Inflation, Primordial Black holes and Gravitational Waves

-- Dawn of Gravitational Wave Cosmology --

Misao Sasaki

Yukawa Institute for Theoretical Physics, Kyoto University

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"General Relativity -- The Next Generation --"

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.

In summary, the picture that emerges is in complete accord with the kinematic generalities of causal cosmology presented in Section 2. For $y < y_0$, one has $p < 0$ ($p \simeq -\sigma$). For $y > y_0$, p becomes positive and λ undergoes an inflection. The situation is summarized in Figs. 1 and 2.

The Creation of the Universe as a Quantum Phenomenon

R. Brout, F. Englert, and E. Gunzig

Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium

Received July 7, 1977

温故知新
(learning from the past)

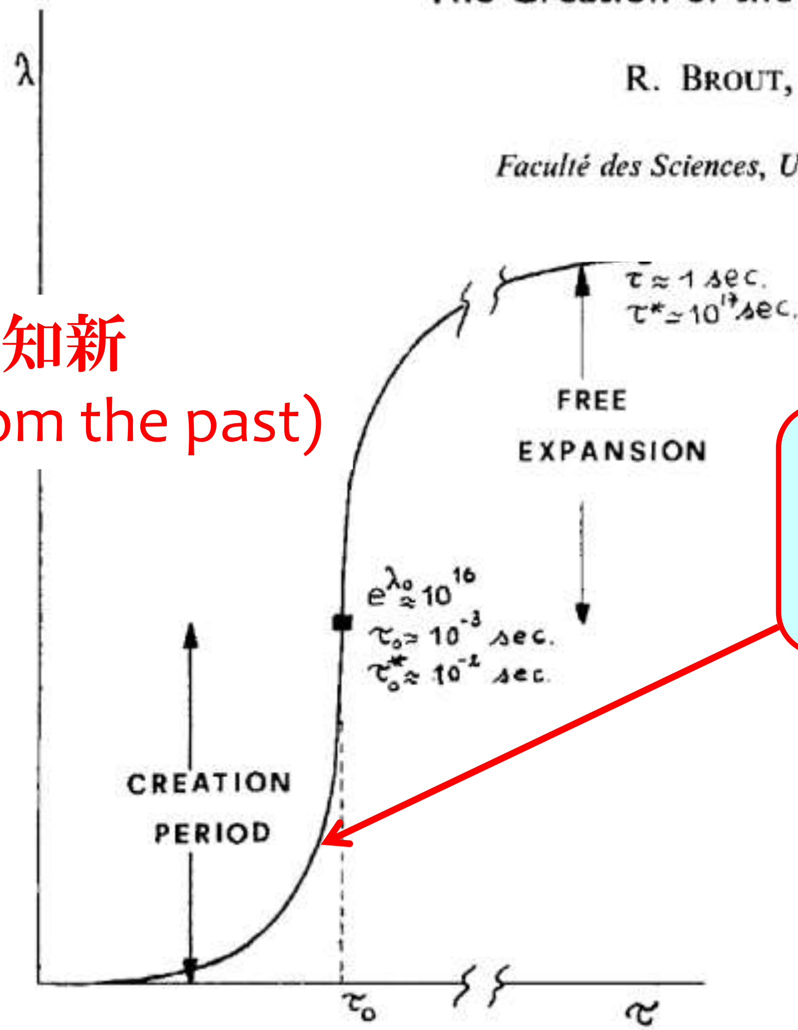


Fig. 1. λ as a function of kinematical time τ for $\delta = 0$. Time scales are calculated for $m = 1$ GeV.

$$ds^2 = -dt^2 + a^2(t) dH^2_{(3)};$$

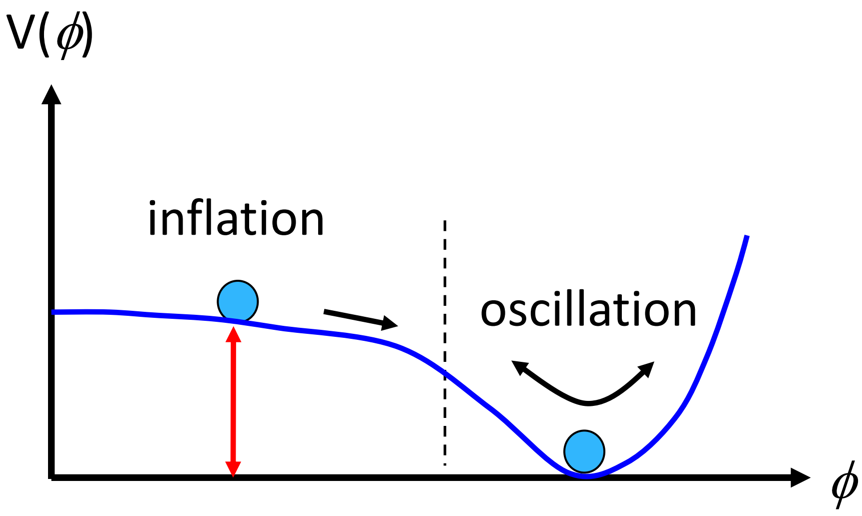
$$a(t) \simeq H^{-1} \sinh Ht$$

Creation of Open Universe!

Now in the context of String Landscape

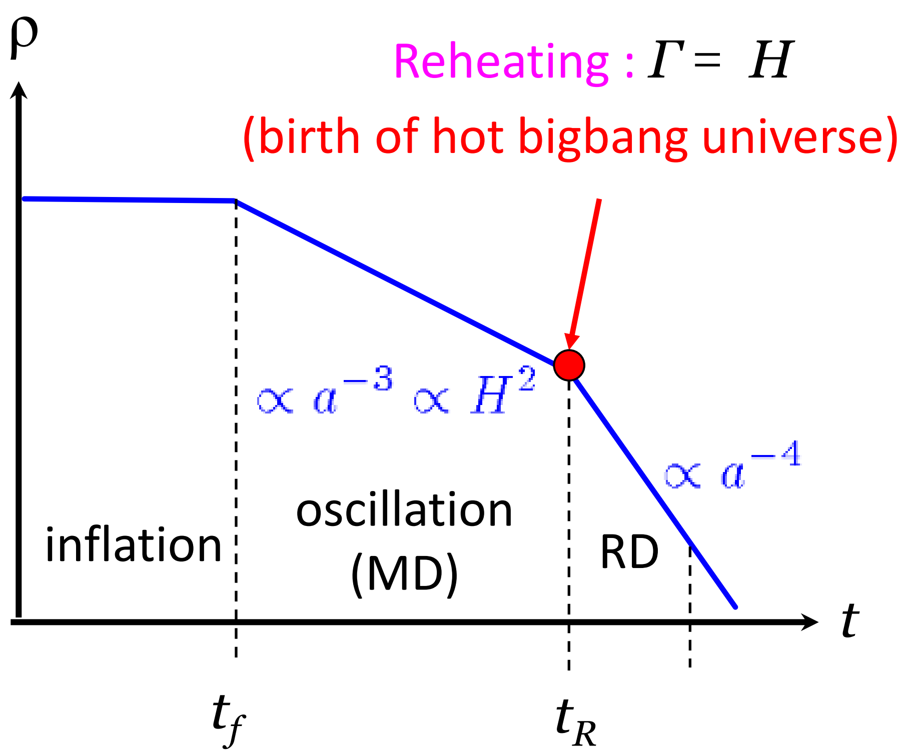
From inflation to bigbang

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



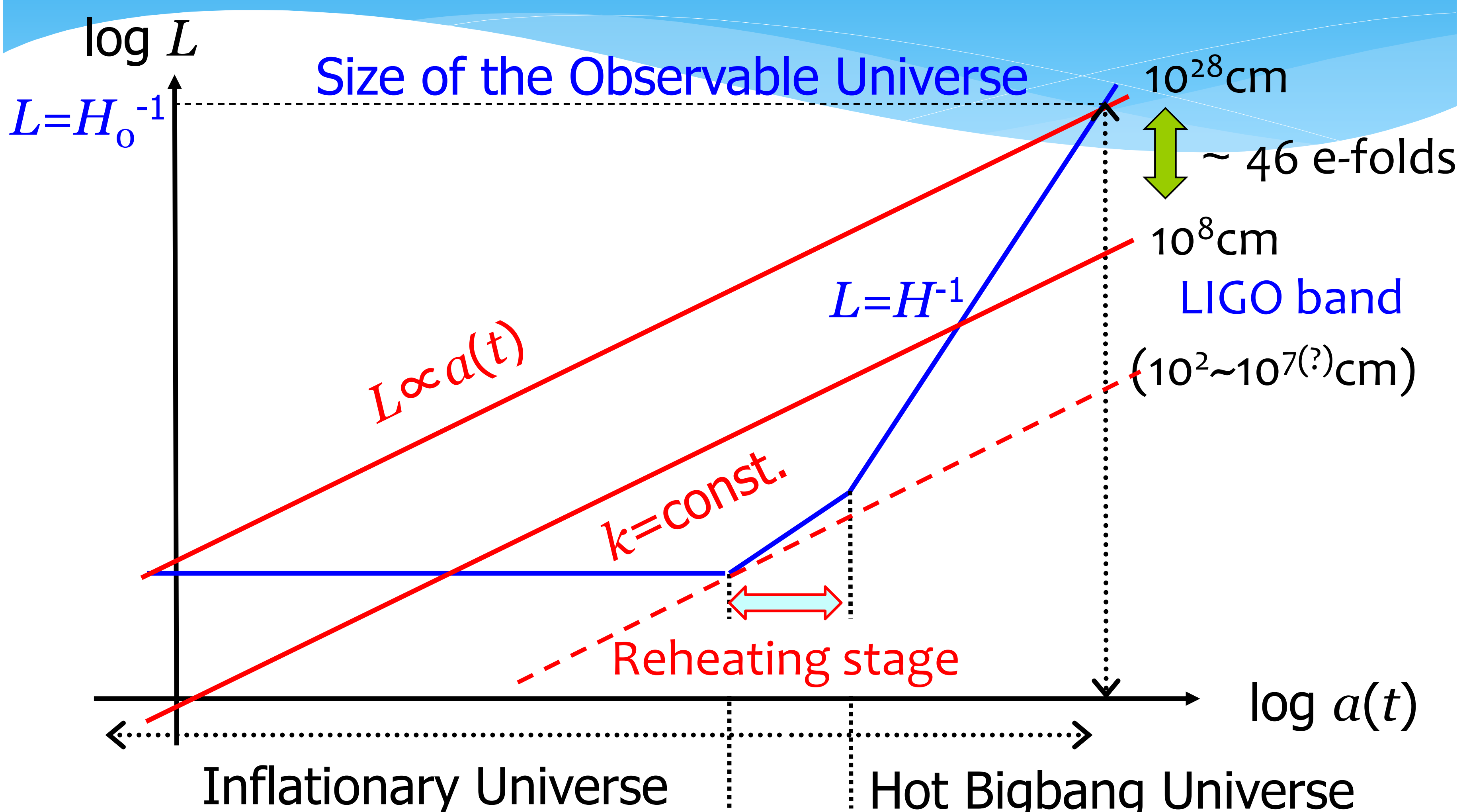
"slow-roll" inflation

Linde '83, ….



length scales of the inflationary universe

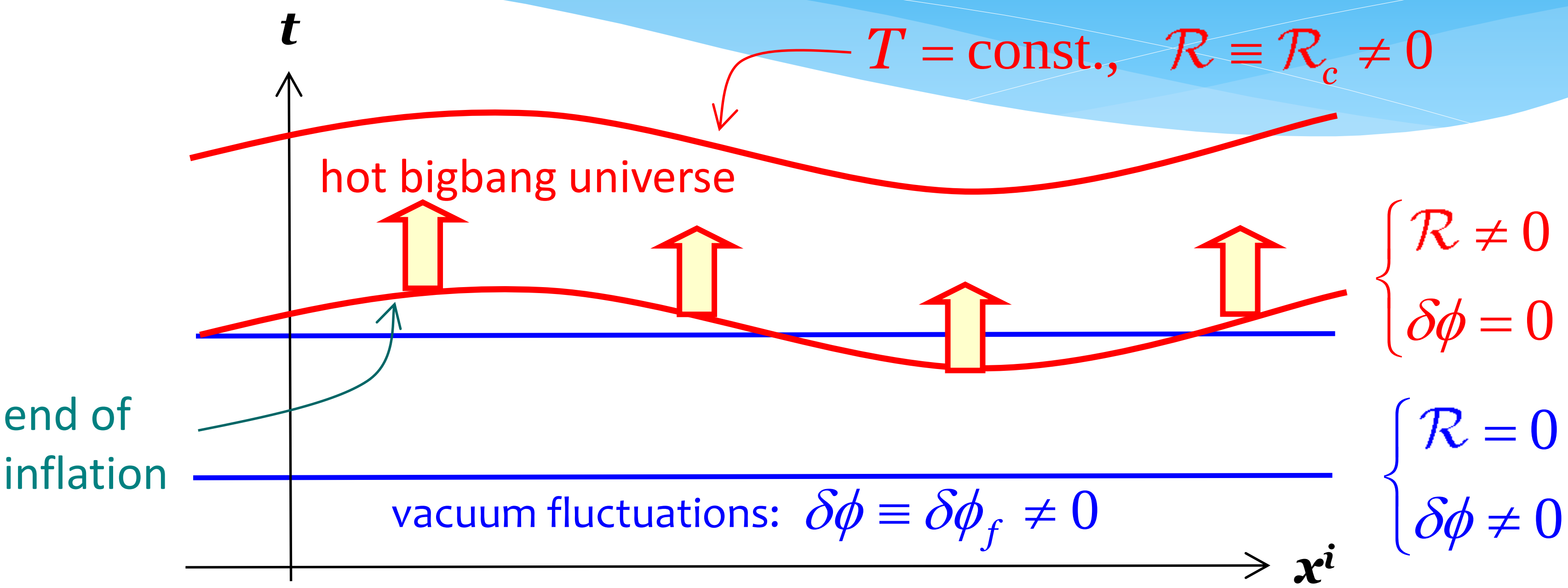
⇔ targets for multi-freq GW astronomy/cosmology



from δϕ to curvature perturbation

Mukhanov & Chibisov '81, ….

