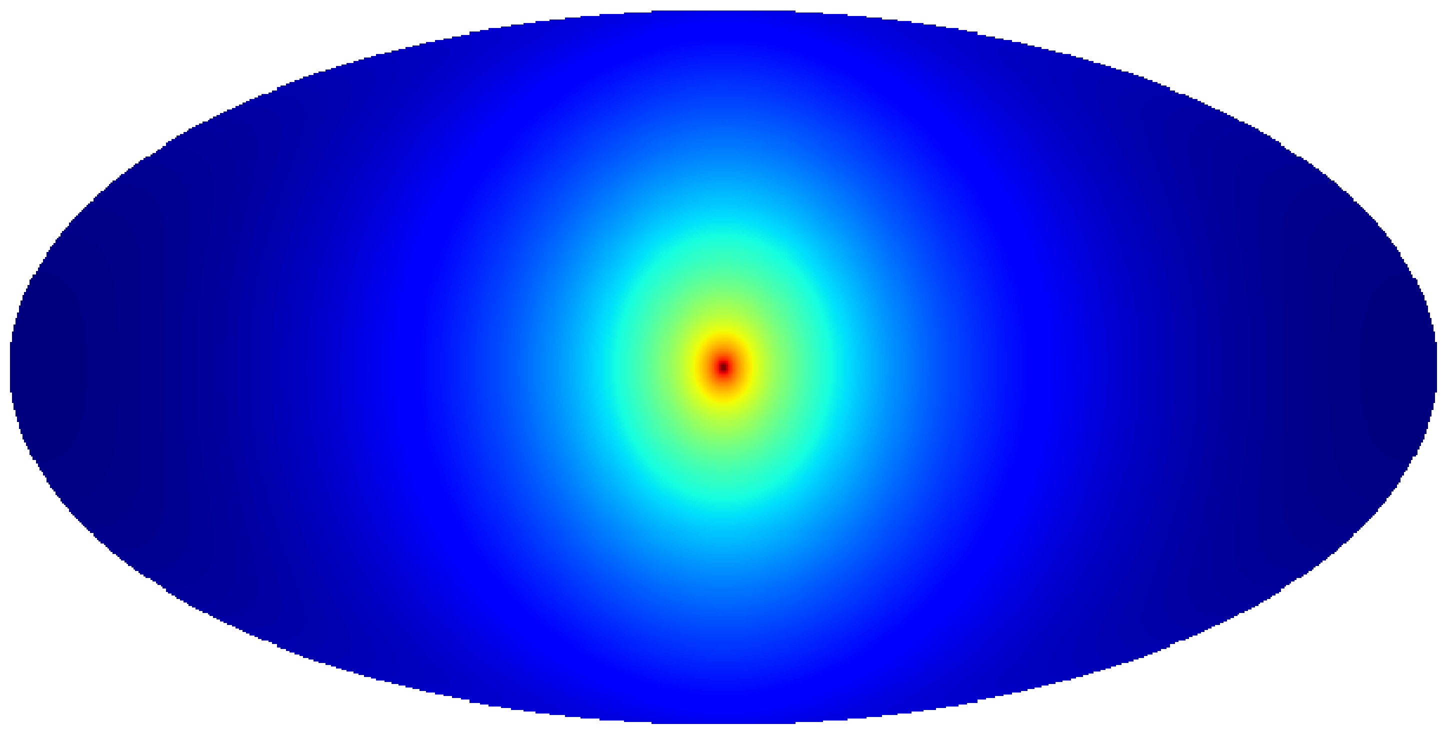
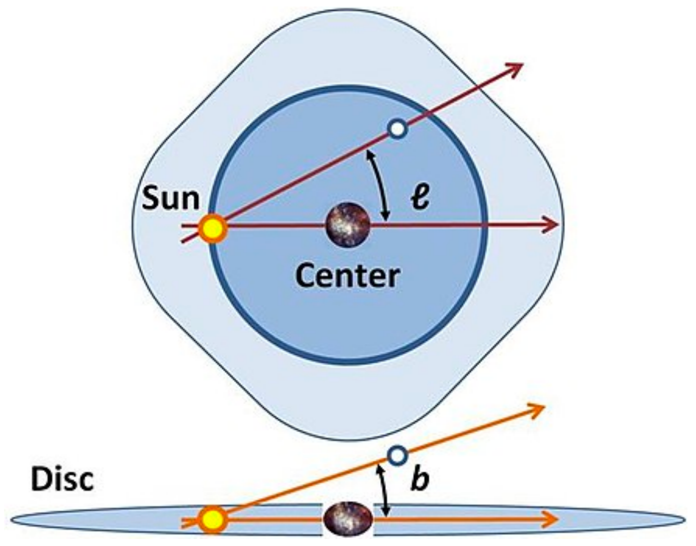


Self-conjugated dark matter annihilation
Differential **gamma-ray** flux

$$\frac{d\Phi_\gamma}{dE}(\ell, b) = \mathcal{A}(\theta_{\rm DM}) \times \frac{dN_\gamma}{dE} \times \int_{\rm l.o.s.} \rho^N_{\rm DM}(s, \ell, b) ds$$

$\theta_{\rm DM} = \{\Gamma_\gamma, m_{\rm DM}\}$ *Decay*

$\theta_{\rm DM} = \{\langle\sigma v\rangle, m^2_{\rm DM}\}$ *Annihilation*



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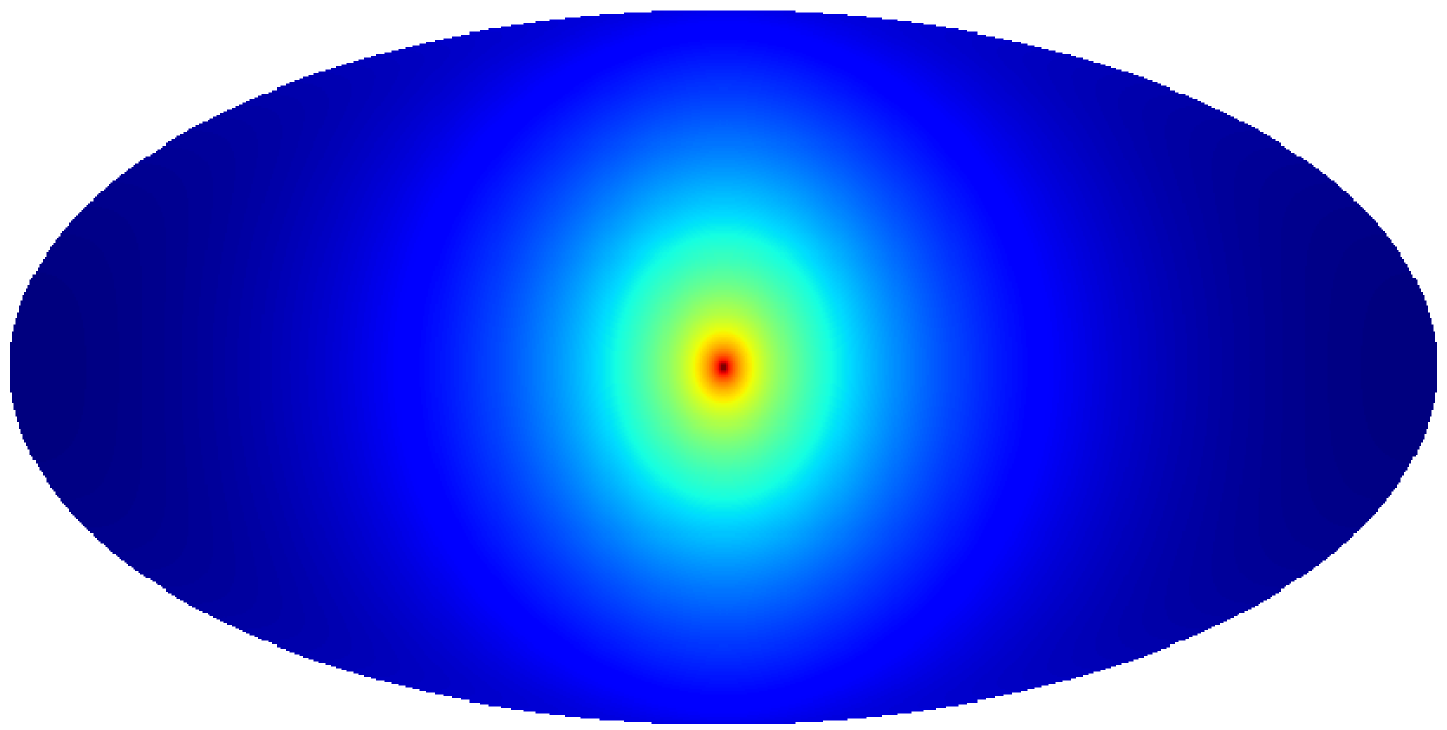

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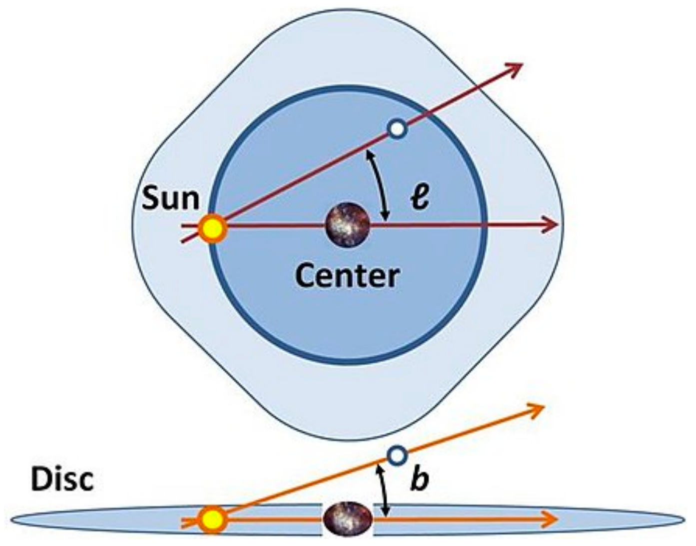
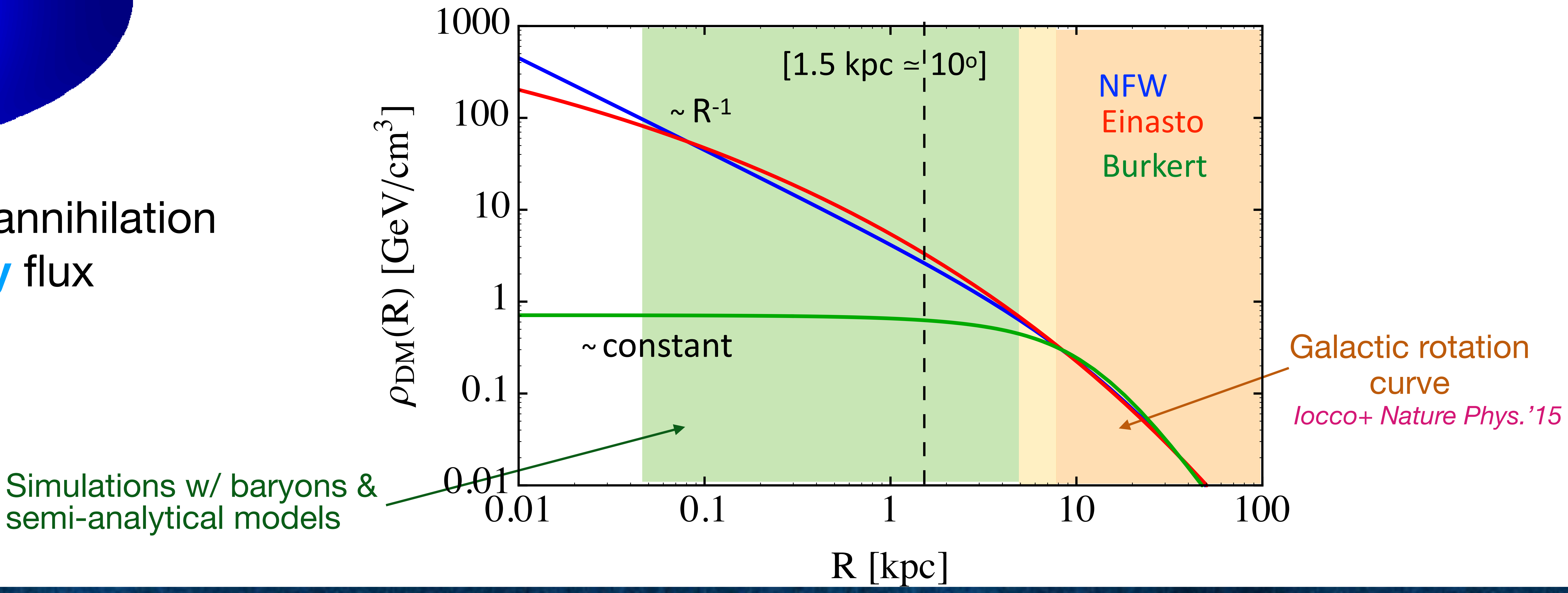




