CosKASI-ICG-NAOC-YITP
joint workshop
7 September, 2017

Primordial Black holes and Gravitational Waves

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Primordial Black Holes

What are Primorial BHs?

- PBH = BH formed before recombination epoch (ie at z>>1000)

  conventionally during radiation-dominated era

- Hubble size region with $\delta\rho / \rho = O(1)$ forms PBH

  Carr (1975), ….

- Such a large perturbation may be produced by inflation

  Carr & Lidsey (1991), …

- PBHs may dominate Dark Matter.

  Ivanov, Naselsky & Novikov (1994), …

- Origin of supermassive BHs ($M \gtrsim 10^6 M_\odot$) may be primordial.

examples

hybrid-type inflation

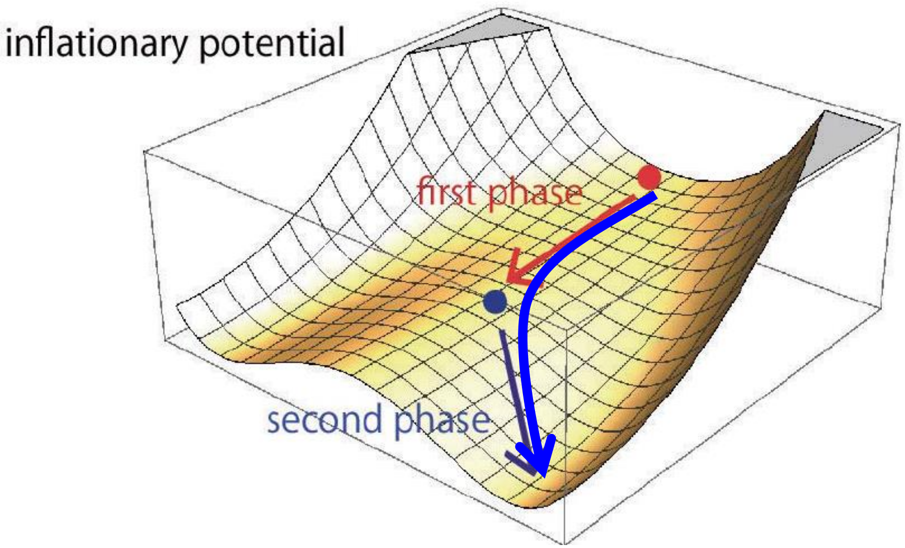
Garcia-Bellido, Linde & Wands '96, …

$\mathcal{R}_C$ grows near the saddle point

non-Gauss may become large

Abolhasani, Firouzjahi & MS '11,..

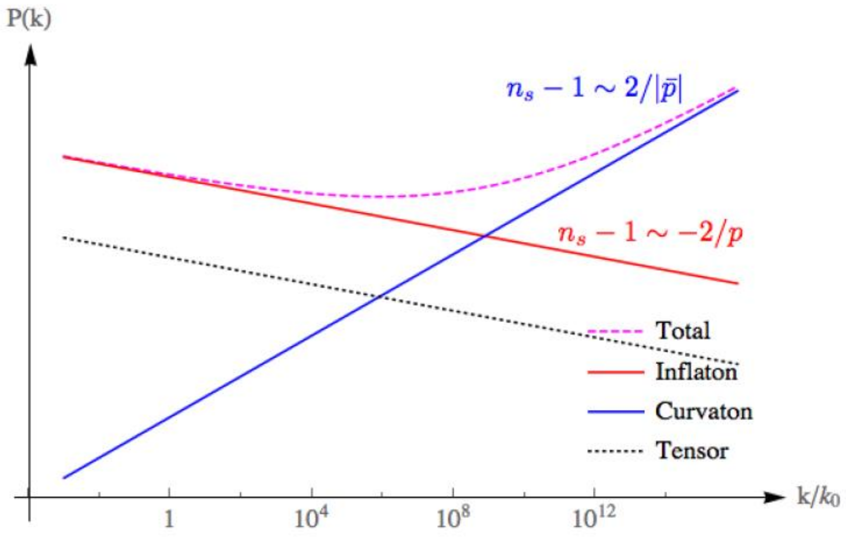
Pattison et al. 1707.00537



non-minimal curvaton

Domenech & MS '16

$$L = -\frac{1}{2} f(\phi) g^{\mu\nu} \partial_\mu \chi \partial_\nu \chi - \frac{1}{2} h(\phi) m^2 \chi^2$$



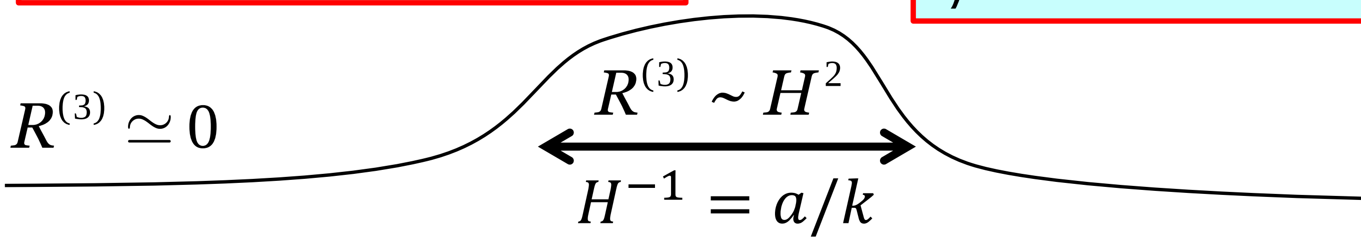
Curvature perturbation to PBH

- gradient expansion/separate universe approach

$$6H^2(t,x)+R^{(3)}(t,x)=16\pi G\rho(t,x)+\cdots$$

Hamiltonian constraint (Friedmann eq.)

$$\Rightarrow \boxed{R^{(3)}\approx-\frac{4}{a^2}\nabla^2\mathcal{R}_c\approx\frac{8\pi G}{3}\delta\rho_c} \Rightarrow \boxed{\frac{\delta\rho_c}{\rho}\sim\mathcal{R}_c \text{ at } \frac{k^2}{a^2}=H^2}$$



- If $R^{(3)}\sim H^2$ $\left(\Leftrightarrow \delta\rho_c/\rho\sim 1\right)$, it collapses to form BH

Young, Byrnes & MS ‘14

$$M_{\rm PBH}\sim\rho H^{-3}\sim 10^5 M_\odot\left(\frac{t}{1s}\right)\sim 20M_\odot\left(\frac{k}{1{\rm pc}^{-1}}\right)^{-2}$$

- Spins of PBHs are expected to be very small

Accretion to PBH?

- Bondi accretion

$$\dot{M} = \lambda \cdot 4\pi r_B^2 \rho c_s : \quad c_s = \sqrt{P/\rho}\left(=1/\sqrt{3}\right), \quad r_B = \frac{GM}{c_s^2}, \quad \lambda \lesssim O(1)$$

- accretion rate/Hubble time

$$\Rightarrow \frac{\dot{M}}{HM} = \lambda \frac{3}{4}\frac{H}{H_M} : \quad M = \frac{4\pi\rho_M}{3}\left(c_s H_M^{-1}\right)^3 = \frac{c_s^3}{2GH_M}, \quad \frac{H}{H_M} = \left(\frac{a_M}{a}\right)^2$$

horizon size at the time of PBH formation

$$\Rightarrow \int_{a_M}^{\infty} \frac{\dot{M}}{H}\frac{da}{a} \simeq \lambda \frac{3}{8} M$$

PBH mass can increase by a factor of 1.5 at most

Mass increase can be ignored, given other ambiguities

Effect on CMB?

accretion can lead to radiative emission

- Eddington luminosity: max luminosity from accretion

$$L_{\text{edd}} = \frac{4\pi G M m_p c}{\sigma_T};$$

m_p = proton mass

σ_T = Thomson cross section

$$L = \varepsilon L_{\text{edd}}; \quad \varepsilon \le 1$$

··· luminosity from PBH

- energy output/Hubble time

$$\frac{\dot{\rho}_R}{H\rho_R} = \varepsilon \frac{n_{PBH} L_{\text{edd}}}{H\rho_R} = \varepsilon \frac{\rho_{PBH}}{\rho_R}\frac{4\pi G m_p}{\sigma_T H} = \varepsilon f_{PBH}\left(\frac{a}{a_{eq}}\right)^3 \frac{4\pi G m_p}{\sigma_T H_{eq}}$$

$$\simeq 10^{-4} \varepsilon f_{PBH}\left(\frac{a}{a_{eq}}\right)^3; \quad f_{PBH} = \frac{\Omega_{PBH}}{\Omega_{CDM}}$$

