Primordial Black Holes

Our only chance to detect Hawking radiation

Alexandra Klipfel

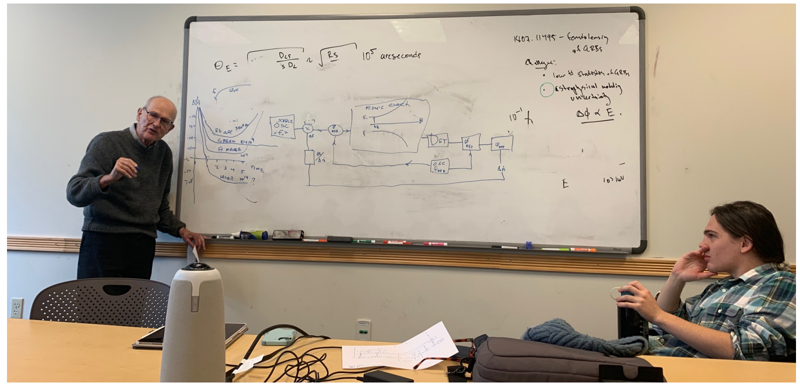
Rai Weiss Memorial Symposium, 27 February 2026

MIT PBH Group

Massachusetts Institute of Technology

MIT Bose Fellows Program

NSF



MIT PBH Group

Rai Weiss — February 5, 2024 at 6:16 PM

How about Friday March 1 in Building NW 22

To: Alexandra Klipfel, David I Kaiser, Peter H Fisher, Noah Wolfe, Salvatore Vitale, Rai Weiss

Colleagues,
I thought it was an informative and delightful meetiing. Suggest that we meet again in NW22 at 2PM Friday March 1. Does this work?
Rainer

Rai forms the group

Rai Weiss — Inbox - MIT — March 3, 2024 at 3:06 PM

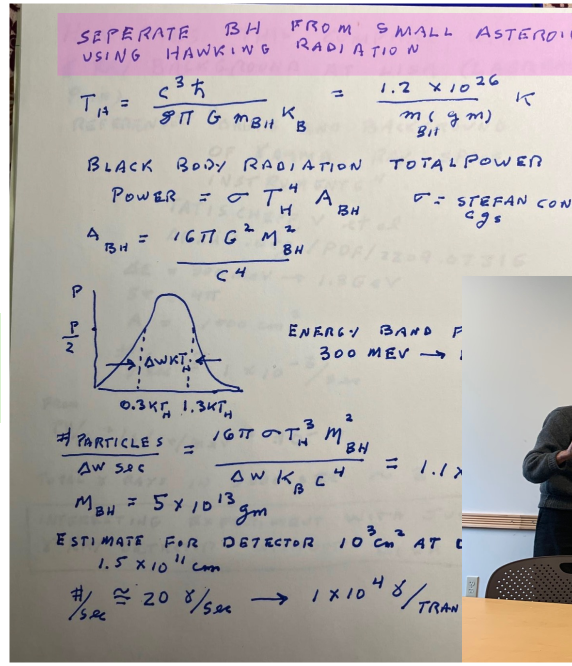
beautiful talk

To: Alexandra Klipfel, David I Kaiser, Evan Hall, Peter … Salvatore Vitale, Rai Weiss

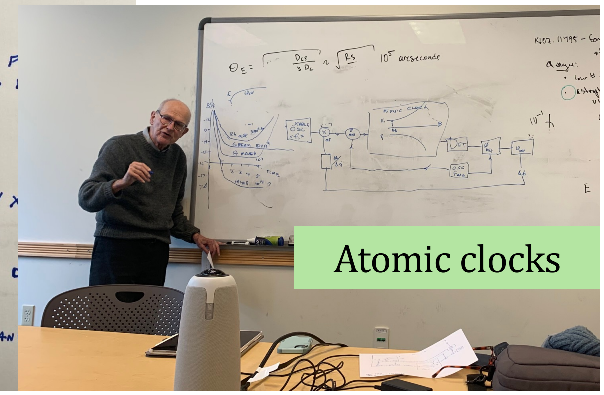
Alex,
I could look at all the figures and text better after you sent the talk. It is really very interesting and innovative. I recommend that you be prepared to deal with data on gamma rays in the cosmic background spectrum before you go to the meeting. You may find that is another constraint on your blackhole mass spectrum. Even if it is not, be prepared to answer questions from the floor about this. Again thank you for sending the slides.

Rainer

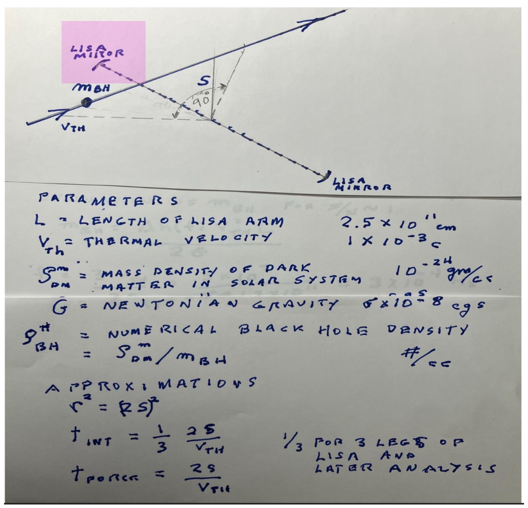
Kind words about my first talk

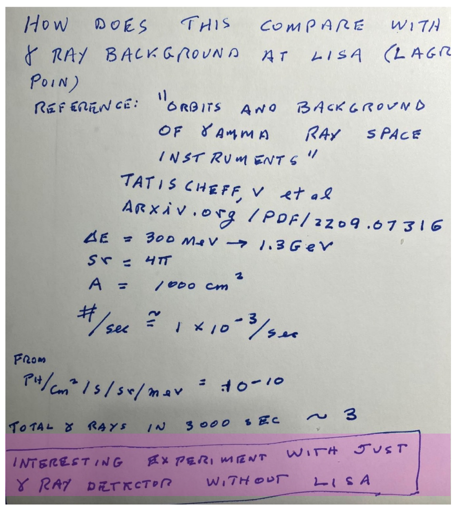


Rai's notes on multi-messenger PBH detection with LISA and Hawking radiation



Atomic clocks





This points out that one could do an interesting multi-messenger astrophysics observation with both LISA and a gamma ray detector. Even an interesting experiment with a single gamma ray detector placed at the Lagrange point.

If there are no serious errors in the estimate several things would be useful to do before making this better known.

1) Estimate how well LISA data analysis can distinguish the motion of the three satellites against the background of large black hole signals by fitting techniques.
2) Determine how the numbers change for different models of BH mass distributions.

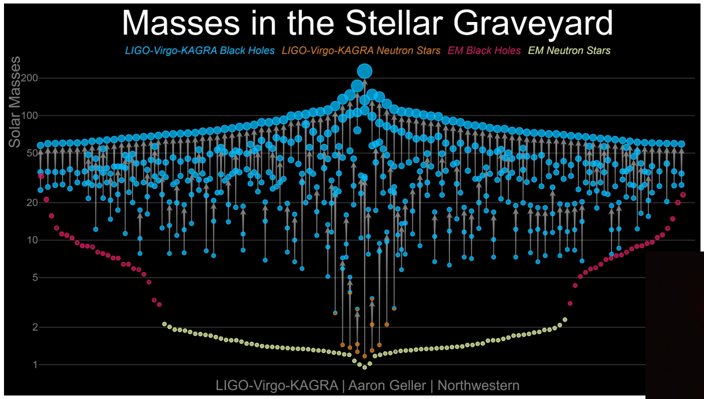
Rainer

raweiss@mit.edu

PBH Formation

We need *stars* to form astrophysical black holes:

- Observations from LVK, EHT, …
- The first stars formed around 100 million years after the Big Bang



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Primordial black holes as dark matter are theorized to form < 1 second after the Big Bang

- Topic of study for the last 50 years
- Form by the direct collapse of primordial over-densities: $M \sim M_H(t_i)$
- Extremely large range of masses:

$$10^{-5}\text{g} \leq M \lesssim 10^6 M_\odot$$

Mon. Not. R. astr. Soc. (1971) **152,** 75–78.