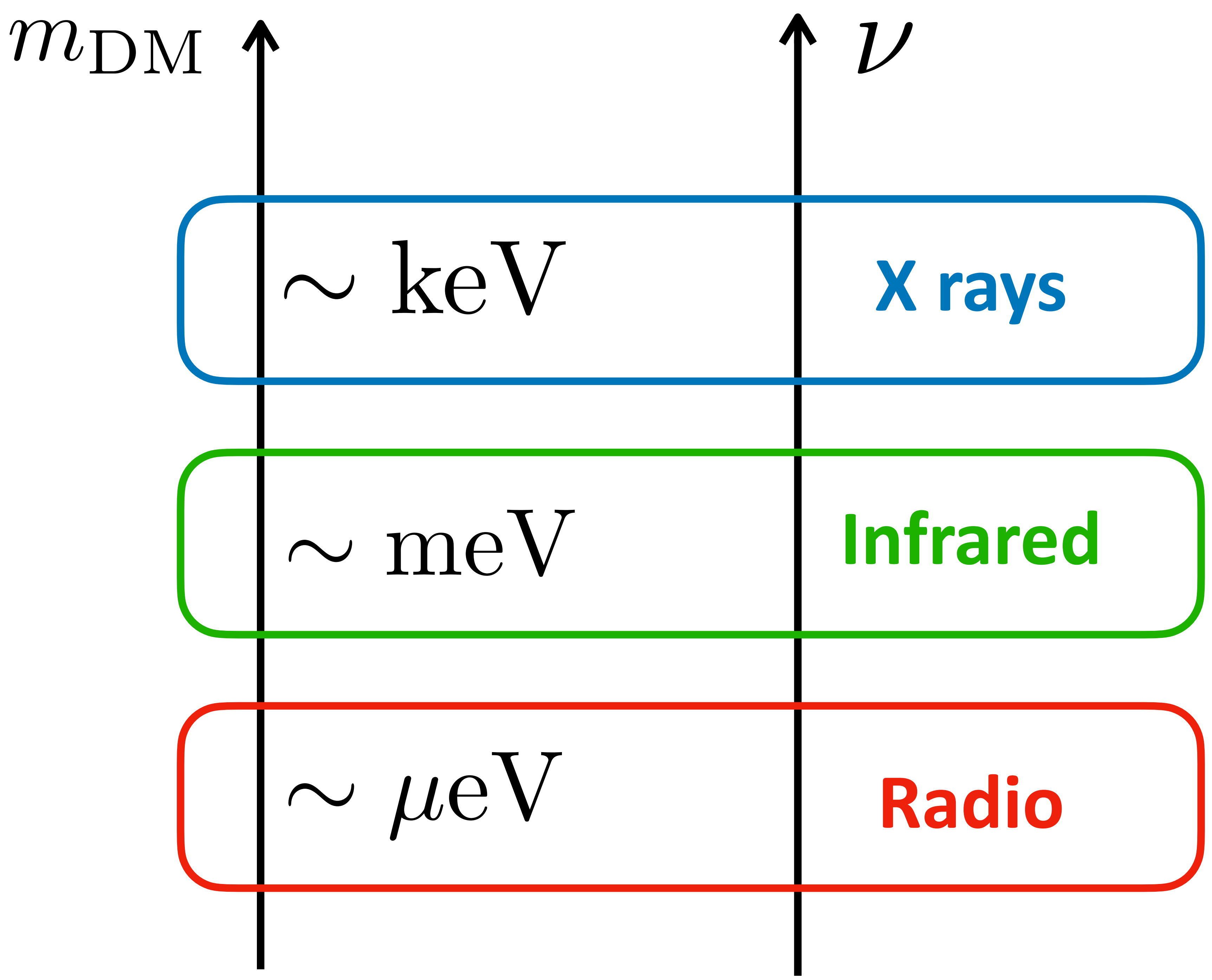
Light dark matter decay: lines

$m_{\rm DM} \lesssim \rm MeV$

Only allowed final state is into photons emitted back-to-back

$$E_\gamma = \frac{m_{\rm DM}}{2}$$

Narrow line signal @ energy scale of the DM mass

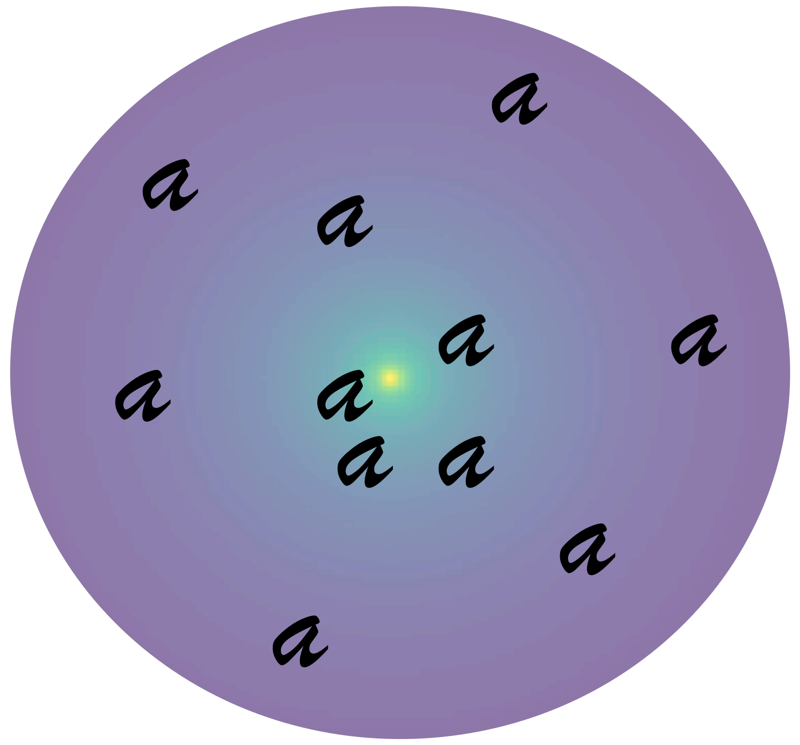


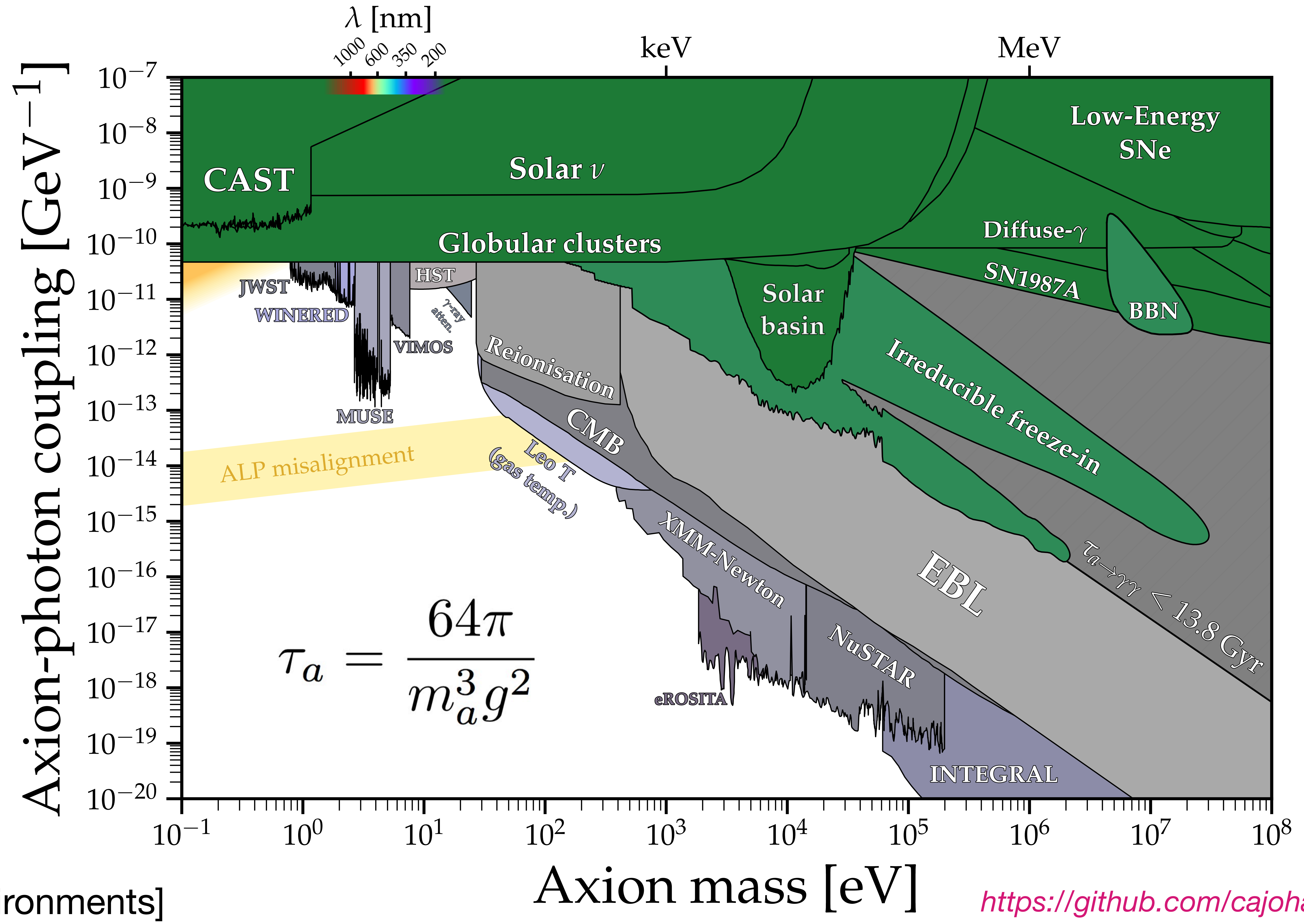
[Contribution from all galaxies in the universe: redshifted line and integral over star-formation history => contribution to **extragalactic backgrounds**]

ALPs dark matter decay

- ALPs can be viable DM candidates in some portions of the parameter space

Preskill+ PLB 1983; Sikivie International Journal of Modern Physics '10





- If DM, ALPs distributed in galaxies according standard DM density distributions (e.g. NFW)
- Search for narrow lines in DM-rich environments

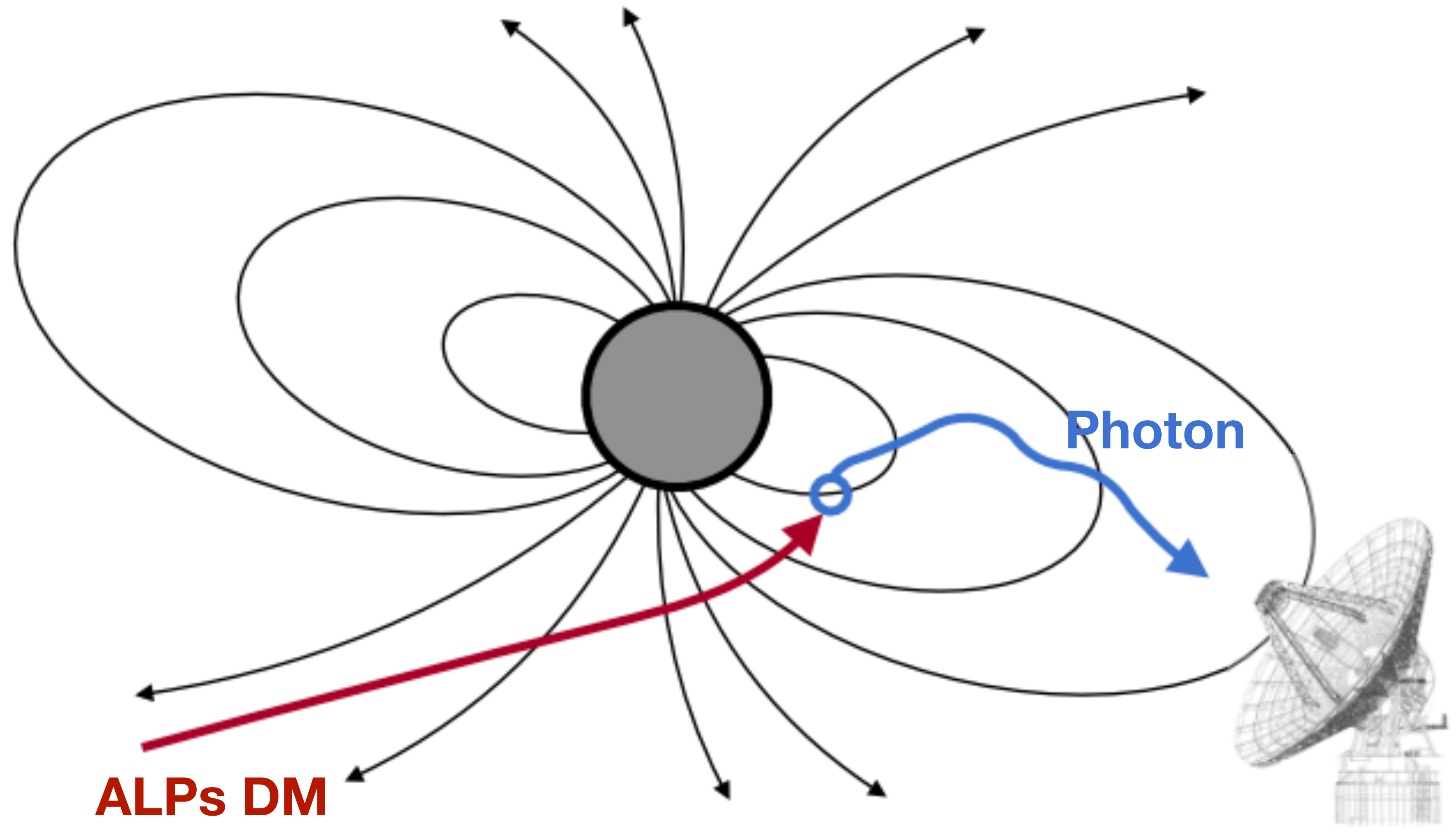
[Lighter ALPs can be probed in HE astro environments]

https://github.com/cajohare/AxionLimits

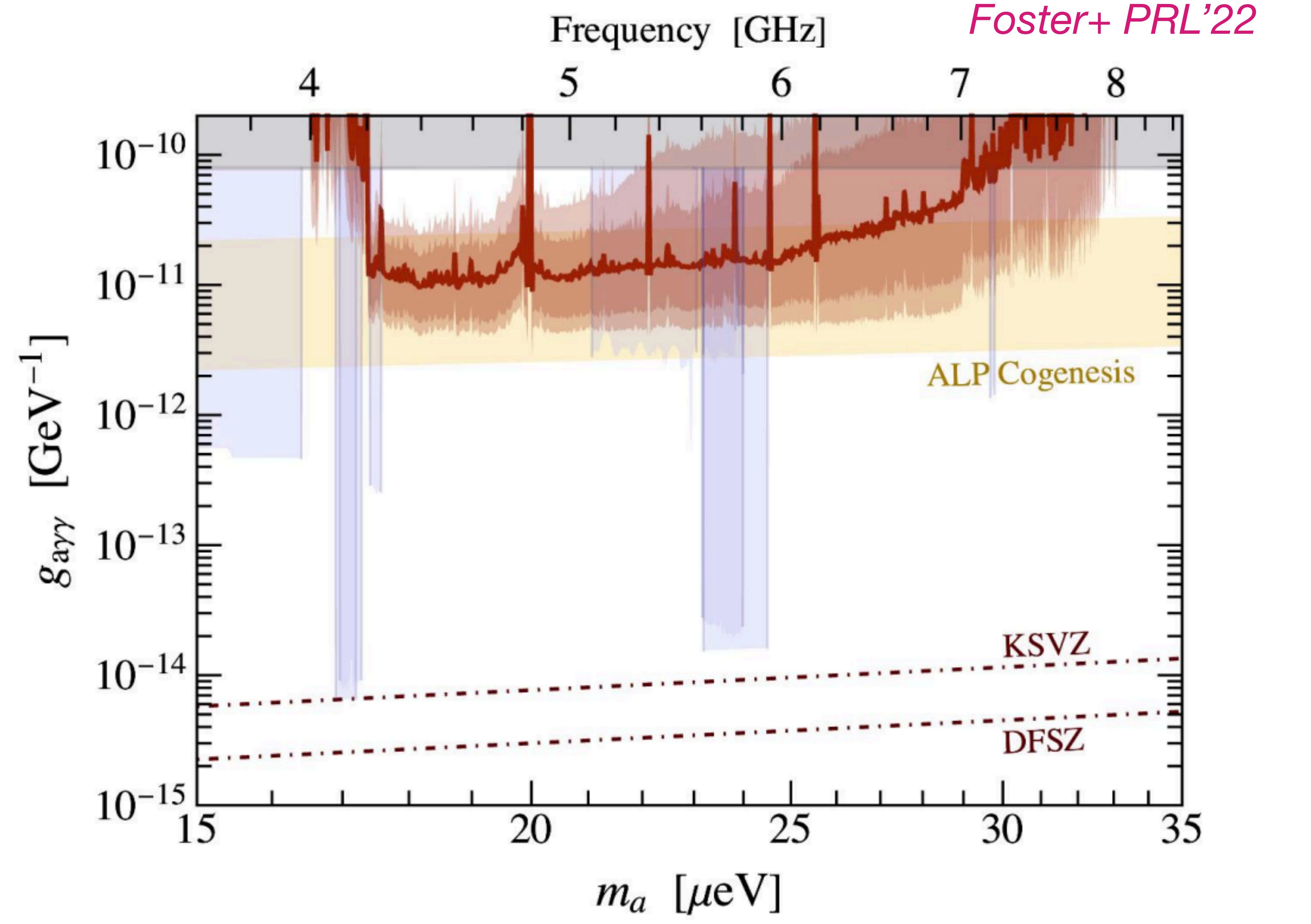
(…) ALPs dark matter resonant conversion

Monochromatic radio emission (MHz - GHz) from **DM axion/ALP-photon conversion**:

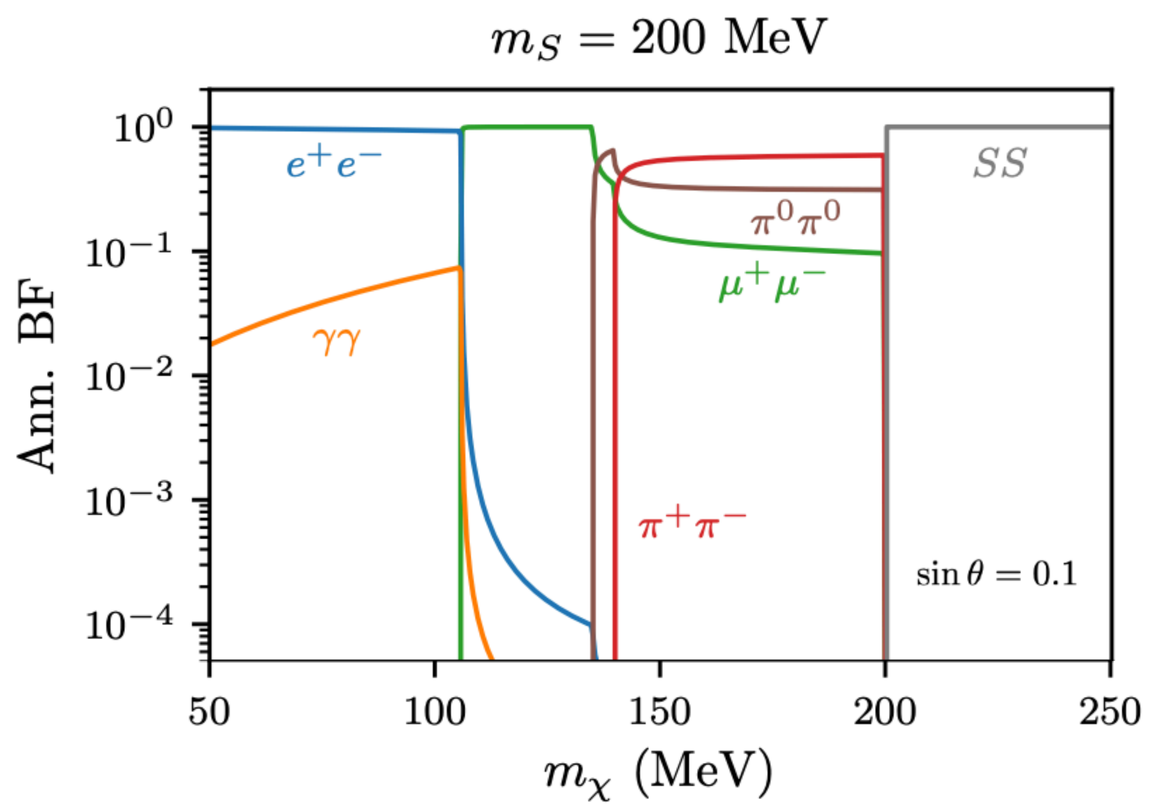
- *Resonant* conversion from highly magnetised neutron stars (NSs), or white dwarf stars
  Pshirkov JETP'09; Huang+2018; Hook+PRL'18
- *Non-resonant* transitions in the Galactic center and/or of discrete astrophysical objects
  Kelley&Quinn ApJ'17; Sigl PRD'17
- Still large **limitations** in **model predictions** Leroy+ PRD'20; Witte+ PRD'21; Battye+ JHEP'21; Millar+JCAP'21; Bhura+JCAP'24



