European Strategy for Particle Physics

PARALLEL 8 / **DM and DS**

(Ultra-)Light Dark Matter Cosmological and Astrophysical Aspects

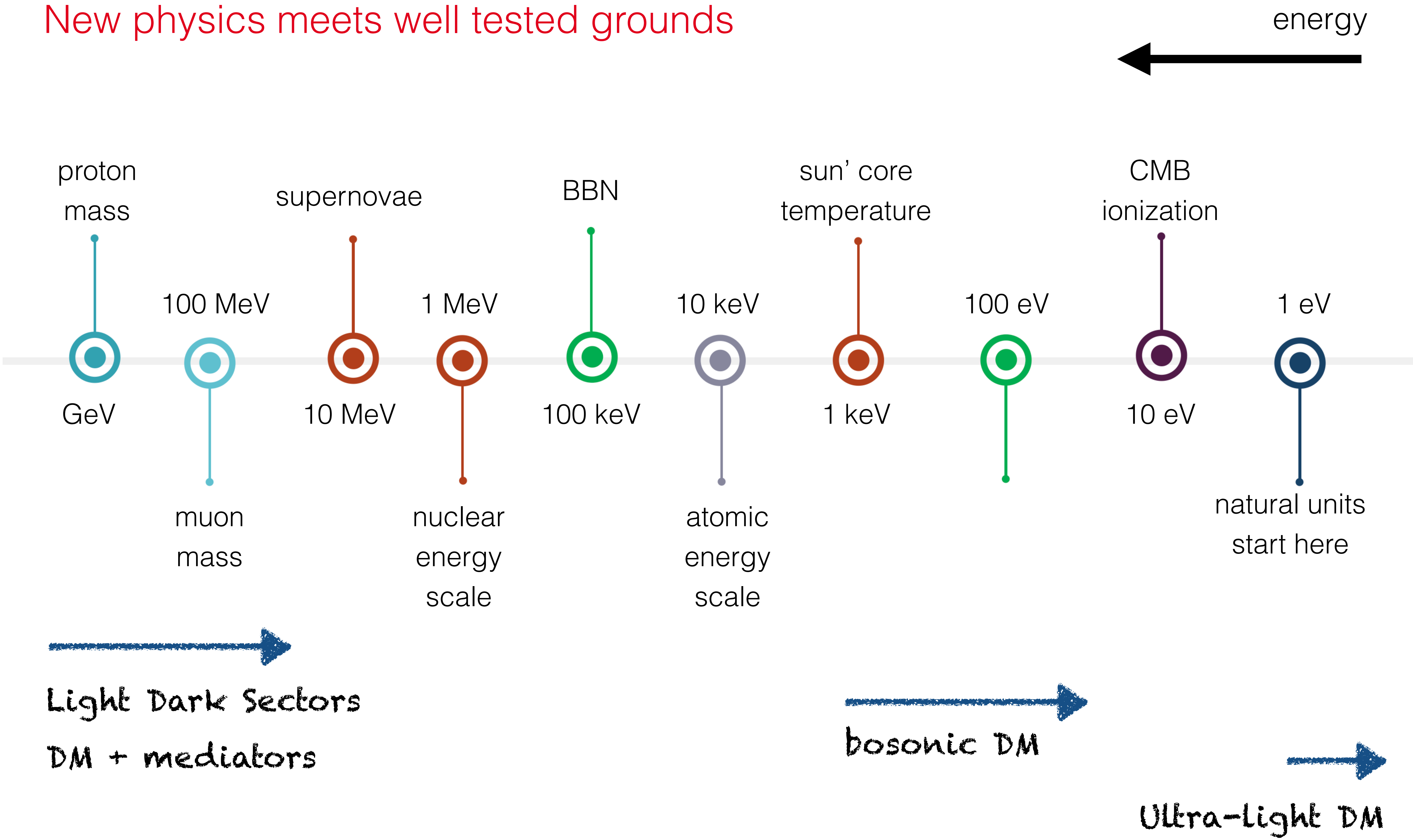
Josef Pradler (University of Vienna and Austrian Academy of Sciences)

Indirect detection

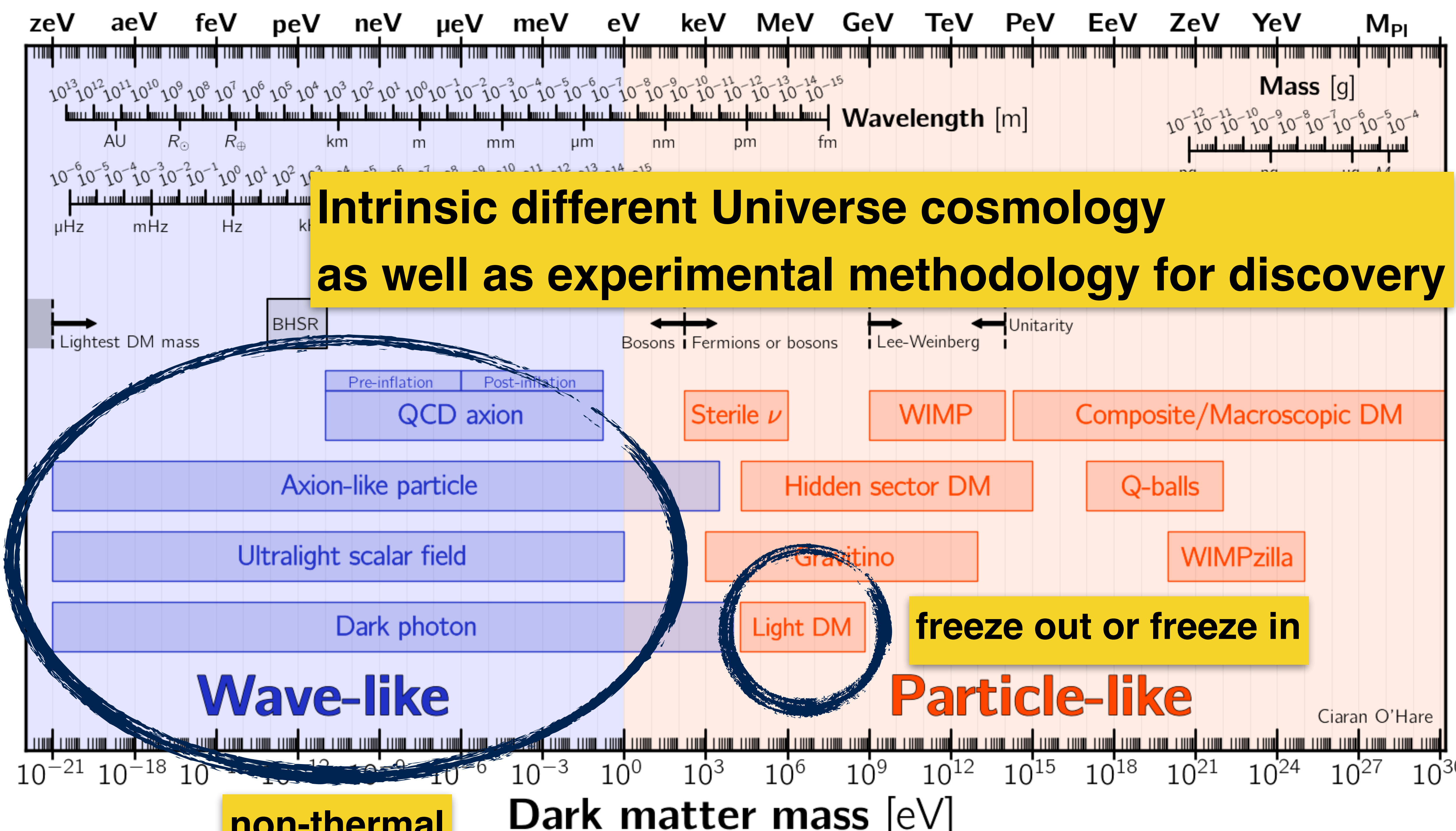
on behalf of Francesca Calore (CNRS-LAPTH)

The BSM danger zone

New physics meets well tested grounds



(Ultra-)Light Dark Matter



Intrinsic different Universe cosmology

as well as experimental methodology for discovery

freeze out or freeze in

non-thermal production

Thermal Light Dark Matter

Early Universe Cosmology - TIMING

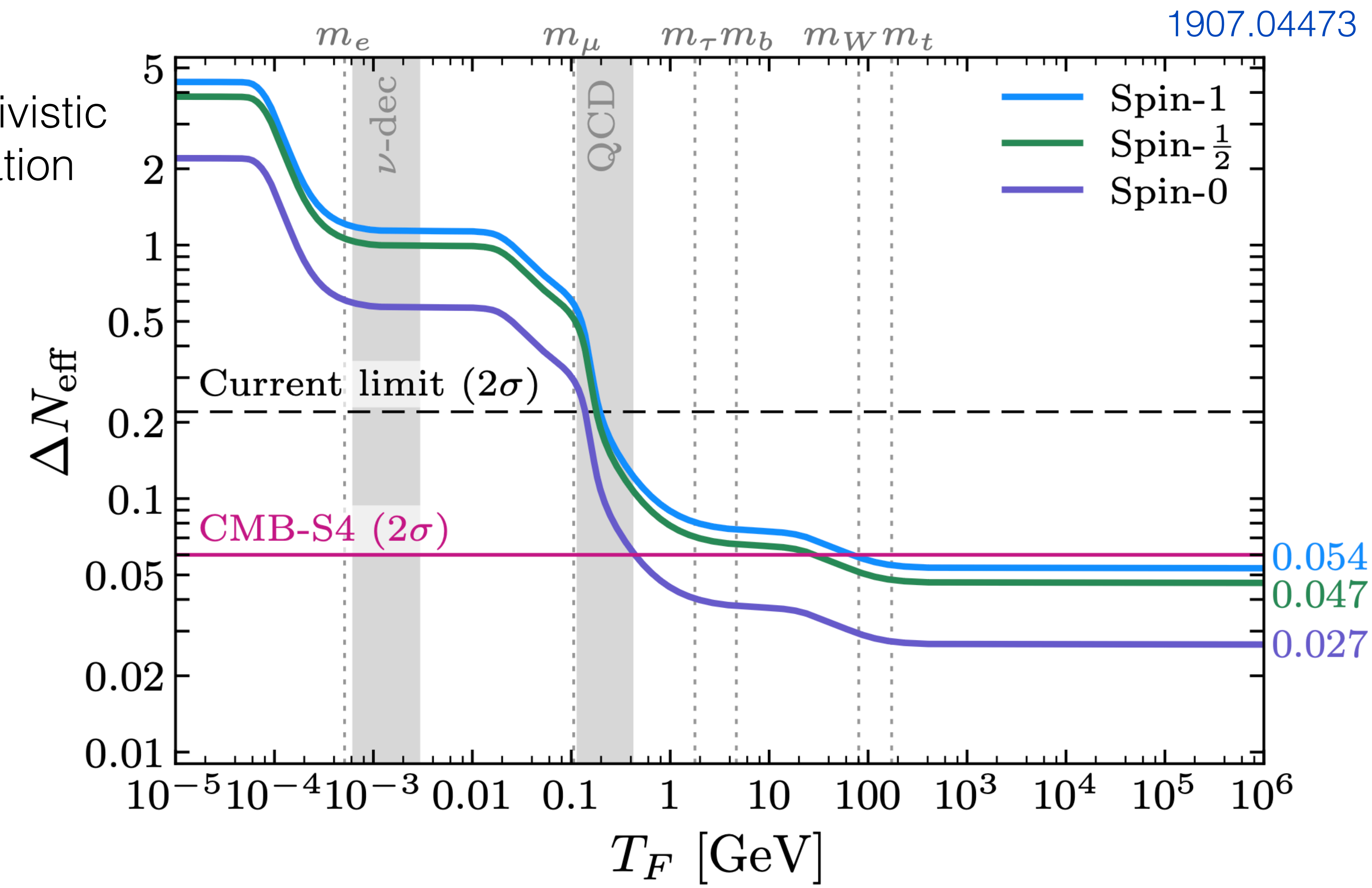
Hubble rate is the Universe's clock

$$H^2 = \frac{8\pi G}{3}\rho_{\rm tot} \quad \longleftarrow \quad \Delta\rho_{\rm dark} = \rho_\gamma \frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\Delta N_{\rm eff}$$

Later freeze out of a relativistic species raises dark radiation energy density

$$\Delta N_{\rm eff} = g_{\rm s}\left(\frac{43/4}{g_\star(T_{\rm F})}\right)^{4/3}$$

