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

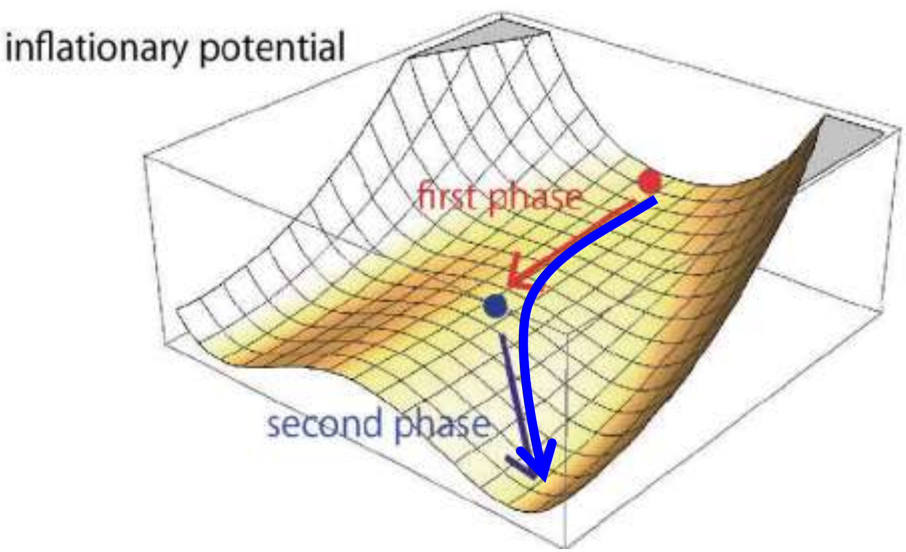
Garcia-Bellido, Linde & Wands '96, …

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

non-Gauss may become large

Abolhasani, Firouzjahi & MS '11,..

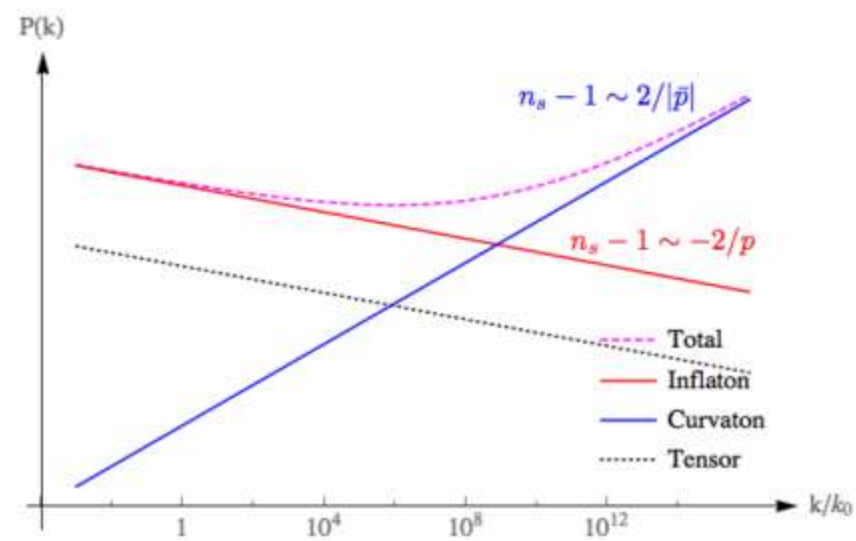
Pattison et al. 1707.00537



non-minimal curvaton

Domenech & MS '16

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



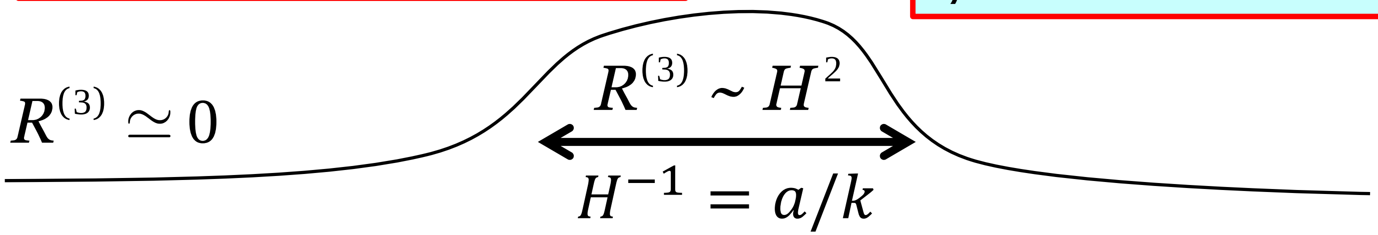
Curvature perturbation to PBH

- gradient expansion/separate universe approach

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

Hamiltonian constraint (Friedmann eq.)

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



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

Young, Byrnes & MS '14

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

- 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

$$L = \varepsilon L_{\text{edd}}; \quad \varepsilon \leq 1$$ … luminosity from PBH

- energy output/Hubble time

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

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

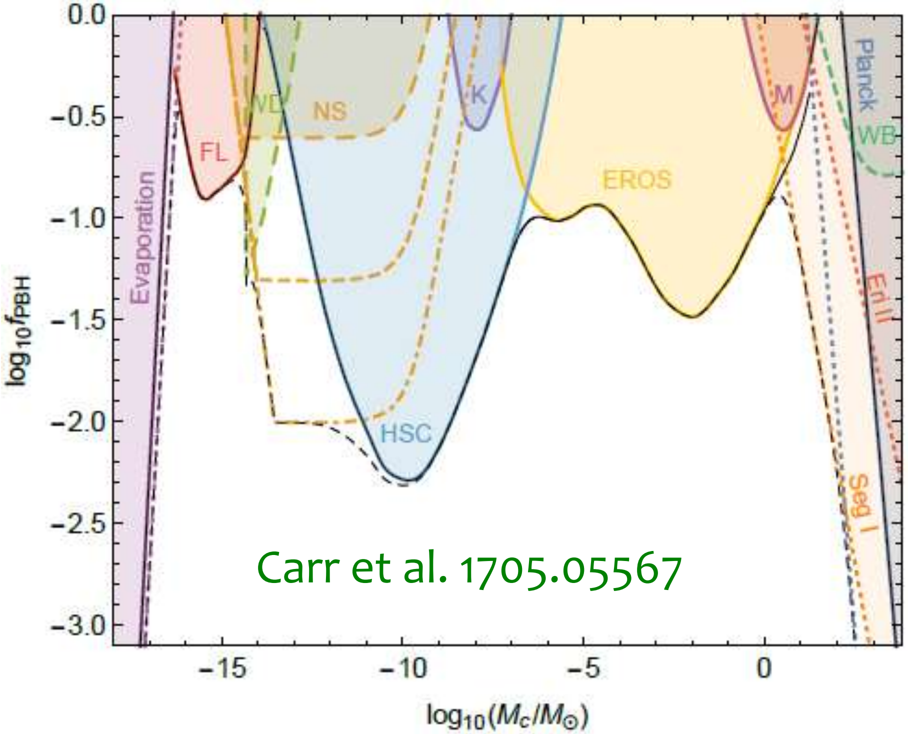
small, but may not be entirely negligible…