Foster+ PRL'22



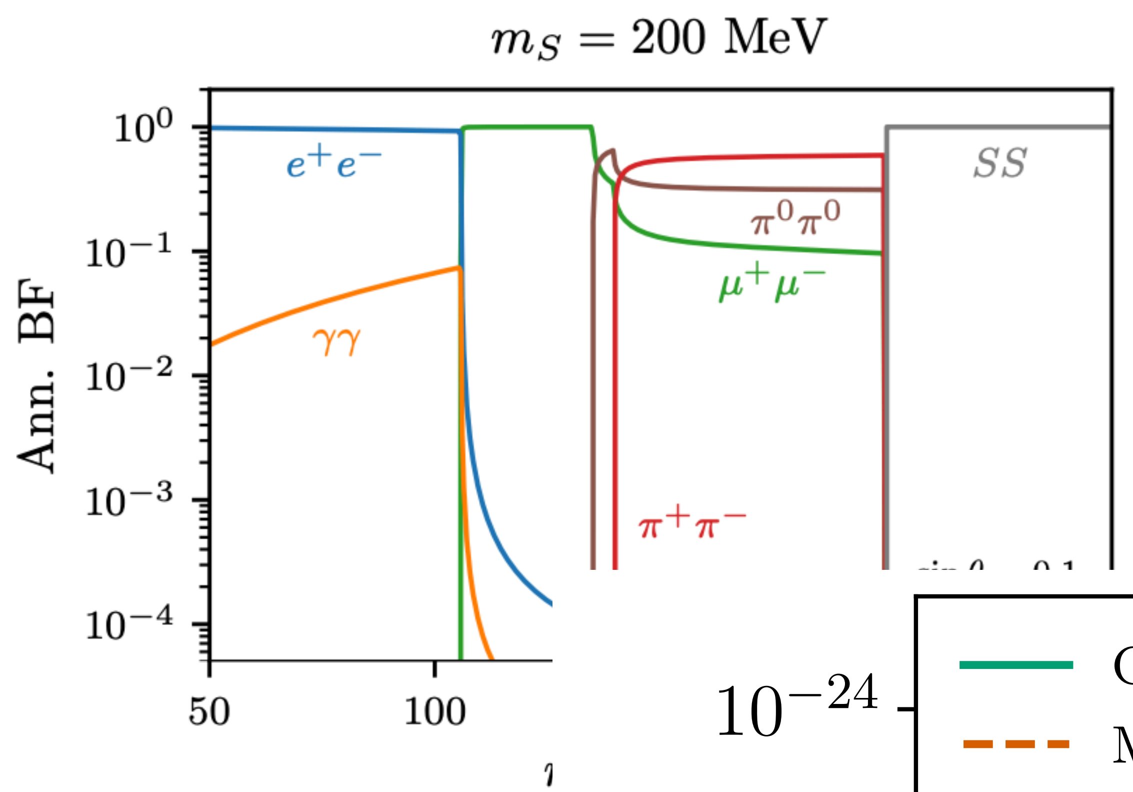
Sub-GeV dark matter limits



Coogan+ JCAP'20

- Simple thermal freeze-out scenario for s-wave annihilation generically ruled out
- But p-wave models (many of the portals) still viable

Sub-GeV dark matter limits



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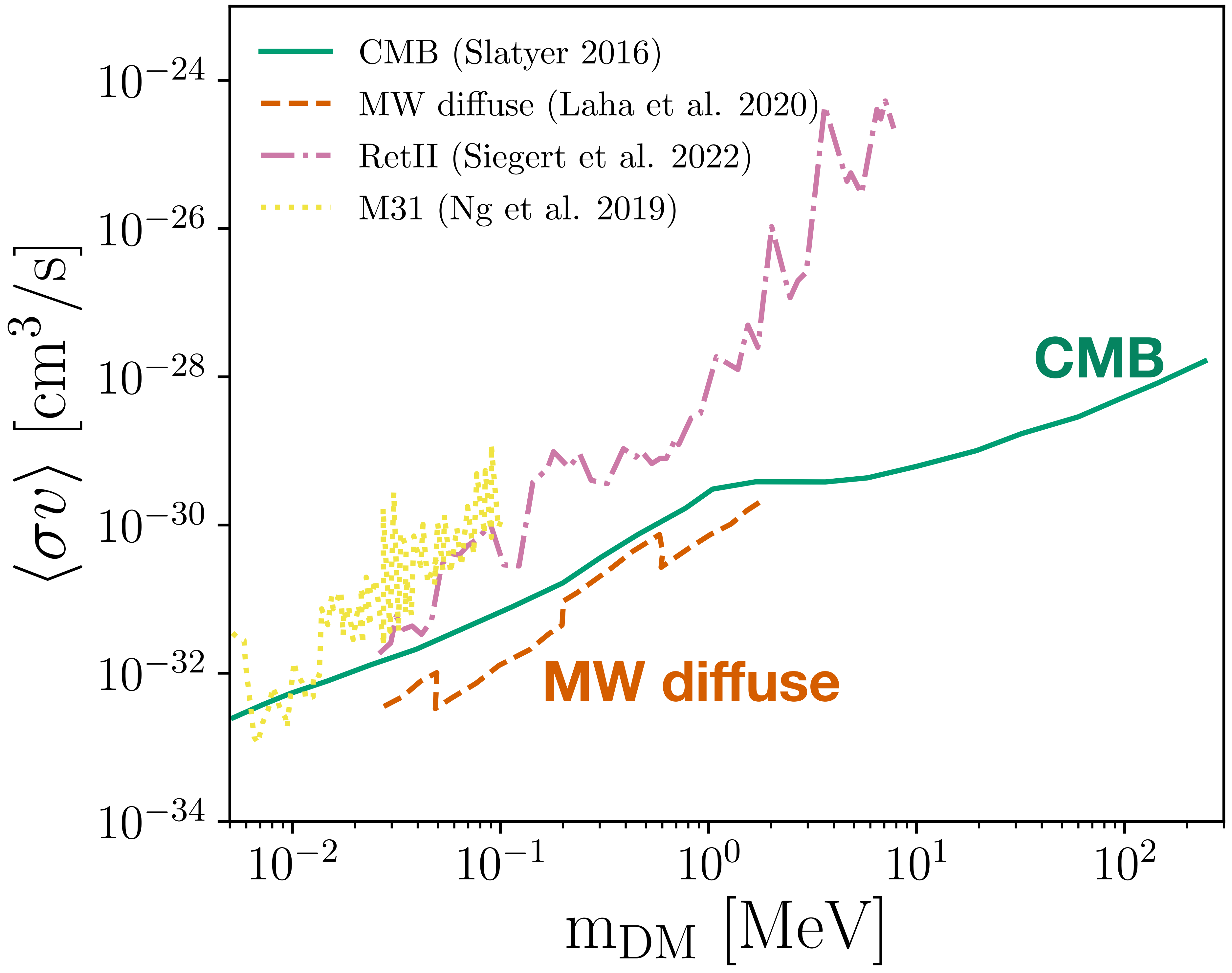
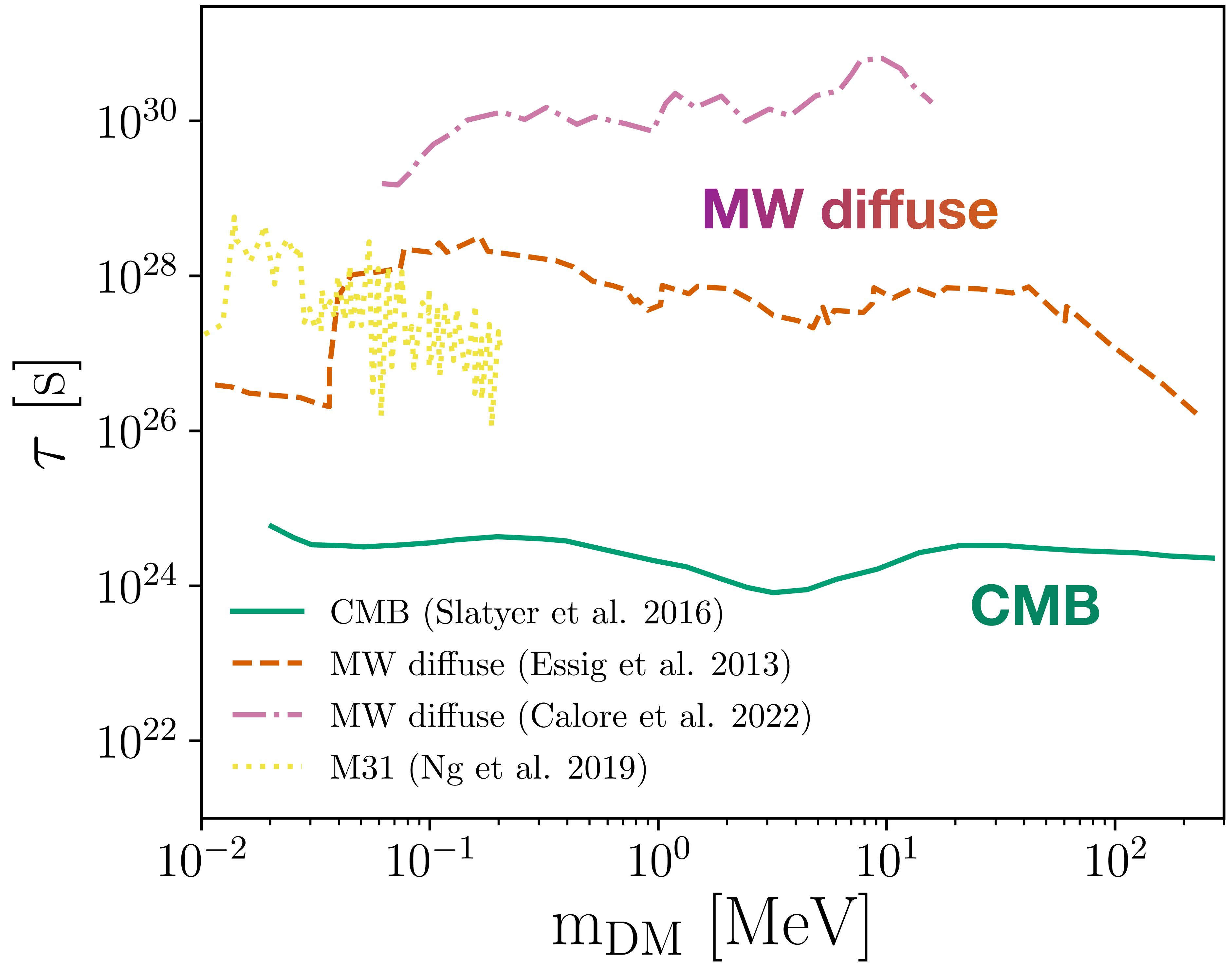
FC FIPs2022 Proceedings



Two-photons annihilation

Siegert, FC+ MNRAS'24



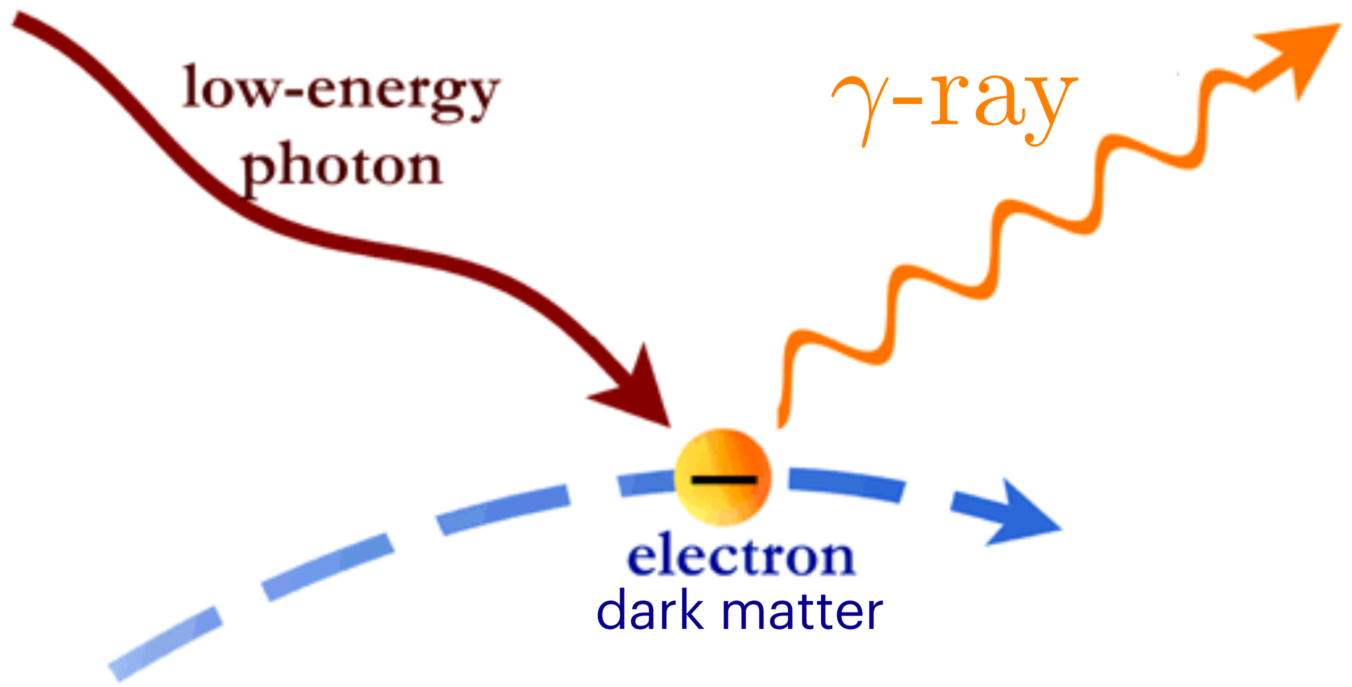
Two-photons decay

FC+ MNRAS'23

https://zenodo.org/record/7984451

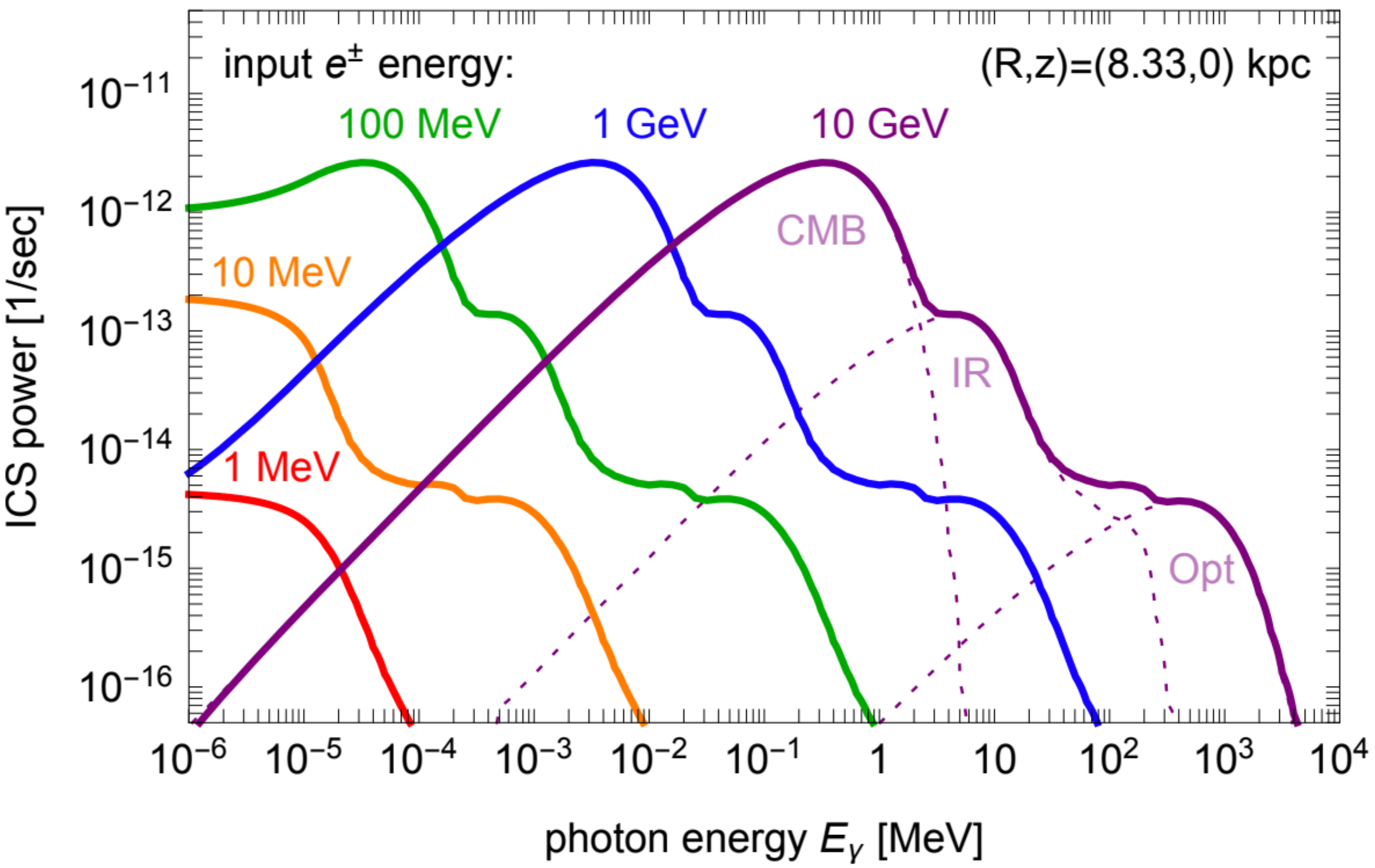
Particle dark matter emission

Inverse Compton scattering from leptonic final states



$$\epsilon_f \simeq \gamma^2 \epsilon_i = 30 \left(\frac{\epsilon_i}{\text{eV}}\right) \left(\frac{E_e}{\text{GeV}}\right)^2 \text{MeV}$$

