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TATA INSTITUTE OF FUNDAMENTAL RESEARCH

Detecting ultra-light primordial black holes as the dark matter candidate

Ranjan Laha

CERN → INDIAN INSTITUTE OF SCIENCE

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

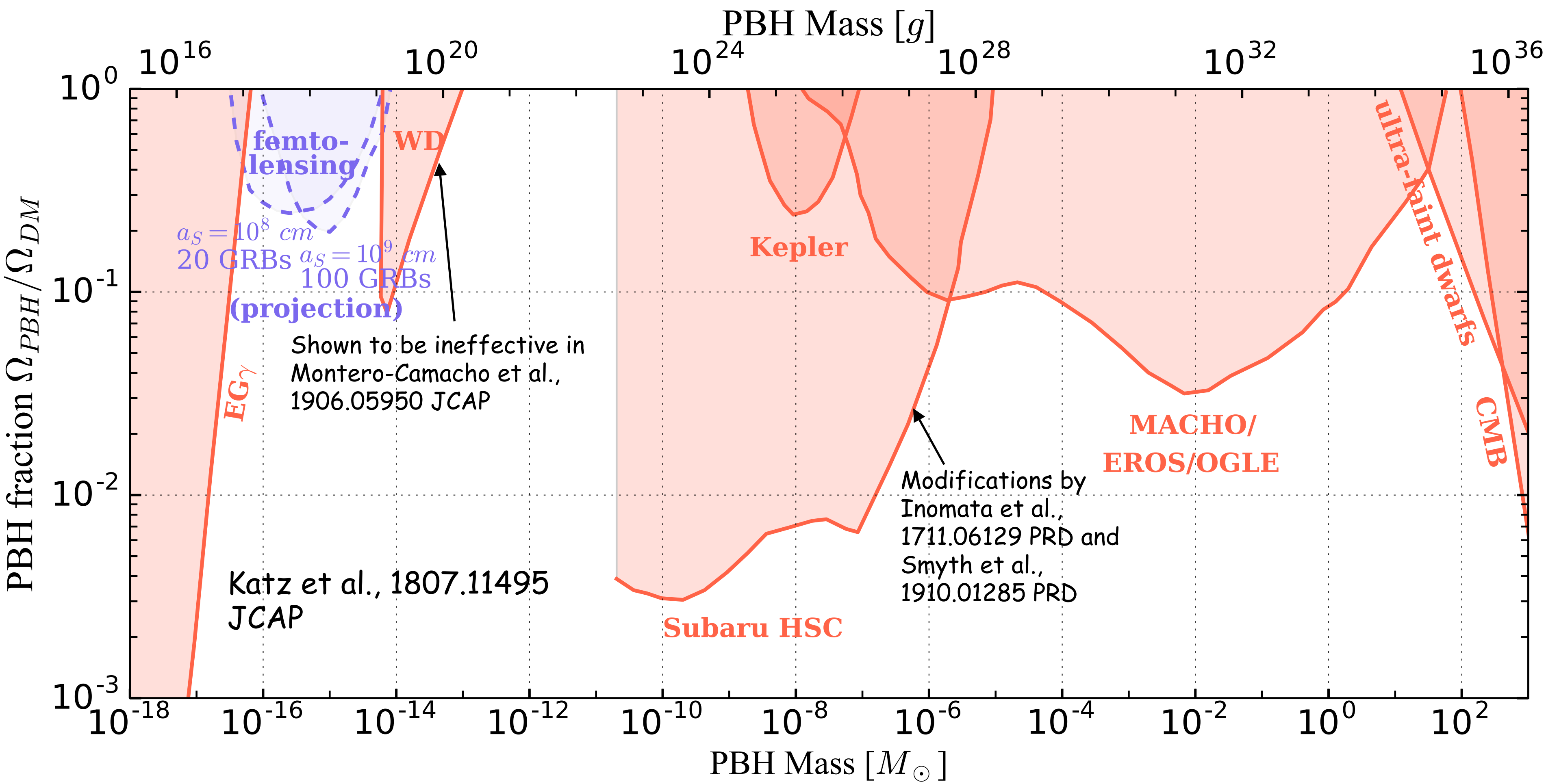
Contents

- Primordial black hole (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
- Probes of ultra-light PBHs using proposed telescopes
- Conclusions

PBH dark matter

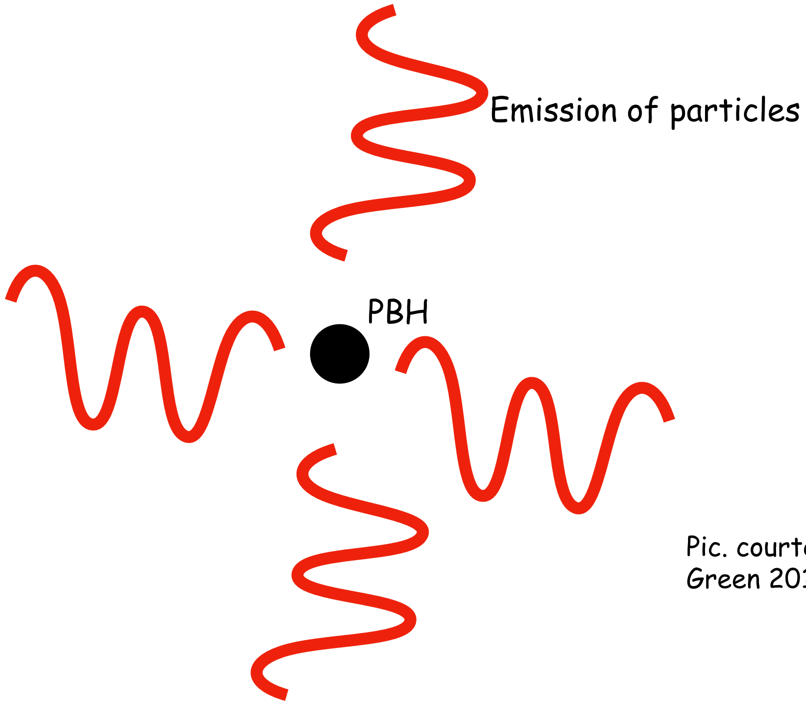
PBH dark matter (in 2018/ early 2019)



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 BHs

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.

