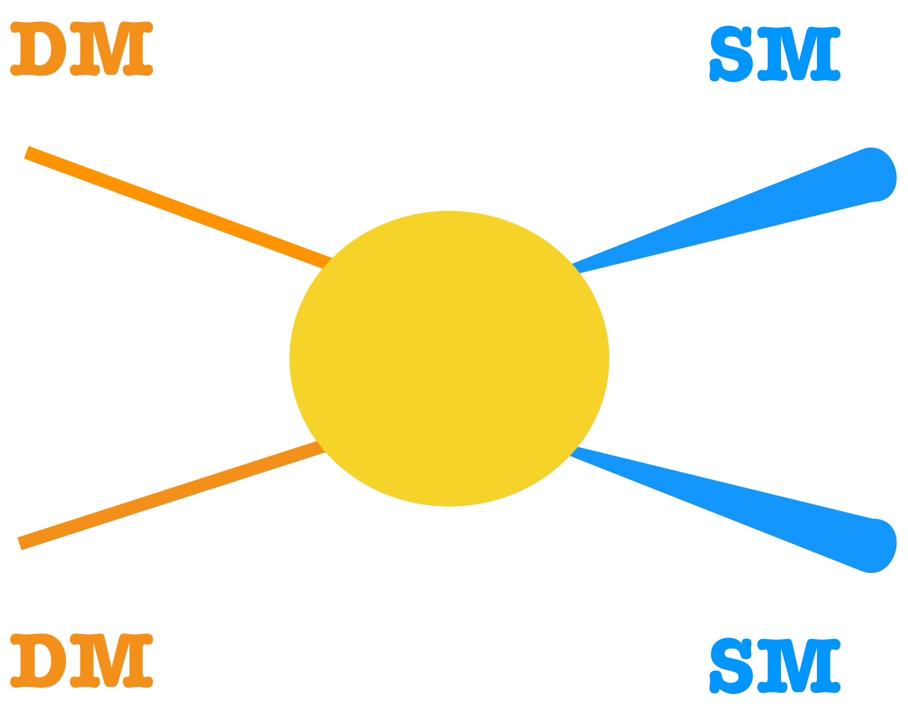
Light MeV-GeV dark matter: Indirect detection searches

FIPs 2022 Workshop, CERN — 19/10/2022

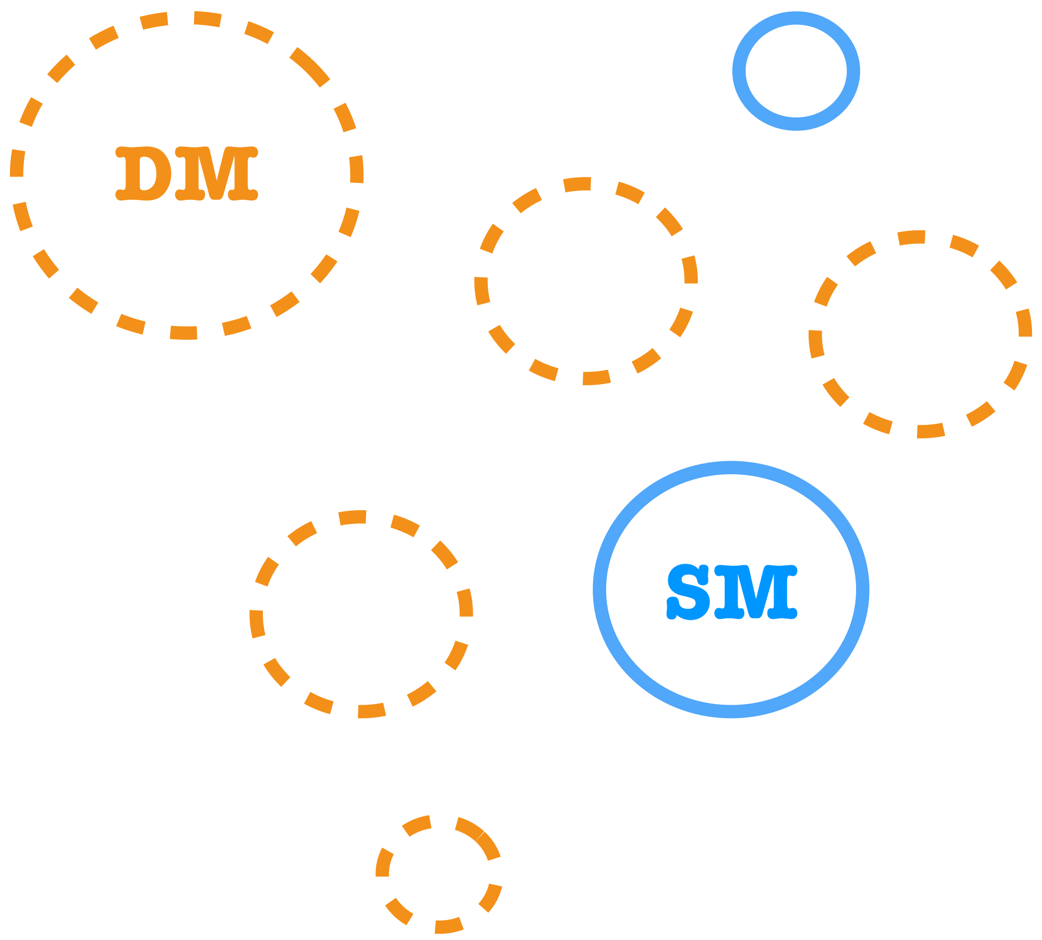
Francesca Calore (CNRS/LAPTh)

Dark matter indirect detection

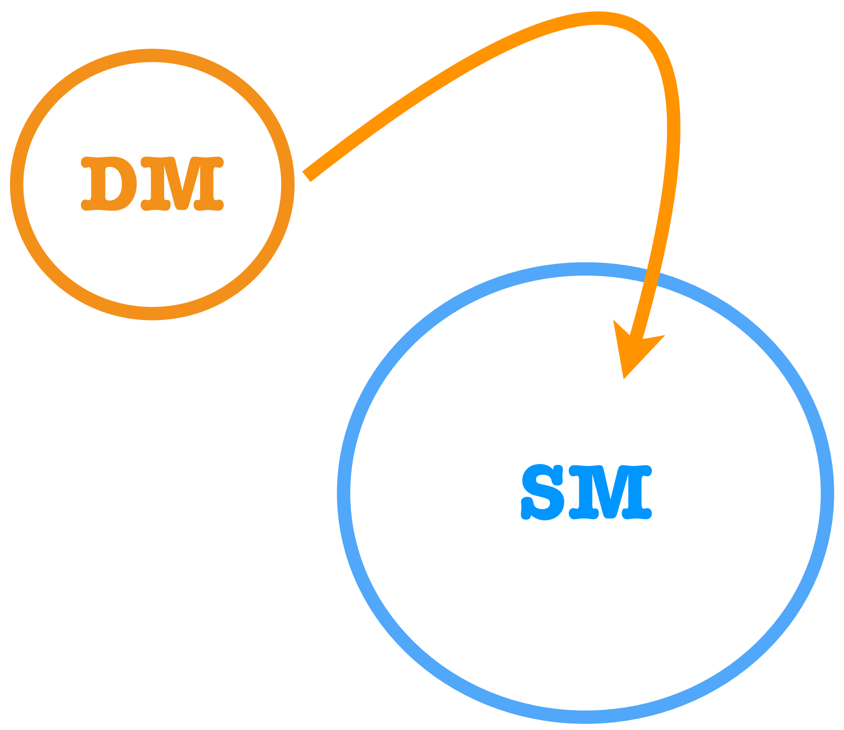
What dark matter does



Energy/particle injection



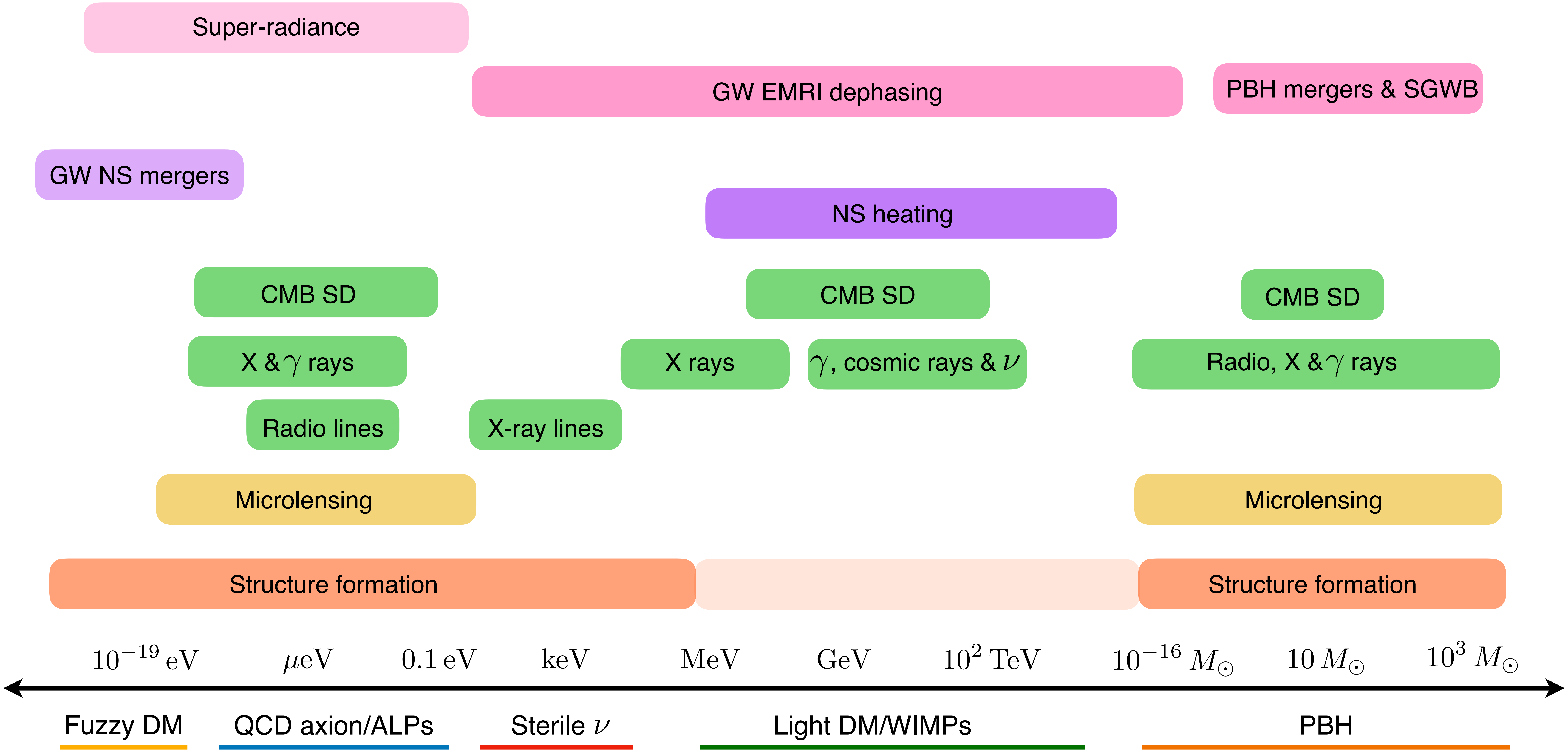
Gravitational interaction



Capture/scattering/accretion in/onto astrophysical objects

Astroparticle observables for dark matter

EuCAPT White Paper, arXiv:2110.10074



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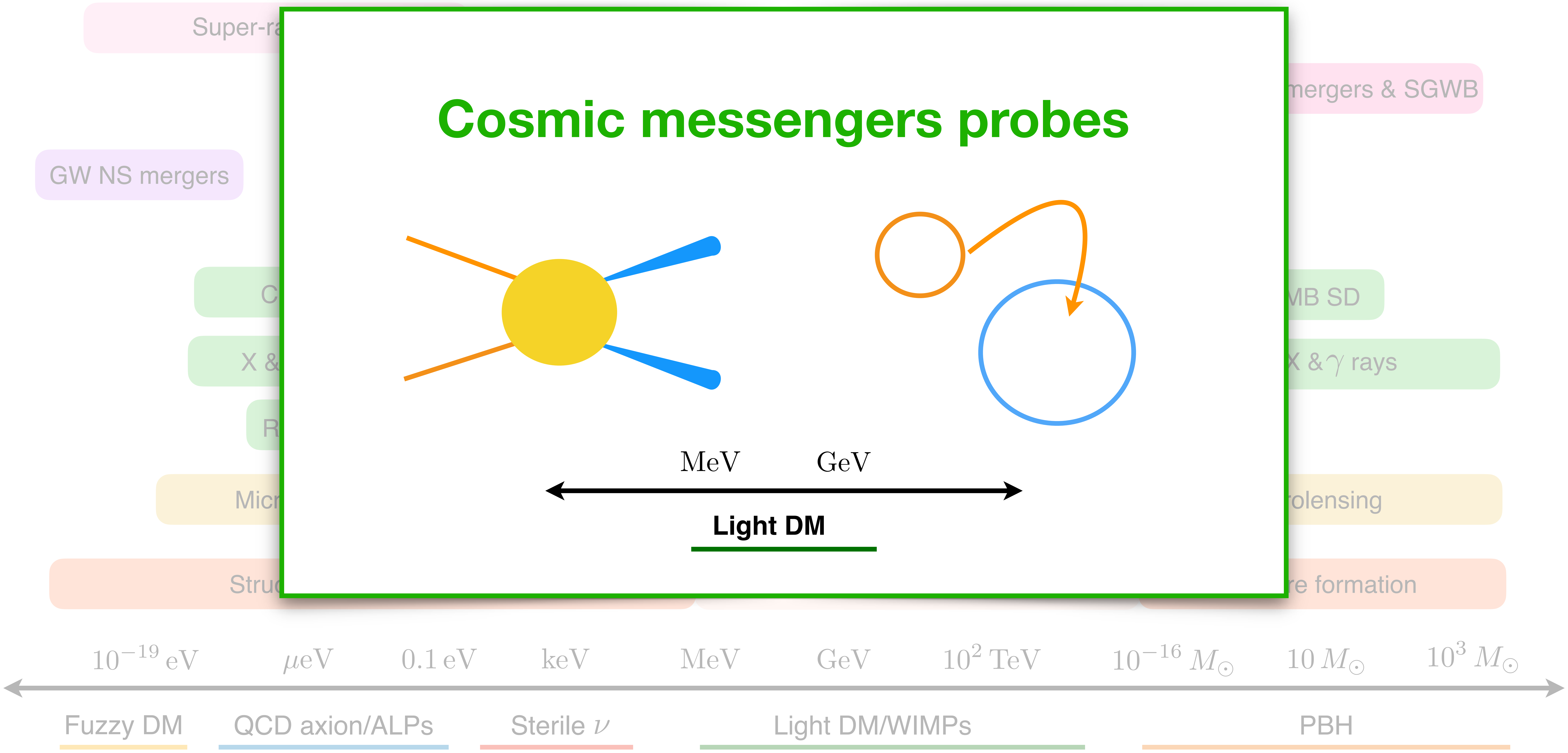
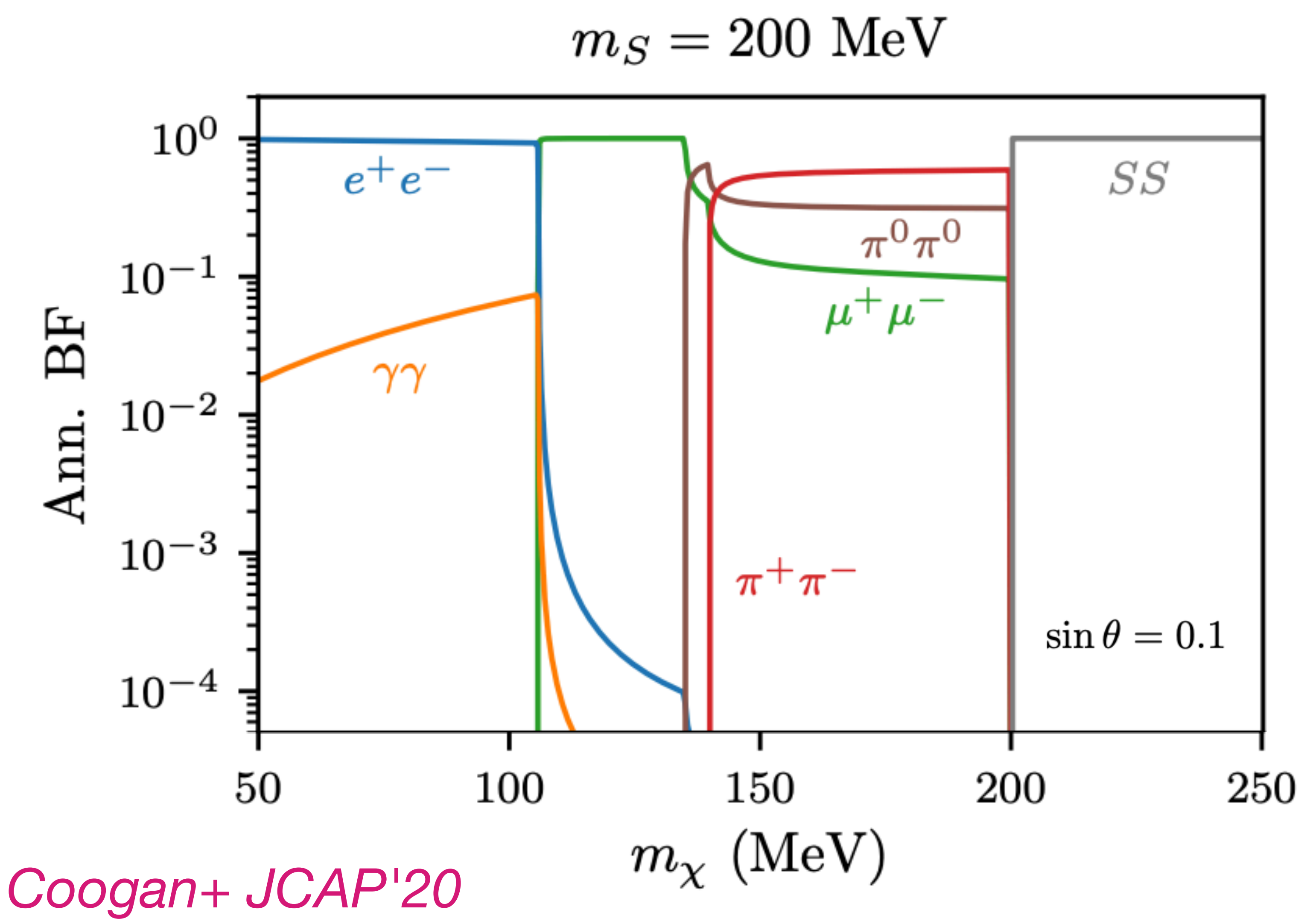


Particle dark matter emission

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

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

Centre of mass energy $\simeq$ Signal energy



Coogan+ JCAP'20

$m_{\rm DM} \lesssim$ MeV

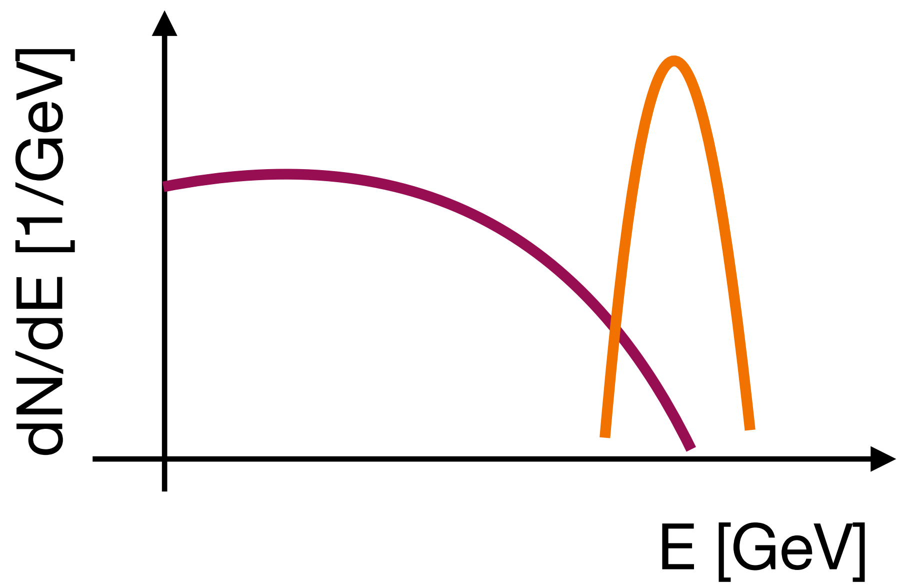
Narrow line signal

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

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

$m_{\rm DM} \gtrsim$ MeV

Broader energy distribution

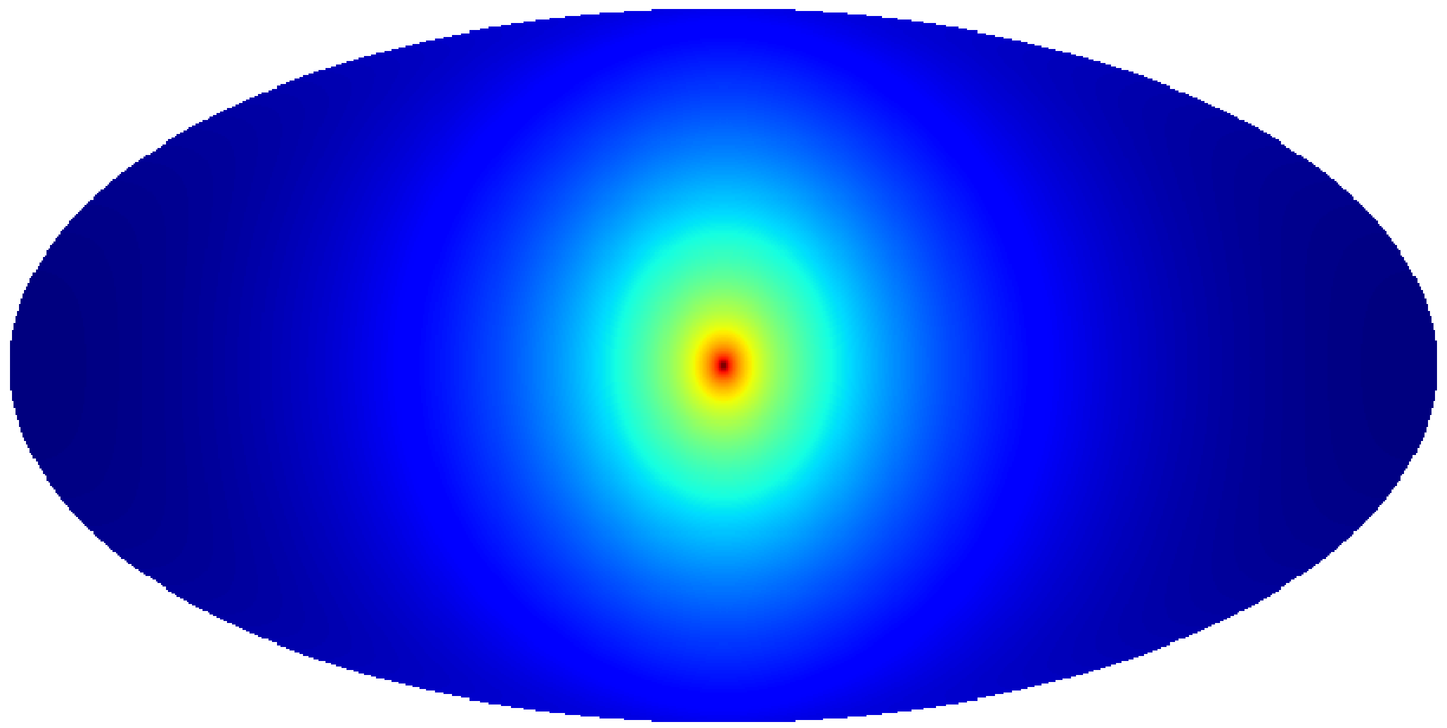


$$\frac{dN_\gamma}{dE} = \left(\frac{dN_\gamma}{dE}\right)_{\gamma\gamma} + \left(\frac{dN_\gamma}{dE}\right)_{\rm sec} + \left(\frac{dN_\gamma}{dE}\right)_{\rm FSR}$$

Particle dark matter emission

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

$E_{\rm CM} = N\, m_{\rm DM}\,,\qquad N = 1\ (\text{decay}),\ 2\ (\text{annih})$ Centre of mass energy $\simeq$ Signal energy

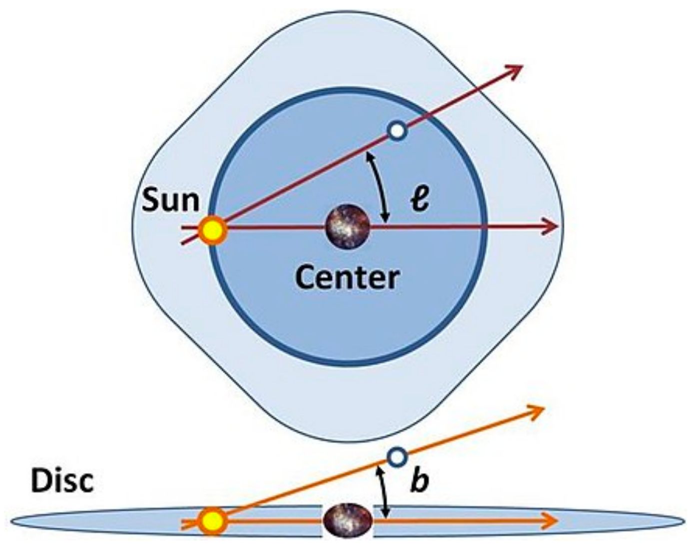


Self-conjugated dark matter annihilation
Differential **gamma-ray** flux

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

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

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



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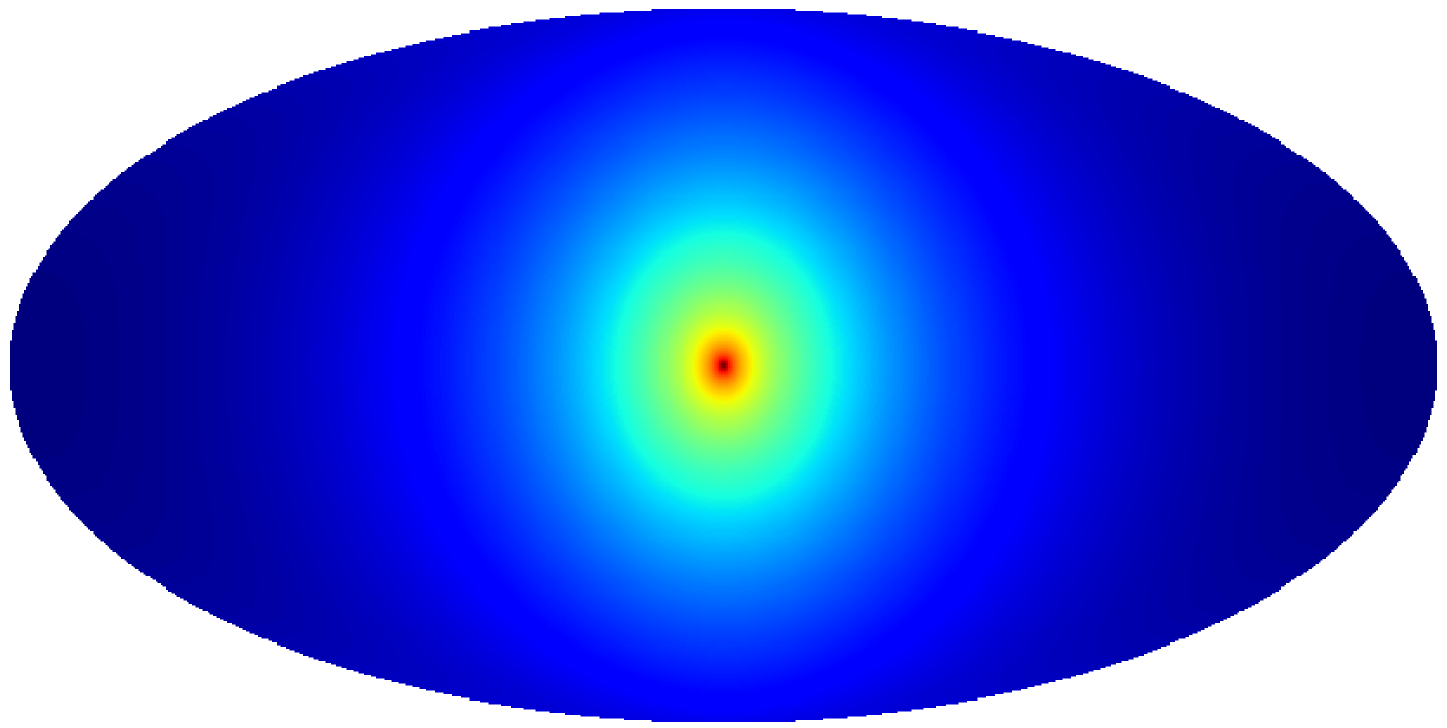

