中国科学技术大学
University of Science and Technology of China

THE HONG KONG
UNIVERSITY OF SCIENCE
AND TECHNOLOGY

Ultrahigh-Energy Gamma Rays and Gravitational Waves from Primordial Exotic Stellar Bubbles

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Based on: 2105.11481

KEK-PH & KEK-Cosmo on PBH

Oct 19

Content

- Multi-messenger astronomy
- Exotic stellar bubble formation mechanism
- Observations of primordial black hole (PBH) stellar bubbles:
  - gamma rays
  - gravitational waves (GWs)
- Summary

ESA/Hubble

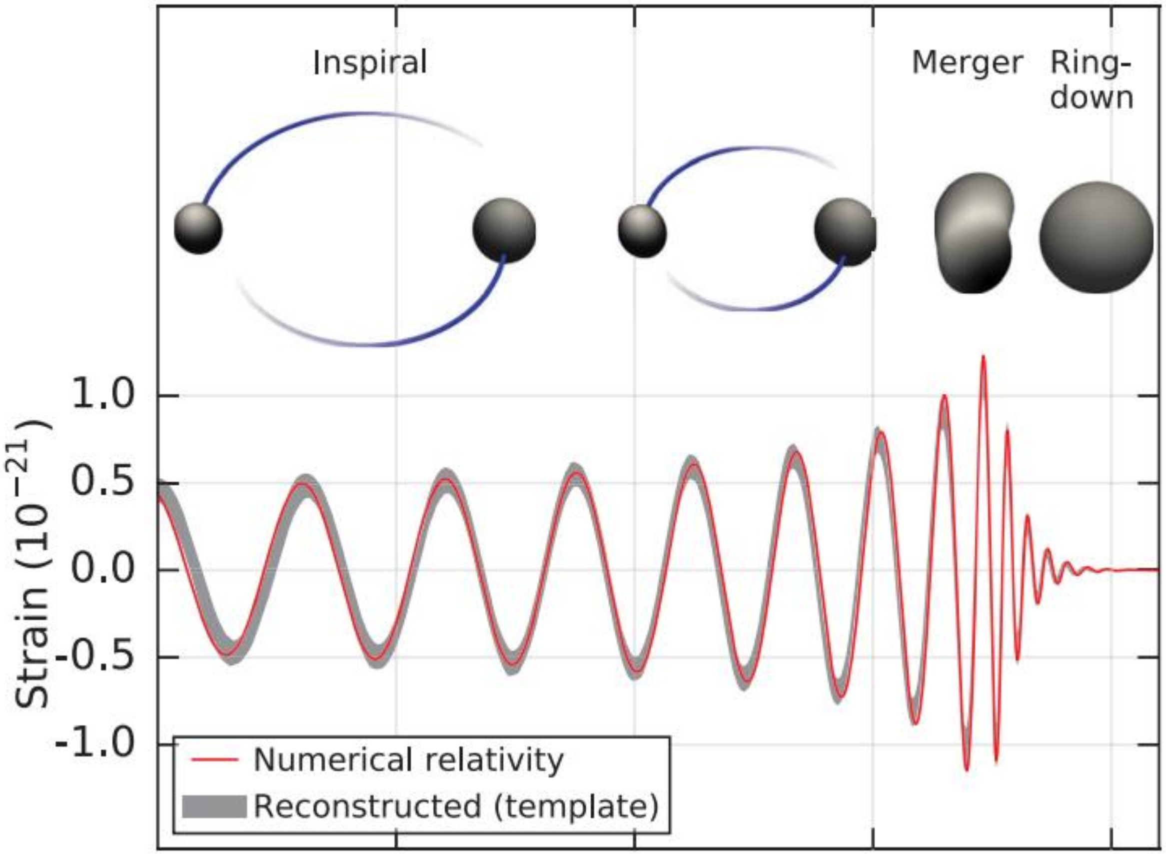

Object Thorne-Zytkow
Quark Star
Dark Matter Star
Frozen Star
Dark Energy Star
Boson Star
Quasi-Star
Blitzar
White Hole
Electroweak Star
Preon Star
Q-Star
By Edw.Aug

How to study them?

How to study them?

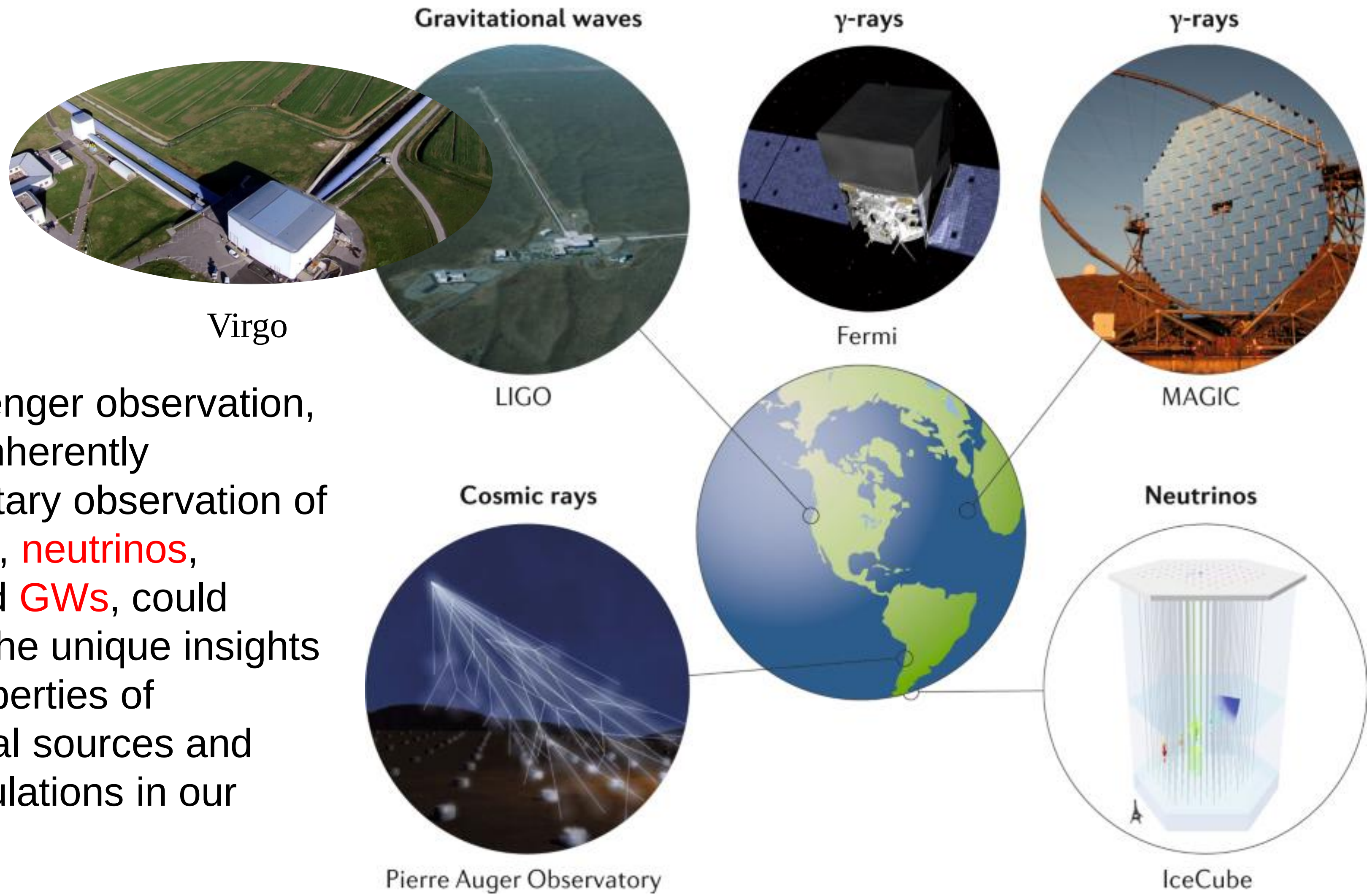
Multi-messenger astronomy!

