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

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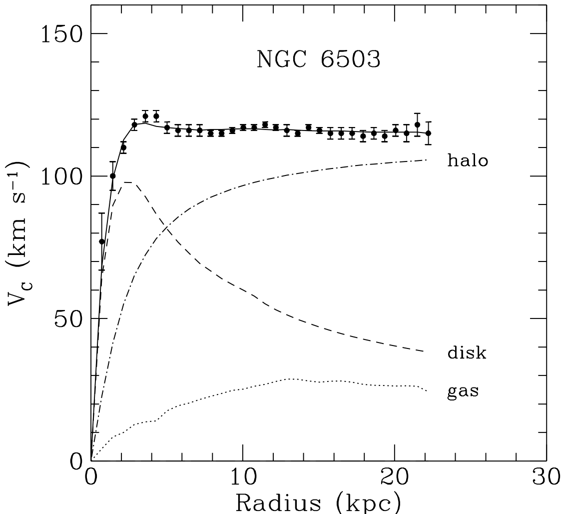
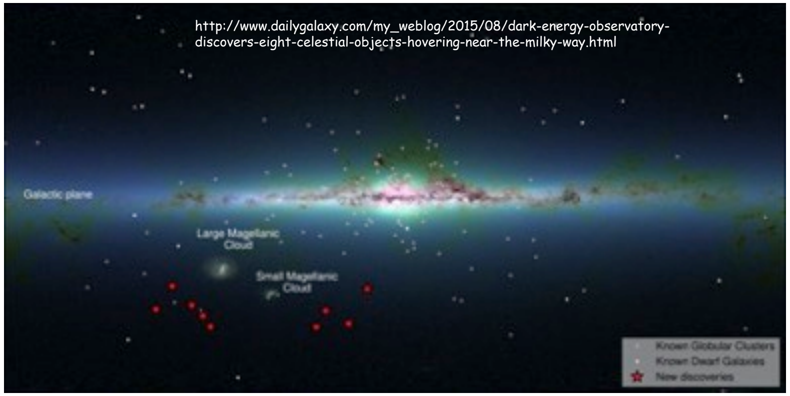
Thanks to my collaborators: Anupam Ray, Regina Caputo, Basudeb Dasgupta, Julian B. Muñoz, Philip Lu, Tracy R. Slatyer, and Volodymyr Takhistov

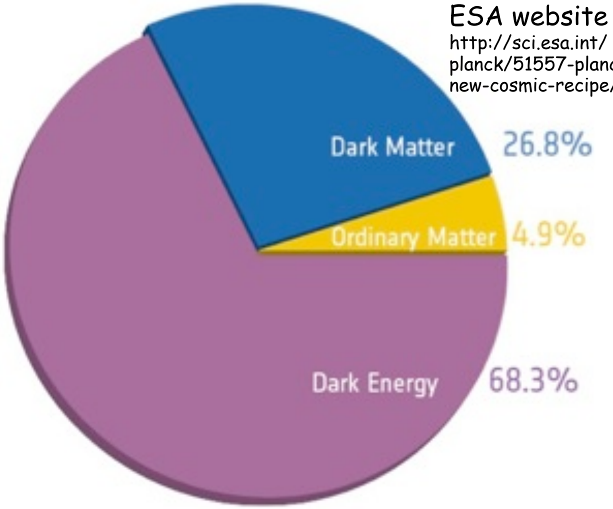
Gravitational detection of dark matter



Begeman, Broeils & Sanders MNRAS 249 (1991) 523



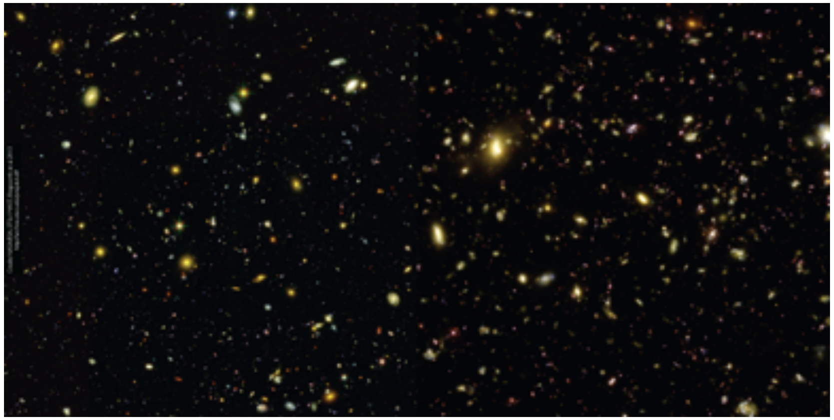
Bullet cluster
https://en.wikipedia.org/wiki/File:1e0657_scale.jpg



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 the parameter space 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 measurement of Galactic Center positrons

  (b) Limits from the measurement of Galactic Center photons

  (c) Future projections from an AMEGO-like experiment
- Conclusions

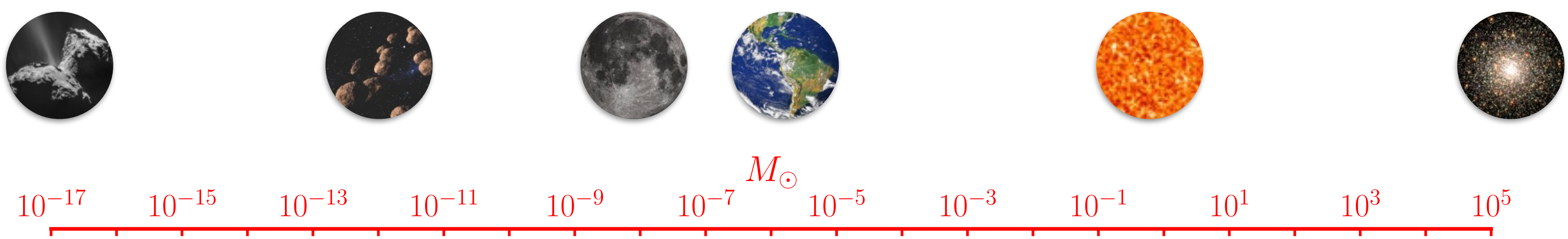
Primordial black holes (PBHs)