Page hep-th/0409024 NJP for historical overview

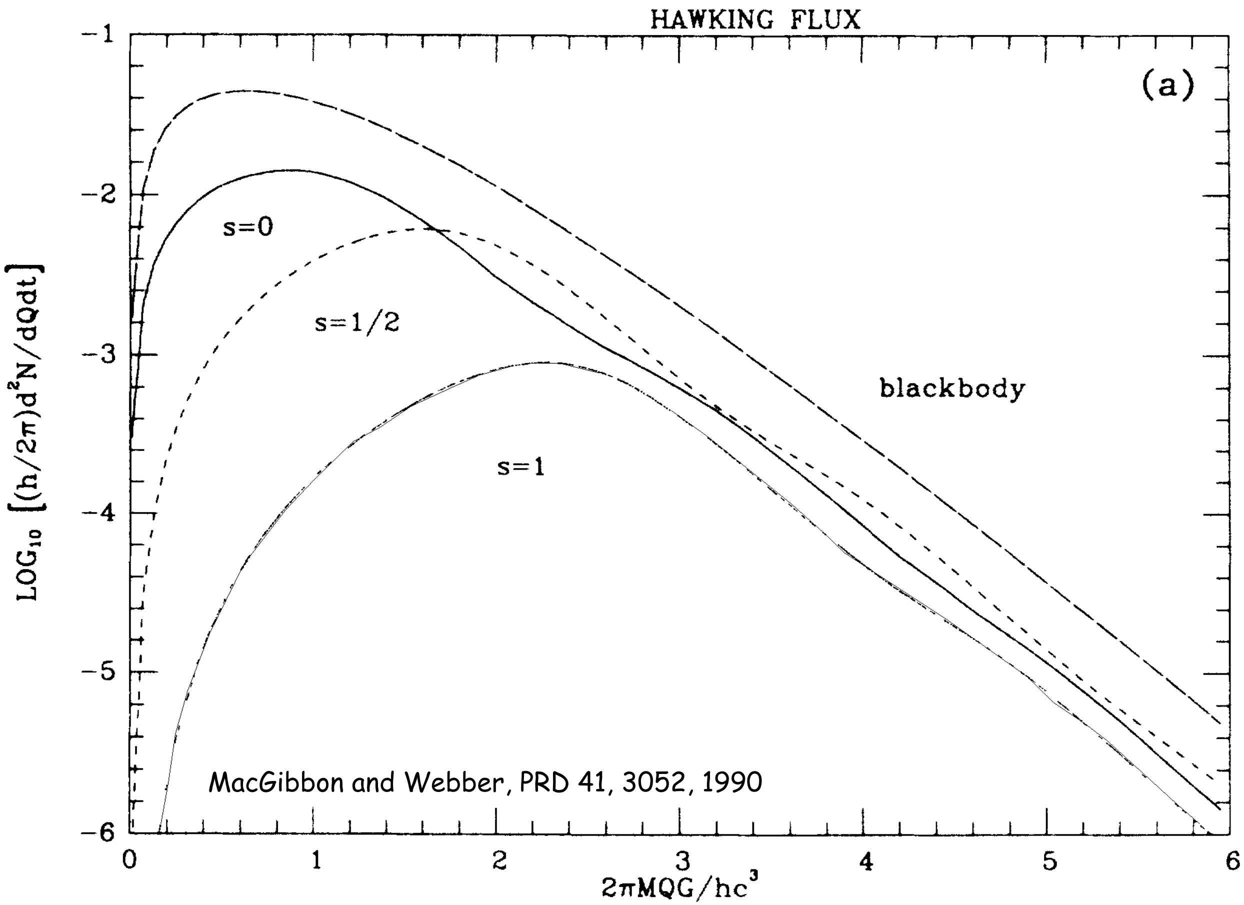
Dimensionless absorption probability for the emitted species

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

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



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

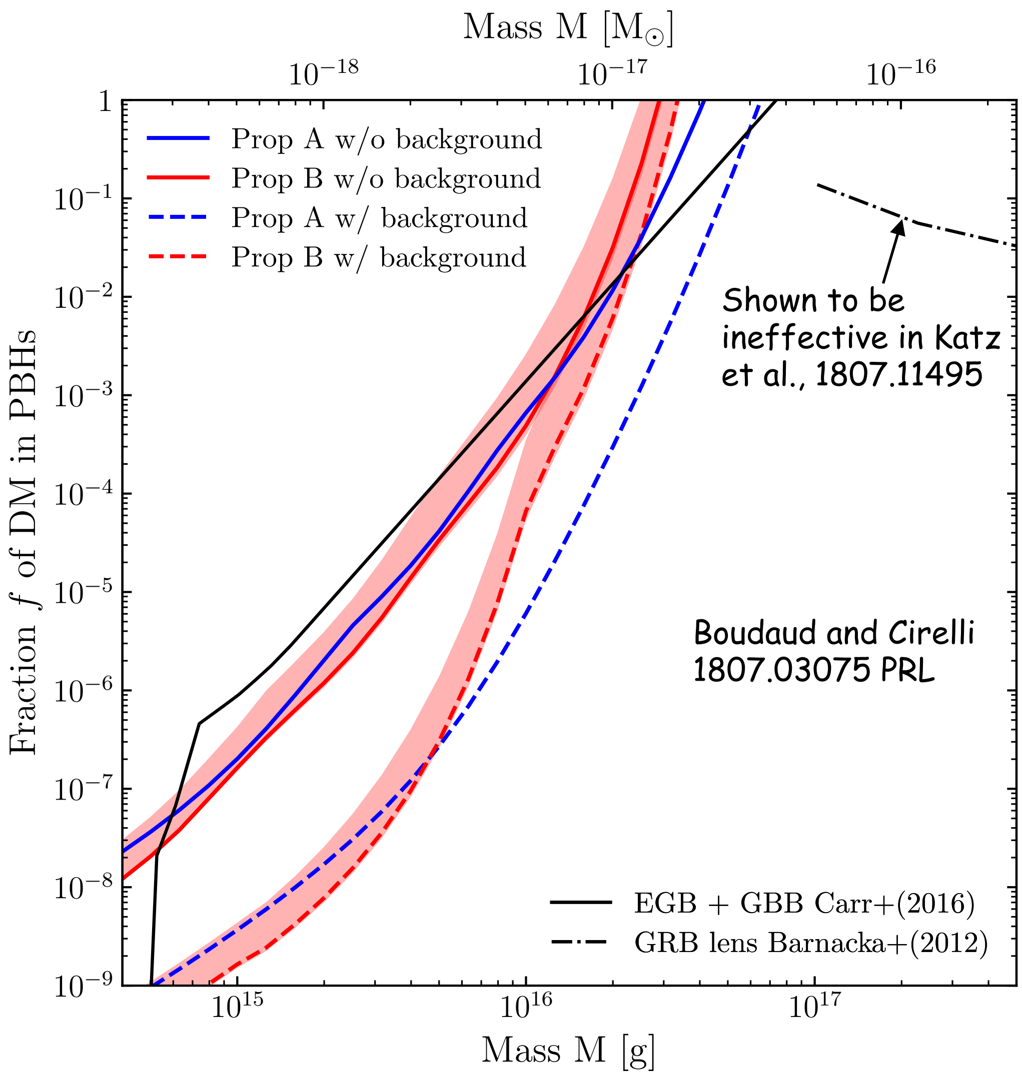
The spectrum closely resembles a black-body radiation

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)



See also Ballesteros etal. 1906.10113 PLB for gamma-ray constraints

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?

