Clustered PBHs and Stellar Bubbles from the Primordial Universe

Yi Wang, The Hong Kong University of Science and Technology

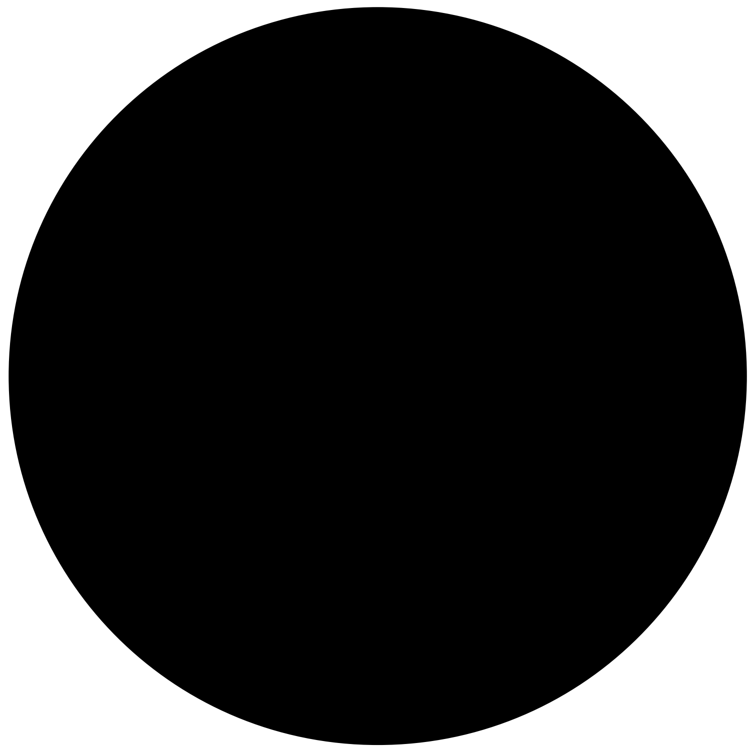
Copernicus Webinar Series, 14 July 2021

References: 0903.2123, Miao Li & YW

1903.07337, Qianhang Ding, Tomohiro Nakama, Joseph Silk & YW

2105.11481, Yi-Ffu Cai, Chao Chen, Qianhang Ding & YW

Primordial black holes (PBHs)



Primordial black holes (PBHs)

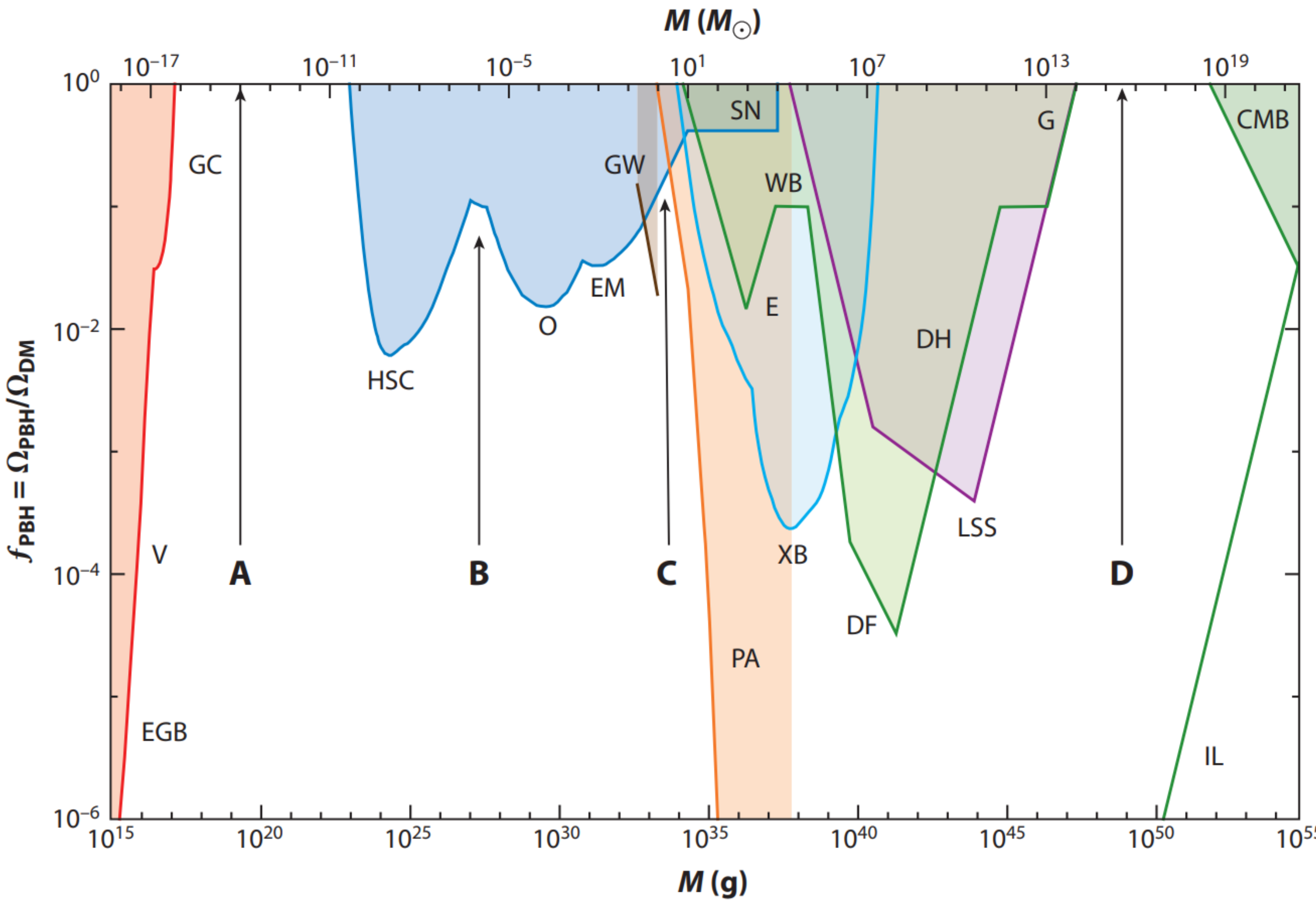
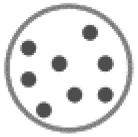


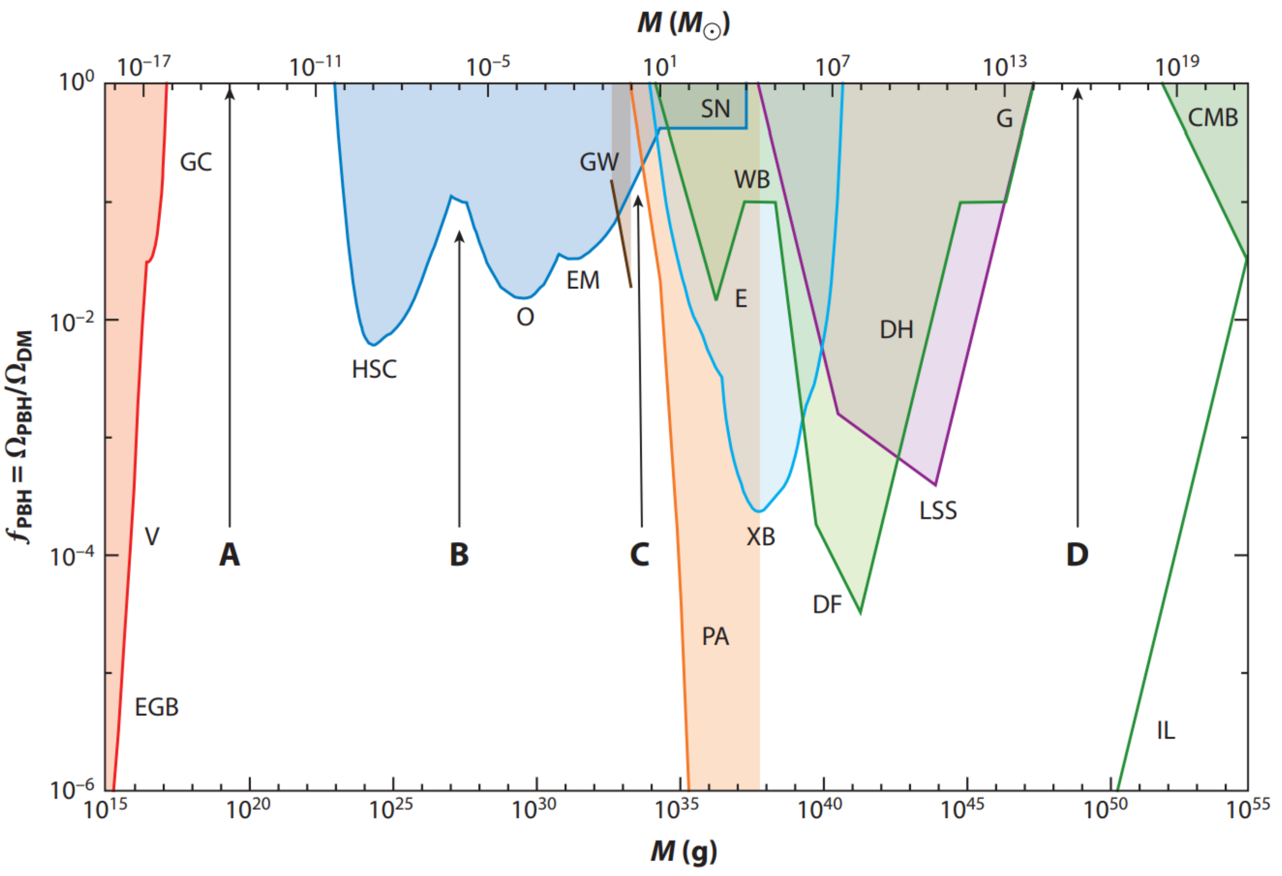
Figure from Carr & Kühnel 2006.02838. See also Carr, Kohri, Sendouda & Yokoyama, 2002.12778
See also Sasaki, Suyama, Tanaka & Yokoyama, 1801.05235 (more accretion constraints)

What if PBHs are initially clustered?



Introduction & Quick Summary

What if PBHs are initially clustered?   Large PBHs & clusters



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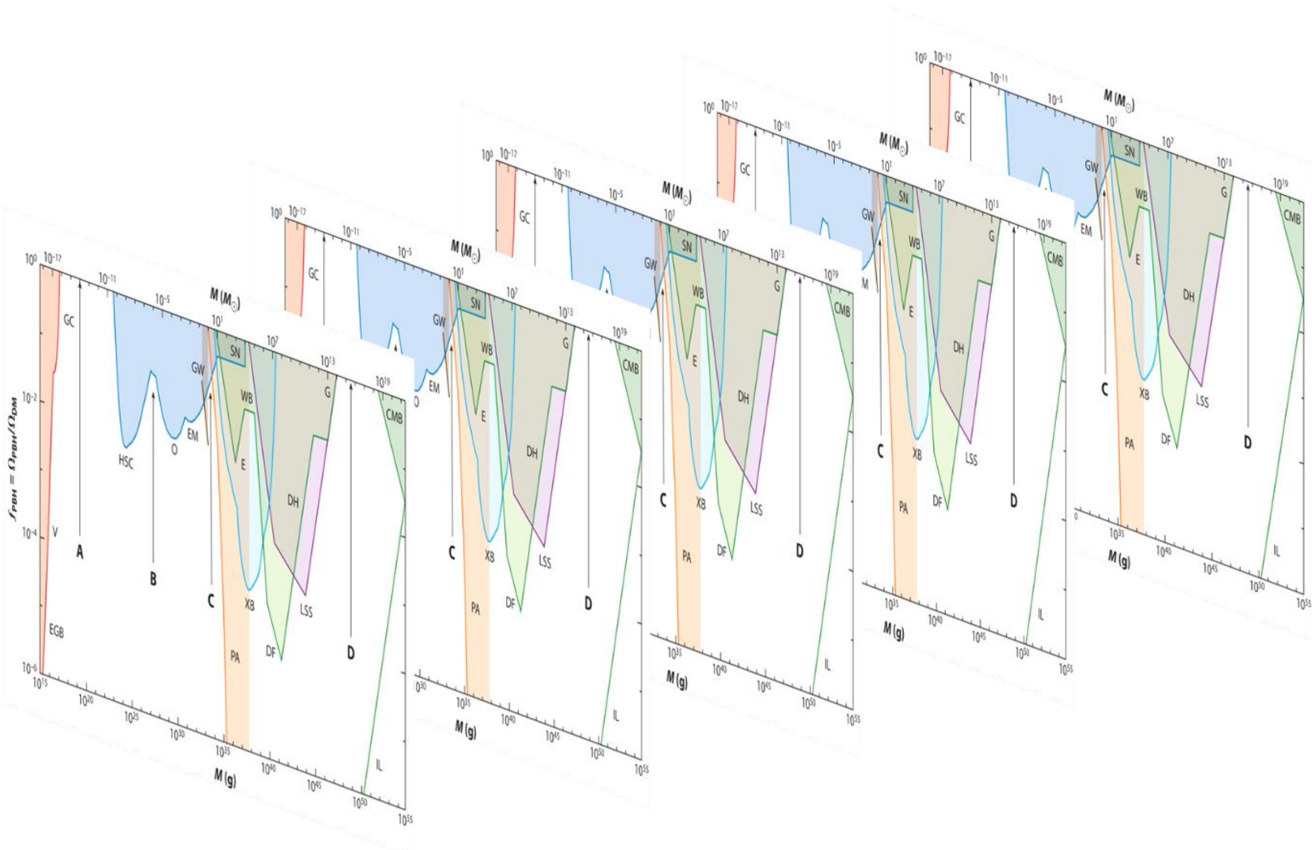

