Searching for decaying and annihilating dark matter from X-rays to gamma-rays

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Identification of Dark Matter 2020
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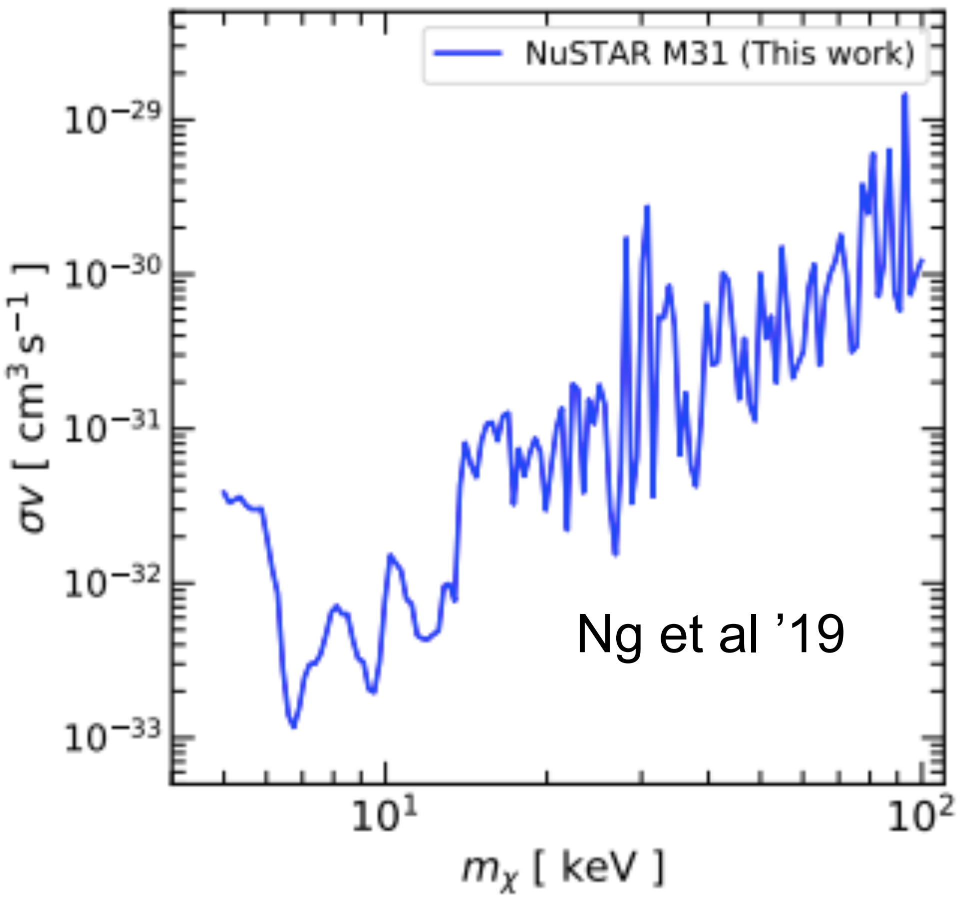
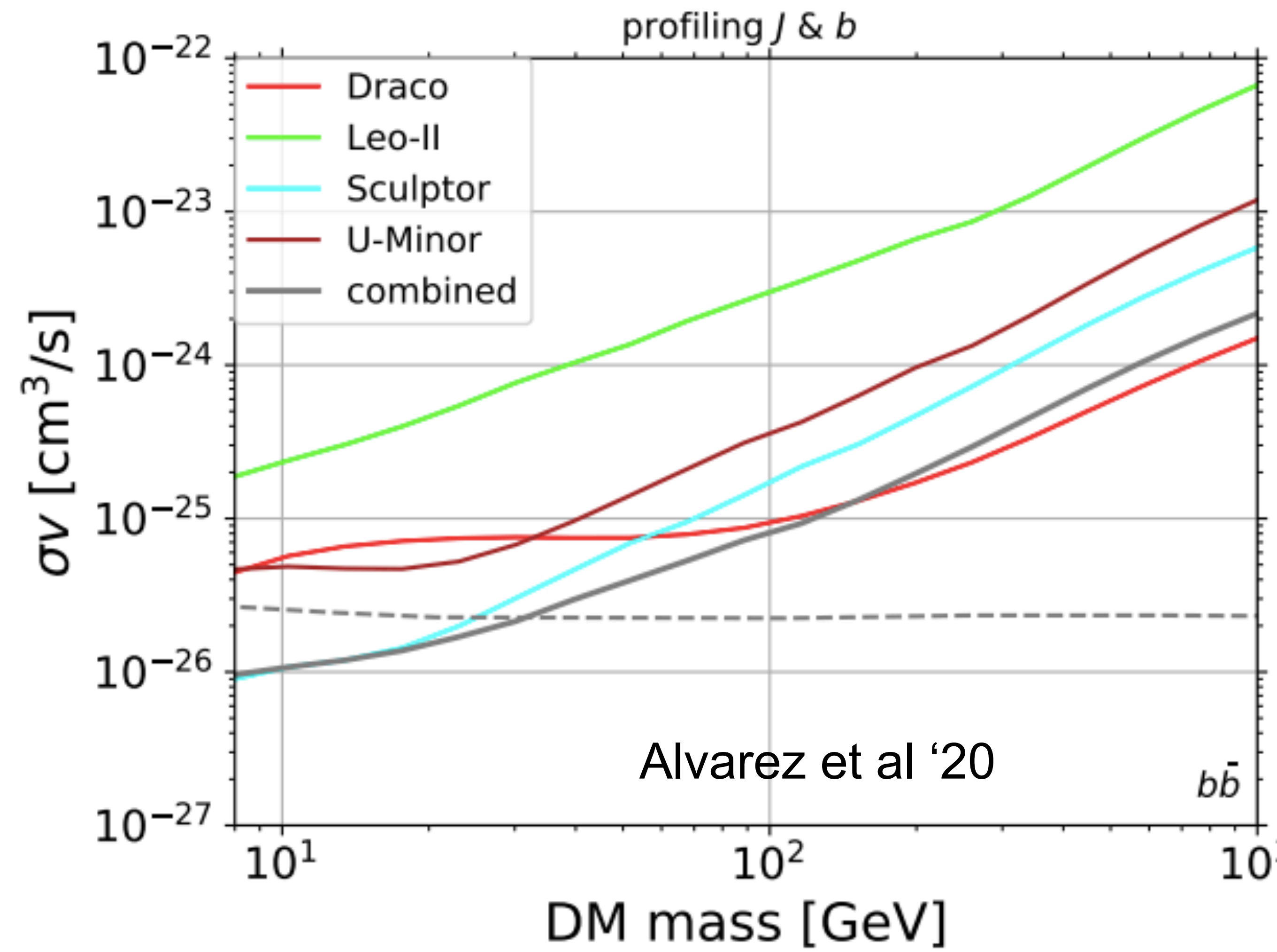
U.S. DEPARTMENT OF ENERGY | Office of Science