CMB-S4 collaboration 1907.04473

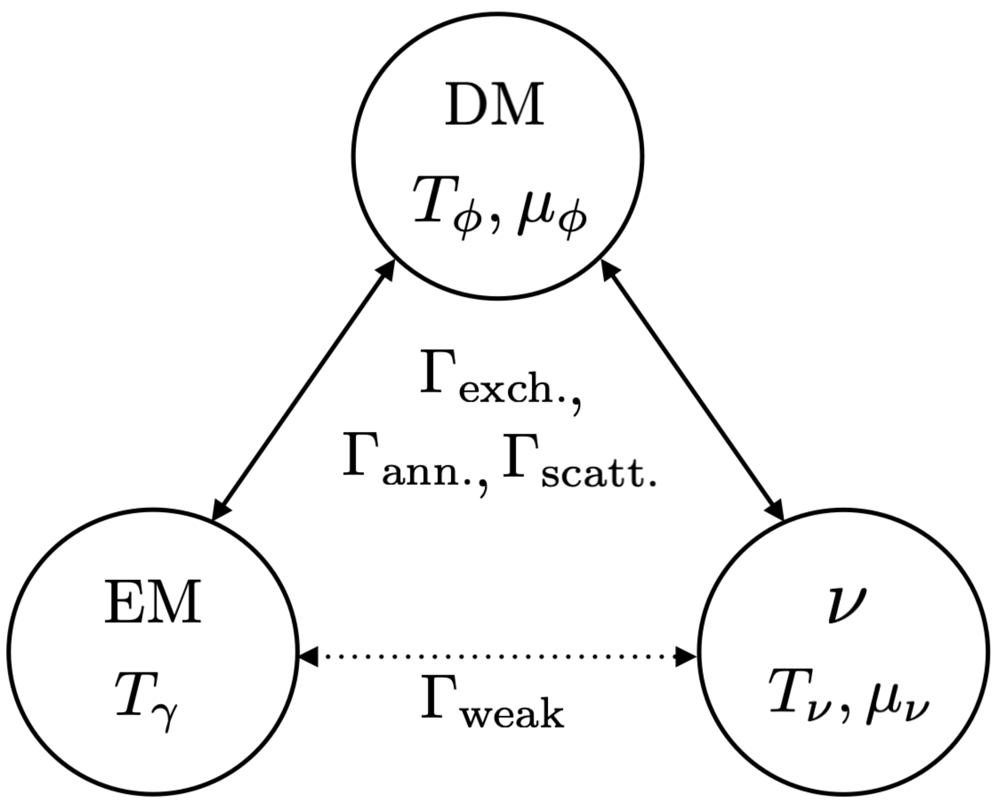


Thermal Light Dark Matter

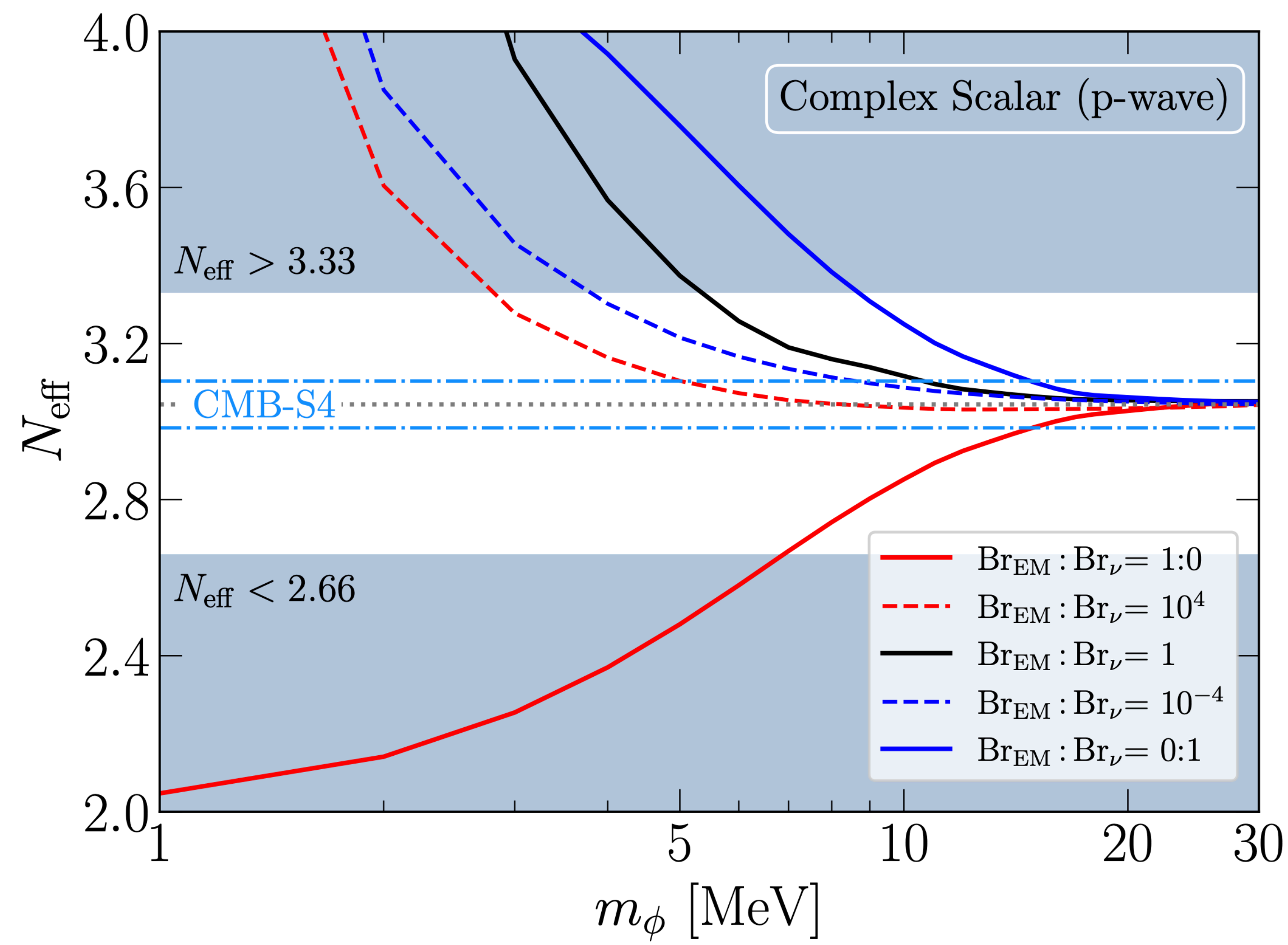
Early Universe Cosmology - TIMING

Hubble rate is the Universe's clock

$$H^2 = \frac{8\pi G}{3}\rho_{\mathrm{tot}} \longleftarrow \rho_{\mathrm{rad}} = \rho_\gamma \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\mathrm{eff}}\right]$$



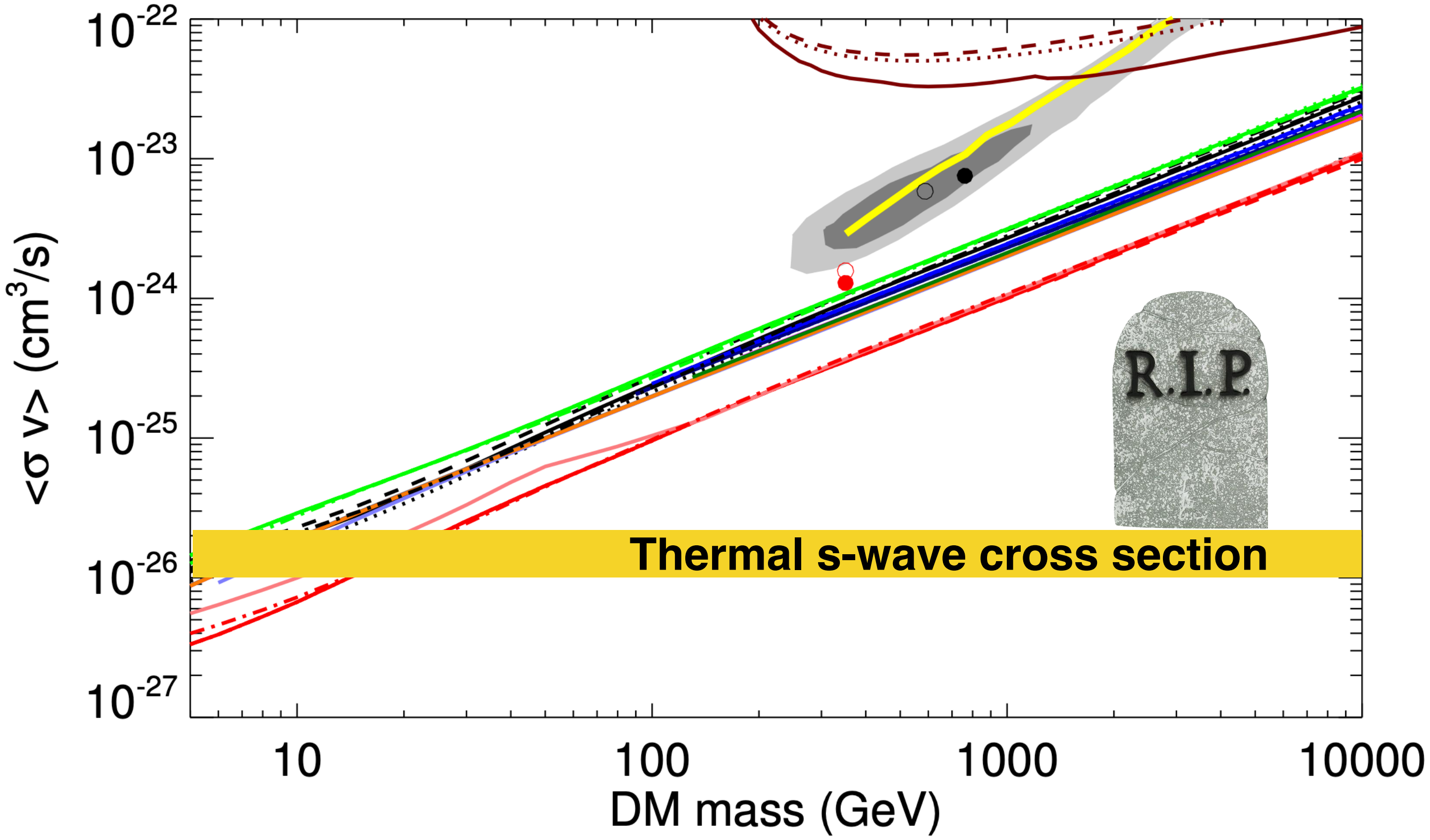
=> few MeV is an absolute lower bound on thermal DM annihilating to SM particles only

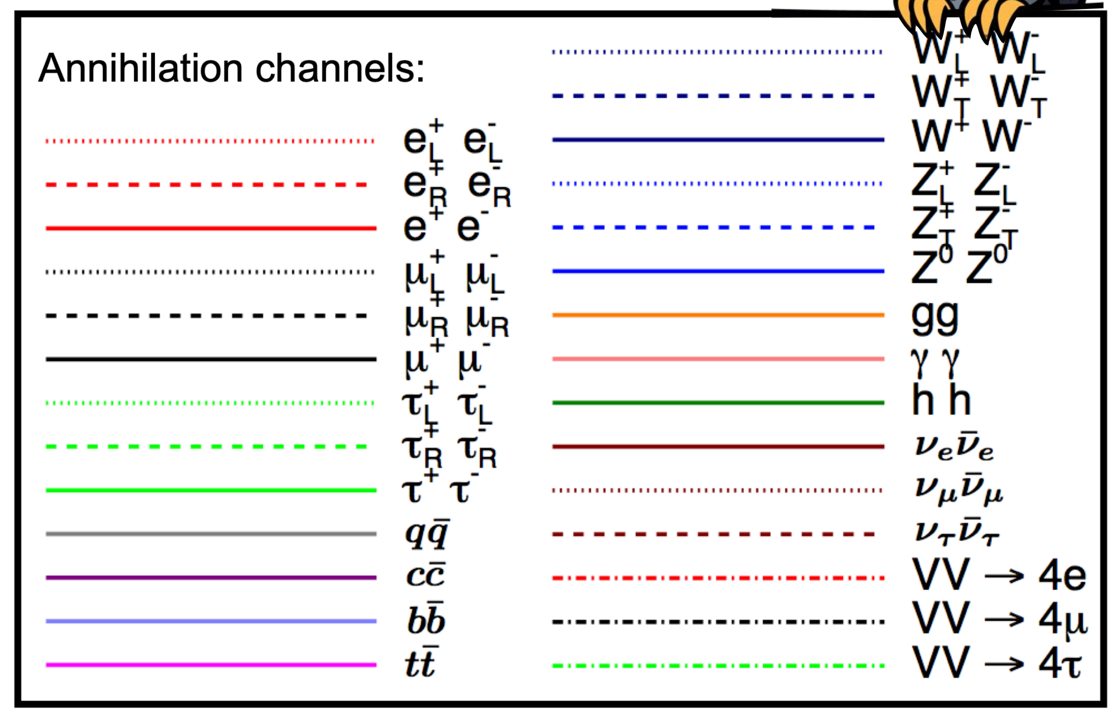


Chu, Kuo, JP 2205.05714 , Chu, JP 2310.06611

Thermal Light Dark Matter

Early Universe Cosmology - ENERGY INJECTION





Slatyer 1506.03811

S-wave thermal DM ann. into charged SM at CMB epoch with mass below 10 GeV excluded

=> **p- or higher wave** ann. (=velocity suppressed) perfectly viable (e.g. complex scalar with Z')

=> **freeze-in** avoids any energy-injection constraints from BBN, CMB, 21cm

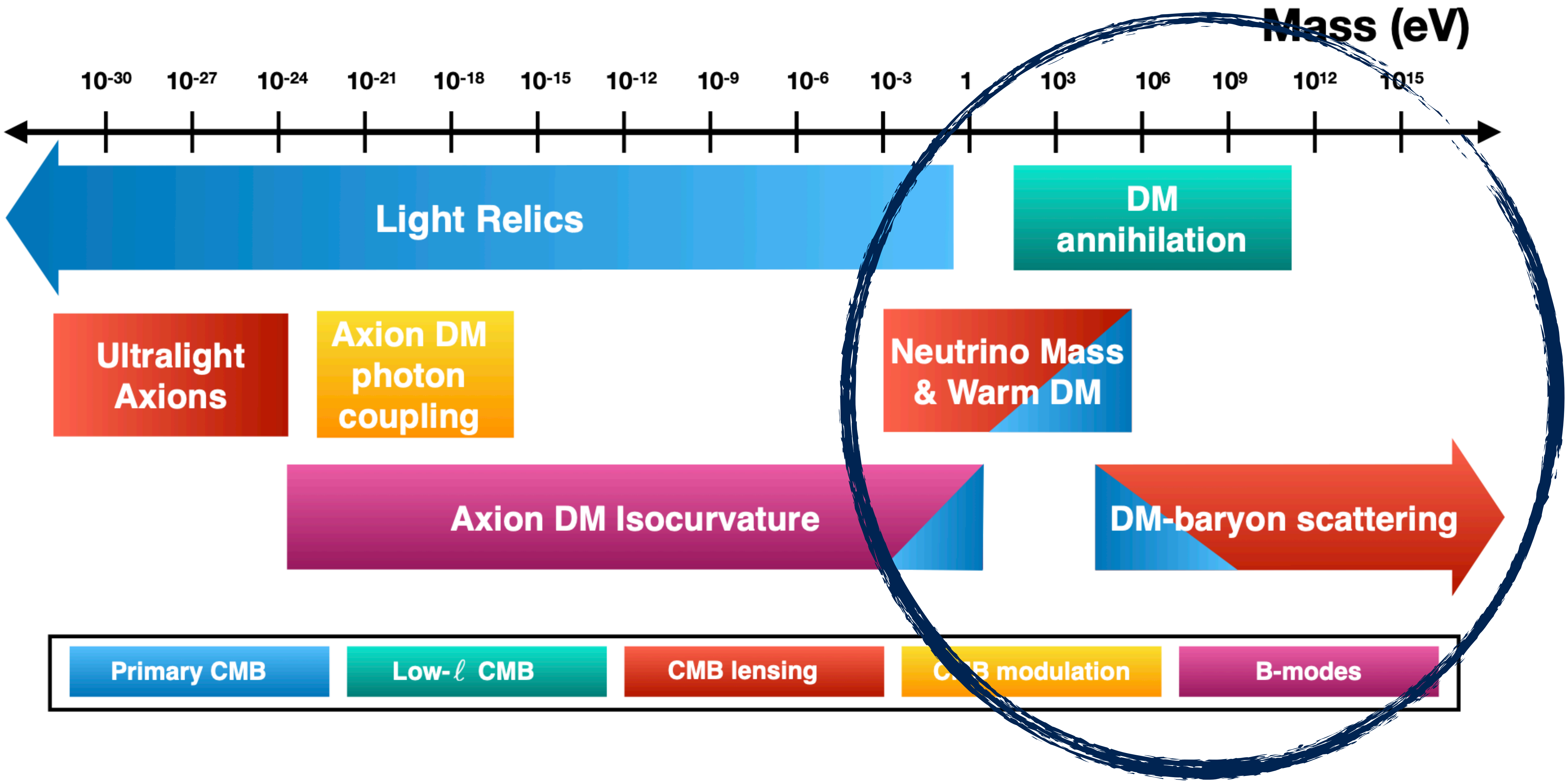
=> DM mass-depletion in the hidden sector (e.g. SIMPs)

=> many possibilities for making viable LDM

Broader CMB sensitivity

Rich science program associated with (ultra-)light DM

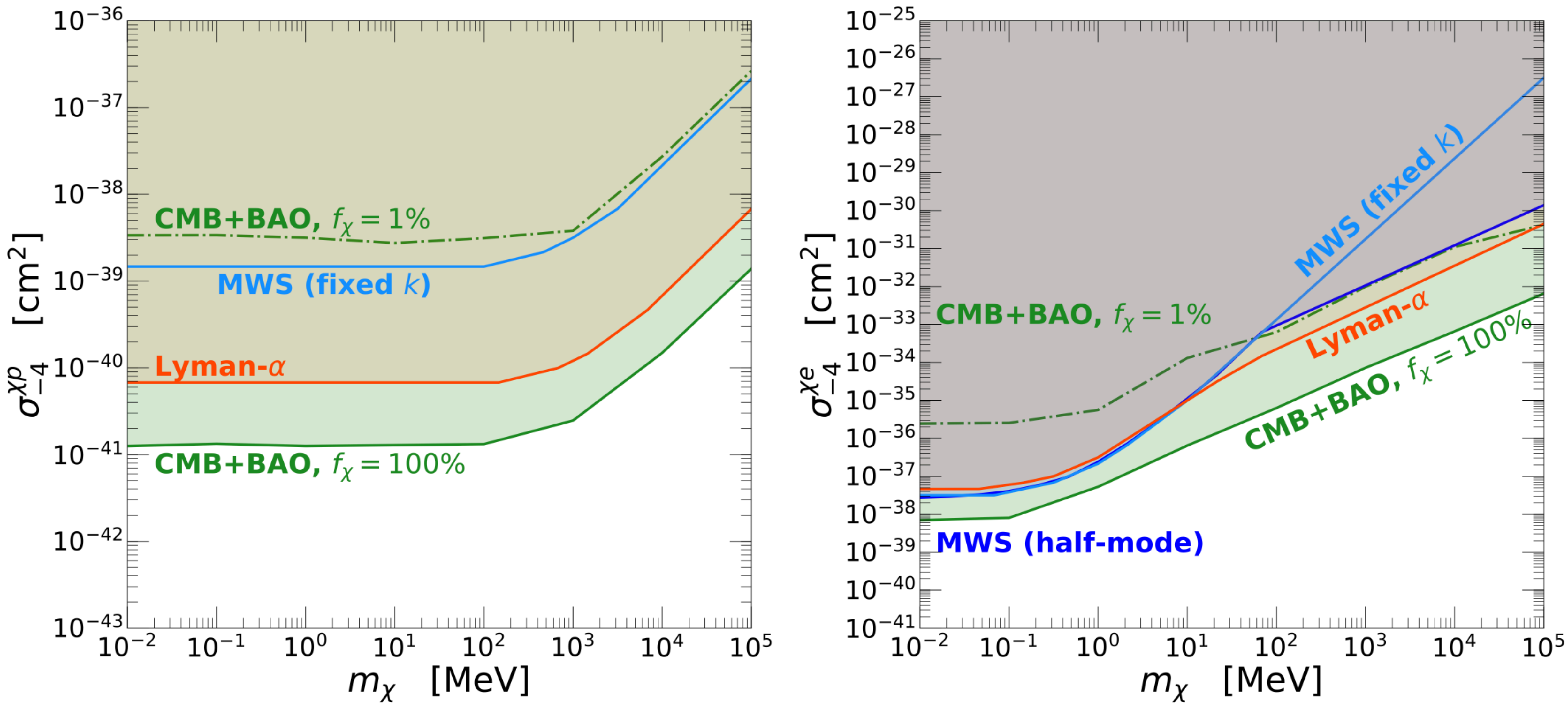
CMB-S4 collaboration
1907.04473



Limits from CMB & structure formation

Elastic DM - proton or electron scattering

e.g. Rutherford-type scattering, realized through very light dark photon mediator