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



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

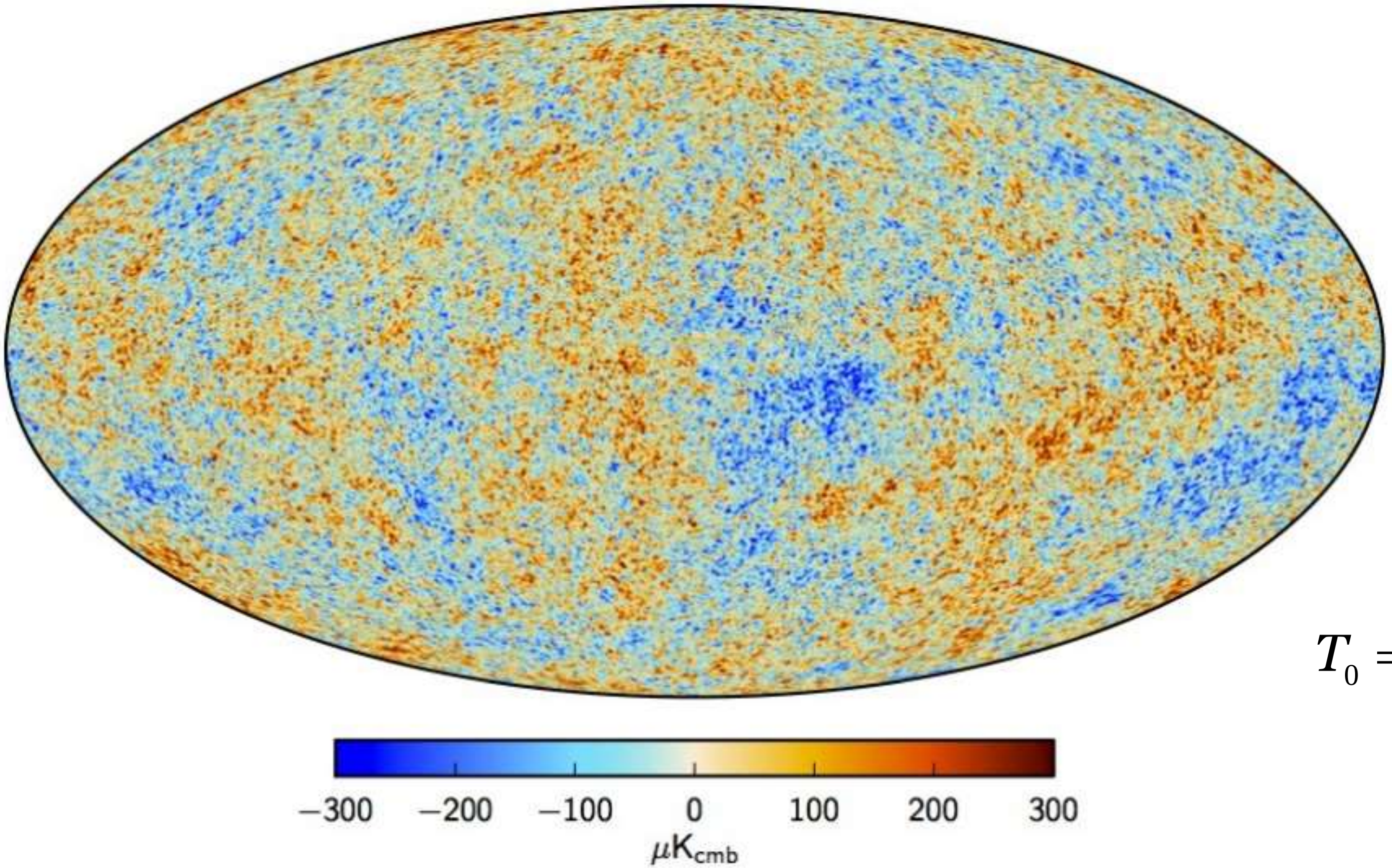
- $\mathcal{R}_c$ gives rise to gravitational potential perturbation Ψ : $\Psi = -\frac{3}{5}\mathcal{R}_c$

Planck CMB map

Planck 2013

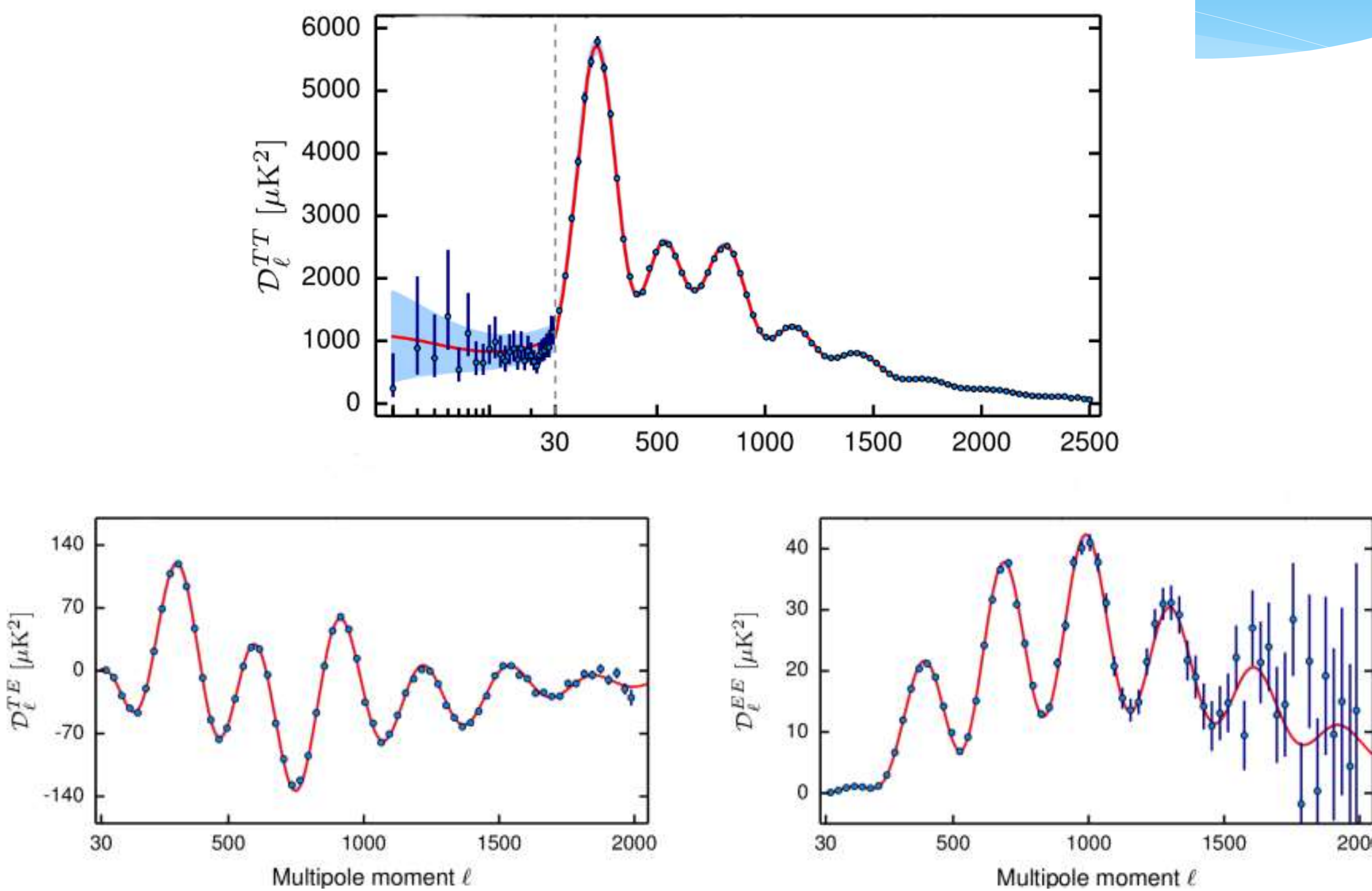
but important!

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



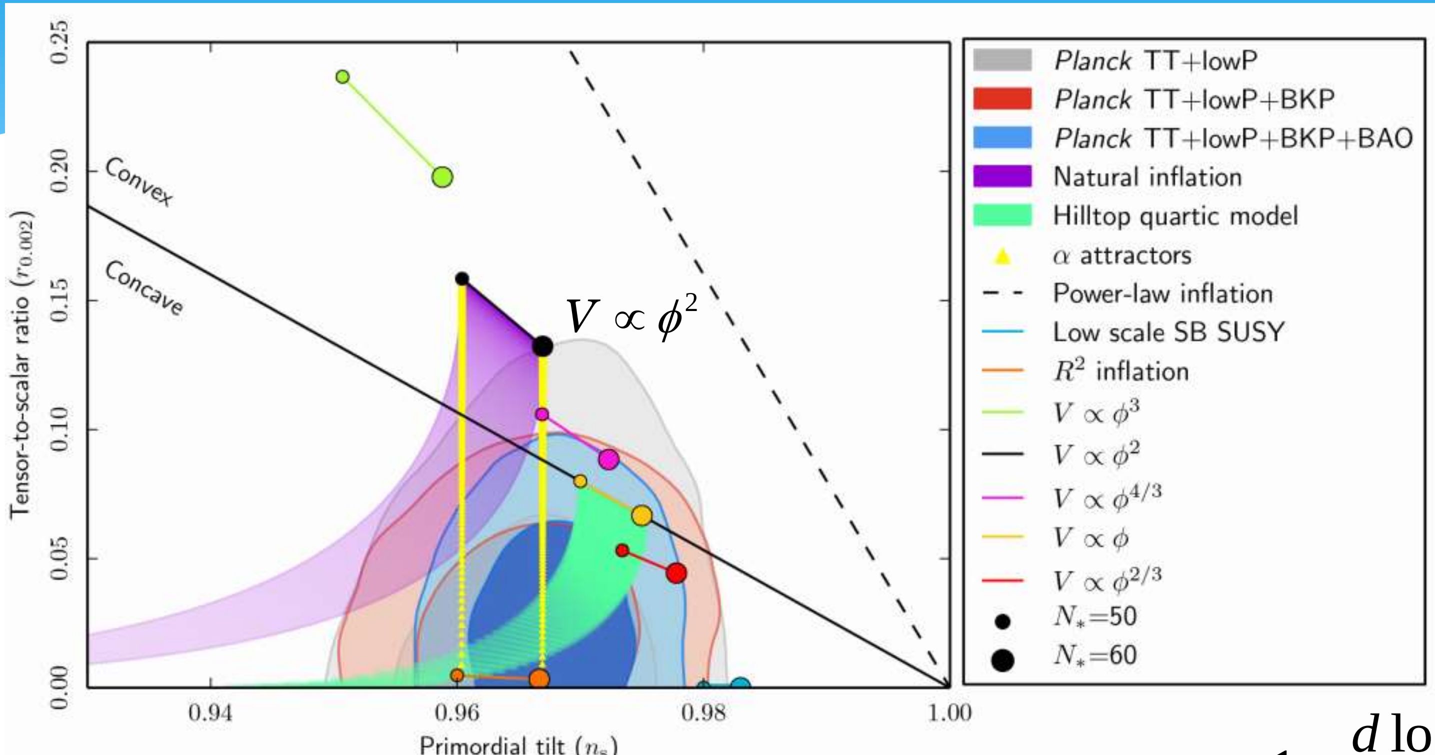
$$T_0 = 2.73K$$

Planck TT, TE & EE spectrum



Planck constraints on inflation

Planck 2015 XX



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

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

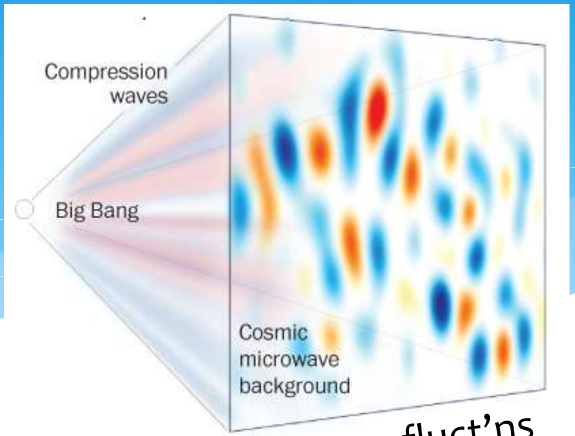
- scalar spectral index: $n_s \sim 0.96$
- tensor-to-scalar ratio: $r < 0.1$
- simplest $V \propto \phi^2$ model is almost excluded

