Primordial black holes and Hawking radiation

Dmitry Malyshev

Ringseminar, 07 May 2021

ERLANGEN CENTRE
FOR ASTROPARTICLE
PHYSICS

FRIEDRICH-ALEXANDER
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Crossing the desert

Quantum Field Theory
in gravitational field

Mathematical
physics

Gravitational
waves

PBHs

Hans Hillewaert
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Cosmology

Astrophysics

Astronomy

Plan

- A bit of history
- A bit of math
    - Primordial black holes (PBHs)
    - Hawking radiation
- Limits on PBHs from Hawking radiation
    - Past evaporations
    - Current evaporations
        - Limits from gamma-rays
- Limits on PBHs with large masses (small temperature)
    - Microlensing
    - Dynamical effects
    - Accretion
- PBHs and gravitational waves
- Conclusions

* In the following I will use units $c = 1$, $k_B = 1$, $\hbar = 1$, but keep M_{Pl}

A bit of history

Primordial black holes

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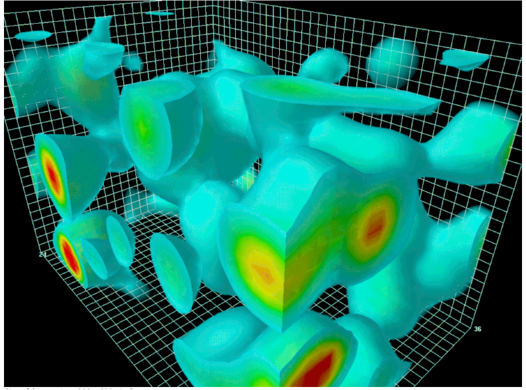


Ahmed Neutron, Wikimedia commons

- High energy density in the Universe shortly after the Big Bang raises a natural question: can some of the fluctuations stay gravitationally bound and collapse into black holes?
- Production of primordial black holes in the early Universe was proposed by
  - Zeldovich, Novikov (1966)
  - Hawking (1971)

Stephen Hawking
NASA, Wikimedia commons

Yakov Zeldovich
Wikipedia

Igor Novikov
trv-science.ru

- Mass range: from Planck mass (if formed at Planck time) to the masses of SMBHs (if formed after about 1 s from the Big Bang)

Black hole temperature

- Information loss paradox
  - Entropy of a body falling into a black hole is lost
  - Is the second law of thermodynamics wrong?

Alain Riazuelo, Wikimedia commons

- In classical gravity, the area of a black hole (or the sum of areas of a system of black holes) is also a non-decreasing function of time (Hawking, 1971)
- Bekenstein (1973) suggested that a linear combination of the classical entropy and the area of a black hole should be a non-decreasing function of time and can be viewed as a generalized entropy

$$S_{gen} = S_c + S_{BH}$$

where the BH entropy is proportional to the BH area

$$S_{BH} \propto A_{BH}$$

Black hole temperature

- If we formally assume that the entropy of a BH is proportional to the area, then we can calculate the temperature

$$\frac{1}{T_{bh}} = \frac{dS_{bh}}{dE} \propto \frac{dM^2}{dM}$$

thus, formally, the temperature of the BH is inversely proportional to the BH mass

$$T_{bh} \propto \frac{1}{M_{bh}}$$

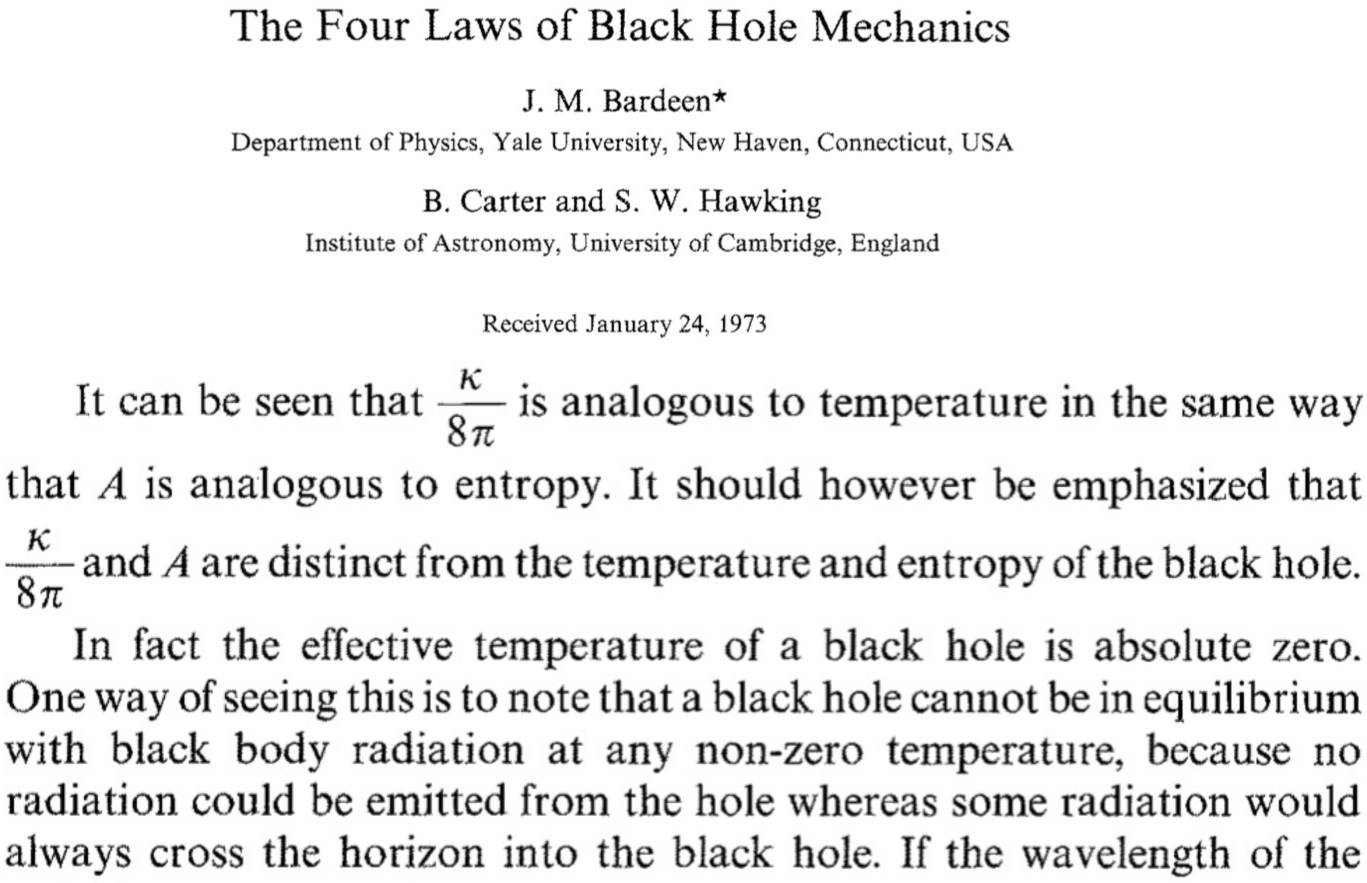
- The heat capacity of the BH is negative

$$C = \frac{dQ}{dT} \propto \frac{dM}{dT} \propto -M^2$$

this is very strange: you add energy to a BH and it gets colder.

Black hole temperature

- Since the heat capacity of a BH is negative, BH temperature and entropy were considered as formal quantities.



The Four Laws of Black Hole Mechanics

J. M. Bardeen*
Department of Physics, Yale University, New Haven, Connecticut, USA

B. Carter and S. W. Hawking
Institute of Astronomy, University of Cambridge, England

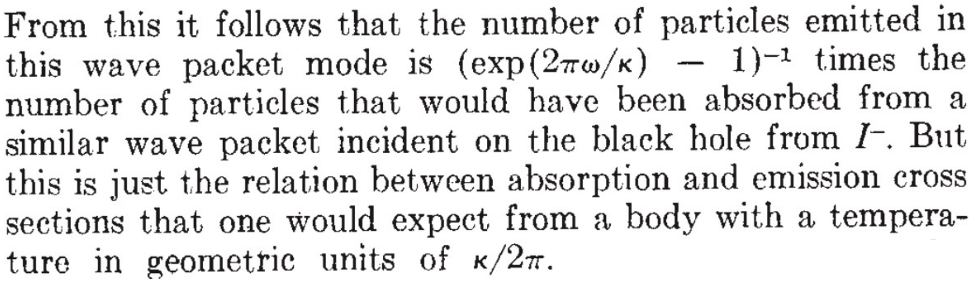
Received January 24, 1973

It can be seen that $\frac{\kappa}{8\pi}$ is analogous to temperature in the same way that A is analogous to entropy. It should however be emphasized that $\frac{\kappa}{8\pi}$ and A are distinct from the temperature and entropy of the black hole.

In fact the effective temperature of a black hole is absolute zero. One way of seeing this is to note that a black hole cannot be in equilibrium with black body radiation at any non-zero temperature, because no radiation could be emitted from the hole whereas some radiation would always cross the horizon into the black hole. If the wavelength of the

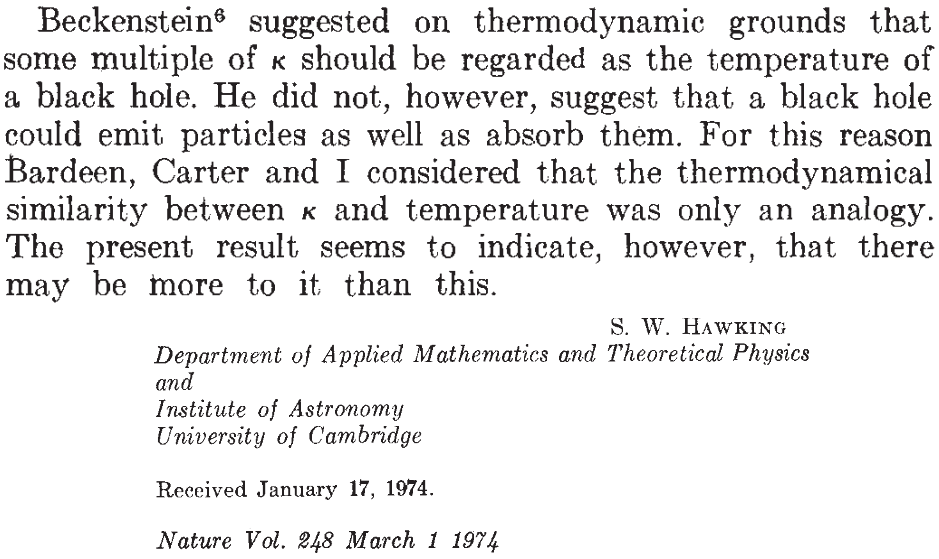
Hawking radiation

- Evidently Hawking decided to check, whether BHs can emit radiation or not and he found out (Hawking, 1974), that BHs indeed emit particles with temperature $T_{bh} \propto \frac{1}{M_{bh}}$:



From this it follows that the number of particles emitted in this wave packet mode is $(\exp(2\pi\omega/\kappa) - 1)^{-1}$ times the number of particles that would have been absorbed from a similar wave packet incident on the black hole from I^-. But this is just the relation between absorption and emission cross sections that one would expect from a body with a temperature in geometric units of $\kappa/2\pi$.

- and further:



Beckenstein[6] suggested on thermodynamic grounds that some multiple of κ should be regarded as the temperature of a black hole. He did not, however, suggest that a black hole could emit particles as well as absorb them. For this reason Bardeen, Carter and I considered that the thermodynamical similarity between κ and temperature was only an analogy. The present result seems to indicate, however, that there may be more to it than this.

S. W. HAWKING

Department of Applied Mathematics and Theoretical Physics
and
Institute of Astronomy
University of Cambridge

Received January 17, 1974.