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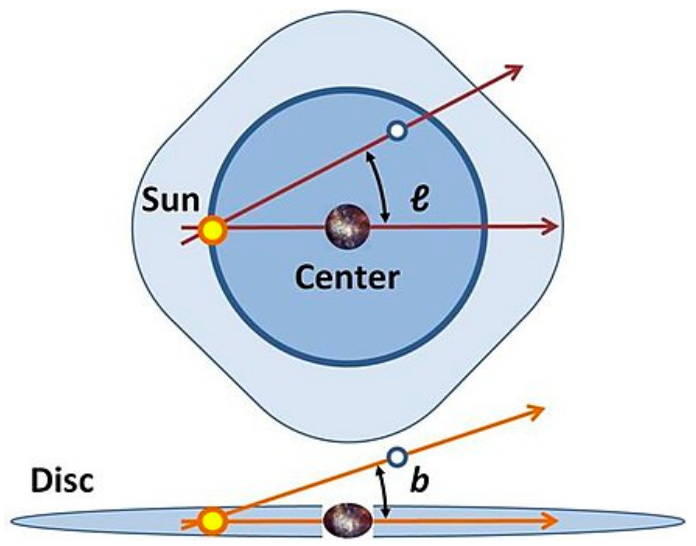
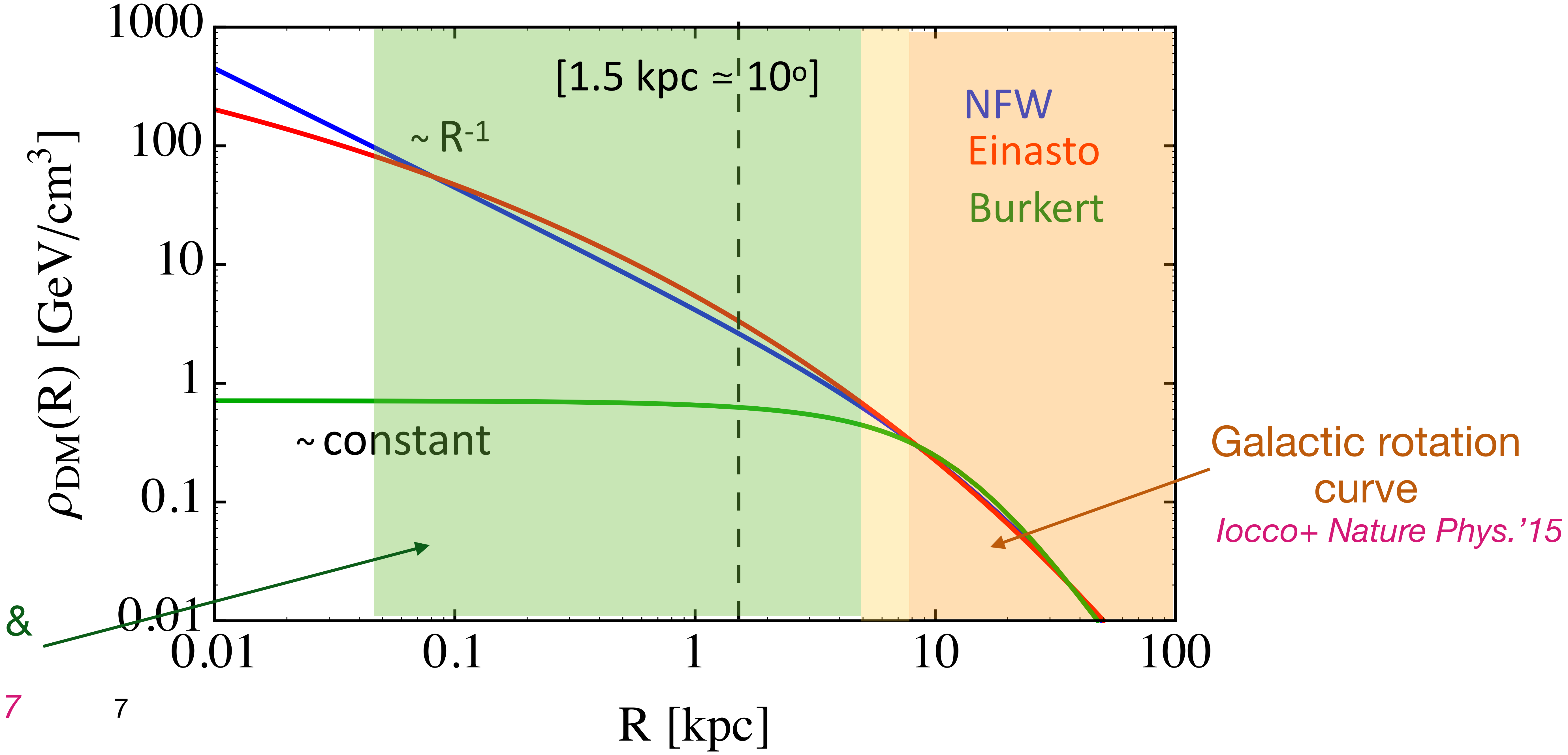
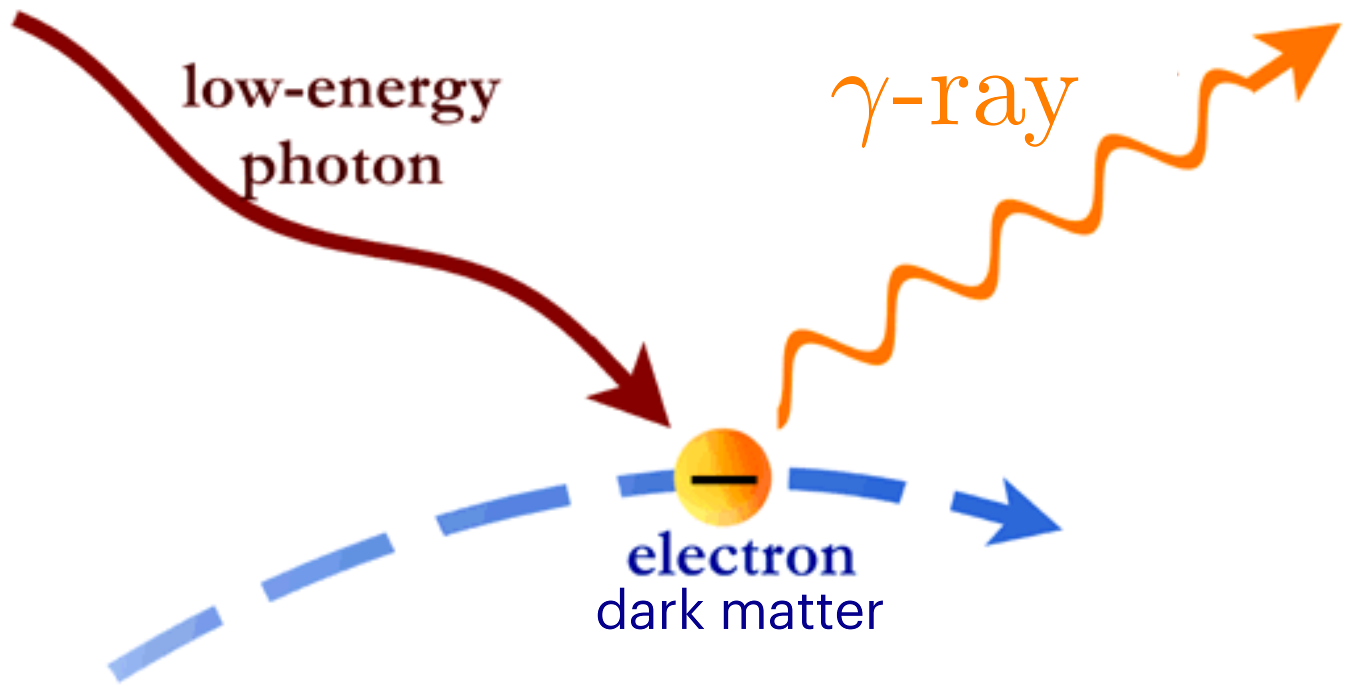




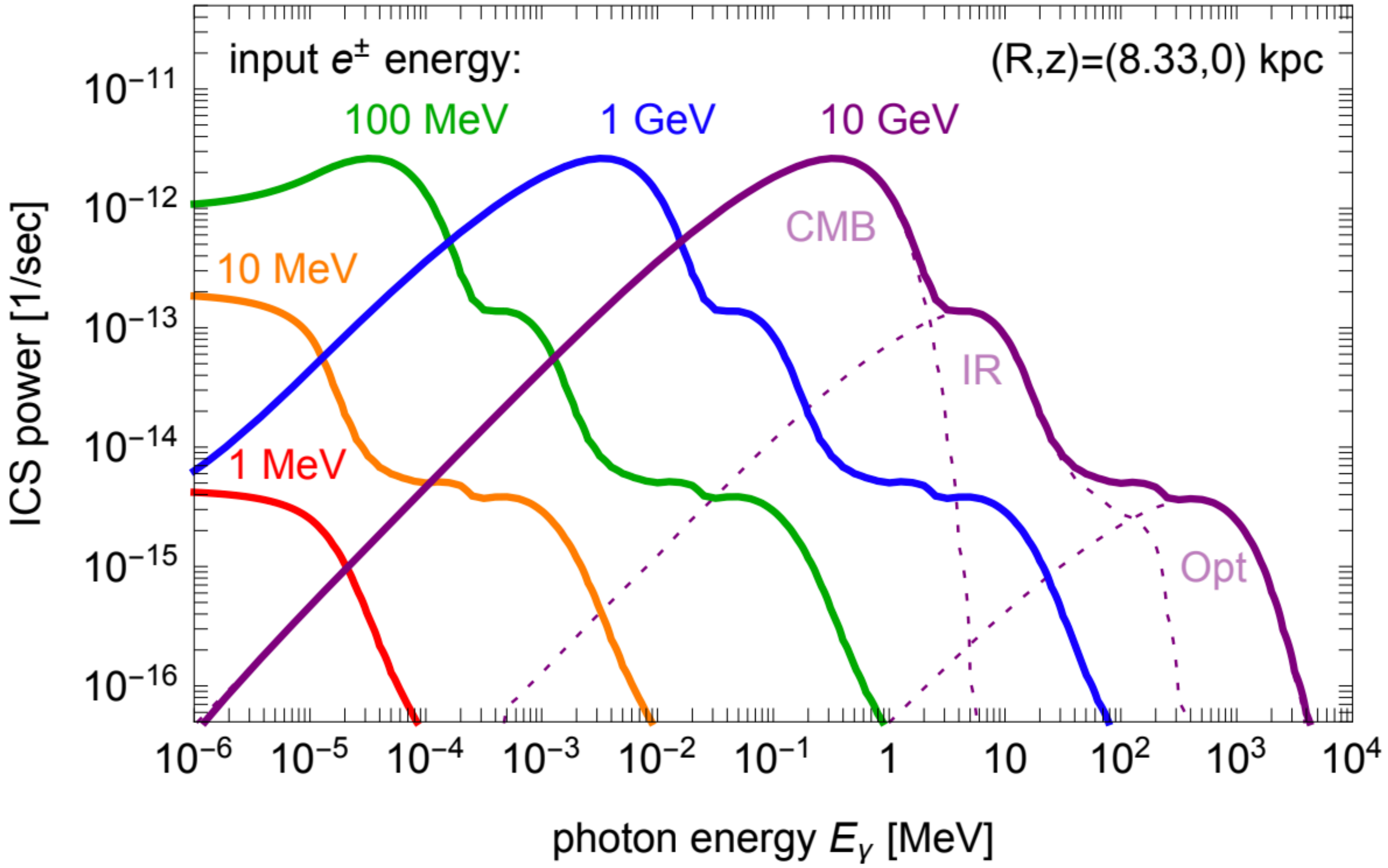
Particle dark matter emission

Inverse Compton scattering



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

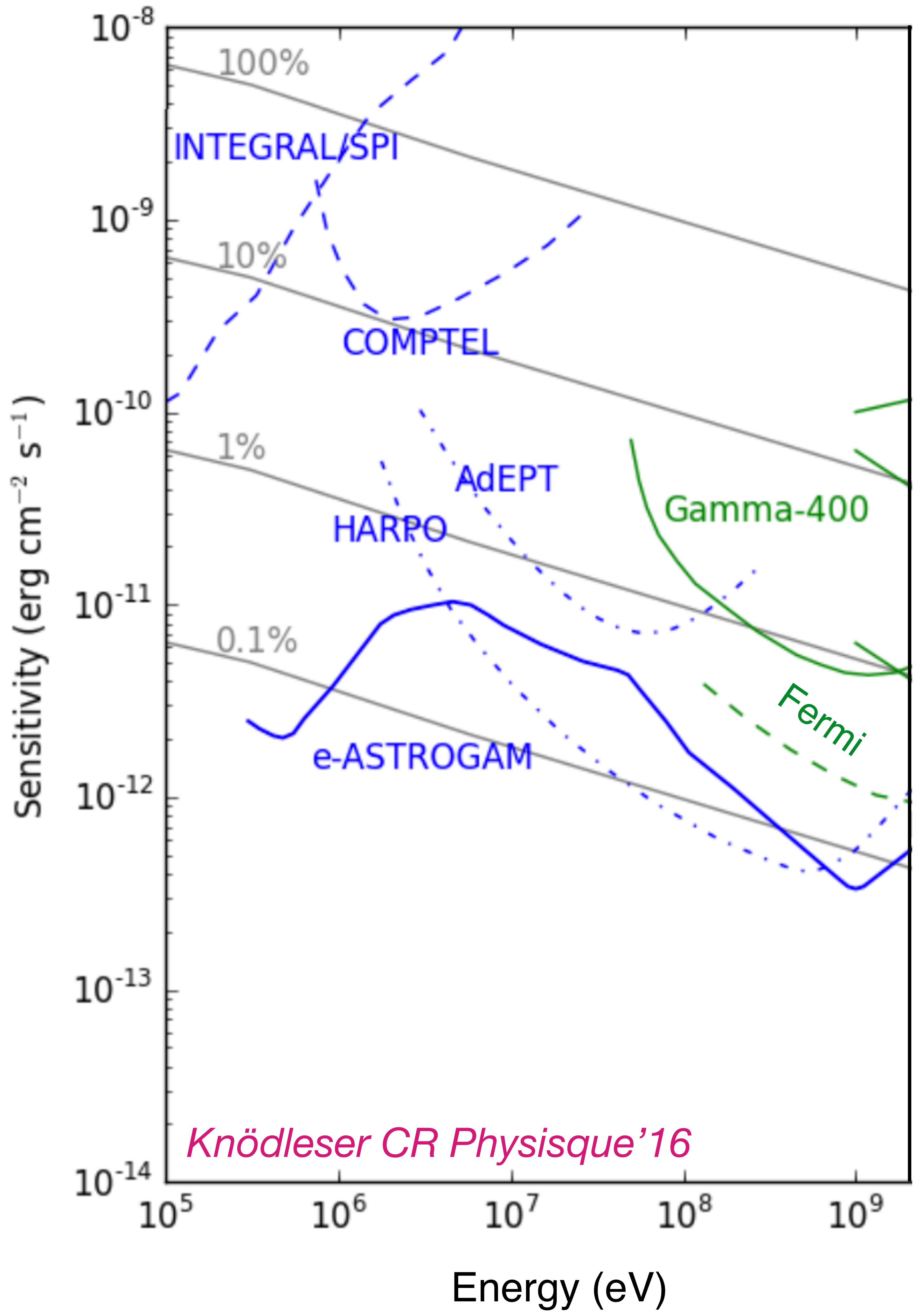
Cirelli+ PRD' 21



Secondary emission processes allow ones to probe DM at much higher masses than their nominal energy scales

The data landscape

Hard X rays and gamma-ray sky



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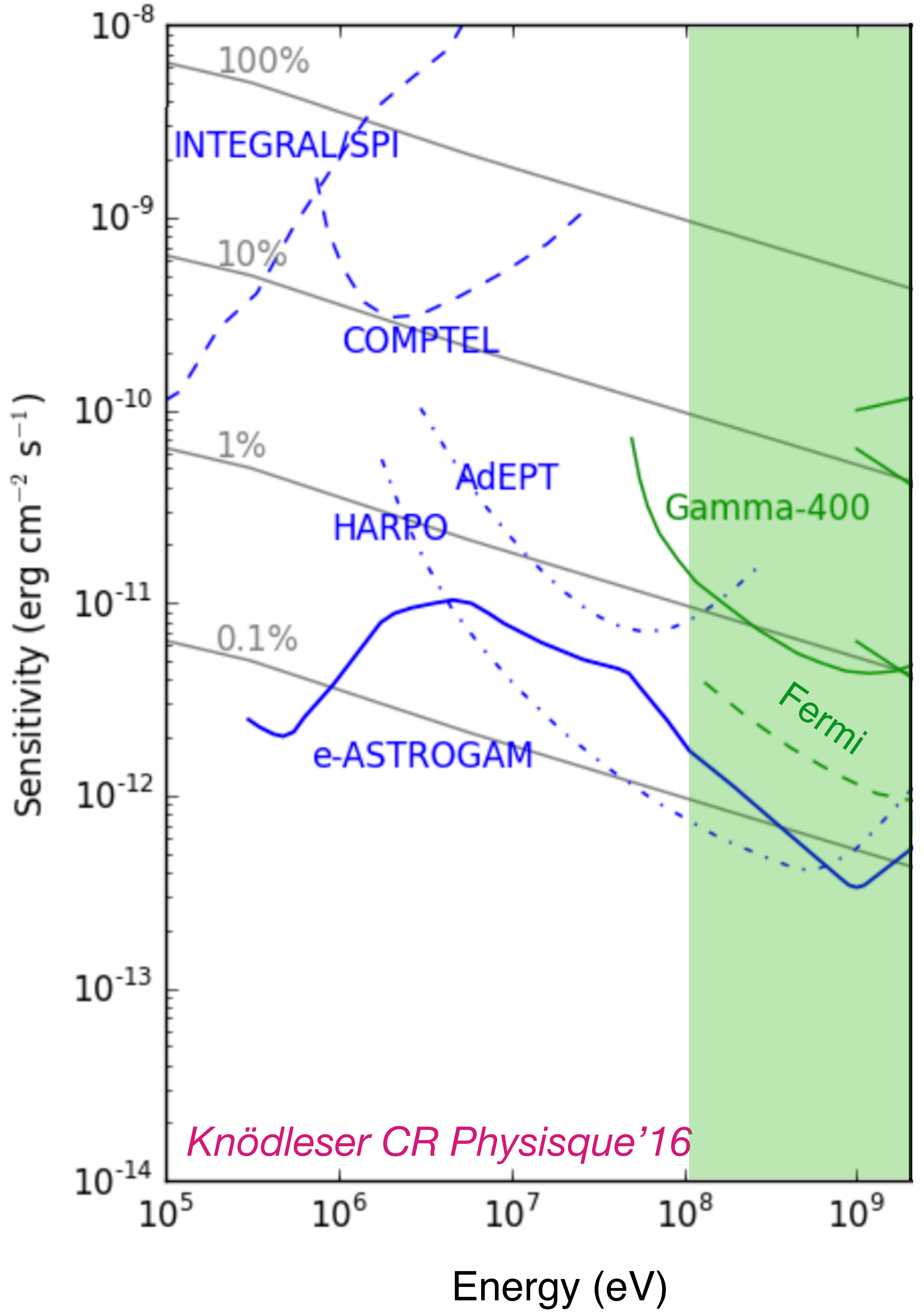
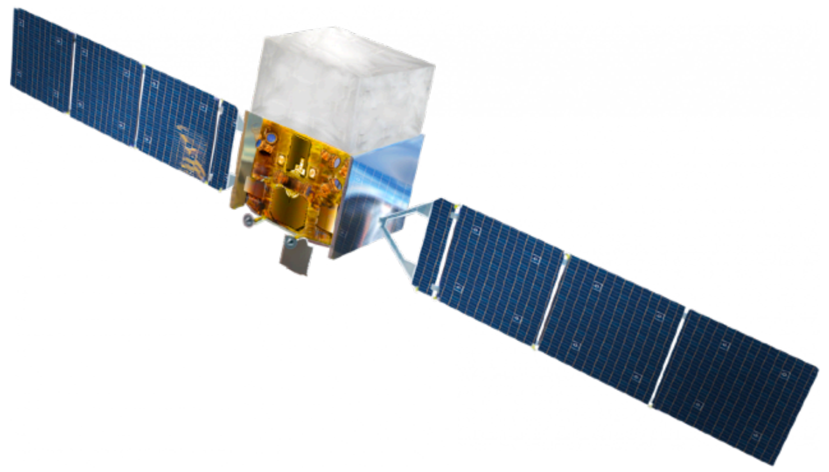
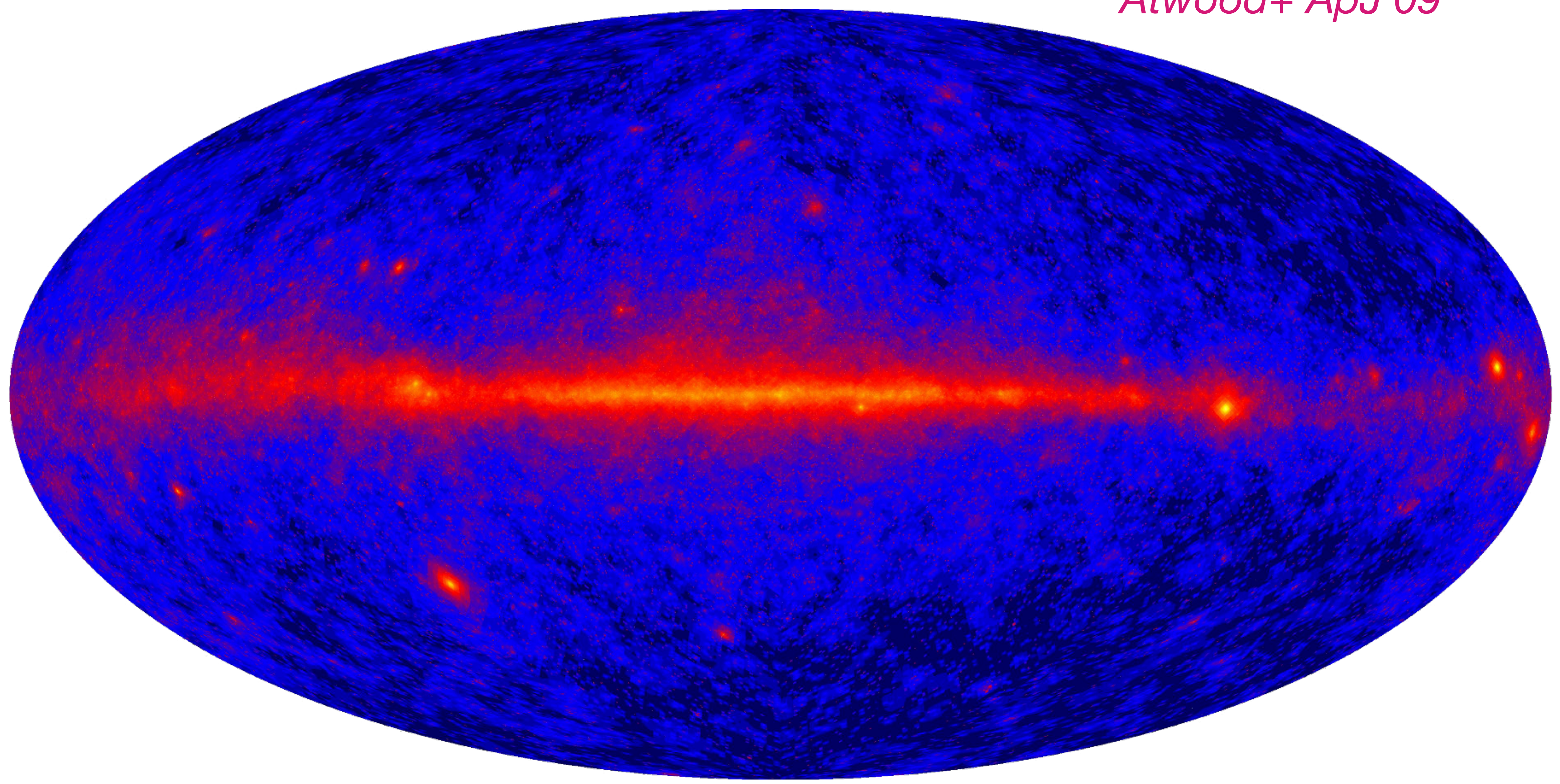




Fermi Large Area Telescope (LAT)

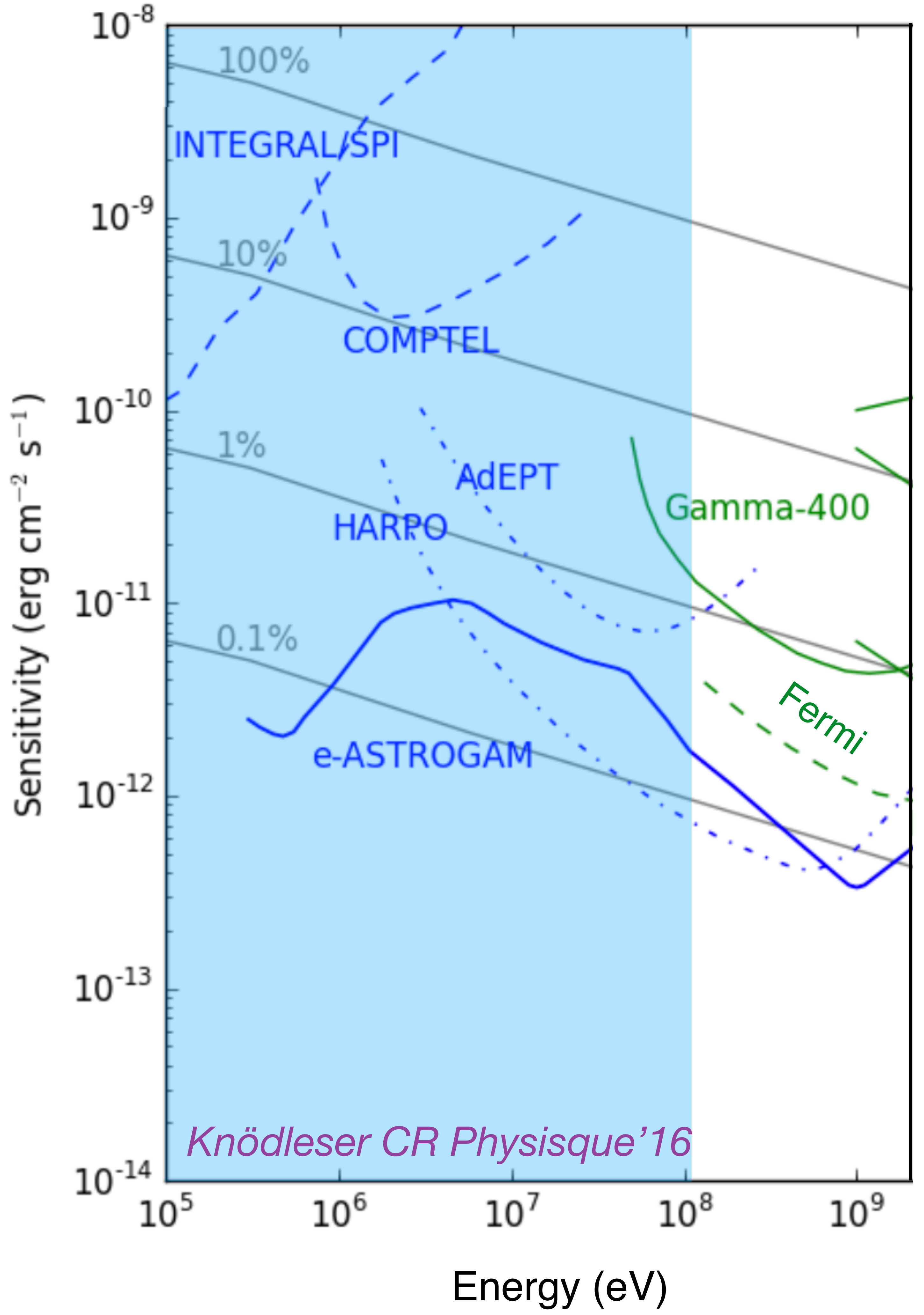
Lifetime: 2008 — present
Energy: 20 MeV - 300 GeV
Large FoV: 2.4 sr
Excellent angular res: 0.1 deg@10 GeV

