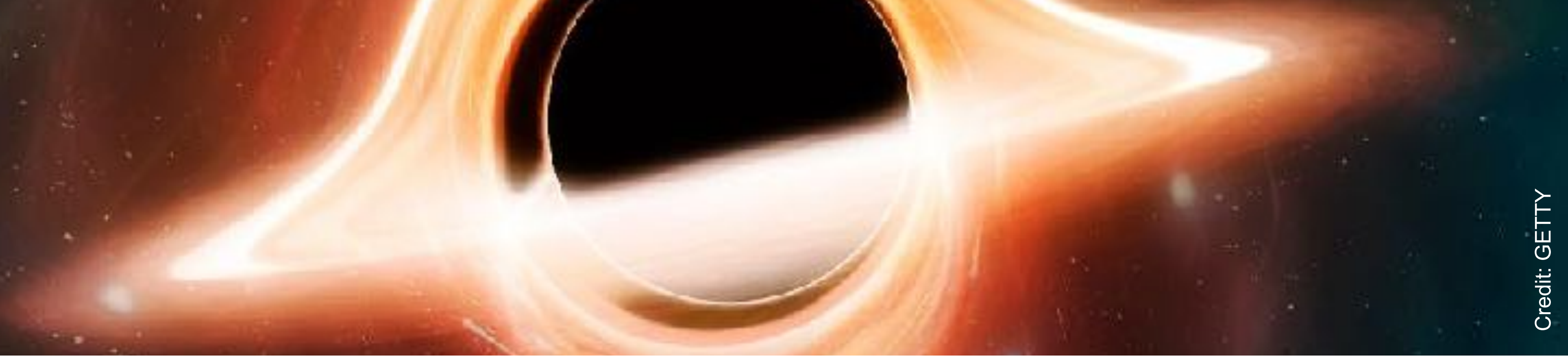

Exploring Primordial Black Holes from Multiverse with Optical Telescopes

Focus week on PBH, Kavli IPMU, Kashiwa (Japan)
December 4, 2019

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Acknowledgments…

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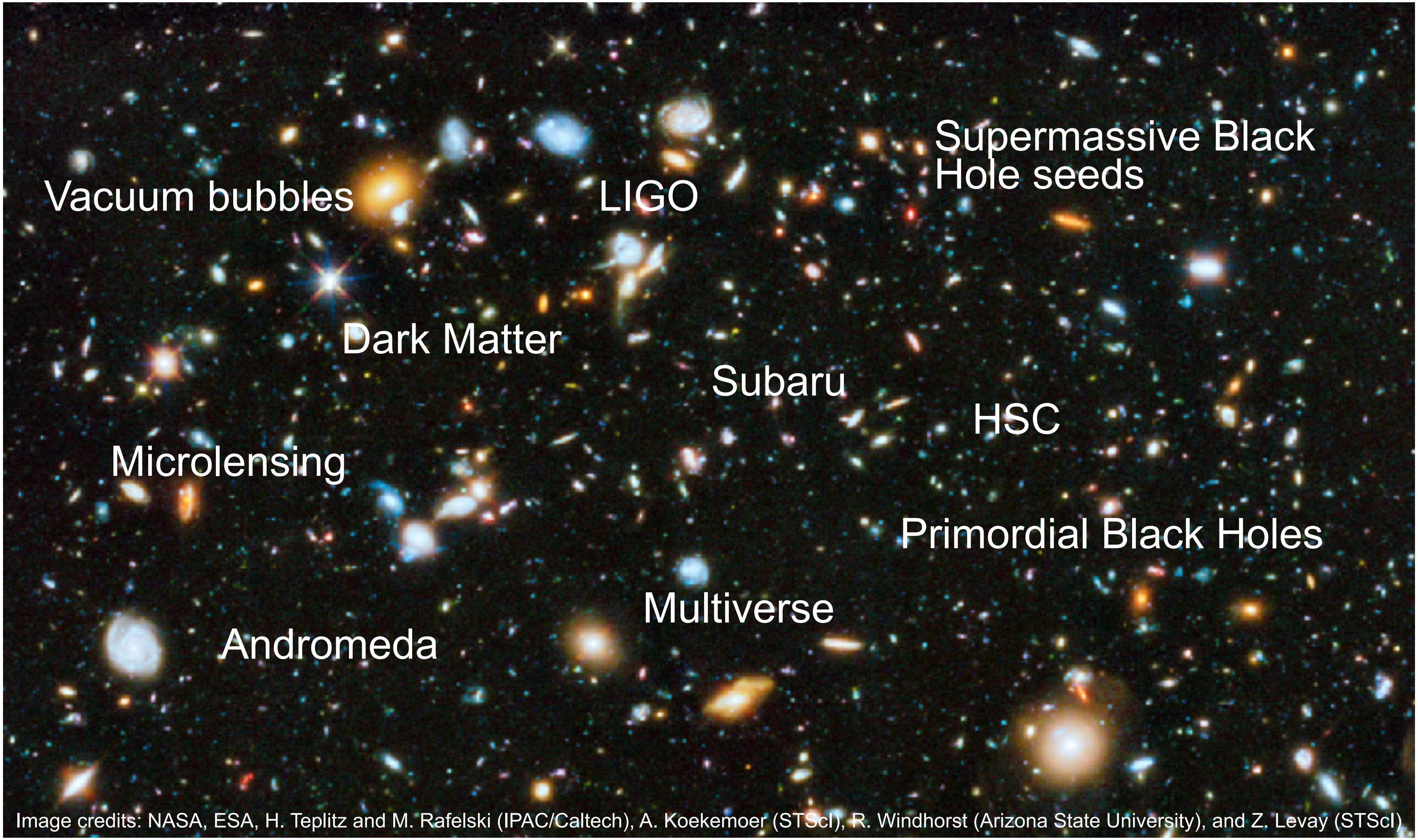
Credit: https://www.japan-guide.com

Thanks to the organizers of the Focus Week on Primordial Black Holes!

A long time ago in a galaxy not too far,
far away....

Images credits: Star Wars (movie, 1977)

Some keywords



Outline of the talk

Primordial Black Holes & multi-messenger astronomy

- Primordial Black Holes in a peanut-shell
- Experimental status: Subaru, LIGO and all of that
- Why multi-messenger astronomy?
- Gravitational waves + photons = Primordial Black Holes

Bubbling bubbles and Primordial Black Holes

- Nucleation of bubbles in the early universe
- From one, many: a multiverse scenario

One spectrum to rule them all

- The shape of the wide mass spectrum
- Discovery potential with Subaru/HSC

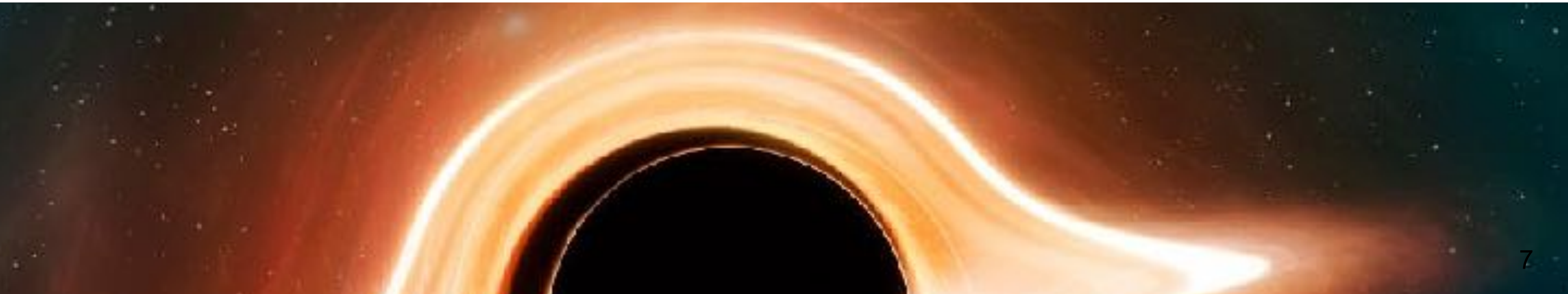
Conclusions

Primordial Black Holes & multi-messenger astronomy

Primordial Black Holes in a peanut

Primordial Black Holes are a type of black hole that formed soon after the Big Bang

- They can solve many cosmological conundra!
- Dark matter: the only dark matter candidate that is not necessarily made of new particles
- OGLE and quasar microlensing events
- Can seed supermassive black holes
- LIGO signal
- Perhaps Subaru detected one
- Miscellanea



Many production mechanisms

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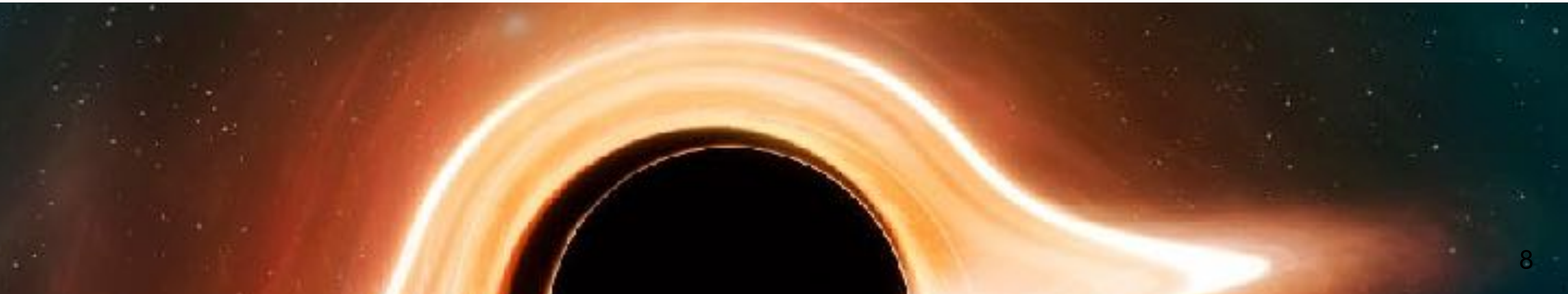
A LOT of possible production mechanisms (Carr’s talk)

- Phase transitions: topological defects are formed through the Kibble mechanism, and shrink to PBH
- Soft equation of state (somewhat related to phase transitions too)
- Large density fluctuations
- Scalar field fragmentation to Q-balls (non-topological solitons) which collapse to PBHs, Kusenko’s talk
- Many possible variations (see references in astro-ph/0310838, 0801.0116), see also Kawasaki’s talk



How can we detect PBHs?