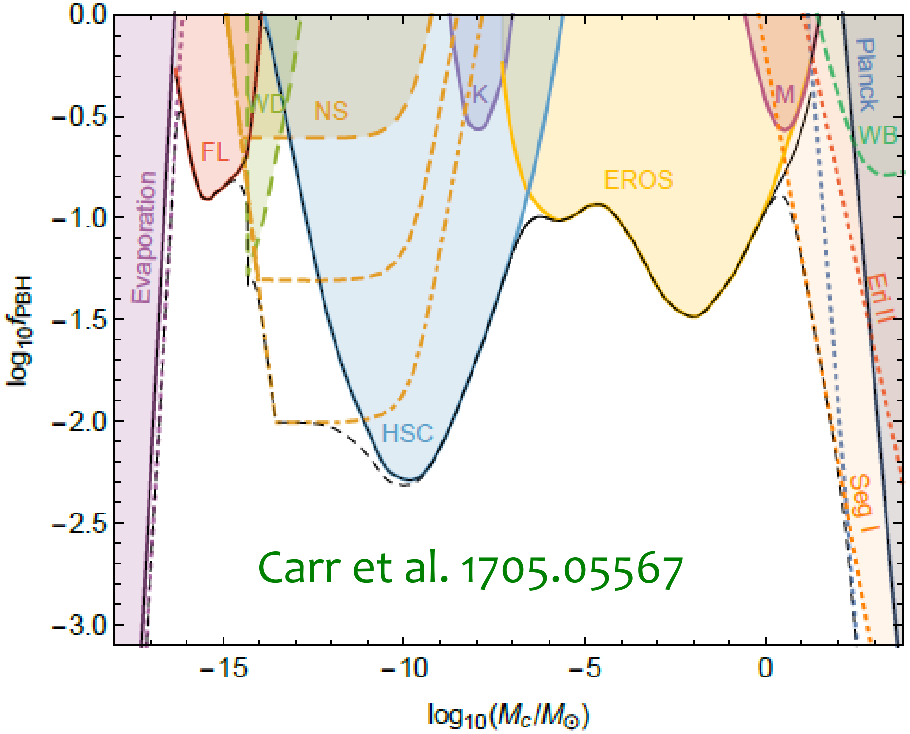
small, but may not be entirely negligible…

Constraints on PBHs

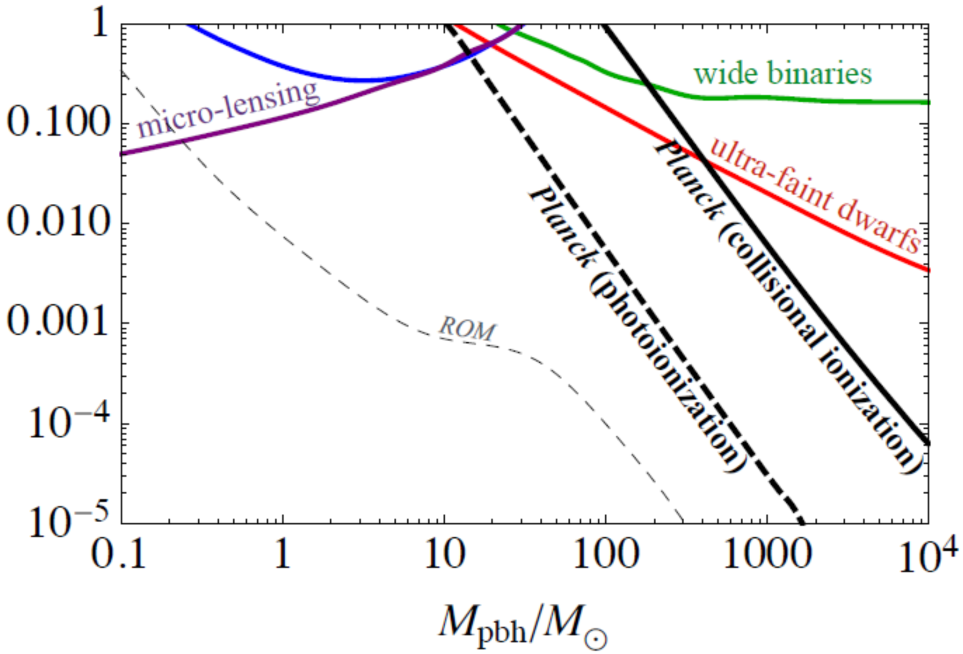
$$f_{PBH} = \frac{\Omega_{PBH}}{\Omega_{DM}}$$

DM can't be dominated by PBHs!

(opinion varies though…, particularly at $M \sim 100 M_{\odot}$)



Carr et al. 1705.05567



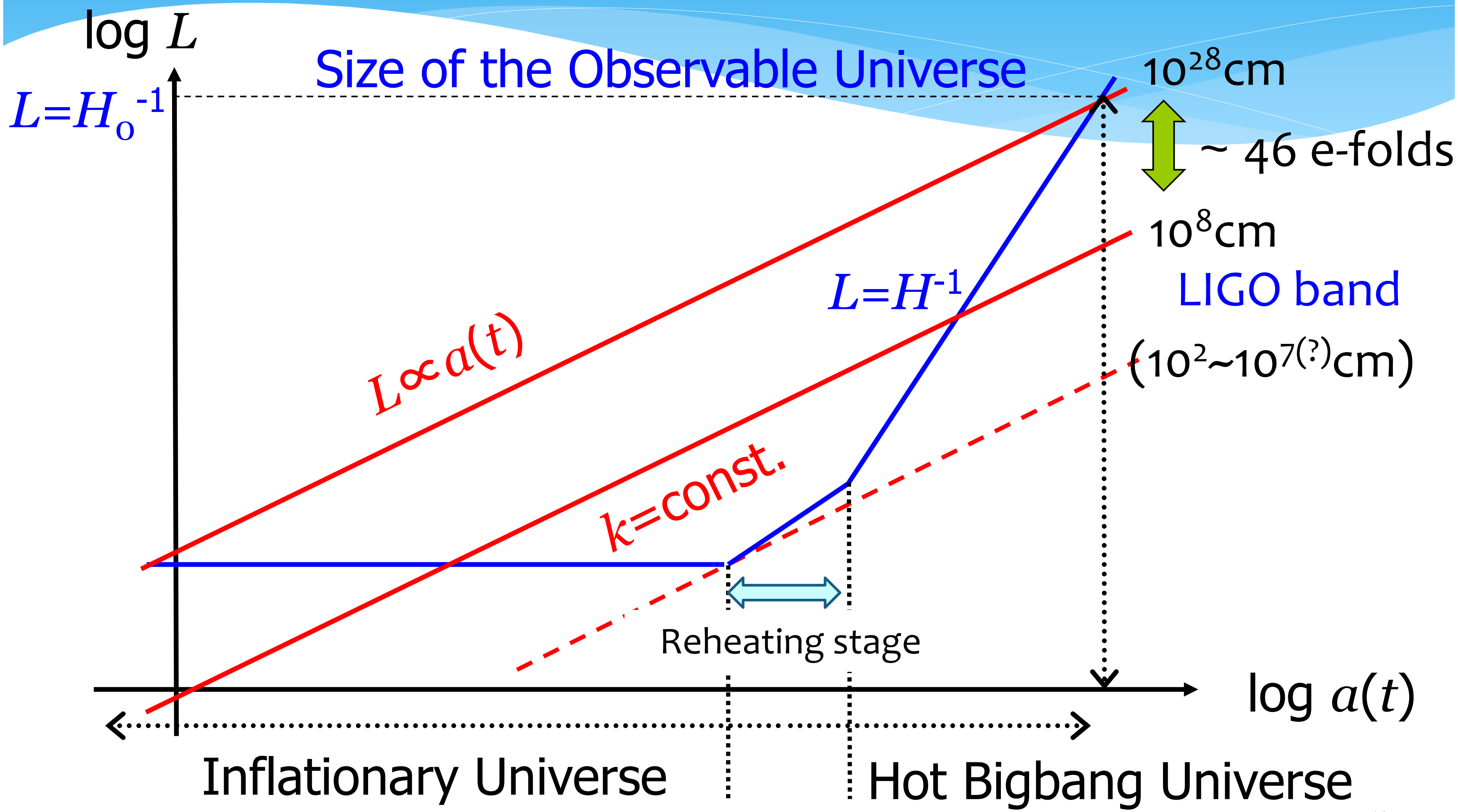
Ali-Haimoud & Kamionkowski, 1612.05644

Ricotti, Ostriker & Mack ('08) overestimated the accretion effect

Gravitational Waves from Inflation

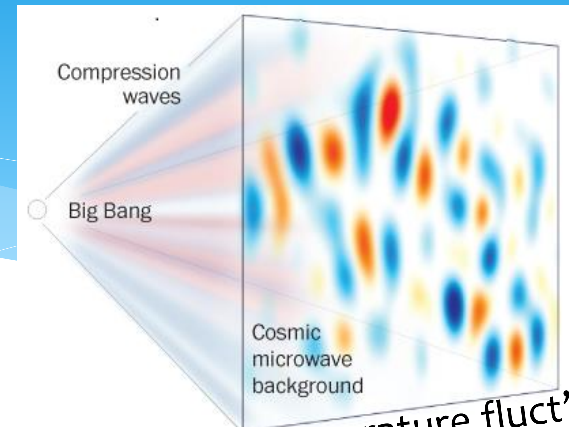
length scales of the inflationary universe