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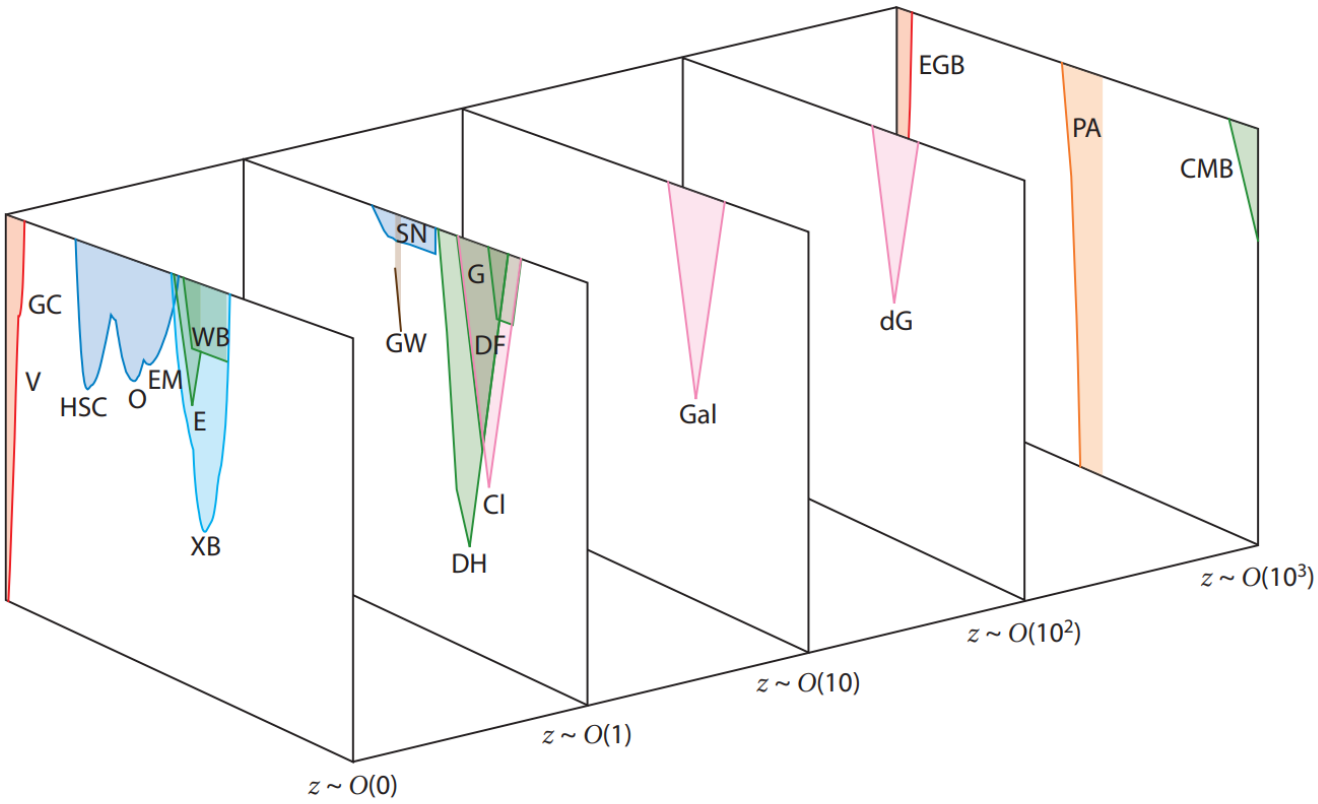
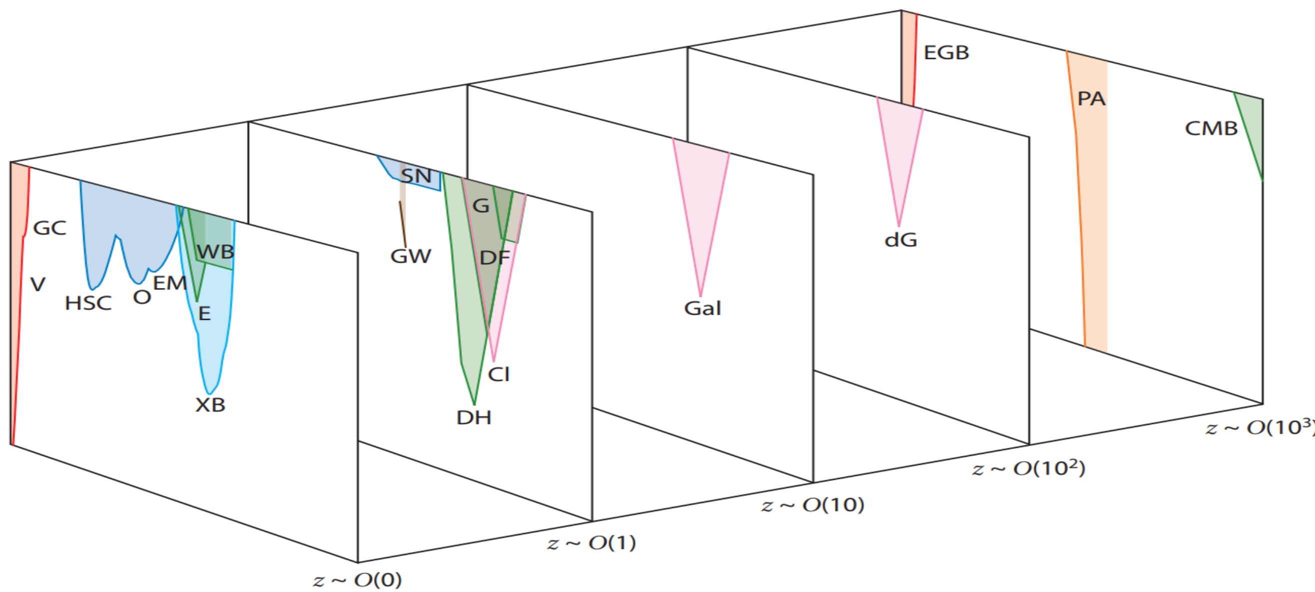


Figure from Carr & Kühnel 2006.02838

What if PBHs are initially clustered?   Large PBHs & clusters



1. Can discard all $z \sim O(0)$ constraints
2. Closer thus more binaries → more GW events

e.g. PBH merger on LISA?

1903.07337, Qianhang Ding, Tomohiro Nakama, Joseph Silk & YW

What if PBHs are initially clustered? Small PBHs & clusters

Page & Hawking 1976: Gamma rays from PBHs?

√ Background (homogeneous/inhomogeneous [Cline 1998])

× Individual

囊萤夜读

yìn gōng qín bú juàn
胤恭勤不倦，
bó xué duō tōng jiā pín bù
博学多通。家贫不
cháng dé yóu xià yuè zé liàn
常得油，夏月则练
náng chéng shù shí yíng huǒ yǐ zhào
囊盛数十萤火以照
shū yǐ yè jì rì yān
书，以夜继日焉。

What if PBHs are initially clustered? Small PBHs & clusters

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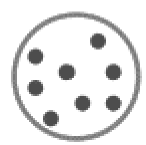
× Individual



Exotic “star”?

Stellar bubbles in the sky

General, also for
other exotic matter

c.f. quark star,
axion star,
dark star,
anti-matter galaxies,
etc

Yi-Fu Cai, Chao Chen, Qianhang Ding & YW, 2105.11481

What if PBHs are initially clustered?

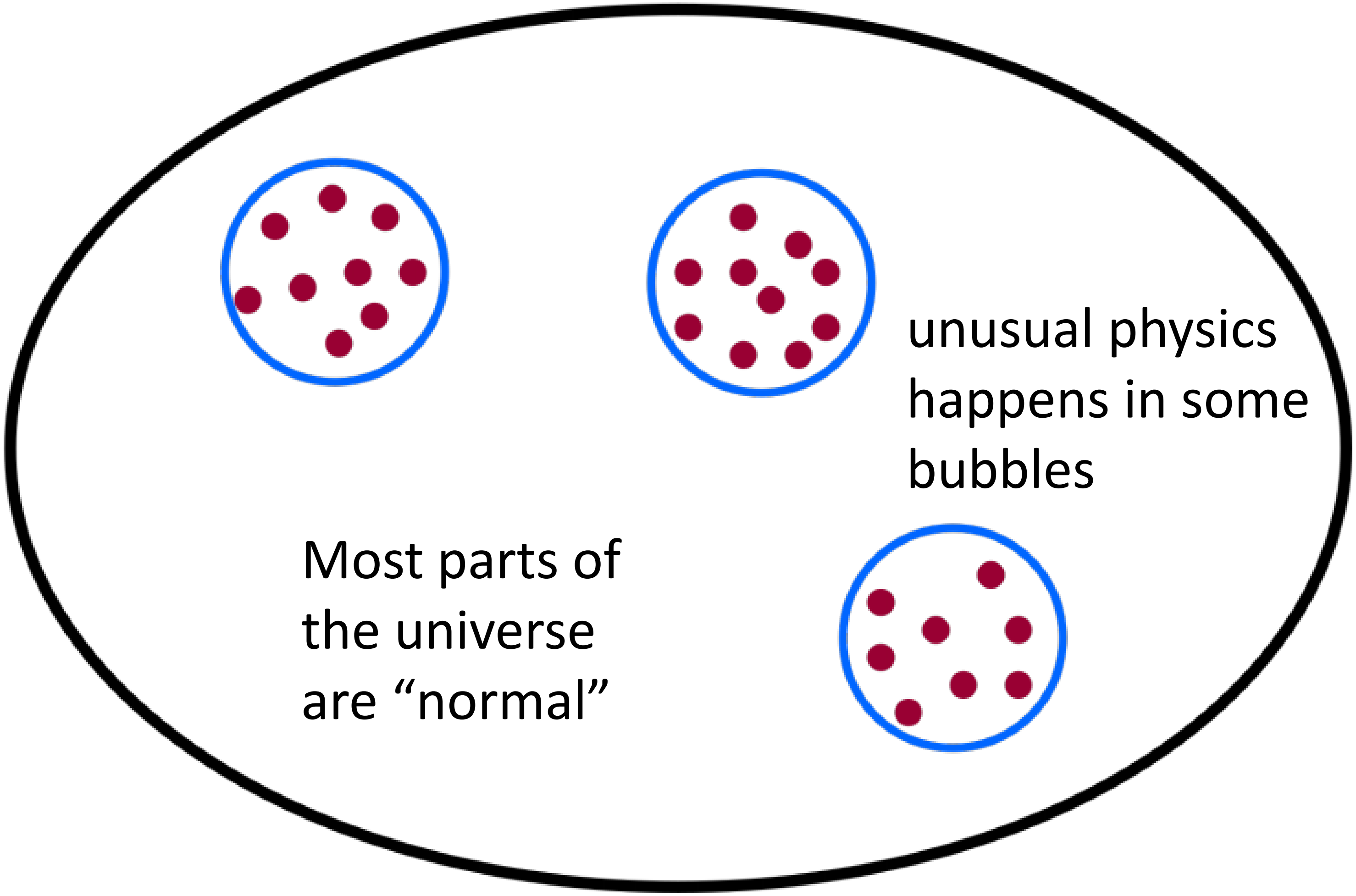
How?

Plan

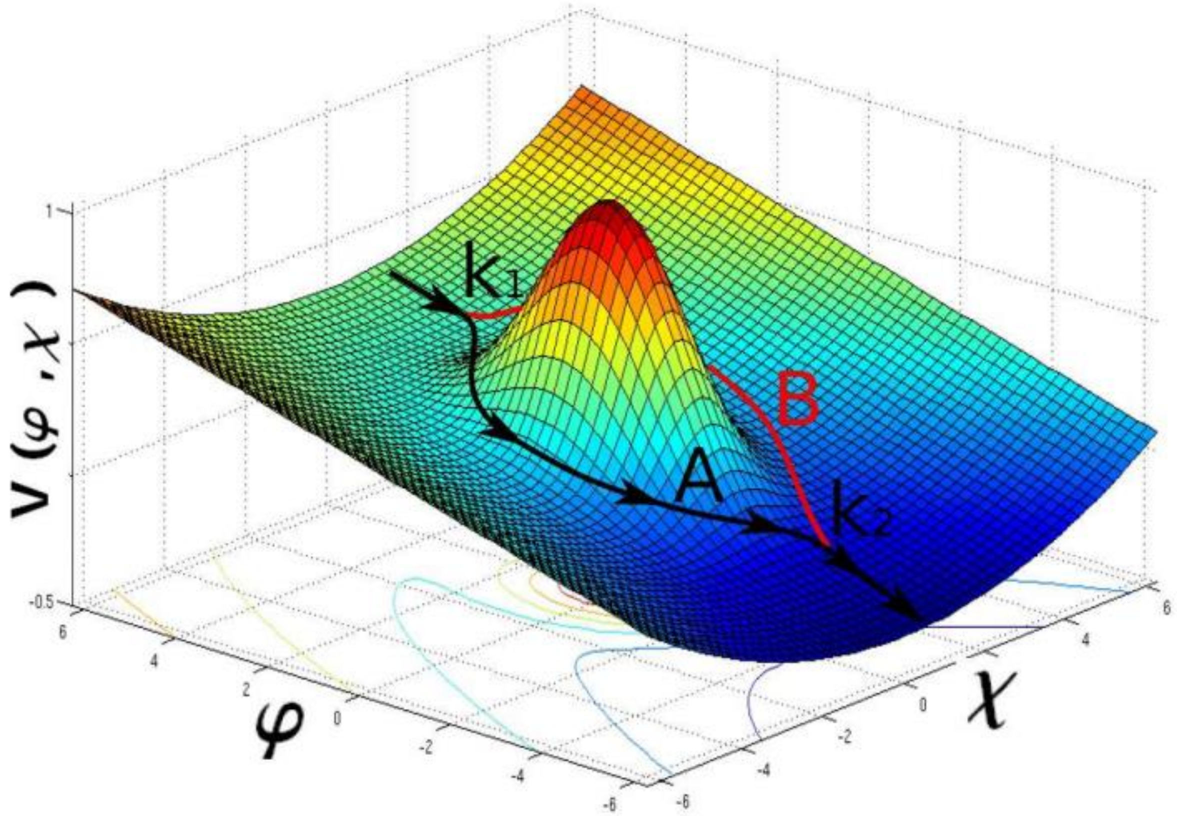
Intro & summary → multi-stream inflation → PBH bubbles $\begin{cases} \text{GW} \\ \text{stellar bubbles} \end{cases}$

What if PBHs are initially clustered?