some element of non-canonicality is perhaps needed

Gravitational Waves from Inflation

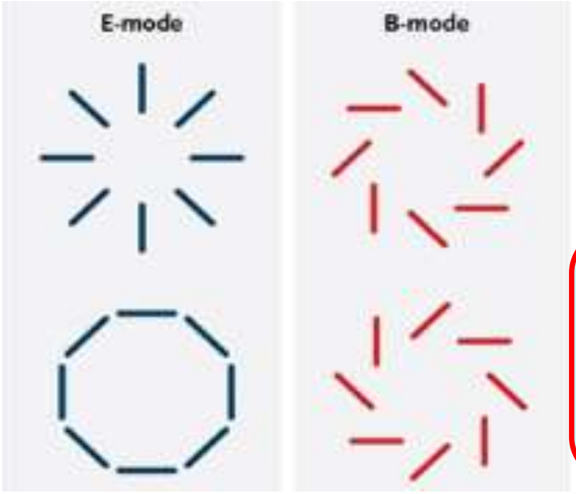
Cosmological GWs

- 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

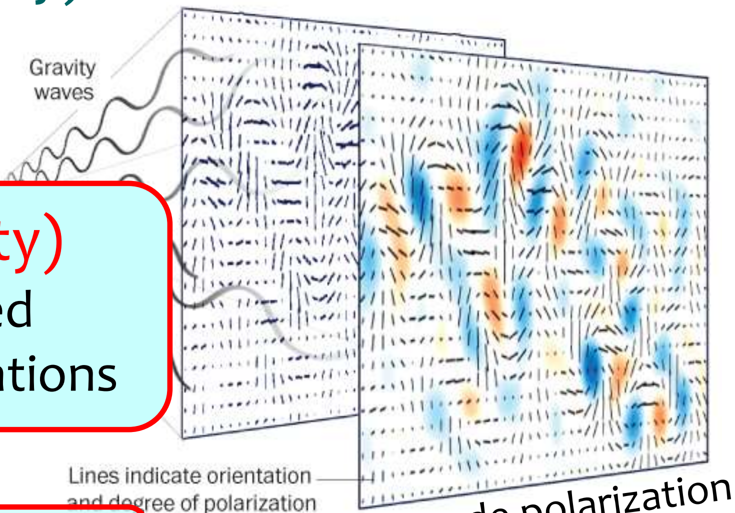


http://www.skyandtelescope.com/

E-mode (even parity)

↕

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



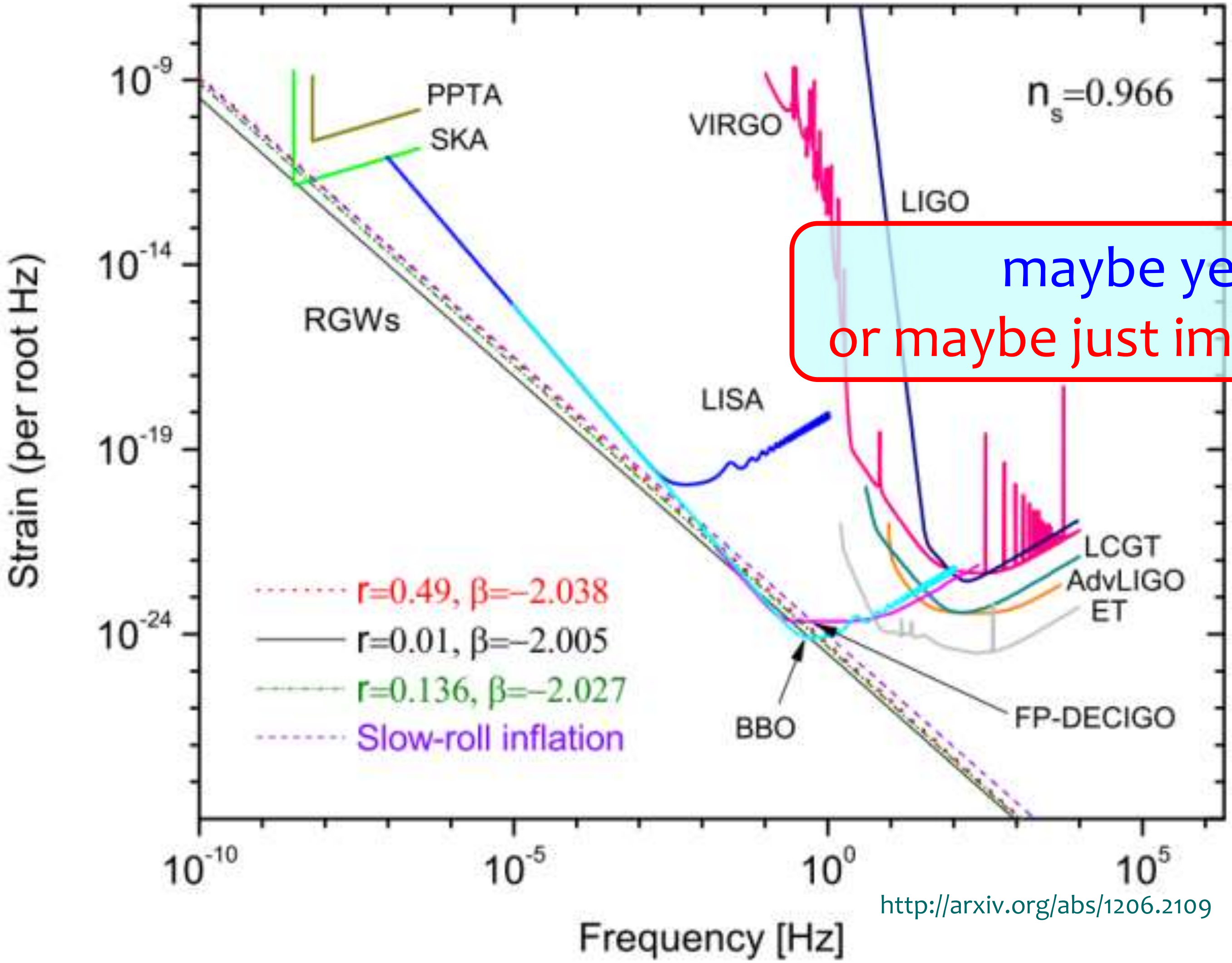
B-mode polarization
Harvard-Smithsonian Center for Astrophysics

CMB B-mode=cosmological GW detector

→ LiteBIRD,...

GWs from "Standard" Inflation

direct detection by GW observatories possible?



maybe yes…

or maybe just impossible…

http://arxiv.org/abs/1206.2109

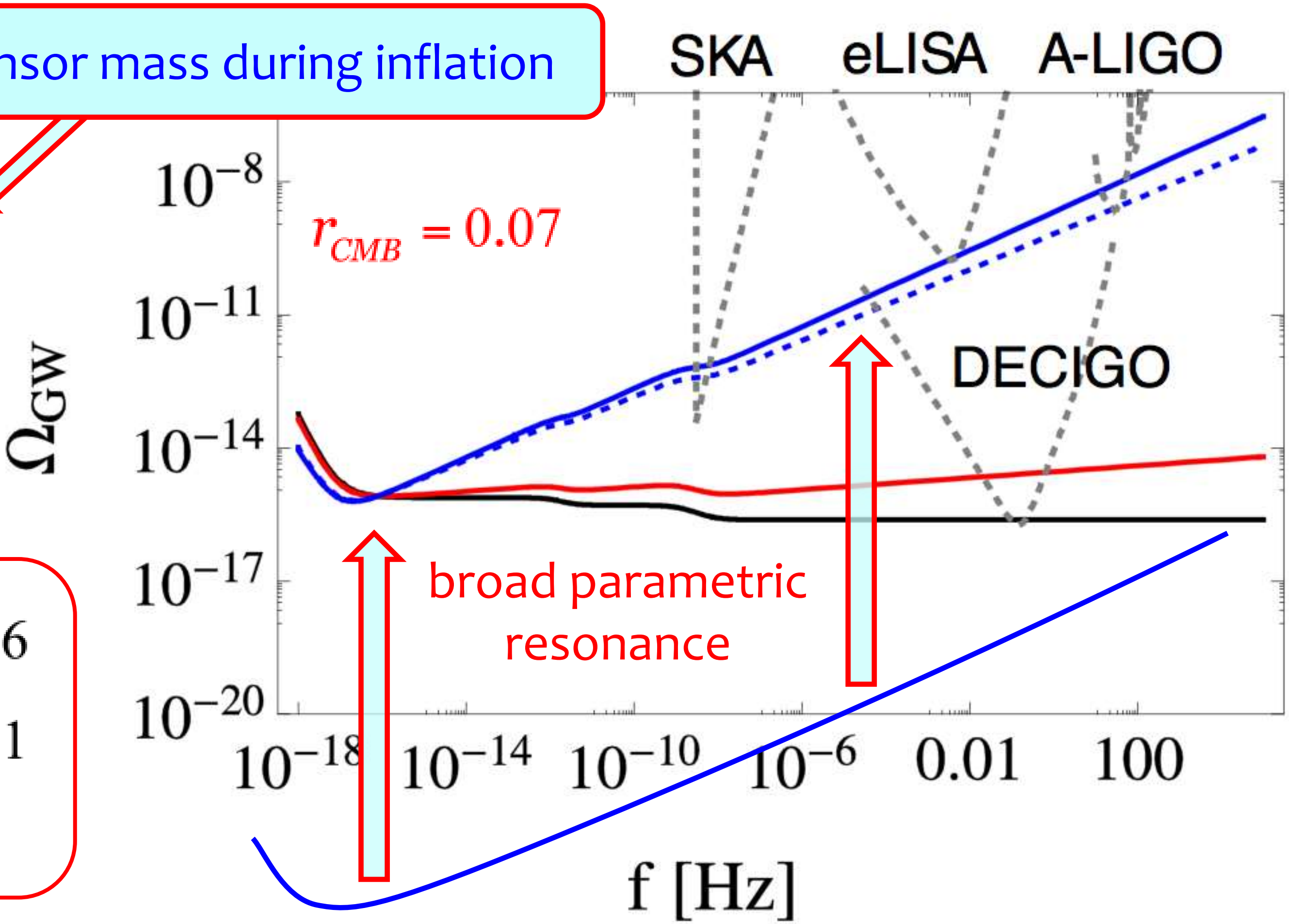
blue-tilted GW spectrum?