⟺ targets for multi-frequency GW astronomy



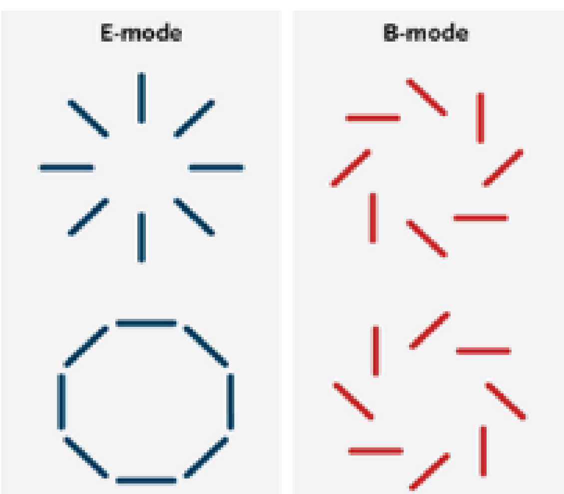
Cosmological GWs

- scalar field(s) produce density fluctuations
  -> CMB temp+E-mode fluctuations



temperature fluct'ns

- tensor (GW) fluctuations
  -> CMB temp+E-mode+B-mode fluct'ns



E-mode (even parity)

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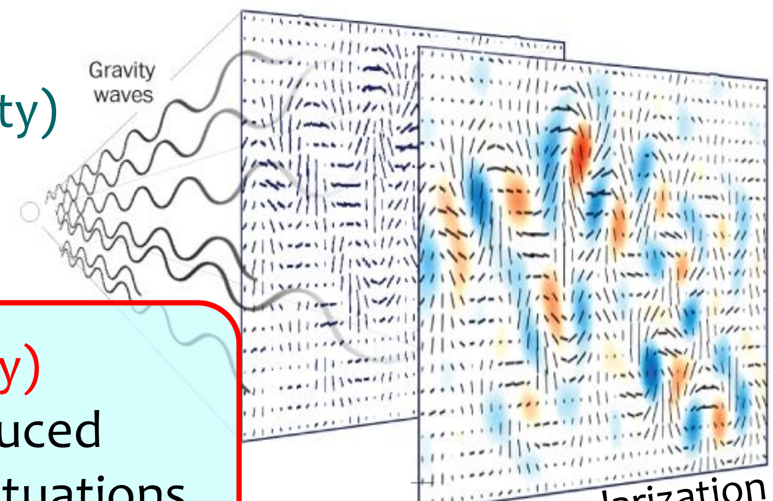
B-mode (odd parity)
= cannot be produced from density fluctuations



B-mode polarization

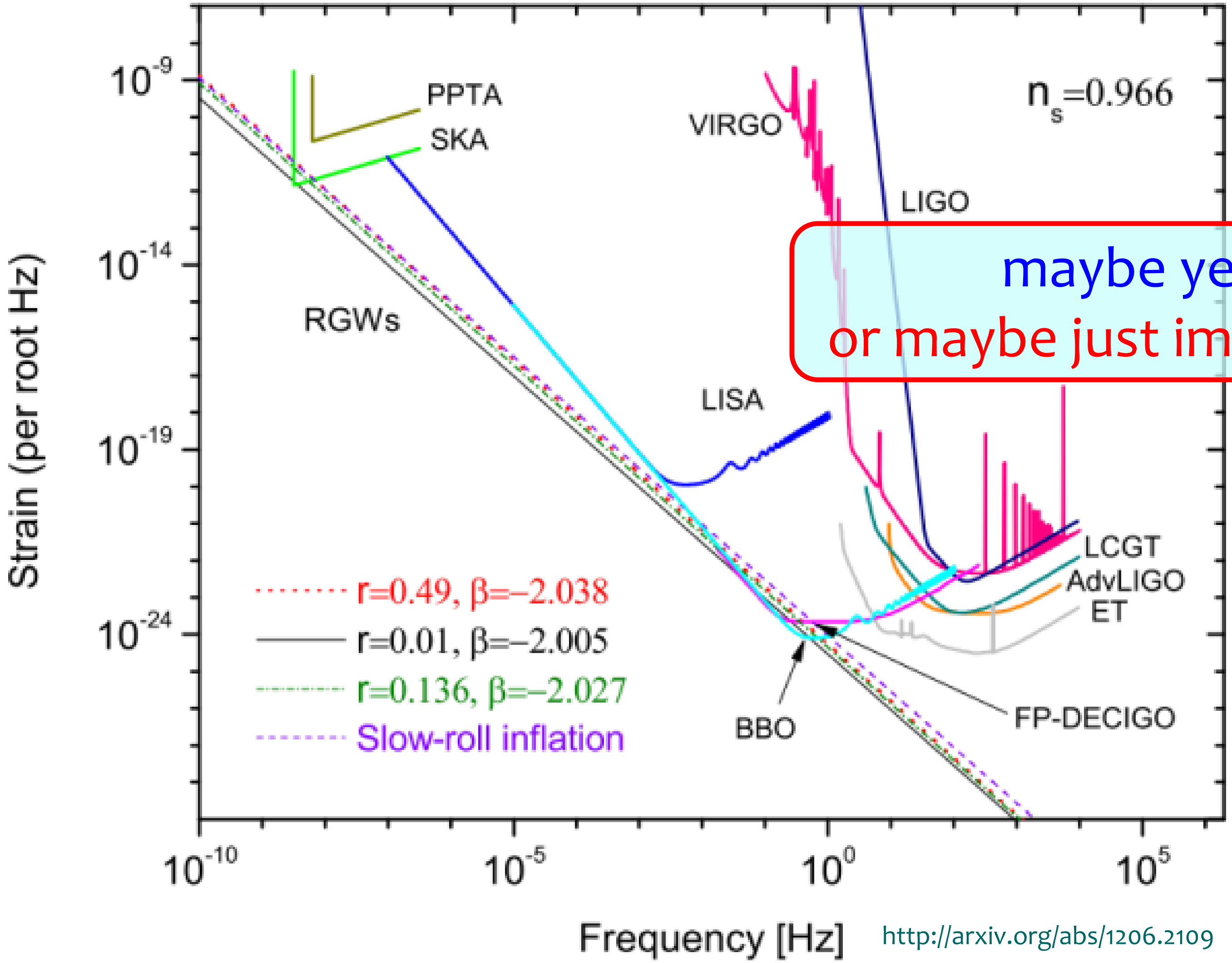
http://www.skyandtelescope.com/

Source: Harvard-Smithsonian Center for Astrophysics

CMB B-mode=cosmological GW detector

GWs from "Standard" Inflation

could direct detection by GW observatories possible?