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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

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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

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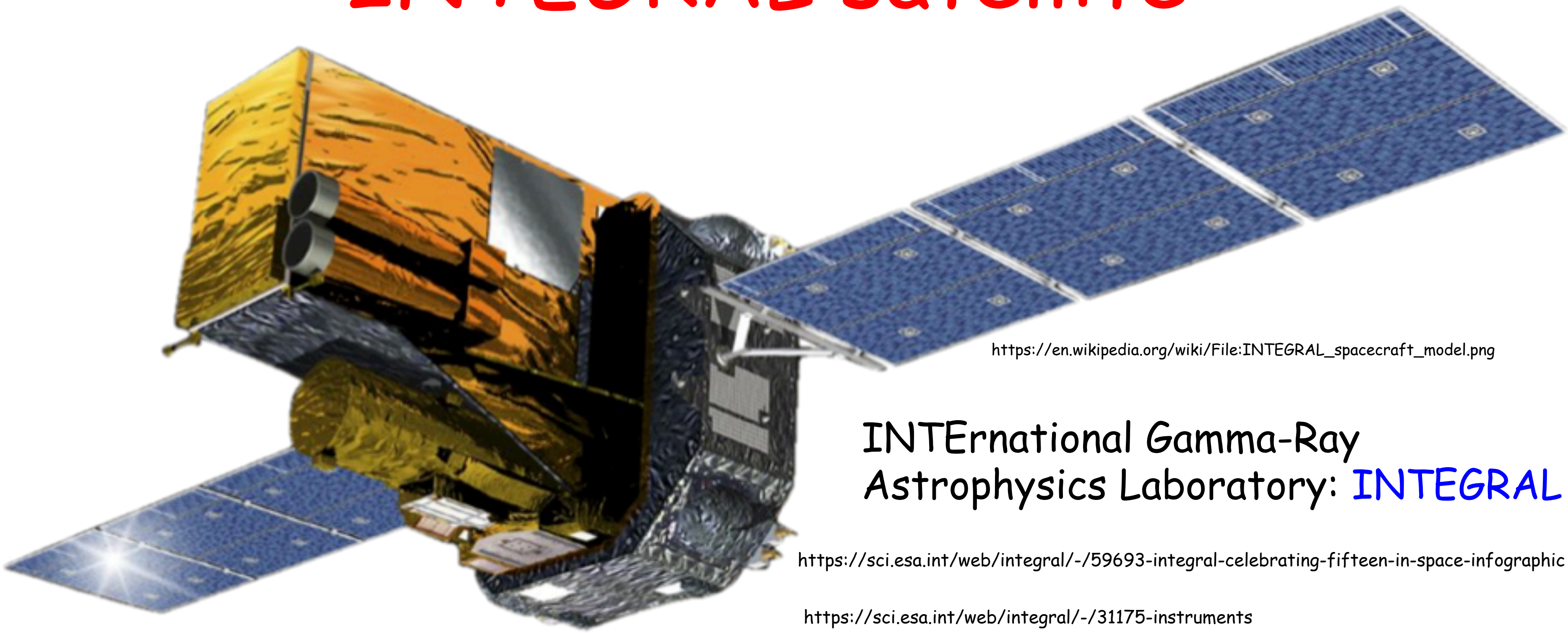
Laha 1906.09994 Physical Review Letters

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

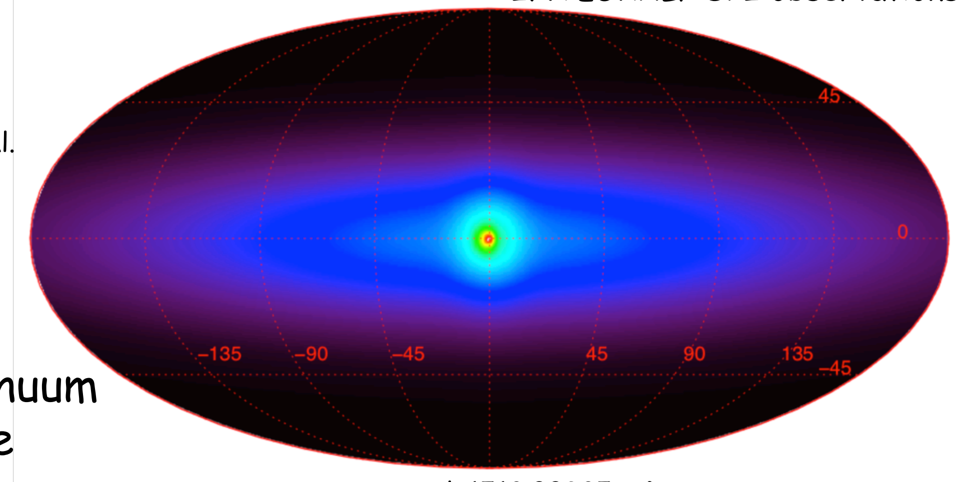
	Energy range	Energy resolution
SPectrometer of INTEGRAL (SPI):	18 keV to 8 MeV	~ 0.2% at 1.33 MeV
Imager on-Board the INTEGRAL Satellite (IBIS):	15 keV to 10 MeV	~ 10% at 1.33 MeV

Other instruments are also present in INTEGRAL

511 keV gamma-ray line

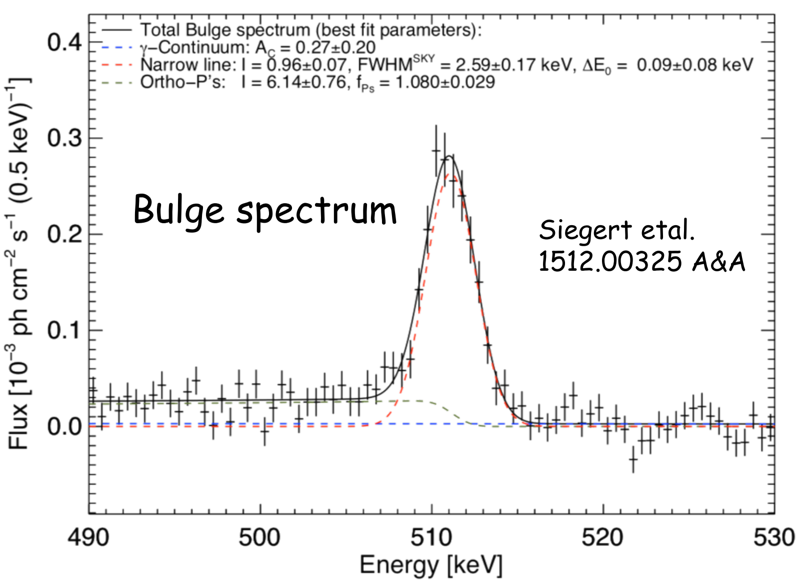
- A ~ 50 year old astrophysics mystery: observation of the 511 keV gamma-ray line in the Galactic bulge and disk (Johnson etal. ApJ 172 L1 1972, Leventhal etal. ApJ 225 L11 1978, ..., Siegert etal. 1512.00325 A&A, Siegert etal. 1906.00498 A&A)