How?


unusual physics happens in some bubbles
Most parts of the universe are “normal”

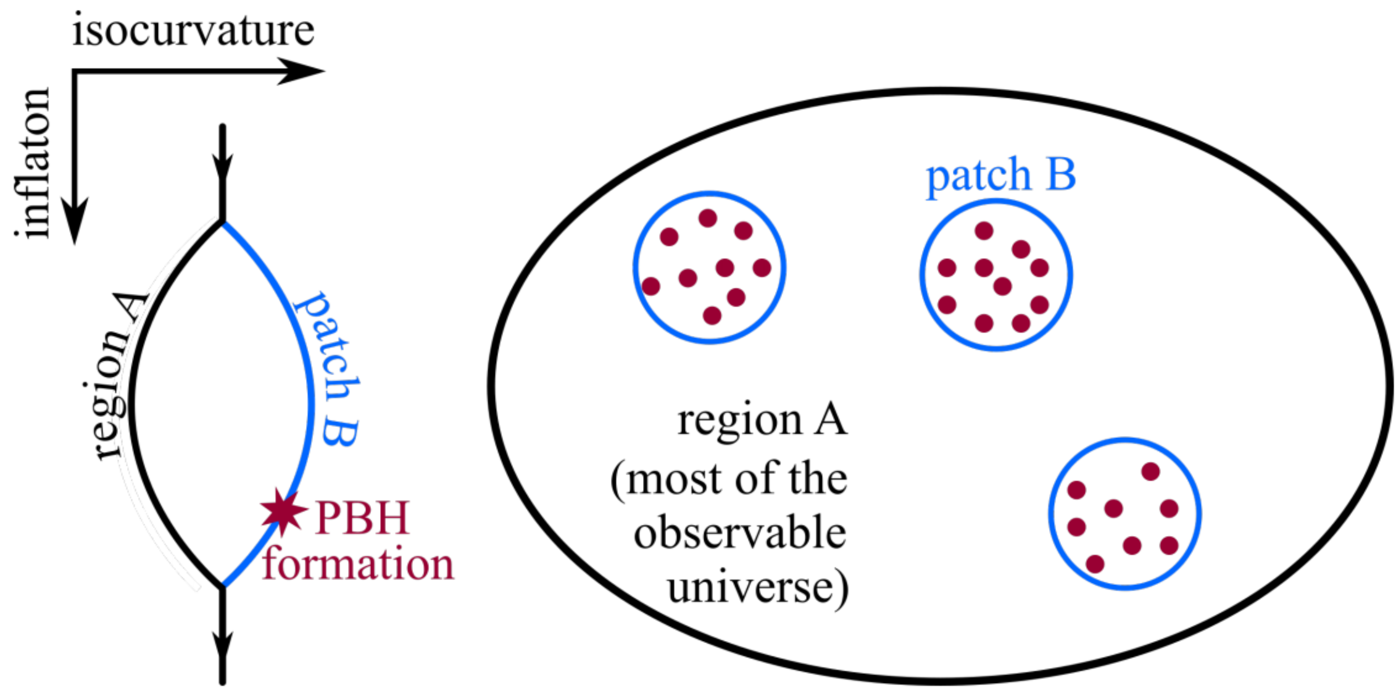
Can PBHs be initially clustered?   Multi-stream inflation

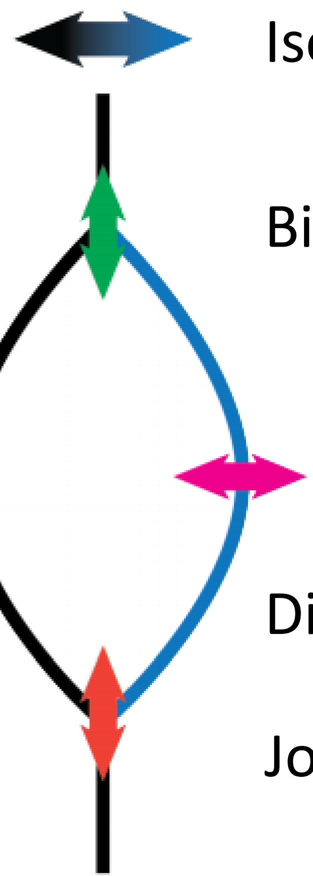


Miao Li & YW, 0903.2123


Chas Addams

Can PBHs be initially clustered?   Multi-stream inflation





Isocurvature: controls which-way & probability

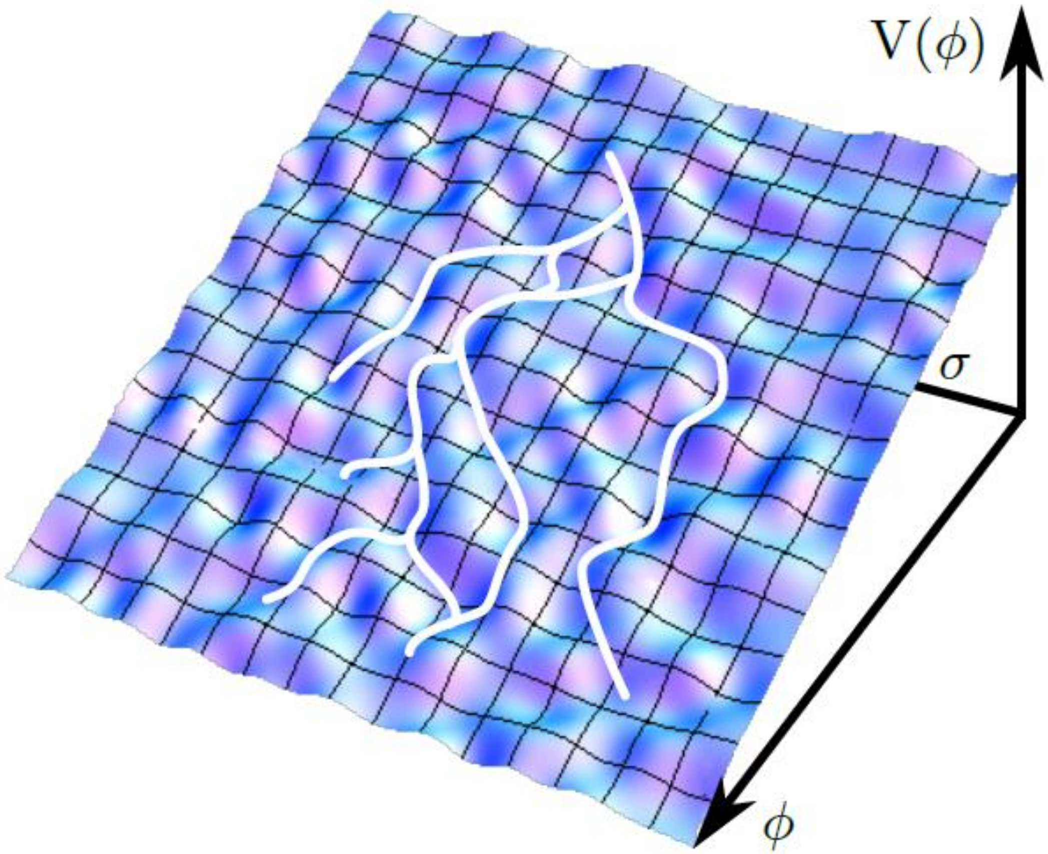
Bifurcation point: controls scale of bubbles

E-folding difference: controls ζ inside/outside at the scale of bifurcation

Difference of local physics: model dependent

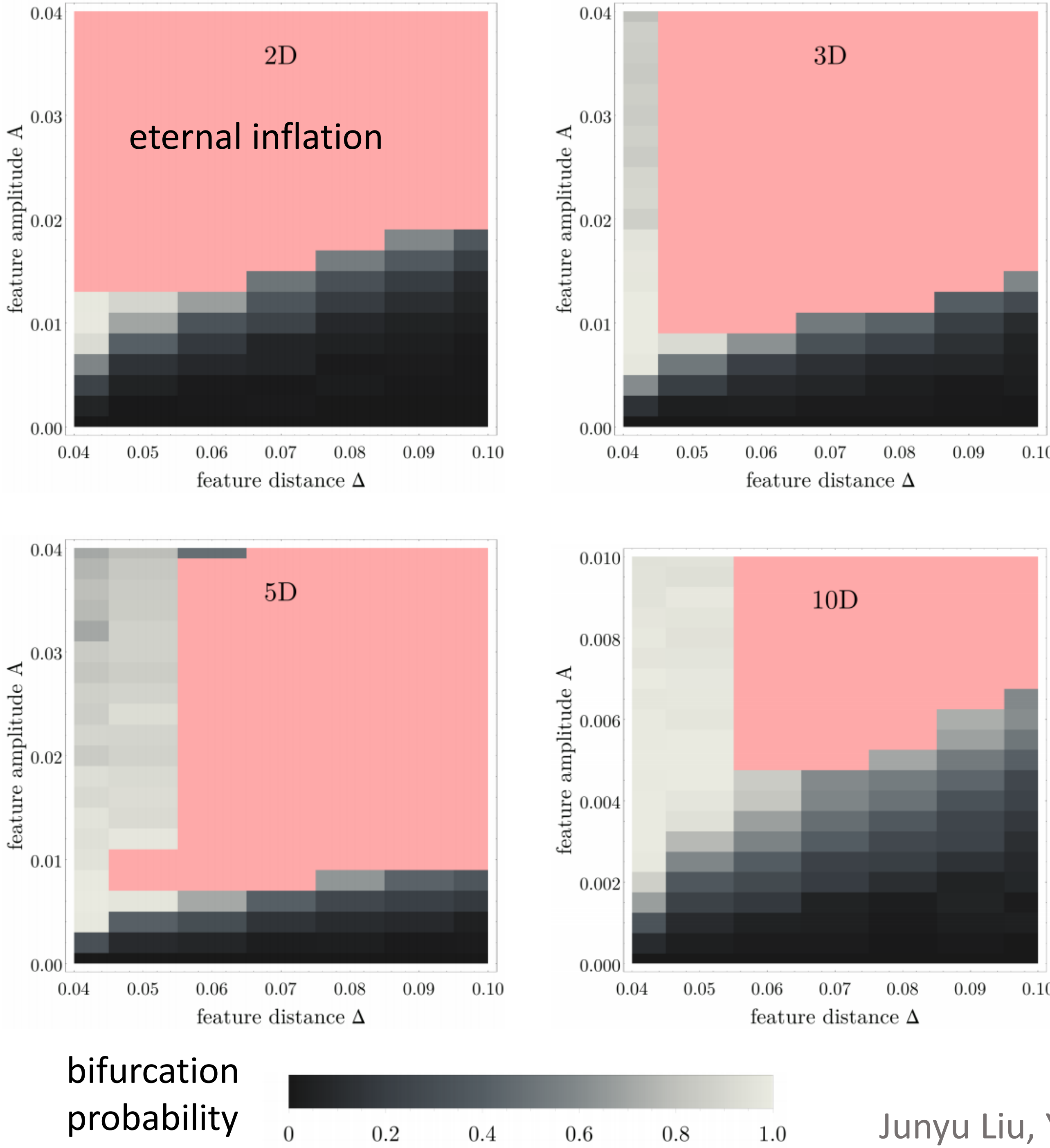
Join point: thickness of bubble wall

Is multi-stream inflation realistic?   A landscape view



Duplessis, YW, Brandenberger, 1201.0029
Junyu Liu, YW, Siyi Zhou, 1501.06785

Figure: YW 1303.1523

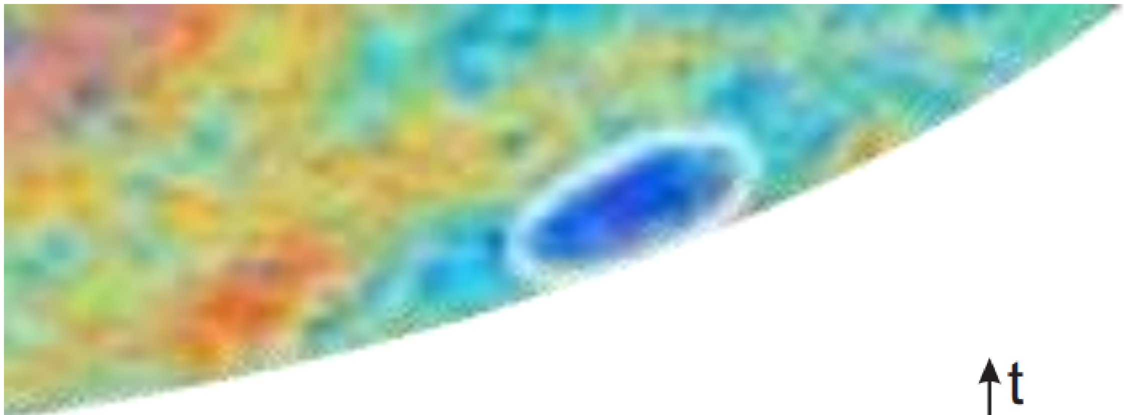


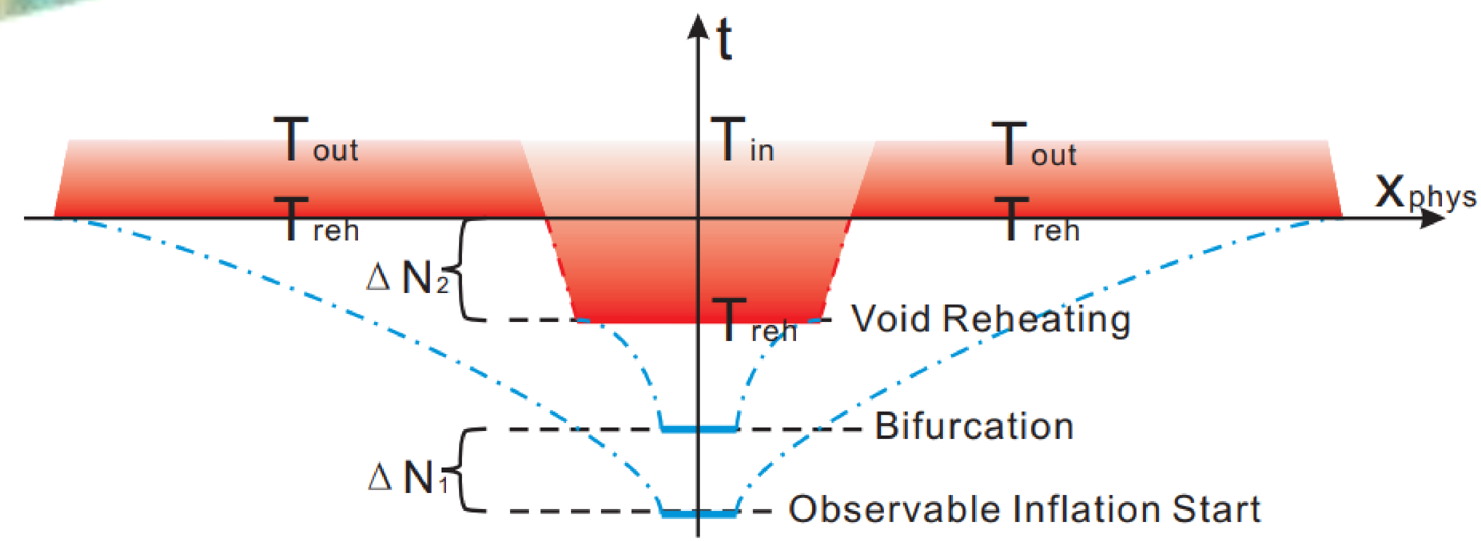
Junyu Liu, YW, Siyi Zhou, 1501.06785

What can multi-stream inflation offer?