Constraints on PBHs

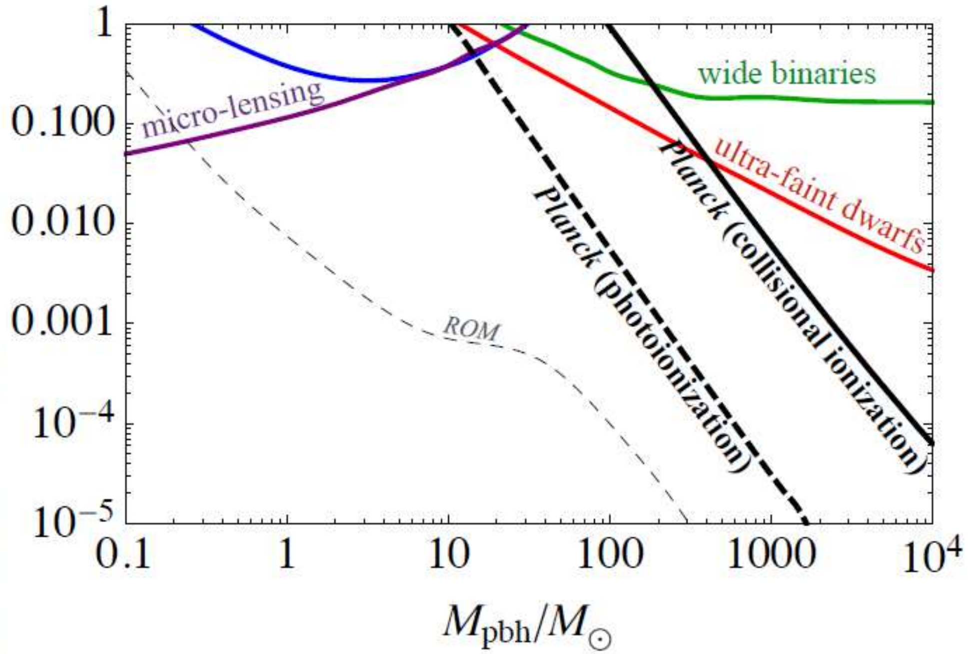
$$f_{PBH} = \frac{\Omega_{PBH}}{\Omega_{DM}}$$

DM can't be dominated by PBHs!

(opinion varies though..., particularly at $M \sim 100 M_\odot$)



Carr et al. 1705.05567



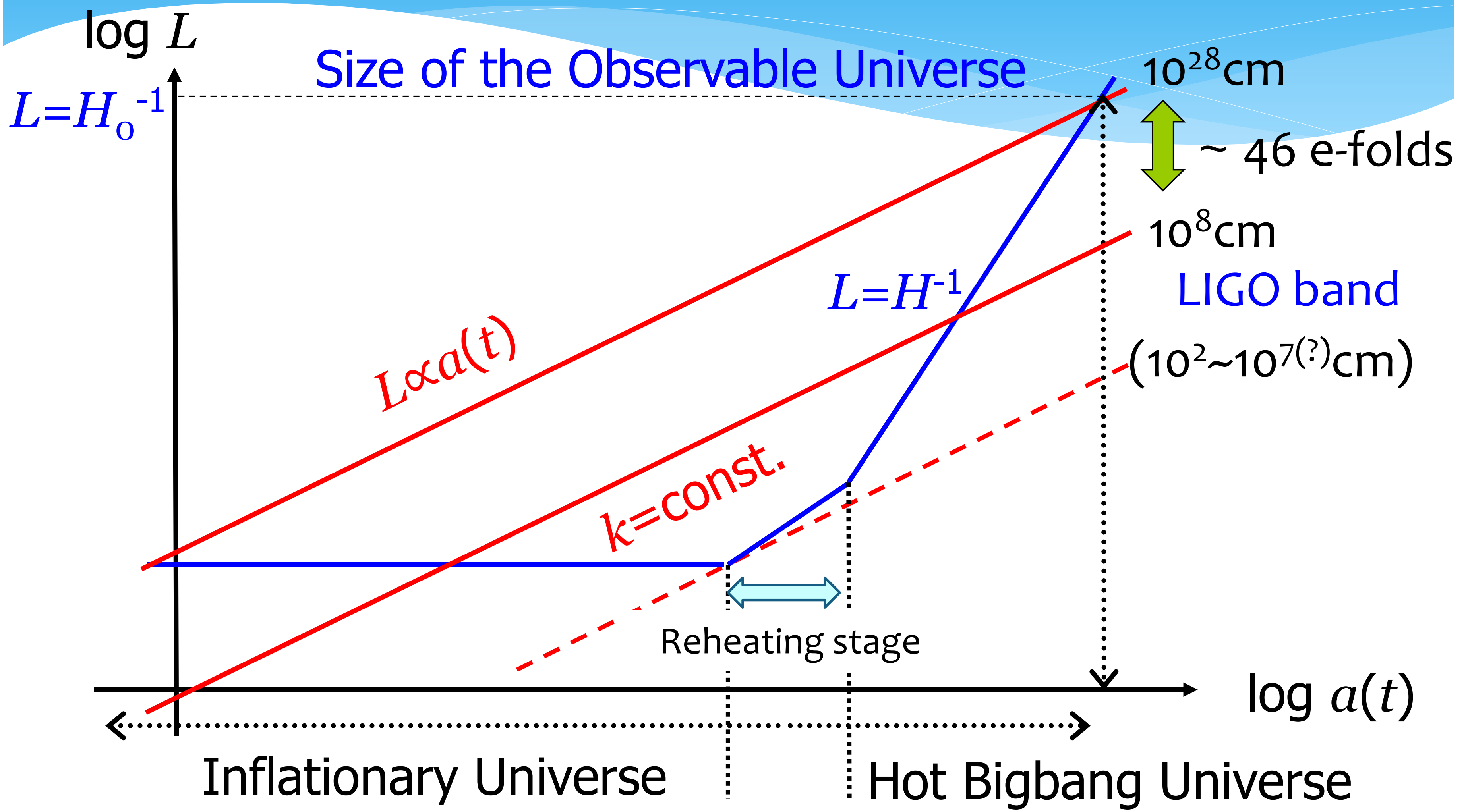
Ali-Haimoud & Kamionkowski, 1612.05644

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

Gravitational Waves from Inflation

length scales of the inflationary universe

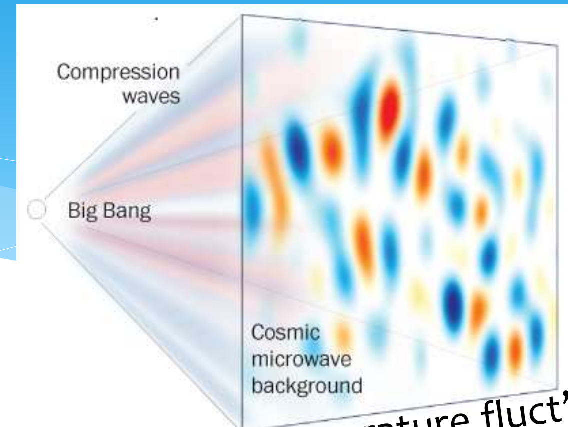
⟺ targets for multi-frequency GW astronomy



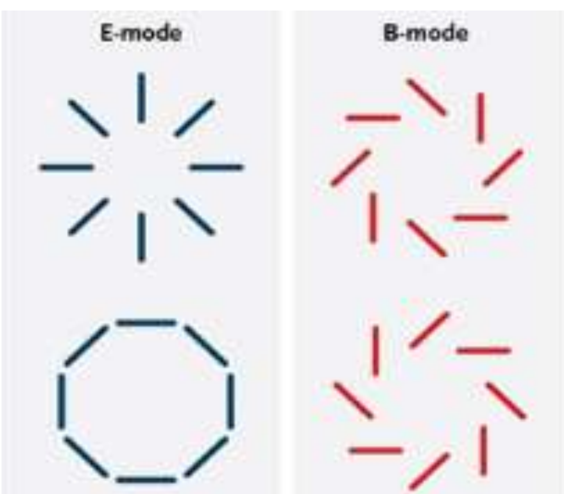
Cosmological GWs

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

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



temperature fluct'ns

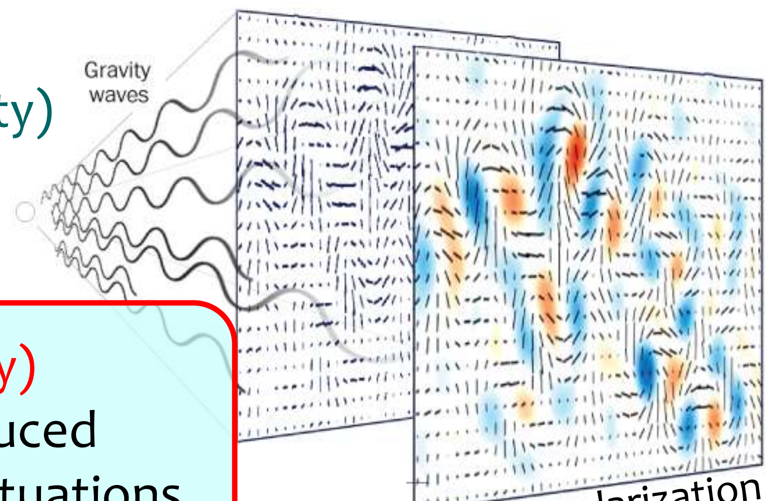


http://www.skyandtelescope.com/

E-mode (even parity)