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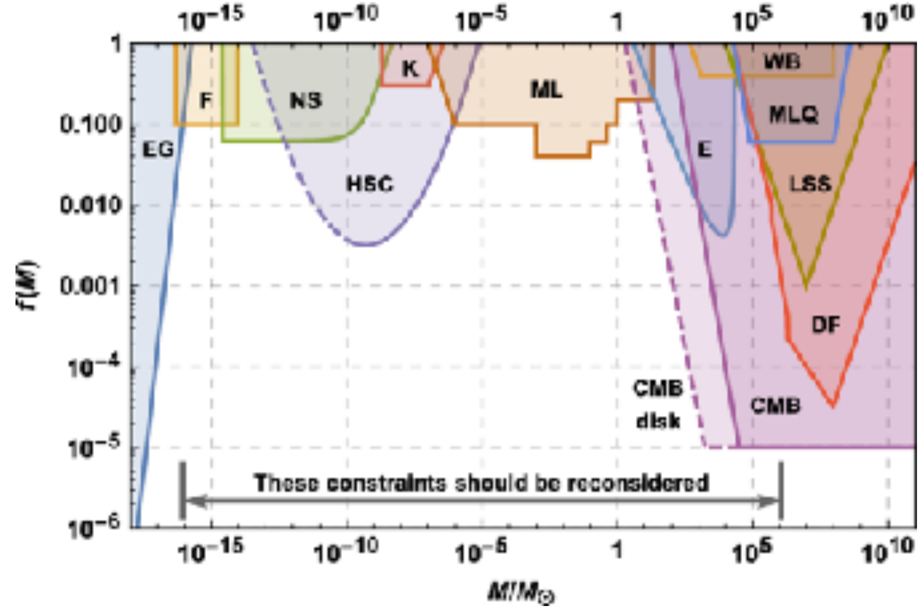
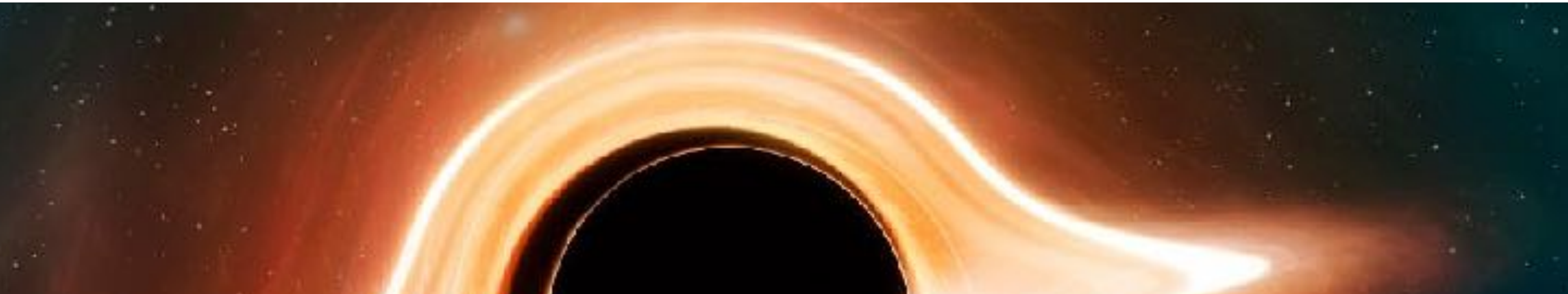
A LOT of constraints (?)

- Hawking's radiation, femtolensing, microlensing, CMB, wide binaries disruption… (not even all shown here!)
- Seems like PBHs cannot account for all the DM





How can we detect PBHs?

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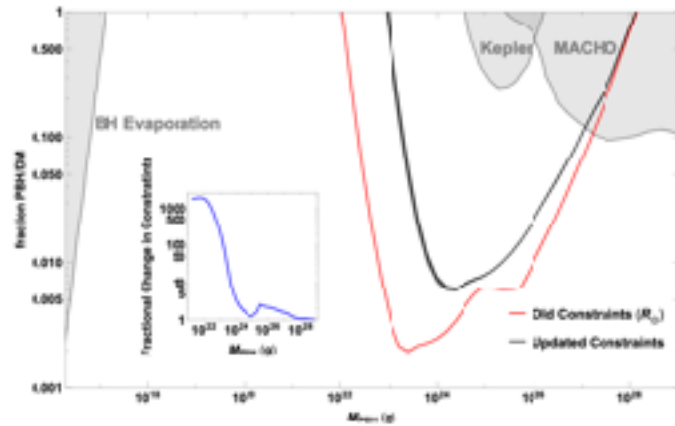
Should we trust all the constraints?

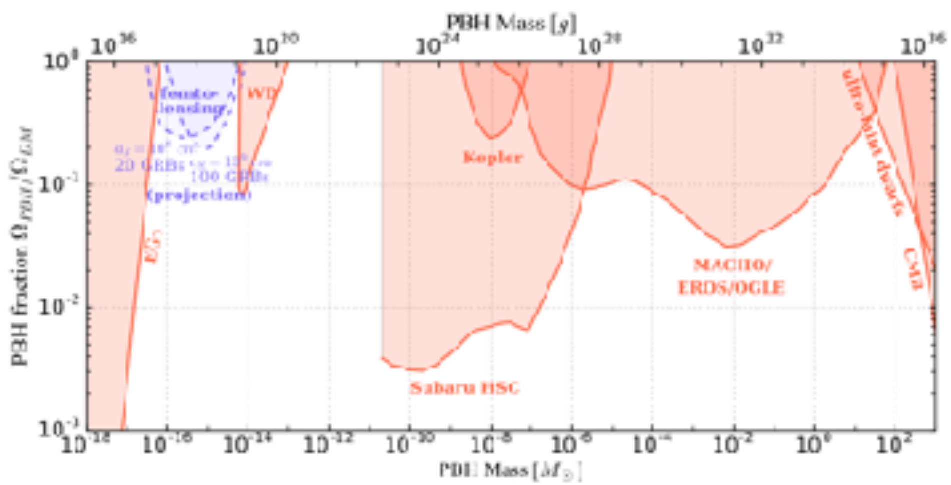
- **HSC bounds** must be modified to account for finite size of the sources (it is more likely to observe $10M_\odot$ than $1M_\odot$ stars), see 1910.01285

- Same goes for **femto-lensing**: most of GRBs previously considered are too large! (on the right it is a projection, not a constraint), see 1807.11495

- **White dwarf** bounds and **neutron star** bounds were initially very naive (see Kusenko's talk)

- Seems like on the one hand we have a new window for PBH as dark matter! **But it is now more difficult to probe…**





How can we detect PBHs?

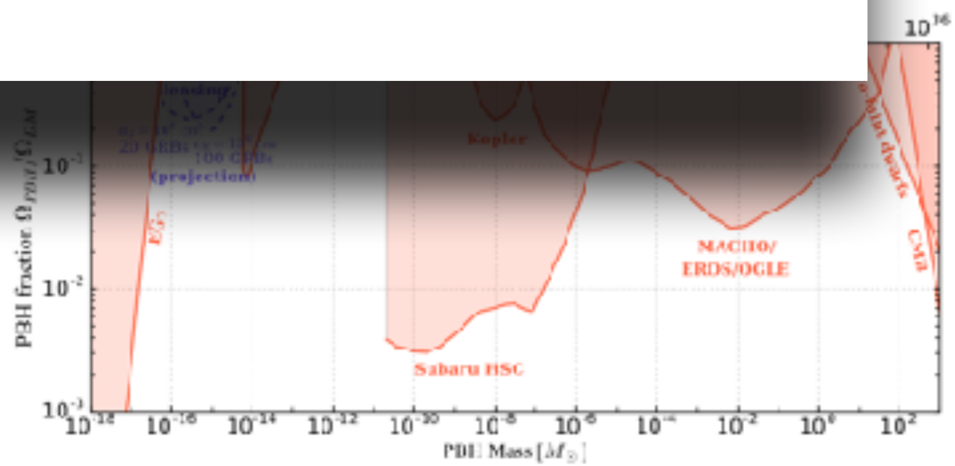
Should we trust all the constraints?