Nature Vol. 248 March 1 1974

Hawking radiation

- We note that Hawking (1974) has established the precise relation between BH mass and temperature

$$T_{BH} = \frac{\kappa}{2\pi}$$

where the surface gravity for the BH is $\kappa = \frac{M_{Pl}^2}{4M_{BH}}$

thus $T_{BH} = \frac{M_{Pl}^2}{8\pi M_{BH}}$

- The precise normalization for the BH temperature allows one to establish the relation between the BH area and entropy

$$S_{BH} = \frac{A_{BH}}{4\ell_{Pl}^2}$$

BH entropy microstates

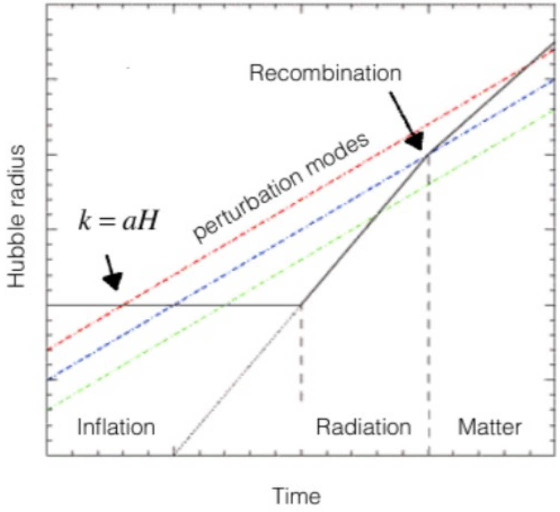
- Is it possible to understand BH entropy from the point of view of microstates counting?
- String theory
  - Strominger & Vafa (1996) arXiv:hep-th/9601029 – BHs in 5D AdS$_5$ space
    - *N* = 4 supergravity theory, soliton bound states with axion charge Q_H and electric charge Q_F
      degeneracy: $S_{stat} = 2\pi\sqrt{Q_H(\frac{1}{2}Q_F^2 + 1)}$
      BH entropy: $S_{BH} = \frac{A}{4} = 2\pi\sqrt{\frac{Q_H Q_F^2}{2}}$
  - Strominger (1998) arXiv:hep-th/9712251 – BHs in 3D AdS$_3$ space
- Entanglement entropy
  - Solodukhin (2011) arXiv:1104.3712
  - Almheiri et al (2020) arXiv:2006.06872
- Loop Quantum Gravity
  - Rovelli (1996) arXiv:gr-qc/9603063
  - Meissner (2004) arXiv:gr-qc/0407052

A bit of math

Primordial black holes

- Produced by fluctuations of density in the early Universe (Carr 1975)

$$\beta(M) \sim \epsilon(M) e^{-\frac{\gamma^2}{2\epsilon(M)^2}}$$



[Valerie Domcke, presentation at CERN (2017)](#)

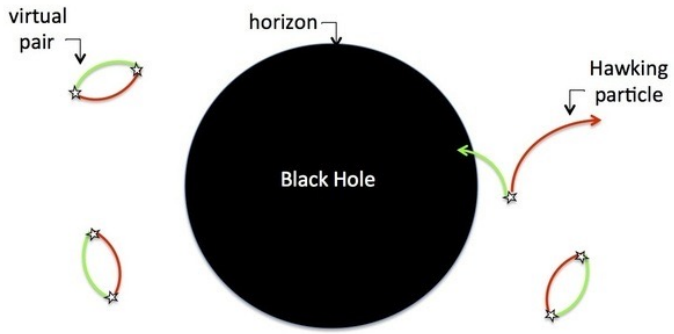
- $\beta(M)$ – fraction of energy density in PBHs
- $\epsilon(M)$ – std of energy density fluctuations
- γ – equation of state parameter $p = \gamma\varepsilon$
- M – mass within horizon
- PBHs production:
  - Large fluctuations of density
    - Non-gaussianity
  - Small pressure states $\gamma \to 0$
    - Short period of matter-dominated universe

$$M_{\mathrm{PBH}} \sim M_{\mathrm{horizon}} \sim 10^5 \left(\frac{t}{1s}\right) M_\odot$$

Hawking radiation

- Hawking (1974, 1975)
  - Black holes emit particles with thermal spectrum

$$F = \frac{1}{2\pi}\frac{\Gamma_{\mathrm{s}}}{e^{E/T} - (-1)^{2s}}$$



  - s – spin, Γ_{s} – grey body factor

$$T = \frac{M_{\mathrm{P}}^2}{8\pi M}$$

Evaporation

- Temperature

$$T_{BH} = \frac{M_{Pl}^2}{8\pi M_{BH}} \approx 10\ MeV \left(\frac{10^{15}g}{M_{BH}}\right)$$

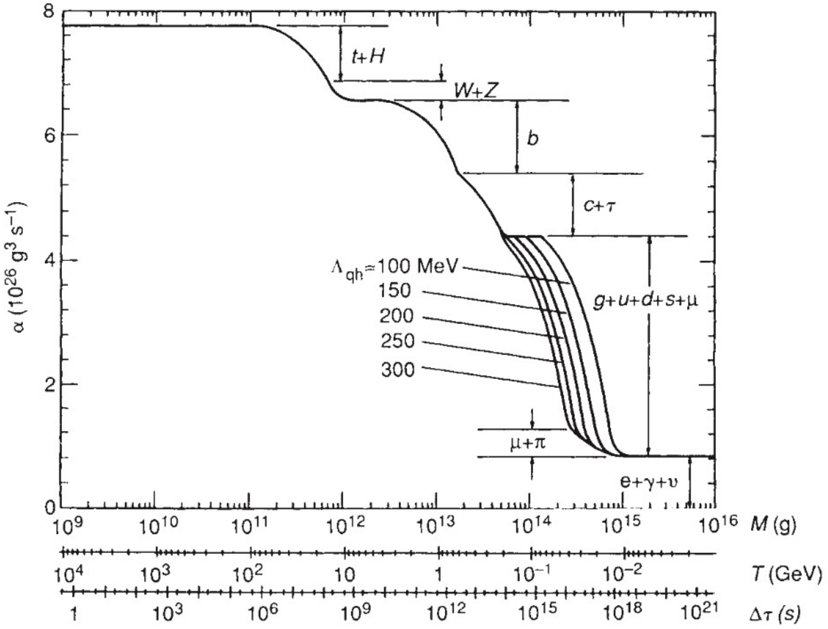
- Mass loss ~ emission power

$$\dot{M} \propto 4\pi R^2 T^4 \propto M_{BH}^{-2}$$

- Integrating the mass loss rate,
  one can obtain the remaining lifetime:

$$t \approx 10^{10}\, yr \left(\frac{M_{BH}}{10^{15}g}\right)^3$$

PBH evaporation rate



Halzen et al, Nature 353 (1991)

- 10 MeV, 10^{15} g, lifetime of the Universe
- 10 GeV, 10^{12} g, 30 years
- 10 TeV, 10^{9} g, 1 second

How to make a small BH

- Black hole with M = 10^{15} g, T ~ 10 MeV
  - Lifetime ~ age of the Universe
  - Size ~ nucleus, 10^{-15} m
  - Mass ~ 1000 large oil tankers

Marekich, Wikimedia commons

US Navy, Wikimedia commons

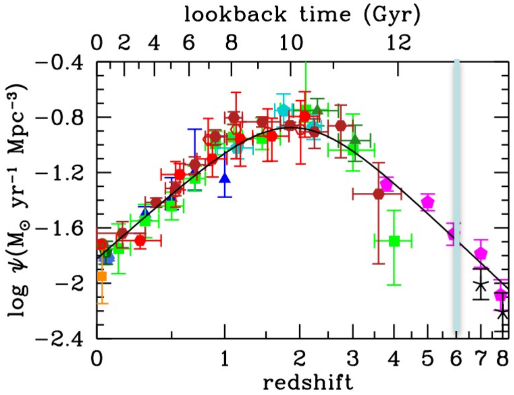
Limits on PBHs for various initial masses

- $M < 10^{15}$ g
  - Have evaporated by now
  - Effects on BBN, CMB, background radiation, e.g., gamma-rays
- $M \sim 10^{15} - 10^{17}$ g
  - Bright gamma-ray emitters now
  - Can be searched for as high energy emitting sources, individual or background
- $M > 10^{17}$ g
  - Can be searched for as small gravitating objects (micro lensing)
  - Affect the survival of weakly bound binaries
  - Can be captured by neutron stars

PBHs in cosmology and astrophysics

- Dark matter
  - A lot of possibilities in terms of initial mass and density of PBHs
  - e.g., Chapline, Nature 253 (1975)
- Supermassive black holes ($10^9\ M_\odot$) at $z > 6$, e.g., at $T < 1$ Gyr after Big Bang
  - The general star formation is only starting but we already have large black holes ~ $10^9\ M_\odot$
- Stellar BH-BH mergers
  - Need many BHs with masses ~ few tens of $M_\odot$
  - e.g., Bird et al., PRL 116 (2016), arxiv:1603.00464
- Constrain cosmological theories on scales much smaller than CMB
  - e.g., Linde et al PRD 87 (2013), arxiv:1212.1693

