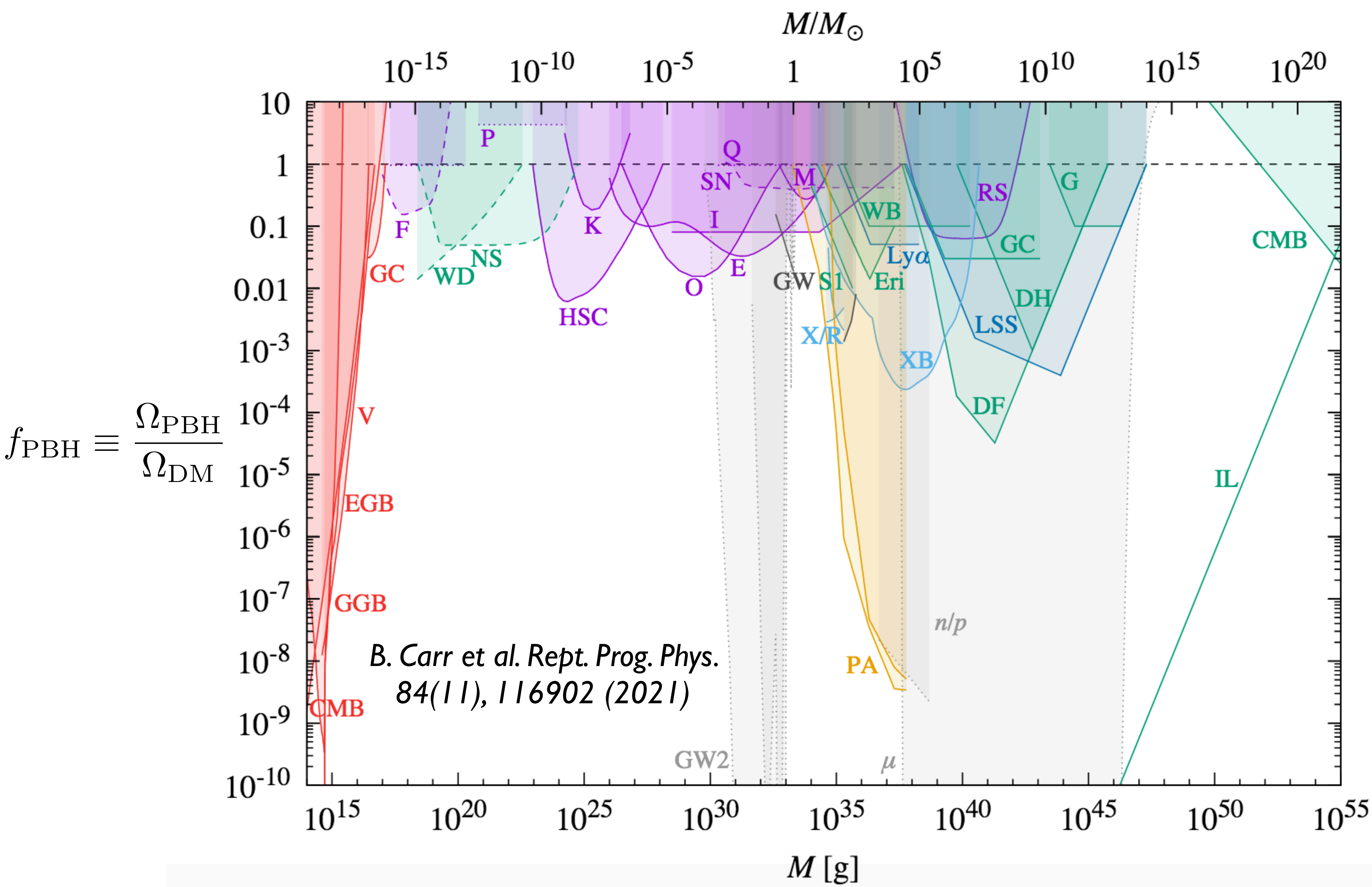
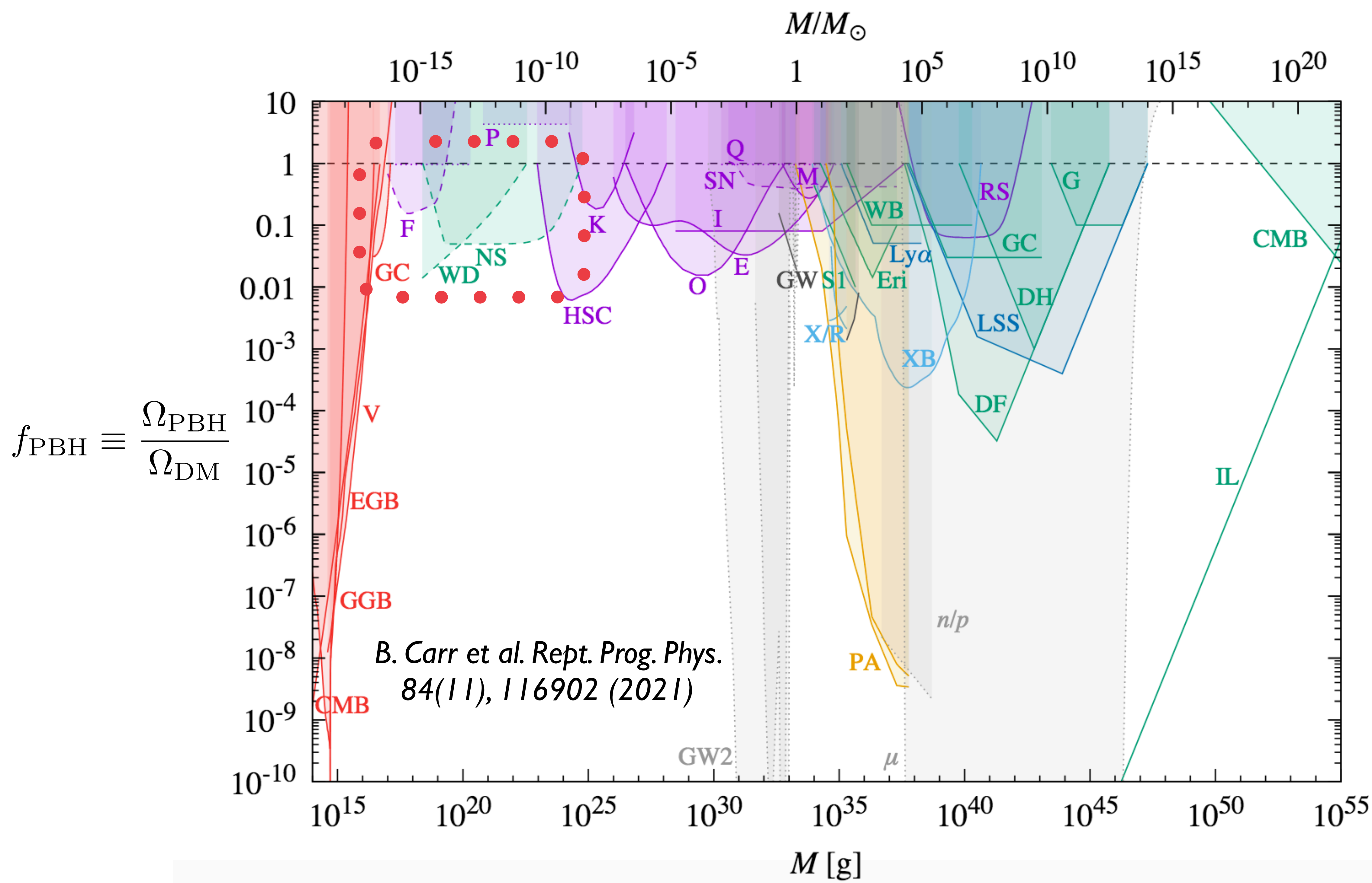
Constraints on Primordial Black Holes



Dark Matters, 30/11/2022

Pasquale Dario Serpico (LAPTh - Annecy, France)

Constraints on Primordial Black Hole Dark Matter



Dark Matters, 30/11/2022

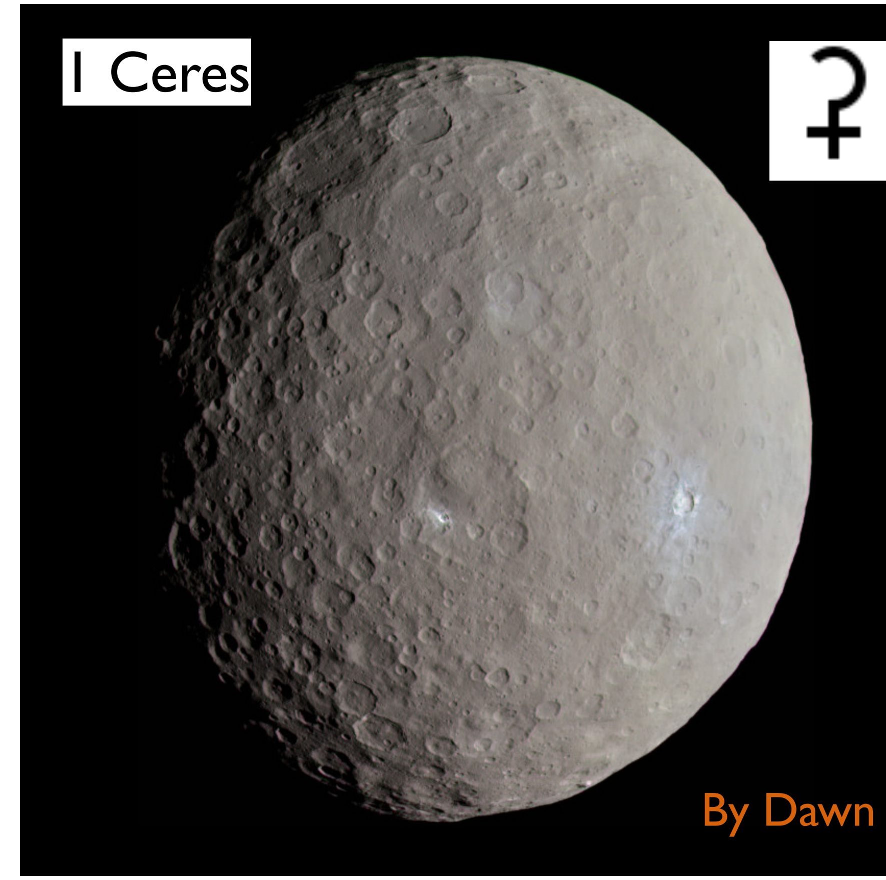
LAPTh

Pasquale Dario Serpico (LAPTh - Annecy, France)

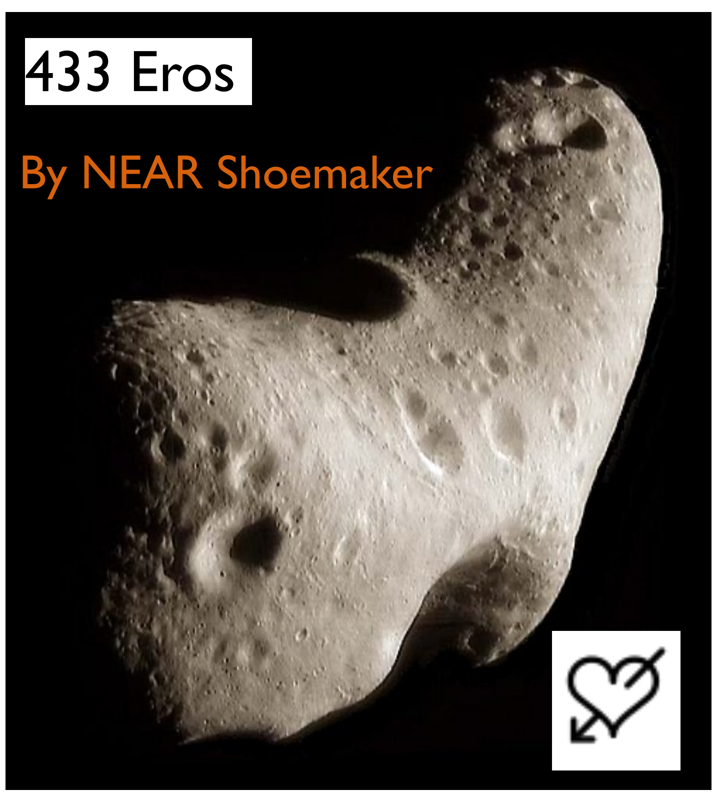
cnrs

Also known as ‘asteroid-mass’ PBH

$2\ 10^{21}$ g ~ $10^{-12}\ M_\odot$

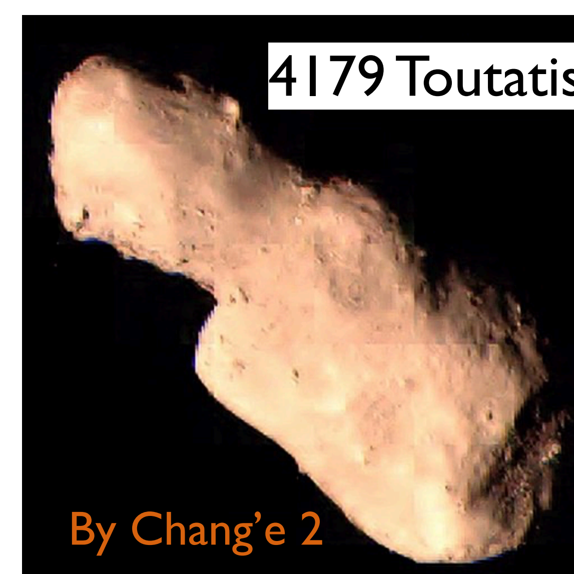


10^{24} g ~$5\times10^{-10}\ M_\odot$
(~ 1% Moon, 0.02% Earth)



$7\ 10^{18}$ g ~ $2.5\times10^{-15}\ M_\odot$

I’m sure you all know your planetary science, but here is a ‘solar system’ reminder of what mass range we’re talking about



$2\ 10^{16}$ g ~ $10^{-17}\ M_\odot$

Outline

1. Hawking radiation
2. PBH transit in stars
3. Lensing
4. Future/perspectives

A couple of dedicated reviews

A.M. Green & B.J. Kavanagh, "PBH as a dark matter candidate," J. Phys. G 48 (2021) 043001
M. Oncins, "Constraints on PBH as dark matter from observations: a review,"2205.14722

Part I
Hawking Radiation

J. Iguaz Juan, P.D.S., and T. Siegert. "Isotropic x-ray bound on primordial black hole dark matter" Phys.Rev.D 103 (2021) 10, 103025.

J. Berteaud, F. Calore, J. Iguaz Juan, P.D.S. and T. Siegert. "Strong constraints on primordial black hole dark matter from 16 years of INTEGRAL/SPI observations" Phys.Rev.D 106 (2022) 2, 023030.

A great lesson by Hawking: BH are like diamonds

(You hear "they are forever", and practically they often are… but truly they're not, and that may matter!)

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BHs emit a blackbody radiation with

$$T_{\rm BH} = \frac{1}{8\pi G M} \simeq 1.06 \left(\frac{10^{13}\,{\rm g}}{M}\right) {\rm GeV}$$

Hawking '74

Observable particles follow black body-like spectra:

$$\frac{d\dot{N}_s}{dE} \propto \frac{\Gamma_s}{e^{E/T_{\rm BH}} - 1(-1)^{2s}}$$

Encode probability that the generated particle escapes to spatial infinity obtained by solving the EoM of relevant particles in curved spacetime, with appropriate boundary conditions

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Encode probability that the generated particle escapes to spatial infinity obtained by solving the EoM of relevant particles in curved spacetime, with appropriate boundary conditions

Dedicated public software (implementing also some BSM scenarios) now exists:

blackhawk.hepforge.org

BlackHawk homepage – Hepforge

blackhawk is hosted by Hepforge, IPPP Durham

BlackHawk

By Alexandre Arbey and Jérémy Auffinger

Calculation of the Hawking evaporation spectra of any black hole distribution

BlackHawk is a public C program for calculating the Hawking evaporation spectra of any black hole distribution. This program enables the users to compute the primary and secondary spectra of stable or long-lived particles generated by Hawking radiation of the distribution of black holes, and to study their evolution in time.

If you use BlackHawk to publish a paper, please cite:

- A. Arbey and J. Auffinger, Eur. Phys. J. C79 (2019) 693, arXiv:1905.04268 [gr-qc]
- A. Arbey and J. Auffinger, Eur. Phys. J. C81 (2021) 910, arXiv:2108.02737 [gr-qc]

When is it important for phenomenology?

$$T_{\rm BH} = \frac{M_{\rm Pl}^2}{8\pi m_{\rm BH}} \approx 1.05\,{\rm MeV} \times \left(\frac{10^{16}\,{\rm g}}{m_{\rm BH}}\right) \qquad \Gamma^{-1}_{\rm PBH} \simeq 4.07 \times 10^{11} \left(\frac{\mathcal{F}(M)}{15.35}\right)^{-1} \left(\frac{M}{10^{13}{\rm g}}\right)^3 {\rm s}\,.$$

If $M \lesssim 10^{15}$ g, lifetime < universe lifetime (unsuitable DM, still could have cosmo implications…)
Above that value, possible DM & with observable consequences if not *too* heavy!