GW150914



B. P. Abbott et al. Observation of Gravitational Waves from a Binary Black Hole Merger. Phys. Rev. Lett., 116(6):061102, 2016.

Multi-messenger astronomy

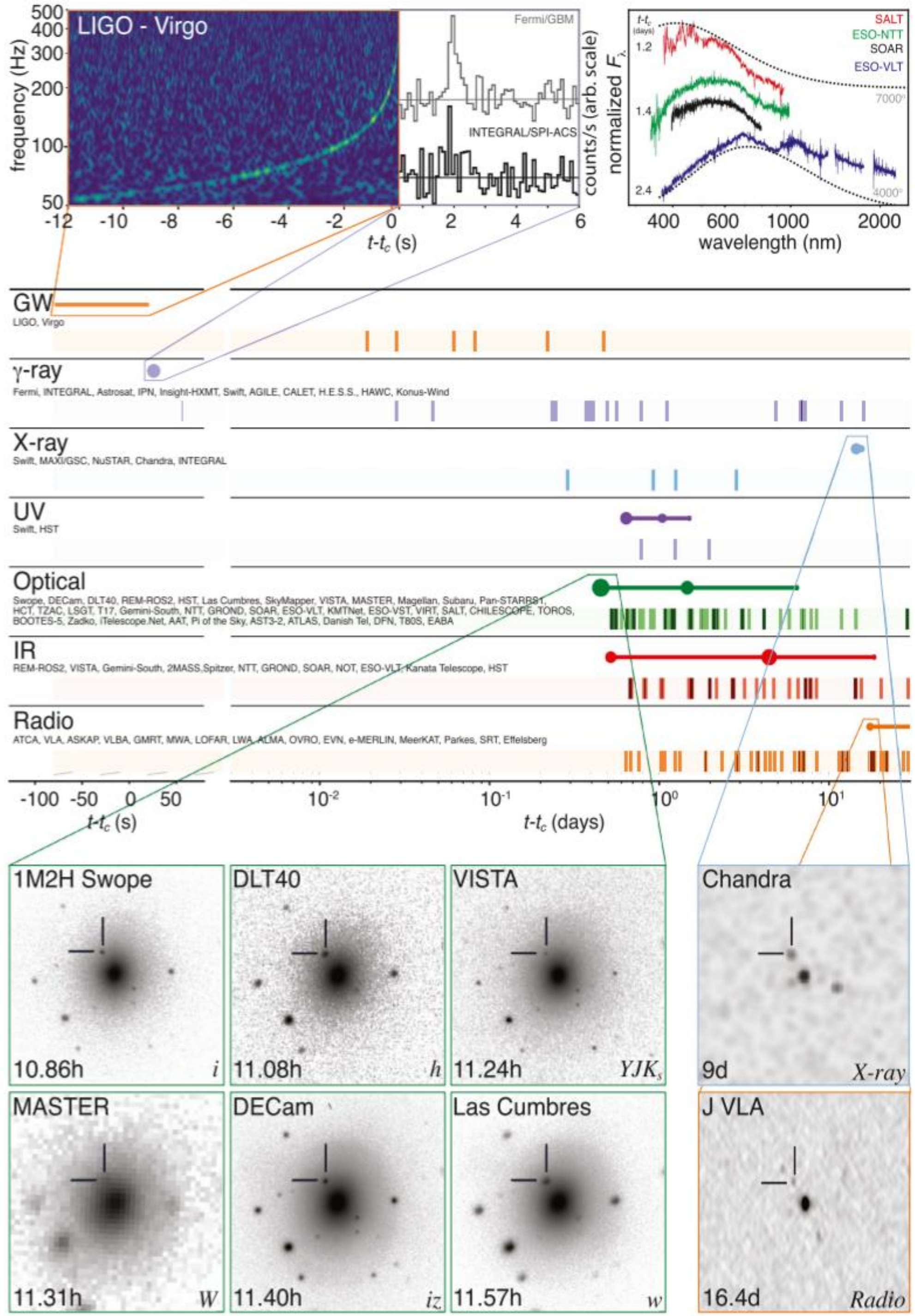


Multi-messenger observation, which is a inherently complementary observation of cosmic rays, neutrinos, photons and GWs, could provide us the unique insights into the properties of astrophysical sources and source populations in our Universe.

[Mészáros et al., Nature Rev.Phys. 1 (2019) 585-599; LIGO-G1200499-v1]

GW170817

Timeline of the discovery of GW170817, GRB 170817A, SSS17a/AT 2017gfo, and the follow-up observations are shown by messenger and wavelength relative to time t_c (GW event).



[Astrophys.J.Lett. 848 (2017) 2, L12]

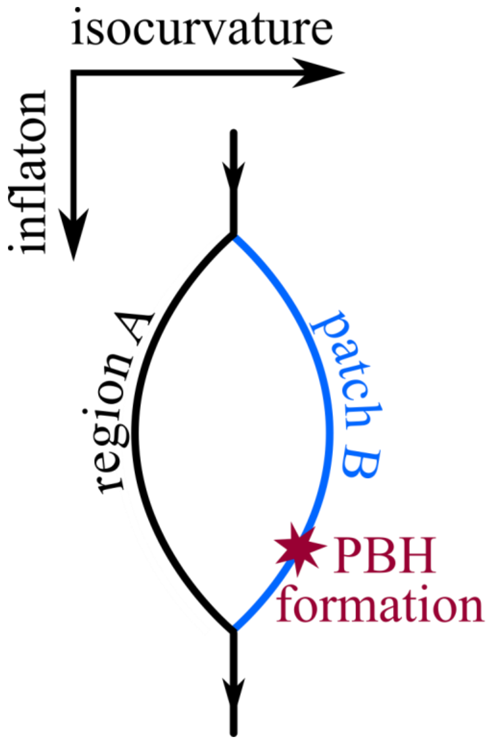
What else can we study?

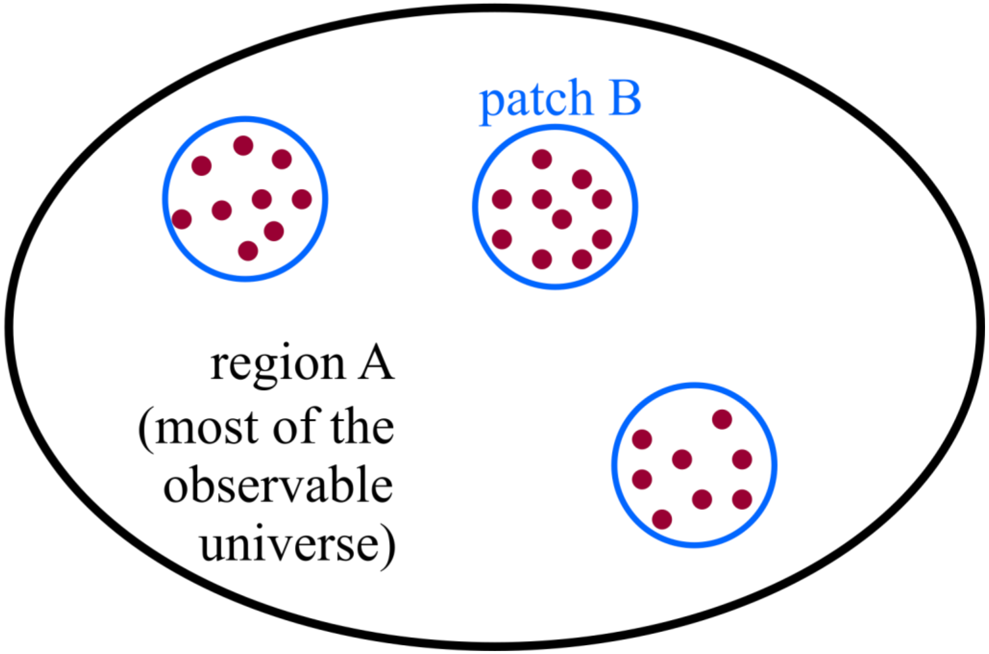
What else can we study?