Star formation rate

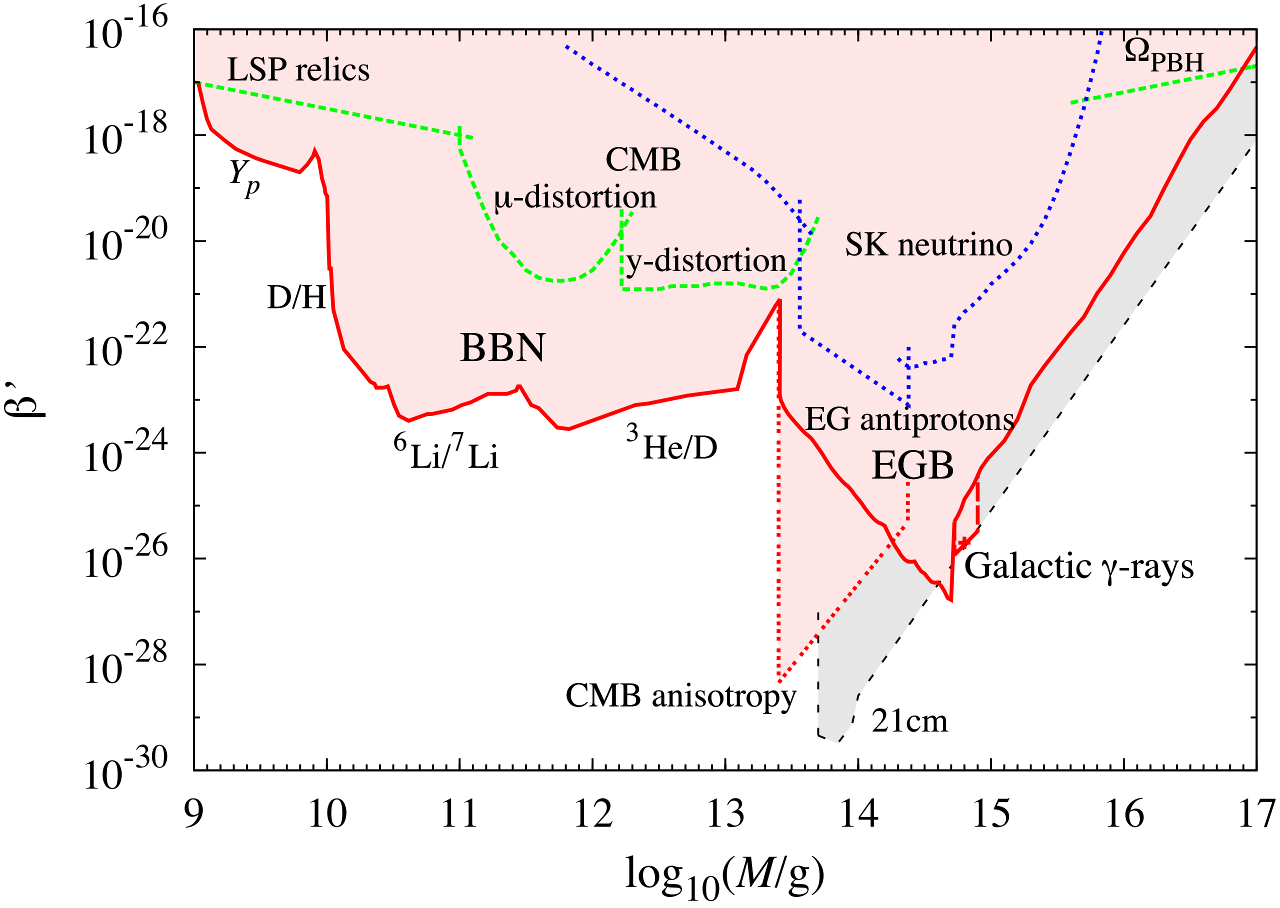


Madau, Dickinson, ARAA 52 (2014) arxiv:1403.0007

Limits on PBHs from Hawking radiation

Limits on PBHs with initial masses < 10^{17} g

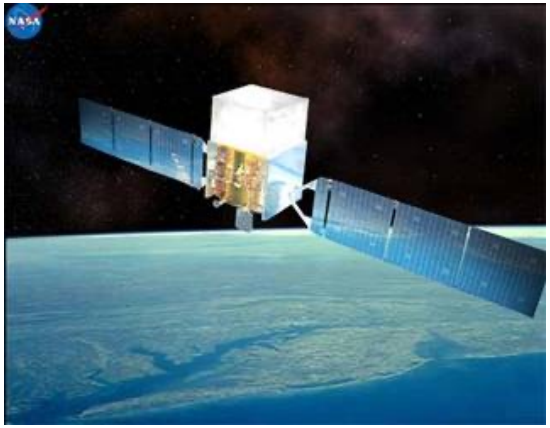
- β' – fraction of energy density in PBHs at the time of formation



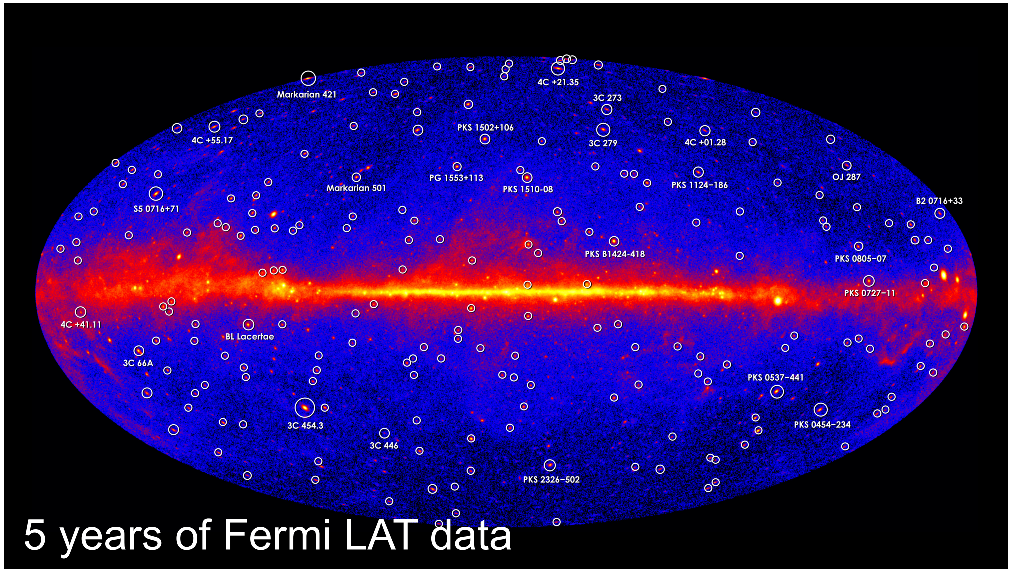
Carr et al, PRD 81 (2010), arxiv:0912.5297

Example of a PBH search

- As an example of the search for evaporating PBHs, let’s have a look in the Fermi Large Area Telescope (LAT) data
  - Ackermann et al. APJ 857 (2018), arxiv:1802.00100
  - Corresponding authors: Christian Johnson, DM, Stefan Funk, Steven Ritz
- Fermi LAT – gamma-ray space telescope
  - E_γ from ~ 20 MeV to ~ 1 TeV
  - Angular resolution < 1^o above 1 GeV



Credits: NASA E/PO,
Sonoma State University, Aurore Simonnet



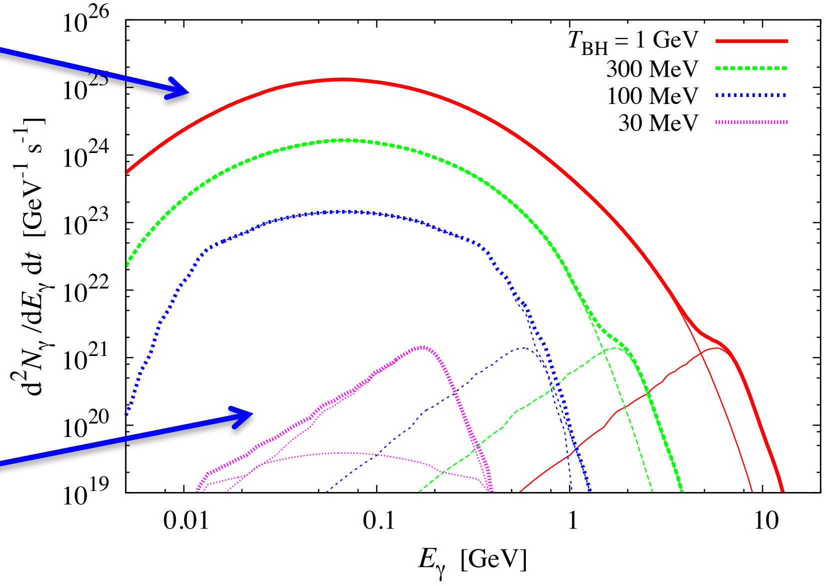
5 years of Fermi LAT data

NASA/DOE/Fermi LAT Collaboration

PBH gamma-ray spectrum

- PBHs evaporate to all elementary particles available at temperature T
- The spectrum has contribution both from primary and secondary (mostly from hadronic cascades) gamma rays

Instantaneous PBH gamma-ray spectrum



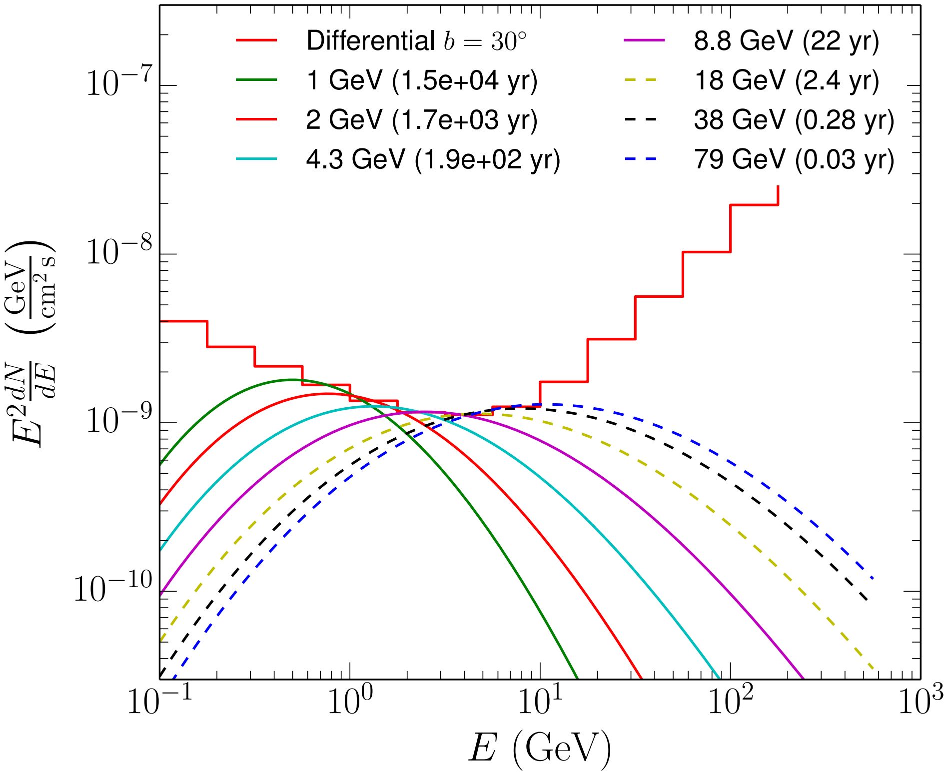
Total including secondary

Primary gamma-rays

Carr et al, PRD 81 (2010), arxiv:0912.5297

Detection radius as a function of temperature

- To estimate the domain of sensitivity of Fermi LAT to individual PBHs we compare the PBH spectra with the differential sensitivity

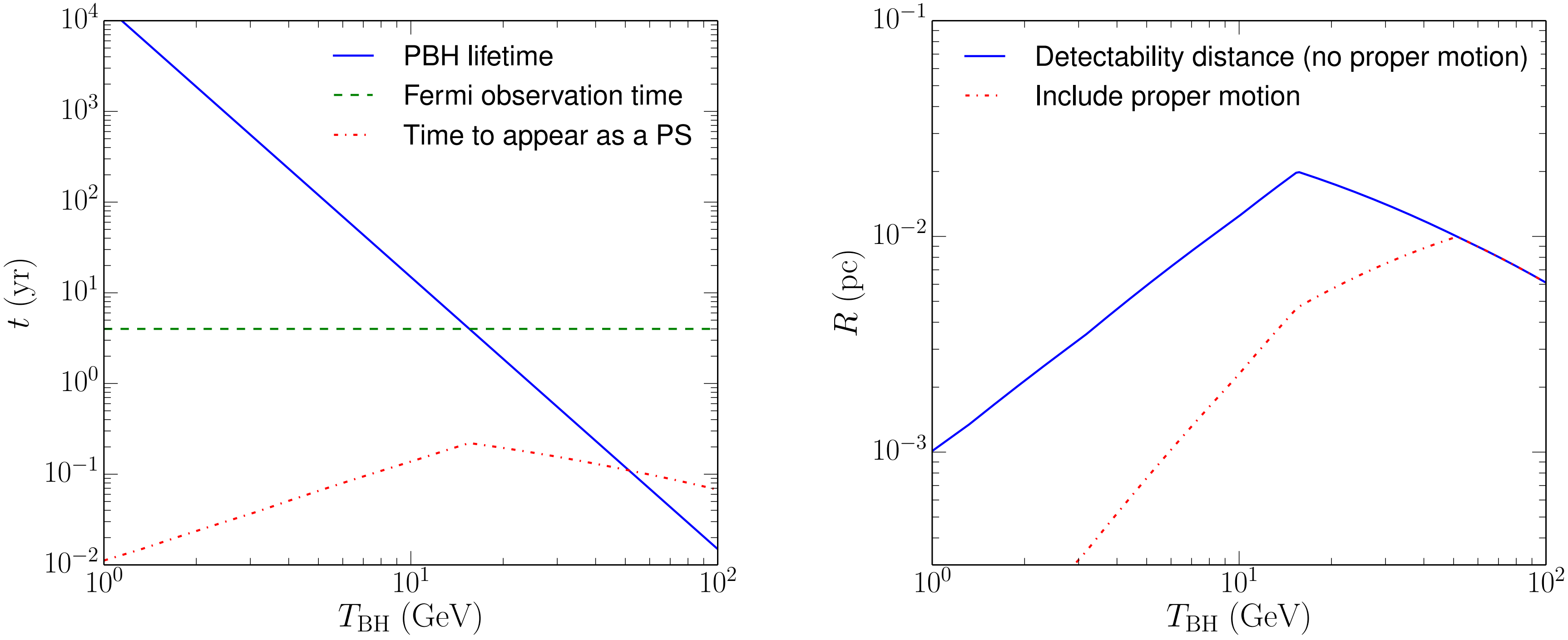


Ackermann et al. APJ 857 (2018), arxiv:1802.00100

The normalization (and hence the distance to PBH) is chosen such that the spectrum does not exceed the differential sensitivity (4 year P7 rep: the same dataset is used for 3FGL catalog)

Dashed lines – PBH lifetime is shorter than Fermi observations.