- **HSC bounds** must be

Uhm. Perhaps we should start trying to detect/constrain wide mass functions…

neutron star bounds were initially very naive (see Kusenko's talk)

- Seems like on the one hand we have a new window for PBH as dark matter! **But it is now more difficult to probe…**

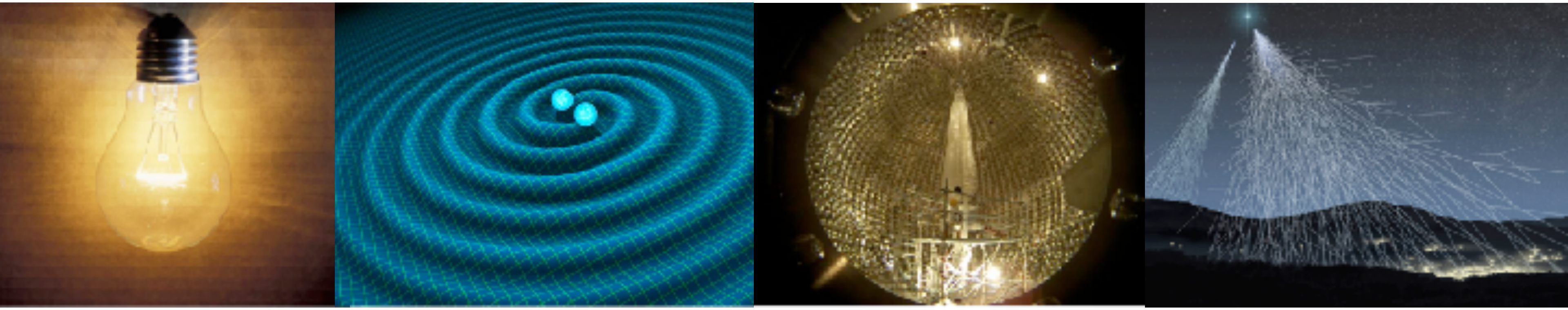


Why multi-messenger astronomy?

From Wikipedia…

Multi-messenger astronomy is astronomy based on the coordinated observation and interpretation of disparate "messenger" signals. The four extrasolar messengers are ***electromagnetic radiation****,* ***gravitational waves****,* ***neutrinos****, and* ***cosmic rays****. They are created by different astrophysical processes, and thus reveal different information about their sources.*

https://en.wikipedia.org/wiki/Multi-messenger_astronomy

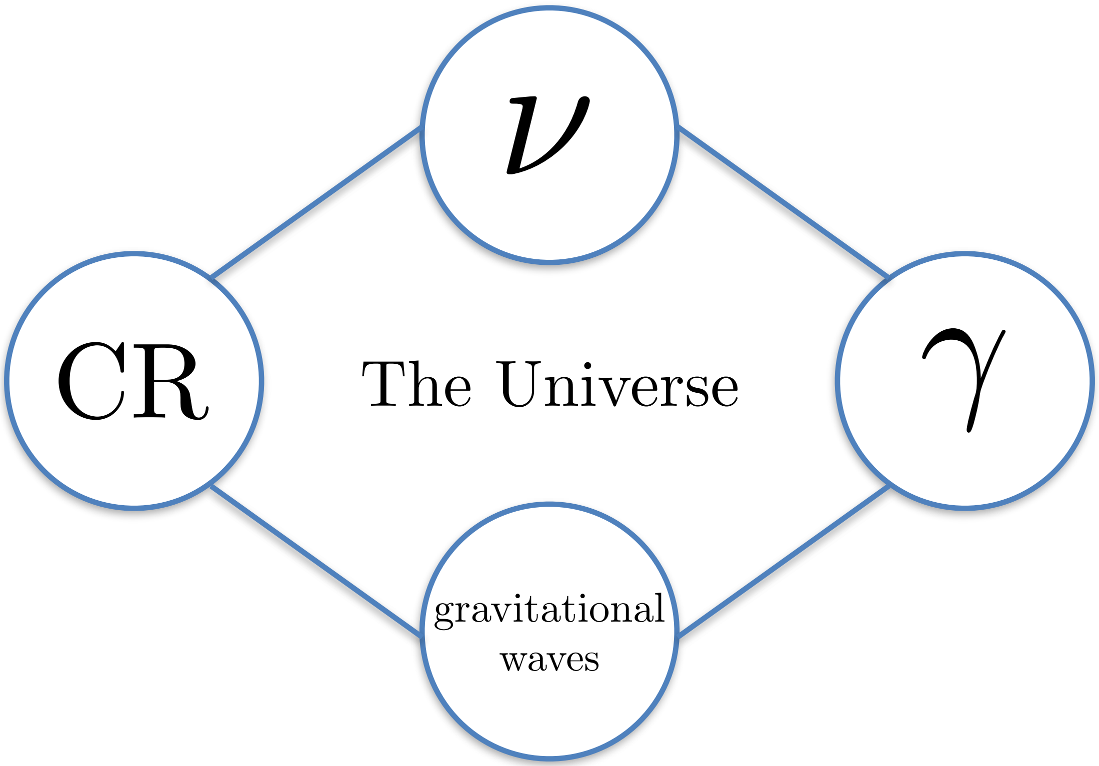


Images credits: Rex, R. Hurt/Caltech-JPL/EPA, Virginia Tech Physics, ASPERA/Novapix/L. Bret

A new way to explore the universe

UCLA

The universe is no longer explored with electromagnetic radiation alone!



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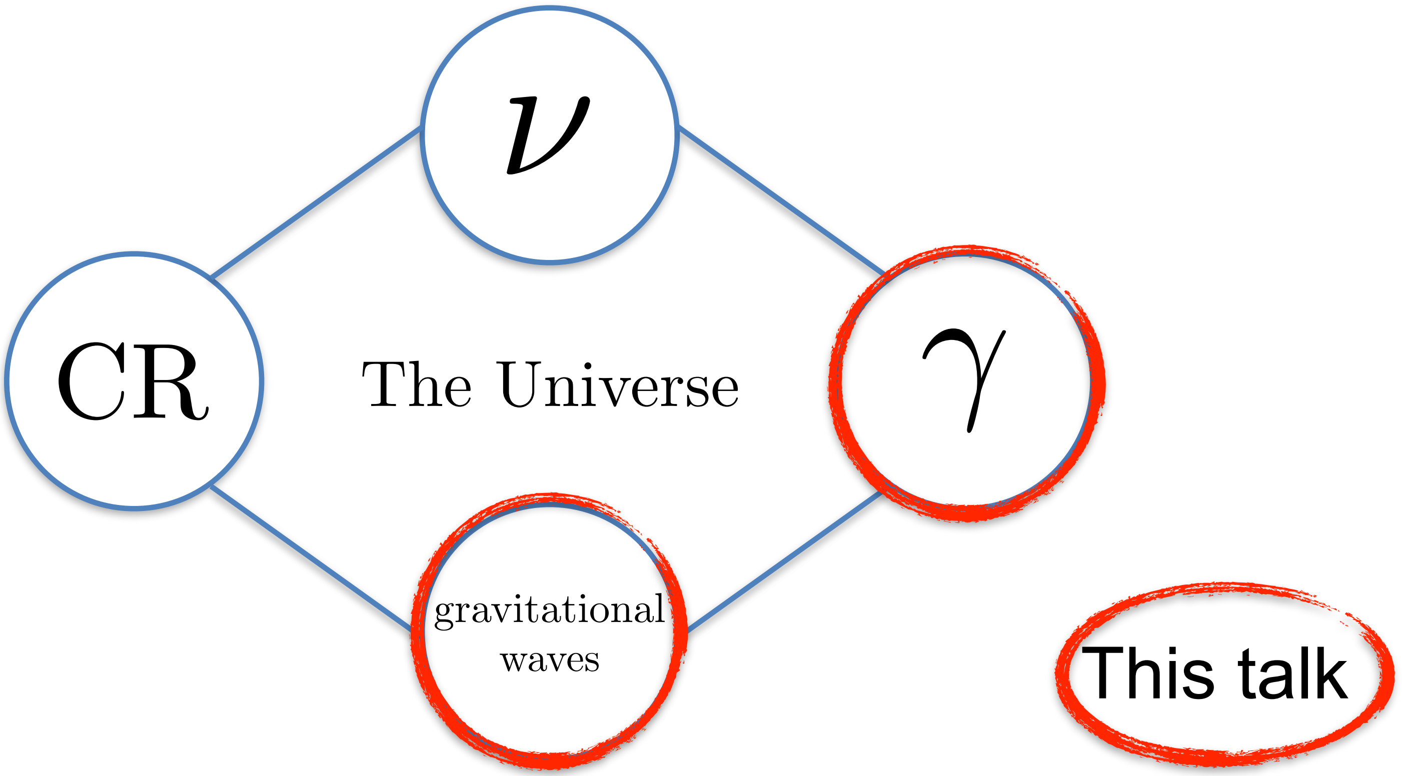
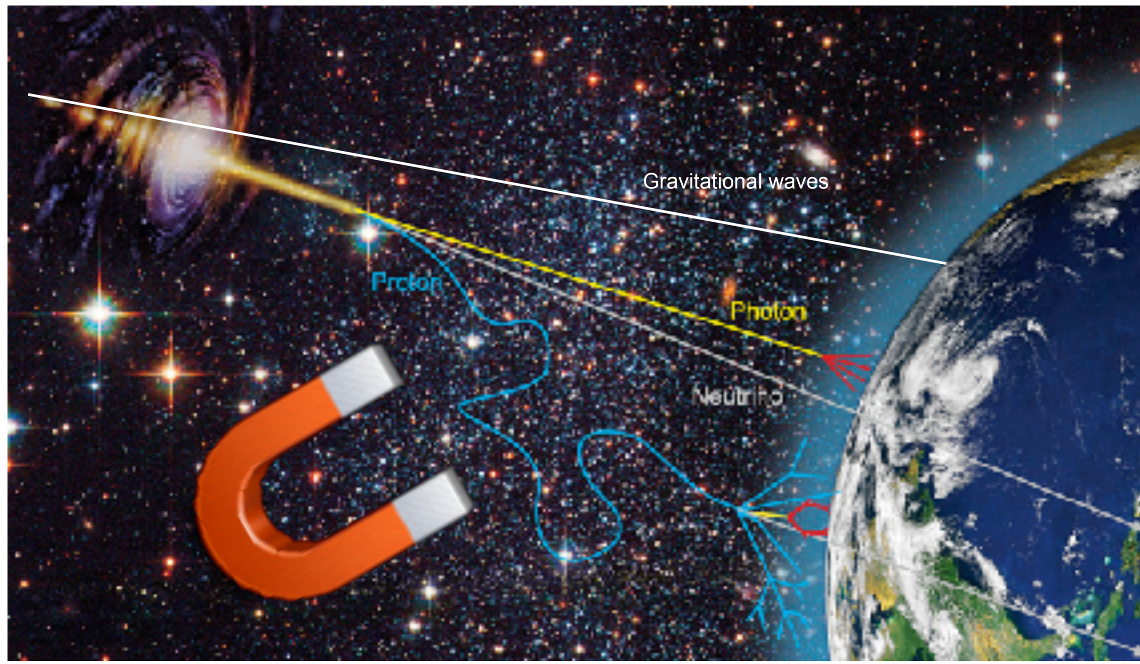