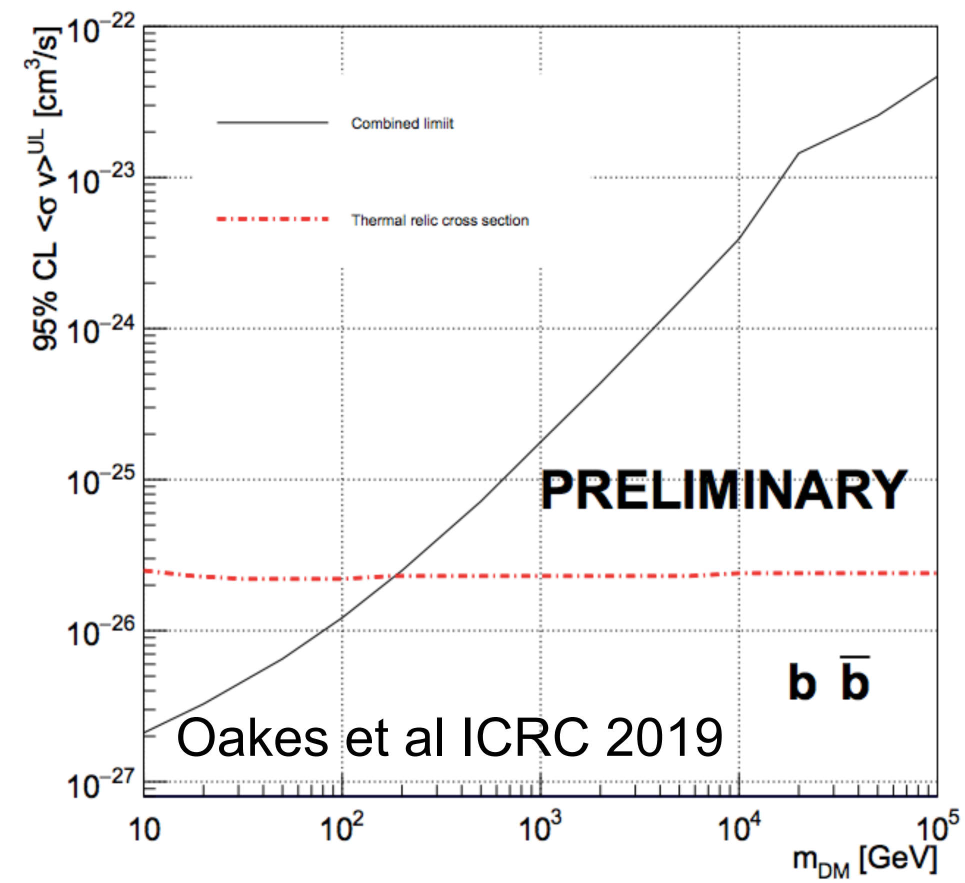
Introduction

- There is an enormous range of indirect searches for dark matter, as we have seen in the other plenary talks.
- The X-ray to gamma-ray range spans direct photon signals from keV-TeV+ dark matter candidates, as well as heavier candidates that release only a small fraction of their mass energy as photons.
- Outline:
  - General background / status quo: what we can currently say about annihilating/decaying DM from X-ray/gamma-ray constraints
  - Primordial black holes: the open window for PBH DM and what we can do with searches for Hawking radiation
  - A new analysis of INTEGRAL data and the resulting limits (led by Ranjan Laha and Julian Muñoz)

Constraints on annihilation

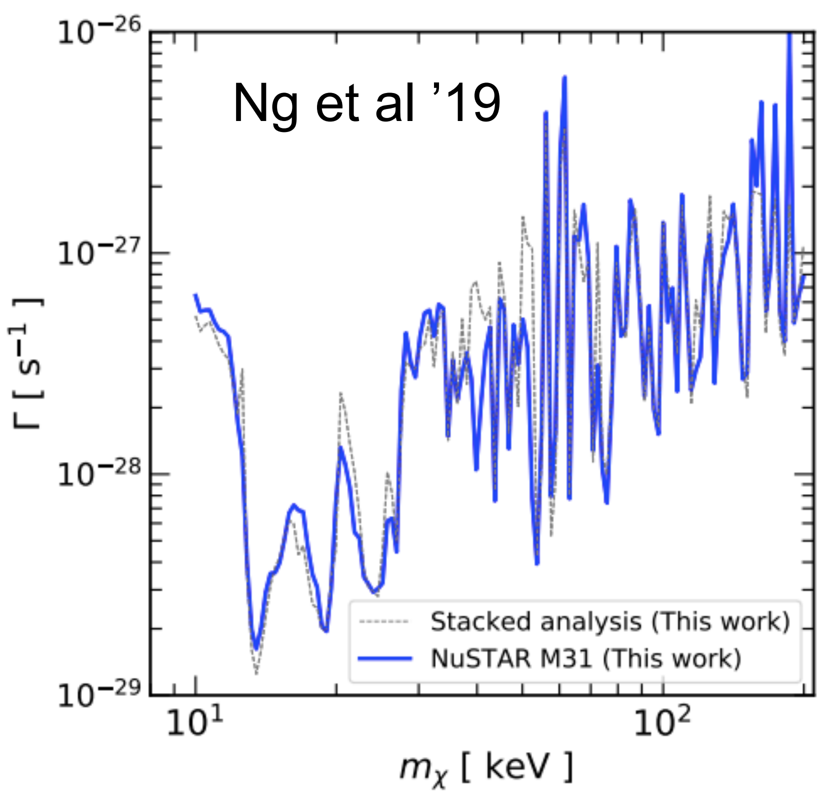


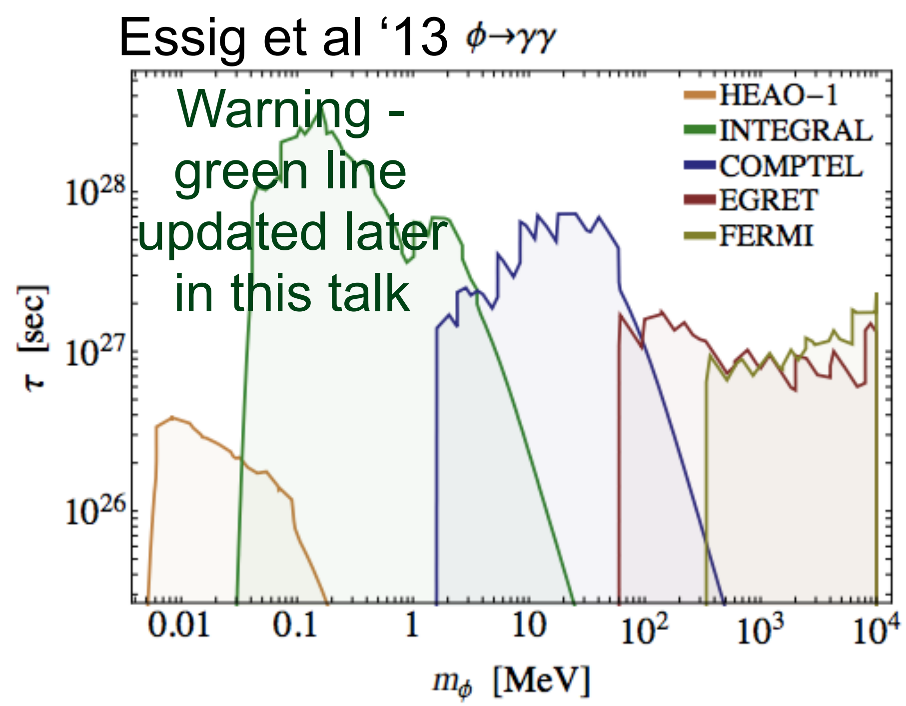


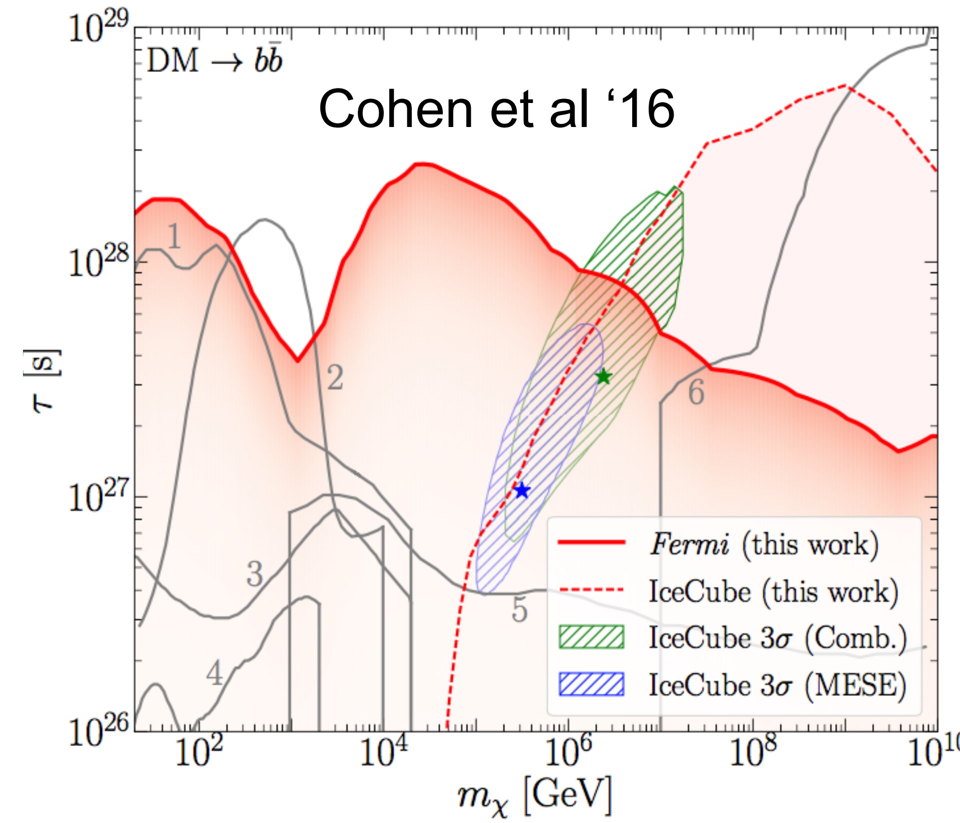


- Observations of X-rays with NuStar constrain annihilation of non-thermal keV-MeV-scale DM [e.g. Ng et al '19] to rates several orders of magnitude below the thermal relic cross section
- Observations of gamma-rays with Fermi (dwarf galaxies [e.g. Alvarez et al '20], galactic halo [e.g. Chang et al '18], other galaxies [e.g. Lisanti et al '18]) probe thermal relic cross sections up to O(10s-100s) GeV
- Ground-based gamma-ray telescopes such as H.E.S.S, VERITAS, MAGIC, HAWC, set limits on large annihilation cross sections up to the 100 TeV mass scale [e.g. Oakes et al '20, Abdallah et al '18, Archambault et al '17, Abdallah et al '16]

Constraints on decay







- Observations of X-rays and soft gamma-rays constrain DM decay to photons or hadronic final states to have lifetimes exceeding $10^{27\text{-}28}$ s, for the full range of masses from several keV to 10^{10} GeV.