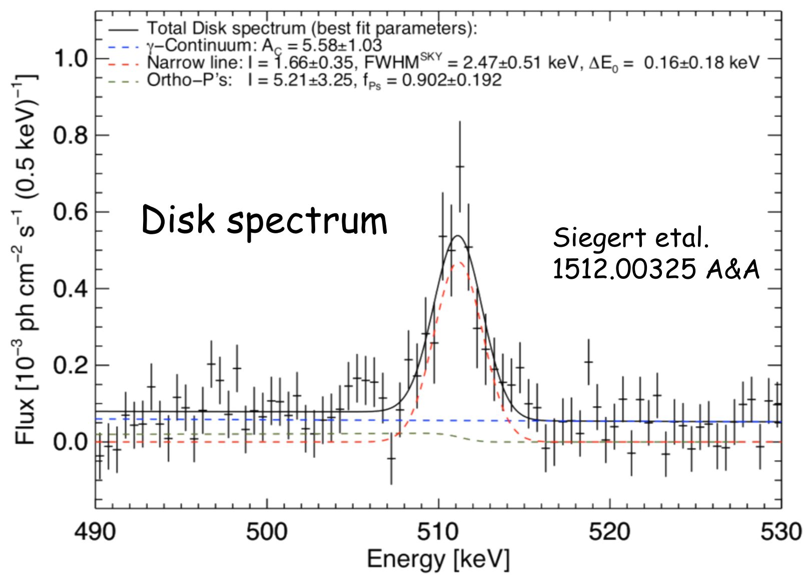
INTEGRAL/ SPI observations



Siegert etal. 1512.00325 A&A

- What is the source of this radiation?
- Ratio of the mono-chromatic to the continuum radiation flux can be used to estimate the positronium fraction: $f_{\rm Ps} \approx 0.99 \pm 0.07$
- Measurement of gamma-rays at higher energies (> 511 keV) help constrain the injection energy of the positron (Beacom and Yuksel astro-ph/0512411 PRL, Sizun etal. astro-ph/0607374 PRD)





511 keV gamma-ray line

- The flux of 511 keV gamma-ray line implies a positron injection rate of $\sim 2 \times 10^{43}\ s^{-1}$ (Prantzos et al. 1009.4620 RMP, Panther 1801.09365 Galaxies, Panther 1905.01806)

- 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)

- Can we derive a robust constraint on PBHs using this observation? (see earlier works in Okele and Rees 1980 A&A, Okeke 1980, MacGibbon & Carr 1991 ApJ, and Bambi etal. 0801.2786 PLB)

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 gamma-ray line observation

Fraction of dark matter in the form of PBHs

Dark matter halo

$$f_{\rm DM}\,\frac{\int dV\,\rho_{\rm DM}(r)}{M_{\rm PBH}}\int dE\,\frac{d^2N_e}{dt\,dE}\lesssim \underbrace{2\times 10^{43}\,{\rm s}^{-1}}_{\text{Positron luminosity required by INTEGRAL/ SPI observation}}$$

Mass of the PBH

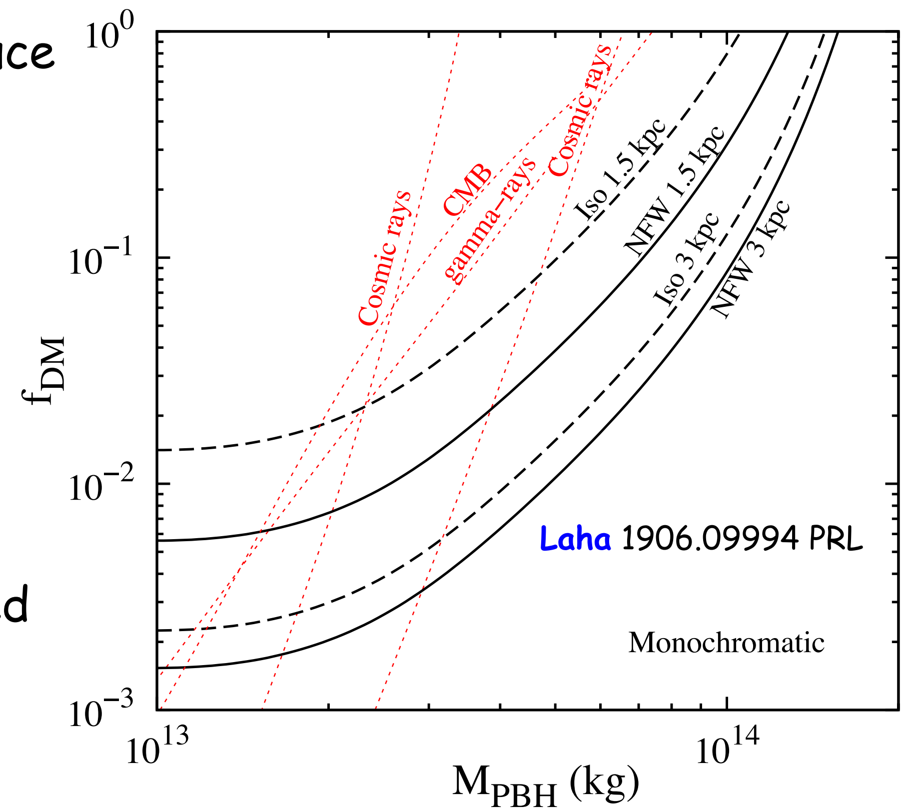
Number of positrons emitted per unit time and per unit energy by PBHs

- The formula for PBHs mimics decaying dark matter

- Positron propagation and dark matter density profile introduce uncertainty

Ultra-light PBHs and Galactic Center 511 keV line

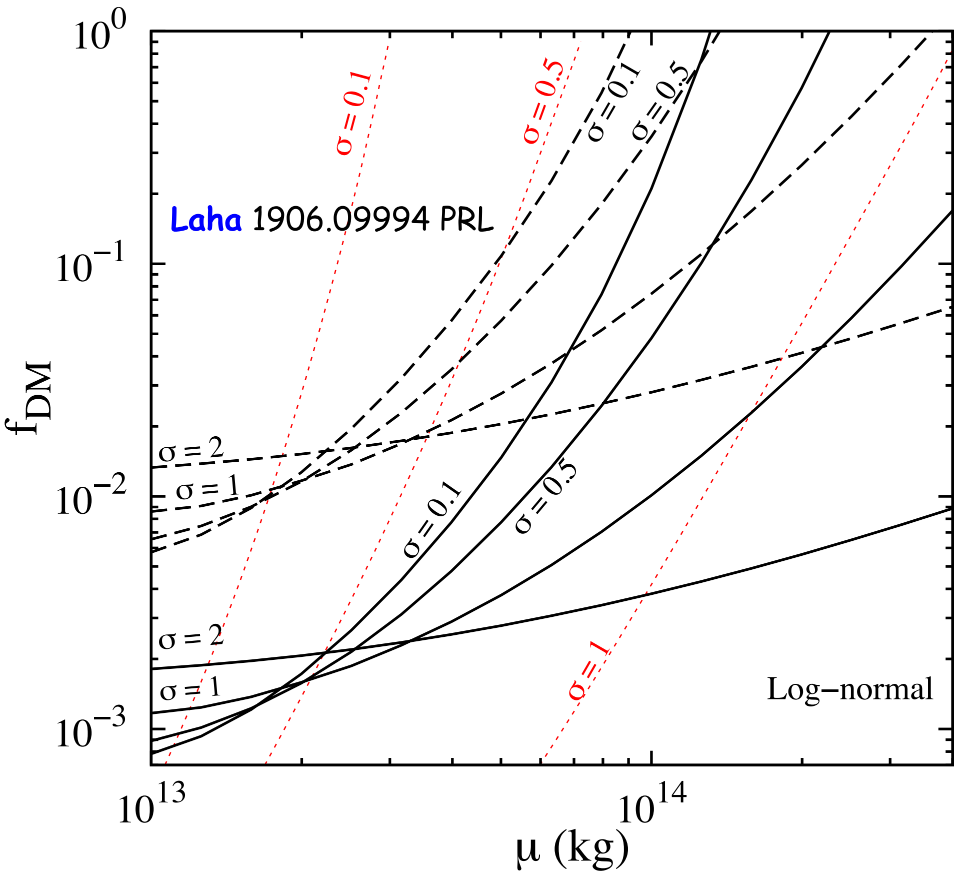
- Ultra-light PBHs can evaporate to produce $e^{\pm}$ pairs
- The positrons will lose energy, become non-relativistic, and annihilate with the ambient electrons to produce photons
- Galactic Center observations reveal an intense flux of 511 keV photons produced by unknown source(s)
- Requiring that the positrons from PBH evaporation do not overshoot the positron luminosity produce 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

