NCTS 20th anniversary
3 August, 2017

Inflation, Primordial Black holes and Gravitational Waves

-- Dawn of Gravitational Wave Astronomy --

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Inflation

What is Inflation?

Brout, Englert & Gunzig '77, Starobinsky '79, Guth '81, Sato '81, Linde '81,…

- Inflation is a quasi-exponential expansion of the Universe at its very early stage; perhaps at $t \sim 10^{-36}$ sec.

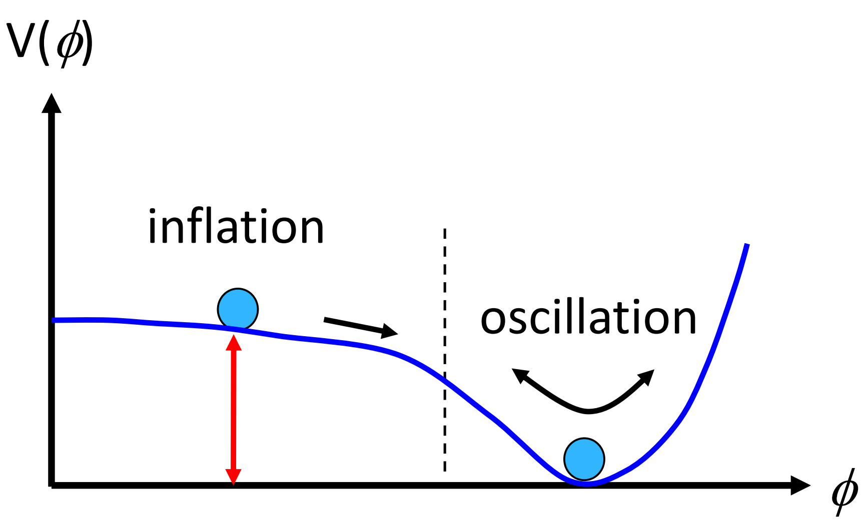
- It was meant to solve the initial condition (singularity, horizon & flatness, etc.) problems in Big-Bang Cosmology:
- if any of them can be said to be solved depends on precise definitions of the problems.

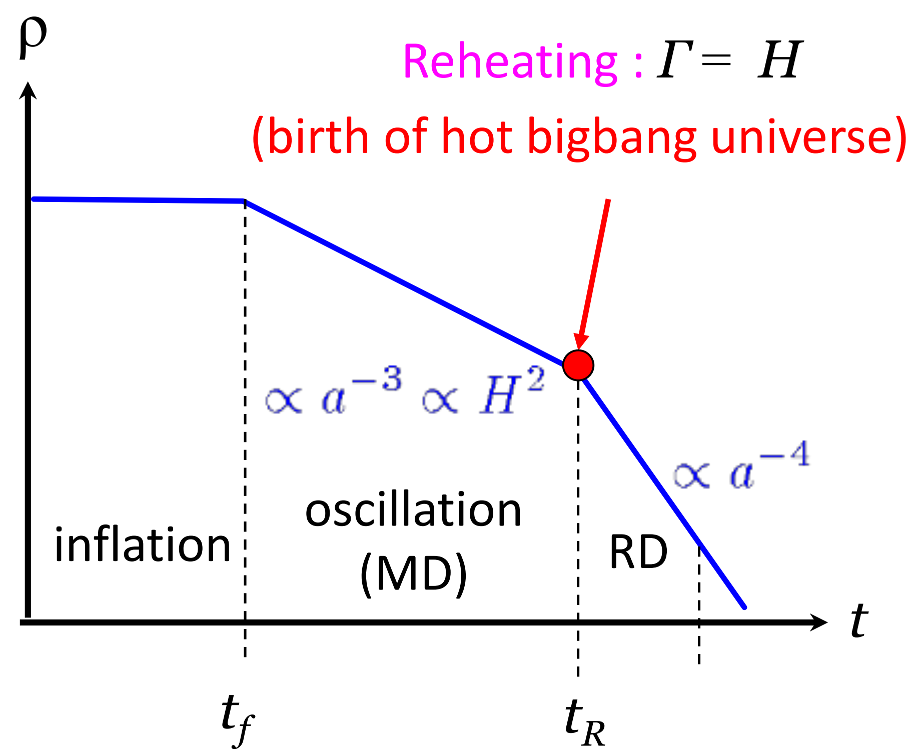
- Quantum vacuum fluctuations during inflation turn out to play the most important role. They give the initial condition for all the structures in the Universe.

- Cosmic gravitational wave background is also generated.

From inflation to bigbang

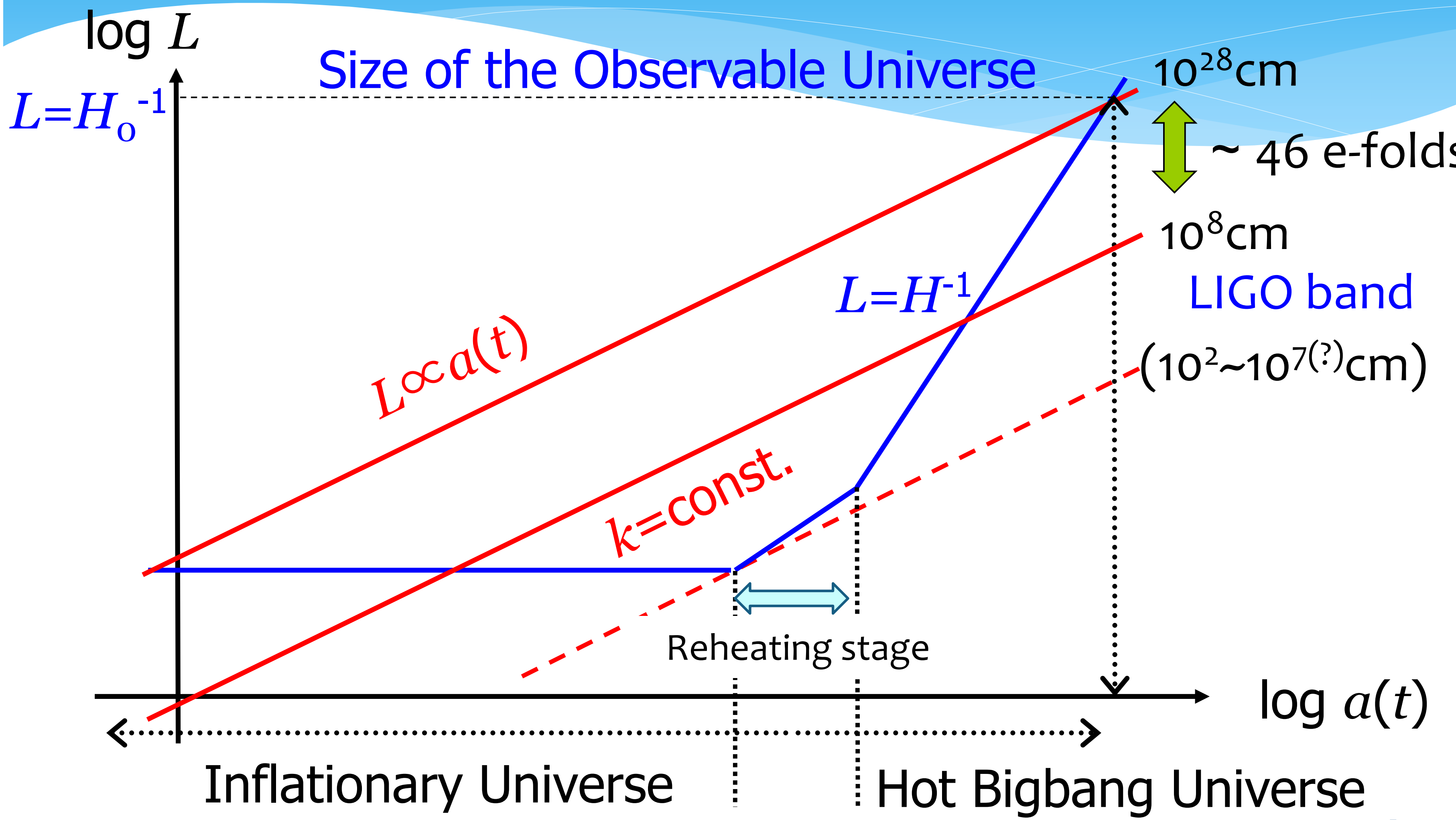
After inflation, vacuum energy is converted to thermal energy (called "re"heating) and hot Bigbang Universe is realized.





length scales of the inflationary universe

⟺ targets for multi-frequency GW astronomy

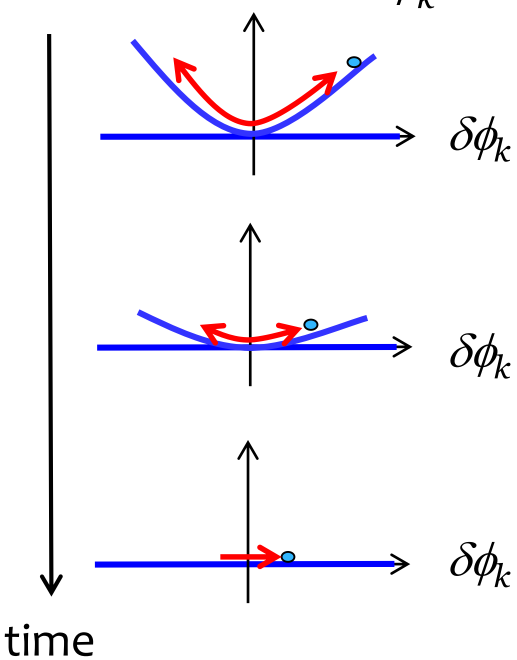


Quantum fluctuations during inflation

Mukhanov & Chibisov '81, ….