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

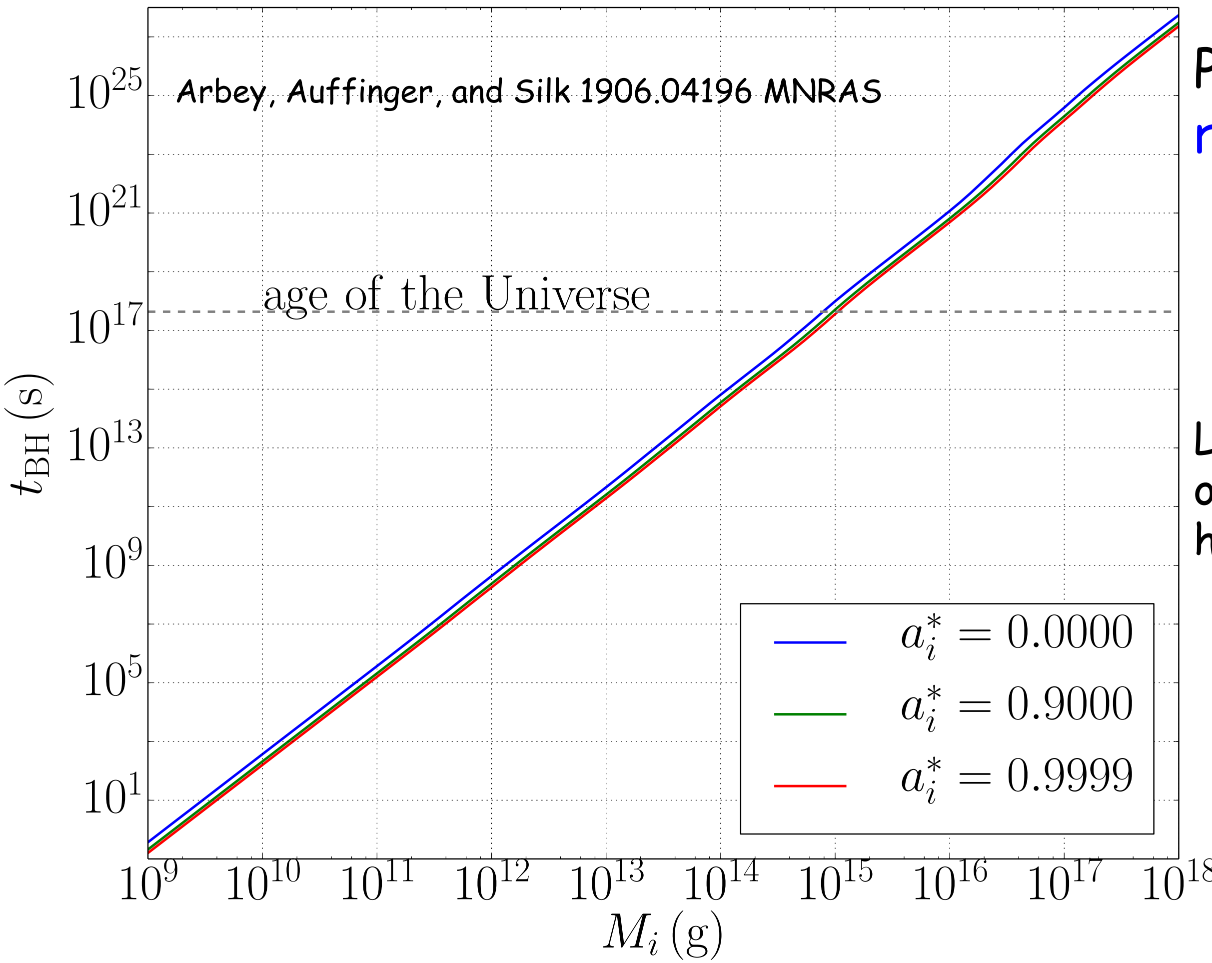


$$1\,M_\odot \approx 2 \times 10^{30}\,{\rm kg} \approx 1.1 \times 10^{57}\,{\rm GeV}$$

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 ($t_{\rm BH}$)

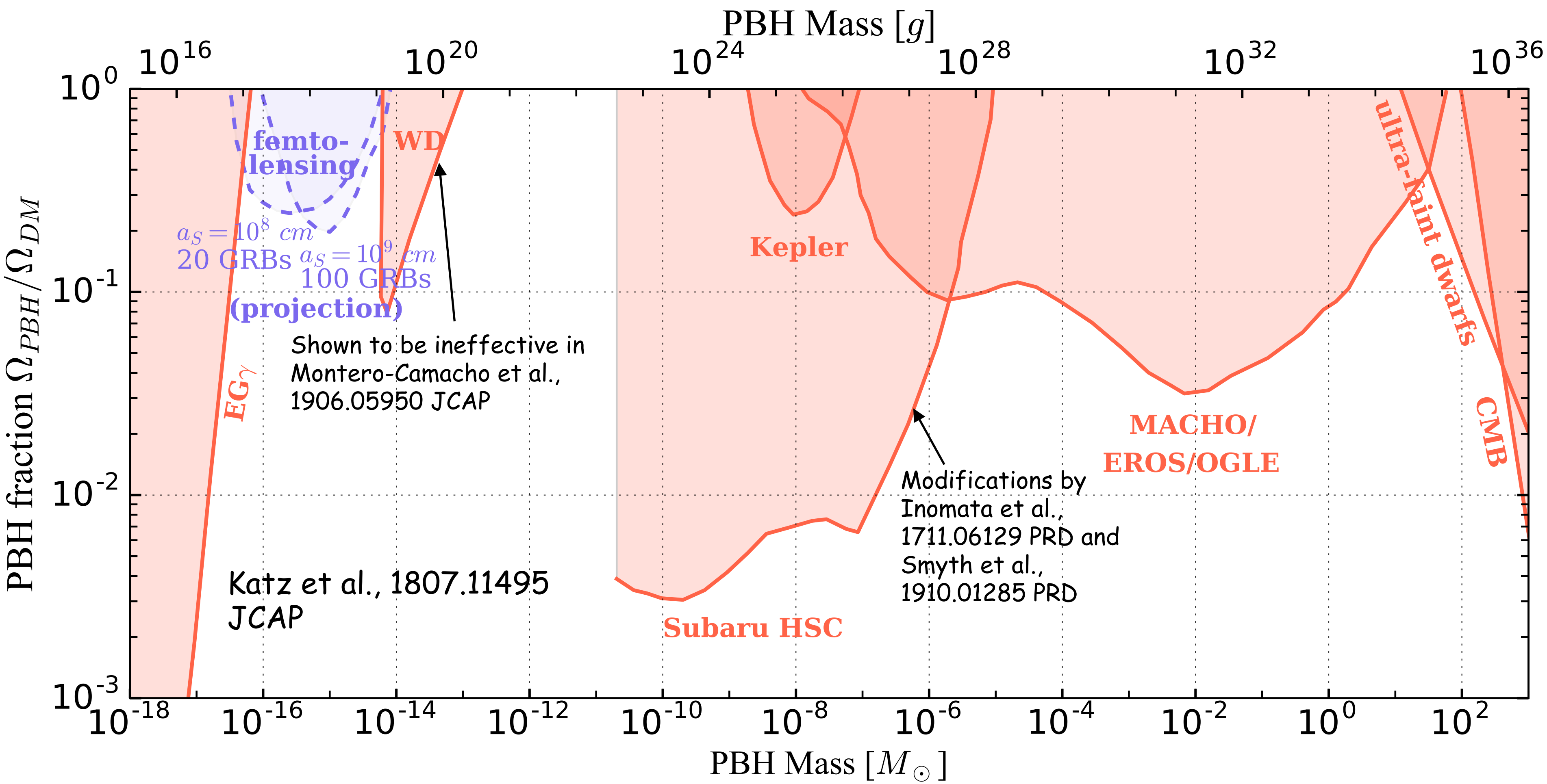
Mass of a black hole ($M_{\rm BH}$)

a_i^* = initial spin of the black hole

Minimum mass of non-spinning PBH DM ≈ 5×10^{14} g

Non-zero spin increases the minimum mass of PBH DM

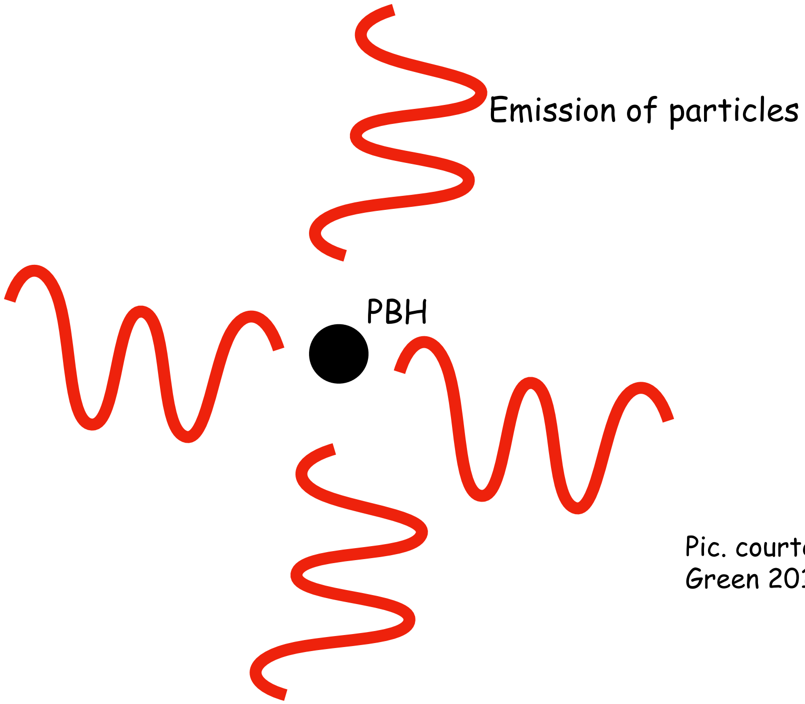
PBH dark matter (in 2018/ early 2019)



Multiple constraints exist over wide range of masses (all of these are not shown for clarity)

Multiple revisions/ many more constraints (see Dasgupta, Laha, and Ray 1912.01014; Carr et al., 2002.12778; Carr and Kuhnel 2006.02838; Green and Kavanagh 2007.10722 for up-to-date constraints)

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.