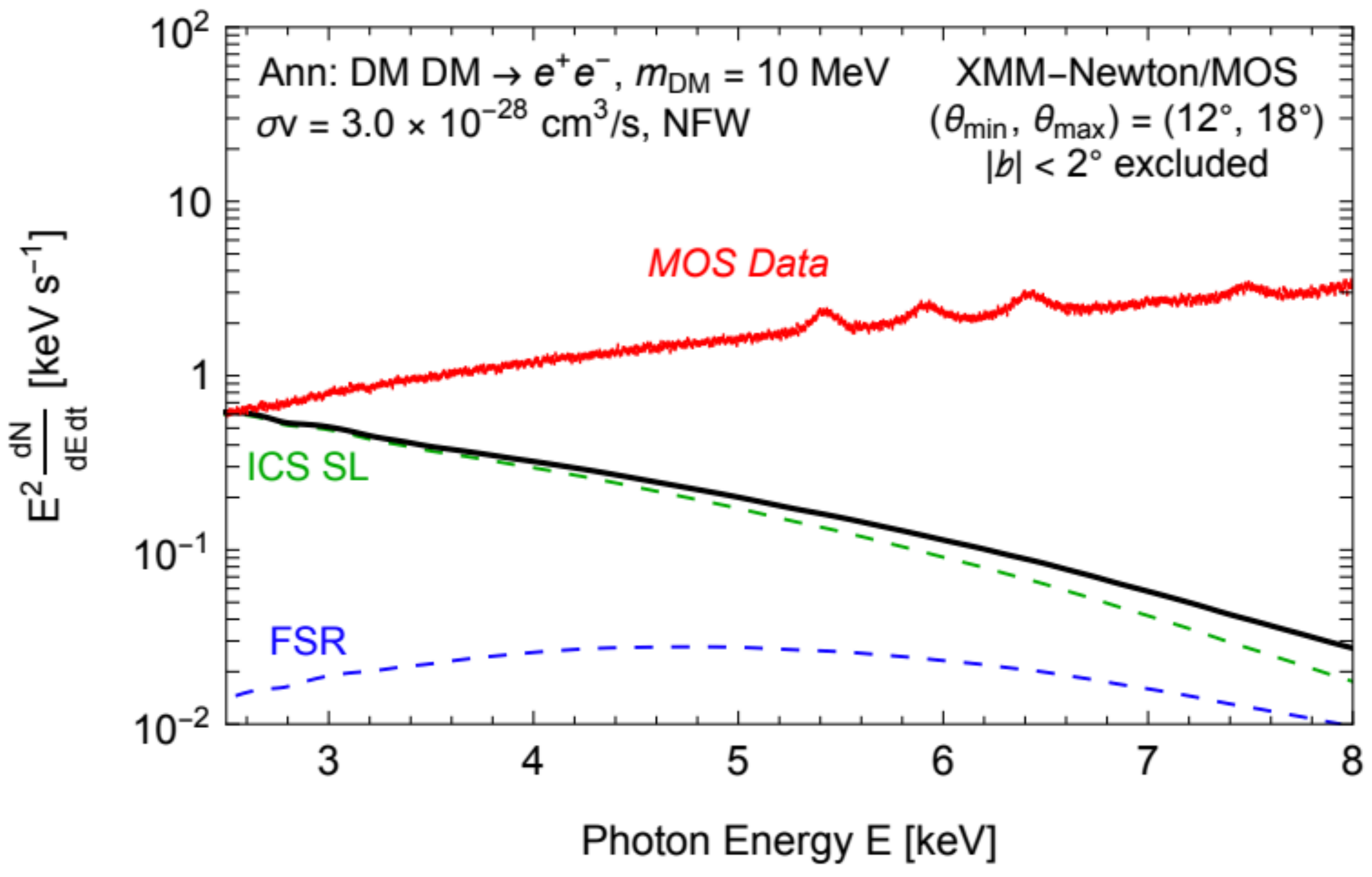
Cirelli+ PRD' 21



Secondary emission processes allow us to probe DM at much higher masses than prompt energy scales

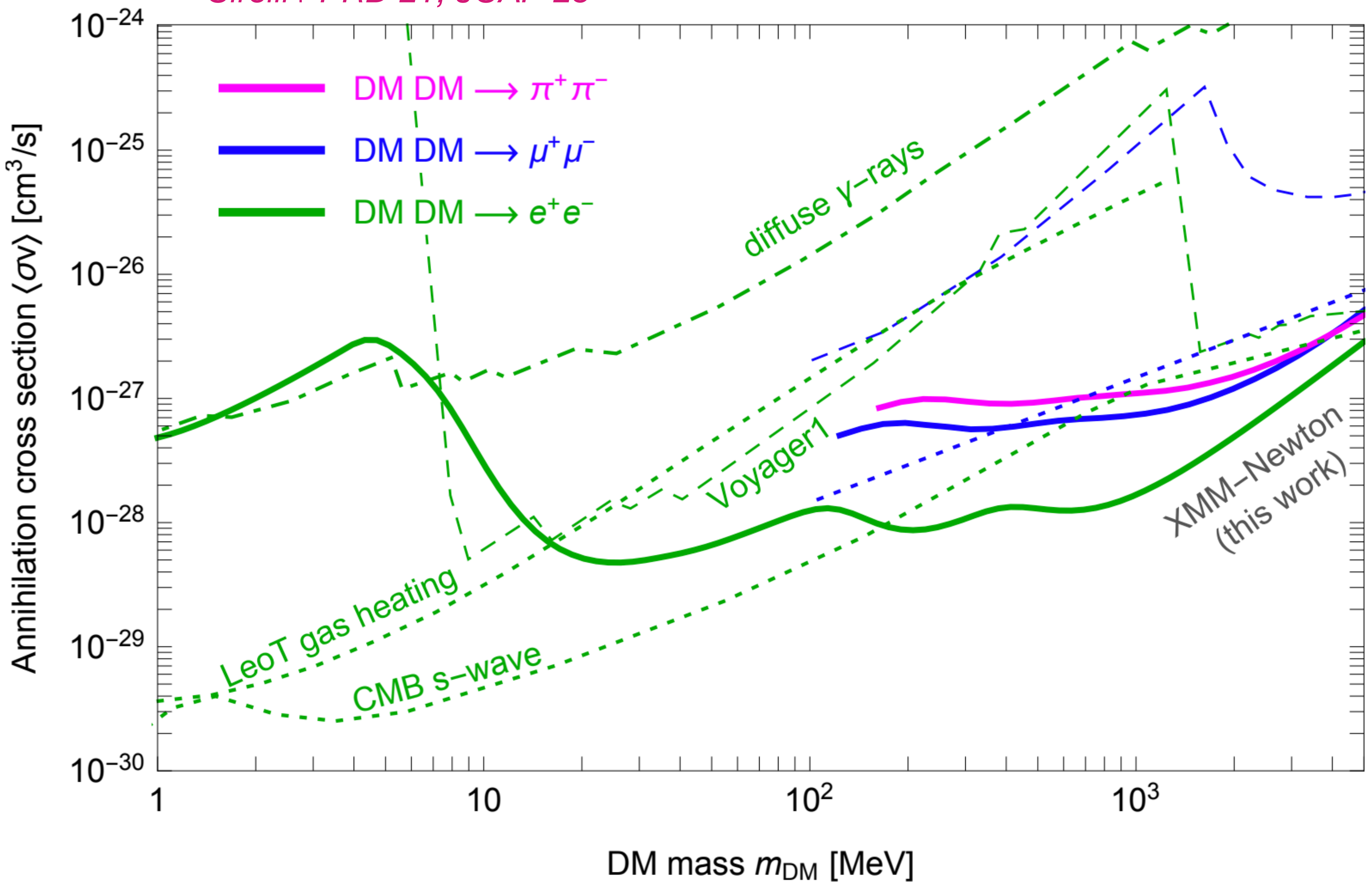
Sub-GeV dark matter limits: X rays

The power of inverse Compton emission



Limits on inverse Compton induced gamma-ray emission from **XMM-Newton blank-sky observations**

Cirelli+ PRD'21; JCAP'23



Sub-GeV dark matter limits: 511 keV line

$$\Phi_{e^+}^{\rm ann} = \frac{1}{2}\frac{4\pi}{m_\chi^2}\langle\sigma v\rangle\int_0^{1.5\rm kpc} dr\, r^2 \rho_{\rm DM}^2(r),$$

$$\Phi_{e^+}^{\rm dec} = \frac{4\pi}{m_\chi}\frac{1}{\tau}\int_0^{1.5\rm kpc} dr\, r^2 \rho_{\rm DM}(r).$$

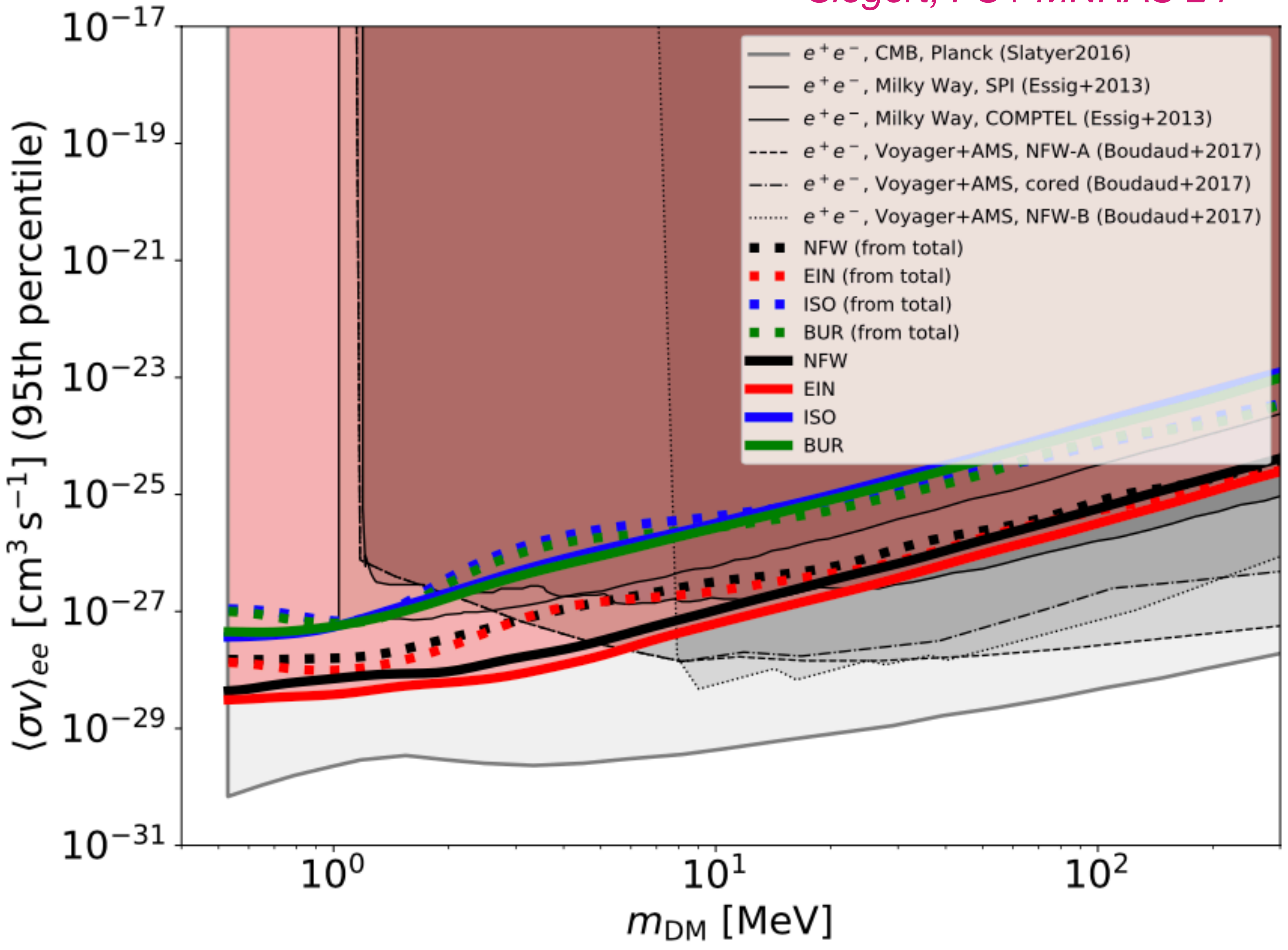
$$\Phi_{e^+}^{\rm ann,dec} < 2\times 10^{43}\,{\rm e^+/s}$$

$$\langle\sigma v\rangle \lesssim 2.3\times 10^{-30}\,{\rm cm^3 s^{-1}}\left(\frac{m_\chi}{\rm MeV}\right)^2,$$