Zero-point (vacuum) fluctuations of ϕ : $\delta\phi = \sum_k \delta\phi_k(t) e^{ik\cdot x}$

$$\delta\ddot{\phi}_k + 3H\delta\dot{\phi}_k + \omega^2(t)\delta\phi_k = 0 \ ; \quad \omega^2(t) = \frac{k^2}{a^2(t)}$$



harmonic oscillator with
friction term and time-dependent ω

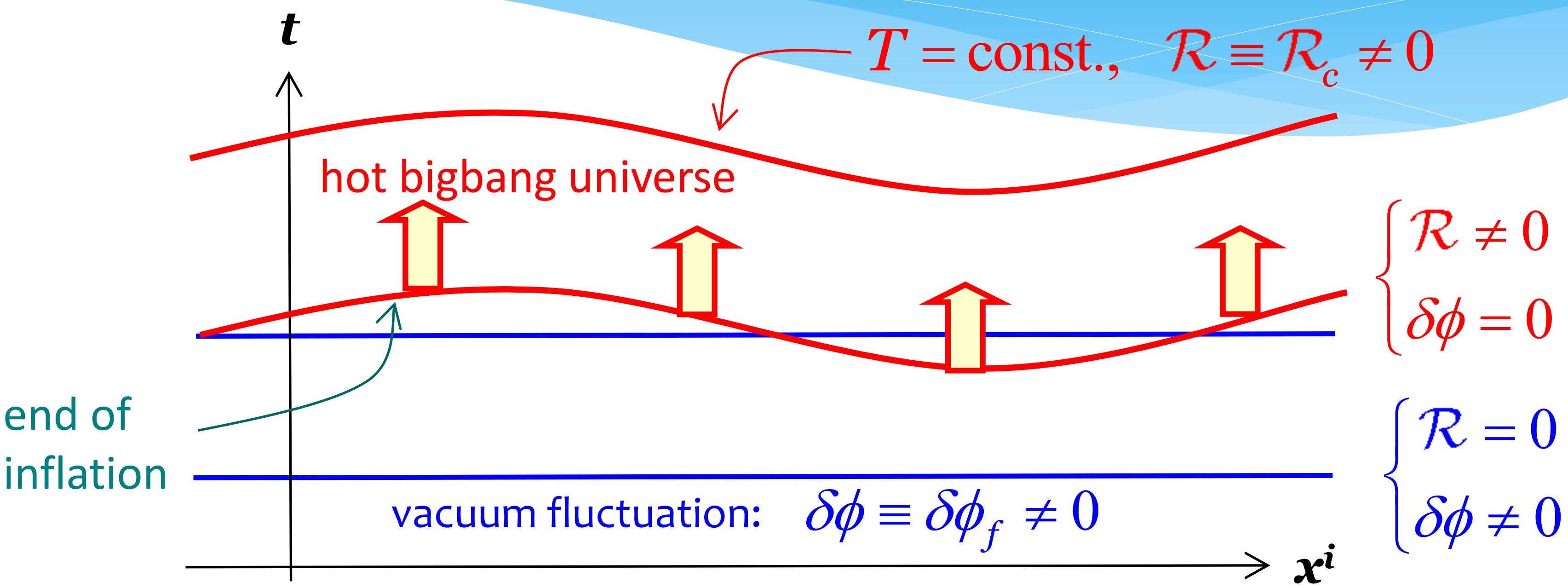
$$\delta\phi_k \rightarrow \text{const.}$$

… frozen when $\omega < H$
(on superhorizon scales)

tensor (gravitational wave) modes also satisfy the same eq.

from δϕ to curvature perturbation

- Inflation ends/damped osc starts on "comoving" (ϕ =const.) 3-surface.

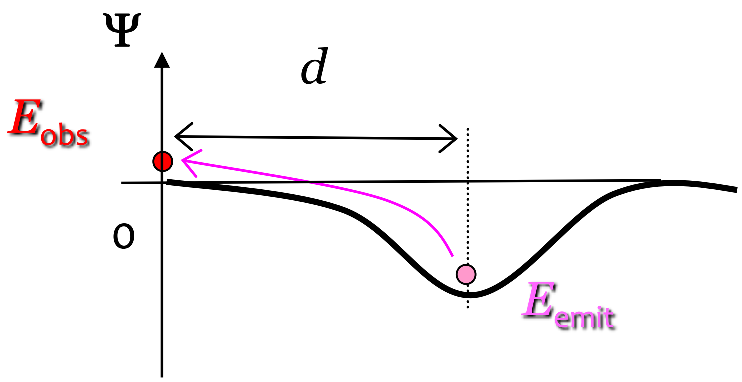


- On ϕ =const. surface, curvature perturbation appears $\mathcal{R} \equiv \mathcal{R}_c = -\dfrac{H}{\dot{\phi}}\delta\phi_f$

- $\mathcal{R}_c$ gives rise to gravitational potential perturbation Ψ : $\Psi = -\dfrac{3}{5}\mathcal{R}_c$

CMB temperature fluctuations

- Photons climbing up from gravitational potential well are redshifted.



For Planck distribution,

$$\frac{\Delta T}{T}(\vec{n}) \equiv \frac{T_{\text{obs}}}{T_{\text{emit}}} - 1 = \Psi(\vec{x}_{\text{emit}})$$

$$\vec{x}_{\text{emit}} = \vec{n}d \ ; \ \ \vec{n} = \text{line of sight}$$

c=1 units

- In an expanding universe, this is modified to be

$$\frac{\Delta T}{T}(\vec{n}) = \frac{1}{3}\Psi(\vec{x}_{\text{emit}})$$

Sachs-Wolfe effect

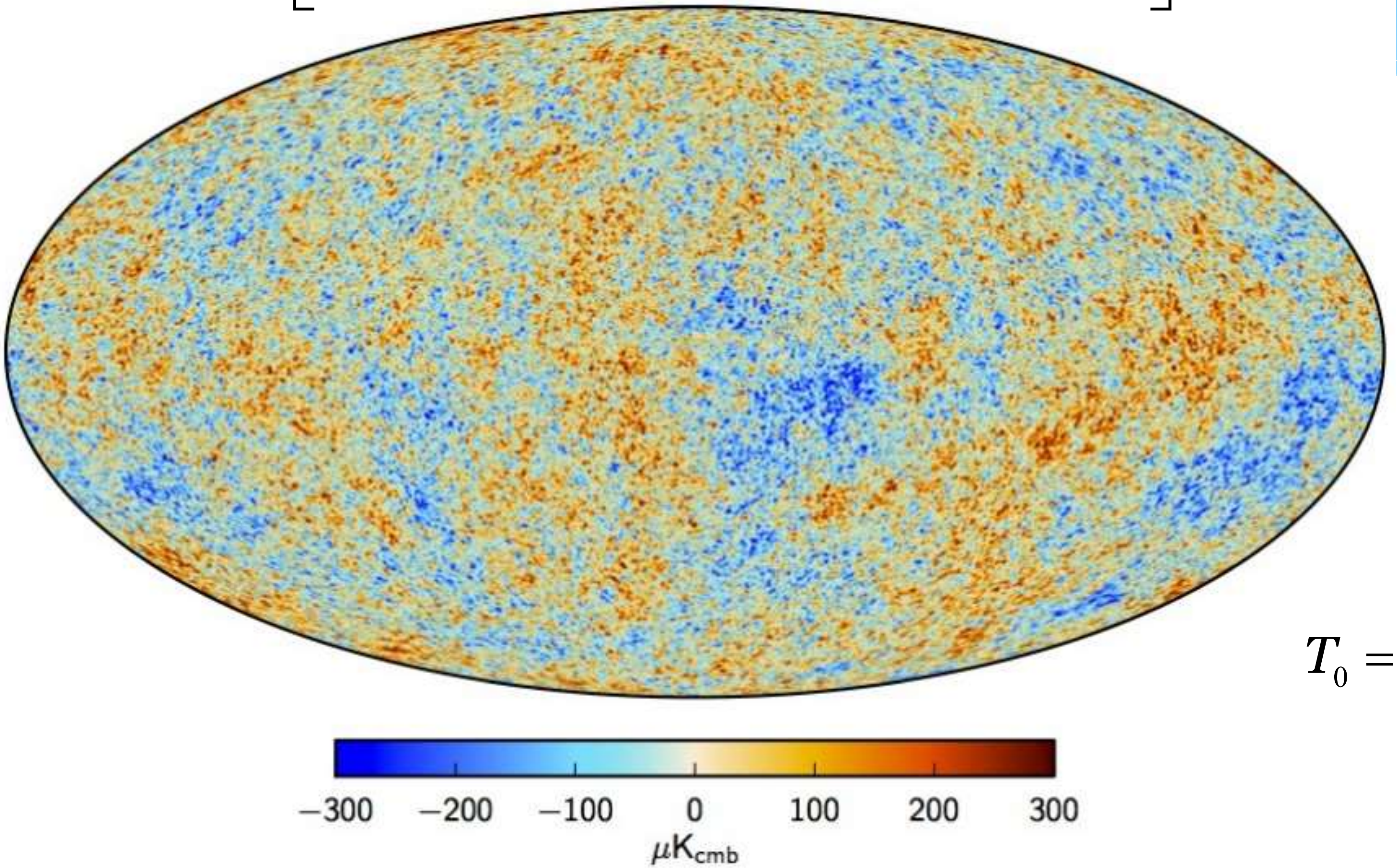
- There is also the standard Doppler effect:

$$\frac{\Delta T}{T}(\vec{n}) = -\vec{n}\bullet\vec{v}(\vec{x}_{emit})$$

Planck CMB map

Planck 2013

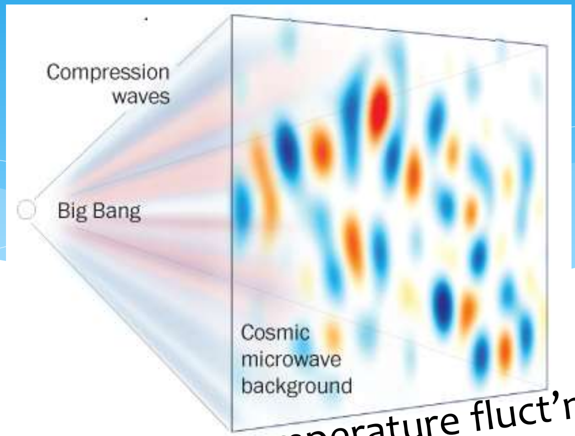
$$\Delta T = \left[\frac{1}{3}\Psi - \vec{n} \bullet \vec{v} + \cdots \text{(minor corrections)} \right] T_0$$



$$T_0 = 2.73K$$

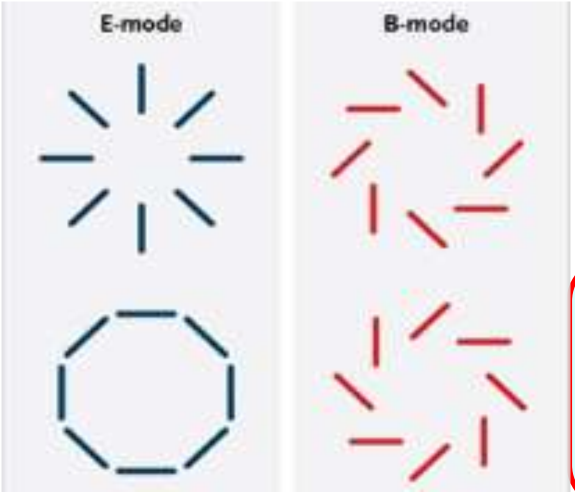
Cosmological GWs

- 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

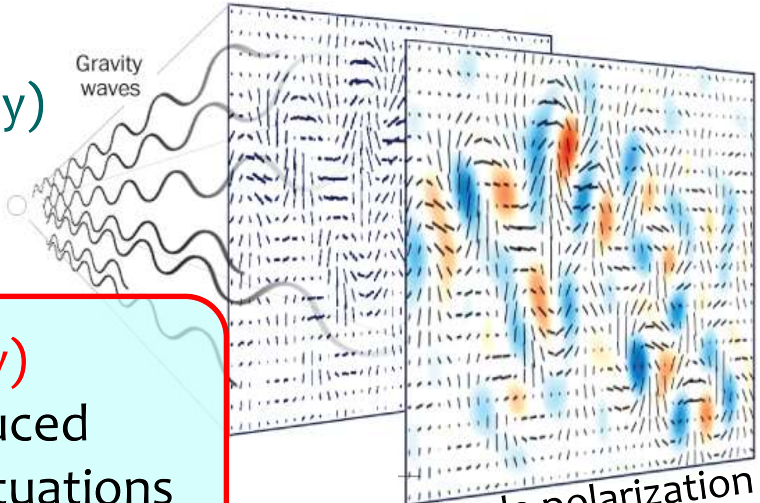


http://www.skyandtelescope.com/

E-mode (even parity)

↕

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



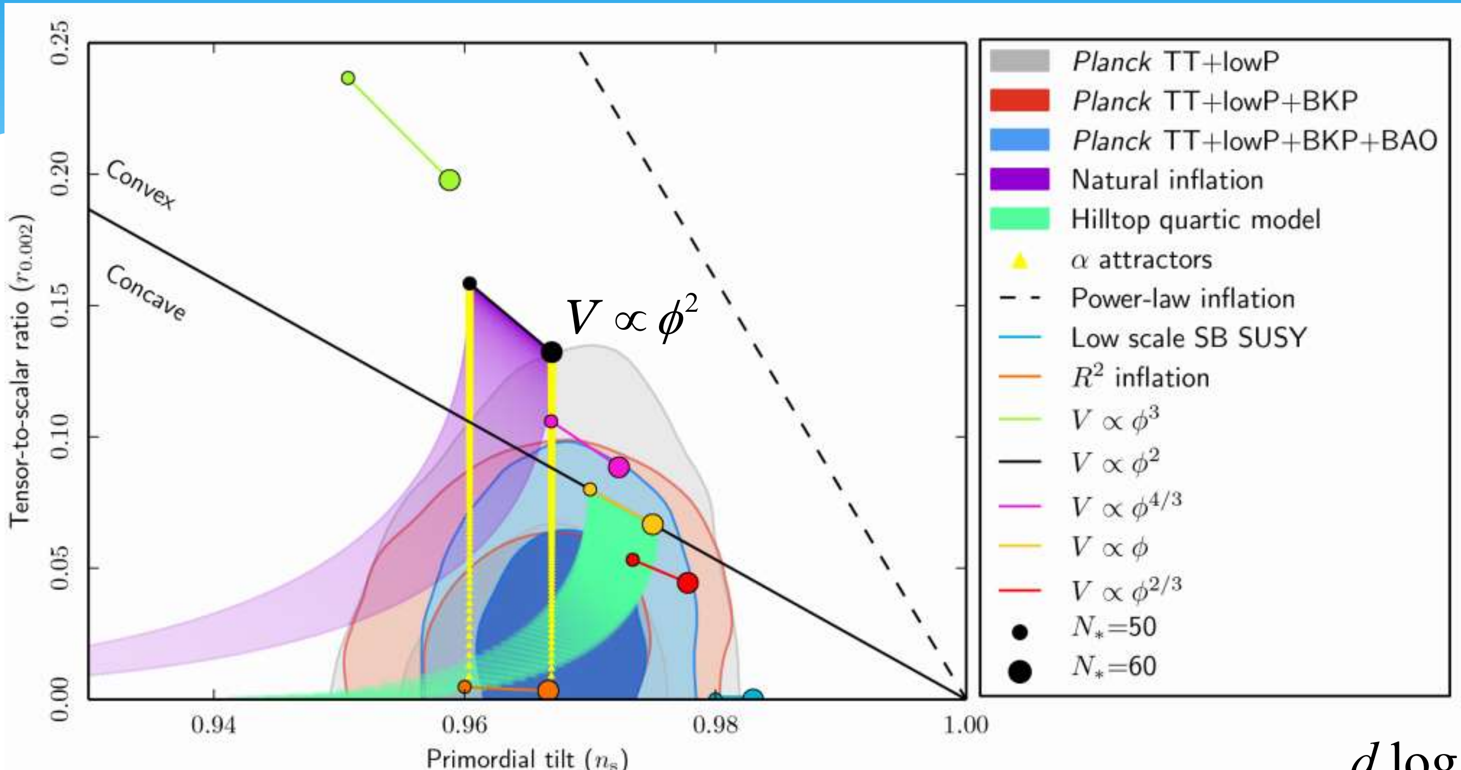
B-mode polarization

Source: Harvard-Smithsonian Center for Astrophysics

CMB B-mode=cosmological GW detector

Planck constraints on inflation

Planck 2015 XX



- scalar spectral index: $n_s \sim 0.96$
- tensor-to-scalar ratio: $r < 0.1$
- simplest $V \propto \phi^2$ model is almost excluded

