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Detecting low-mass primordial black holes as the dark matter candidate

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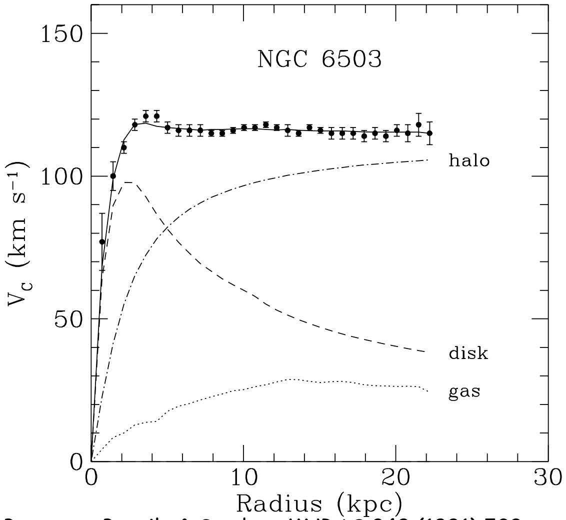
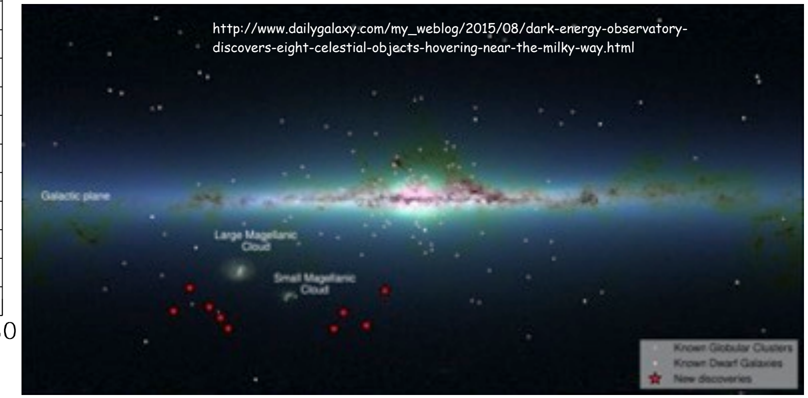
Thanks to my collaborators: Anupam Ray, Regina Caputo, Basudeb Dasgupta, Julian B. Muñoz, Philip Lu, Akash Kr. Saha, Tracy R. Slatyer, and Volodymyr Takhistov

Gravitational detection of dark matter

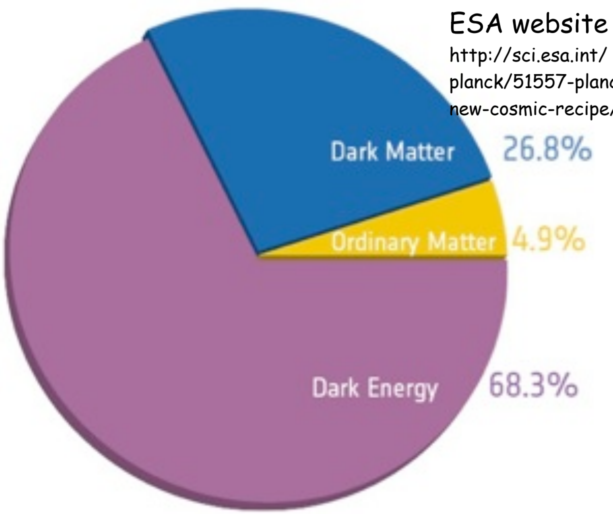


Begeman, Broeils & Sanders MNRAS 249 (1991) 523



Bullet cluster
https://en.wikipedia.org/wiki/File:1e0657_scale.jpg

ESA website
http://sci.esa.int/planck/51557-planck-new-cosmic-recipe/



Real observation from Hubble eXtreme Deep Field Observations: left side

Mock observation from Illustris: right side
Illustris website

Dark matter candidates

10^{-22} eV ——————————————————— $\sim 100\ M_{\odot}$

Wide range in dark matter candidate masses

We need to thoroughly test all well-motivated candidates

It is important to test all regions of dark matter parameter space, esp. regions where dark matter candidates saturate the cosmic dark matter density

Contents

- Primordial black hole (PBH) introduction
- PBH dark matter
- PBH constraints from Hawking radiation
  - (a) Limits from the isotropic diffuse gamma-ray background
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  - (c) Limits from the measurement of Galactic Center photons
  - (d) Projections from near future gamma-ray experiments
  - (e) Other probes
- Conclusions

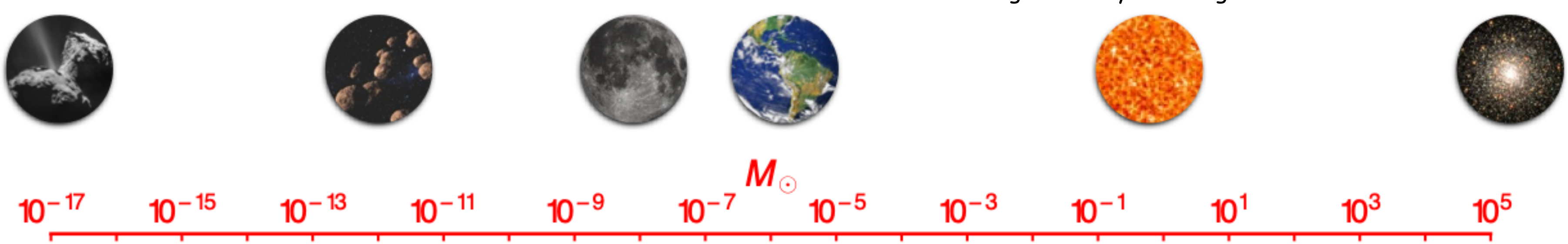
Primordial black holes (PBHs)

What are primordial black holes? PBHs are exotic compact objects which can form in the early Universe due to large density perturbations (numerous formation models) and/ or due to new physics (Zel'dovich and Novikov Astron. Zhu, 1966, Hawking MNRAS 1971, Carr and Hawking MNRAS 1974, Chapline Nat. 1975 and many others)

$$M_{\rm PBH} \approx 10^{15} \left(\frac{t}{10^{-23}\,{\rm s}} \right)\,{\rm g}$$ (for PBHs formed in the early Universe)

PBHs can have a wide range of masses and can form the entire dark matter density of the Universe

Fig. courtesy: Kavanagh GW4FP 2019

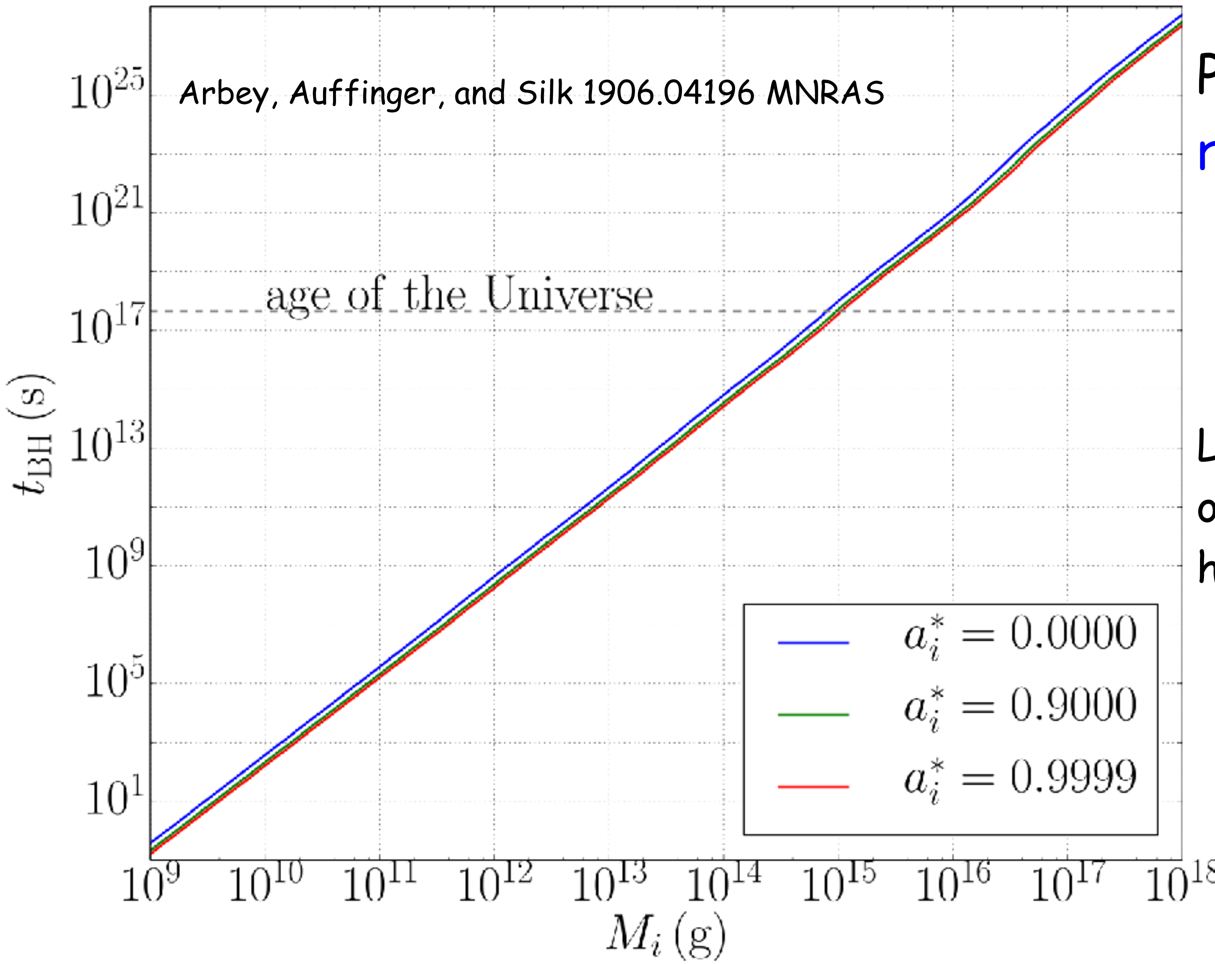


$$1\,M_\odot \approx 2 \times 10^{30}\,{\rm kg} \approx 1.1 \times 10^{57}\,{\rm GeV}$$

PBHs can have a log-normal mass function or a power law mass function and can have a wide range of spins

PBH dark matter

Masses of PBHs for dark matter



PBHs evaporate via Hawking radiation

$$t_{\rm BH} \propto M_{\rm BH}^3$$

Lifetime of a black hole

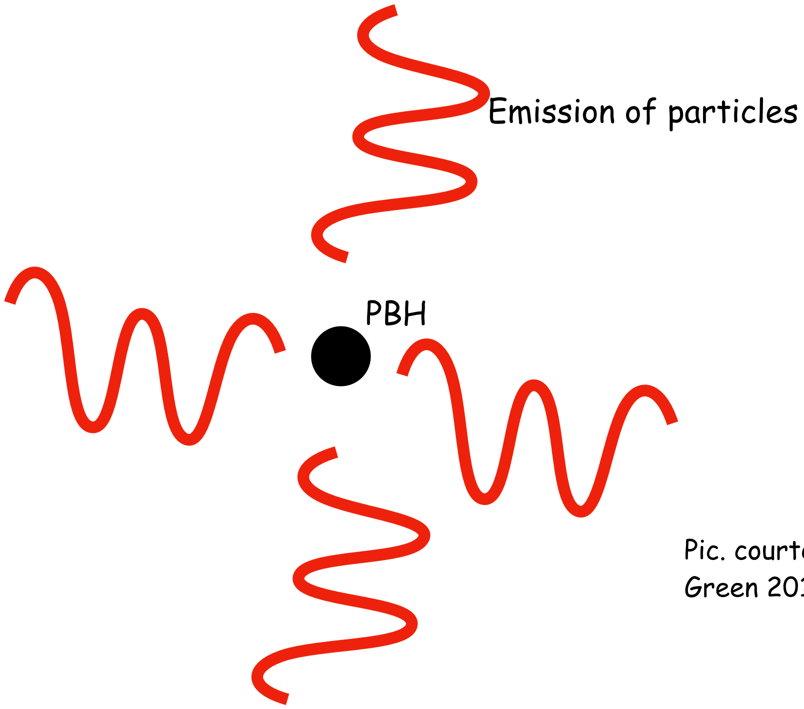
Mass of a black hole

a_i^* = initial spin of the black hole

Minimum mass of non-spinning PBH DM ≈ 6×10^{14} g

Non-zero spin increases the minimum mass of PBH DM

PBH constraints
from Hawking evaporation



Pic. courtesy:
Green 2019 talk

Evaporation of low-mass PBHs

Black holes evaporate to produce Standard Model particles and can have observable consequences

