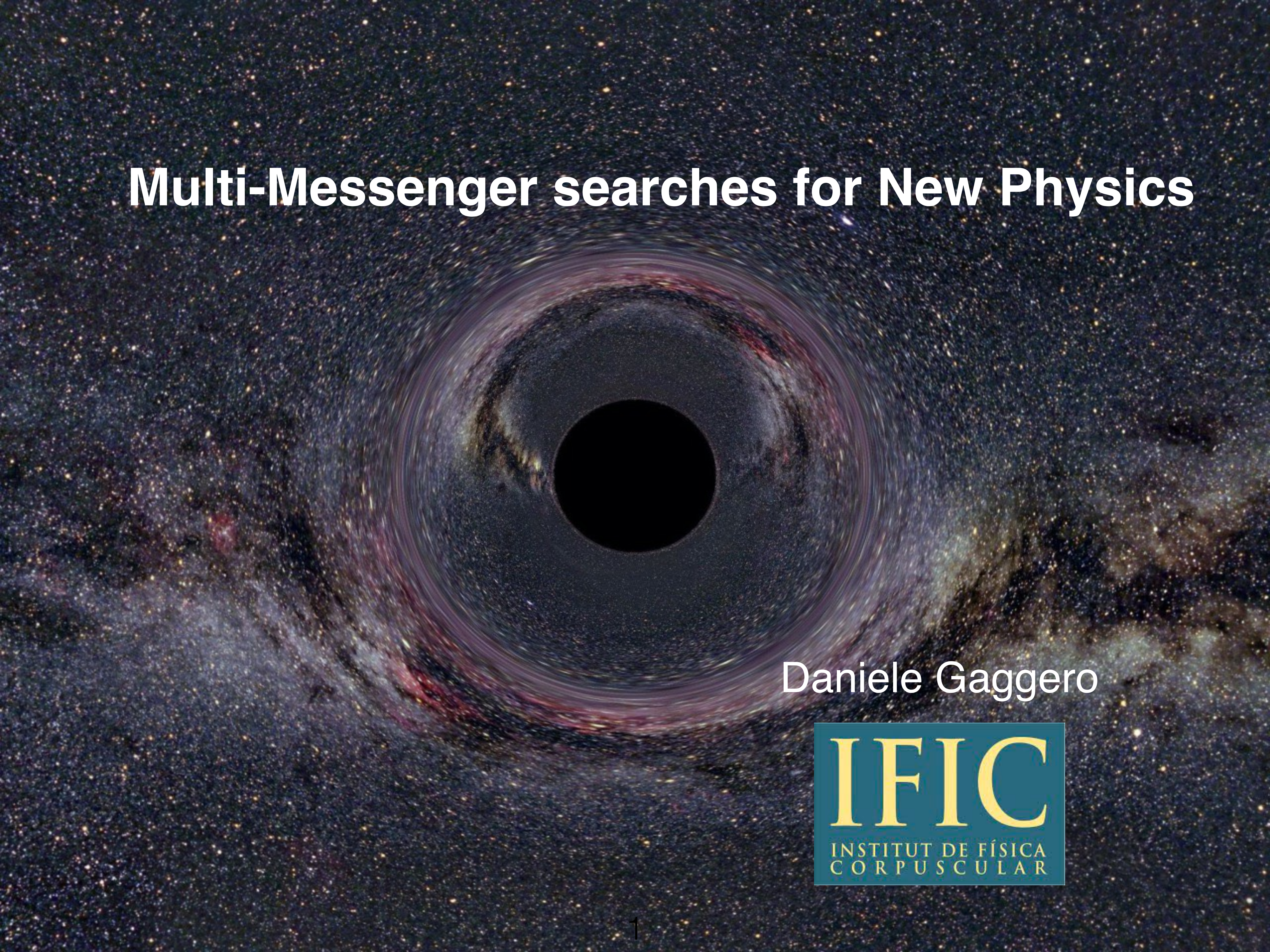
Multi-Messenger searches for New Physics



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The neverending quest for new (astro)physics based on multi-wavelength and multi-messenger astronomy

- **A plethora of messengers from highly energetic events**
  - Charged *CRs*
  - High-energy *photons* - from keV to PeV domain -
  - Gravitatational waves
- **All these messenger originate from events characterized by a very high release of energy**
  - Reveal aspects of *particle acceleration and transport* in turbulent environments, (astro)physics of *compact objects*…
  - *Portals to new physics?* In particular, can shed light on the Dark Matter problem

The Dark Matter problem: Candidates

10^{-22} eV

Axion-like particles

1 GeV 1 TeV

10^{19} GeV (10^{-5} g)

10^{57} GeV (10^{33} g)

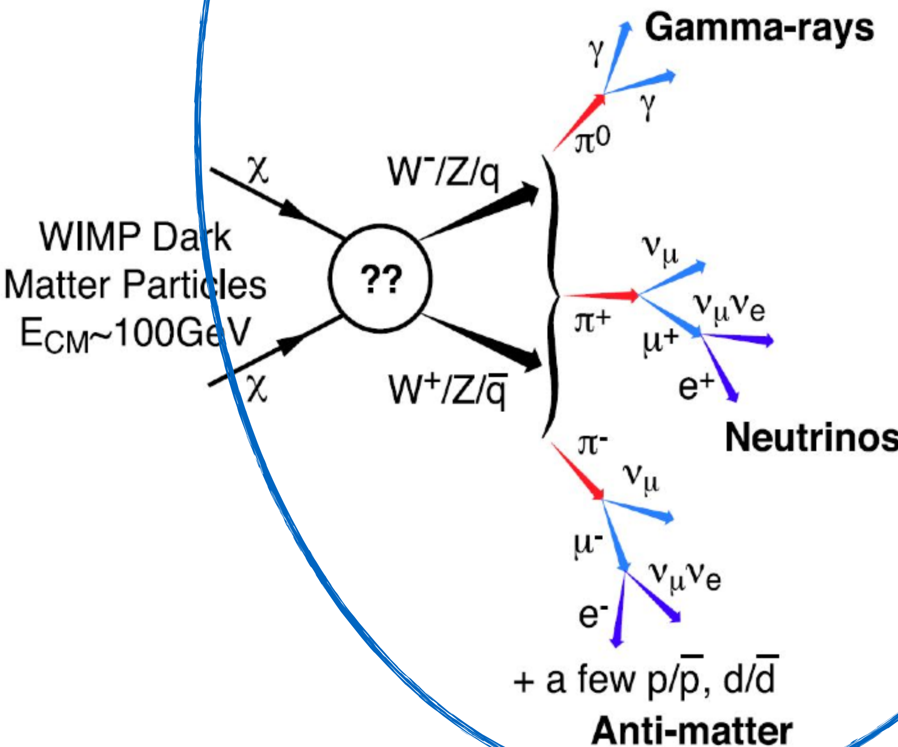
"Fuzzy" Dark Matter

λ_{dB} ~ 1 kpc ~ size of a dSph Galaxy

[Hui, Ostriker, Tremaine, Witten 2016]

Weakly interacting massive particles (WIMPS)

e.g. lightest neutralino state in MSSM



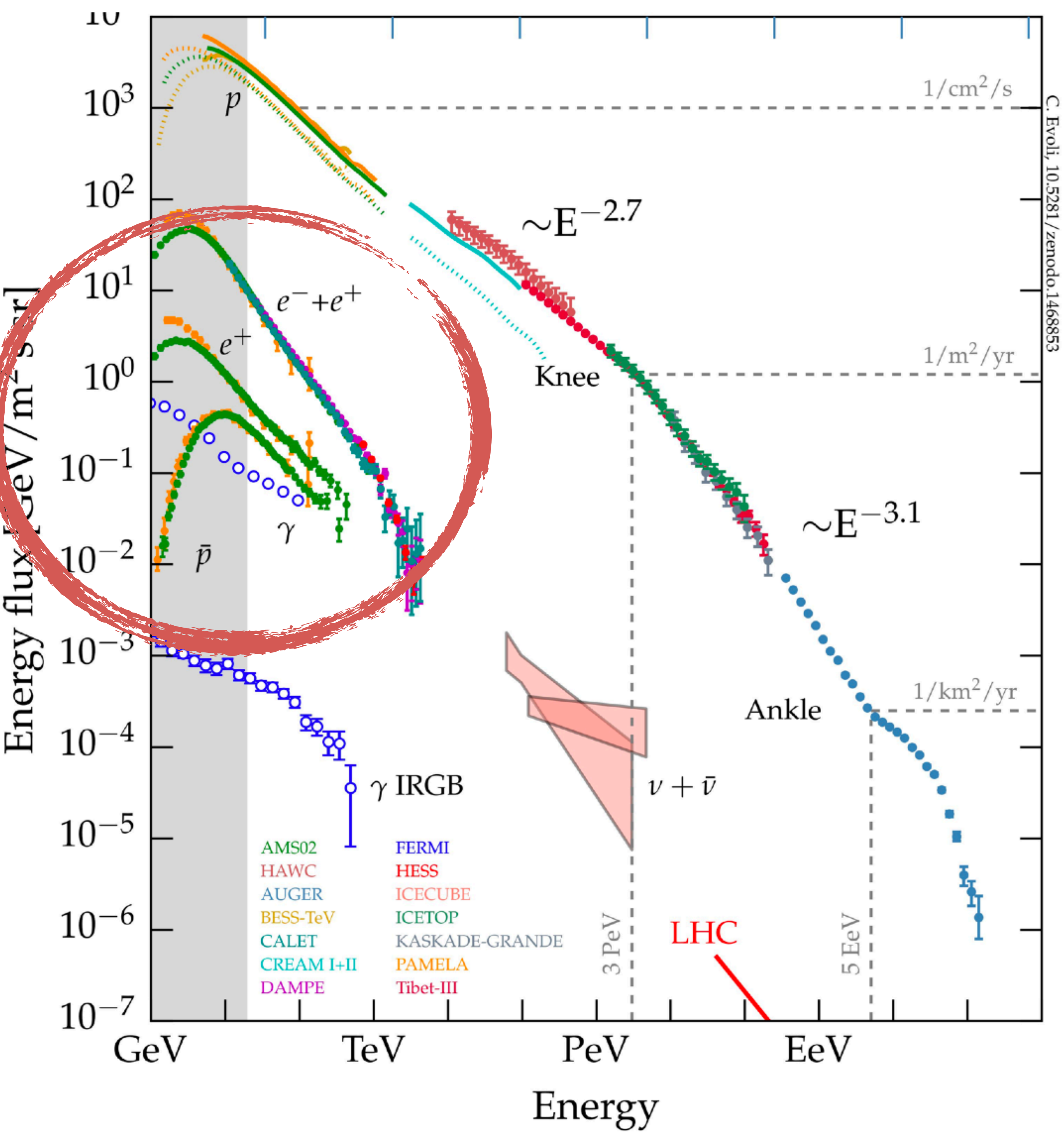
Primordial black holes (PBHs)

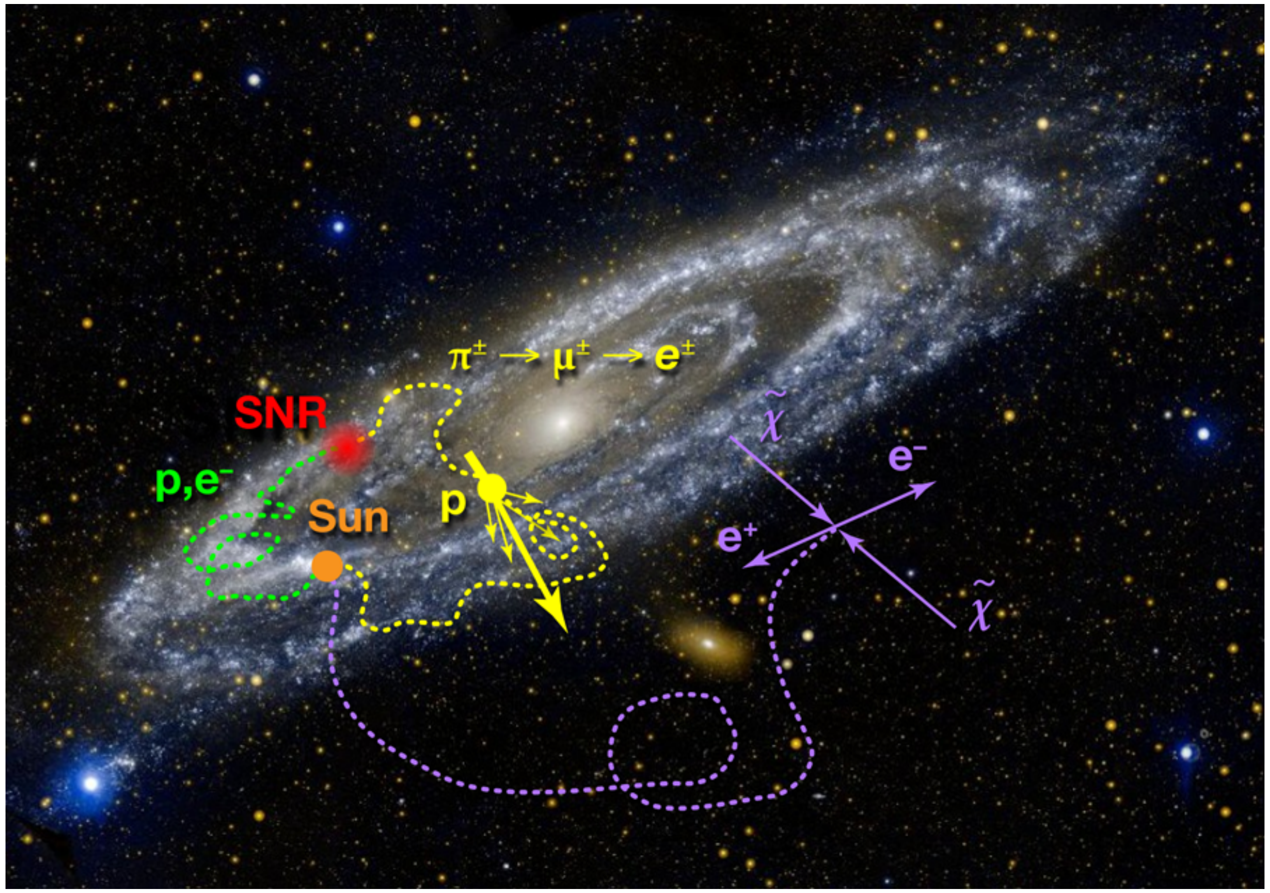
Proposed more than 40 years ago *[Zeld'ovich and Novikov 1966, Hawking 1971]*

1st wave of popularity following microlensing hints by MACHO collaboration *[Alcock et al. 1997]*

Recently **reconsidered in the DM community**

- Focus on Antiparticles. **Relevant channels: antiprotons, positrons.**



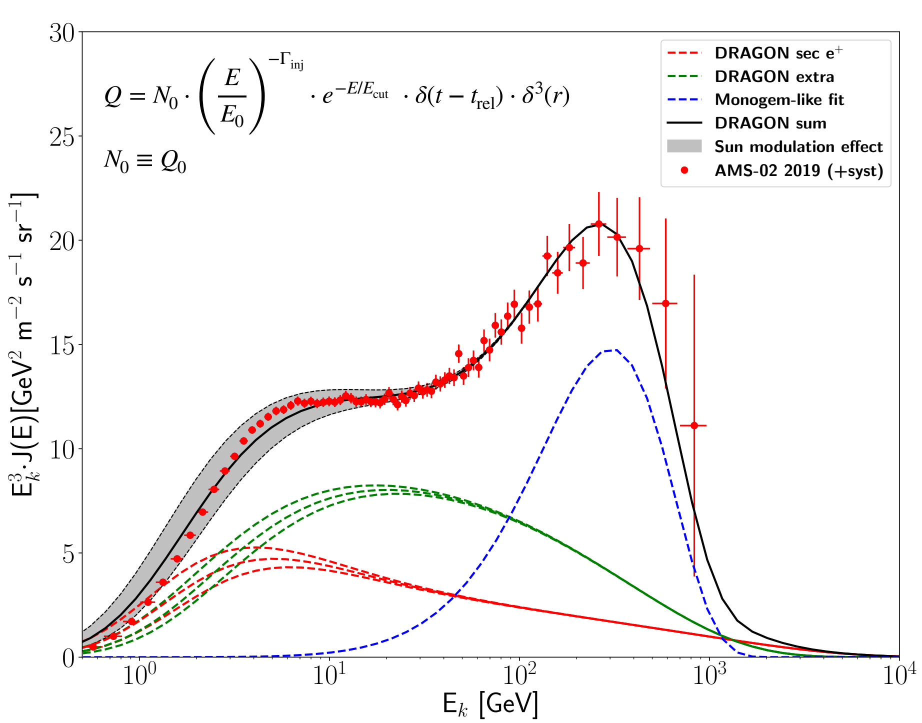


Charged CRs and the WIMP quest

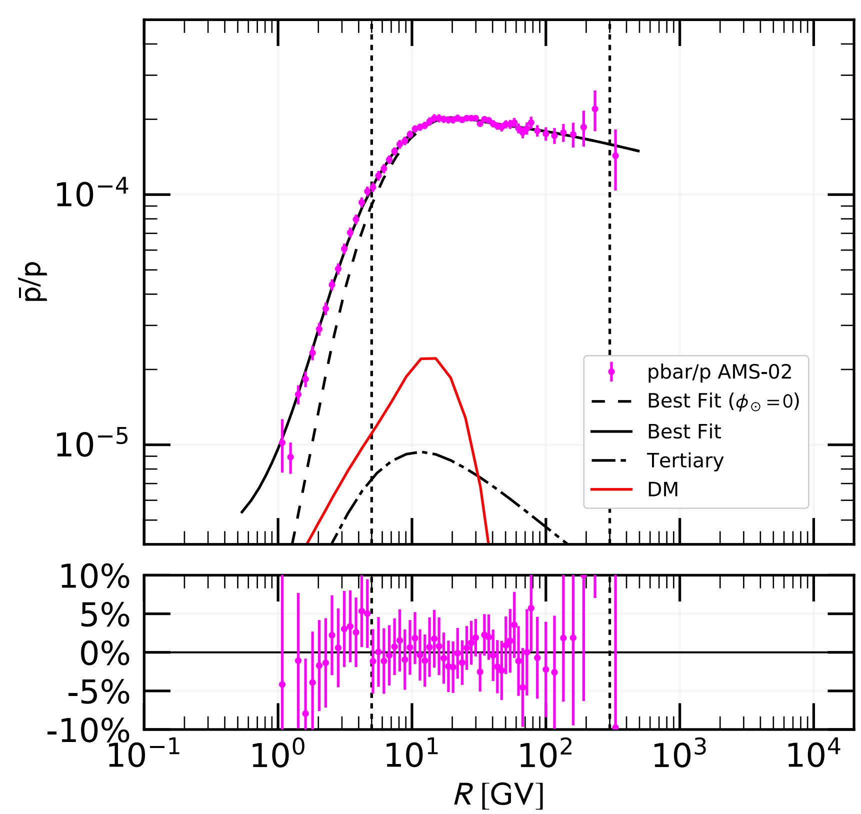
- Several anomalies were discussed in both channels.