Maybe some objects from primordial Universe

Exotic stellar bubbles

We put forward a novel class of exotic celestial objects that can be produced through new-physics phenomena occurred in the primordial Universe, such as quantum tunnelings, inhomogeneous baryogenesis and multi-stream inflation etc.

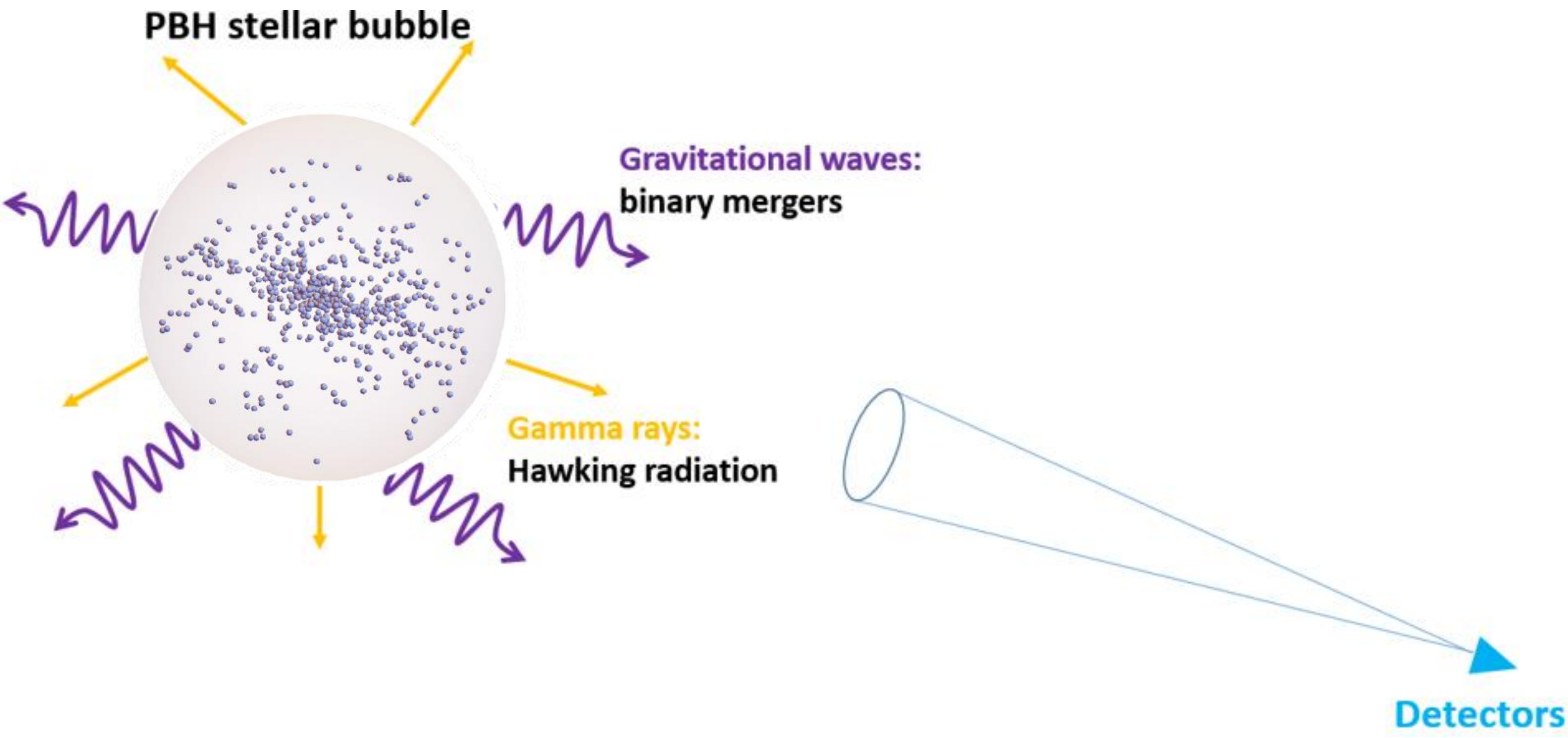




Multi-stream inflation potential

Position space of universe

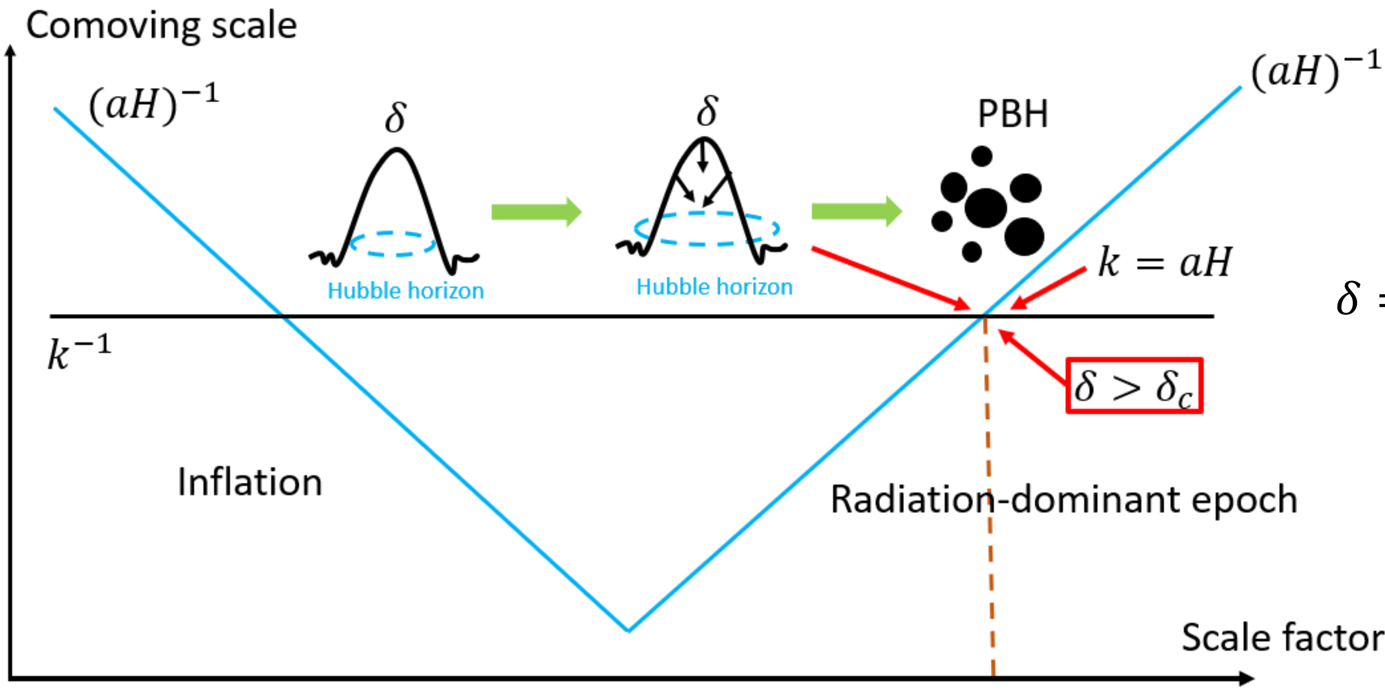
PBH stellar bubbles



Two observational windows for a PBH bubbles:

- gamma rays (Hawking radiation)
- gravitational waves (binary mergers)

PBH formation



$$\delta = \frac{\delta\rho}{\rho}$$

$$R_H \sim R > R_J$$

Hubble radius

Overdense region $\delta = \delta\rho/\rho$

Jeans length

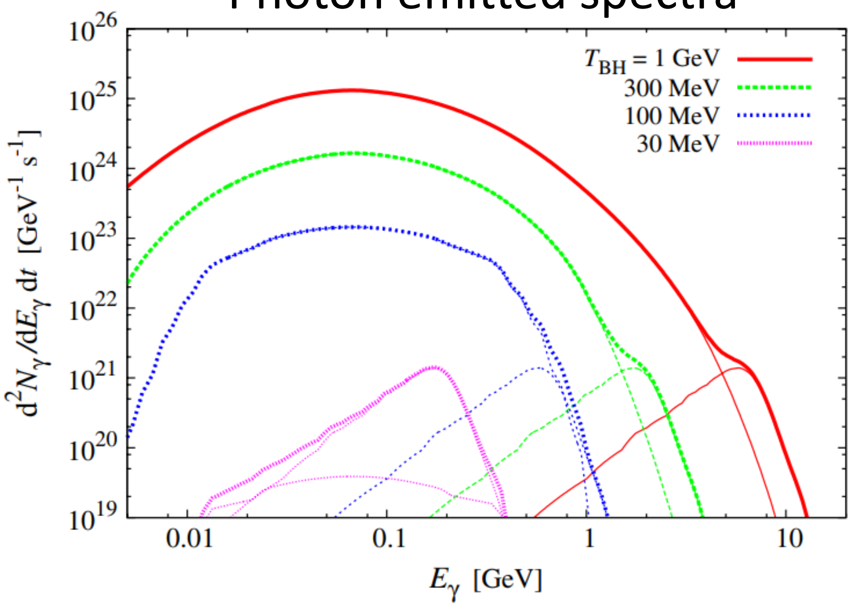
$$M_{PBH} \sim M_H \sim \frac{c^3}{G} t$$

Hawking radiation

Hawking radiation: $$\frac{d^2N}{dtdE} = \frac{1}{2\pi}\frac{\Gamma_s(E,M)}{e^{8\pi GME}-(-1)^{2s}}$$

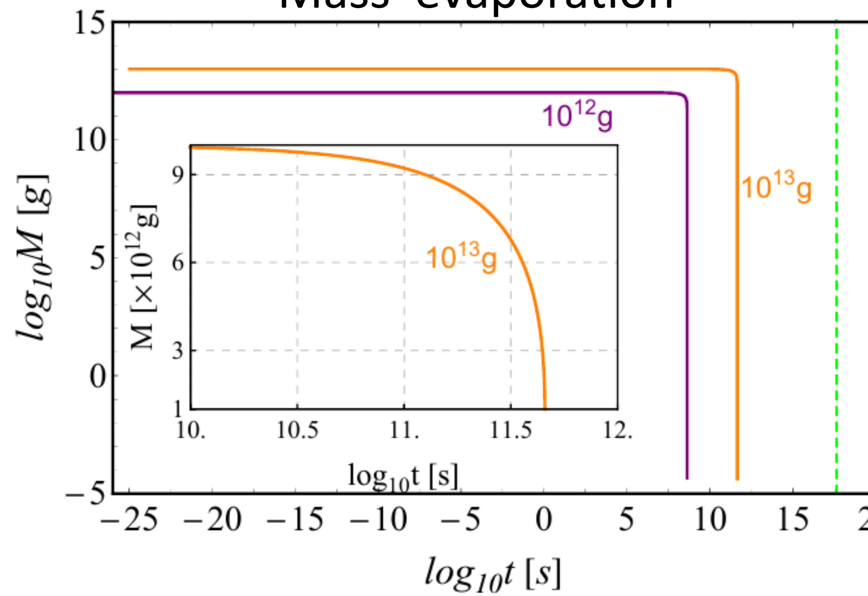
Standard emission picture: a BH emits only those particles which appear elementary on the scale of the radiated energy (A BH should emit all elementary particles whose rest masses are less than or of the order of the BH temperature).

Photon emitted spectra



[Carr et al., PRD 81, 104019 (2010)]

Mass evaporation



Radiation from Bubble

PBH bubble with lognormal distribution PBHs
The lognormal mass function

$$\psi_{\rm LN}(M) = \frac{f_{\rm PBH}}{\sqrt{2\pi}\sigma M}\exp\left[-\frac{\ln^2(M/M_{\rm pk})}{2\sigma^2}\right] \quad \psi(M) \equiv M n_{\rm PBH}(M)/\rho_{\rm DM}$$

The time-dependent physical number density of elementary particle emitted by a distribution of PBHs per unit time and per unit energy (BlackHawk):

$$\frac{{\rm d}^2 n_i}{{\rm d}t{\rm d}E}(E) = \int_{M_{\rm min}}^{M_{\rm max}} \frac{{\rm d}^2 N_i}{{\rm d}t{\rm d}E}(E,M) n_{\rm PBH}(M){\rm d}M$$

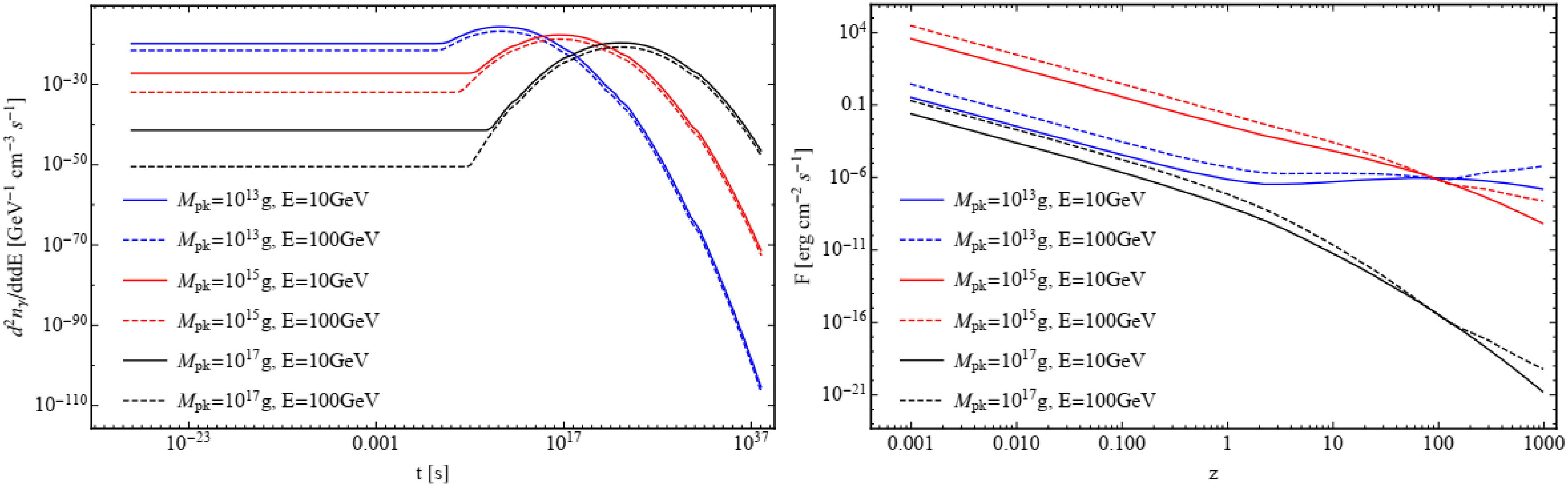
Radiation from Bubble

A PBH stellar bubble located at redshift z with an initial lognormal mass distribution