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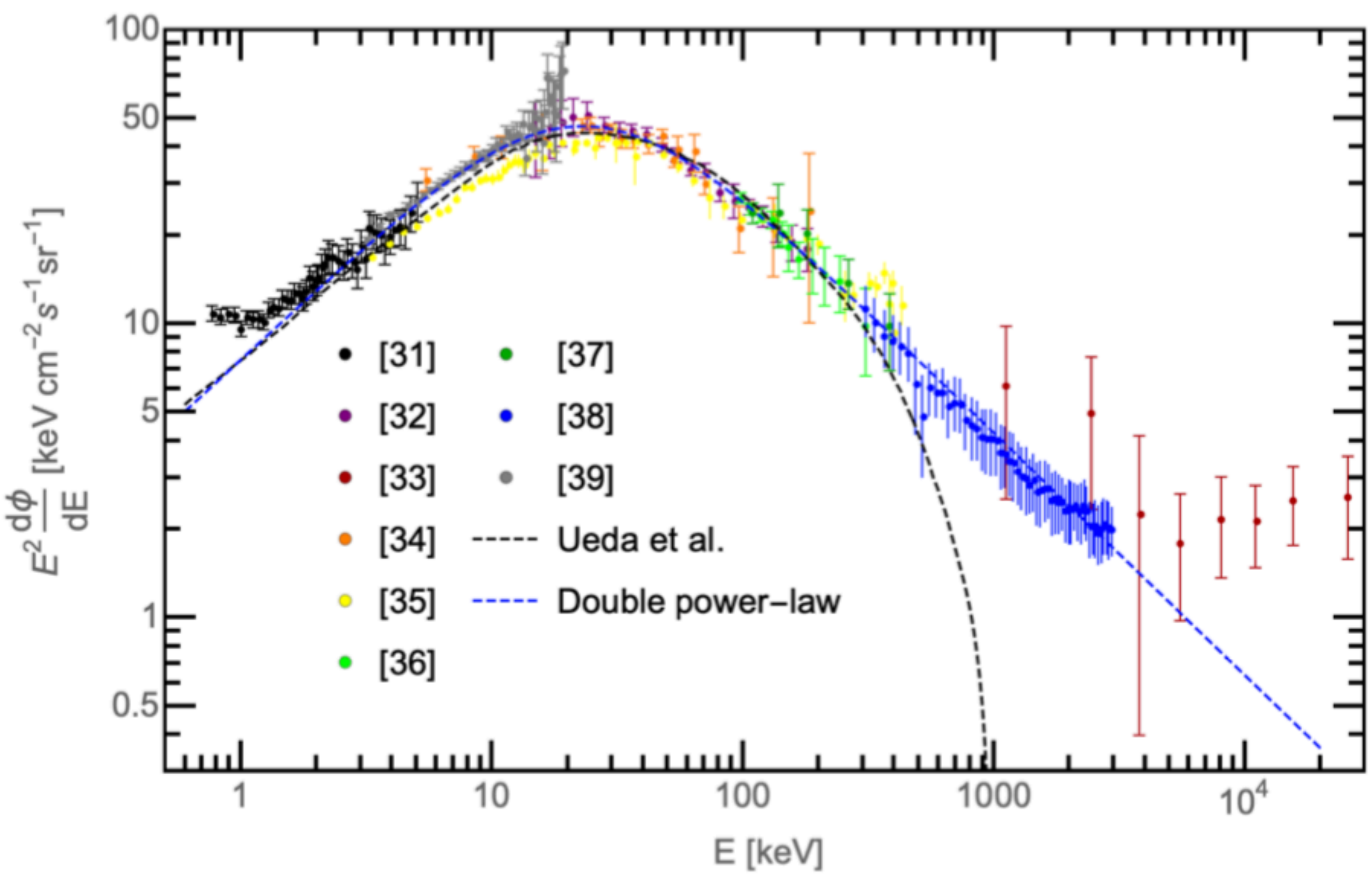
Usual approach:
Compare isotropic X/soft gamma ray flux with expected prompt photons from PBH evaporating all over the universe

$$\frac{{\rm d}\phi_{\rm PBH}}{{\rm d}E} = \frac{{\rm d}\phi_\gamma^{\rm ext}}{{\rm d}E} = \frac{f_{\rm PBH}\,\Omega_{\rm DM}\rho_c}{4\pi M}\int_0^{z_{\max}}\frac{{\rm d}z}{H(z)}\frac{{\rm d}^2N_\gamma}{{\rm d}E{\rm d}t}(E(1+z))$$

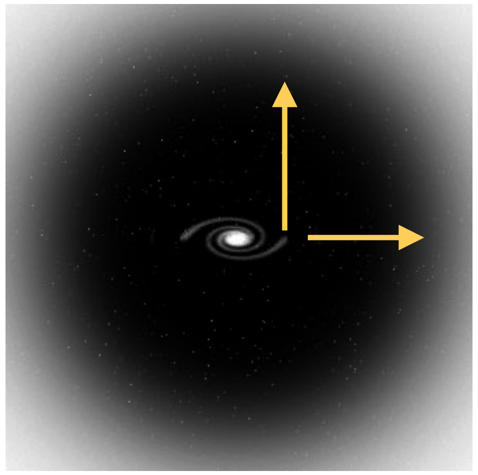


ASCA [31], Swift/BAT [32], Comptel [33], Integral [34], HEAO-1 [35], HEAO-A4 [36], Nagoya [37], SMM [38] and RXTE [39].

Not the whole story!

1. We are embedded in the MW halo, hence there is a residual, quasi-isotropic flux from the galaxy

$$\frac{\mathrm{d}\phi_{\mathrm{PBH}}}{\mathrm{d}E} = \boxed{\frac{\mathrm{d}\phi_\gamma^{\mathrm{gal}}}{\mathrm{d}E}} + \frac{\mathrm{d}\phi_\gamma^{\mathrm{ext}}}{\mathrm{d}E}$$



$$\frac{\mathrm{d}\phi_\gamma^{\mathrm{gal}}}{\mathrm{d}E} \geq \left.\frac{\mathrm{d}\phi_\gamma^{\mathrm{gal}}}{\mathrm{d}E}\right|_{\mathrm{min}} \equiv \frac{f_{\mathrm{PBH}}}{4\pi M}\frac{\mathrm{d}^2 N_\gamma}{\mathrm{d}E\mathrm{d}t}\left(\int_{\mathrm{l.o.s.}} \mathrm{d}s\, \rho_g\right)_{\mathrm{min}}$$

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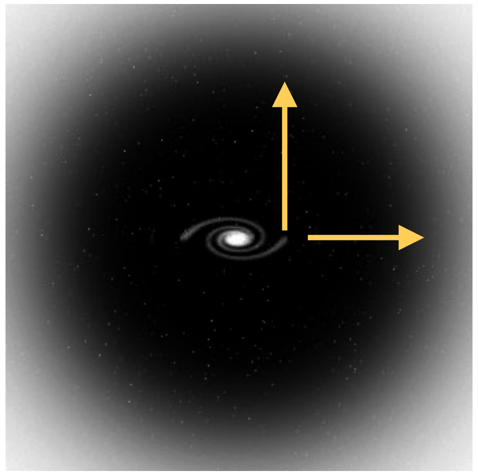
II. Additional γ's come from the 2 and 3-body annihilation of the e^+ emitted via evaporations, both in the Galactic and extragalactic environment (e^+ do cool down 'fast' wrt cosmological times)

$$\frac{\mathrm{d}\phi_{\rm PBH}}{\mathrm{d}E} = \frac{\mathrm{d}\phi_\gamma^{\rm gal}}{\mathrm{d}E} + \frac{\mathrm{d}\phi_\gamma^{\rm ext}}{\mathrm{d}E} + \begin{cases} \dfrac{\mathrm{d}\phi_0^{\rm gal}}{\mathrm{d}E} + \dfrac{\mathrm{d}\phi_0^{\rm ext}}{\mathrm{d}E} & \text{if } f_{\rm Ps} = 0 \\ \dfrac{\mathrm{d}\phi_1^{\rm gal}}{\mathrm{d}E} + \dfrac{\mathrm{d}\phi_1^{\rm ext}}{\mathrm{d}E} & \text{if } f_{\rm Ps} = 1 \end{cases}$$

MW-like



$$\frac{\mathrm{d}\phi_\gamma^{\rm gal}}{\mathrm{d}E} \geq \left.\frac{\mathrm{d}\phi_\gamma^{\rm gal}}{\mathrm{d}E}\right|_{\rm min} \equiv \frac{f_{\rm PBH}}{4\pi M}\frac{\mathrm{d}^2 N_\gamma}{\mathrm{d}E\mathrm{d}t}\left(\int_{\rm l.o.s.} \mathrm{d}s\, \rho_g\right)_{\rm min}$$

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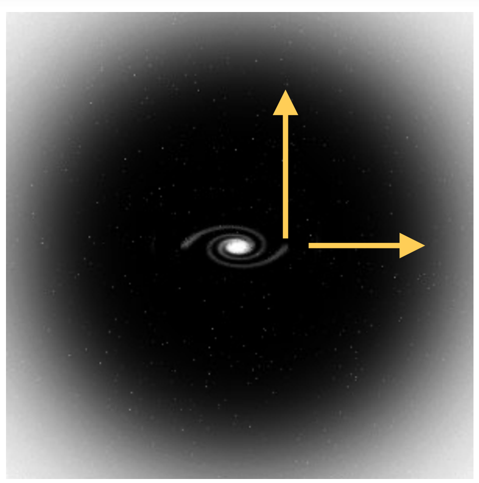
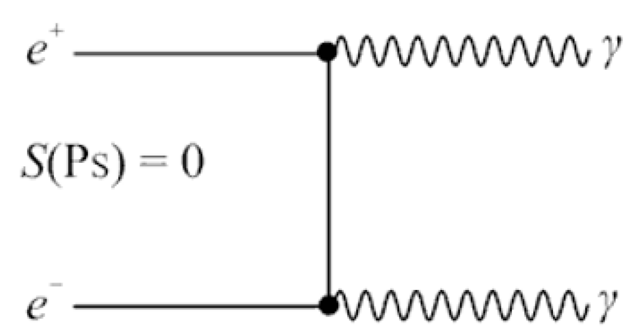
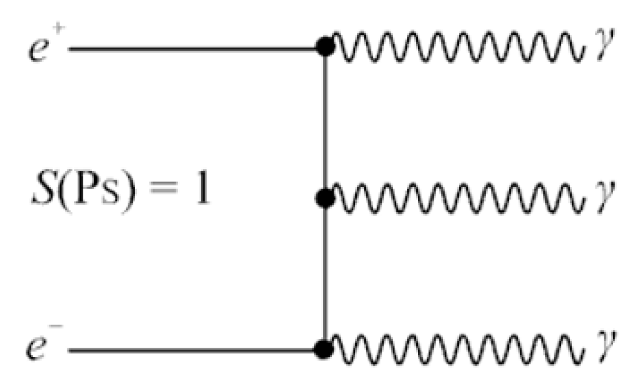




Para



Ortho

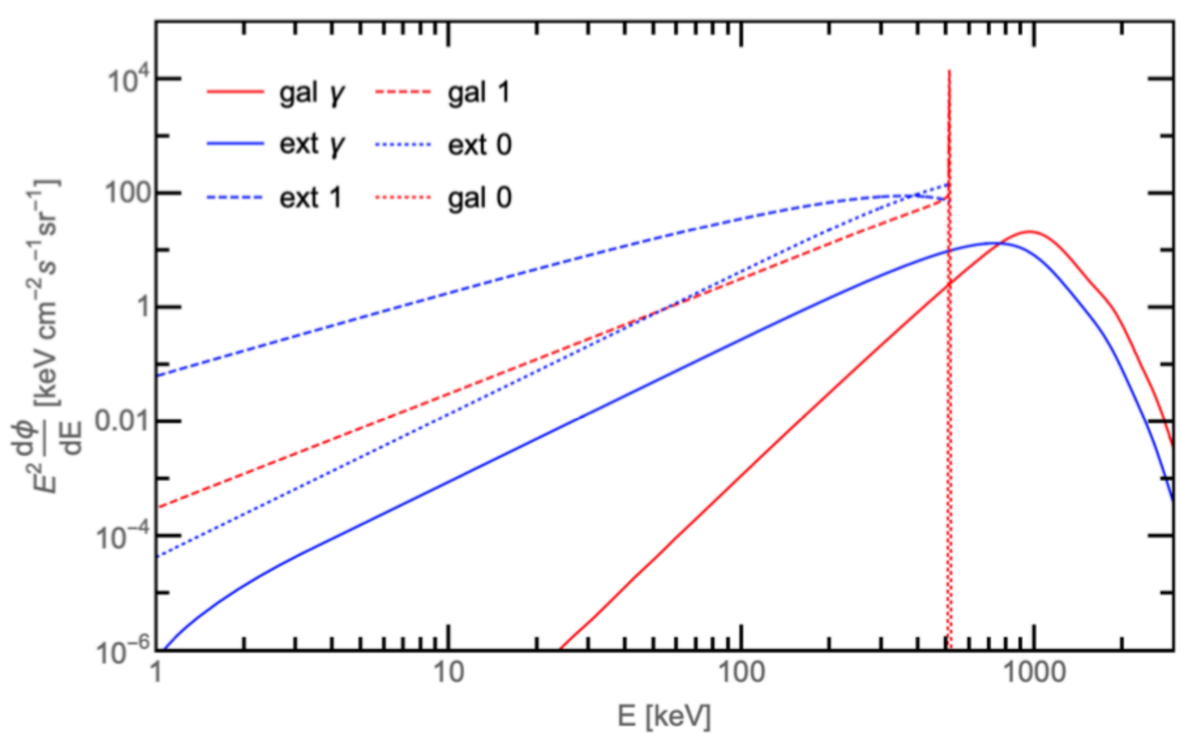
$$\frac{\mathrm{d}\phi_\gamma^{\rm gal}}{\mathrm{d}E} \geq \left.\frac{\mathrm{d}\phi_\gamma^{\rm gal}}{\mathrm{d}E}\right|_{\rm min} \equiv \frac{f_{\rm PBH}}{4\pi M}\frac{\mathrm{d}^2 N_\gamma}{\mathrm{d}E\mathrm{d}t}\left(\int_{\rm l.o.s.} \mathrm{d}s\, \rho_g\right)_{\rm min}$$

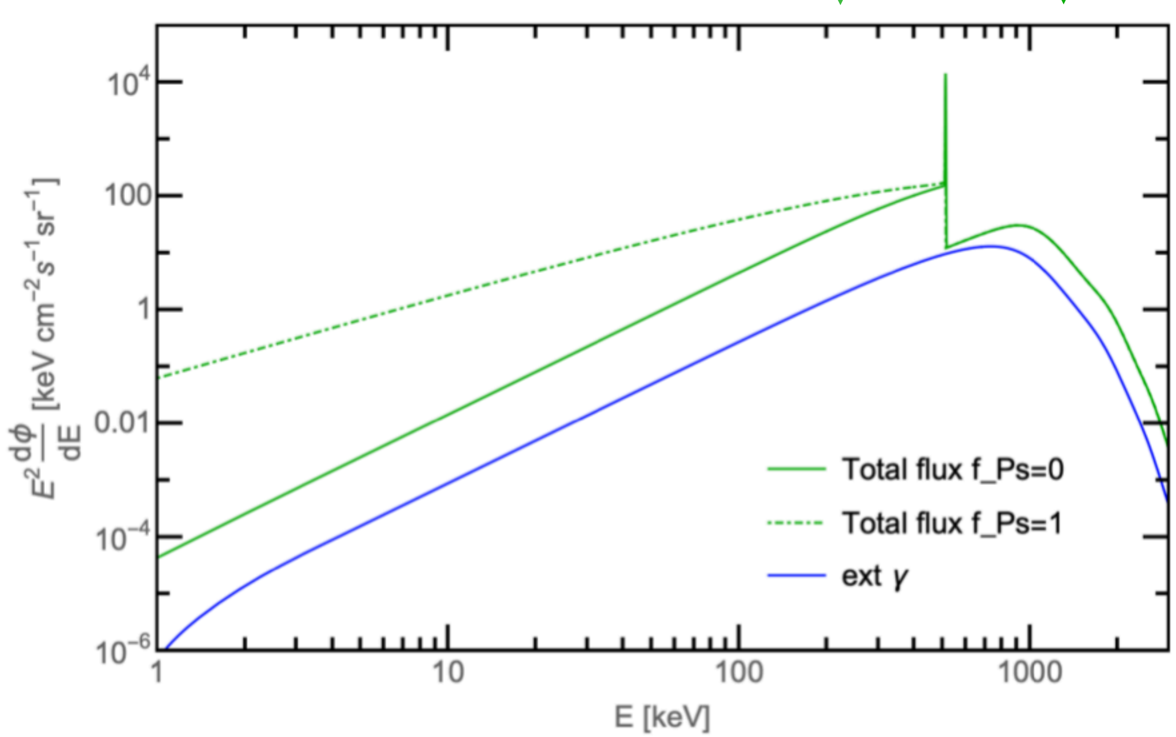
Fraction of particles forming Ps depends on environmental parameters (temperature, density…)

Comparison

$$\frac{\mathrm{d}\phi_{\mathrm{PBH}}}{\mathrm{d}E} = \frac{\mathrm{d}\phi_{\gamma}^{\mathrm{gal}}}{\mathrm{d}E} + \frac{\mathrm{d}\phi_{\gamma}^{\mathrm{ext}}}{\mathrm{d}E} + \begin{cases} \frac{\mathrm{d}\phi_{0}^{\mathrm{gal}}}{\mathrm{d}E} + \frac{\mathrm{d}\phi_{0}^{\mathrm{ext}}}{\mathrm{d}E} & \text{if } f_{\mathrm{Ps}} = 0 \\ \frac{\mathrm{d}\phi_{1}^{\mathrm{gal}}}{\mathrm{d}E} + \frac{\mathrm{d}\phi_{1}^{\mathrm{ext}}}{\mathrm{d}E} & \text{if } f_{\mathrm{Ps}} = 1 \end{cases}$$