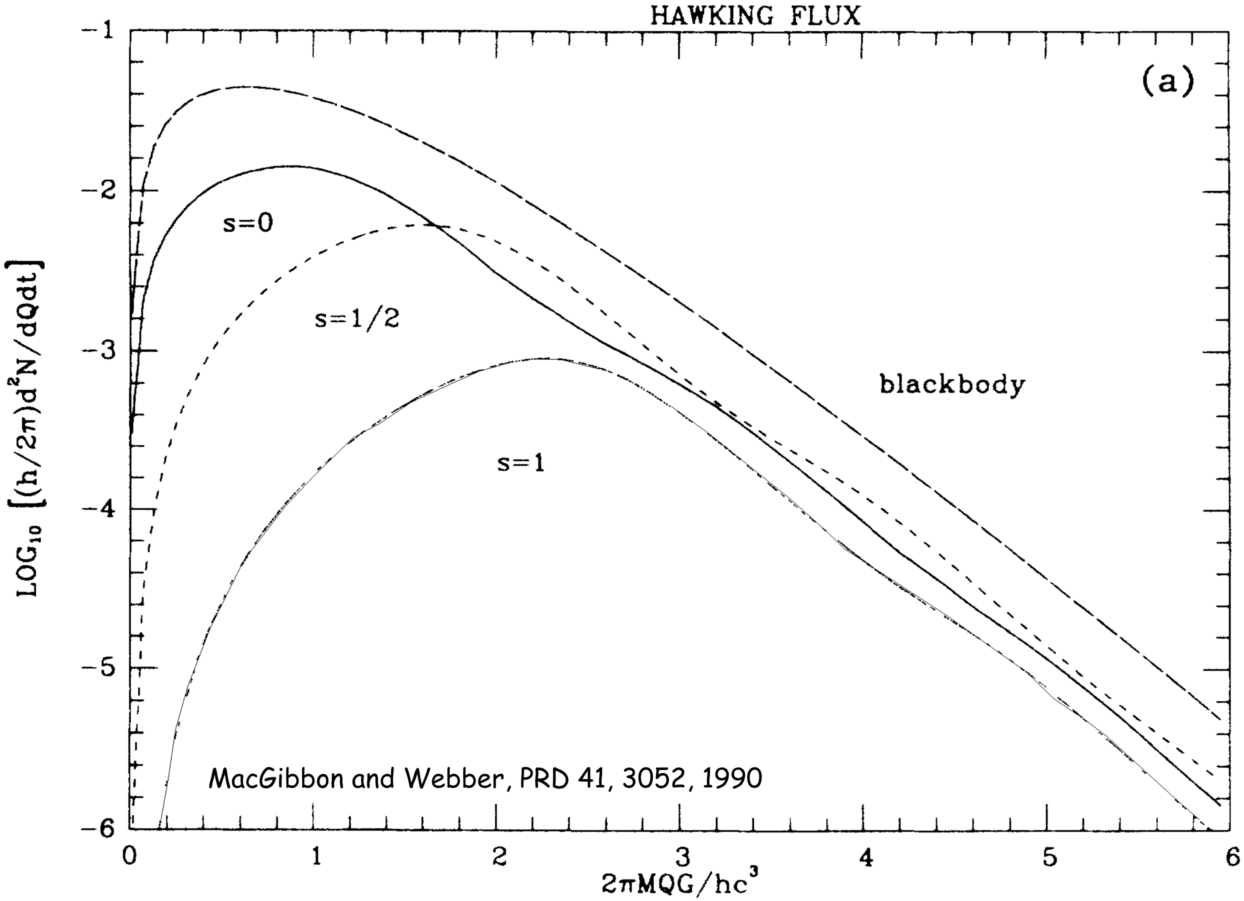
Dimensionless absorption probability for the emitted species → $\Gamma_{\rm s}$

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

↑ 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



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

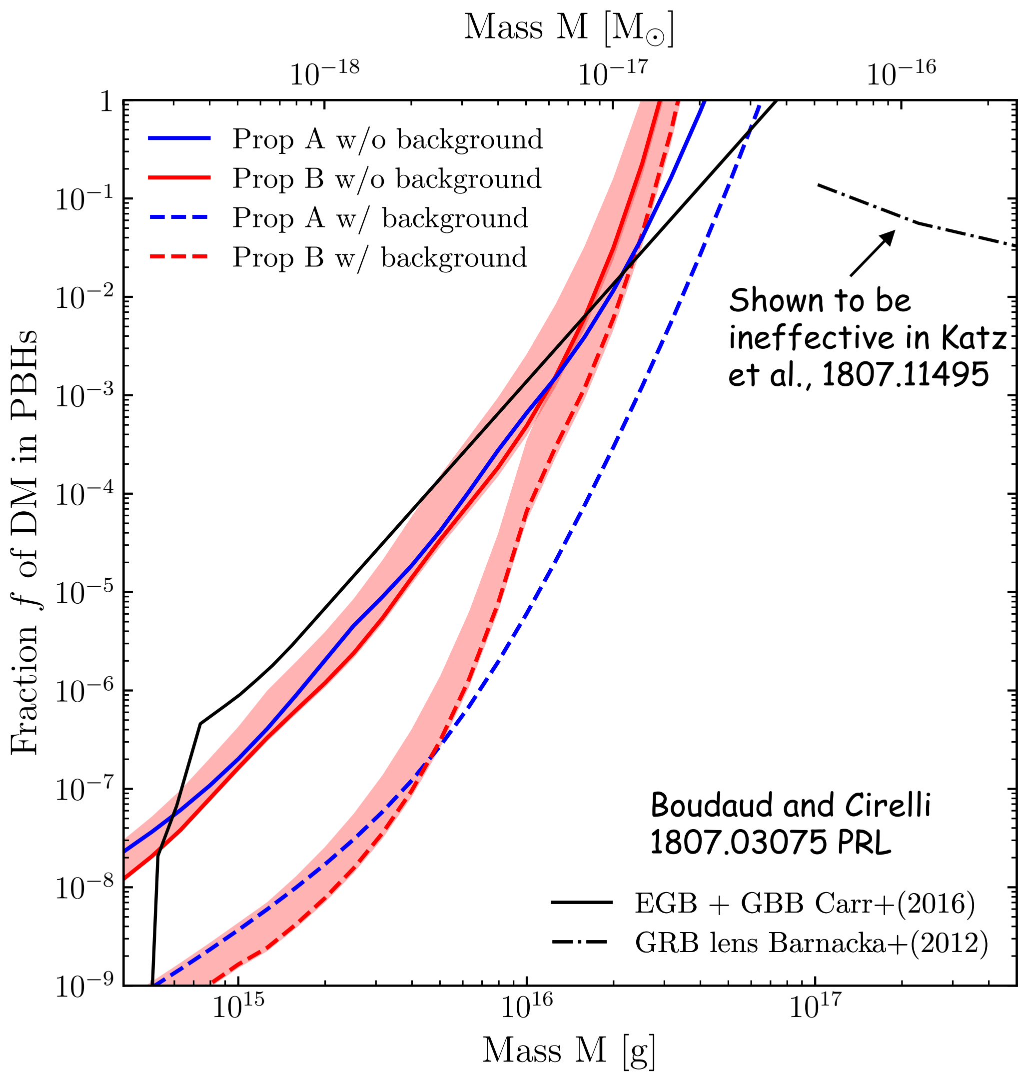
The spectrum closely resembles a black-body radiation

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

Ultra-light PBH (in 2018)



Ultra-light PBH dark matter ($M_{PBH} \lesssim 10^{17}$ g) are most strongly constrained via its Hawking radiation into Standard Model particles

The strongest constraint on ultra-light PBHs in late-2018 were from gamma-ray (Carr et al., 0912.5297) and Galactic cosmic-ray measurements (Boudaud and Cirelli 1807.03075)

Can we probe new regions of parameter space using Hawking radiation?