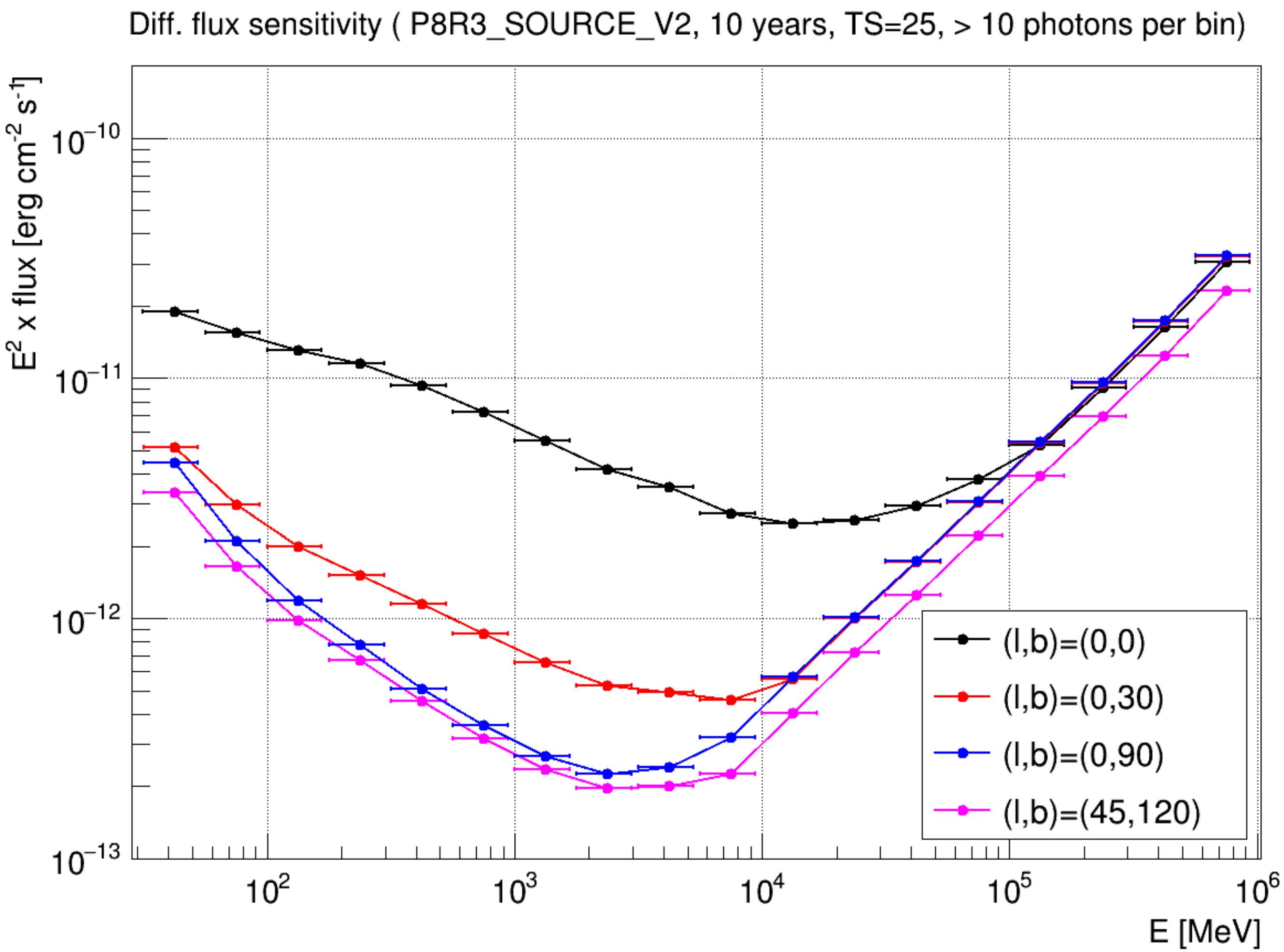
Bubble volume

The intrinsic luminosity: $$L(E,t) = E\frac{\mathrm{d}^2 n_\gamma}{\mathrm{d}t\mathrm{d}E} V\mathrm{d}E \simeq E^2 \frac{\mathrm{d}^2 n_\gamma}{\mathrm{d}t\mathrm{d}E} V$$

The photon flux observed on Earth: $$F(E,z) = \frac{L(E,z)}{4\pi d_L^2(z)}$$



Observation



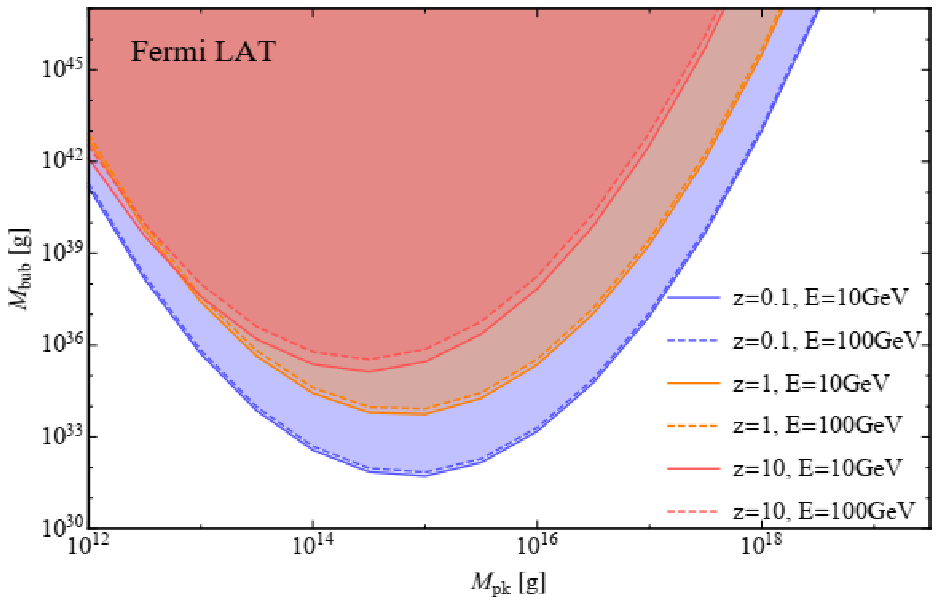
The point-source differential sensitivity in the 10-year observation of Fermi LAT for a high Galactic latitude (around the north Celestial pole) source:

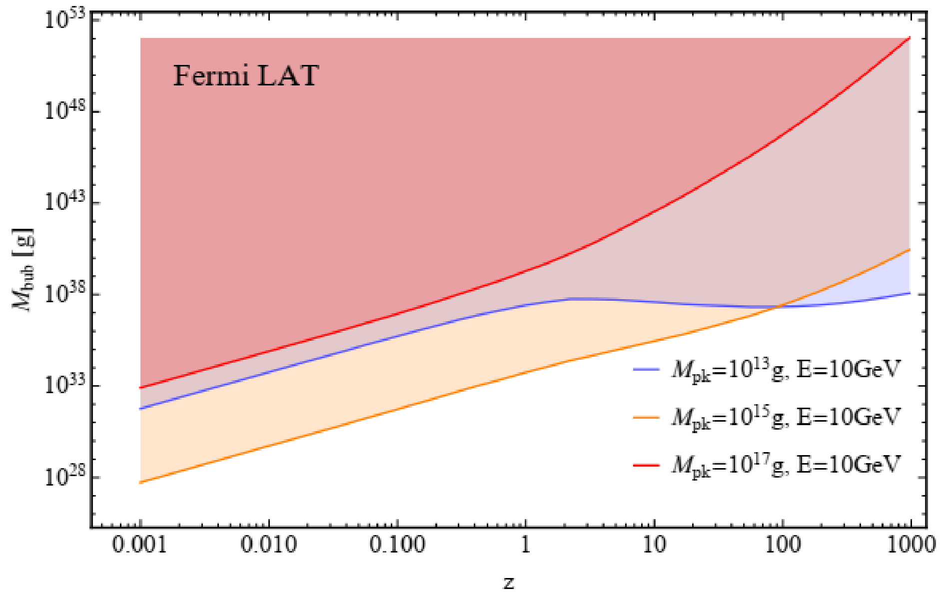
[https://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm]

Parameter Space

Parameter space: $\sigma, M_{pk}, M_{bub}, z$

$(M_{\rm bub},\ M_{\rm pk})$ σ=1 $(M_{\rm bub},\ z)$





The lowest bound:

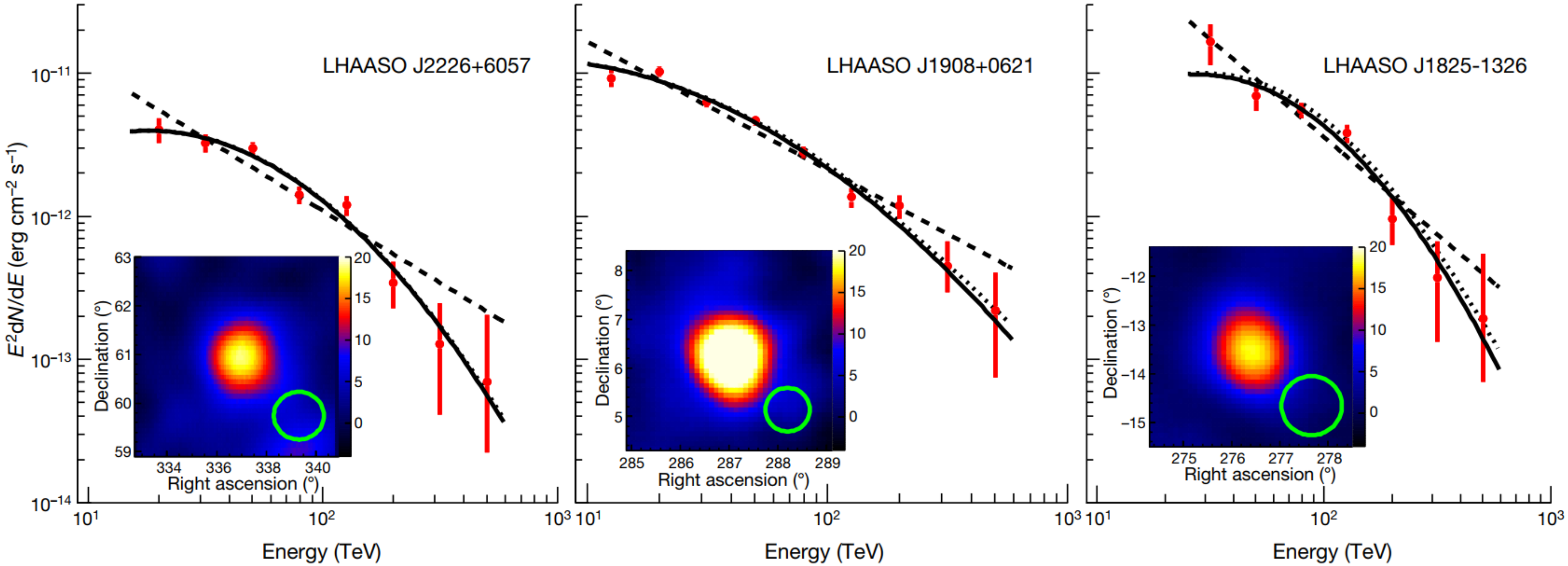
$$M_{\rm pk} \simeq 10^{15}{\rm g}$$

$$M_{\rm bub} \simeq 10^{32}{\rm g} \sim M_\odot$$

The closer the stellar PBH bubbles are to the Earth, the easier they could be probed.

UHE gamma ray astronomy

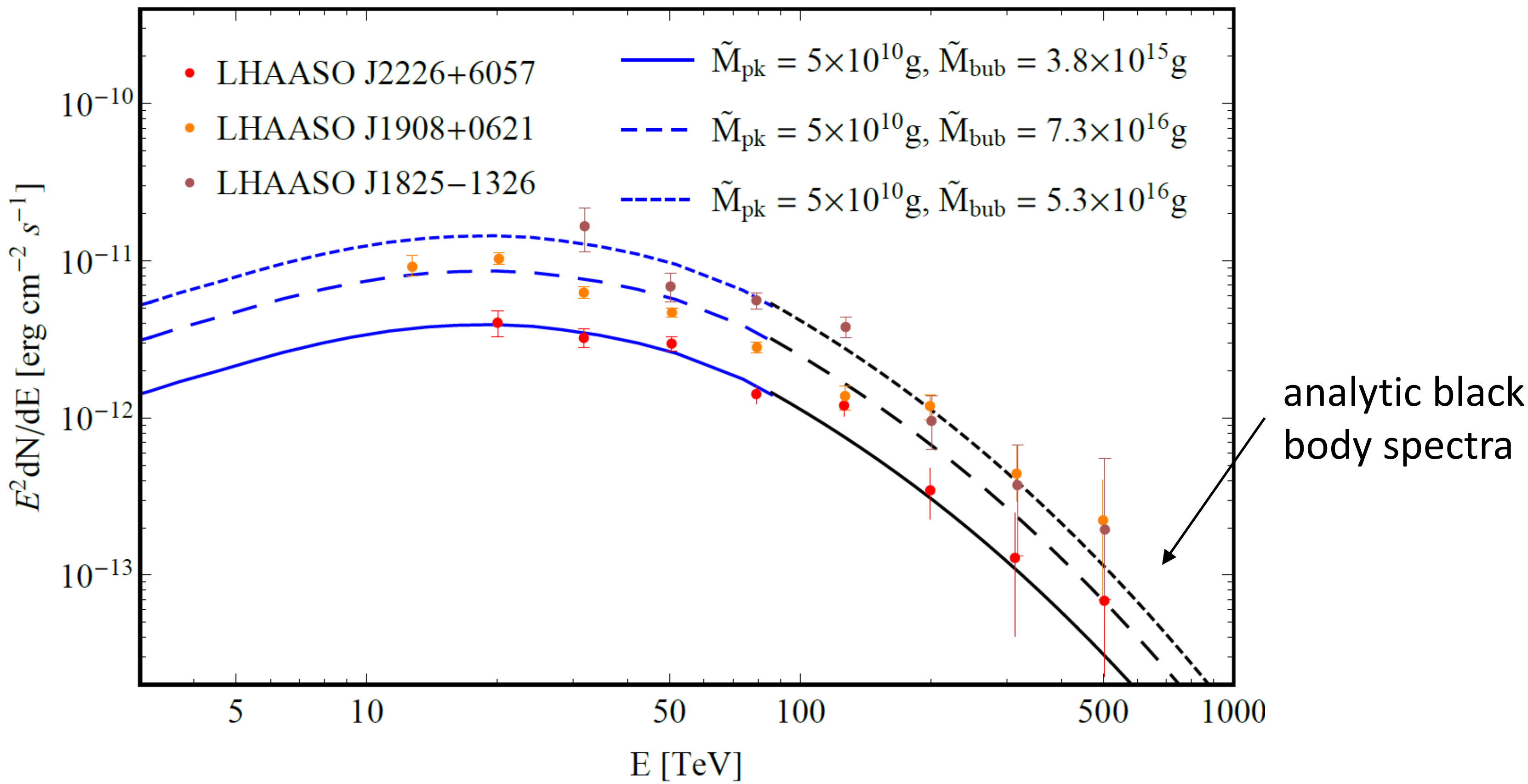
Recently, LHAASO reported the detection of more than 530 photons at energies above 100 teraelectronvolts and up to 1.4 PeV from 12 ultrahigh-energy γ-ray sources. These findings overturn our traditional understanding of the Milky Way and open up an era of UHE gamma astronomy.