Temperature of the black hole

$$T_{\rm BH} = 1.06 \left(\frac{10^{10}\,{\rm kg}}{M_{\rm BH}} \right) {\rm GeV}$$

Mass of the black hole

S. W. Hawking, Nature 248 (1974) 30-31.

S. W. Hawking,, Commun. Math. Phys. 43 (1975) 199-220.

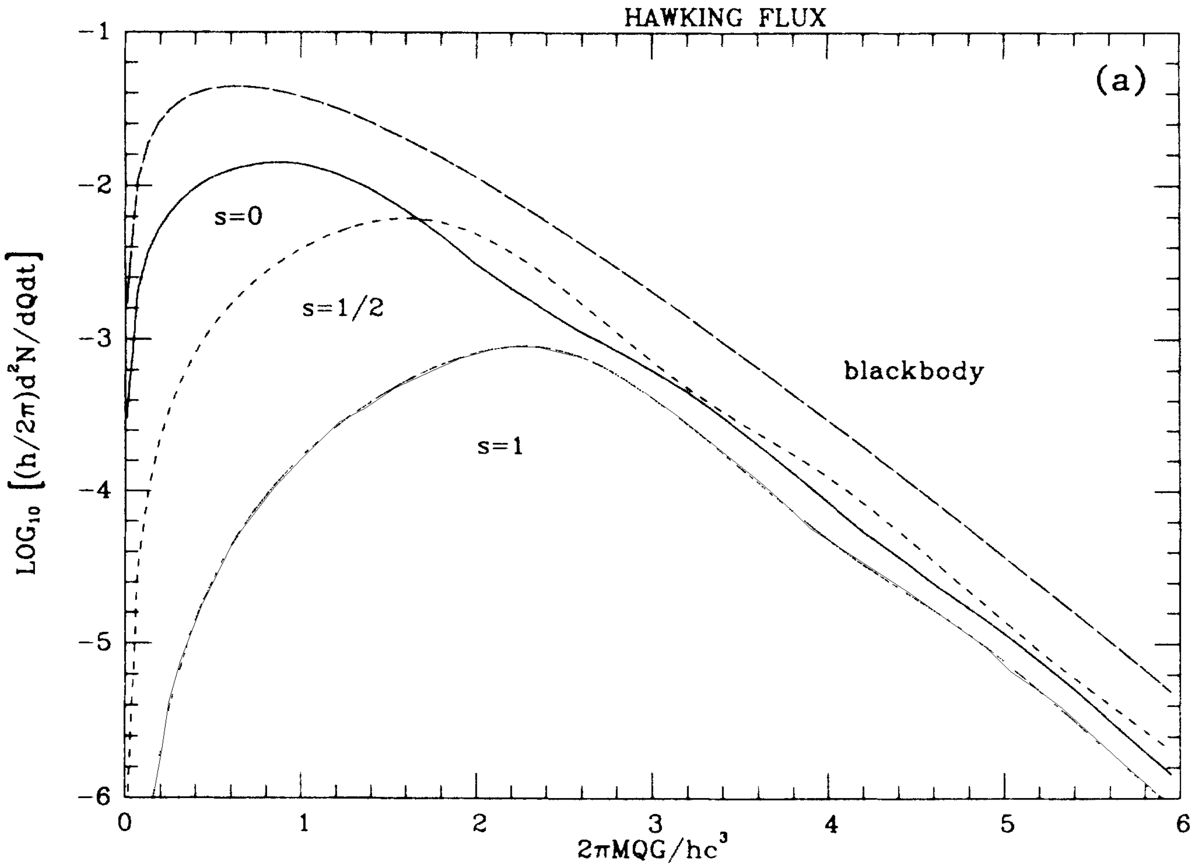
Dimensionless absorption probability for the emitted species

$$\frac{dN_s}{dE} = \frac{\Gamma_{\rm s}}{2\pi} \int dt \, \frac{1}{\exp(E/T_{\rm BH}) - (-1)^{2{\rm s}}}$$

Evaporation energy spectrum of particle of spin s from a non-spinning black hole

Page PRD 13, 198, 1976
Page PRD 14, 3260, 1976
Page PRD 16, 2402, 1977
Arbey and Auffinger, EPJC 79, 693, 2016

Hawking radiation spectrum



MacGibbon and Webber, PRD 41, 3052, 1990

Q = total energy of the emitted particles

This is for a non-rotating uncharged black hole

Emission of pion, $e^{\pm}$, and photon via Hawking radiation

The spectrum closely resembles a black-body radiation

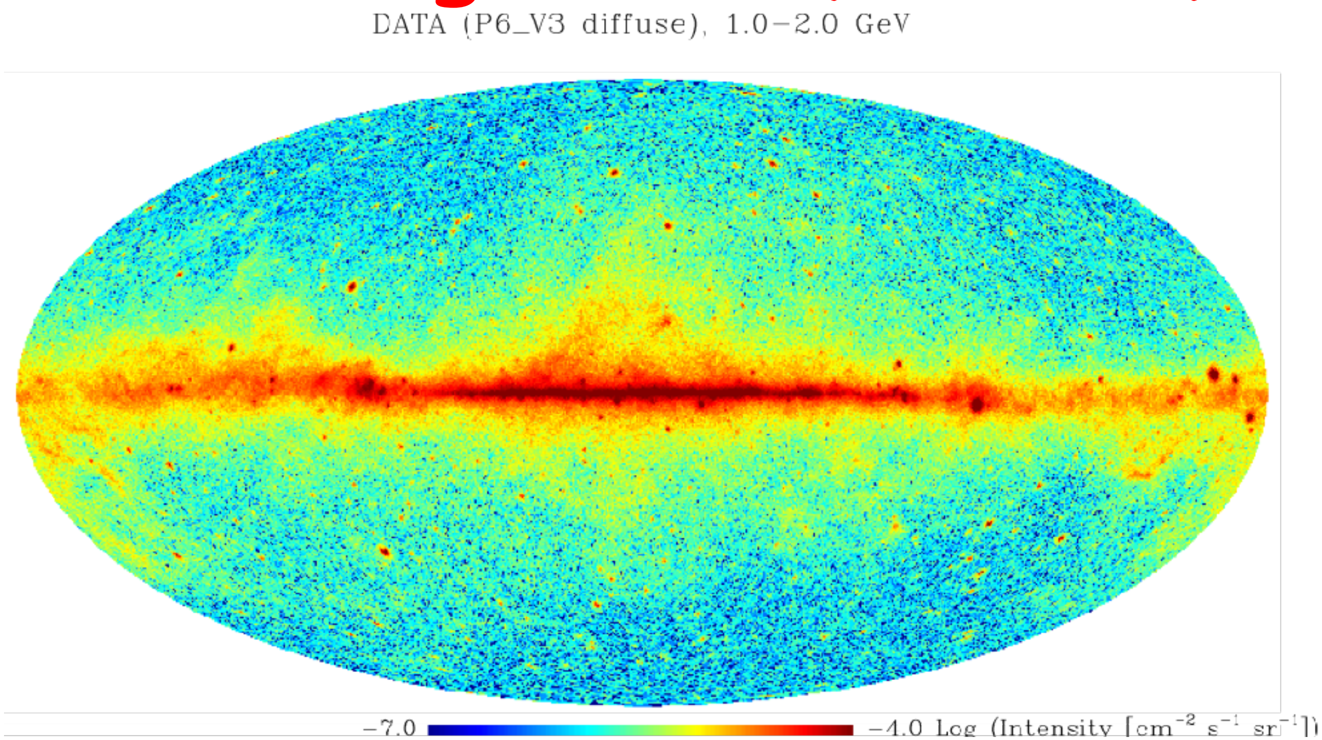
The peaks in the flux per particle mode measured at infinity occur at:

$$Q_{\mathrm{s}=0} \approx 2.81\, T_{\mathrm{BH}} \qquad Q_{\mathrm{s}=1/2} \approx 4.02\, T_{\mathrm{BH}} \qquad Q_{\mathrm{s}=1} \approx 5.77\, T_{\mathrm{BH}}$$

MacGibbon, Carr, and Page PRD 2008

Limits from the isotropic diffuse gamma-ray background

Isotropic diffuse gamma-ray background (IDGRB)



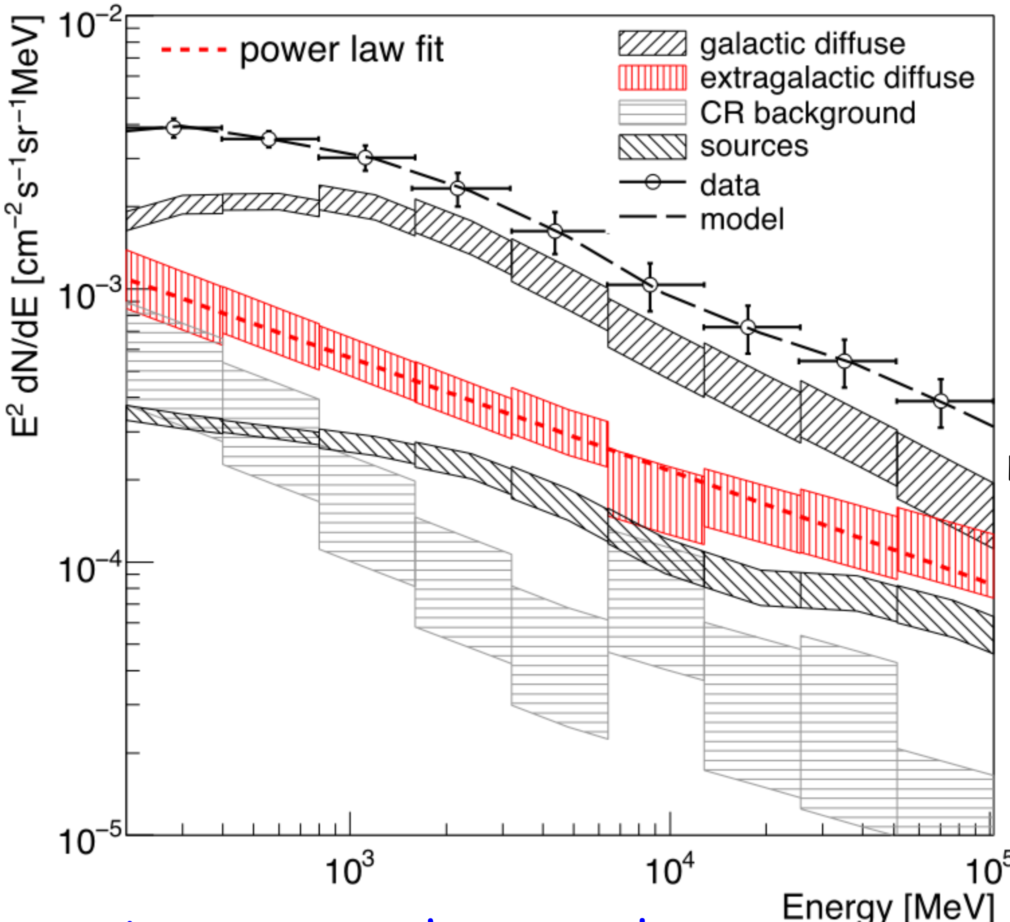
Fermi-LAT coll.