possible e.g. in massive gravity inflation model Lin & MS (2015)
[also in axion-SU(2) model Dimastrogiovanni et al . (2016)]

tensor mass during inflation

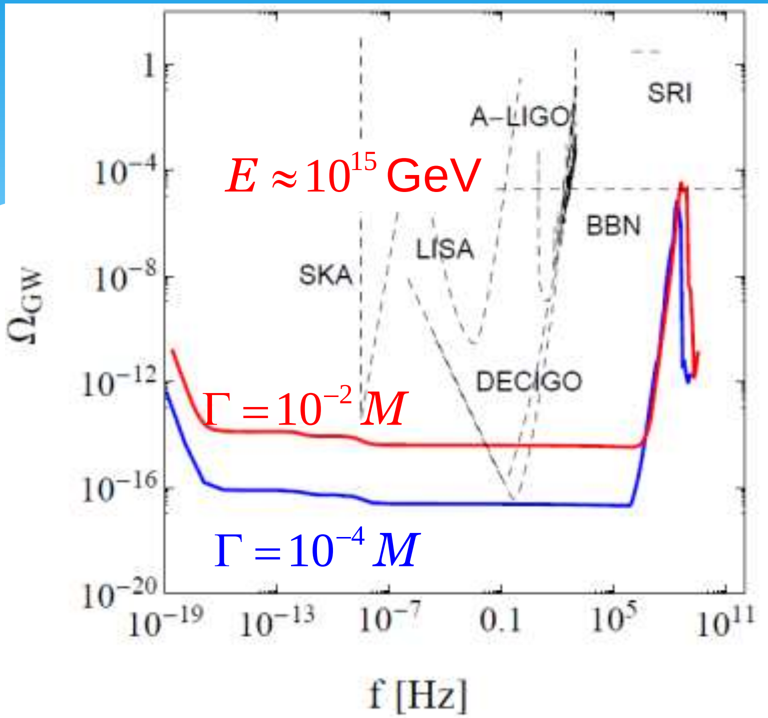
tensor (=GW) spectral index:

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



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

inflationary massive gravity: examples



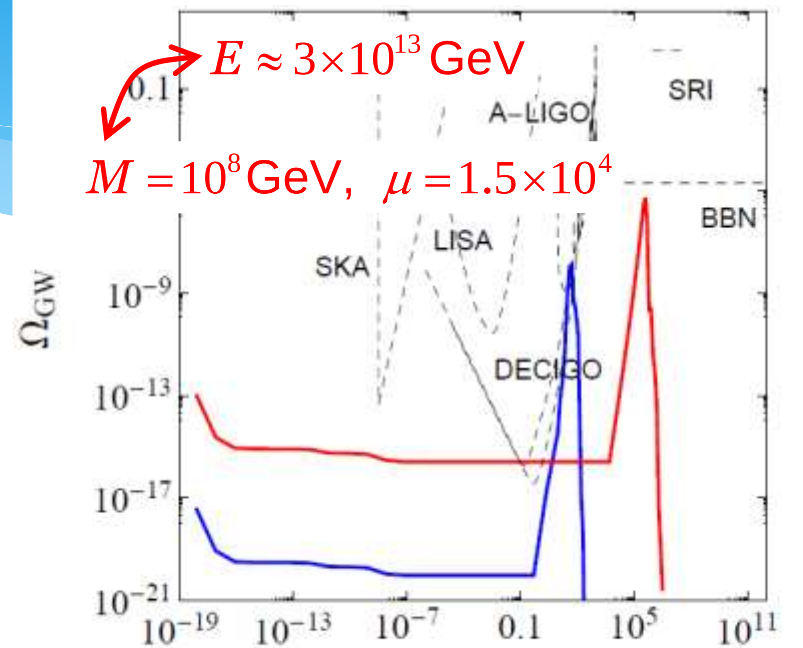
Starobinsky model

$$V = \frac{3}{4} M^2 M_{pl}^2 \left[1 - \exp\left(-\frac{\sqrt{6}\phi}{3M_{pl}} \right) \right]^2$$

with $m_g^2 = \lambda \phi^2 \exp[-2(\phi / M_{pl})^2]$

$\lambda = 4.8 \times 10^{-7}$

Kuroyanagi, Lin, MS & Tsujikawa '17



$M = 1$GeV, $\mu = 4.8 \times 10^4$ $E \approx 3 \times 10^9$ GeV

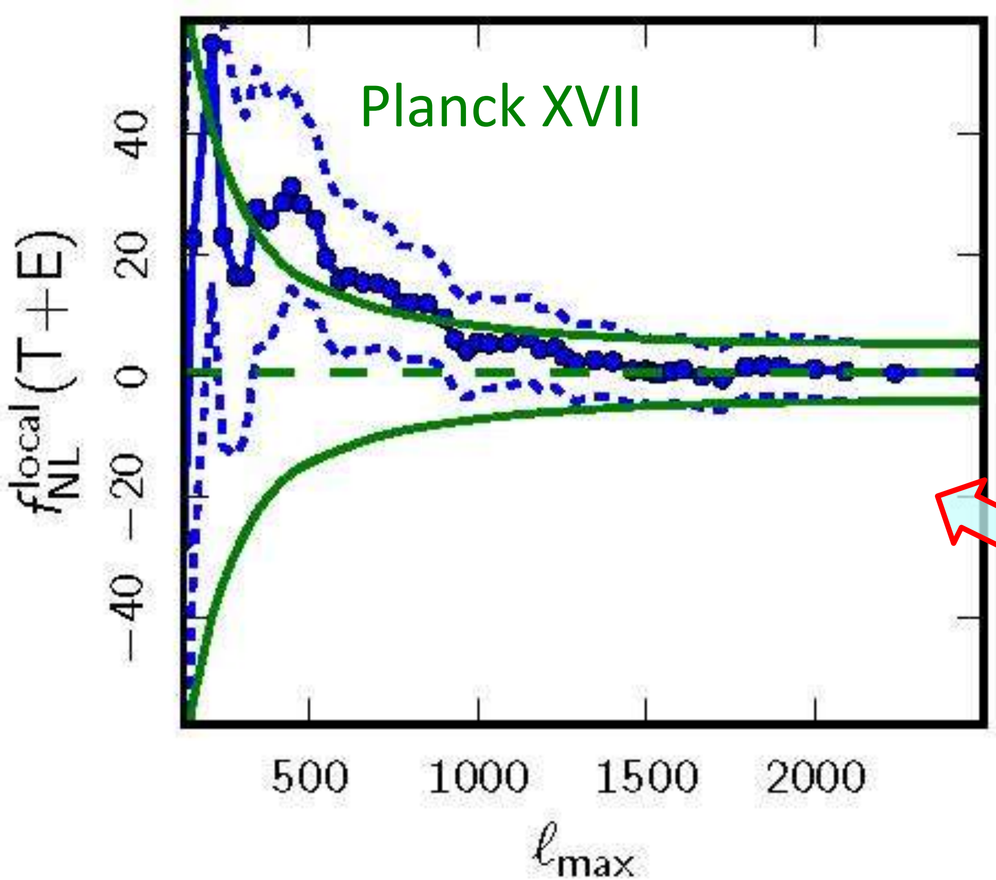
low-scale model $\left(\varepsilon_{\rm inf} \ll 10^{-4} \right)$

$$V = \frac{1}{2} M^2 \phi^2, \quad H_{\rm end} = \frac{2}{3} M, \quad \Gamma = 10^{-3} M$$

with $m_g^2 = \mu \frac{\dot{\phi}^2}{M_{pl}^2}$

BBN gives stringent constraints

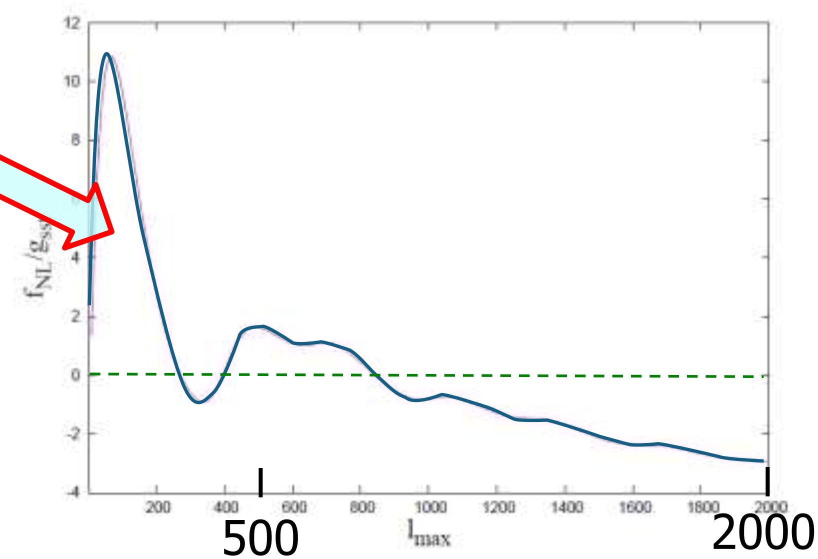
scale-dependent non-Gaussianity?



$f_{NL}^{\rm local} = 32 \pm 21$ for $\ell_{\max} \simeq 500$ WMAP 2010

$f_{NL}^{\rm local} = 0.8 \pm 5.0$ for $\ell_{\max} \simeq 2500$ Planck 2015

- Slightly above 1-σ deviation
- What if this is primordial?

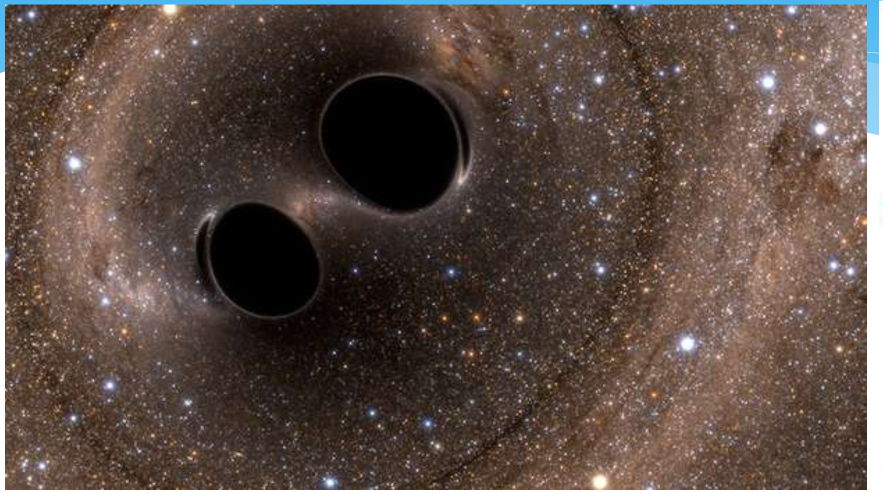


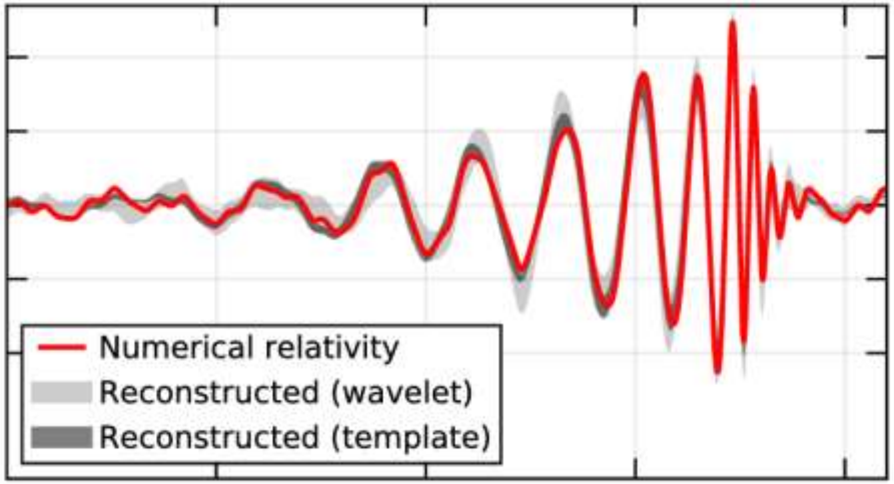
may be due to TSS coupling in a massive tensor theory

Domenech, Hiramatsu, Lin, MS, Shiraishi, Wang '16

Gravitational Wave Astronomy/Cosmology

The Dawn has arrived!