maybe yes…

or maybe just impossible…

http://arxiv.org/abs/1206.2109

2^{nd} order GW constraints on PBH

Saito & Yokoyama '09, Alabidi et al. '12, …

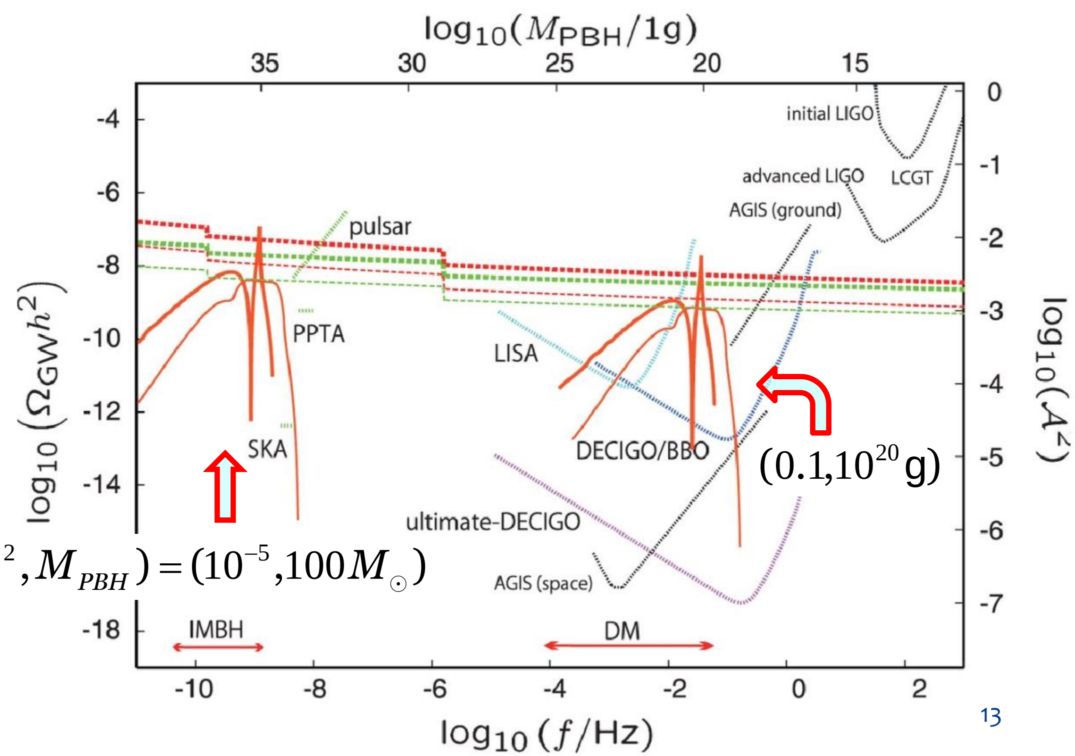
- Non-negligible PBH formation means $\mathcal{P}_S(k) \sim 10^{-2.5} - 10^{-2}$

$$\ddot{h}_{ij} + 3H\dot{h}_{ij} - a^{-2}\Delta h_{ij} = S_{ij} \qquad S_{ij} \simeq \frac{1}{a^2}\partial_i \mathcal{R}_c \partial_j \mathcal{R}_c + \cdots \sim \frac{k^2}{a^2}\mathcal{P}_S(k)$$

- GWs are produced with amplitude:

$$h_{ij} \sim \frac{k^2}{a^2 H^2}\mathcal{P}_S(k) \sim \mathcal{P}_S(k)$$

2^{nd} order GWs would dominate at $f>10^{-10}$ Hz ($k>10^4\ \mathrm{Mpc}^{-1}$)



$(0.1, 10^{20}\,\mathrm{g})$

$(\Omega_{PBH}h^2, M_{PBH}) = (10^{-5}, 100 M_\odot)$

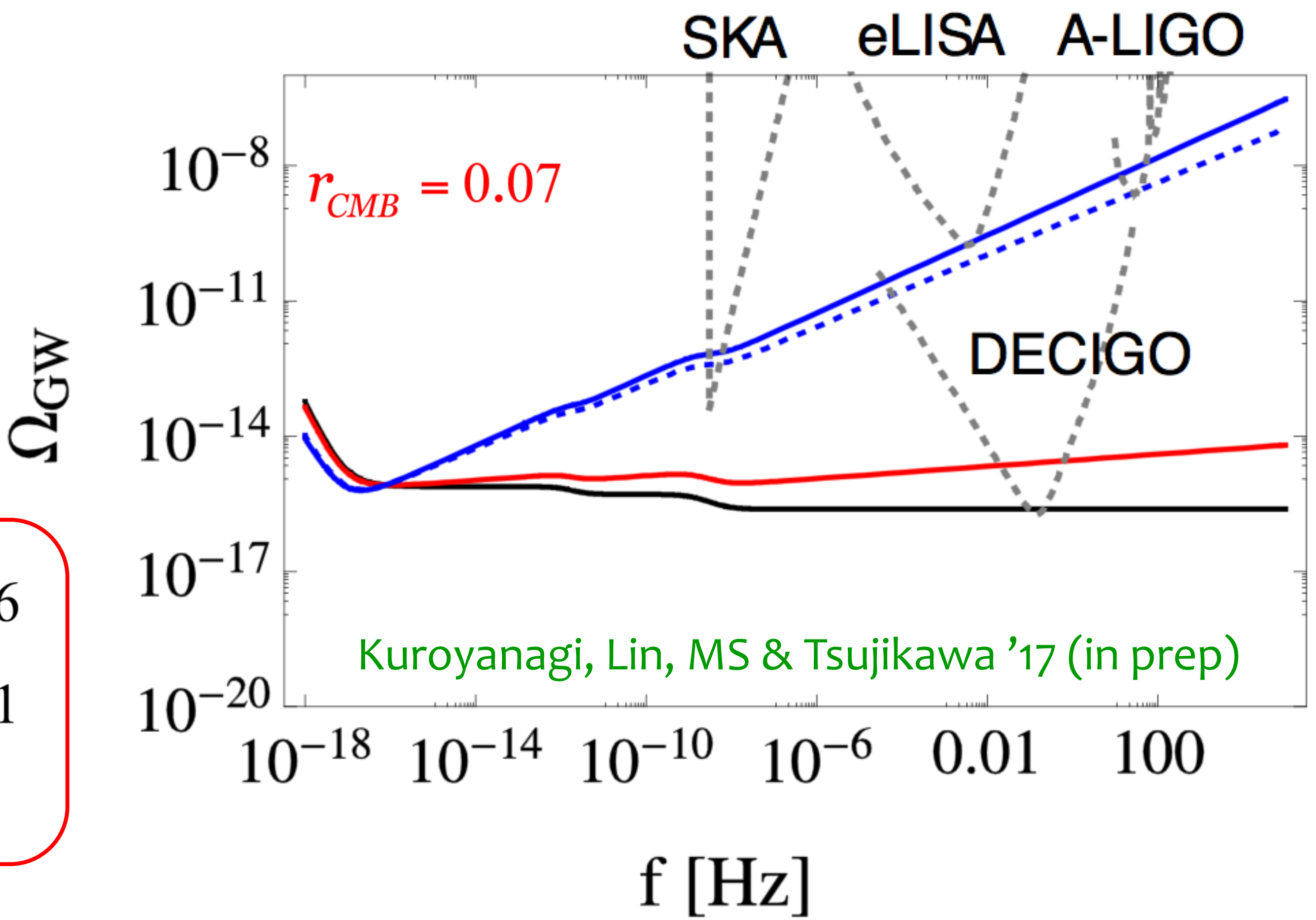
blue-tilted GW spectrum?

possible in inflationary massive gravity   Lin & MS '15

tensor (=GW) spectral index:

$$n_T \approx \frac{2m_g^2}{3H^2}$$

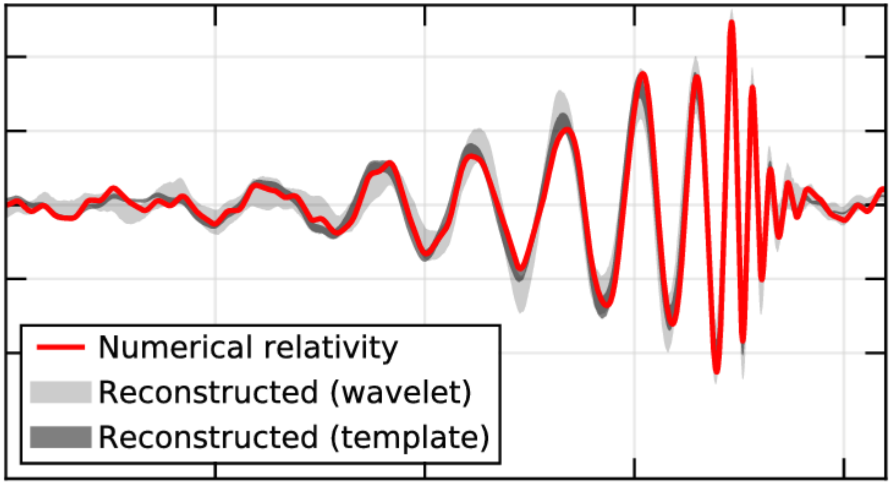
- blue: $m_g^2 / H^2 = 0.6$
- red: $m_g^2 / H^2 = 0.1$
- black: $n_T = 0$



Kuroyanagi, Lin, MS & Tsujikawa '17 (in prep)

Gravitational Wave Physics/Astronmy

The Dawn has arrived!



LIGO

- GWs from binary BH merger were detected for the first time on Sep14, 2015 (GW150914).