- DM decays to other channels can also be constrained by these observations; for MeV-GeV DM decaying leptonically, Voyager limits on low-energy cosmic rays [e.g. Boudaud et al '16] and bounds from early-universe cosmology [e.g. Wu & TRS '17] are somewhat stronger than photon-based limits.

Primordial black holes (PBHs) as dark matter

- General idea: black holes can be formed from inhomogeneities in the high-density early universe [see Carr et al 2002.12778 for a recent review containing more comprehensive references].

- Black holes are electrically neutral (or quickly become so) and interact primarily via gravity.

- Sufficiently heavy black holes have a lifetime >> age of the universe.

- Black holes would be heavy, non-relativistic “particles”, and would play the cosmological role of DM provided they are formed well before matter-radiation equality - hence only primordial BHs are viable DM candidates, not those formed from stars.

- Perhaps the most plausible DM scenario that does not require DM to be comprised of new particles beyond the Standard Model (although probably requires a non-minimal inflation model or other BSM physics).

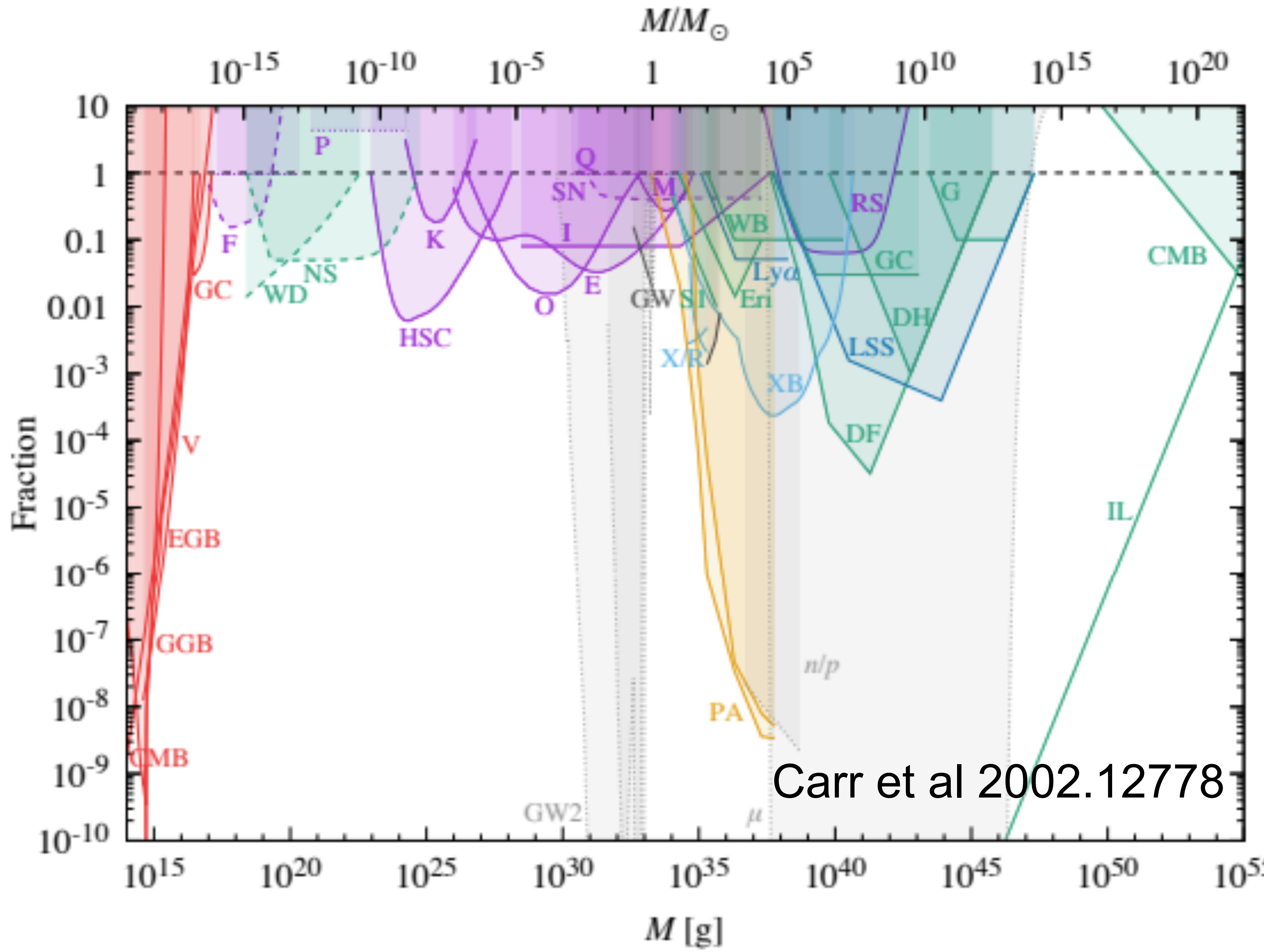
- PBHs are decaying DM - they slowly decay through Hawking radiation (with temperatures far less than the BH mass), PBHs in an observationally interesting mass range can produce X-ray and soft gamma-ray radiation.

Constraints on PBHs as DM

- Too-light PBHs evaporate via Hawking radiation - null searches for the radiation constrain lifetimes longer than the age of the universe

$$T_{\rm BH} = \frac{M_{\rm Pl}^2}{8\pi M} \qquad \tau \sim \frac{M^3}{M_{\rm Pl}^2}$$

- Over a wide mass range, PBHs can be probed with a combination of gravitational lensing + dynamical effects in astrophysical systems



Carr et al 2002.12778

- Dashed lines = constraints have been proposed, but are not reliable or have been refuted
- There is an open window for f=1 (all DM=PBHs) from M~10^{17}-10^{23}g