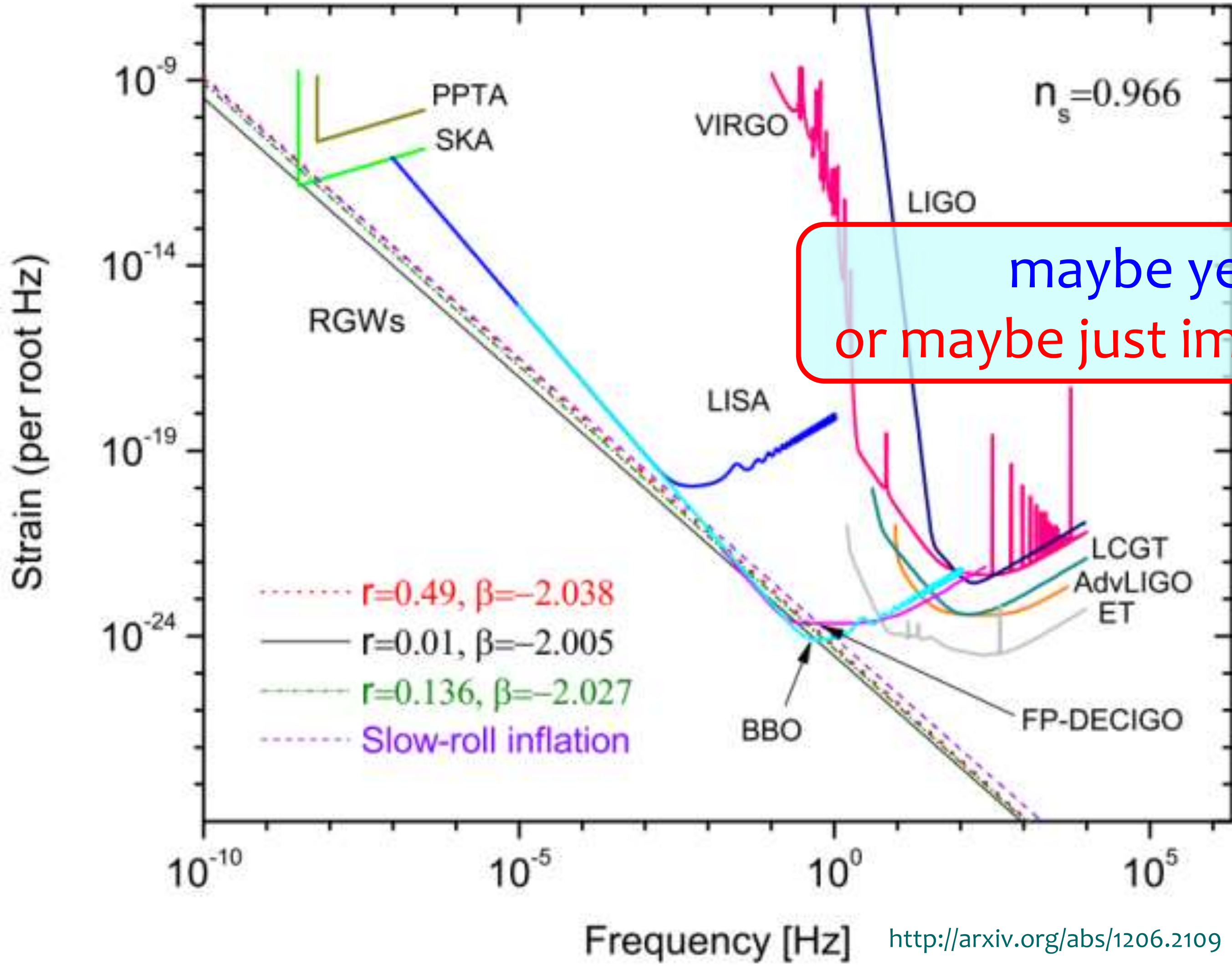
$$n_s - 1 \equiv \frac{d \log[k^3 P_S(k)]}{d \log k}$$

$$r \equiv \frac{P_T(k)}{P_S(k)}$$

some element of non-canonicality needed

GWs from “Standard” Inflation

could direct detection by GW observatories possible?



maybe yes…

or maybe just impossible…

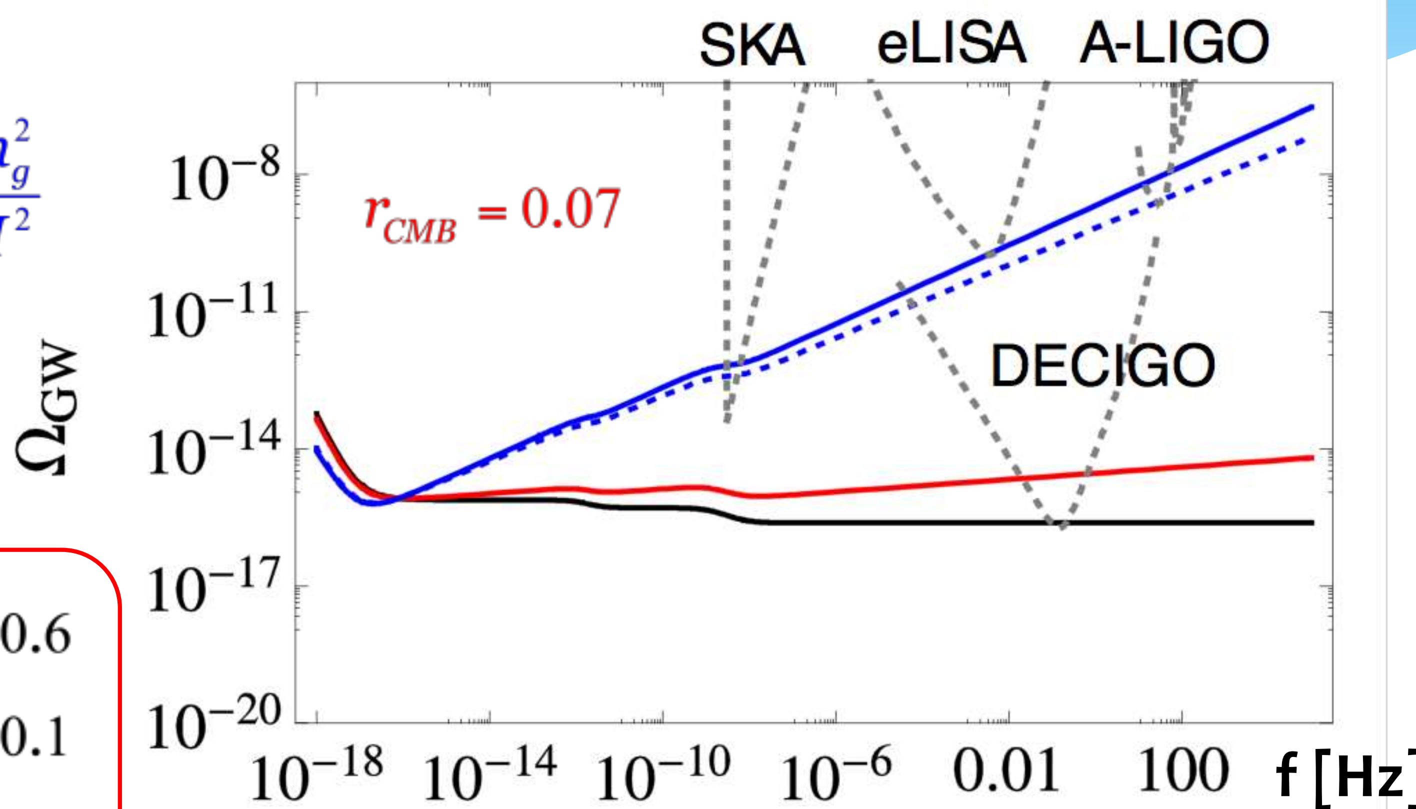
http://arxiv.org/abs/1206.2109

blue-tilted GW spectrum?

possible in massive gravity inflation model Lin & MS (2015)

tensor (=GW) spectral index:

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



- : $m_g^2 / H^2 = 0.6$

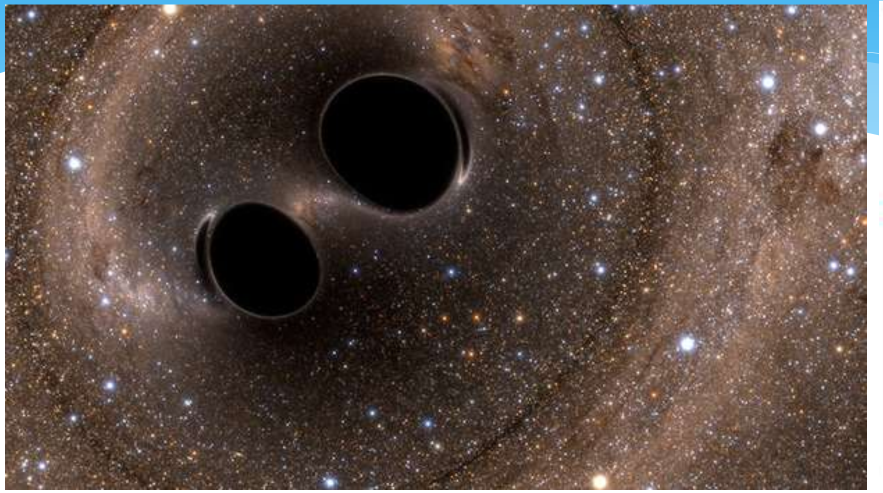
- : $m_g^2 / H^2 = 0.1$

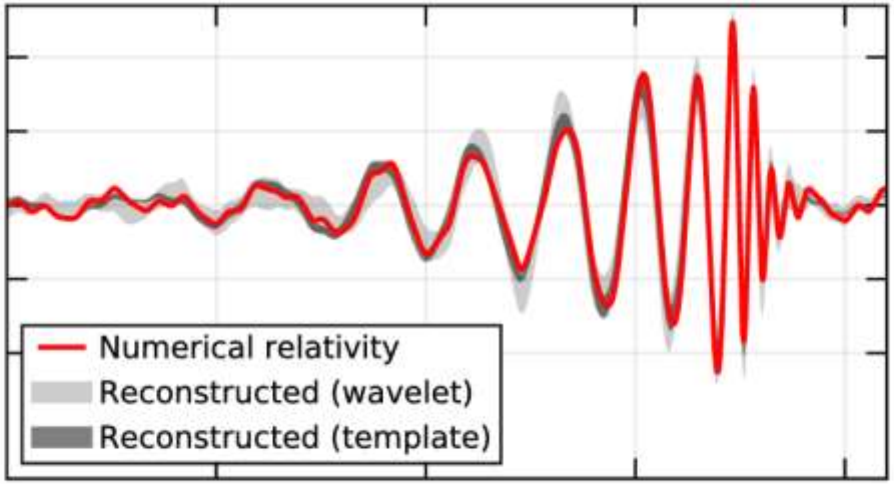
- : $n_T = 0$

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

Gravitational Wave Physics/Astronomy

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

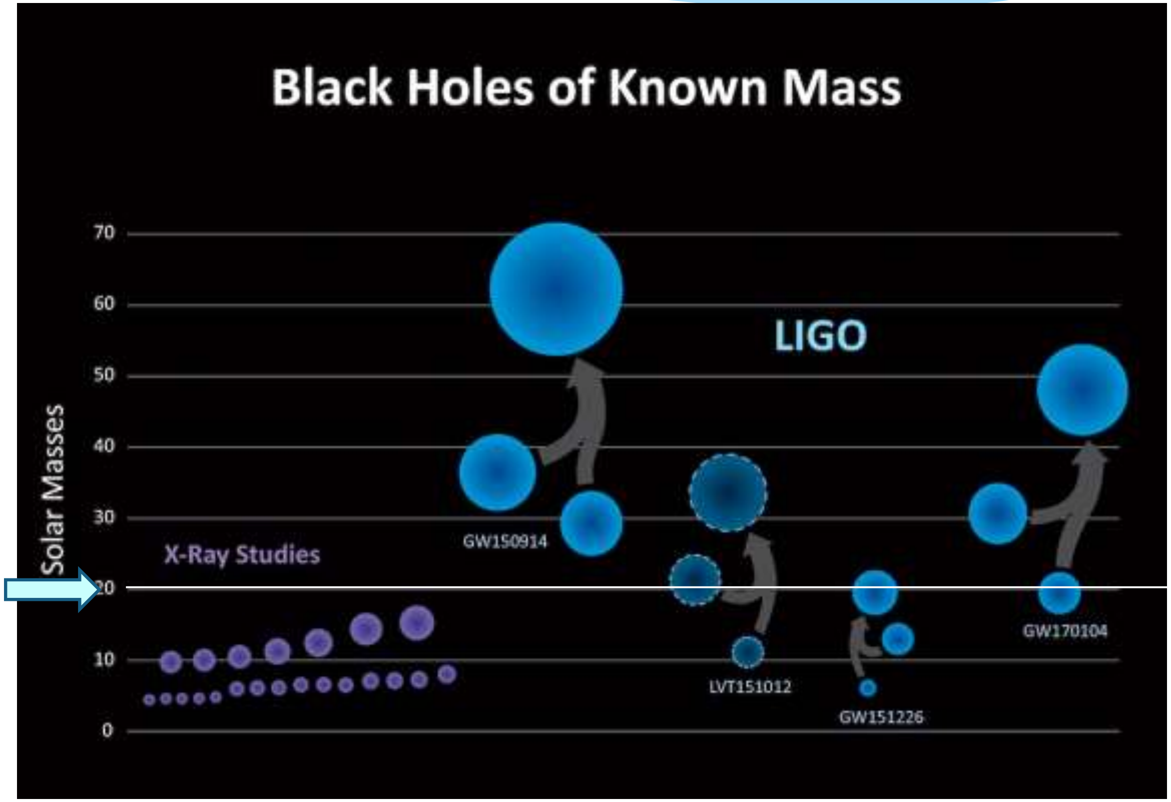
LIGO has detected 3BBH mergers (+1 candidate) so far.

Any implications ?

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

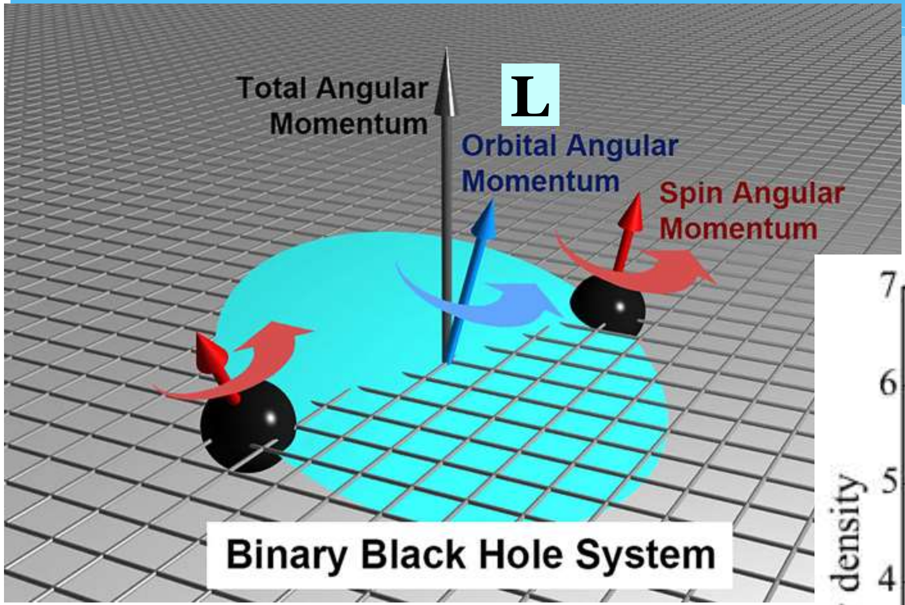
- Their spins seem to be unusually small!

20 $M_{\odot}$



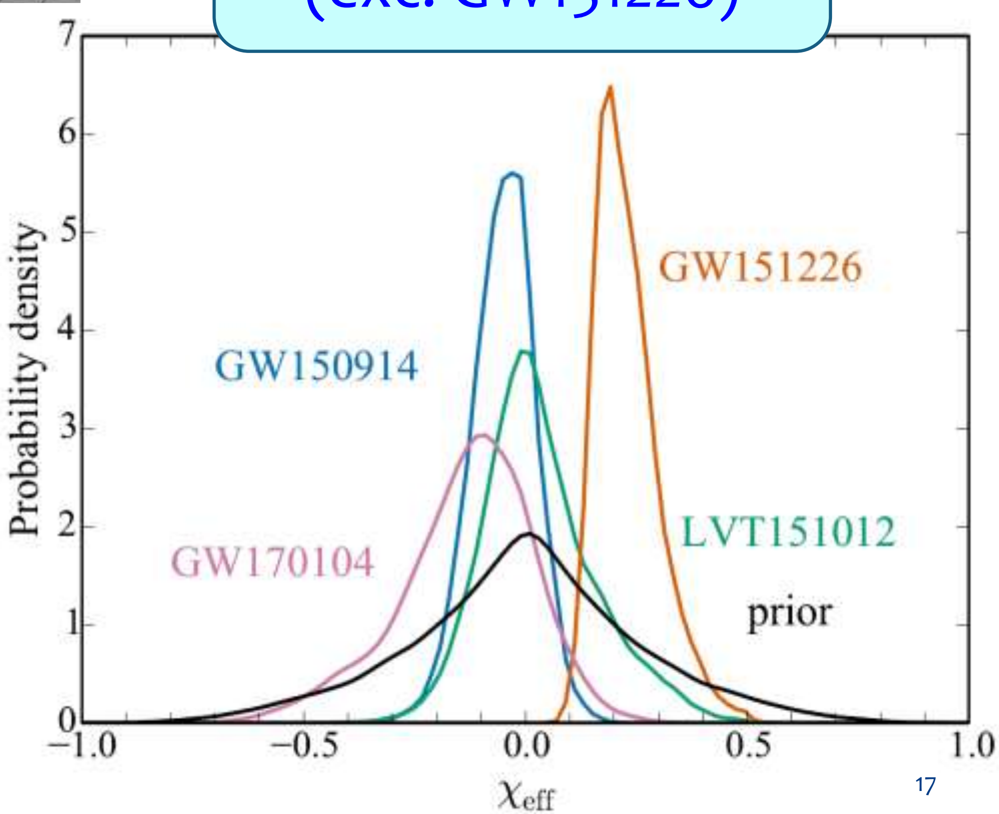
LIGO BH spins

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



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

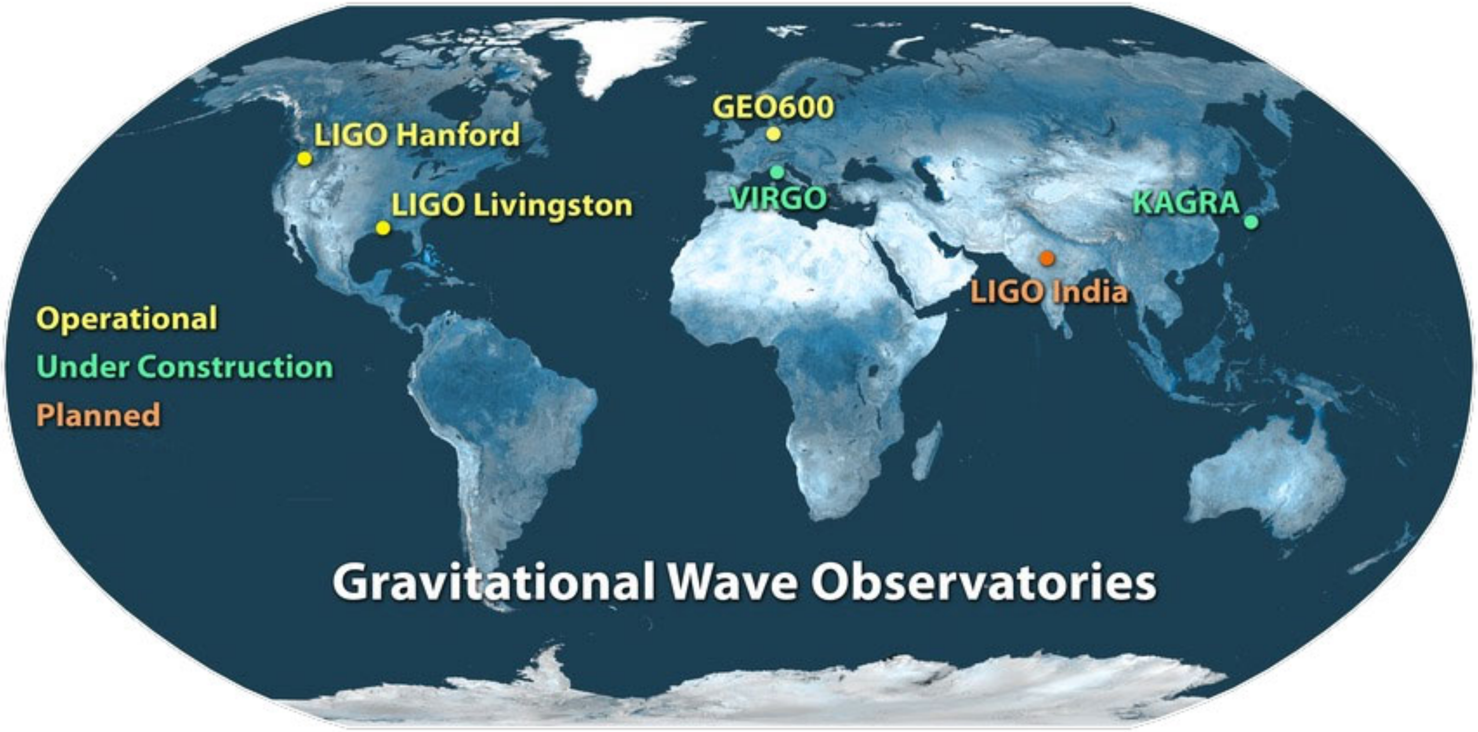
χ_{eff} =0 is consistent (exc. GW151226)