Atwood+ ApJ'09



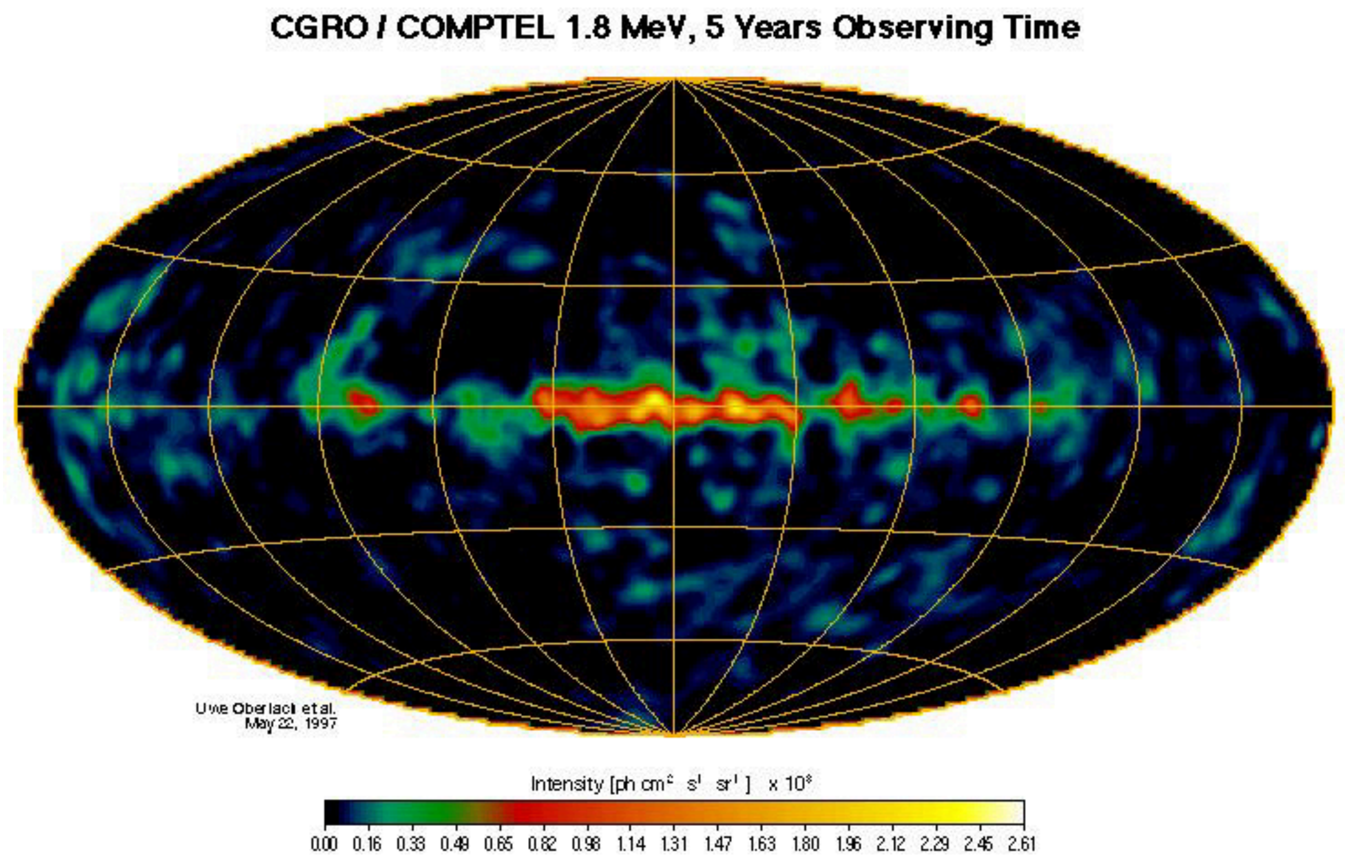
The data landscape

Hard X rays and gamma-ray sky



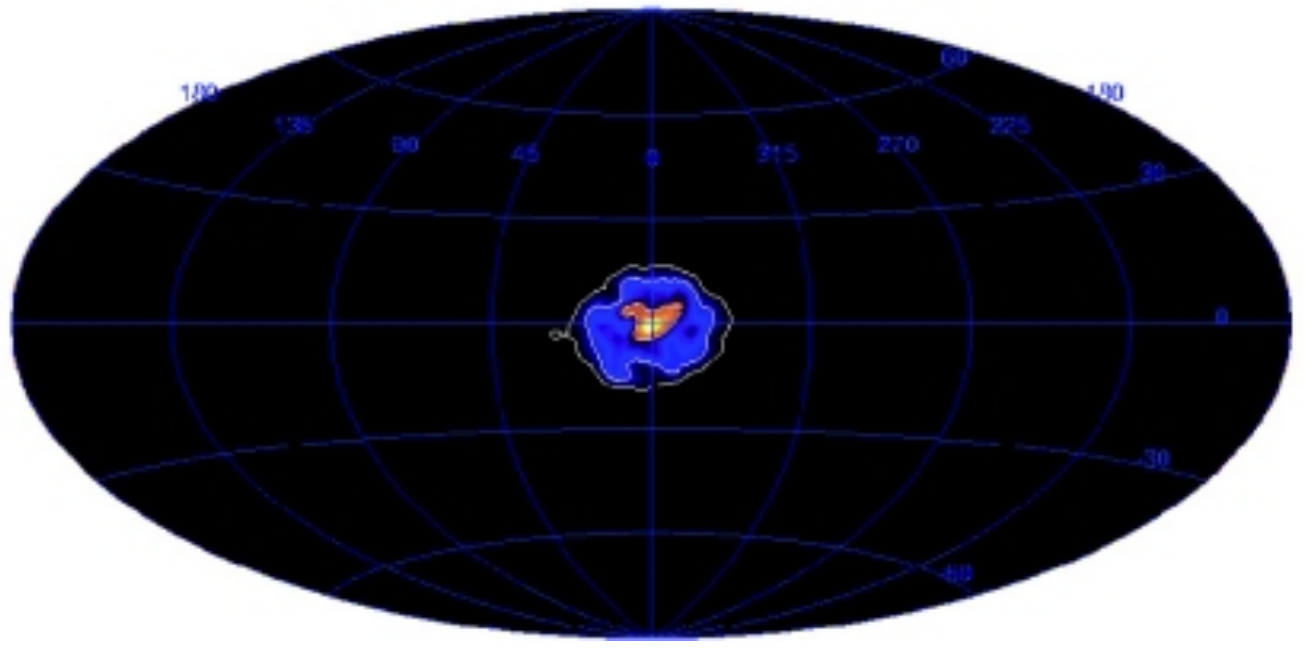
CGRO Compton Telescope (COMPTEL)

Lifetime: 1991 — 2000
Energy: 0.8 MeV - 30 MeV
Large FoV: 1 sr
Angular res: 1 deg



INTEGRAL Spectrometer (SPI)

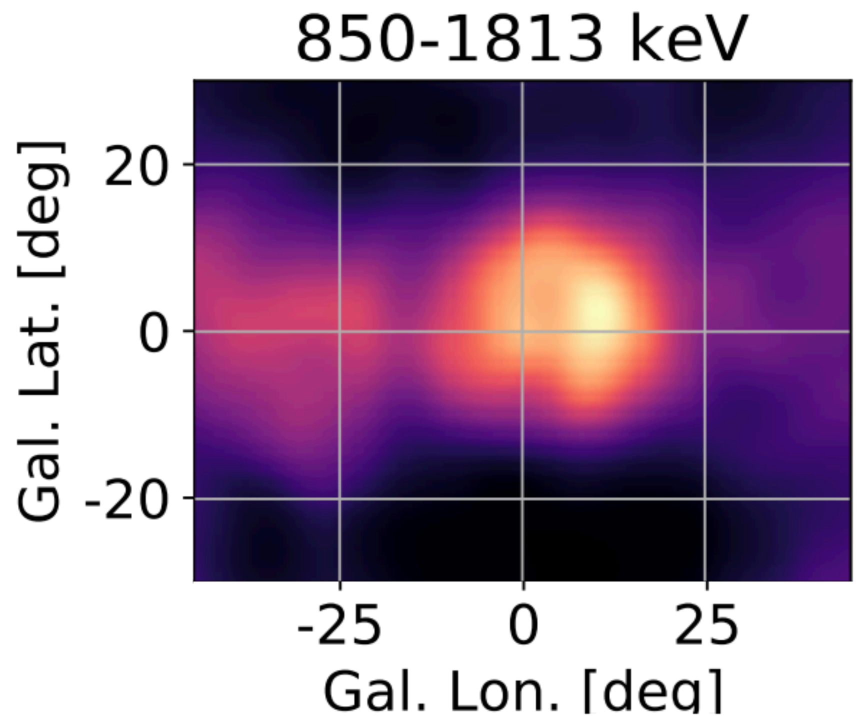
Lifetime: 2002 — present
Energy: 20 keV - 8 MeV
Good energy res
Angular res: 2.5 deg



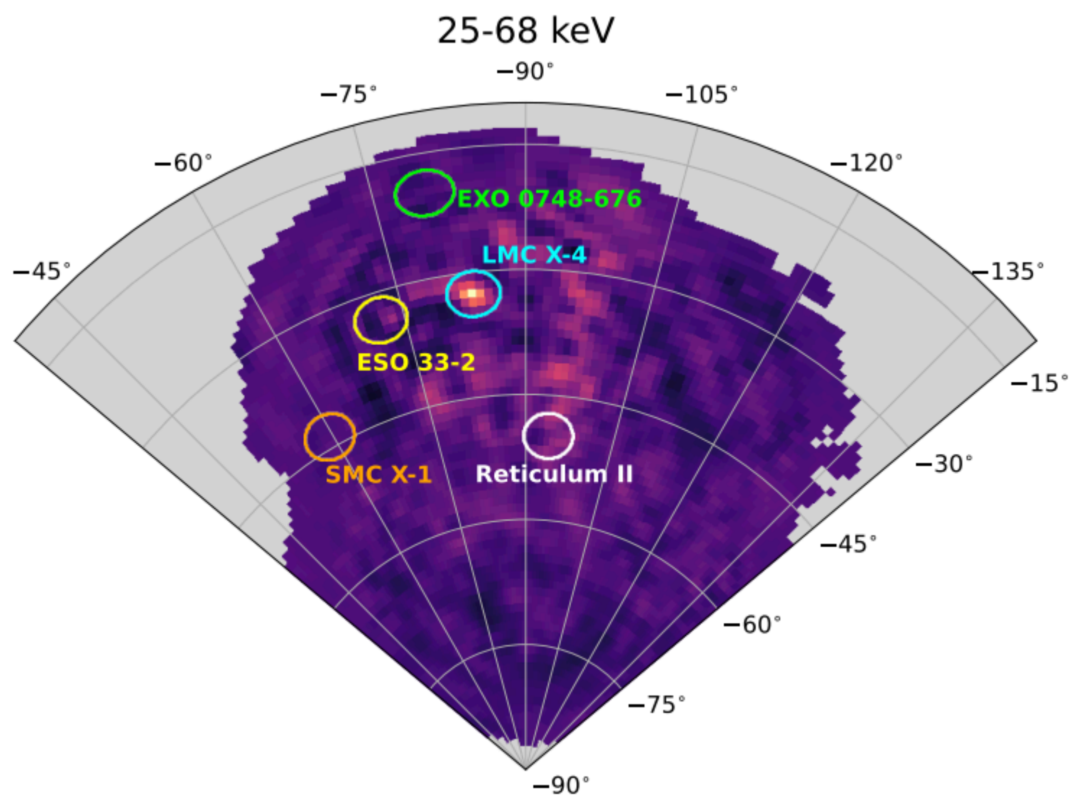
511 keV electron-positron line

The data landscape

Observables for dark matter



Milky Way diffuse emission

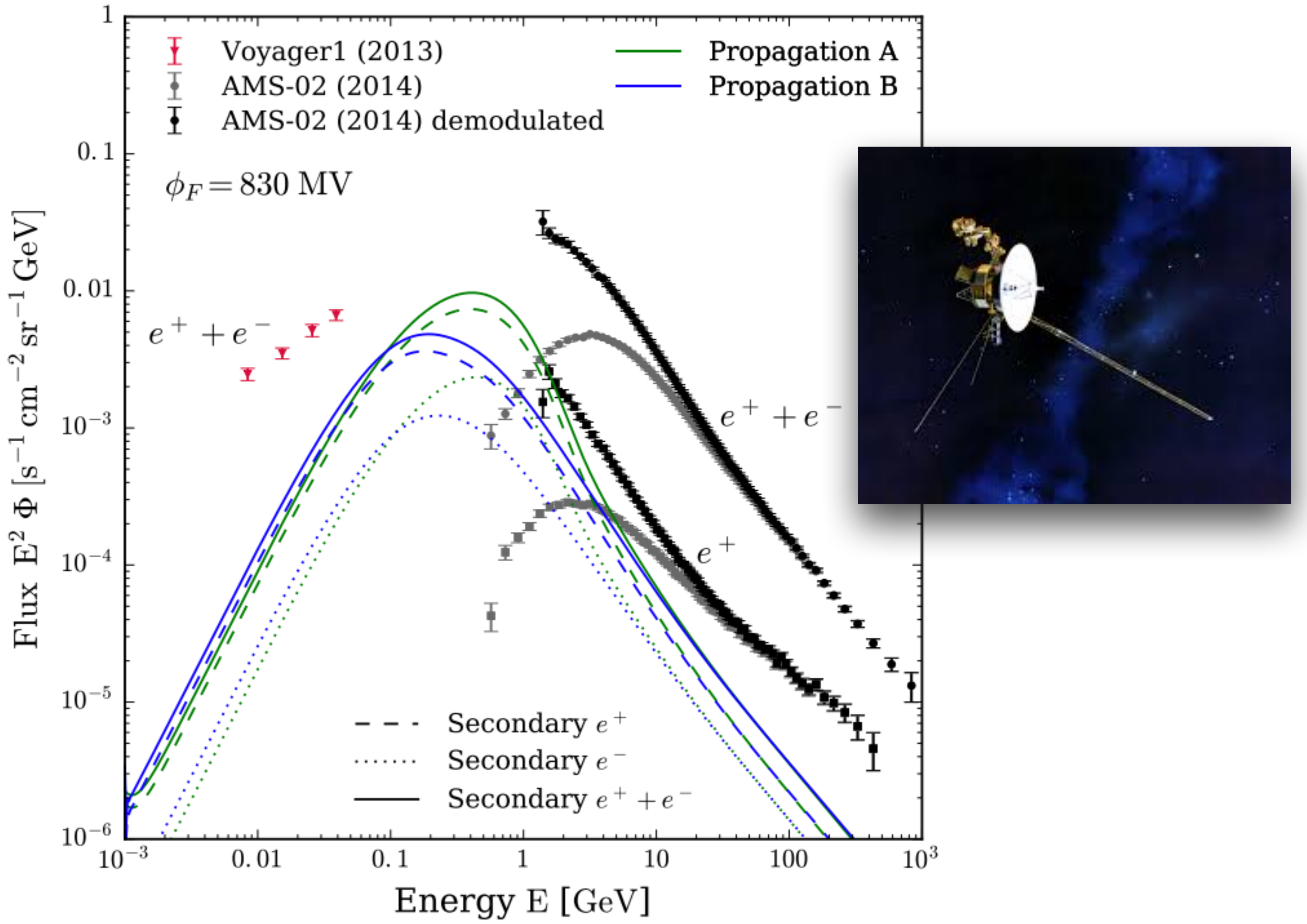


Single target

1. Continuum gamma-ray emission

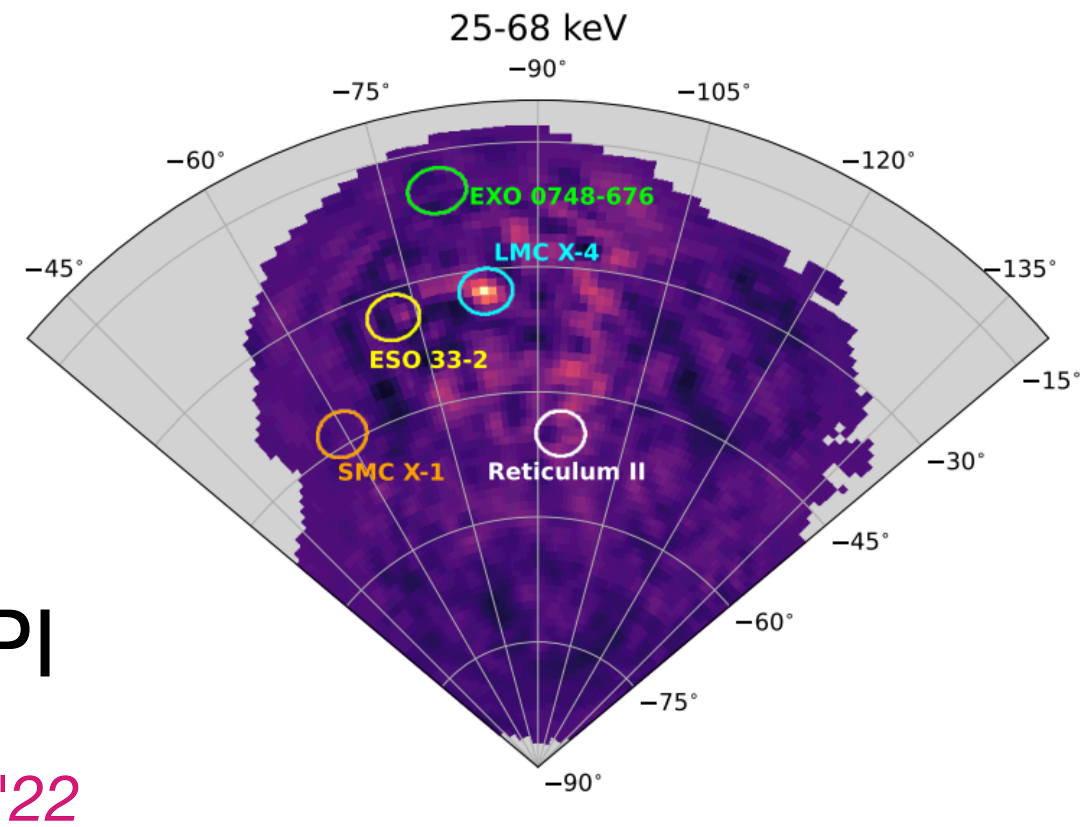
2. 511 keV electron-positron annihilation line