Anomalies with respect to what?

- **Orthodox picture:** Bulk of CRs accelerated by SNRs. Antiparticles mostly secondary. Transport parametrized by (scalar) diffusion equation.
- Anomalies may be hints of “new astrophysics”, mismodeling of background… we have to be *very careful*!

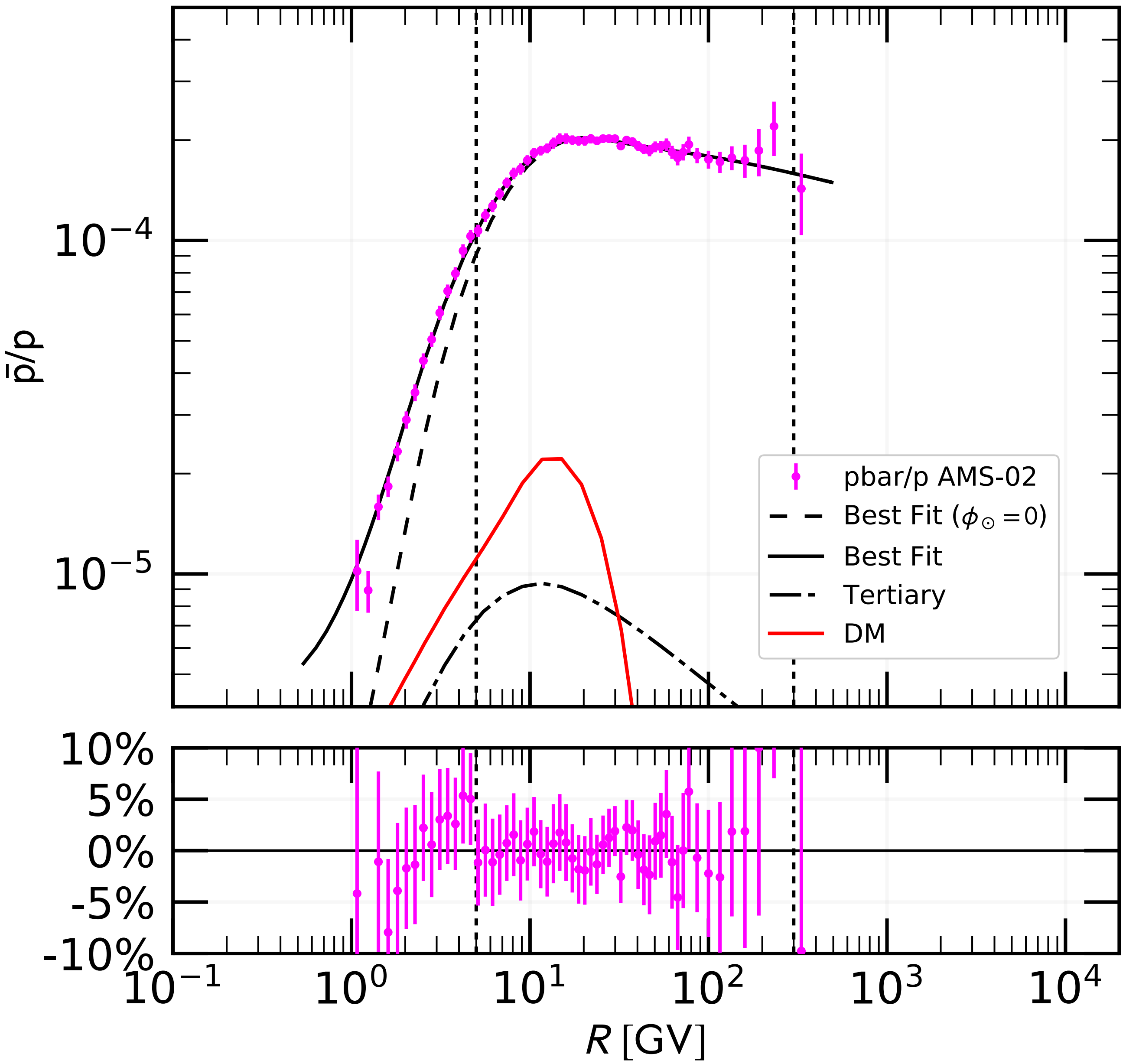


arXiv:1907.03696



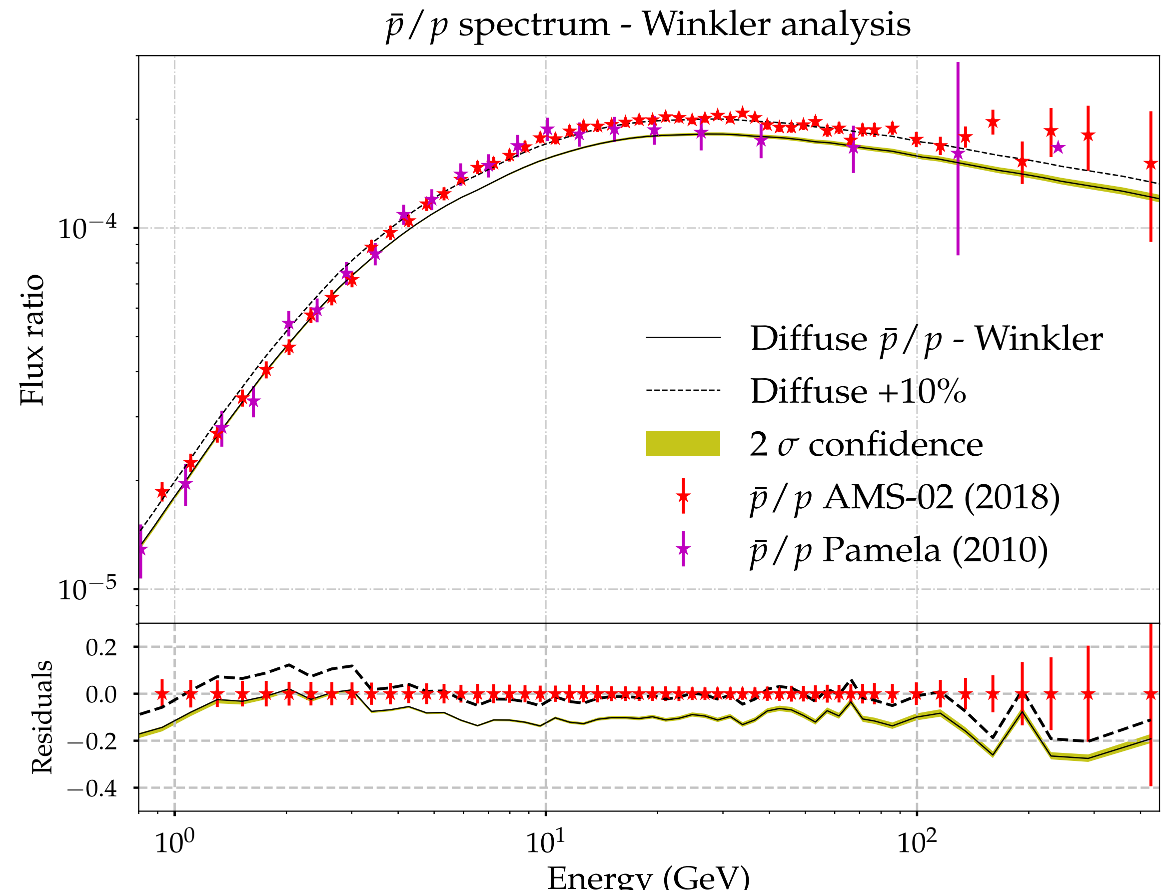
arXiv:1903.01472

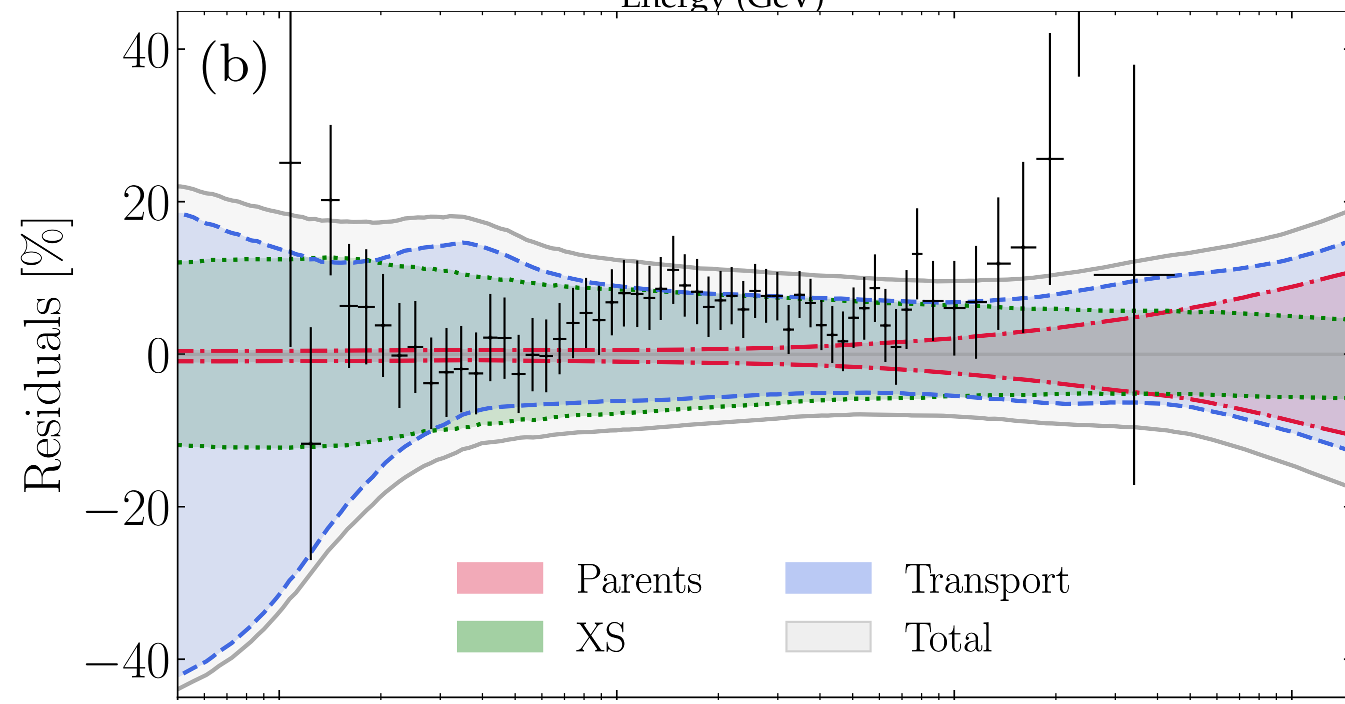
Focus on antiprotons: A DM hint? Role of uncertainties?