χ_{eff} would be larger if astrophysical origin

Future Network of GW Observatories

VIRGO has just begun to take data (on 1st Aug: 2 days ago!)
KAGRA will start operation by 2019~2020 (iKAGRA has started!)
LIGO-India has been recently approved by Indian gov.



KAGRA

KAmioka GRAvitational wave detector

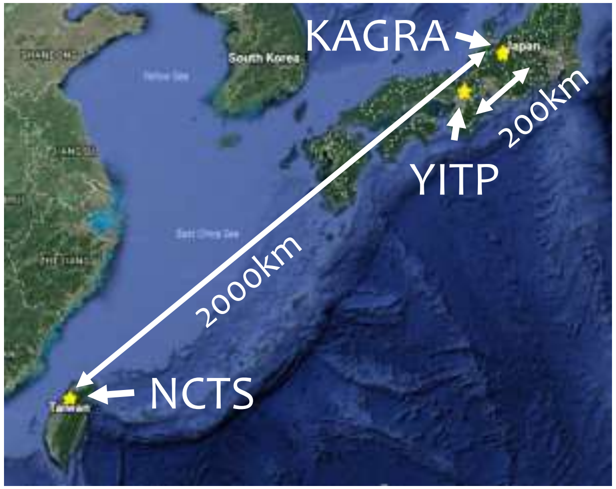
In Japanese it is pronounced as Kagura, which means "God Music"（神楽）

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

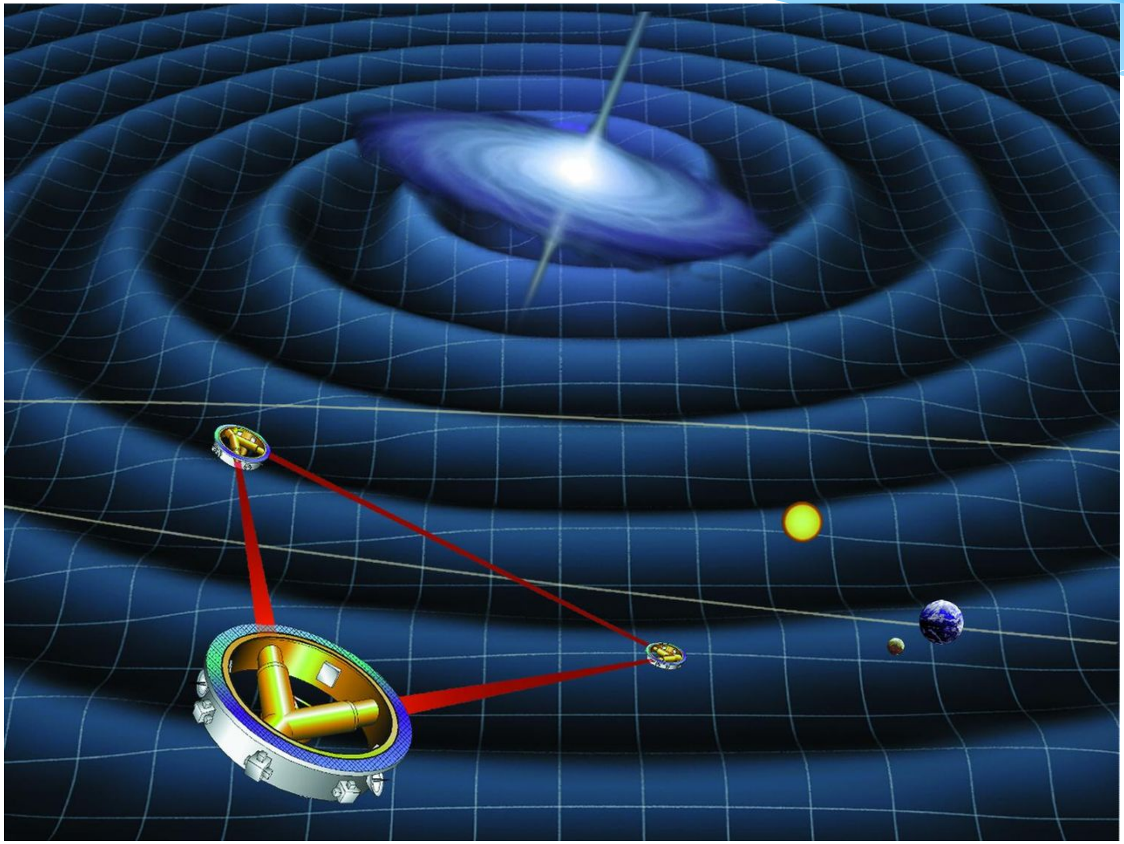
Previously called LCGT

Large Cryogenic
Gravitational wave Telescope

Arm length 3km
Cooled to 20K



Space-based Future Projects



http://lisa.nasa.gov/

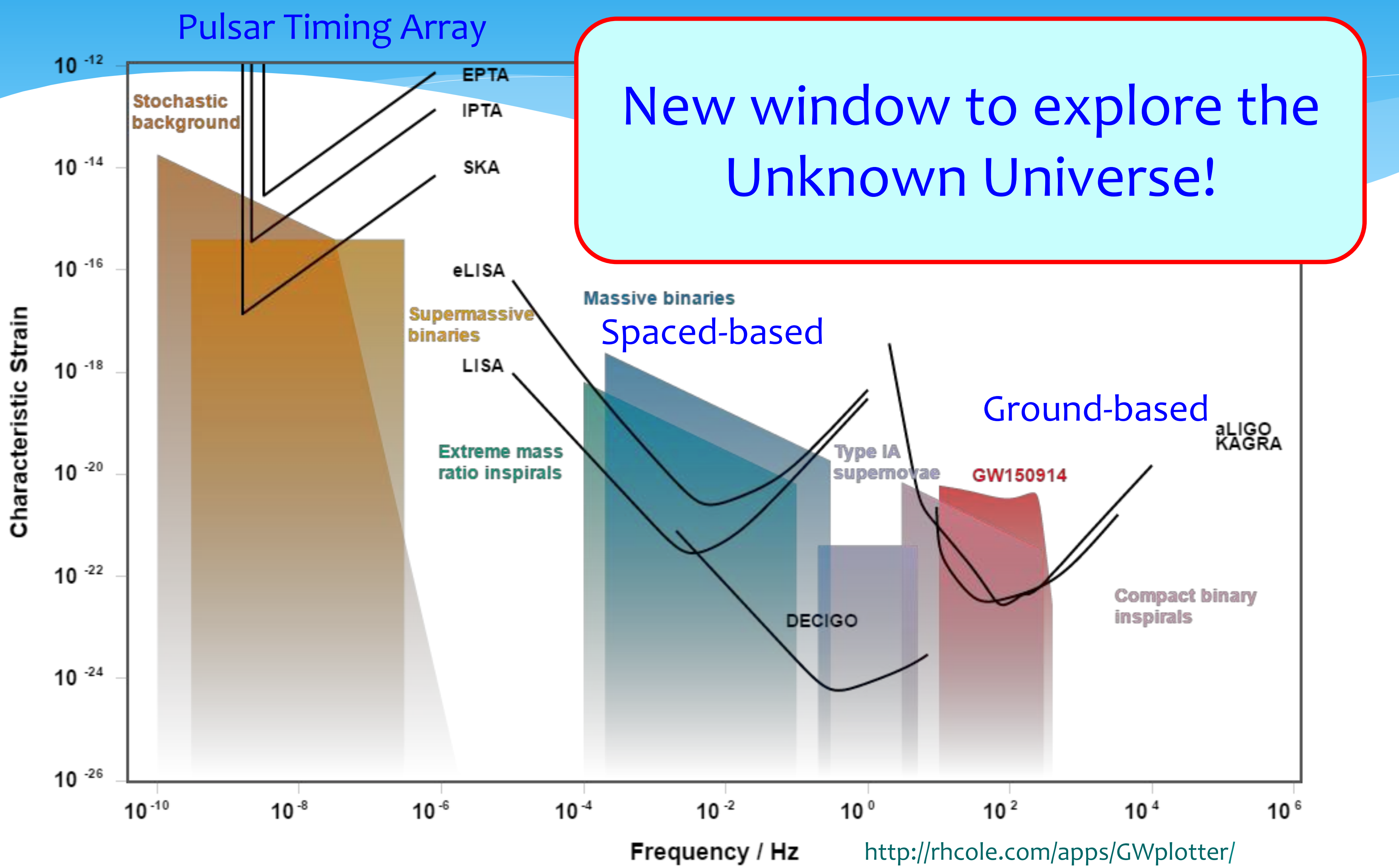
Arm Length

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

TAIJI: 1,000,000 km
target freq: ~ 10^{-2}Hz
Launched by ~2030?