- More observable e-folds
- E-folds behind the scenes

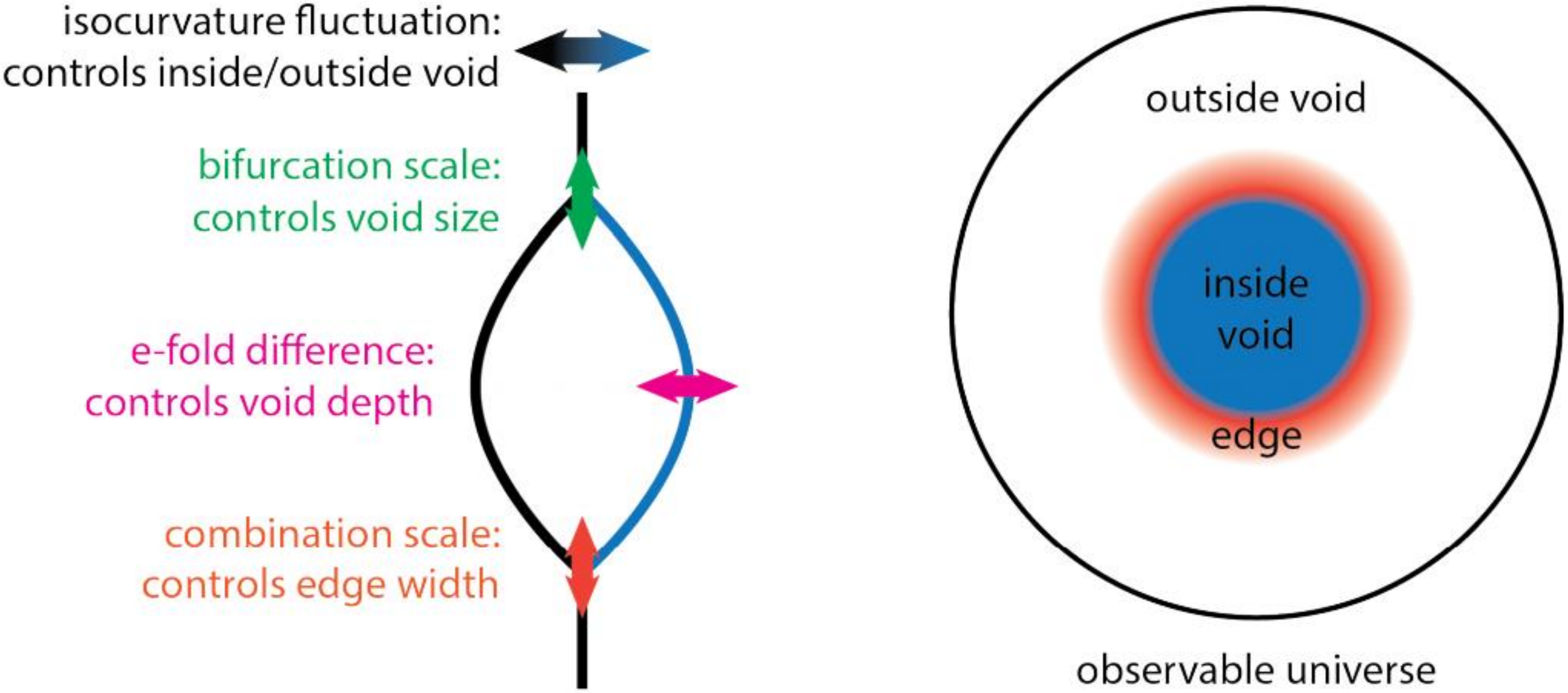
Multi-stream inflation in more observable e-folds: CMB cold spot





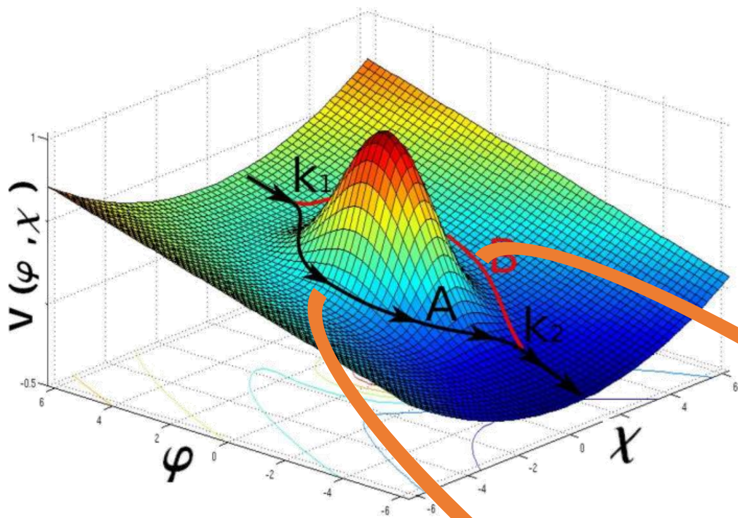
Niayesh Afshordi, Anže Slosar & YW, 1006.5021

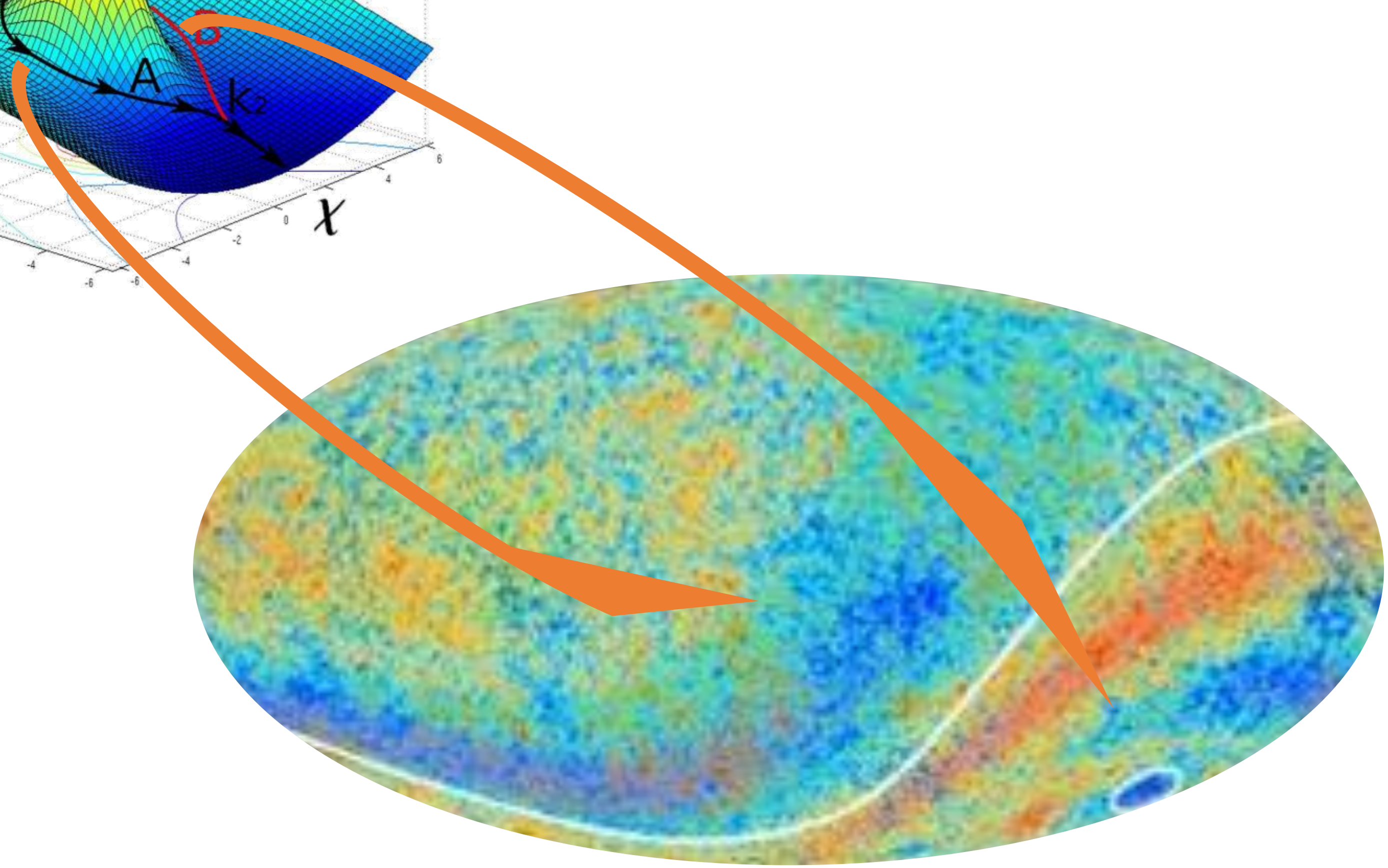
Ease the Hubble tension?



Qianhang Ding, Tomohiro Nakama & YW 1912.12600

Hemi-spherical asymmetry?





Miao Li & YW, 0903.2123

Multi-stream inflation in more observable e-folds: non-Gaussianity

$$P(\delta\zeta_{k_1}^{S,N},\zeta_k) = P(\delta\zeta_{k_1}^{S,N}) \left[\frac{e^{-\frac{\zeta_k^2}{2\sigma_A^2}}}{\sqrt{2\pi}\sigma_A}\theta(\delta\zeta_{k_1}^S) + \frac{e^{-\frac{\zeta_k^2}{2\sigma_B^2}}}{\sqrt{2\pi}\sigma_B}\theta(-\delta\zeta_{k_1}^S) \right]$$

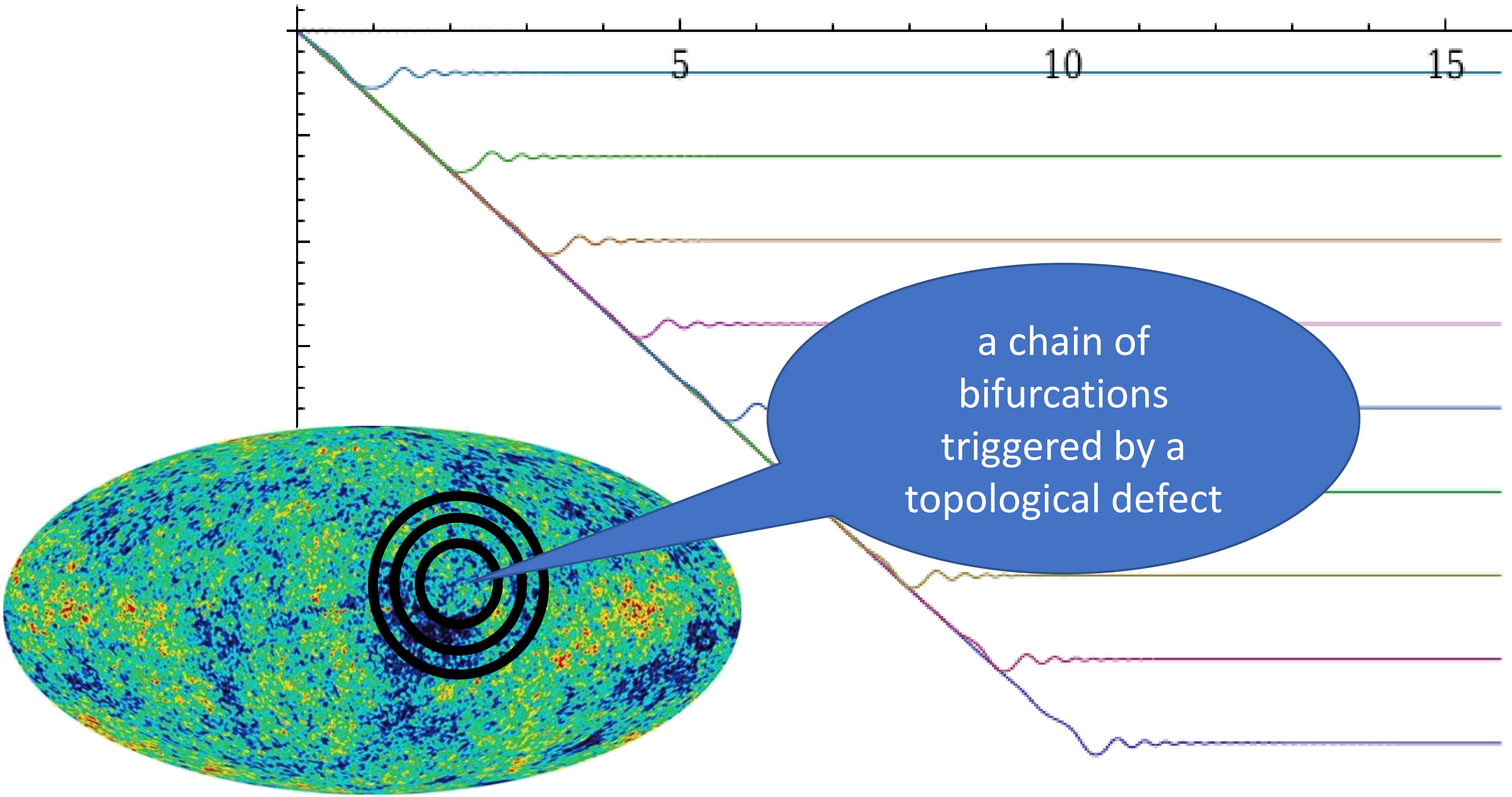
$$f_{NL} \simeq x P_\zeta^{-1/2} \left(\frac{P_\zeta^A - P_\zeta^B}{P_\zeta} \right)$$

$x \equiv \delta\zeta_{k_1}/\zeta_{k_1}$ denotes the fraction of extra fluctuation from the multi-stream effect.

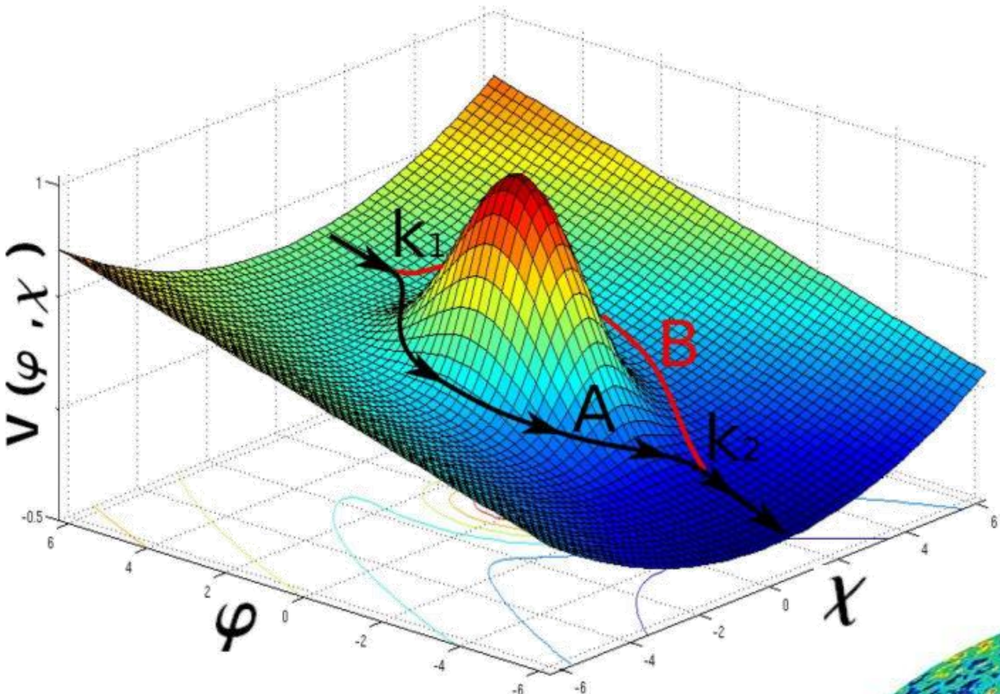
Miao Li & YW, 0903.2123

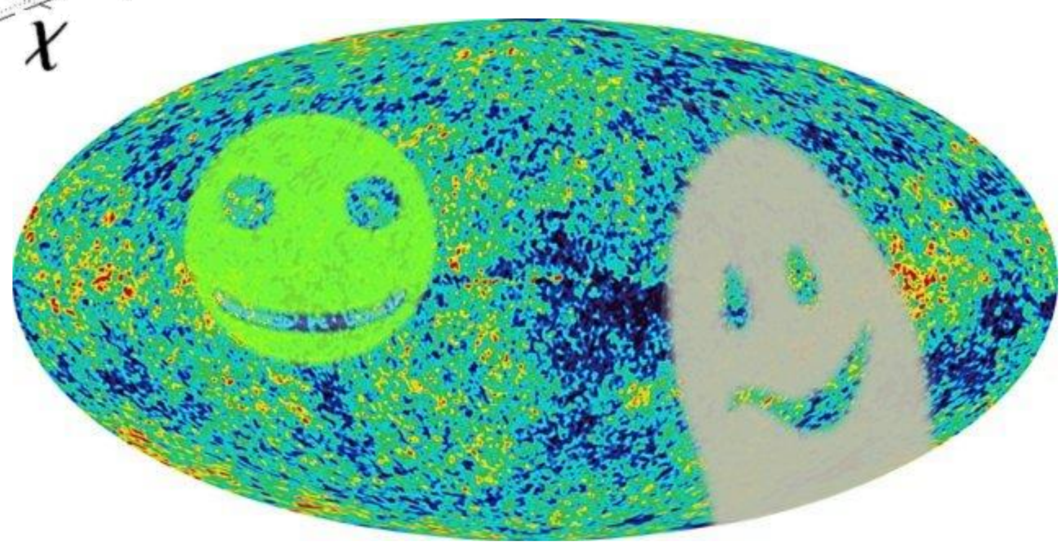
Multi-stream inflation in more observable e-folds: low var cycles