↕

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



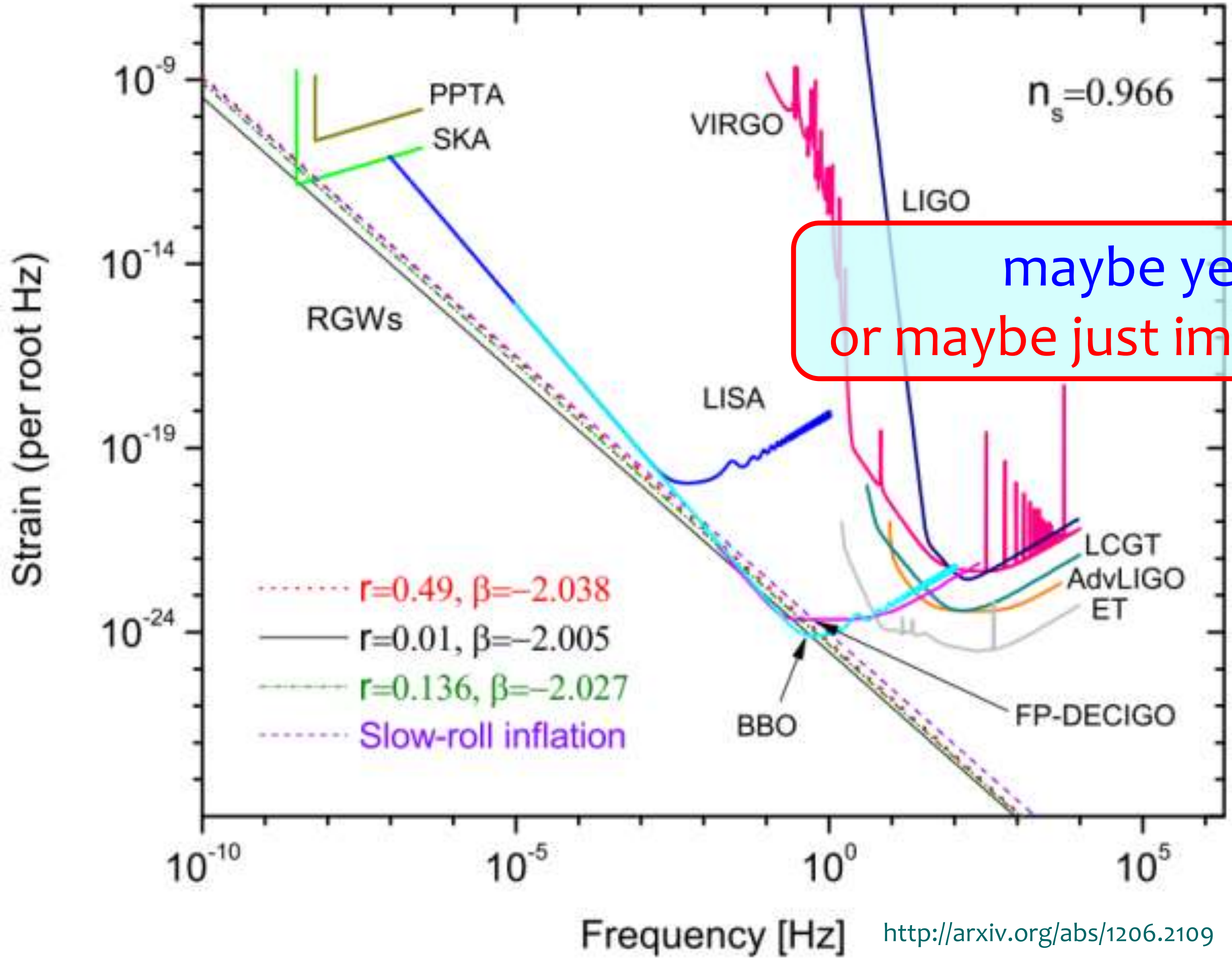
B-mode polarization

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, …

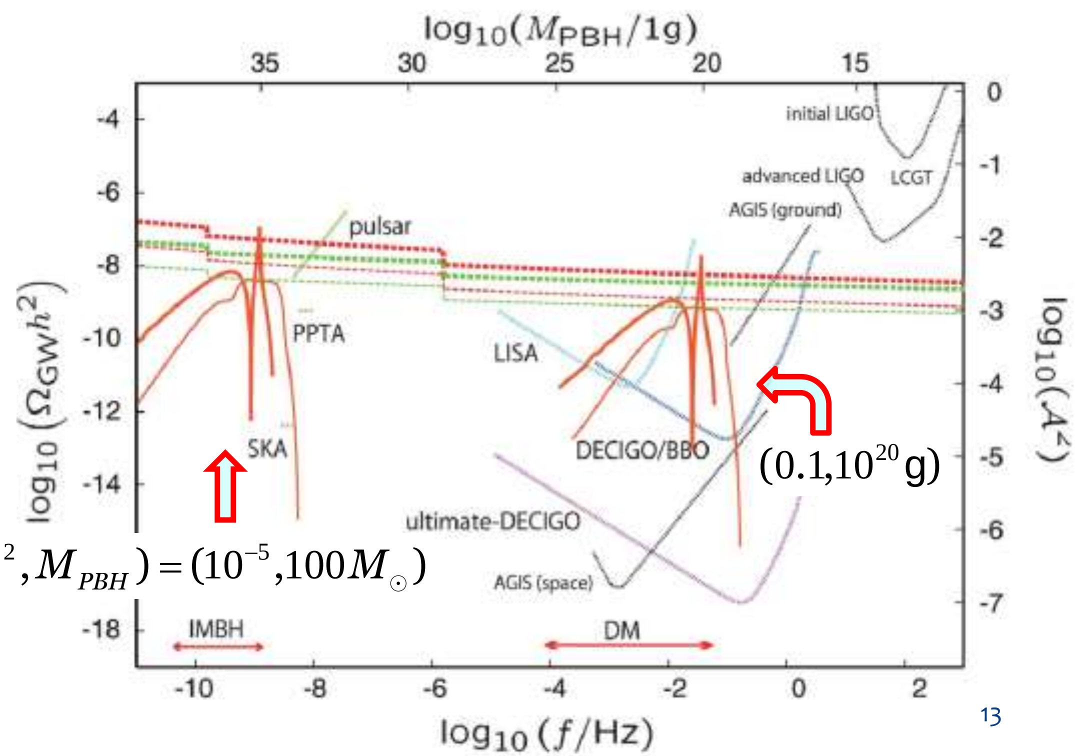
- Non-negligible PBH formation means $\mathcal{P}_S(k) \sim 10^{-2.5} - 10^{-2}$

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

- 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 ($k>10^4$ Mpc^{-1})