Cuoco+ 1610.03071
Cuoco+ 1903.01472
Cholis+ 1903.02549

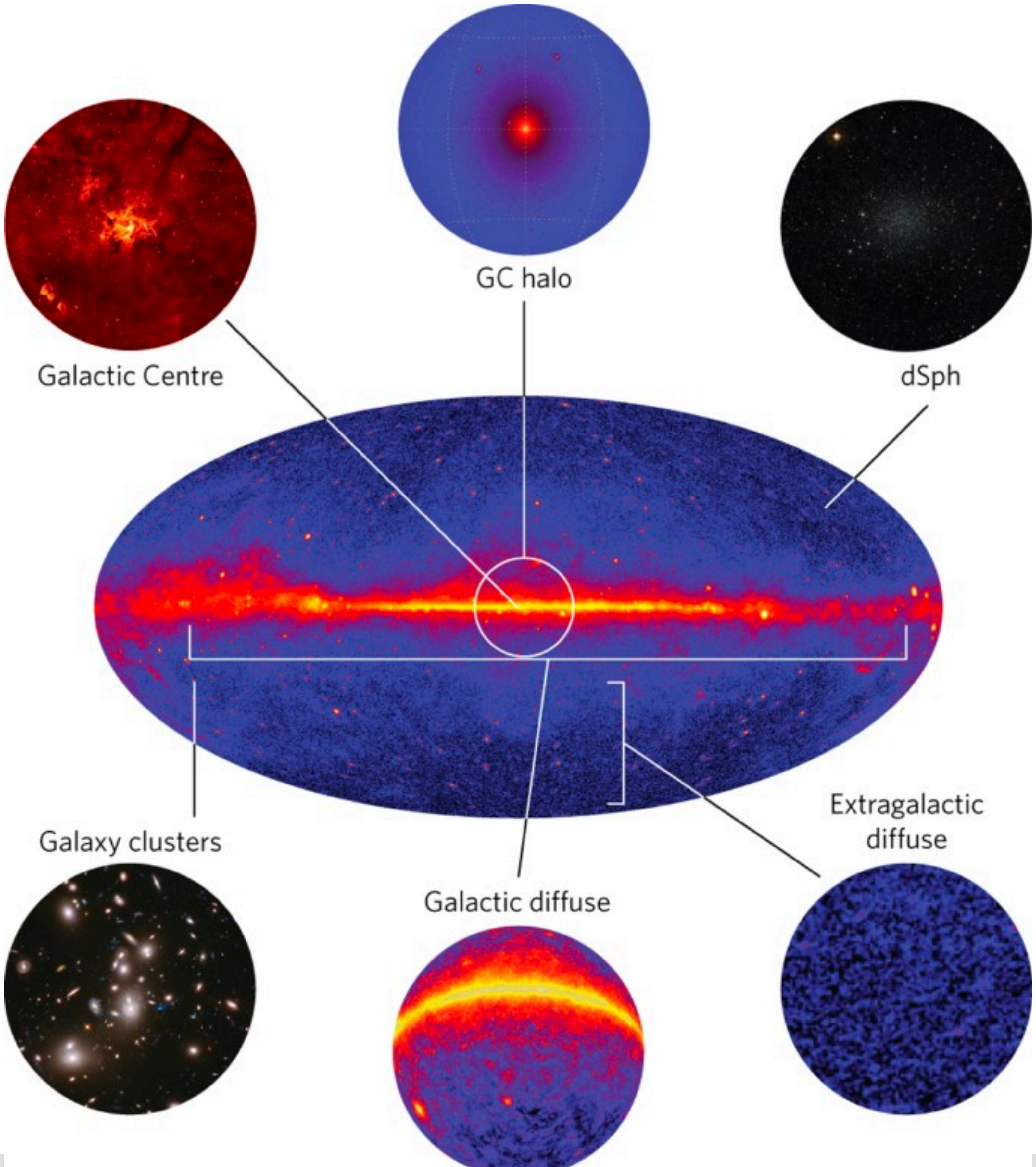
De La Torre arXiv:2107.06863



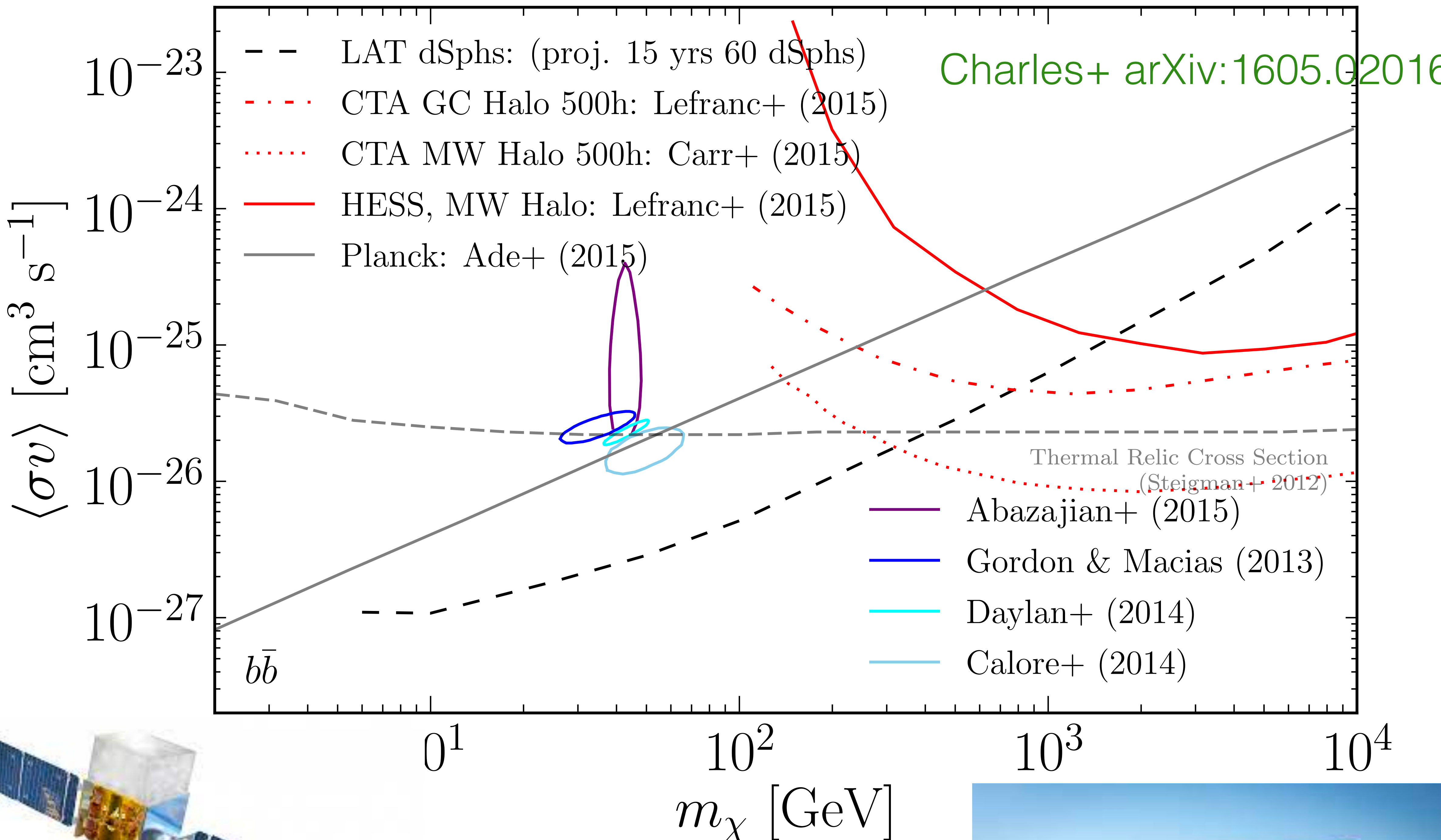


Boudaud+ arXiv:1906.07119

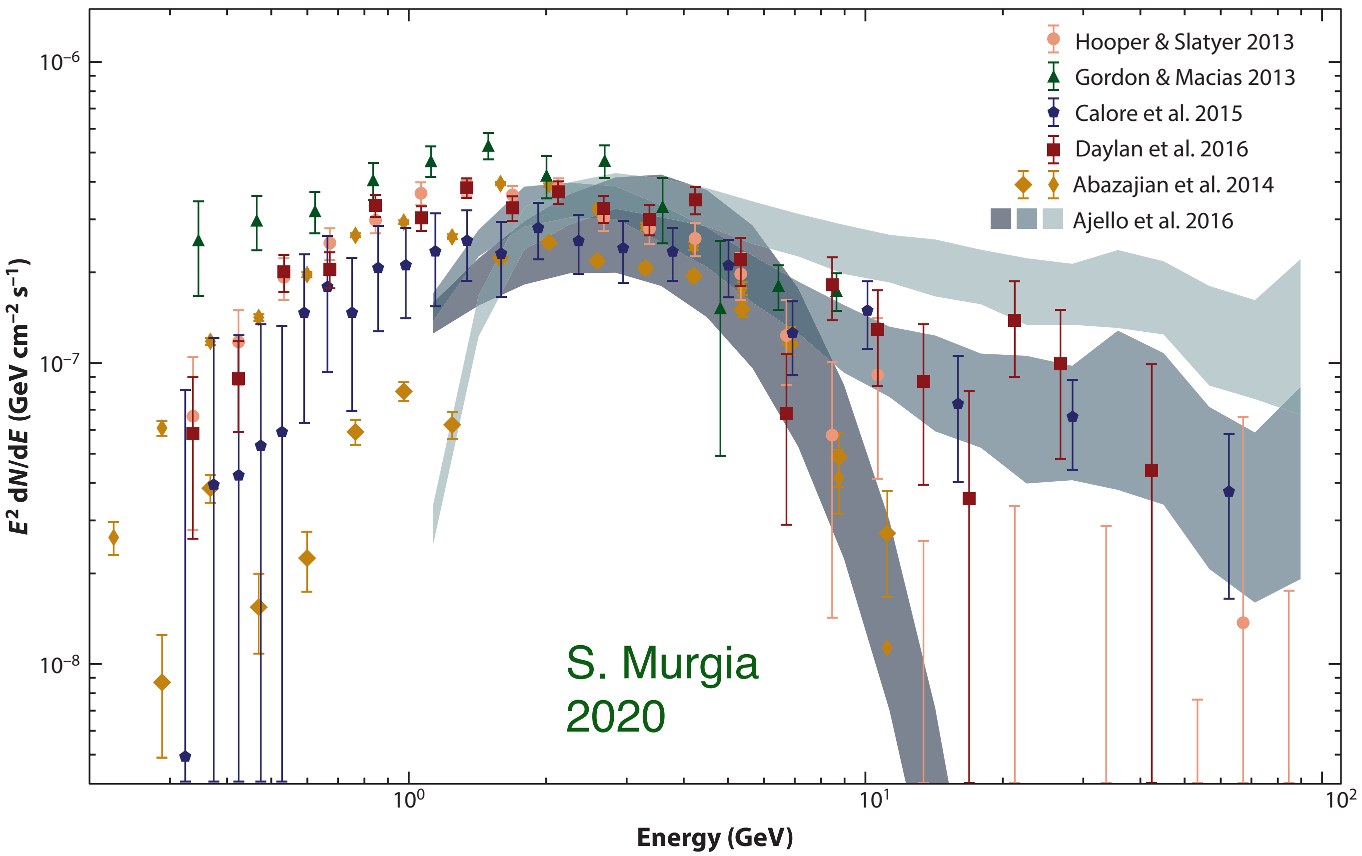
Gamma rays: GeV domain. Targets

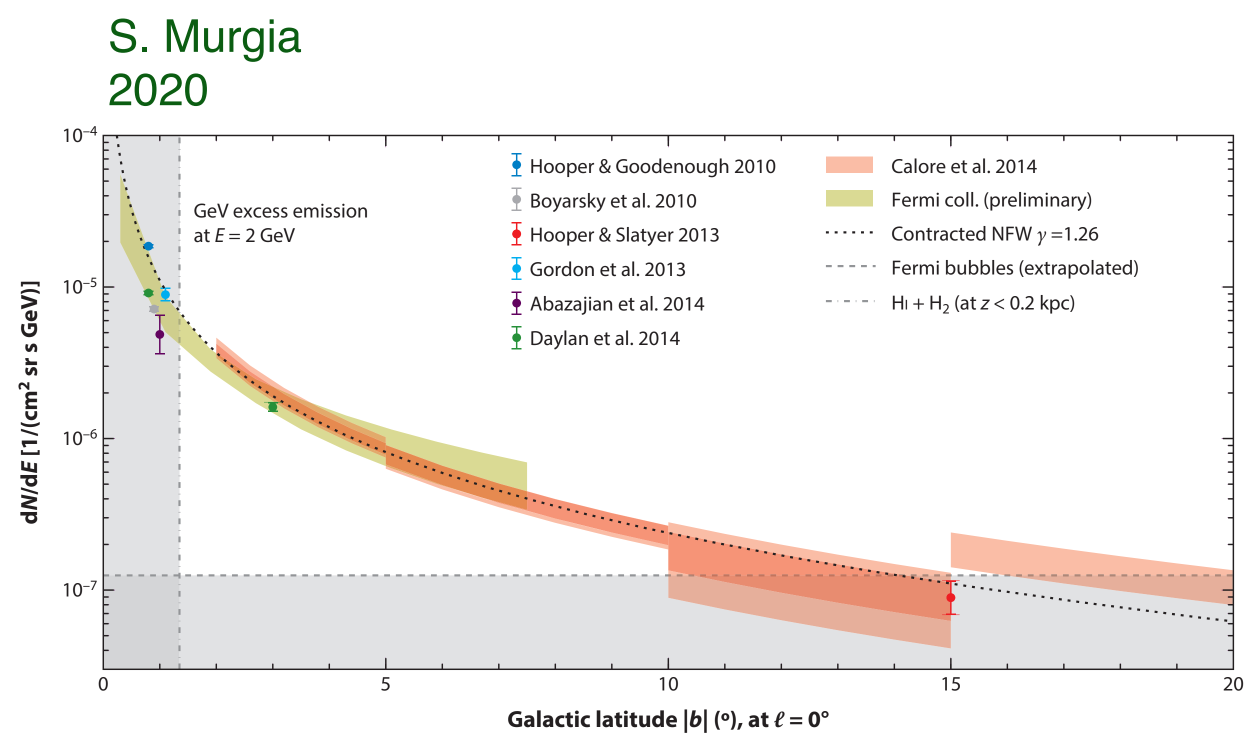


Gamma rays: GeV domain. Claims and bounds. State of the art (pre-CTA)



Gamma rays: GeV domain. Claims and bounds: The GC excess

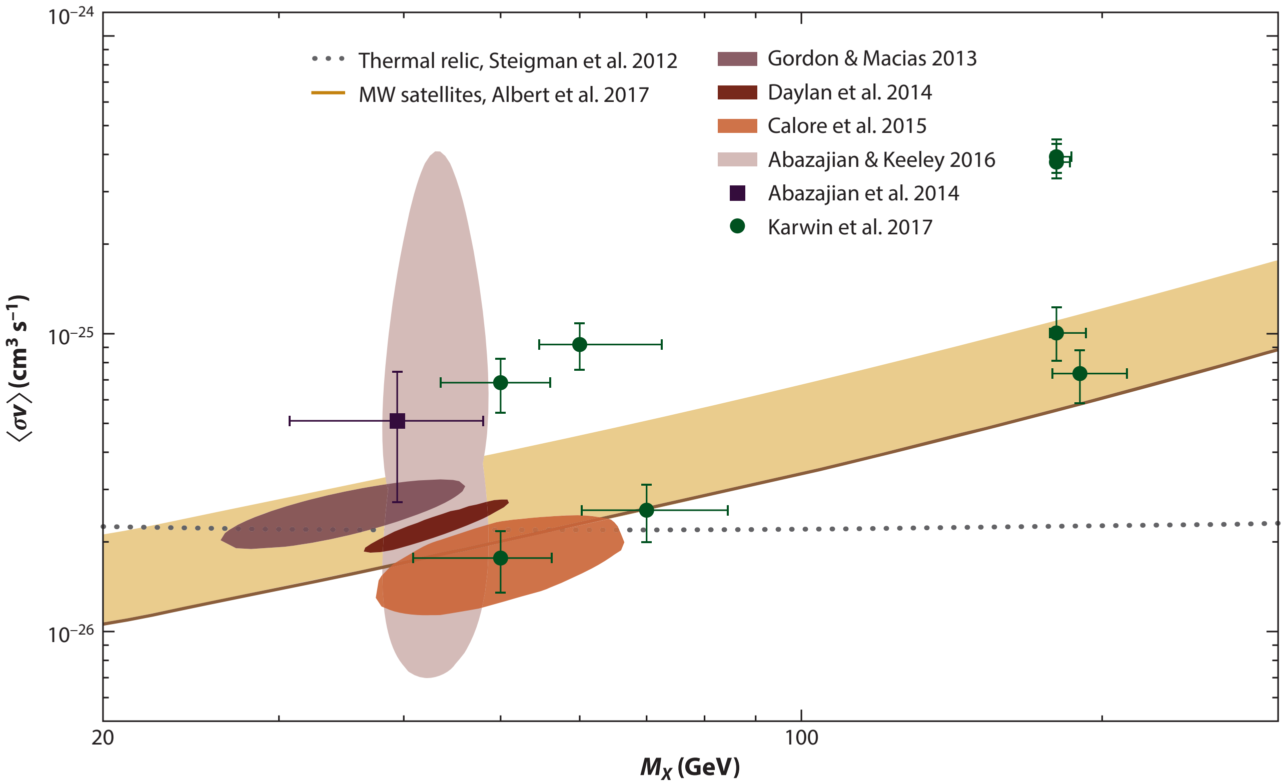




- An extended, spherical **signal** from the **inner Galaxy**
- Outlined by a ***template fitting*** technique
- **DM interpretation**: M_{DM} ~ *30* GeV; σ_{ann} close to thermal cross section
- Very rich literature!

D. Dixon et al. 1998 [arXiv:9803237]; V. Vitale et al. 2009 [arXiv:0912.3828]; L Goodenough and D. Hooper, 2009; D. Hooper and L. Goodenough, 2010 D. Hooper and T. Linden, 2011; K. N. Abazajian and M. Kaplinghat, 2012 D. Hooper and T. R. Slatyer, 2013; C. Gordon and O. Macias, 2013 T. Daylan, D. P. Finkbeiner, D. Hooper, T. Linden; S. Portillo, N. L. Rodd and T. R. Slatyer, 2014 [arXiv:1402.6703]; F. Calore, I. Cholis, C. Weniger, 2014 [arXiv:1409.0042]; F. Calore et al. 2015 [arXiv;1411.4647]

Gamma rays: GeV domain. Claims and bounds: The GC excess



- **DM interpretation**
tension with constraints from dwarf spheroidal galaxies?
connection with other channels?

- **MSP interpretation**
suggested by wavelet analyses and photon statistics

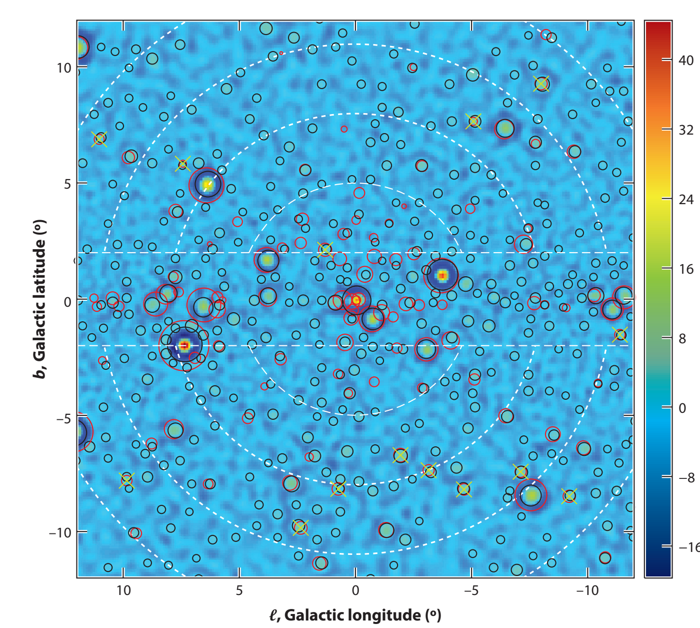
R. Bartels et al. 2016 [1506.05104]
S. Lee et al. 2016 [1506.05124]
F. Calore et al. 2021 [2102.12497]

- **Is it really an excess** (normalization issues)**?**

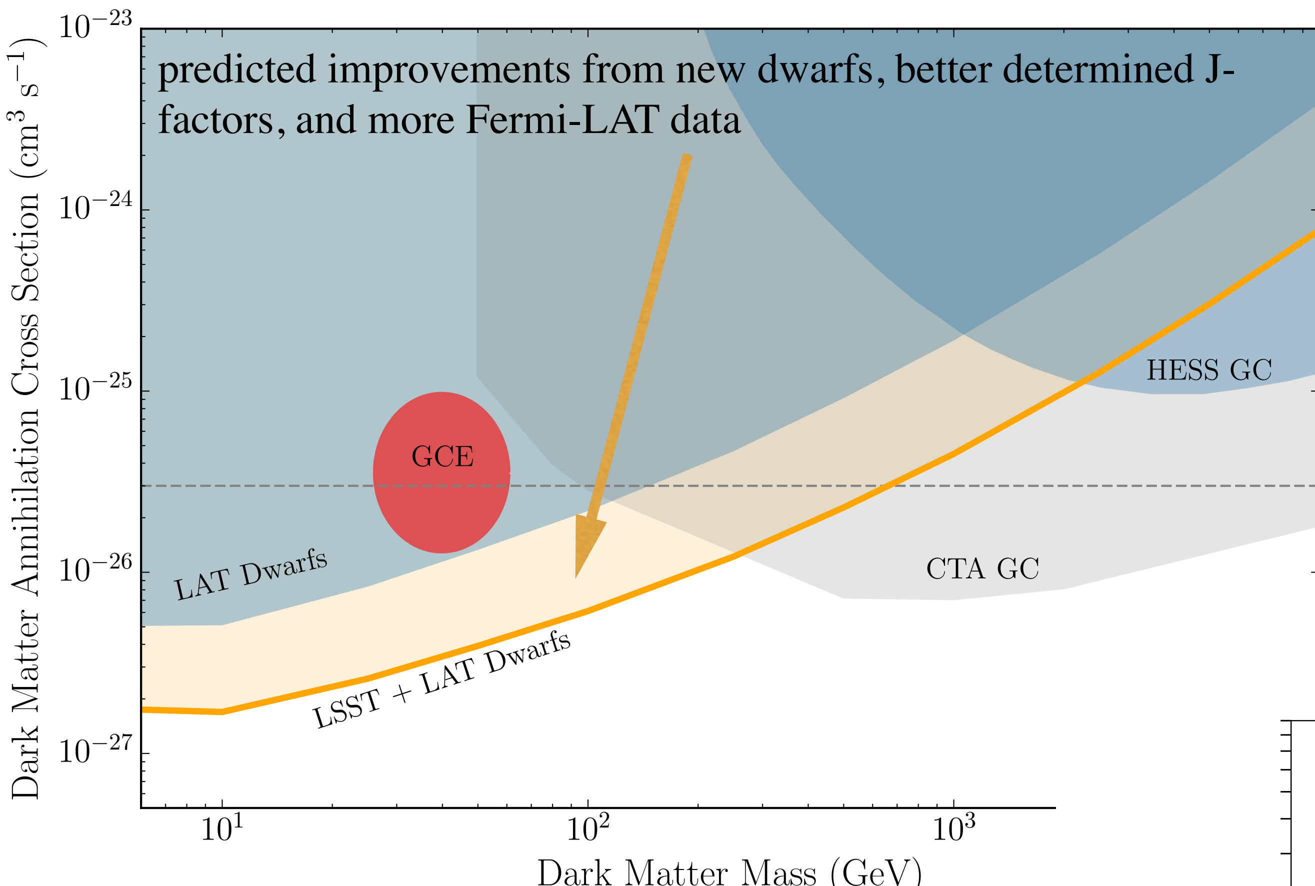
D. Gaggero et al. 2015 [1507.06129]
E. Carlson et al. 2015 [1510.04698]