GRAVITATIONALLY COLLAPSED OBJECTS OF VERY LOW MASS

1971

Stephen Hawking

(Communicated by M. J. Rees)

(Received 1970 November 9)

SUMMARY

It is suggested that there may be a large number of gravitationally collapsed objects of mass 10^{-5} g upwards which were formed as a result of fluctuations in the early Universe. They could carry an electric charge of up to ±30 electron units. Such objects would produce distinctive tracks in bubble chambers and could form atoms with orbiting electrons or protons. A mass of 10^{17} g of such objects could have accum… star later became a neutro… a central collapsed object … about ten million years.

Mon. Not. R. astr. Soc. (1974) **168,** 399–415.

BLACK HOLES IN THE EARLY UNIVERSE

B. J. Carr and S. W. Hawking

1974

(Received 1974 February 25)

SUMMARY

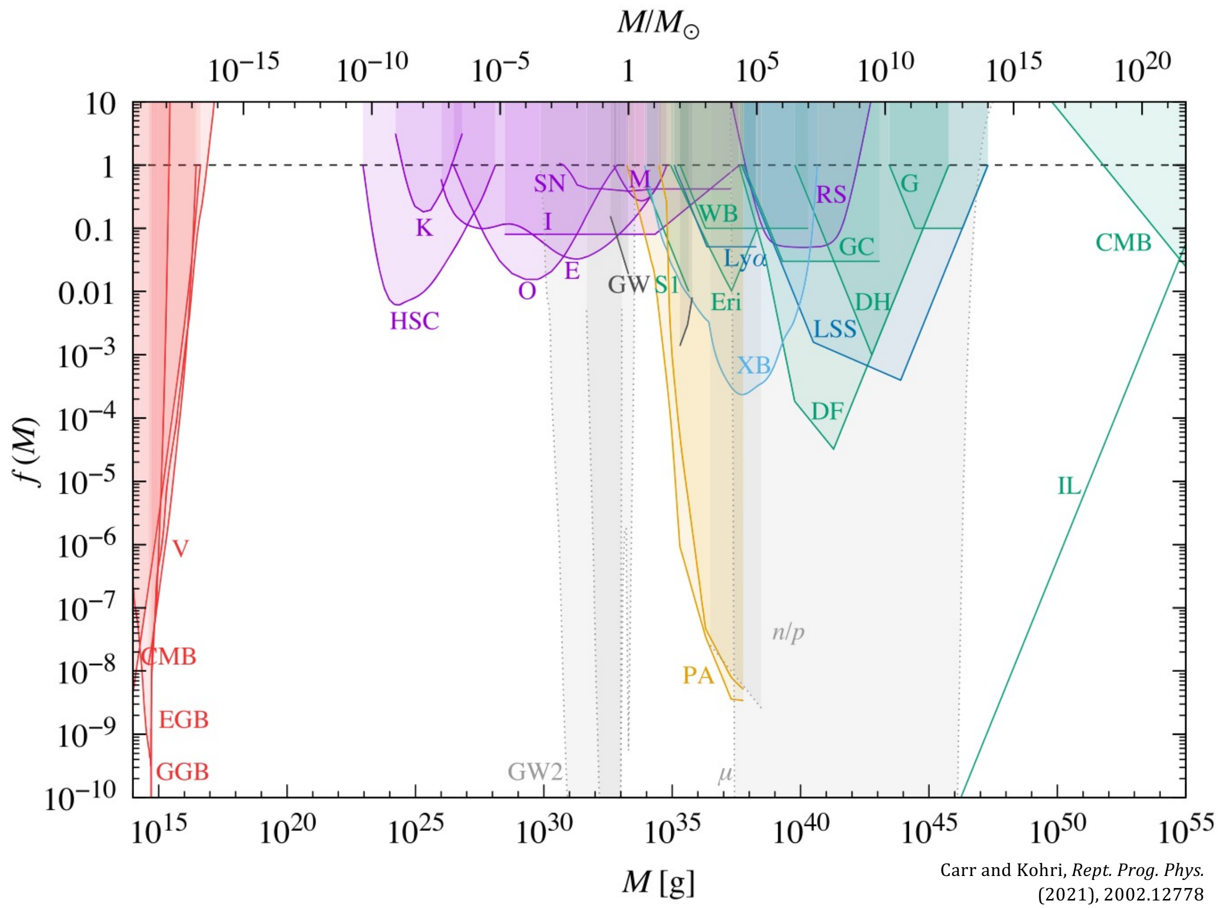
The existence of galaxies today implies that the early Universe must have been inhomogeneous. Some regions might have got so compressed that they underwent gravitational collapse to produce black holes. Once formed, black holes in the early Universe would grow by accreting nearby matter. A first estimate suggests that they might grow at the same rate as the Universe during the radiation era and be of the order of 10^{15} to 10^{17} solar masses now. The observational evidence however is against the existence of such giant black holes. This motivates a more detailed study of the rate of accretion which shows that black holes will not in fact substantially increase their original mass by accretion. There could thus be primordial black holes around now with masses from 10^{-5} g upwards.

PBHs as Dark Matter

Dark matter candidate

- Very massive ⇒ **non-relativistic/cold**
- Formed before BBN ⇒ contribute to **non-baryonic Ω_{DM}**
- No SM charge ⇒ **only interact gravitationally**