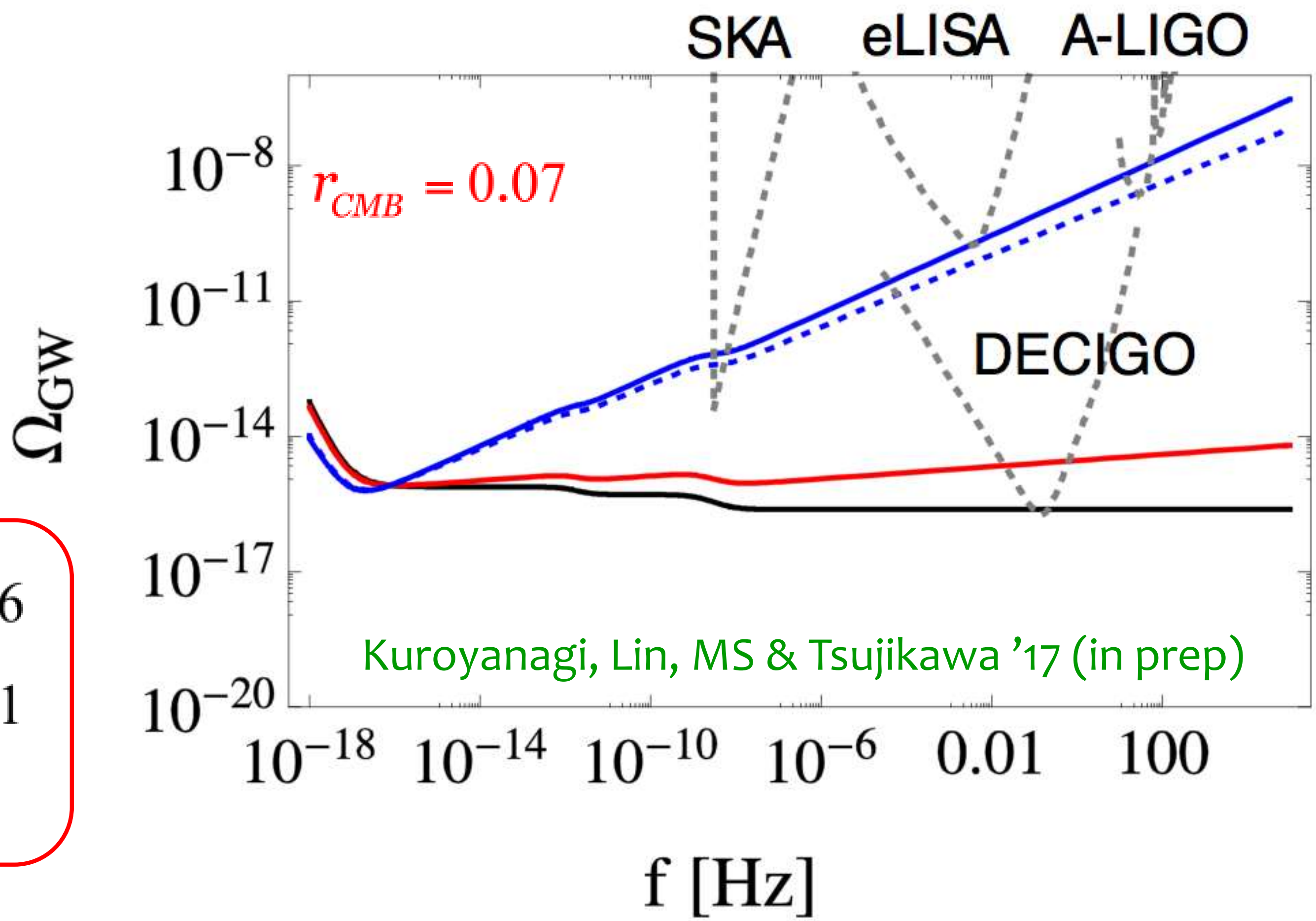


blue-tilted GW spectrum?

possible in inflationary massive gravity Lin & MS '15

tensor (=GW) spectral index:

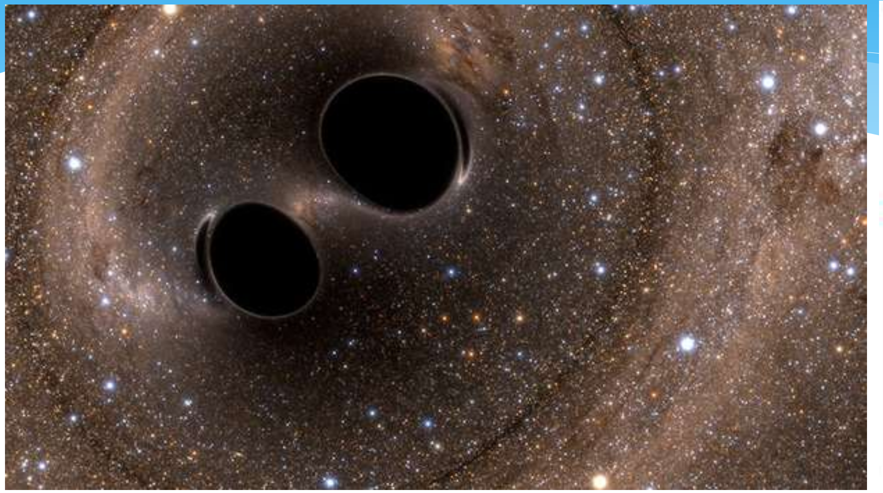
$$n_T \approx \frac{2m_g^2}{3H^2}$$

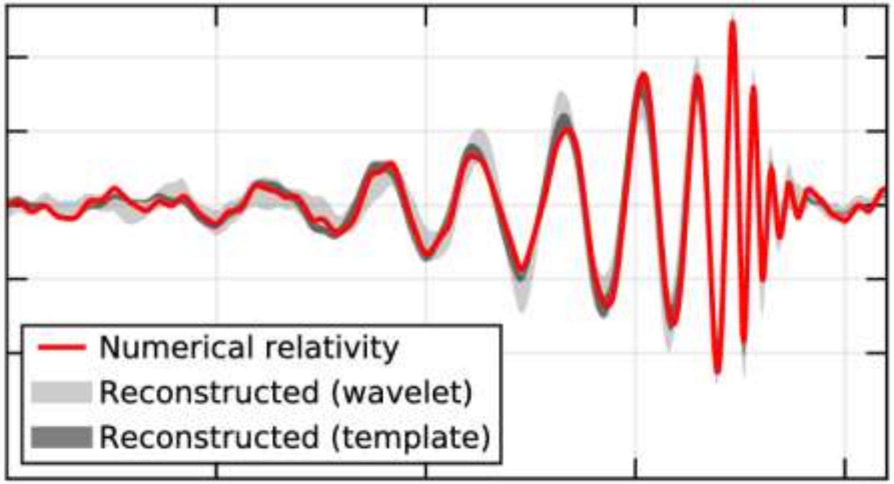


- (blue): $m_g^2 / H^2 = 0.6$
- (red): $m_g^2 / H^2 = 0.1$
- (black): $n_T = 0$

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

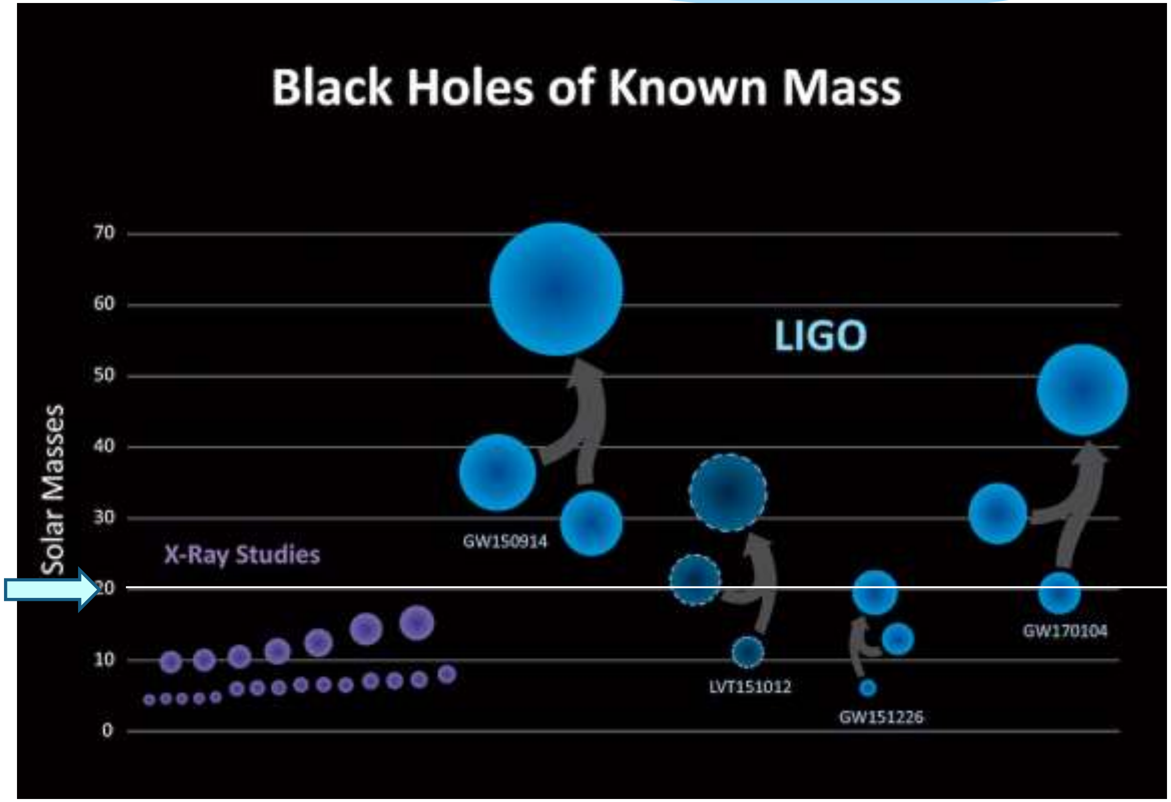
Unusual properties of LIGO BHs

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

Any implications ?

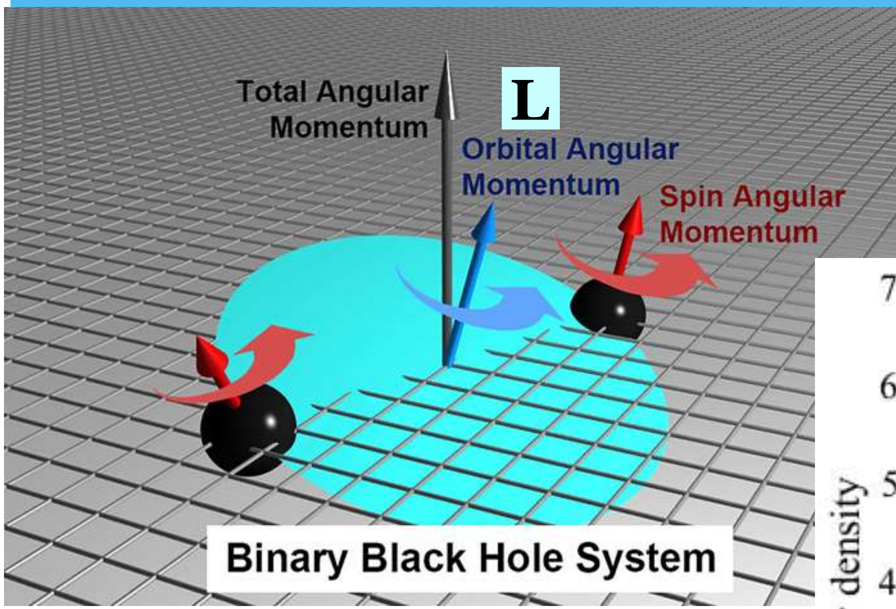
- They seem to be unusually heavy! (exc. GW151226)
- Their spins seem to be unusually small!

$20\ M_{\odot}$



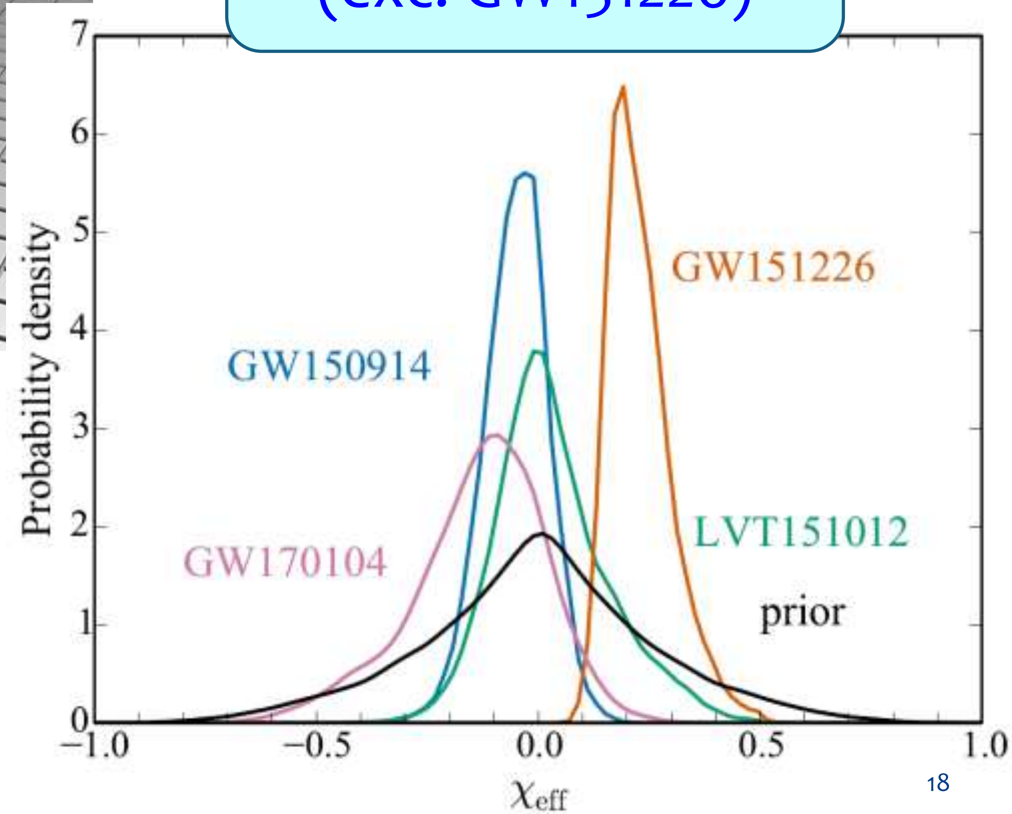
LIGO BH spins

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



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

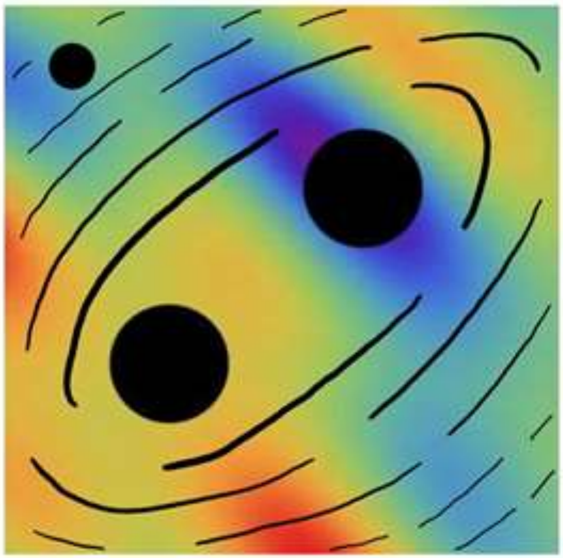
χ_{eff} =0 is consistent (exc. GW151226)



χ_{eff} would be larger if of astrophysical origin

LIGO BHs = PBHs?