LIGO

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

2017 Nobel Prize!

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-Virgo BHs

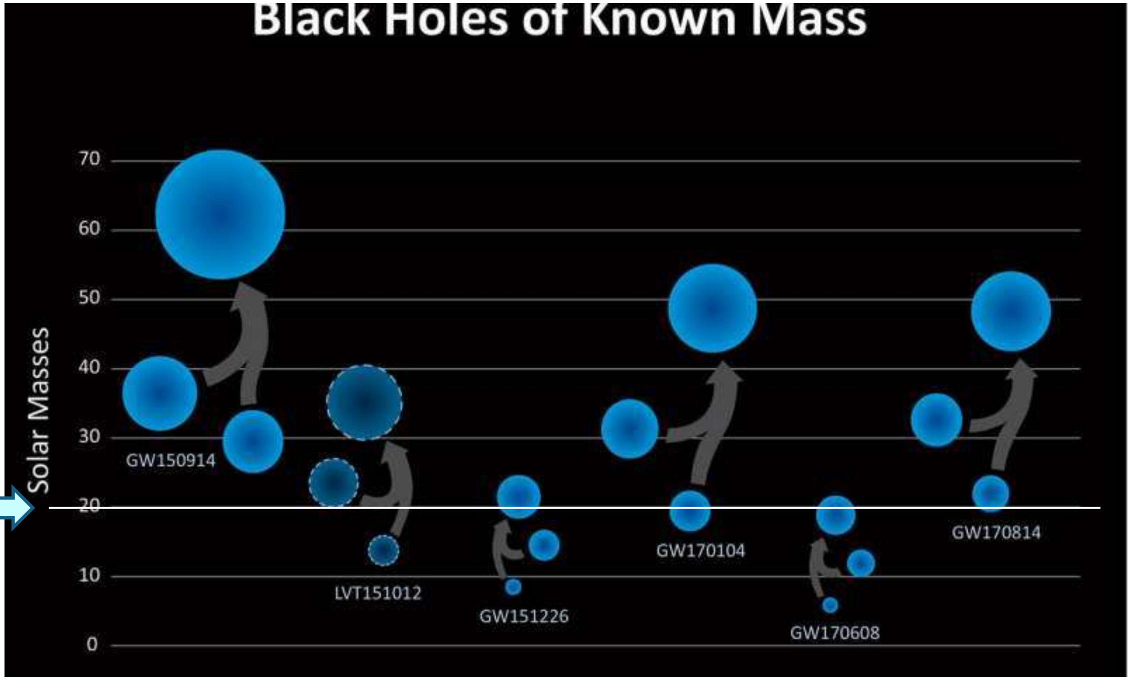
LIGO-Virgo has detected 5.5 BBH mergers so far.

Any implications ?

Gw150914,LVT151012
GW170104,GW170814

- Many of them seem to be unusually heavy!

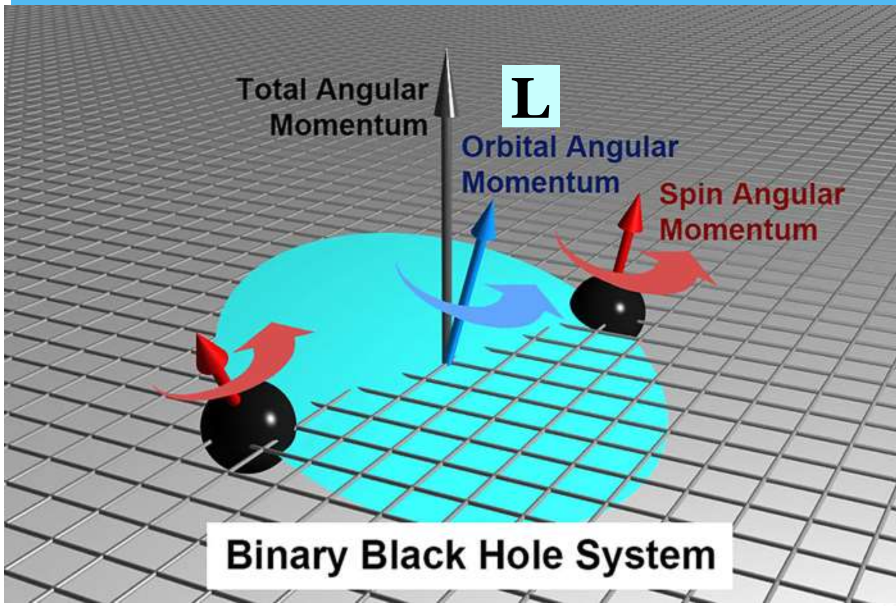
20 $M_{\odot}$



- Their spins seem to be unusually small!

LIGO BH spins

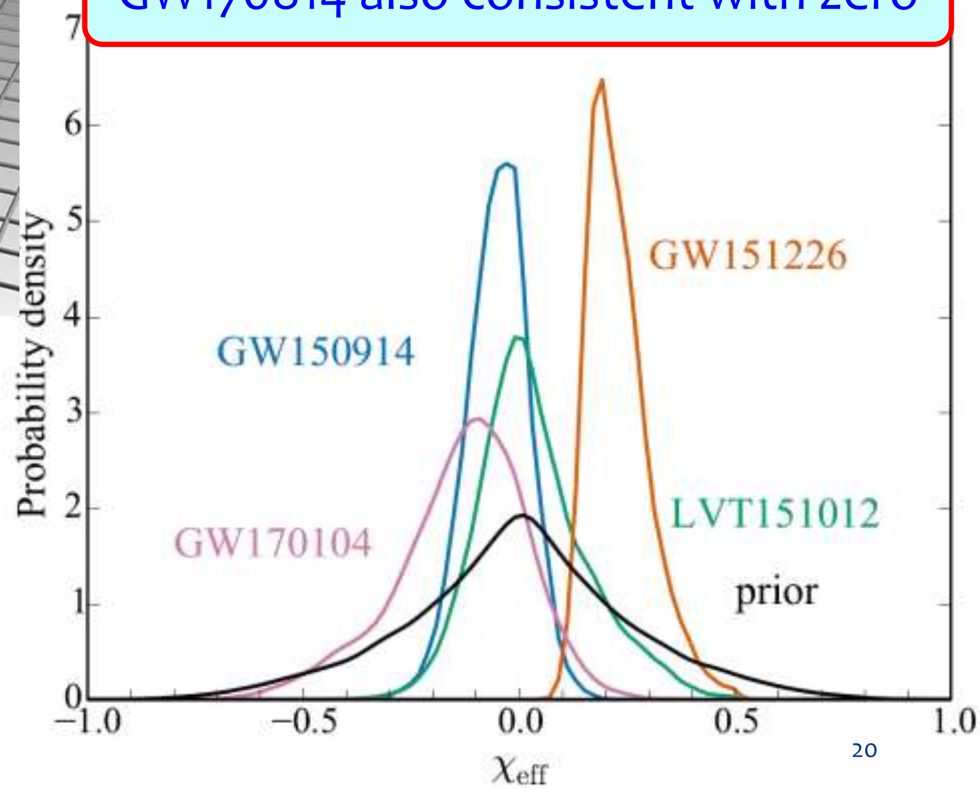
$$\chi_{\rm eff} = (m_1 \mathbf{s}_1 + m_2 \mathbf{s}_2) \cdot \mathbf{n}_L / (m_1 + m_2): \quad \mathbf{n}_L = \mathbf{L} / L$$



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

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

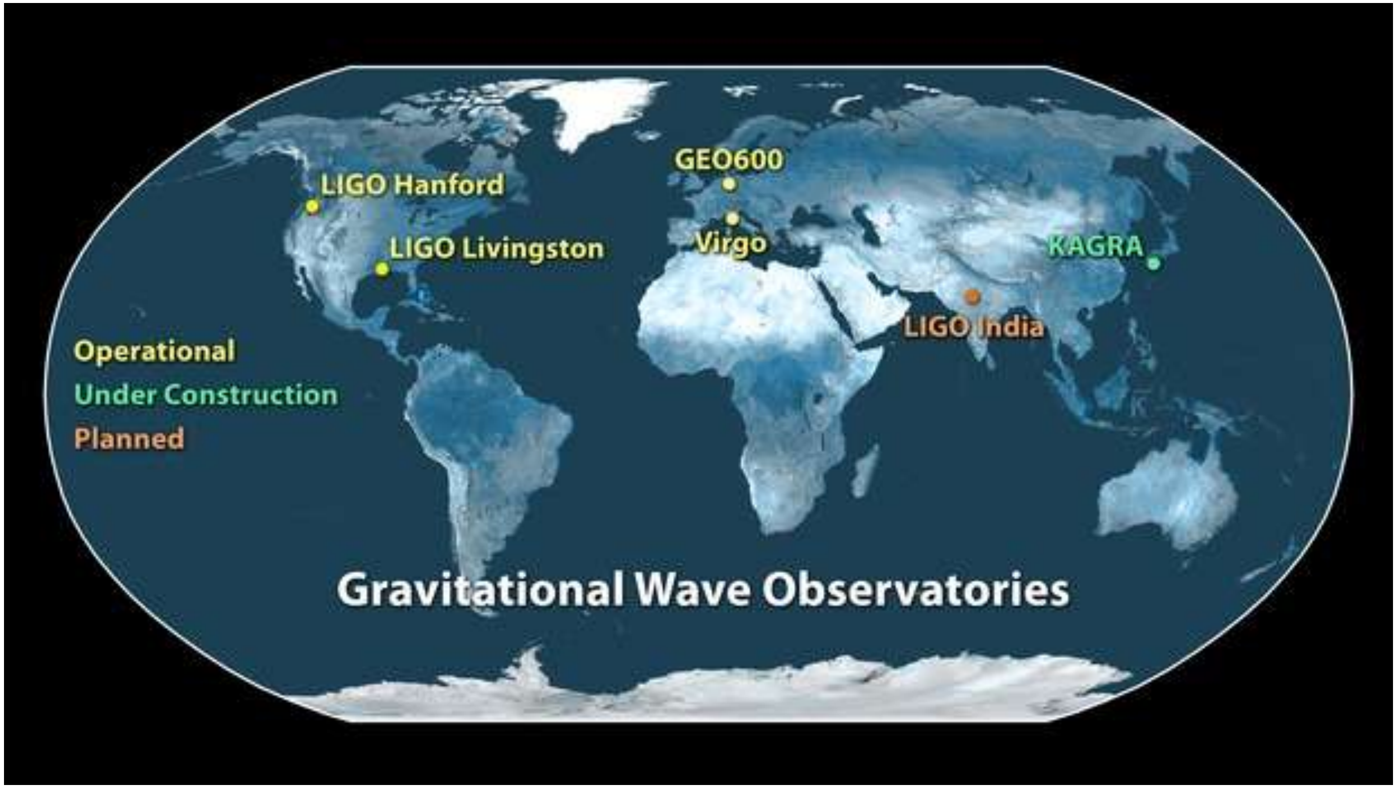
GW170814 also consistent with zero



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

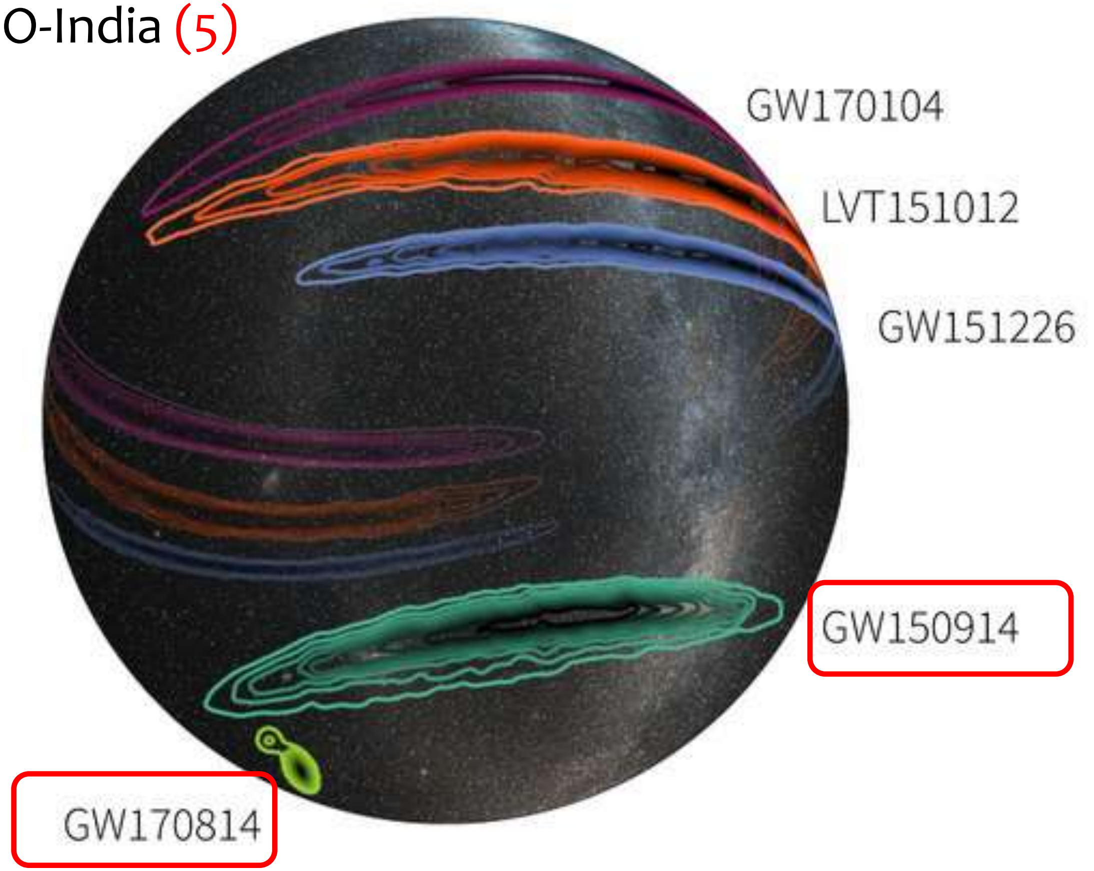
Future Network of GW Observatories

KAGRA will start operation by 2020-2021
(iKAGRA successful, bKAGRA is under way)
LIGO-India has been recently approved by Indian gov.