Constraints on PBH DM fraction



Carr and Kohri, *Rept. Prog. Phys.* (2021), 2002.12778

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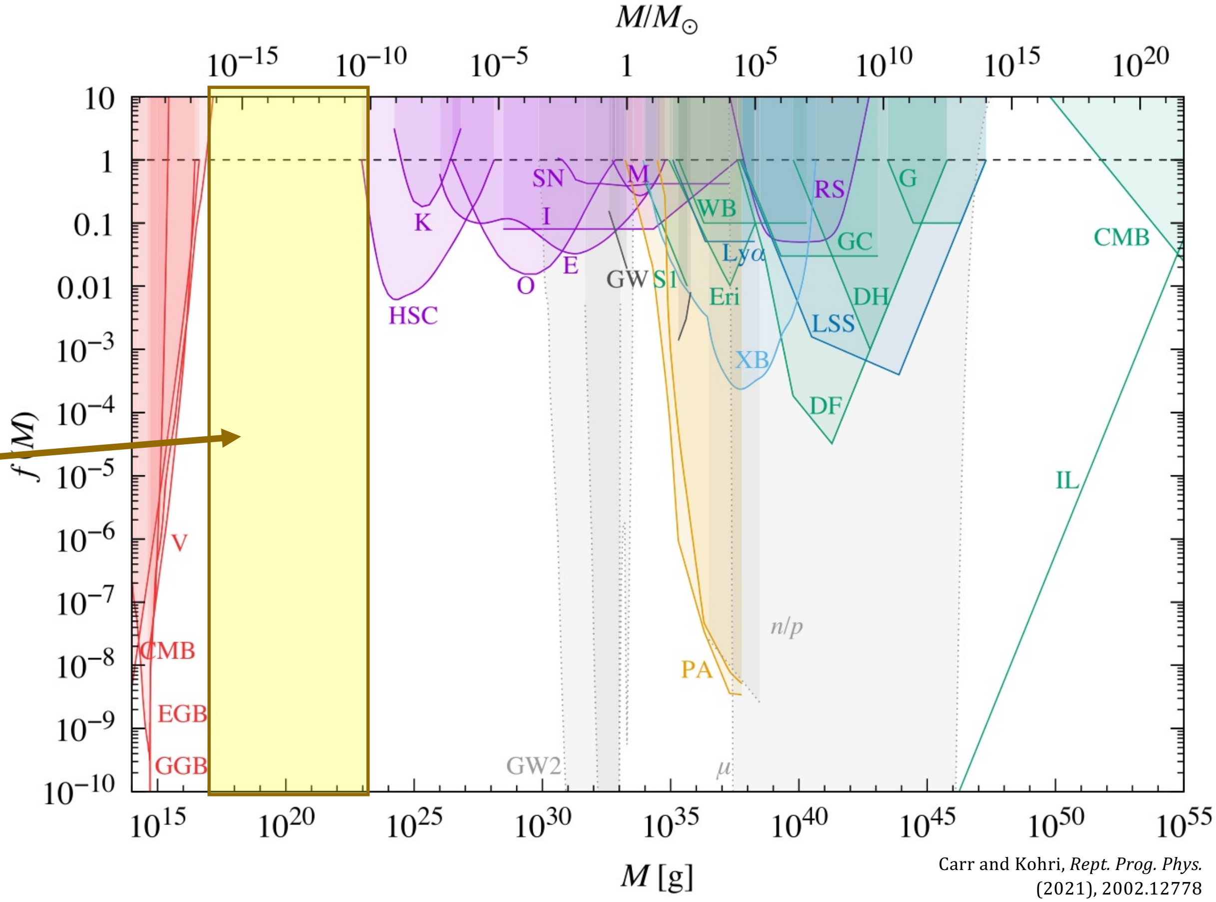
"Asteroid-Mass Window"
$10^{17} g \leq M \leq 10^{23}$g

PBHs could make up all the dark matter

Very hard to detect:

- $r_S \lesssim 10^{-6}$ m
- No accretion disks
- Minimal Hawking emission

Constraints on PBH DM fraction



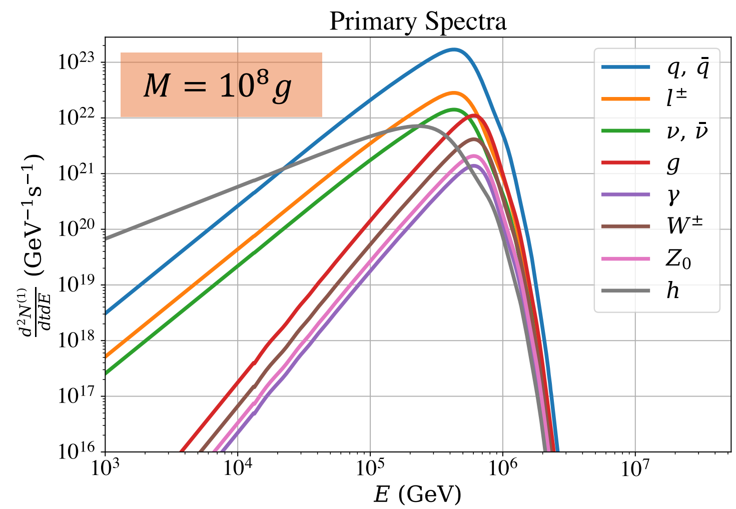
Carr and Kohri, *Rept. Prog. Phys.* (2021), 2002.12778

Hawking Radiation

Black holes radiate all SM particles according to a modified blackbody spectrum

Hawking temperature: $T_H = \frac{1}{8\pi G \boldsymbol{M}}$

Lifetime: $\tau \propto \boldsymbol{M}^3$



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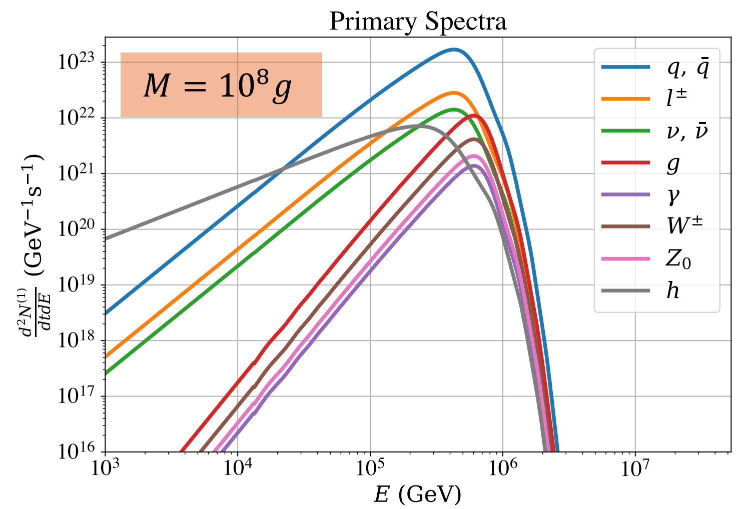
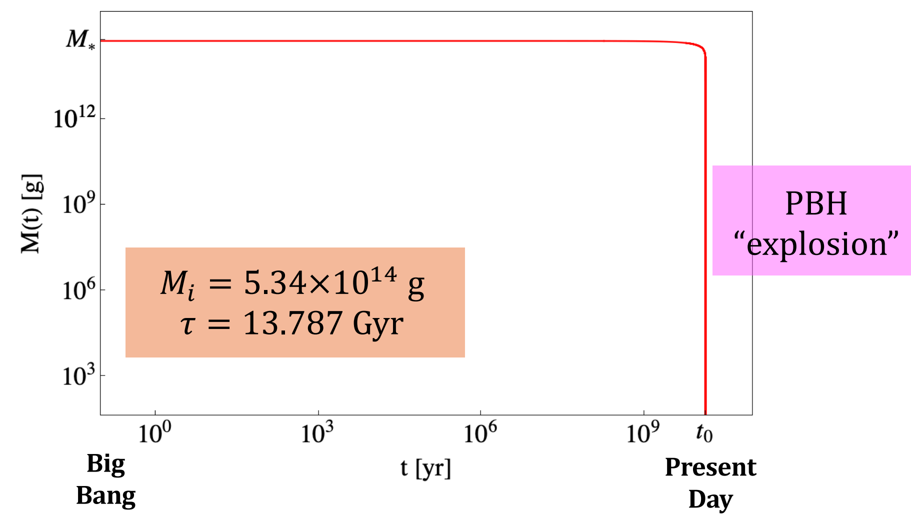
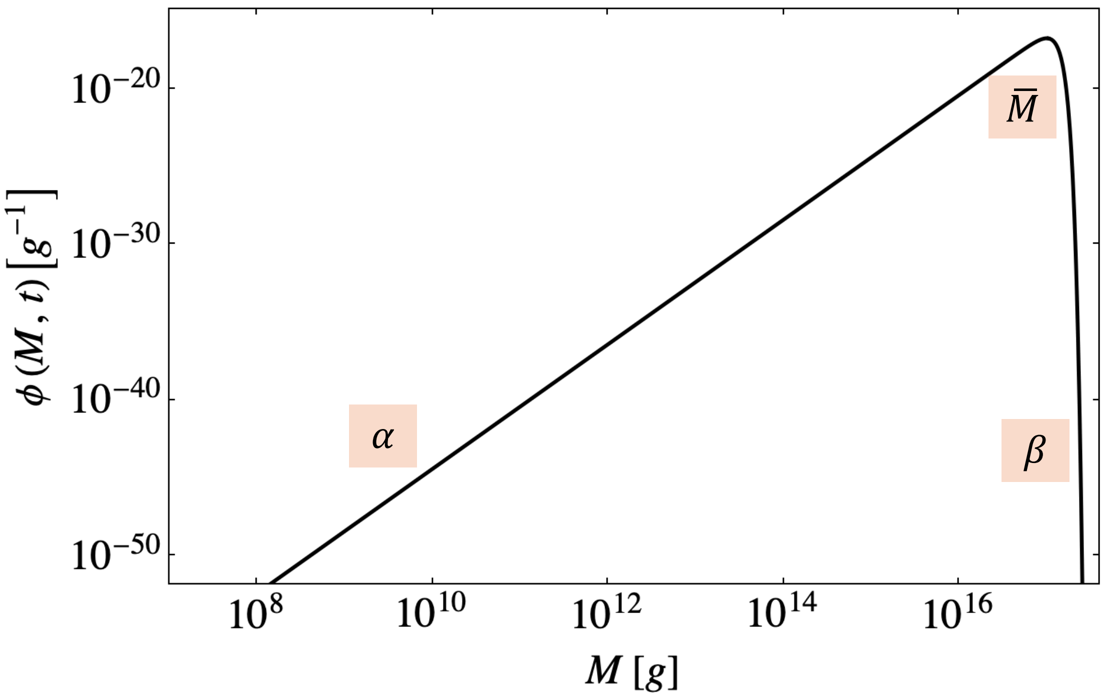
Lifetime: $\tau \propto \boldsymbol{M}^3$