Detectability radius and lifetime

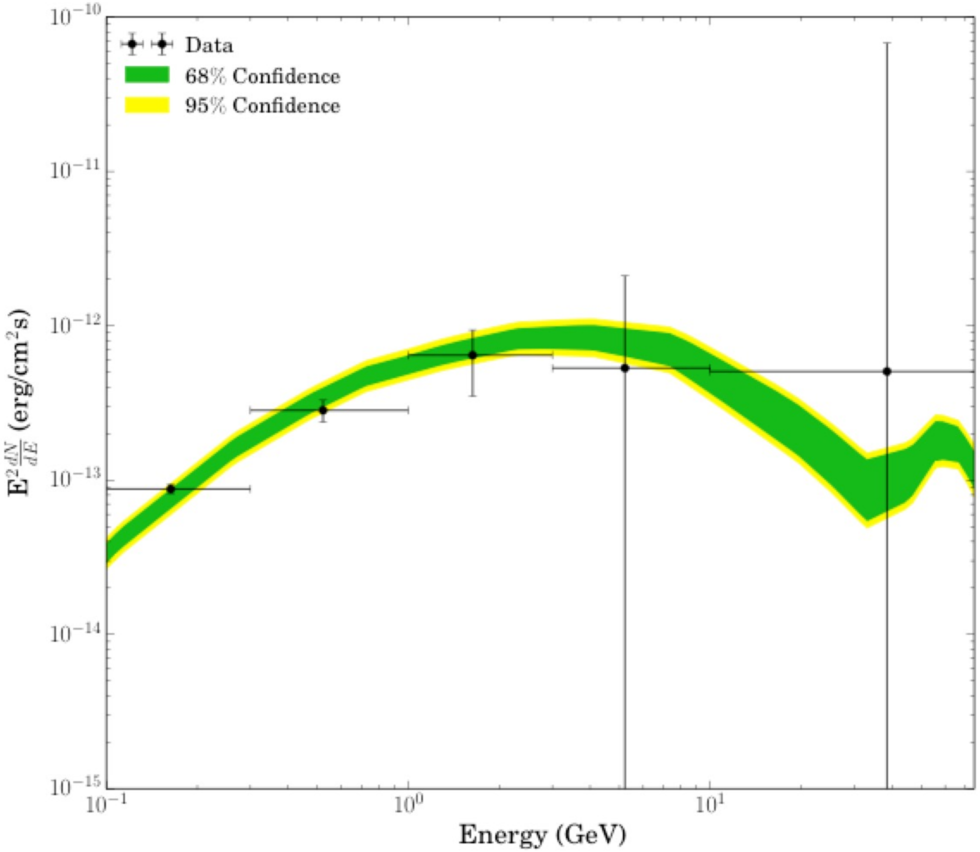


Ackermann et al. APJ 857 (2018), arxiv:1802.00100

- If we include the motion of PBHs relative to the Earth, then most of PBHs with temperatures below ~ 50 GeV would appear as moving gamma-ray sources

Search for PBHs in Fermi Catalogs

- Compare the PBH spectra with 3FGL spectra
  - An example of a matching spectrum (J0342.8-1321)

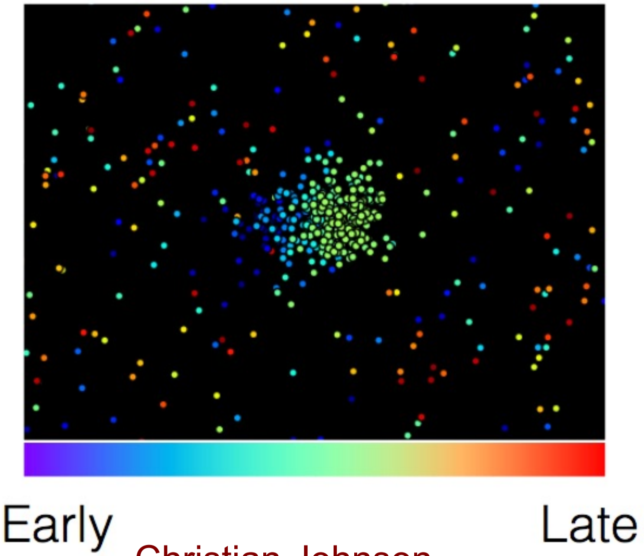


Christian Johnson

Example of a PS with a proper motion

- Fermi LAT is sensitive to PBHs with
  - temperatures at few tens of GeV
  - lifetime of a few years
  - distances ~ 0.01 – 0.1 pc
- A typical PBH with these parameters will shift a few degrees during the several years – a moving source in the Fermi-LAT data
- We looked for moving sources with hard spectra among the non-identified Fermi LAT sources
- No candidates were found

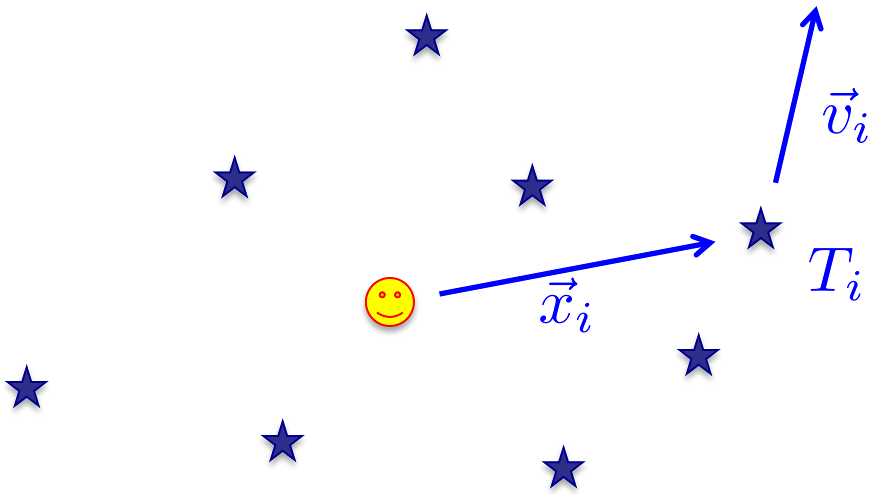
Energy: >3 GeV
Color: Arrival time



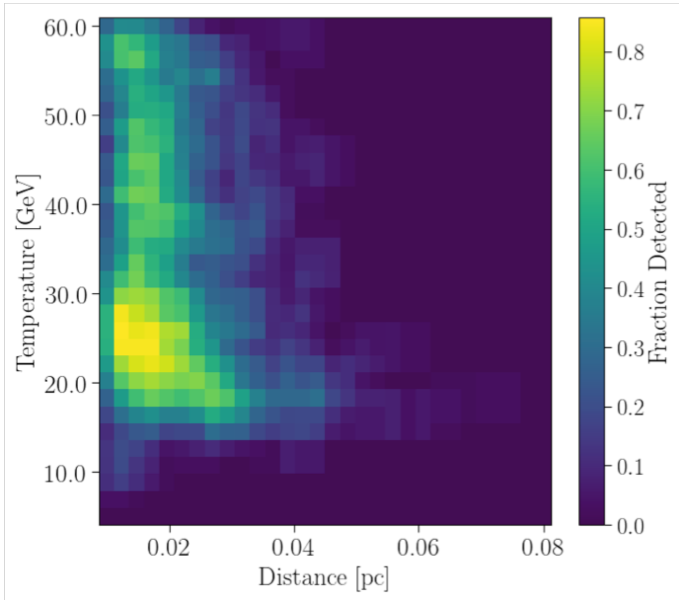
Christian Johnson

Search for individual PBHs in Fermi-LAT data

- Since no PBH candidates were detected in the Fermi-LAT data we put a limit on the PBH evaporation rate
- Monte Carlo simulation
  - Generate PBHs with a distribution over temperature, position, velocity
  - Increase the density of PBHs until the non-detection probability is less than 1%