LISA: 5,000,000 km
target freq: ~10^{-3}Hz
Launched by 2035?

Multi-frequency GW Astronomy



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

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 $\delta\rho/\rho=O(1)$ collapses to form BH

  Carr (1975), … .

- Such a large perturbation may be produced by inflation

  Carr & Lidsey (1991), …

- PBHs may dominate Dark Matter.

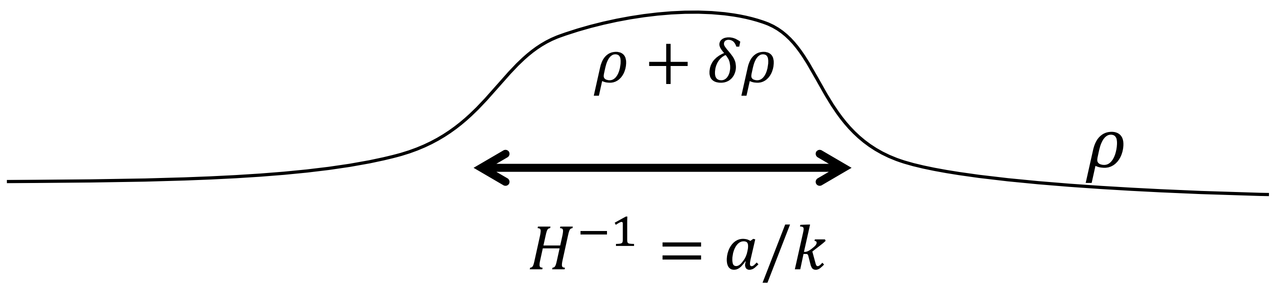
  Ivanov, Naselsky & Novikov (1994), …

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

Curvature perturbation to PBH

$$\boxed{\delta R^{(3)} = -\frac{4}{a^2}\nabla^2\mathcal{R} \approx 16\pi G\delta\rho}$$ ⇐ Einstein equation

$$\Rightarrow \quad \frac{\delta\rho}{\rho} \approx \frac{k^2}{4\pi G a^2\rho}\mathcal{R}_c = \frac{2}{3}\frac{k^2}{a^2H^2}\mathcal{R}_c \quad \Rightarrow \quad \boxed{\frac{\delta\rho}{\rho} \sim \mathcal{R}_c \ \text{ at } \ \frac{k^2}{a^2} = H^2}$$

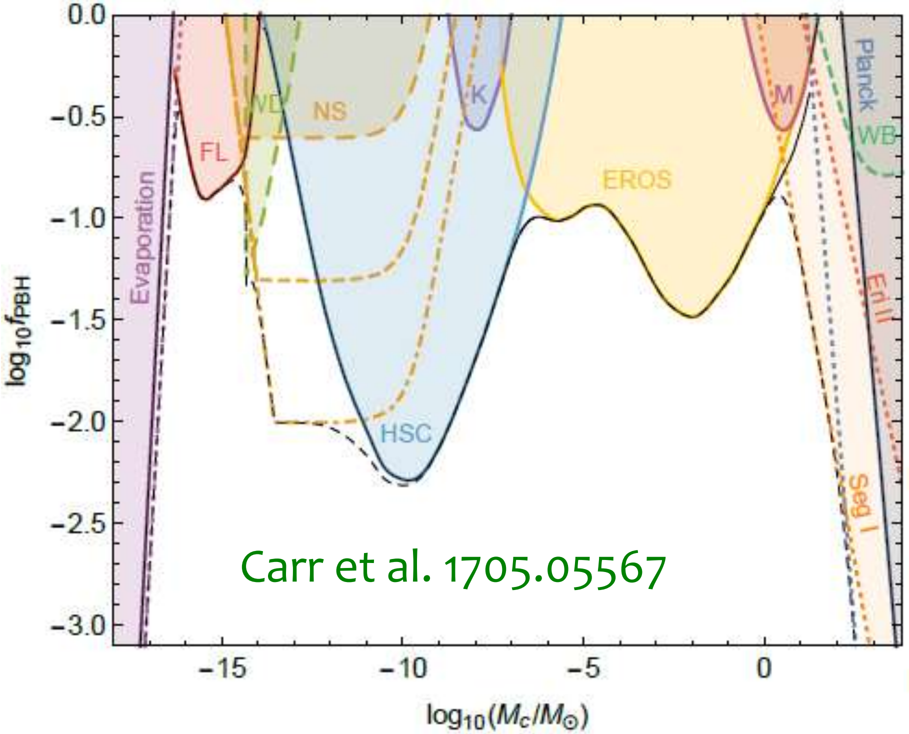


- If δρ/ρ=O(1) at horizon entry, it will collapse to BH

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

- Spins of PBHs are expected to be very small

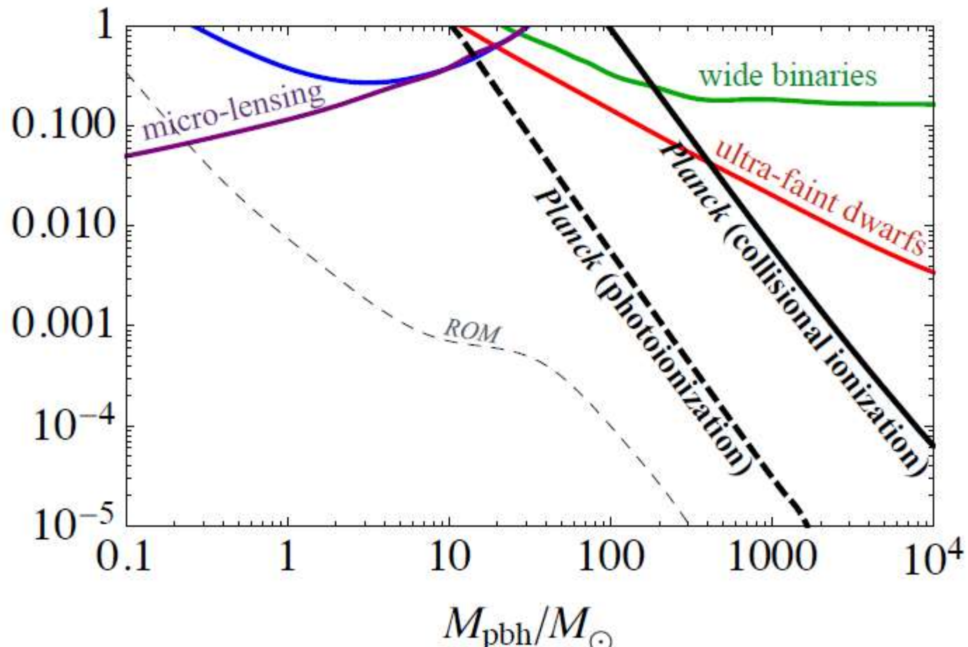
Constraints on PBHs



Carr et al. 1705.05567

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

Kamionkowski et al. 1612.05644

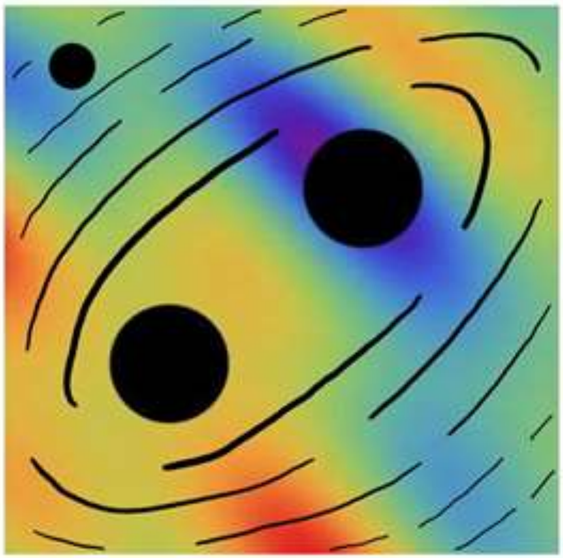


DM can't be dominated by PBHs!