- **Lighter PBHs are smaller and hotter**
- **Astrophysical BHs are *colder than the CMB:*** so PBHs are our only chance to detect Hawking radiation
- **Emission is a runaway process** that ends with an "explosion"





PBH Mass Distribution



Initial-time **number distribution function**:

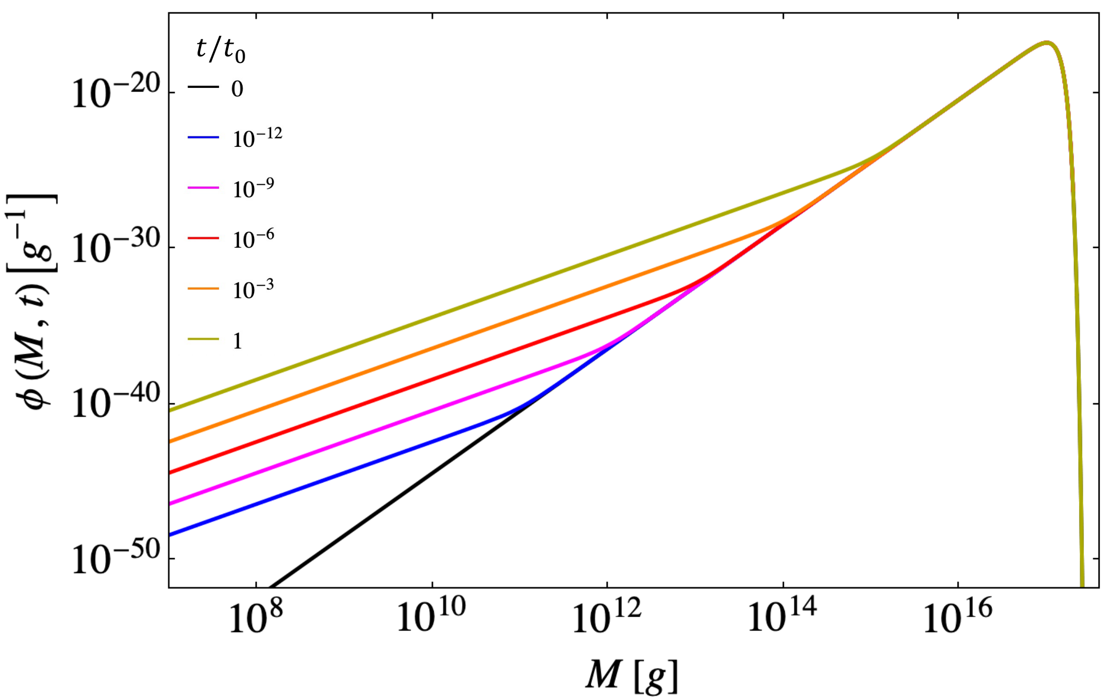
$$\phi(M_i) \equiv \frac{1}{n_{\mathrm{PBH},i}} \frac{dn_{\mathrm{PBH}}}{dM_i}$$

PBH number density

$$\phi(M_i) \propto \left(\frac{M_i}{\bar{M}}\right)^{\alpha-1} \exp\left[-\left(\frac{M_i}{\bar{M}}\right)^{\beta}\right]$$

Typical PBH mass at formation, $\bar{M}$, is determined by the size of the universe at formation time (Hubble volume)

PBH Mass Distribution



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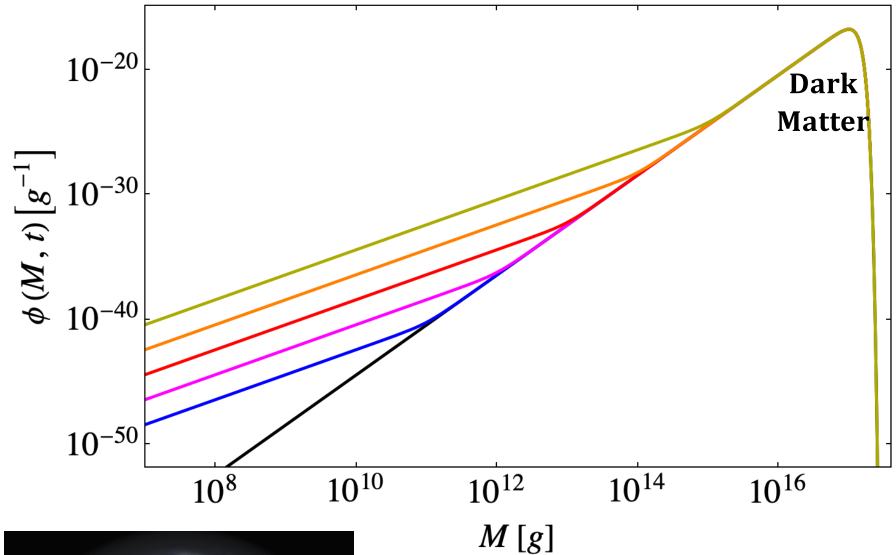
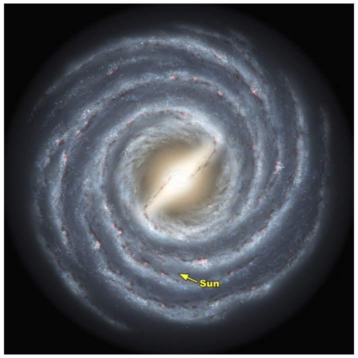
Mass distribution evolves with time due to Hawking emission and PBH explosions

Ultra-high Energy Neutrinos from PBH Explosions





- Assume all DM in the Milky Way is comprised of asteroid-mass PBHs
- Spatial distribution of DM is known