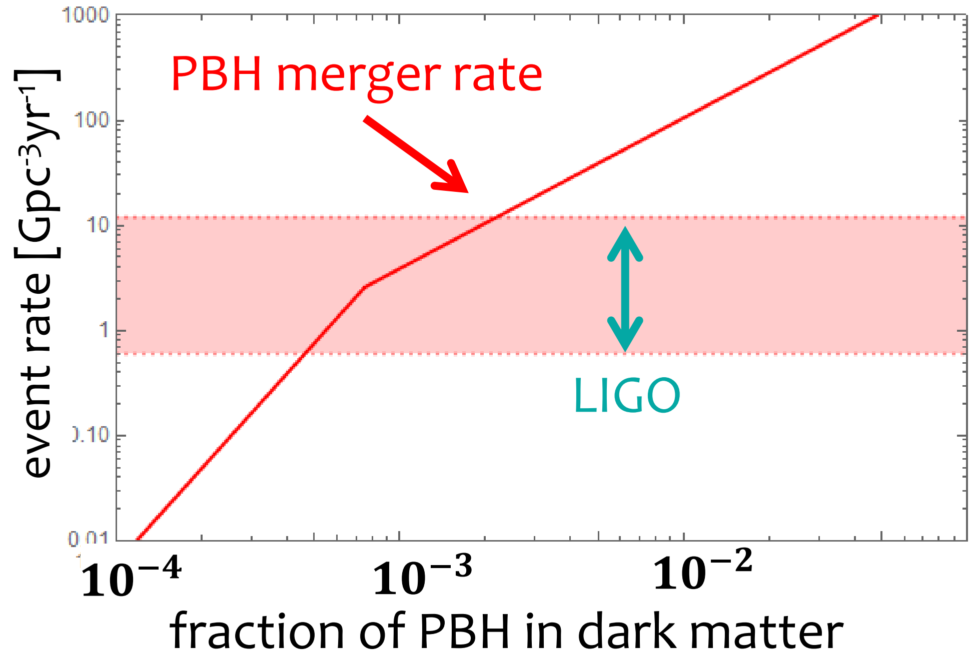
MS, Suyama, Tanaka & Yokoyama '16



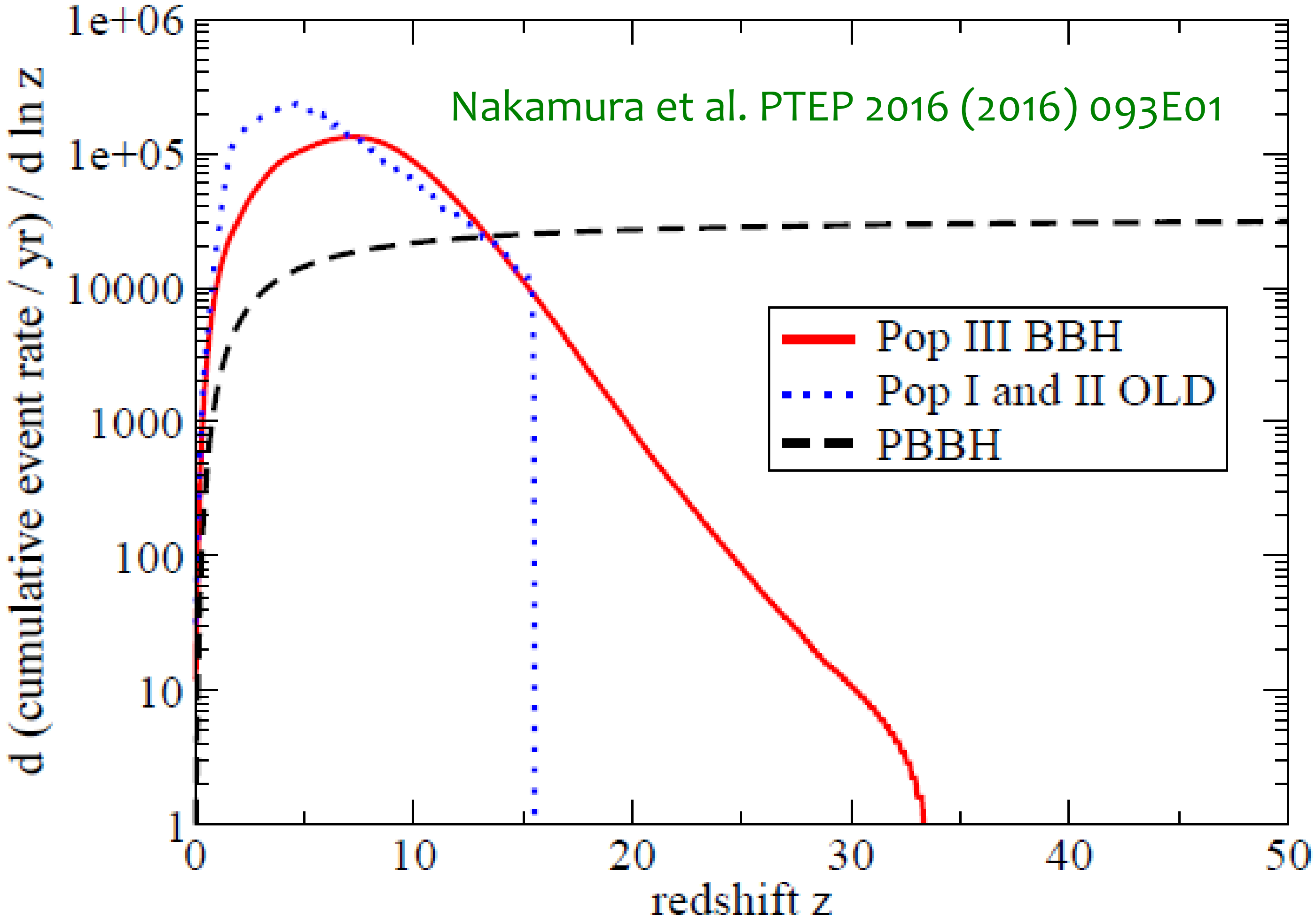
3-body interaction leads to formation of BH binaries

Nakamura, MS, Tanaka & Thorne '97

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

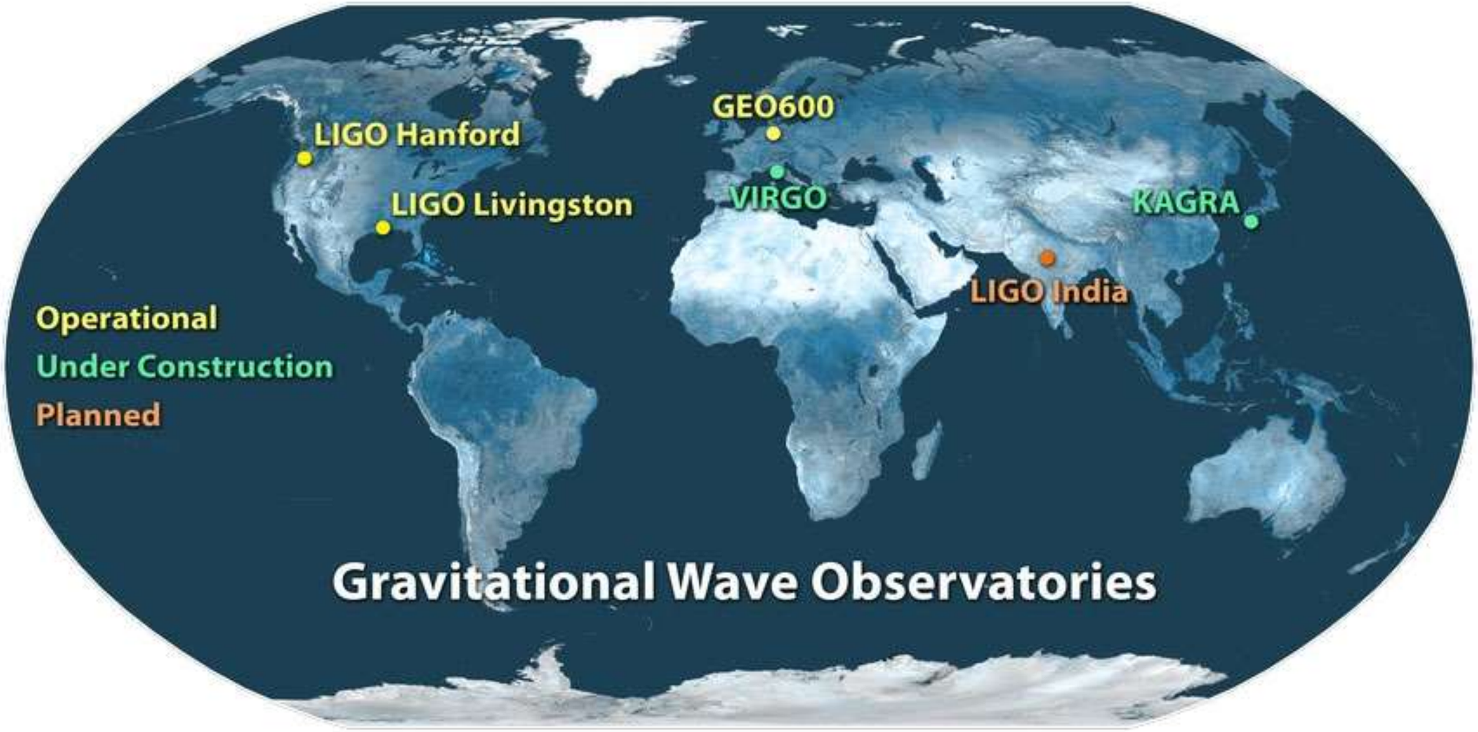


testing PBH hypothesis



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)