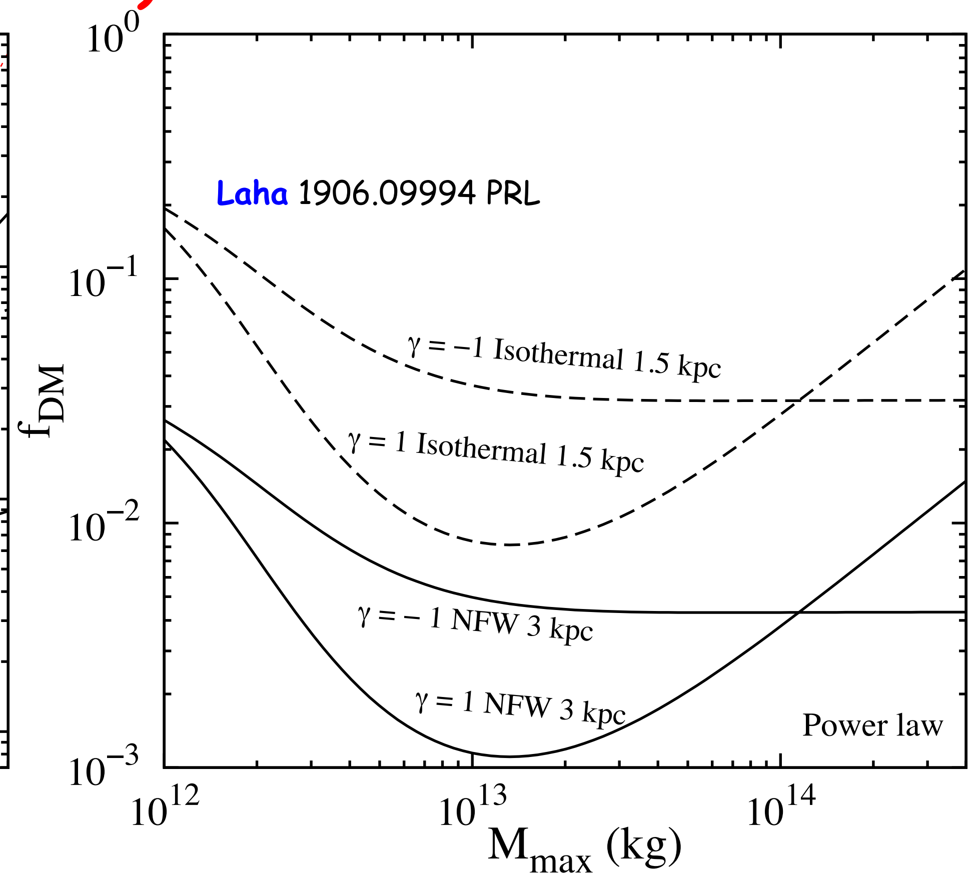
$$\frac{dN}{dM} \propto \delta(M - M_{\rm PBH})$$

Ultra-light PBHs & 511 keV line (extended mass functions)



$$\frac{d\Phi_{\rm PBH}}{dM_{\rm PBH}} = \frac{e^{-[\ln^2(M_{\rm PBH}/\mu)]/2\sigma^2}}{\sqrt{2\pi}\sigma M_{\rm PBH}}$$

Log-normal mass function



$$\frac{d\Phi_{\rm PBH}}{dM_{\rm PBH}} = \frac{\gamma}{M_{\rm max}^{\gamma} - M_{\rm min}^{\gamma}} \frac{1}{M_{\rm PBH}^{1-\gamma}}$$

Power-law mass function

- Galactic Center positrons (511 keV gamma-ray line) provide some of the strongest constraints on ultra-light PBHs with extended mass functions

Can we probe spinning PBHs?

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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

Article | References | No Citing Articles | Supplemental Material | PDF | HTML | Export Citation

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.