BBH masses: 36 $M_{\odot}$+ 29 $M_{\odot}$

Source redshift: 0.09 (~ 1.2 Glyr)

Event rate: 0.6-12 /Gpc^3 /yr

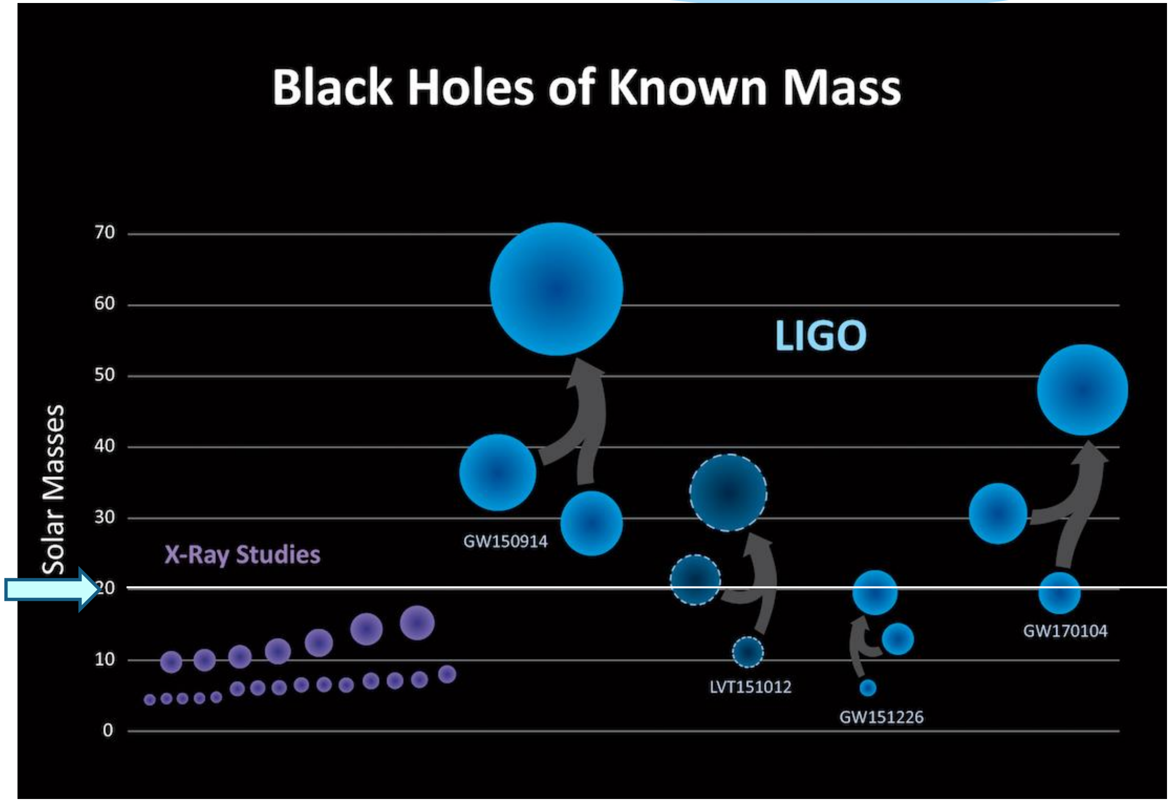
Unusual properties of LIGO BHs

LIGO has detected 3BBH mergers (+1 candidate) so far.

Any implications ?

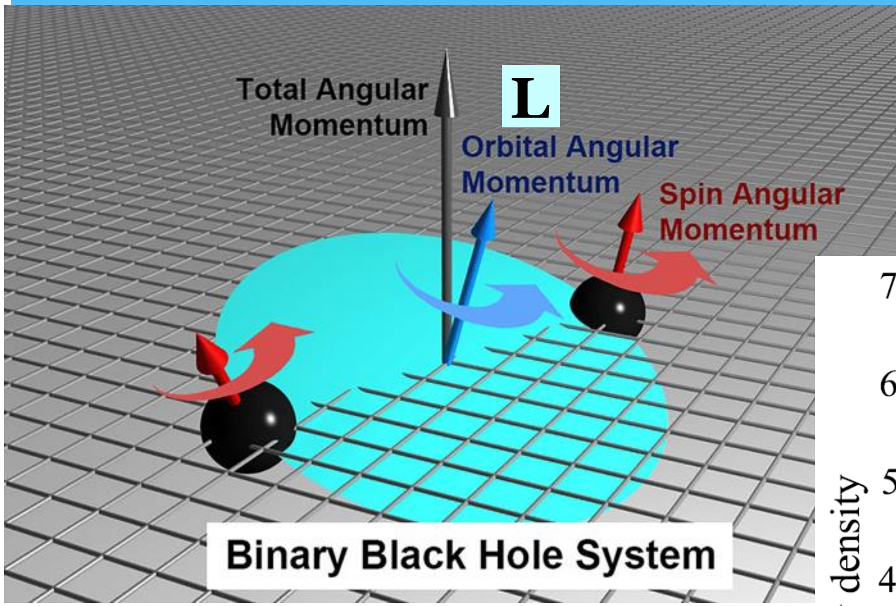
- They seem to be unusually heavy! (exc. GW151226)
- Their spins seem to be unusually small!

$20\ M_{\odot}$



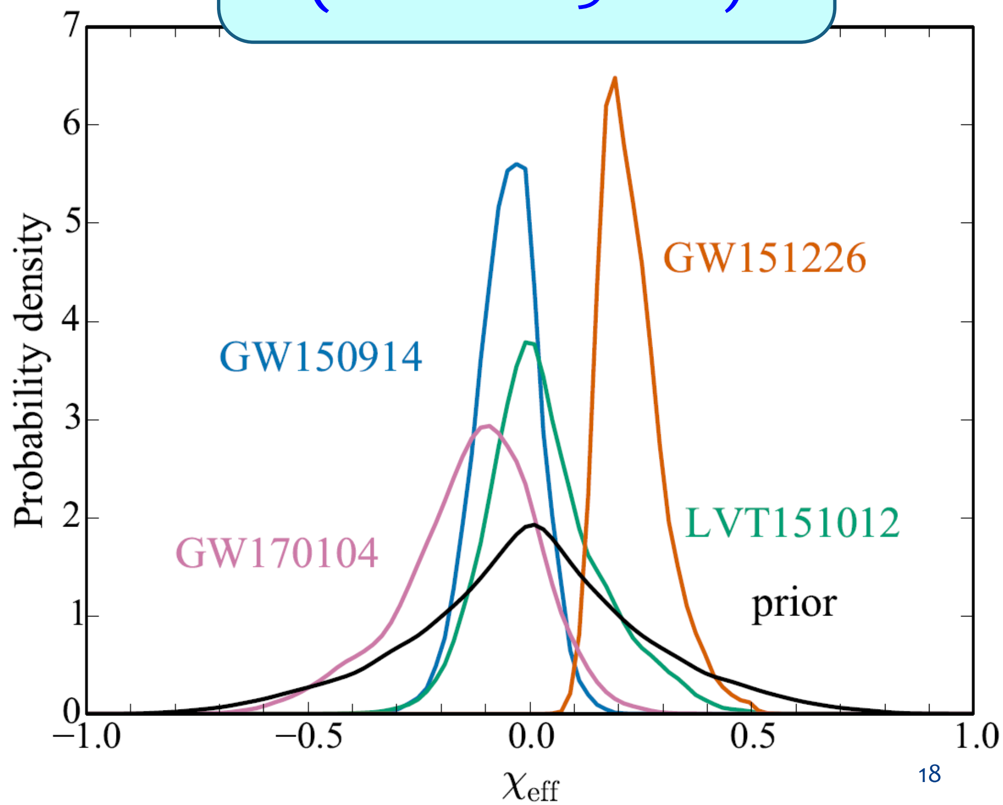
LIGO BH spins

$$\chi_{\rm eff} = (m_1 \mathbf{s}_1 + m_2 \mathbf{s}_2) \cdot \mathbf{n}_L / (m_1 + m_2): \quad \mathbf{n}_L = \mathbf{L}/L$$



http://www.ctc.cam.ac.uk/

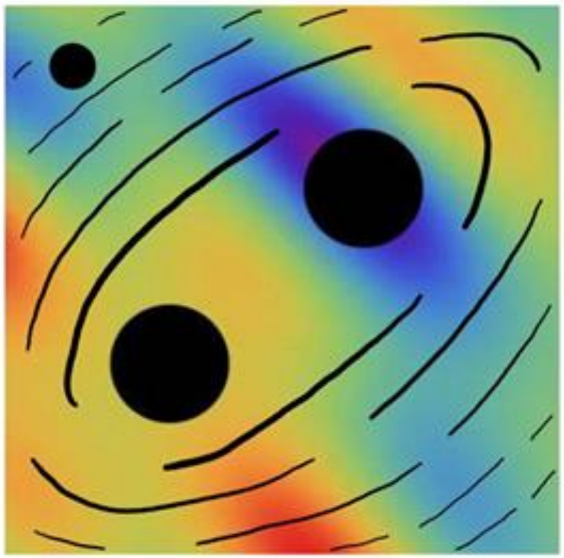
$\chi_{\rm eff}$ =0 is consistent (exc. GW151226)



$\chi_{\rm eff}$ would be larger if of astrophysical origin

LIGO BHs = PBHs?