More about the various messengers

A short recap:

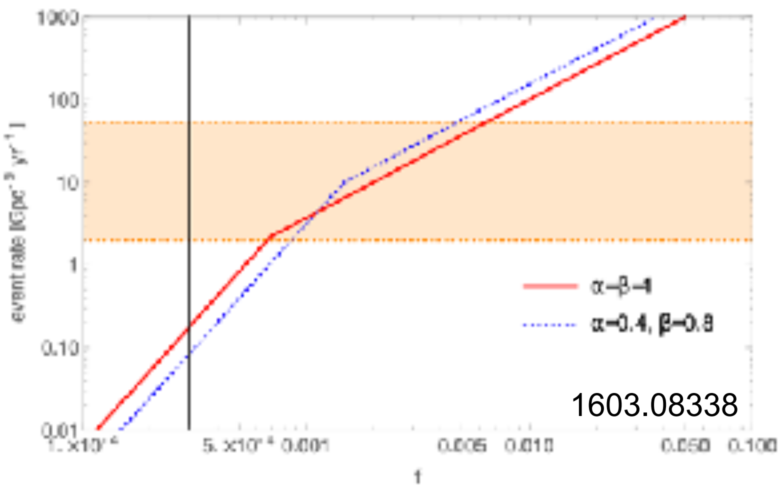
- **Photons:**
  easy to detect 👍
  point back at the source(s) 👍
  get absorbed 👎
- **Cosmic rays:**
  easy to detect 👍
  don’t point back 👎
- **Neutrinos:**
  point back at the source(s) 👍
  don’t get absorbed 👍 difficult to detect 👎
- **Gravitational waves:**
  point back at the source(s) 👍
  get absorbed 👎
  very difficult to detect 👎



Images credits: NASA/Aurore Simonnet, Sonoma State University, NAOJ/HSC Project, http://www.phys.lsu.edu/faculty/gonzalez/

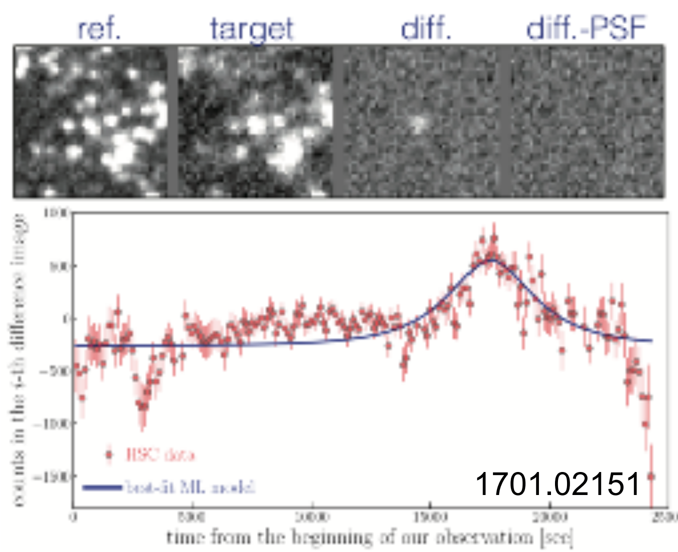
Experimental status: LIGO

- The **Laser Interferometer Gravitational-Wave Observatory** (**LIGO**) detects cosmic gravitational waves and to develop gravitational-wave observations as an astronomical tool.
- 2017 Nobel prize to Barish, Thorne and Weiss!
- We have detected GWs, but we still do not know where they come from. It is possible that the BHs involved in the mergers are PBHs (see 1603.08338)



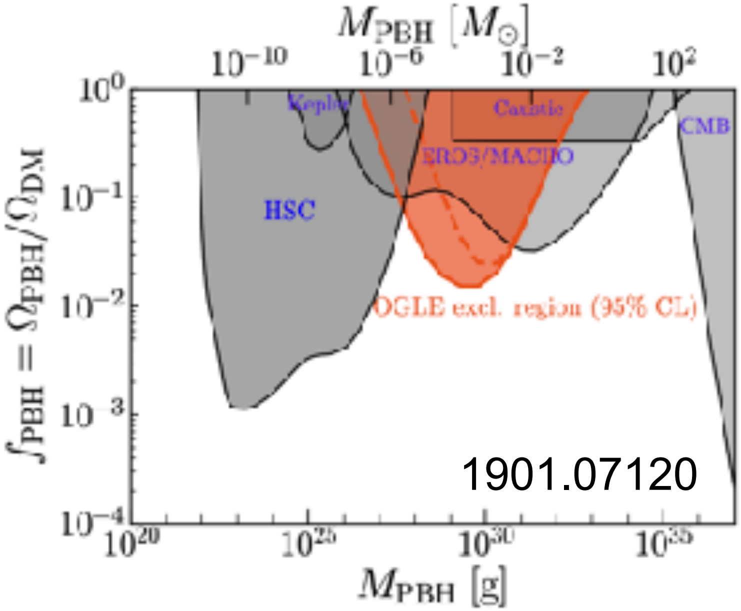
Experimental status: Subaru

- The **Subaru telescope** (8.2 m, FoV 9 full moons, 104 CCDs for 1 gigapixel) is located at the Mauna Kea Observatory on Hawaii (northern emisphere, so it can look at **Andromeda**, which is 770 kph away)
- The Hyper Suprime-Cam (HSC) is used to search for lensing events
- Subaru/HSC has detected a potential candidate event: it has all the features needed to be a PBH (1701.02151)



Experimental status: OGLE

- The **Optical Gravitational Lensing Experiment (OGLE)** is a telescope based at Las Campanas Observatory in Chile, run by the University of Warsaw
- "More interestingly, we also show that **Earth-mass PBHs can well reproduce the 6 ultrashort-timescale events**, without the need of free-floating planets, if the mass fraction of PBH to DM is at a per cent level, which is consistent with other constraints such as the microlensing search for Andromeda galaxy (M31) and the longer timescale OGLE events." (1901.07120)
- As an aside, the range has been used also to explain Planet IX (1909.11090)



1901.07120

Recent bonus: 70 solar mass BH

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Article

A wide star–black-hole binary system from radial-velocity measurements

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Jifeng Liu, Haotong Zhang, Andrew W. Howard, Zhongrui Bai, Youjun Lu, Roberto Soria, Stephen Justham, Xiangdong Li, Zheng Zheng, Tinggui Wang, Krzysztof Belczynski, Jorge Casares, Wei Zhang, Hailong Yuan, Yiqiao Dong, Yajuan Lei, Howard Isaacson, Song Wang, Yu Bai, Yong Shao, Qing Gao, Yilun Wang, Zexi Niu, Kaiming Cui, Chuanjie Zheng, Xiaoyong Mu, Lan Zhang, Wei Wang, Alexander Heger, Zhaoxiang Qi, Shilong Liao, Mario Lattanzi, Wei-Min Gu, Junfeng Wang, Jianfeng Wu, Lijing Shao, Rongfeng Shen, Xiaofeng Wang, Joel Bregman, Rosanne Di Stefano, Qingzhong Liu, Zhanwen Han, Tianmeng Zhang, Huijuan Wang, Juanjuan Ren, Junbo Zhang, Jujia Zhang, Xiaoli Wang, Antonio Cabrera-Lavers, Romano Corradi, Rafael Rebolo, Yongheng Zhao, Gang Zhao, Yaoquan Chu & Xiangqun Cui

All stellar-mass black holes have hitherto been identified by X-rays emitted from gas that is accreting onto the black hole from a companion star. These systems are all binaries with a black-hole mass that is less than 30 times that of the Sun[1–4]. Theory predicts, however, that X-ray-emitting systems form a minority of the total population of star–black-hole binaries[5,6]. When the black hole is not accreting gas, it can be found through radial-velocity measurements of the motion of the companion star. Here we report radial-velocity measurements taken over two years of the Galactic B-type star, LB-1. We find that the motion of the B star and an accompanying Hα emission line require the presence of a dark companion with a mass of 68^{+11}_{-13} solar masses, which can only be a black hole. The long orbital period of 78.9 days shows that this is a wide binary system. Gravitational-wave experiments have detected black holes of similar mass, but the formation of such massive ones in a high-metallicity environment would be extremely challenging within current stellar evolution theories.

Could it be a PBH?