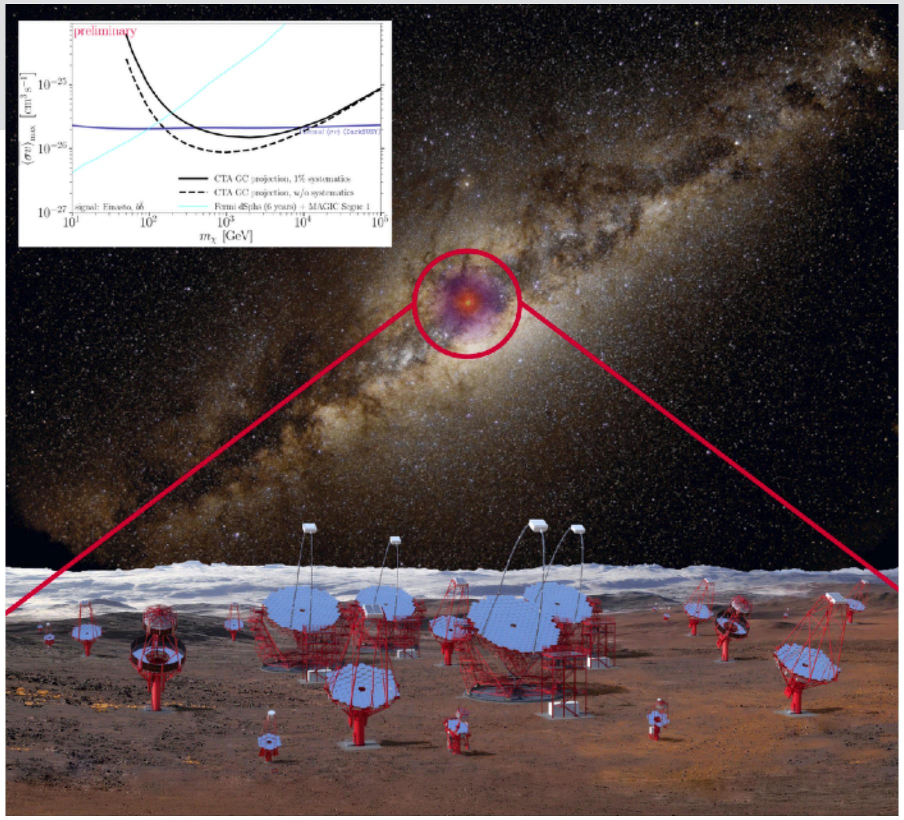
- **Is it really spherically symmetric** (morphology issues)**?**

R. Bartels et al. 2017 [1711.04778]
O. Macias et al. 2017 [1611.06644]



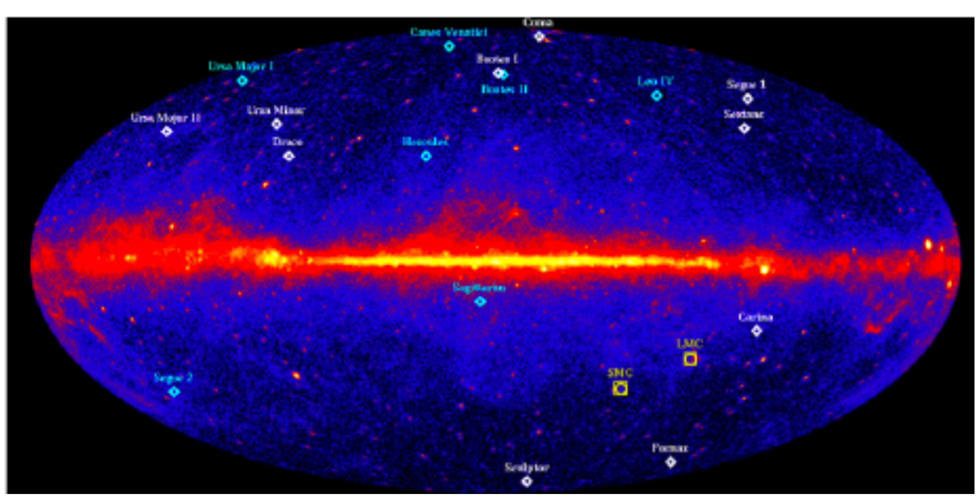
Gamma rays and WIMPs: future prospects (LSST+LAT, CTA)