Huge advantage in angular resolution

- Impressive increase from LIGO alone (2) to LIGO+VIRGO (3)
- +KAGRA (4)
- +LIGO-India (5)



S/N=24

S/N=18.3 (LIGO+Virgo)

KAGRA

KAmioka GRAvitational wave detector

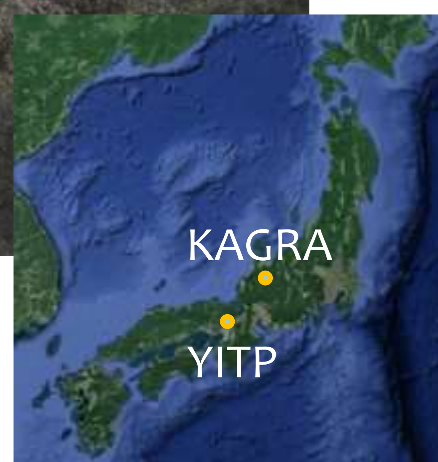
In Japanese it is pronounced as Kagura, which means "God Music" (神楽)

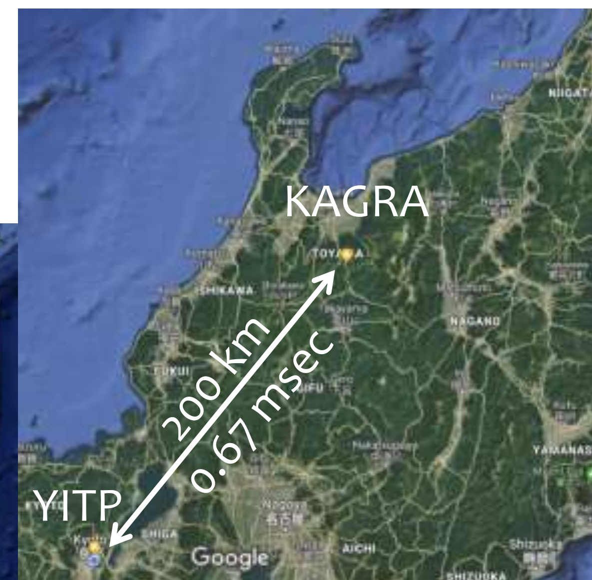
http://gwcenter.icrr.u-tokyo.ac.jp/en/

Previously called LCGT

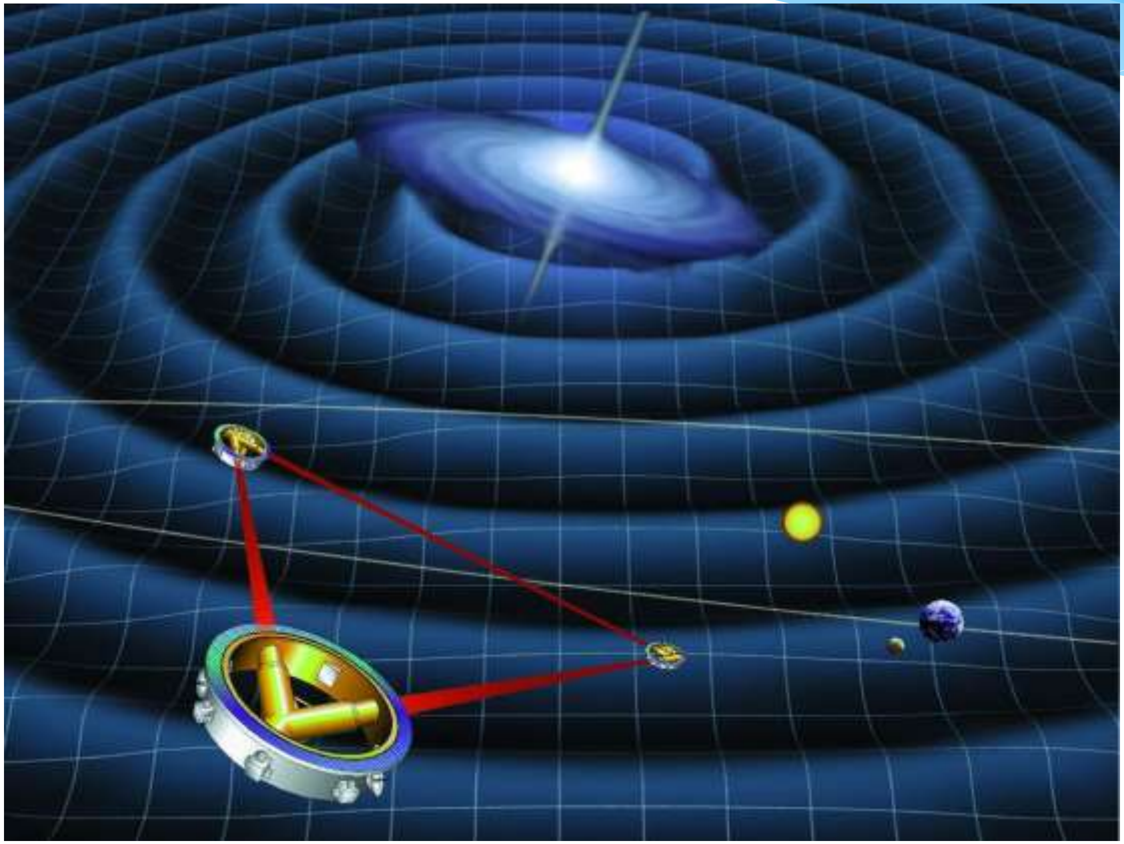
Large Cryogenic
Gravitational wave Telescope

Arm length 3km
Cooled to 20K





Space-based Future Projects



http://lisa.nasa.gov/

Arm Length

⇩

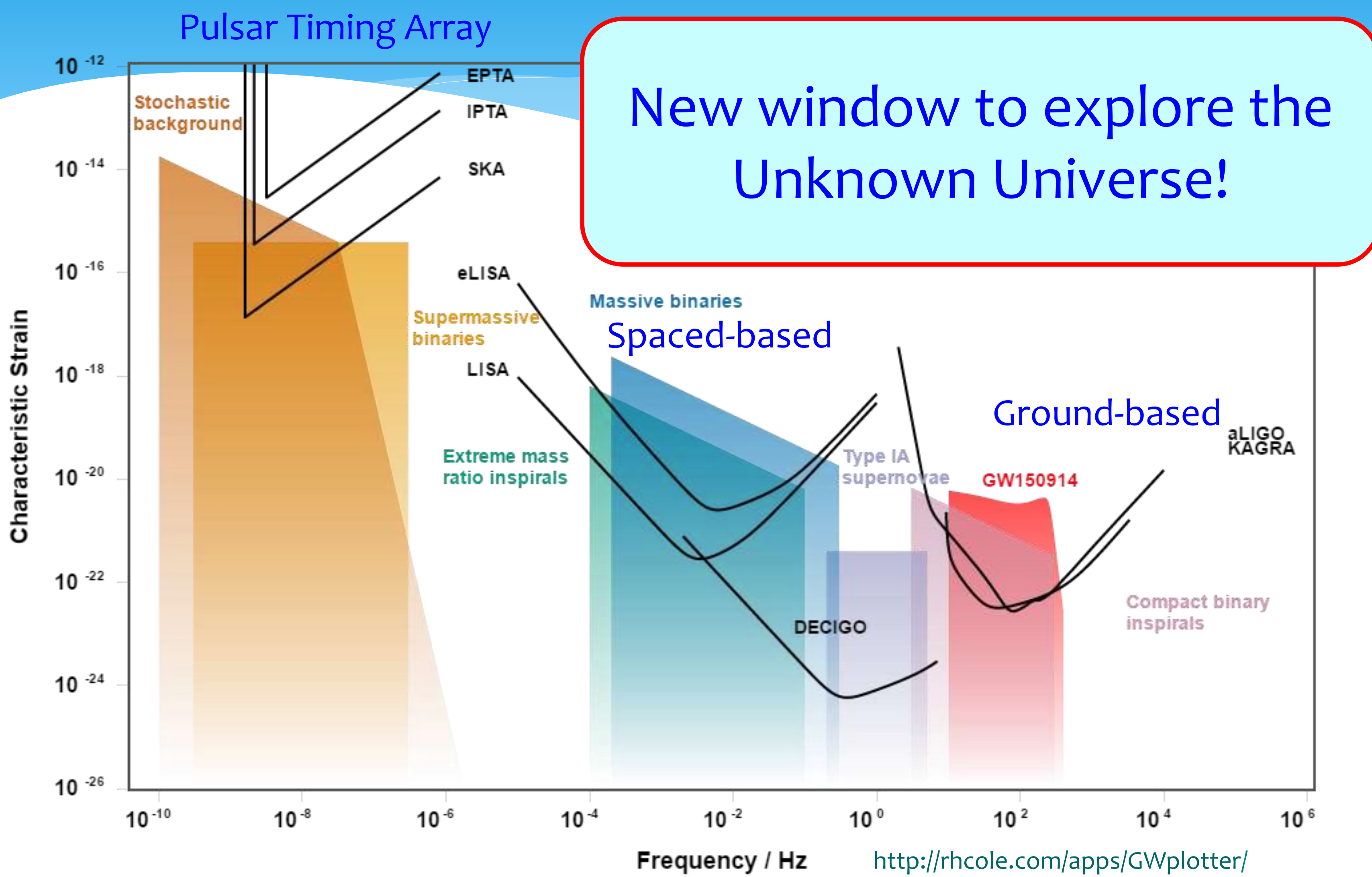
DECIGO: 1,000 km
launched by ~2030?
target freq: ~ 0.1 Hz

Deci-hertz Interferometer Gravitational wave Observatory

LISA: 2,500,000 km
launched by ~2034?
target freq: ~10^{-3}Hz

Laser Interferometer Space Antenna

Multi-freq GW Astronomy



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

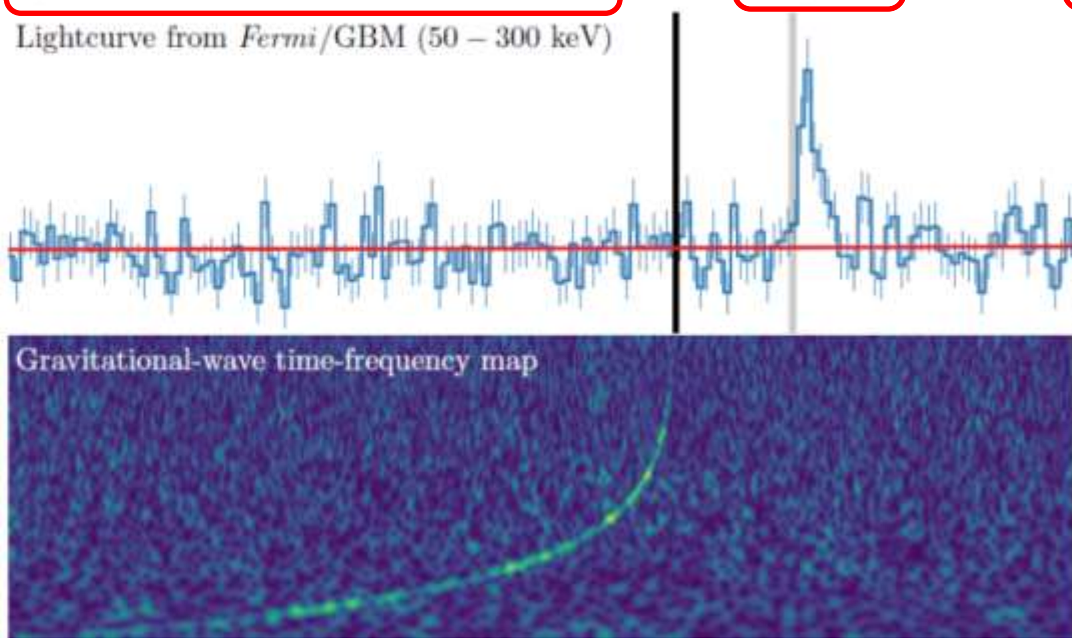
Binary Neutron Star merger found!