Messengers from PBHs

Gravitational waves and photons could hint to a wide Primordial Black Hole mass spectrum!*

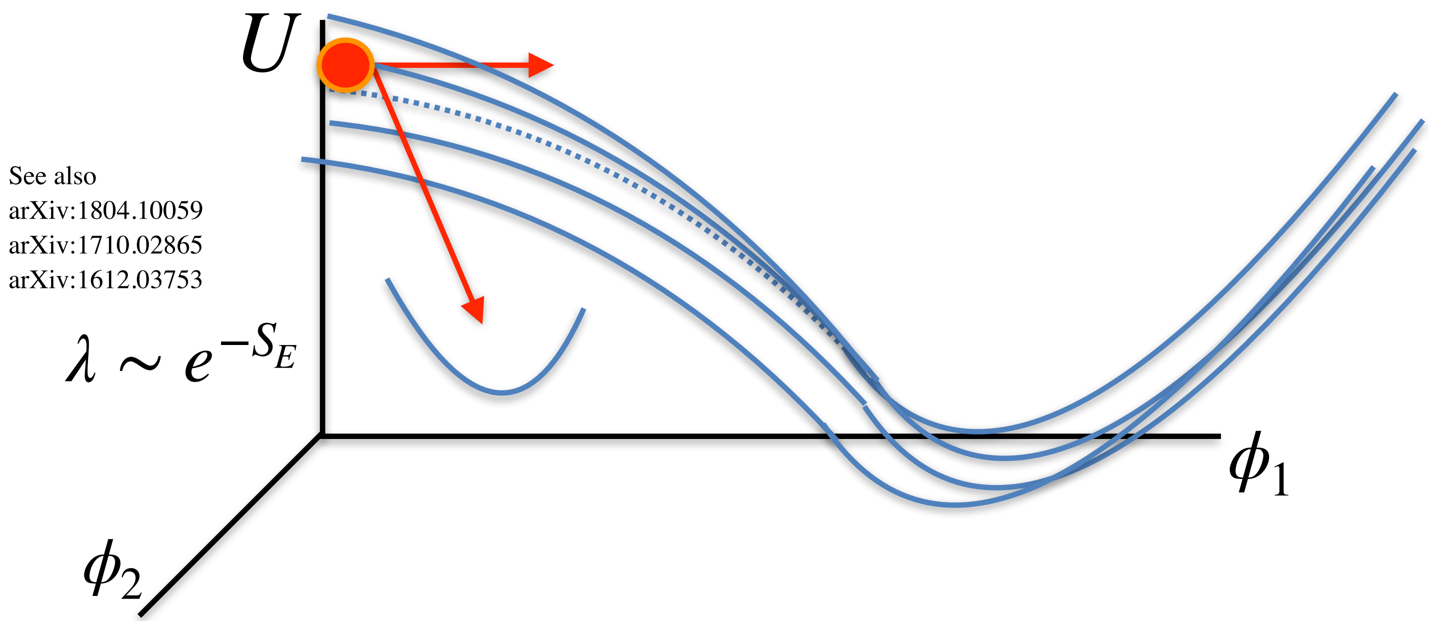
* So we have to think about how we can exclude this possibility

Bubbling bubbles and Primordial Black Holes

Primordial Black Holes from bubble nucleation

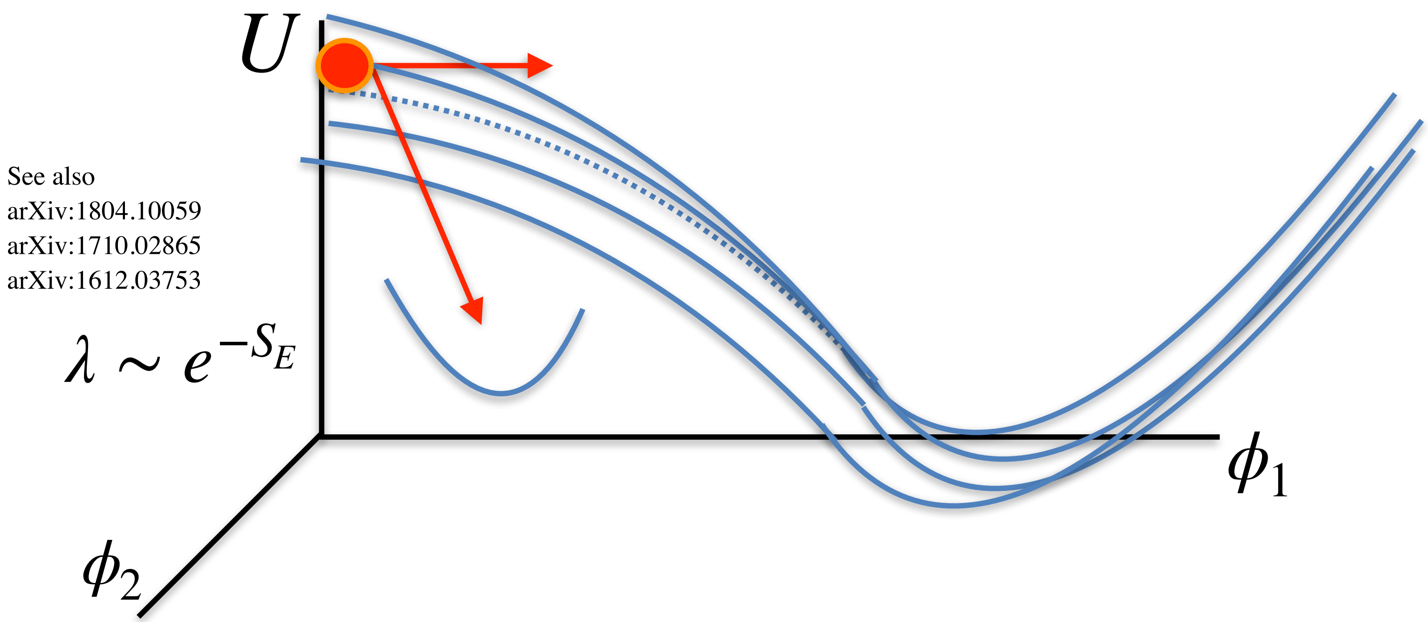
Domain walls can be formed in phase transitions. However, if we want to avoid the domain wall problem, we need a very low energy scale for the wall's tension

This can be avoided! Instead of having a phase transition, we can have bubble nucleation



Garriga, Vilenkin and Zhang (1512.01819) built on the Coleman-De Luccia scenario (Phys.Rev. D21, 3305) this idea. Basically, new inflation in one direction and old inflation in another direction

Primordial Black Holes from bubble nucleation



- The main idea: we start from a large energy density $\rho_{\rm in} > \rho_b$ where the latter is the bubble energy density
- Later, $\rho_b < \rho_i$, where the latter is the energy density in the universe at the end of inflation
- The universe will form vacuum bubbles with different energy density. These bubbles initially expand, later they collapse

Subcritical bubbles

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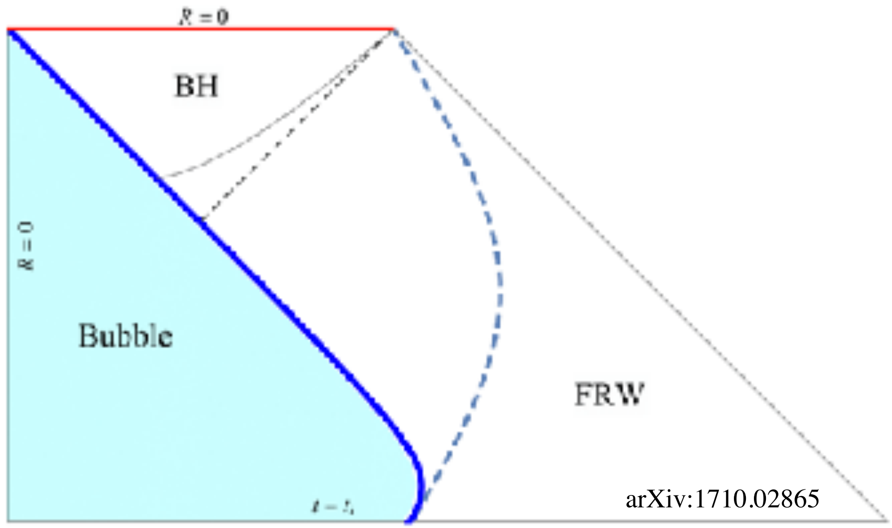
- There are two possibilities, depending if during expansion the radius is the bubble becomes larger of the Hubble radius fixed by ρ_b
- If $R < H_b^{-1}$ at all times, the bubble is subcritical



There is a conserved quantity, which is a mass parameter

$$G\mathcal{M}_b = \frac{1}{2}(H_b^2)R_w^3 + 2H_\sigma R_w^2\sqrt{1+\dot{R}_w - H_b^2 R_w^2} - 2H_\sigma^2 R_w^3$$

Energy of the vacuum + Kinetic energy of the wall - Wall tension

For subcritical bubbles

$$M \propto R^3$$

Subcritical bubbles

How large can a subcritical bubble be?