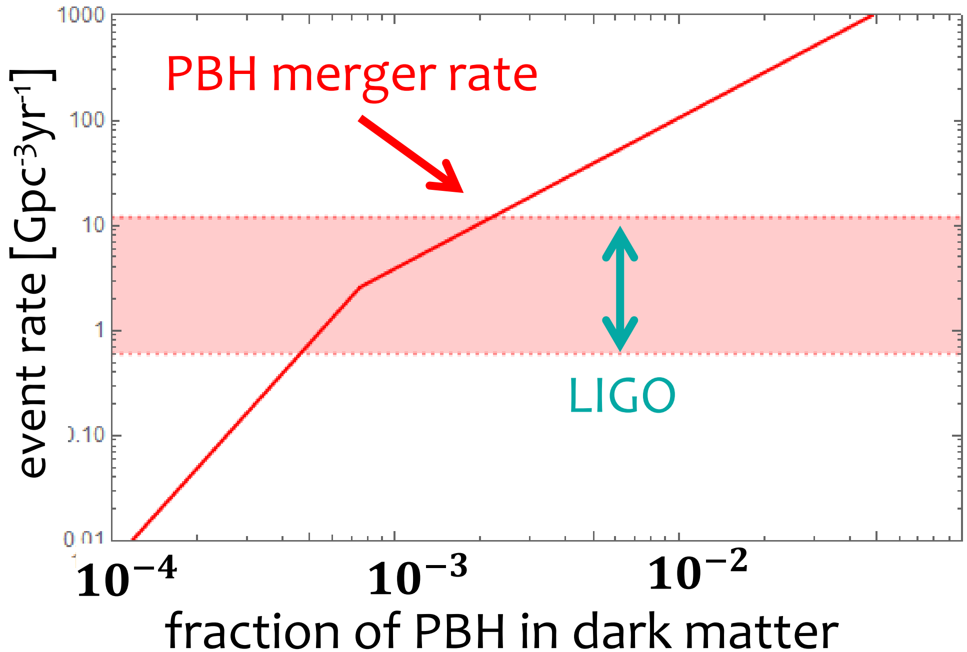
MS, Suyama, Tanaka & Yokoyama ‘16



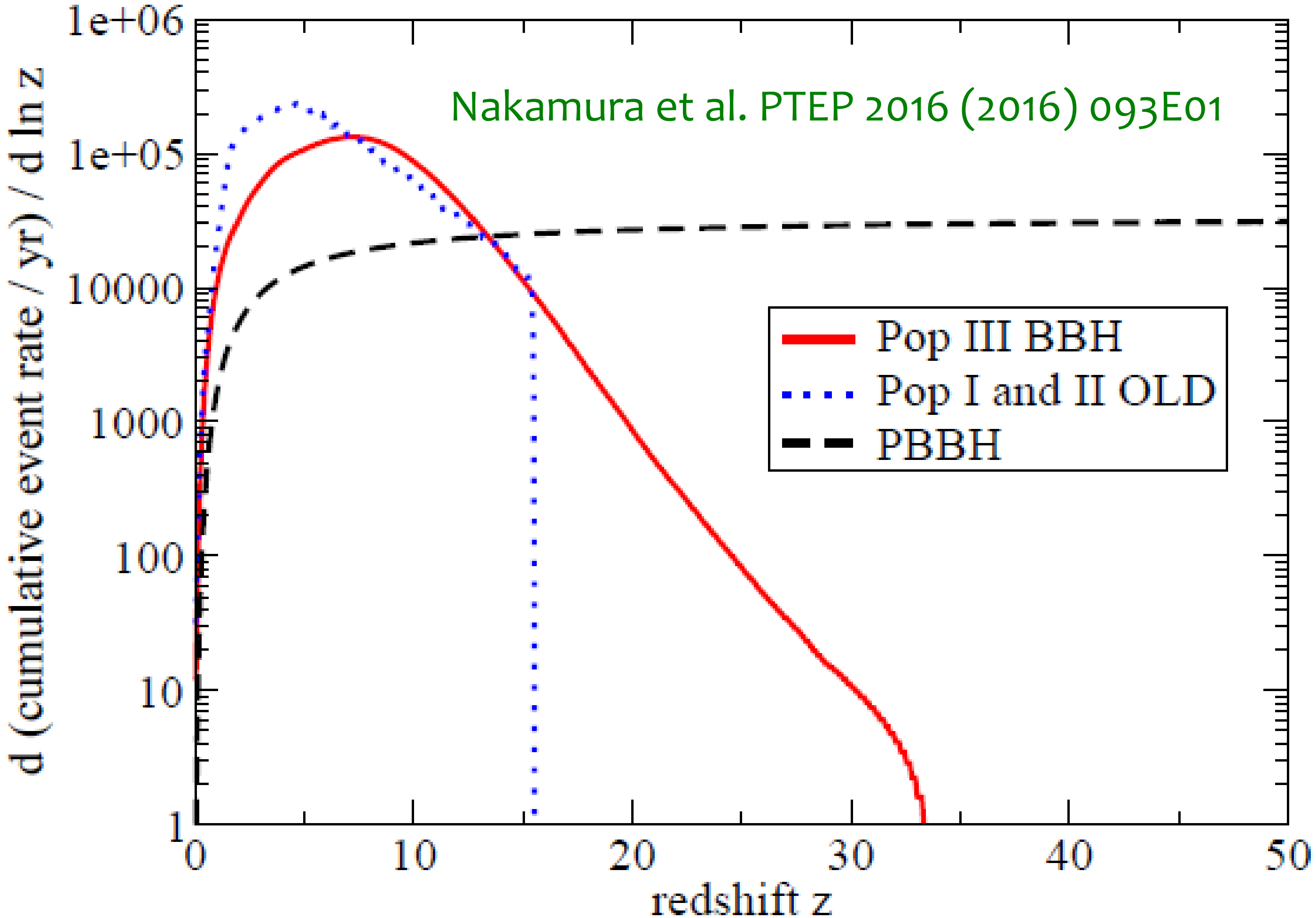
3-body interaction
leads to formation of
BH binaries

Nakamura, MS, Tanaka & Thorne ‘97

$$M_{PBH} \simeq 20\left(\frac{k}{\mathrm{kpc}^{-1}}\right)^{-2} M_\odot \simeq 20\left(\frac{100\mathrm{MeV}}{T}\right)^{2} M_\odot$$