(although it's unlikely to be there in the CMB…)

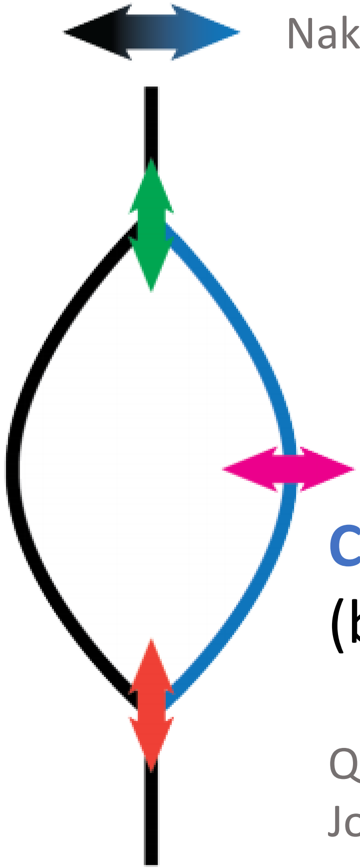


A model for primordial position space features





PBH: two ways to relate to multi-stream inflation



Nakama, Suyama & Yokoyama 1609.02245

(see also Sheng Li, Yang Liu and Yun-Song Piao, 0906.3608)

Clustered PBH, if only one path has (by other ways) PBH production

Qianhang Ding, Tomohiro Nakama, Joseph Silk & YW, 1903.07337

Possibility of two peaks

What if PBHs are initially clustered?

Details about GW & stellar bubbles

GW from clustered PBH

What if PBHs are initially clustered? Large PBHs & clusters

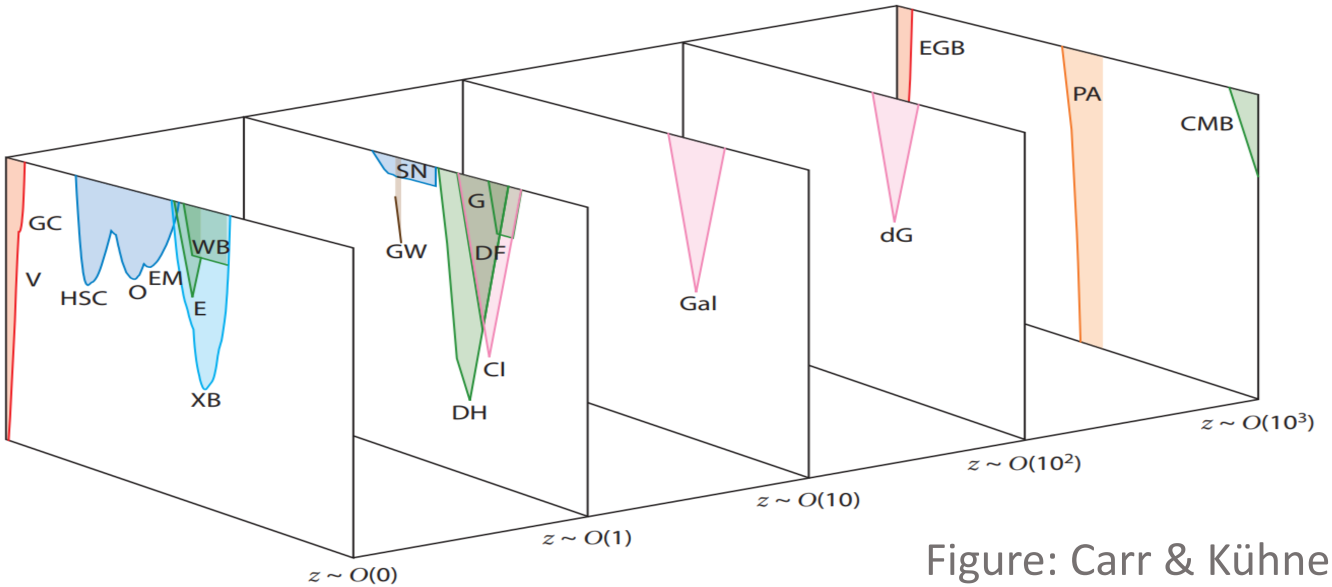


Figure: Carr & Kühnel 2006.02838

1. Can discard all $z \sim O(0)$ constraints
2. **Closer thus more binaries → more GW events**

1903.07337, Qianhang Ding, Tomohiro Nakama, Joseph Silk & YW

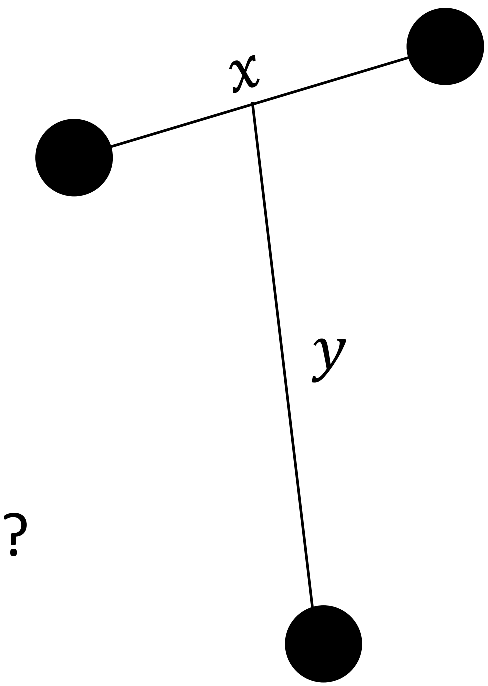
How (and when) is a PBH binary formed?

Consider comoving distances, taking scale factor $R_{eq} \equiv 1$

PBH mean separation: $\bar{x} = \left(M_{BH}/\rho_{BH}(z_{eq})\right)^{1/3}$

Two close PBHs: separated by x

A third PBH: y away



When did the PBH pair decouple from expansion?

"Energy density" of 2 PBH exceeds BG:

$$\rho = f\rho_{eq}(\bar{x}/x)^3 R^{-3} > \rho_r = \rho_{eq} R^{-4} \quad \rightarrow \quad R > R_m \equiv \frac{1}{f}\left(\frac{x}{\bar{x}}\right)^3$$

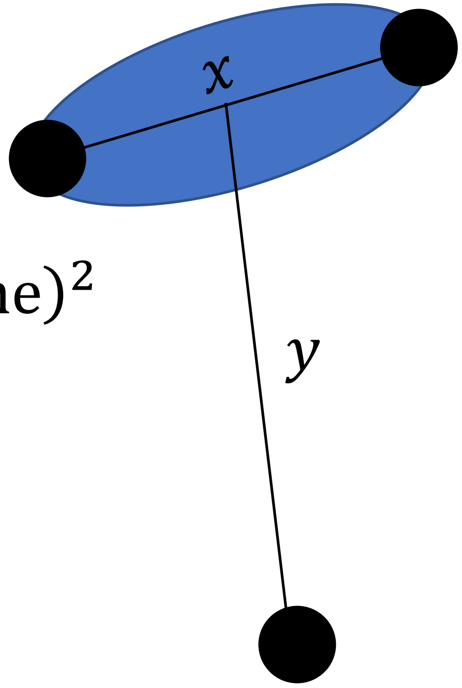
Sasaki, Suyama, Tanaka, Yokoyama, 1603.08338

Feature of the orbit:

Semi-major axis: $a \sim xR_m$

(comoving distance at decouple time)

Semi-minor axis: $b \sim (\text{force difference}) \times (\text{fall time})^2$



$$(\text{fall time})^2 \times \frac{GM_{BH}}{x^2} \sim a$$

$$(\text{force difference}) \sim \frac{GM_{BH}}{y^2} - \frac{GM_{BH}}{(y-x)^2} \sim \frac{GM_{BH}x}{y^3}$$

Thus $b \sim \left(\frac{x}{y}\right)^3 a$

Eccentricity: $e = \sqrt{1-(x/y)^6}$. Note $y \leq \bar{x}$ $\rightarrow$ $e_{\max} = \sqrt{1 - f^{3/2}\left(\frac{a}{\bar{x}}\right)^{3/2}}$

Sasaki, Suyama, Tanaka, Yokoyama, 1603.08338

From standard formula of gravitational radiation:

Coalescence time: $t = Qa^4(1-e^2)^{7/2}, \qquad Q = \frac{3}{170}(GM_{\rm BH})^{-3}$

Probability: $dP = \frac{9}{\bar{x}^6}x^2y^2dxdy \qquad dP = \frac{3}{16}\left(\frac{t}{T}\right)^{3/8}e(1-e^2)^{-\frac{45}{16}}\frac{dt}{t}de, \qquad T \equiv \frac{\bar{x}^4Q}{f^4}$

Sasaki, Suyama, Tanaka, Yokoyama, 1603.08338

$$dP = \frac{3}{16}\left(\frac{t}{T}\right)^{3/8} e(1-e^2)^{-\frac{45}{16}}\frac{dt}{t}de, \qquad T \equiv \frac{\bar{x}^4 Q}{f^4}$$

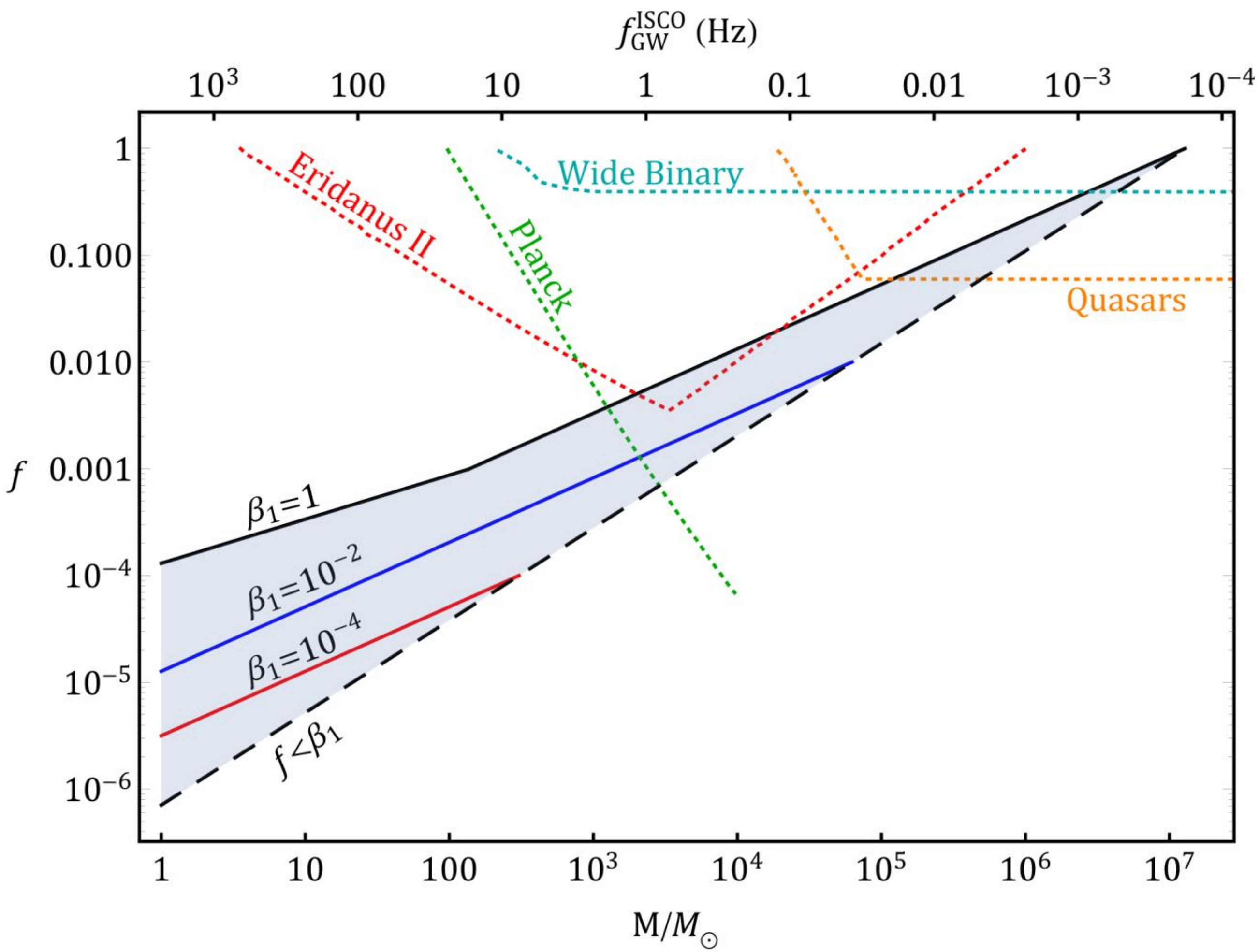
$$e_{\rm upper} = \begin{cases} \sqrt{1-\left(\frac{t}{T}\right)^{\frac{6}{37}}} & \text{for } t < t_c \\ \sqrt{1-f^2\left(\frac{t}{t_c}\right)^{\frac{2}{7}}} & \text{for } t \geq t_c, \end{cases} \qquad t_c = Q\bar{x}^4 f^{\frac{25}{3}}$$

$$dP_t = \begin{cases} \frac{3}{58}\left[-\left(\frac{t}{T}\right)^{3/8} + \left(\frac{t}{T}\right)^{3/37}\right]\frac{dt}{t} & \text{for } t < t_c \\ \frac{3}{58}\left(\frac{t}{T}\right)^{\frac{3}{8}}\left[-1 + \left(\frac{t}{t_c}\right)^{-\frac{29}{56}} f^{-\frac{29}{8}}\right]\frac{dt}{t} & \text{for } t \geq t_c. \end{cases}$$

$$\text{event rate} = n_{\rm BH}\lim_{\Delta t \to 0}\frac{P_c(t_0) - P_c(t_0 - \Delta t)}{\Delta t} = \frac{3H_0^2}{8\pi G}\frac{\Omega_{\rm BH}}{M_{\rm BH}}\frac{dP_c}{dt}\bigg|_{t_0}.$$