Sum of gamma-rays from all unresolved sources in the Universe

Powerful probe of dark matter interactions in the whole Universe

There is some contribution from the Milky Way

Spectrum of IDGRB



Fermi-LAT coll.

Spectrum is an approximate smooth power law

Conservatively the contribution from all dark matter interactions should not exceed the data --- one can use the shape of the gamma-rays from dark matter interactions to set better limits

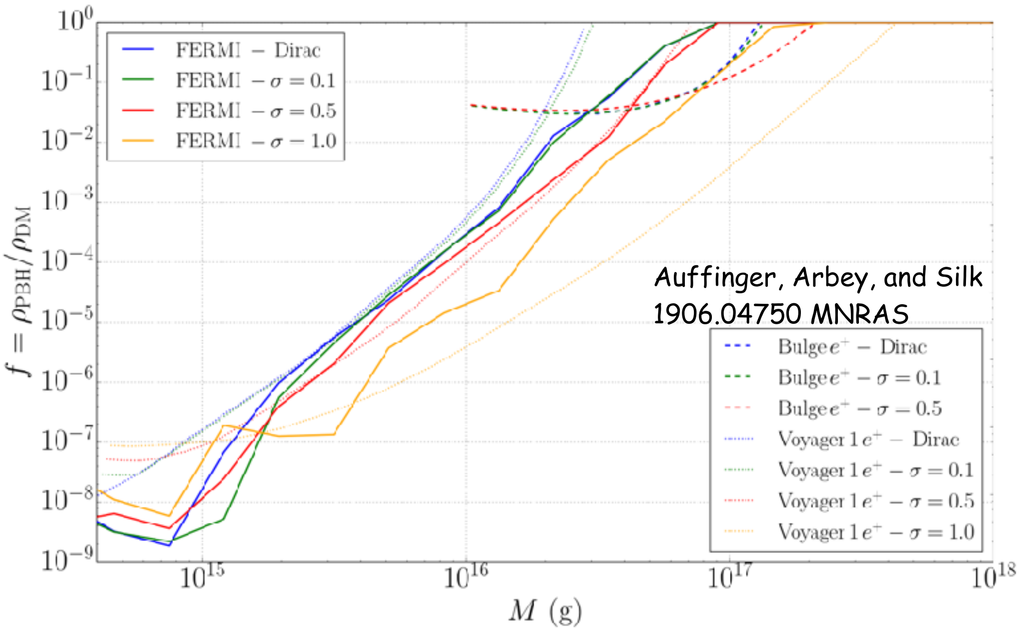
Low-mass PBHs and photons

PBHs can evaporate to produce photons

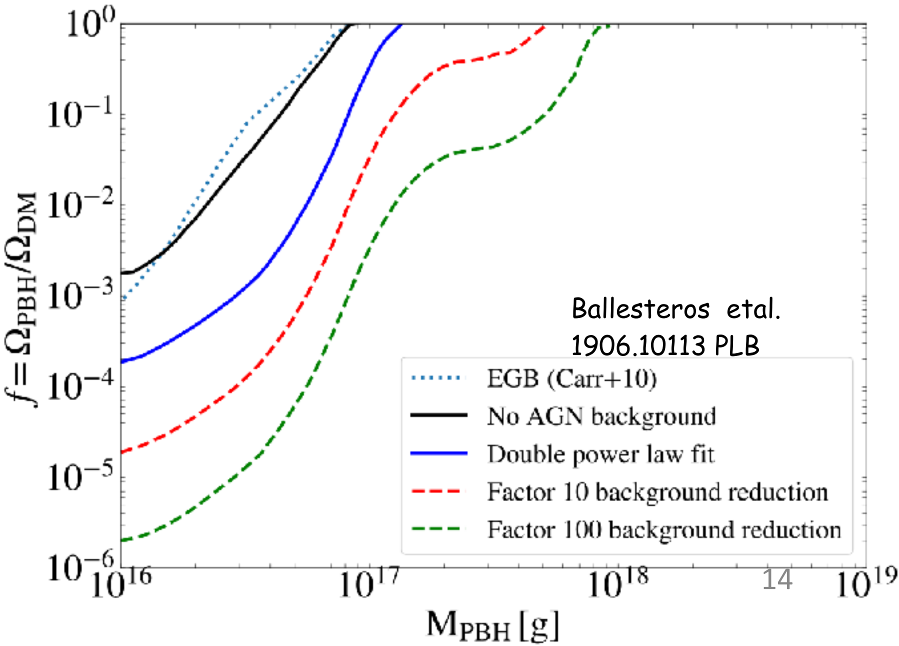
The photons can contribute to the cosmic photon background

The isotropic gamma-ray background and the cosmic MeV background have been used to constrain the density of primordial black holes

The constraint can be derived by either assuming astrophysical contribution(s) to the photon background or by assuming no modelling (to derive a more conservative limit)



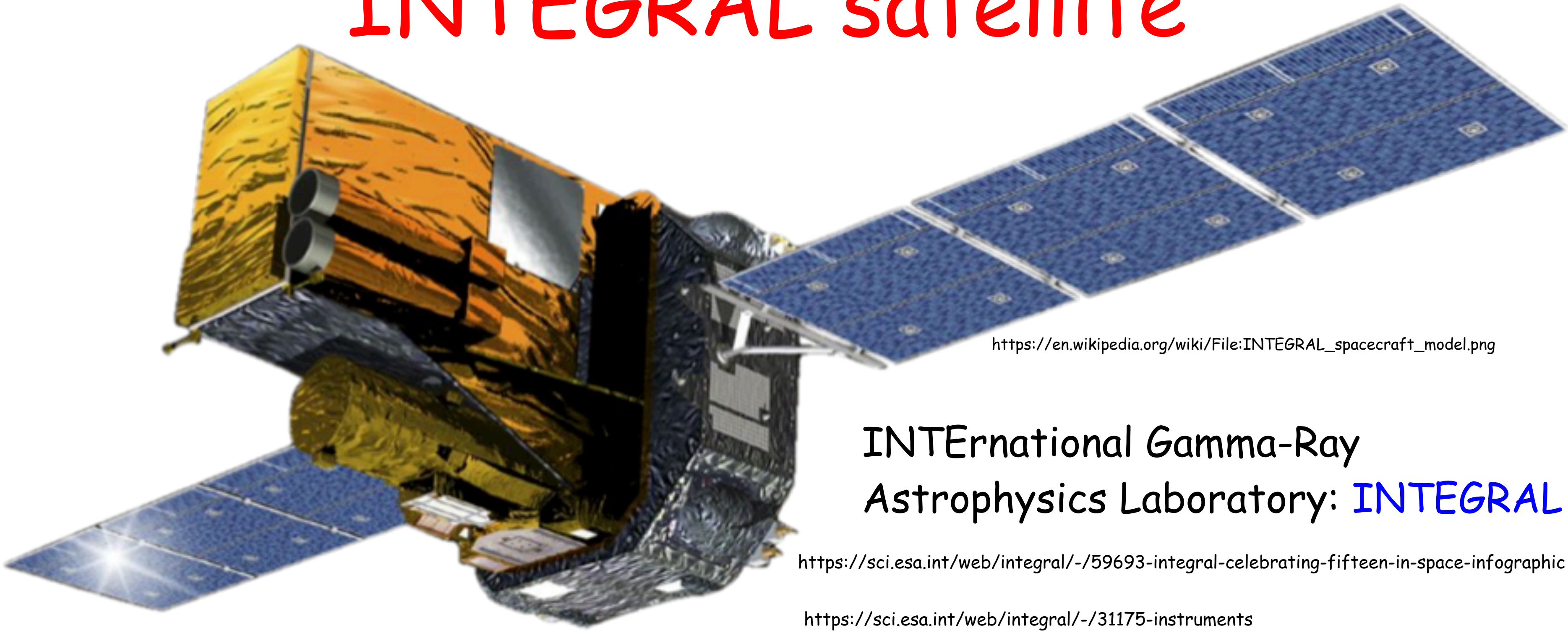
Auffinger, Arbey, and Silk
1906.04750 MNRAS



Ballesteros etal.
1906.10113 PLB

Limits from the measurement of low-energy Galactic positrons

INTEGRAL satellite



https://en.wikipedia.org/wiki/File:INTEGRAL_spacecraft_model.png

INTErnational Gamma-Ray Astrophysics Laboratory: INTEGRAL

https://sci.esa.int/web/integral/-/59693-integral-celebrating-fifteen-in-space-infographic

https://sci.esa.int/web/integral/-/31175-instruments

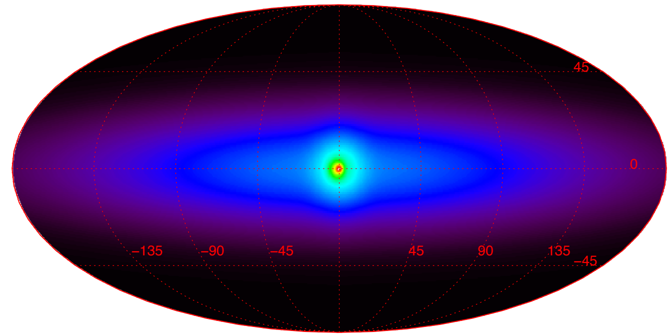
	Energy range	Energy resolution
SPectrometer of INTEGRAL (SPI):	18 keV to 8 MeV	~ 0.2% at 1.33 MeV
Imager on-Board the INTEGRAL Satellite (IBIS):	15 keV to 10 MeV	~ 10% at 1.33 MeV

Other instruments are also present in INTEGRAL

511 keV gamma-ray line

An enduring astrophysics mystery:
observation of the 511 keV gamma-ray line in the Galactic bulge and disk (Johnson etal. ApJ 172 L1 1972, Leventhal etal. ApJ 225 L11 1978, Cheng etal. ApJ 481 L43 1997, …., Siegert etal. 1512.00325 A&A, Siegert etal. 1906.00498 A&A)