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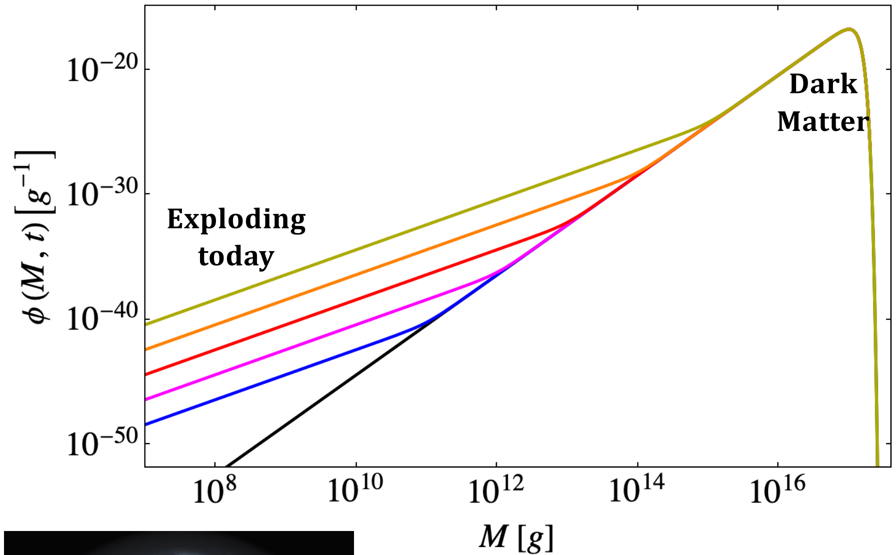
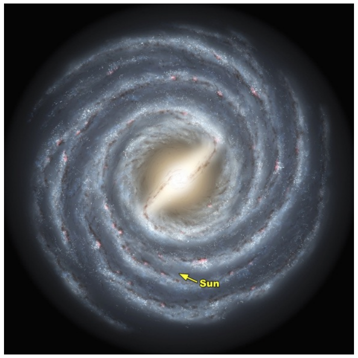


A small **sub-population** of PBHs would be **exploding today**, generating **ultra-high energy cosmic rays**

- **What would the signal look like?**
- **Have we observed any?**
- **Are multi-messenger detections possible?**



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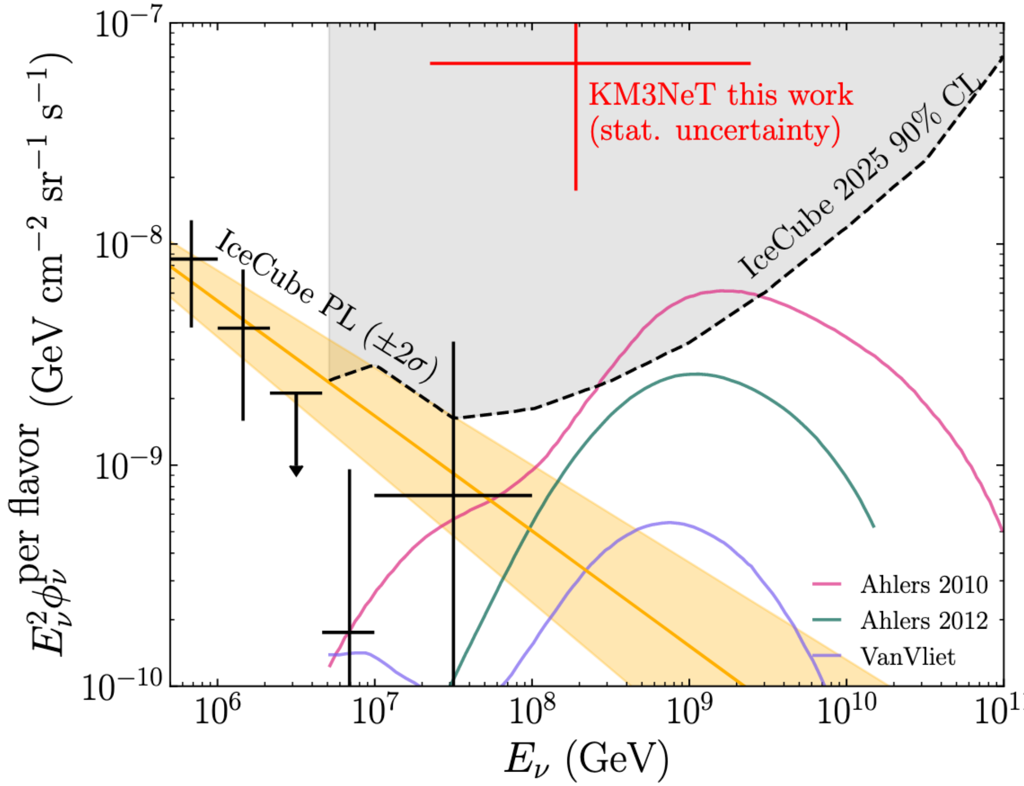
Ultra-high Energy Neutrinos from PBH Explosions

KM3NeT measured the **highest energy neutrino event ever reported**:

$$\mathcal{O}(100\text{ PeV} = 10^{17}\text{eV})$$

IceCube has observed 5 events above 1 PeV

$> 3\sigma$ **tension** between the IceCube and KM3NeT ultra-high energy isotropic fluxes



Li et al (2025), 2502.04508

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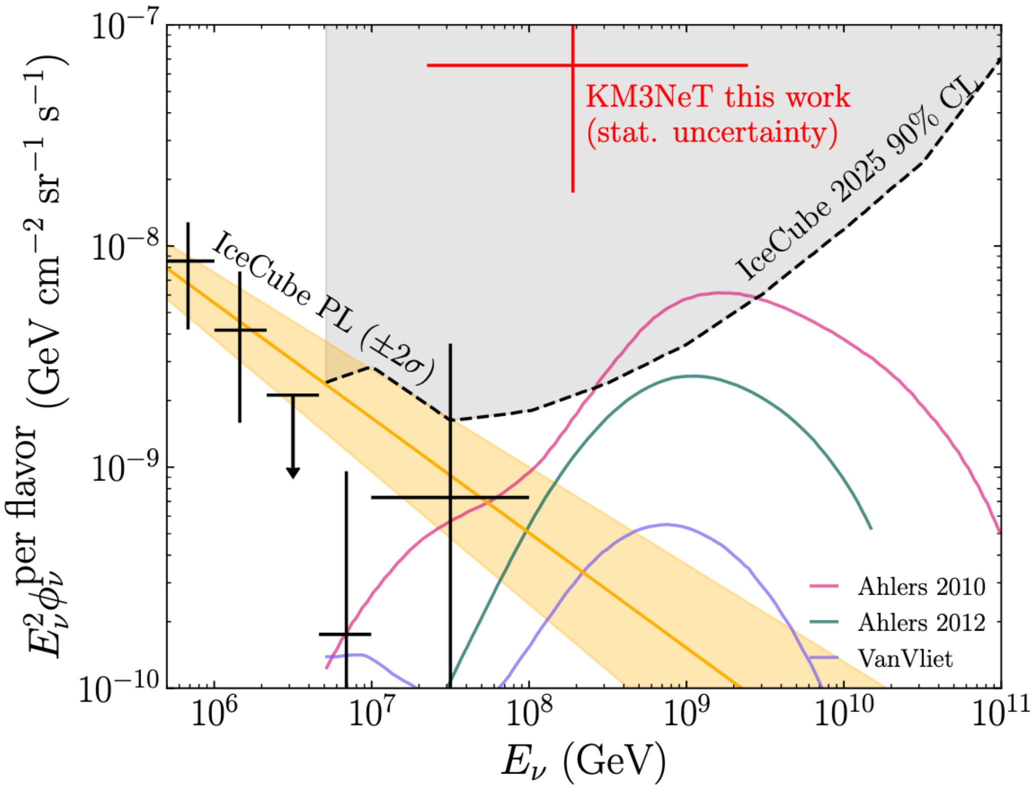
We can account for the IceCube **diffuse isotropic flux** above 1 PeV with a sub-population of **exploding PBHs** throughout the galaxy