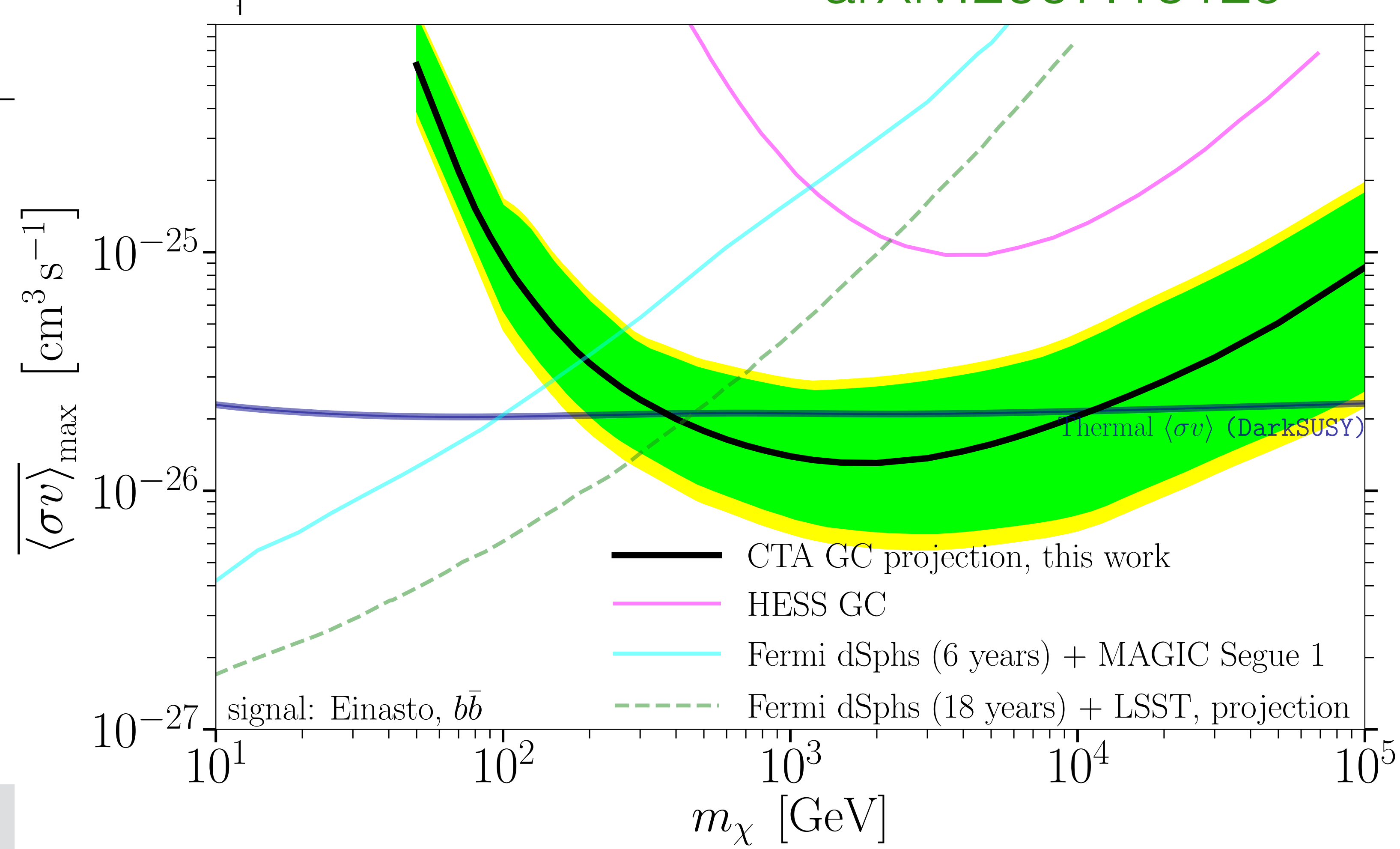




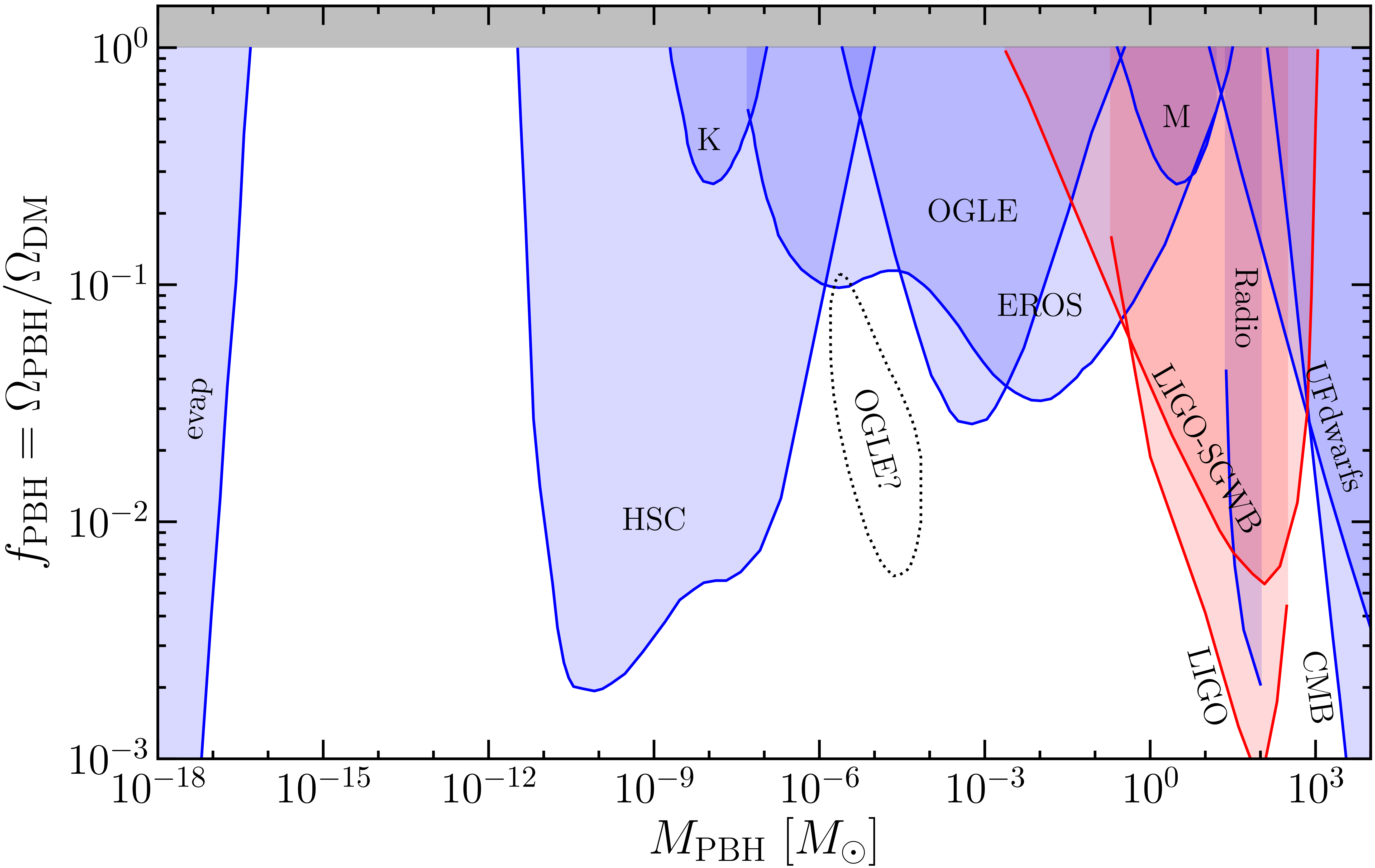
arXiv:2007.16129

arXiv:1902.01055

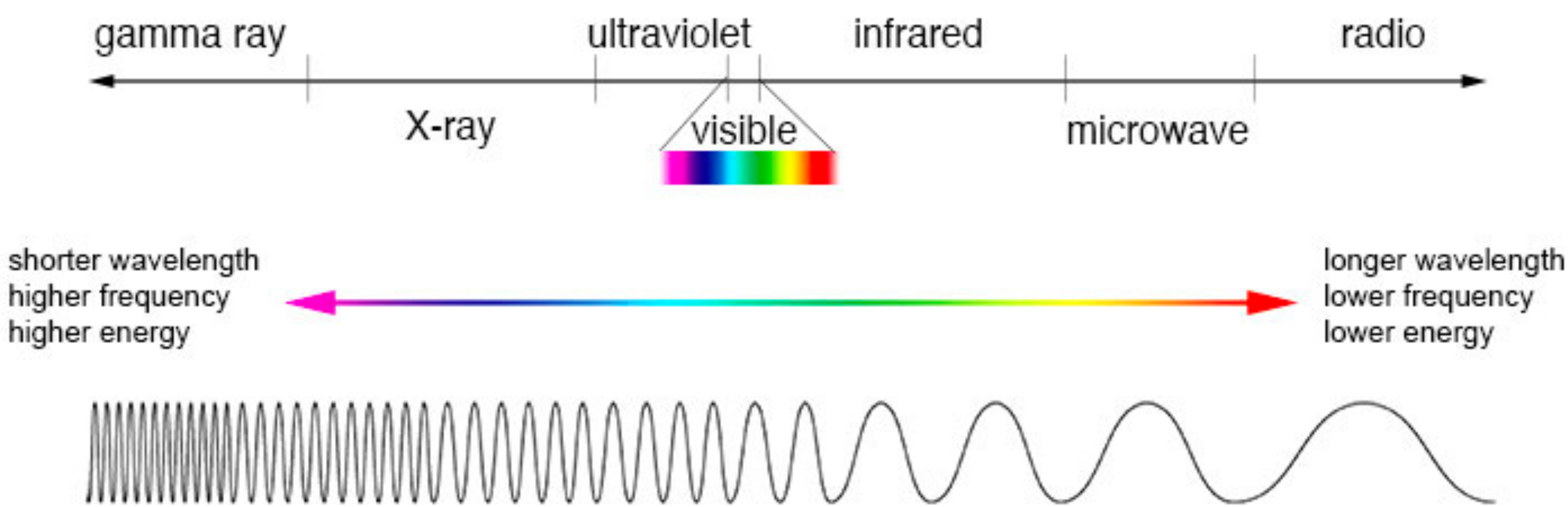




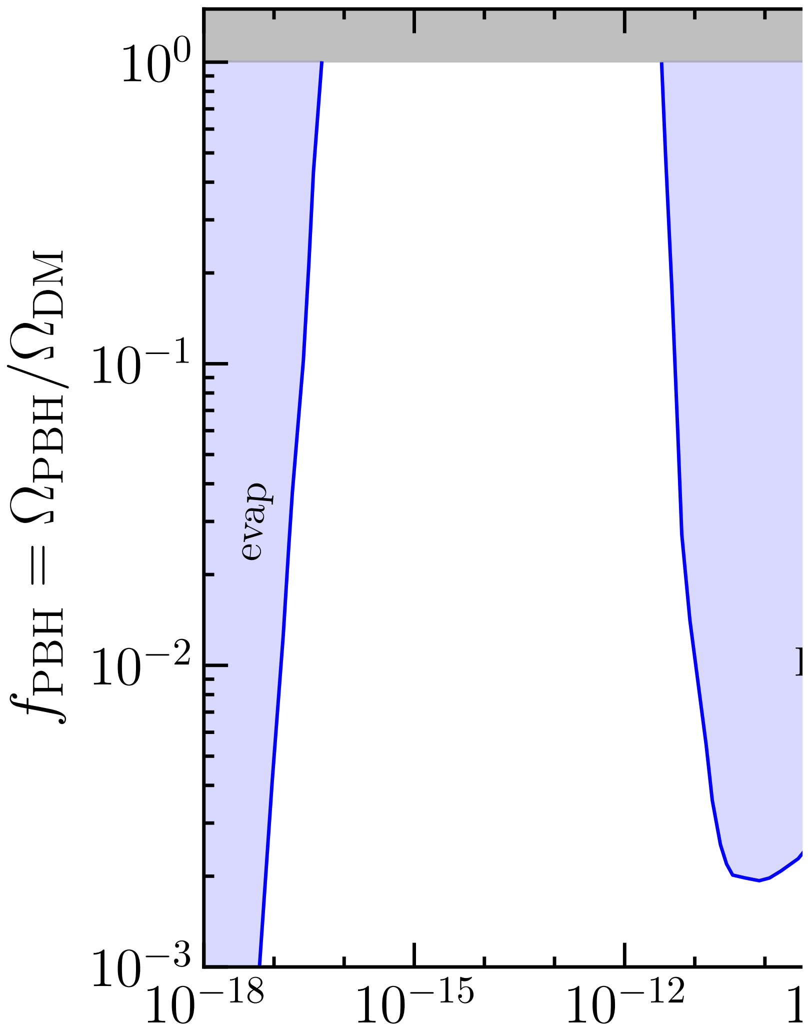
The Primordial Black Hole quest…



…and the low-energy part of the e.m. spectrum



Low-energy gamma rays and Black Holes: Evaporation



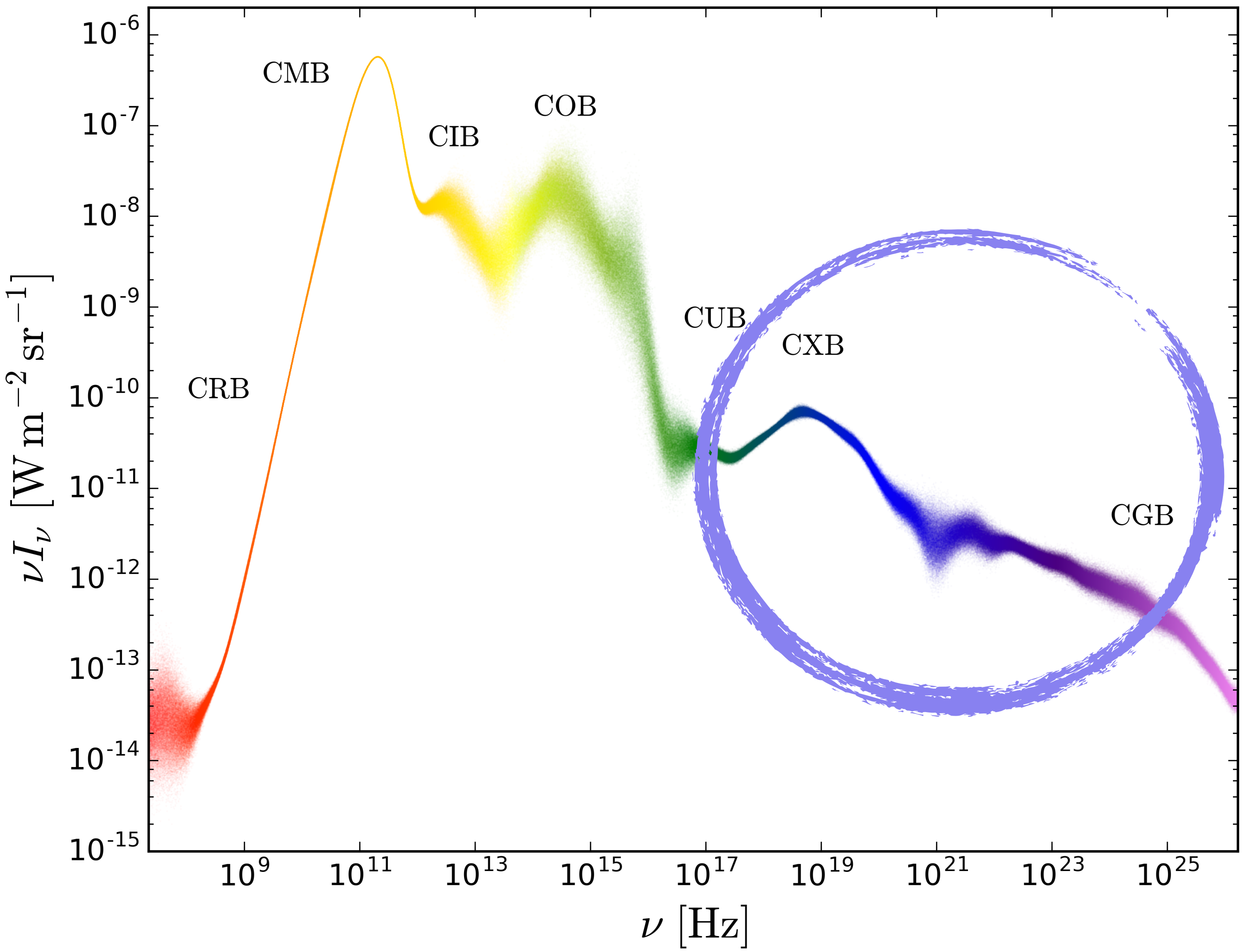
An open window!

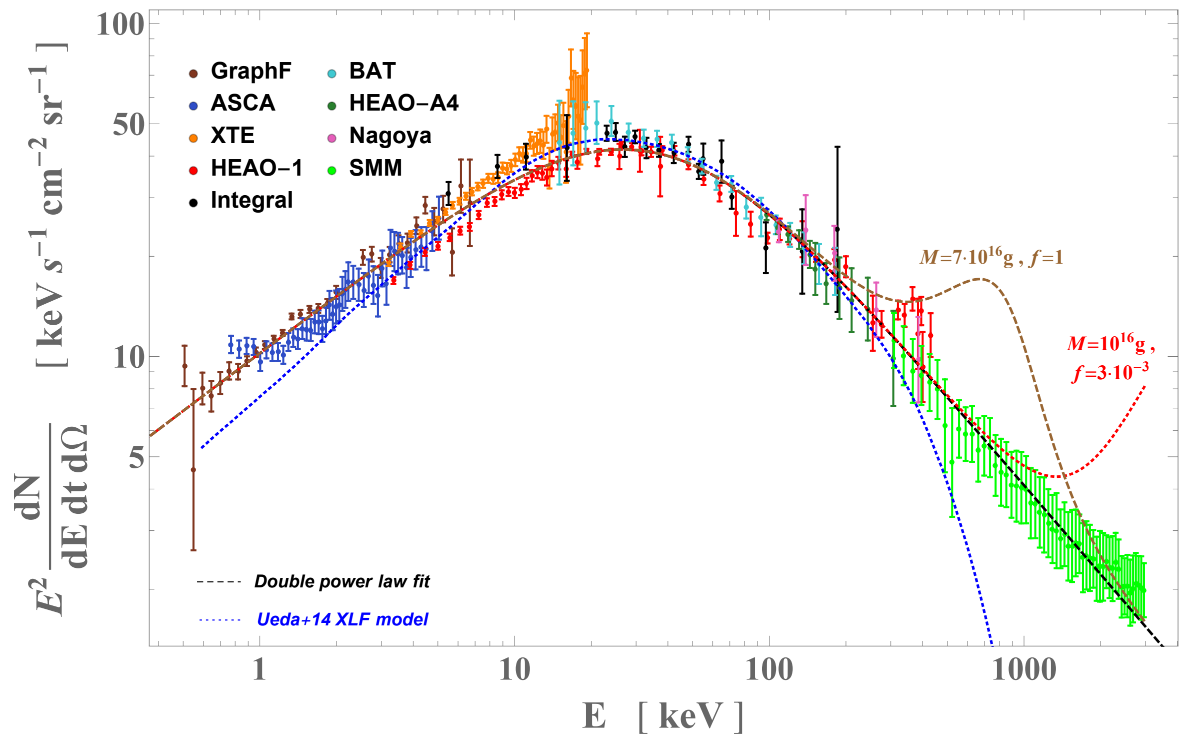
- Several constraints (1204.2056, 1505.04444, 1301.4984) recently challenged (1807.11495, 1906.05950)
- Can be probed by studying low-energy (MeV) **gamma-ray** data.
- PBHs can produce Hawking Radiation

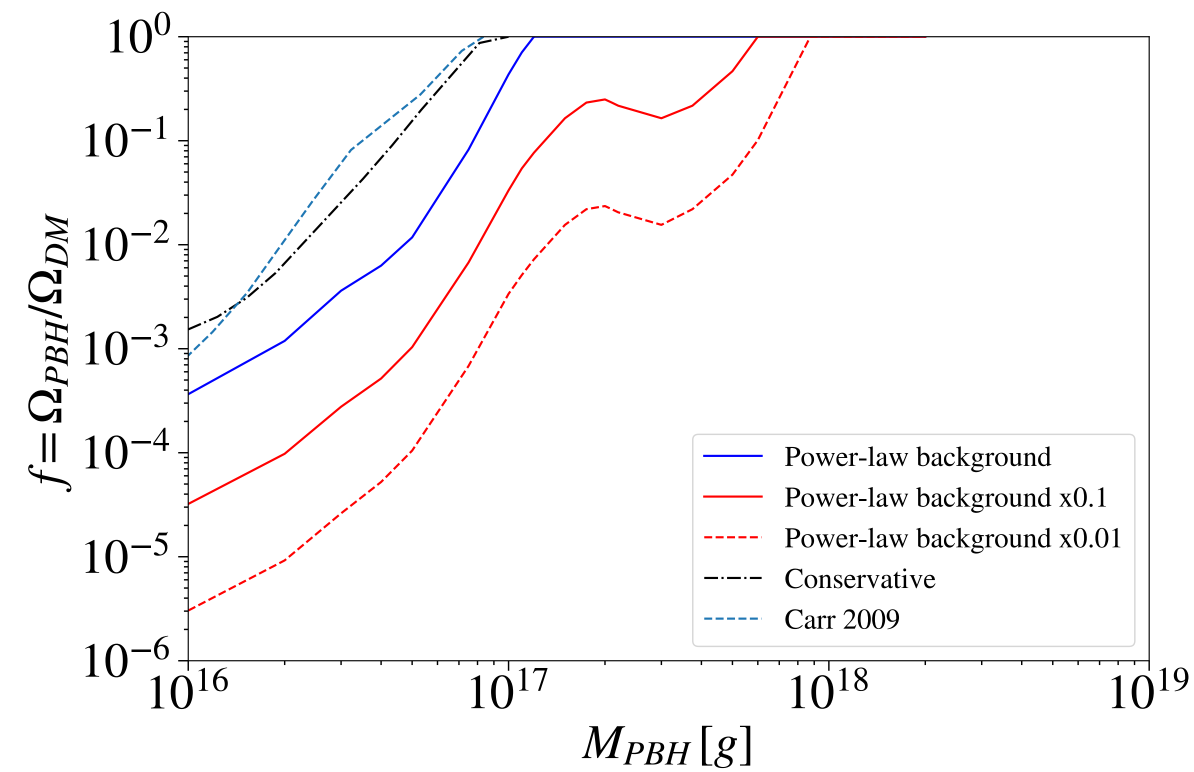
$$\Phi_M = \frac{\mathrm{d}N}{\mathrm{d}E\,\mathrm{d}t} = f\,\frac{c\,\rho}{4\pi\,M}\int \mathrm{d}z\,\frac{e^{-\tau(z)}}{H(z)}\,\Psi_M[(1+z)E]$$

$$\Psi_M[E] = (2\pi\hbar)^{-1}\Gamma_s/(\exp(E/k_B T)-1)$$

Low-energy gamma rays and Black Holes: Evaporation







- Science case for **future experiments** (AMEGO, e-ASTROGAM…)

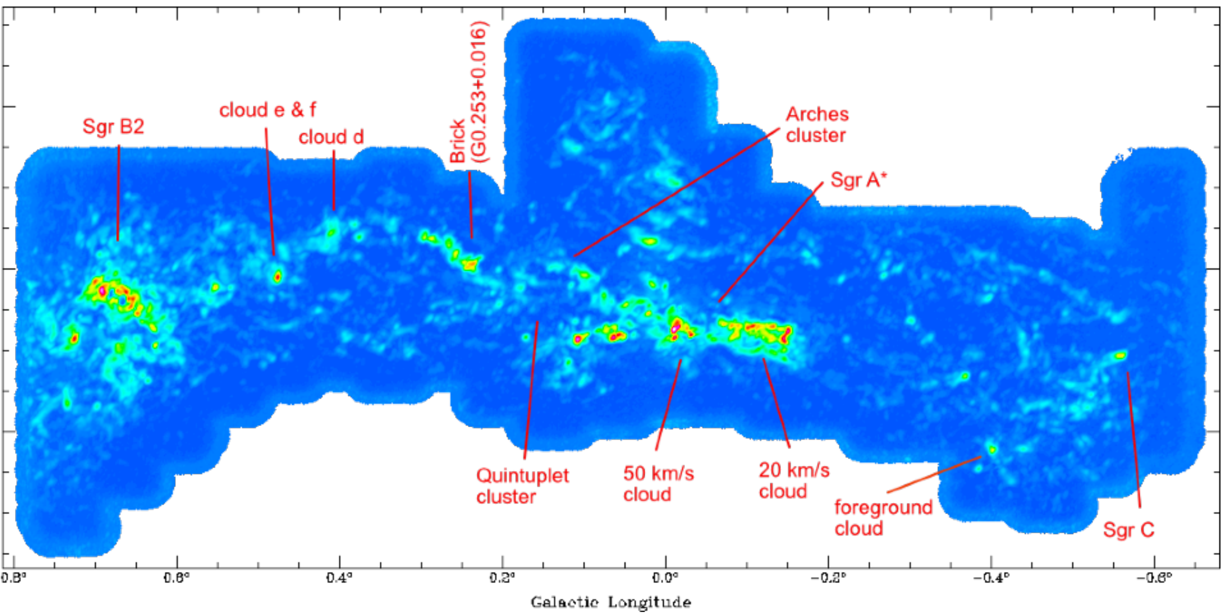
- Nice opportunity to either detect a signal in the hard X-ray — soft gamma-ray band or to further constrain this window!

Low-energy gamma rays and Black Holes: Accretion

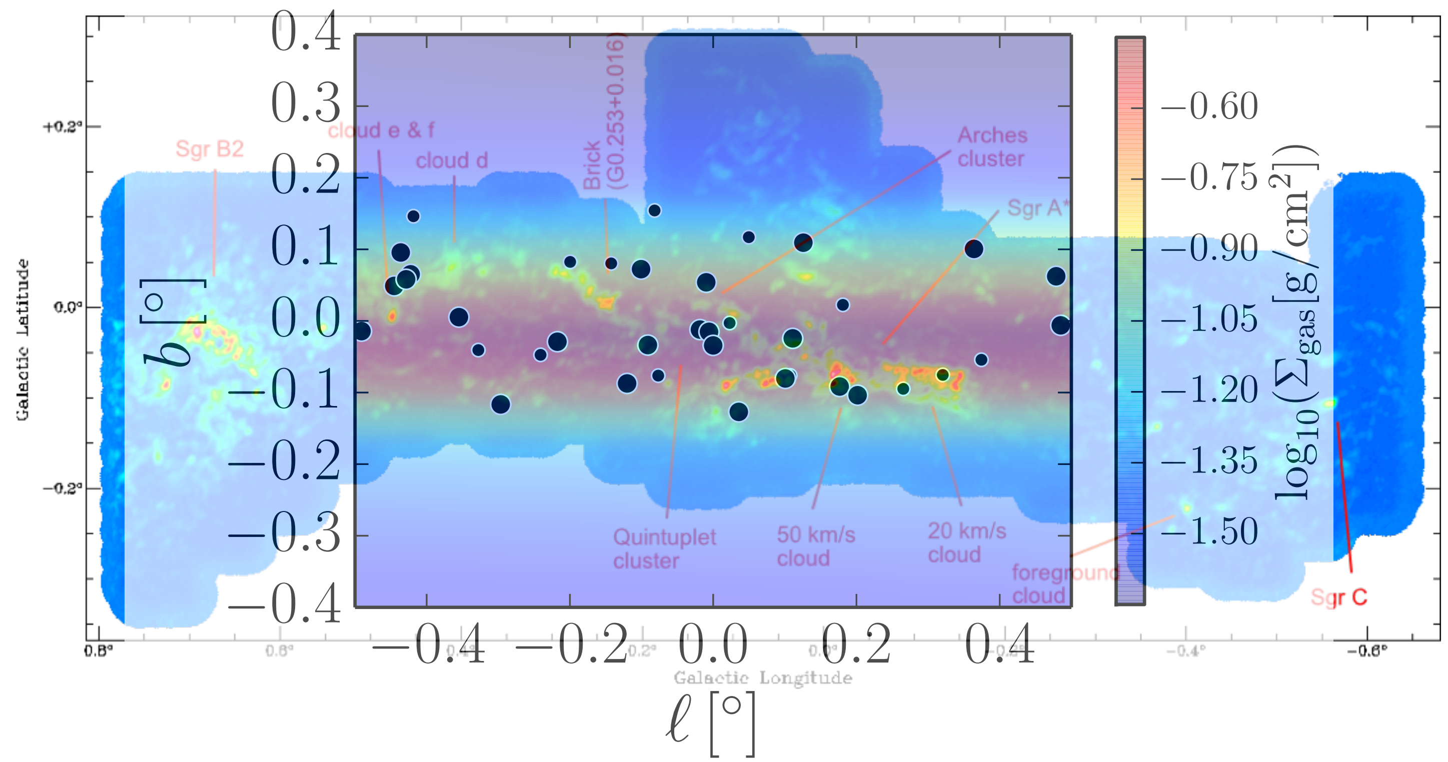
- **A new window of detection**: Multi-wavelength (**Radio** + **X-ray**) emission from gas accreted onto isolated BHs in the Milky Way

- **Potential of discovery** for a sub-dominant population with future radio observatories (SKA)