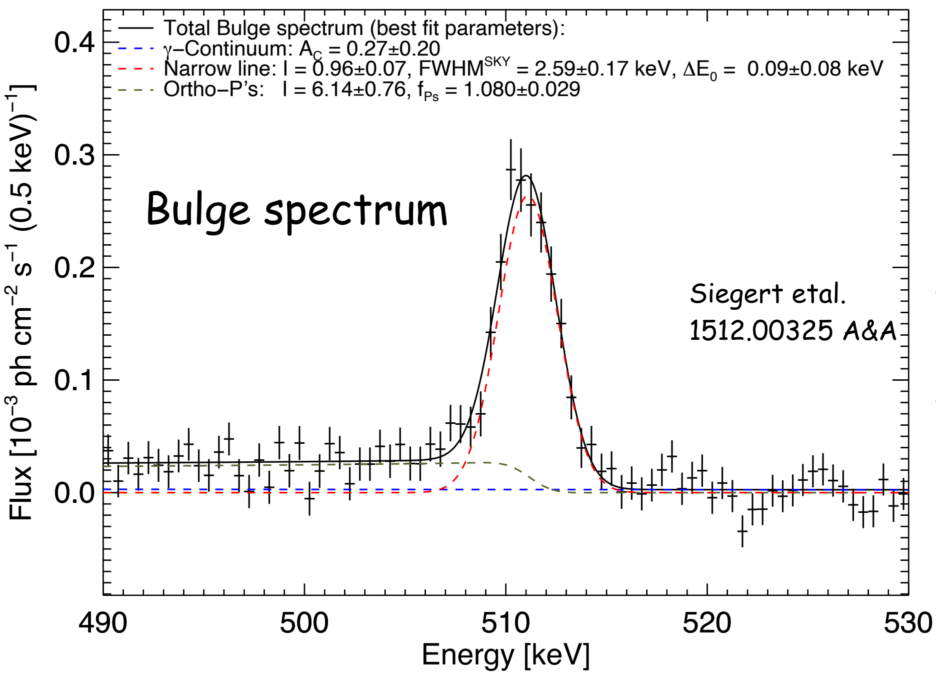
INTEGRAL/ SPI observations

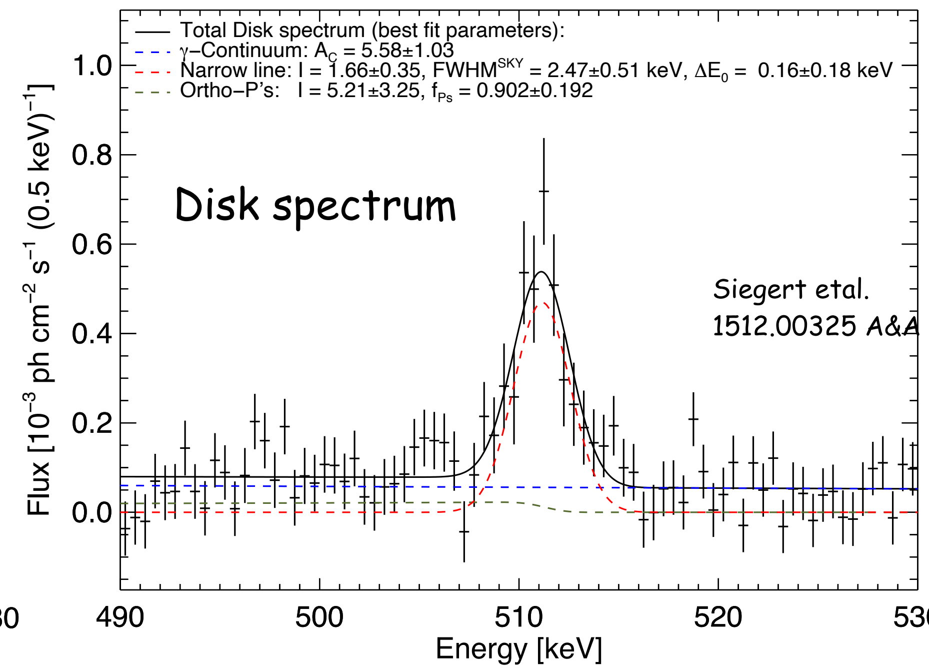


Siegert etal. 1512.00325 A&A

Detected via different instruments

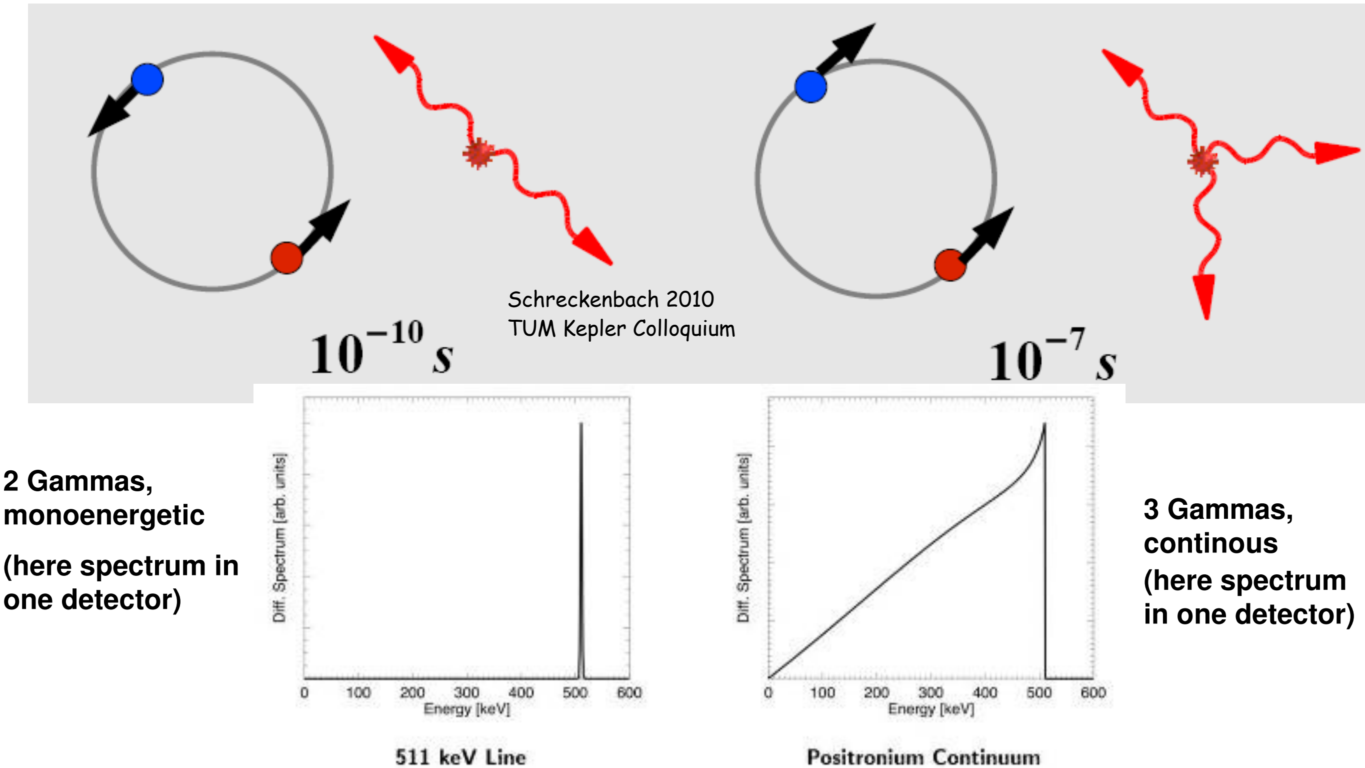
What is the source of this radiation?





Positron annihilation

Para Positronium, l=0 Ortho Positronium l=1



Positron annihilation can produce two monochromatic 511 keV photons or 3 photons with a total energy of 1.022 MeV (production to larger number of photons are suppressed)

Ratio of the mono-chromatic to the continuum radiation flux can be used to estimate the positronium fraction: $f_{\mathrm{Ps}} \approx 0.99 \pm 0.07$ (Siegert etal. 1512.00325 A&A)

Measurement of gamma-rays at higher energies (> 511 keV) help constrain the injection energy of the positron (Beacom and Yuksel astro-ph/0512411, Sizun etal. astro-ph/0607374 PRD)

511 keV gamma-ray line

The flux of 511 keV gamma-ray line and low-energy continuum gamma-ray measurements imply a positron injection rate of $\sim 2 \times 10^{43}\ s^{-1}$

Multiple sources are postulated to give rise to these positrons: millisecond pulsars, low-mass X-ray binaries, neutron star mergers, supernovae, pair-plasma jets from Sgr A* or dark matter, although none are confirmed to give rise to this entire emission (Kierans etal. 1903.05569) (Siegert et al 2109.03691 claim a nucleosynthesis origin of this signal)

Can we derive a robust constraint on PBHs using this observation? (see earlier works in Okele and Rees 1980, Okeke 1980, MacGibbon & Carr 1991, and Bambi etal. 2009)

A robust and conservative bound on PBHs

Any exotic dark sector source cannot inject more positrons than what is allowed by the Galactic Center 511 keV and continuum gamma-ray measurements

Fraction of dark matter in the form of PBHs

dark matter density

$$f_{\rm DM} \, \frac{\int dV \, \rho_{\rm DM}(r)}{M_{\rm PBH}} \int dE \, \frac{d^2 N_e}{dt\,dE} \lesssim 2 \times 10^{43}\,{\rm s}^{-1}$$

Mass of the PBH

Number of positrons emitted per unit time and per unit energy by PBHs

Positron luminosity required by INTEGRAL/ SPI observation

PBHs are like decaying dark matter: the formula mimic those of decaying dark matter

Positron propagation and dark matter density profile introduces uncertainty

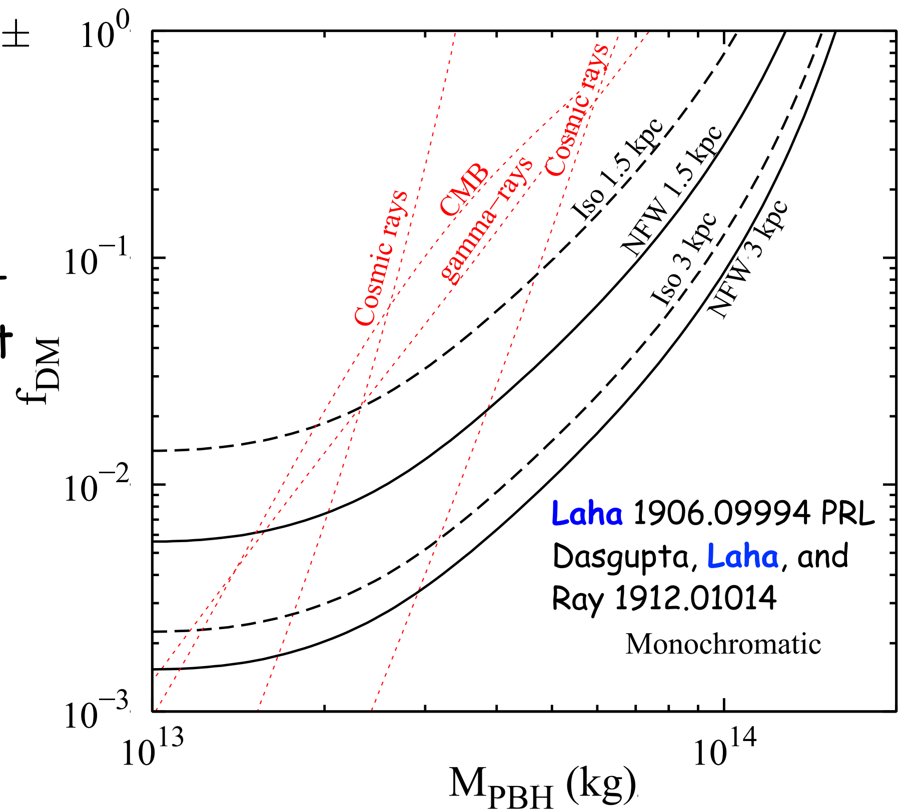
Low-mass PBHs and Galactic Center 511 keV line

Low-mass PBHs can evaporate to produce $e^{\pm}$ pairs

The positrons will lose energy, become non-relativistic, and annihilate with the ambient electrons to produce photons

Galactic Center observations reveal an intense flux of 511 keV and associated continuum gamma-ray photons produced by unknown source(s)

Requiring that the positrons from PBH evaporation do not overshoot the positron luminosity produces one of the strongest limit on their abundance with masses between ~ 10^{13} kg to 10^{14} kg



Similar results in DeRocco and Graham 1906.07740 PRL

See also Keith and Hooper 2103.08611 PRD

$$\frac{dN}{dM} \propto \delta(M - M_{\mathrm{PBH}})$$

Limits from the measurement of Galactic Center photons

Gamma-ray measurements of the cosmic-ray electrons and positrons

The Astrophysical Journal, 739:29 (15pp), 2011 September 20 doi:10.1088/0004-637X/739/1/29

DIFFUSE EMISSION MEASUREMENT WITH THE SPECTROMETER ON *INTEGRAL* AS AN INDIRECT PROBE OF COSMIC-RAY ELECTRONS AND POSITRONS