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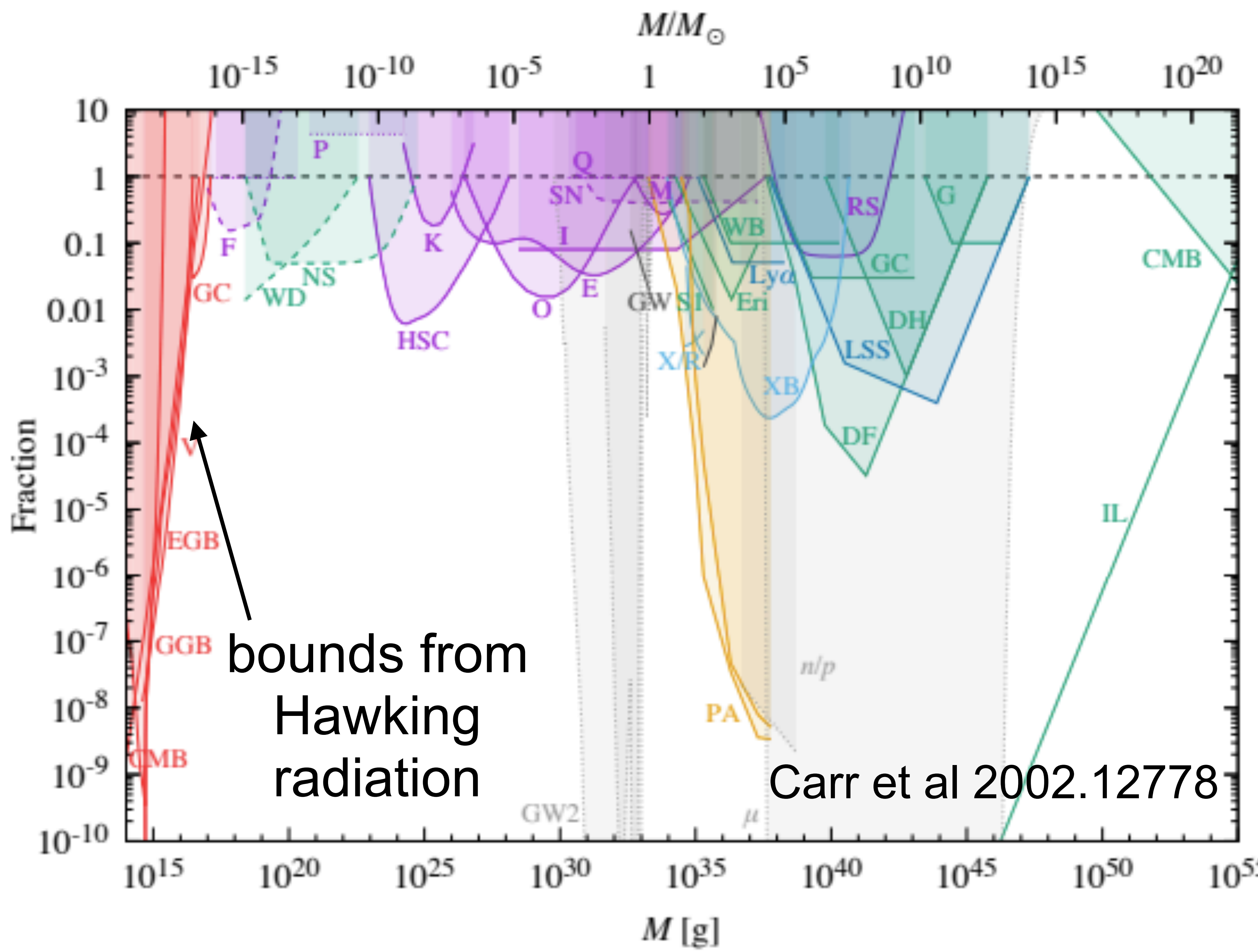

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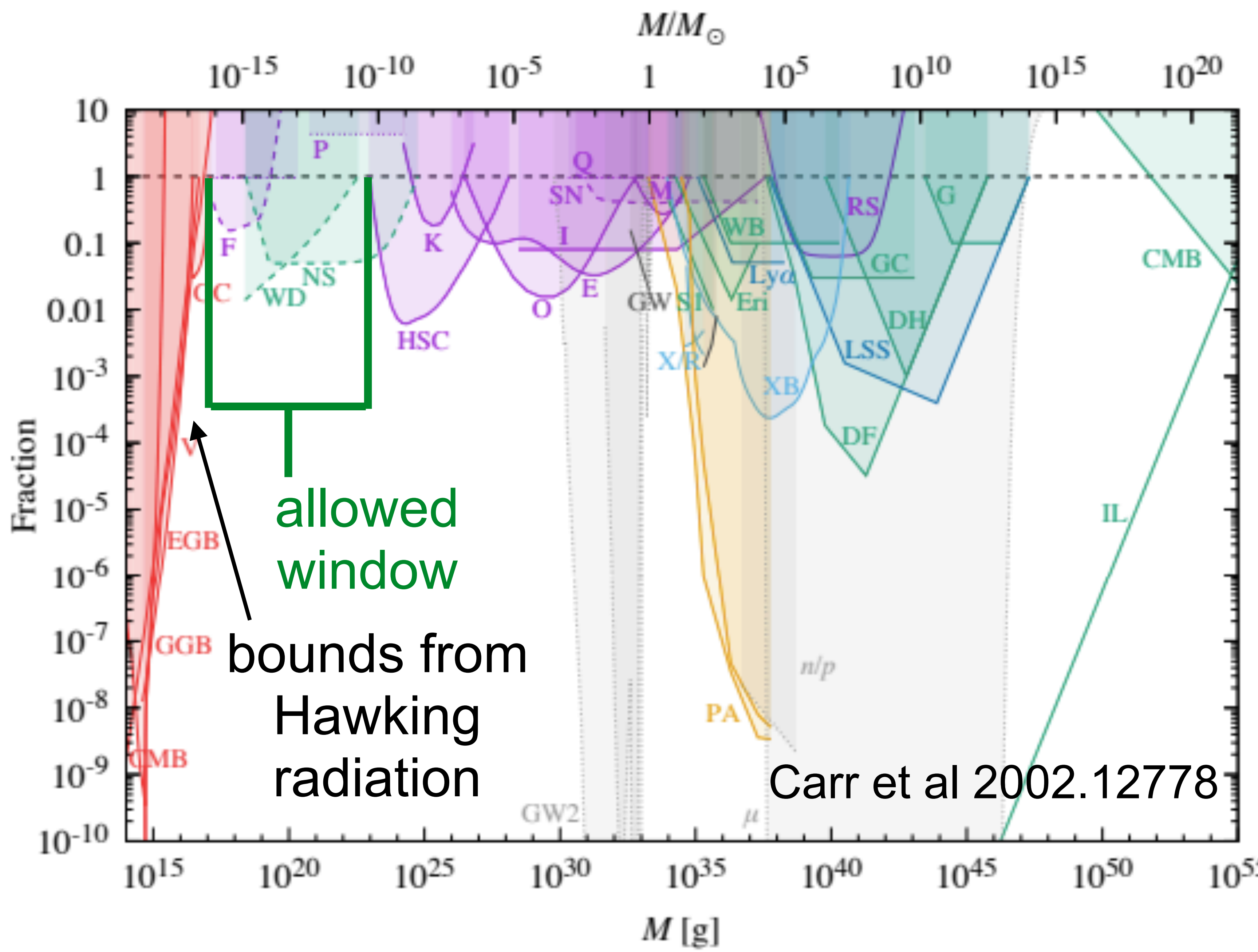

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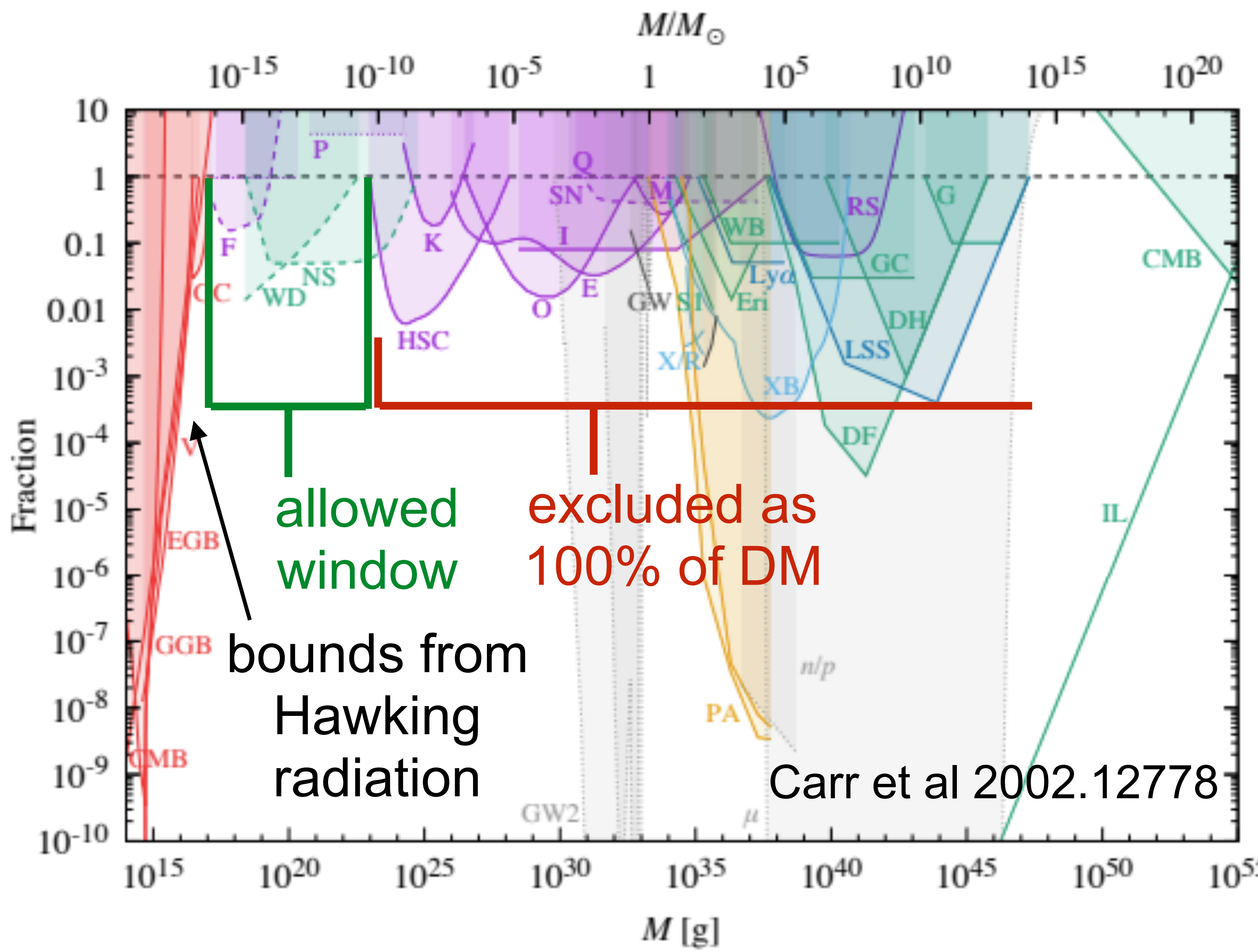