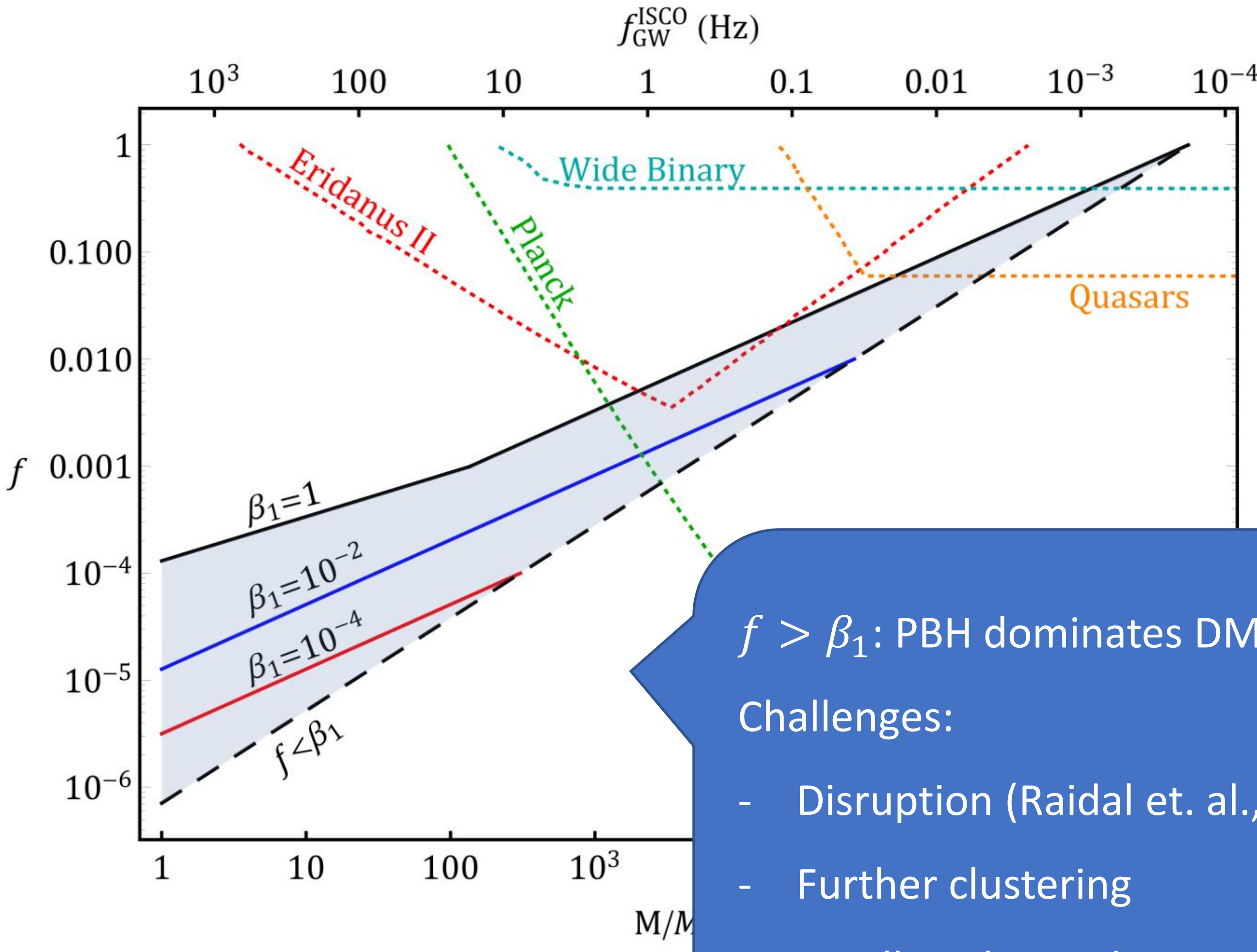
Sasaki, Suyama, Tanaka, Yokoyama, 1603.08338

Can we have observable event rates of PBH, say 1 /Gpc^3 /yr?



1903.07337, Qianhang Ding, Tomohiro Nakama, Joseph Silk & YW

Can we have observable event rates of PBH, say 1 /Gpc^3 /yr?

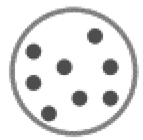


$f > \beta_1$: PBH dominates DM

Challenges:

- Disruption (Raidal et. al., 1812.01930)
- Further clustering
- Locally enhanced structure formation

Stellar bubbles



1. Hawking radiation in practice
2. Put them together

Yi-Fu Cai, Chao Chen, Qianhang Ding & YW, 2105.11481

Hawking radiation in practice

$$\frac{\mathrm{d}^2 N}{\mathrm{d}t\mathrm{d}E} = \frac{1}{2\pi}\frac{\Gamma_s(E,M)}{e^{8\pi GME} - (-1)^{2s}}$$

$$T_{\mathrm{BH}} = \frac{1}{8\pi GM} \simeq 1.06 \times M_{10}^{-1}\ \mathrm{TeV}$$

$$\frac{\mathrm{d}M_{10}}{\mathrm{d}t} \simeq -5.34 \times 10^{-5}\phi(M)M_{10}^{-2}\ \ \mathrm{s}^{-1}$$

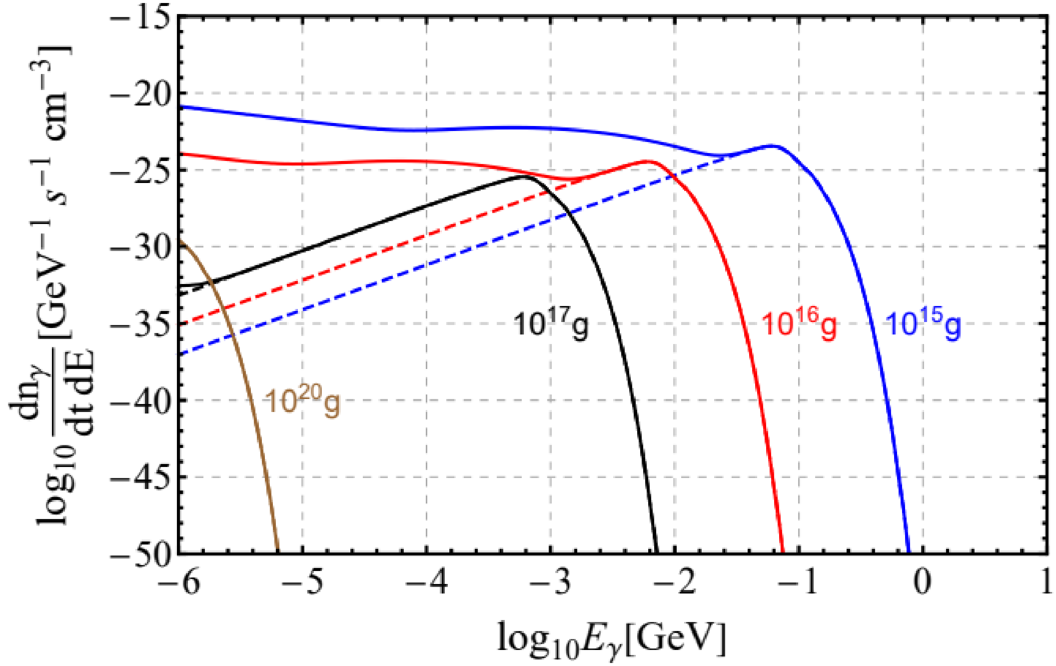
$$\tau \sim 407\left(\frac{\phi(M)}{15.35}\right)^{-1} M_{10}^3$$

$$M \simeq 1.35 \times 10^9 \left(\frac{\phi(M)}{15.35}\right)^{1/3}\left(\frac{\tau}{1\mathrm{s}}\right)^{1/3}\ \ \mathrm{g}$$

The relativistic contributions to $\phi(M)$ per degree of particle freedom are $\phi_{s=0} = 0.267, \phi_{s=1} = 0.060, \phi_{s=3/2} = 0.020, \phi_{s=2} = 0.007, \phi_{s=1/2} = 0.147$ (neutral), $\phi_{s=1/2} = 0.142$ (charge $\pm e$) [68].

MacGibbon & Webber (1990)

Photon emission: primary and secondary



$$\frac{\mathrm{d}\dot{N}}{\mathrm{d}E}(E,M) = \frac{\mathrm{d}\dot{N}^{\mathrm{pri}}}{\mathrm{d}E}(E,M) + \frac{\mathrm{d}\dot{N}^{\mathrm{sec}}}{\mathrm{d}E}(E,M)$$

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

Carr, Kohri, Sendouda, Yokoyama, 0912.5297

Arbey & Auffinger, BlackHawk homepage – Hepforge

Putting individual radiation together: distribution

Lognormal distribution as an example   ($\sigma = 1$ in plots)

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

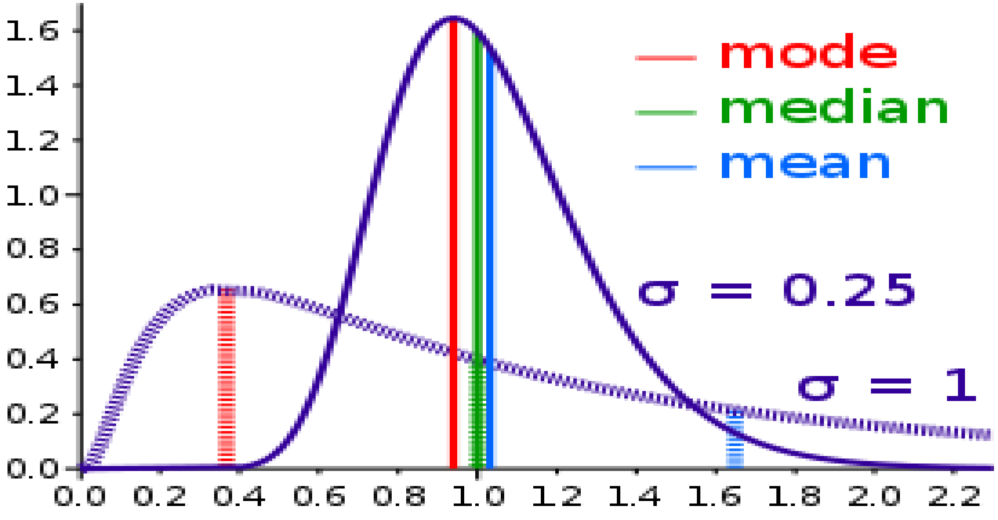
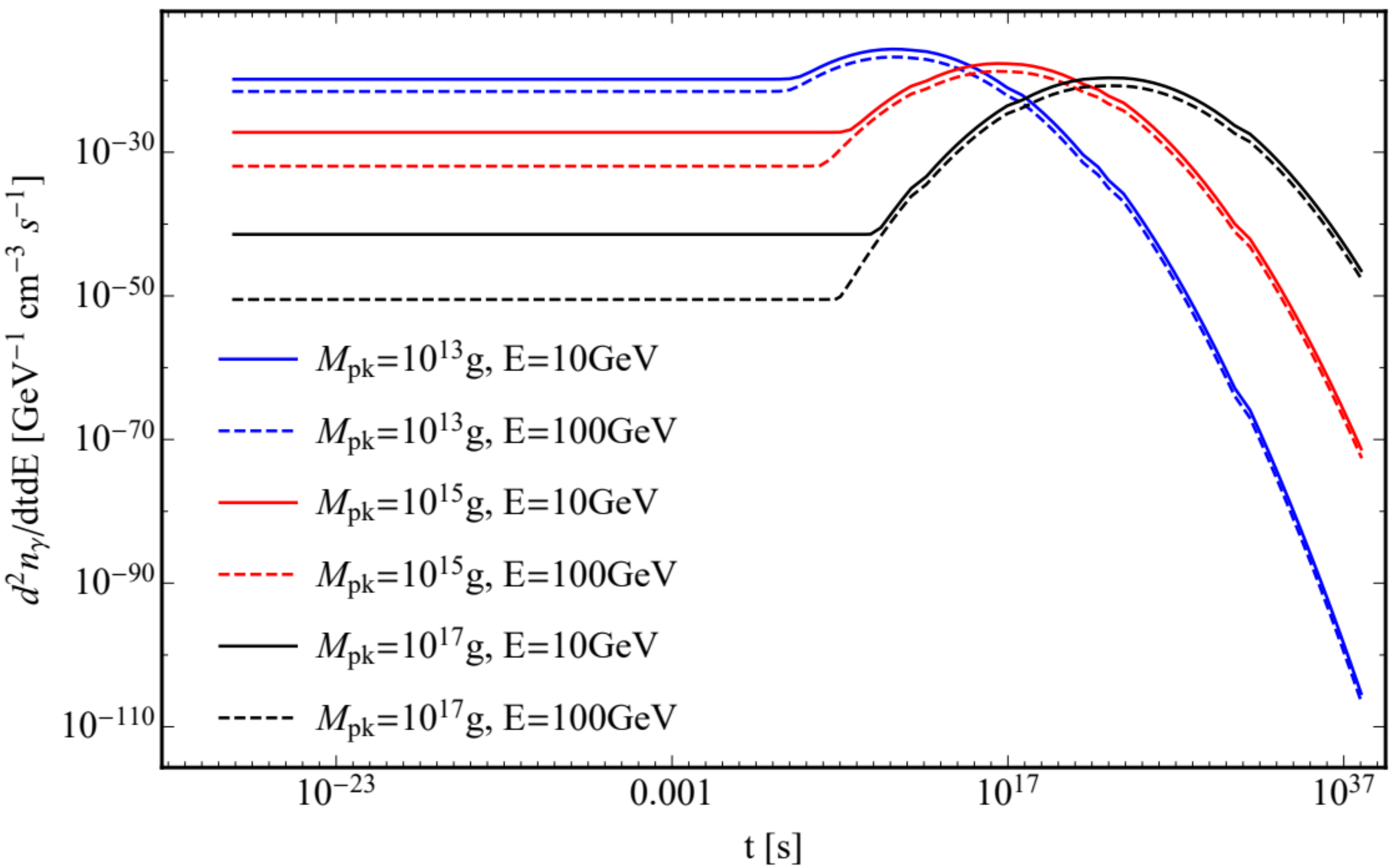
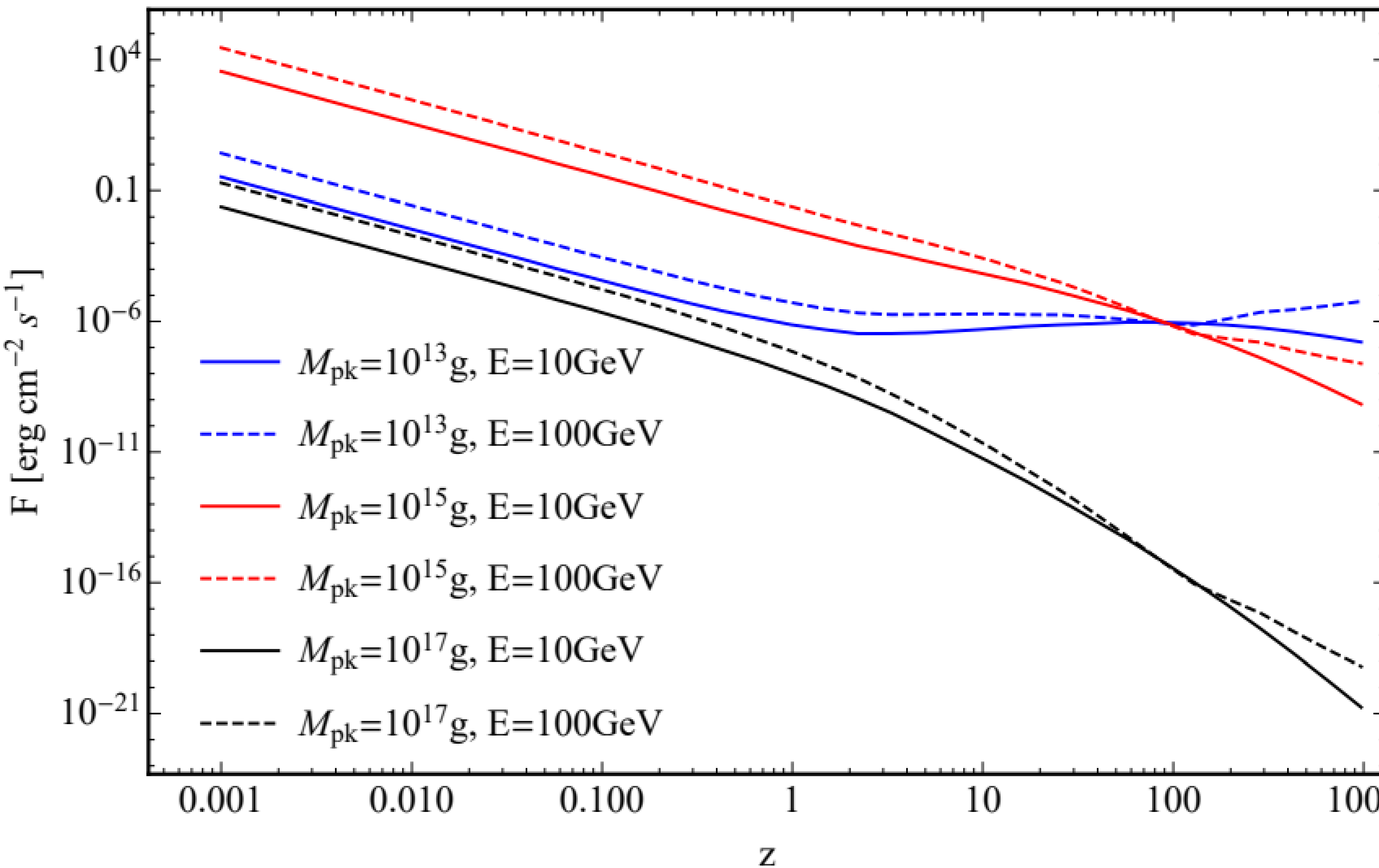