[Cao, Z., Aharonian, F.A., An, Q. *et al*. *Nature* (2021).]

The astrophysical sources responsible for these events are under debate.

LHAASO data fit



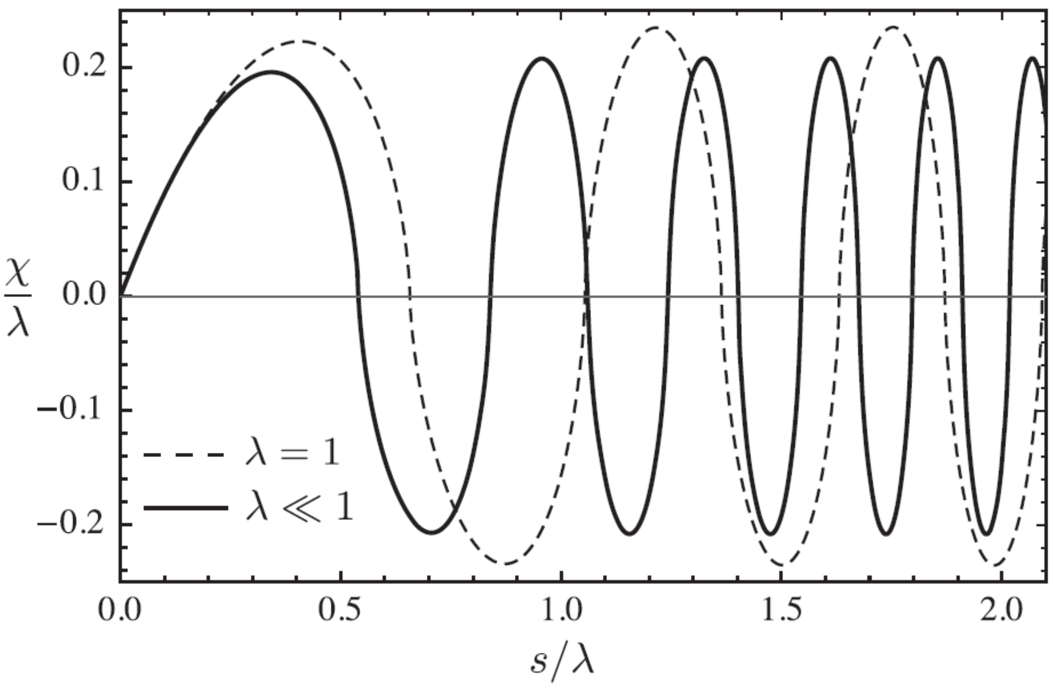
- The present lognormal mass distribution;
- $\sigma = 1$, which is allowed to vary and leads to better fits to observations.

PBH binary formation

The equation of proper separation r of two nearby PBHs with mass M is

$$\ddot{r} + \left(\dot{H} + H^2\right)r + \frac{2M}{r^2}\frac{r}{|r|} = 0$$

Initially PBHs follow Hubble flow, $r(a) = a\, r_{ini}$, the numerical solution is



According to the solution, the PBH decouple at

$$z \approx \frac{3(1 + z_{eq})}{\lambda} - 1$$

λ is ratio of ρ_{eq} and binary PBH density

Ali-Haïmoud, Yacine, Ely D. Kovetz, and Marc Kamionkowski. "Merger rate of primordial black-hole binaries." *Physical Review D* 96.12 (2017): 123523.

GW radiation

After PBH binary decoupling from the background, the merger time is

$$t = \frac{3}{85}\frac{a^4}{G^3 m_1 m_2 M} j^4$$

Applying the initial distribution of major axis a and dimensionless angular momentum j, the comoving merger rate of PBH binaries is

$$R(t) = \sum \rho_{PBH} \min(\frac{P(m_j)}{m_i}, \frac{P(m_i)}{m_j}) \Delta \frac{dP}{dt}$$