Isotropic flux for $M_{PBH}=7\times10^{16}$ g



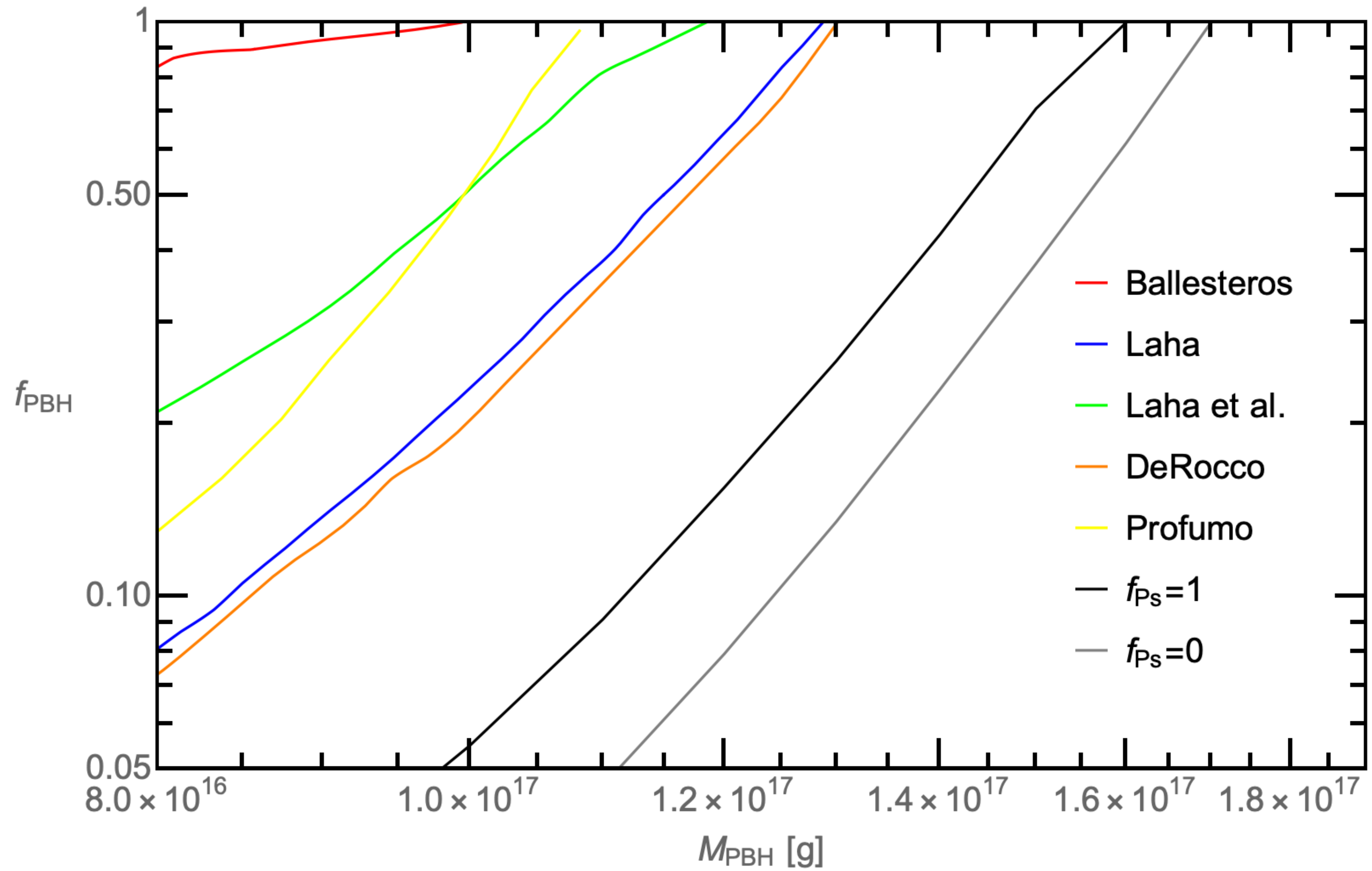


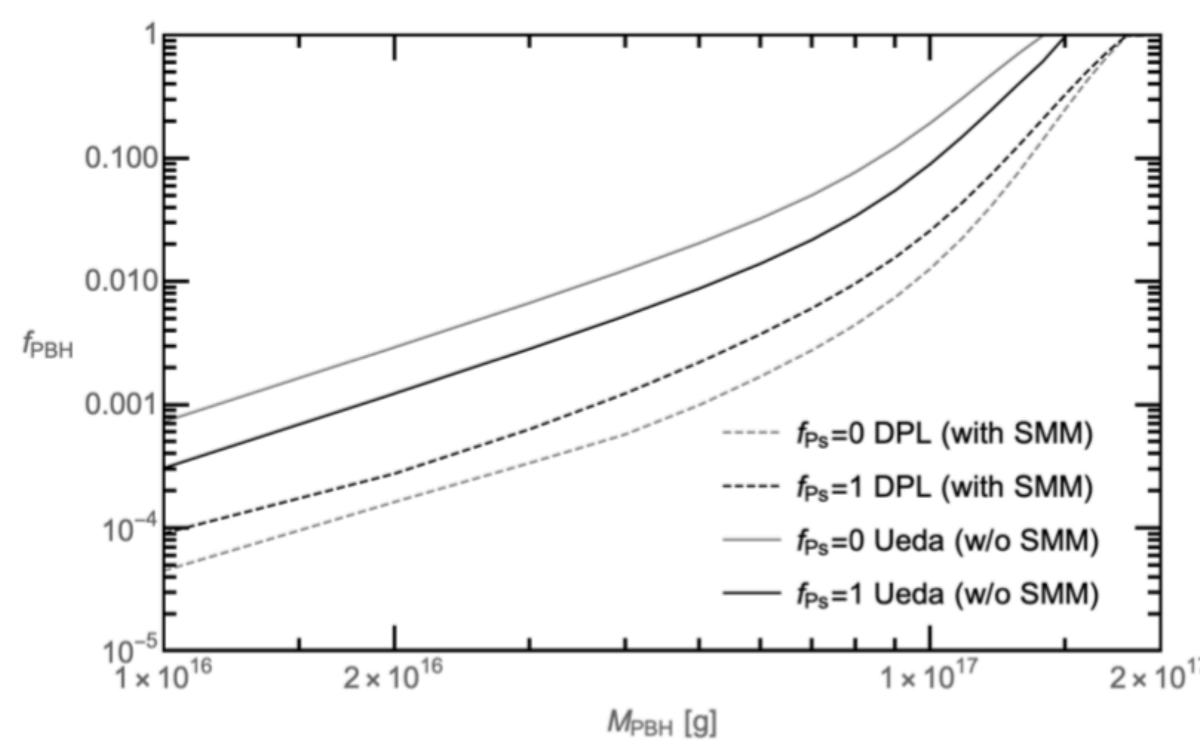
These neglected contributions dominate the emission almost over all the spectrum!

Best bounds via Hawking radiation

Only requiring that the PBH-only flux does not exceed the measurements by more than 2 σ

$M_{PBH} > 1.6 - 1.7 \times 10^{17}$ g (if DM)





With astrophysical background modeling, bounds extend in mass space by a factor up to ~2 *(depending how well the background fits the data)*

Ad hoc Galactic data analyses

Till now, Galactic bounds based on requiring PBH spectra not exceeding residuals obtained in ‘standard’ analyses of X-ray data: Potential bias/loss of sensitivity!

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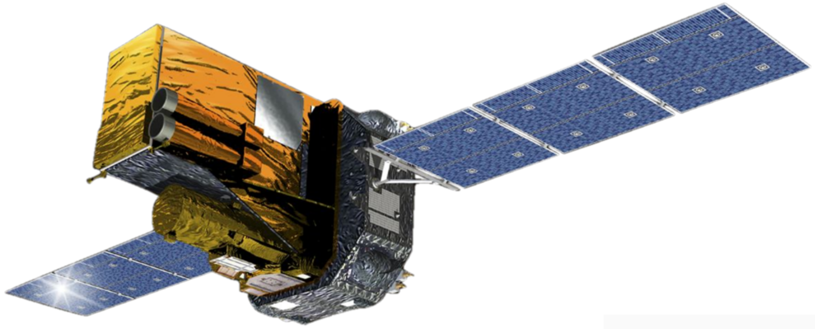
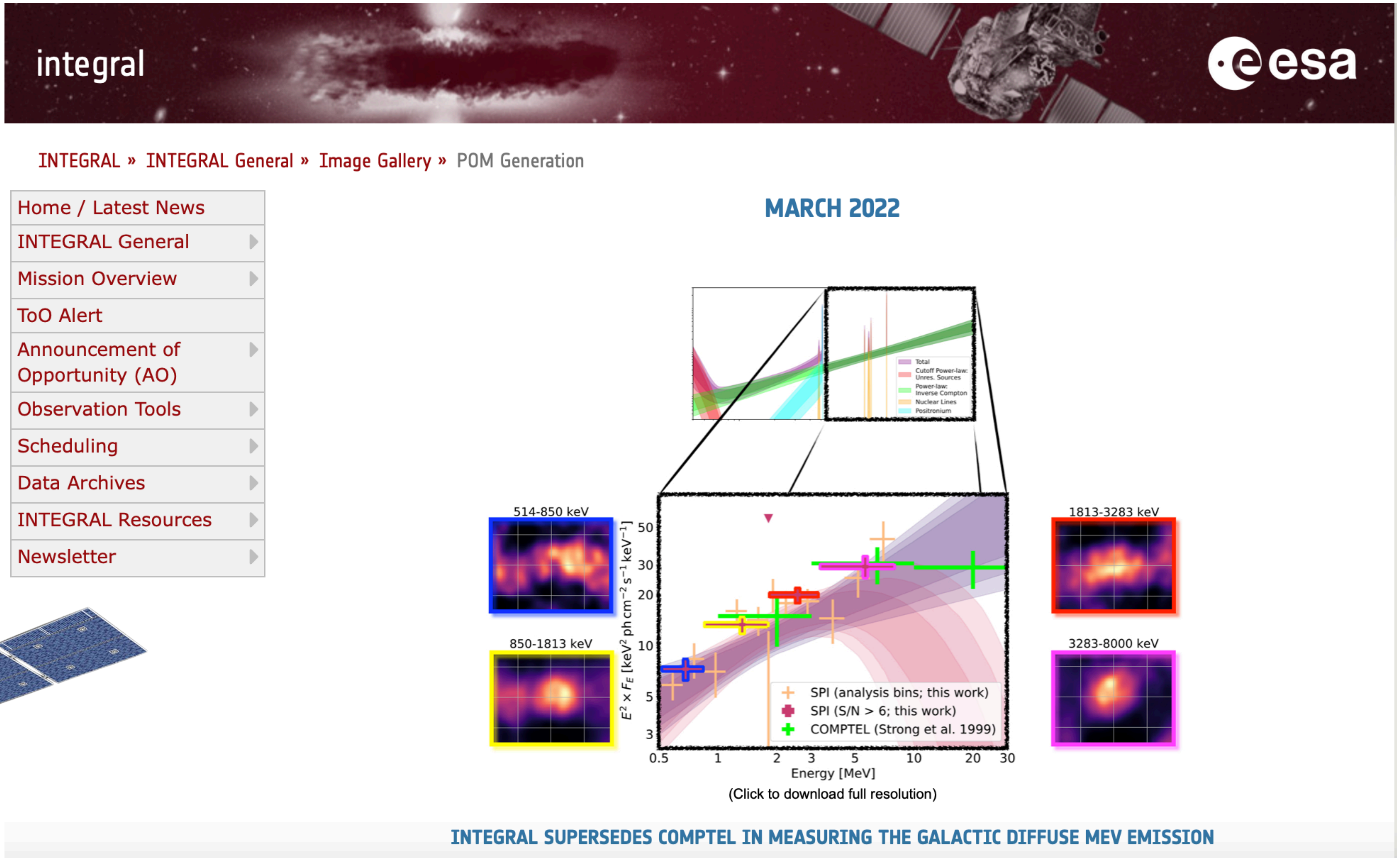
Dedicated pipeline to reanalyise 16 yr of Integral-SPI data, new instrumental background model, careful data selection (e.g. accounting for solar activity), systematics assessed on dedicated GALPROP templates of Galactic Compton emission…

T. Siegert, Würzburg





T. Siegert, J. Berteaud, F. Calore, P. D. Serpico and C.Weinberger, Astron. Astrophys. 660 (2022), A130 [2202.04574]

Ad hoc Galactic data analyses

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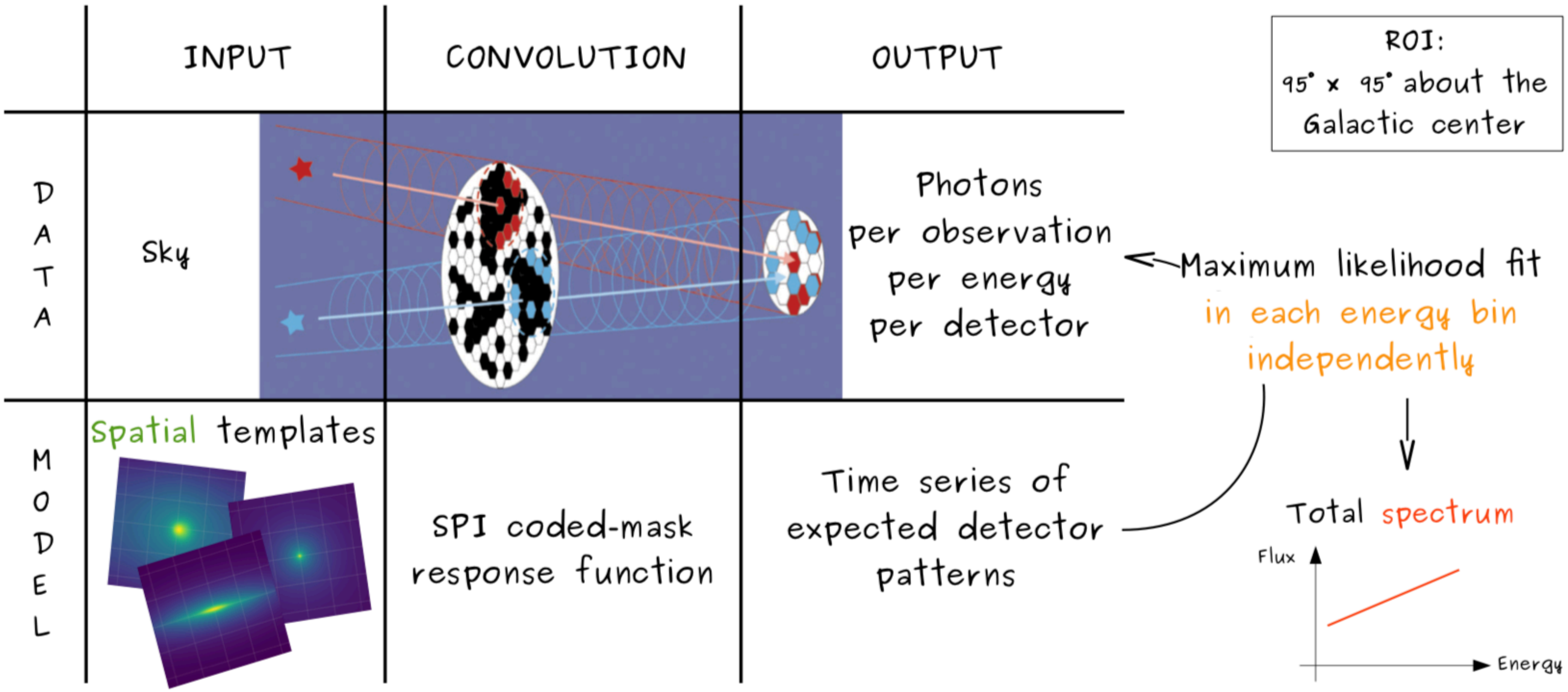
SPI data analysis

Slide credit: Joanna Berteaud

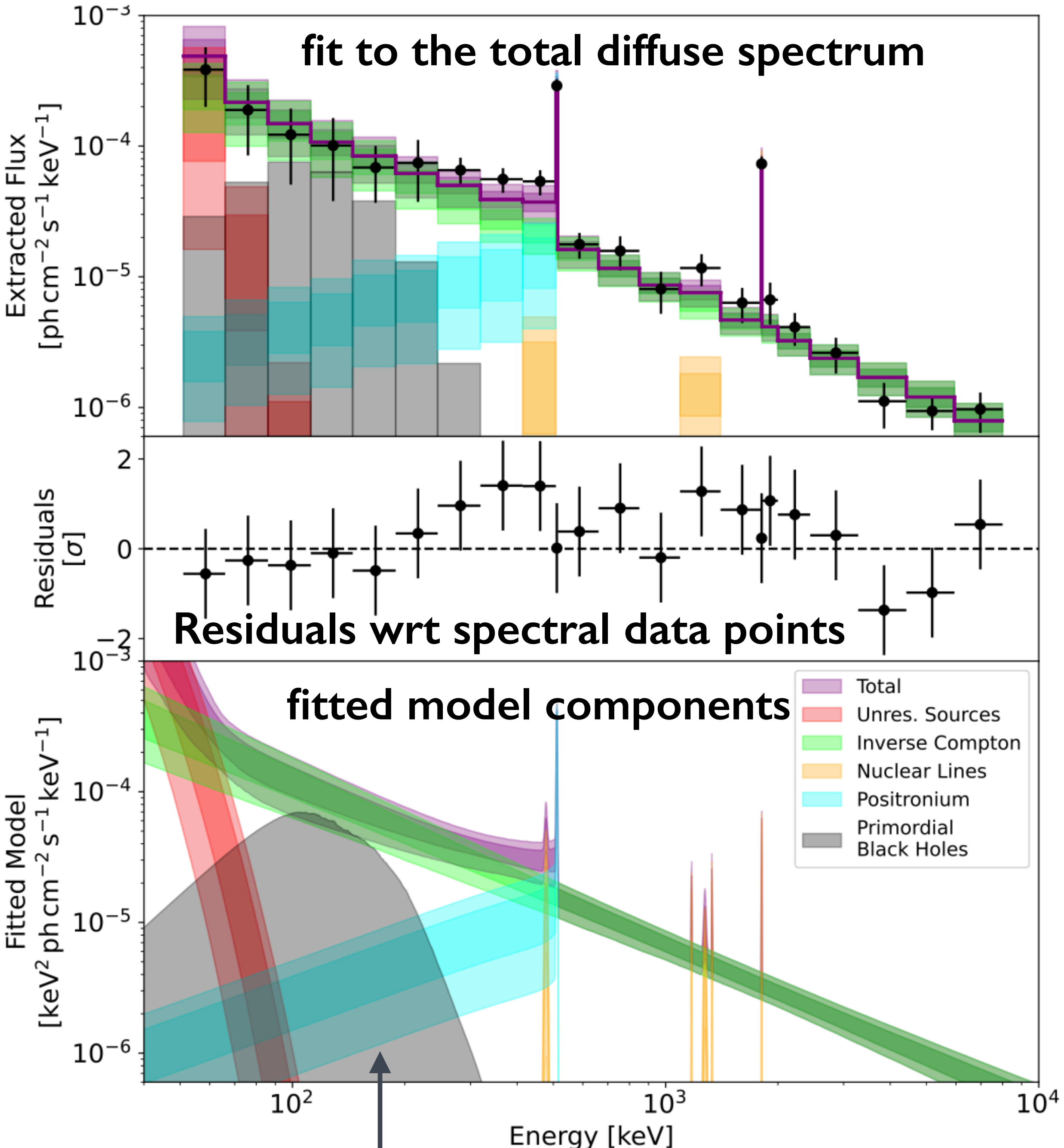


Included **spatial templates**:

- ICS
- Unresolved sources
- Nuclear lines
- Positronium annihilation

\+ instrumental background

Results



2σ upper limit from our heaviest excluded PBH (~ 4 × 10^{17} g)

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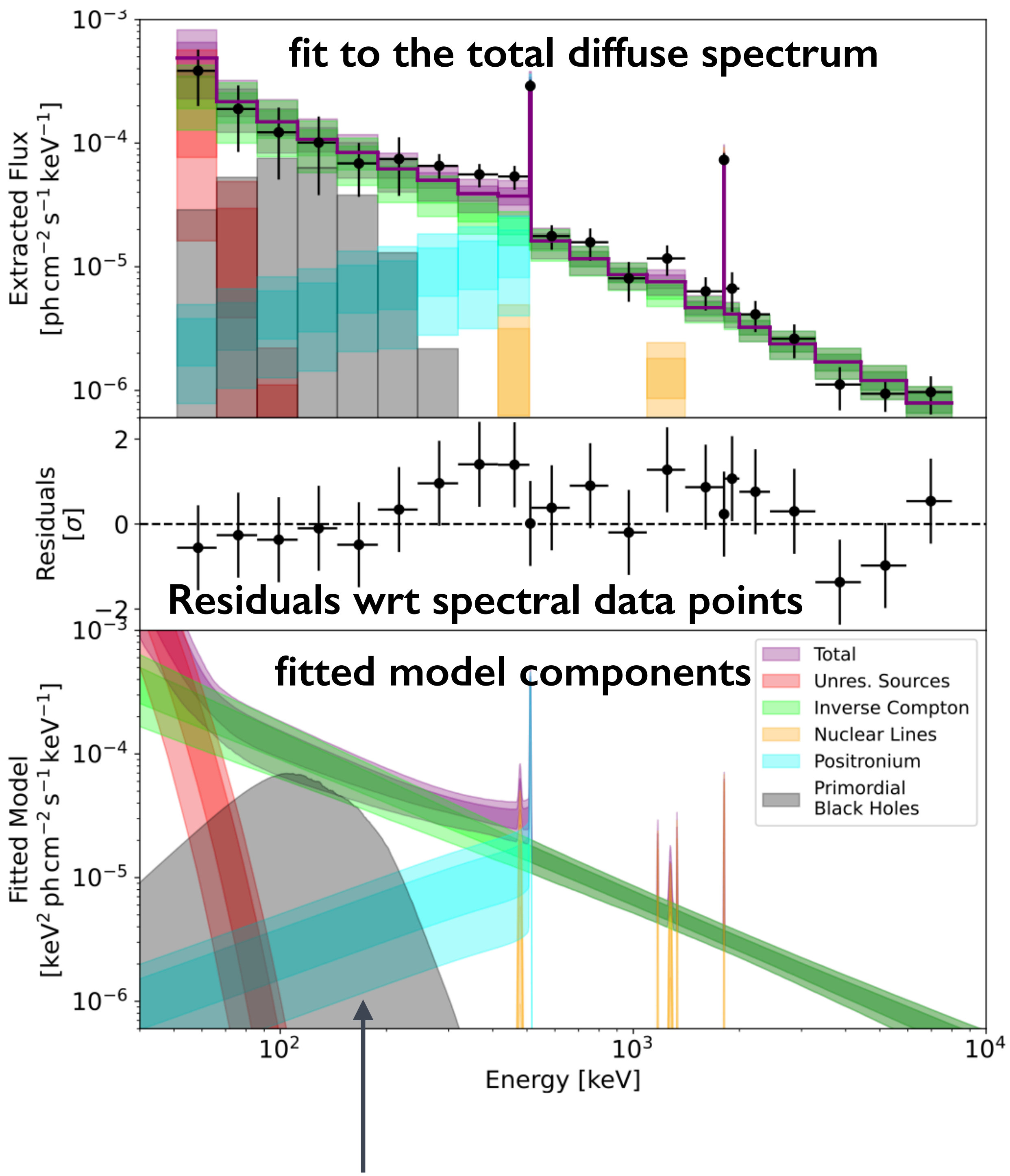

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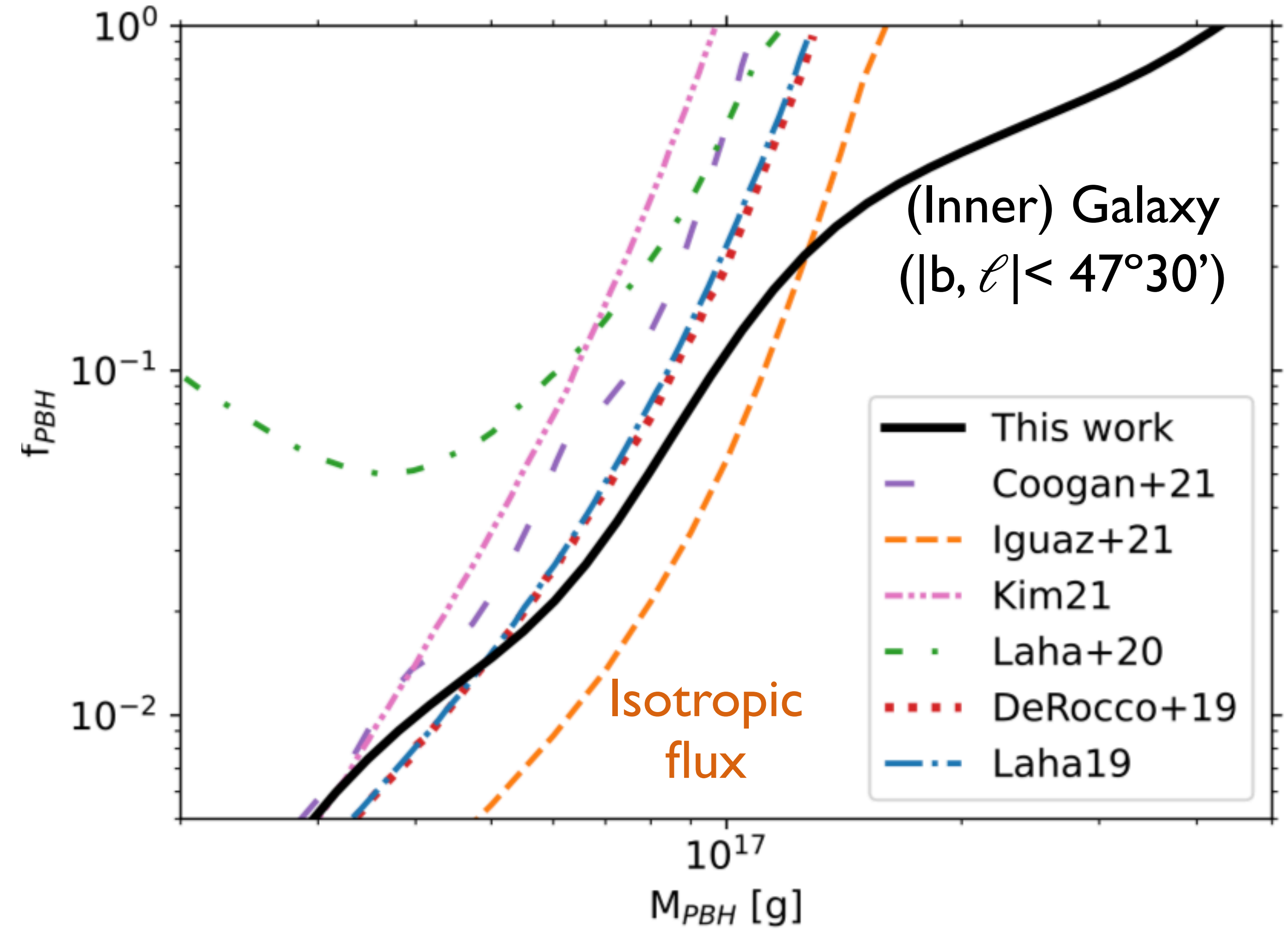
Most constraining bounds on f_{PBH} from Hawking evaporation in the literature!



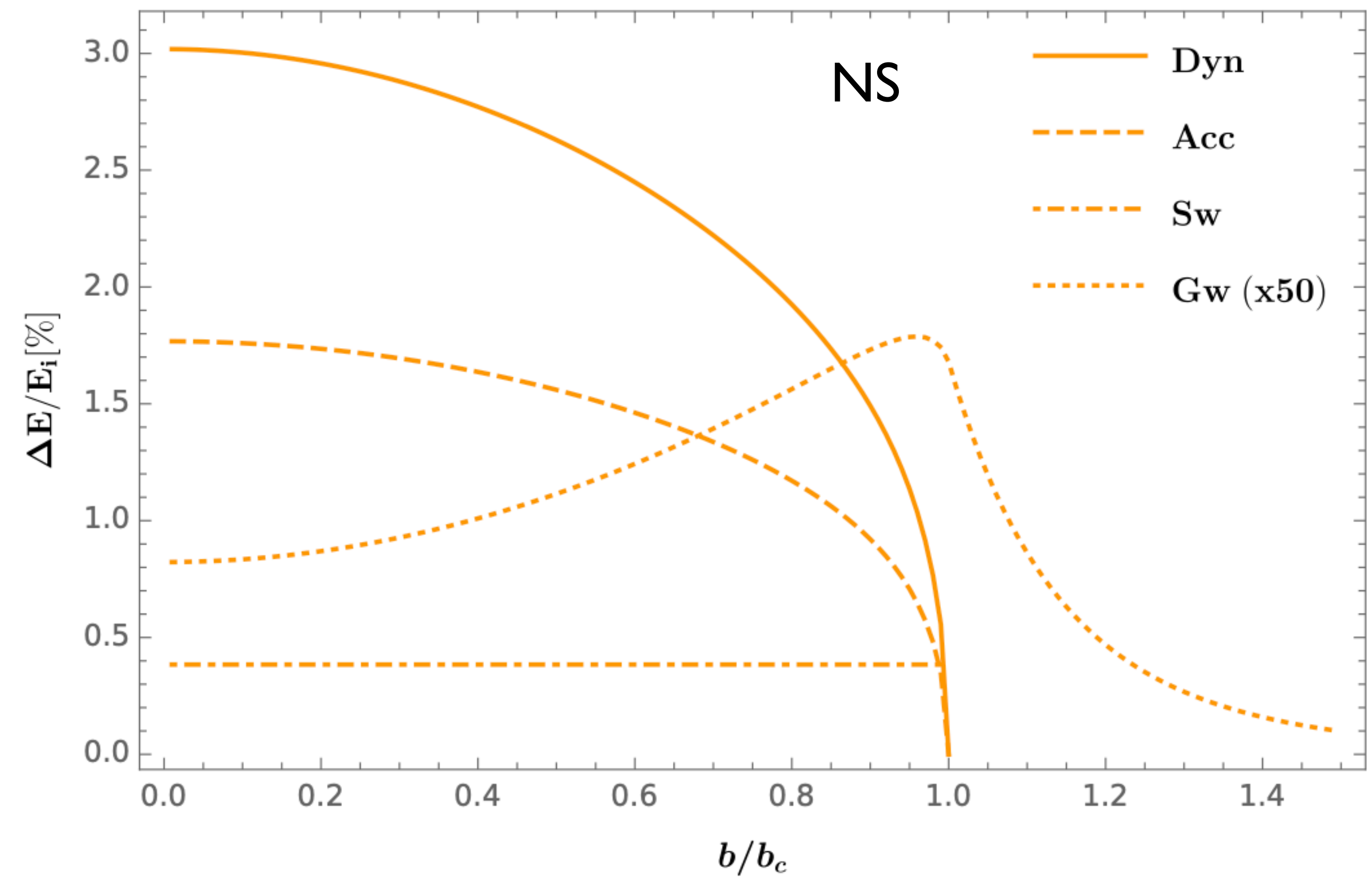
Part II
PBH transit in stars

Y. Génolini, P. D.S. and P. Tinyakov, "Revisiting primordial black hole capture into neutron stars," Phys. Rev. D 102 (2020) no.8, 083004 [arXiv:2006.16975]

Basics

As a PBH passes through (or near!) a star, it loses energy by a number of processes: Dominated by dynamical friction in NS, which are also the most promising objects

If, as a result, PBH is captured, it will eventually sink towards the centre, accrete matter and eventually swallowing & destroying the star, leaving a BH behind (*transmutation*)



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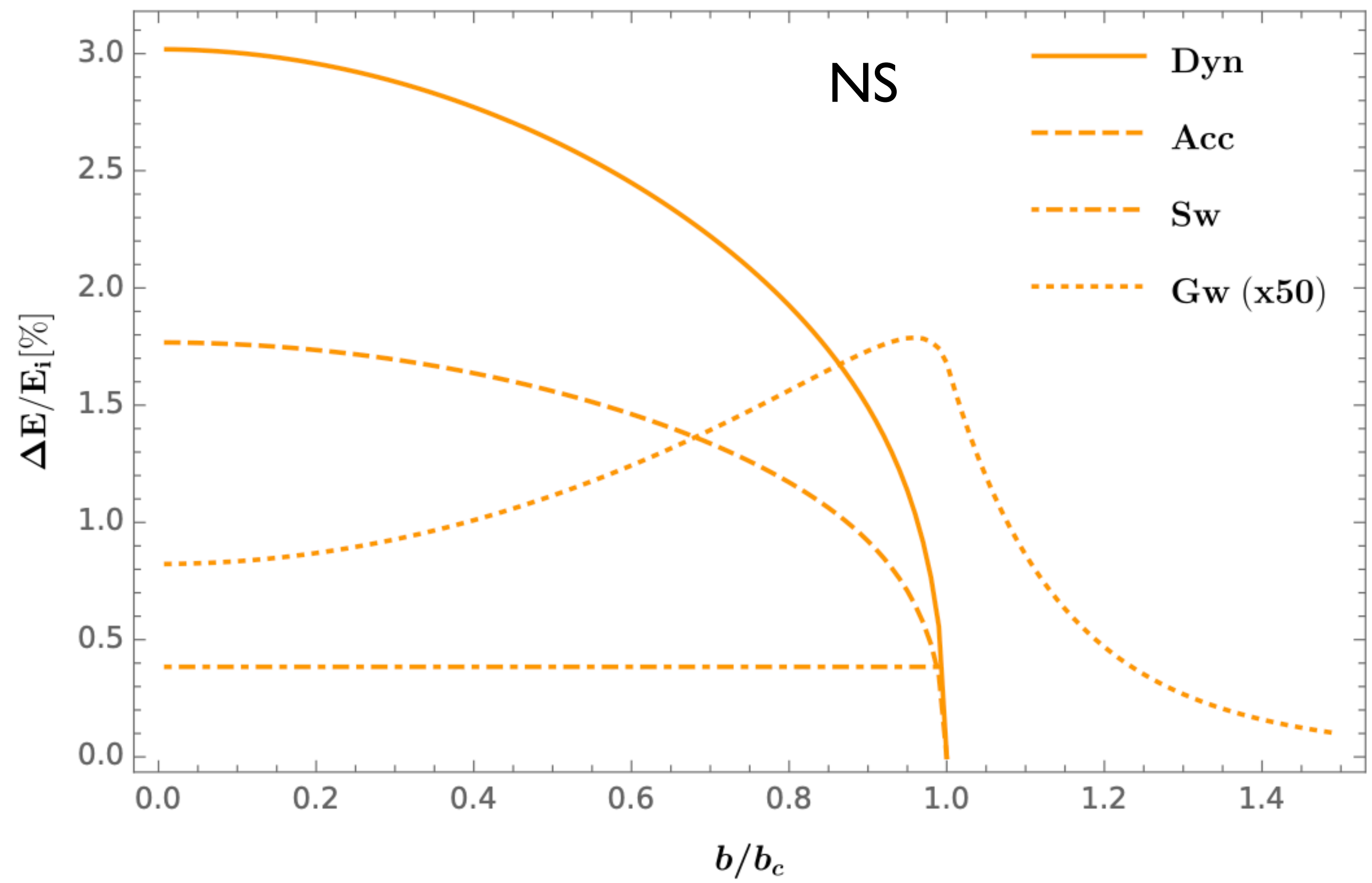