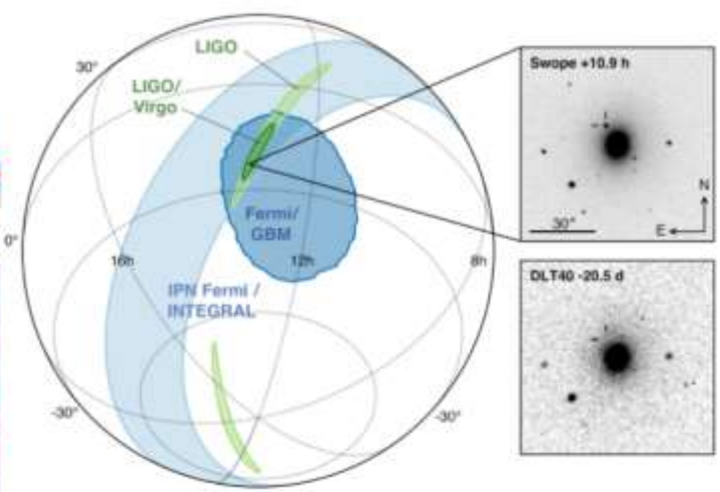
LIGO Scientific Collaboration

GW170817 / GRB170817A

Detections | News | About | LIGO science | Educational resources | Multimedia | For researchers | LIGO Lab site

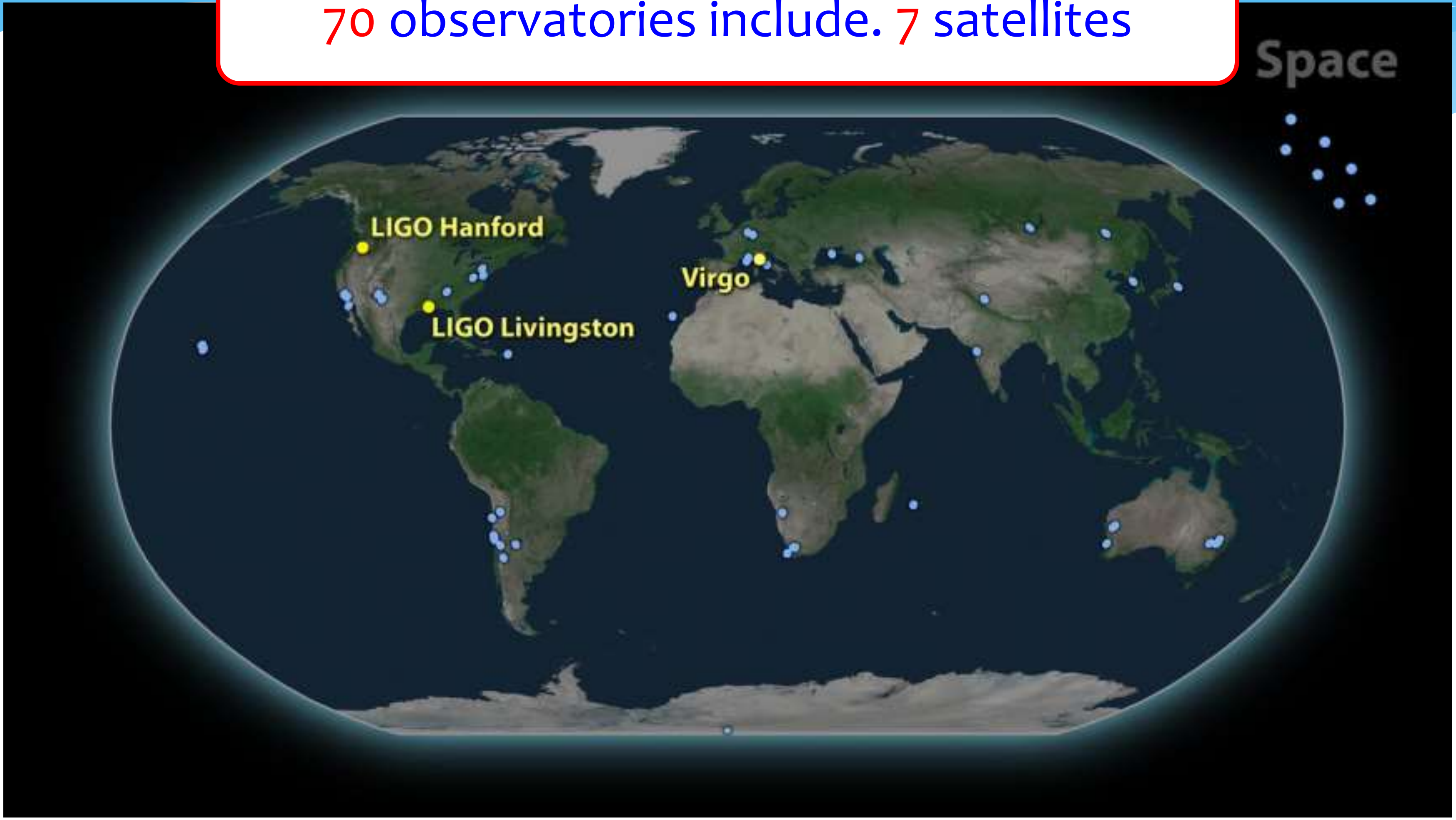
LIGO, Virgo, and partners make first detection of gravitational waves and light from colliding neutron stars





multi-messenger astronomy!

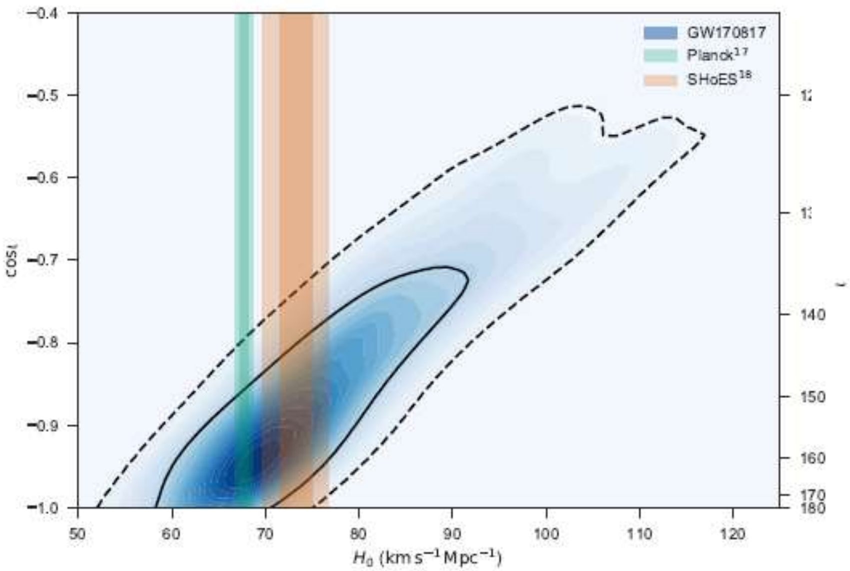
70 observatories include. 7 satellites

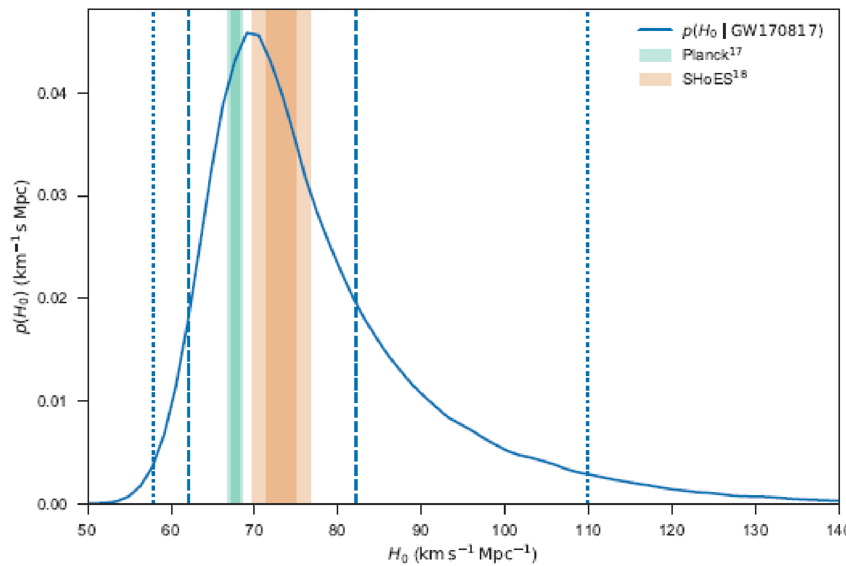


Cosmological Implication!

A GRAVITATIONAL-WAVE STANDARD SIREN MEASUREMENT OF THE HUBBLE CONSTANT

THE LIGO SCIENTIFIC COLLABORATION AND THE VIRGO COLLABORATION, THE 1M2H COLLAB
THE DARK ENERGY CAMERA GW-EM COLLABORATION AND THE DES COLLABORATION,
THE DLT40 COLLABORATION, THE LAS CUMBRES OBSERVATORY COLLABORATION,
THE VINROUGE COLLABORATION, THE MASTER COLLABORATION, et al.





$$H_0 = 70.0^{+12.0}_{-8.0}\ \mathrm{km\,s^{-1}\,Mpc^{-1}}.$$

from just a single event!

Primordial Black Holes

What are Primordial 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.

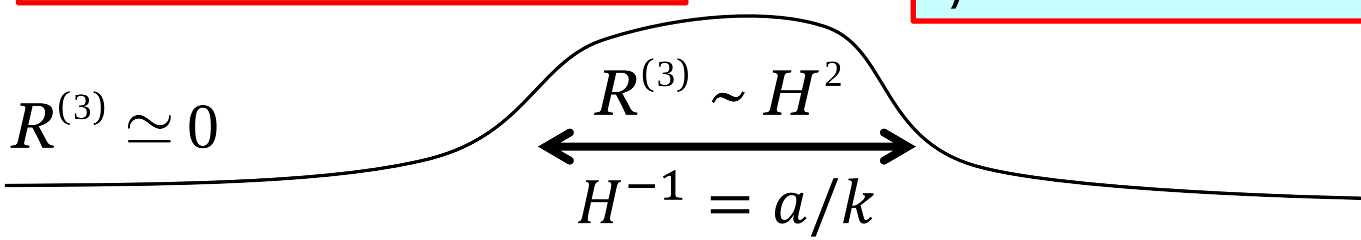
Curvature perturbation to PBH

- 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

examples

hybrid-type inflation

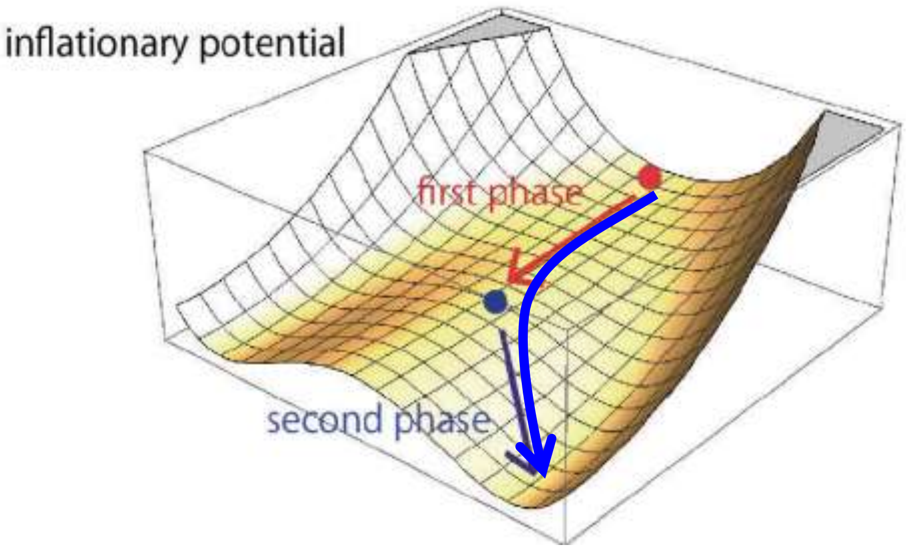
Garcia-Bellido, Linde & Wands '96, …

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

non-Gauss may become large

Abolhasani, Firouzjahi & MS '11,..