How to probe higher PBH masses?

Limits from the measurement of Galactic Center positrons

PHYSICAL REVIEW LETTERS

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Primordial Black Holes as a Dark Matter Candidate Are Severely Constrained by the Galactic Center 511 keV γ-Ray Line

Ranjan Laha
Phys. Rev. Lett. **123**, 251101 – Published 16 December 2019

ABSTRACT

We derive the strongest constraint on the fraction of dark matter that can be composed of low mass primordial black holes by using the observation of the Galactic Center 511 keV γ-ray line. Primordial black holes of masses $\lesssim 10^{15}$ kg will evaporate to produce $e^{\pm}$ pairs. The positrons will lose energy in the Galactic Center, become nonrelativistic, then annihilate with the ambient electrons. We derive robust and conservative bounds by assuming that the rate of positron injection via primordial black hole evaporation is less than what is required to explain the SPI/INTEGRAL observation of the Galactic Center 511 keV γ-ray line. Depending on the primordial black hole mass function and other astrophysical uncertainties, these constraints are the most stringent in the literature and show that primordial black holes contribute to less than 1% of the dark matter density. Our technique also probes part of the mass range which was completely unconstrained by previous studies.

Issue
Vol. 123, Iss. 25 — 20 December 2019

Laha 1906.09994
Physical Review Letters

PHYSICAL REVIEW LETTERS

Open Access

Neutrino and Positron Constraints on Spinning Primordial Black Hole Dark Matter

Basudeb Dasgupta, Ranjan Laha, and Anupam Ray
Phys. Rev. Lett. **125**, 101101 – Published 31 August 2020

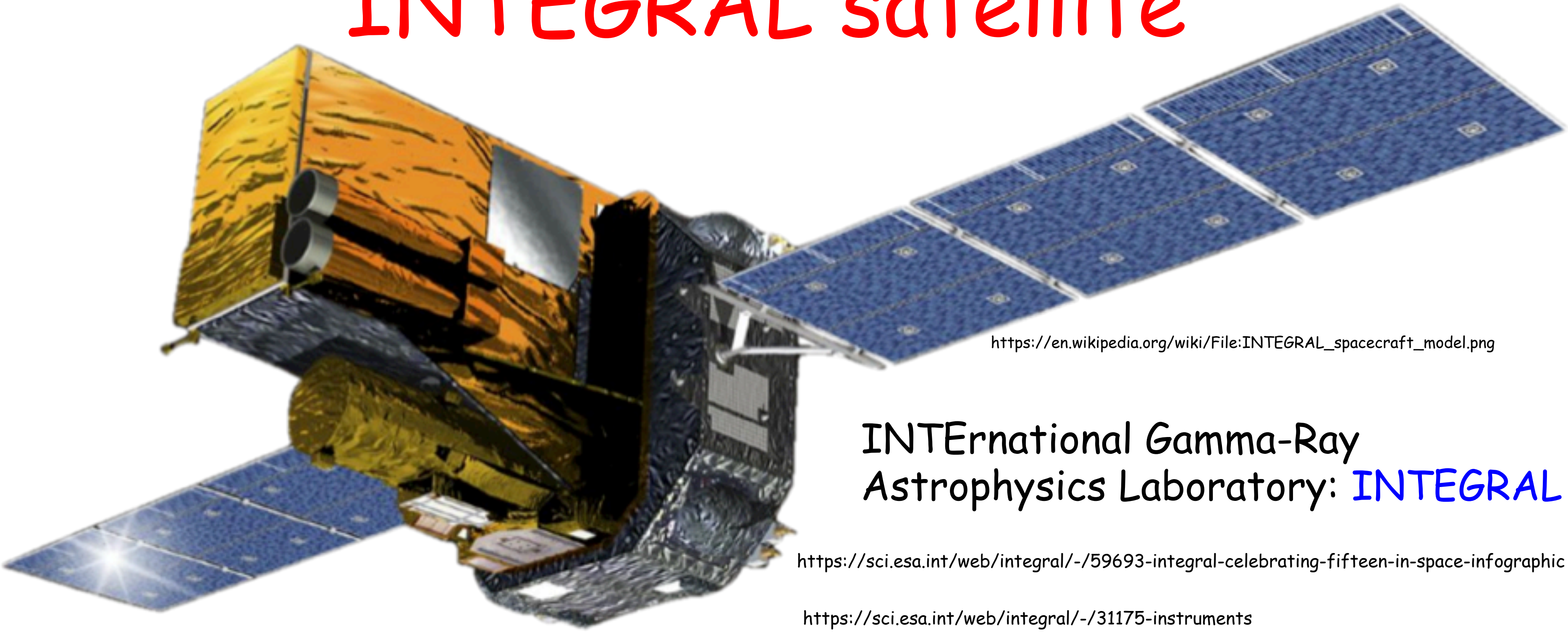
ABSTRACT

Primordial black holes can have substantial spin—a fundamental property that has a strong effect on its evaporation rate. We conduct a comprehensive study of the detectability of primordial black holes with non-negligible spin, via the searches for the neutrinos and positrons in the MeV energy range. Diffuse supernova neutrino background searches and observation of the 511 keV gamma-ray line from positrons in the Galactic center set competitive constraints. Spinning primordial black holes are probed up to a slightly higher mass range compared to nonspinning ones. Our constraint using neutrinos is slightly weaker than that due to the diffuse gamma-ray background, but complementary and robust. Our positron constraints are typically weaker in the lower mass range and stronger in the higher mass range for the spinning primordial black holes compared to the nonspinning ones. They are generally stronger than those derived from the diffuse gamma-ray measurements for primordial black holes having masses greater than a few $\times 10^{16}$ g.

Issue
Vol. 125, Iss. 10 — 4 September 2020

Dasgupta, Laha, and Ray 1912.01014
Physical Review Letters

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

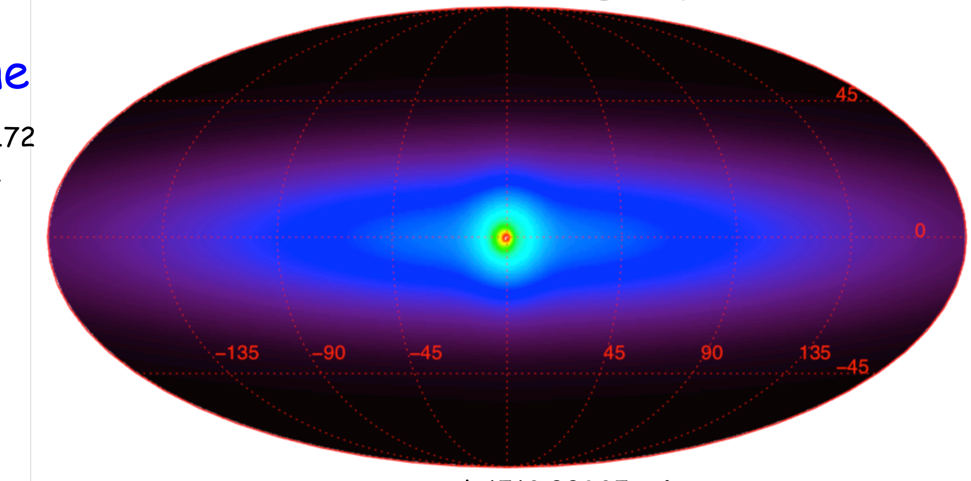
	Energy range	Energy resolution
SPectrometer of INTEGRAL (SPI):	18 keV to 8 MeV	~ 0.2% at 1.33 MeV
Imager on-Board the INTEGRAL Satellite (IBIS):	15 keV to 10 MeV	~ 10% at 1.33 MeV

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)