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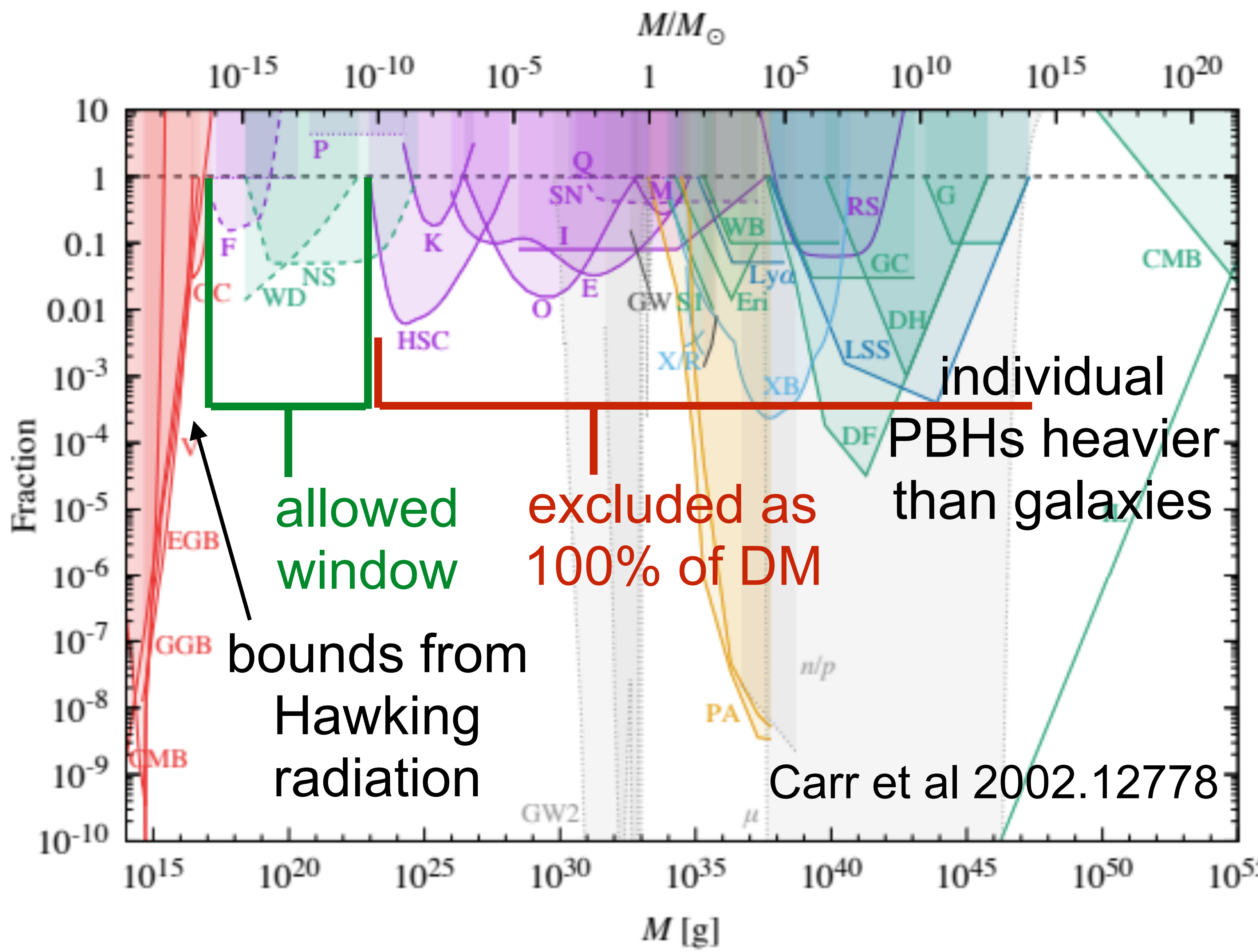

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The International Gamma-Ray Astrophysics Laboratory (INTEGRAL)

- Launched 2002 by the European Space Agency.
- SPI (spectrometer): covers 18 keV-8 MeV energy range, 2.5 degree angular resolution, 0.2% energy resolution.
- IBIS (imager): covers 15 keV-10 MeV energy range, 12 arcminute angular resolution, 8-10% energy resolution.
- <u>Note:</u> INTEGRAL does not measure isotropic gamma-ray background - isotropic signals are absorbed into the background model (also includes cosmic rays, instrumental backgrounds).