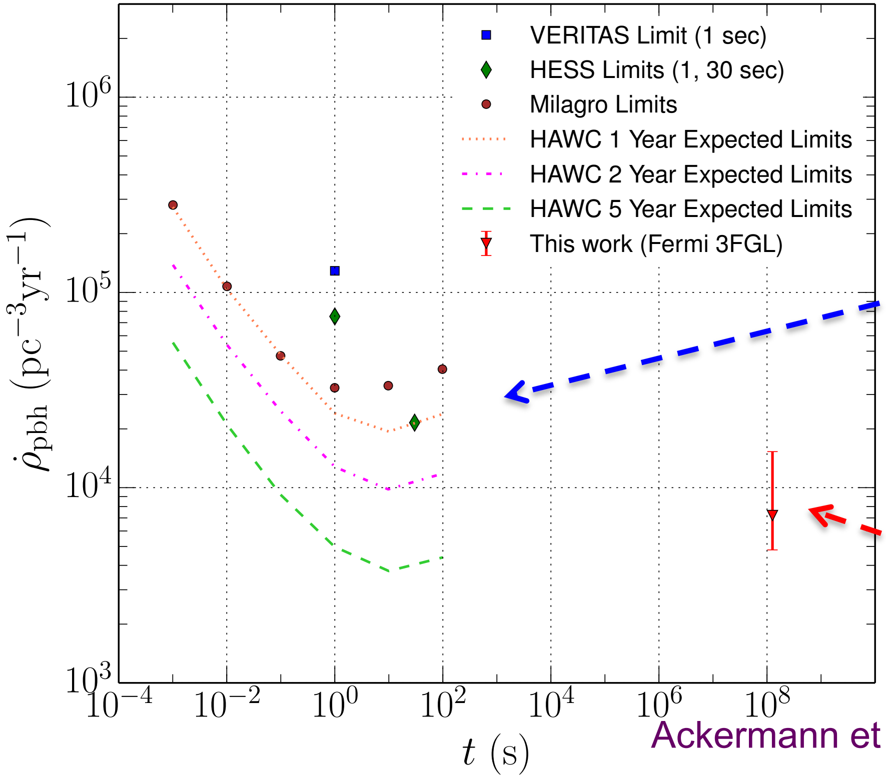


PBH detection efficiency



Ackermann et al. APJ 857 (2018), arxiv:1802.00100

Comparison with limits from Cherenkov telescopes



Cherenkov telescopes timescale – several seconds

Fermi LAT timescale – several years

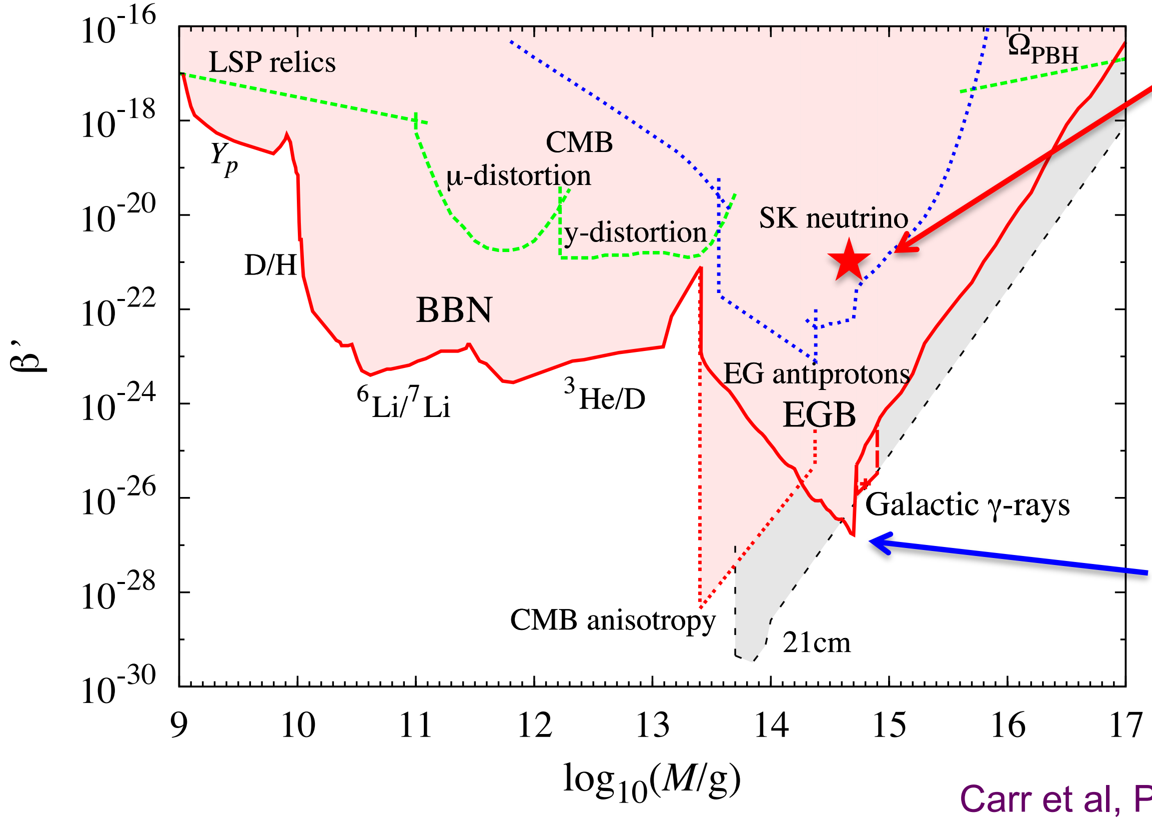
Ackermann et al. APJ 857 (2018), arxiv:1802.00100

$$\dot\rho_{\rm PBH} < (7.2^{+8.1}_{-2.4}) \times 10^3\ {\rm pc}^{-3}\ {\rm yr}^{-1}$$

- Fermi LAT limit is better than existing limits on individual PBHs, it is comparable to expected HAWC limit after 2 to 5 years of observations

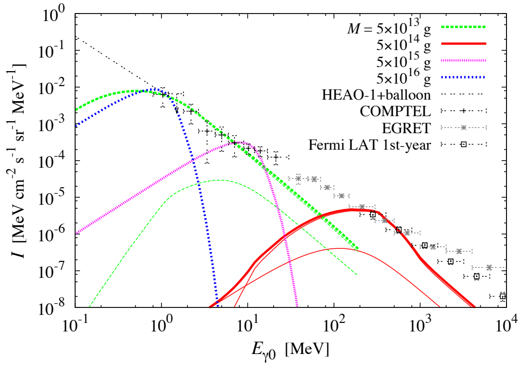
Comparison with other limits

- The limit on individual PBHs is about 5 orders of magnitude worse than the limit from extragalactic gamma-ray background (EGB) even taking into account 10^5 local DM concentration factor



Fermi LAT limit on individual PBHs

EGB

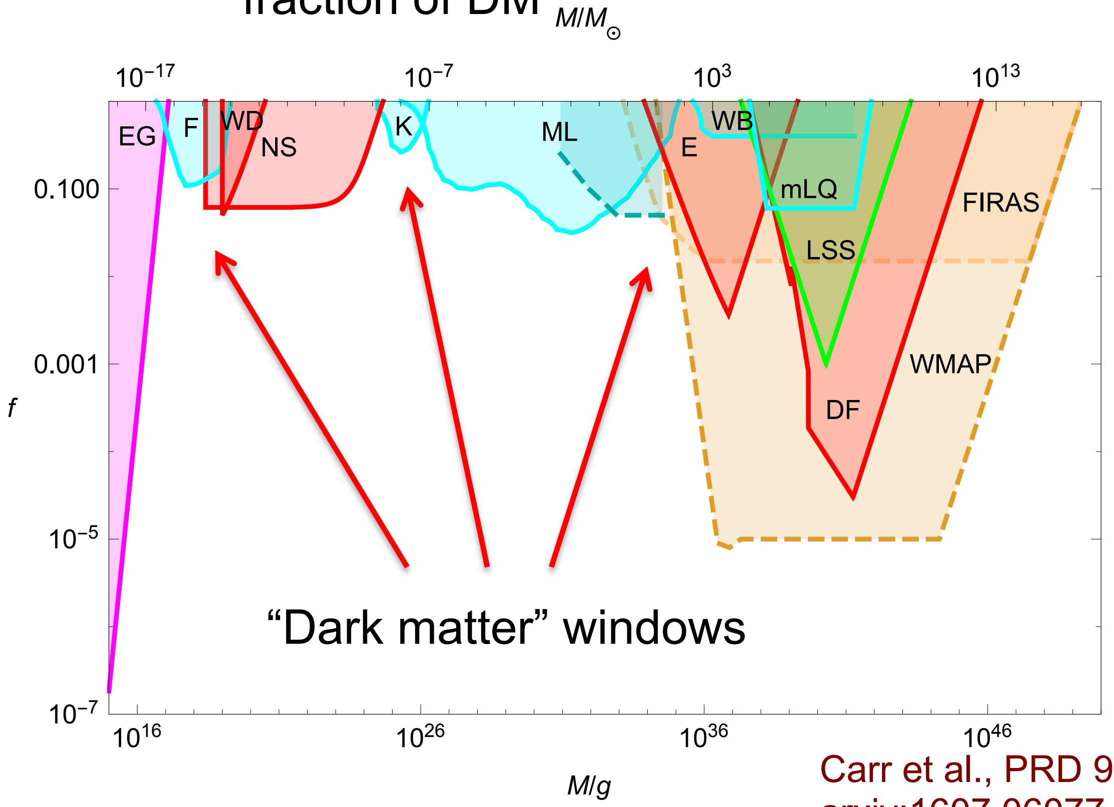


Carr et al, PRD 81 (2010), arxiv:0912.5297

Limits on PBHs from Gravitational effects

Limits on PBHs with initial masses >~ 10^{17} g

- For PBHs with masses >~ 10^{17} g the constraints come from various gravitational or accretion effects
  - There are also a few windows, where PBHs can provide a significant fraction of DM



"Dark matter" windows

Carr et al., PRD 94 (2016)
arxiv:1607.06077

$$f = \frac{\Omega_{PBH}}{\Omega_{CDM}} \approx 4.8\Omega_{PBH}$$

$$\approx 4 \times 10^8 \beta'(M) \left(\frac{M}{M_\odot}\right)^{-\frac{1}{2}}$$

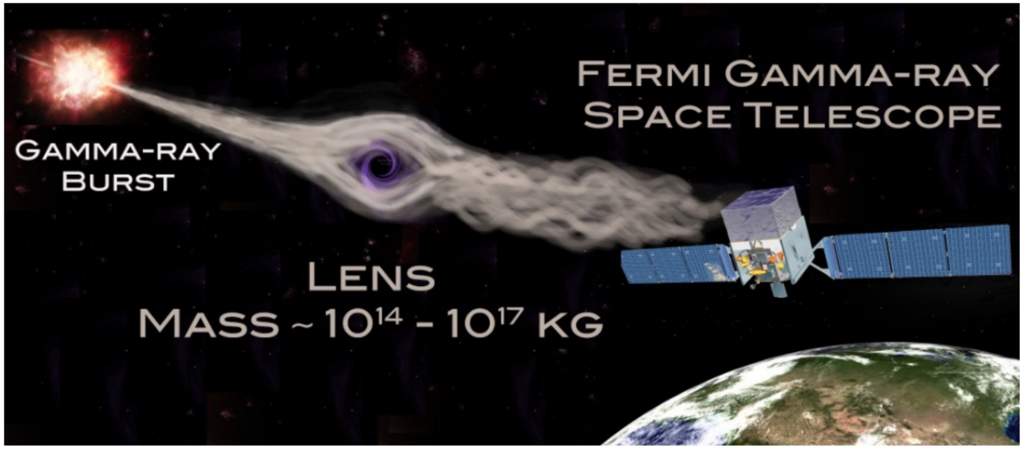
$$M_\odot \approx 2 \times 10^{33}\ g$$

At $M = 2 \cdot 10^{17}$ g = $10^{-16}\ M_\odot$:

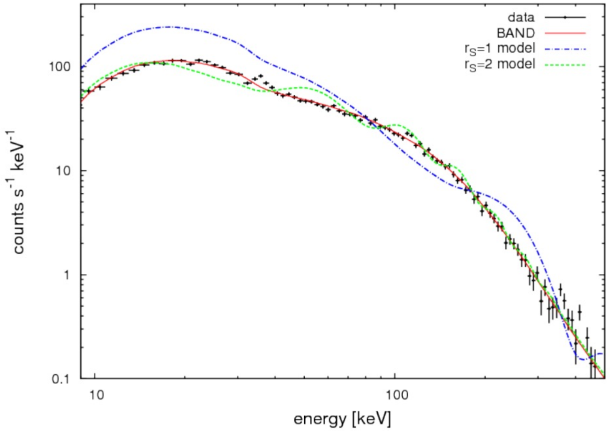
$$f \approx 4 \times 10^{16} \beta'$$

Femtolensing of GRBs

- Lensing by PBHs in the mass range 10^{17} – 10^{20} g causes interference of X-ray photons as a function of their energy
- This interference can manifest itself as spectral features in the X-ray spectrum of gamma-ray bursts (GRBs) observed by, e.g., Fermi gamma-ray burst monitor (GBM)
- However, Katz et al (2017) notice that point-like approximation for GRB and lens do not apply and the limits are not valid



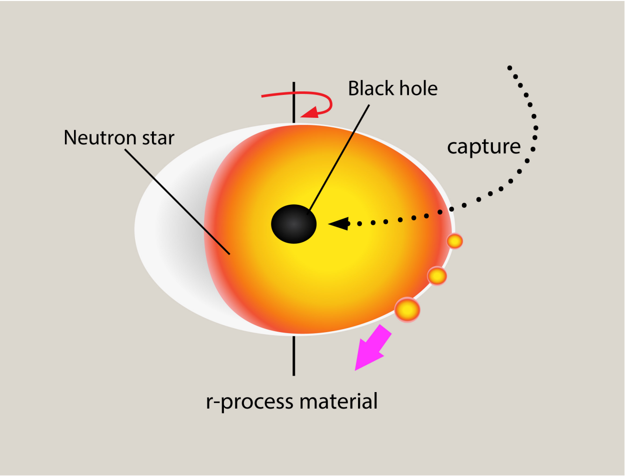
Anna Barnacka ICRC 2013



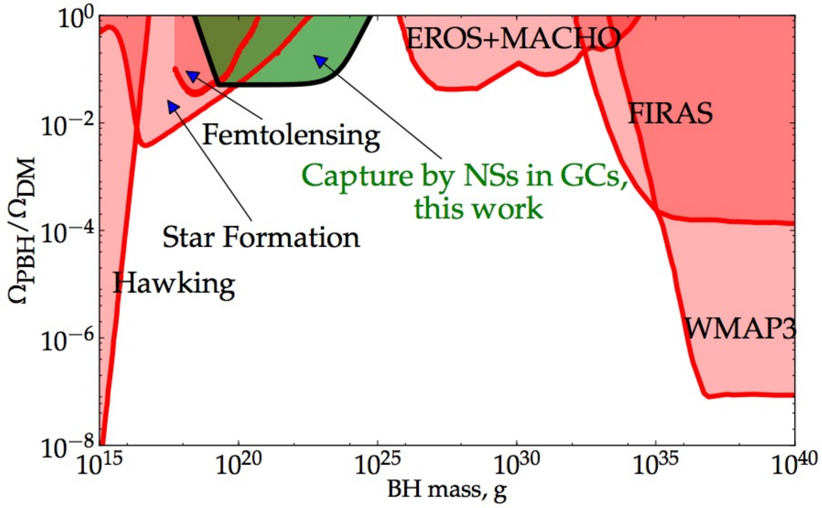
Barnacka et al. PRD 86 (2012) arxiv:1204.2056