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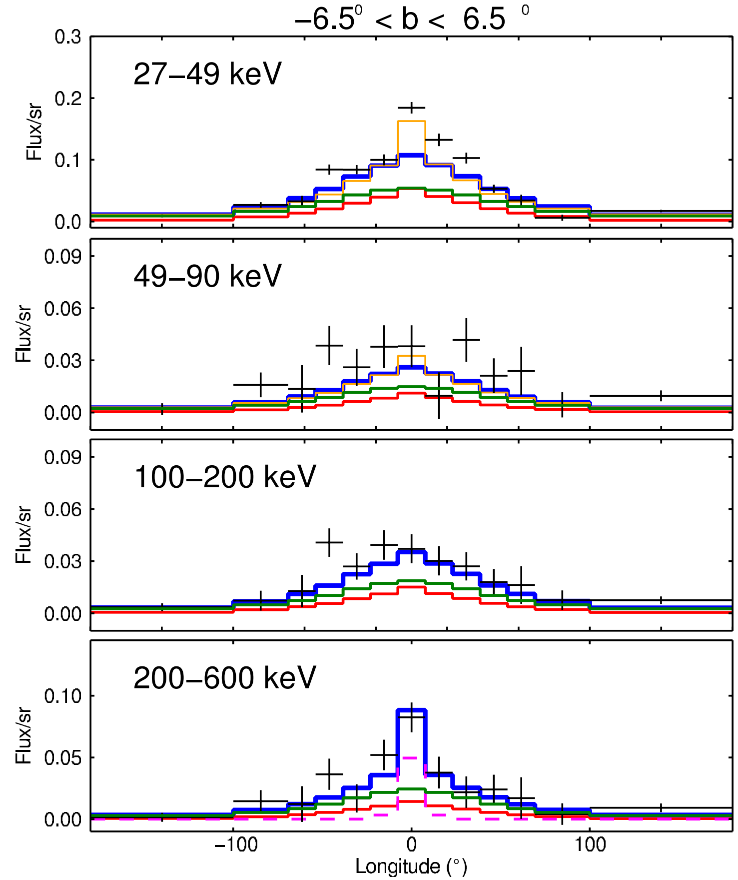
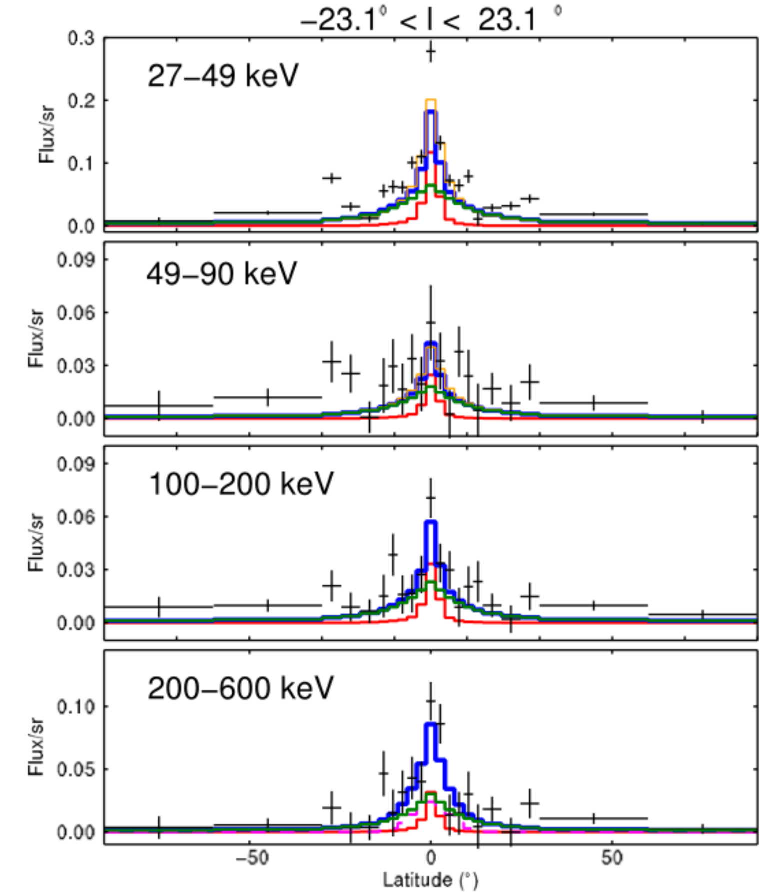
Measurement of the gamma-ray emission in the inner Galaxy and the contribution of cosmic-ray electrons and positrons

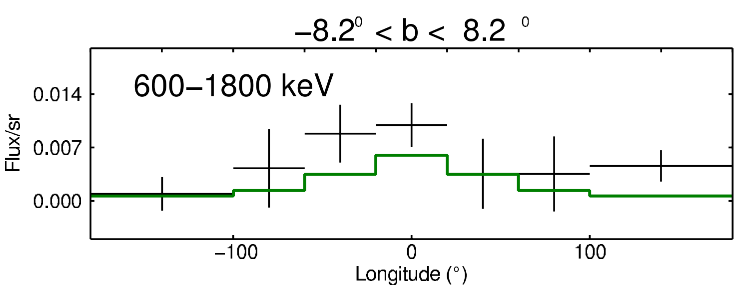
Gamma-ray measurements of the cosmic-ray electrons and positrons

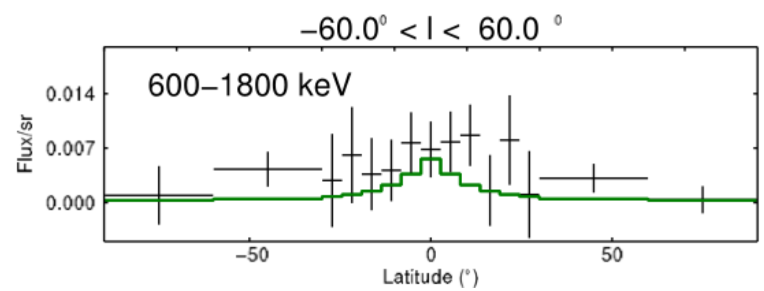


A good description of the data due to inverse Compton emission, stellar emission, and annihilation radiation

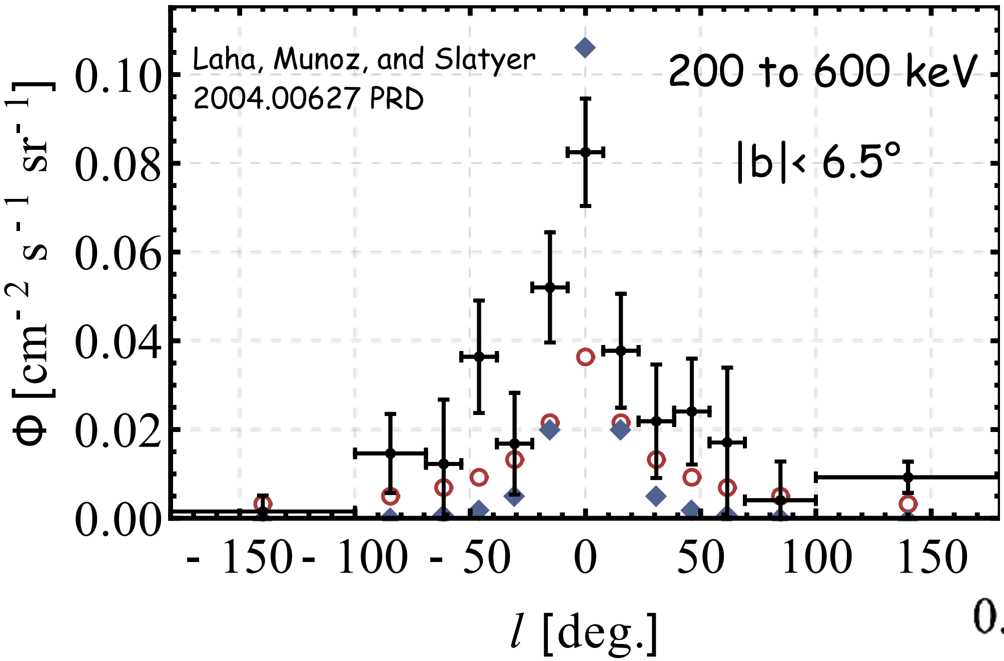
Bouchet et al., 1107.0200







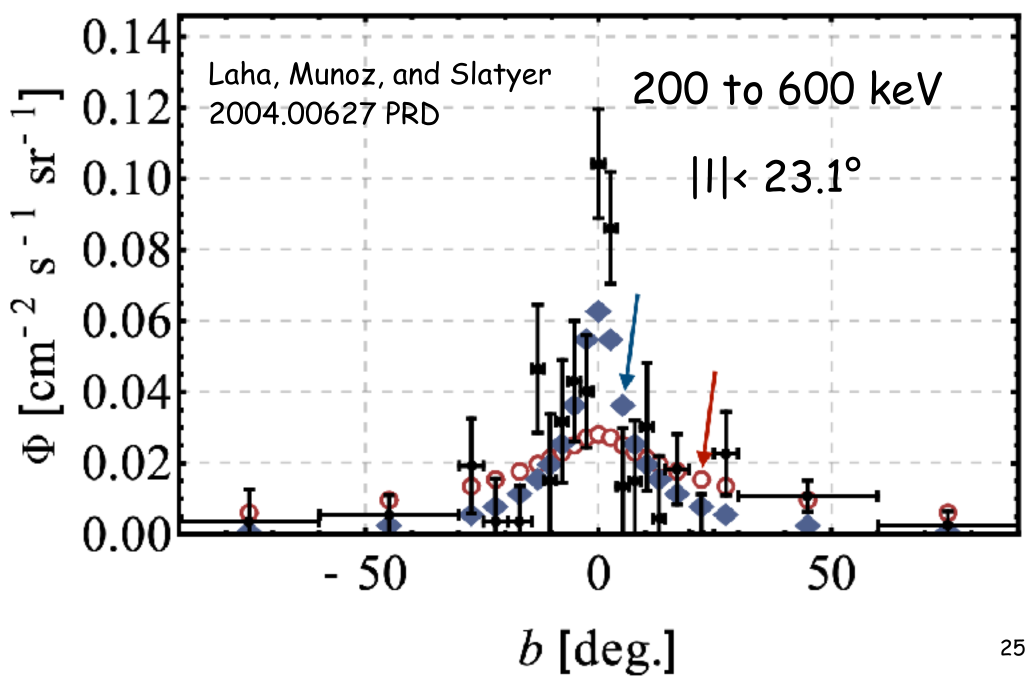
Angular dependence of the PBH signal and the INTEGRAL data



Red circle = Predicted photon emission from Hawking-evaporating PBHs with $M_{PBH} = 1.5 \times 10^{17}$ g