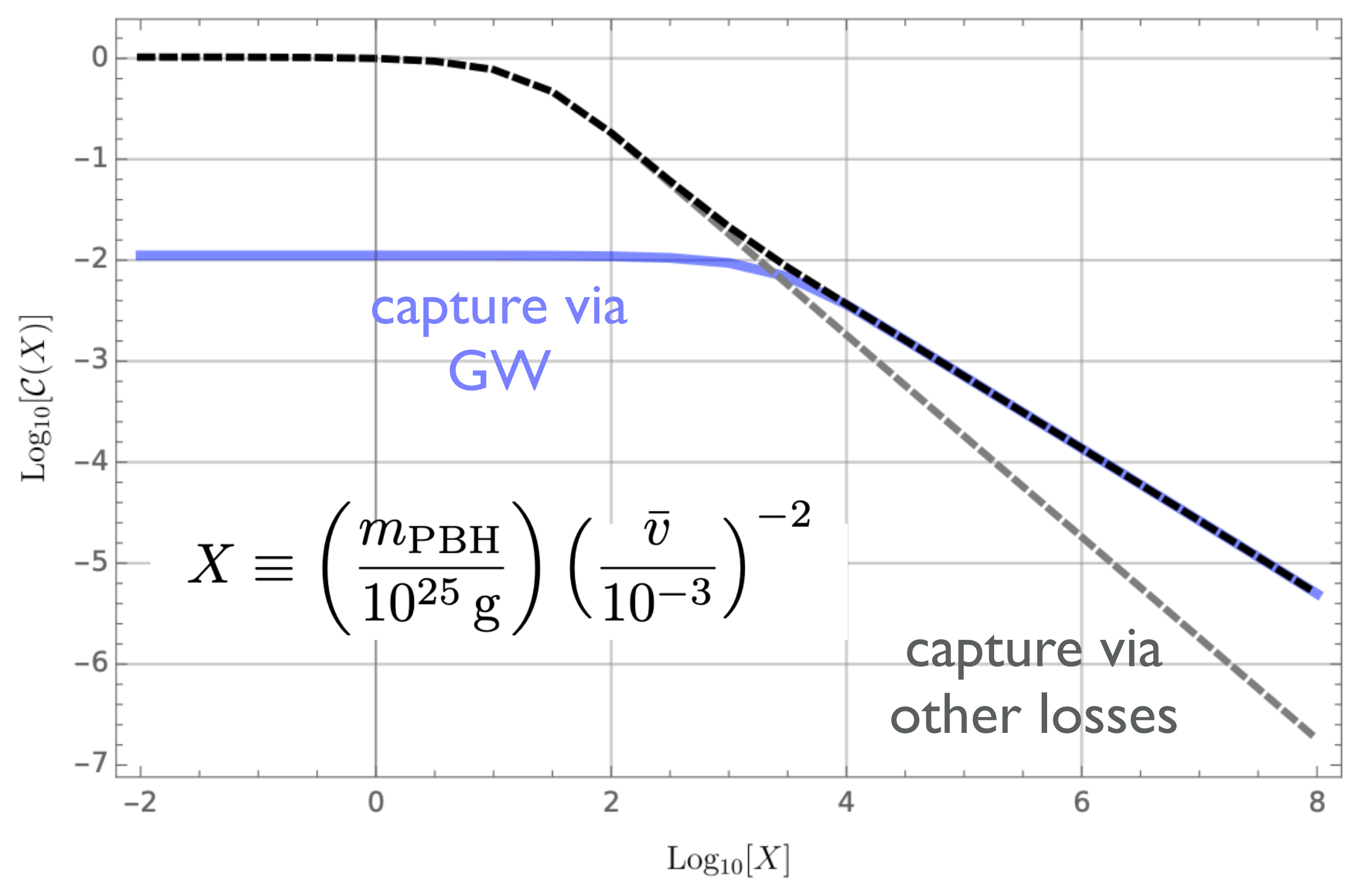
Note that the (NS) crossing rate

$$\Gamma_\star = \int \frac{d^3n}{dv^3}\, \pi b_c^2(v)\, v\, d^3v =$$

$$\simeq 3.8 \times 10^{-16} \left(\frac{\rho_{\rm BH}}{1{\rm GeV\,cm^{-3}}}\right)\left(\frac{10^{25}{\rm g}}{m}\right)\left(\frac{10^{-3}}{\bar v}\right){\rm yr^{-1}}$$

is much larger, at small m_{PBH}, than the capture rate

$$\mathcal{G}_\star \simeq 2.1 \times 10^{-17} \left(\frac{\rho_{\rm PBH}}{\rm GeV\,cm^{-3}}\right)\left(\frac{10^{-3}}{\bar v}\right)^3 \mathcal{C}\,[X]\,{\rm yr^{-1}}$$



Some consequences

Stellar survival constraints (e.g. observing NS in globular clusters), as in

F. Capela, M. Pshirkov and P. Tinyakov, Phys. Rev. D 87 (2013) 123524 [1301.4984]

argued not to be robust against relaxing hypotheses on DM density there.

The transit of a PBH through a carbon/oxygen white dwarf will lead to localized heating by dynamical friction, which could ignite the carbon and potentially cause a runaway explosion

P. W. Graham, S. Rajendran and J. Varela, Phys. Rev. D 92 (2015) 063007 [1505.04444]

Triggering explosion harder than thought for 'low' masses not excluded otherwise, see

P. Montero-Camacho, X. Fang, G. Vasquez, M. Silva and C. M. Hirata, JCAP 08 (2019), 031 [1906.05950]

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Perhaps more promising a 'positive' evidence

The explosion delivers observable energy at least associated to the B-field. In NS:

$$E_B = \frac{B^2}{8\pi}\frac{4\pi}{3}R_\star^3 \simeq 2\times 10^{41}\left(\frac{B}{10^{12}\mathrm{G}}\right)^2\left(\frac{R_\star}{10\,\mathrm{km}}\right)^3 \mathrm{erg}$$

(This benchmark ≈ energy emitted by the Sun in 1 yr…in a few ms!)

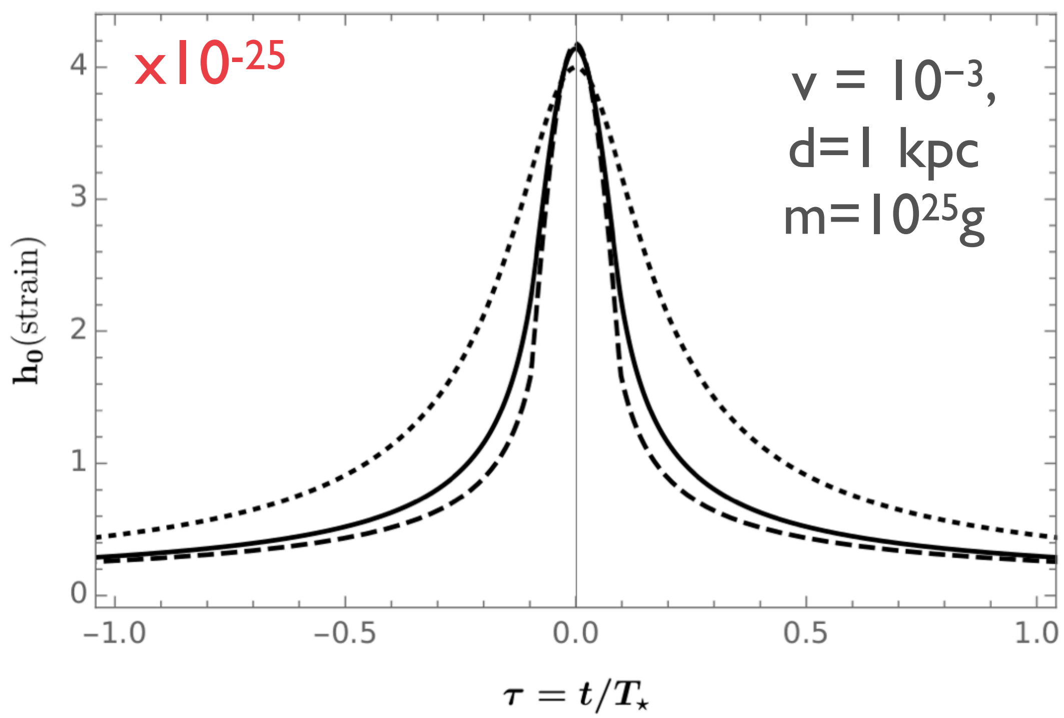
Signature(?)

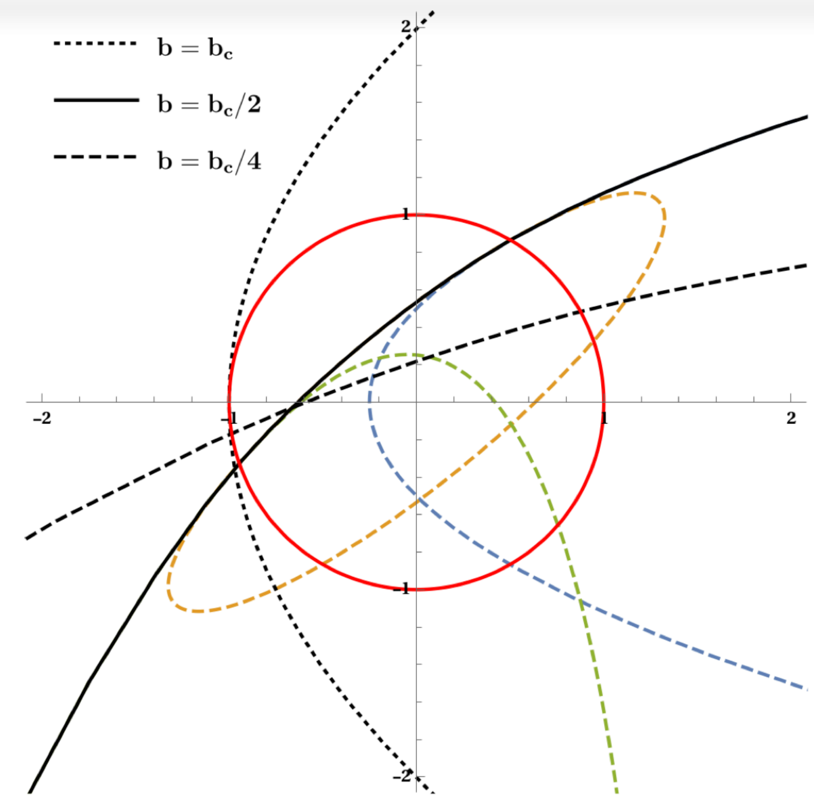
Poynting flux + small amount of ejecta, since virtually no kilo-nova is found in simulations of

W. E. East and L. Lehner, Phys. Rev. D 100 (2019) 124026 [1909.07968]

Gravitational wave signals?

Teardrop signal associated to first transit





followed (if PBH captured) by ~monochromatic kHz emission, lasting $t_B = \frac{c_s^3 R_\star^3}{3\,G^2\,M_\star\,m} \approx 9\left(\frac{10^{25}\mathrm{g}}{m}\right)$ hours

with amplitude $$h_0 = \frac{4\sqrt{2}G}{dc^4} m r^2 \omega_\star^2 \approx 2.5\times 10^{-25}\left(\frac{m}{10^{25}\mathrm{g}}\right)\left(\frac{1\ \mathrm{kpc}}{d}\right)\ .$$

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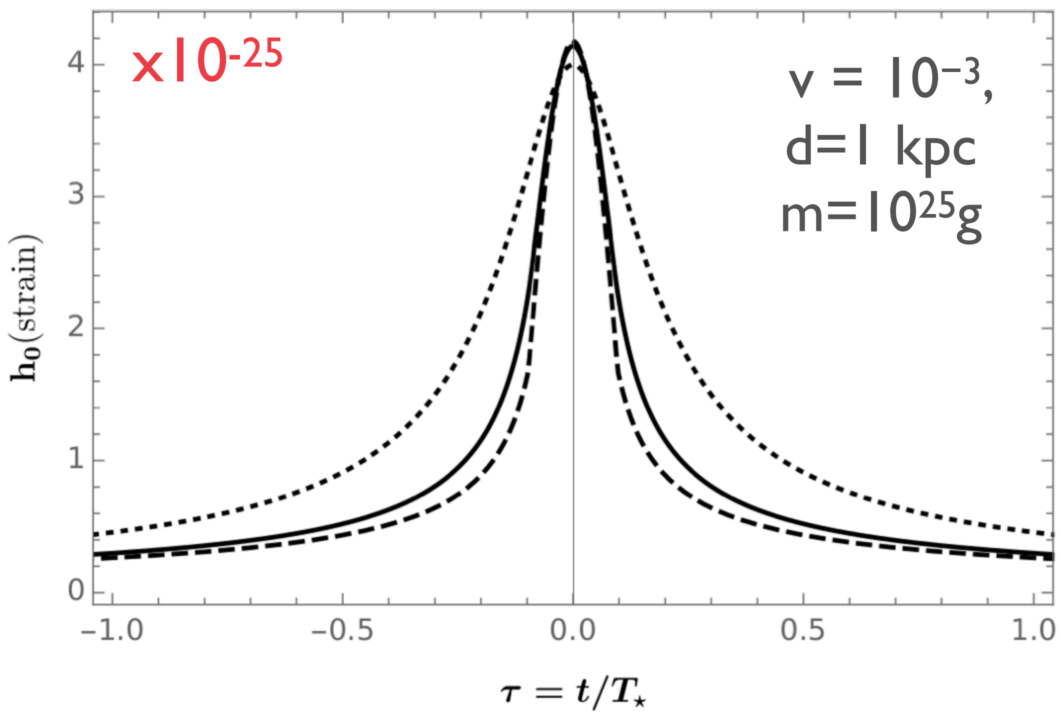

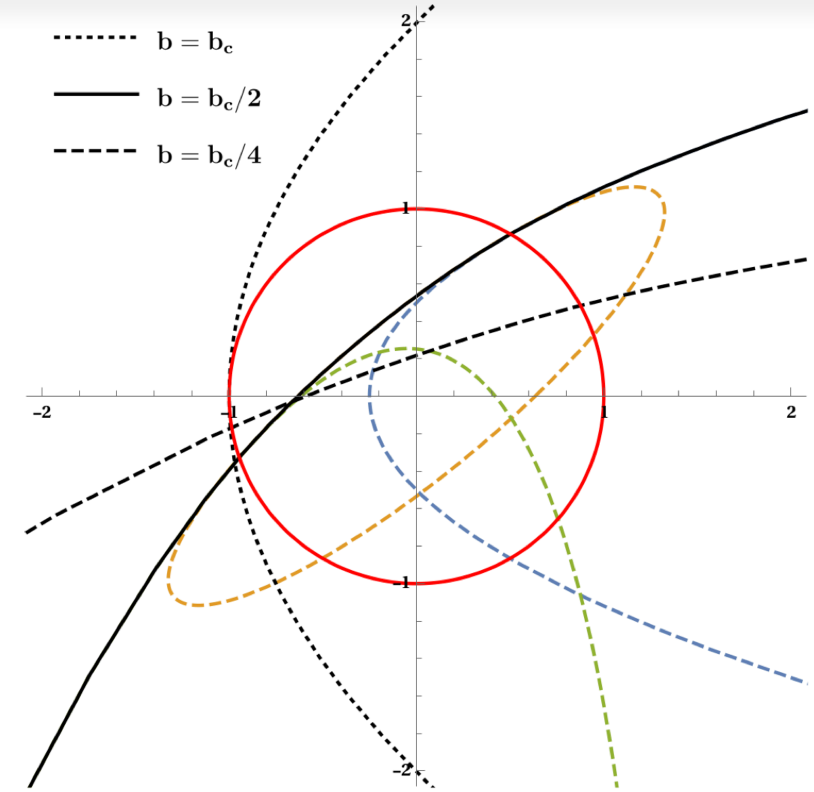

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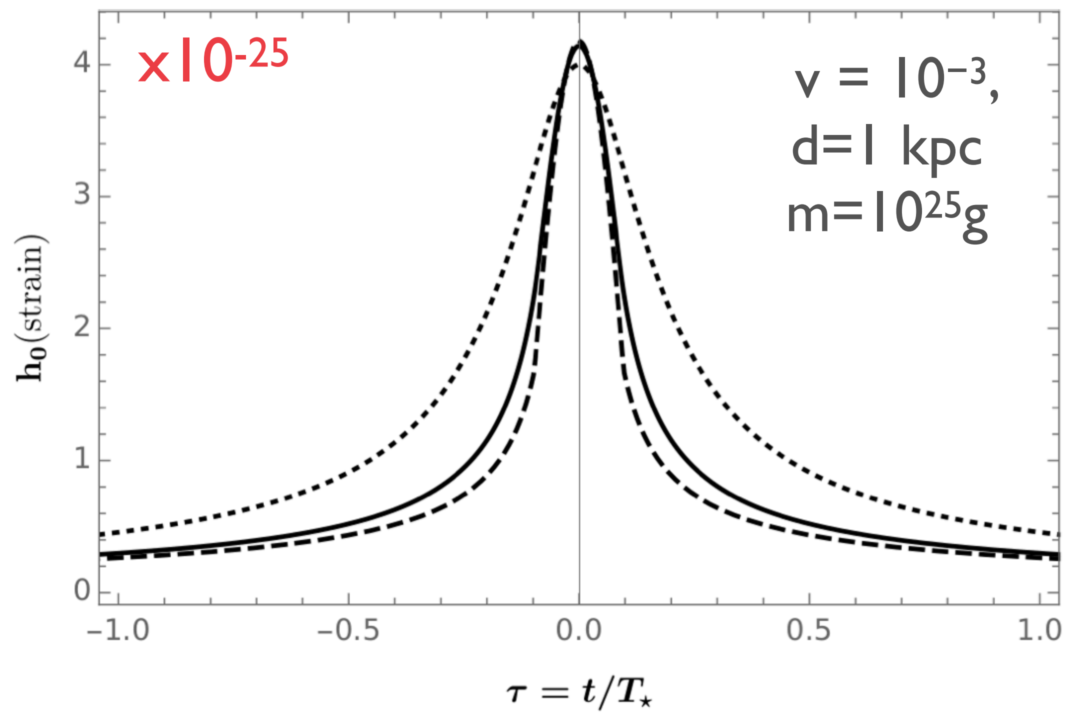
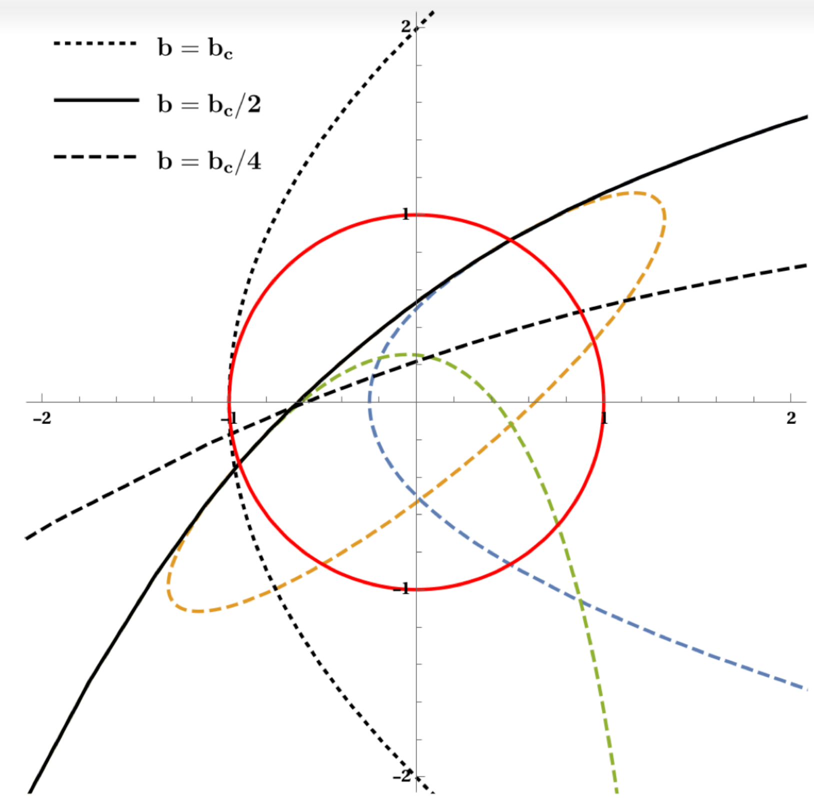
Eventually, additional GW can be associated to the transmutation event, requiring ad hoc simulations

[Perhaps current dim perspectives are too pessimistic, assuming PBH exactly at the center]

Gravitational wave signals?