- The **Galactic Center**, once again, is an ideal target



Gas Distribution

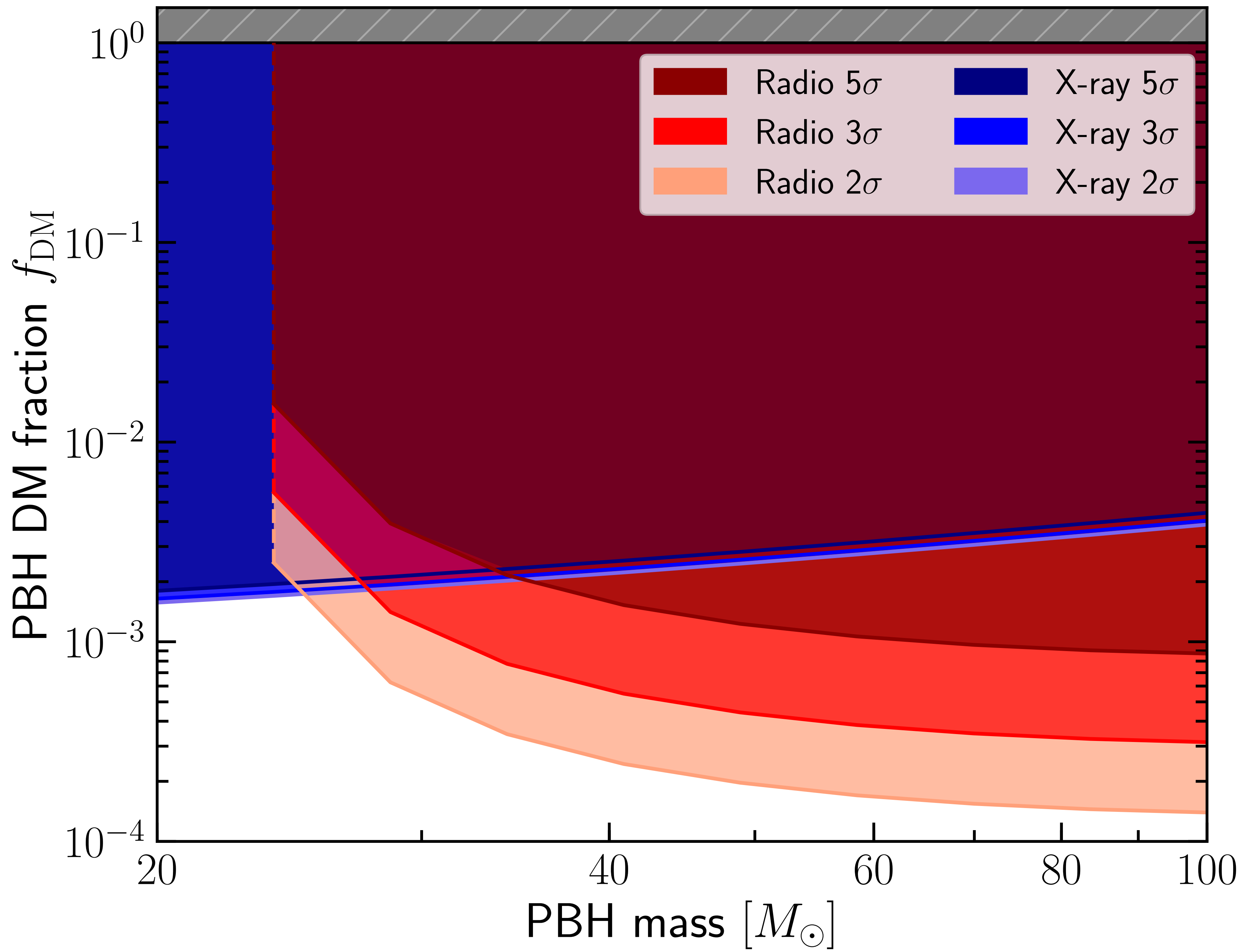


Simulated sources associated to PBHs

Low-energy gamma rays and Black Holes: Accretion

- **Robust upper limit** on the PBH abundance.

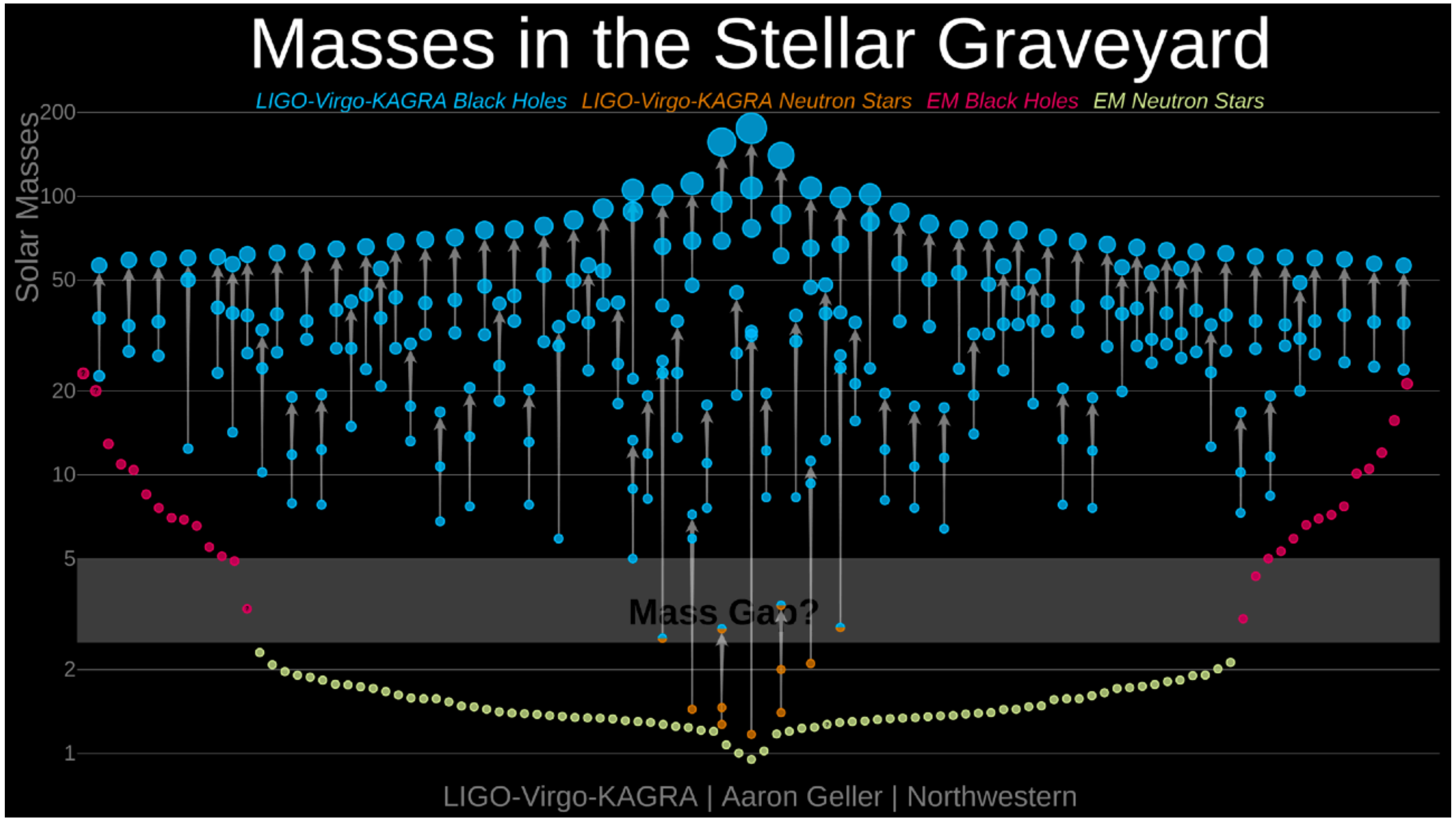
- *Touching some "Astrophysical Floor"?*
- *Threshold effect at low energy?*
- *Weaker for multi-modal mass functions?*



- **DG** et al., arXiv:1612.00457 (**PRL**)
- J. Manshanden, **DG** *et al.*, 1812.0796 (**JCAP**)
- F. Scarcella, **DG** *et al.*, arXiv:2012.10421 (**MNRAS**)

Dark Matter and Gravitational Waves

PBHs or ABHs? BHs as portals to DM?



Two fundamental questions:

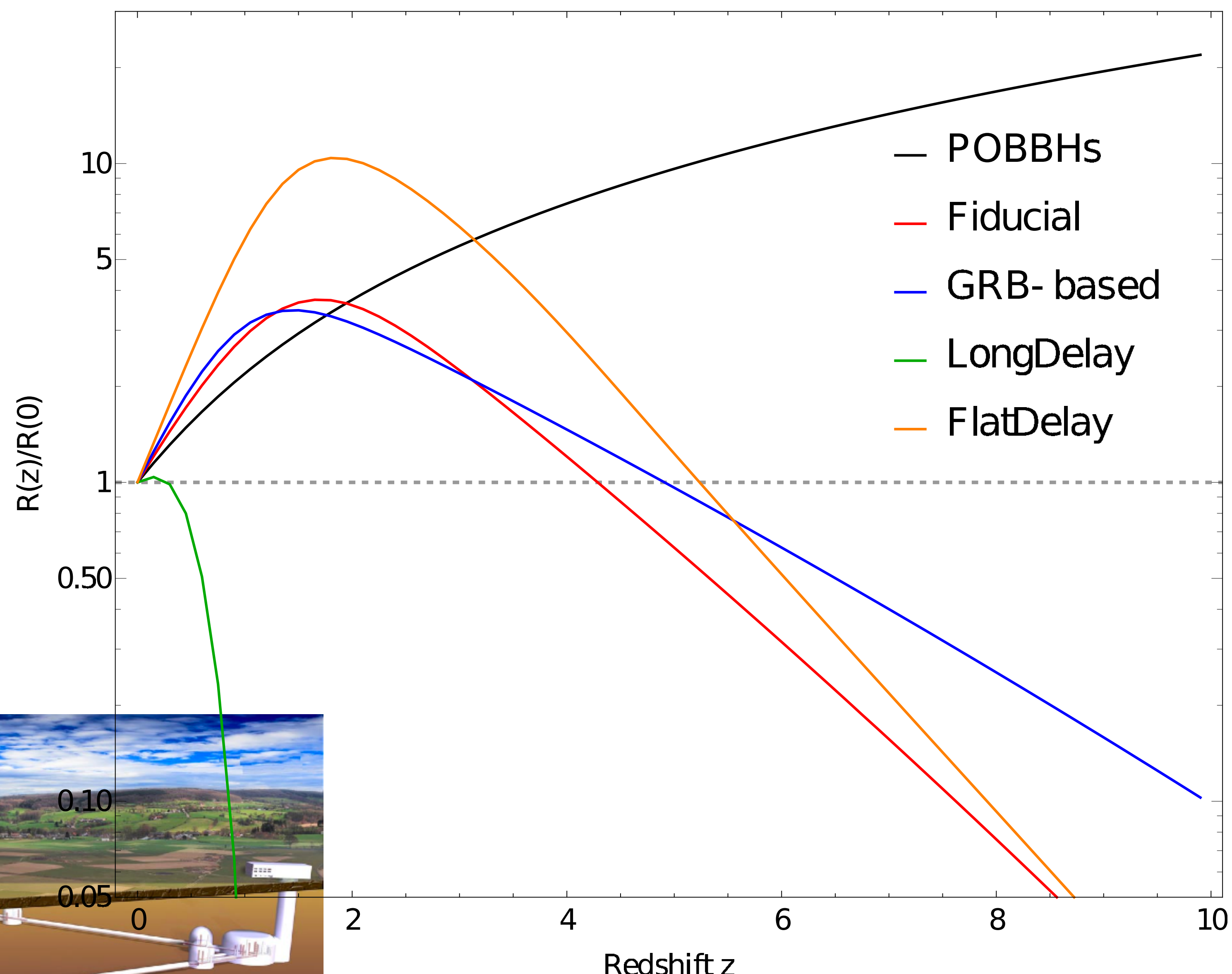
1) Can **PBHs** be part (or all) of the **Dark matter** that permeates the Universe? Can we study the GW **merger events** to study this question?

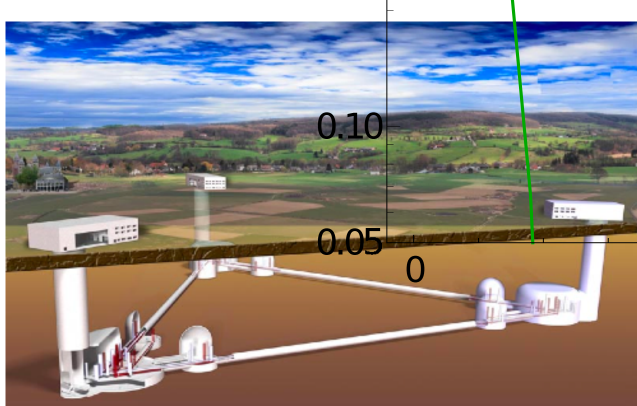
2) Can GW events be used to understand the **nature** of the **DM** (whatever the candidate)?

PBHs or ABHs? Population studies

1) Can **PBHs** be part (or all) of the **Dark matter** that permeates the Universe? Can we study the GW **merger events** to study this question?

—> **Redshift dependence** may be the key! Interesting **science case** for future ground-based observatories (Einstein Telescope, Cosmic Explorer)



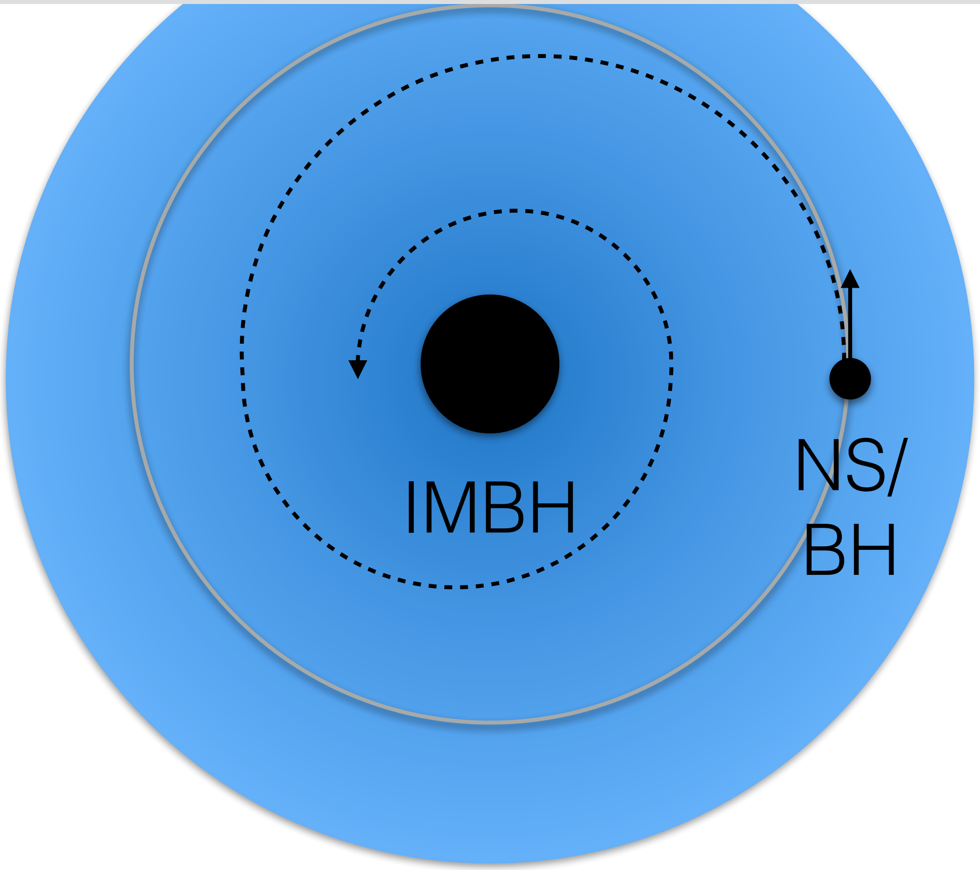


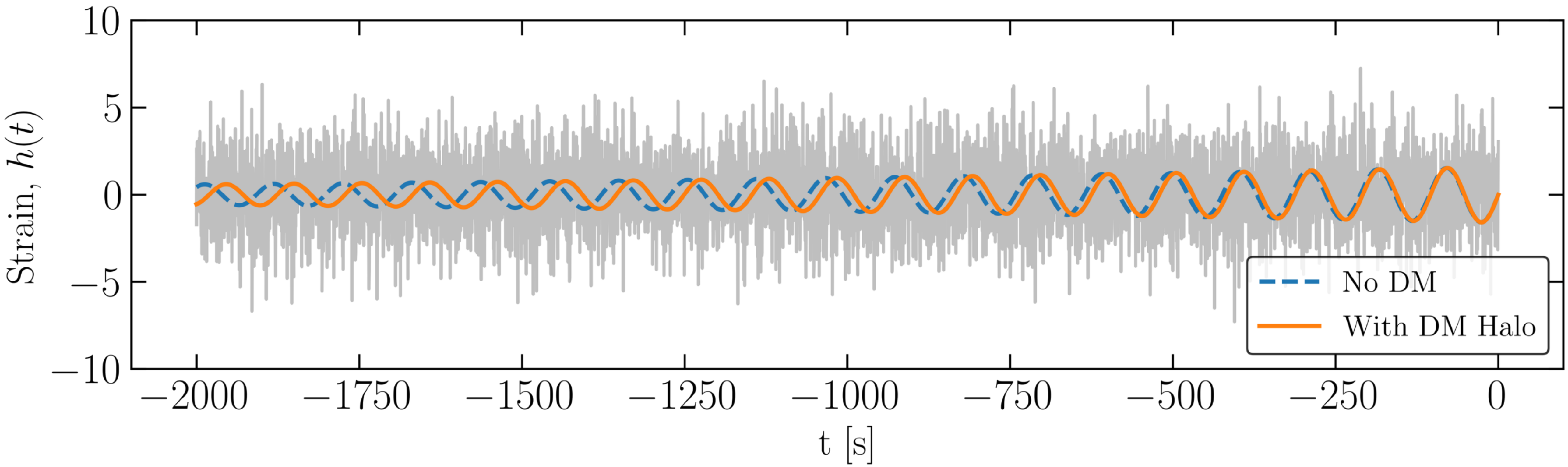
- **Chen+ 1904.02396**
- De Luca+ 2102.03809
- De Luca+ 2106.13769
- Ng+ 2012.09876
- Ng+ 2108.07276
- C. Fernández, P. Fleury, **DG**, N. Hogg, B.J. Kavanagh, M. Martinelli, F. Scarcella, *in preparation*

BHs as portals to a potential DM discovery: Study of anomalous waveforms

2) Can GW events be used to understand the **nature** of the **DM** (whatever the candidate)?