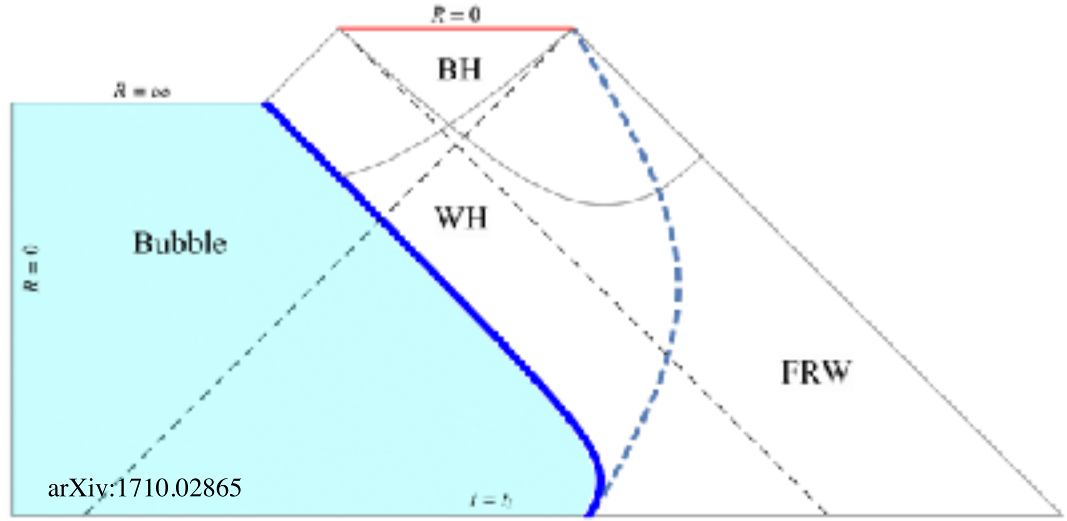
$$G\mathcal{M}_b = \frac{1}{2}(H_b^2)R_w^3 + 2H_\sigma R_w^2\sqrt{1+\dot{R}_w - H_b^2 R_w^2} - 2H_\sigma^2 R_w^3$$

- Set the velocity to zero and solve for the radius
- from dimensional arguments

$$GM_{\rm cr} \simeq \min\{\mathrm{H_b^{-1}}, \mathrm{H_\sigma^{-1}}\}$$

Supercritical bubbles

- With larger masses, at some moment in time, inflation will start inside the bubble. A baby universe is born we live in a **multiverse**
- We do not have a conserved quantity as in the subcritical case… how do we find the mass dependence on the radius?



Supercritical bubbles

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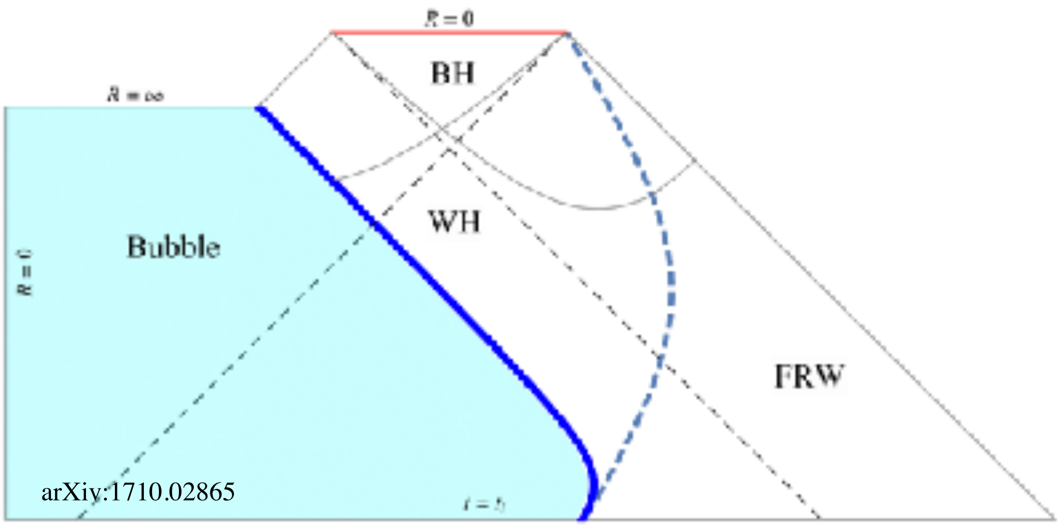

- Suppose we form a bubble with radius much smaller than the Hubble radius $R_{in} \ll H_{in}^{-1}$
- At time $t_h = a(t_h)R_i$ the radius will be larger than the Hubble radius of the parent universe. This happens when

$$t_h = H_i R_i^2 \qquad t_h = H_i^2 R_i^3$$

Radiation dominated era — Matter dominated era

$$M < \frac{4\pi}{3}\rho(t_h)H^{-3}(t_h) = H_i R_i^2 \text{ or } \mathrm{H_i^2 R_i^3}$$

$$M \propto R^2 \text{ or } R^3$$

One spectrum to
rule them all

Mass function: basic features

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We are now ready to obtain the mass spectrum. During inflation the metric is described by

$$ds^2 = -dt^2 + a(t)^2 d\mathbf{x}^2$$

where

$$a(t) = \exp H_i t$$

After a bubble is nucleated with small radius, it grows as

$$R(t) = H_i^{-1}[e^{H_i(t-t_n)} - 1]$$

(just set $ds = 0$ because they expand at the speed of light, and multiply times $a(t)$). The number of bubbles per spacetime volume is

$$dN = \lambda H_i^4 e^{3H_i t_n} d^3\mathbf{x} dt_n$$

where λ is the rate per Hubble space-time volume H_i^{-4}

Mass function: basic features

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The number density at the end of inflation is

$$dn(t_i) = \frac{dN}{dV} = \lambda \frac{dR_i}{(R_i + H_i^{-1})^4}$$

(where $dV = e^{3H_i t} d^3\mathbf{x}$) which evolves as

$$dn(t) = dn(t_i)[\frac{a(t_i)}{a(t)}]^3$$

with
- radiation $a(t) = \sqrt{t/t_i}$
- matter $a(t) = (t/t_i)^{2/3}$

We can now define as usual the mass function as

$$f(M) = \frac{M^2}{\rho_{cdm}(t)} \frac{dn(t)}{dM}$$

where

$$\rho_{cdm}(t) = \frac{1}{BGt^2} \sqrt{(t/t_{eq})} = \frac{M^3_{planck}}{Bt^{3/2} M_{eq}}$$

$B \simeq 10$

Mass function

We can now construct our mass function. For subcritical bubbles

$$M < M_{cr} = M^*$$

the mass spectrum will be

$$f(M) = B\lambda(M_{eq}/M^*)^{1/2}$$

For supercritical bubbles in a radiation dominated universe

$$f(M) = B\lambda(M_{eq}/M)^{1/2}$$

while for supercritical bubbles in a matter dominated universe the spectrum is flat like for subcritical bubbles

$$f(M) = B\lambda(M_{eq}/M_k^*)^{1/2}(M_k^*/M_{k-1}^*)^{1/2}$$

where k is the index for various radiation-matter transitions

Mass function

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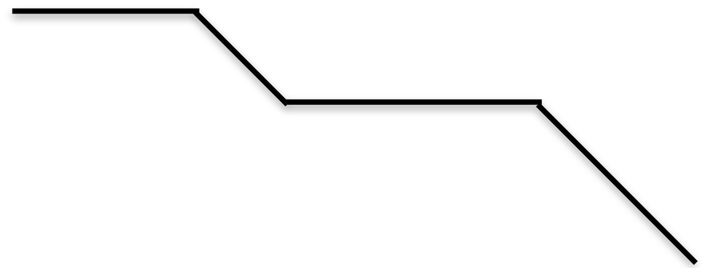
The mass function is then a trapezoid with $M^{-1/2}$ or $M = \text{const}$



As many breaks in the mass function as the number of radiation-matter transition (+1, the transition from subcritical to supercritical bubbles). Plan: let us try to explain

- Dark matter: the only dark matter candidate that is not necessarily made of new particles
- OGLE and quasar microlensing events
- Can seed supermassive black holes
- LIGO signal
- Perhaps Subaru detected one

Mass function: fixing the parameters

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- Dark matter: the only dark matter candidate that is not necessarily made of new particles: fixes the nucleation rate

$$\Omega_{PBH}/\Omega_{cdm} = \rho_{PBH}(t)/\rho_{cdm}(t) = \int \frac{dM}{M} f(M) = 1$$

- OGLE and quasar microlensing events

$$\int_{0.5M_\oplus}^{20M_\oplus} f(M)\frac{dM}{M} \simeq 0.005$$

- Can seed supermassive black holes

$$n_M \sim B\lambda \left(\frac{M_{eq}}{M}\right)^{1/2} \frac{\rho_{CDM}}{M} \sim 10^{20}\lambda \left(\frac{M}{M_\odot}\right)^{-3/2} \mathrm{Mpc}^{-3} \longrightarrow \lambda > 10^{-17}$$

- LIGO signal

$$f(M \sim 30M_\odot) \sim 10^{-3}$$

- Perhaps Subaru detected a PBH…

Mass function: fixing the parameters

UCLA

- Dark matter: the only dark matter candidate that is not necessarily made of new particles: fixes the nuc...

$$\Omega_{PBH}/\Omega_{cdm} = \rho_{PBH}(t)/\rho_{cdm}(t)$$

- OGLE and ...

Gravitational waves and photon observations hint to a wide PBH mass function. Can we exploit observations to probe this scenario?

$\lambda > 10^{-17}$

$$f(M \sim 30 M_{\odot}) \sim 10^{-3}$$

- Perhaps Subaru detected a PBH…

Probing the multiverse scenario

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We can use microlensing measurement of M31 (Andromeda) stars (see also Takada's and Kusenko's talk)

Subaru, at last!