$$\tau > 1.1\times 10^{26}\,{\rm s}\left(\frac{\rm MeV}{m_\chi}\right)$$

Vincent+JCAP'12

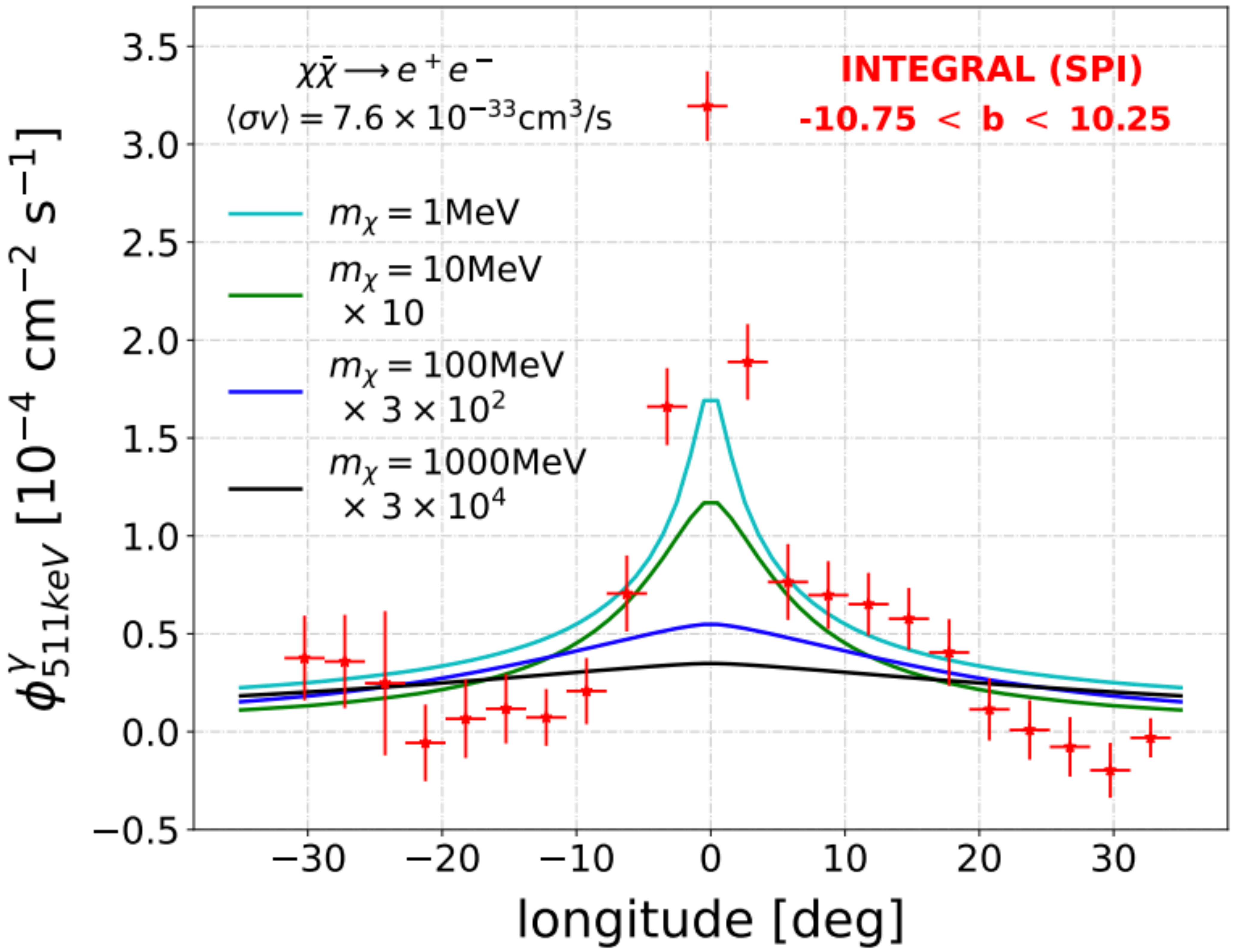
Siegert, FC+ MNRAS'24

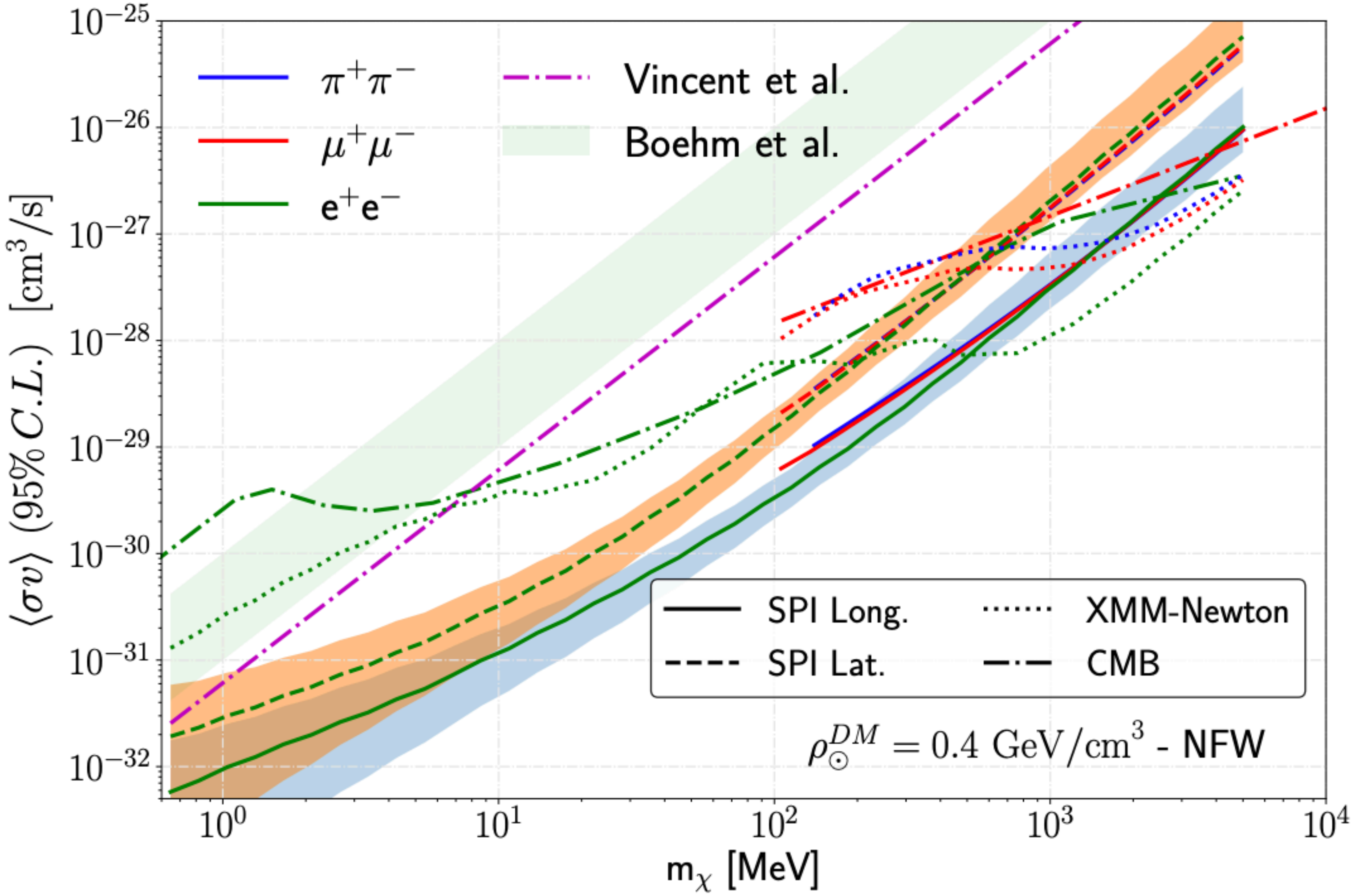


[*Caputo+ JCAP'23* COSI projection]

Sub-GeV dark matter limits: 511 keV line

De La Torre Luque+ ApJL'24, PRD'24

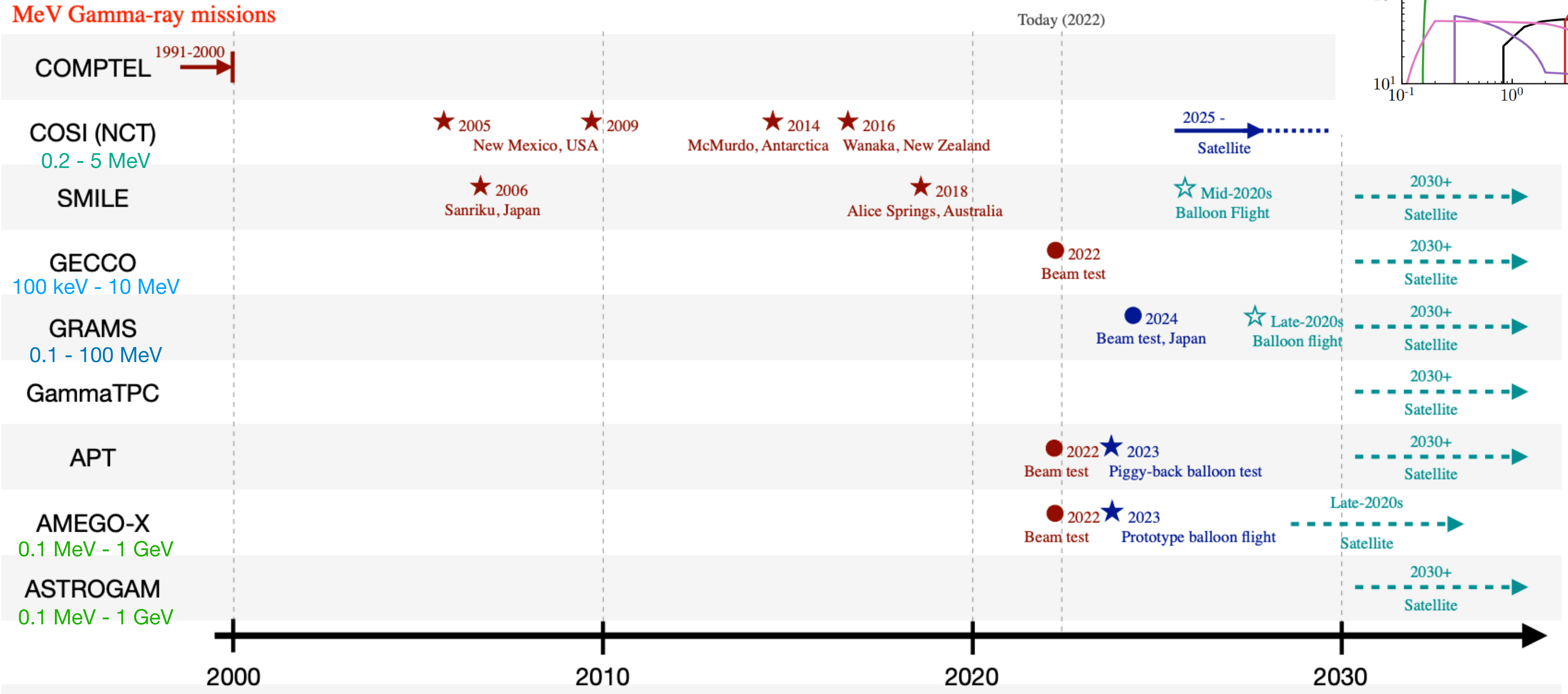




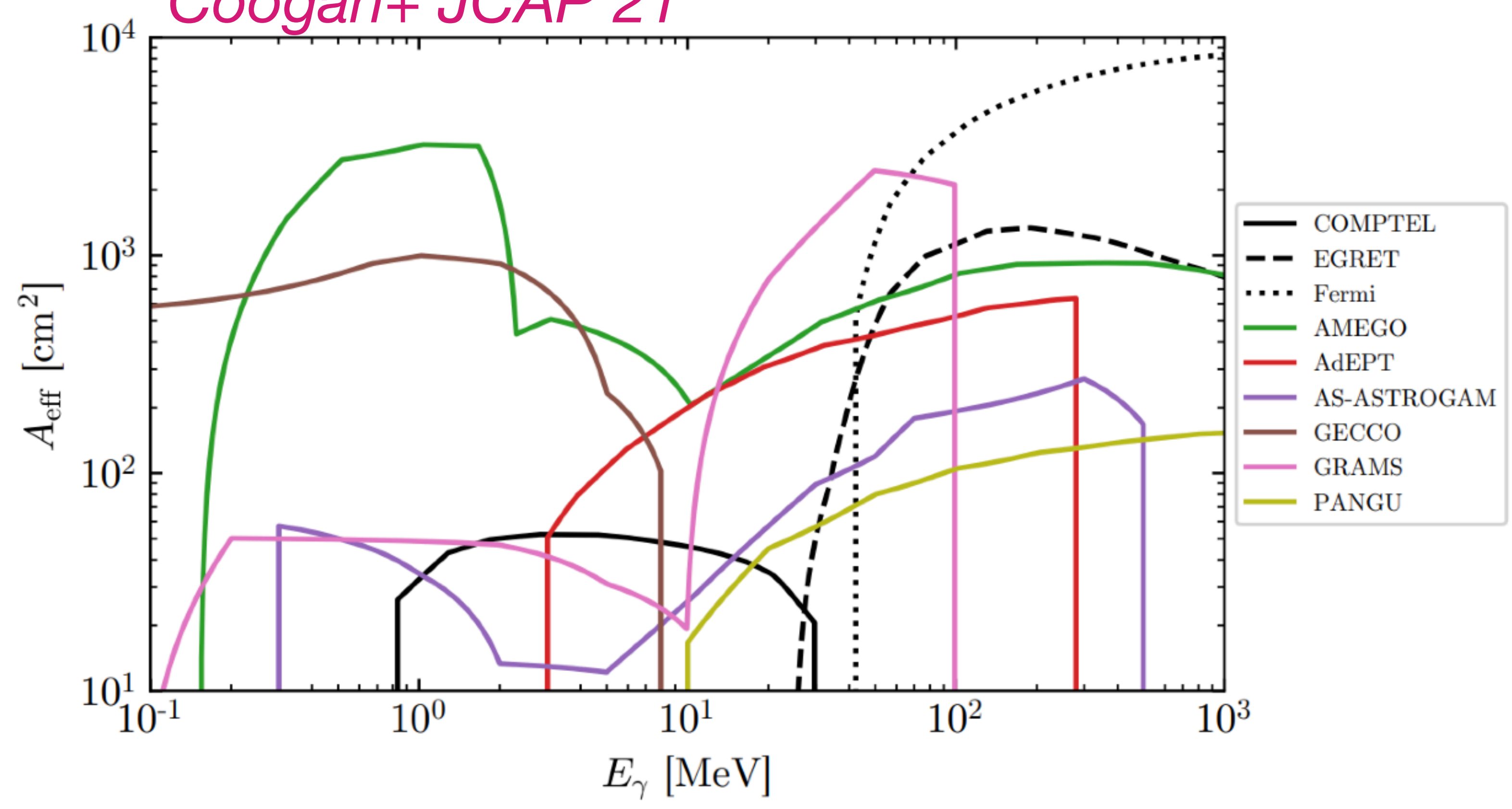
$$\frac{d\phi^{511}_\gamma}{d\Omega} = 2k_{ps} \int ds\, s^2 \frac{\phi_e(x_{s,b,l}, y_{s,b,l}, z_{s,b,l})}{4\pi s^2}$$

Accounts for changes in morphology due to **diffusion** (prior to thermalisation)

Future: Covering the MeV sensitivity gap



Coogan+ JCAP'21



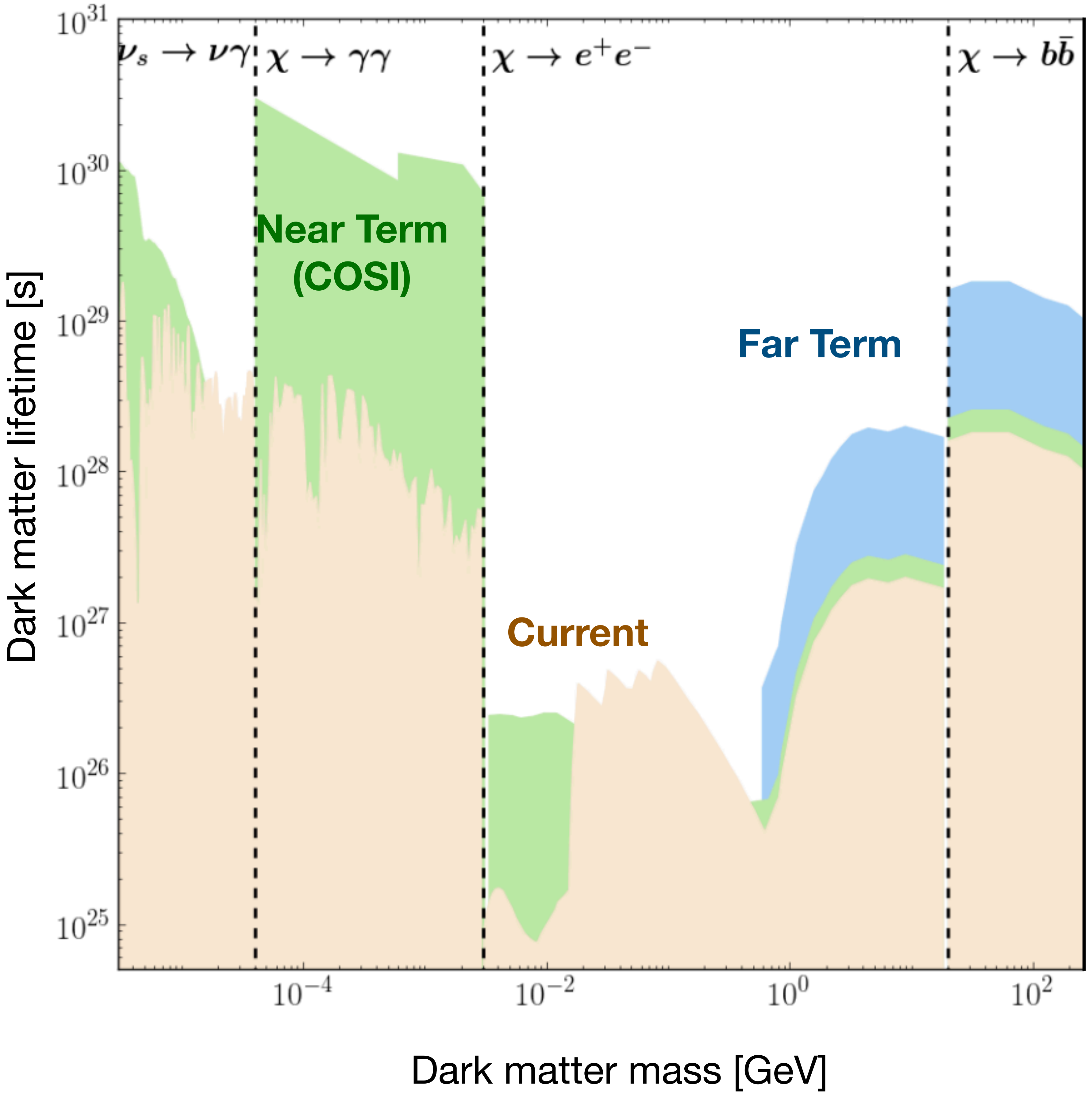
$$N_\gamma = T_{\rm obs} \int_{E_{\rm min}}^{E_{\rm max}} dE\, A_{\rm eff} \frac{d\Phi}{dE_\gamma}$$

Aramaki+ Snowmass'21 CF

Future: Covering the MeV sensitivity gap

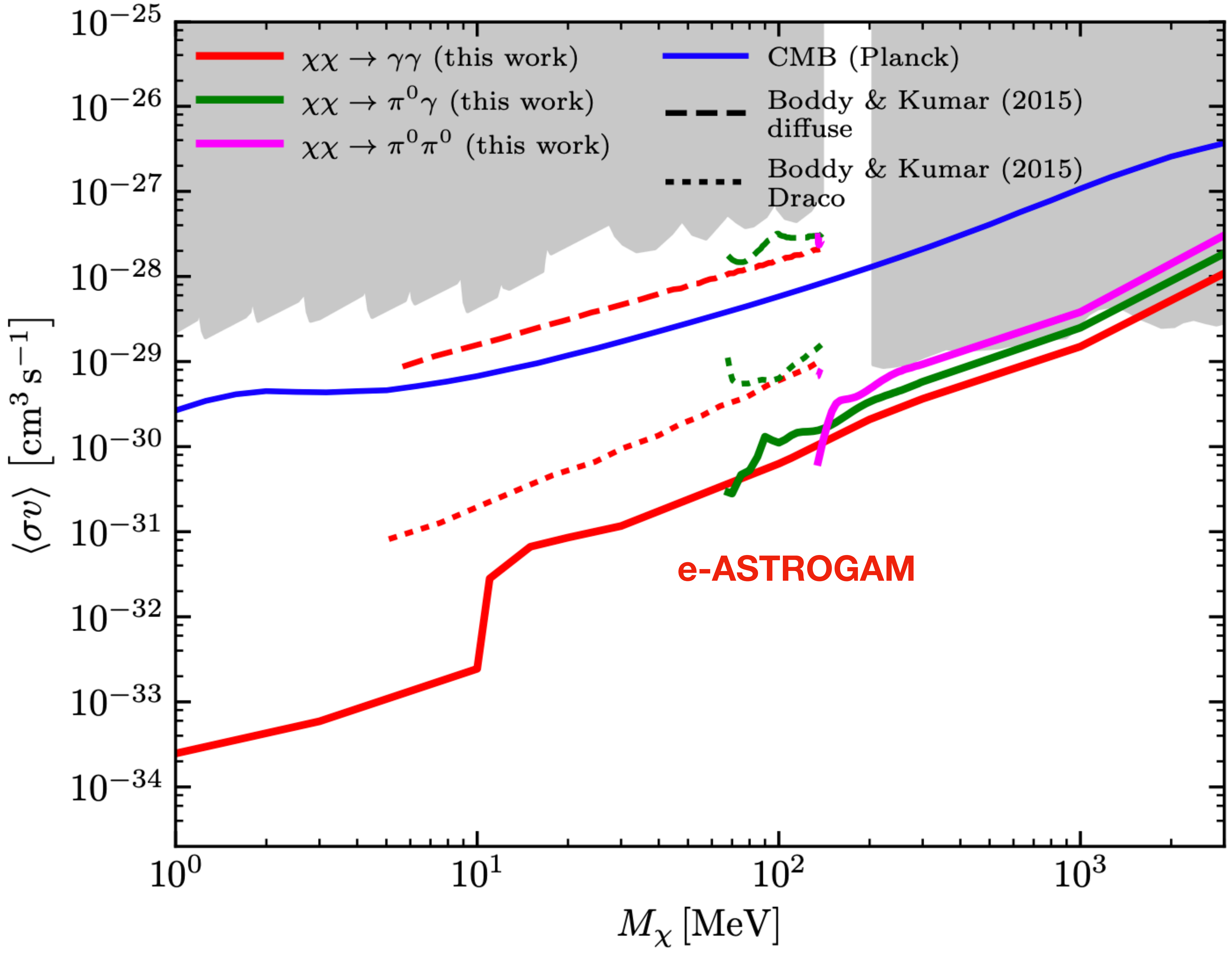
Sensitivity to dark matter

Cooley+ Snowmass'21 CF1 Report



Decay

Bartels+ JCAP'17



Annihilation

Conclusions and outlook

- ✓ Dark matter evidence requires new BSM physics, however the **landscape for particle and non-particle models is broad and diverse**
- ✓ Current search strategy inspired by a **“delve deep, search wide”** approach, with ultimate reach for classical WIMPs and QCD axion in the next decade
- ✓ **Cosmological & astroparticle observables** are sensitive to **different light dark matter models** probing a large portion of their parameter space
- ✓ **Diversified program** to tackle dark matter over a wide spectrum of models and signatures
- ✓ Experimental progress in the MeV domain can provide **access to yet uncharted portions of the DM parameter space** and **full complementarity with accelerator programme**!