3. Cosmic-ray electron-positron fluxes



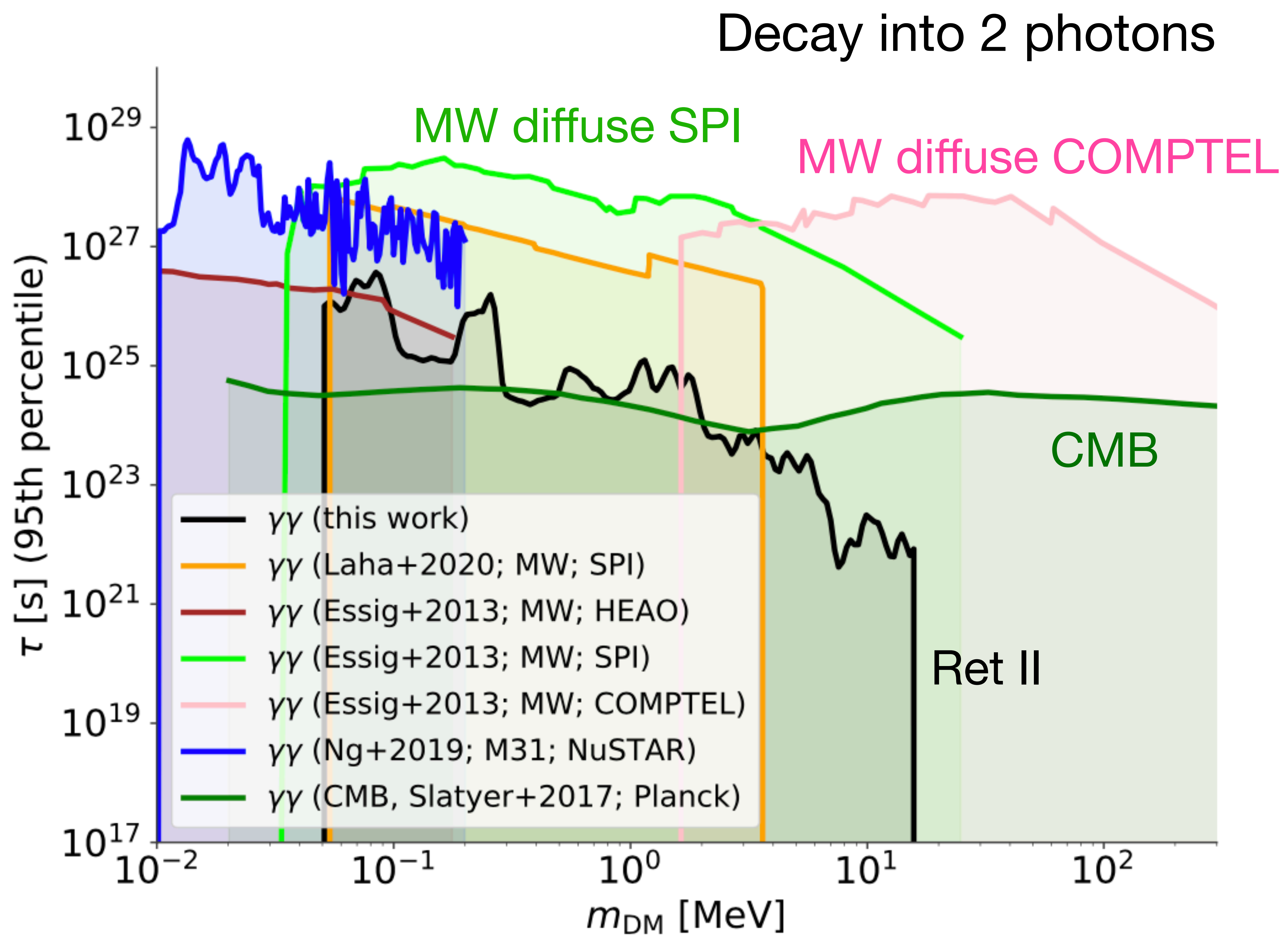
Summary: Limits on light DM decay

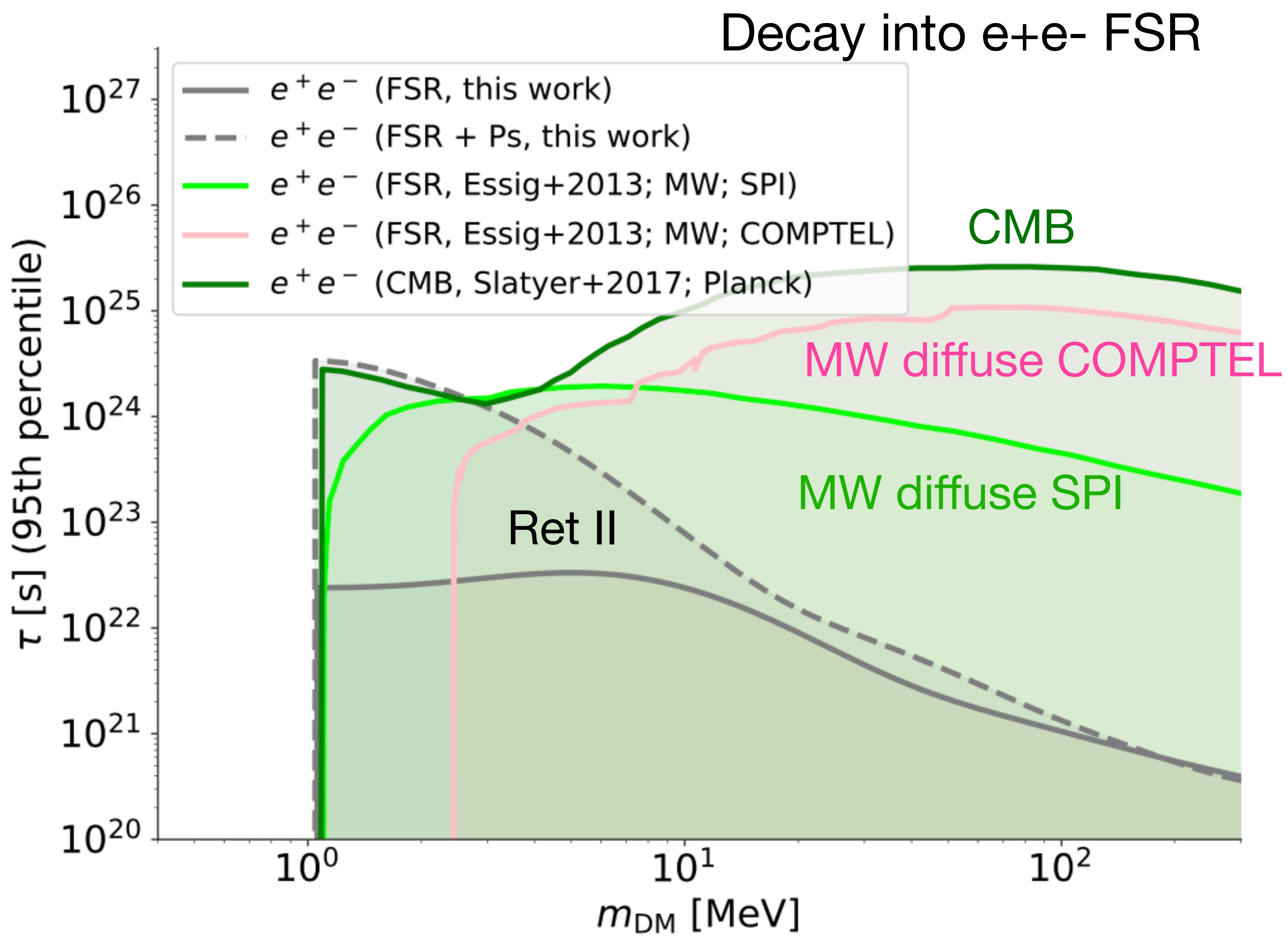
DM prompt gamma-ray emission



Single target: 1.5 Ms observation of **Reticulum II** dwarf galaxy with SPI

Siegert, FC+ MNRAS'22





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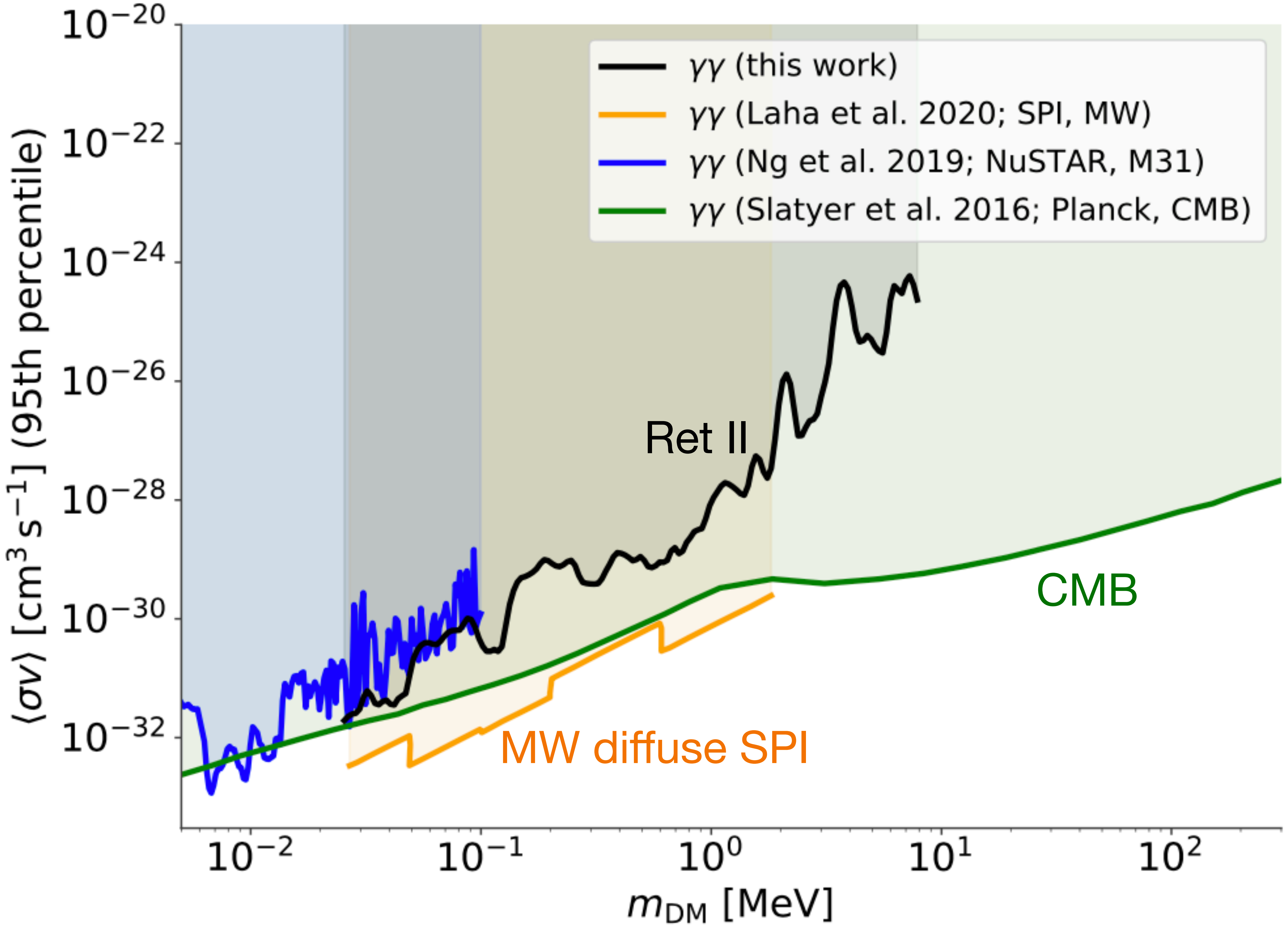
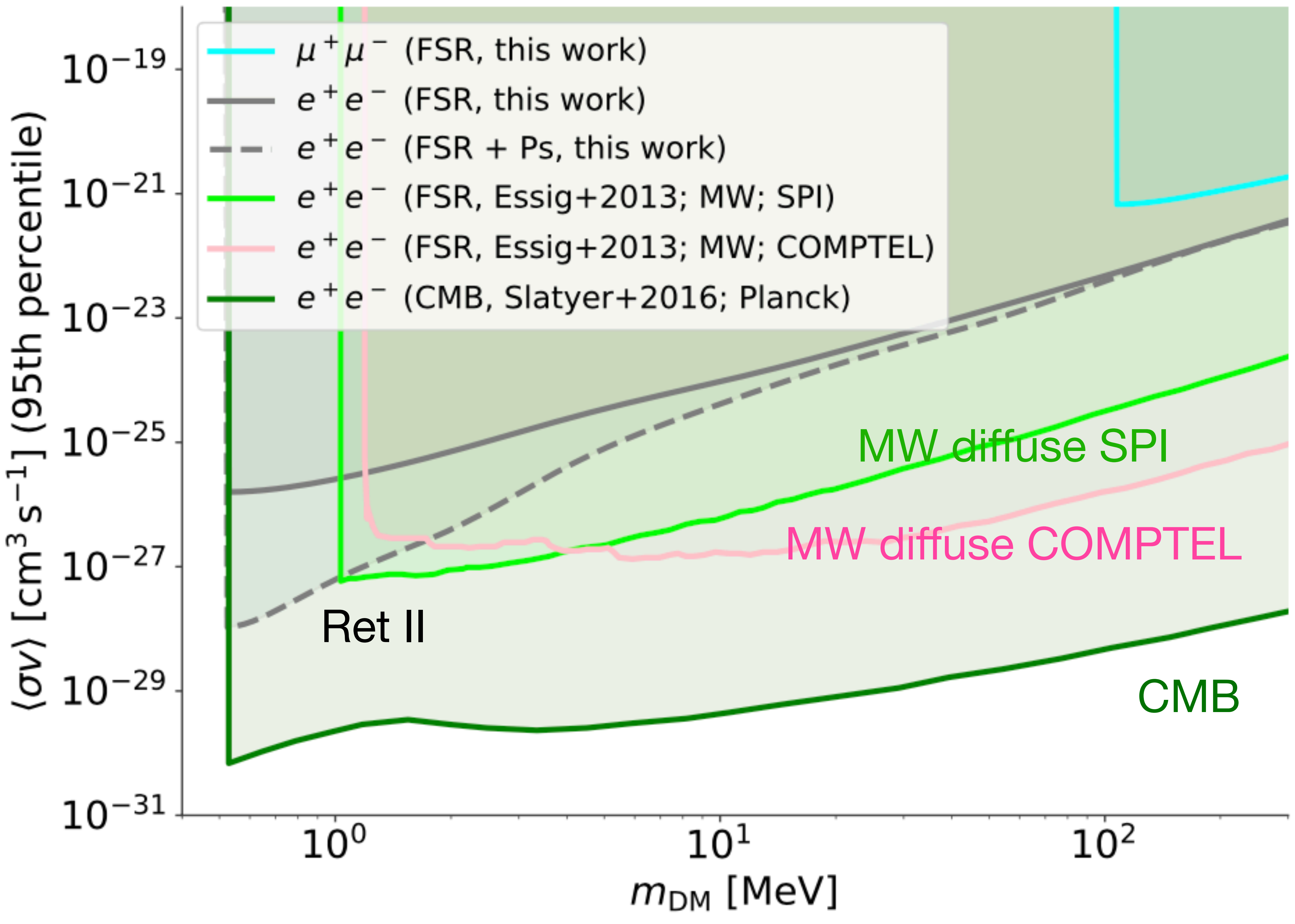
Siegert, FC+ MNRAS'22



Annihilation into 2 photons

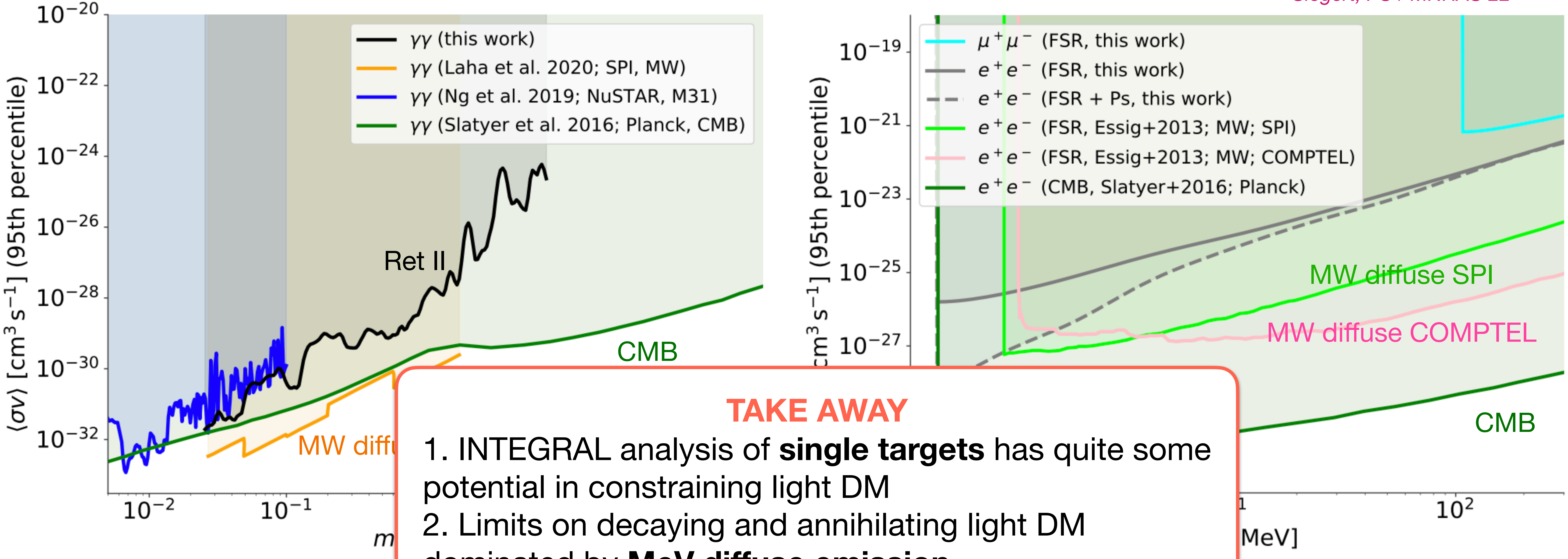


Annihilation into e+e- FSR

Summary: Limits on light DM annihilation

DM prompt gamma-ray emission

Siegert, FC+ MNRAS'22



Annihilation in ... e+e- FSR

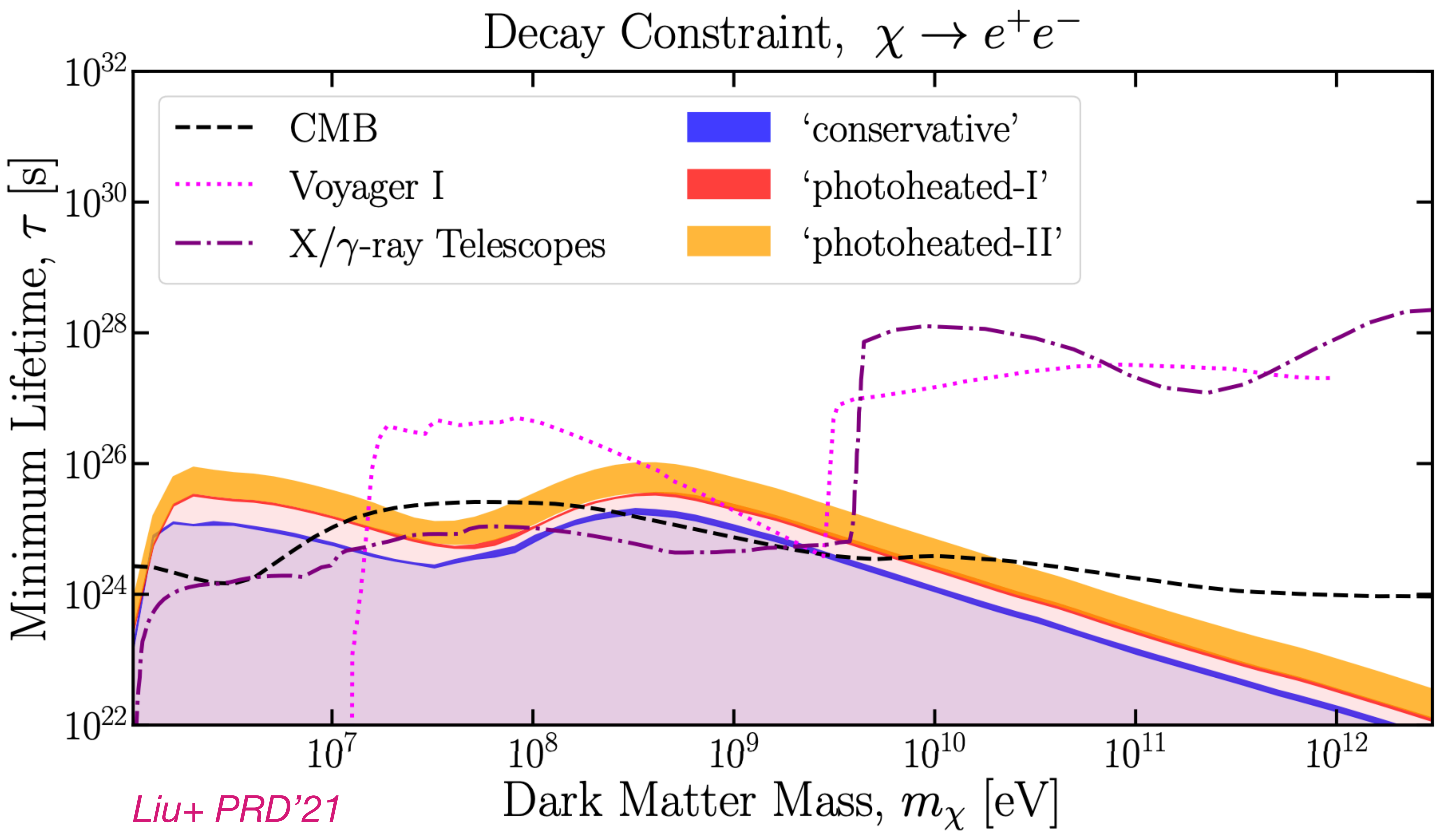
TAKE AWAY

1. INTEGRAL analysis of **single targets** has quite some potential in constraining light DM
2. Limits on decaying and annihilating light DM dominated by **MeV diffuse emission**

Summary: Limits on light DM

DM prompt electron-positron emission

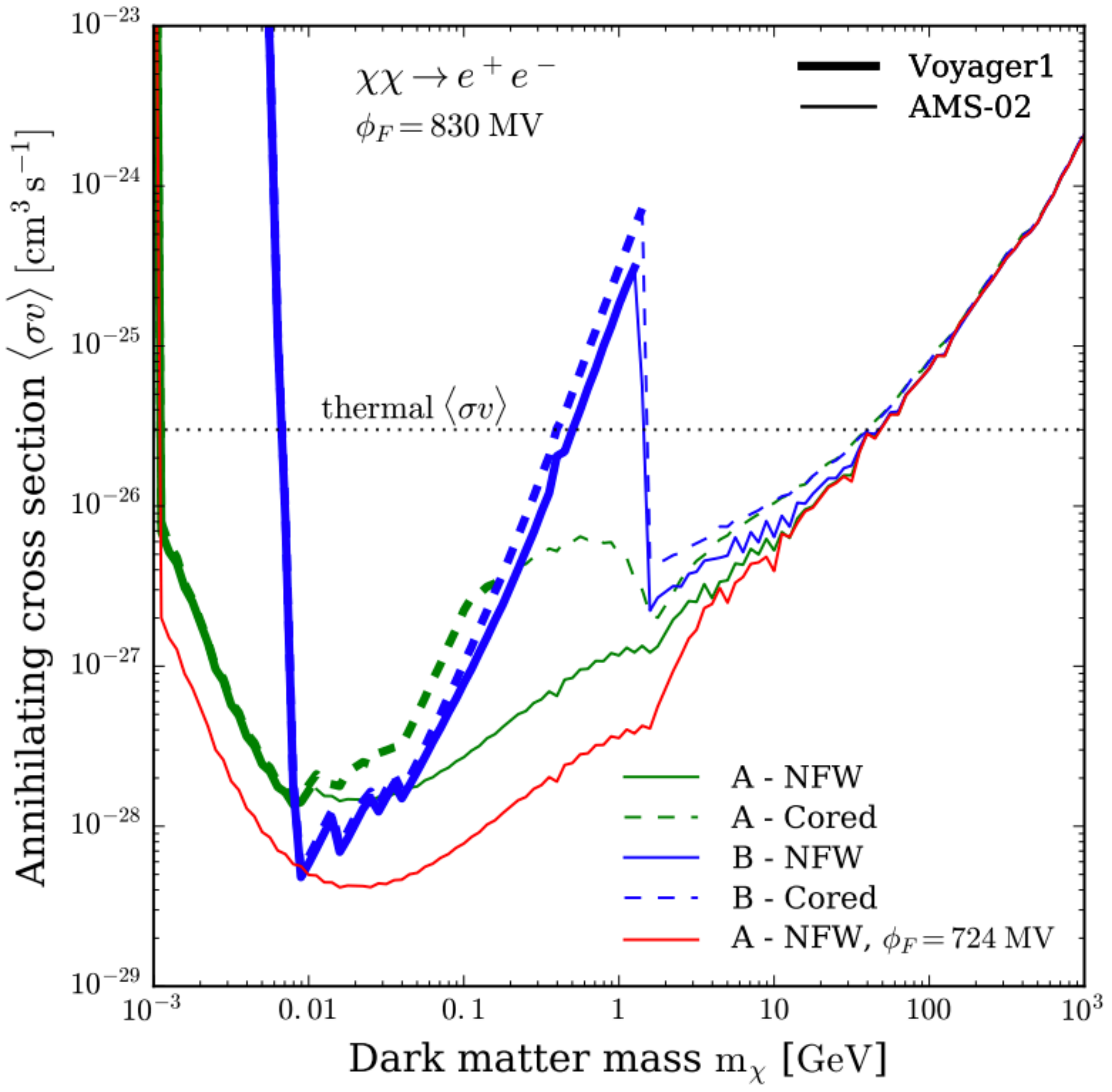
New probe with Voyager 1 data offers competitive bounds



Liu+ PRD'21

Decay into e+e-

Boudaud+ PRL'17

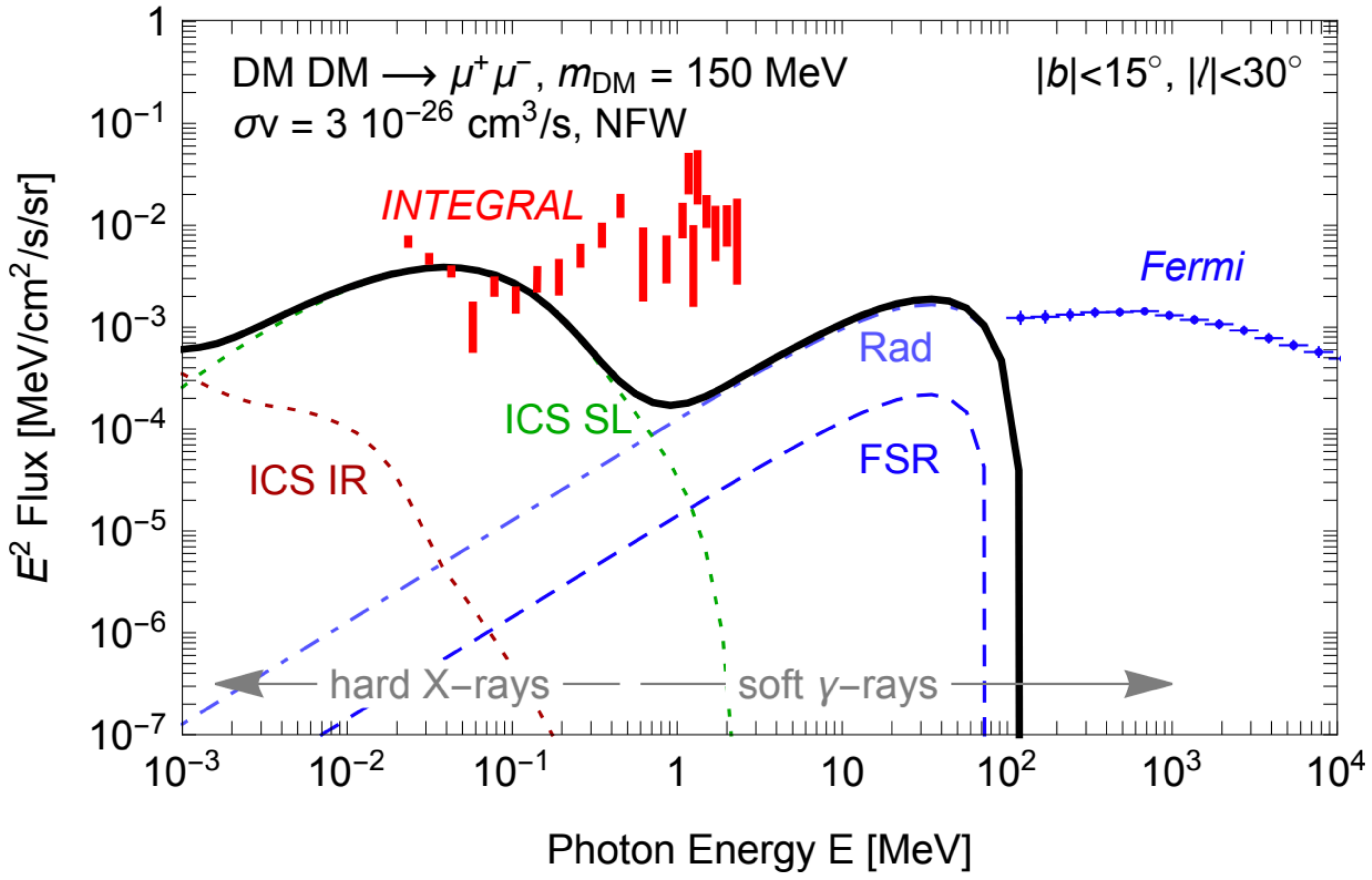


Annihilation into e+e-

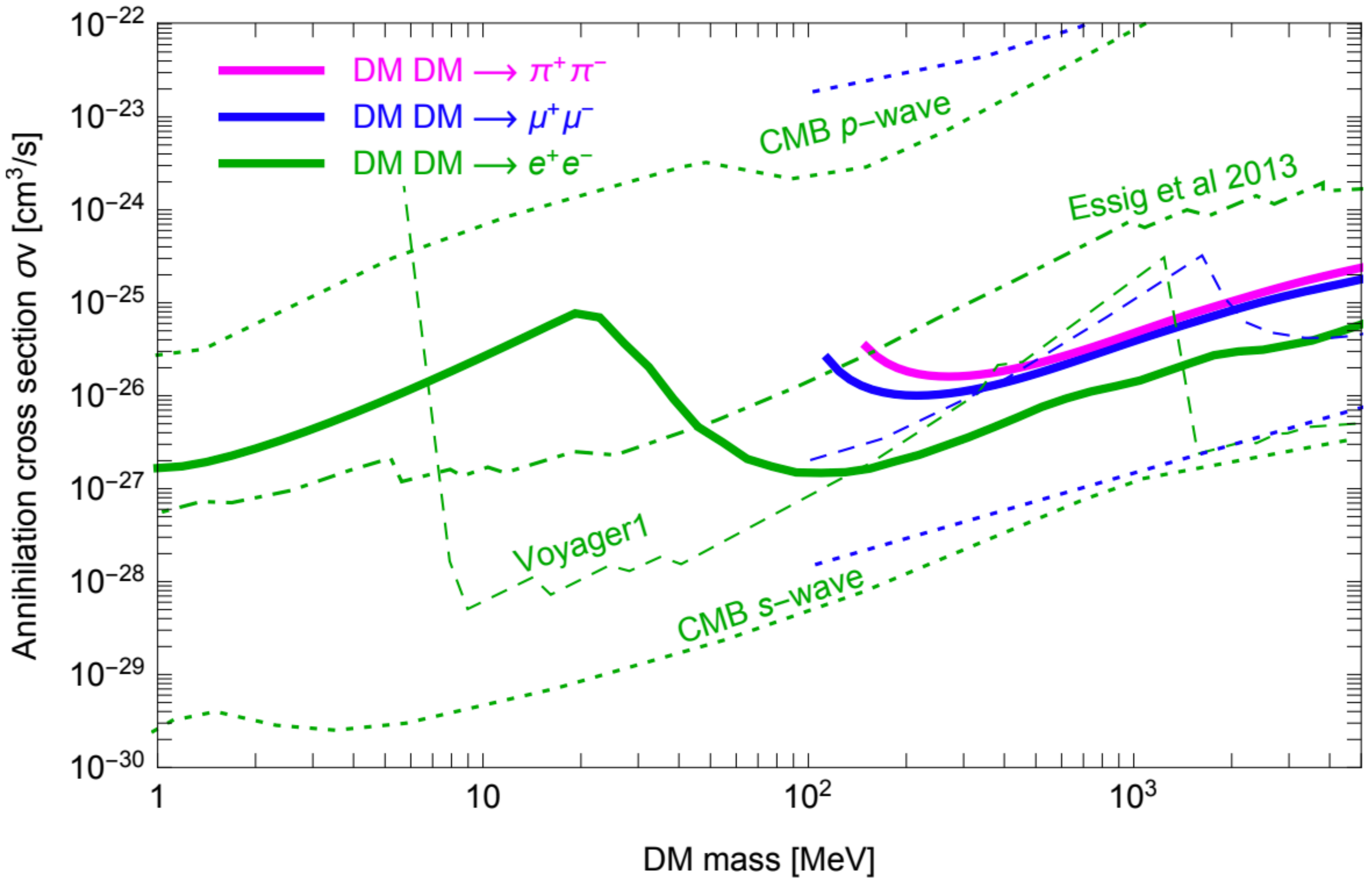
Summary: Limits on light DM annihilation