Probing the multiverse scenario

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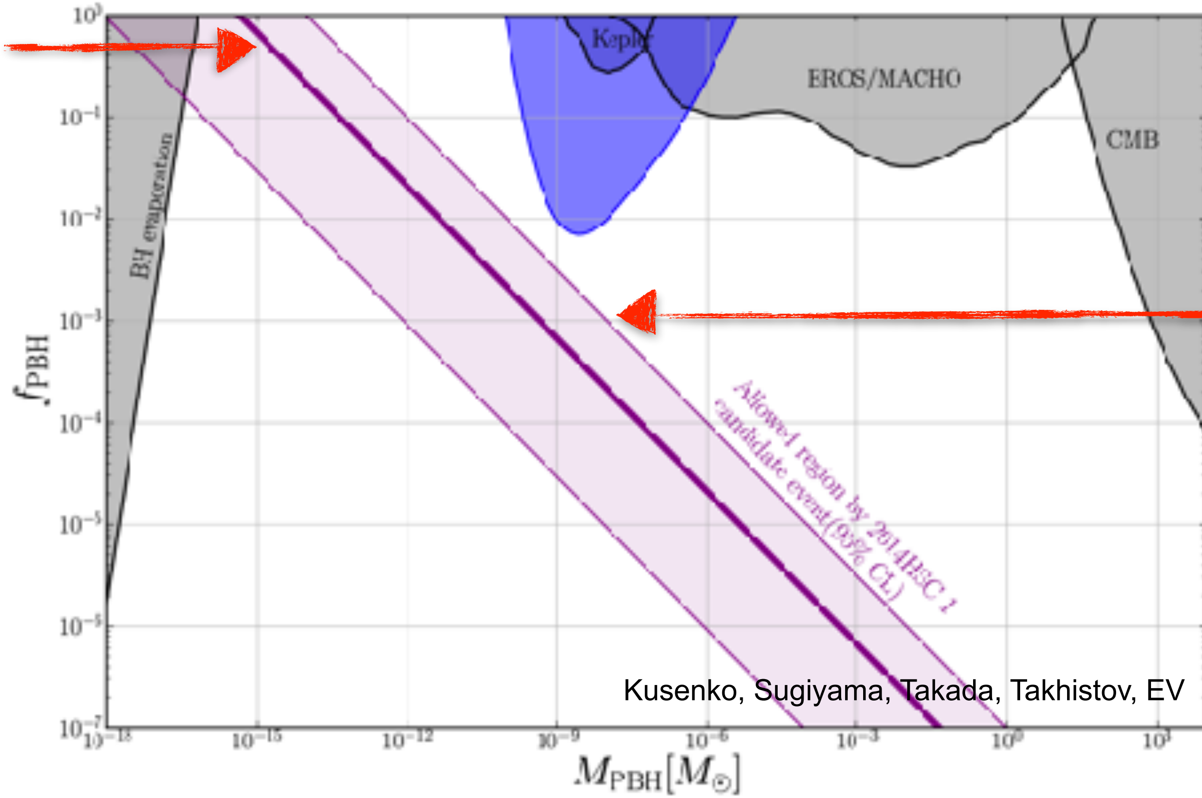
can't measure most DM…



…but the devil's in the tail!

Fit consistent with 1 event observation at Subaru/HSC from M31. NB: the exclusion is smaller than the fit because you have to integrate over the mass range (see e.g. arXiv:1705.05567)

Probing the multiverse scenario

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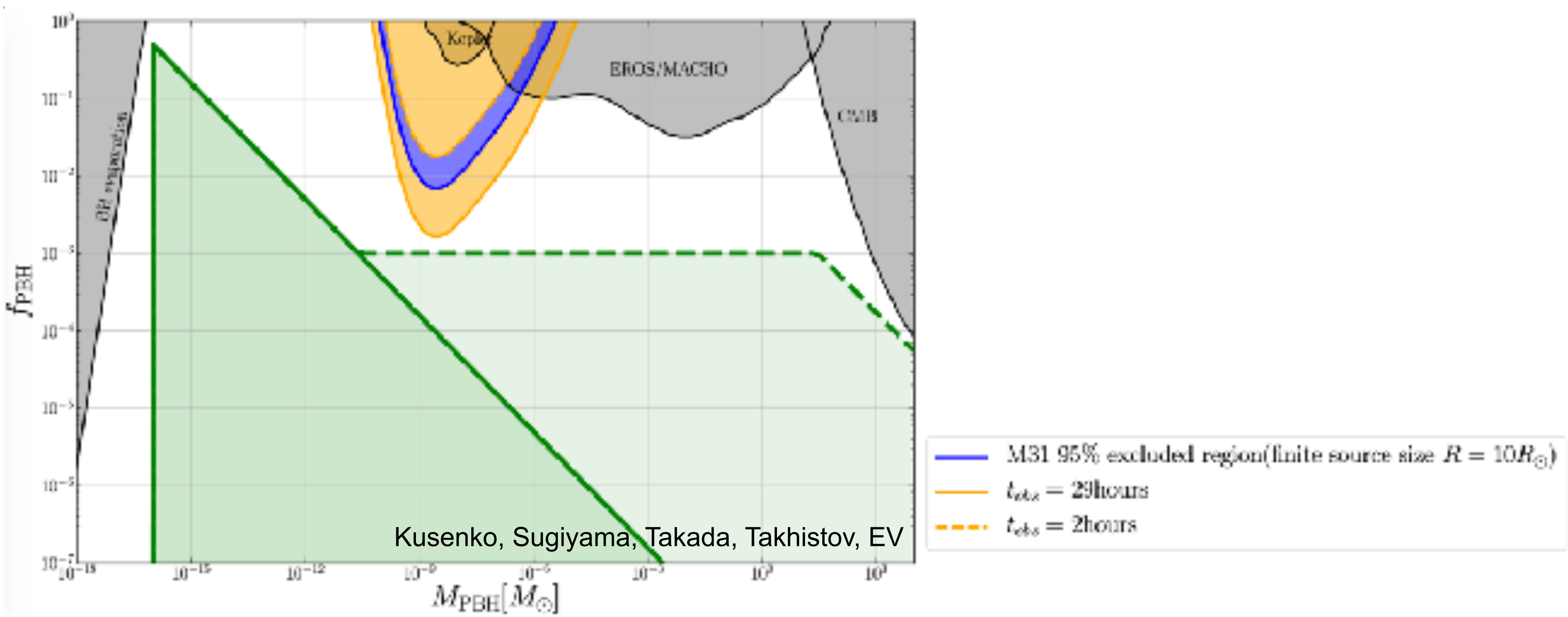
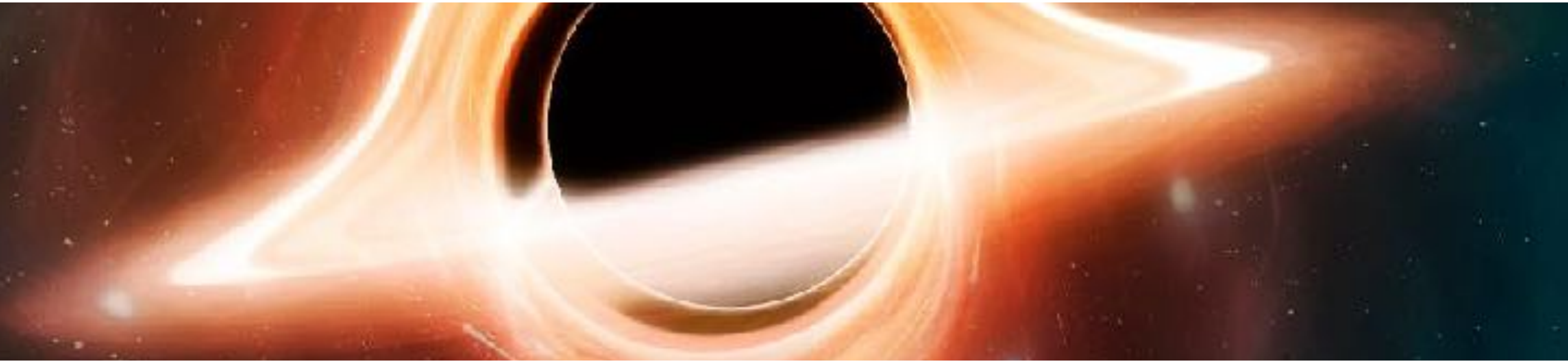


- 2 hours observation: we already probe the CDM+LIGO+seeds+OGLE parameters. However, with Poisson statistics with 7 hours data we should have seen 3 events. This is still compatible with the dashed line. 14 hours observation would completely exclude this possibility
- 29 hours observation: we can entirely exclude PBH from vacuum bubbles as CDM!

Conclusions

Conclusions

- There is (again!) an available window for PBHs to be CDM



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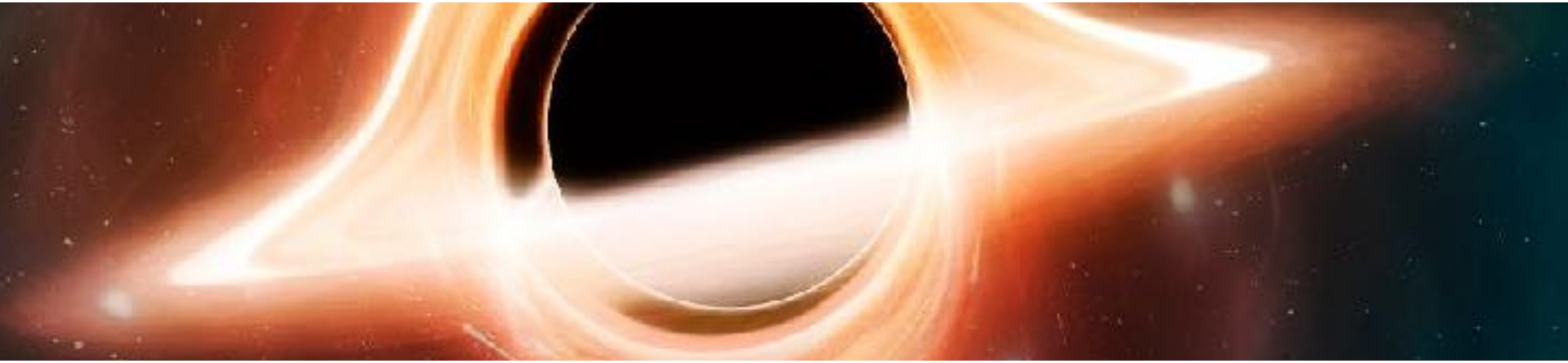
- There is (again!) an available window for PBHs to be CDM
- PBHs could be produced via collapse of vacuum bubbles nucleated during inflation