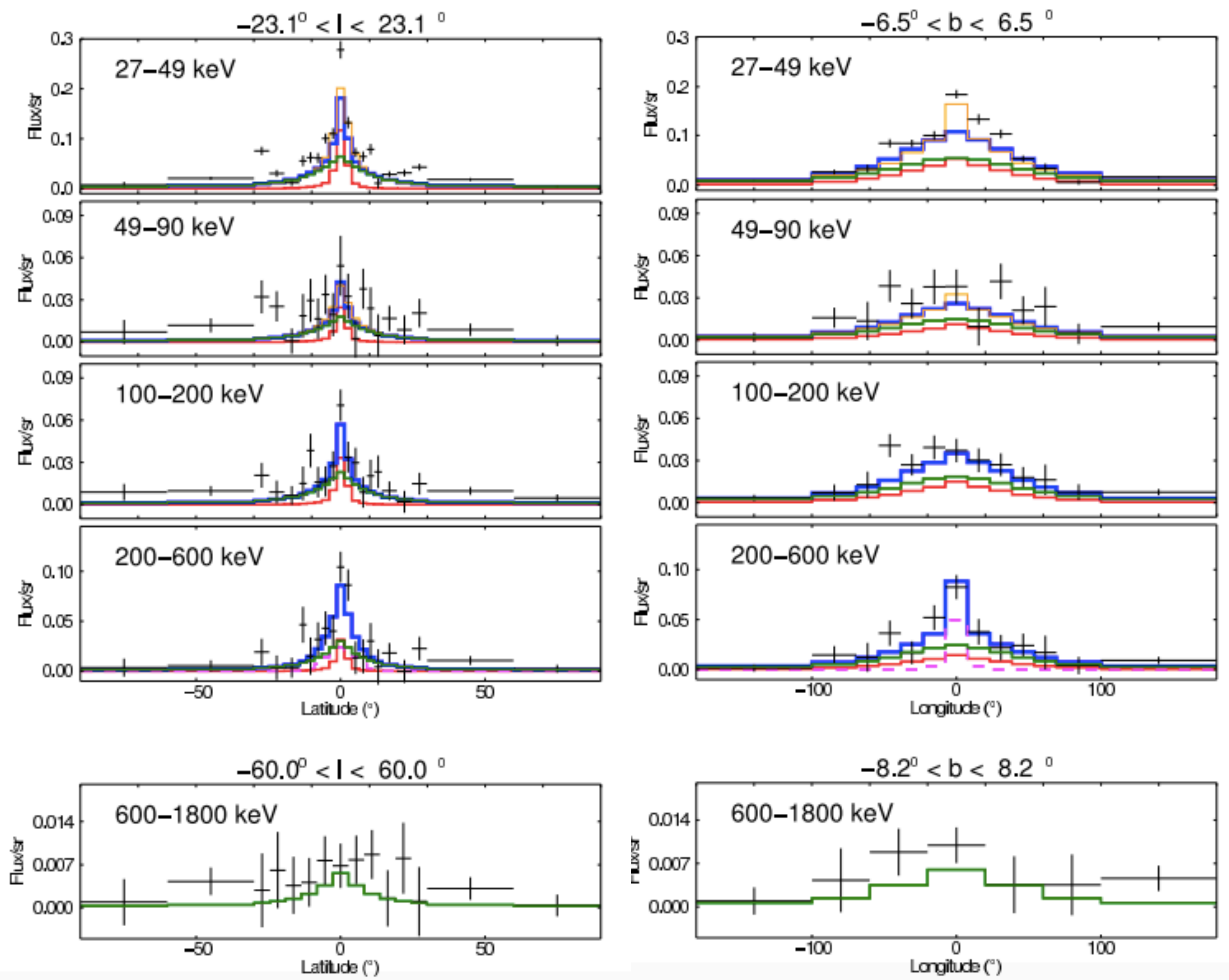
Analyzing INTEGRAL data

L. Bouchet, A. W. Strong, T. A. Porter, I. V. Moskalenko, E. Jourdain, & J.-P. Roques 2011 (1107.0200)

- Two approaches to modeling the diffuse gamma-ray emission:
  - Sky imaging - introduce point source locations as a priori information, simultaneously fit for intensities of diffuse pixels and point sources
  - Sky model fitting - introduce spatial templates for various expected contributions to the diffuse emission, fit for their intensity (together with point sources)
- Second approach provides more information to the fit, can lead to smaller uncertainties, but not clear how it will behave if there is a component (e.g. Hawking radiation from PBHs) not matching any of the assumed templates
- Ideally one would re-do the second approach including a template for the signal of interest
- As a simpler first-pass alternative, we can simply require that our signal not overproduce the model-independent diffuse emission from the sky-imaging approach

INTEGRAL data from the sky-imaging approach

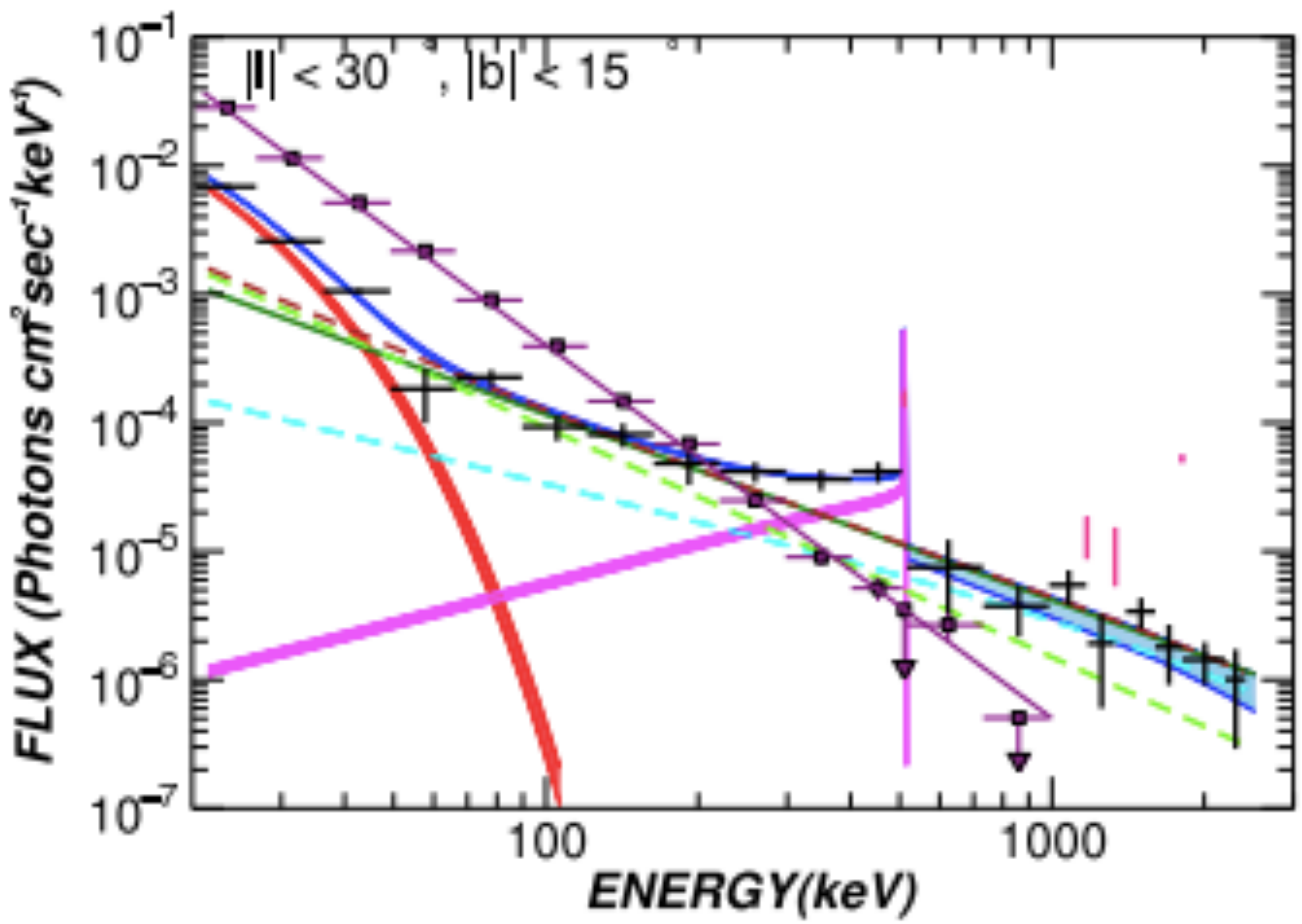
- The total diffuse gamma-ray emission is coarsely binned in latitude, longitude and energy
- We employ these results for our main constraints



INTEGRAL data from the sky-modeling approach

- The authors of 1107.0200 also present results for the spectrum of each diffuse-emission template, and the summed spectrum, in the region |l|<30°, |b|<15°

- These data give stronger constraints on a PBH signal, but there is a potentially large systematic uncertainty, since this spectrum does not account for all observed photons, only those following a specific (not DM-like) spatial morphology

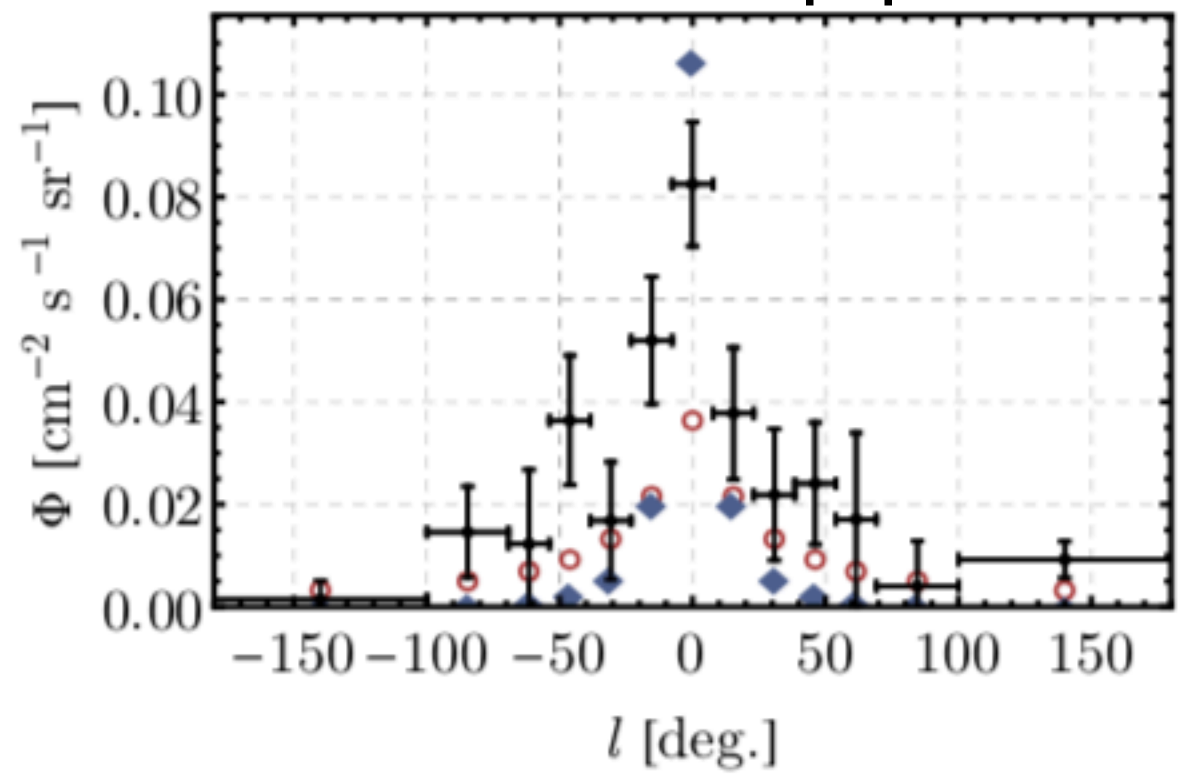


- These data were employed by Essig et al 1309.4091 to set bounds on light annihilating/decaying DM - we will revisit these limits