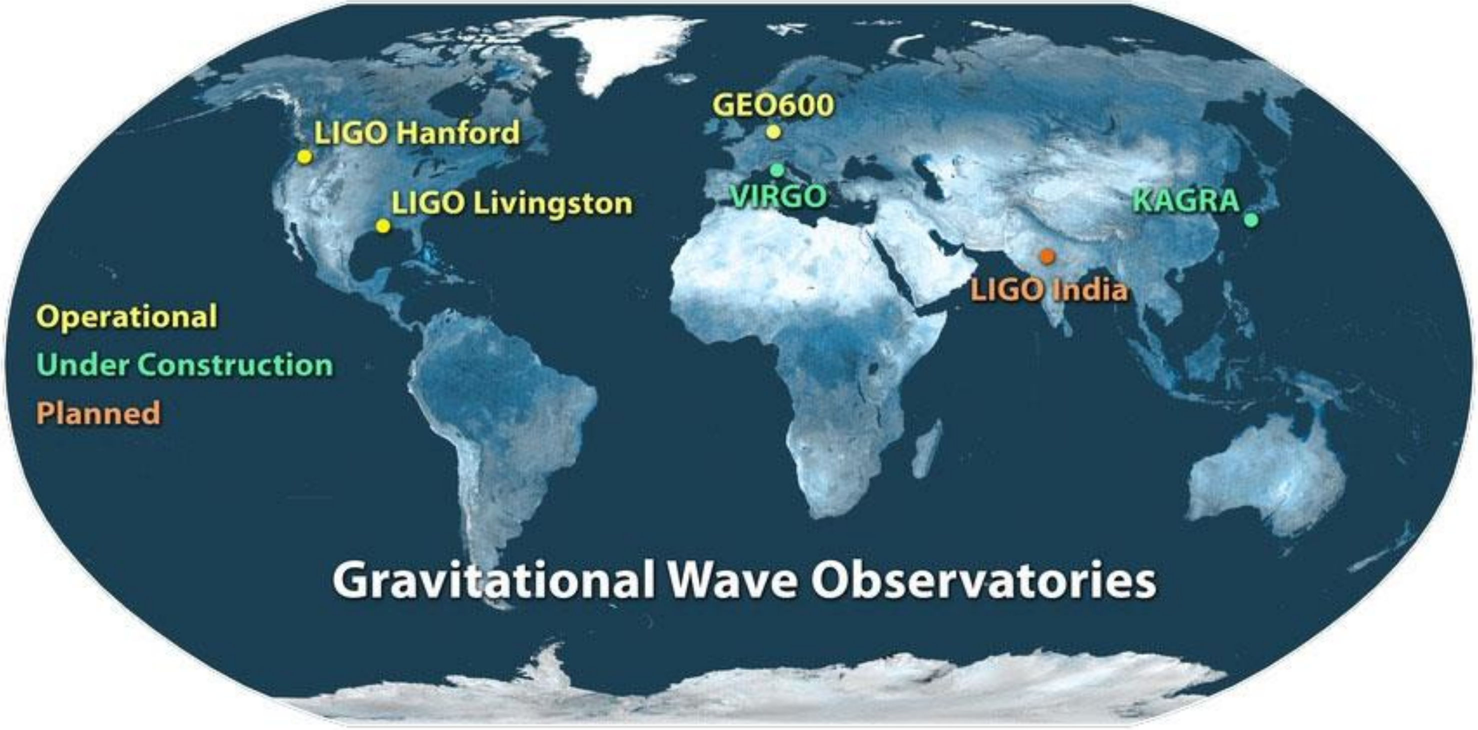


testing PBH hypothesis



Future
Network of GW Observatories

VIRGO has just begun to take data (on 1st Aug!)
KAGRA will start operation by 2019~2020 (iKAGRA has started!)
LIGO-India has been recently approved by Indian gov.



KAGRA

KAmioka GRAvitational wave detector

In Japanese it is pronounced as Kagura, which means "God Music" (神楽)

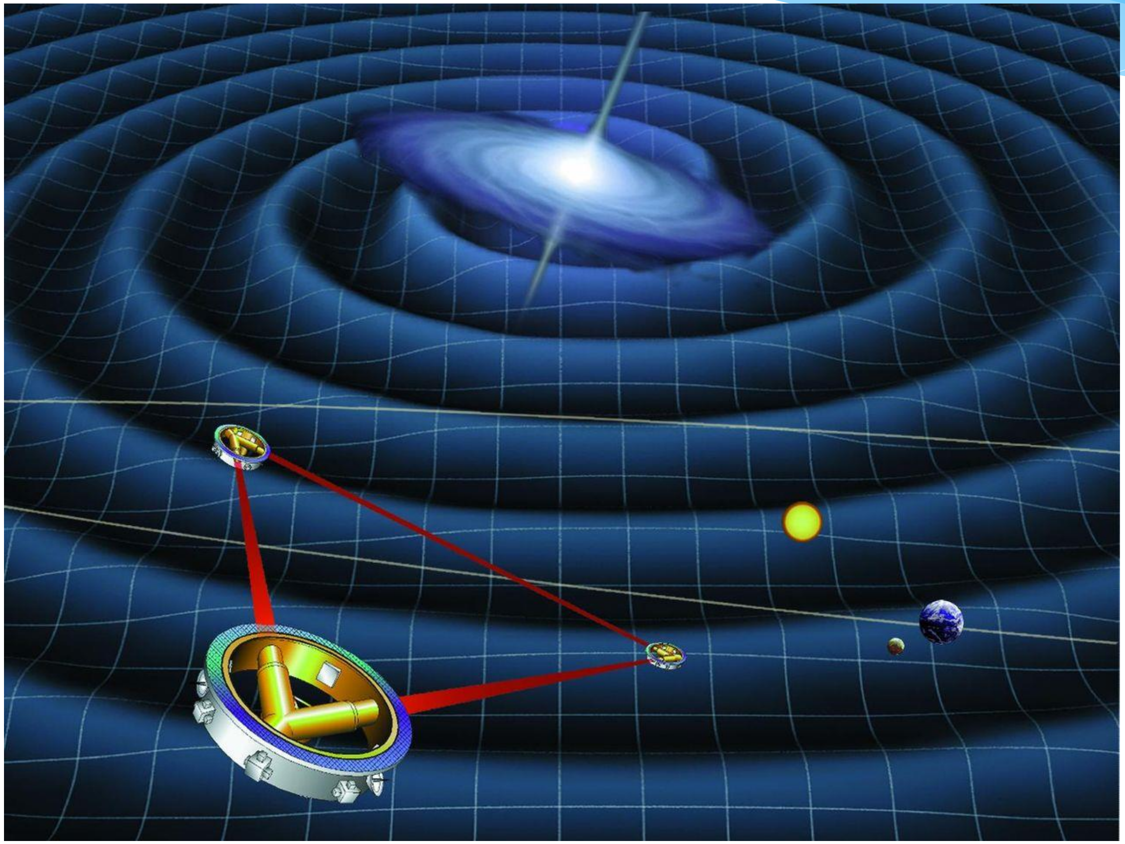
http://gwcenter.icrr.u-tokyo.ac.jp/en/

Previously called LCGT

Large Cryogenic
Gravitational wave Telescope

Arm length 3km
Cooled to 20K

Space-based Future Projects



http://lisa.nasa.gov/

Arm Length

⇩

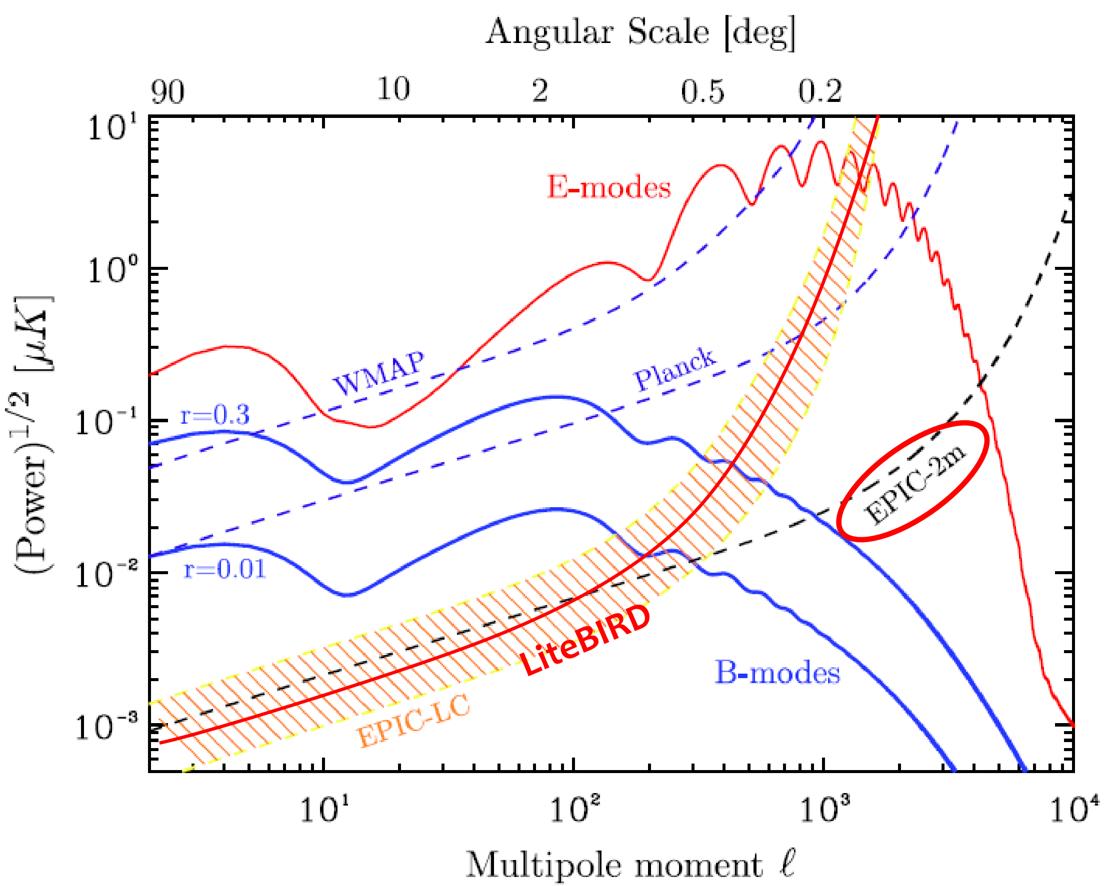
DECIGO: 1,000 km
launched by ~2030?
target freq: ~ 0.1 Hz