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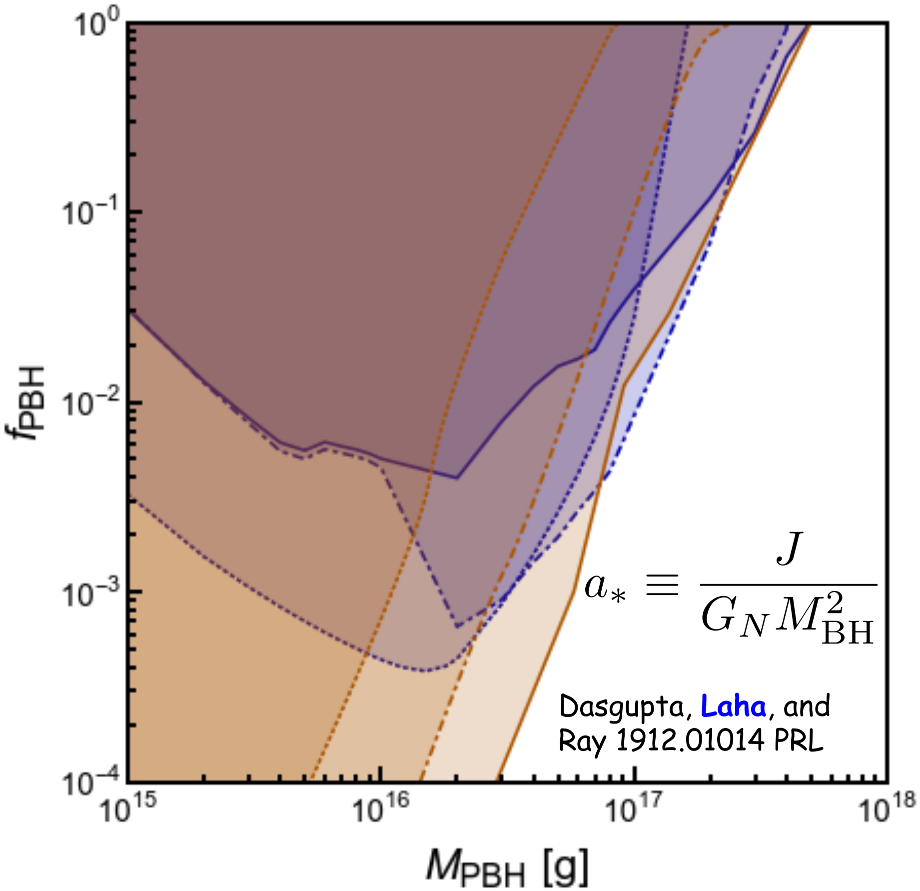
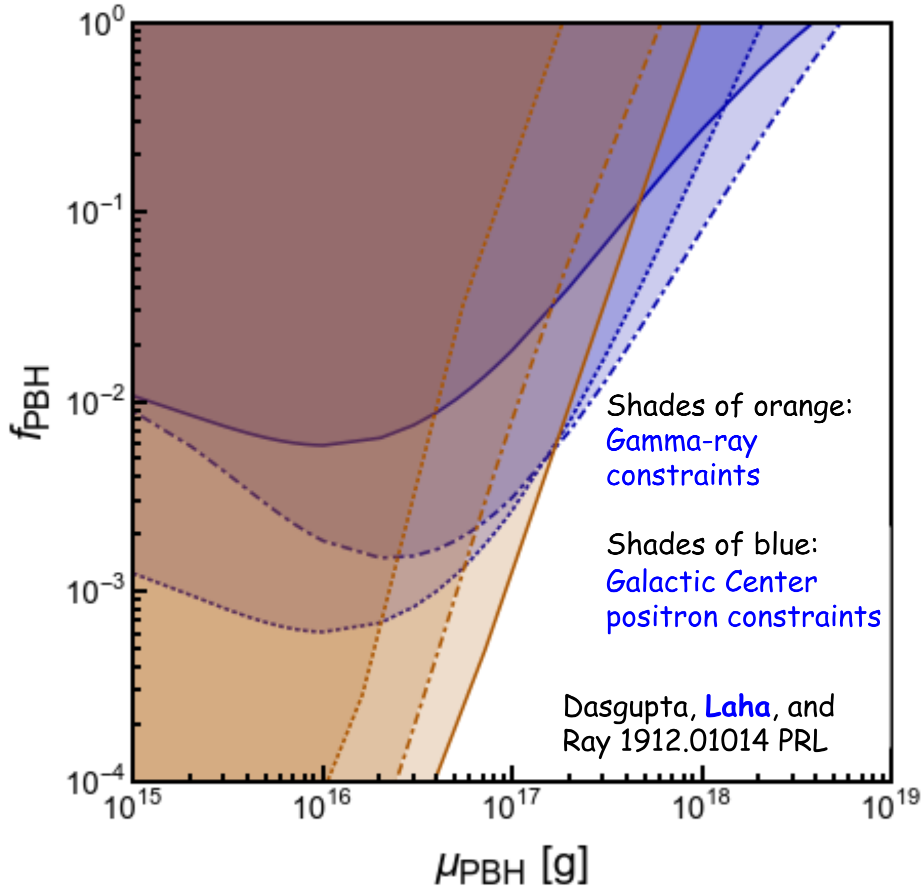
Dasgupta, Laha, and Ray 1912.01014 Physical Review Letters

Ultra-light spinning PBHs and Galactic Center 511 keV line





Solid line: $a_* = 0.9999$

Dot-dashed line: $a_* = 0.9$

Dotted line: $a_* = 0$

$$T_{\rm BH} = \frac{1}{4\pi G_N M_{\rm BH}} \frac{\sqrt{1-a_*^2}}{1+\sqrt{1-a_*^2}}$$

Arbey and Auffinger, EPJC 79, 693, 2016
BlackHawk code

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

Article | References | Citing Articles (3) | PDF | HTML | Export Citation

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 $E \approx 5.77/(8\pi G M_{\mathrm{PBH}})$, for a PBH of mass M_{PBH}. We use the *INTEGRAL*

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Vol. 101, Iss. 12 — 15 June 2020

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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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[2] CNRS, IRAP, 9 Av. colonel Roche, BP 44346, F-31028 Toulouse cedex 4, France
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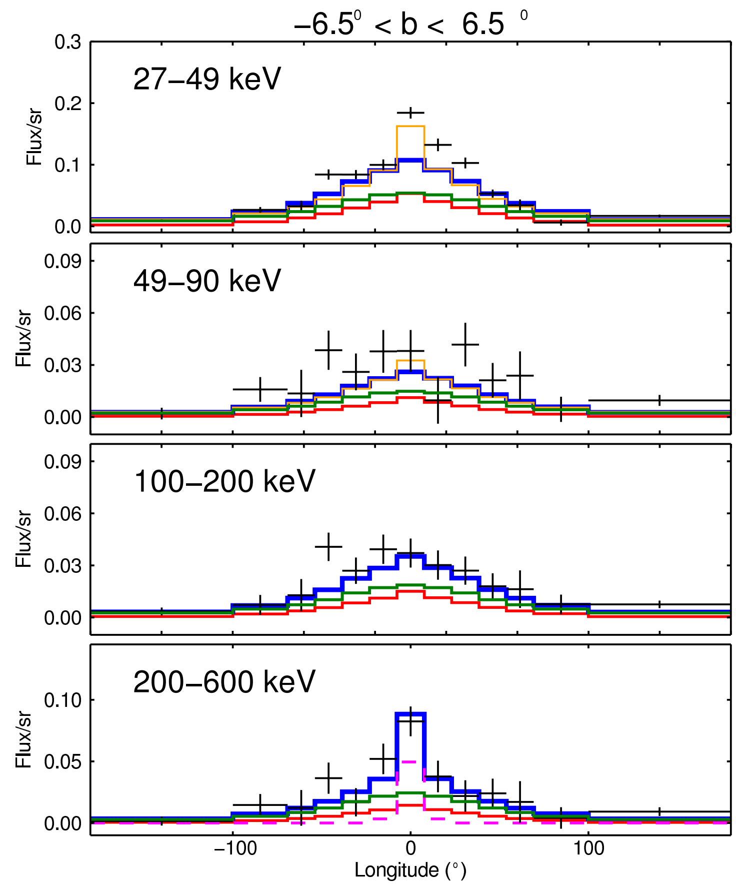
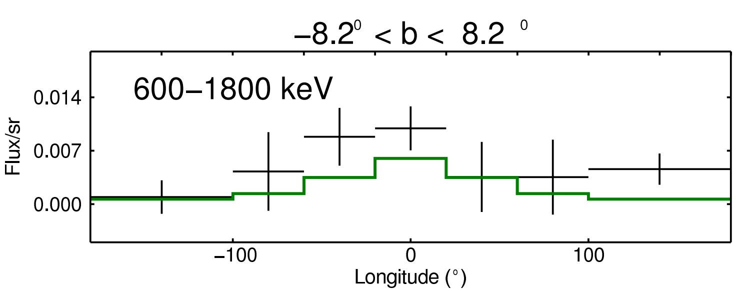
Received 2011 May 3; accepted 2011 June 29; published 2011 September 1