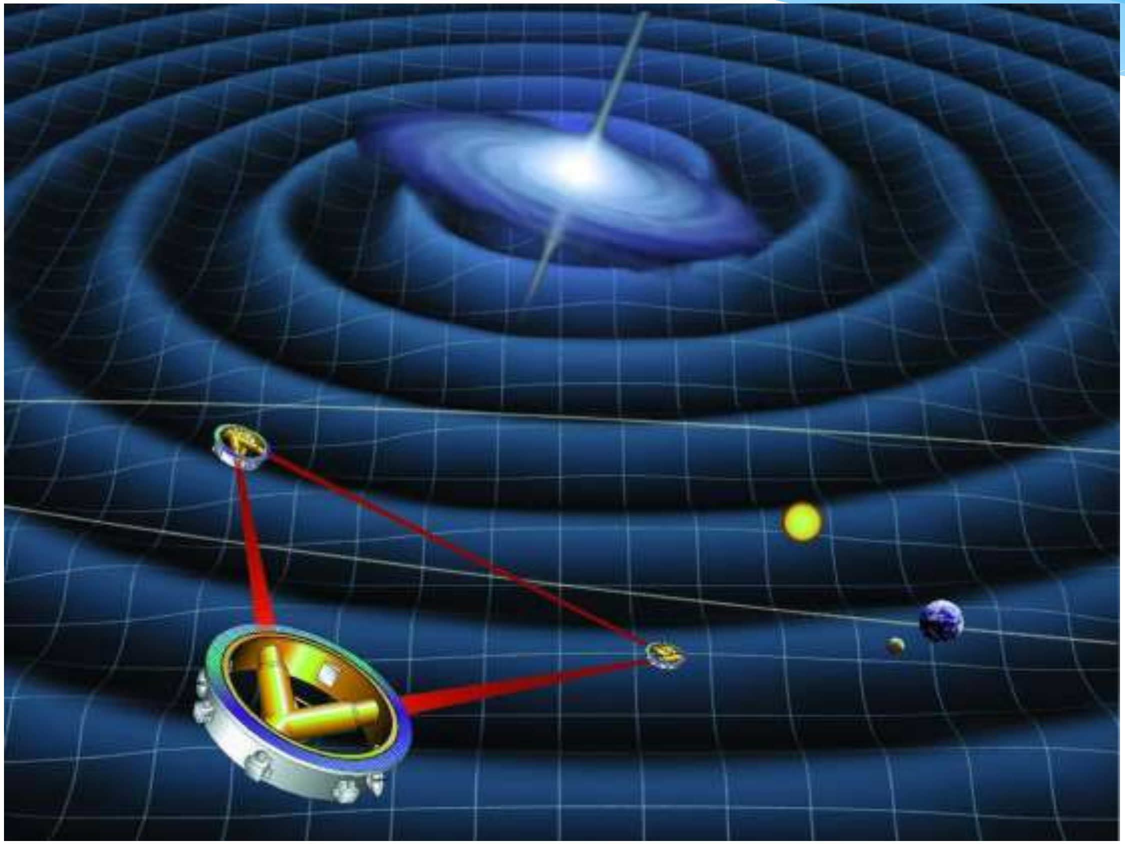
Previously called LCGT

Large Cryogenic
Gravitational wave Telescope

Arm length 3km
Cooled to 20K

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

Space-based Future Projects



http://lisa.nasa.gov/

Arm Length

⇩

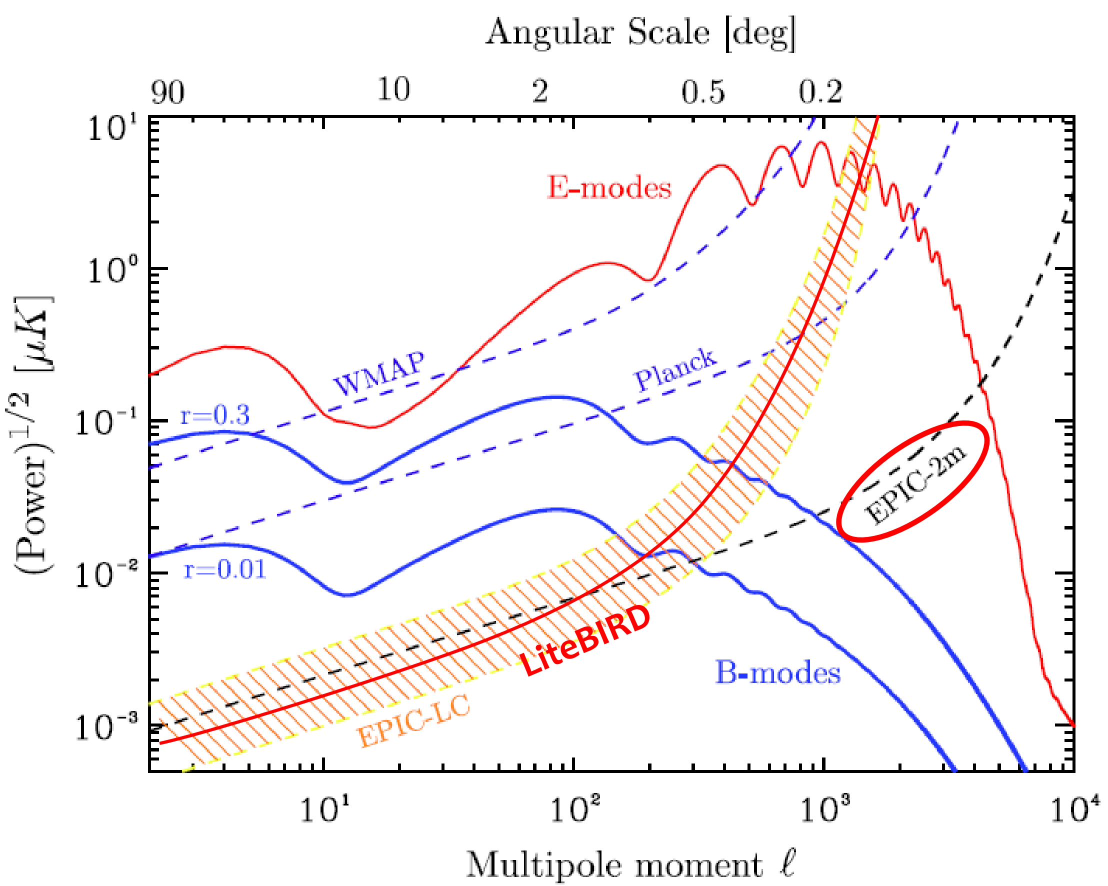
DECIGO: 1,000 km
launched by ~2030?
target freq: ~ 0.1 Hz

Deci-hertz Interferometer Gravitational wave Observatory

LISA: 5,000,000 km
launched by ~2034?
target freq: $\sim 10^{-3}$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/