Teardrop signal associated to first transit





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Eventually, additional GW can be associated to the transmutation event, requiring ad hoc simulations

[Perhaps current dim perspectives are too pessimistic, assuming PBH exactly at the center]

Alternative: any chance to see (e.g. via GW from binares) BHs with mass significantly below 3 $M_\odot$?

No bounds from all that, but possible signals in GW/E.M. if one is lucky*…interesting to dig further

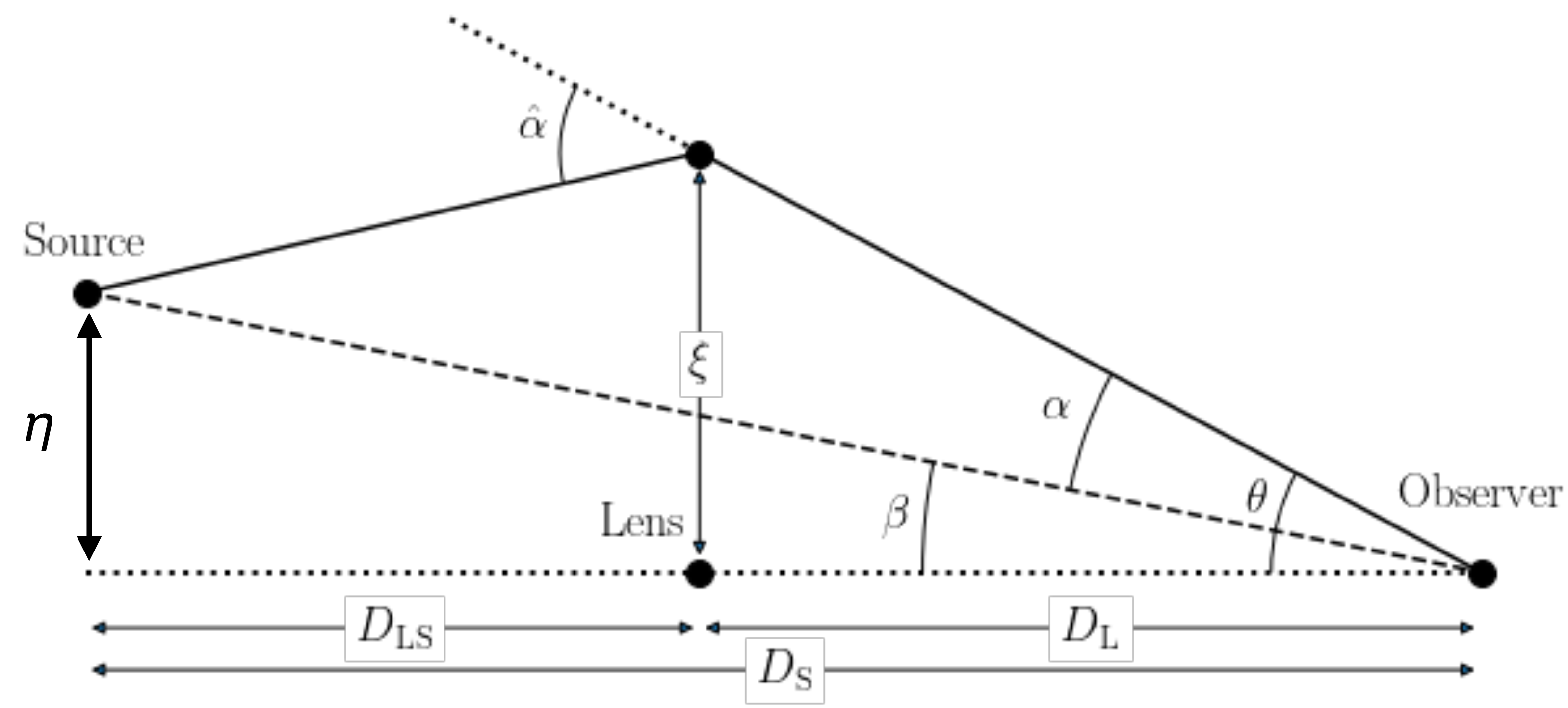
*(*In general, sufficiently frequent events are too dim/quiet, bright/loud events are rare)*

Part III
(Micro)Lensing

Lensing

A gravitational potential deflects (light) rays.

How much… depends on the potential (lens mass and distribution) and geometry



$$\beta = \theta - \alpha(\theta) \qquad \hat{\alpha}(\theta) = \frac{D_S}{D_{LS}}\alpha(\theta) = 4G\int \mathrm{d}^2\xi'\Sigma(\xi')\frac{\xi-\xi'}{|\xi-\xi'|^2}$$

In the pointlike source and lens approximation, a ray with impact parameter ξ is characterised by

$$\hat{\alpha} = 4GM/\xi$$

Single most important scale: **Einstein radius**

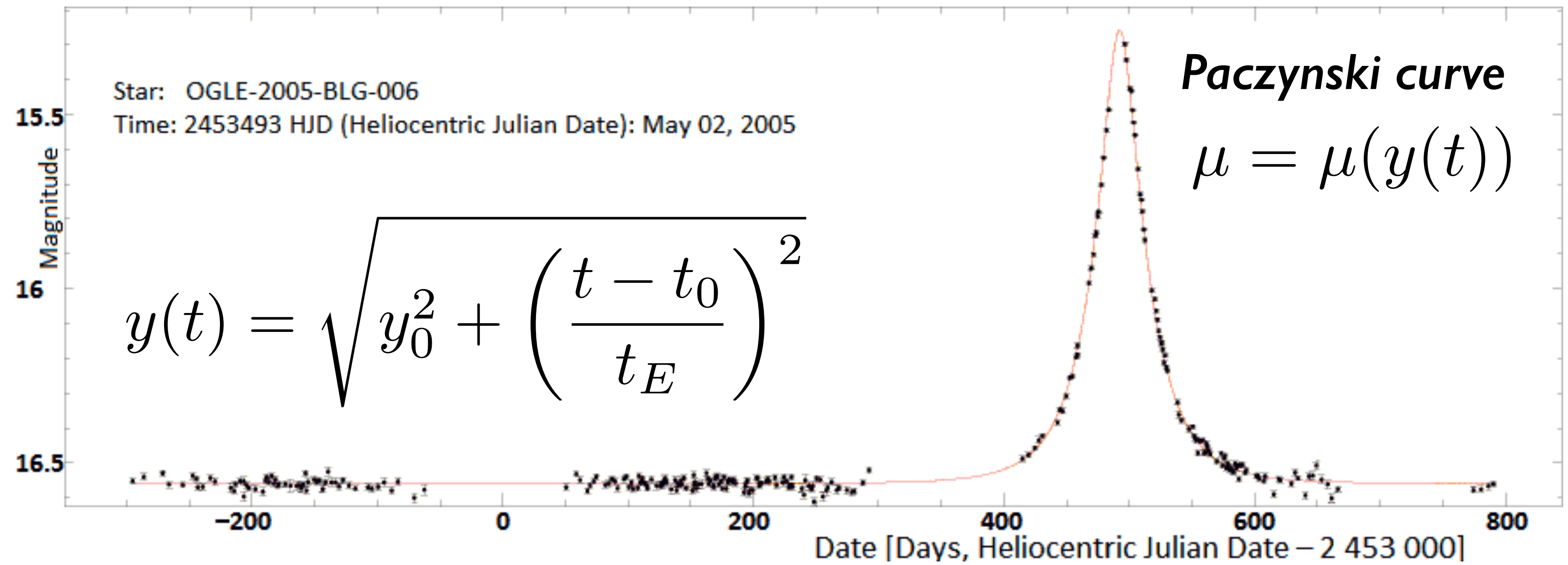
$$R_E^2 = 4GM\frac{D_L D_{LS}}{D_S}$$

Micro-lensing (μ-lensing)

If ***multiple images are not resolved (Typical scale of the Einstein angle — μ-arcsecond)*** but the overall amplification μ measured, the signature is ***magnification vs. time***.

$$\mu = \frac{y^2 + 2}{y\sqrt{y^2 + 4}}$$

$$y = \frac{\eta\, D_L}{D_S\, R_E}$$



$$y(t) = \sqrt{y_0^2 + \left(\frac{t - t_0}{t_E}\right)^2}$$

$$\mu = \mu(y(t))$$

Traditionally used to search for (and largely exclude) MACHO DM candidates for (sub)stellar masses and hundreds of days (e.g. OGLE). Currently even used to discover exoplanets!

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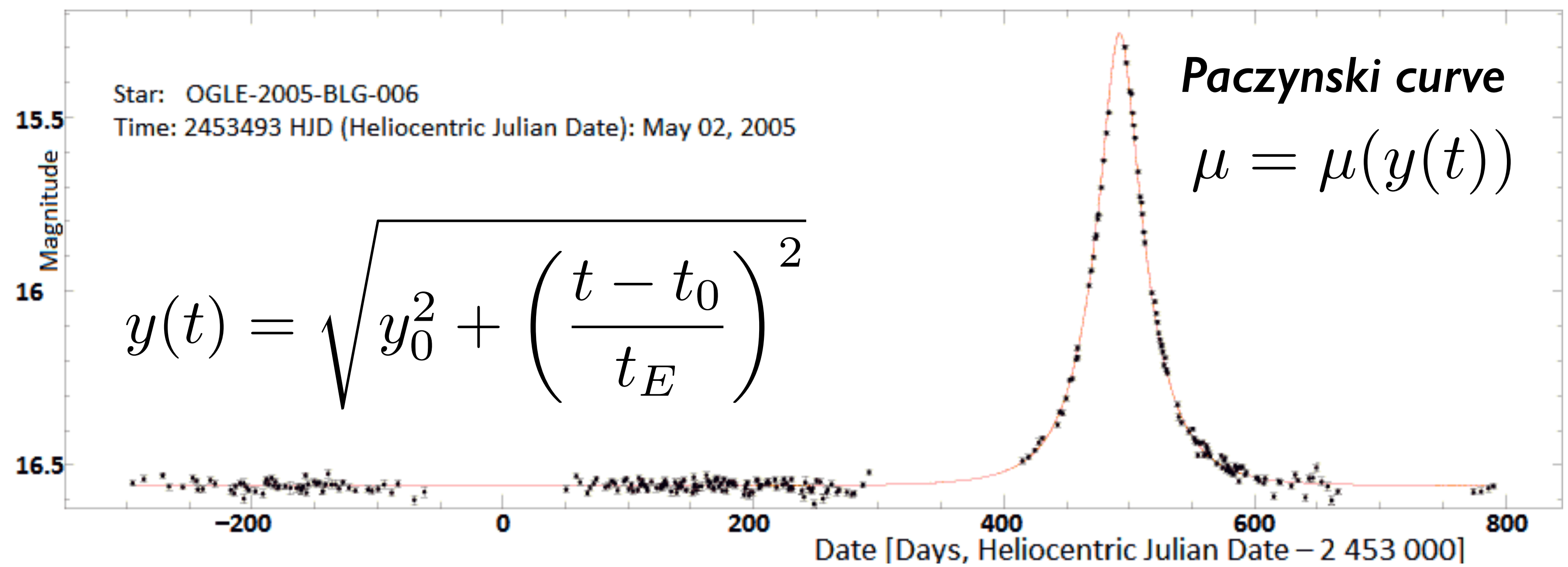

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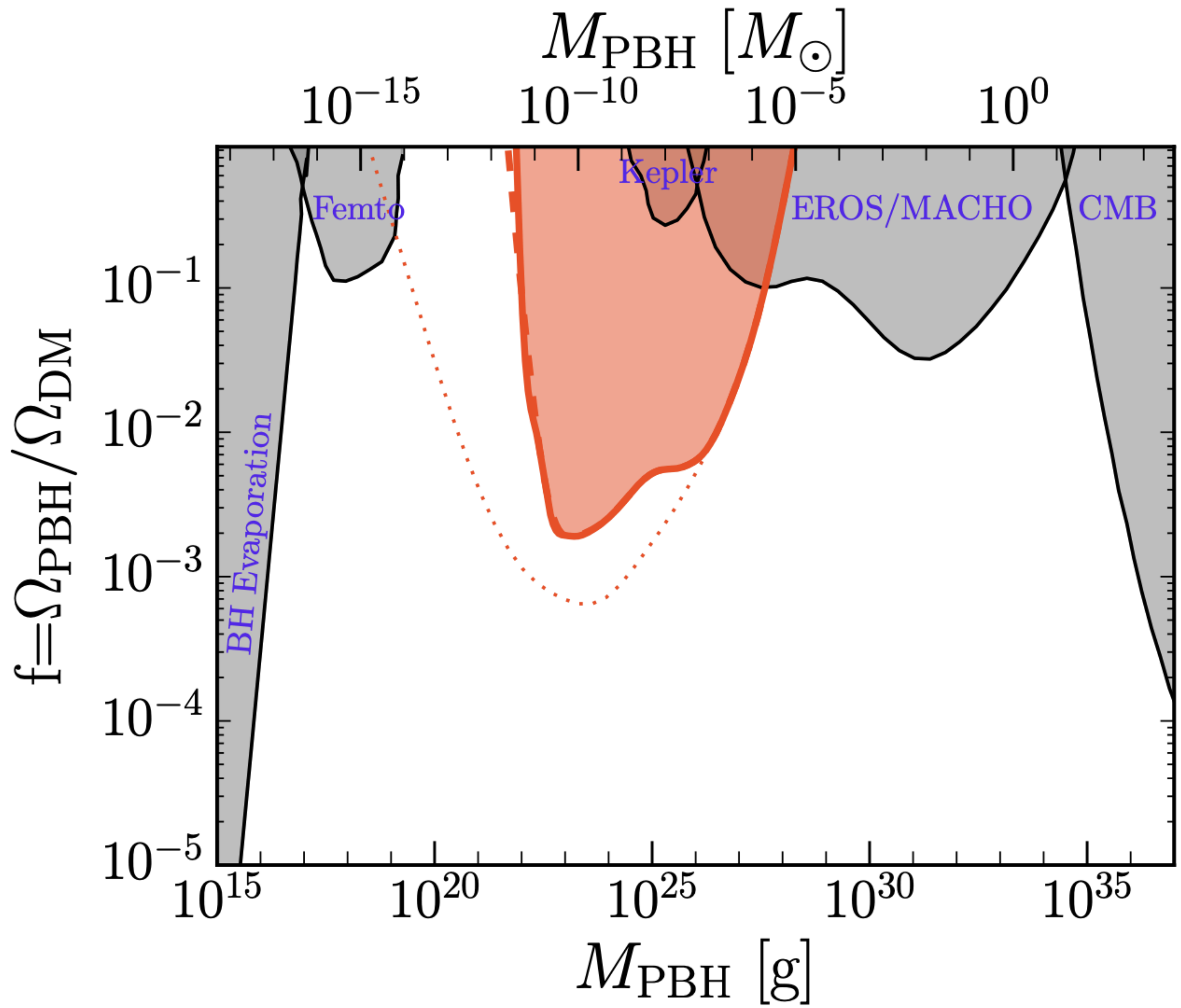
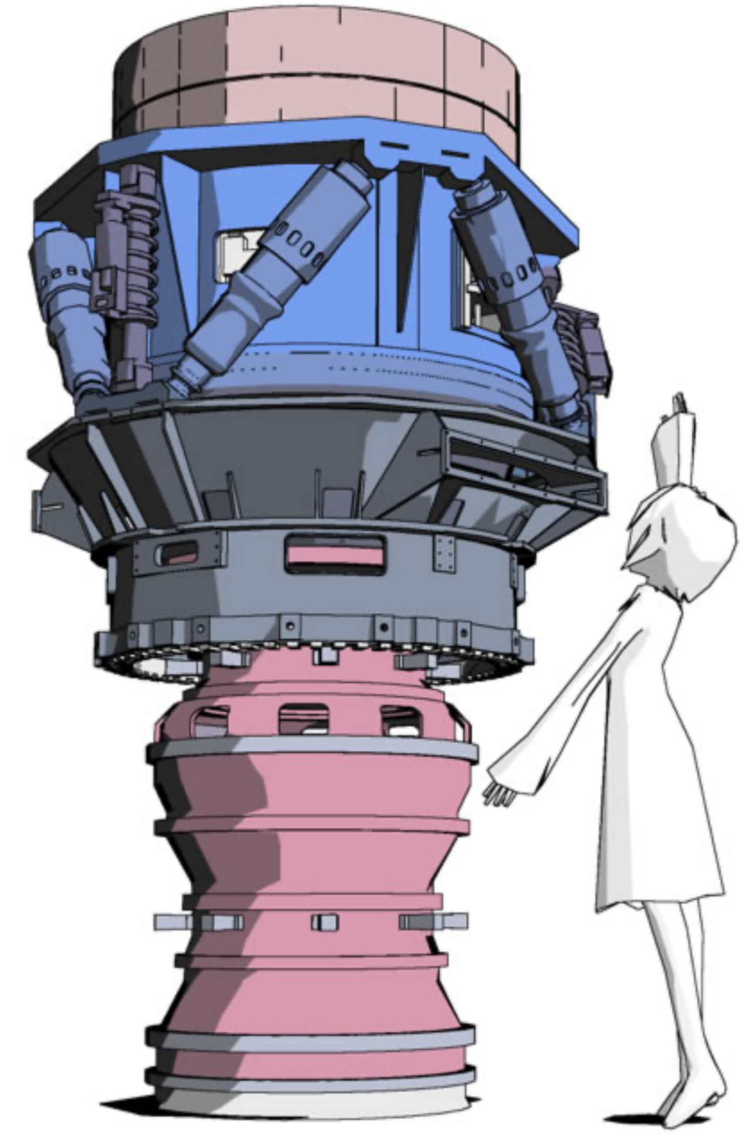
Surveys on much shorter timescale can be used for PBH DM!

$$t_E = \frac{R_E}{v_\perp} \sim 30\,\mathrm{min}\left(\frac{M}{10^{-8}M_\odot}\right)^{1/2}\left(\frac{D_L}{100,\mathrm{kpc}}\right)^{1/2}\left(\frac{200\,\mathrm{km/s}}{v_\perp}\right)$$

Naive bounds

High cadence (2 min sampling), 7 hour-long observation of M31 with the **Subaru Hyper Suprime-Cam** targeting μ-lensing of M31 stars by PBHs in the halo regions of the MW & M31





Satoshi Miyazaki, www.naoj.org

H. Niikura et al. "Microlensing constraints on primordial black holes with Subaru/HSC Andromeda observations," Nature Astron. 3 (2019) no.6, 524-534 [1701.02151]

Actual sensitivity degraded!