DM Inverse Compton gamma-ray emission

Cirelli+ PRD' 21



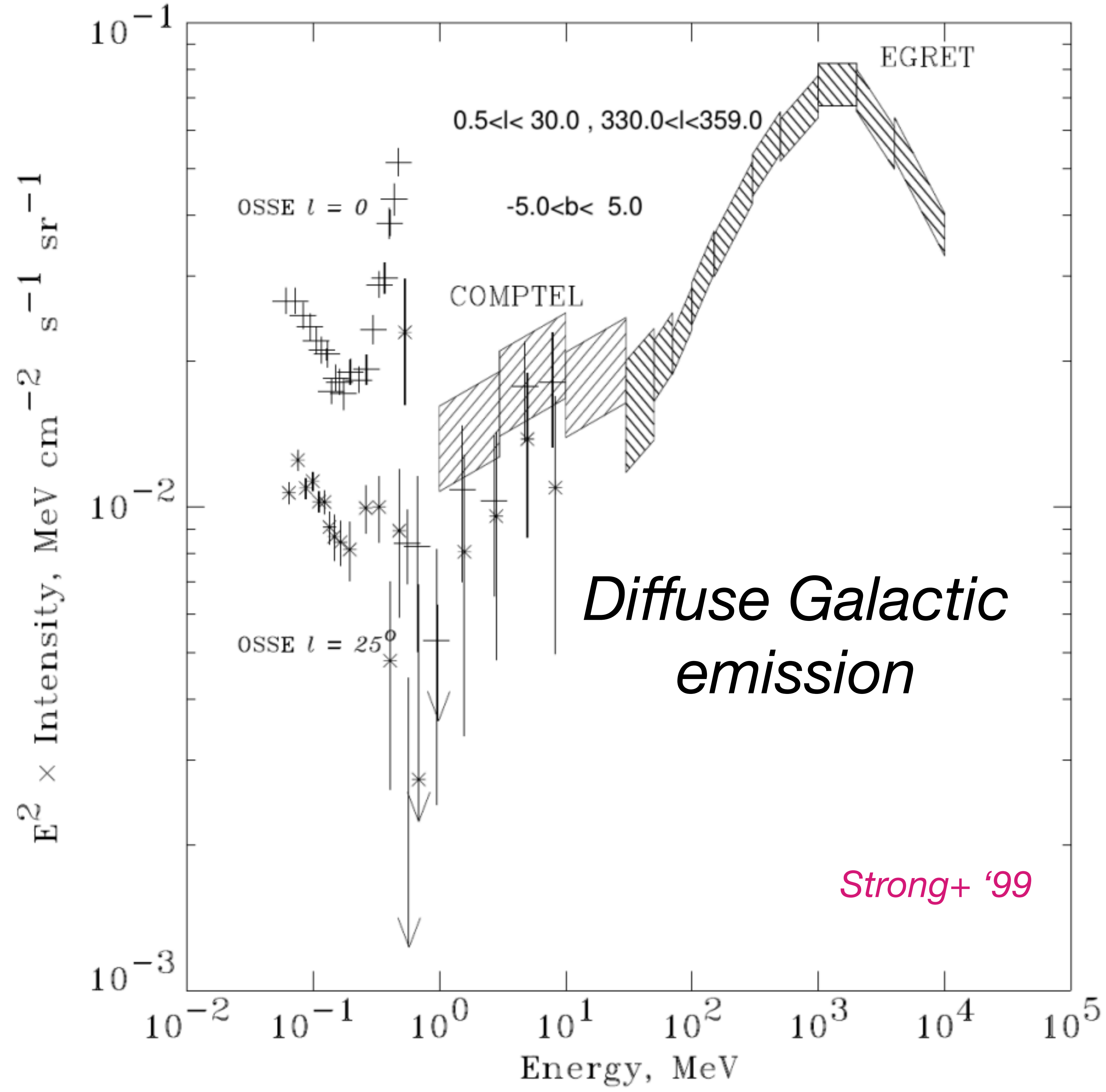
Bounds on annihilating Dark Matter



Continuum gamma-ray emission

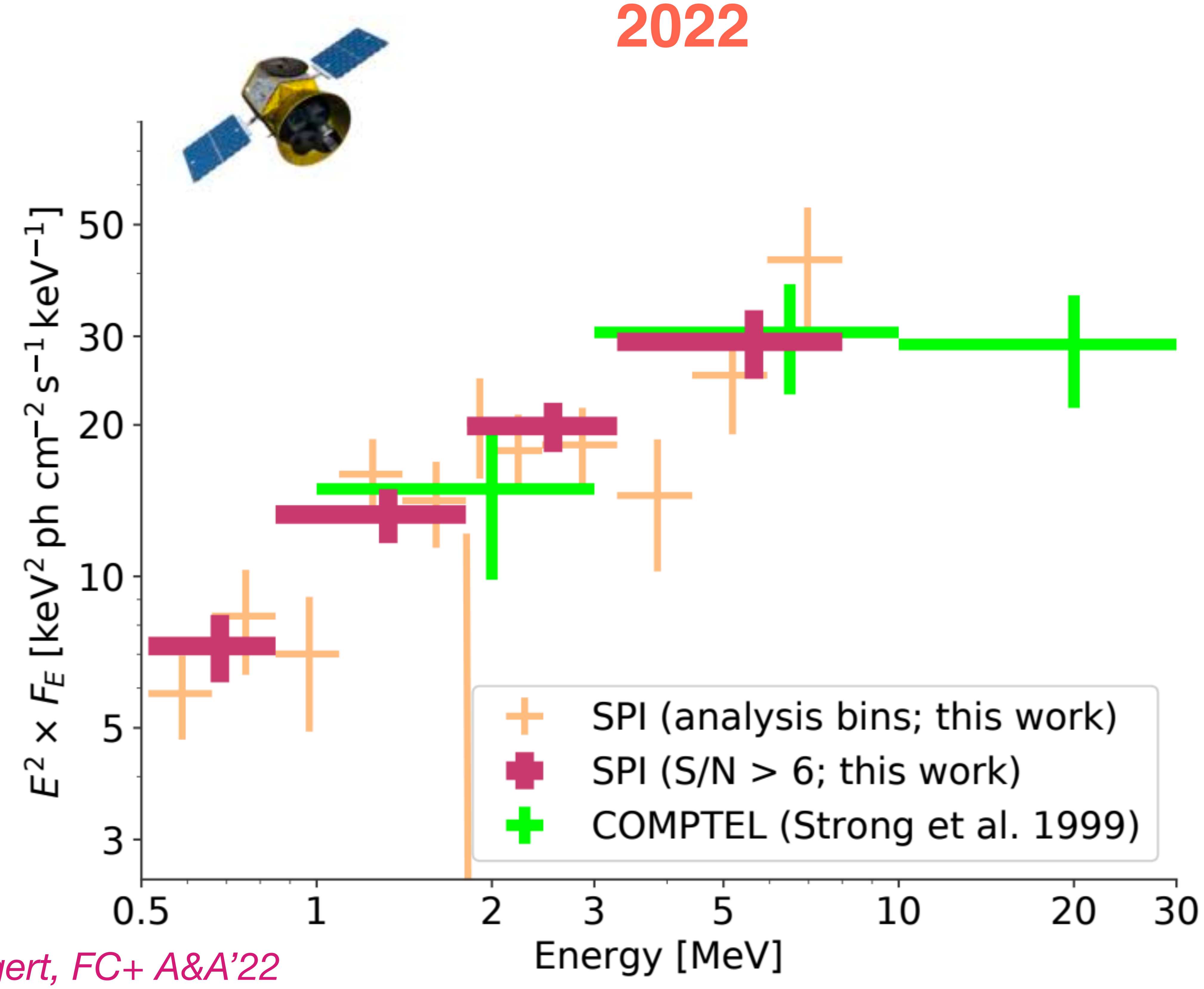
MeV Galactic diffuse emission above 0.5 MeV

1999



Strong+ '99

2022



Siegert, FC+ A&A'22

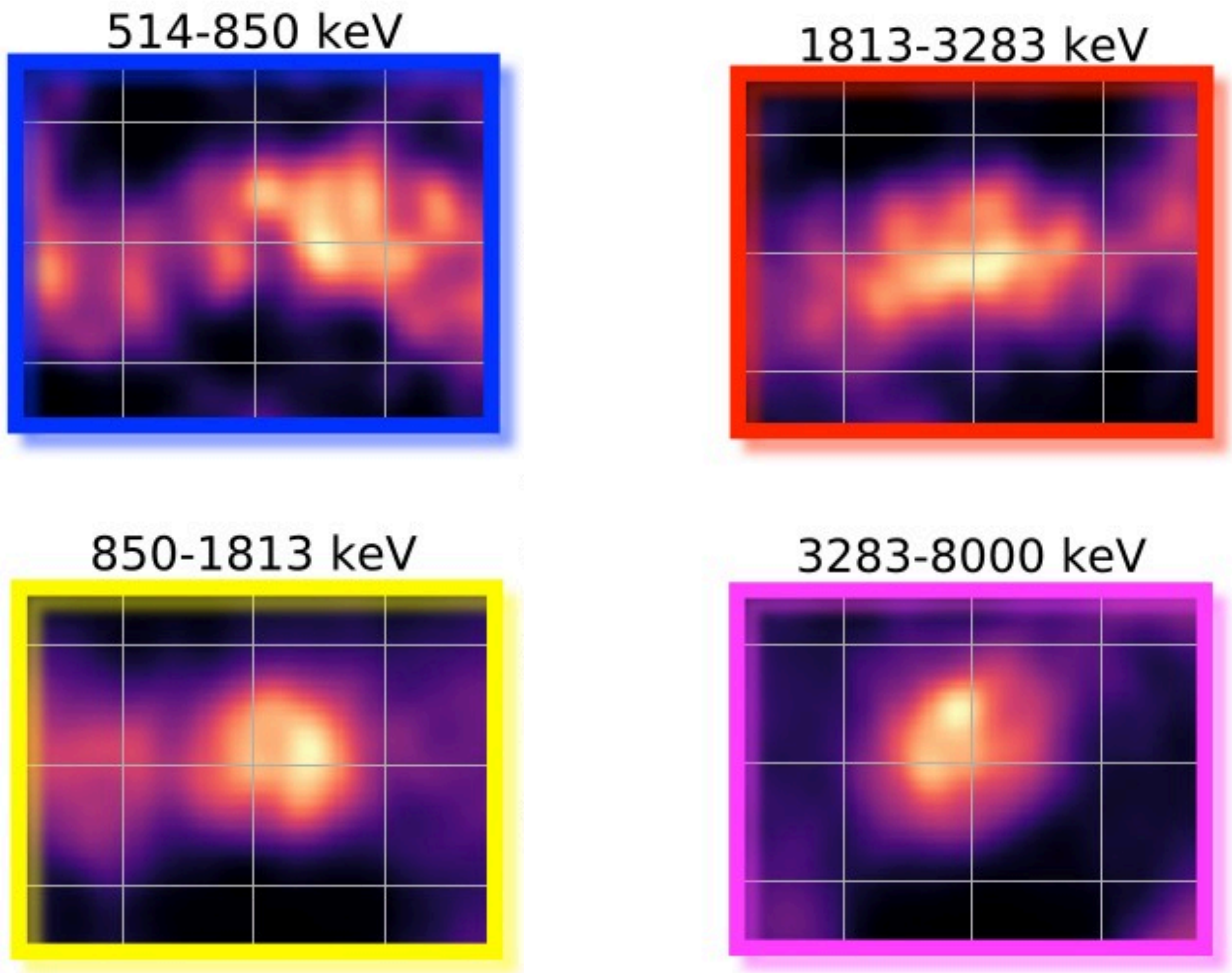
New analysis of 16yr-data from SPI
0.5 — 8 MeV

Continuum gamma-ray emission

MeV Galactic diffuse emission above 0.5 MeV

Modeled spatial templates

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



Integral picture of the month, March 2022

Continuum gamma-ray emission

MeV Galactic diffuse emission above 0.5 MeV

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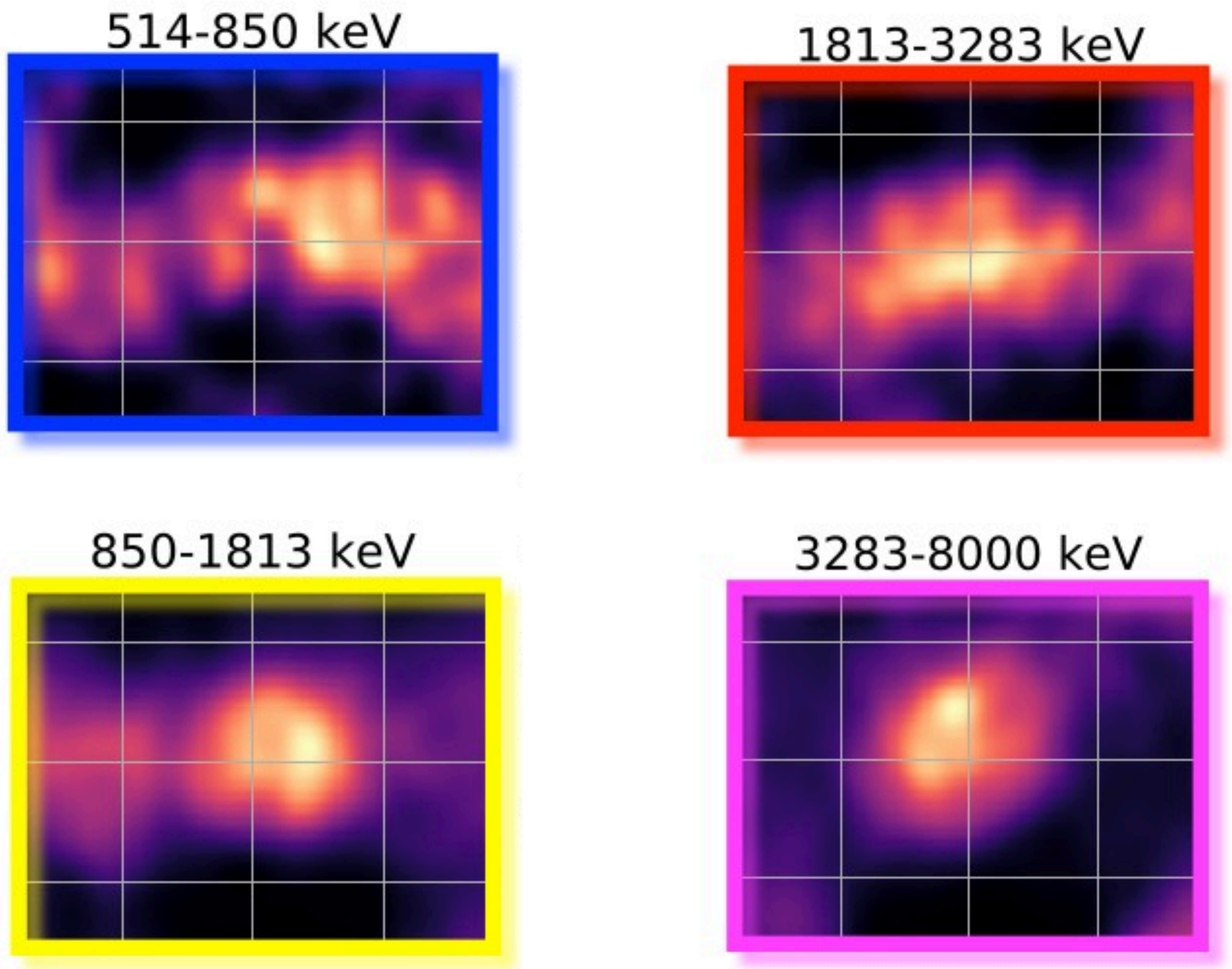

Constraints on **cosmic-ray transport** at MeV energy but also on **exotic emission mechanisms**: particle and non-particle dark matter

Integral picture of the month, March 2022

MeV Galactic diffuse emission

Is there evidence for an additional dark matter component?

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- **Inverse Compton scattering** of electrons off the interstellar radiation field $e^{\pm}_{\rm CR} + \gamma \longrightarrow e^{\pm} + \gamma_{\rm MeV}$
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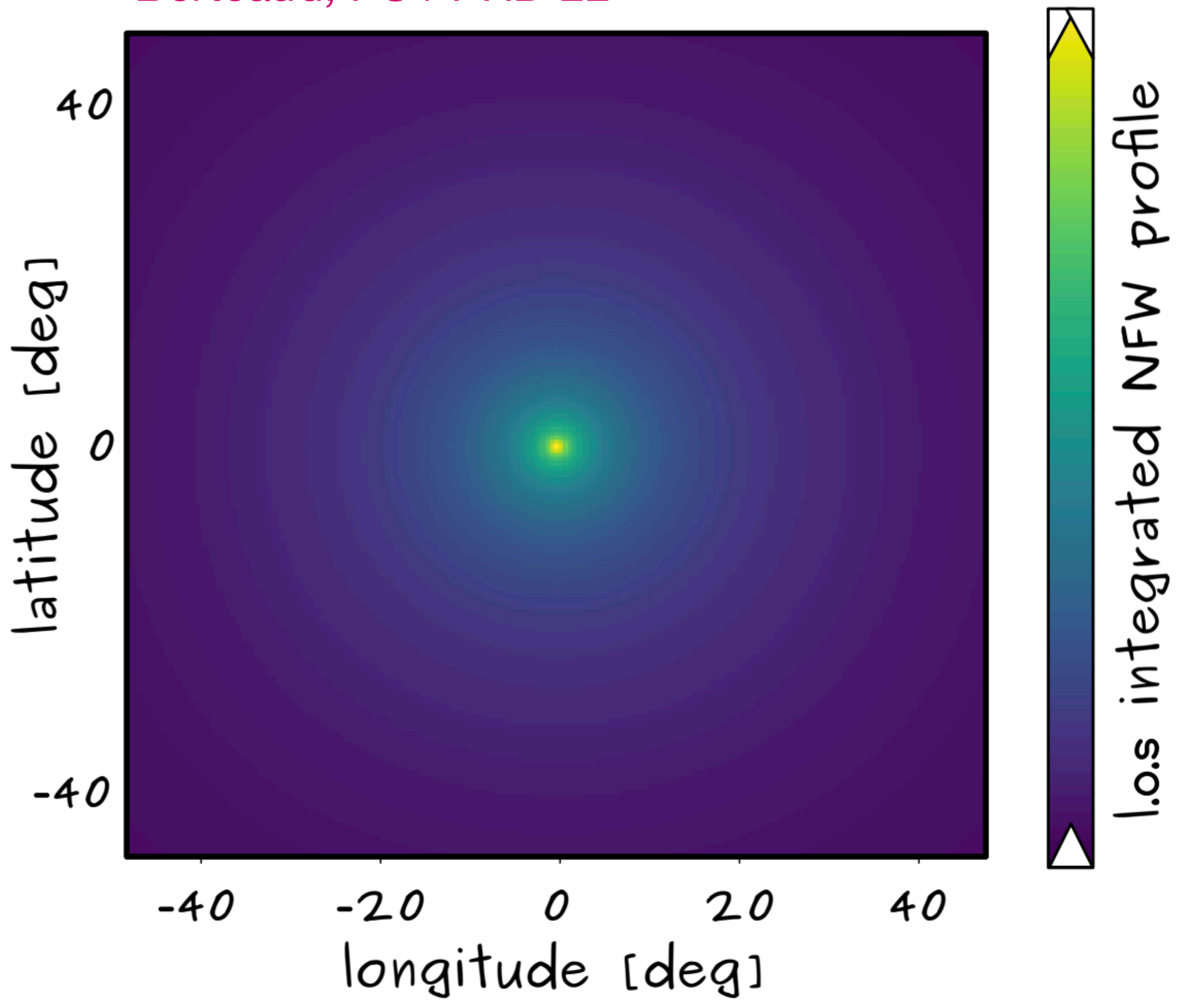
- **Decaying dark matter ?**

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

Berteaud, FC+ PRD'22



MeV Galactic diffuse emission

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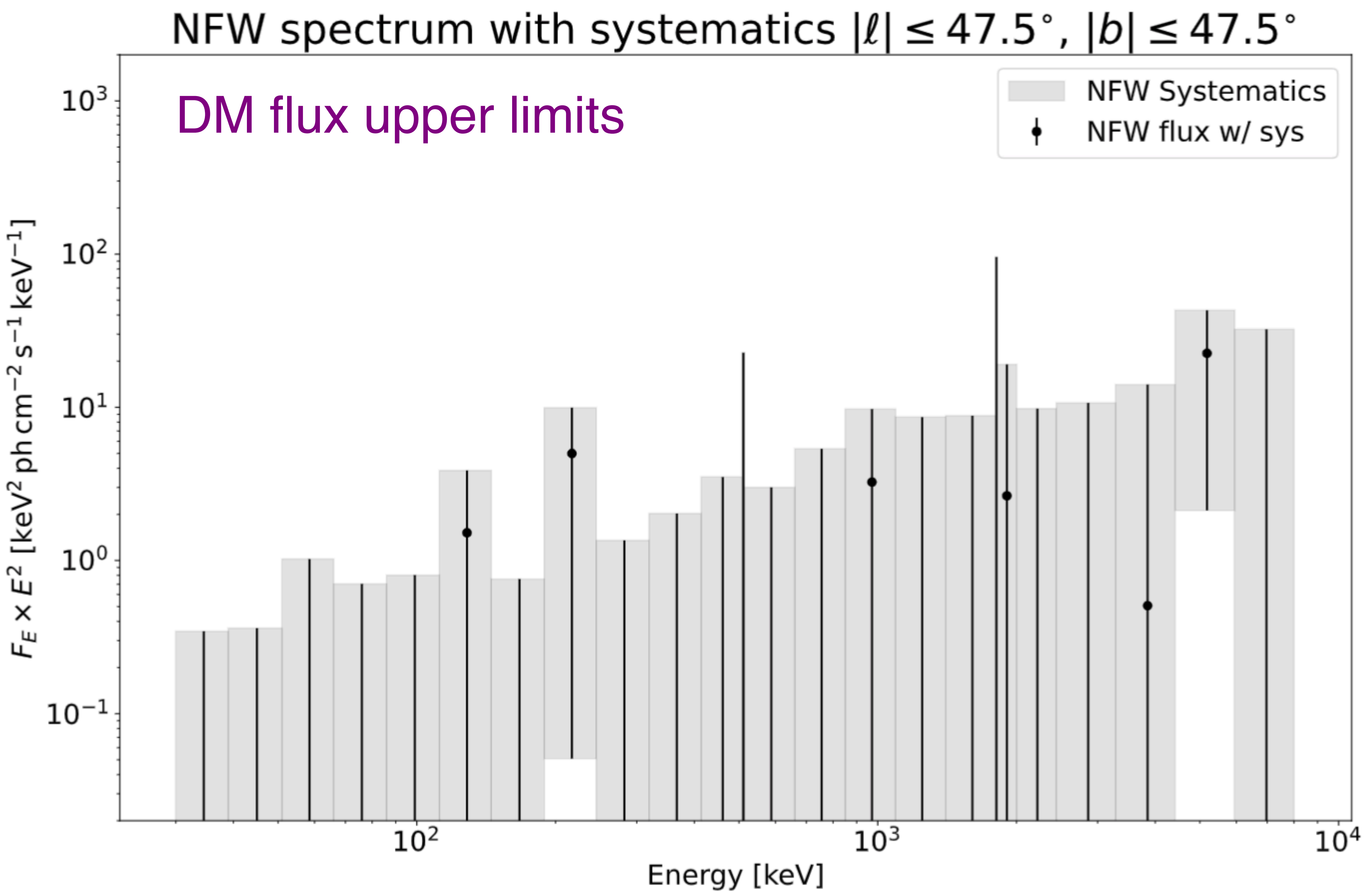
No signal detected

=> Upper limits on **DM decay flux**



MeV Galactic diffuse emission

Limits on light dark matter decay

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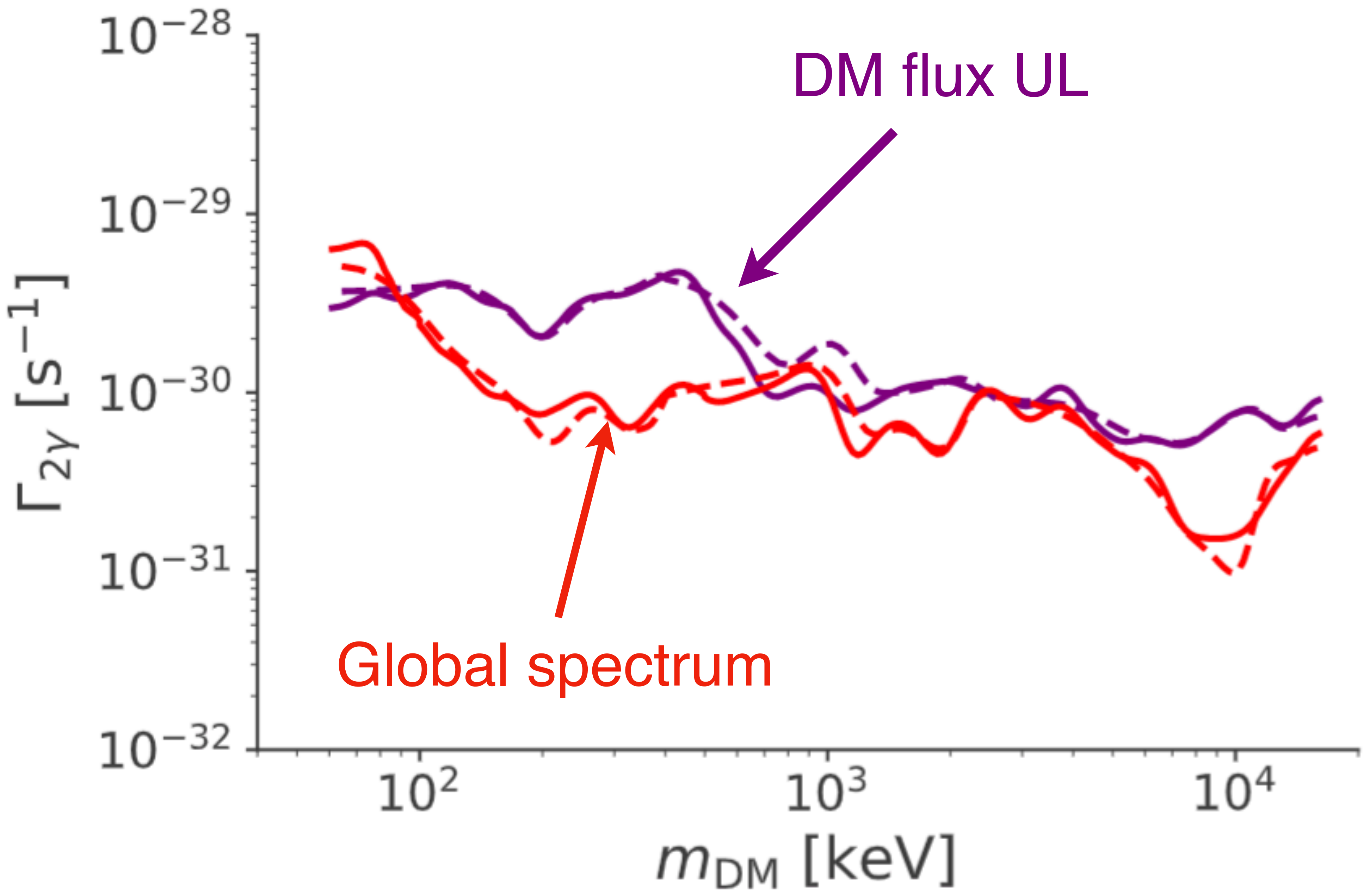
Multi-component **spectral fit** to extracted SPI spectrum

=> Upper limits on **decay rate** into 2 photons, $\Gamma_{2\gamma}$

$m_{\mathrm{DM}} \lesssim \mathrm{MeV}$ $\qquad E_\gamma = \frac{m_{\mathrm{DM}}}{2}$

Dekker, FC+'22 arXiv:2209.06299



MeV Galactic diffuse emission

Limits on light dark matter decay

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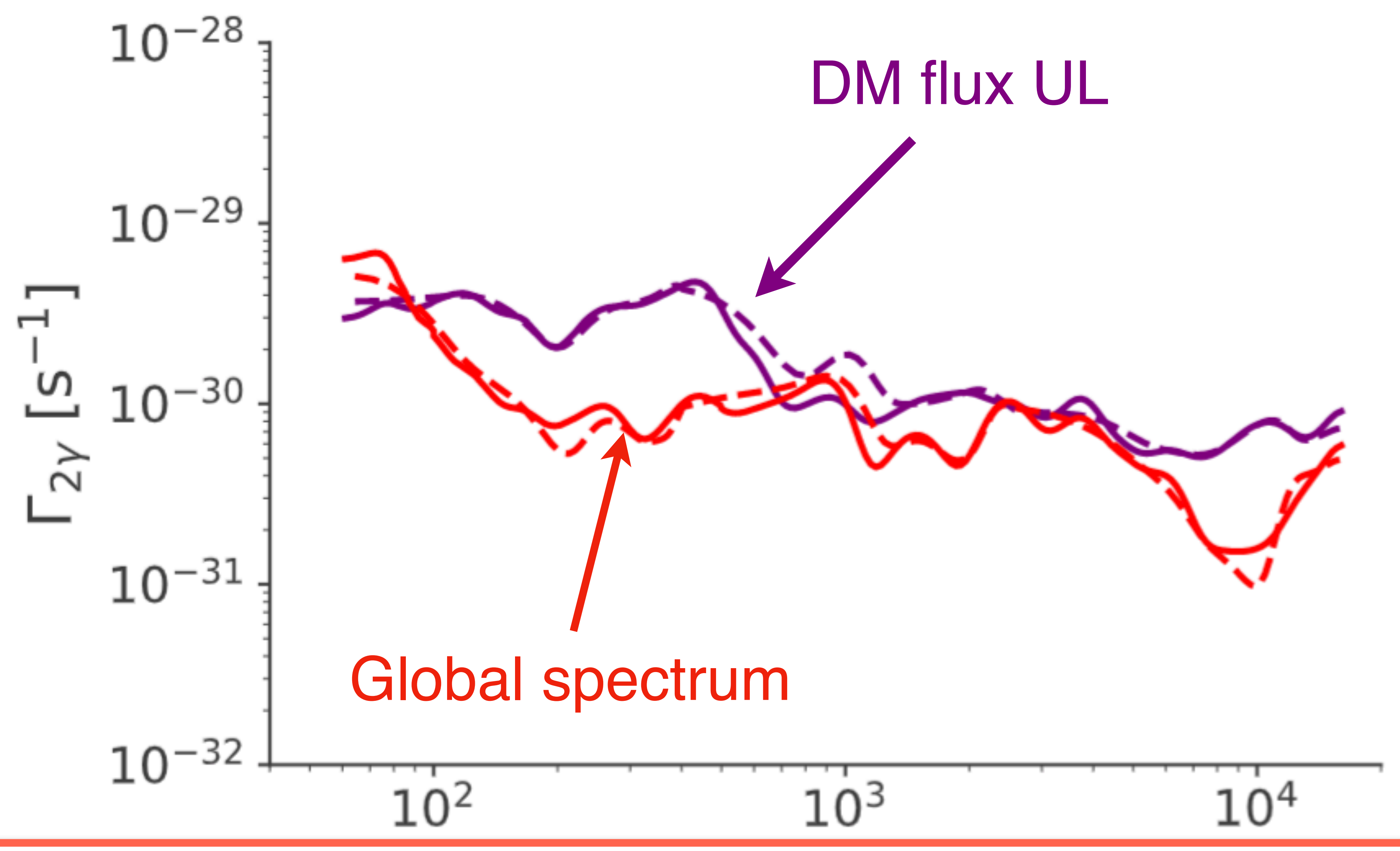
Dekker, FC+'22 arXiv:2209.06299