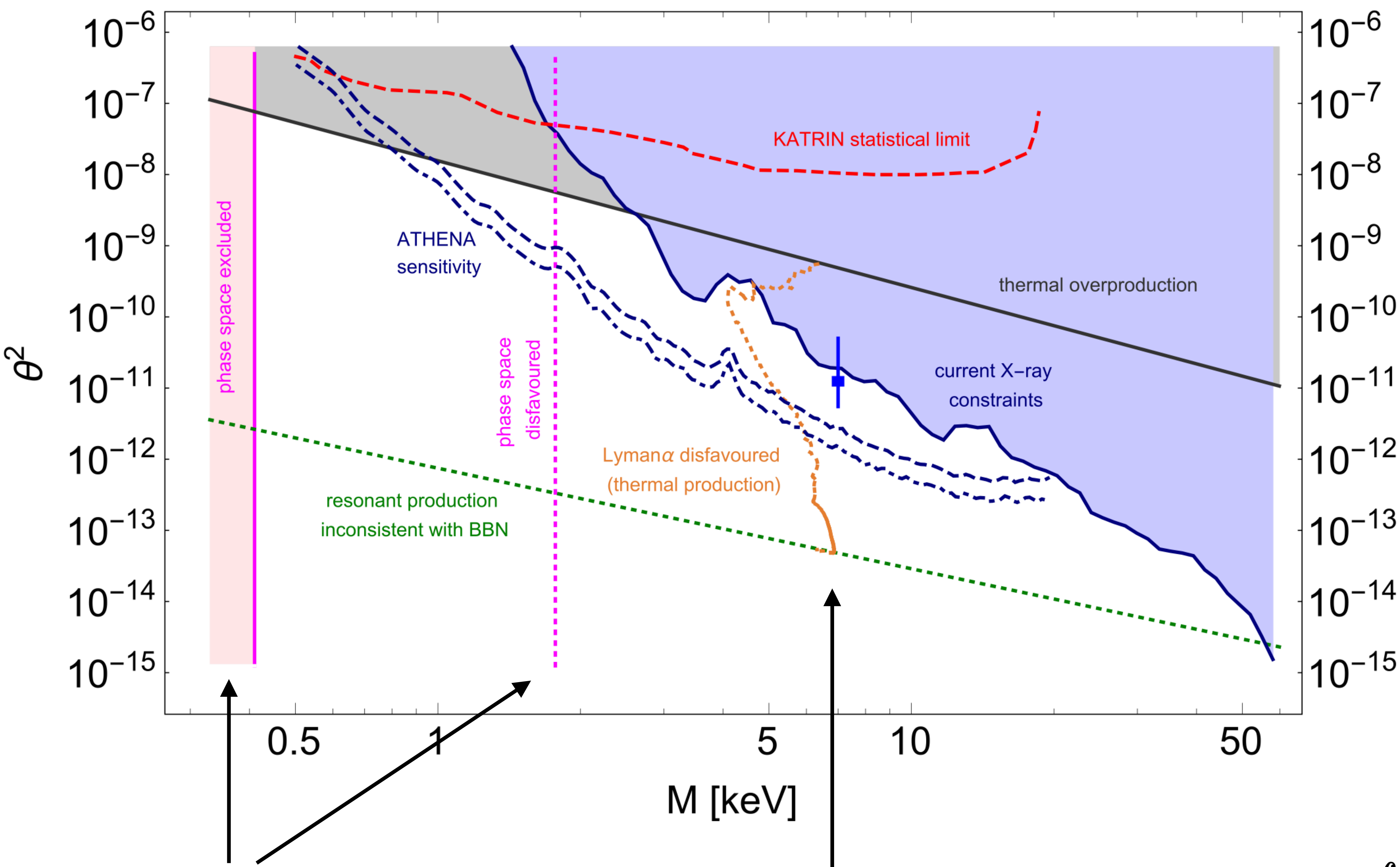


Buen-Abad+ 2107.12377

Limits from structure formation

Sterile neutrinos as warm dark matter

Boyarsky+ 1807.07938



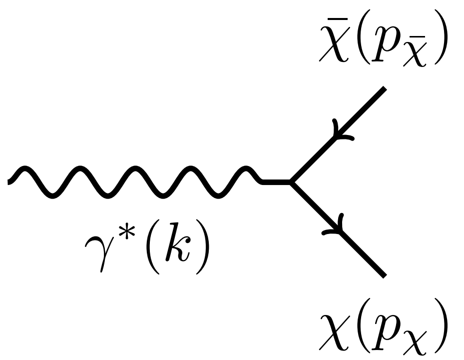
Phase space limit
(details matter)

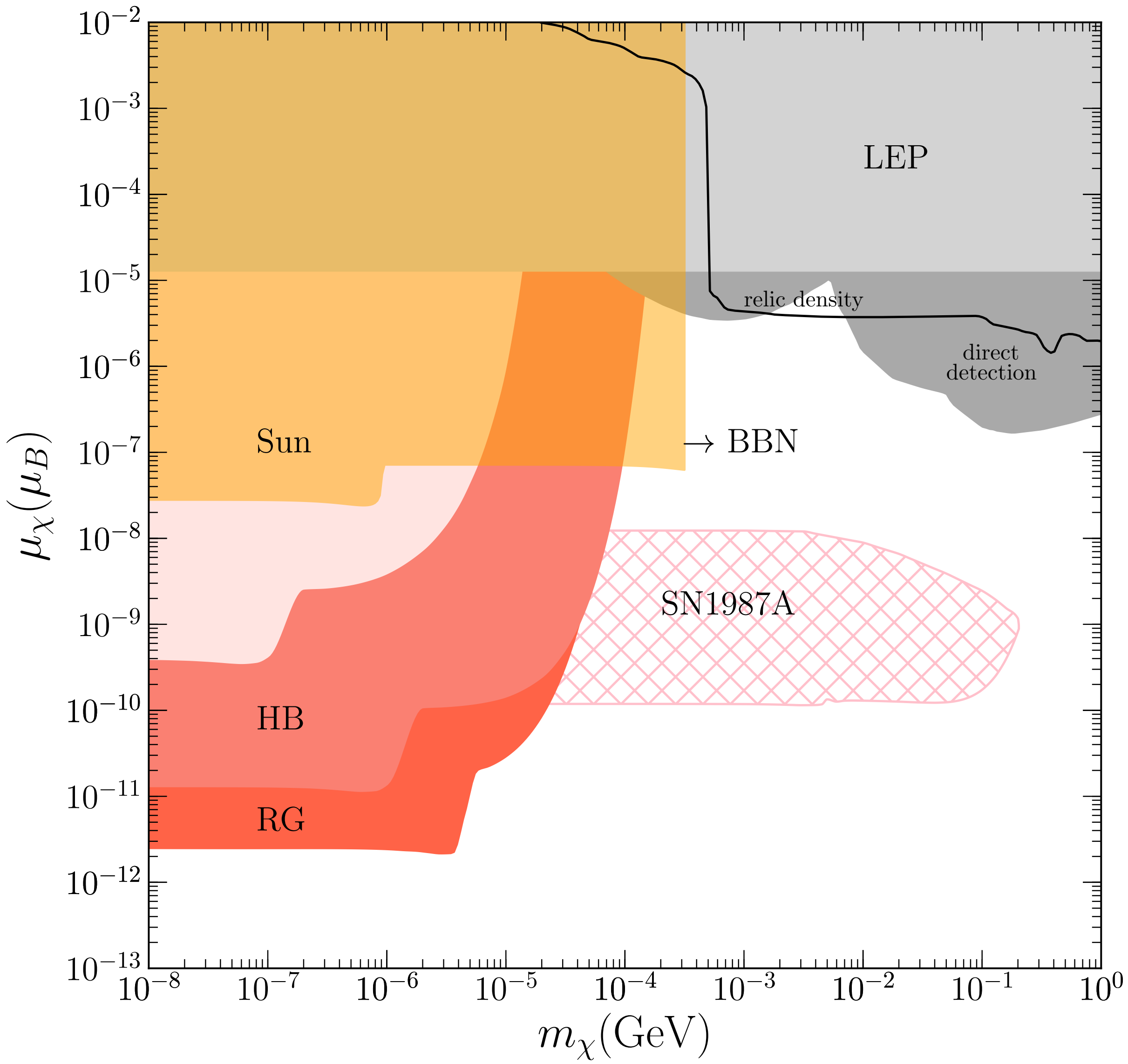
Free streaming bound
(details matter)

$$\lambda_{\rm fs}(t) \equiv a(t) \int_{t_i}^{t} dt' \, \frac{v\,(t')}{a\,(t')}$$

Astrophysical aspects I

15 years ago: stellar energy loss was the only game in town



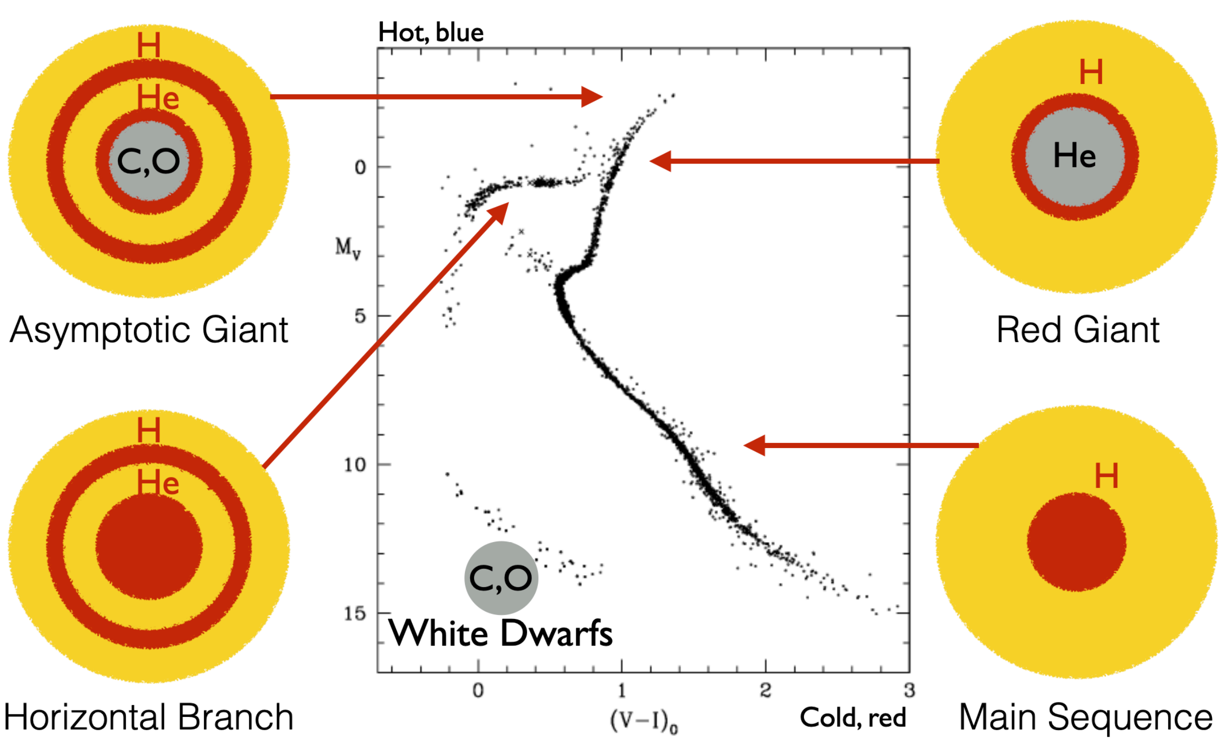


e.g. Chu+ 1908.00553, 2303.13643

Dark state production alters stellar evolution as soon as kinematically accessible