Capture by neutron stars

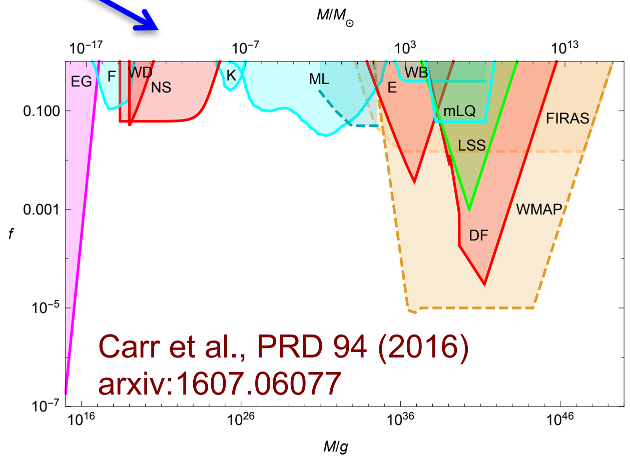
- PBH flying through sufficiently dense objects, e.g., neutron stars, can be captured
- PBH eventually destroys the NS by accretion
- Existence of NS places a limit on PBHs in the range $10^{18} - 10^{24}$ g



Alexander Kusenko / UCLA



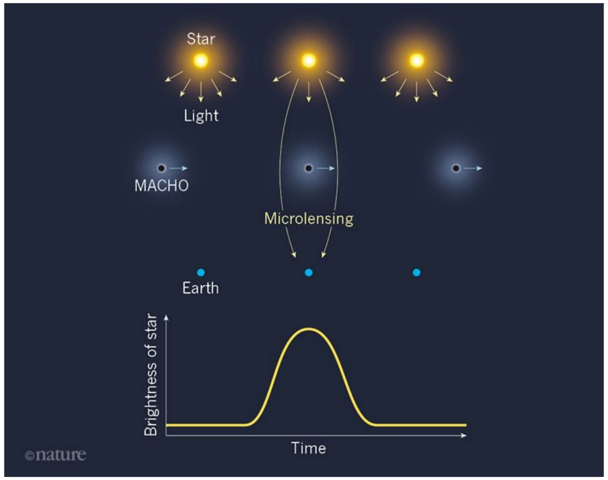
Capela et al. PRD 87 (2013), arxiv:1301.4984



Carr et al., PRD 94 (2016) arxiv:1607.06077

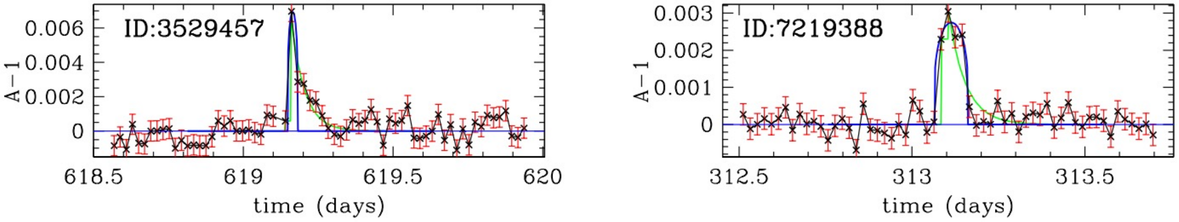
Microlensing

- A massive object passing close to the line of sight towards a star causes an increase in brightness
- Stars in Kepler field of view
- Backgrounds:
  - Stellar flairs
  - Passing bright objects (comets) in the field of view



Pietrzynski, Nature 562 (2018)

Flares – modeled by asymmetric light curves



Griest et al. ApJ 786 (2014), arxiv:1307.5798

Comet C/2006 Q1

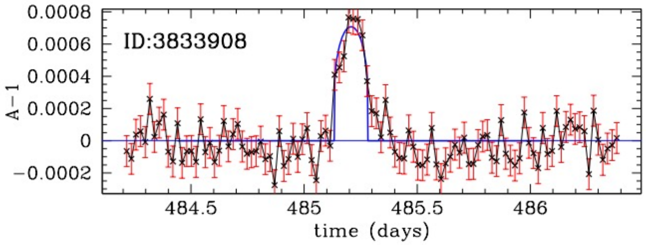


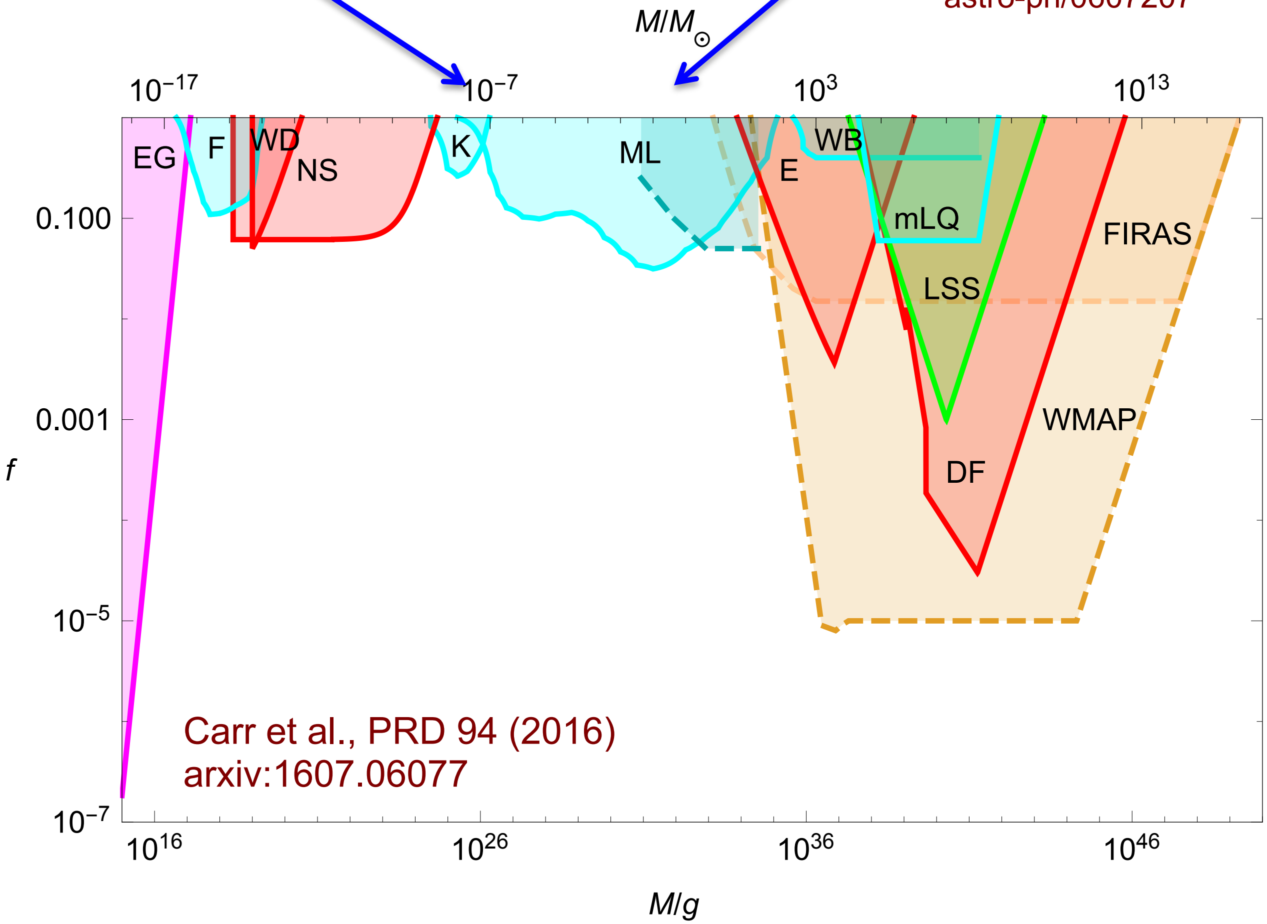
Fig. 3.— Examples of bumps in Kepler lightcurves caused by comet C/2006 Q1 (Mc-

Microlensing

Kepler field of view
$M_{PBH} \sim 10^{-9} - 10^{-7}\,M_\odot$

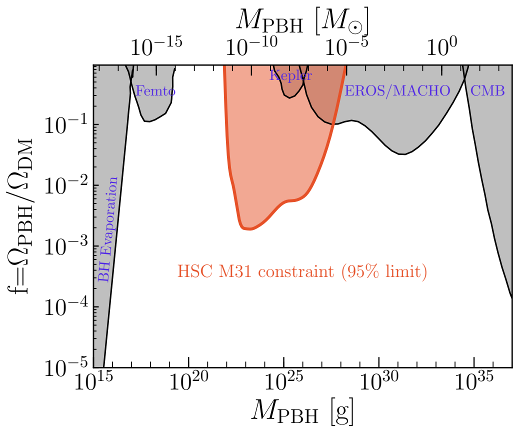
Magellanic clouds
$M_{PBH} \sim 10^{-8} - 10^{2}\,M_\odot$

Tisserand et al. (EROS-2), A&A 469 (2007)
astro-ph/0607207



Carr et al., PRD 94 (2016)
arxiv:1607.06077

Subaru/HSC Andromeda observation



Niikura et al, Nature Astronomy, 3 (2019)
arxiv:1701.02151

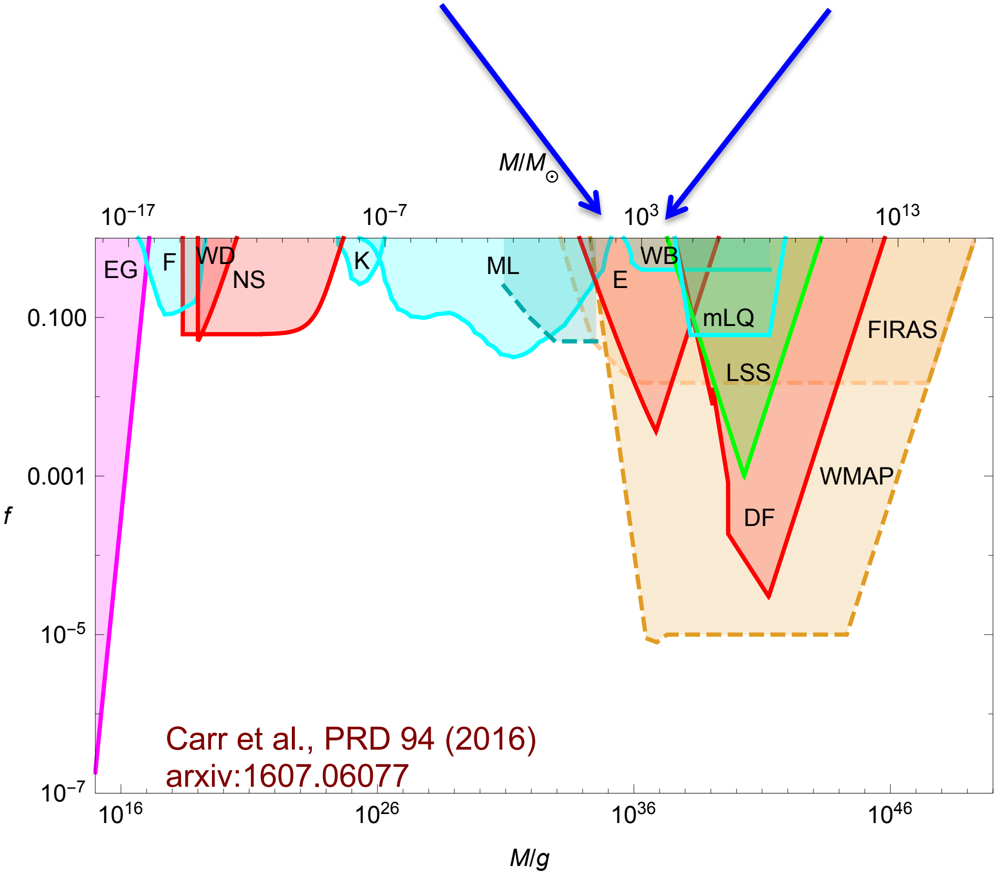
Dynamical effects

- Disruption of stellar clusters
  - Stellar clusters , e.g., the cluster near the center of Eridanus II dwarf galaxy can be disrupted by PBHs > 10 M$_\odot$