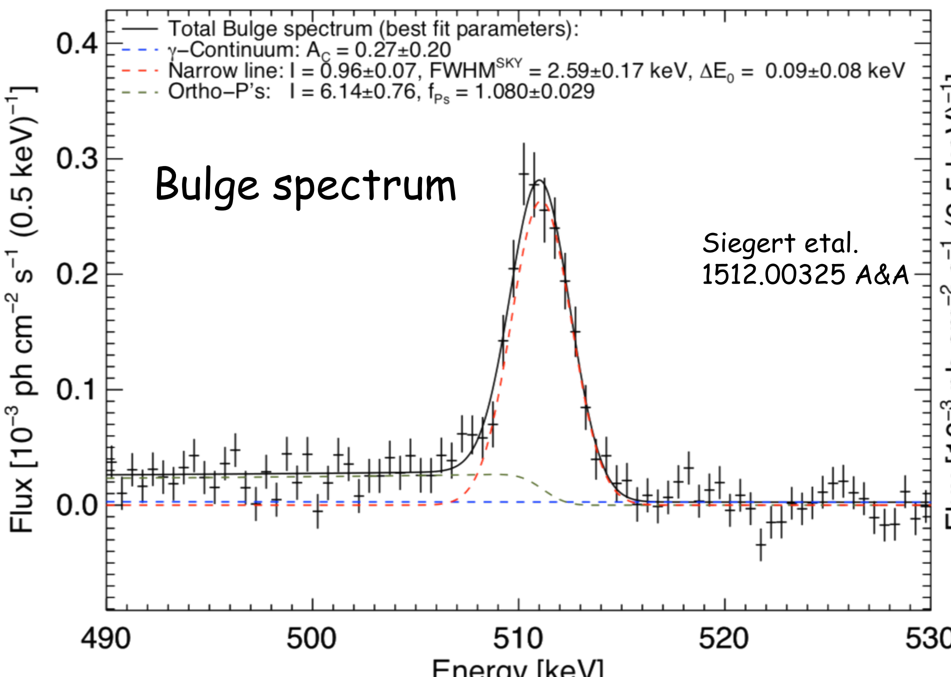
INTEGRAL/ SPI observations

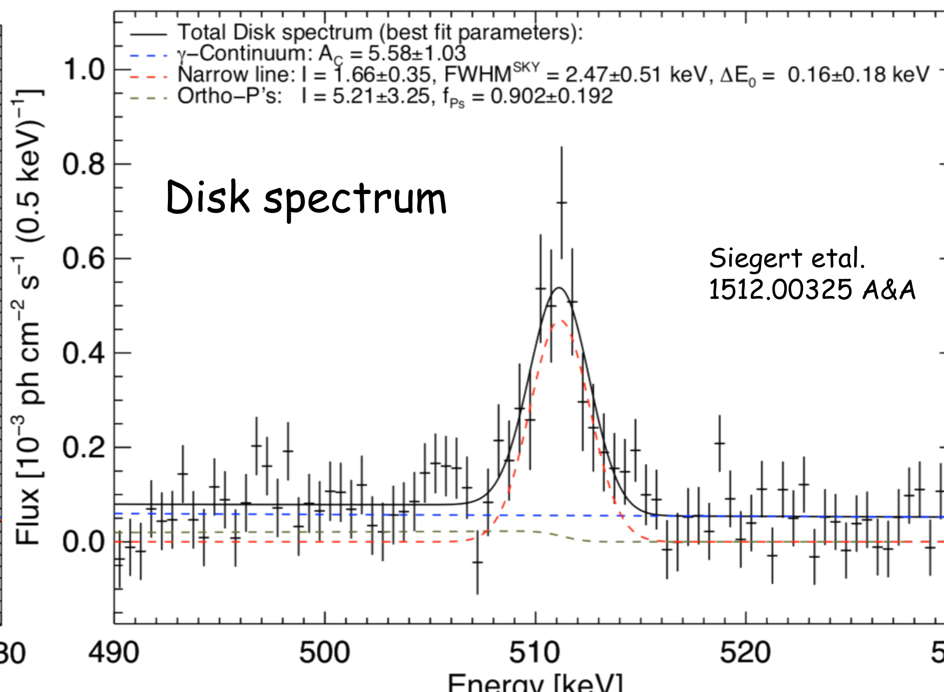


Siegert etal. 1512.00325 A&A

Detected via different instruments

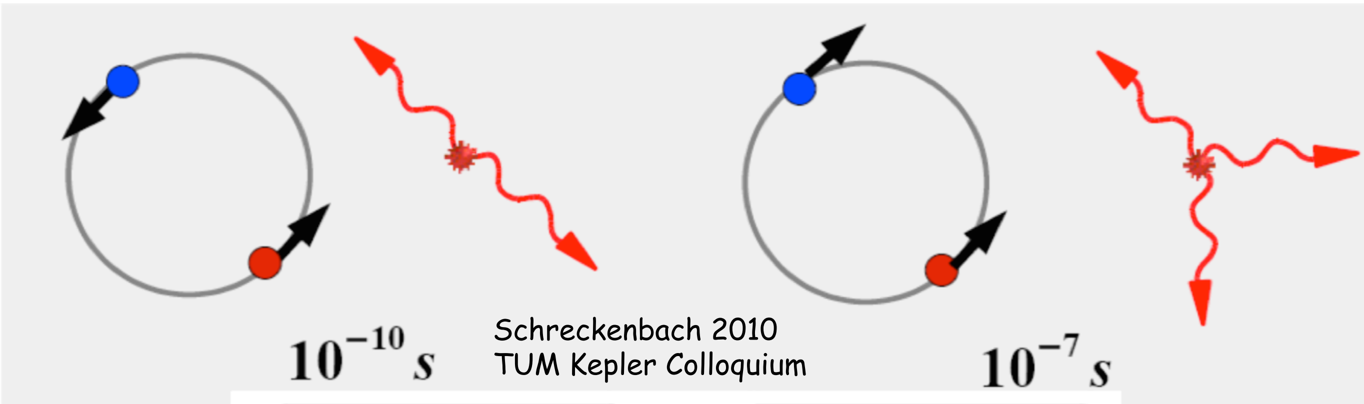
What is the source of this radiation?





Positron annihilation

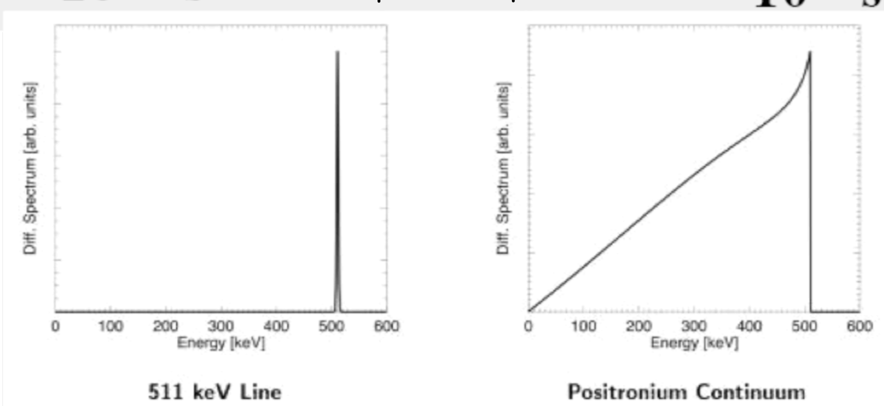
Para Positronium, l=0 | Ortho Positronium l=1



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)

2 Gammas, monoenergetic

(here spectrum in one detector)



3 Gammas, continous

(here spectrum in one detector)

Ratio of the mono-chromatic to the continuum radiation flux can be used to estimate the positronium fraction: $f_{\rm Ps} \approx 0.99 \pm 0.07$ (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

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

- $f_{\rm DM}$: Fraction of dark matter in the form of PBHs
- $\rho_{\rm DM}(r)$: dark matter density
- $M_{\rm PBH}$: Mass of the PBH
- $\frac{d^2 N_e}{dt\, dE}$: Number of positrons emitted per unit time and per unit energy by PBHs
- $2 \times 10^{43}\, {\rm s}^{-1}$: 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