Deci-hertz Interferometer Gravitational wave Observatory

LISA: 5,000,000 km
launched by ~2034?
target freq: ~10^{-3}Hz

Laser Interferometer Space Antenna

B-mode Space-based Projects



http://arxiv.org/abs/0811.3911v1

$$r \equiv \frac{P_T(k)}{P_S(k)} \quad (\text{at } k = 0.05\,\text{Mpc}^{-1})$$

: tensor-to-scalar ratio

LiteBIRD (~ 2025)

http://litebird.jp/eng/

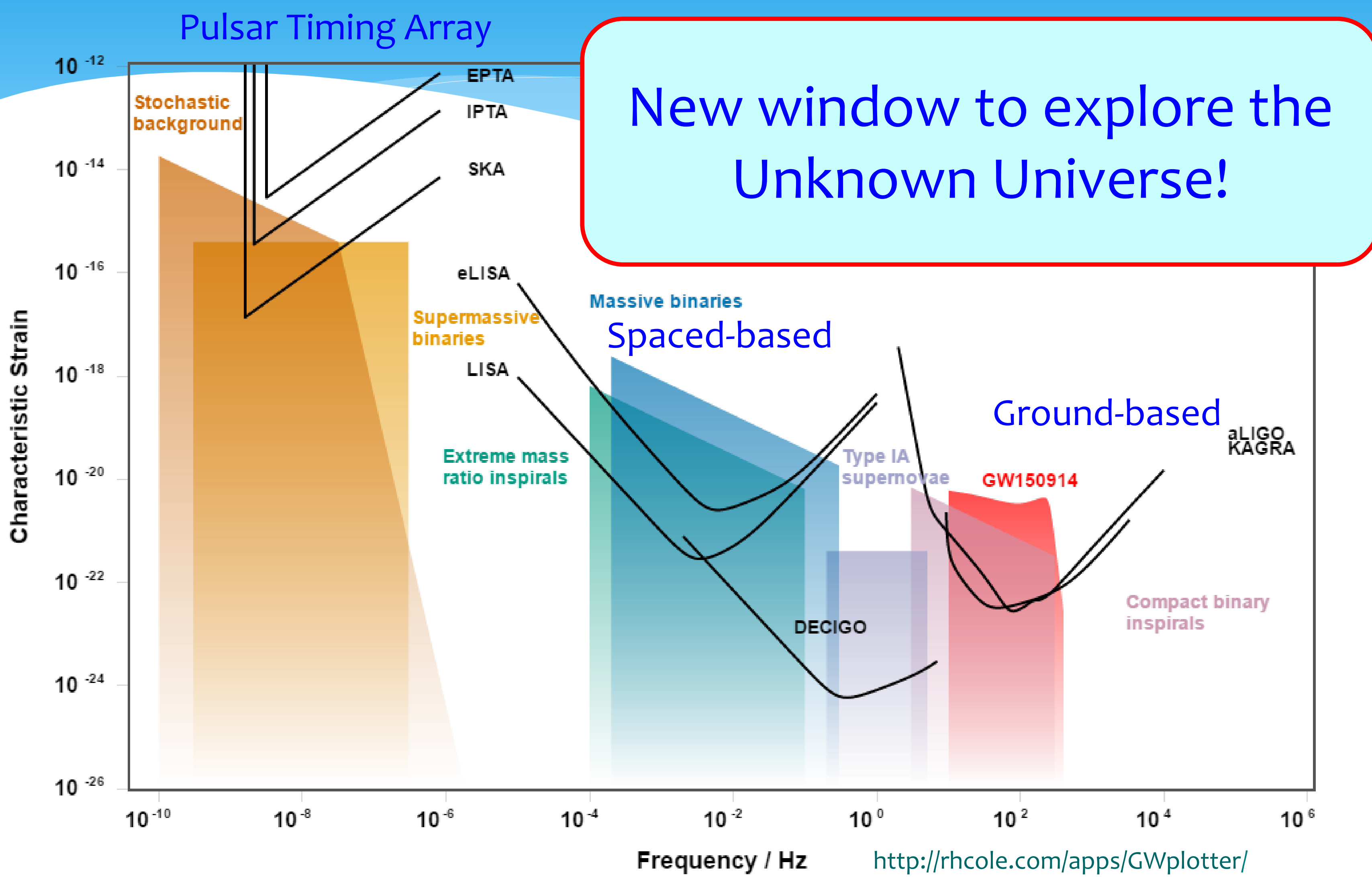
Lite (light) Satellite for the studies of B-mode polarization and Inflation from cosmic background Radiation Detection

EPIC (~2030?)

http://arxiv.org/abs/0906.1188

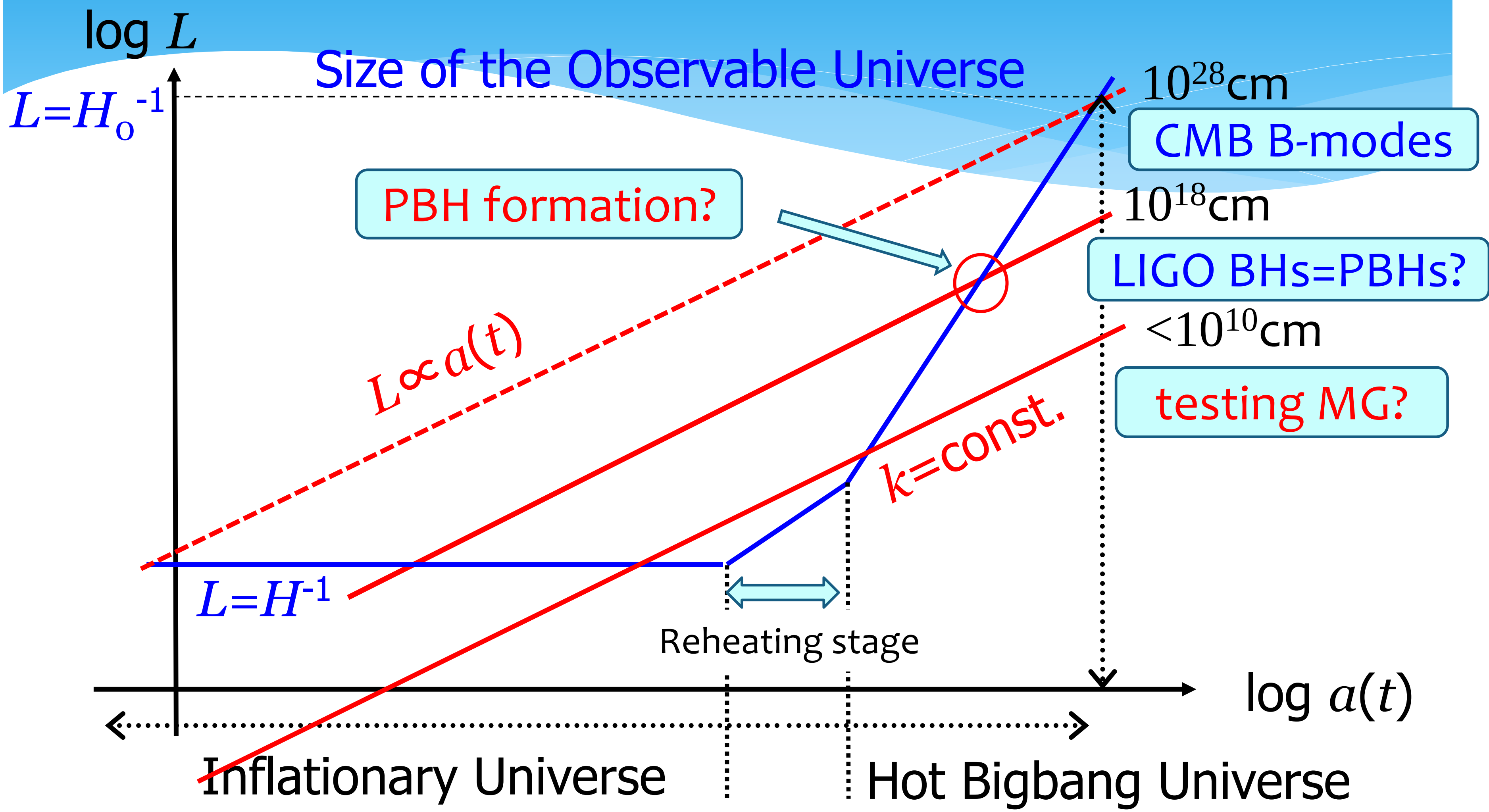
Experimental Probe of Inflationary Cosmology

Multi-frequency GW Astronomy



http://rhcole.com/apps/GWplotter/

testing inflation by GW astronomy



Summary

* Inflation has become the standard model of the Universe.
* Cosmological GWs are the key to confirmation of inflation.

* LIGO detection of GWs marked the 1^{st} milestone in GW physics/astronomy. The Dawn has arrived!
* LIGO BHs may be primordial: advanced GW detectors will prove/disprove the scenario.

* Multi-frequency GW astronomy/astrophysics is arriving soon.

GWs will be an essential tool for exploring the Physics of the Unknown Universe