—> Study of **Dephased waveforms** in "Dressed" **IMRIs** (*Intermediate-Mass Inspiral Events*)





Dark Matter Mini-Spikes

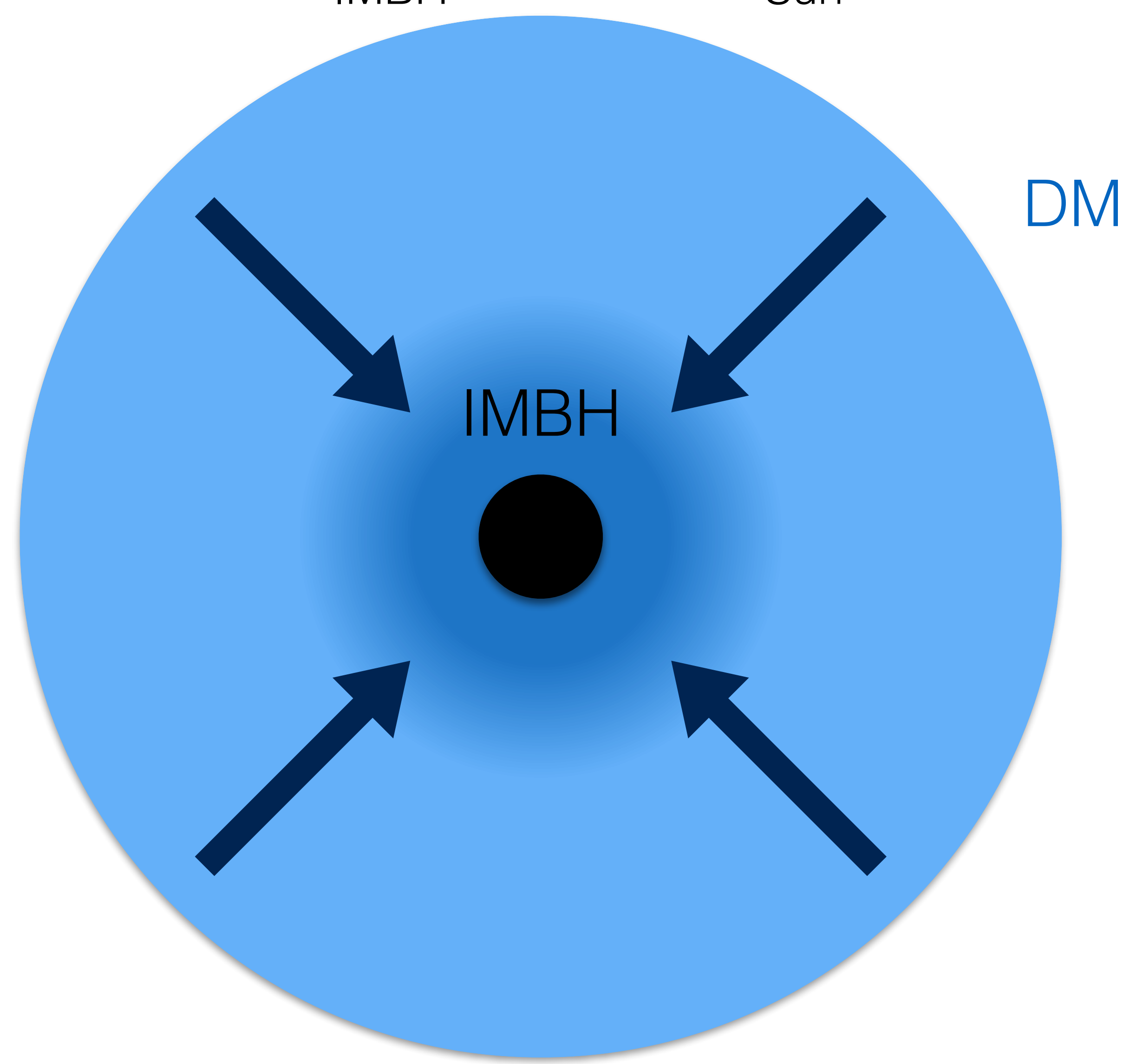
We expect **over-densities of DM** with power-law density profile around black holes formed in the early Universe

$$\rho_{\rm DM}(r) = \rho_{\rm sp}\left(\frac{r_{\rm sp}}{r}\right)^{\gamma_{\rm sp}}$$

- **Around PBHs** from early in the radiation era to z ~ 30 [Mack+ 0608642, Eroshenko 1607.00612, Adamek+ 1901.08528]
- **Around hypothetical IMBHs and SMBHs** [Gondolo&Silk 9906391, Zhao&Silk 0501625, Hannuksela+ 1906.11845]

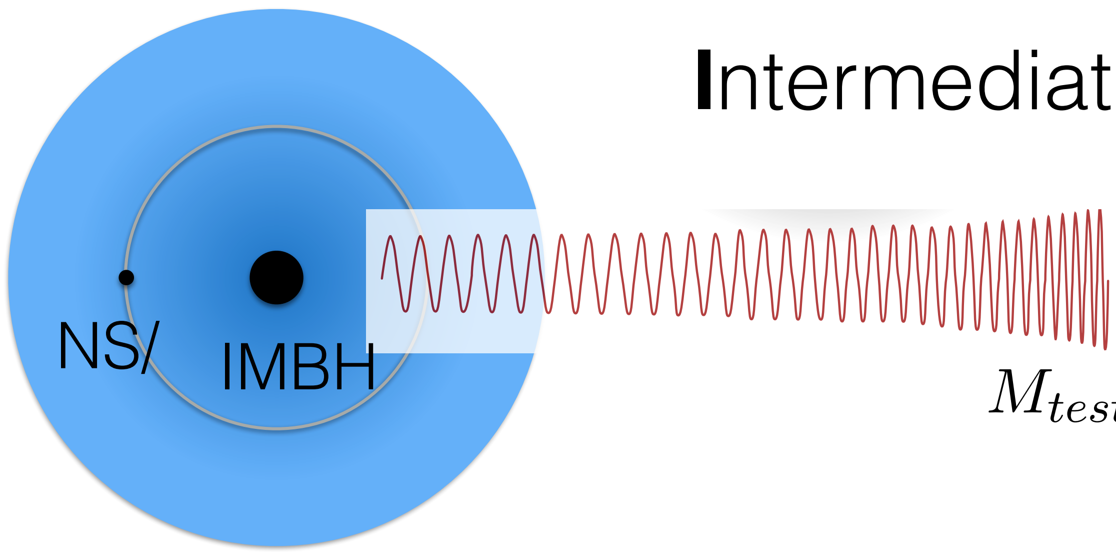
Parameter	Astrophysical	Primordial
m_1 [M$_\odot$]	10^3	10^3
m_2 [M$_\odot$]	1.4	1.4
ρ_6 [10^{15} M$_\odot$/pc^3]	5.448	5.345
$\rho_{\rm sp}$ [M$_\odot$/pc^3]	226	1.798×10^4
$\gamma_{\rm sp}$	$7/3 = 2.\bar{3}$	$9/4 = 2.25$
D_L [Mpc]	76	76
$m_{\rm DM}(< 10^{-6}$ pc) [M$_\odot$]	0.102	0.090

$M_{\rm IMBH}$ = 1000 $M_{\rm Sun}$



$$\rho_{\rm sp} = 200\, M_\odot\, {\rm pc}^{-3}$$
$$r_{\rm sp} = 0.5\,{\rm pc}$$

A novel way to look for DM with GWs



Intermediate **M**ass **R**atio **I**nspirals

$$M_{test}\,\ddot{\mathbf{r}} \;=\; \mathbf{F}_{grav}(r,v) + \mathbf{F}_{dyn}(r,v) + \mathbf{F}_{rad}(r,v)$$

$$\mathbf{F}_{grav}(r,v) = -M_{test}\frac{G(M_{IMBH}+M_{halo,enclosed})}{r^3}\mathbf{r}$$

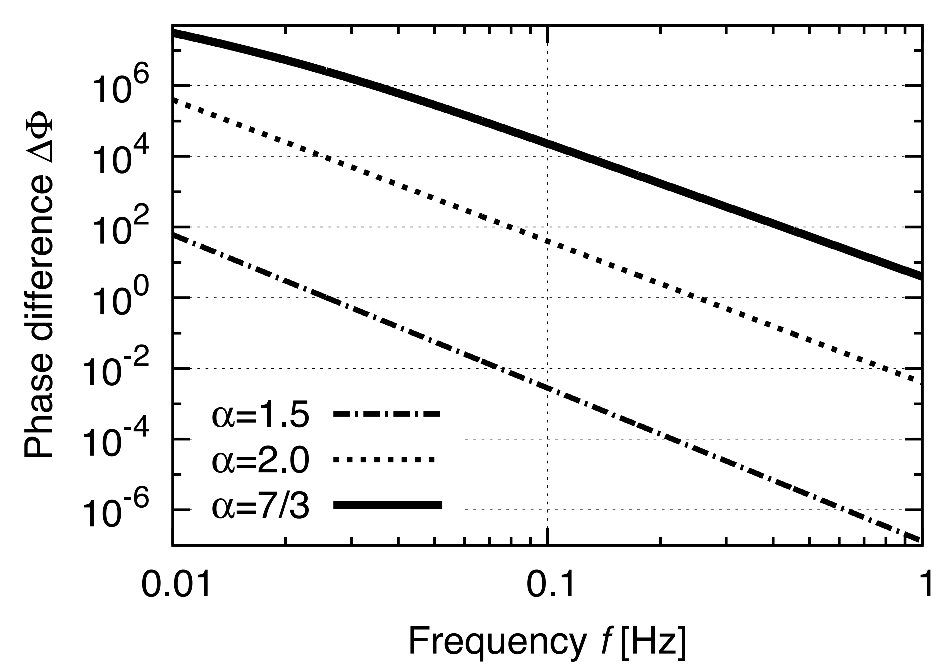
$$\mathbf{F}_{dyn}(r,v) = -M_{test}\,\frac{4\pi\, ln(\Lambda)\, G^2 M_{test}\, \rho(r)}{v^3}\,\mathbf{v},$$

$$\mathbf{F}_{rad}(r,v) = -\frac{32}{5}M_{test}\frac{G^3\, M_{tot}^3\, \nu}{c^5 r^4}\left(1+\gamma\left(-\frac{743}{336}-\frac{11}{4}\nu\right)\right)\mathbf{v}$$

- The IMRI evolves due to:
  - gravitational pull
  - dynamical friction from the DM
  - back-reaction from its gravitational wave (GW) radiation

- Resulting inspiral gravitational wave is modified and shows a **dephasing**

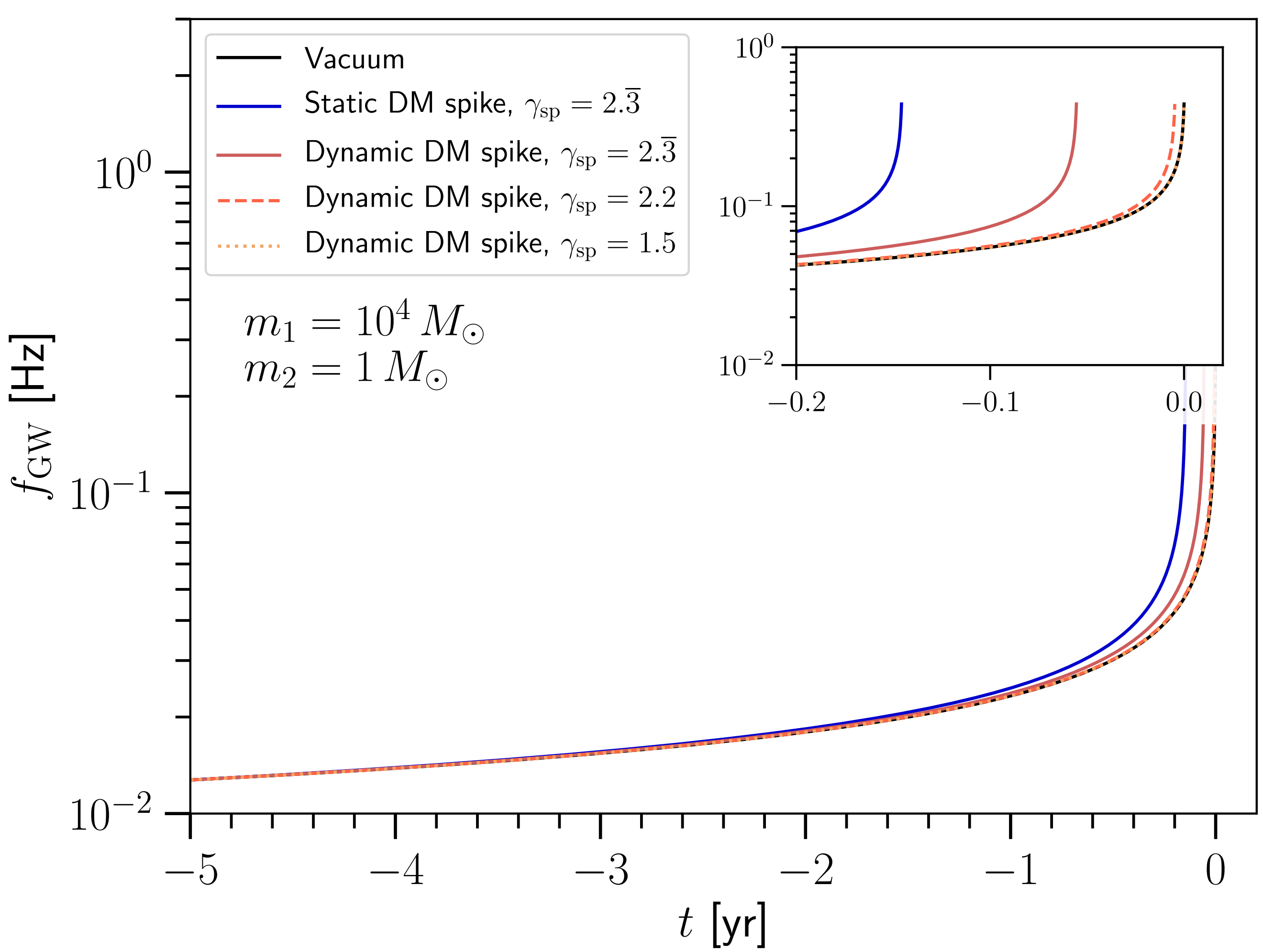
- Eda et al. 1301.5971
- Eda et al. 1408.3534

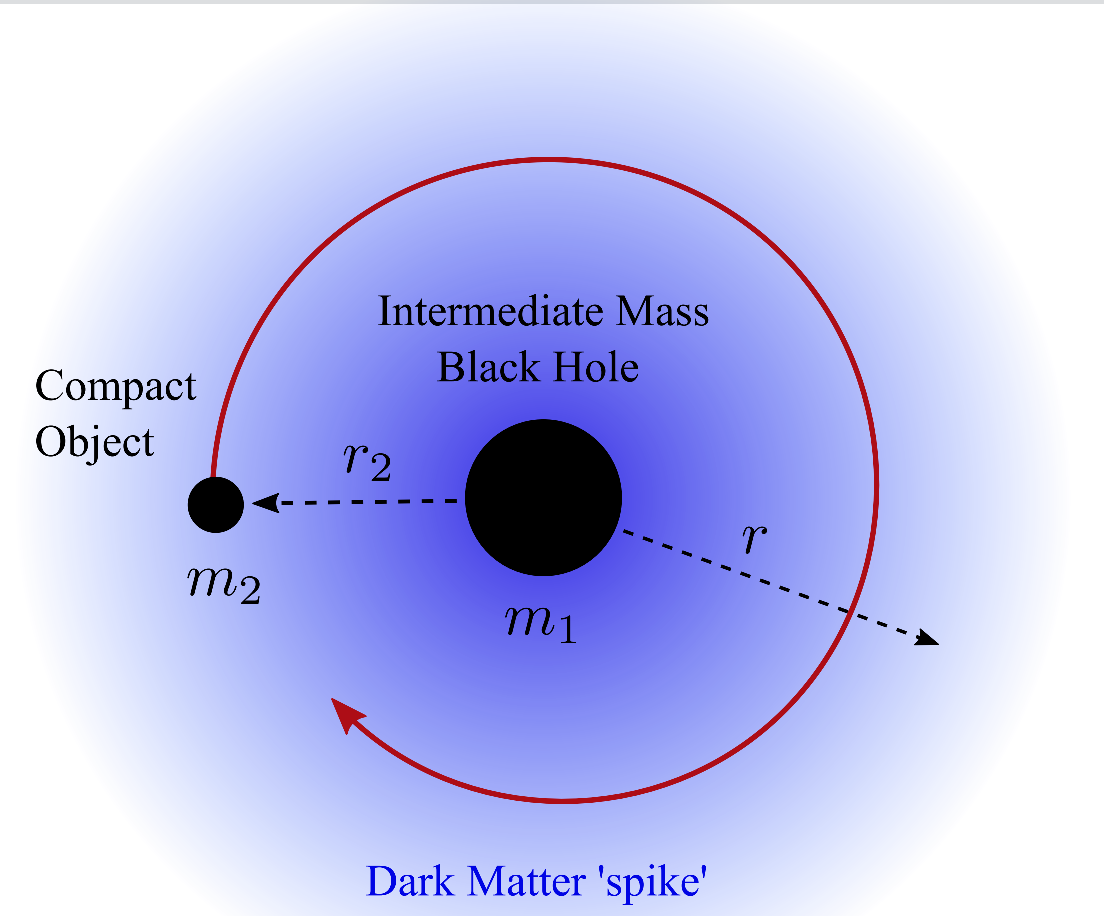


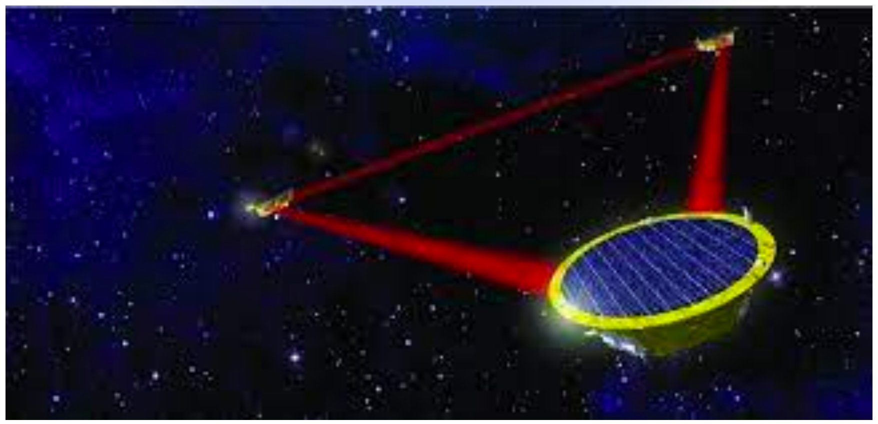
A novel way to look for DM with GWs

- Realistic assessments (taking into account the *feedback on the DM spike*):
  - *Anticipated merger* and *dephased signal* can be **detectable**.
  - *"DM spike"* parameters **measurable**!