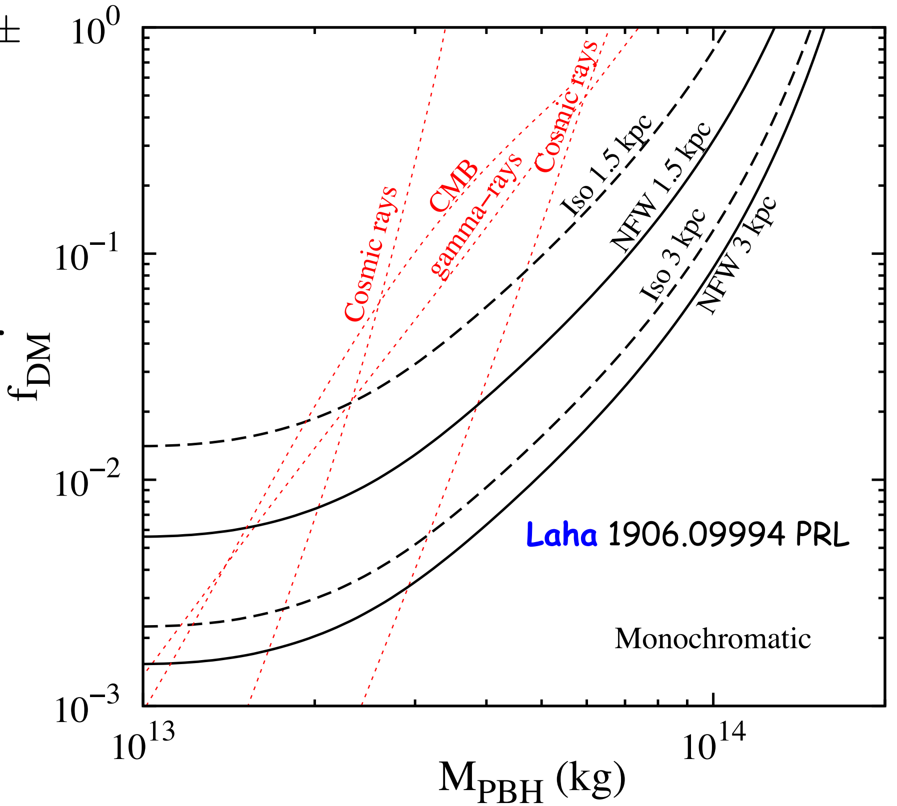
Low-mass PBHs and Galactic Center 511 keV line

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 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

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

How to probe higher PBH masses?

Limits from the measurement of Galactic Center photons

Can we probe PBHs using Galactic Center gamma-ray emission?

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INTEGRAL constraints on primordial black holes and particle dark matter

Ranjan Laha, Julian B. Muñoz, and Tracy R. Slatyer
Phys. Rev. D **101**, 123514 – Published 15 June 2020

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Issue
Vol. 101, Iss. 12 — 15 June 2020

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ABSTRACT

The International Gamma-Ray Astrophysics Laboratory (*INTEGRAL*) satellite has yielded unprecedented measurements of the soft gamma-ray spectrum of our Galaxy. Here we use those measurements to set constraints on dark matter (DM) that decays or annihilates into photons with energies $E \approx 0.02$–2 MeV. First, we revisit the constraints on particle DM that decays or annihilates to photon pairs. In particular, for decaying DM, we find that previous limits were overstated by roughly an order of magnitude. Our new, conservative analysis finds that the DM lifetime must satisfy $\tau \gtrsim 5 \times 10^{26}\,\mathrm{s} \times (m_\chi/\mathrm{MeV})^{-1}$ for DM masses $m_\chi = 0.054$–3.6 MeV. For MeV-scale DM that annihilates into photons *INTEGRAL* sets the strongest constraints to date. Second, we target ultralight primordial black holes (PBHs) through their Hawking radiation. This makes them appear as decaying DM with a photon spectrum peaking at $E \approx 5.77/(8\pi G M_{\rm PBH})$, for a PBH of mass $M_{\rm PBH}$. We use the *INTEGRAL*

Laha, Muñoz, and Slatyer 2004.00627 Physical Review D

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

Laurent Bouchet[1,2], Andrew W. Strong[3], Troy A. Porter[4], Igor V. Moskalenko[4],
Elisabeth Jourdain[1,2], and Jean-Pierre Roques[1,2]
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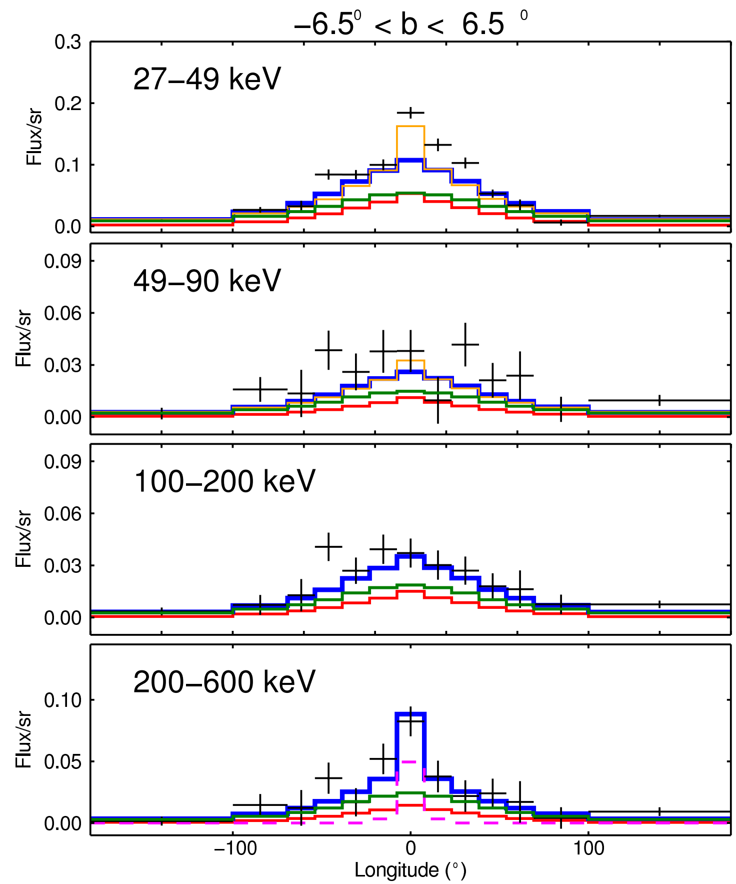
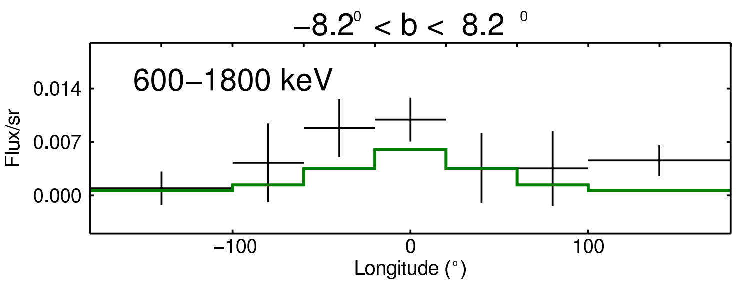
Received 2011 May 3; accepted 2011 June 29; published 2011 September 1