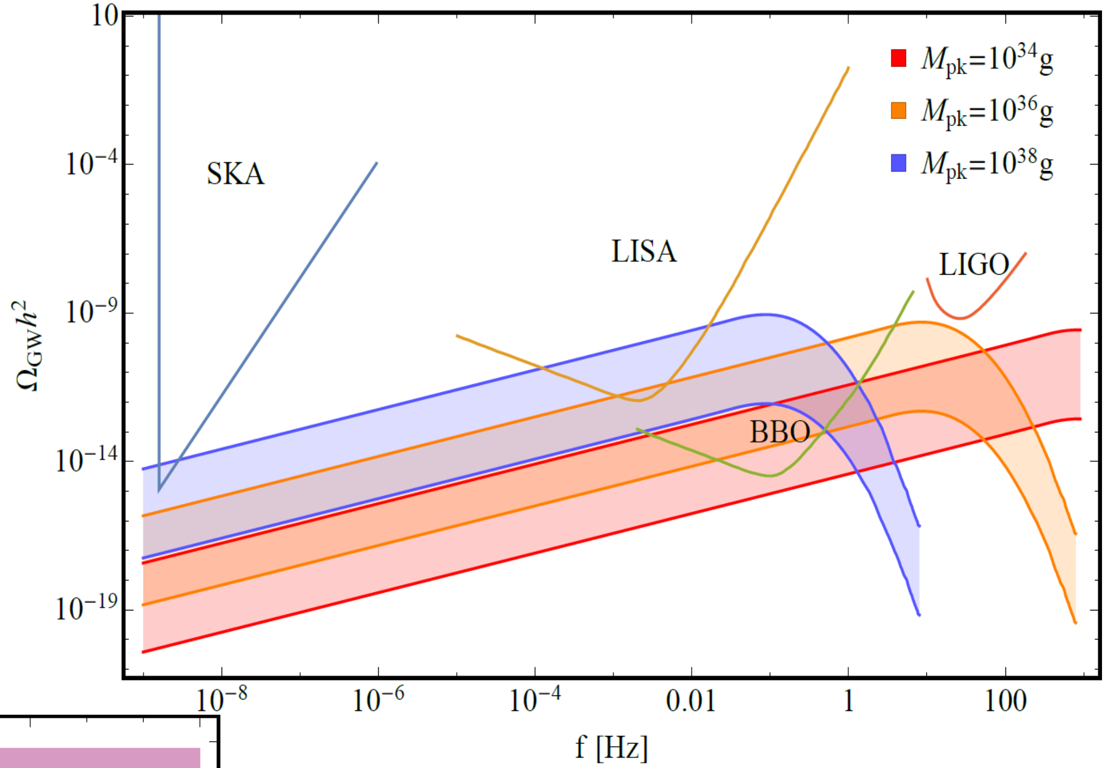
Observed GW energy density

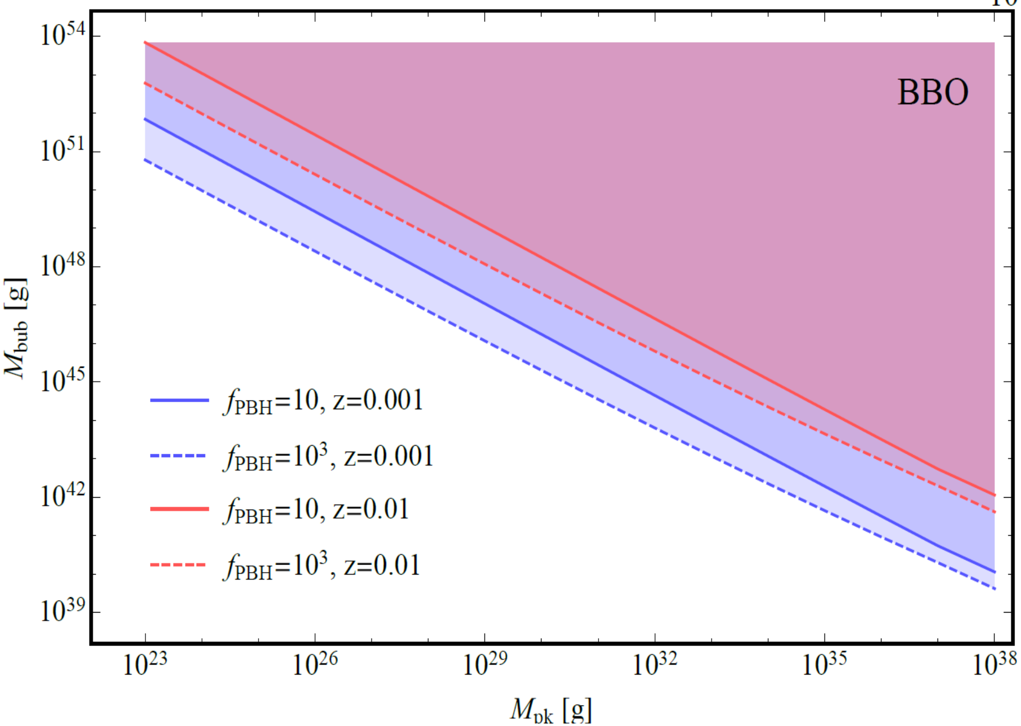
$$\Omega_{GW}(f) = \frac{1}{\rho_c}\frac{1}{4\pi d_L^2} f_r \frac{dE_{GW}}{df_r} R$$

The energy emission per frequency interval in the rest frame of source

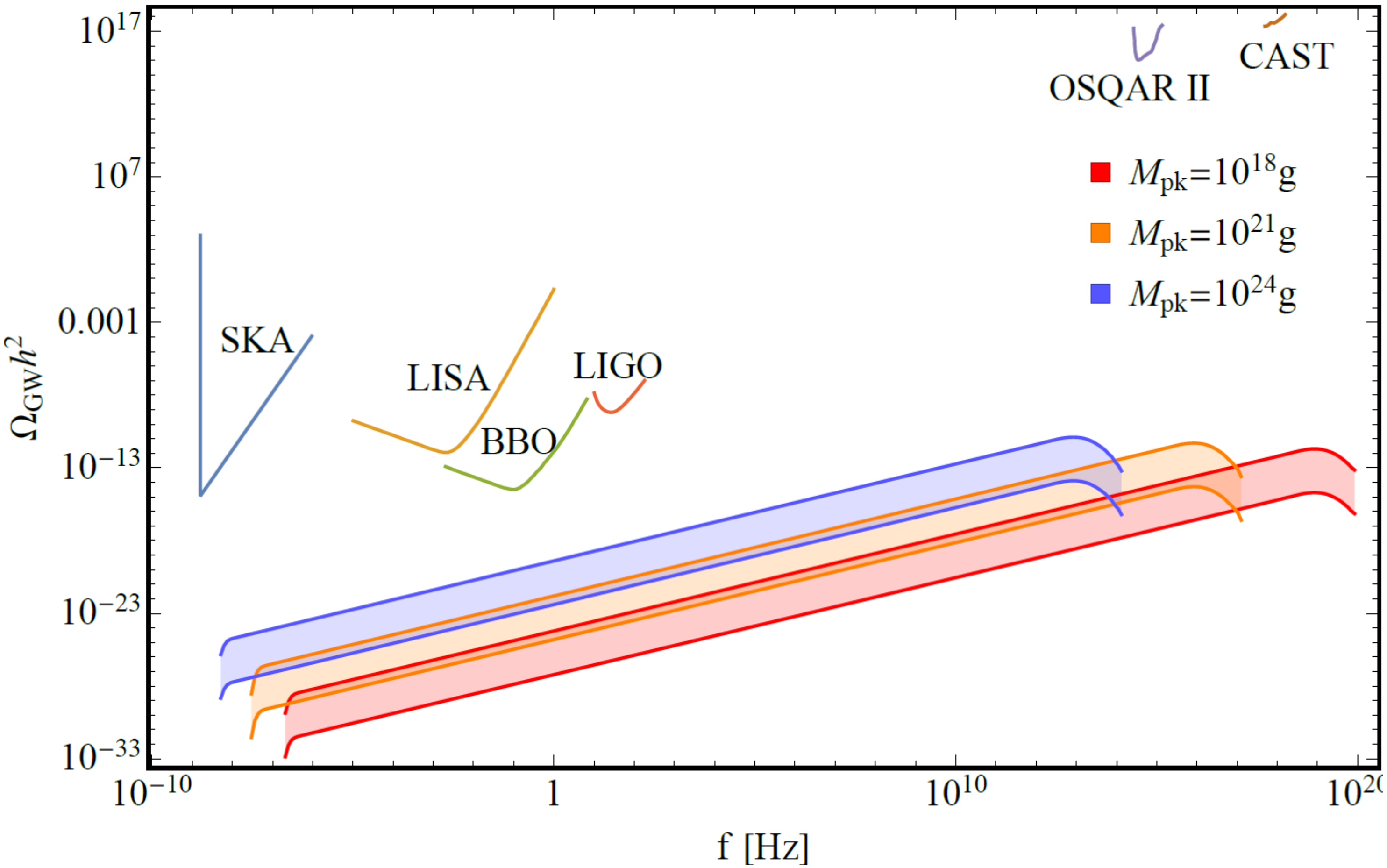
$$\frac{dE_{GW}}{df_r} = (\pi G)^{2/3}\mathcal{M}_c^{5/3} \times \begin{cases} f_r^{-1/3} & , f_r < f_1 \\ f_r^{2/3} f_1^{-1} & , f_1 \le f_r < f_2 \\ f_4^4 f_r^2 [f_1 f_2^{4/3} (4(f_r - f_2)^2 + f_4^2)^2]^{-1} & , f_2 \le f_r < f_3 \end{cases}$$

Parameter Space





UHF GW



$$\Omega_{GW,pk} \sim M_{pk}^{5/37}$$

Potential detection in future ultrahigh frequency experiment

Summary

- We propose the hypothetical possibility of stellar bubbles, which are starlike objects in the sky with exotic features;
- We analyze EM and GW observational windows for a PBH stellar bubble. Impressively, this scenario can make a decent fit to the ultrahigh-energy gamma-ray events discovered by LHAASO;
- Cosmic neutrinos and ultra-high frequency GWs could also be observational windows for these primordial stellar bubbles.

Thank You

PBH Stellar Bubble