image: wikipedia

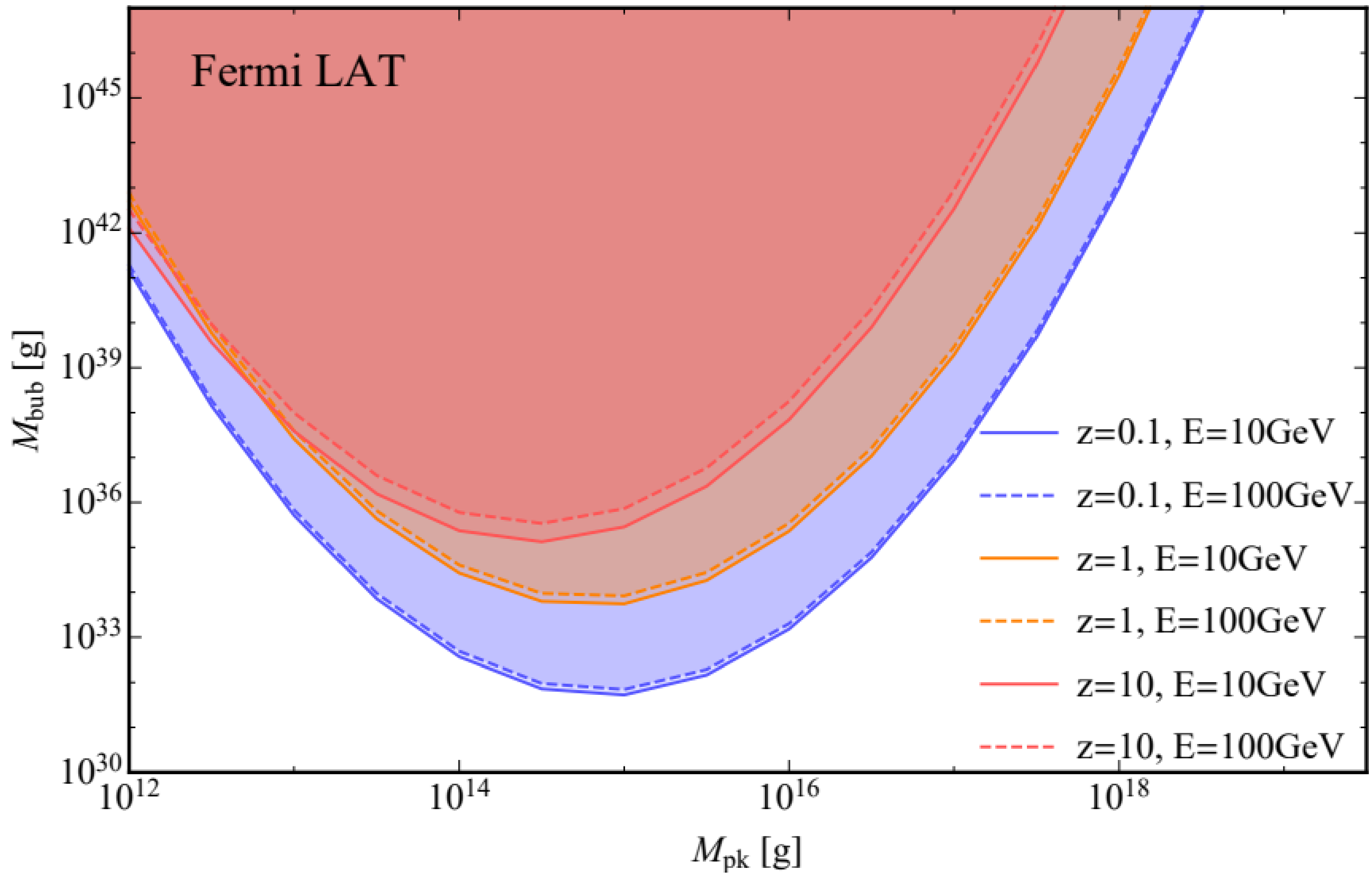
Putting individual radiation together: "light curve"



Yi-Fu Cai, Chao Chen, Qianhang Ding & YW, 2105.11481



Yi-Fu Cai, Chao Chen, Qianhang Ding & YW, 2105.11481



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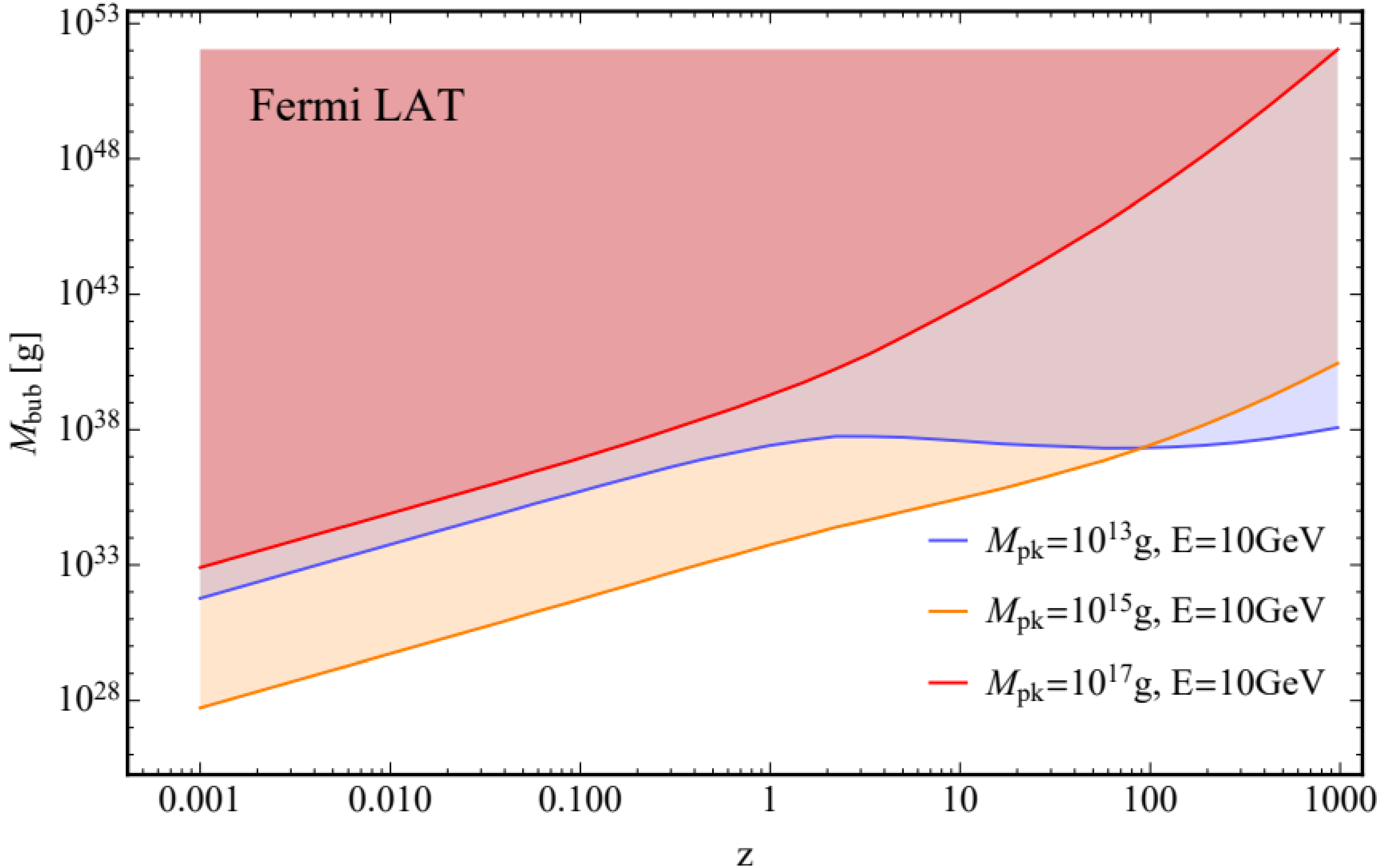
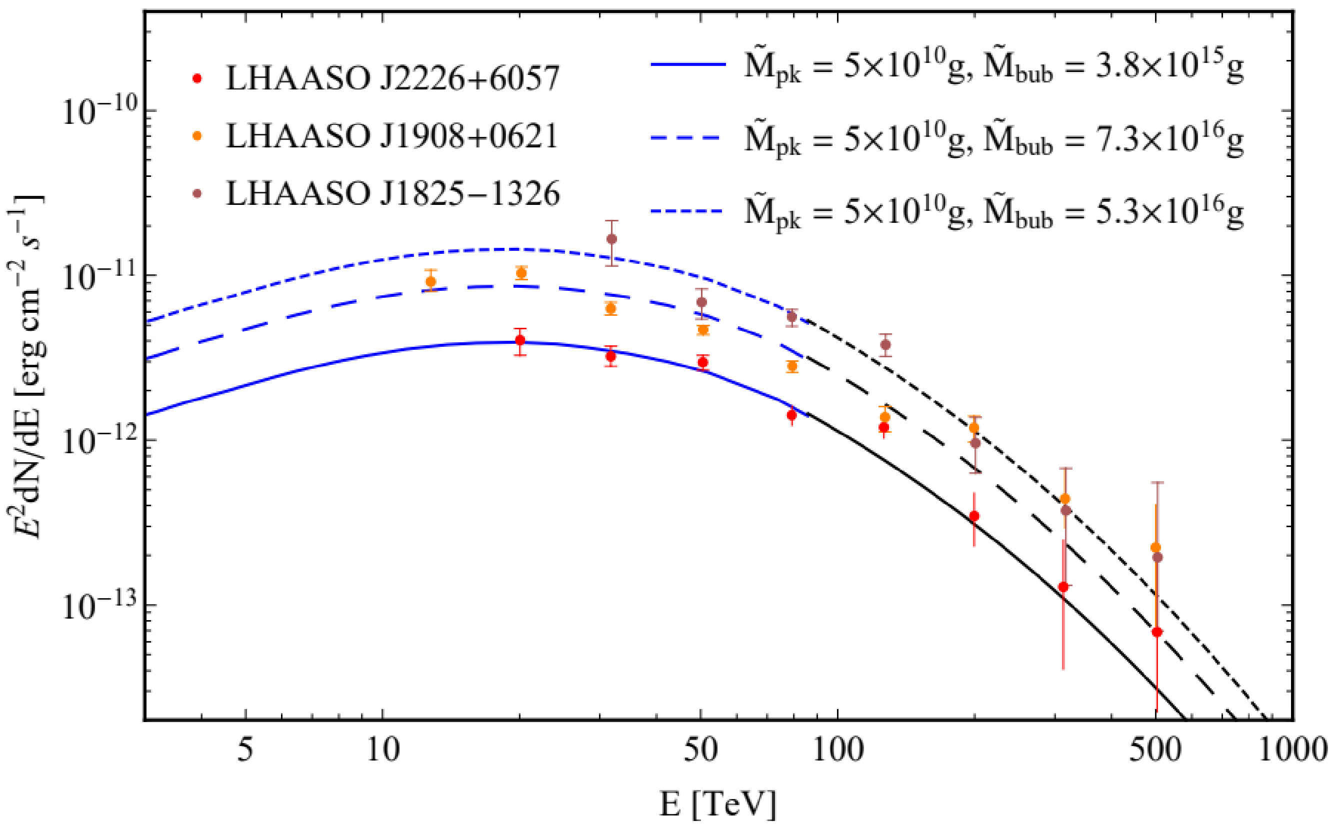