    Brandt, ApJL 824 (2016), arxiv:1605.03665
- Wide binaries
  - Binary systems can be disrupted by encounter with PBHs > ~ 100 M$_\odot$

    e.g., Quinn et al., MNRAS Lett. 396 (2009)

    arxiv:0903.1644



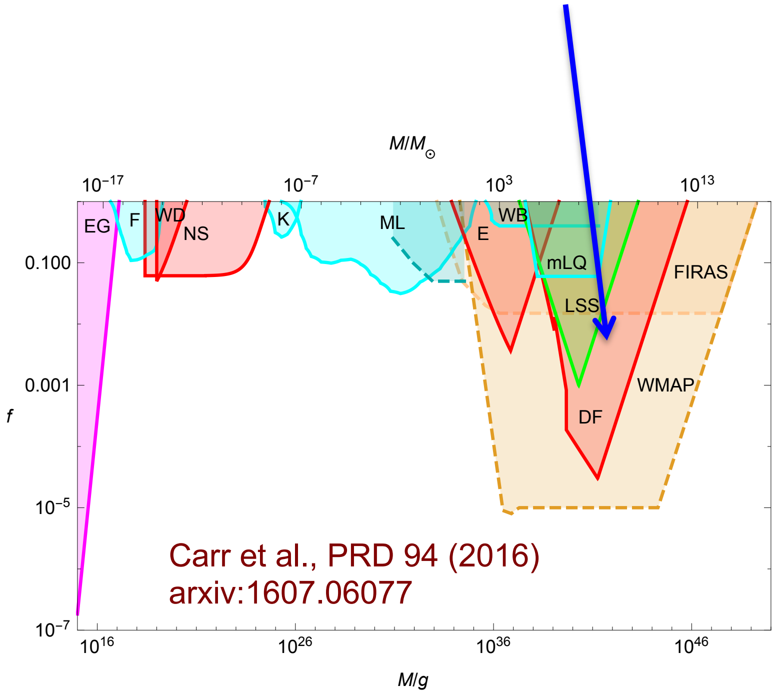
Stellar cluster in
Eridanus II galaxy
$M_{PBH} > 10\ M_\odot$

Wide binaries
$M_{PBH} > 100\ M_\odot$

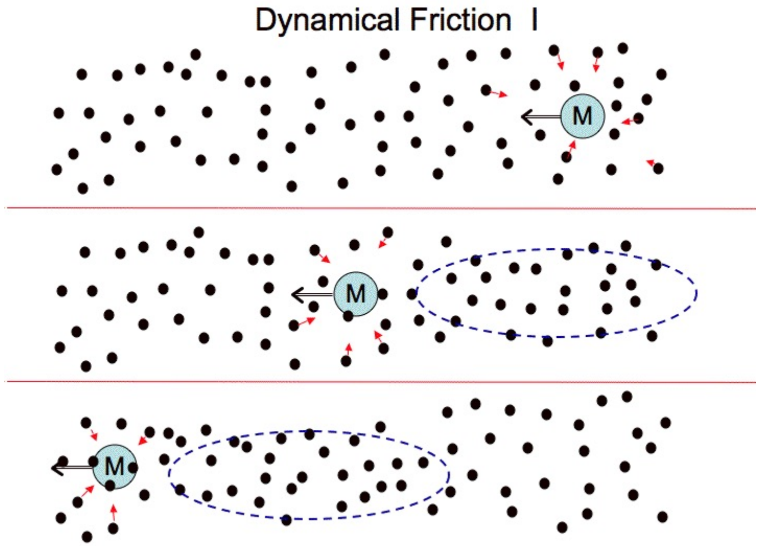
Carr et al., PRD 94 (2016)
arxiv:1607.06077

Dynamical friction

- PBHs with masses > ~ $10^6\ M_\odot$ will be dragged by dynamical friction to the Galactic center and can violate constraints on the mass of the nucleus (DF)



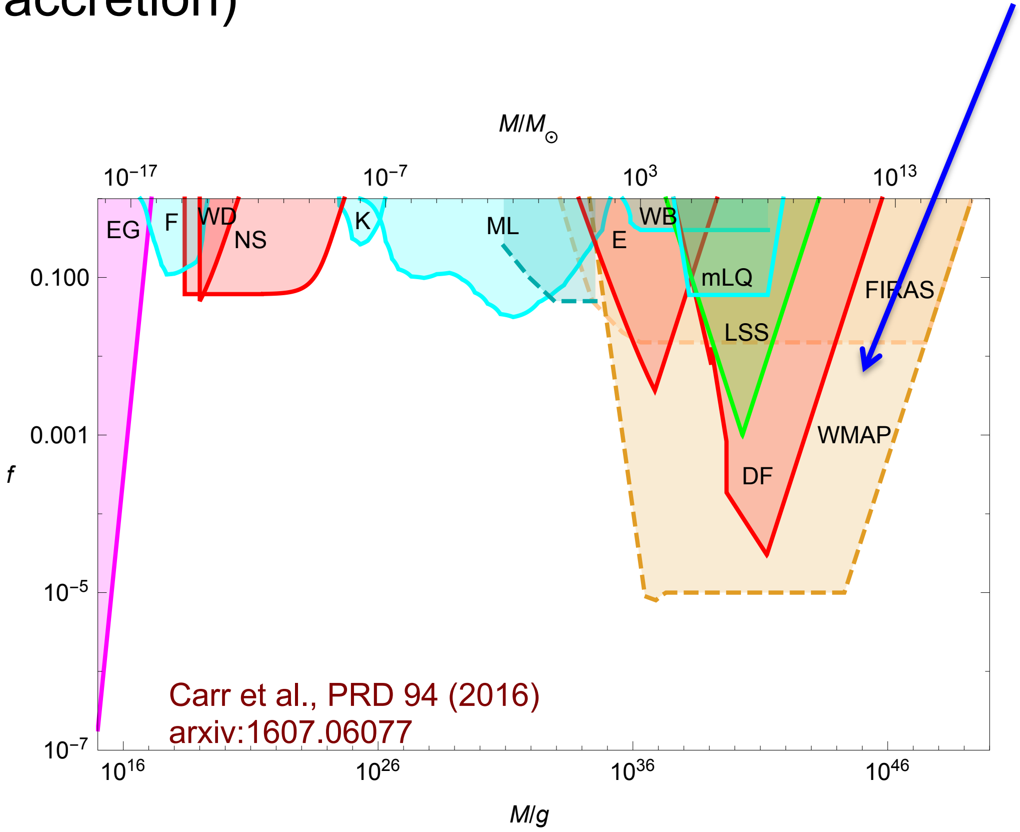
Carr et al., PRD 94 (2016)
arxiv:1607.06077



Mark Whittle/UVa, lecture notes

Accretion effects

- Accretion on PBHs with masses > ~ 1 $M_\odot$ can affect ionization and temperature evolution of the Universe – this can be constrained from the observations of CMB (constraints depend on modeling of the accretion)

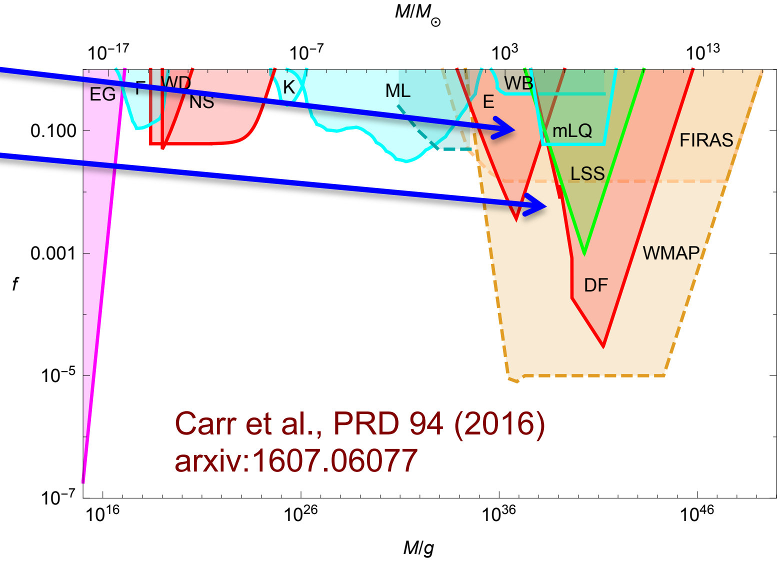


Carr et al., PRD 94 (2016)
arxiv:1607.06077

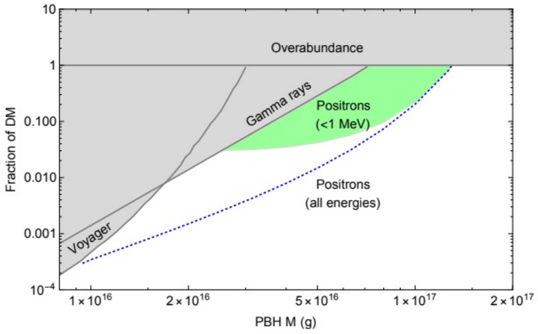
Other effects

- There are many other effects that can be used to detect or put constraints on PBHs
  - Millilensing of quasars
  - Formation of large scale structures
  - Overheat the distribution of stars in the disc
- Or even constraints from overproduction of the 511 keV line from the GC