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 $e^{\pm}$

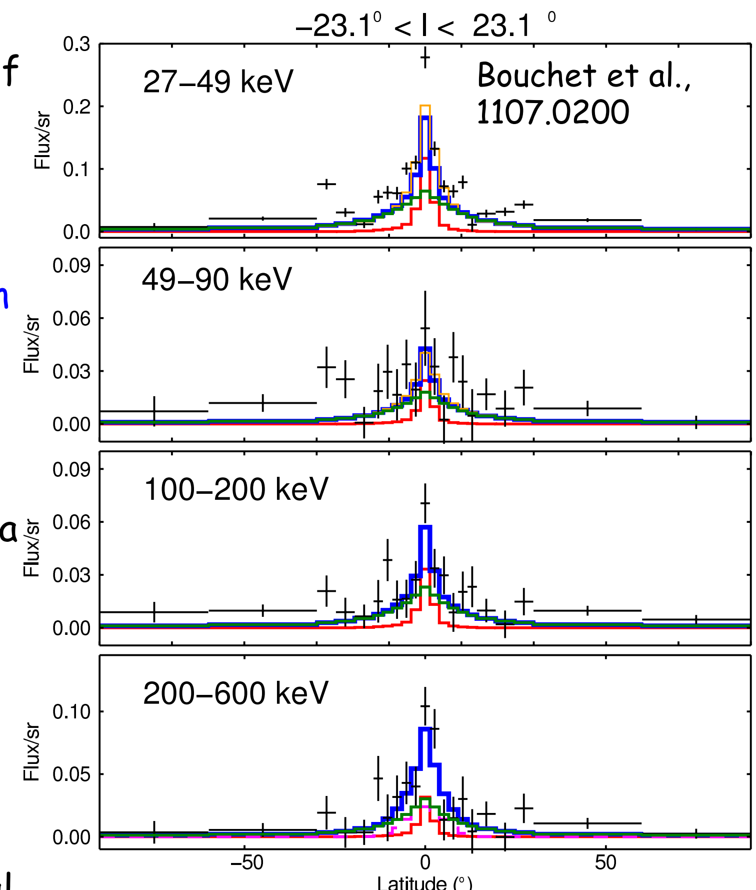


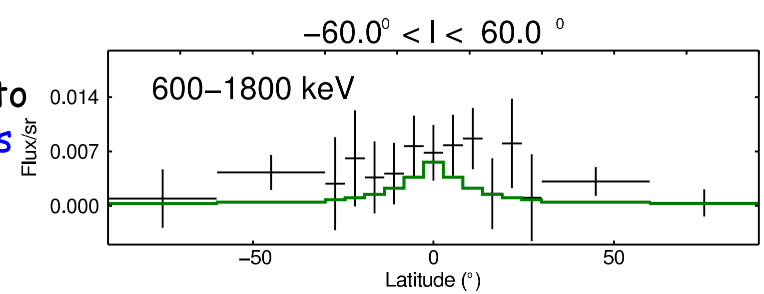


A good description of the data due to inverse Compton emission, stellar emission, and annihilation radiation

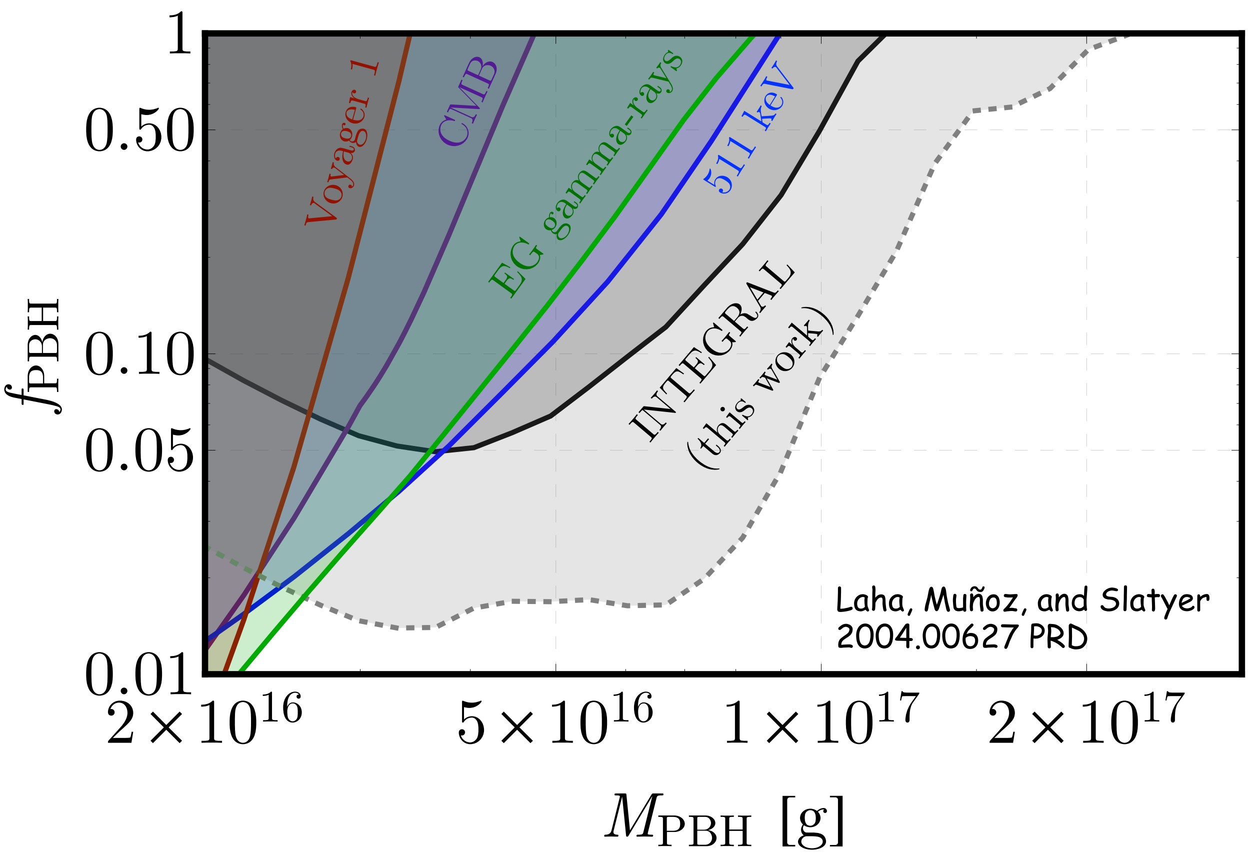
Constraint strategy: PBH signal not overproduce any data point by more than 2 x the error bar

Modeling the PBH signal + astrophysical background (due to emission of Galactic Center $e^{\pm}$) will lead to stronger constraints





Constraints on PBHs from INTEGRAL Galactic Center gamma-ray 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
- COMPTEL data can also be used to derive similar limits on PBHs (Coogan et al., 2010.04797)

Probes of ultra-light PBHs using proposed telescopes

Snowmass2021 - Letter of Interest

Electromagnetic probes of ultralight primordial black holes

Thematic Areas: (check all that apply □/■)

■ (CF3) Dark Matter: Cosmic Probes
■ (CF7) Cosmic Probes of Fundamental Physics
■ (TF9) Astro-particle physics & cosmology