Supernova bound < O(100) MeV

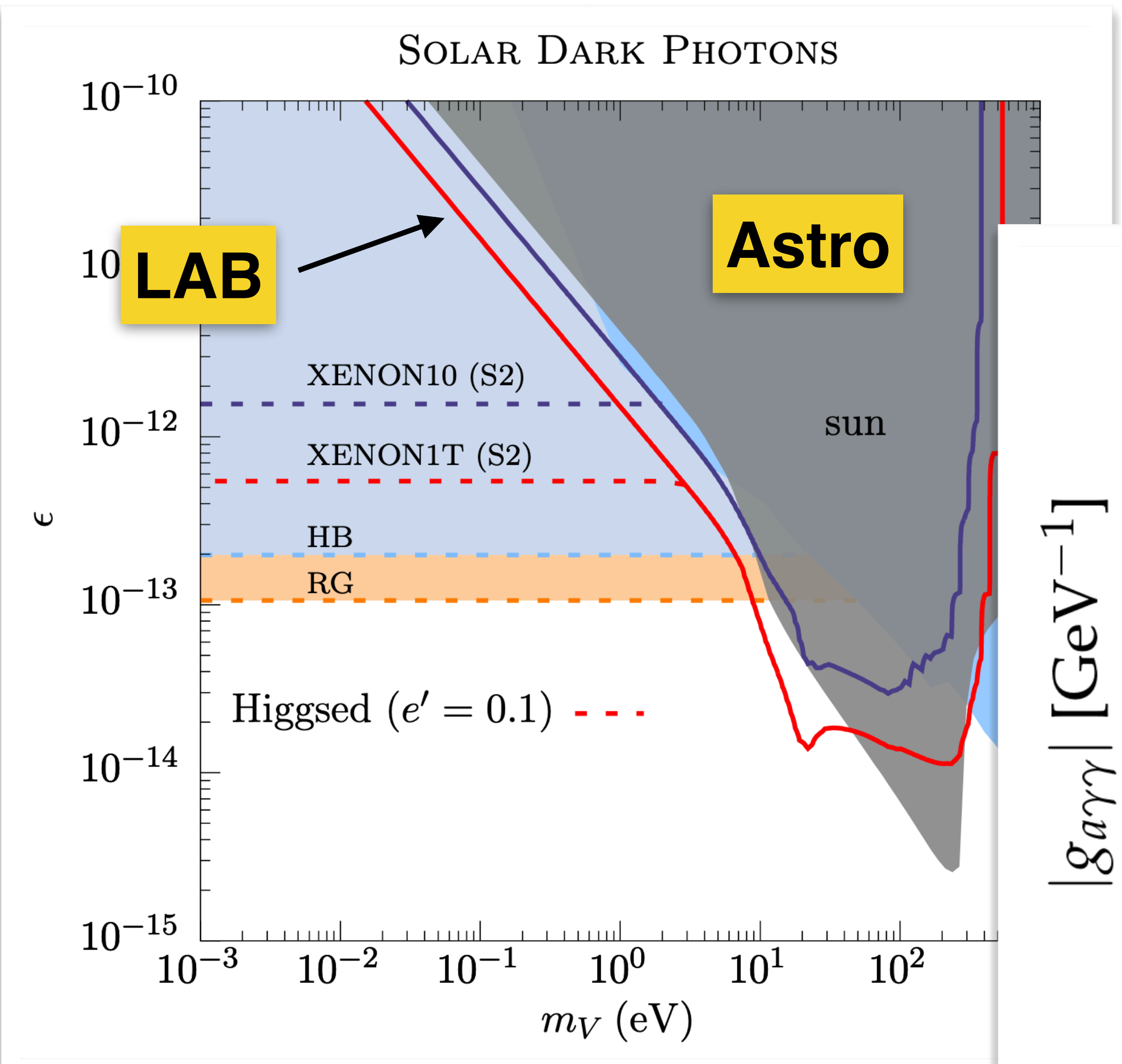
Stars < O(100) keV



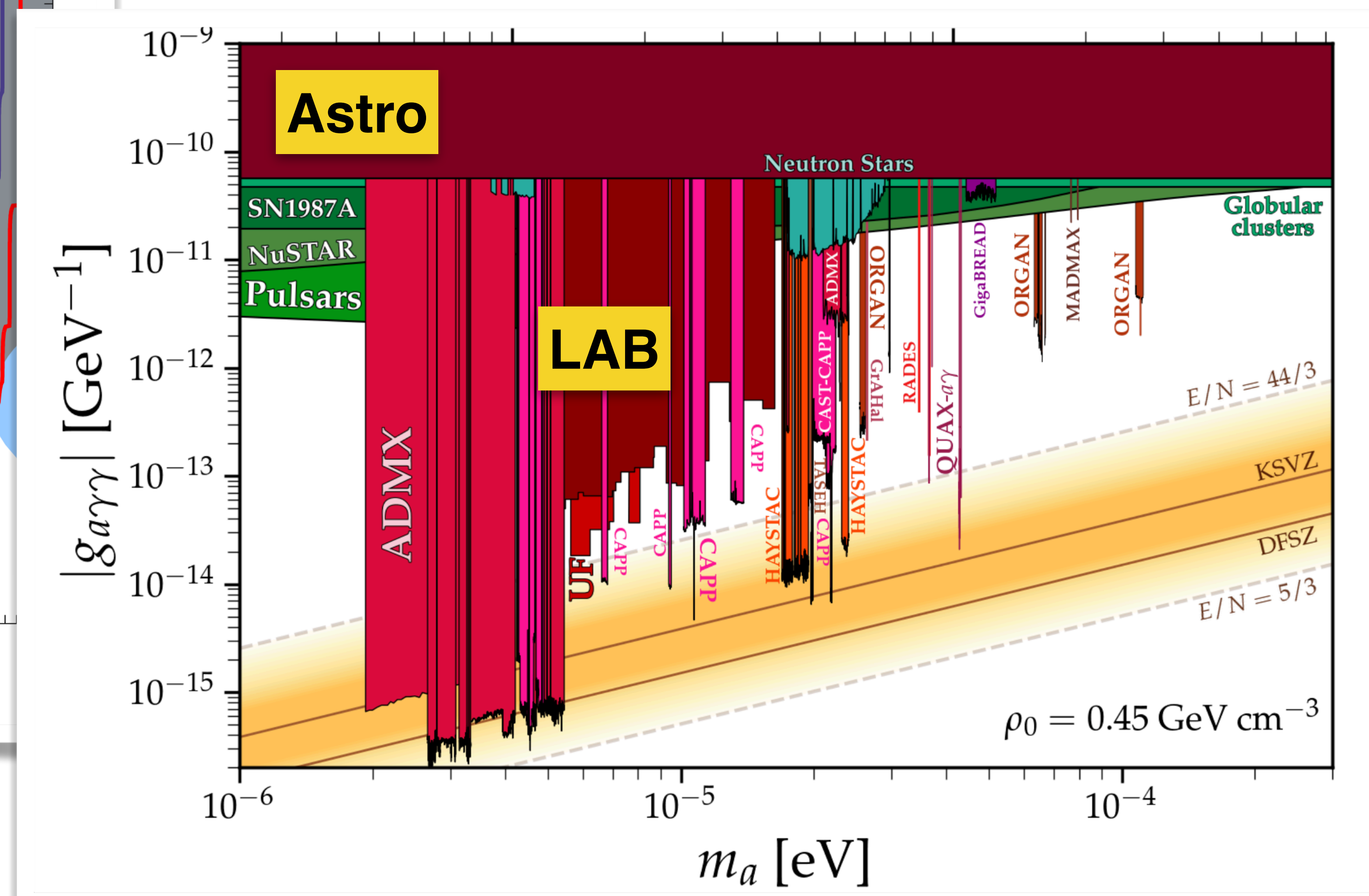
Globular Cluster color-magnitude diagram

Astrophysical aspects I

Today: laboratory tests beat stellar energy loss constraints



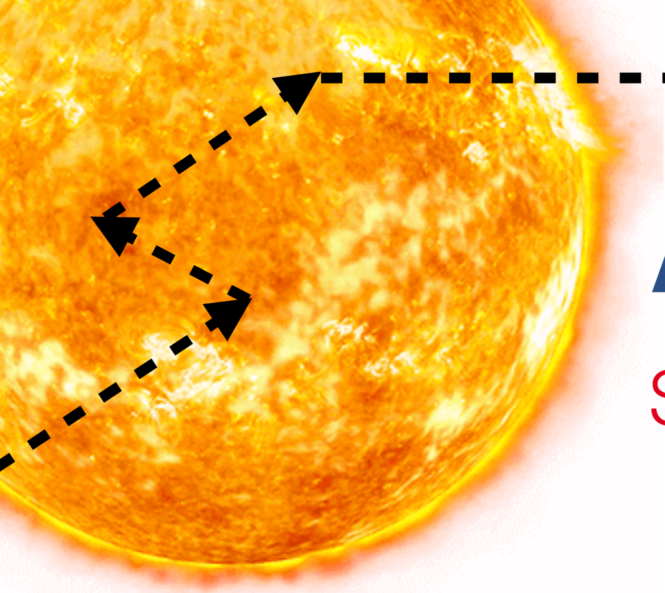
An+ 2006.13929



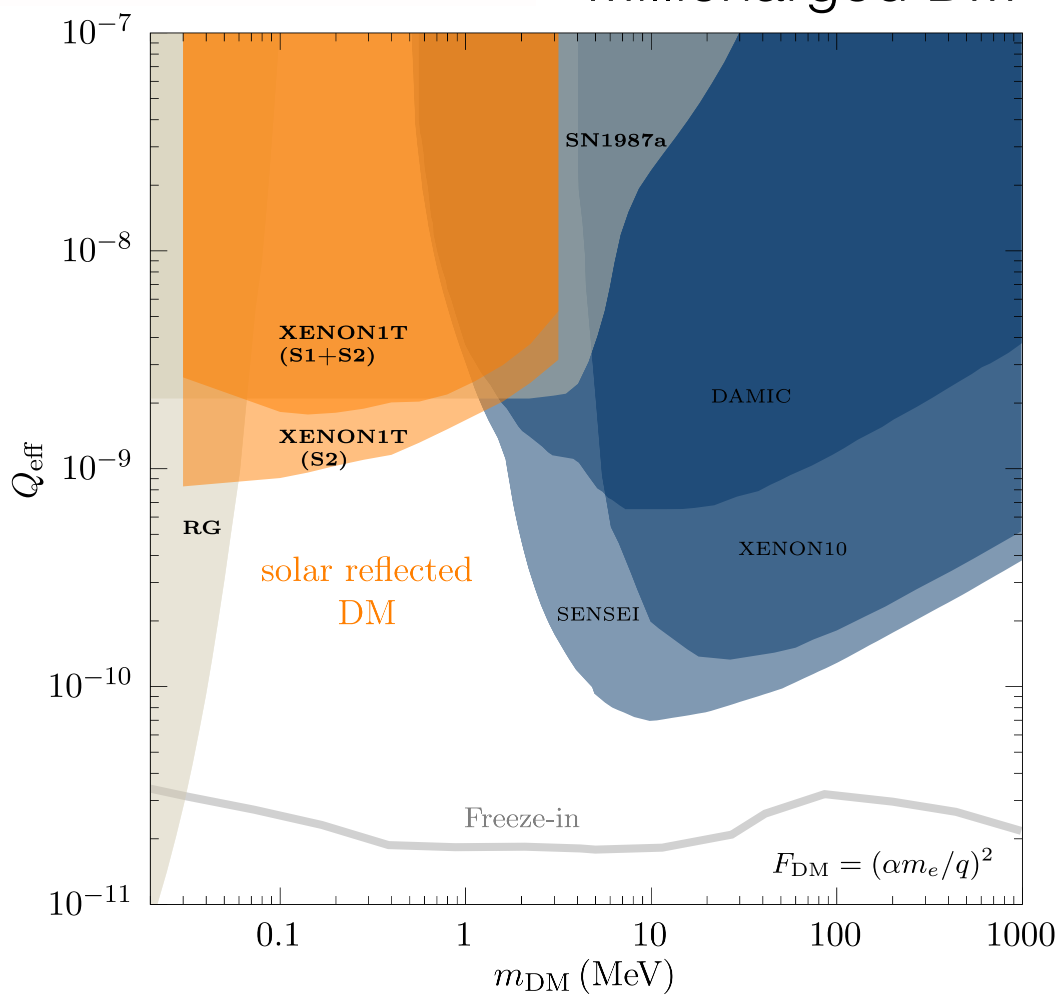
https://github.com/cajohare/AxionLimits

Astrophysical aspects II

Solar and cosmic ray boost

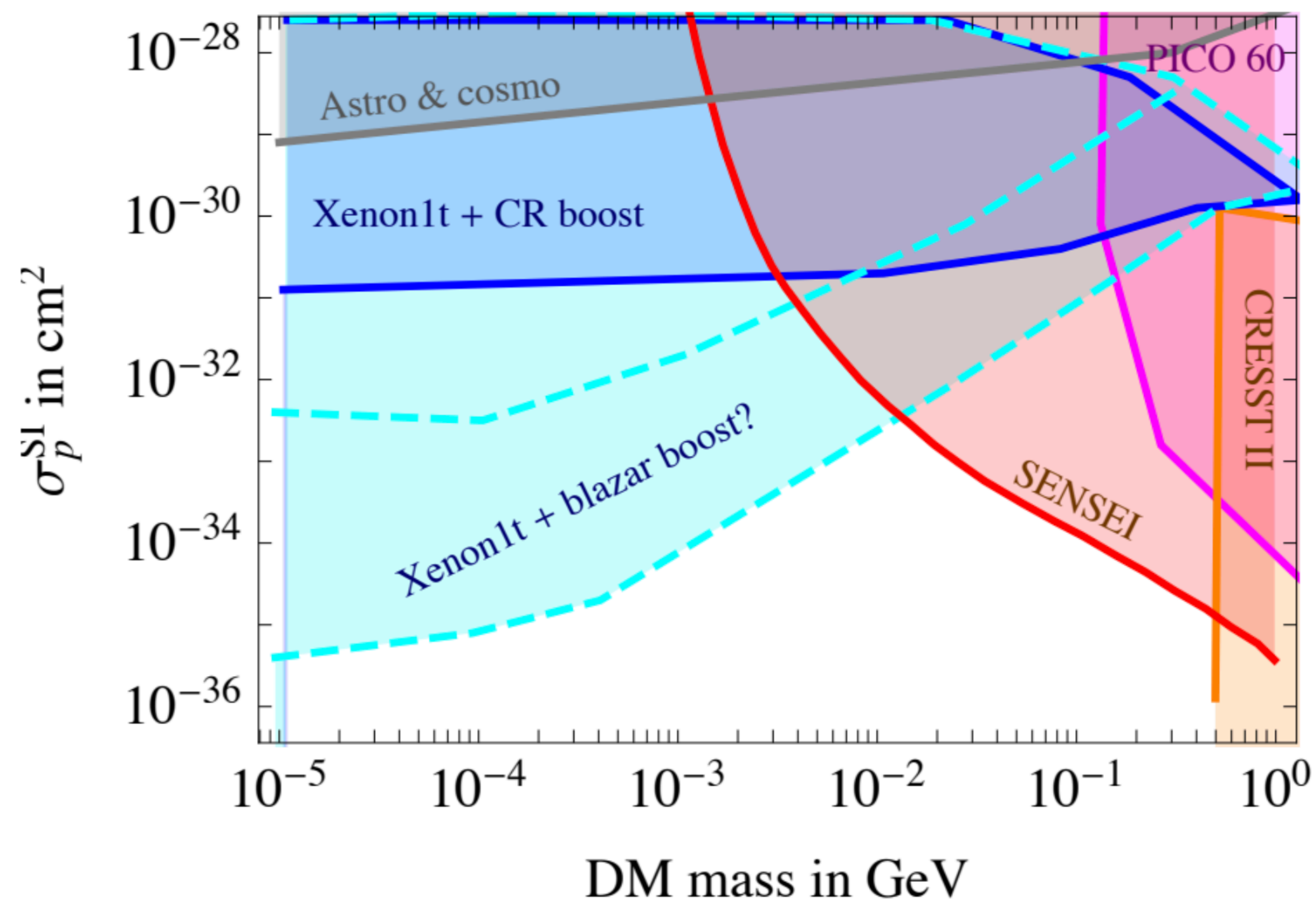


Millicharged DM



An+ 2108.10332

sub-GeV DM on protons

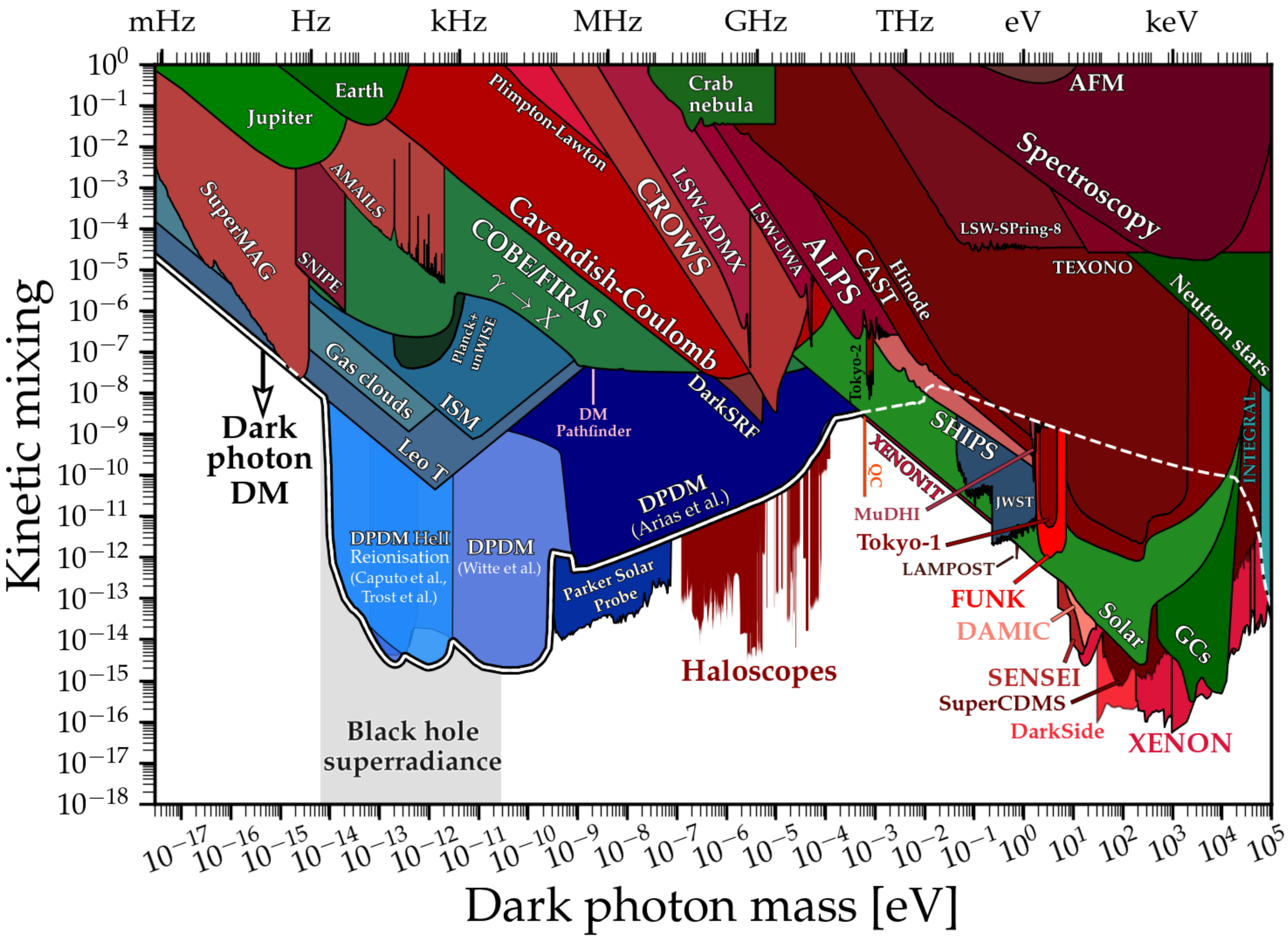


Cirelli+ 2406.01705

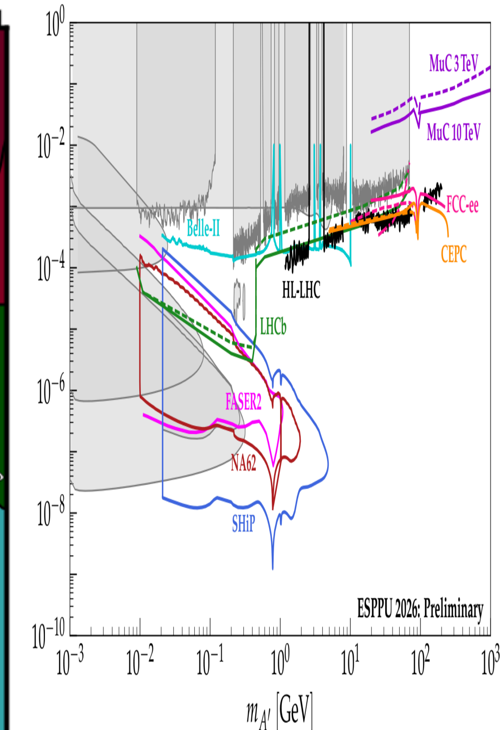
Probes unchartered territory between galactic direct detection and stellar constraints