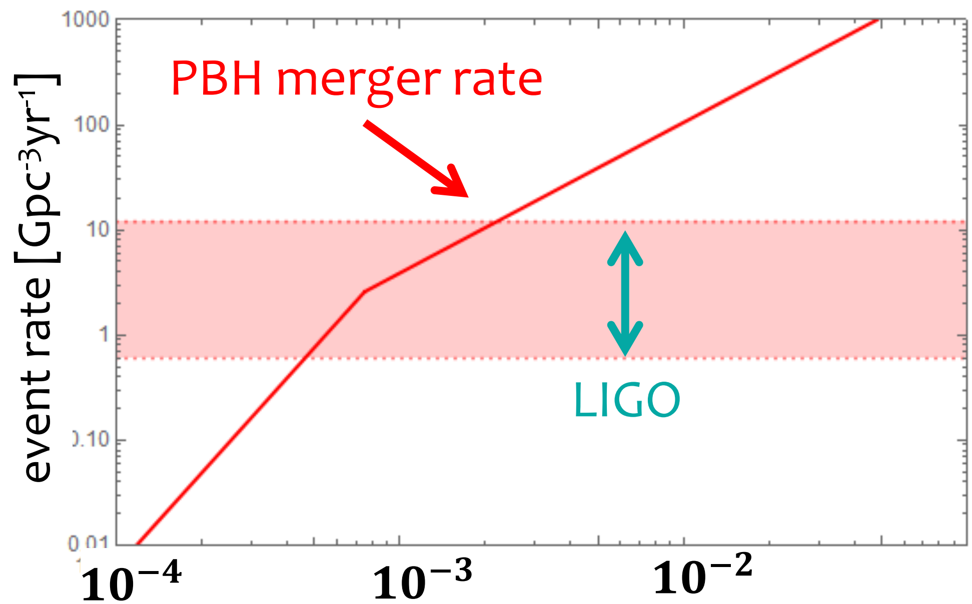
(opinion varies…)

LIGO BHs = PBHs?

MS, Suyama, Tanaka & Yokoyama '16

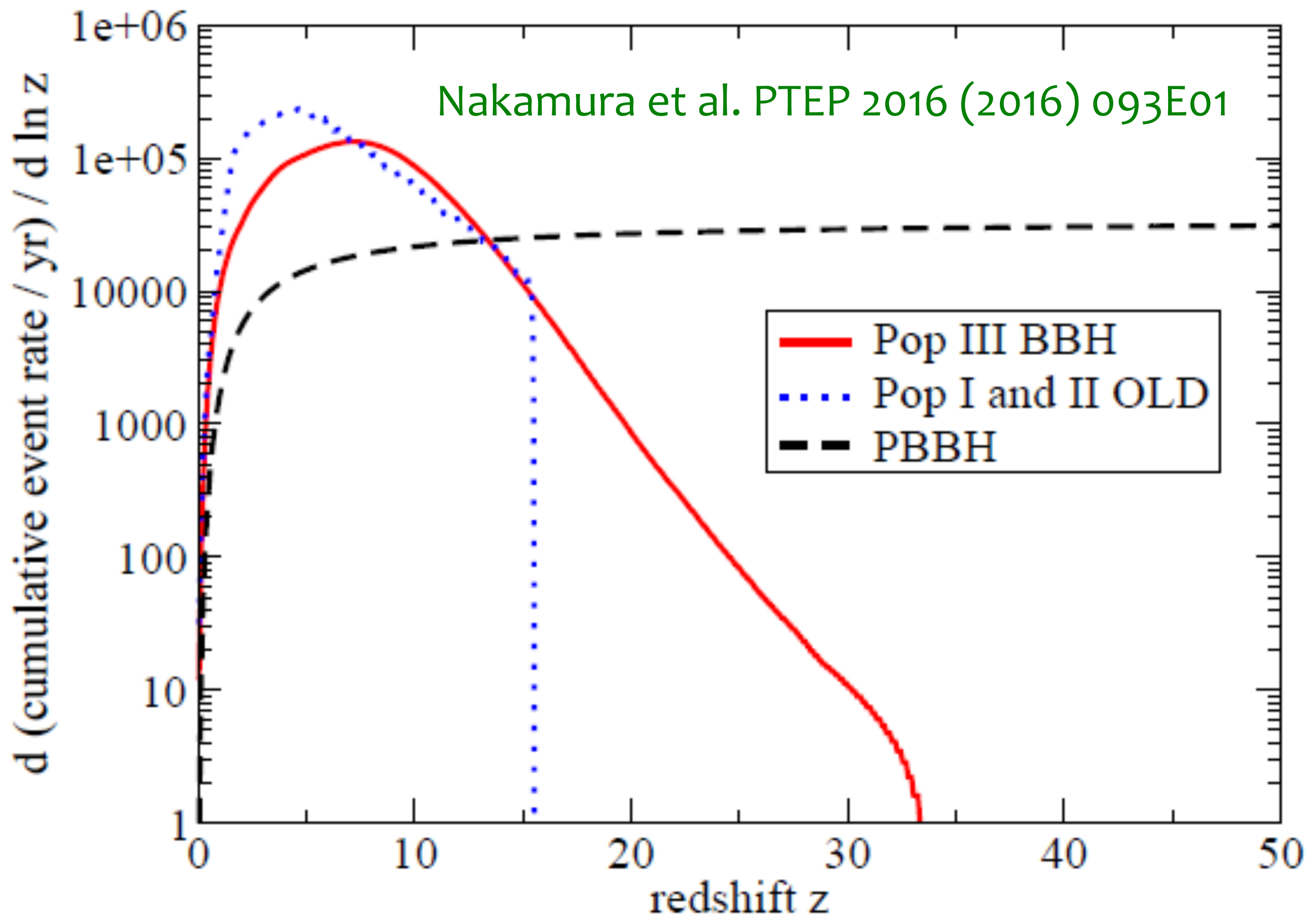


$$M_{PBH} \simeq 20 \left(\frac{k}{\text{kpc}^{-1}} \right)^{-2} M_{\odot} \simeq 20 \left(\frac{100\text{MeV}}{T} \right)^{2} M_{\odot}$$

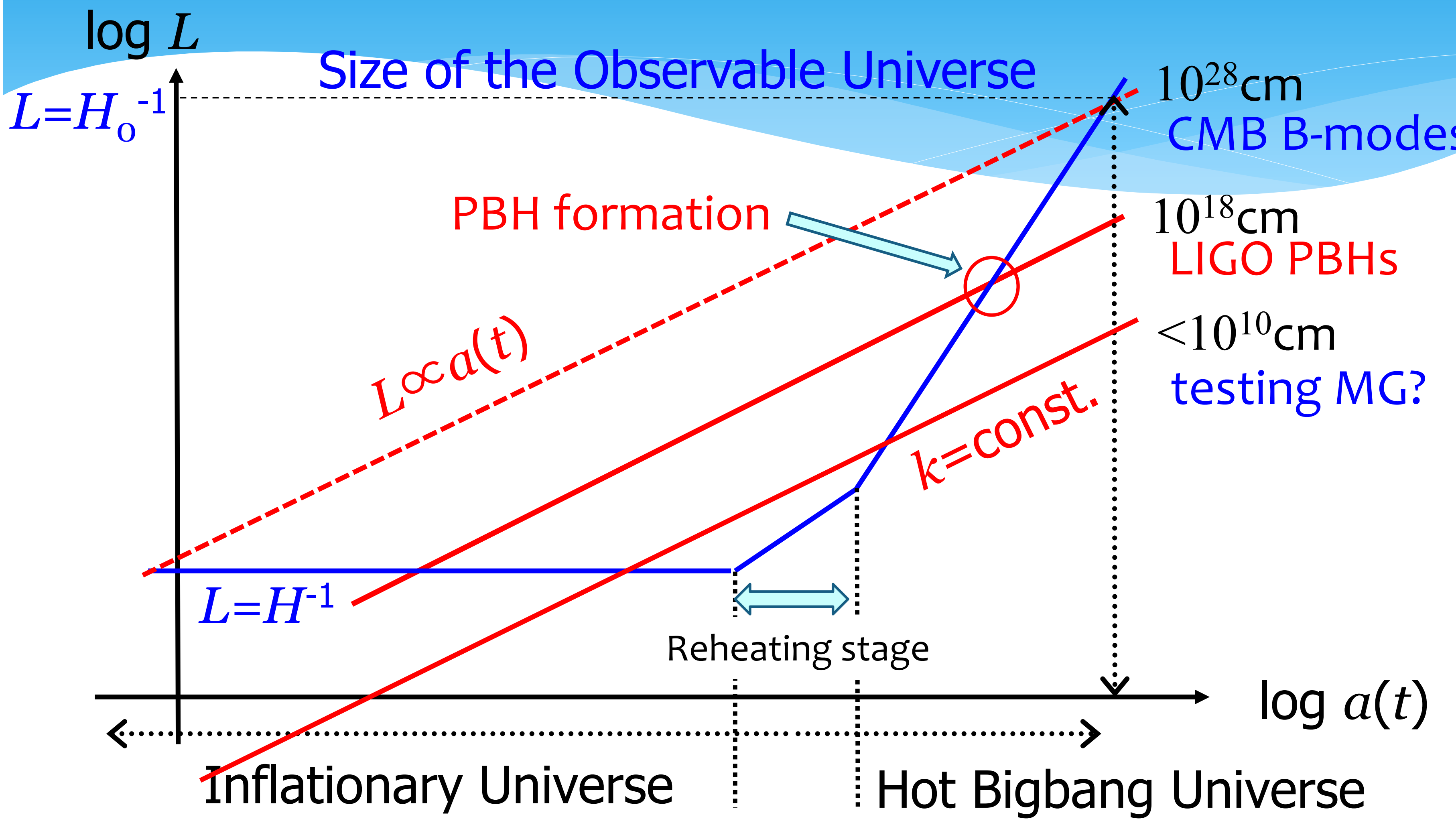


3-body interaction leads to formation of BH binaries

testing PBH hypothesis



testing inflation by GW astronomy



Summary

* Inflation has become the standard model of the Universe.
  further tests are needed to confirm inflation.
* Cosmological GWs are the key to understanding/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