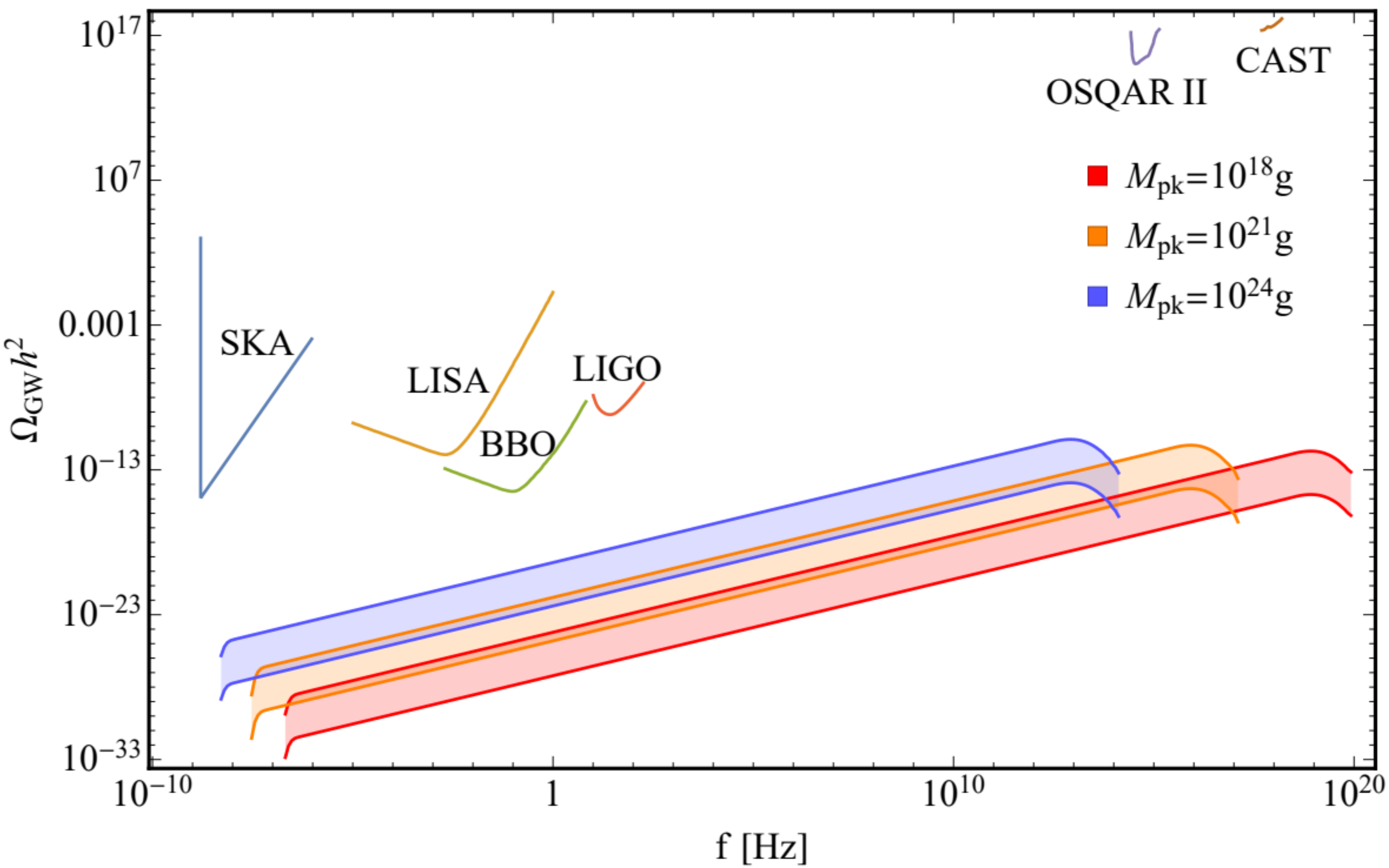
Yi-Fu Cai, Chao Chen, Qianhang Ding & YW, 2105.11481

Can PBH stellar bubbles explain some gamma-ray observations?



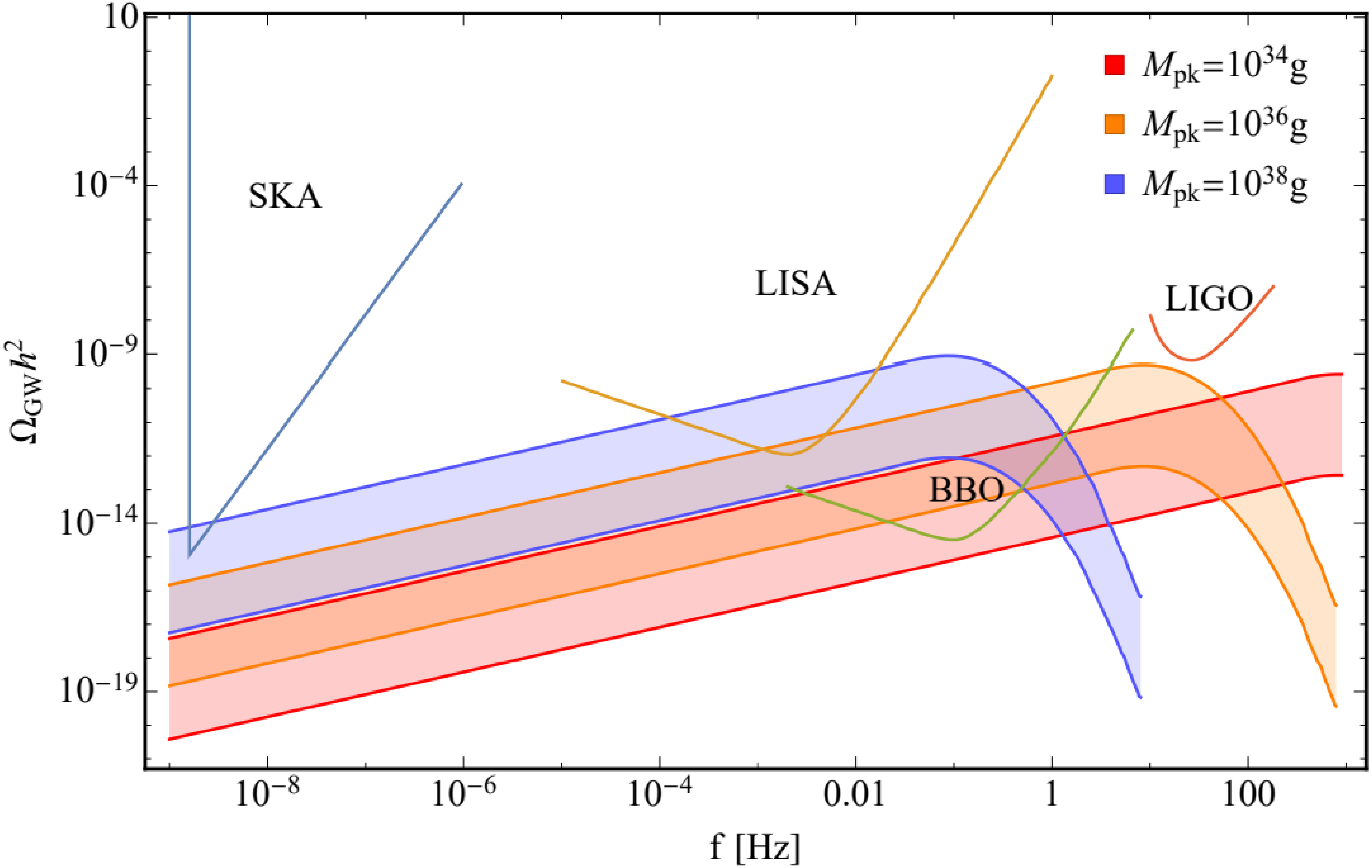
Yi-Fu Cai, Chao Chen, Qianhang Ding & YW, 2105.11481

Optical PBH stellar bubbles: GW too weak



Yi-Fu Cai, Chao Chen, Qianhang Ding & YW, 2105.11481

GW stellar bubbles: if Mpk greater



Yi-Fu Cai, Chao Chen, Qianhang Ding & YW, 2105.11481

Summary & discussions

- Multi-stream inflation
  - Now δN. More on perturbations & simulations?
  - UV models with PBH trajectories, etc?
- GW from PBH-rich bubbles
  - CMB constraints? Is LISA PBH indeed possible?
  - Parameter regime $f > \beta_1$?
- Stellar bubbles
  - Multi-messenger, e.g., neutrino?
  - Survey of parameter space?
  - Stellar bubbles with other exotic matter?

Thank you!

Acknowledgement: Some works in this talk were supported in part by ECS Grant 26300316, GRF Grants 16301917, 16304418 and 16303621 from the Research Grants Council of Hong Kong SAR, and EYS Grant 12022516 by the National Natural Science Foundation of China

Appendix

Discussion on observational bounds:

1. Milky Way or local group: invalided.

Eridanus II, wide-binary disruption

Brandt 1605.03665

Eridanus II:

ultra-faint dwarf galaxy

discovered by DES

distance from us: 366 kpc

$M > 10 M_{\odot}$ DM can disturb it

until it dissolves into host galaxy

Quinn et al 0903.1644

Binaries separated by ~1pc

sample distances: 200~350pc

Discussion on observational bounds:

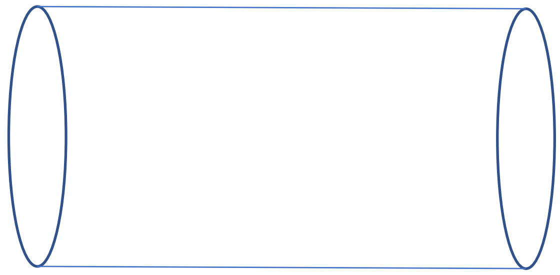
2. Millilensing of quasars: depending on if line-of-sight

of quasar to us encounter B patches.

Wilkinson et al astro-ph/0101328

Studied 300 quasar sources, and lens is at cosmological distance

If many B patches, this limit is valid.



radius: impact parameter of lensing

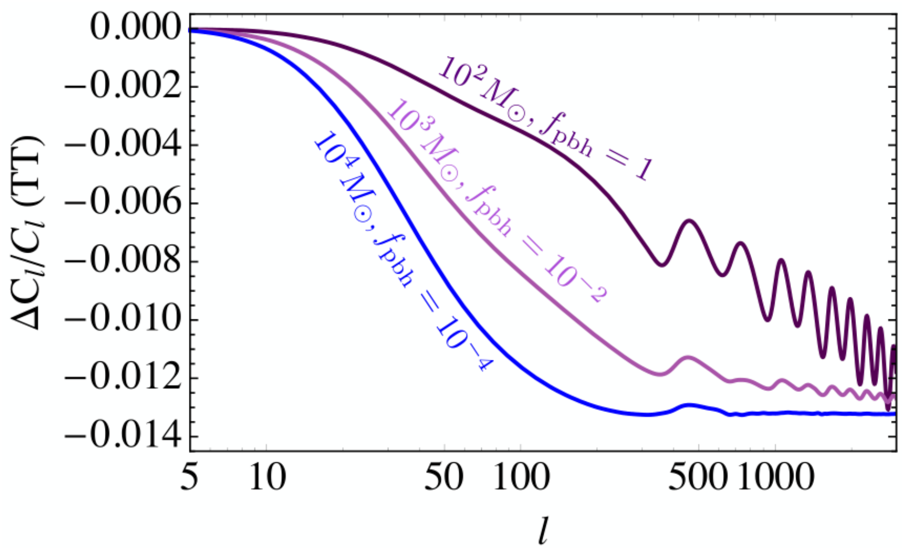
If no B patch, this limit is invalid.

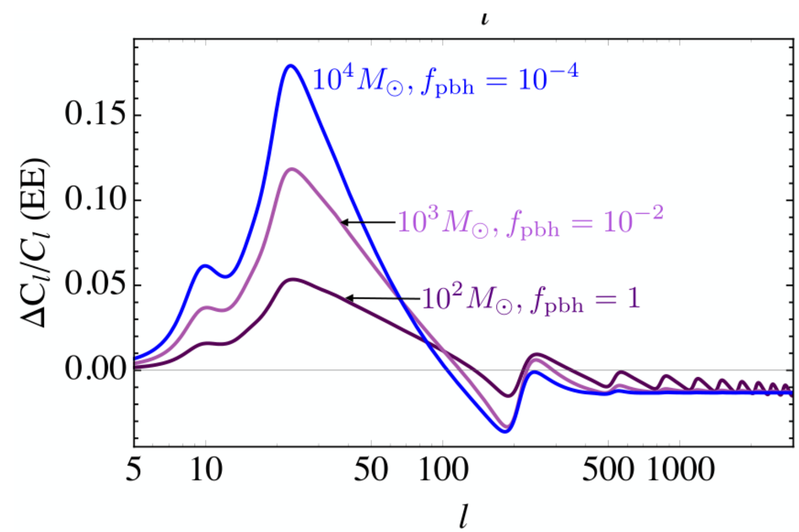
Discussion on observational bounds:

3. Accretion: astrophysical uncertainties.

For CMB: the larger BH mass, affecting the lower ℓ.

Bubbles: high ℓ. Thus constraints become weaker?





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2.3 Photons spectra from Hawking radiation

In 1974, Hawking found that a black hole could emit particles similar to the black-body radiation, with energies in the range $(E, E + dE)$ at a rate [5, 80]

$$\frac{d^2N}{dtdE} = \frac{1}{2\pi} \frac{\Gamma_s(E, M)}{e^{8\pi GME} - (-1)^{2s}}, \tag{2.18}$$

per particle degree of freedom (e.g. spin, electric charge, flavor and color). Here M is the mass of the black hole, s is the particle spin and the black hole temperature is thus defined as

$$T_{\rm BH} = \frac{1}{8\pi GM} \simeq 1.06 \times M_{10}^{-1}\text{TeV}, \tag{2.19}$$

where M_{10} is related to the black hole mass $M \equiv M_{10} \times 10^{10}$ g. And $\Gamma_s(E, M)$ is the dimensionless absorption coefficient which accounts for the probability that the particle would be absorbed if it were incident in this state on the black hole. It appears in the emission formula on account of detailed balance between emission and absorption. In general, $\Gamma_s(E, M)$ depends on the spin, the energy of emitted particle and the black hole mass. The absorption coefficient is expressed as $\Gamma_s(E, M) = E^2\sigma_s(E, M)/\pi$, here $\sigma_s(E, M)$ is the corresponding absorption cross section. In the high-energy limit $E \gg T_{\rm BH}$, $\sigma_s(E, M)$ approaches to geometric optics limit $\sigma_g = 27\pi G^2M^2$ which is independent of the energy of emitted particle. The functional expressions of $\Gamma_s(E, M)$ for massless and massive particles can be found in Refs. [81–83]. Hawking temperature (2.19) tells us that a smaller black hole is much hotter than a larger black hole, naturally, the emission is also stronger. So that in this sense, PBHs can be small enough for Hawking radiation to be significant.

V. LIMITS ON A LOCAL VOID FROM THE LINEAR KSZ EFFECT

Spatial fluctuations in the electrons in the Universe cause distortions of the CMB spectrum due to interactions between high energy electrons and the CMB photons, which is called kSZ effect [35]. The temperature perturbation in direction $\hat{n}$ induced by a local void is given by [43]

$$\Delta T_{\rm kSZ}(\hat{n}) = T_{\rm CMB} \int_0^{z_e} \delta_e(\hat{n}, z) \frac{V_H(\hat{n}, z) \cdot \hat{n}}{c} d\tau_e \ . \tag{27}$$

Here, $T_{\rm CMB} = 2.73{\rm K}$, δ_e is the density contrast of electrons, and τ_e is the optical depth alonge the line of sight. As in [59], we choose $z_e = 100$, and we assume

$$V_H \simeq [\widetilde{H}(t(z), r(z)) - \widetilde{H}(t(z), r(z_e))] R(t(z), r(z)) \ , \tag{28}$$

where, $\widetilde{H} = \dot{R}'/R'$. We use [60, 61]