Dark photons below the electron mass

Enormous parameter space to explore



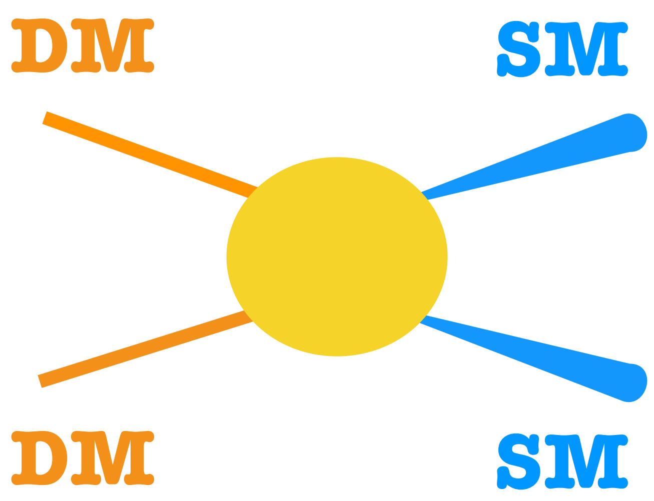
accelerator probes



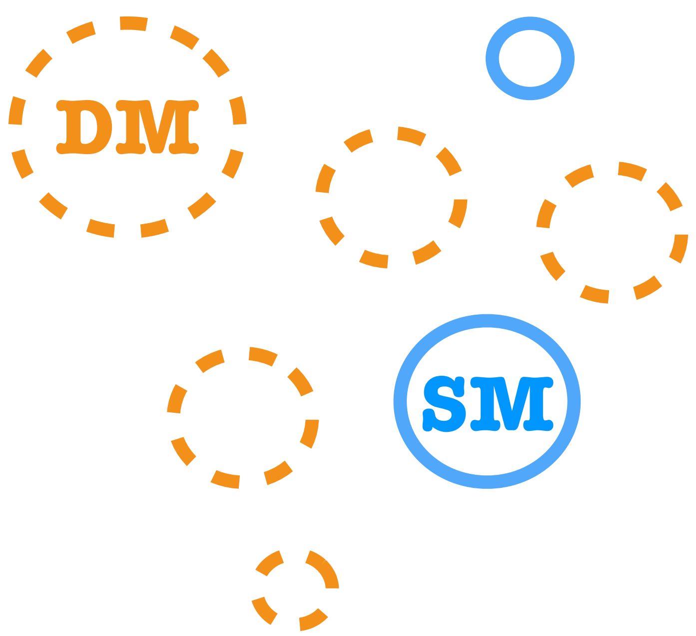
https://github.com/cajohare/AxionLimits

INDIRECT DETECTION of DM

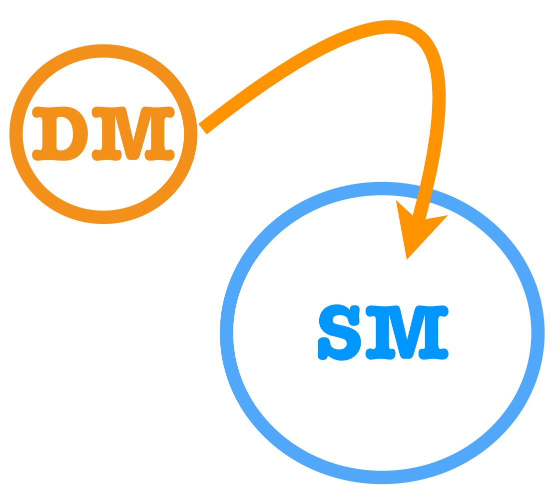
What dark matter does with/to the environment **at low redshift**



Alters expected energetic particle fluxes



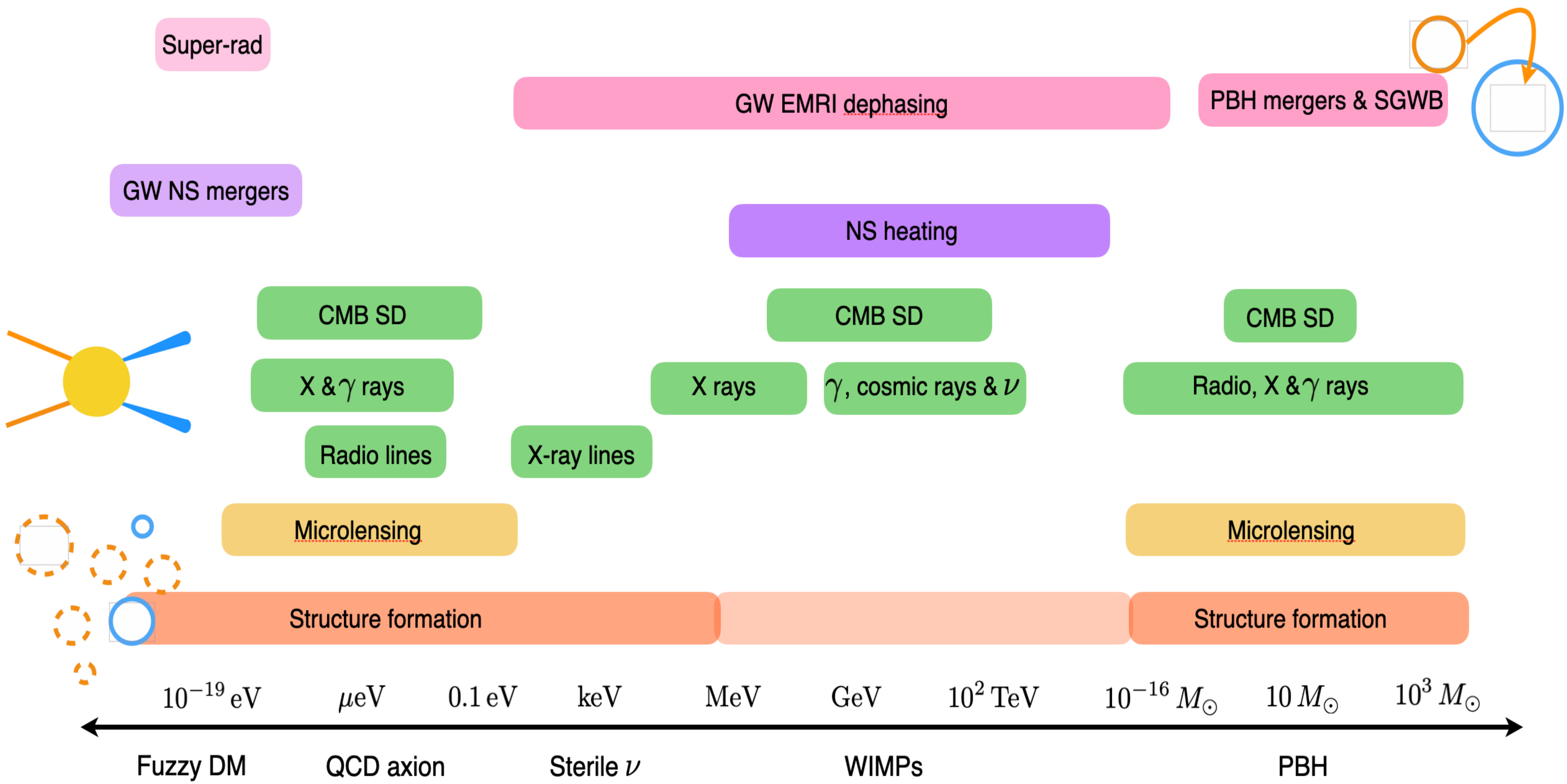
Alters the dynamics of astrophysical objects through gravitational interaction



Capture/scattering/accretion in/onto astrophysical objects

INDIRECT DETECTION observables

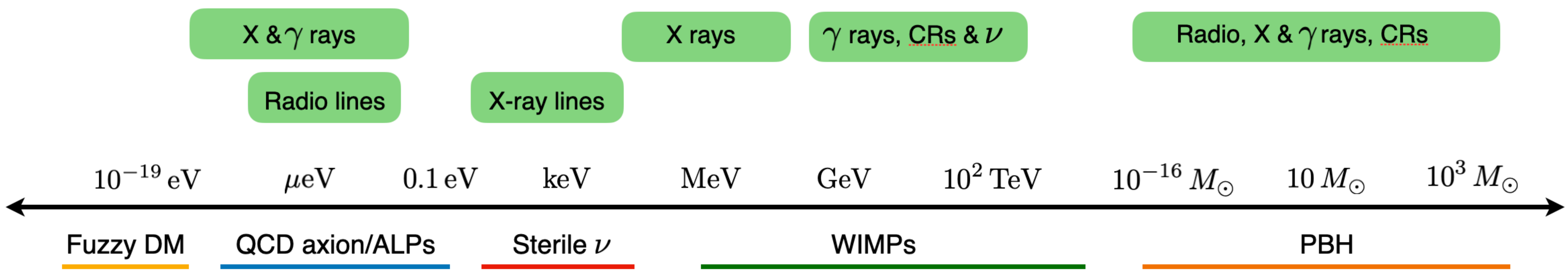
EuCAPT White Paper, arXiv:2110.10074



INDIRECT DETECTION

A focus on multi-wavelength photons

EuCAPT White Paper, arXiv:2110.10074

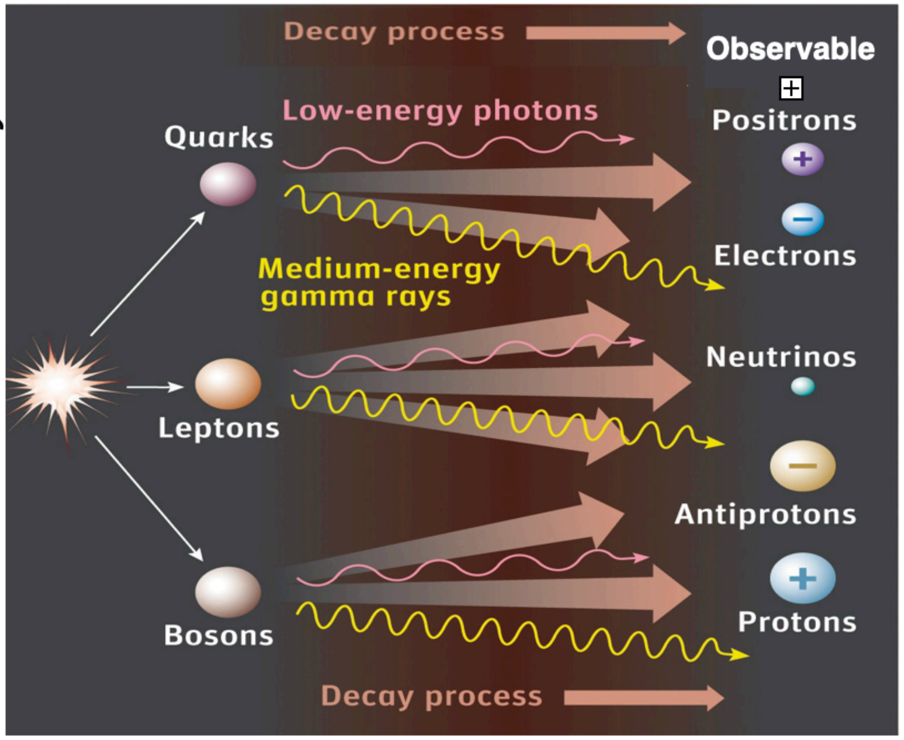


Indirect searches for dark matter successfully **test different dark matter models** (WIMPs, ALPs, PBHs, etc), probing a large portion of their parameter space