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

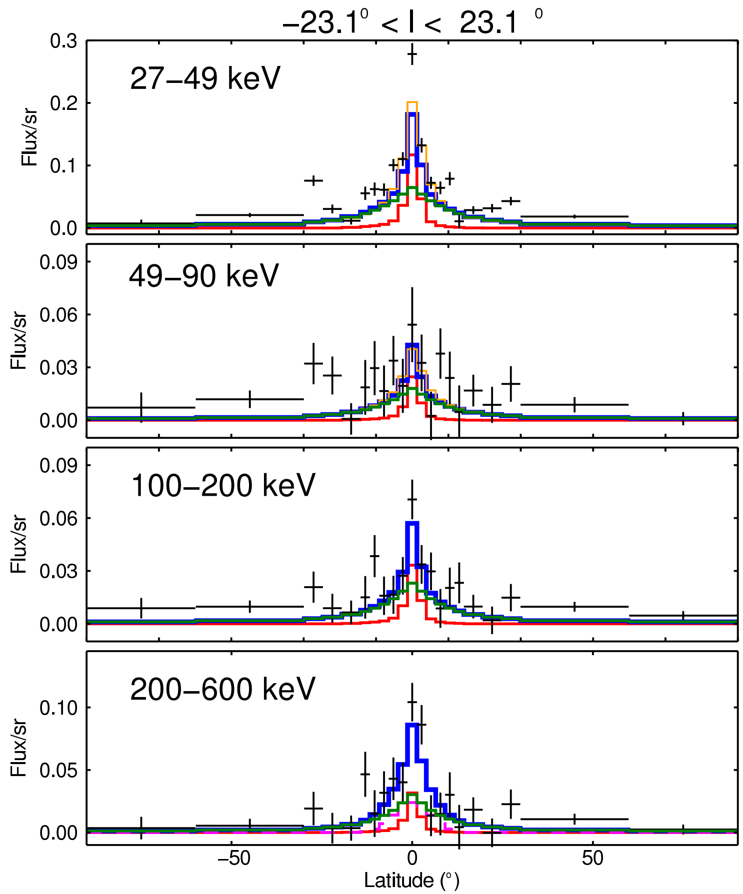
Gamma-ray measurements of the cosmic-ray electrons and positrons

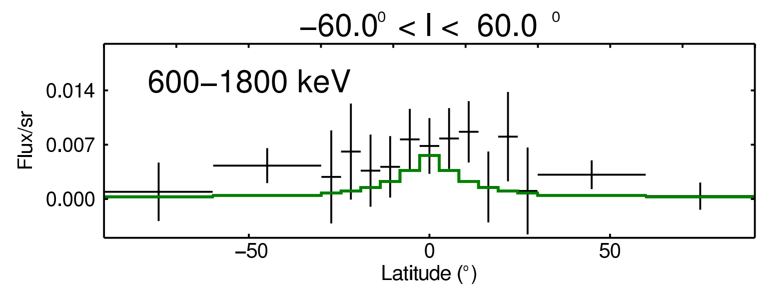




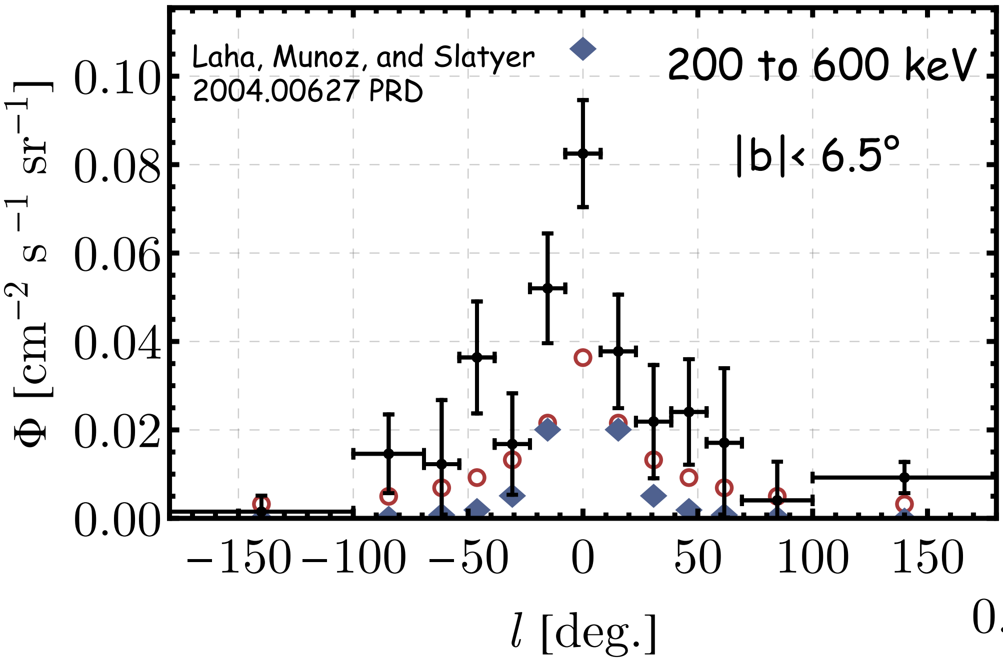
A good description of the data due to inverse Compton emission, stellar emission, and annihilation radiation

Bouchet et al., 1107.0200





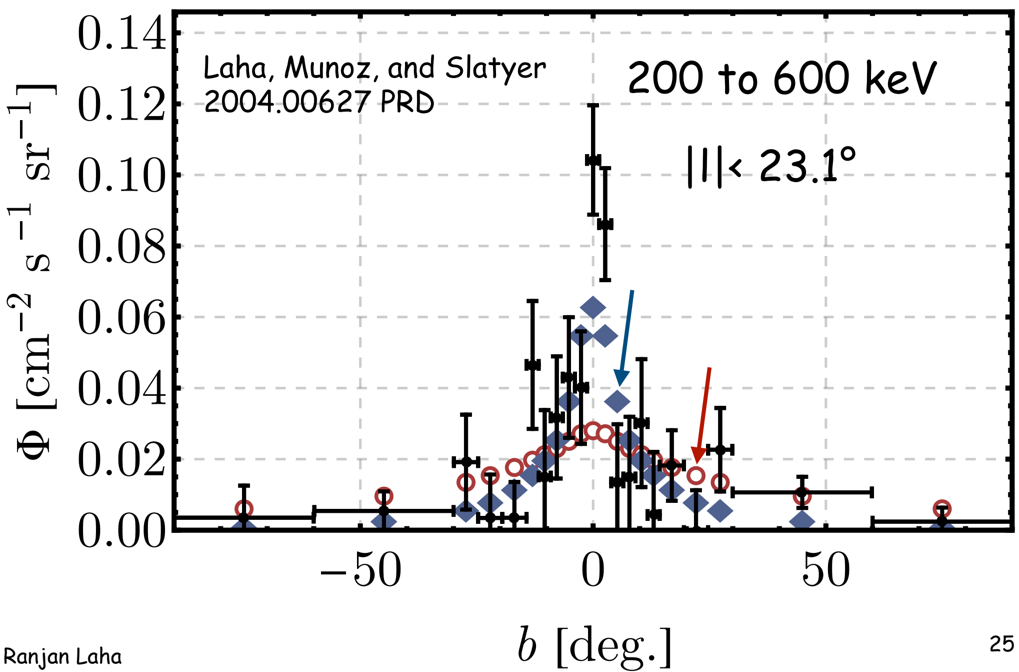
Angular dependence of the PBH signal and the INTEGRAL data