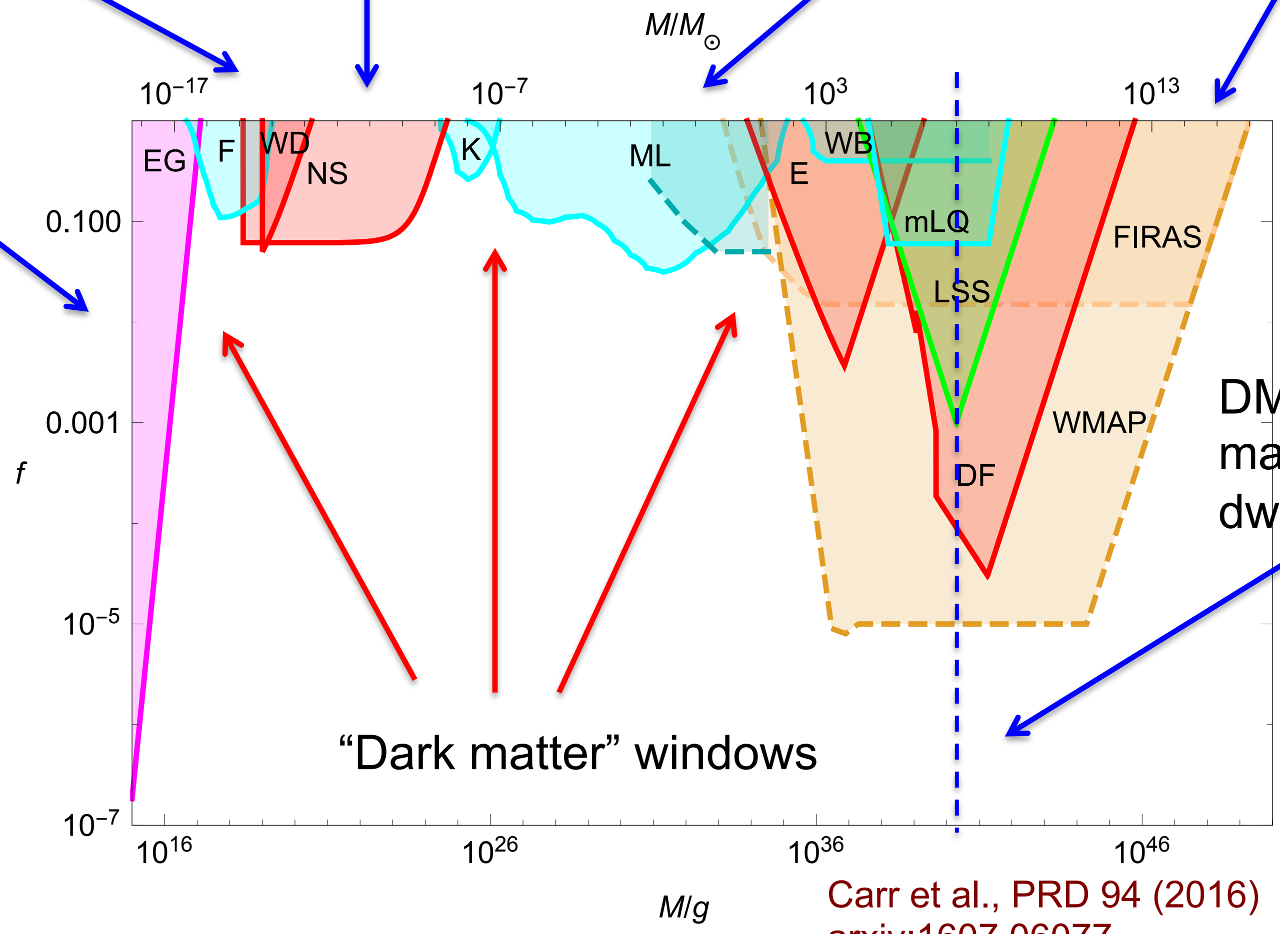
DeRocco & Graham, arxiv:1906.07740



Carr et al., PRD 94 (2016)
arxiv:1607.06077



Limits on PBHs with initial masses >~ 10^{17} g



Femtolensing (GRBs)

Captures by neutron stars and white dwarfs

Microlensing (stars)

Accretion effects on CMB

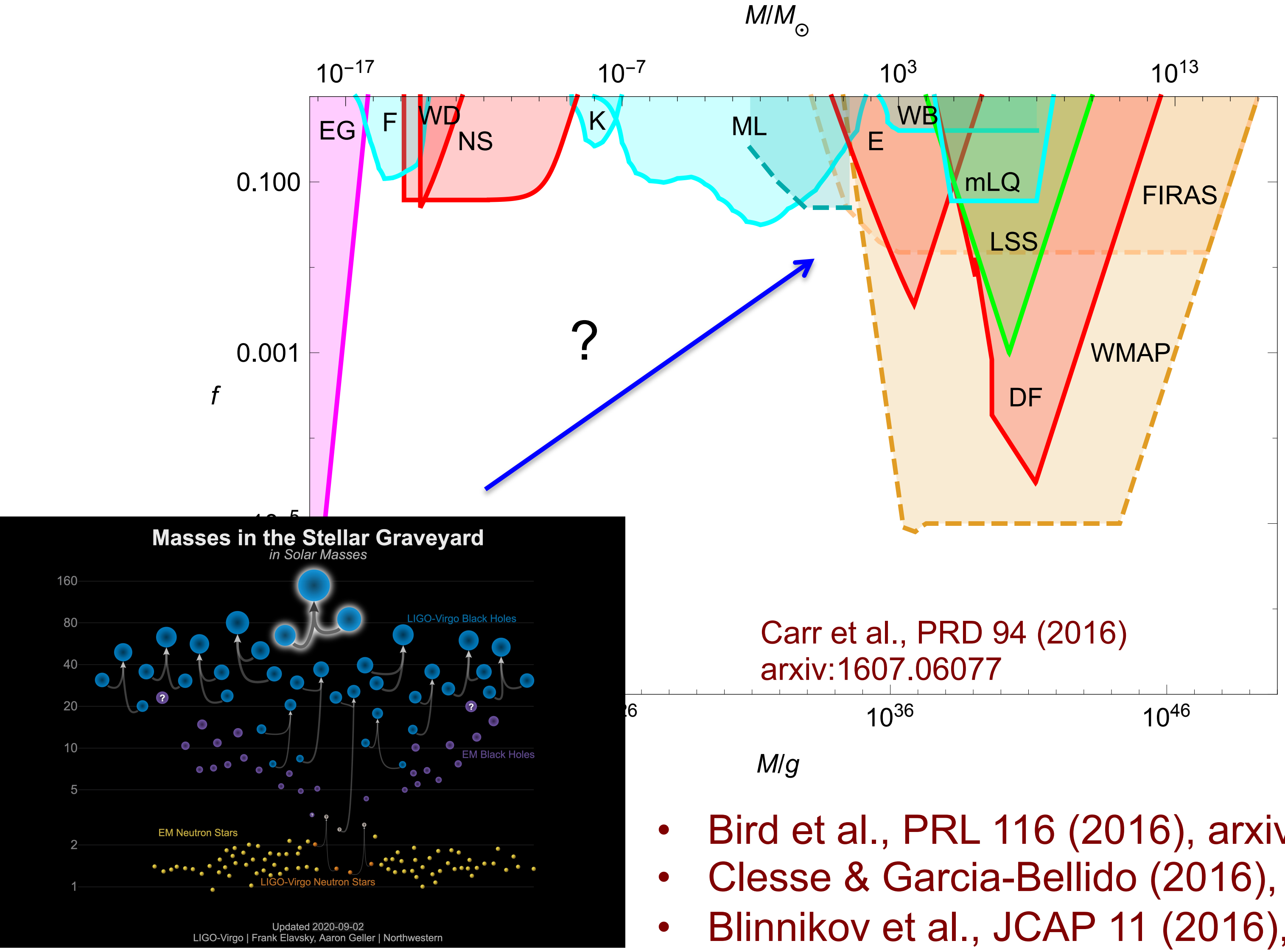
Gamma-ray background

DM halo masses of dwarf galaxies

“Dark matter” windows

Carr et al., PRD 94 (2016) arxiv:1607.06077

Did LIGO/VIRGO detect DM?



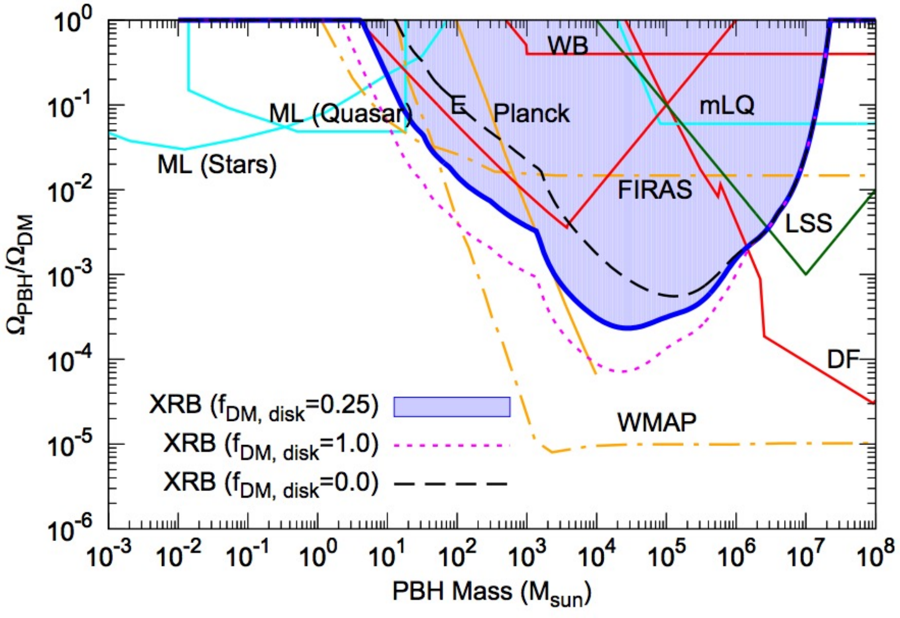
Carr et al., PRD 94 (2016)
arxiv:1607.06077

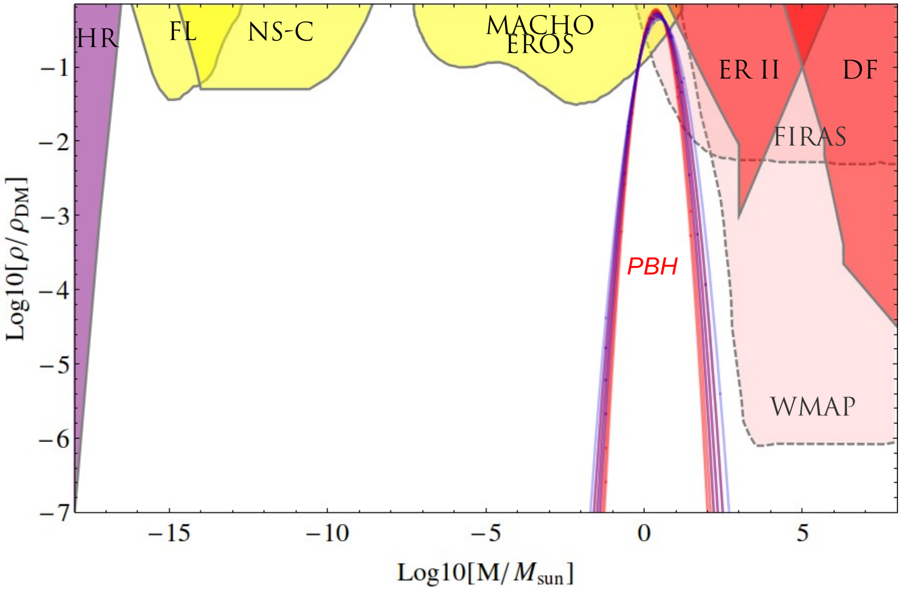
- Bird et al., PRL 116 (2016), arxiv:1603.00464
- Clesse & Garcia-Bellido (2016), arxiv:1610.08479
- Blinnikov et al., JCAP 11 (2016), arxiv:1611.00541

Credit: LIGO-Virgo/Northwestern U./Frank Elavsky & Aaron Geller

Constraints from X-ray and radio

- Radio and X-ray searches for accreting BHs puts constraints on PBH interpretation of GW merger events
  - Gaggero et al., PRL 118 (2017), arxiv:1612.00457
  - Inoue & Kusenko, JCAP, 10 (2017), arxiv:1705.00791
  - but cannot yet exclude it





Inoue & Kusenko, JCAP, 10 (2017), arxiv:1705.00791

Blinnikov et al JCAP11(2016)036, arxiv:1611.00541

Summary

Crossing the desert

Quantum Field Theory
in gravitational field

Mathematical
physics

Gravitational
waves

Cosmology

Astrophysics

Astronomy

Hans Hillewaert
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