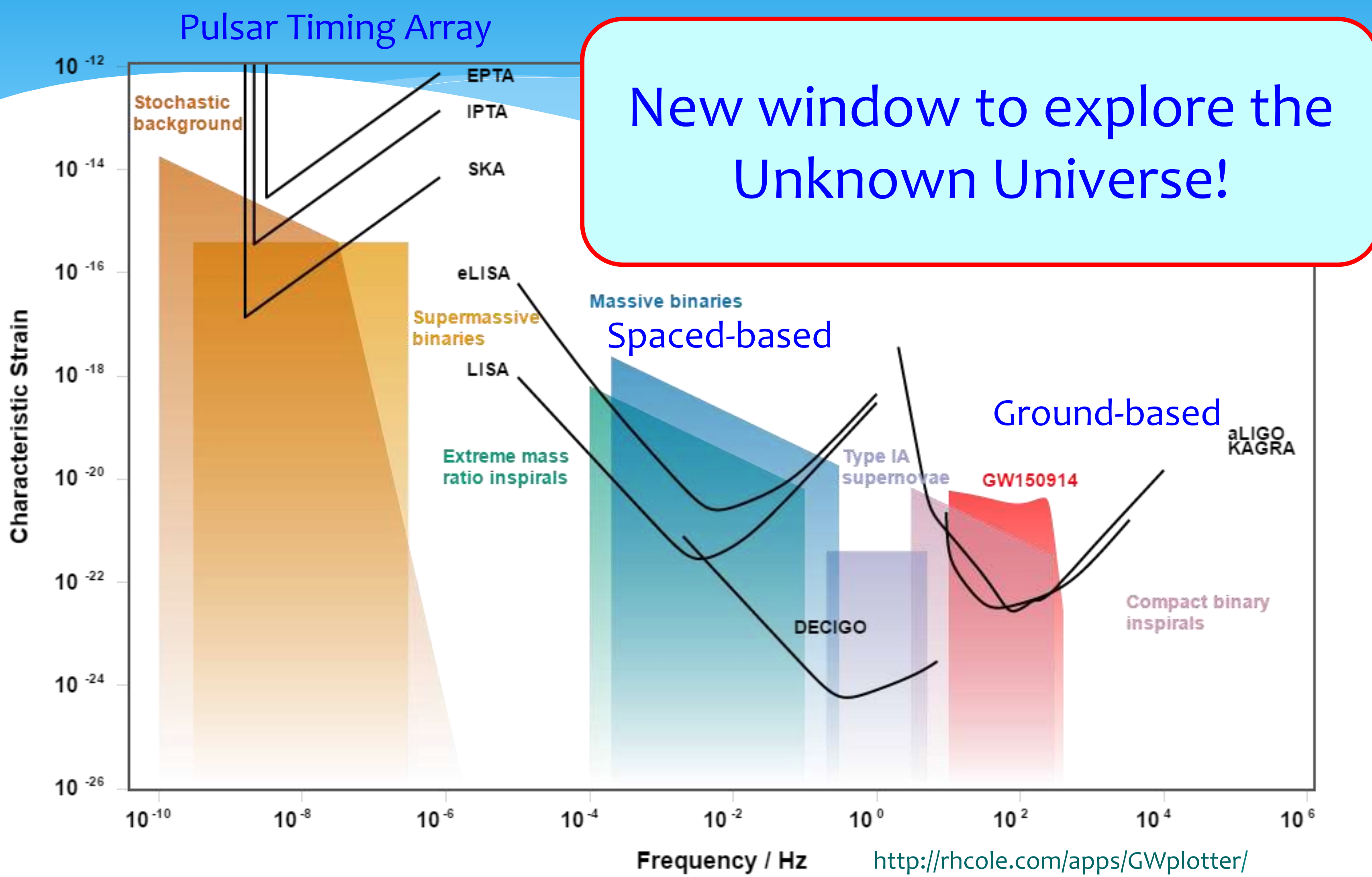
Lite (light) Satellite for the studies of B-mode polarization and Inflation from cosmic background Radiation Detection

EPIC (~2030?)

http://arxiv.org/abs/0906.1188

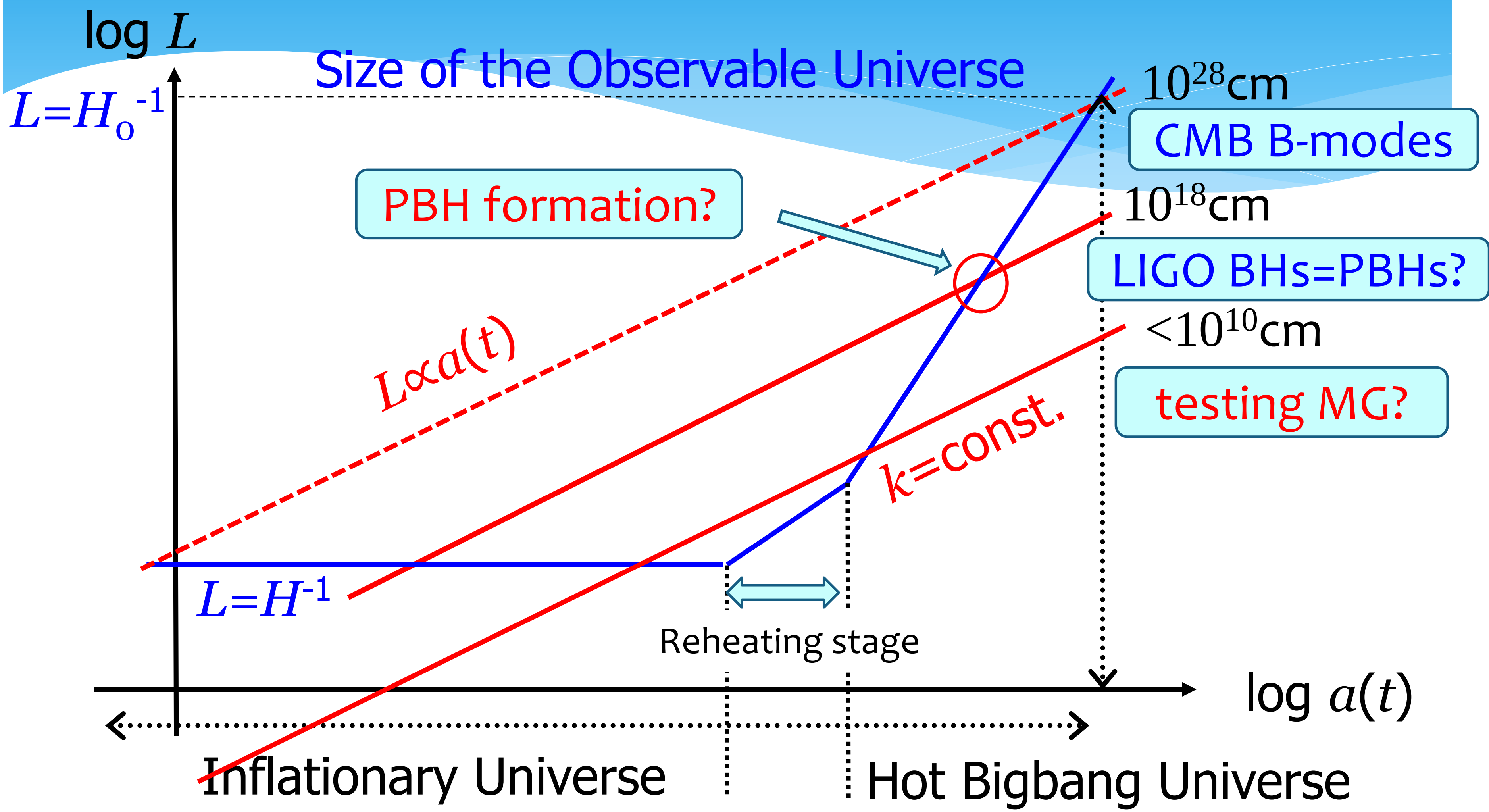
Experimental Probe of Inflationary Cosmology

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 1st 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