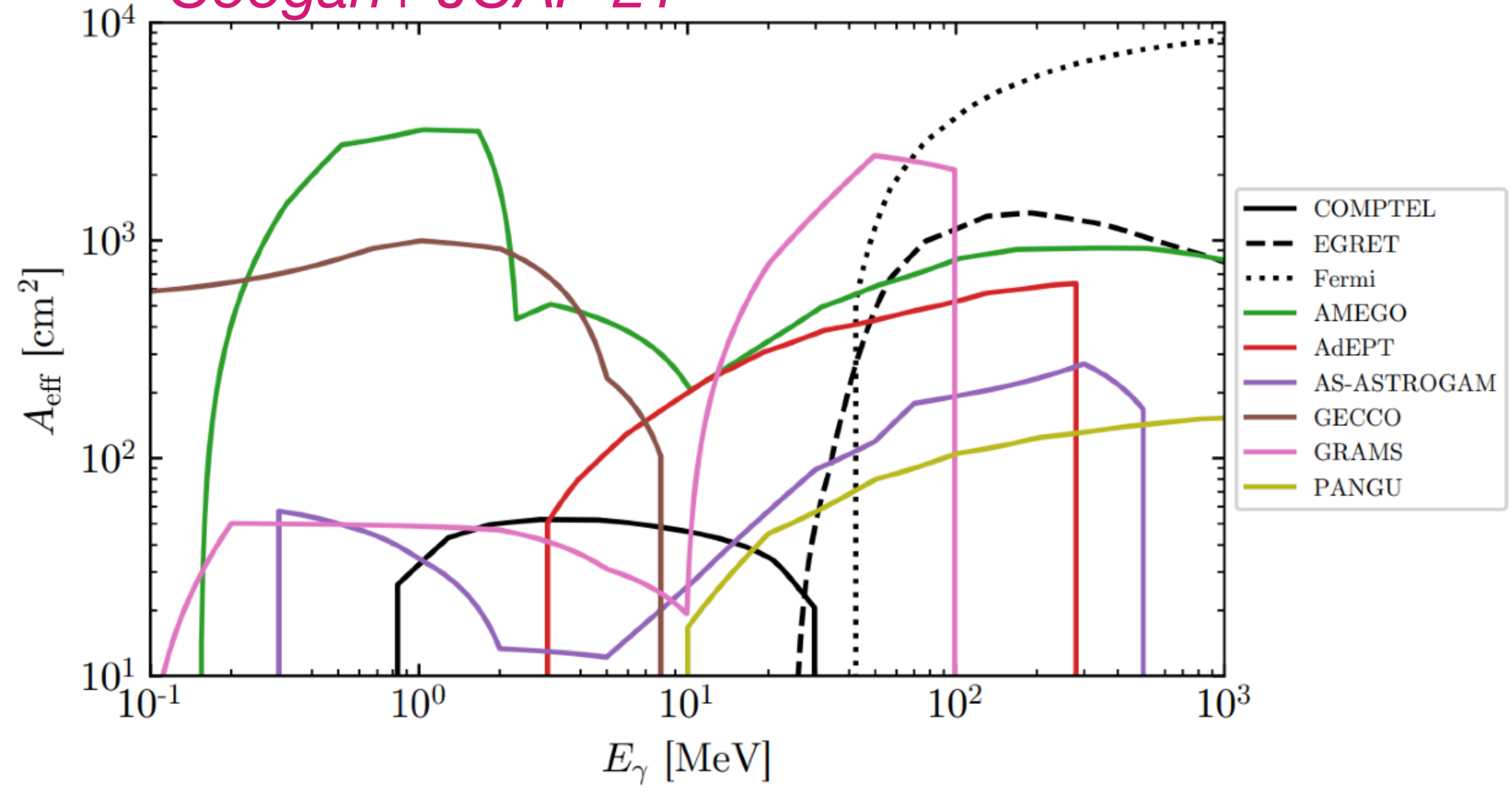


TAKE AWAY: Re-analysis of INTEGRAL data provides the strongest constraints on light DM ~0.1 - 10 MeV

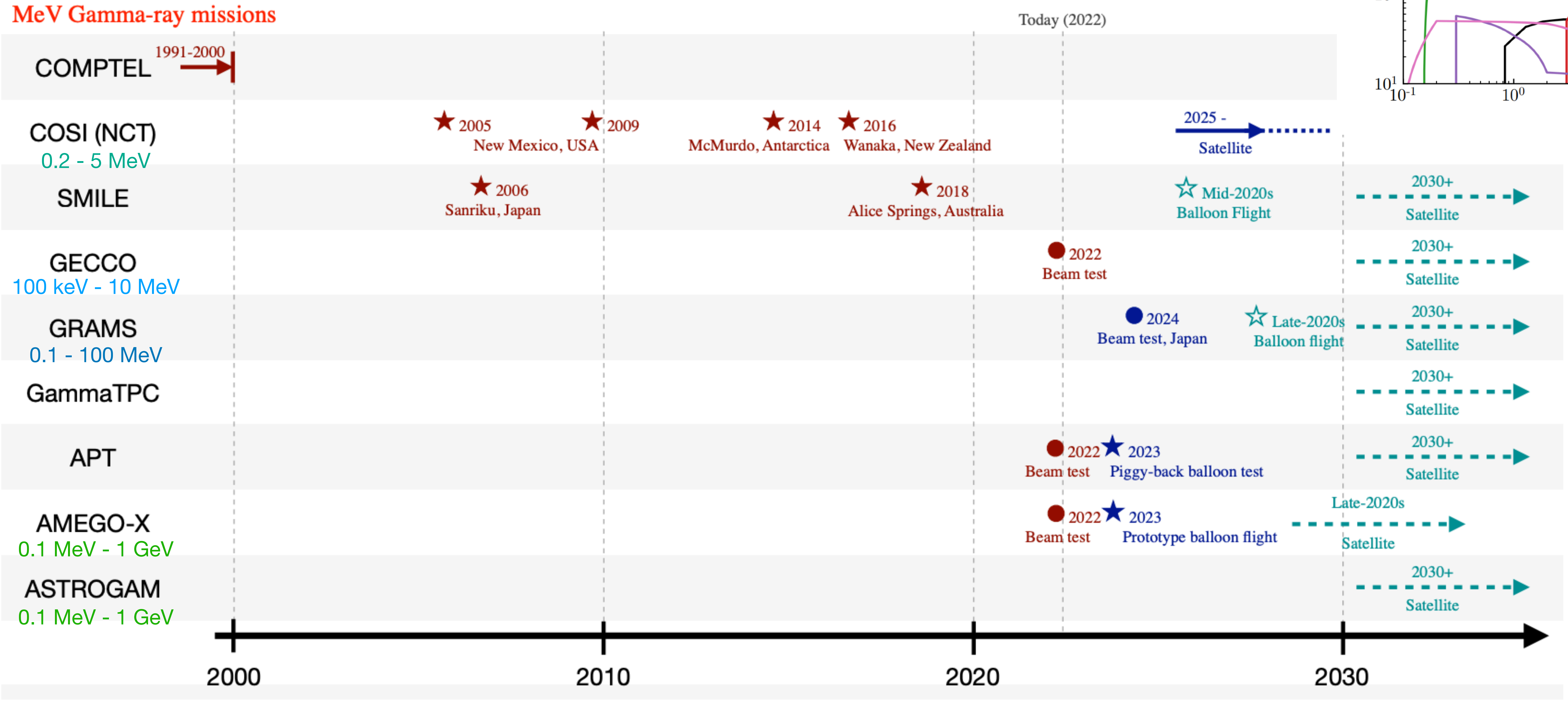
Future: MeV Galactic diffuse emission

Covering the MeV sensitivity gap

Coogan+ JCAP'21



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

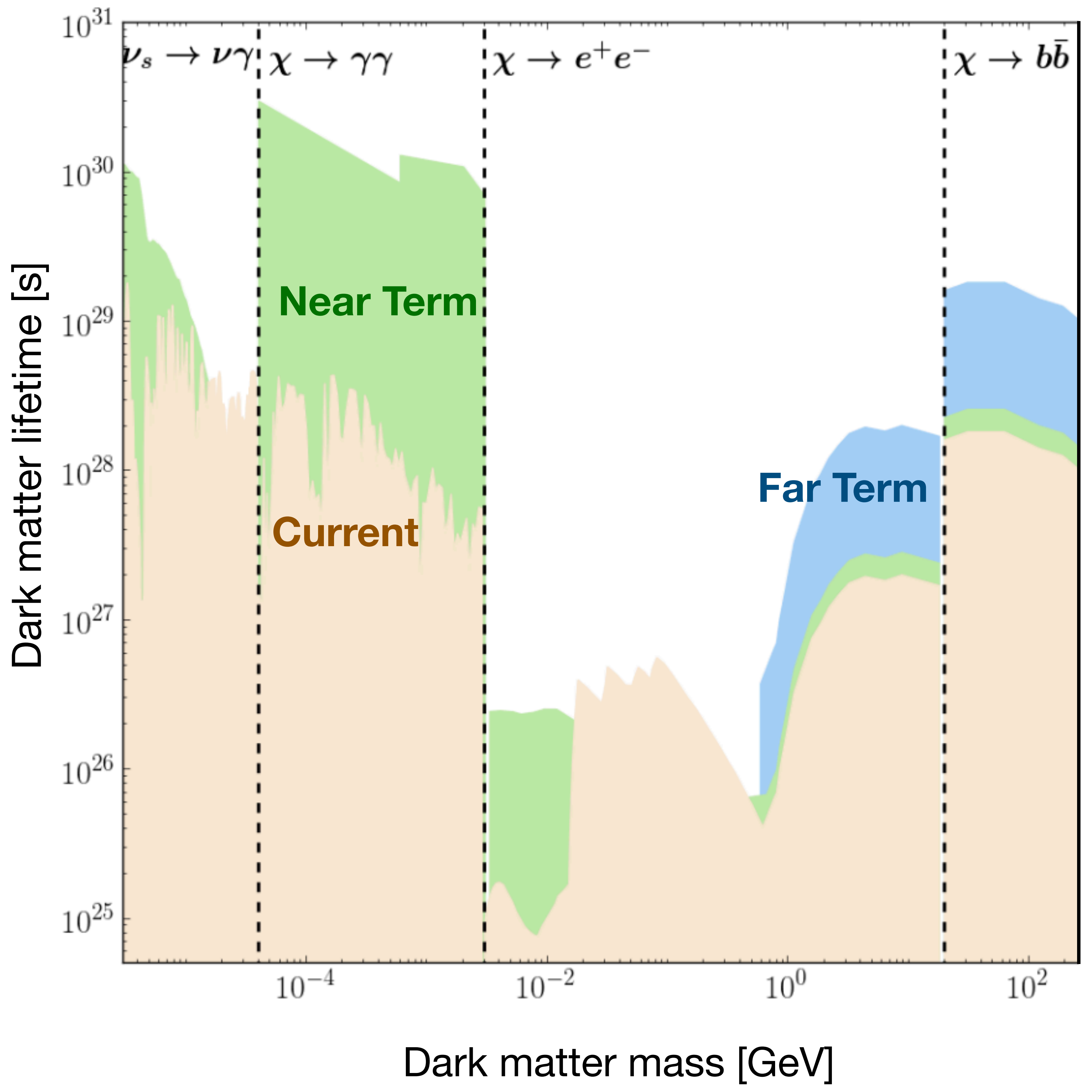


Aramaki+ Snowmass'21 CF

Future: MeV Galactic diffuse emission

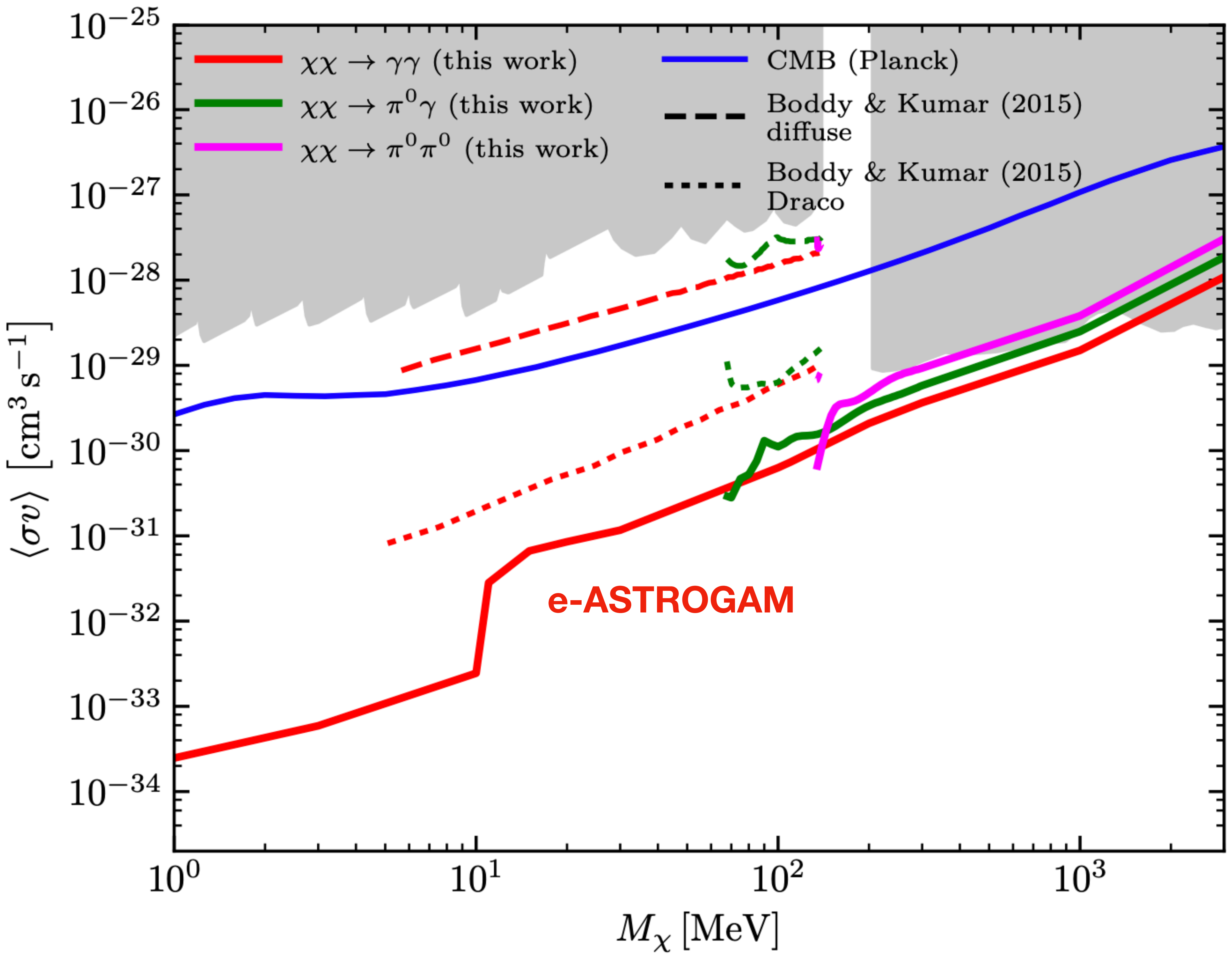
Sensitivity to dark matter decay and annihilation

Cooley+ Snowmass'21 CF1 Report



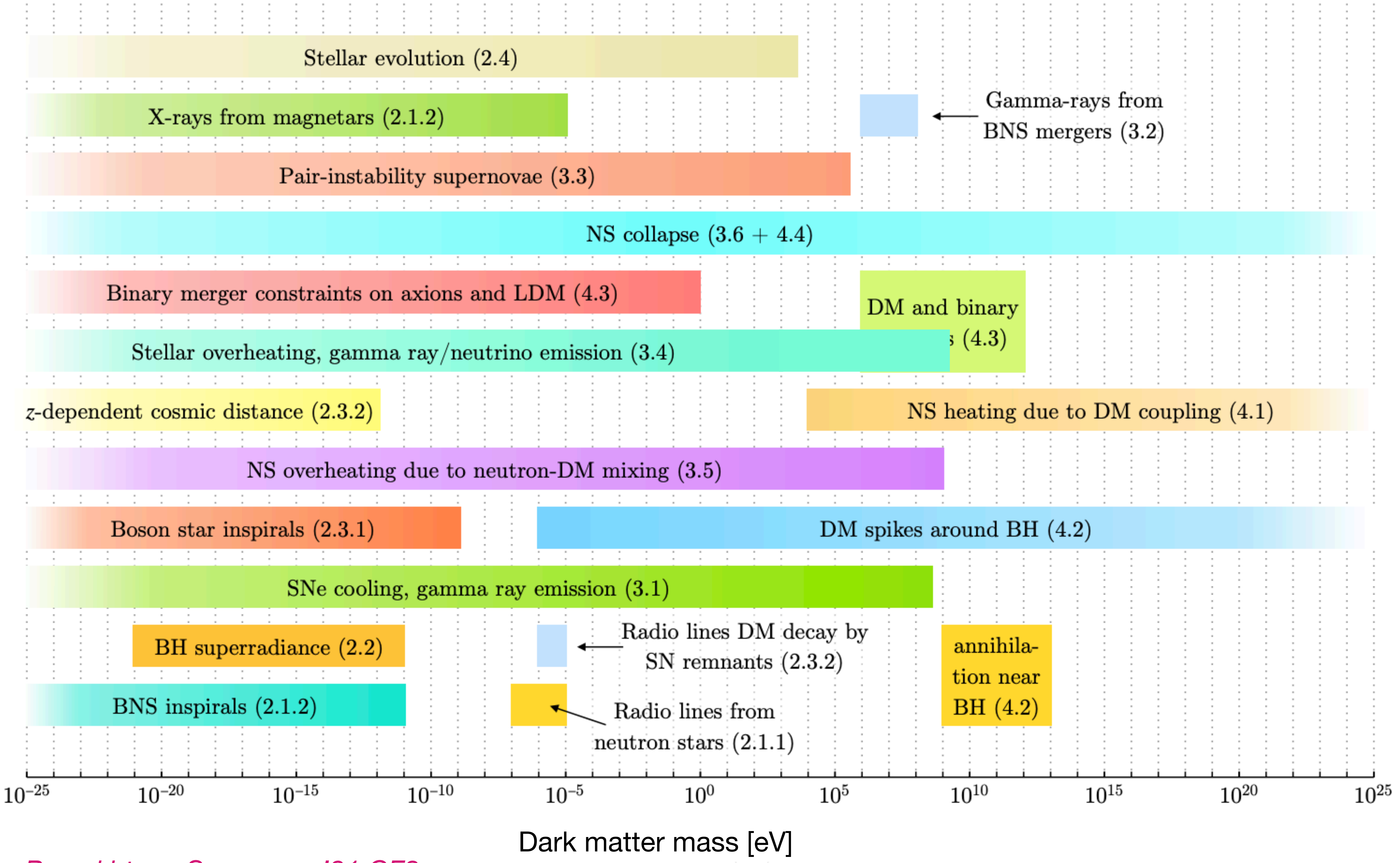
Decay

Bartels+ JCAP'17



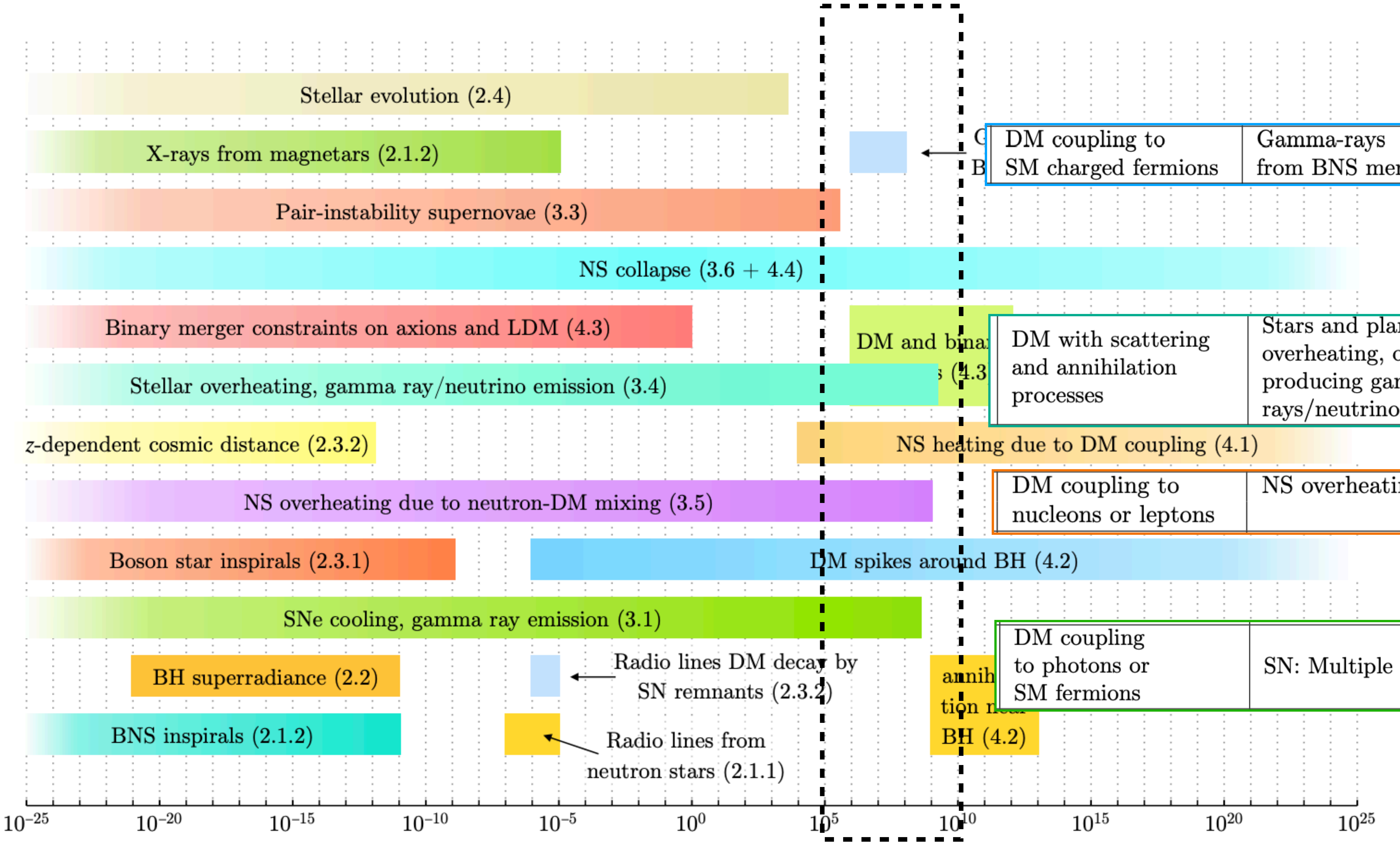
Annihilation

DM in (extreme) astrophysical environments



Baryakhtar,+ Snowmass'21 CF3

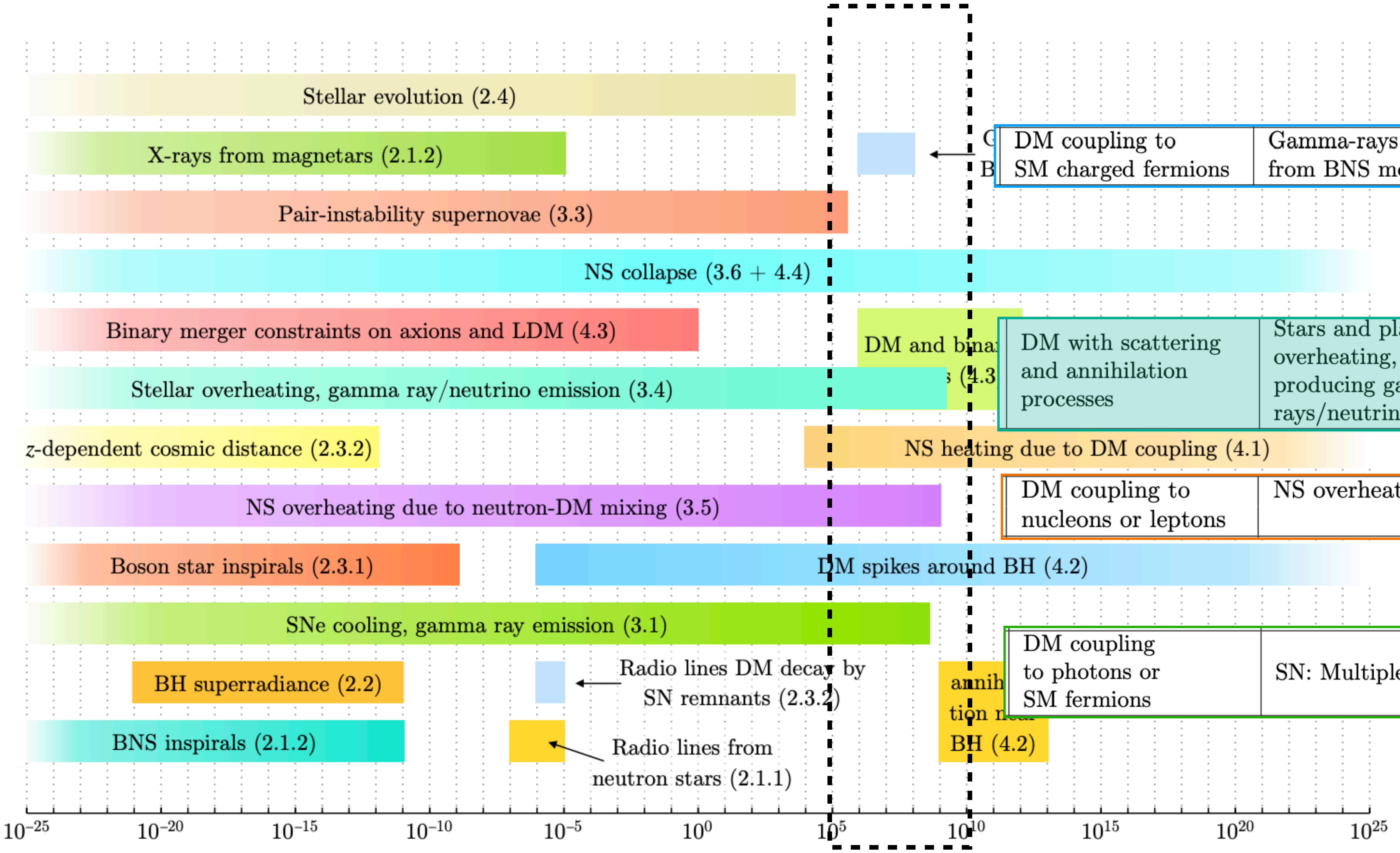
DM in (extreme) astrophysical environments