Primary reason: Stellar size!

Angle under which the Sun radius is seen from M31 $\theta_s = \frac{R_s}{d_s} \simeq 5.8 \times 10^{-9} \text{arcsec}$

To be compared with $\theta_E \equiv \frac{R_E}{d} \simeq 3 \times 10^{-8} \text{arcsec} \left(\frac{M}{10^{-8} M_\odot} \right)^{1/2} \left(\frac{100\,\text{kpc}}{d} \right)^{1/2}$

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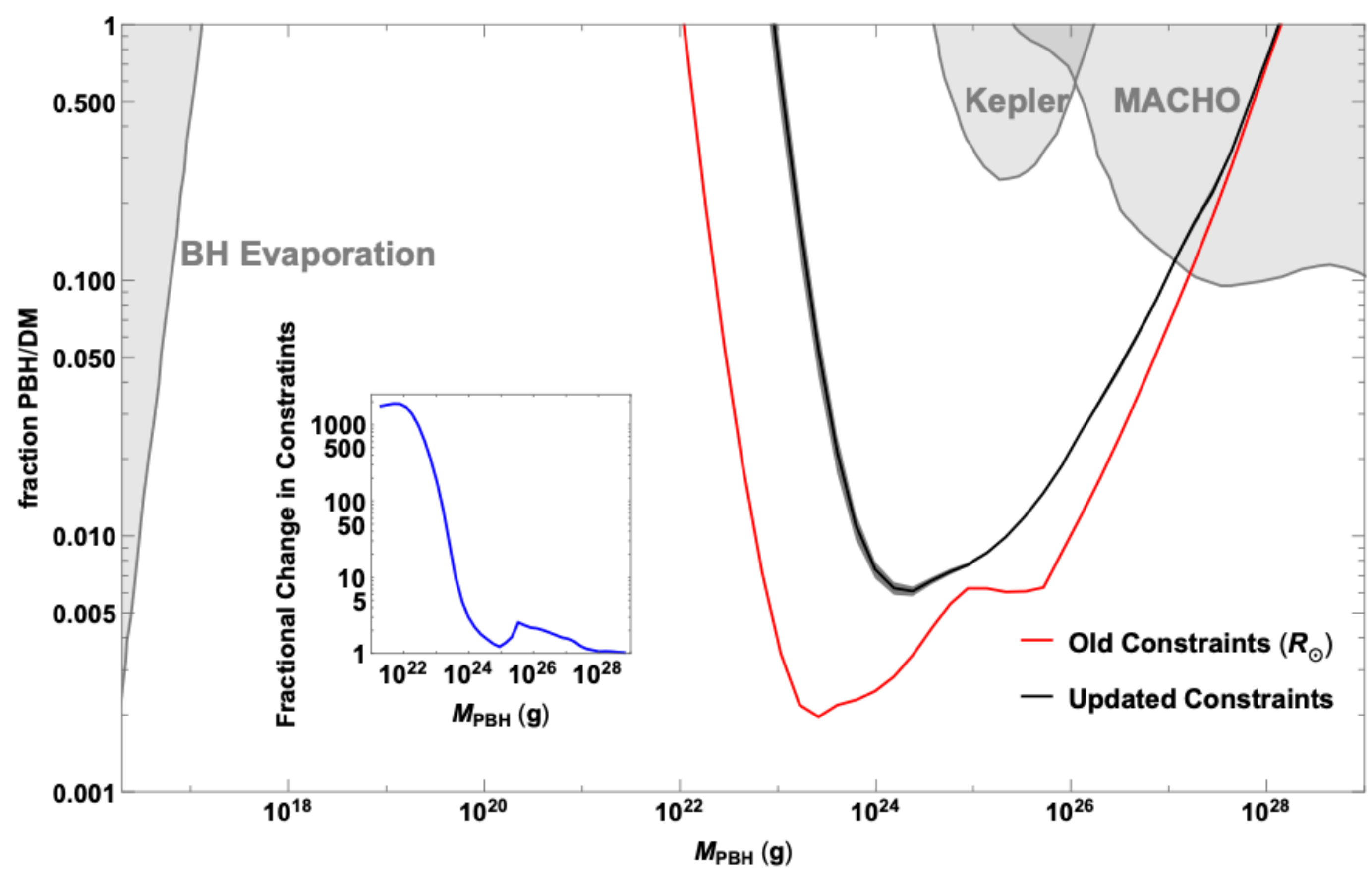
Actually, stars bright enough dominating the survey are much bigger than the Sun, hence bounds are degraded

N. Smyth, S. Profumo, S. English, T. Jeltema, K. McKinnon, P. Guhathakurta PRD 101 (2020), 063005 [1910.01285]



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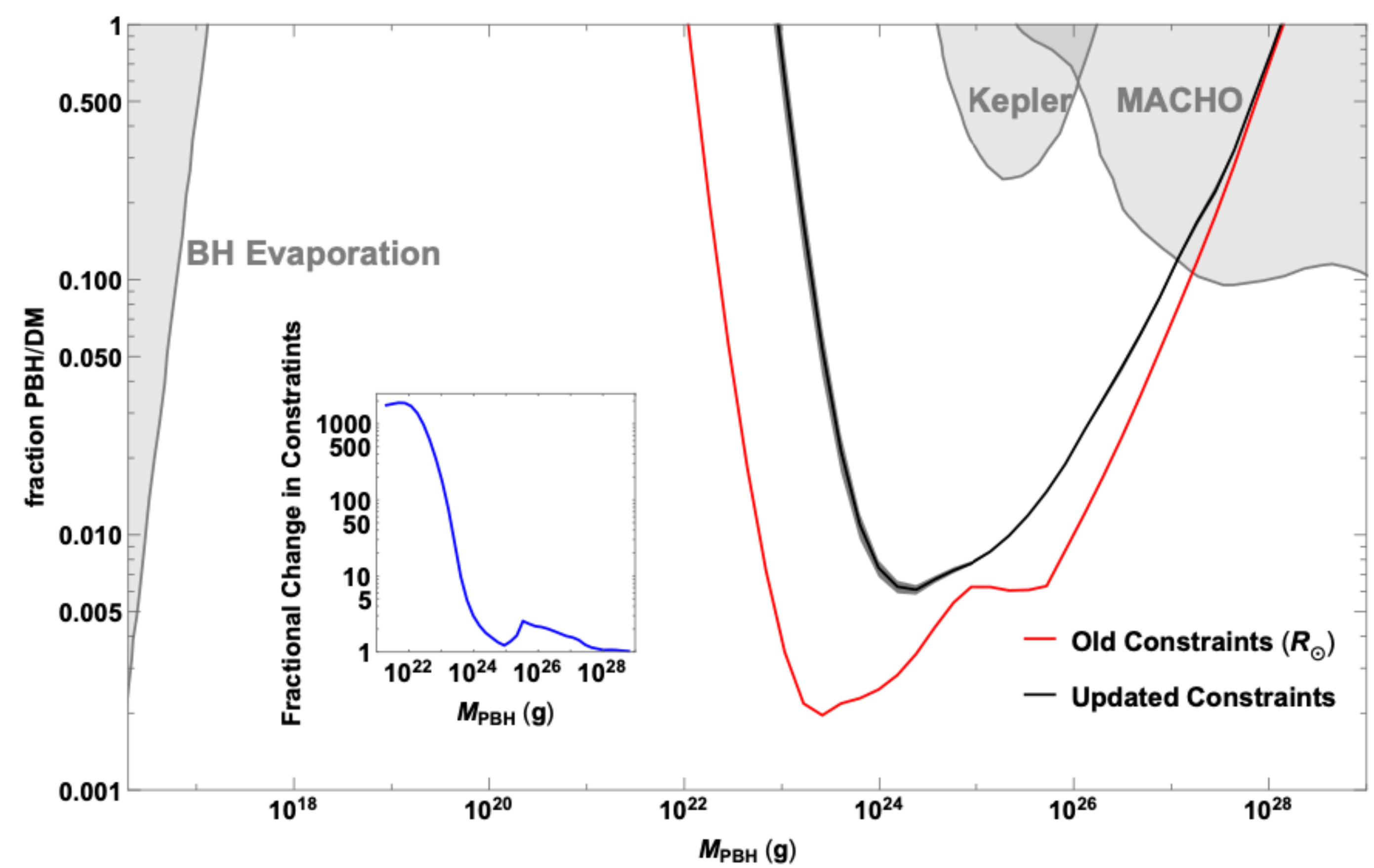


Secondary reasons: Wave optics!

R_E comparable to wavelength, further sensitivity reduction below $10^{-10}\,M_\odot$

Femtolensing, in short

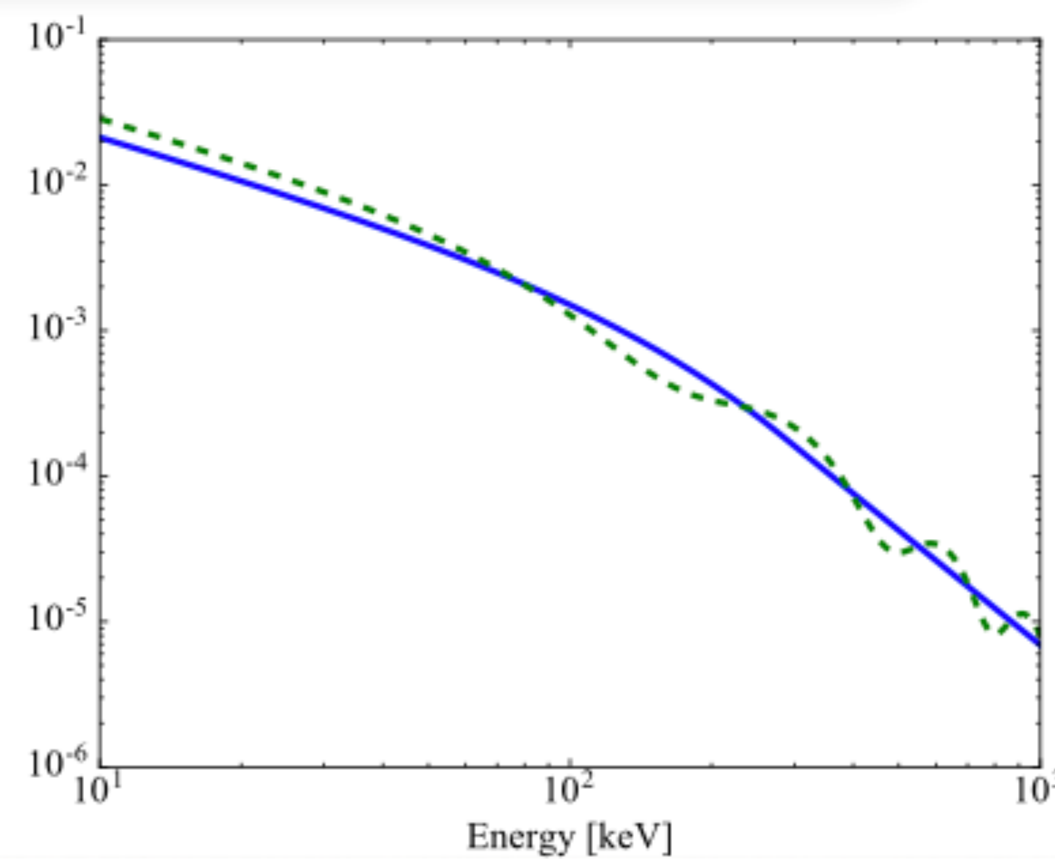
Old idea: *A. Gould, Femtolensing of gamma-ray bursters, ApJ 386 L5 (1992)*

Two images (of a GRB, typically) created by a tiny lens cannot be resolved, but their wave fronts acquire different phases travelling through different paths & gravitational potentials

If the phase shift is of order one → fringes in the spectrum

$$\Delta\phi = \omega \Delta t \qquad \Delta t \sim 4GM$$

$$E \sim 10\,\mathrm{keV} \Rightarrow \Delta t \sim 10^{-19}\,s \Rightarrow M \simeq 3 \times 10^{-15}\,M_\odot$$



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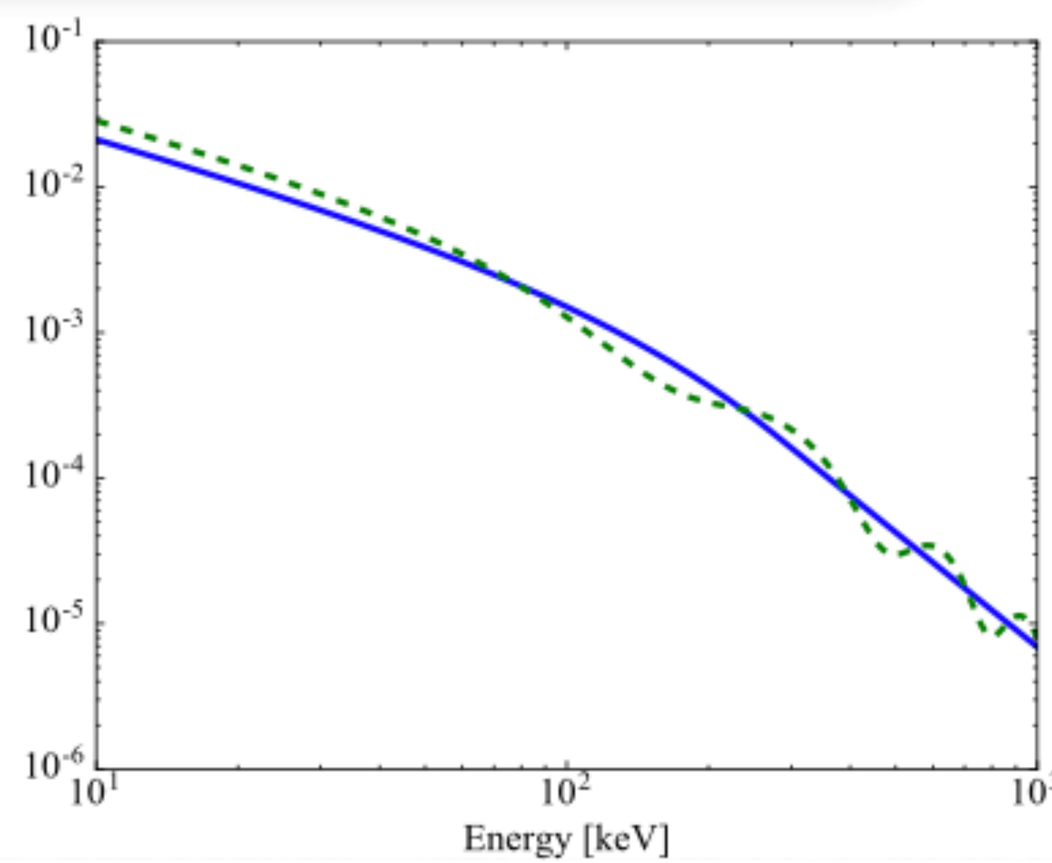
Bounds obtained a decade ago from spectral analysis of 20 Fermi-GRB events with known z

A Barnacka, J.-F. Glicenstein, R. Moderski, PRD 86 (2012) 043001 [1204.2056]

But :

- *point-like approximation of source in plane of lens broken, sizes larger than Einstein radius*
- *Wave optics also kicks in…*



A. Katz, J. Kopp, S. Sibiryakov and W. Xue, "Femtolensing by Dark Matter Revisited," JCAP 12 (2018), 005 [1807.11495]

→The 2012 bound simply disappears!