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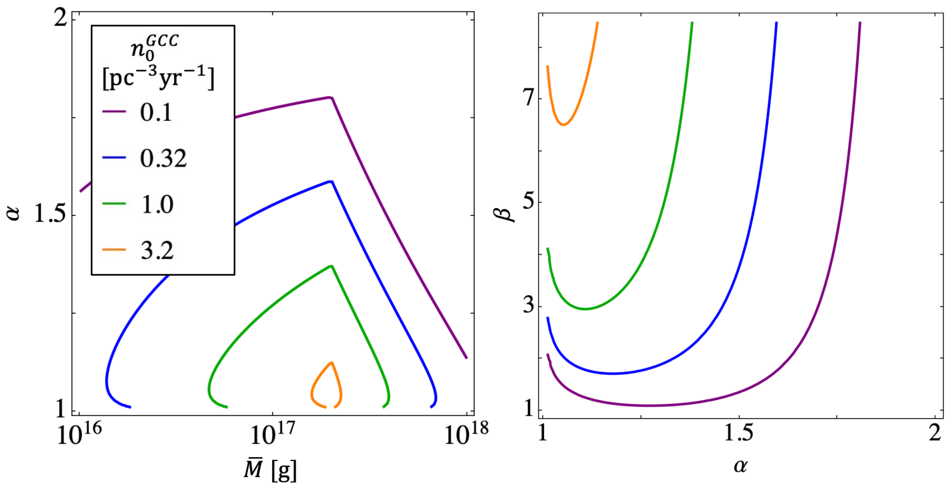

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We find a class of **realistic PBH number distributions** compatible with $n_0^{\rm IC}$ within 2σ that would comprise **all the dark matter**

The necessary explosion rate $n_0^{\rm IC}$ is consistent with the tightest experimental constraints from HAWC and LHAASO

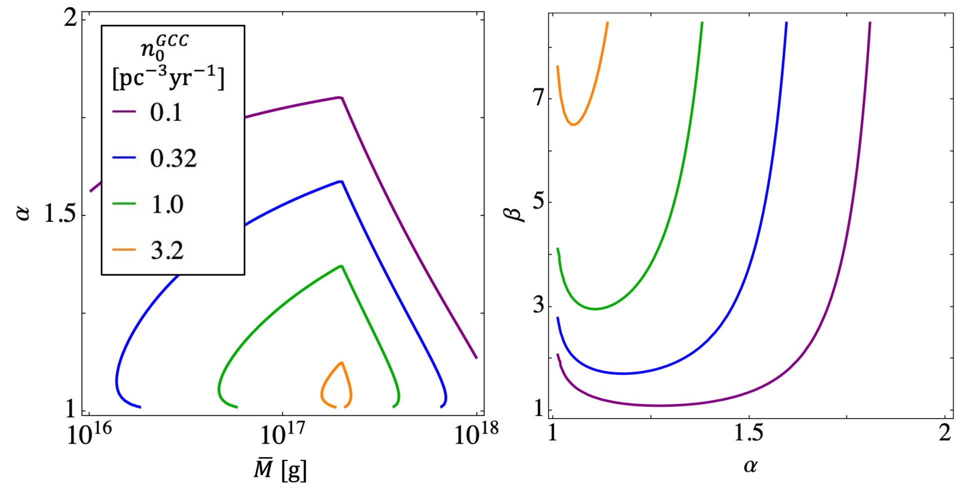
Klipfel and Kaiser, *Phys. Rev. Lett.* (2025), 2503.19227

Ultra-high Energy Neutrinos from PBH Explosions

Assume the KM3NeT event was due to a very **local PBH explosion:** a rare fluctuation governed by Poisson statistics

$$P\left(1 \text{ event} \middle| T = 14 \text{ yr}, b \sim 1800 \text{ AU}, n_0 = n_0^{\mathrm{IC}}\right) = 7.6\%$$

This scenario **reduces the statistical tension** between KM3NeT and IceCube



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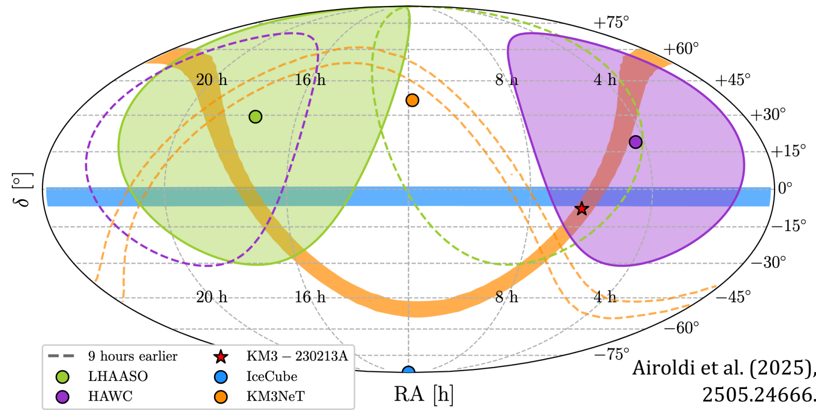
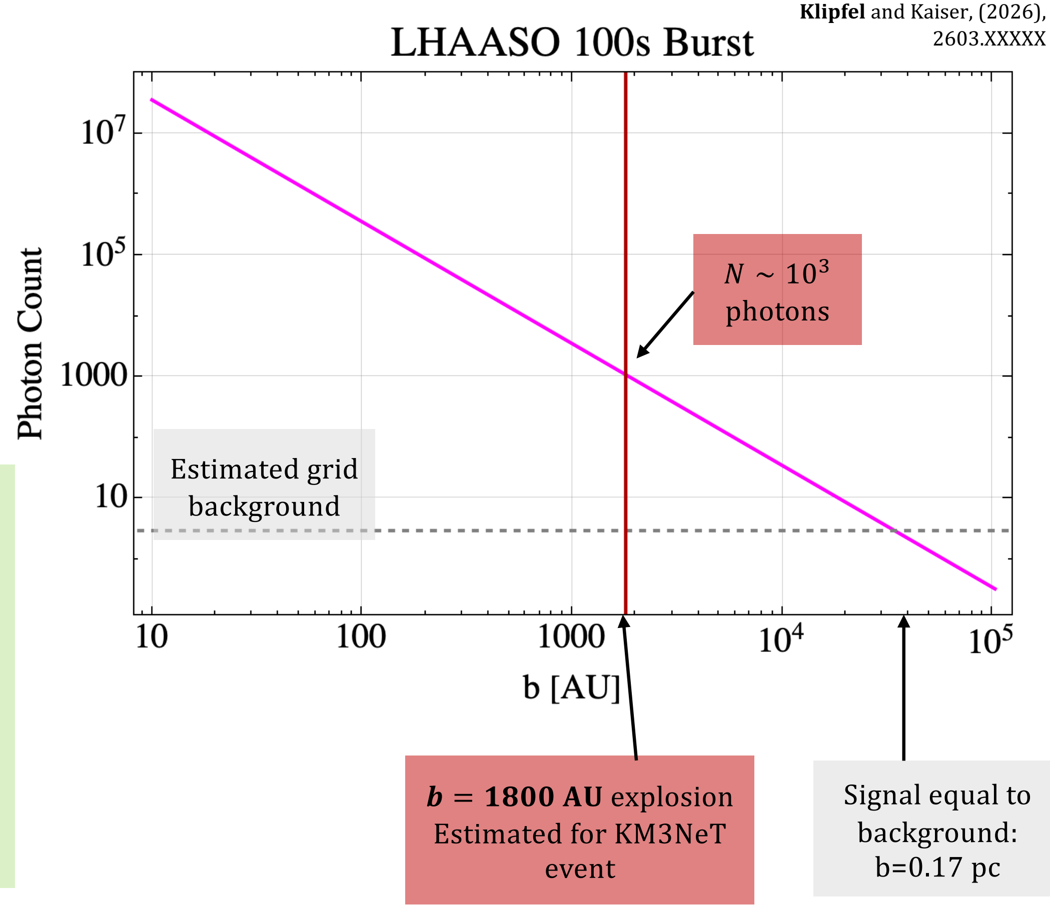
Multi-Messenger Detection?