DM coupling to SM charged fermions	Gamma-rays from BNS merger	$\sim$ 1-100 MeV	$10^{-12} < \epsilon < 10^{-9}$ (kinetic mixing)
DM with scattering and annihilation processes	Stars and planets overheating, or producing gamma rays/neutrinos	$\gtrsim \mathcal{O}$(keV) (depending on object and particle model)	$\sigma_{n\chi} \gtrsim 10^{-47}$ cm^2 (depending on object and particle model)
DM coupling to nucleons or leptons	NS overheating	10 keV–10^{19} GeV	$\sigma_{n\chi} \gtrsim 10^{-45}$ cm^2
DM coupling to photons or SM fermions	SN: Multiple	$\lesssim$ 500 MeV	$10^{-12} \lesssim G_{a\gamma\gamma}$ GeV $\lesssim 5 \times 10^{-5}$

Baryakhtar,+ Snowmass'21 CF3

DM in (extreme) astrophysical environments



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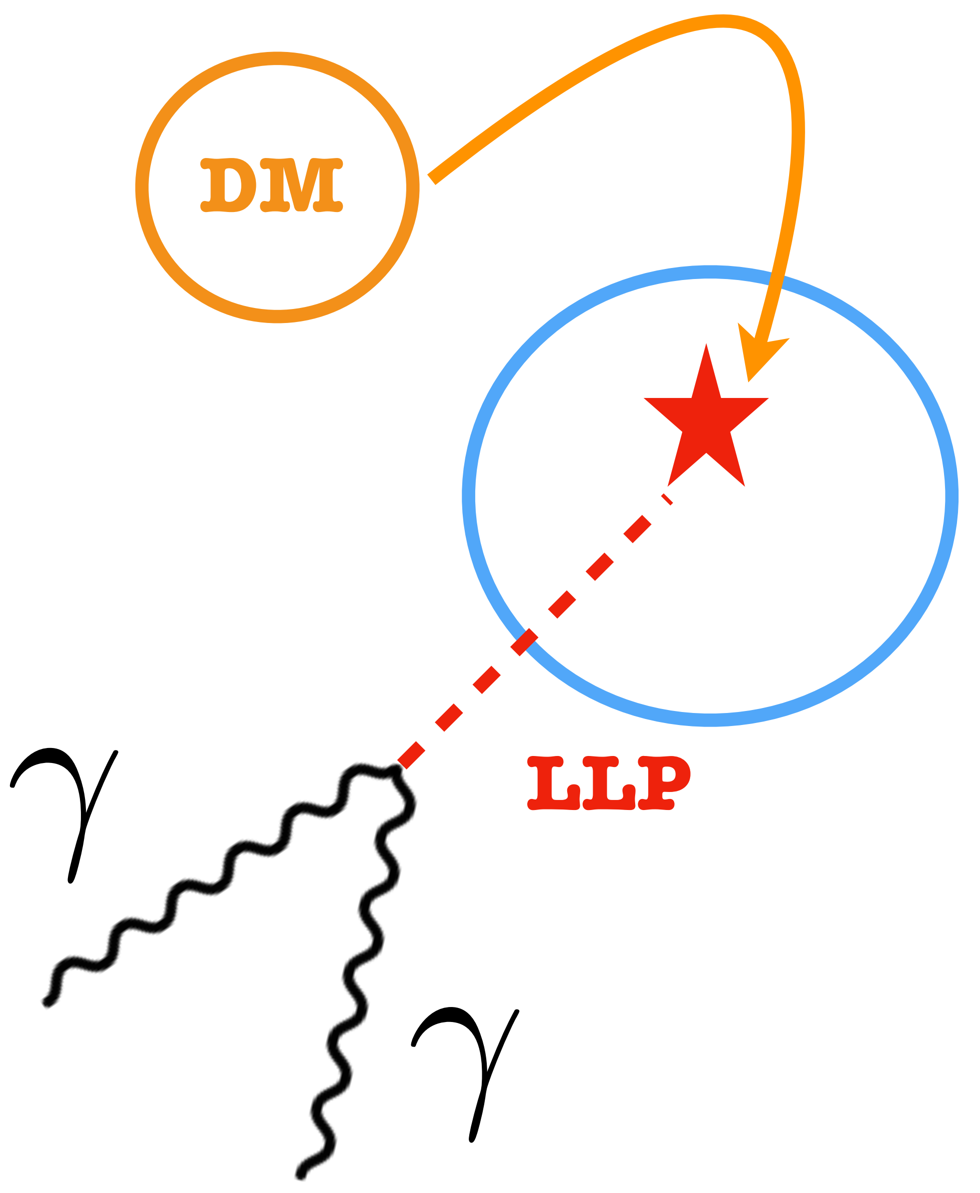
Baryakhtar,+ Snowmass'21 CF3

DM capture in celestial bodies



Steigman+ 1978
Press & Spergel 1985
Gould 1987
Griest, Seckel 1987

$$\frac{dN_\chi(t)}{dt} = \mathcal{C} - \mathcal{A}\, N_\chi^2(t) - \mathcal{E}\, N_\chi(t)$$

Capture $\sigma_{\chi N}$
Gravitational capture and thermalisation

Annihilation $\langle \sigma v \rangle$

$\chi\chi \to \phi\phi$

Evaporation
If DM too light, scattering of thermalised particles boosts DM to speed higher then escape velocity

If **evaporation not efficient** and **object old enough**

$$N_\chi \simeq \mathcal{C}\, \tau_{\rm eq} = \sqrt{\mathcal{C}/\mathcal{A}}$$

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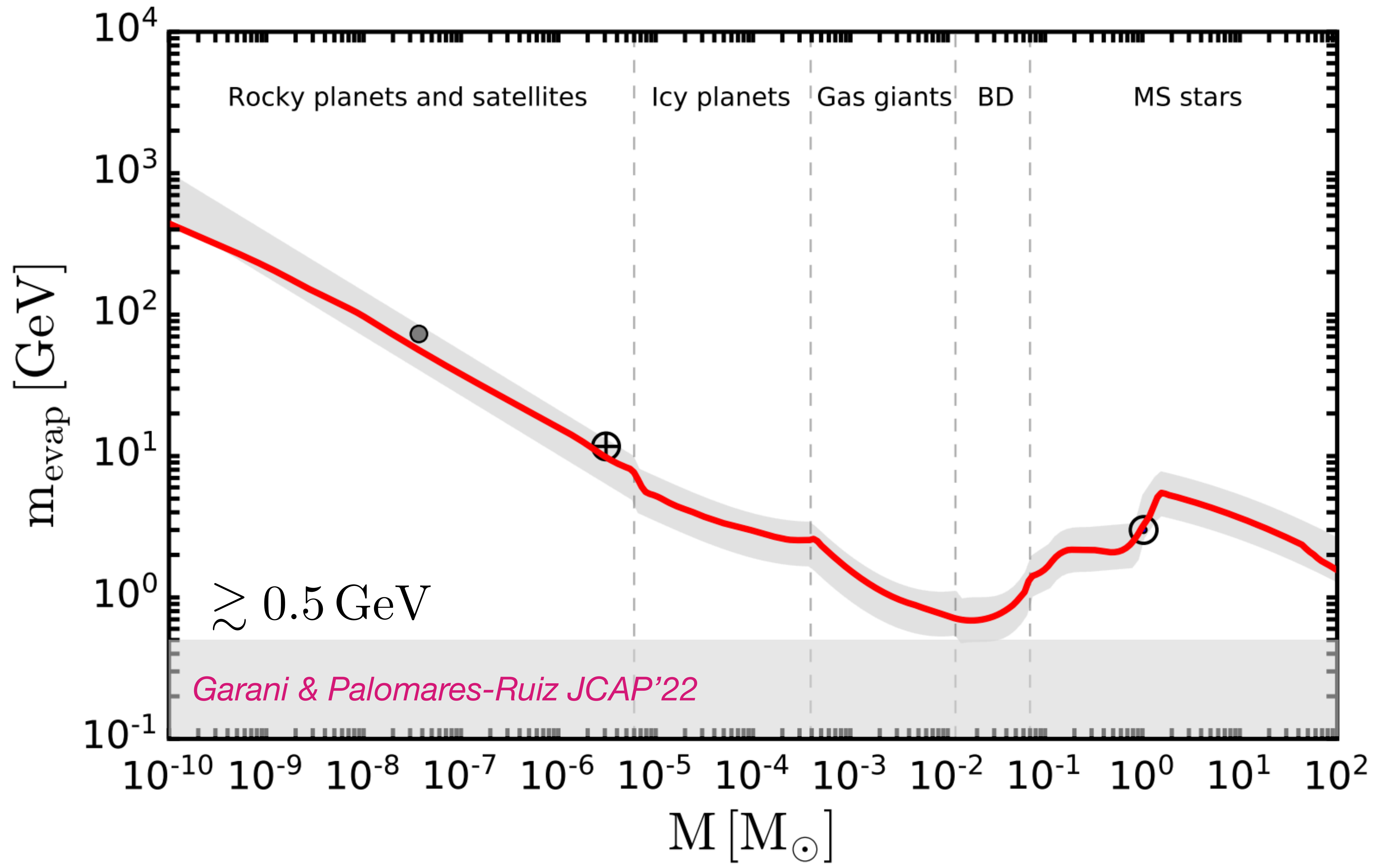


Evaporation sets a **lower limit of DM mass** for which these **bounds are valid**!!

Optimal targets?

* Large radius => More DM captured
* High density => Easier to trap DM
* Cold temperature => Low kinetic energy to DM particles

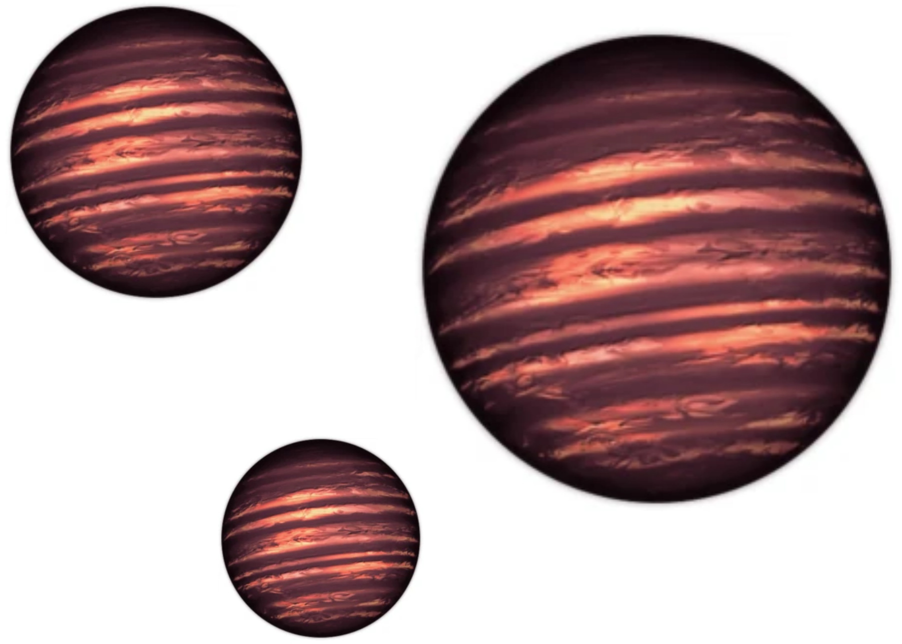
Brown dwarfs (BDs):
Big, Cold, Dense!

+ Large statistics (> 800 objects within 100 pc)
+ Very nearby (closest at 2 pc)
+ Up to 10^9 objects expected in the GC

Leane+ PRD'21

Sun (*Leane+ PRD'17, 18*) and Jupiter (*Leane & Linden PRD'21*)

Gamma-ray signals from know BDs



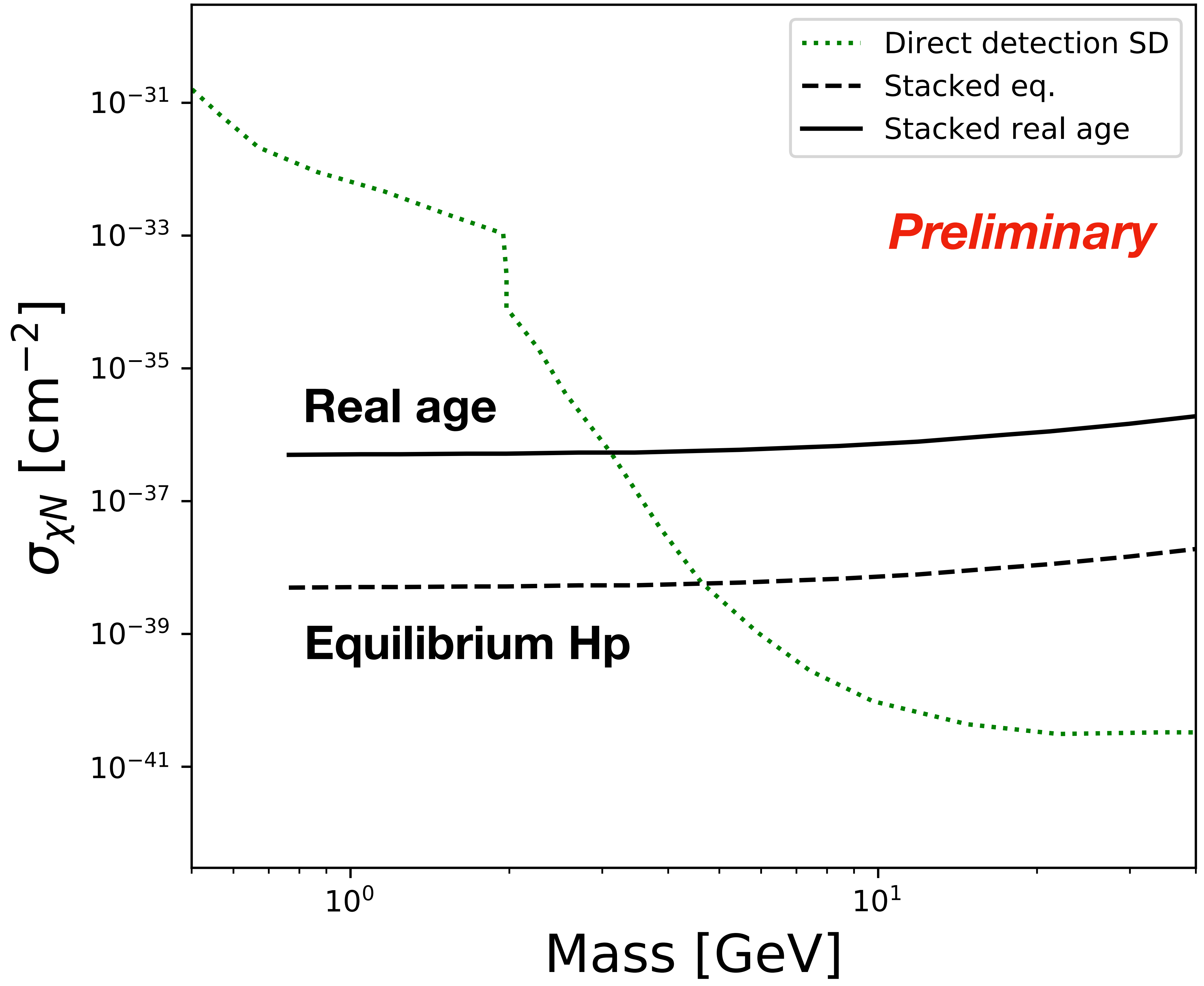
Bhattacharjee, FC & Serpico, In prep

* Selection of **9 nearby** (< 10pc), **massive, cold BDs**
* Only BDs with **age estimate (2 - 10 Gyr)**
* Search for gamma-ray point-like excesses in *Fermi*-LAT data
* No excess found => Upper limits on photon flux

$$\chi\chi \to \phi\phi \qquad m_\phi \ll m_\chi$$

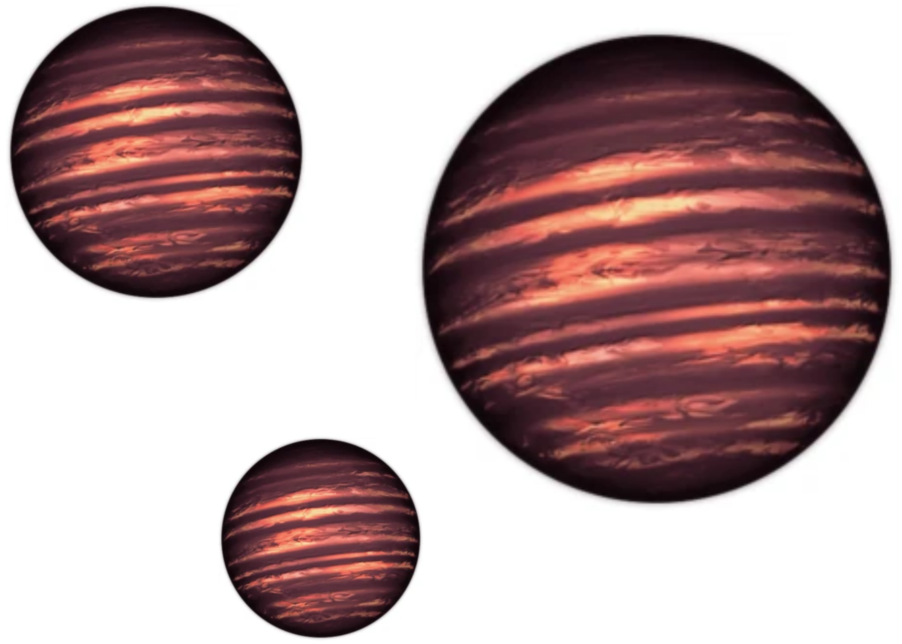
$$\phi \to \gamma\gamma \qquad E^2 \frac{\mathrm{d}\Phi}{\mathrm{d}E} \propto \frac{\mathcal{C}}{4\pi d_\star^2} \times E^2 \frac{\mathrm{d}N}{\mathrm{d}E}$$

$$\mathcal{C} = f(M_\star, R_\star, d_{\mathrm{GC}}, \rho_{\mathrm{DM}}, \sigma_{\chi N})$$



[Lower evaporation mass for *neutron stars* and *white dwarfs* but larger uncertainties on system T and density]

Gamma-ray signals from know BDs



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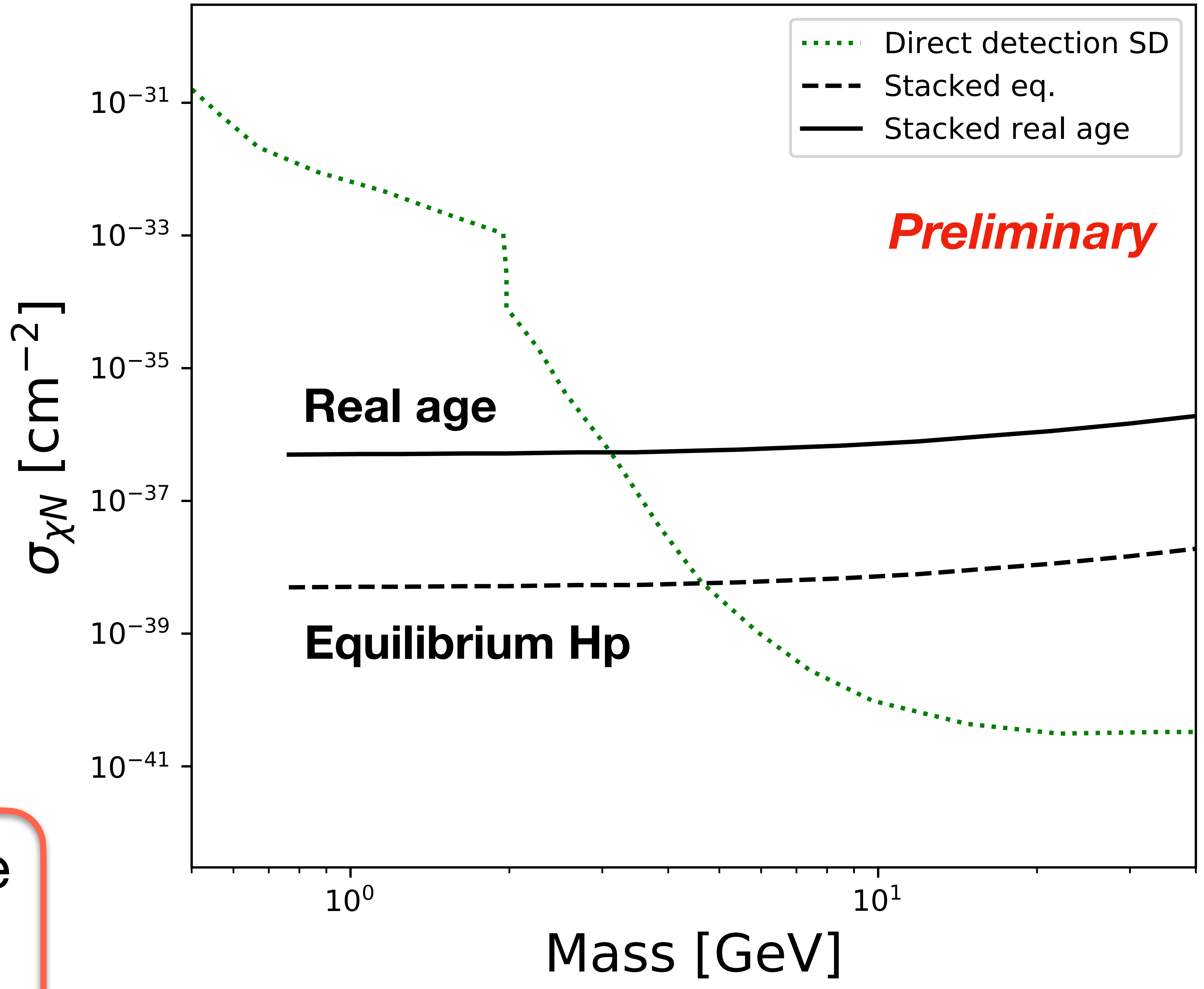

TAKE AWAY: Celestial body capture provides comparable bounds to DM direct detection in sub-GeV mass range. Many more systems to be discovered with JWST!

Conclusions & Outlook

- ✓ **Indirect searches** for dark matter **successfully test different dark matter (and FIP) models** at the MeV-GeV scale, probing a large portion of their parameter space
- ✓ **Diversified program** to tackle dark matter over a wide spectrum of models and signatures
- ✓ Also **lighter FIPs** (ALPs, sterile neutrinos) can be looked for with **indirect detection probes,** from radio wavelengths to very high-energy gamma rays
- ✓ The most urgent (*experimental*) need is the exploration of the **MeV gap** with future instruments, which can provide **access to yet uncharted portions of the DM parameter space** and **new windows of opportunity for dark matter detection**!

Apply to join the WGs on the Action webpage
https://www.cost.eu/actions/CA21106/

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COSMIC WISPERS
CA 21106

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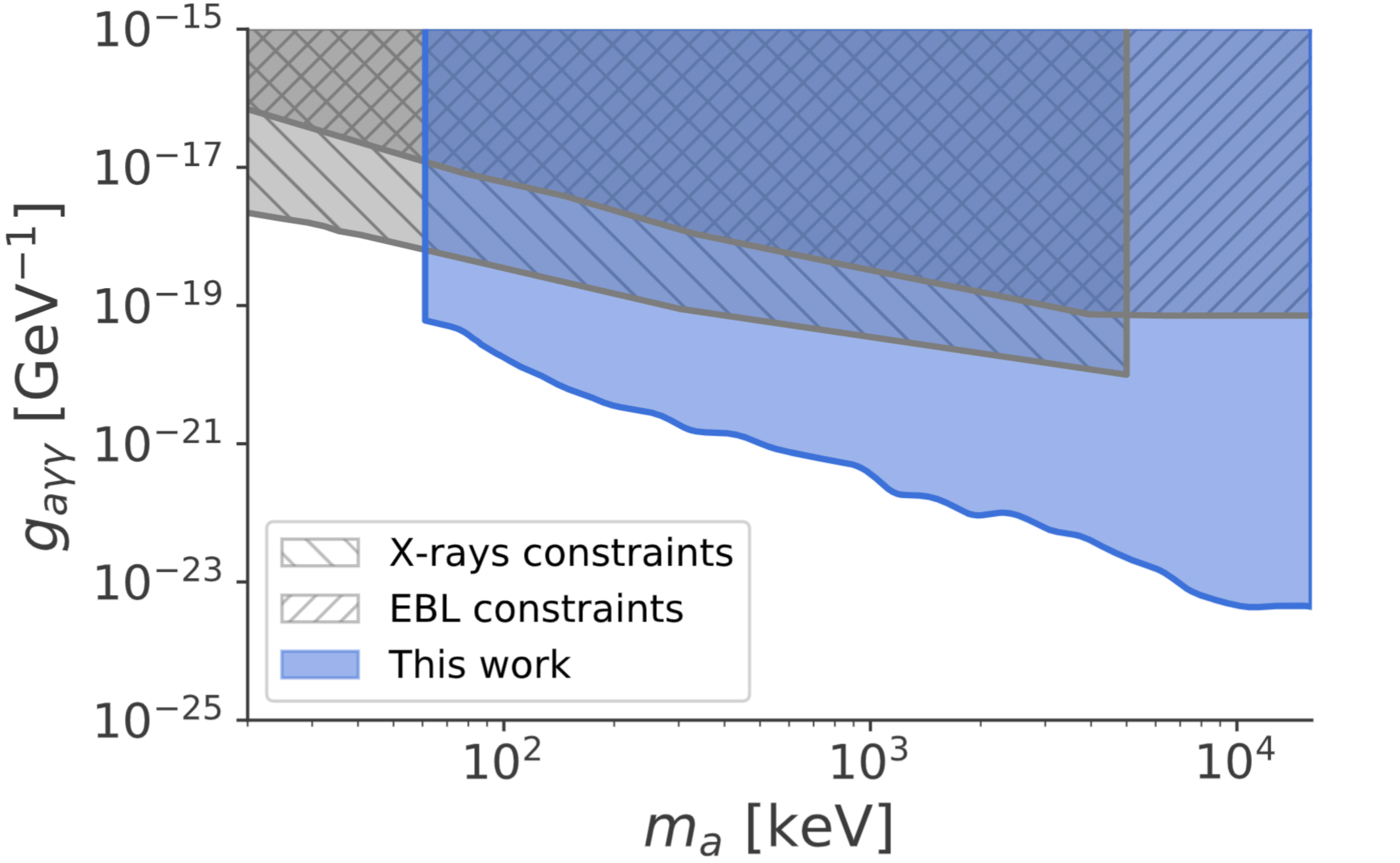
Thank you for the attention