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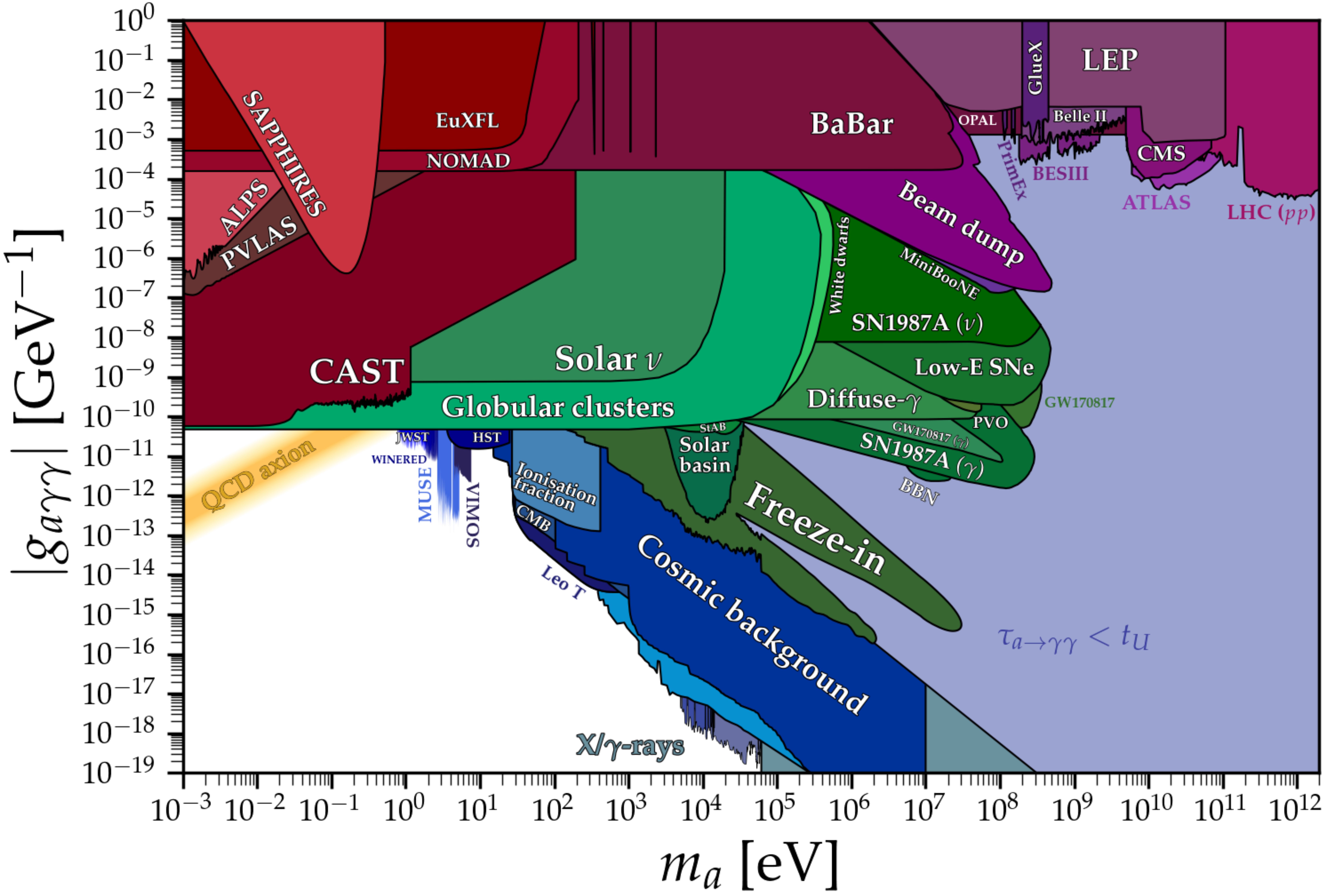
Thank you for the attention

Supplemental material


SAPPHIRES
EuXFL
NOMAD
BaBar
OPAL
GlueX
LEP
Belle II
PrimEx
BESIII
CMS
ATLAS
LHC (pp)
ALPS
PVLAS
Beam dump
MiniBooNE
White dwarfs
SN1987A (ν)
Low-E SNe
GW170817
CAST
Solar ν
Globular clusters
Diffuse-γ
PVO
GW170817 (γ)
SN1987A (γ)
BBN
StAB
Solar basin
JWST
HST
WINERED
MUSE
VIMOS
QCD axion
Ionisation fraction
CMB
Leo T
Freeze-in
Cosmic background
X/γ-rays
$\tau_{a\to\gamma\gamma} < t_U$
$|g_{a\gamma\gamma}|$ [GeV^{-1}]
m_a [eV]

Constraints on FIPs from CC SNe

The case of dark photons

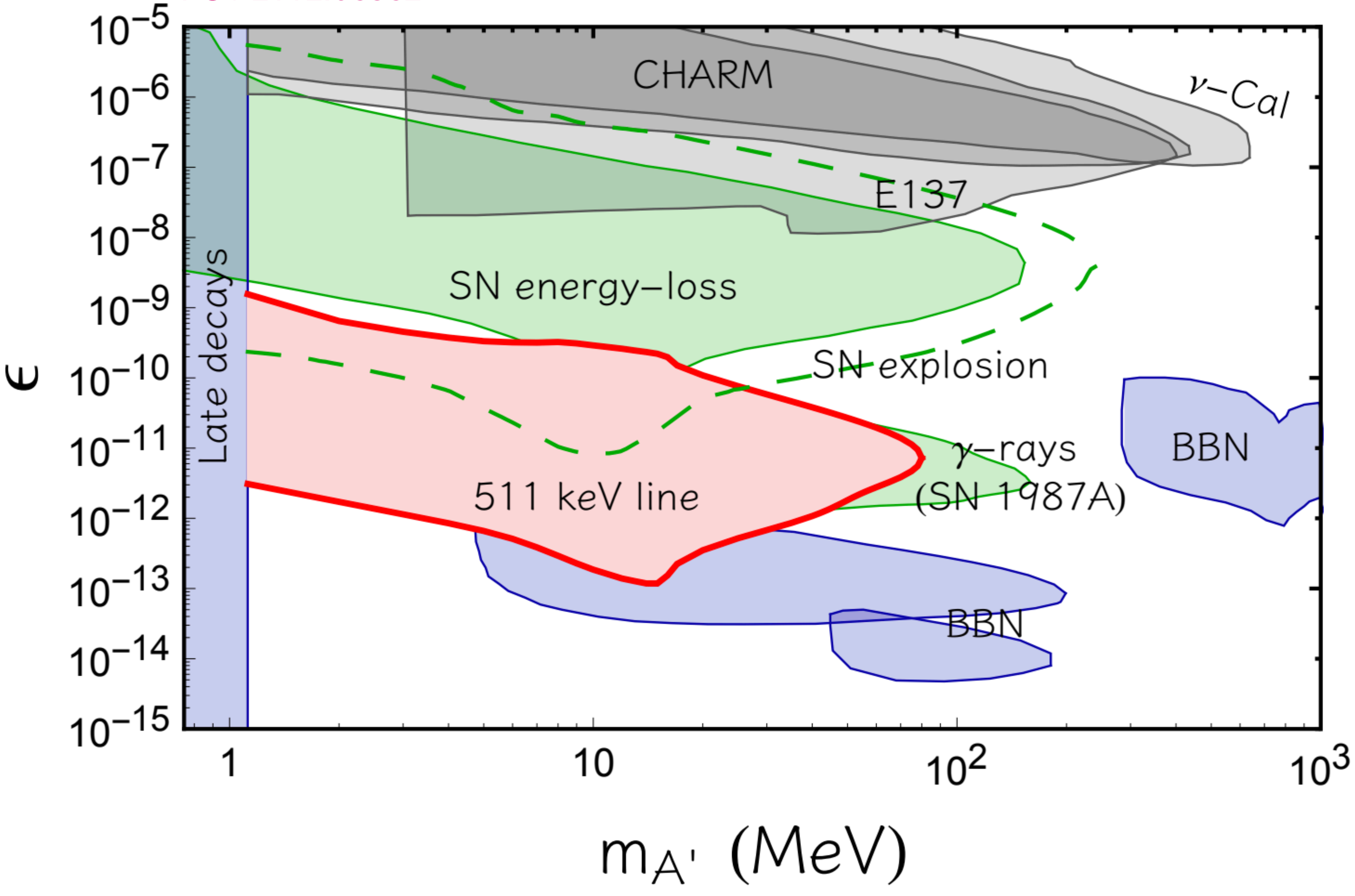
The **dark photon** (DP) is a $U(1)_0$ gauge boson kinetically mixed with the SM photon

$$\mathcal{L} = \frac{1}{2} m_{A'} \, A'_\mu \, A'^\mu - \frac{1}{4} F'_{\mu\nu} \, F'^{\mu\nu} - \frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu}$$

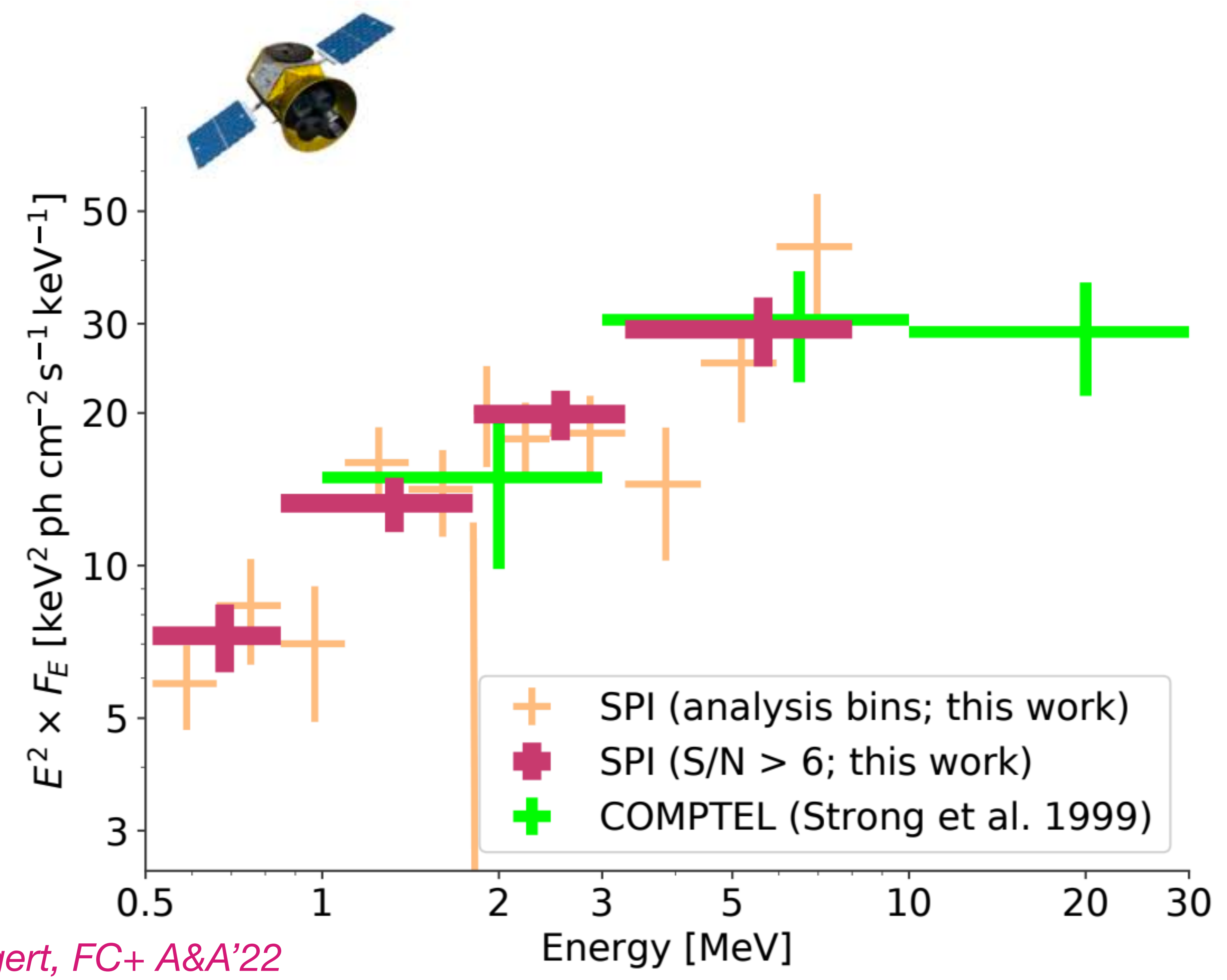
Transverse and longitudinal d.o.f can be produced in SN core

Chang+ JHEP'17

FC+ 2112.08382



Soft gamma rays with Integral/SPI



Siegert, FC+ A&A'22

New analysis of 16yr-data from SPI
30 keV — 8 MeV

Constraints on **cosmic-ray transport** at MeV energy but also on **exotic emission mechanisms**: particle and non-particle dark matter

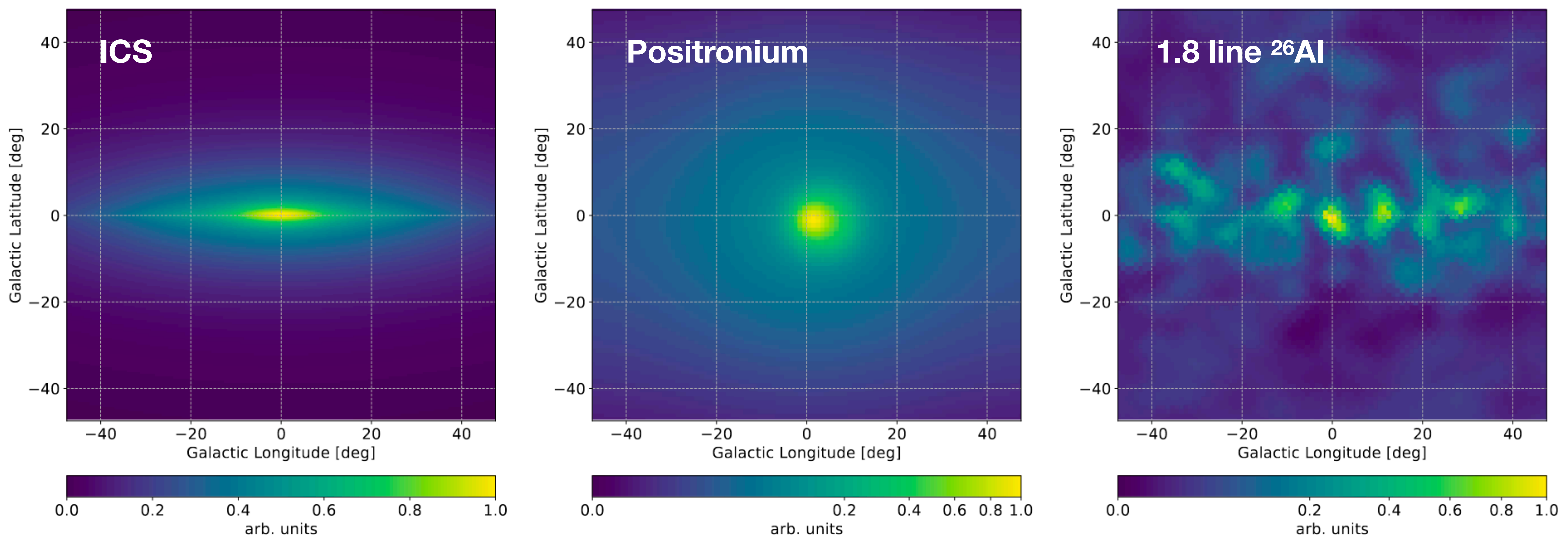
Berteaud, FC+ PRD'22 ; FC+ MNRAS'23

Soft gamma rays with Integral/SPI

Astrophysical contributions

Modelled spatial templates (30 keV — 8 MeV)