INDIRECT DETECTION

Particle dark matter emission

DM annihilation/decay



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

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

Centre of mass energy $\simeq$ Signal energy

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

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

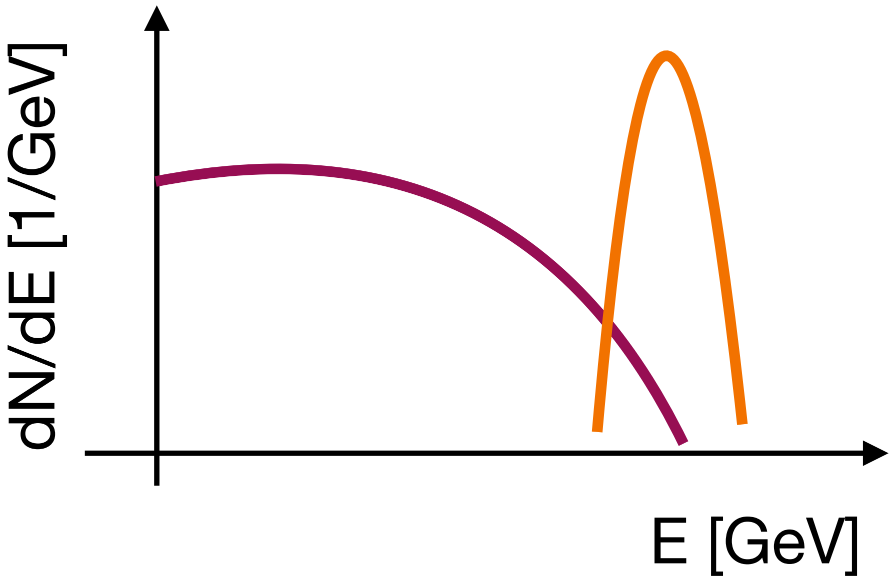
Narrow line signal

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

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

Broader energy distribution

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

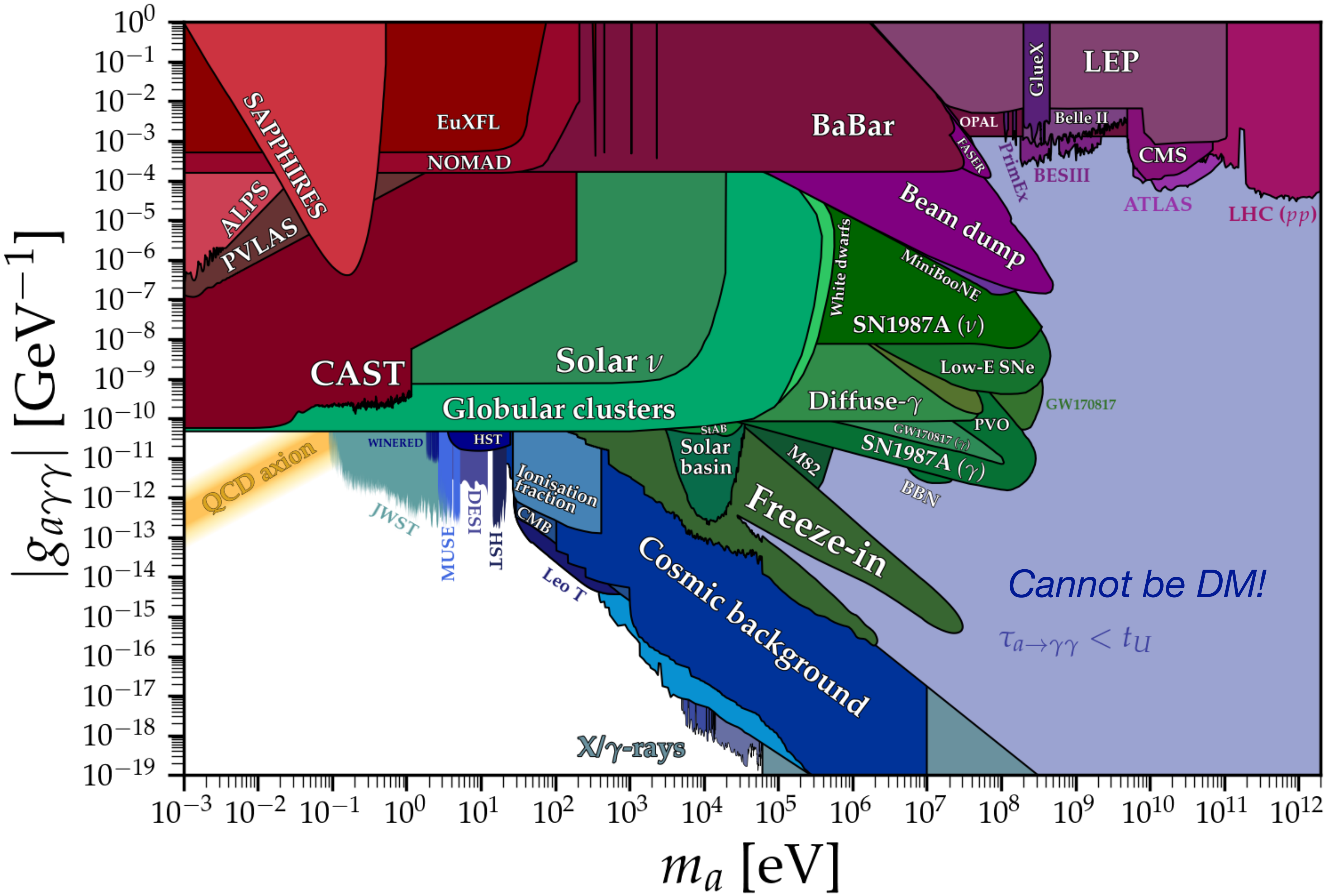


INDIRECT DETECTION

ALPs dark matter decay

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

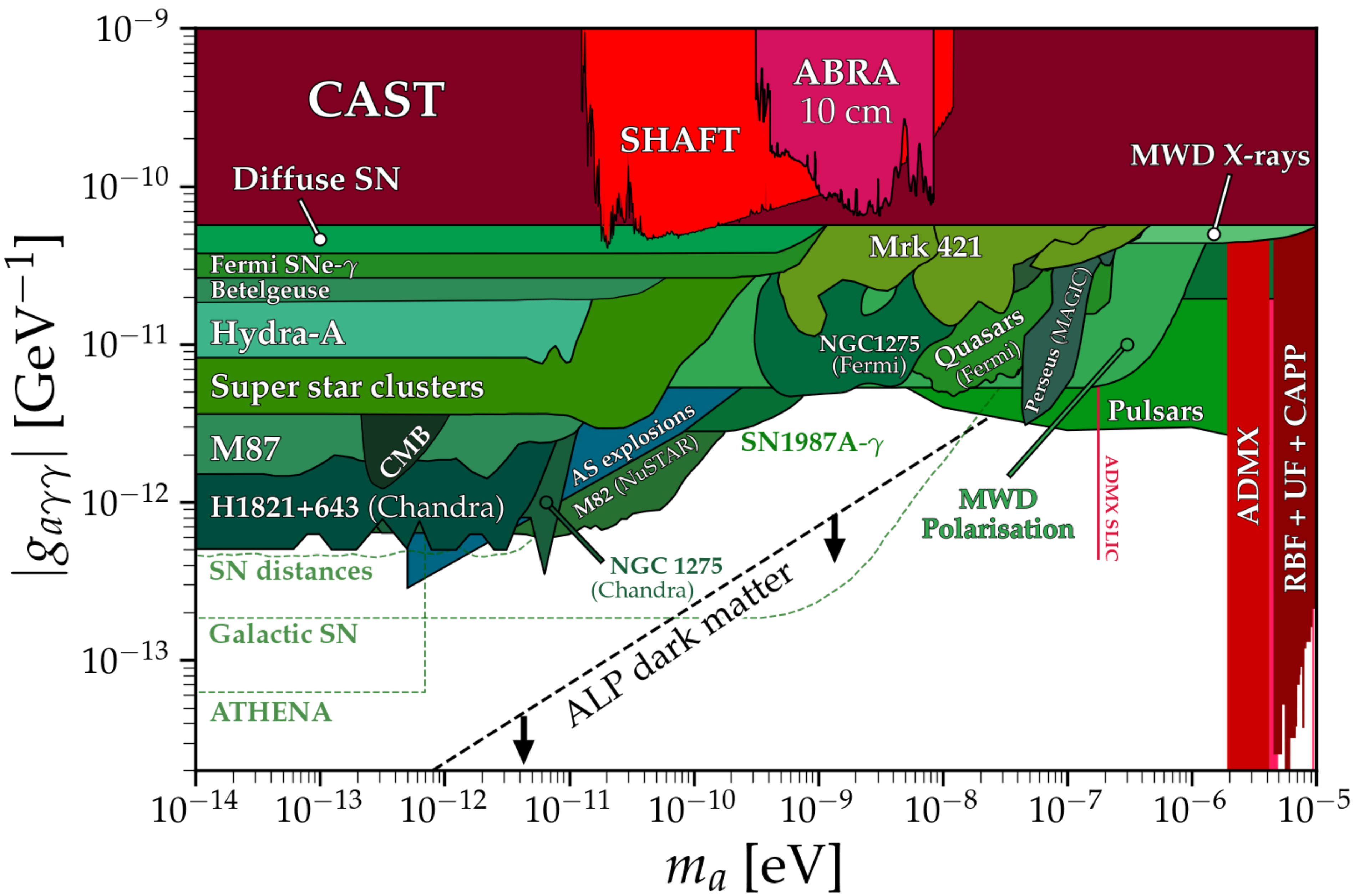
- If DM, ALPs distributed in galaxies according standard DM density distributions (e.g. NFW)
- Search for narrow lines in DM-rich environments



INDIRECT DETECTION

Light ALPs

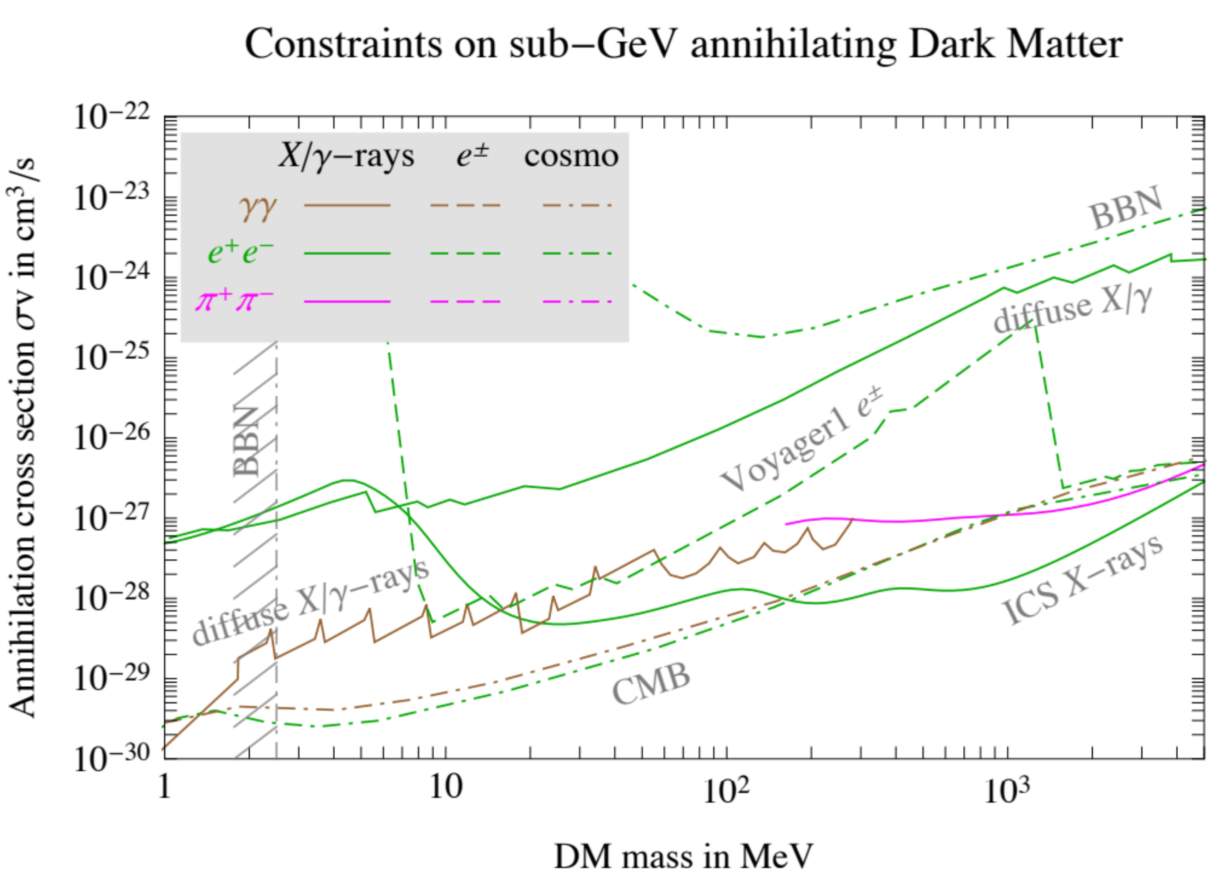
- Light ALPs are strongly probed by astrophysical systems
- Production in stars and/or high-energy gamma-ray emitters and conversion in external magnetic fields
- Search for photon appearance/ disappearance in astrophysical observables
- Future Galactic SN can touch ALP DM parameter space

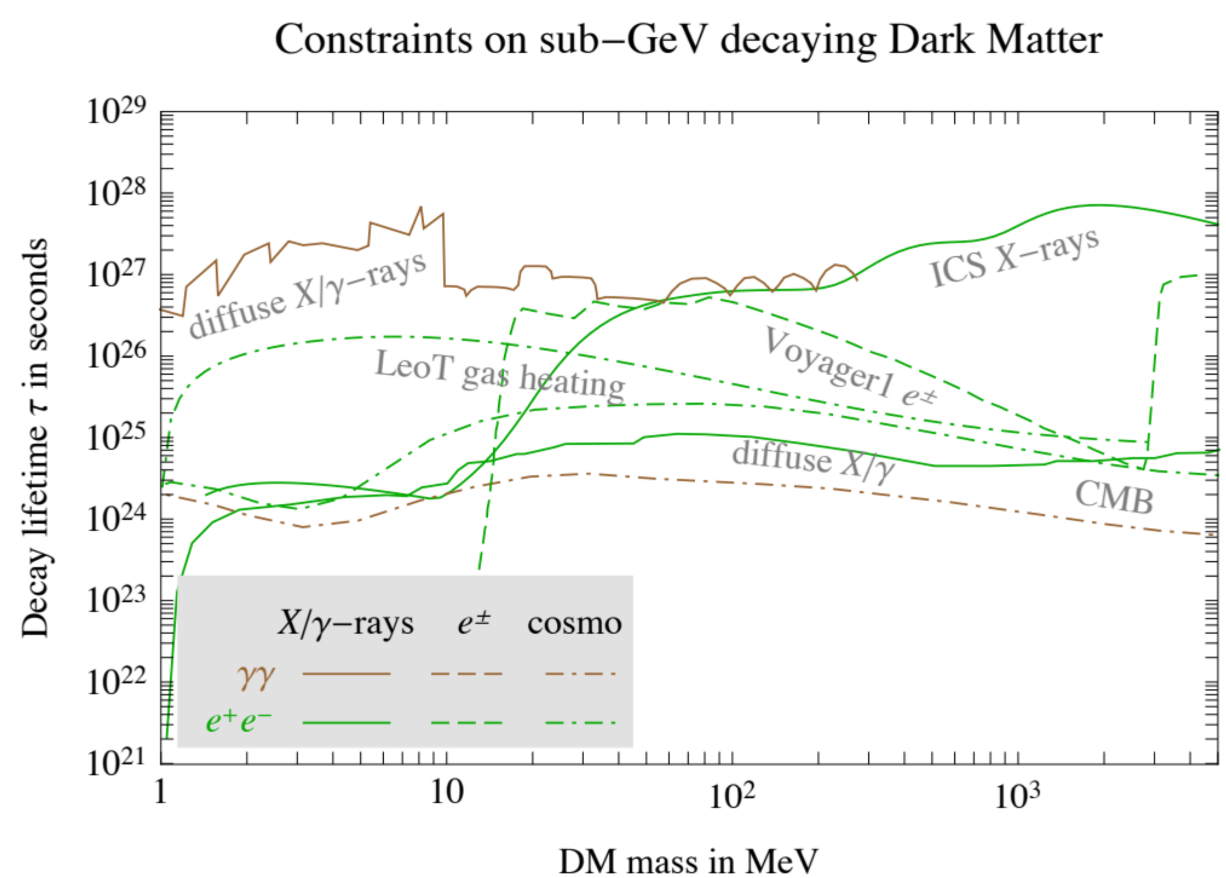


INDIRECT DETECTION

Sub-GeV dark matter: annihilation/decay XS

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



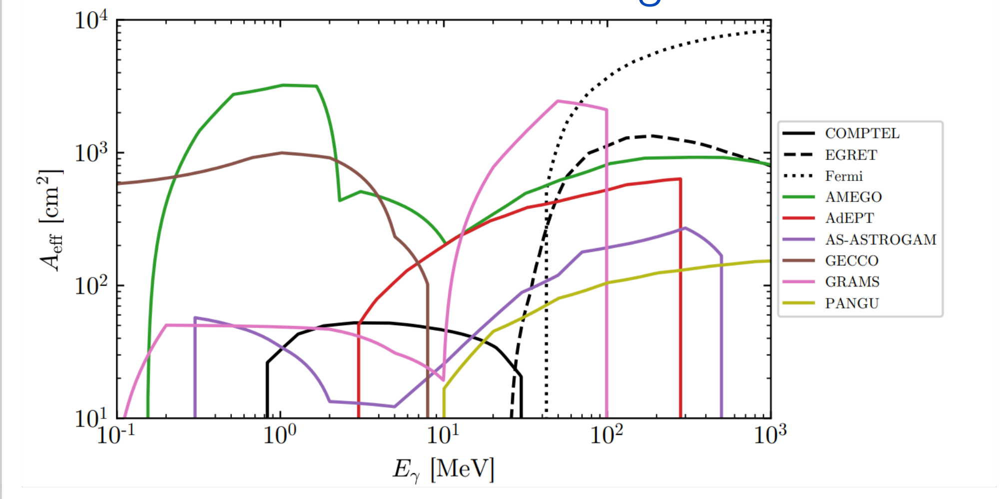


Diffuse X and soft-gamma ray emission provide the strongest constraints today but **MeV sensitivity gap**