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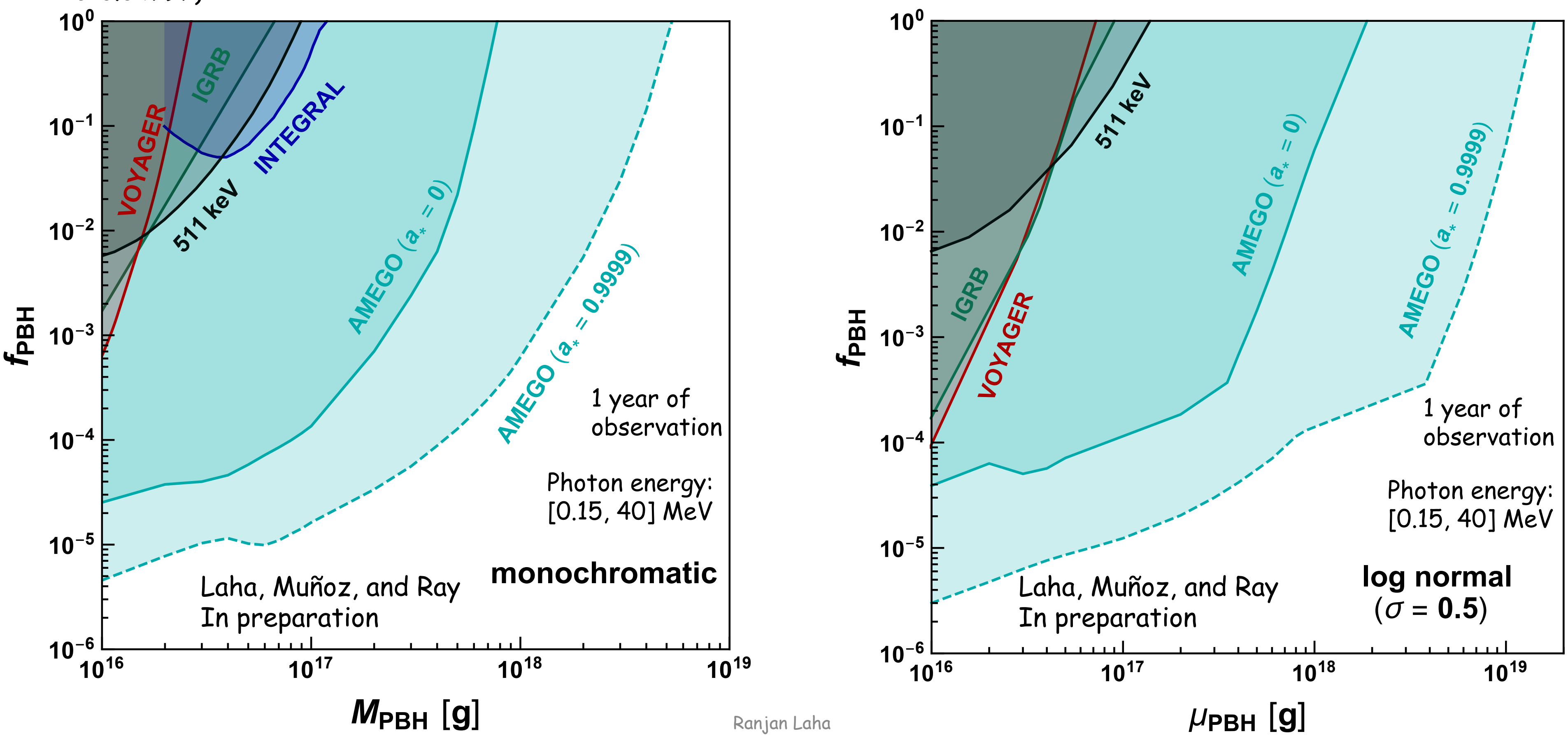
Abstract: Dark matter (DM) is omnipresent in the universe, from sub-Galactic scales to galaxy clusters. Despite its abundance, the nature of DM remains mysterious, as it has evaded all nongravitational direct and indirect probes thus far. Primordial black holes (PBHs), formed out of regular-matter overdensities in the early universe, provide an attractive alternative to new-physics models of DM. If these PBHs are ultralight (with masses $M_{\rm PBH} \lesssim 10^{18}$ g), their gravitational effects are indistinguishable from those of regular particle DM. However, due to their black-hole nature, ultralight PBHs Hawking evaporate over time, emitting high-energy particles that can be directly detected. Here we outline what next-generation MeV telescopes ought to do to better detect ultralight PBHs.

Probes of ultra-light PBHs using proposed telescopes

- Can we probe PBHs with masses greater than 10^{17} g using upcoming telescopes?
- Observation of Galactic Center via a proposed telescope like AMEGO can discover/ constrain non-spinning (maximally spinning) PBHs up to a mass of ~ 8 x 10^{17} g (~ 4 x 10^{18} g) for the monochromatic distribution (see similar results in Coogan et al., 2010.04797)



Ranjan Laha

Conclusions

- Ultra-light primordial black holes can make up 100% of the dark matter density
- Galactic Center positrons and gamma-rays can be used to constrain or discover ultra-light primordial black holes
- Proposed telescopes like AMEGO can probe ultra-light primordial black holes in a large region of the parameter space

Questions & comments:
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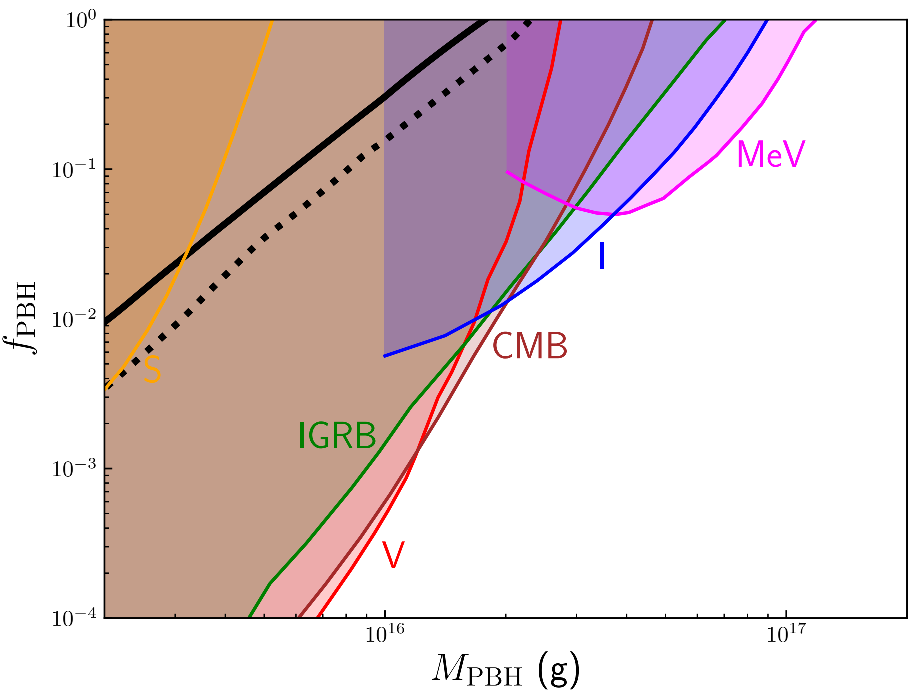
Some other probes of ultra-light PBHs

(1) Neutrinos: upper limits on the diffuse supernova neutrino background can constrain abundance of PBHs too (Carr et al., 0912.5297 PRD; Dasgupta, Laha, and Ray 1912.01014 PRL; Wang et al., 2010.16053)

(2) 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)



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