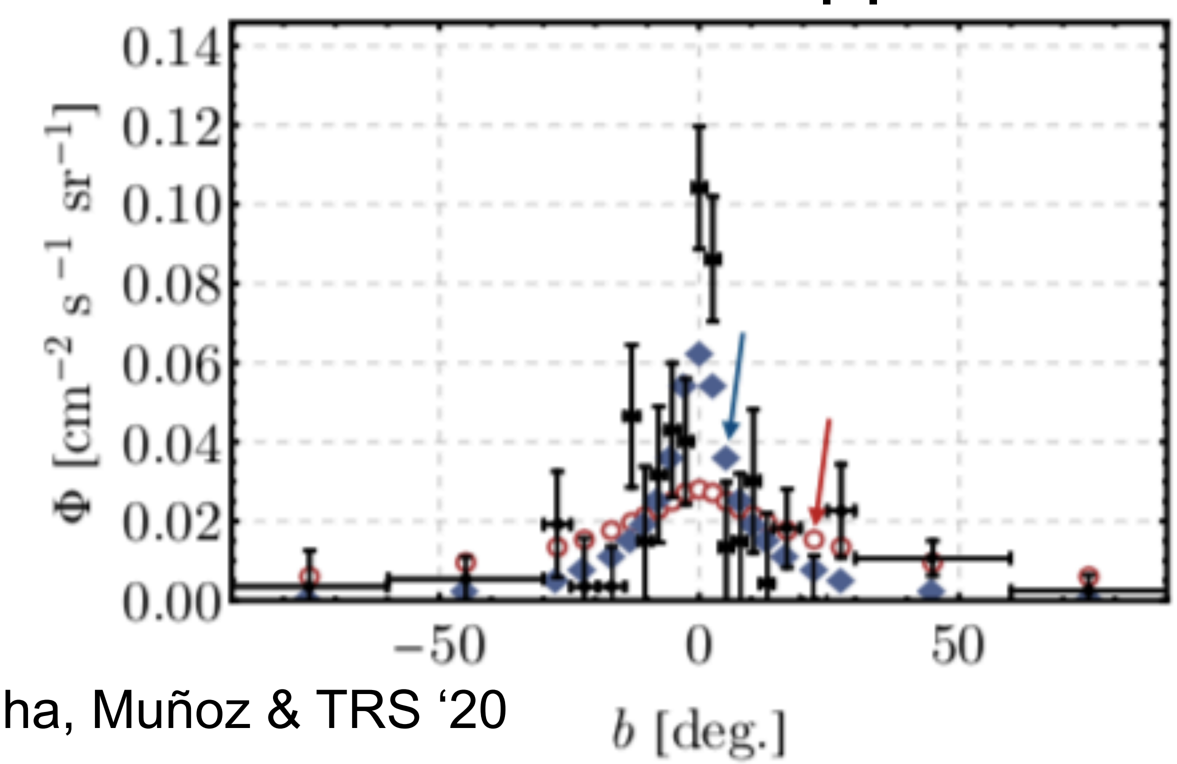
INTEGRAL data vs PBH decay signal

- We consider the INTEGRAL-SPI sky-imaging dataset for diffuse emission as a function of Galactic position
- Energy bin boundaries are E/MeV = [0.027, 0.049, 0.1, 0.2, 0.6, 1.8]
- We require that the PBH signal not overproduce any data point by more than 2x the error bar
- Stronger constraints could be obtained by simultaneously modeling the signal + astrophysical background

200-600 keV, |b|<6.5°



200-600 keV, |l|<23.1°

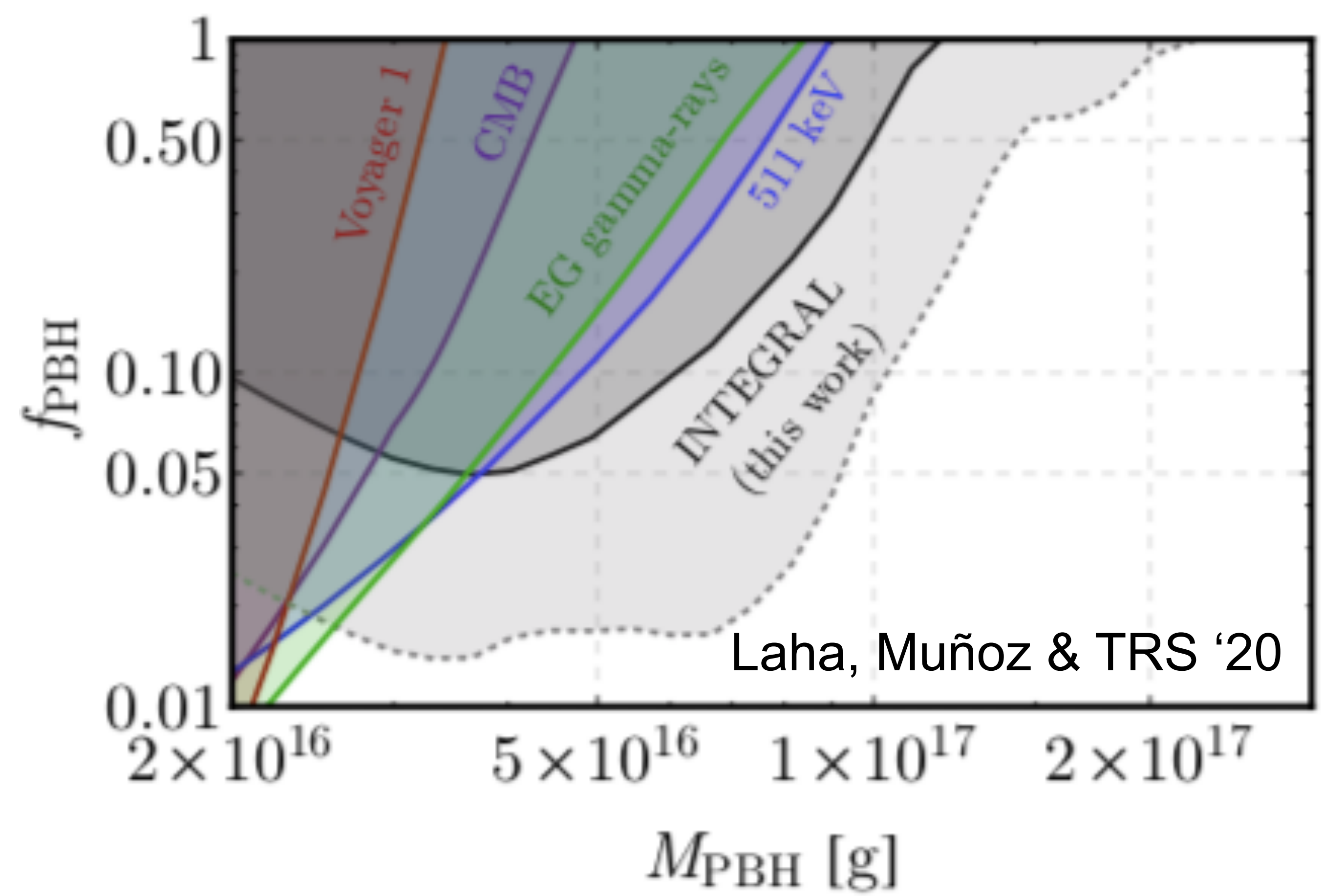


Laha, Muñoz & TRS ‘20

New constraints on PBHs

- We exclude f=1 for M_{PBH} < 1.2×10^{17} g, for our baseline assumptions.

- Our limits do not change if the NFW profile has a flat-density central core of radius up to 5 kpc.