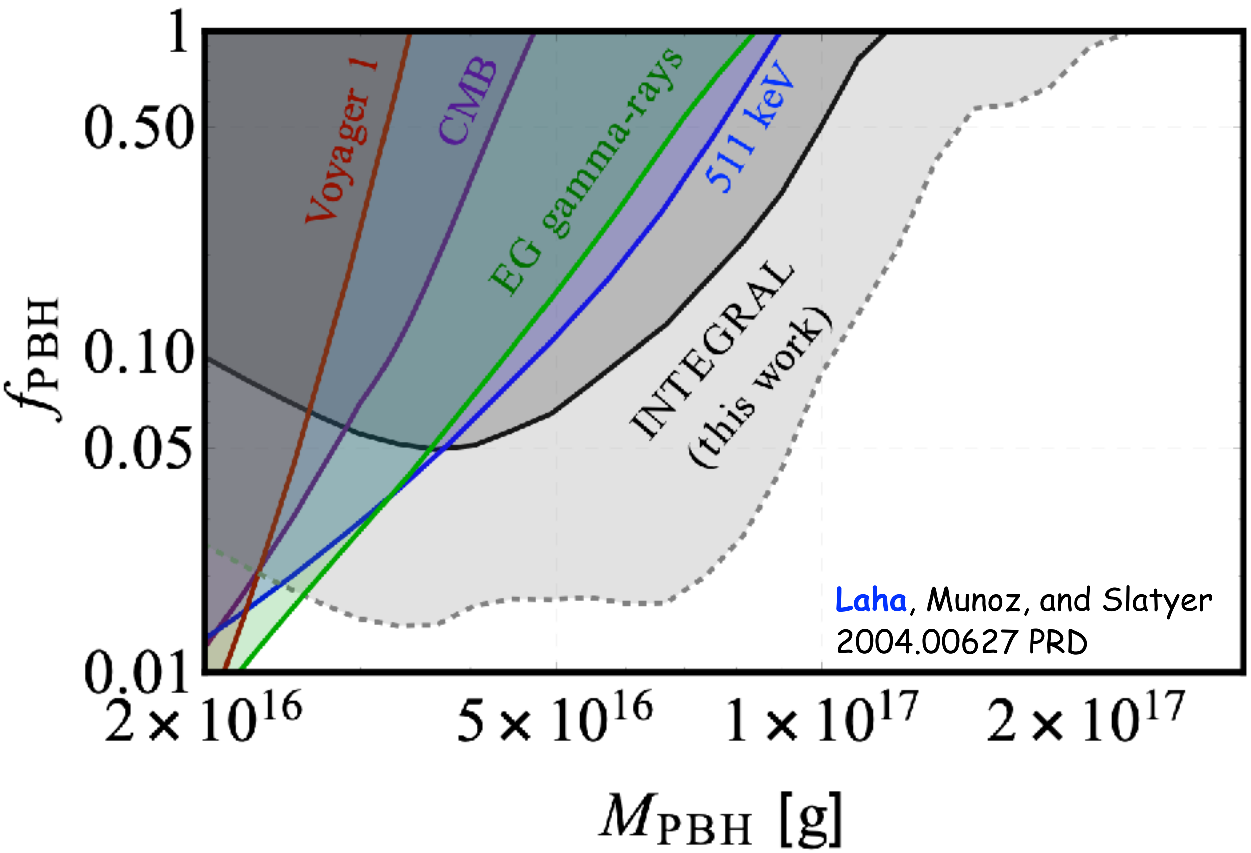
Energy range considered 0.027 to 1.8 MeV

Constraint strategy: PBH signal not overproduce any data point by more than 2x the error bar



Modeling the PBH signal + astrophysical background (due to emission of Galactic Center e±) will lead to stronger constraints (see recent work by Berteaud et al 2202.07483)

Angular dependence of the PBH signal and the INTEGRAL data



One of the best probes of low-mass PBHs

This constraint is relatively insensitive to the dark matter profile

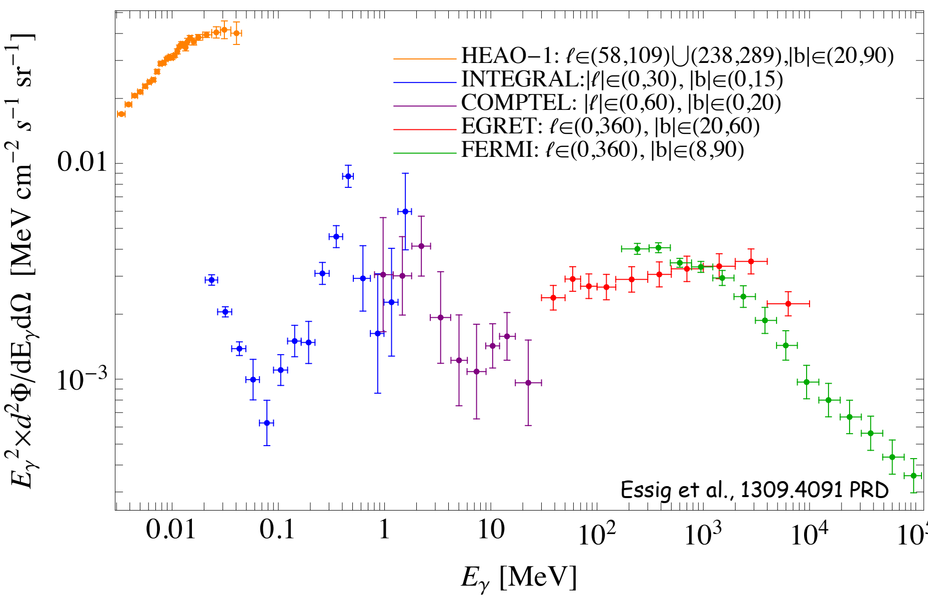
Assumes a mono-chromatic mass function of non-spinning PBHs

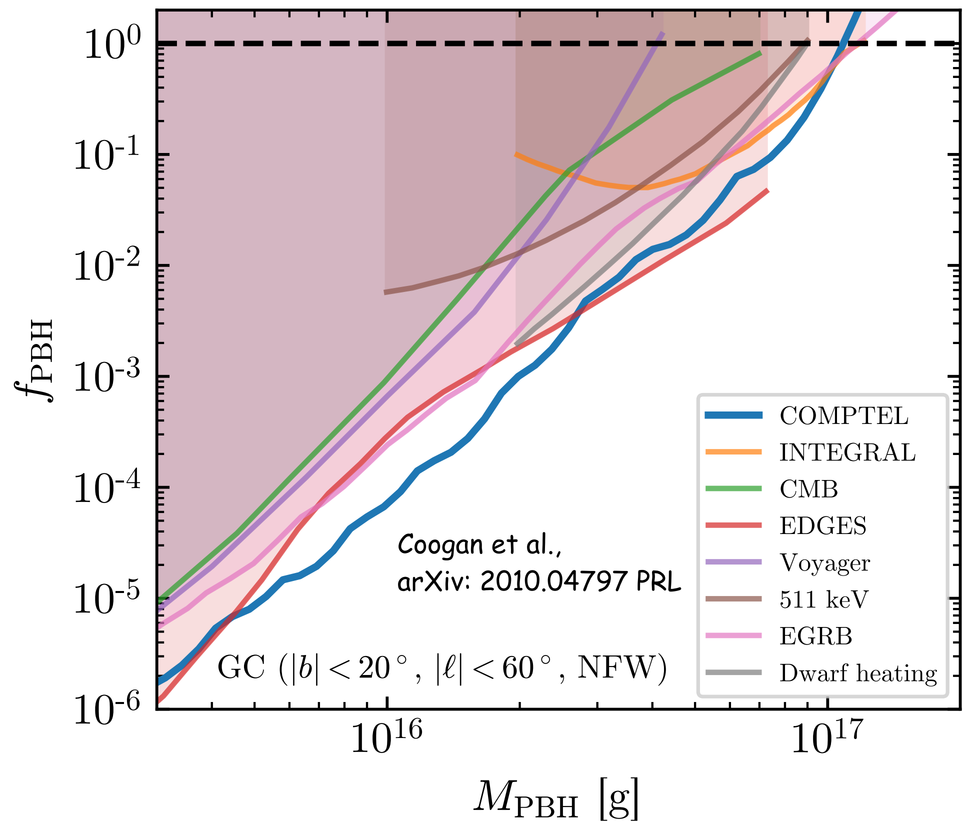
Equally constraining probe for an extended mass function of PBHs and for spinning PBHs