Backup

Limits on feebly interacting particles

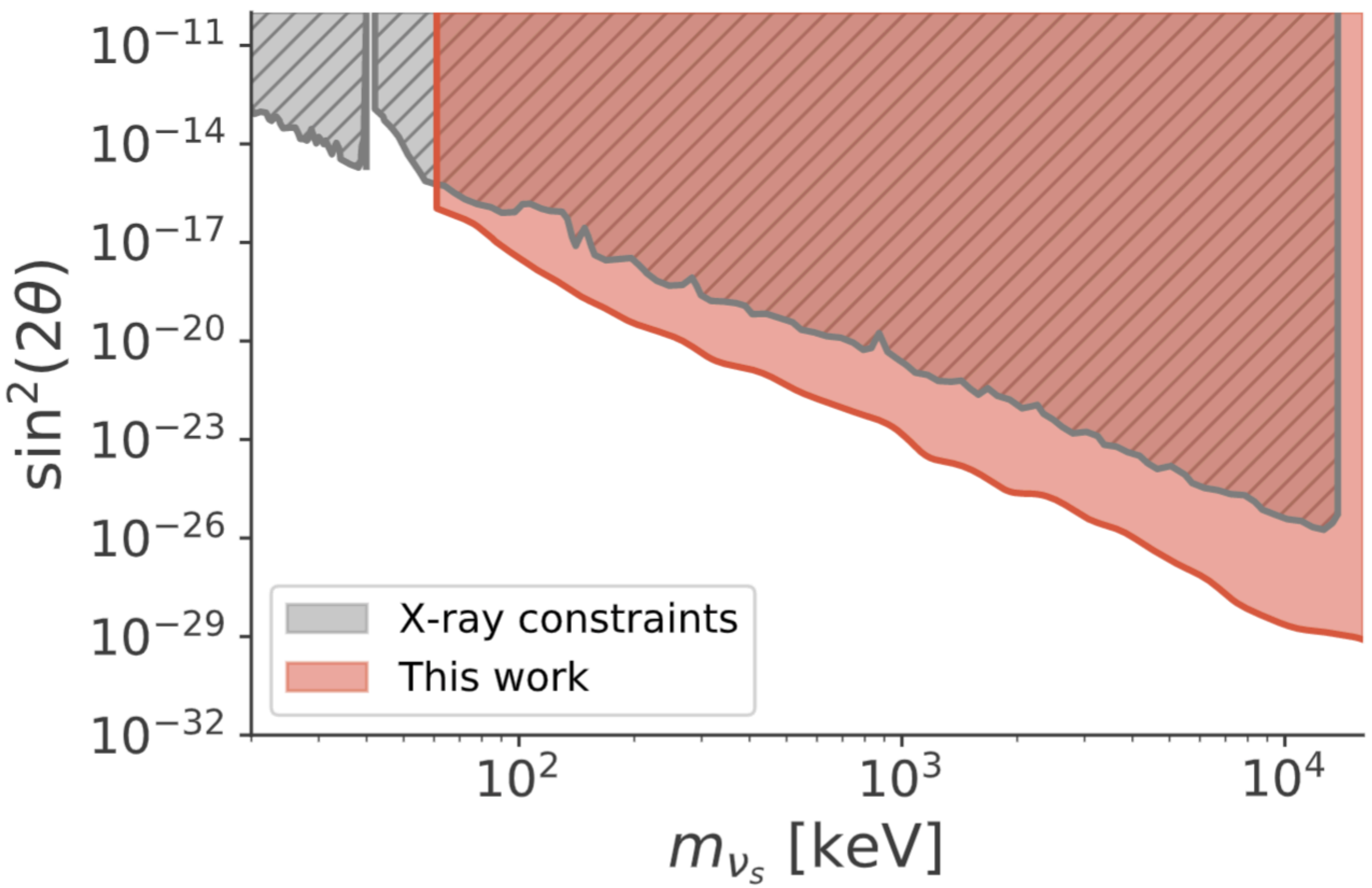
Axion-like particles

$$\Gamma_{2\gamma} = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi} = 0.755 \times 10^{-30} \left(\frac{g_{a\gamma\gamma}}{10^{-20}\,\mathrm{GeV}^{-1}}\right)^2 \left(\frac{m_a}{100\,\mathrm{keV}}\right)^3 \mathrm{s}^{-1}$$



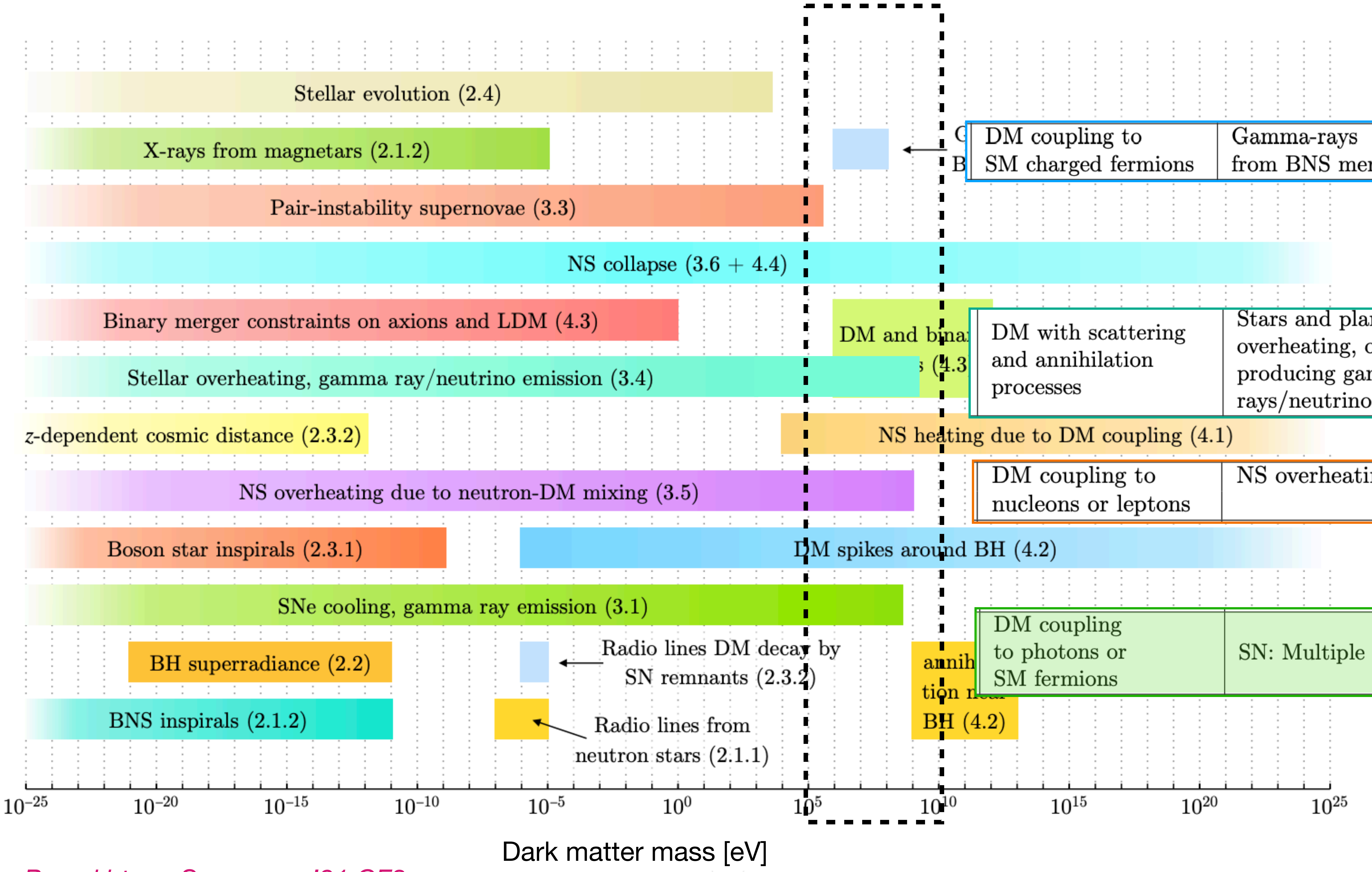
Sterile neutrinos

$$\Gamma_{\nu\gamma} \simeq \frac{9\alpha G_F^2 m_s^5 \sin^2(2\theta)}{1024\pi^4} \simeq 1.36 \times 10^{-29}\ \mathrm{s}^{-1} \left[\frac{\sin^2(2\theta)}{10^{-7}}\right] \left(\frac{m_{\nu_s}}{1\ \mathrm{keV}}\right)^5$$



Dekker, FC+'22 arXiv:2209.06299

DM in (extreme) astrophysical environments



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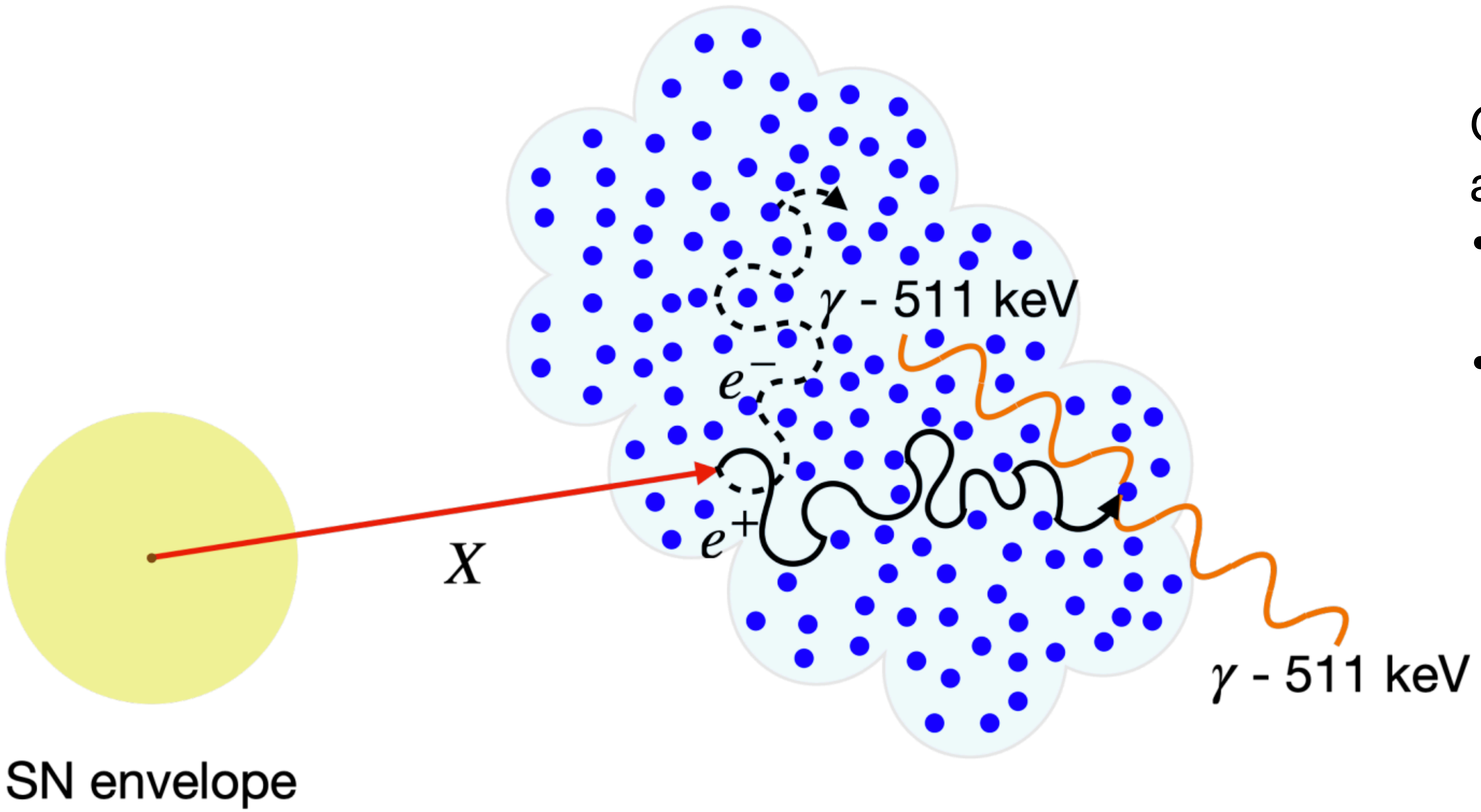
Baryakhtar,+ Snowmass'21 CF3

Constraints on heavy FIPs from CC SNe



General rationale can be applied to all **FIPs** that:

- Can be **produced through mixing with SM particles**
- Have **decay channels with positrons** in the final state

➡ Limits on **heavy ALPs**

➡ Limits on **sterile neutrinos**

➡ Limits on **dark photons**

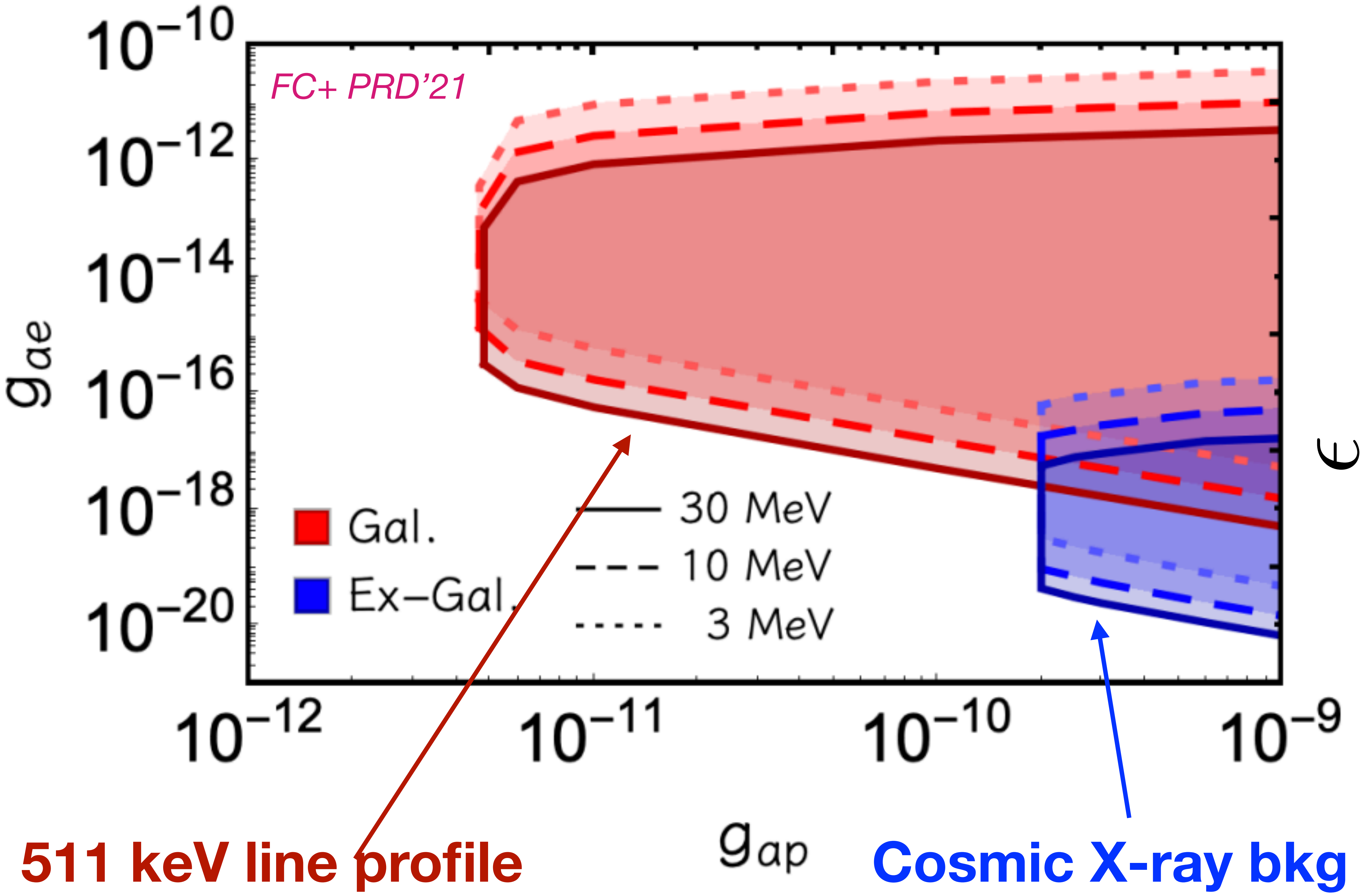
FC+ PRD'21, PRD'22

Dar+ PRL 1987; DeRocco+ JHEP'19

Constraints on heavy FIPs from CC SNe

Axion-like particles

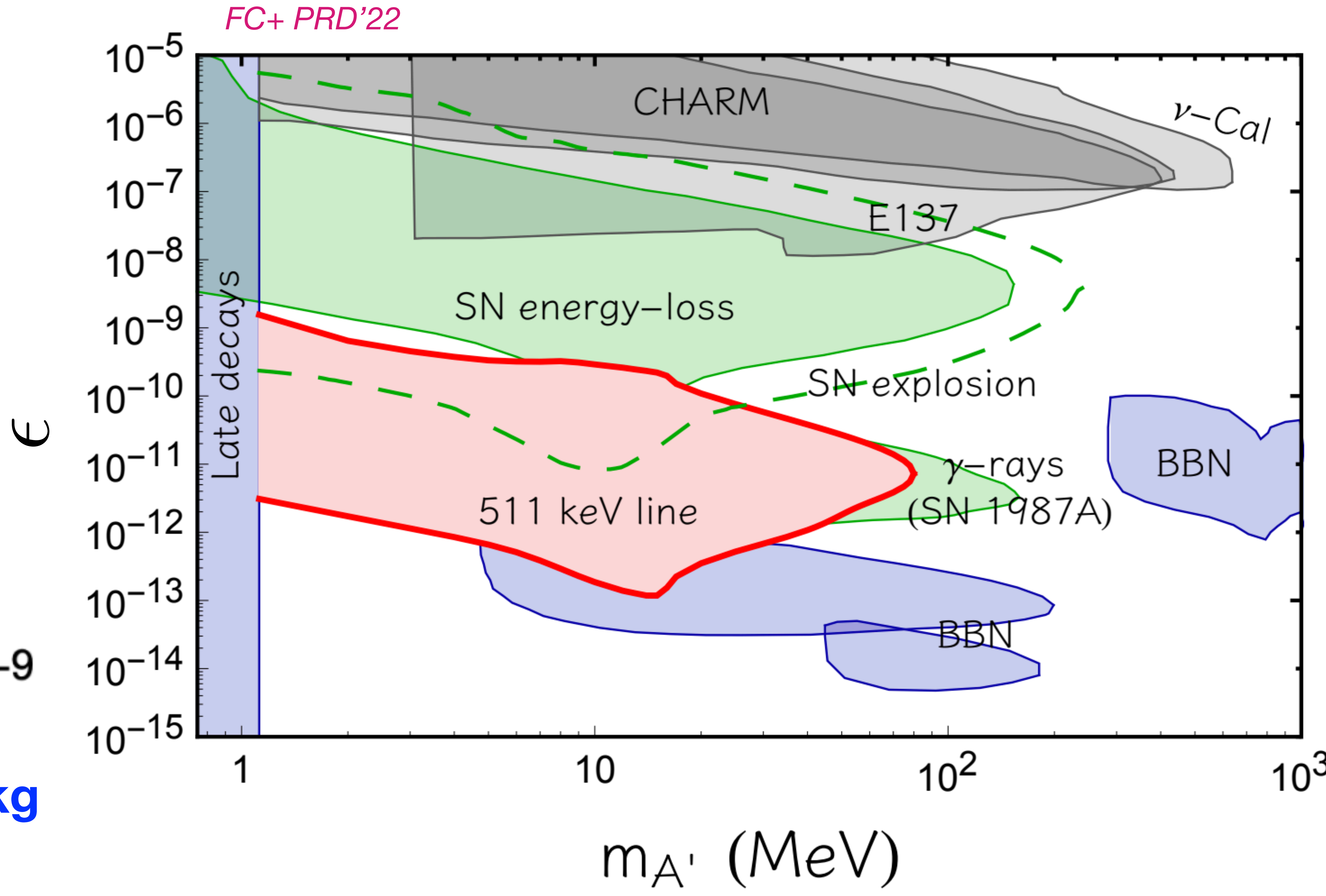
Coupled with nucleons and electrons



511 keV line profile

Cosmic X-ray bkg

Dark photons



Constraints on ALP-photon mixing

GeV - TeV gamma rays

Core-collapse SNe

- Searches for **single SNe** events or cumulative flux from **all past SNe**

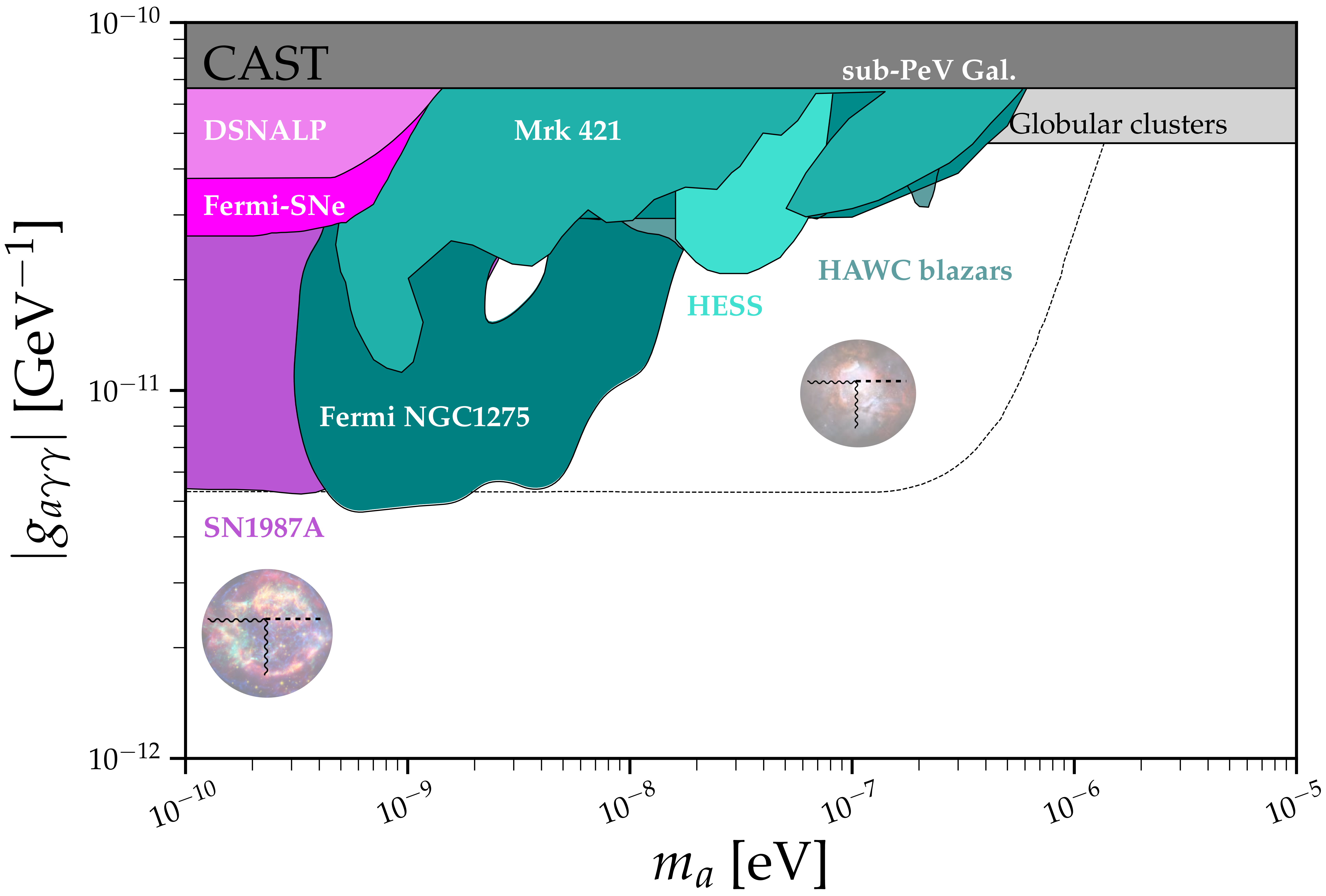
Payez+ JCAP'14; Meyer & Petrushevska PRL'20;
Crnogorcevic+ PRD'21
FC+ PRD'20, Eckner, FC+PRD'22

- MeV to GeV cosmic backgrounds offer a unique window on this production mechanism

High-energy gamma-ray sources

- Search for **spectral distortion** of high-energy Galactic and extra-galactic sources from X- to gamma rays (e.g. NGC1275, Mrk421)
- Search for **photons appearance** from photon-ALPs *in source* conversion (HAWC blazars, sub-PeV Gal.)

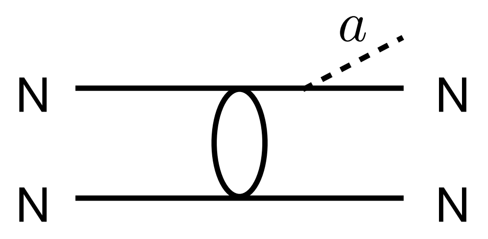
Jacobsen+2203.04332; Eckner&FC PRD'22



https://github.com/cajohare/AxionLimits

Heavy ALPs decay

Constraints from enhanced NN brems



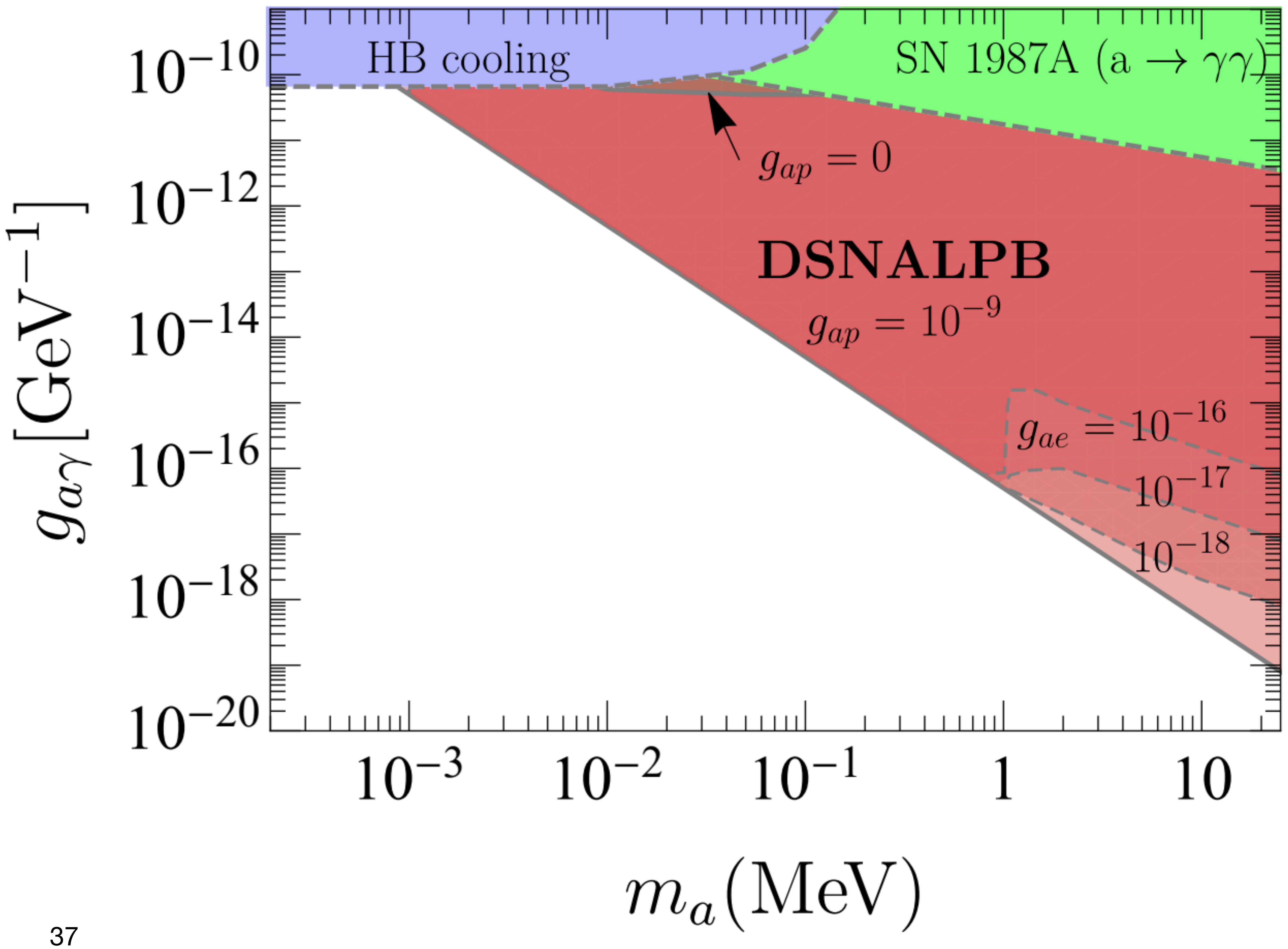
Using **COMPTEL** data (< 30 MeV), strong constraints on heavy *decaying* ALPs (10 - 100 keV) from gamma-ray decay

$$\Gamma_{a\gamma\gamma} = \frac{g_{a\gamma}^2 m_a^3}{64\pi}$$

The decay into e+e- pairs tends to reduce the decay length as well as the total number of photons produced from ALP decays

[See also Caputo+ 2201.09890]

FC+ PRD'20



Constraints on FIPs from CC SNe

Sterile neutrinos and dark photons