- **Inverse Compton scattering** of electrons off the interstellar radiation field $e^{\pm}_{CR} + \gamma \longrightarrow e^{\pm} + \gamma_{MeV}$
- Unresolved sources (<100 keV)
- Nuclear lines
- Positronium annihilation line+continuum



Berteaud, FC+ PRD'22

Soft gamma rays with Integral/SPI

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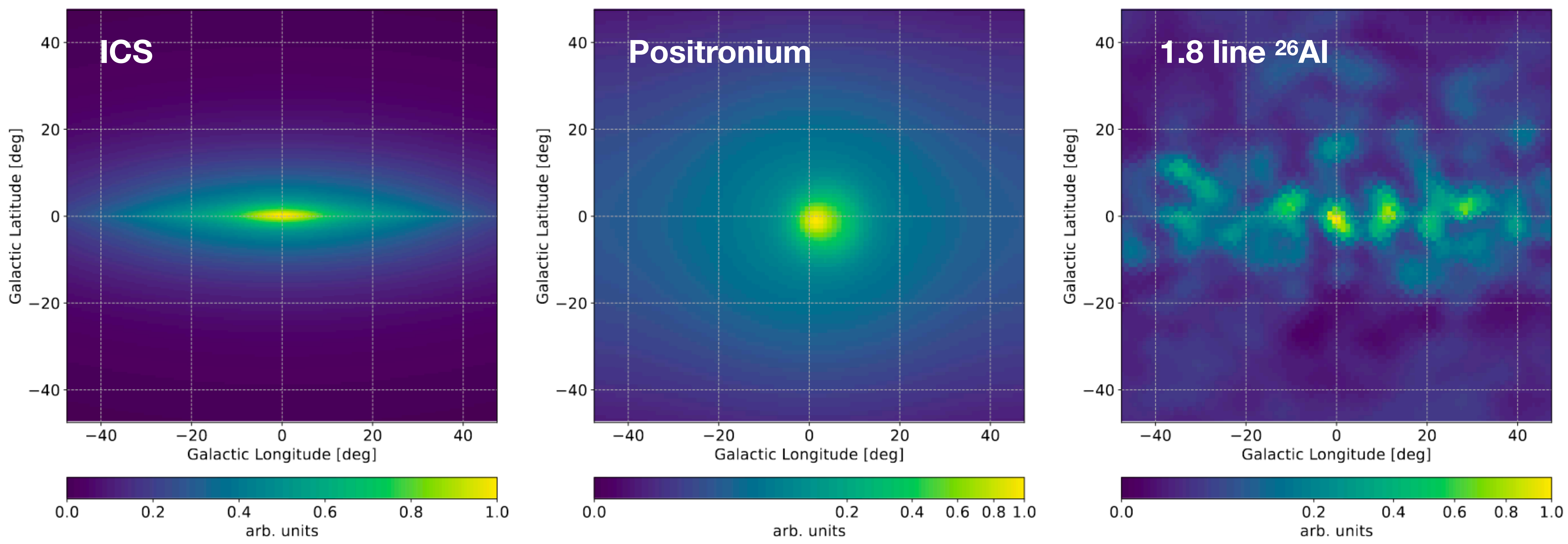
- Additional **DM signal**?

$$\frac{d\Phi_\gamma}{dE}(\ell, b) = \mathcal{A}(\theta_{DM}) \times \frac{dN_\gamma}{dE} \times \int_{l.o.s.} \rho^N_{DM}(s, \ell, b) ds$$



Berteaud, FC+ PRD'22

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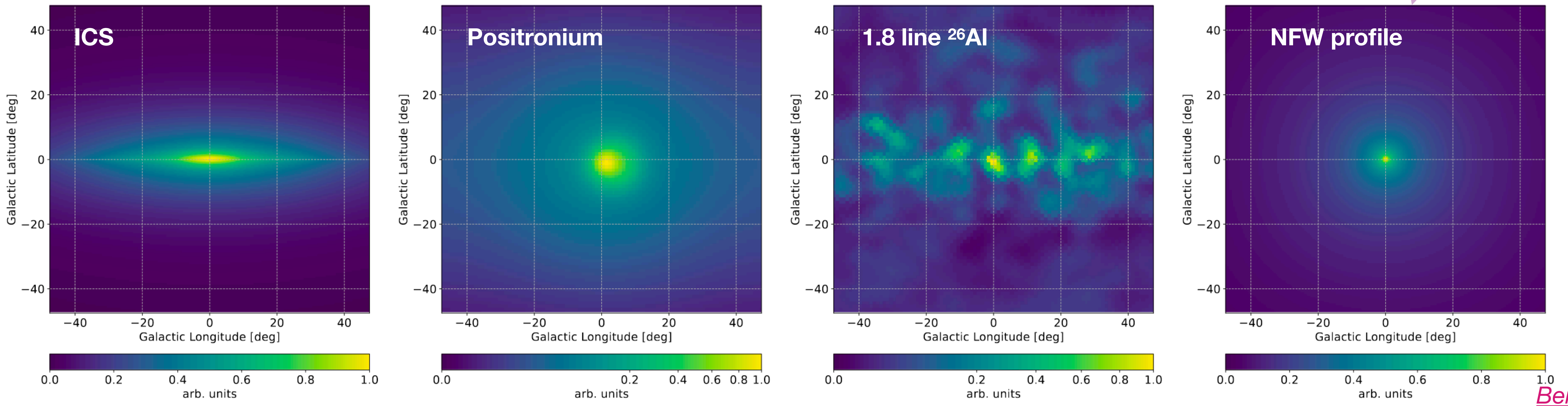


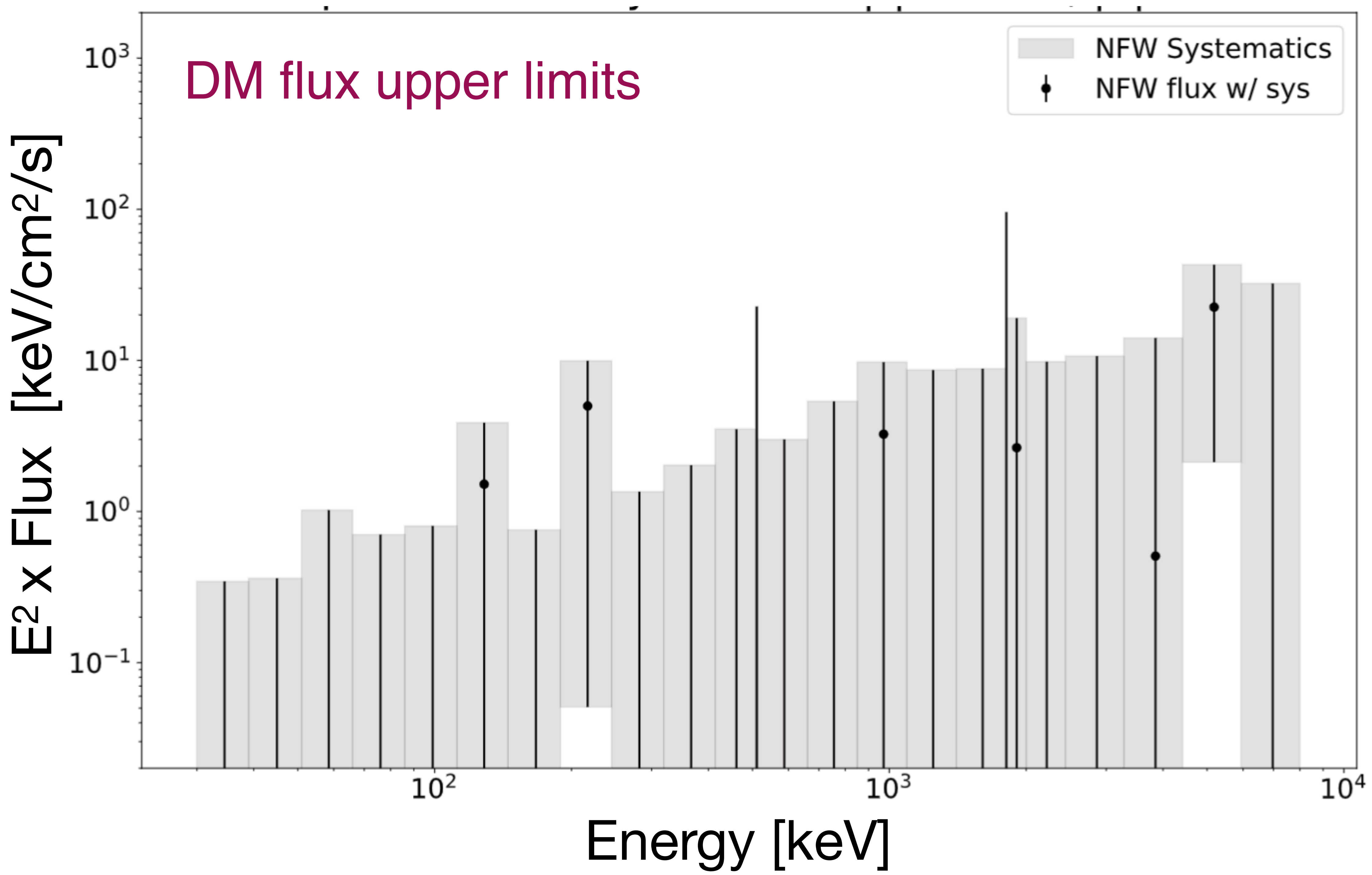
Berteaud, FC+ PRD'22

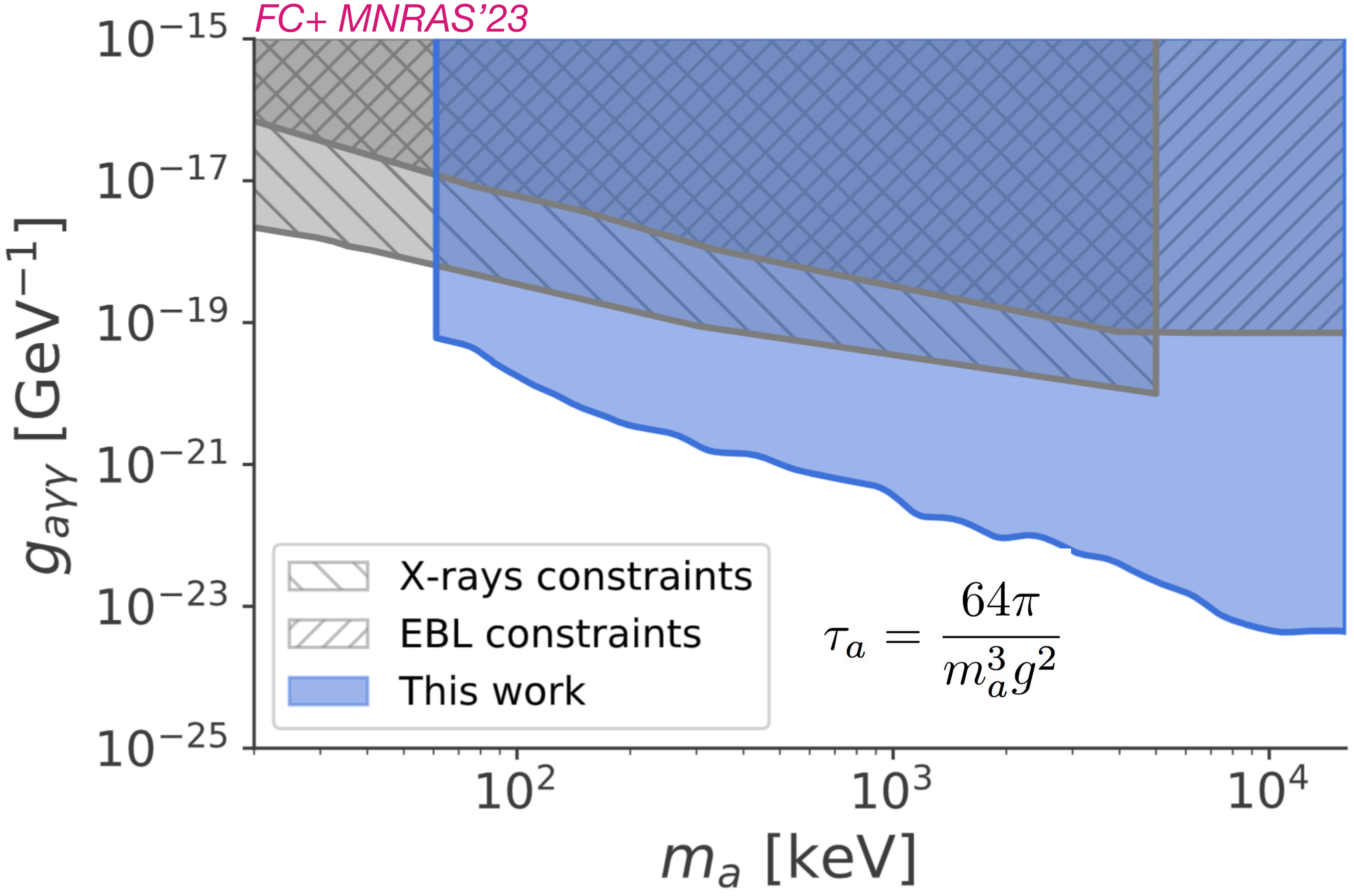
Soft gamma rays with Integral/SPI

Constraints on decaying dark matter

No signal detected

→ Upper limits on **light particle decay**





Re-analysis of Integral/SPI data provides the **strongest constraints** on (light) particle and non-particle DM PBHs

https://zenodo.org/record/7984451

Summary: Limits on light DM

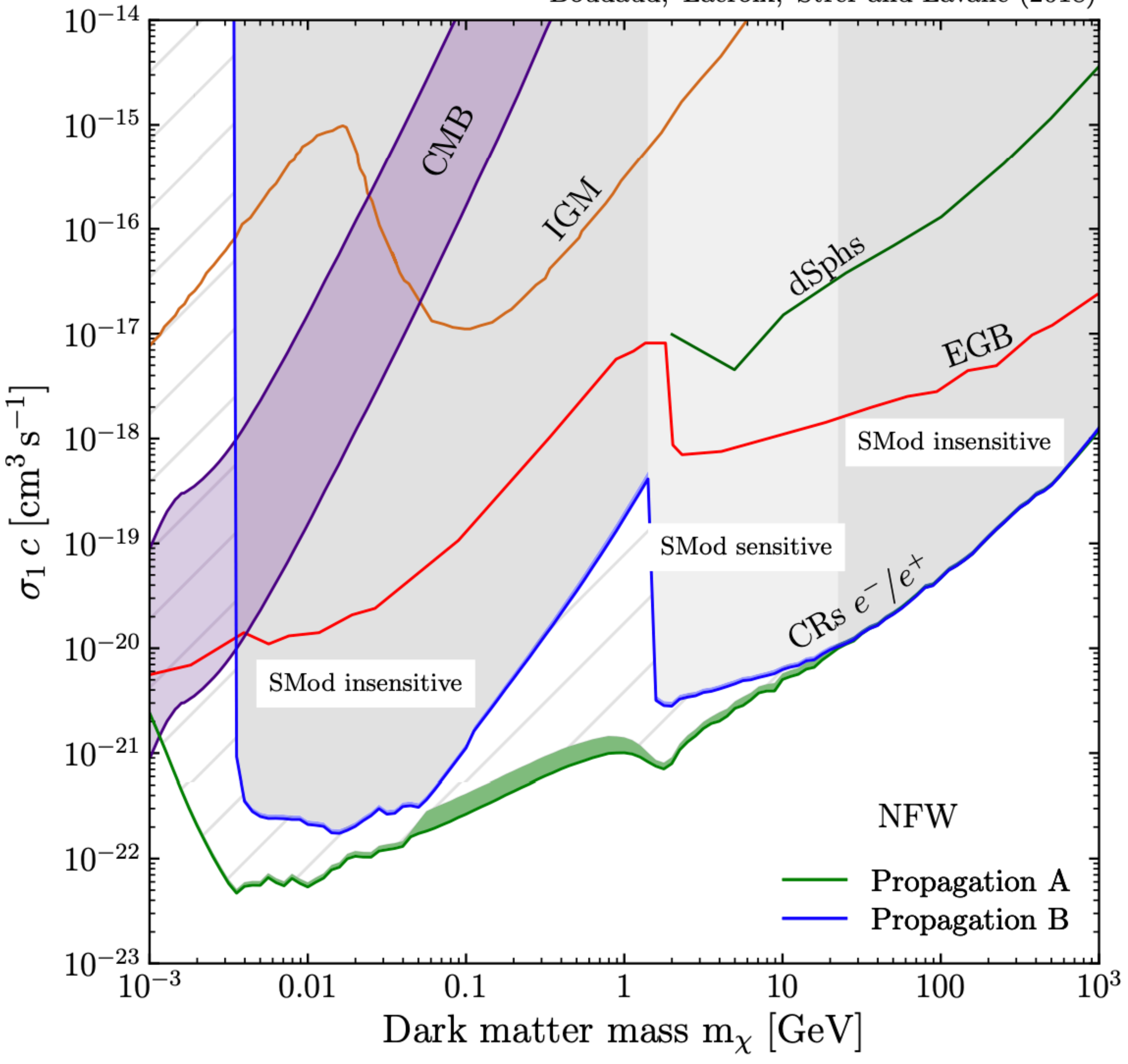
P-wave annihilating DM

$$\langle \sigma v \rangle = \langle \sigma v \rangle_{s\text{-wave}} + \langle \sigma v \rangle_{p\text{-wave}} + \text{higher orders}$$
$$= \sigma_0\, c + \sigma_1\, c \langle \frac{v_r^2}{c^2} \rangle + \mathcal{O}\left(\frac{v_r^4}{c^4} \right) ,$$