Part IV
Future

(Near?) future reach of current techniques

With future X-ray & MeV gamma satellites, possible to stretch evaporation sensitivity up to $\sim 10^{18}$ g

A. Coogan, L. Morrison and S. Profumo, PRL 126 (2021), 171101 [2010.04797]
A. Ray, R. Laha, J. B. Munoz and R. Caputo, PRD 104 (2021) 023516 [2102.06714]

Femtolensing of fraction of highly variable GRB (→ small emission zone) could probe $M_{PBH} \sim 10^{17}-10^{19}$ g

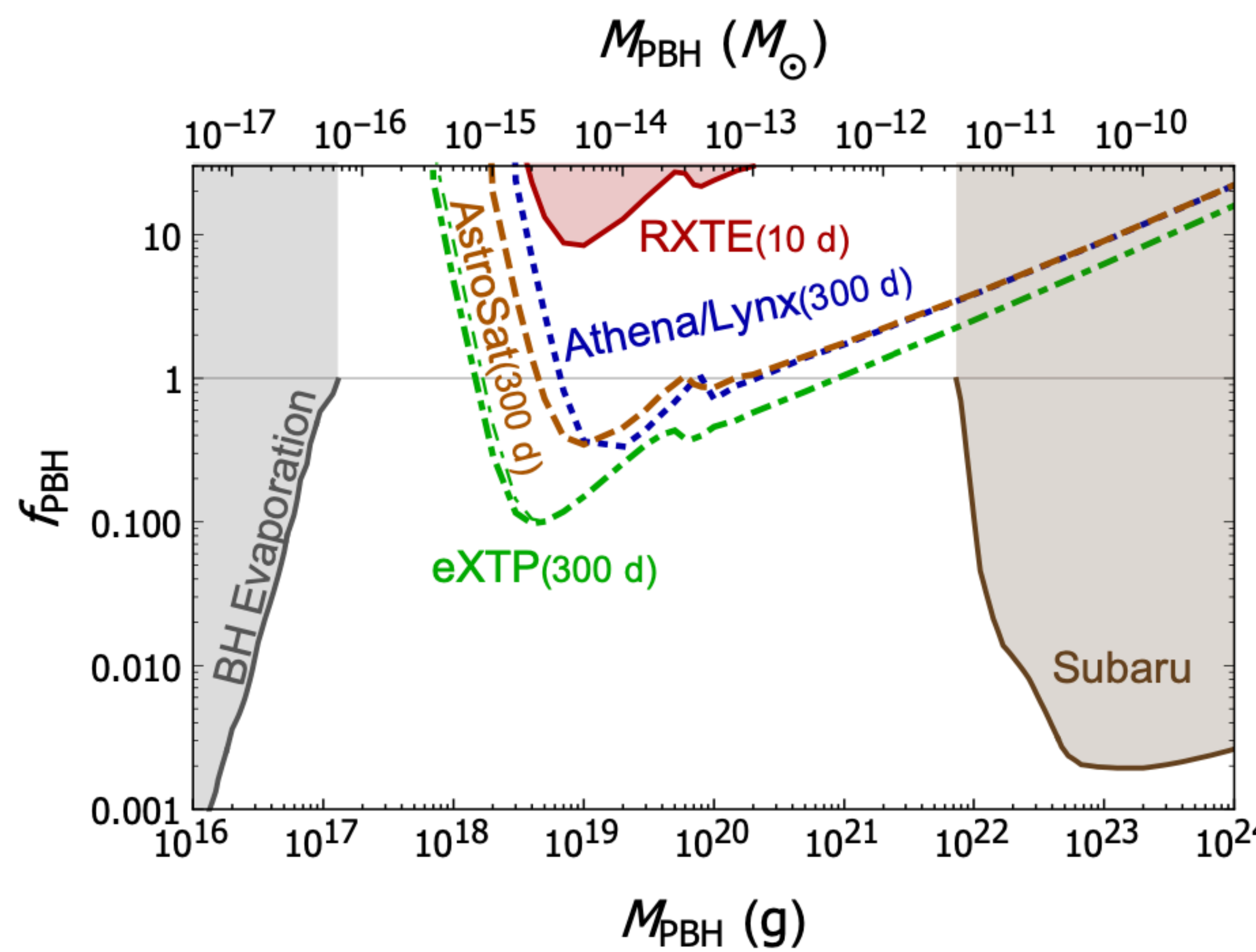
A. Katz et al. 1807.11495

High-cadence μ-lensing in the LSST era may push back by a few, to former nominal sensitivity $\sim 10^{22}$ g.

S. Sugiyama, T. Kurita and M. Takada, MNRAS 493 (2020) no.3, 3632 [1905.06066]

μ-lensing of X-ray pulsars with large area X-ray telescopes like AstroSat, Athena… can probe $M_{PBH} \sim 10^{18}-10^{21}$ g

Y. Bai and N. Orlofsky, PRD 99 (2019) 123019 [1812.01427]



GRB lensing parallax

Old idea: *R. J. Nemiroff & A. Gould, ApJ 452 L111, (1995) astro-ph/9505019*

Relative source brightness at *detectors spatially separated by Δr> R_E* could be sensitive to the entire unconstrained range $M_{PBH} \sim 10^{17}$–10^{23} g

$$\Delta r \gtrsim r_E \Leftrightarrow \left(\frac{M}{10^{-7}M_\odot}\right) \lesssim \left(\frac{\Delta r}{\mathrm{AU}}\right)^2 \left(\frac{D}{\mathrm{Gpc}}\right)^{-1}$$

Revisited in

Sunghoon Jung & TaeHun Kim, Phys. Rev. Res. 2, 013113 (2020) [1908.00078]

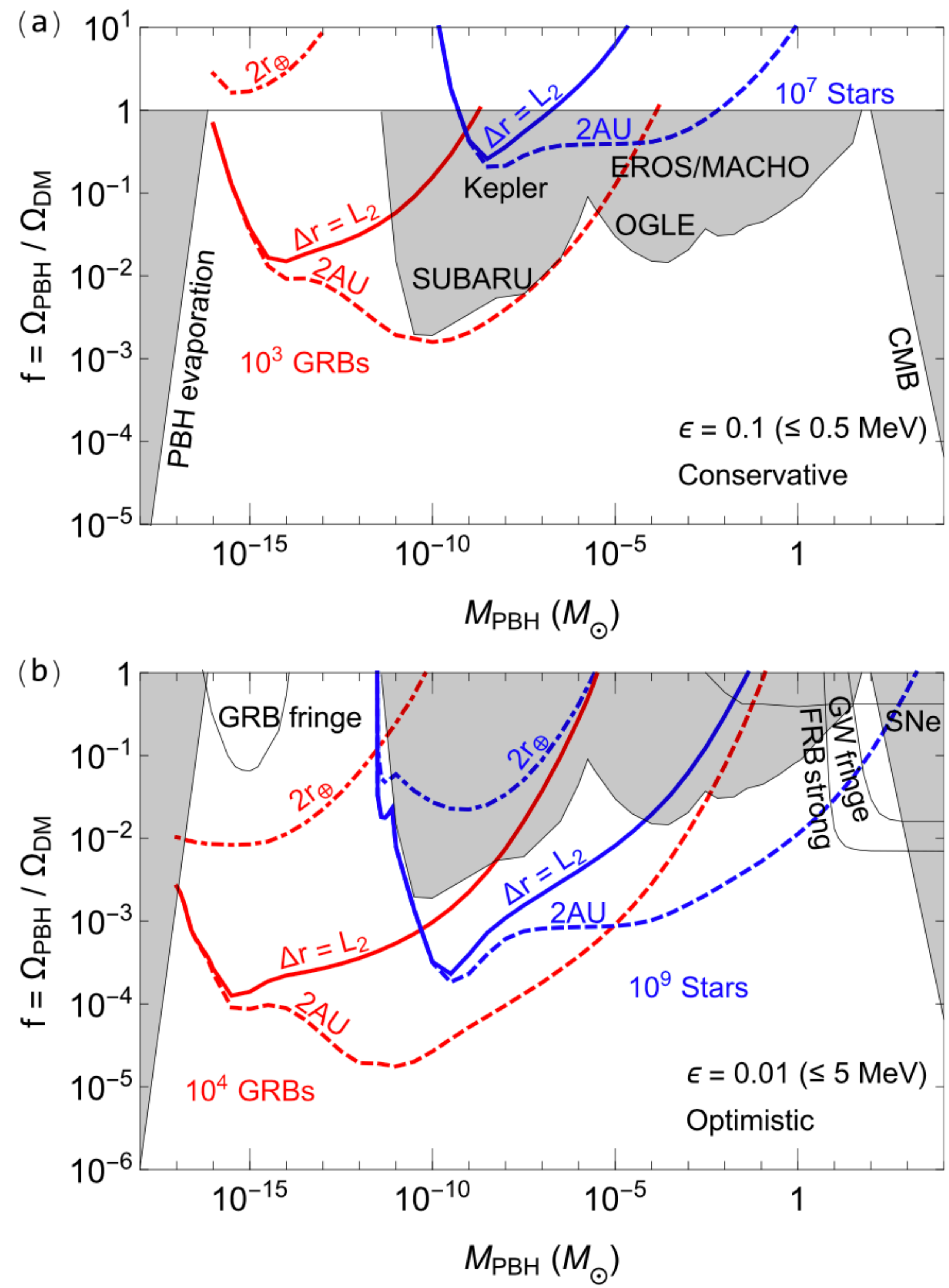
y = relative angle of a source with respect to a lens, normalized to the lens Einstein angle, differs between different detector locations!

Require sufficient magnification resolution

$$\delta\mu = \frac{|\mu_A - \mu_B|}{(\mu_A + \mu_B)/2} \gtrsim \epsilon$$

Finite size limits sensitivity to

$$\left(\frac{M}{10^{-12}M_\odot}\right) \gtrsim \epsilon \left(\frac{D}{\mathrm{Gpc}}\right)^{-1} \left(\frac{r_S}{r_\odot}\right)^2$$



GW background

PBH generation requires large energy density fluctuations → GW background

By expanding Einstein's equations to second order, one can show that the tensor degrees of freedom of the metric are sourced by terms quadratic in first-order scalar perturbations

Under some assumptions (e.g. Gaussianity) using the notation of

N. Bartolo et al. "Primordial Black Hole Dark Matter: LISA Serendipity," PRL 122 (2019), 21130 [1810.12218]

$$\frac{\Omega_{\rm GW}(f)}{\Omega_{r,0}} \simeq \frac{c_g}{72} \int_{-\frac{1}{\sqrt{3}}}^{\frac{1}{\sqrt{3}}} {\rm d}u \int_{\frac{1}{\sqrt{3}}}^{\infty} {\rm d}s \left[\frac{(u^2-1/3)(s^2-1/3)}{s^2-u^2}\right]^2 P_\zeta\left(\pi\sqrt{3}f(s+u)\right) P_\zeta\left(\pi\sqrt{3}f(s-u)\right) \mathcal{I}^2(u,s)$$

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LISA should also independently probe the DM parameter space

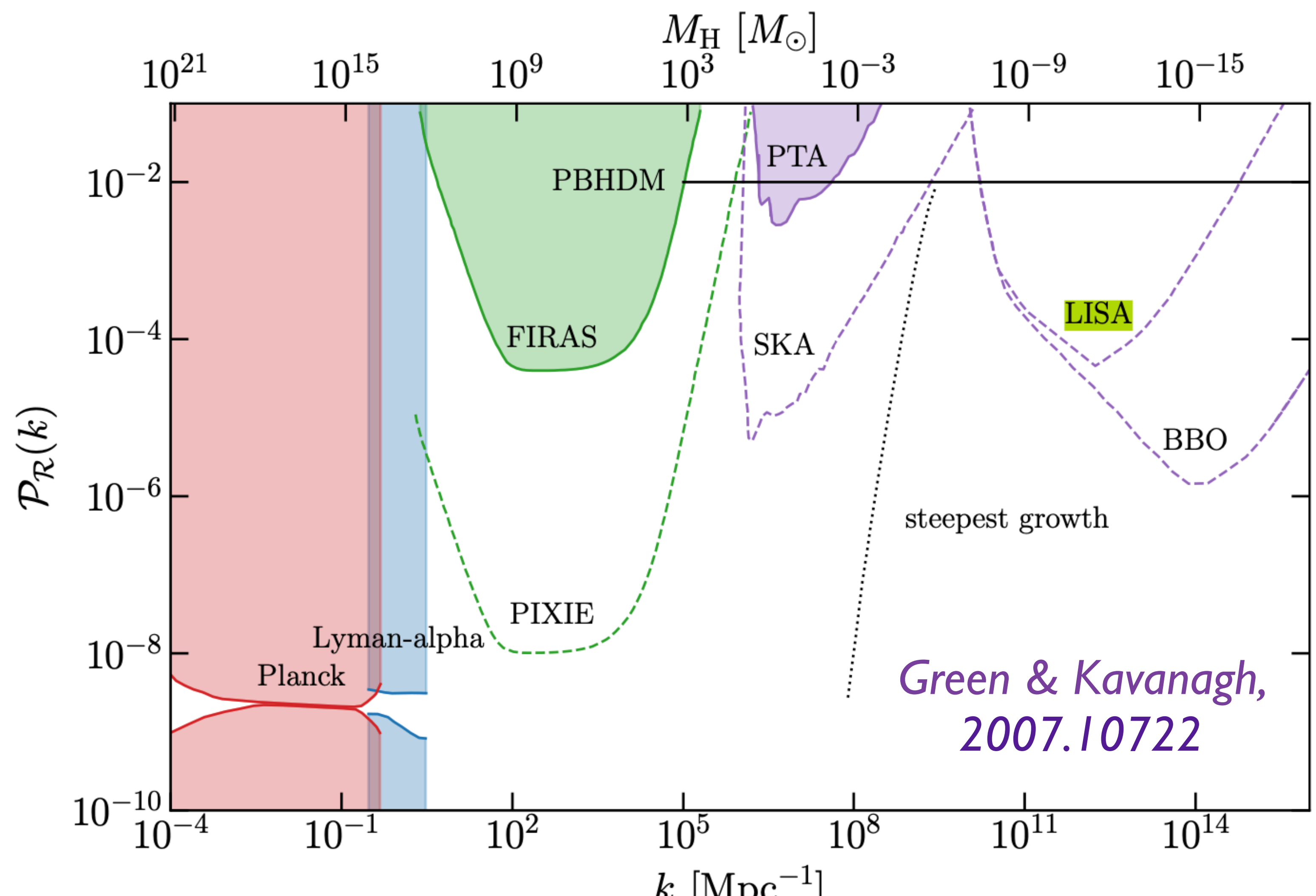
(That is, if no other major background swamps this one…)

N.B.: Transverse-traceless tensor part of the metric at second order is gauge-dependent, while the energy density of GW is a (gauge-invariant) observable.

Heuristic argument can be used to argue that the GW energy density obtained by 'standard prescriptions' yields the correct result only if h^{TT} is computed in the Newtonian gauge.

For a review:

G. Domènech, "Scalar Induced Gravitational Waves Review," Universe 7 (2021) 11, 398 [2109.01398]



Green & Kavanagh, 2007.10722

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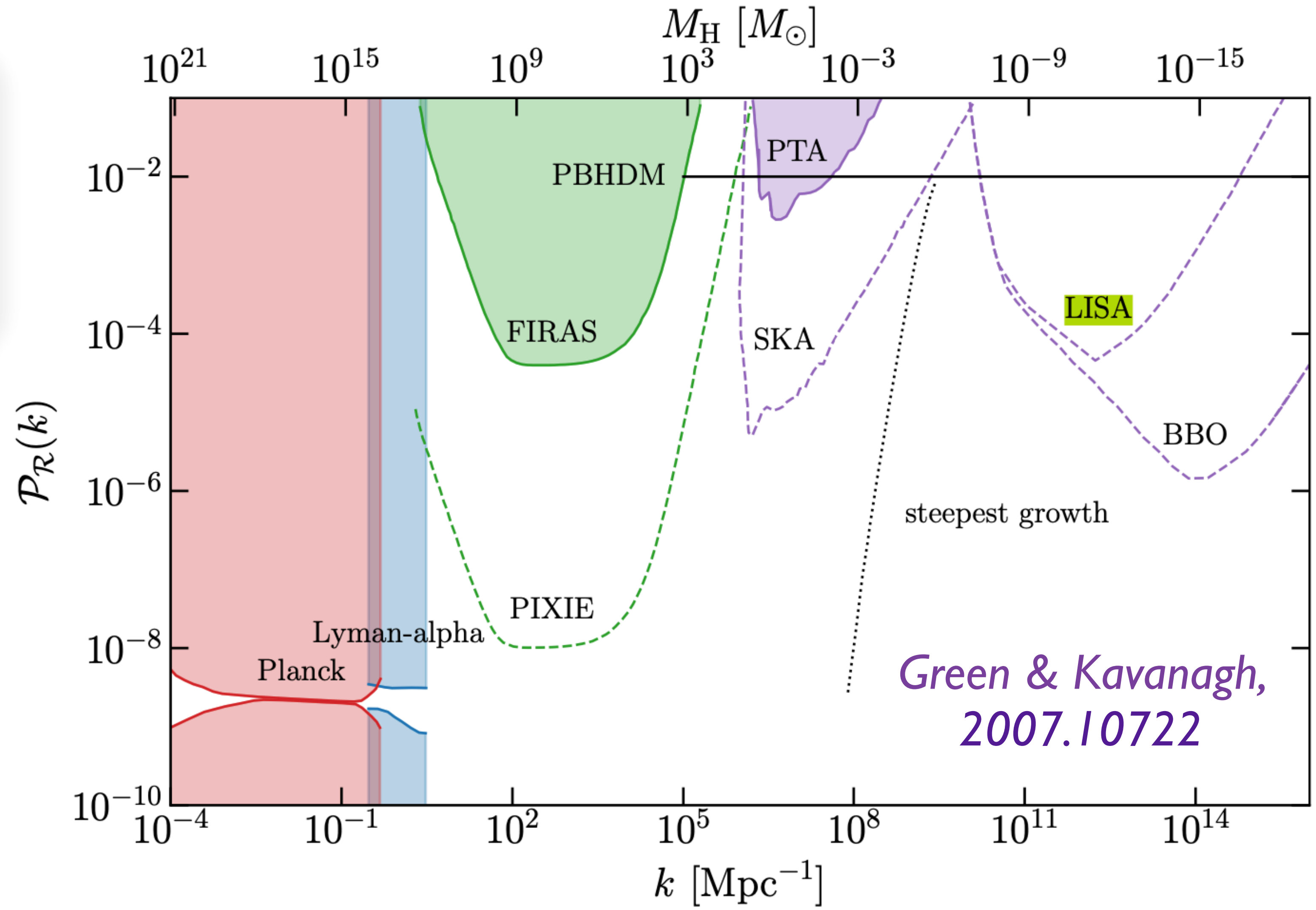

Green & Kavanagh, 2007.10722

Conclusion

The possibility that (asteroid-mass) PBH constitute the totality of the DM is still open

High-energy astrophysics bounds from Hawking radiation have been tightened with improved and dedicated analyses

High-cadence microlensing constraints cover less parameter space than initially thought

A number of arguments put forward in the past excluding the parameter space in between have been shown not to be robust, and bounds have been relaxed or lifted

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Independent of its theoretical appeal, I take PBH-DM as a textbook example of a virtuous circle involving theory, phenomenology and experiments, stimulating each other in a creative and innovative way