Constraints on PBH from COMPTEL observations

COMPTEL performed observations between ~ 1991 to ~ 2000

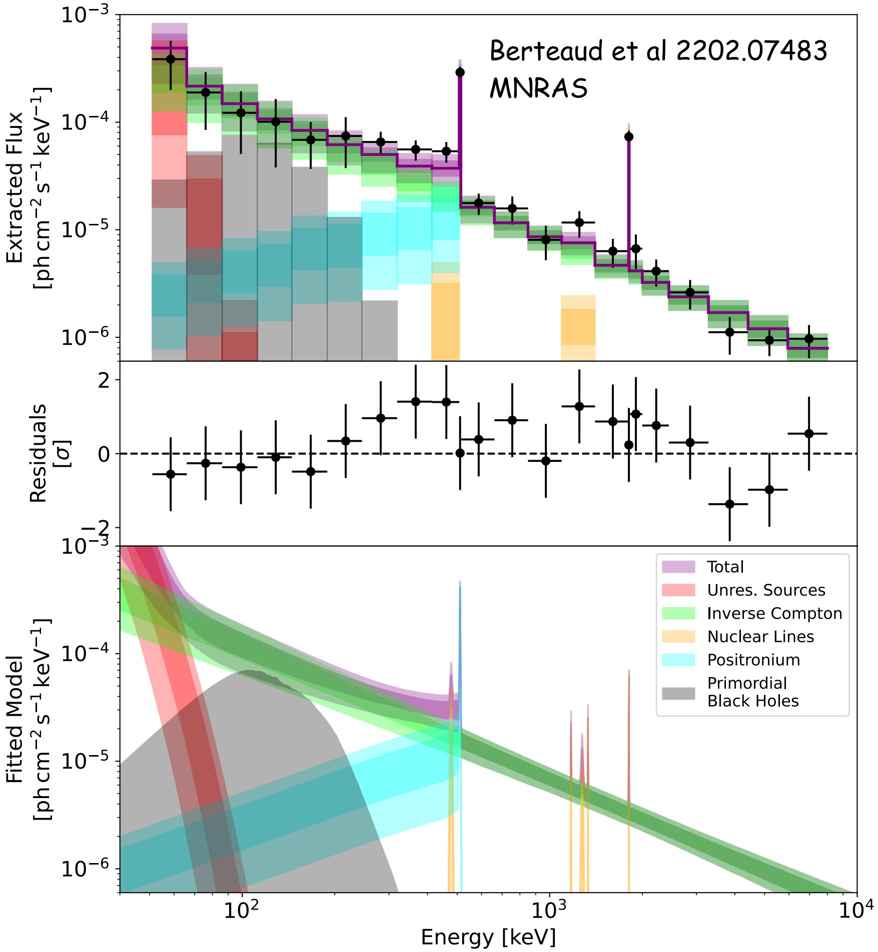
Sensitive between 0.75 to 30 MeV

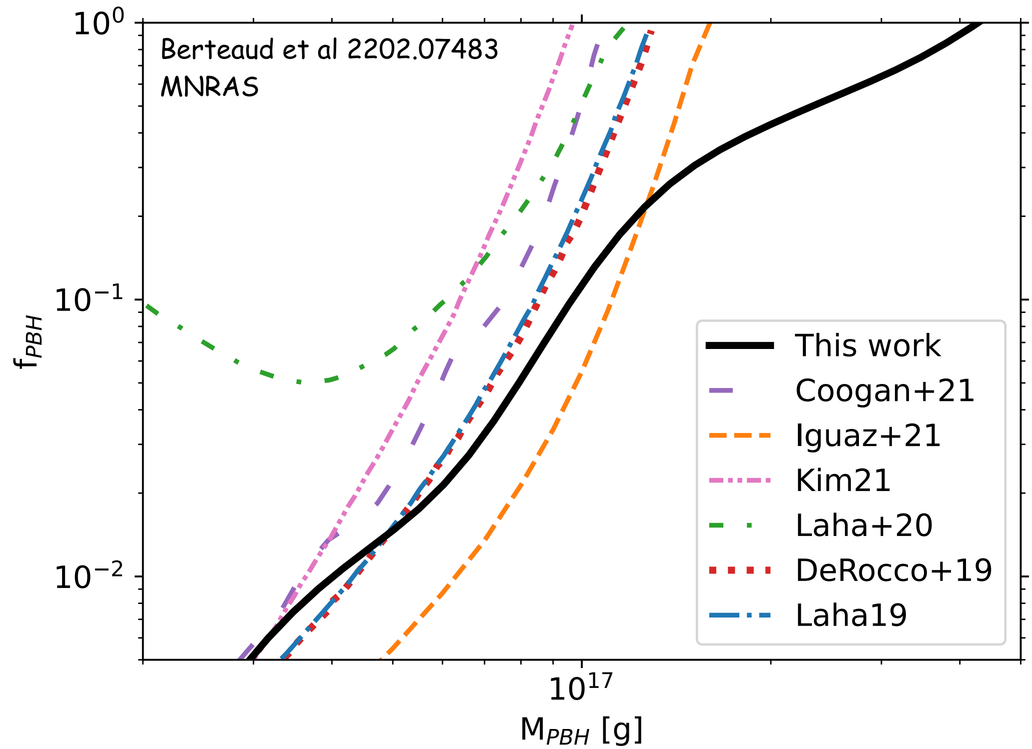




Strong constraints on PBH DM density using archival COMPTEL observations

Constraints on PBH from 16 years of INTEGRAL/ SPI observations



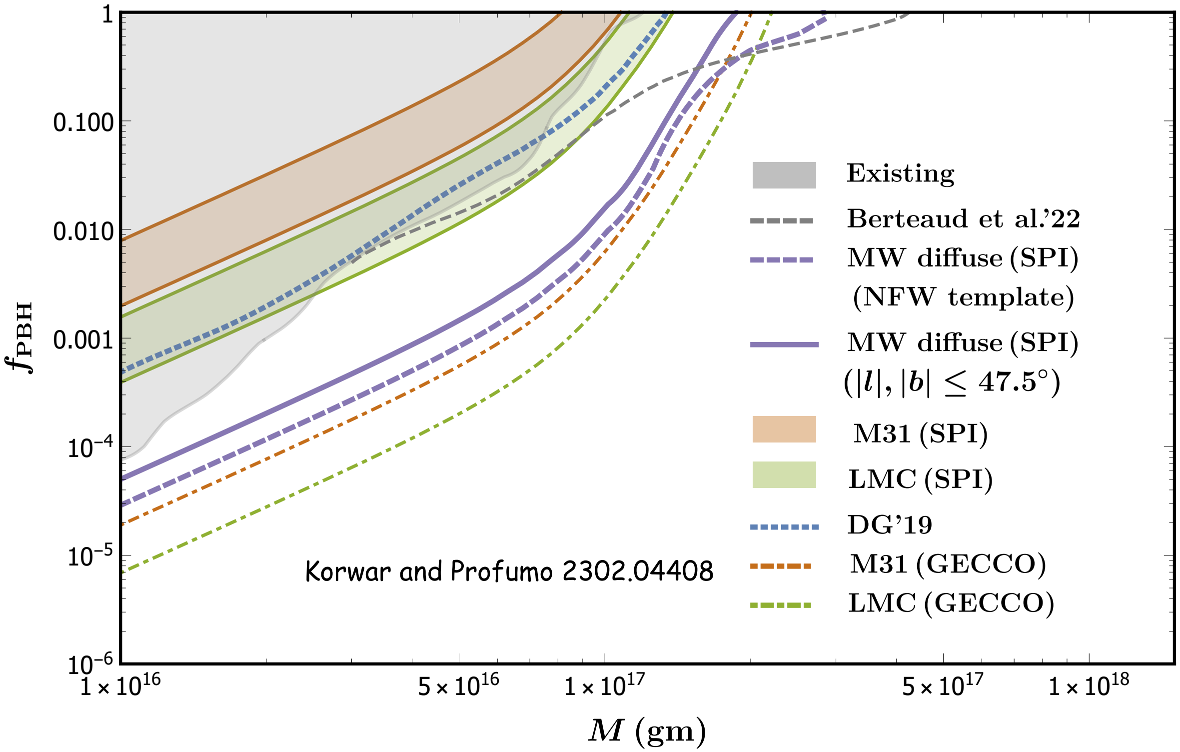


Observation of diffuse soft gamma-rays from the inner galaxy and its fit using various astrophysical components

No excess observed in the entire energy range

Strong constraints on PBH DM density

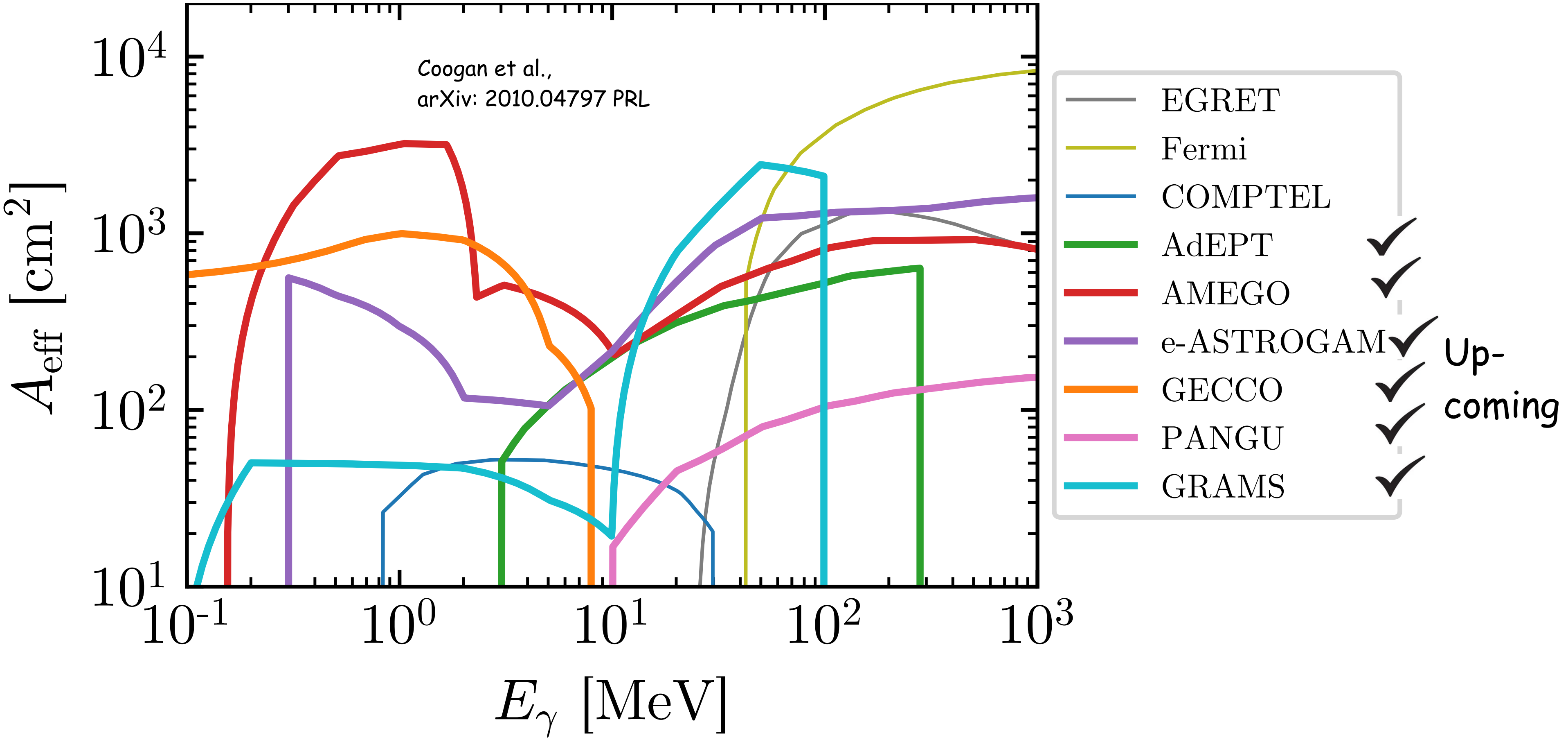
Constraints on PBH from gamma-ray observations of the Milky Way and LMC



Constraint on PBH DM using various observations of the Milky Way and Large Magellanic Cloud

Future prospects

Near future MeV telescopes

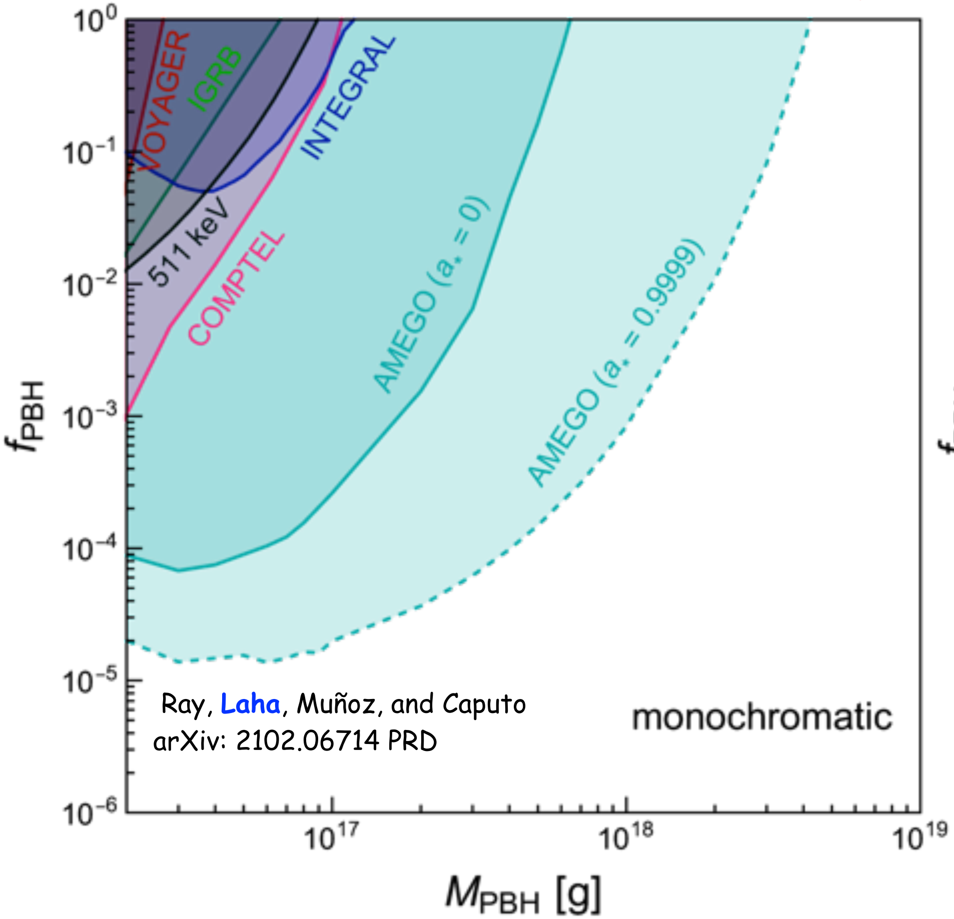


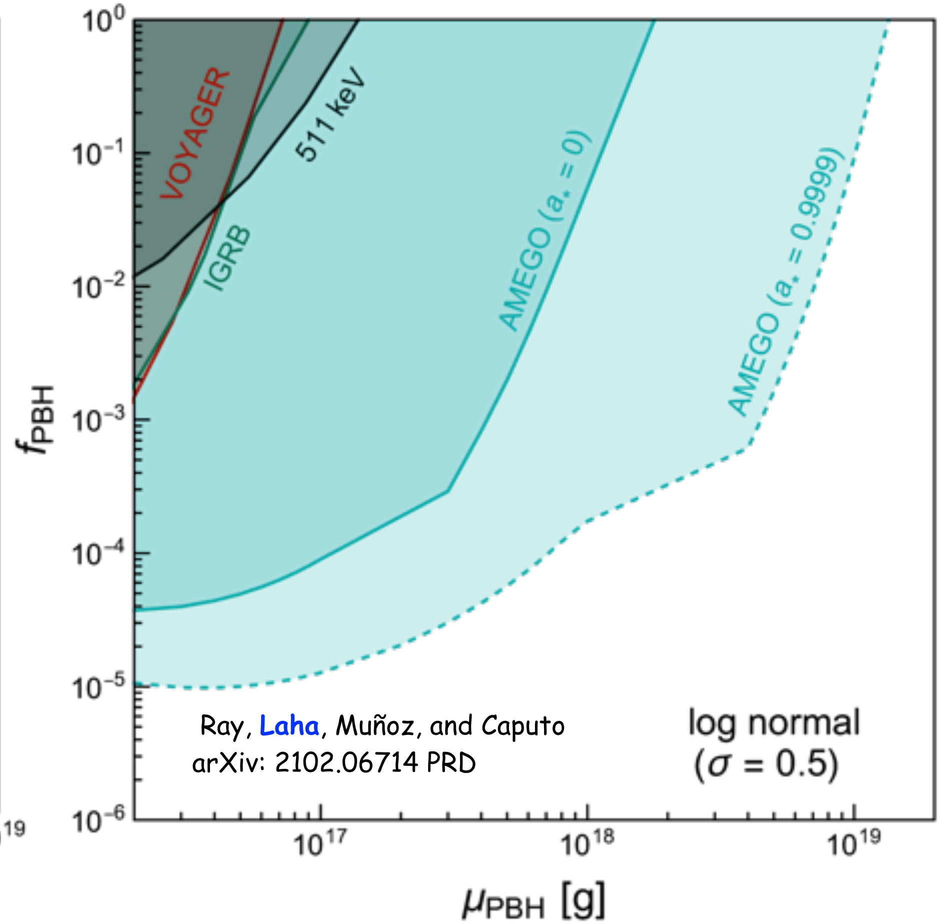
Various gamma-ray telescopes with sensitivity in the MeV range are being planned