A Science Case for LISA!







- B. Kavanagh, D. Nichols, G. Bertone, **DG**, arXiv:2002.12811 **(PRD)**
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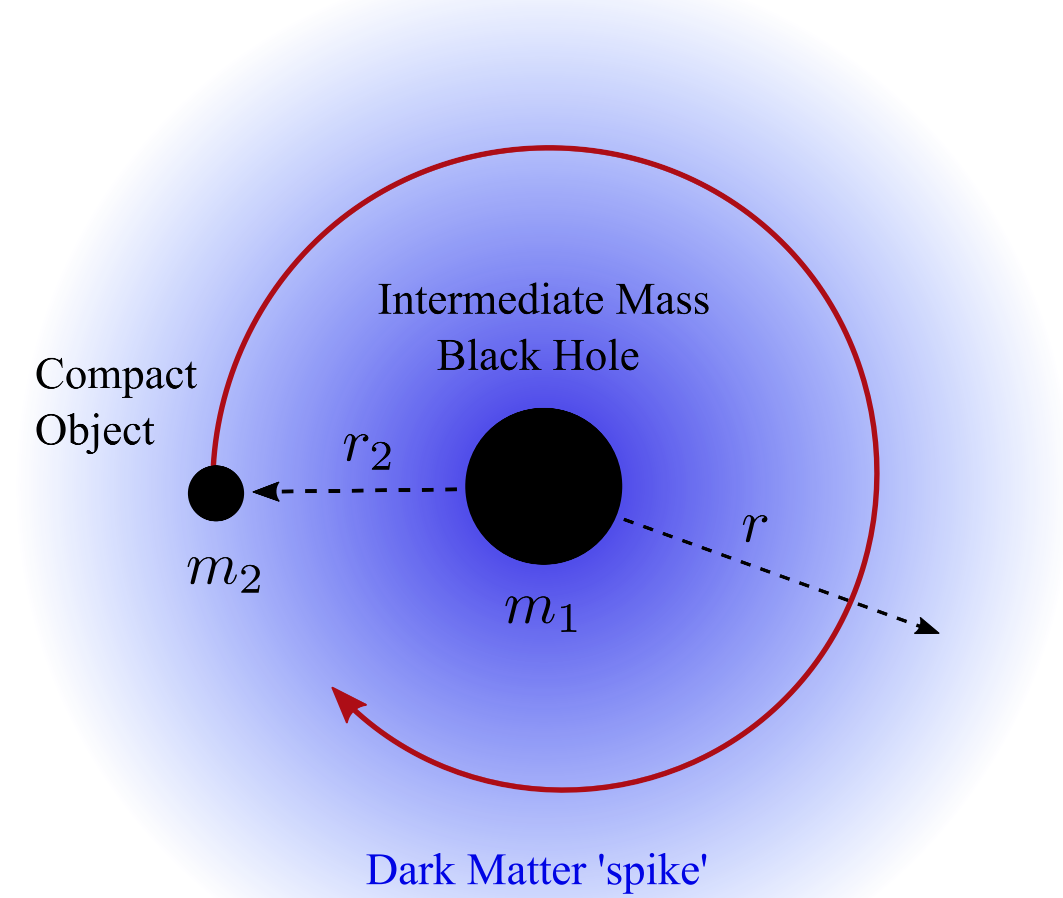

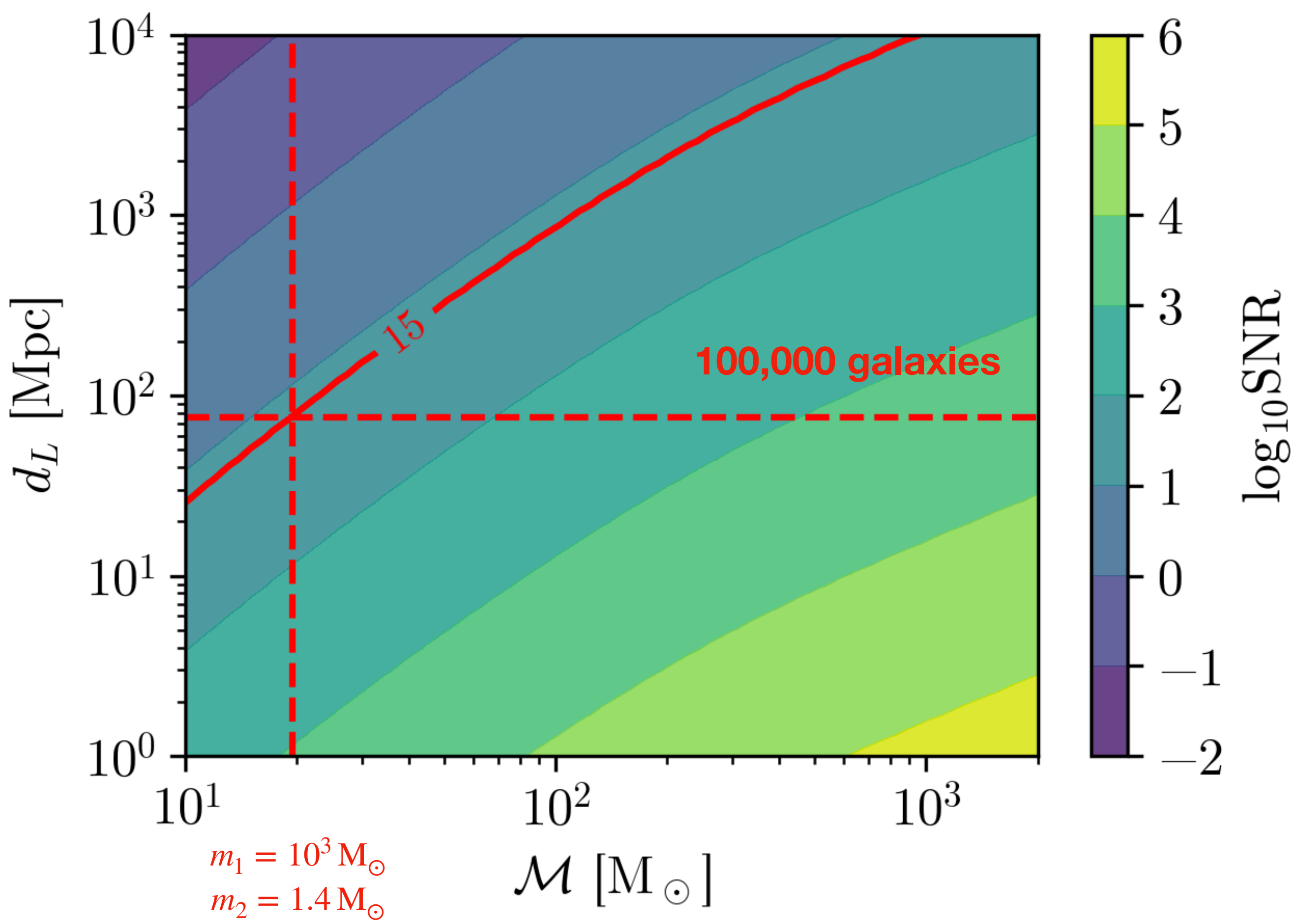

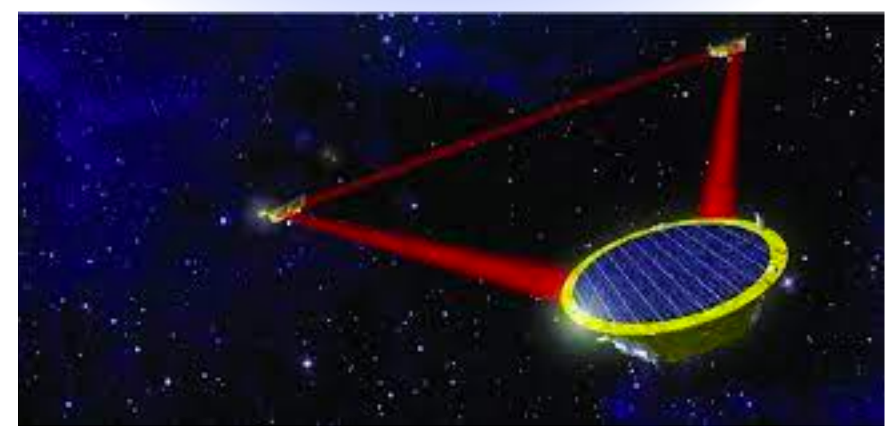

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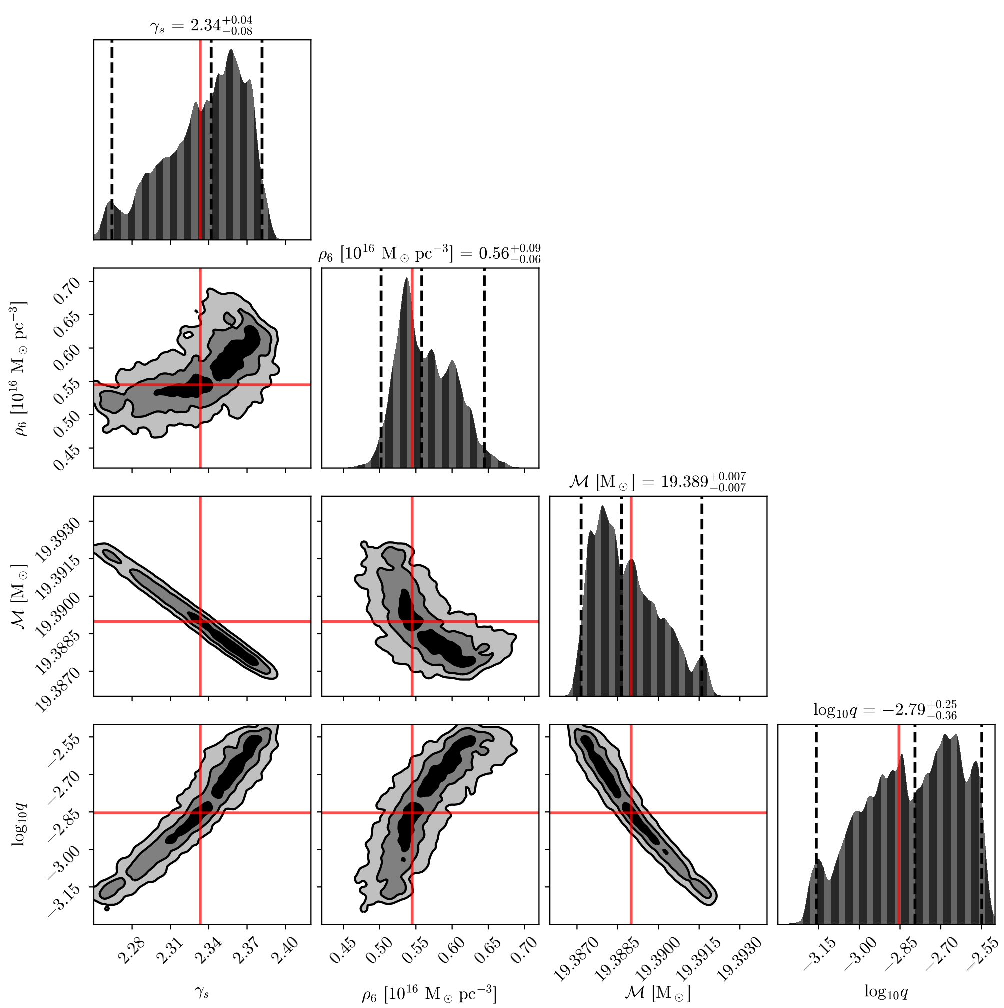
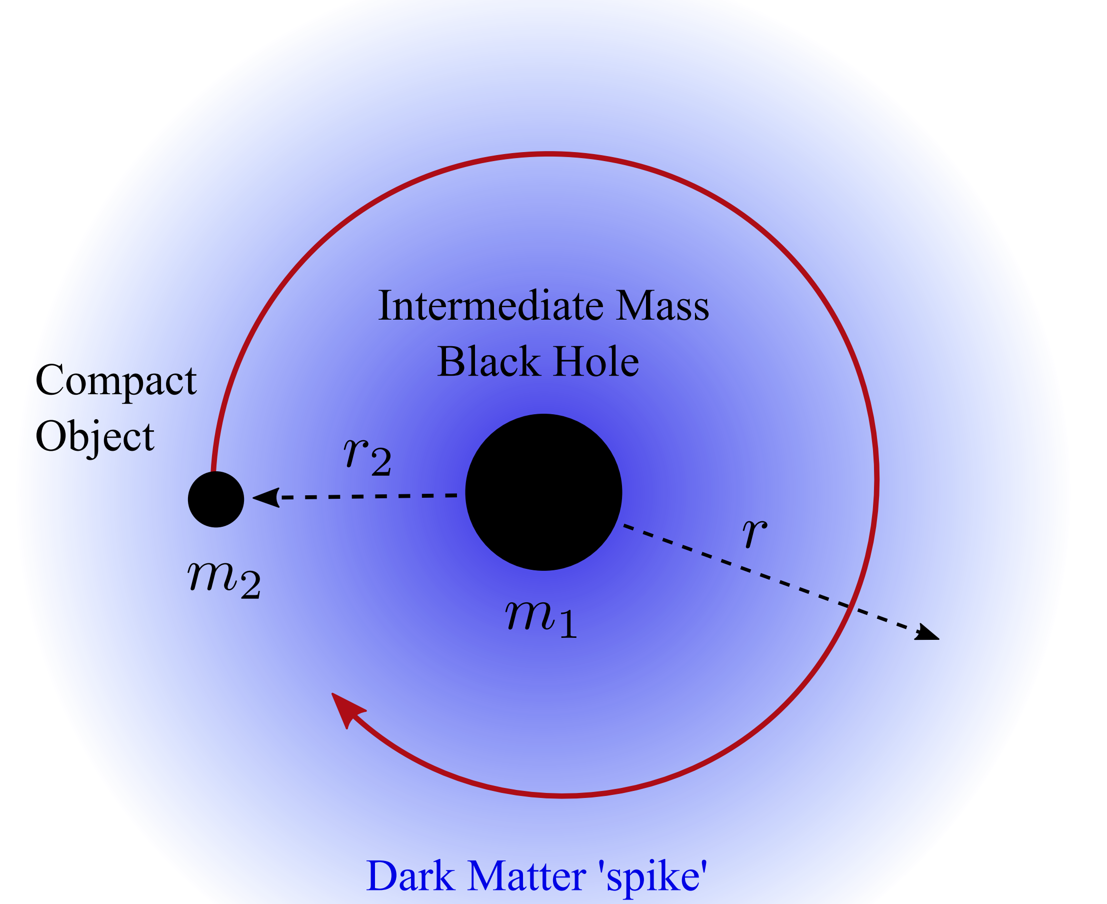
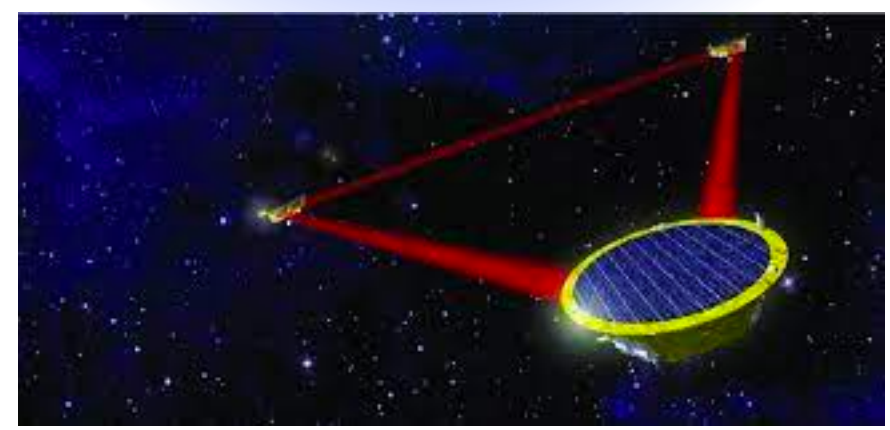
A Science Case for LISA!







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Conclusions

- The field of **Indirect Dark Matter Detection** became broader and more complex over the years. Many **DM candidates** under scrutiny.

- Many **claims** were discussed and challenged, espacially in the antiparticle and gamma-ray channel. No claim was firmly confirmed

- Waiting for new amazing data on both ends of the gamma-ray spectrum: from **sub-GeV** to **multi-TeV**

- **Gravitational Wave window is extremely promising.** Contribution of Primordial Black Holes to the Dark Matter? Exploting Black Holes as portals to a Dark Matter discovery?

Thank you for your attention!

Daniele Gaggero

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