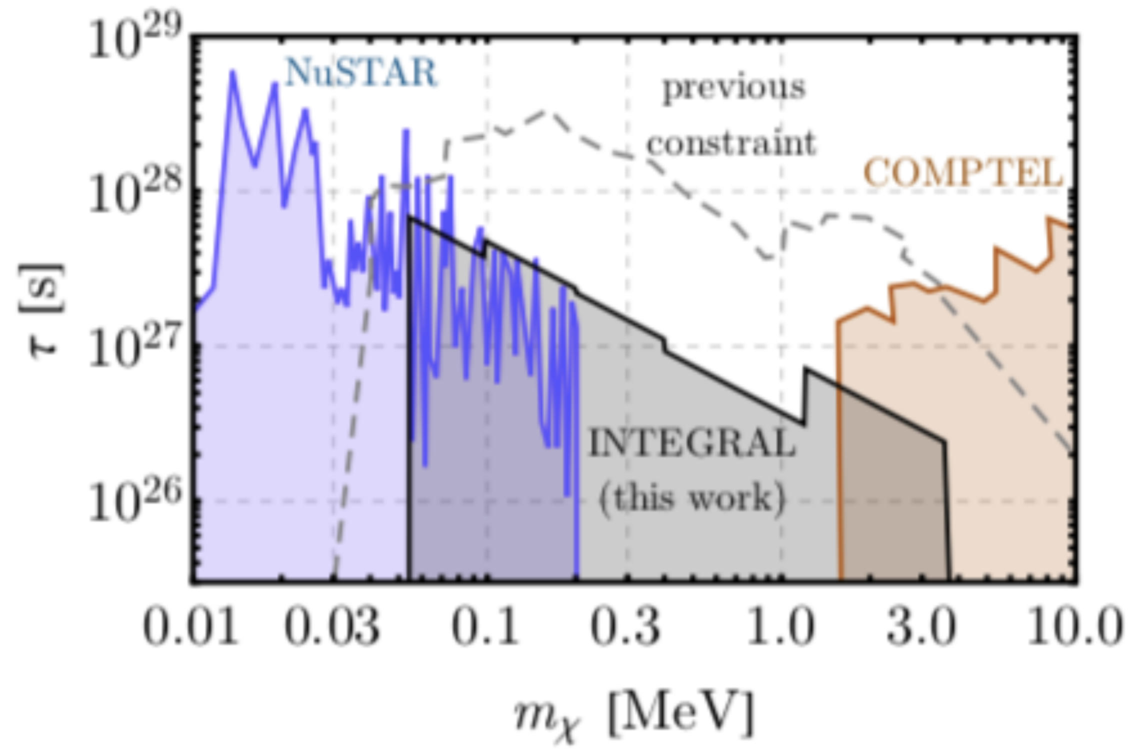


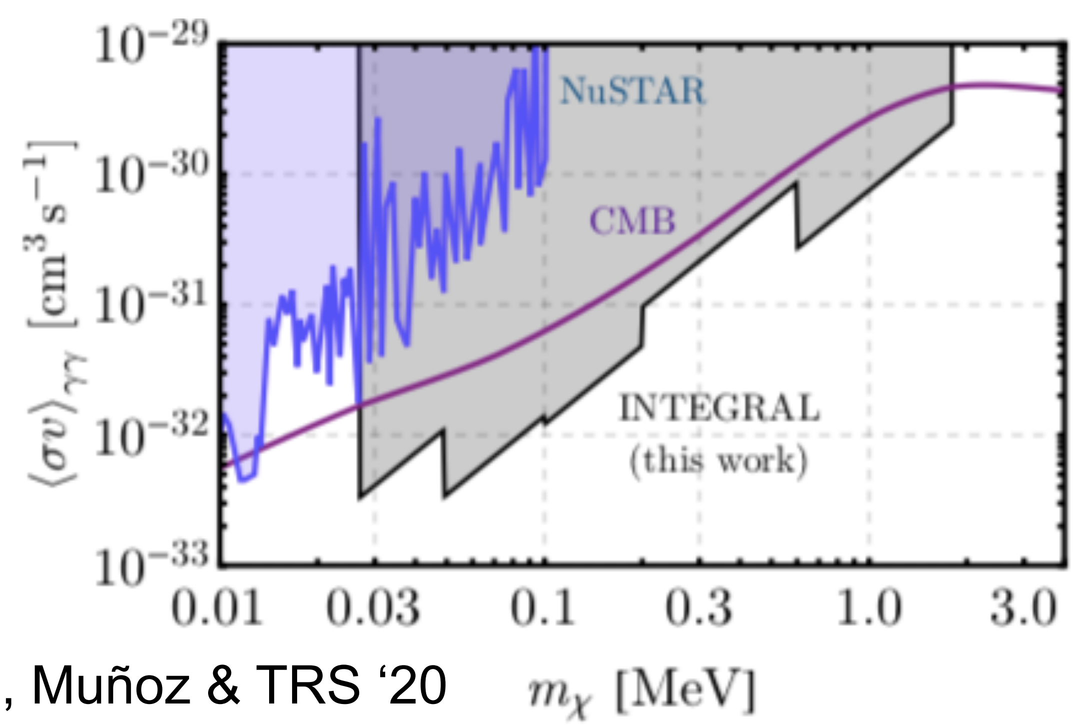
- We also tested the results of using the alternative SPI dataset (based on template fitting) assuming the sum of the templates provides an upper limit for the DM signal [as in Essig et al 1309.4091].

- In this case we find a stronger bound, excluding f=1 for M_{PBH} < 2×10^{17} g.

Updated constraints on decaying/annihilating DM

- We can perform the same analysis for photons from decay/annihilation of particle DM
- For DM with mass in the INTEGRAL energy range, INTEGRAL can provide the strongest bounds on annihilations/decays to photons (in agreement with previous studies)
- However, our limits are weaker than those previously claimed [Essig et al ’13] as (a) that work included extragalactic (isotropic) signal contributions, (b) it used the data obtained from an astrophysical template fit, as discussed earlier





Laha, Muñoz & TRS ‘20

Conclusions

- Using existing X-ray and gamma-ray data, we can probe thermal relic annihilation cross sections up to O(100) GeV (and much lower cross sections for lower masses), and decay lifetimes up to 10^{27-28} s for DM decaying to photons across a broad mass range.

- Very conservative analyses of coarsely-binned INTEGRAL data already provide the best limits on O(10^{17} g) PBHs, as well as decay/annihilation of DM to photons in the 30 keV-MeV DM mass range.

- A more detailed analysis of INTEGRAL data, including astrophysical background models and exploiting the full energy and angular resolution, could potentially significantly improve the sensitivity

- Future experiments covering the O(MeV) energy range (e.g. AMEGO) may be able to improve these limits even further

- Due to the steep M_{PBH} scaling of the evaporation signal, alternative probes will be needed to cover the current “gap” extending up to 10^{23} g

BONUS SLIDES

Probing asteroid-mass PBHs

- Previous attempts to constrain this region have exploited [see e.g. 1906.05950 for a discussion]:
  - femtolensing of gamma-ray bursts (challenged due to not taking source extension into account),
  - the possibility of PBHs to trigger white dwarf explosions (found to be ineffective),
  - PBH capture onto neutron stars and white dwarfs (relies on assumptions about DM density in dense stellar systems, such as globular clusters).
- At present none of these limits seem to constrain the possibility of PBHs being 100% DM, although stellar disruption by captured PBHs might be constraining in the future
- How far can we push up the low-mass limit from Hawking evaporation?
- At present the bound is around $M \sim 10^{17}$ g - corresponds to peak of emission in the hard X-ray / soft gamma rays, O(100) keV

Predicting the PBH signal

- M_{PBH} controls both the signal spectrum and the overall signal strength
  - Peak energy $E \approx 5.77 T_{\rm BH} \approx \left(\frac{10^{17}\mathrm{g}}{M_{\rm PBH}}\right) 0.4\mathrm{MeV}$
  - Decay rate scales as $1/M_{PBH}^3$, PBH density as f/M_{PBH}
- We also need to know the DM density in the region of interest; by default we assume a NFW profile with local DM density 0.4 GeV/cm^3
- Changing the DM density directly rescales the constraint on the PBH DM fraction f (the strong scaling with M_{PBH} means the constraint on M_{PBH} is usually much less affected)

The DM density profile

- The DM density profile in the Milky Way is not well known toward the Galactic Center, where baryonic matter comes to dominate the potential
- The DM local density can be measured by observing stellar motions, but still has large uncertainties / scatter between different methods
- N-body simulations suggest DM density should rise toward GC (following the NFW or Einasto forms), but flatten out at some “core” radius
- Core size depends on details of baryonic physics - but from current simulations, expected to be ~1-2 kpc or smaller in the Milky Way
- We take the Earth-GC distance to be 8.3 kpc