Conclusions

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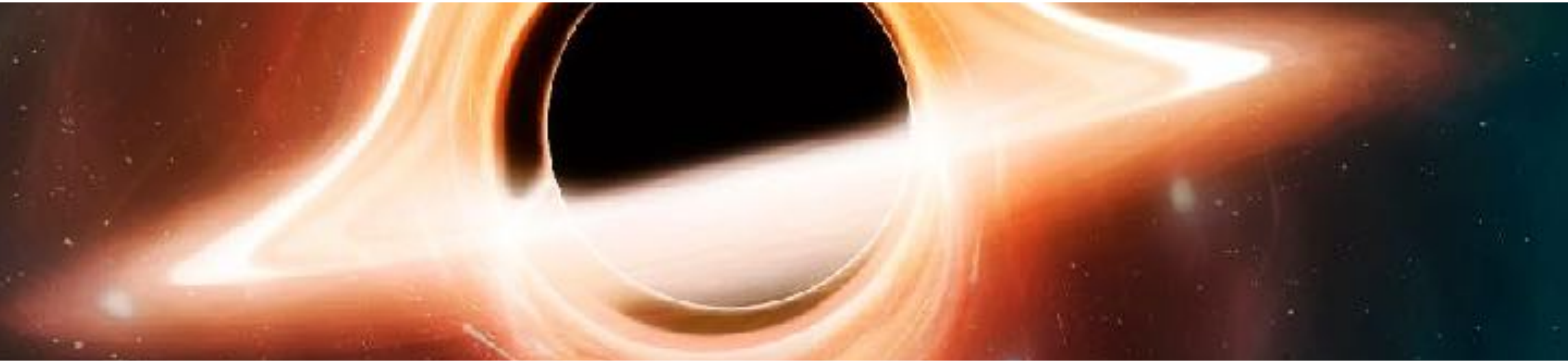
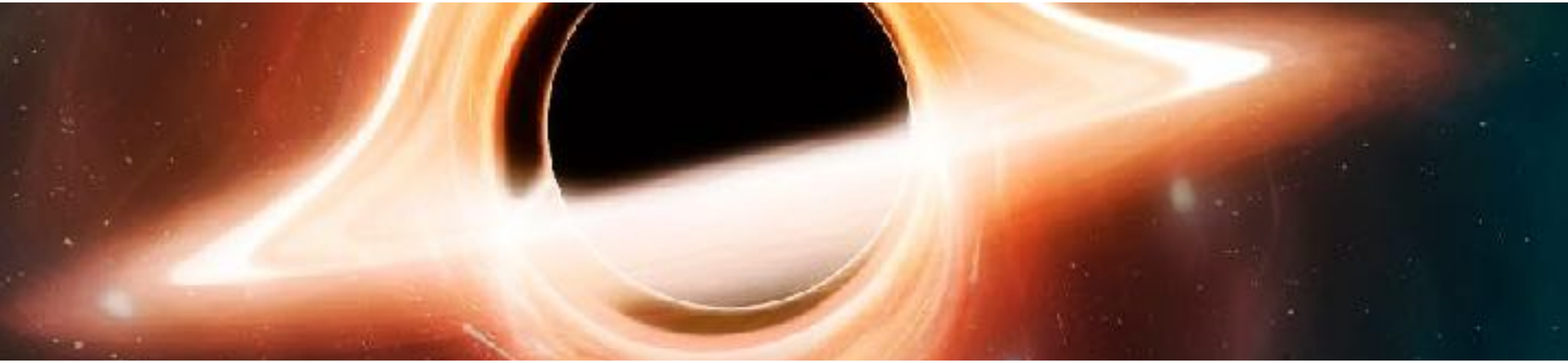
- There is (again!) an available window for PBHs to be CDM
- PBHs could be produced via collapse of vacuum bubbles nucleated during inflation
- This scenario could explain many observations (CDM abundance, 1 Subaru event, LIGO, OGLE)



Conclusions

- There is (again!) an available window for PBHs to be CDM
- PBHs could be produced via collapse of vacuum bubbles nucleated during inflation
- This scenario could explain many observations (CDM abundance, 1 Subaru event, LIGO, OGLE)
- Subaru can probe large part of the parameter space and possibly exclude it, given enough observation time



This project has received funding/support from the DOE through UCLA.

Thank you

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Mass function: low mass cutoff

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We have to take small R in

$$GM_b = \frac{1}{2}H_b^2 R_w^3 + 2H_\sigma R_w^2 - 2H_\sigma^2 R_w^3$$

$$dn(t_i) = \frac{dN}{dV} = \lambda \frac{dR_i}{(R_i + H_i^{-1})^4}$$

$$R_i << H_i^{-1}$$

→ $M^{4/3}$ or $M^{3/2}$

However, there could be a sharp cutoff due to quantum fluctuations spoiling the bubbles:

$$M > \rho_b^2 (\frac{\rho_i M_{planck}}{\rho_b \sigma})^{3/2}$$

Mass function: large mass cutoff

What about the high mass cutoff? This is non-existent. A high mass cutoff to these calculations exist for radii larger than $R_i > H_i^{-1} e^N$ with N number of e-folds. This is a huge number, so we can really forget about this large mass cutoff.

An aside: new dark matter paradigms

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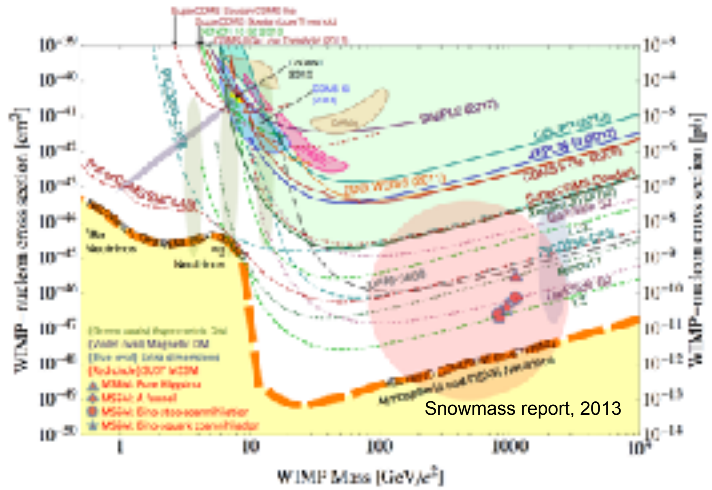
WIMPs searches are a success (*WIMP-Moore's Law*: factor of 10 every 6.5 years!)

During the last few years lot of discussions about several dark matter candidates (from axions to MACHOs…)



Slide adapted from K.Zurek Elusives Webinar, https://projects.ift.uam-csic.es/VirtualInstitute/

An aside: new dark matter paradigms

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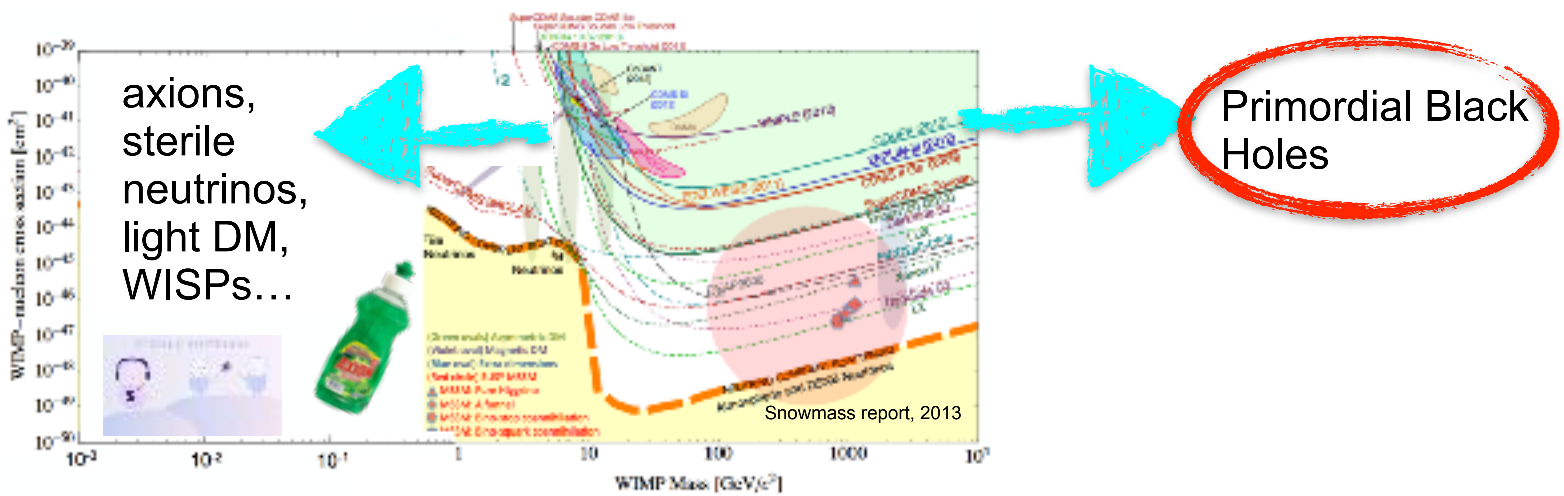

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