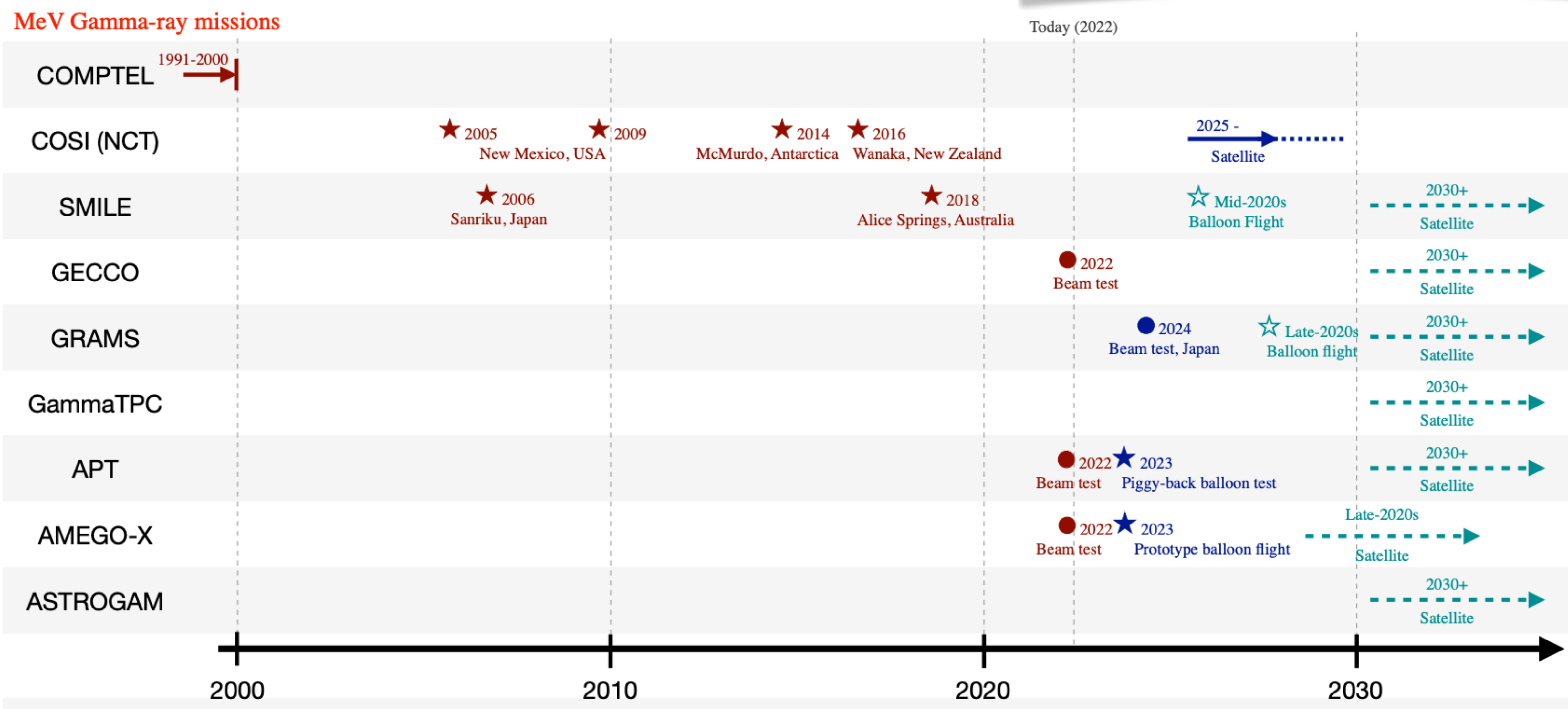
Cirelli+ 2406.01705

INDIRECT DETECTION

Coogan+ JCAP'21



Future: Covering the MeV sensitivity gap

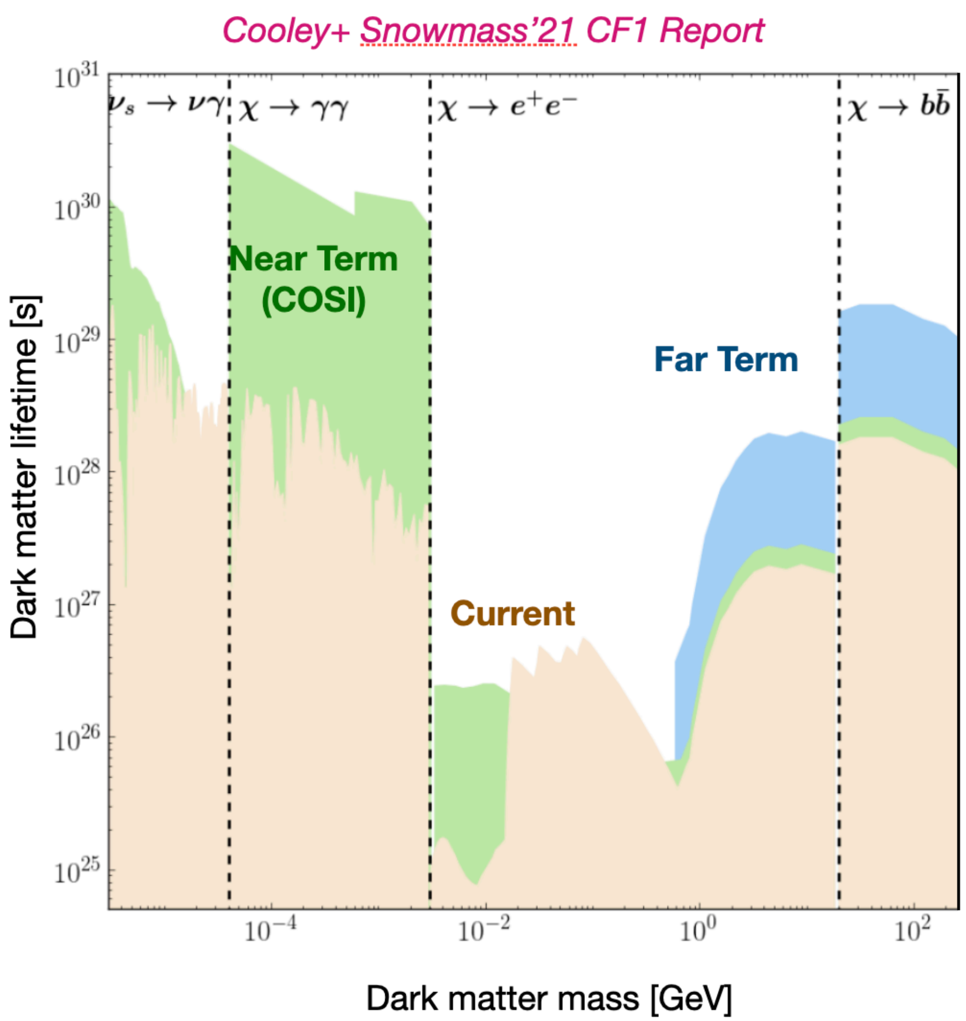


Aramaki+ Snowmass'21 CF

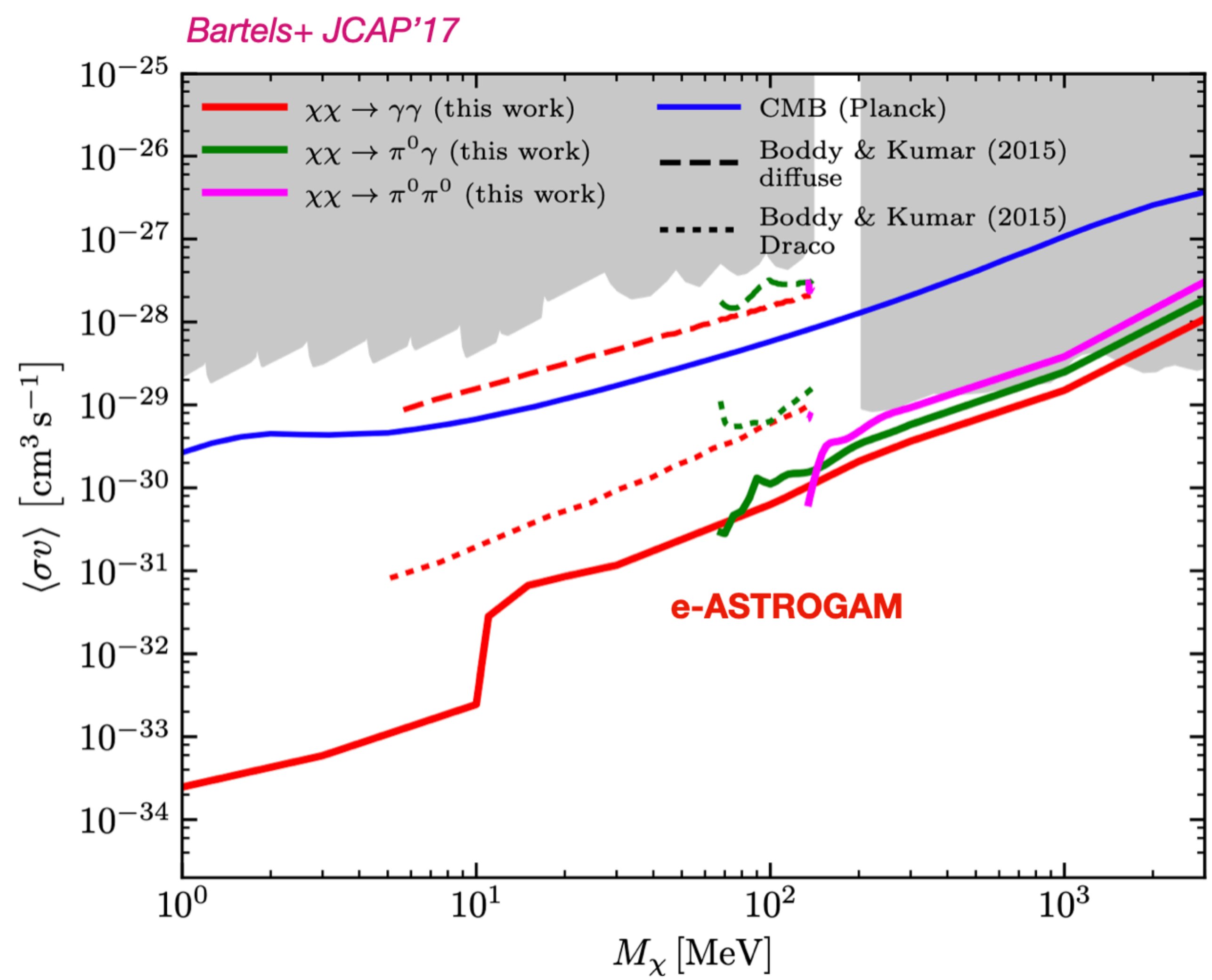
INDIRECT DETECTION

Future: Covering the MeV sensitivity gap

Decay

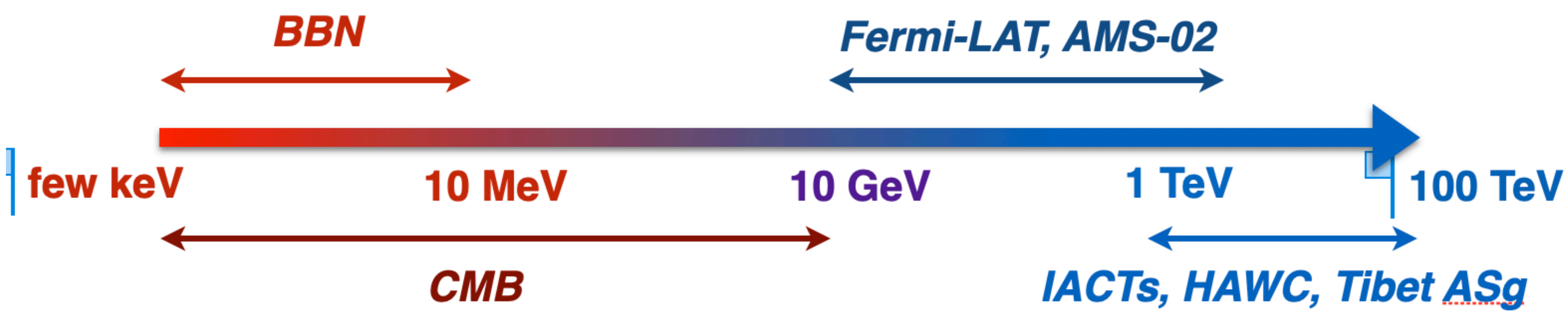


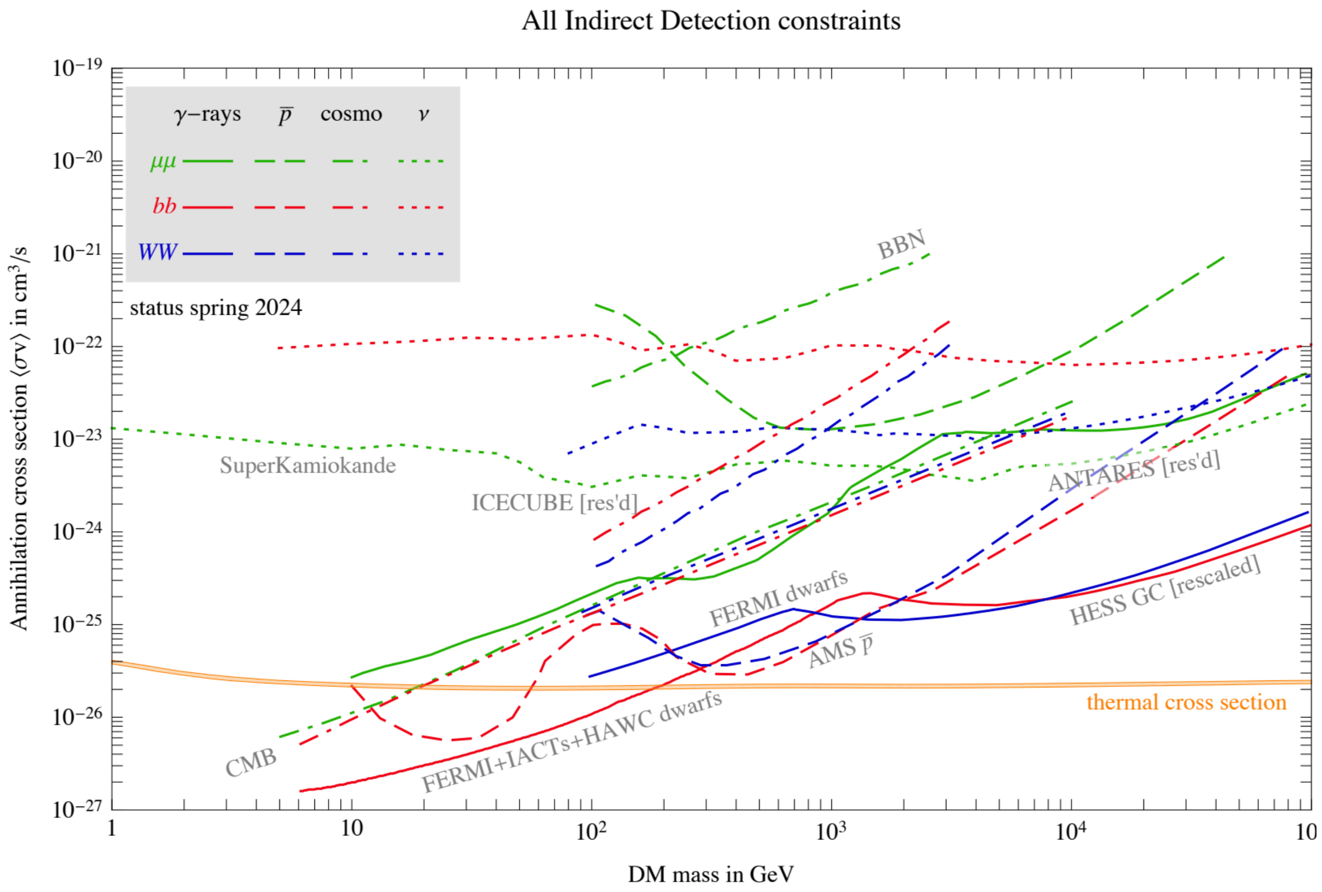
Annihilation

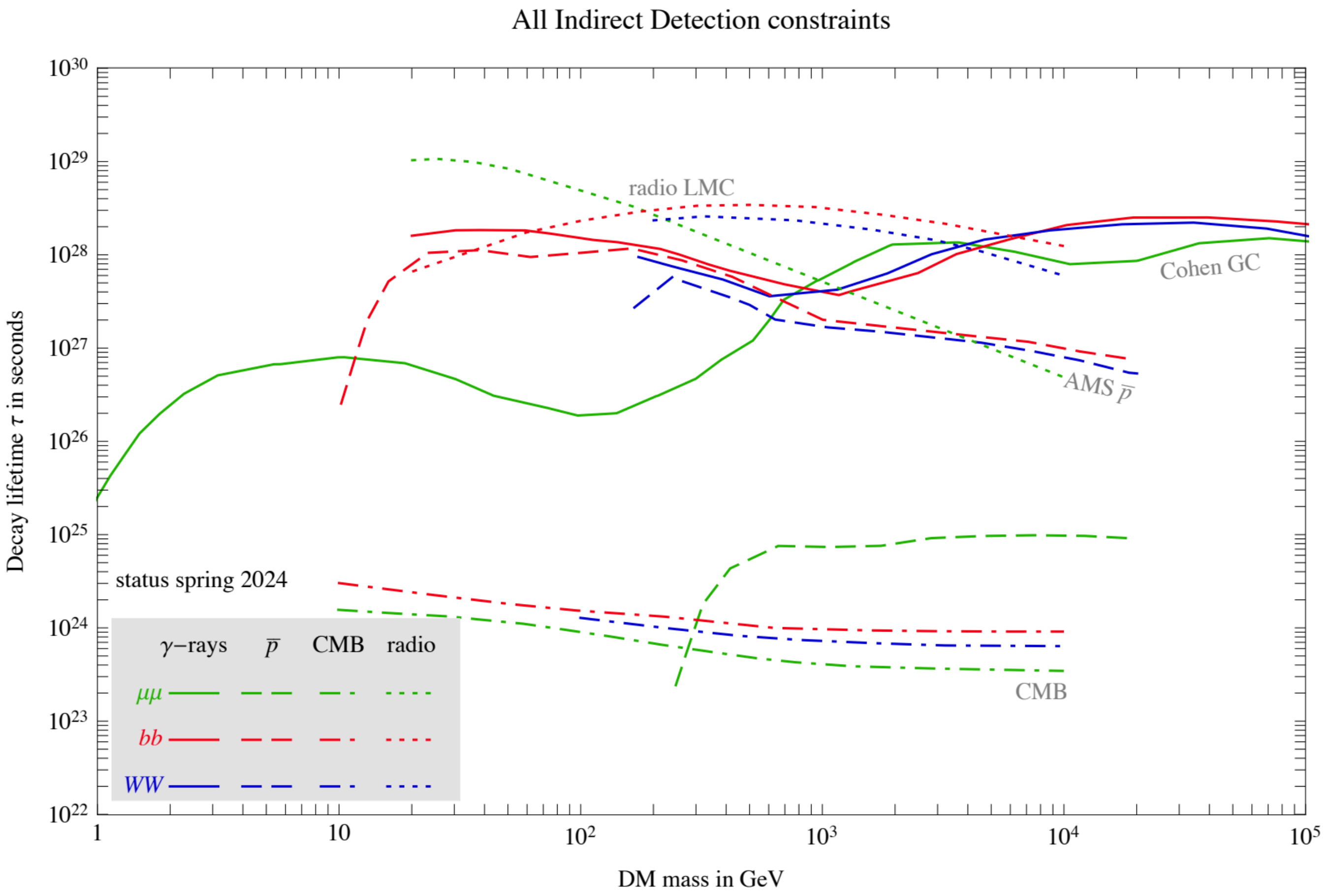


INDIRECT DETECTION

WIMP annihilation window







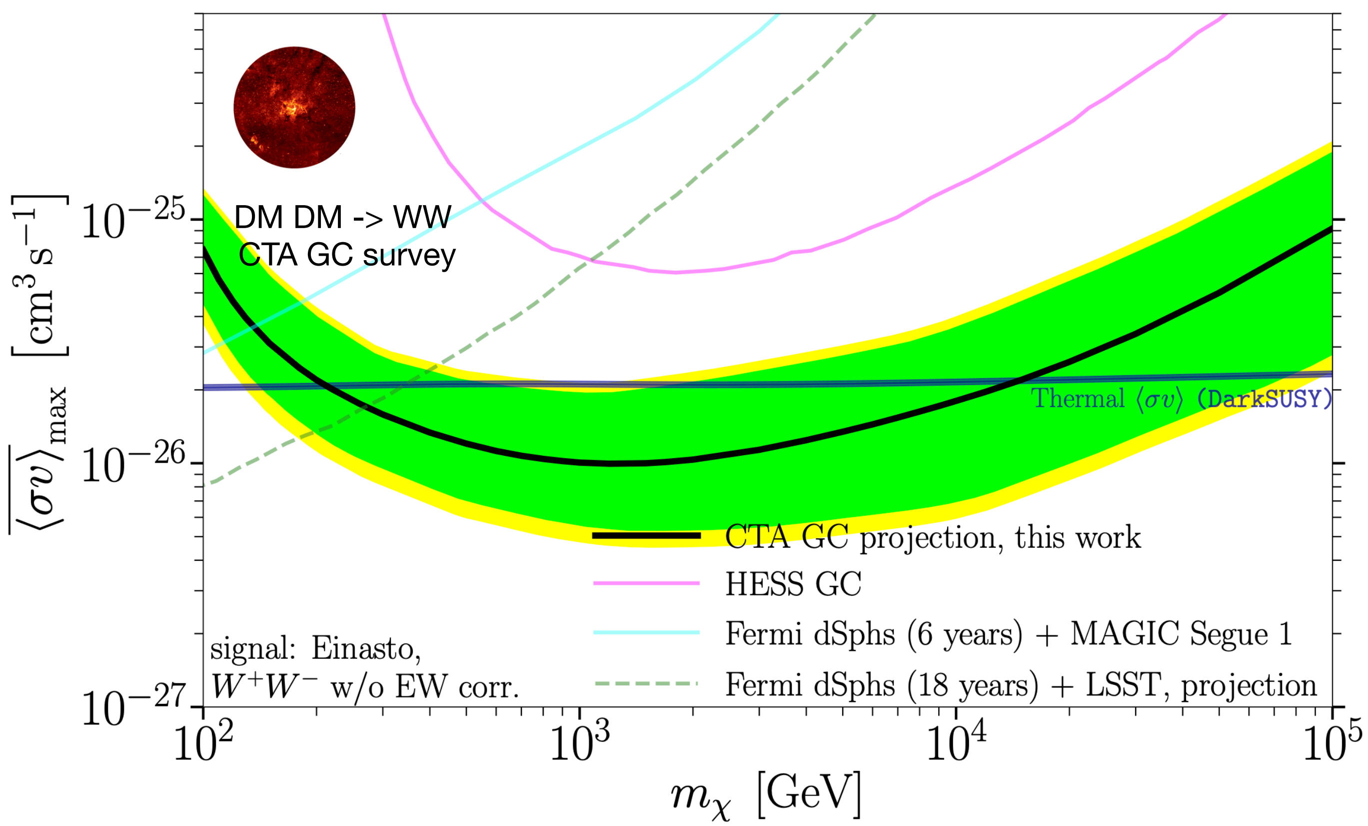
Cirelli+ 2406.01705

INDIRECT DETECTION

Future: The Cherenkov Telescope Array Observatory

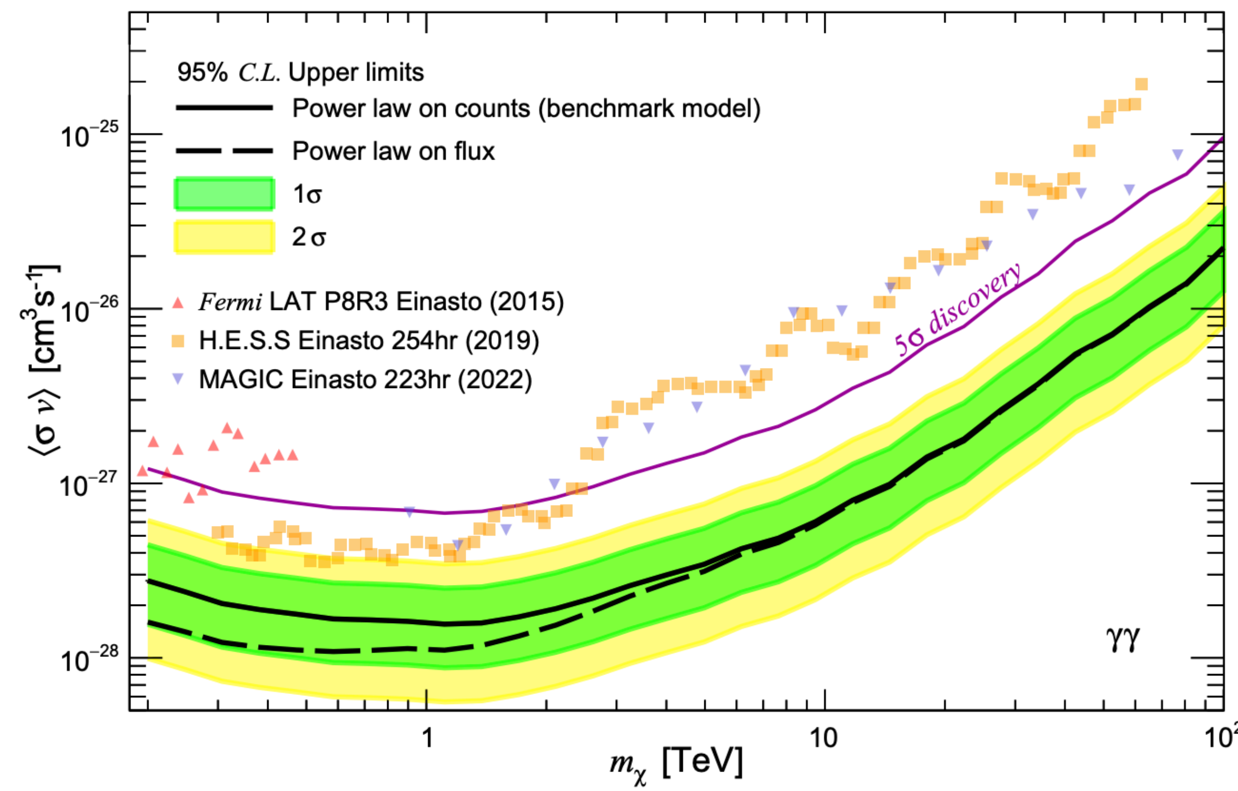
Gamma ray continuum

CTA Collab JCAP'21



Gamma ray lines

CTA Collab 2403.04857



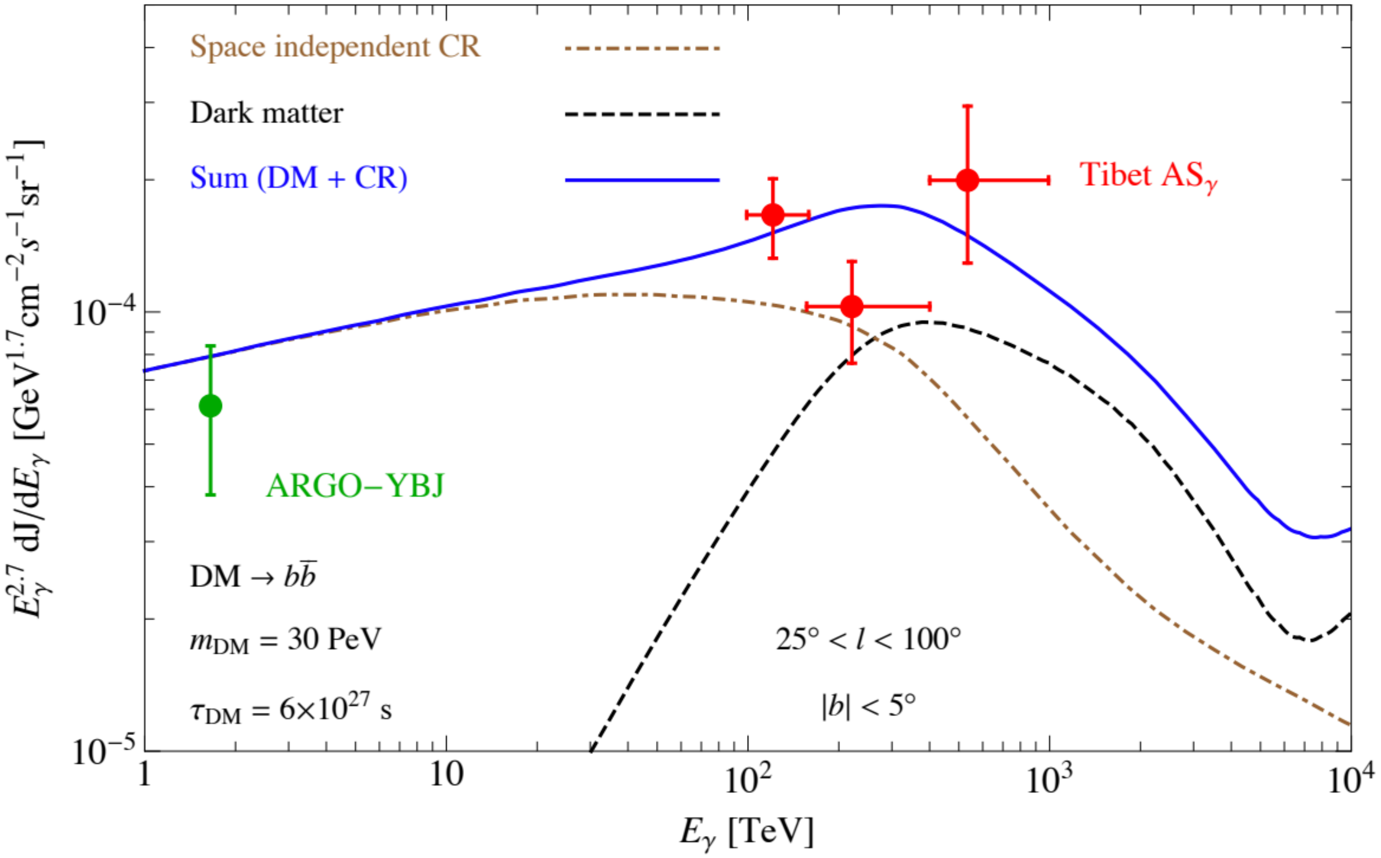
Take away: **Wino** DM strongly in tension with current data & **Higgsino** DM in the reach of CTAO

Rodd+ PRD'24; Montanari+ PRD'22; Rinchiuso+ PRD'21; Abe+2506.08084

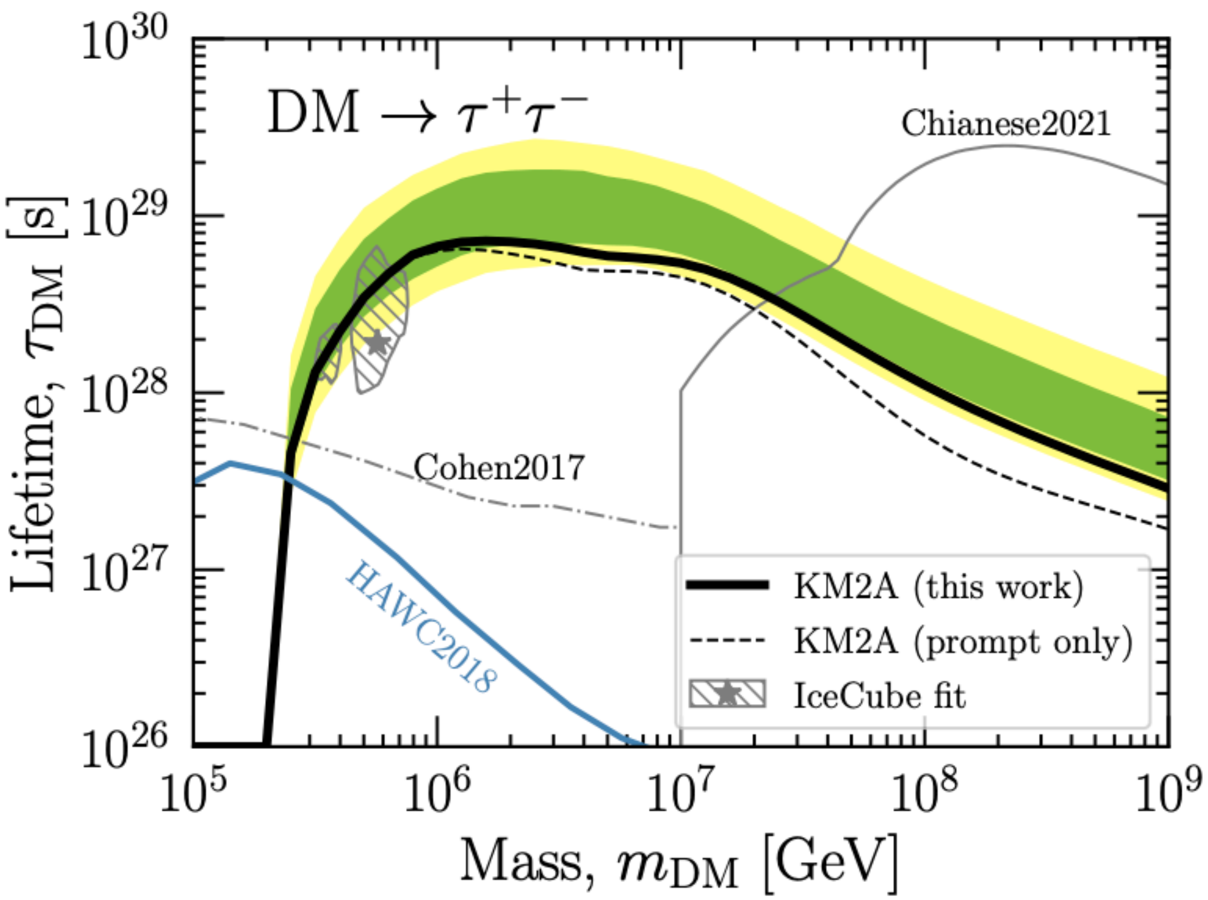
INDIRECT DETECTION

Dark matter at PeV energies

Esmaili & Serpico, PRD Letters'21; Tarak+ PRD'21



LHAASO Collab, Ando+ PRL'22



Challenges: 1. Production and propagation of UHE gamma rays;
2. DM spectra at production for $E_{CM} >> E_{LHC}$

Take away: Strong potential from VHE gamma rays

Conclusions

Cosmology and Astrophysics of (ultra-)light Dark Matter and Dark Sectors
Indirect Detection of Dark Matter

- eV-keV scale is the dividing line between bosonic-only, wave-like and any-spin particle dark matter. "Light Dark Matter" = keV-GeV scale. Thermal relics at the low mass end are amply probed in cosmology (CMB, BBN, structure formation) and through astrophysics (stellar energy loss). Freeze-in Dark Matter make for good, challenging targets.
- Many orders of magnitude in mass-space for ``ultra-light'' ALPs and dark photons to be probed. Stellar constraints provide a ``calibration lines'' for laboratory searches: beat them!
- Indirect DM detection at low z is a multi-pronged approach: alters fluxes, dynamics, or nature of astrophysical objects
- Current ``blind spot'' in the MeV energy range, but progress expected
- Thermal Wino DM already severely challenged, with CTA also Higgsino DM probed