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

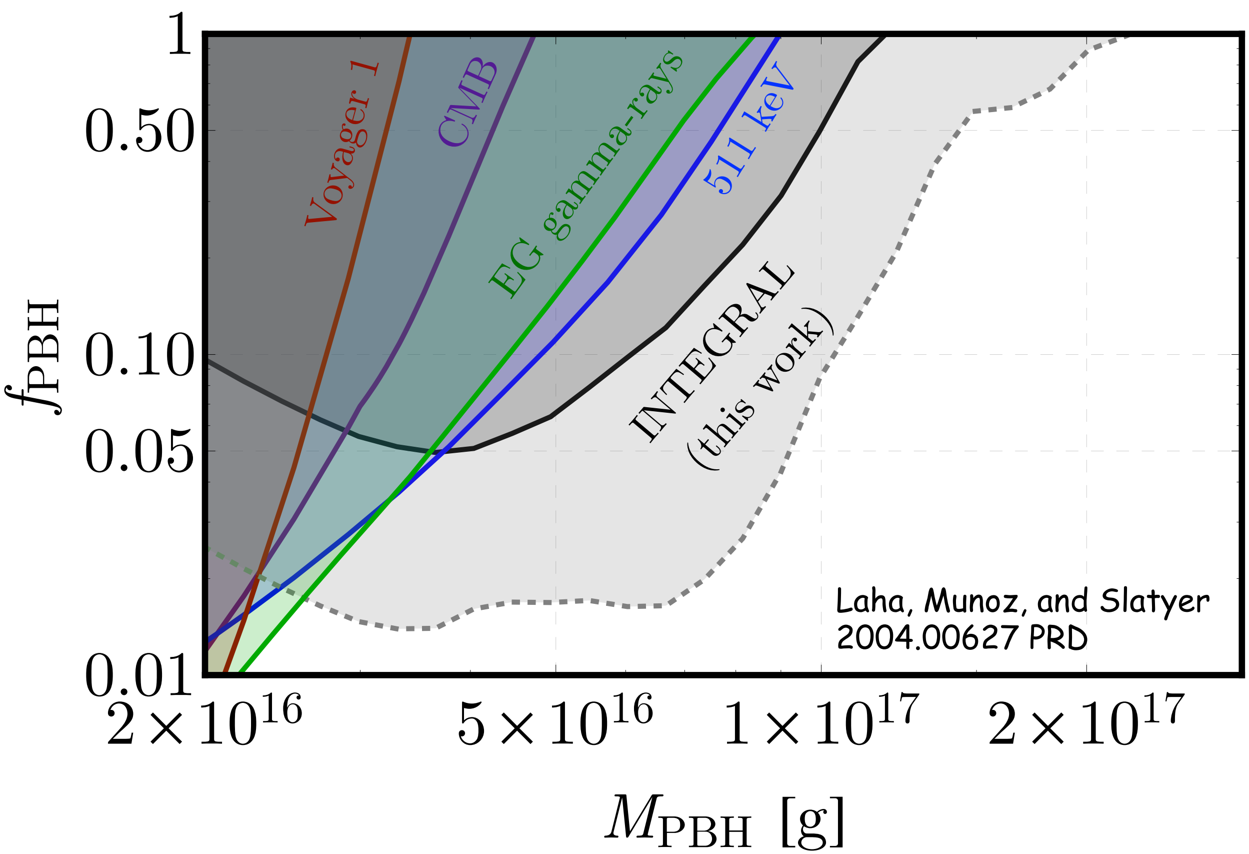
Energy range considered 0.027 to 1.8 MeV

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 $e^{\pm}$) will lead to stronger constraints

Angular dependence of the PBH signal and the INTEGRAL data



One of the best probes of ultra-light 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

Similar constraints from COMPTEL measurements by Coogan et al., arXiv: 2010.04797

How to probe higher PBH masses?

Future prospects

Can we probe PBHs using near-future gamma-ray instruments?

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Near future MeV telescopes can discover asteroid-mass primordial black hole dark matter

Anupam Ray, Ranjan Laha, Julian B. Muñoz, and Regina Caputo
Phys. Rev. D **104**, 023516 – Published 15 July 2021

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ABSTRACT

Primordial black holes (PBHs), formed out of large overdensities in the early Universe, are a viable dark matter (DM) candidate over a broad range of masses. Ultralight, asteroid-mass PBHs with masses around 10^{17} g are particularly interesting as current observations allow them to constitute the entire DM density. PBHs in this mass range emit $\sim$ MeV photons via Hawking radiation which can directly be detected by the gamma ray telescopes, such as the upcoming AMEGO. In this work we forecast how well an instrument with the sensitivity of AMEGO will be able to detect, or rule out, PBHs as a DM candidate, by searching for their evaporating signature when marginalizing over the Galactic and extra-Galactic gamma-ray backgrounds. We find that an instrument with the sensitivity of AMEGO could exclude nonrotating PBHs as the only DM component for masses up to 7×10^{17} g at 95% confidence level for a monochromatic mass distribution, improving upon current bounds by nearly an order of magnitude. The forecasted constraints are more stringent for PBHs that have rotation, or which follow extended mass distributions.

Issue
Vol. 104, Iss. 2 — 15 July 2021

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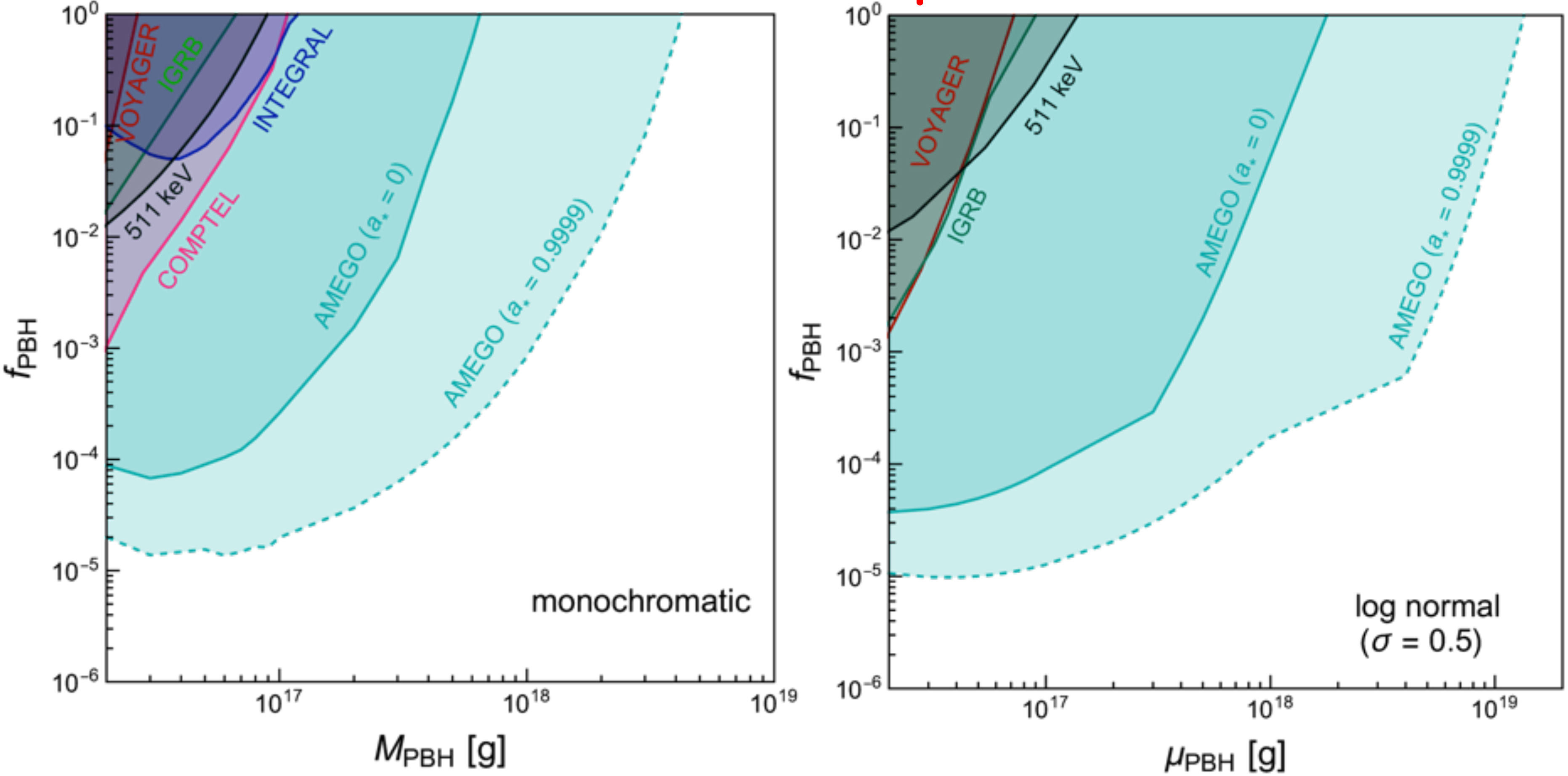
Ray, Laha, Muñoz, and Caputo arXiv: 2102.06714
Physical Review D

Projections in PBH parameter space using an AMEGO-like experiment



Ray, **Laha**, Muñoz, and Caputo arXiv: 2102.06714
(similar work by Coogan et al. arXiv: 2010.04797 and Ghosh et al arXiv: 2110.03333)

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

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

Questions & comments: ranjanlaha@iisc.ac.in