Useful for various astrophysics and particle physics studies

Can be a probe of various beyond the Standard Model scenarios

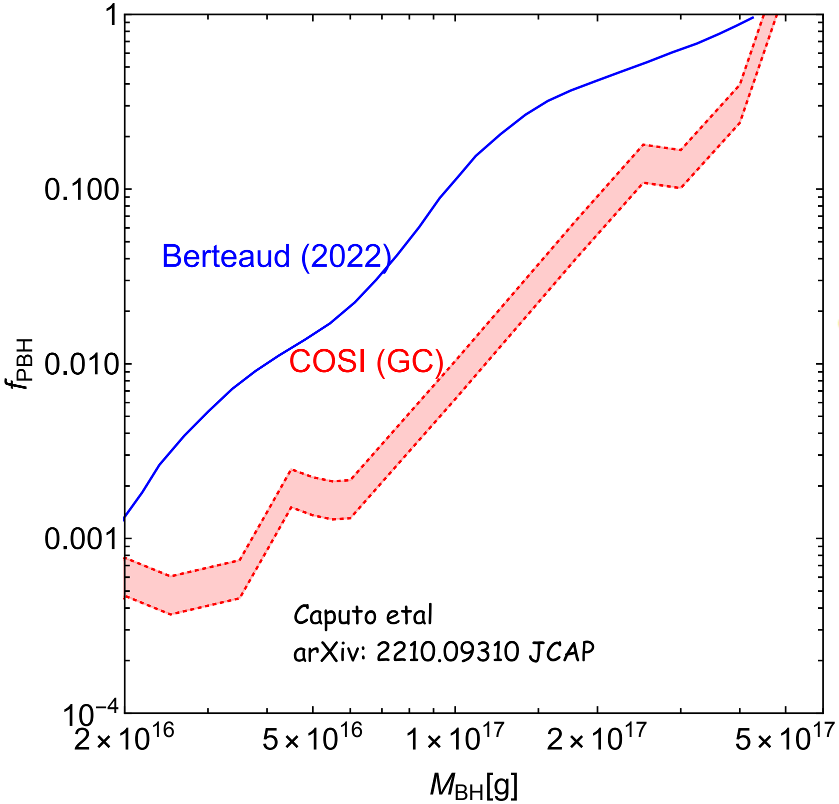
Projections in PBH parameter space using an AMEGO-like experiment

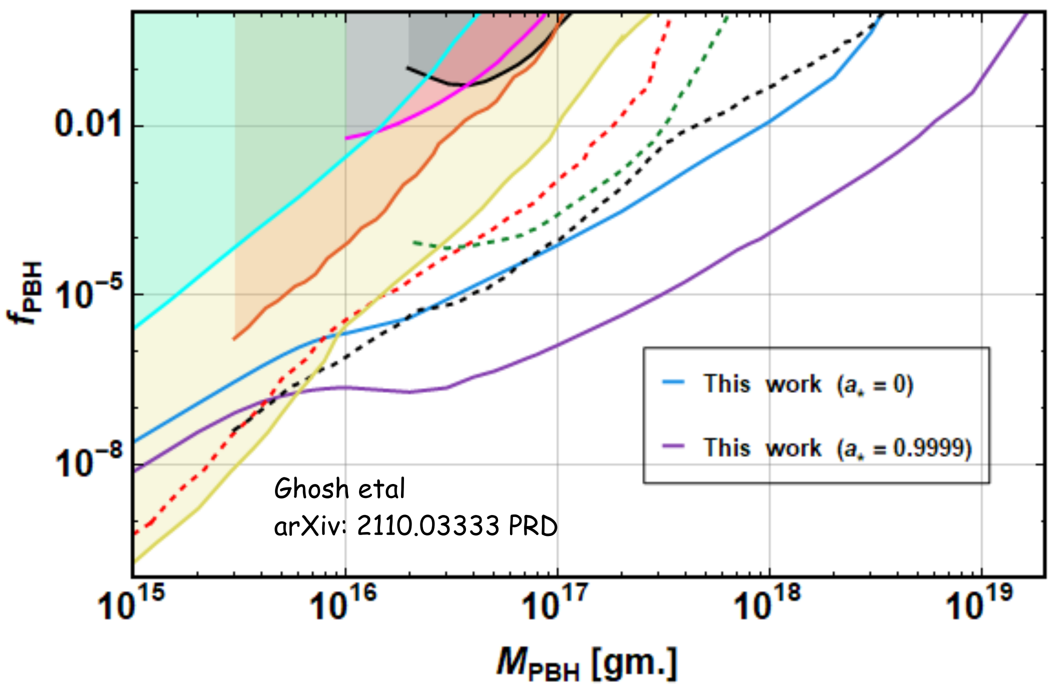




Very promising discovery probe for PBH DM

Projections in PBH parameter space using COSI and XGIS-THESEUS





Very promising discovery probe for PBH DM

Other probes

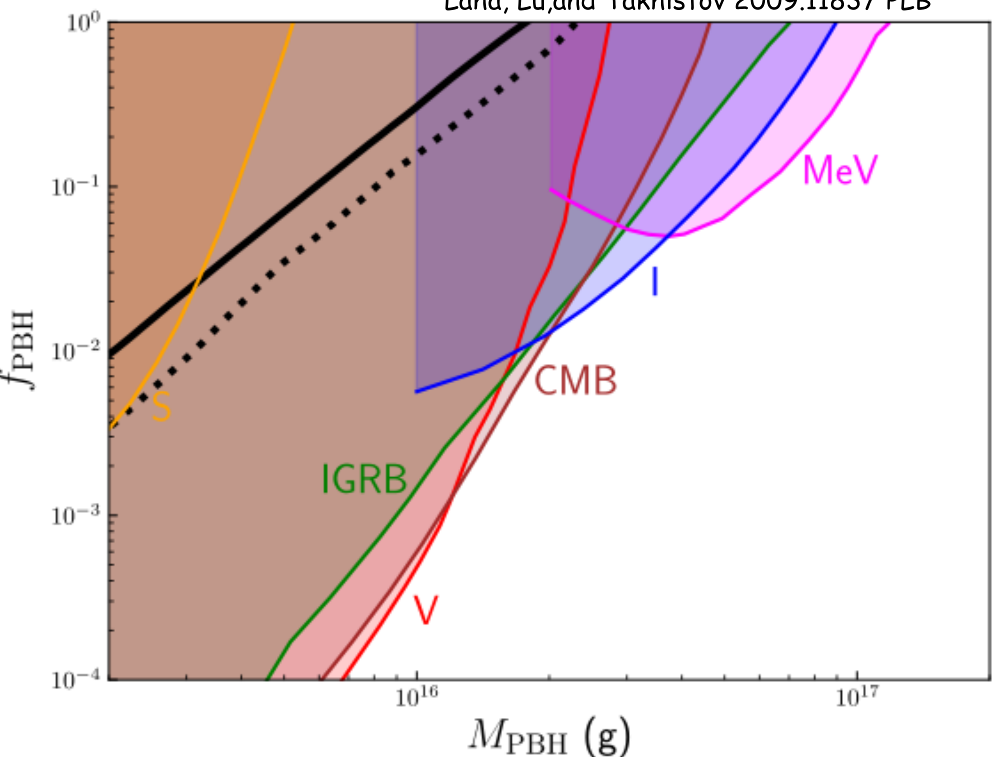
Some other probes of low-mass PBHs

(1) 21 cm measurements: Effect of energy injection due to Hawking radiation (Saha and Laha 2112.10794 PRD, Clark et al., 1803.09390 PRD; Halder and Pandey 2101.05228)

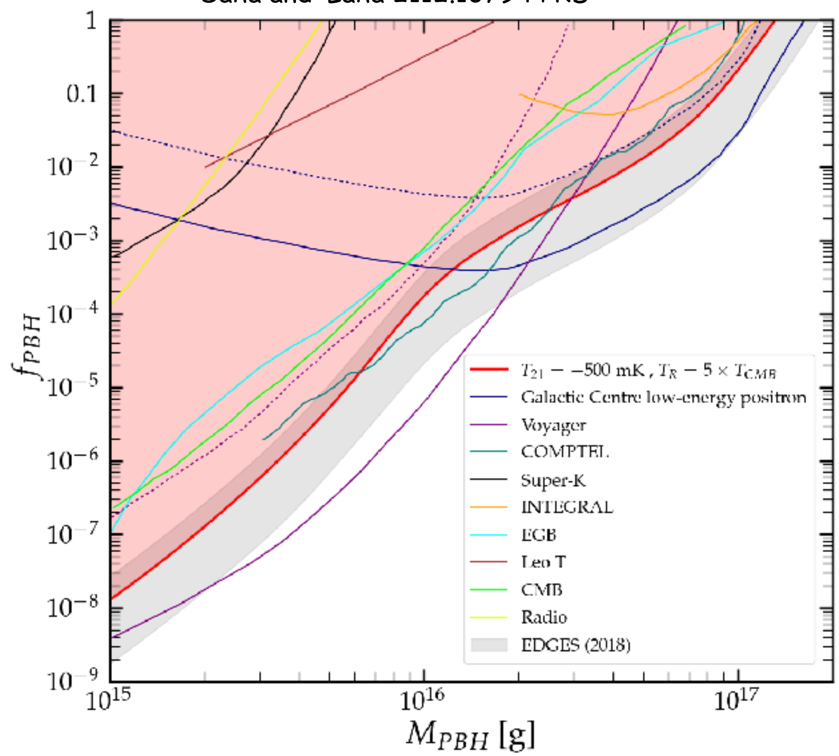
(2) Leo-T: gas heating (Kim 2007.07739; Laha, Lu,and Takhistov 2009.11837 PLB)

(3) Radio observations: synchrotron or inverse Compton energy losses of $e^{\pm}$ from PBH evaporation can be observed via radio telescopes (Chan and Lee 2007.05677 MNRAS; Dutta, Kar, and Strigari 2010.05977)

Laha, Lu,and Takhistov 2009.11837 PLB



Saha and Laha 2112.10794 PRD



Conclusions

Primordial black hole (PBH) is a well motivated dark matter candidate

There are large regions of the parameter space where PBHs can make up the entire dark matter density or a substantial portion of it

The observation of low-energy positrons in the Galactic Centre via the 511 keV and associated continuum gamma-ray photons put a strong constraint on low-mass PBHs

The observation of Galactic Center photons also puts an equally strong constraint on low-mass PBHs

Near future MeV telescope, like AMEGO, can probe new parts of the PBH DM parameter space. Other probes include dwarf galaxy heating, 21 cm emission, etc.

It is important to probe this entire parameter space to as small a cosmic density as possible

Questions & comments: ranjanlaha@iisc.ac.in