- CMB limits suppressed by low velocity of DM at recombination (~10^{-5} c)
- Present limits to be re-scaled using appropriate average of DM density over phase-space distribution
- For typical velocities at freeze out (0.15 c), we can expect

$$(\sigma_1 c)^{f.o.} \sim 10^{-25}\, \mathrm{cm}^3/\mathrm{s}$$

Boudaud, Lacroix, Stref and Lavalle (2018)



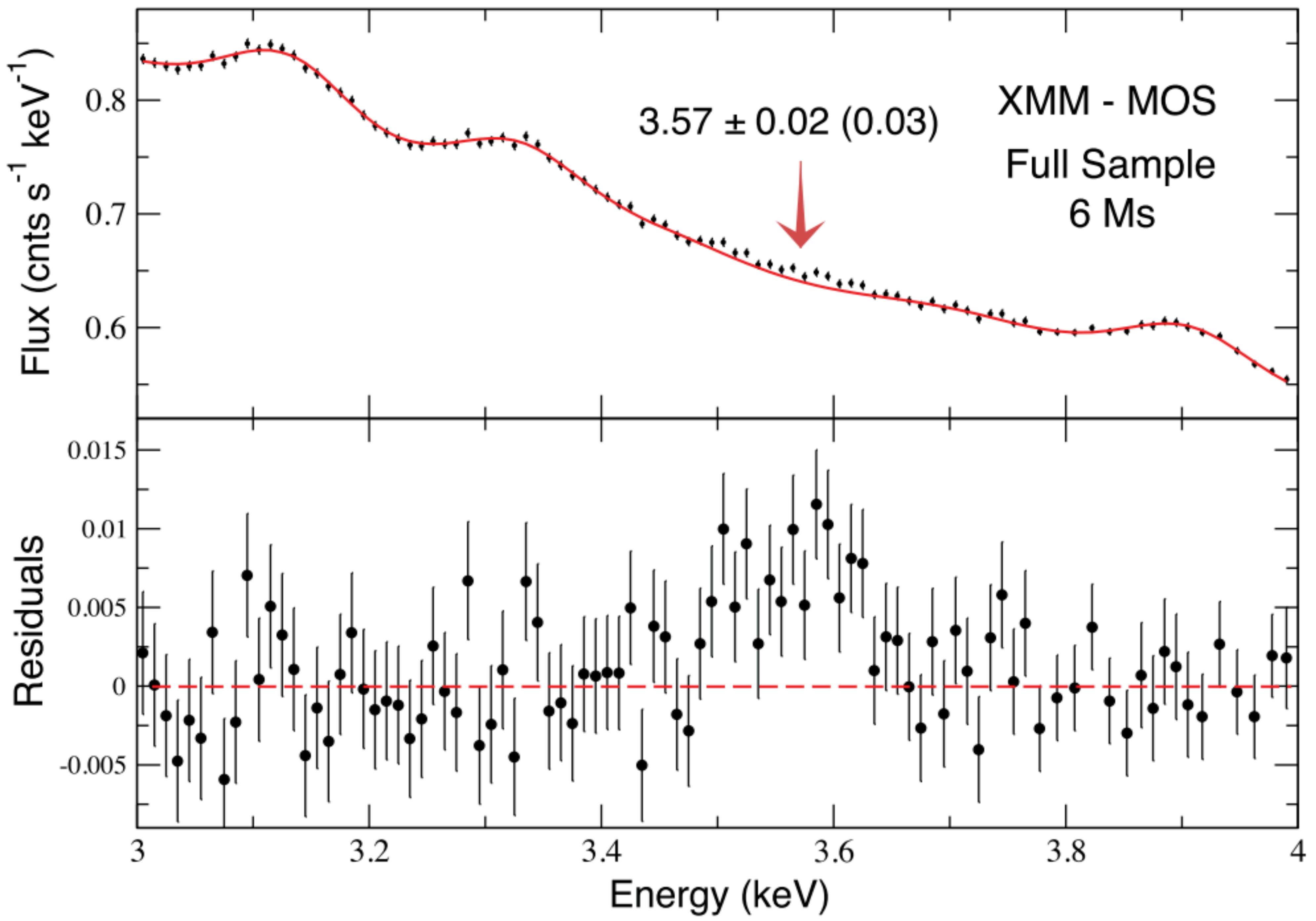
Review: K. N. Abazajian, Phys. Rept. 711-712, 1 (2017)

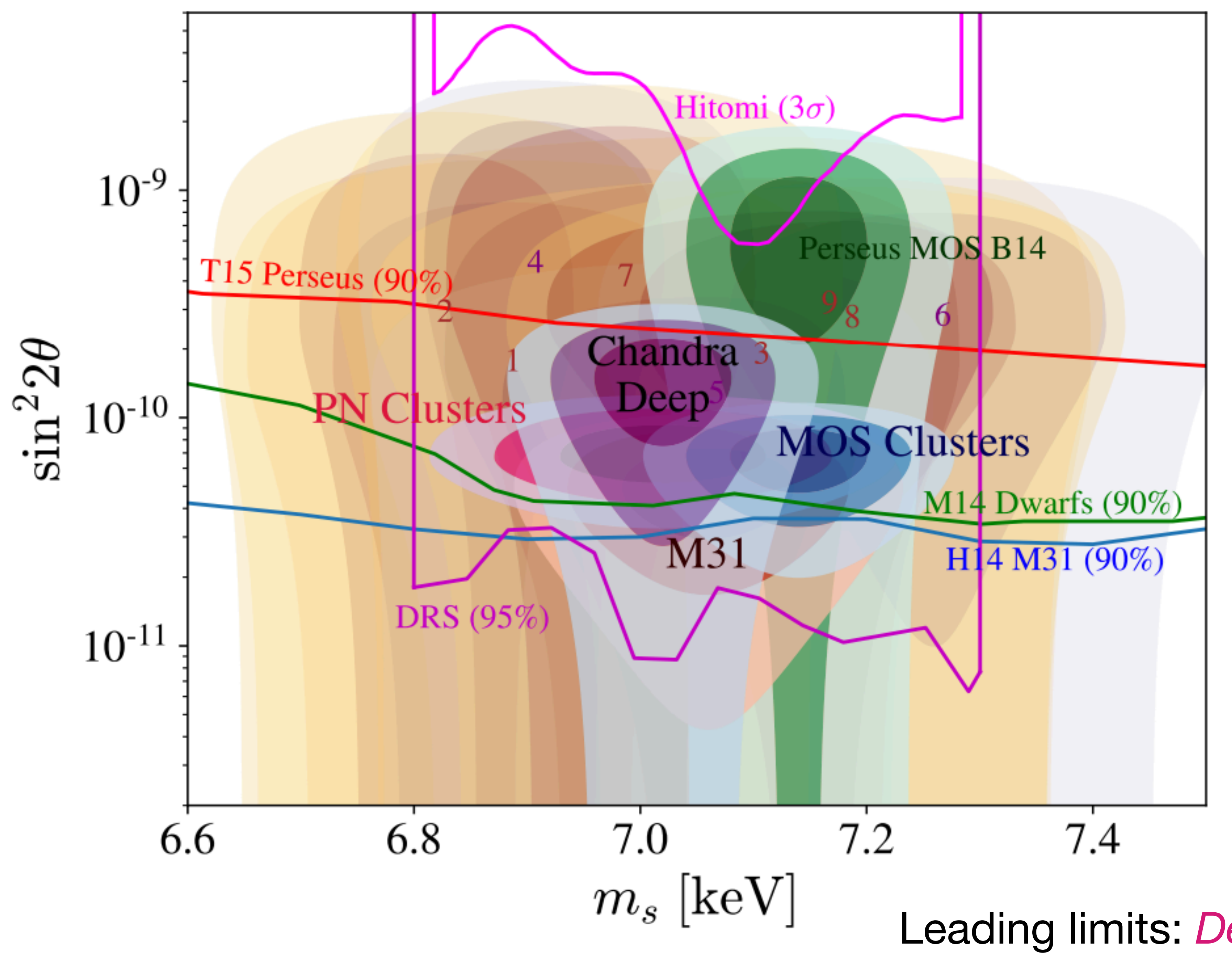
Sterile neutrinos X-ray lines

X-ray telescopes and spectral analysis

Starting from early 2014:

- **Detection** of an unidentified line at **3.5 keV**: XMM-Newton (6 Ms) & *Chandra*, Perseus cluster; XMM-Newton, M31; Suzaku, Perseus; etc
- **Constraints** from *Chandra* M31; XMM-Newton/Chandra 80 galaxies; blank field pointings Chandra and XMM-Newton, etc





Leading limits: *Dessert+ Science' 20*

Constraints on eV ALPs

IR - optical wavelengths

Search for **narrow lines** in IR and optical data

- **MUSE**: search in the direction of 5 known dwarf galaxies

  Todarello+ JCAP'24

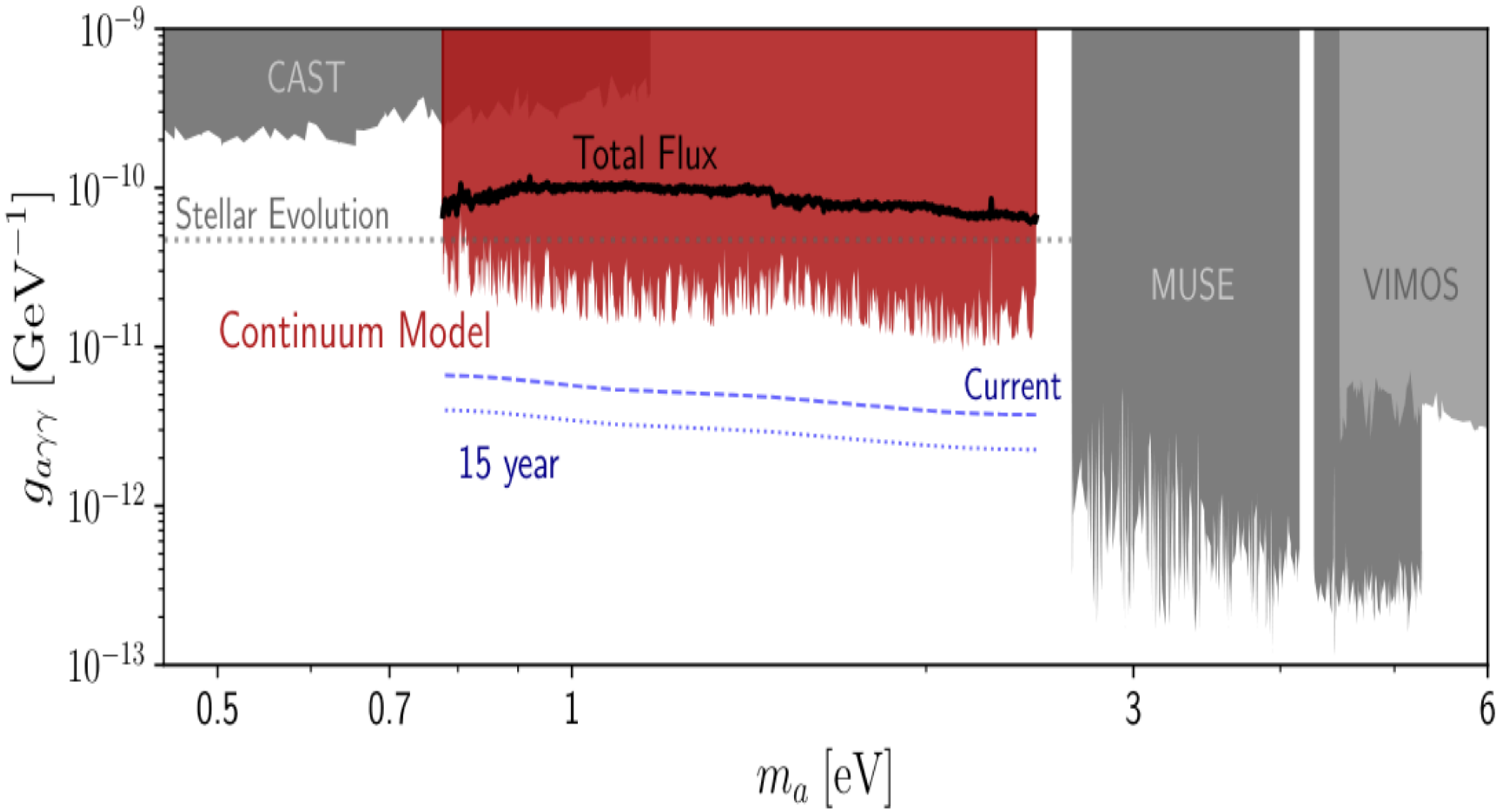
- **VIMOS (Visible Multi-Object Spectrograph)**: galaxy clusters Abell 2667 and 2390

  Grin+ PRD'06

- **JWST:** public blank sky observations from the NIRSpec IFU

  Janish & Pinetti 2310.15395

Janish & Pinetti 2310.15395



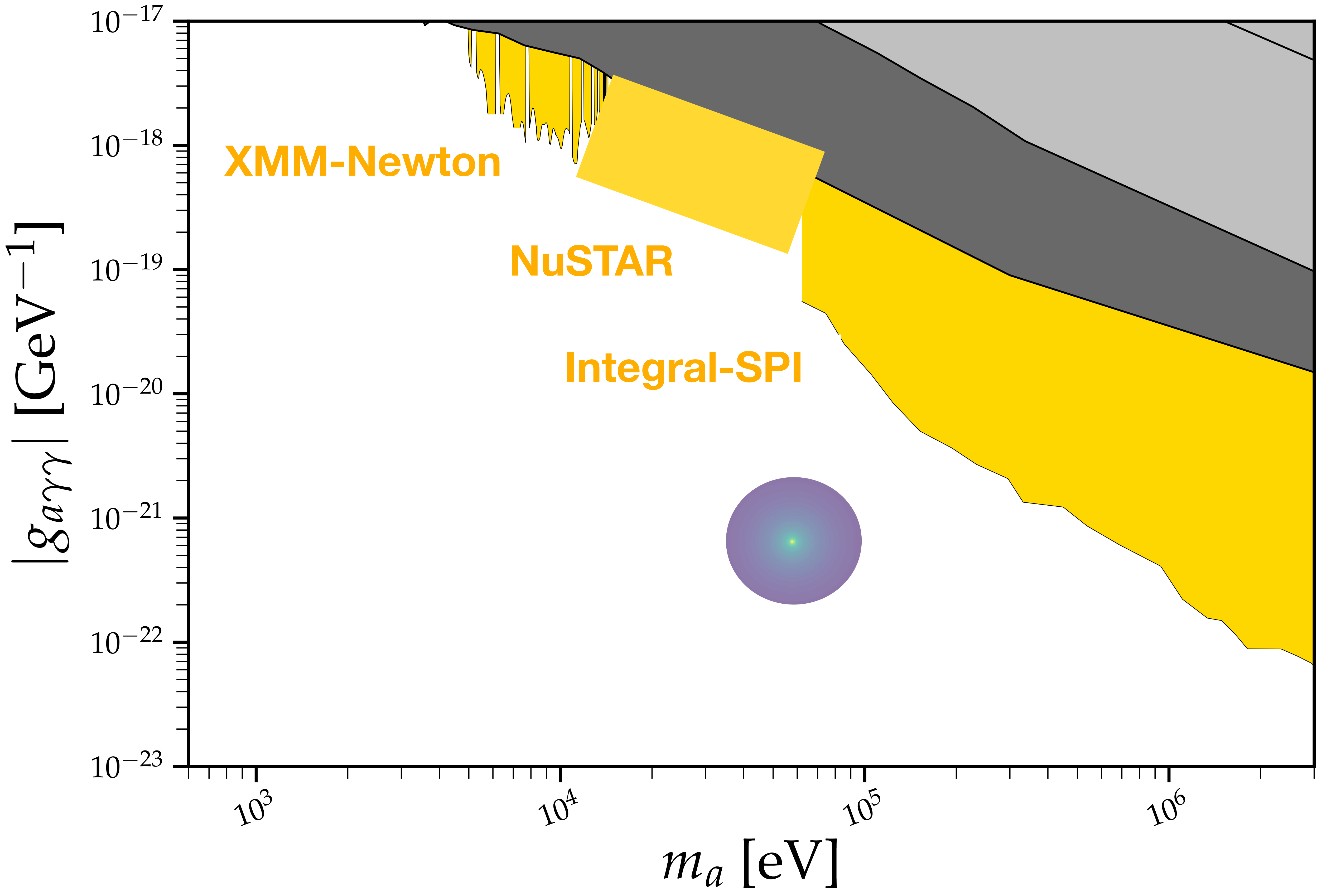
Constraints on keV - MeV ALPs

X-ray and soft gamma rays energies

Heavy ALPs DM decay

Search for **narrow lines** in X and gamma-ray data

- **XMM-Newton**: 5-16 keV, archival data => No evidence found for unassociated X-ray lines *Foster+ PRL'21*
- **NuSTAR**: 7-Ms/detector deep blank-sky exposures *Roach+ PRD'23*
- **Integral-SPI**: new analysis of 16yr data with dedicated search for DM component in continuum Galactic emission *Berteaud, FC+PRD'22; FC+ MNRAS'23*



https://github.com/cajohare/AxionLimits