High energy γ-rays

Klipfel and Kaiser, (2026), 2603.XXXXX



Airoldi et al. (2025), 2505.24666.



The source of the KM3NeT neutrino event was **not inside the LHAASO field of view** during the burst.

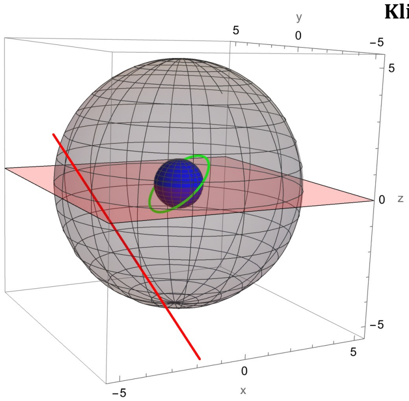
We find that **LHAASO is sensitive to PBH explosions at distances ~1800 AU.**

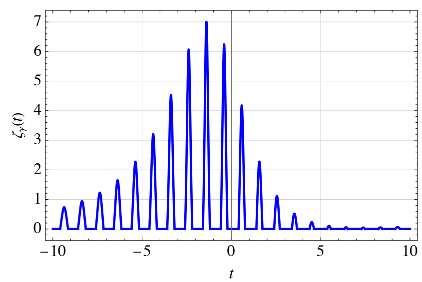
Detection of UHE **neutrinos and photons** from future PBH explosions at comparable distances is possible and could lead to **identification of PBH explosion**

Other PBH Projects...

Hawking radiation signatures from PBHs transiting through the inner Solar System

Klipfel, Fisher, and Kaiser, *Phys. Rev. D.* (2025), 2506.14041
Klipfel and Kaiser, (2026), 2603.XXXXX

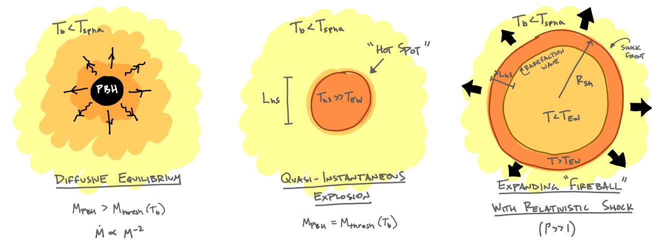




Purpose-built spacecraft for multi-messenger PBH detection in the Solar System

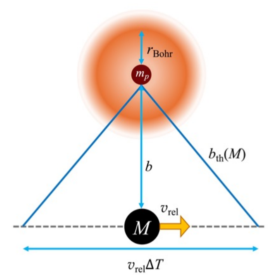
Baryogenesis from PBH explosions in the early universe

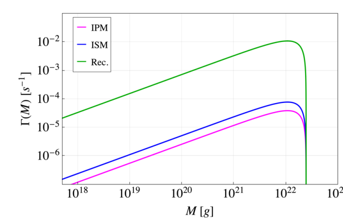
Klipfel, Kaiser, Trifinopoulos, and Vanvlasselaer
2603.XXXXX

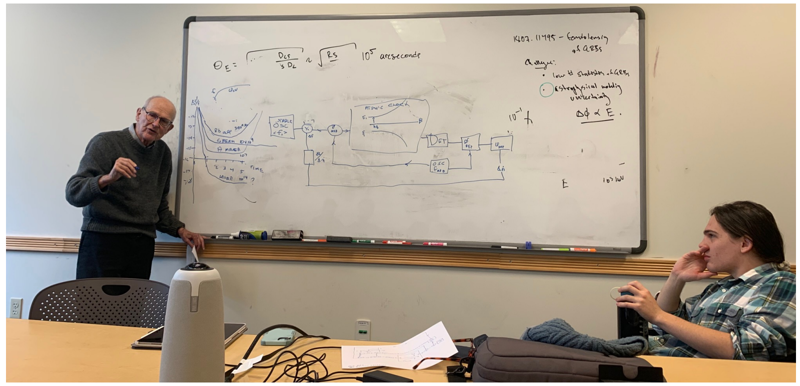


Gravitational ionization of neutral media by asteroid mass PBHs

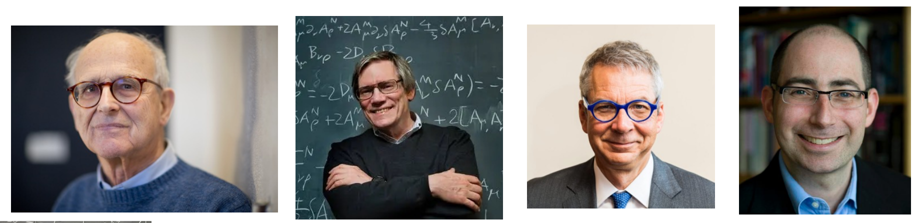
Klipfel and Kaiser, *Phys. Rev. D.* (2026), 2601.05935







Thank You



Recent Interest in PBHs

Seeds of earliest SMBHs and galaxies
- JWST observations with $z \gtrsim 10$

LIGO/Virgo/KAGRA observations:
- Searches for sub-solar mass black holes
- Mass-gap black holes

Dark matter candidate
- Very massive ⇒ **non-relativistic/cold**
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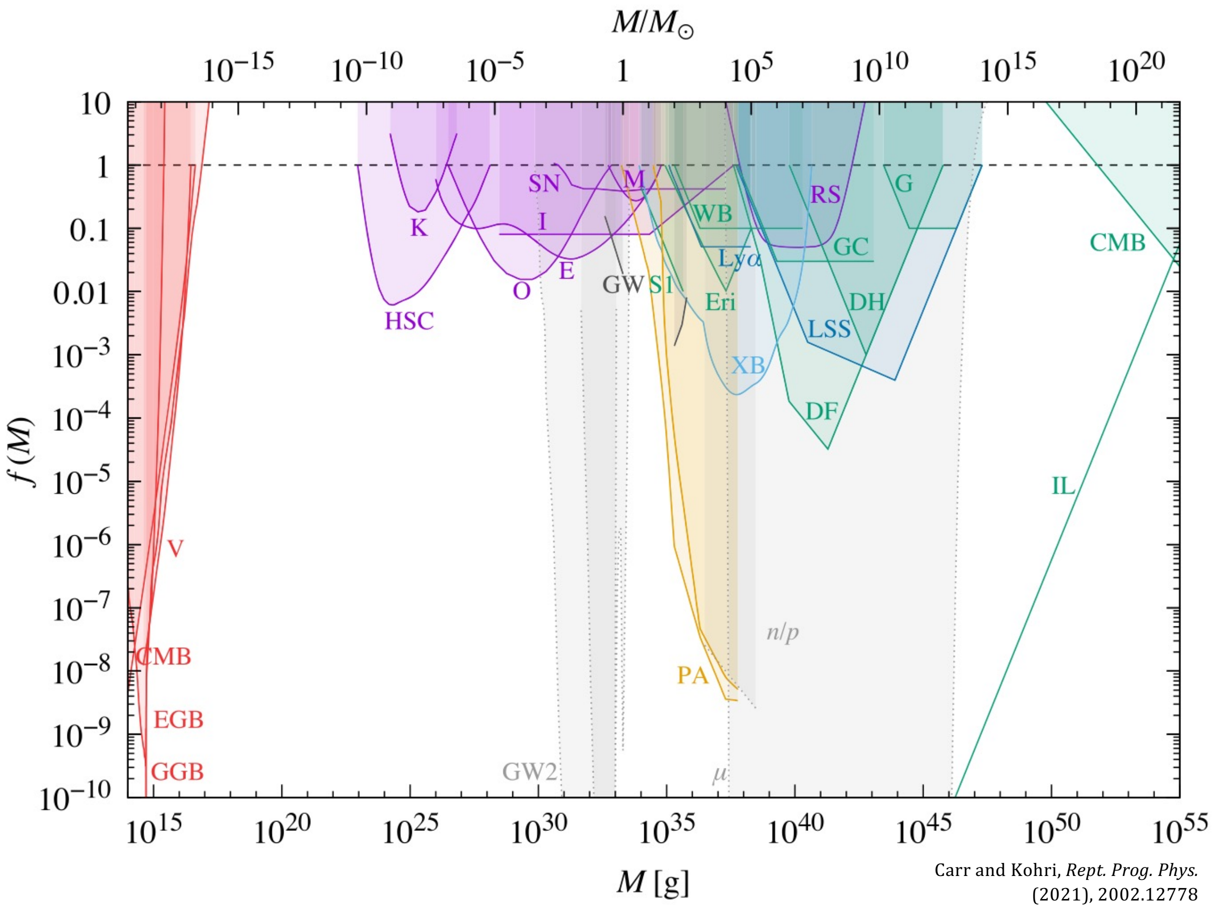
Constraints on PBH DM fraction



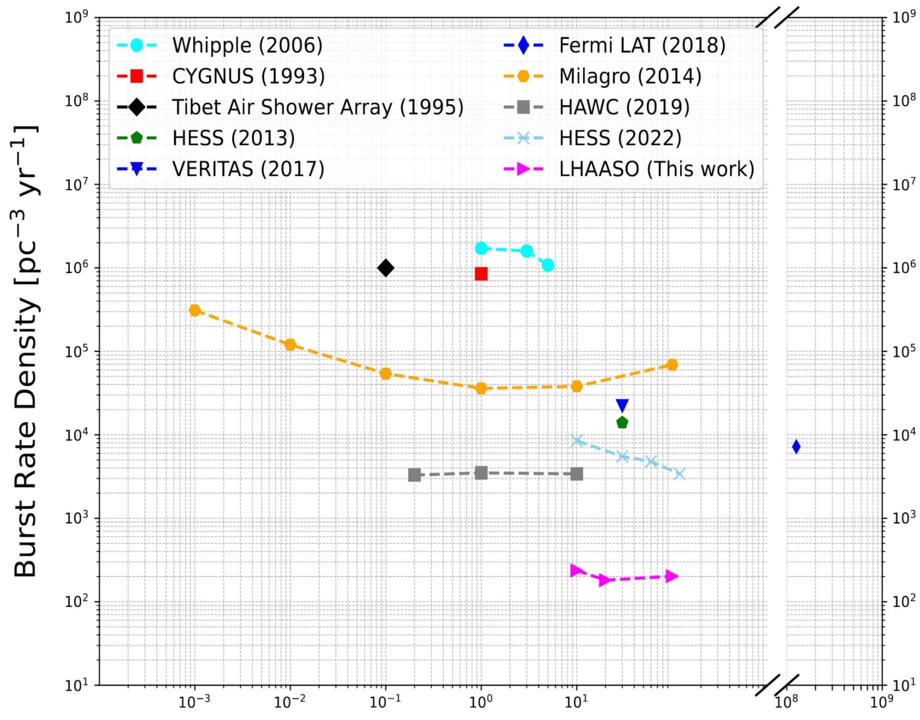
Carr and Kohri, *Rept. Prog. Phys.* (2021), 2002.12778

Multi-Messenger Detection?

A **nearby PBH explosion** in the Oort Cloud around 1800AU away would also generate **a γ-ray signal** across many instrumented energy bands

Could we see it?

	E_{min}	E_{max}	Signal Duration	Ref.
Fermi-LAT	20 MeV	100 GeV	3.2 yr	1802.00100
LHAASO	100 GeV	1 PeV	10-100 s	2505.24586
HAWC	100 GeV	50 TeV	0.1-10 s	1911.04356



Cao et al. (2025), 2505.24586.

Multi-Messenger Detection?

LHAASO:
Properties:
Energy range: ~100 GeV-10 PeV
$A_{\text{eff}} \sim 1000\ m^2$
Instantaneous FOV ~ 2.1 sr
Efficiency ~ 60%

Burst Search parameters:
Max burst duration: 100 s
Grid resolution: $1.2^o \times 1.2^o$

Estimated background:
~ 3 photons per grid square per 100 s

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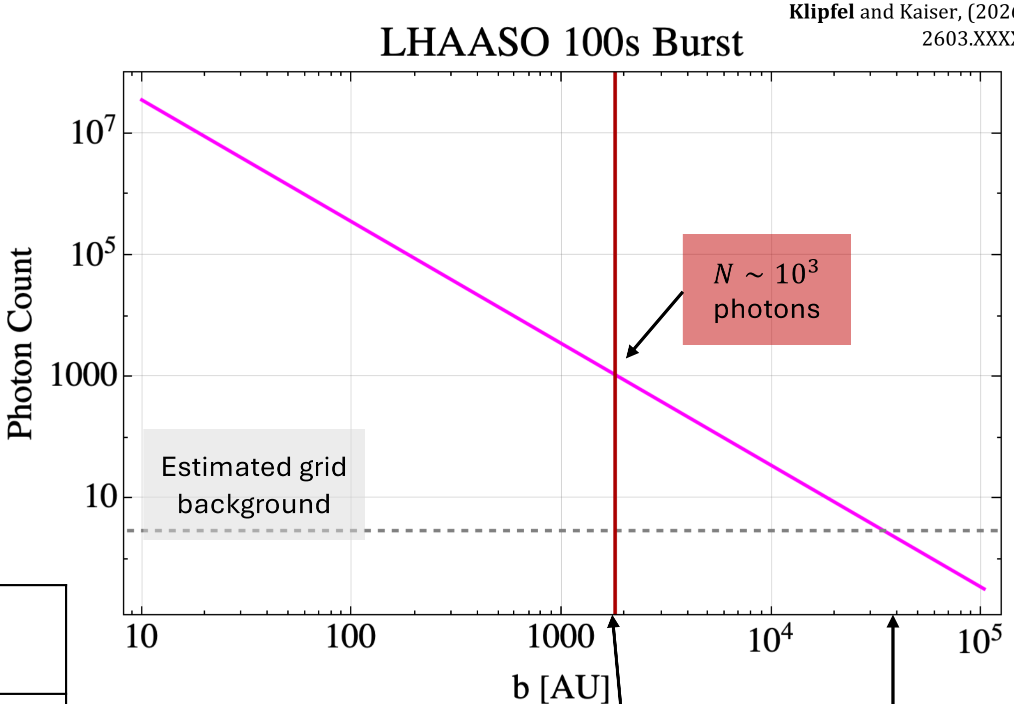

b = **1800 AU** explosion Estimated for KM3NeT event

Signal equal to background: b=0.17 pc