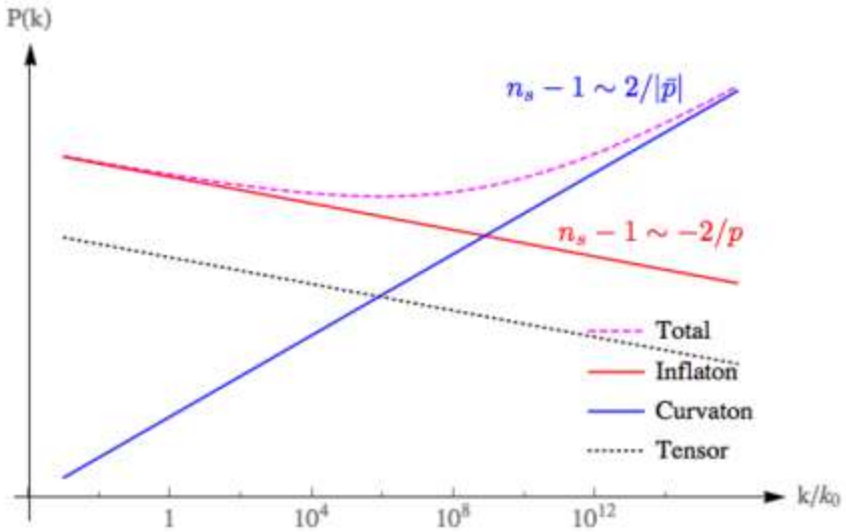
Pattison et al. 1707.00537



non-minimal curvaton

Domenech & MS '16

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



Constraints on PBHs

Can DM be PBHs?

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

LIGO BBHs may occupy ~10% of DM

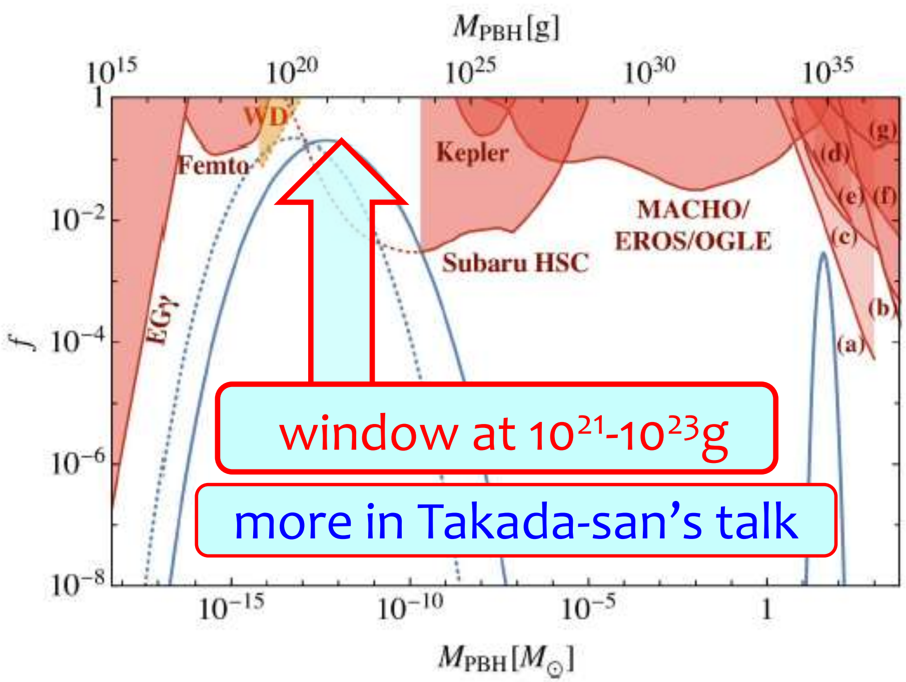
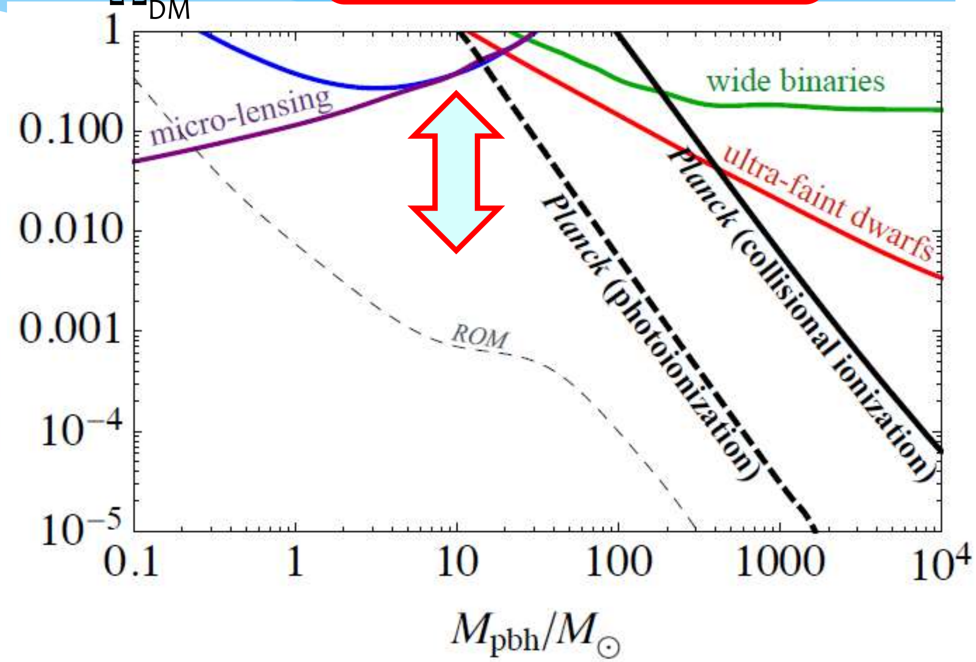


fig from Inomata et al., 1711.06129



Ali-Haimoud & Kamionkowski, 1612.05644

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

PBHs as CDM

S Pi, YL Zhang, QG Huang, M Sasaki, [1712.09896].

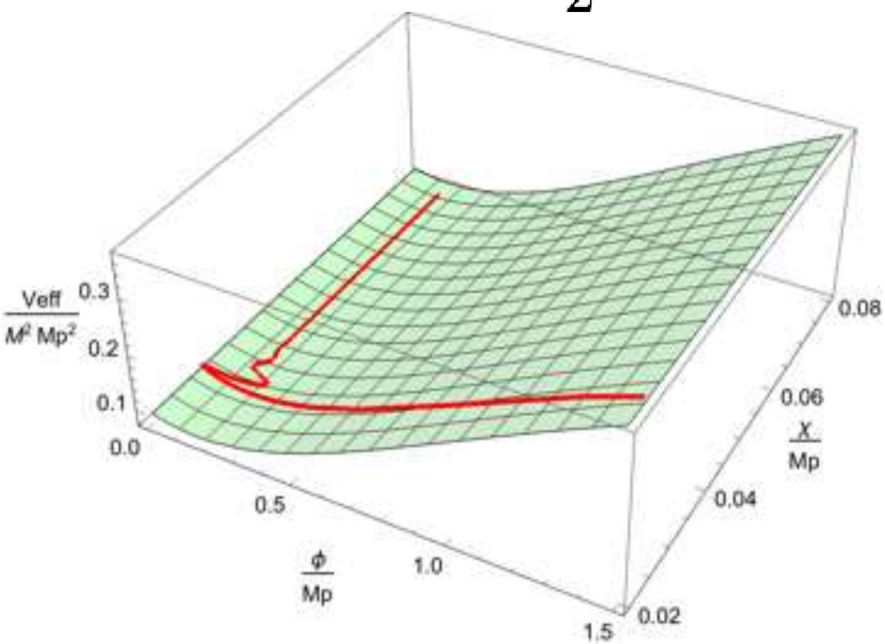
- Starobinsky R^2 gravity + non-minimally coupled scalar χ,:

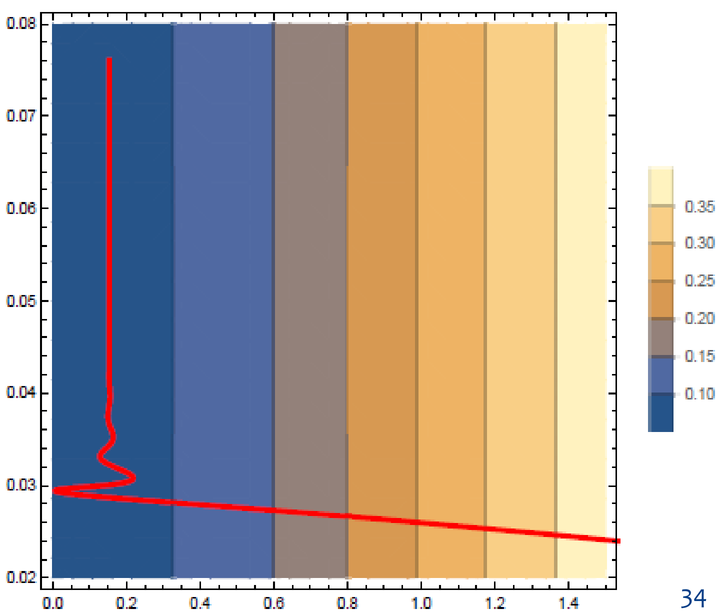
$$S_J = \int d^4x\sqrt{-g}\left\{\frac{M_{\rm Pl}^2}{2}\left(R+\frac{R^2}{6M^2}\right)-\frac{1}{2}g^{\mu\nu}\partial_\mu\chi\partial_\nu\chi-V(\chi)-\frac{1}{2}\xi R\chi^2\right\}.$$

- $V(\chi)$ in the small-field form:

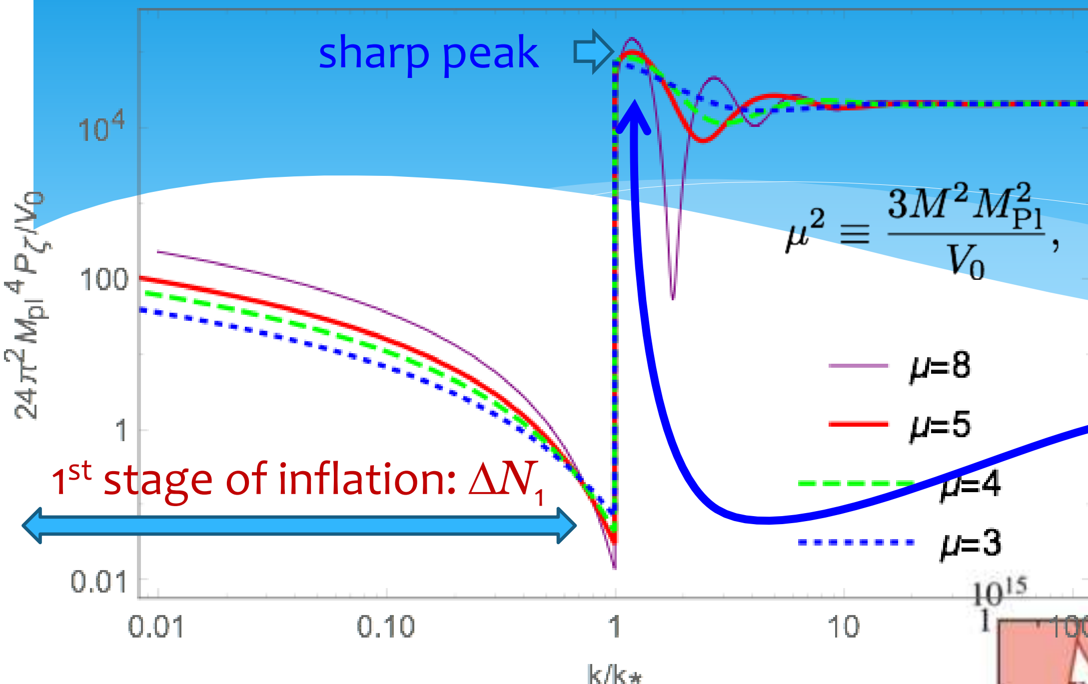
$$V(\chi)=V_0-\frac{1}{2}m^2\chi^2+\cdots$$

- ξ-term stabilizes initial condition





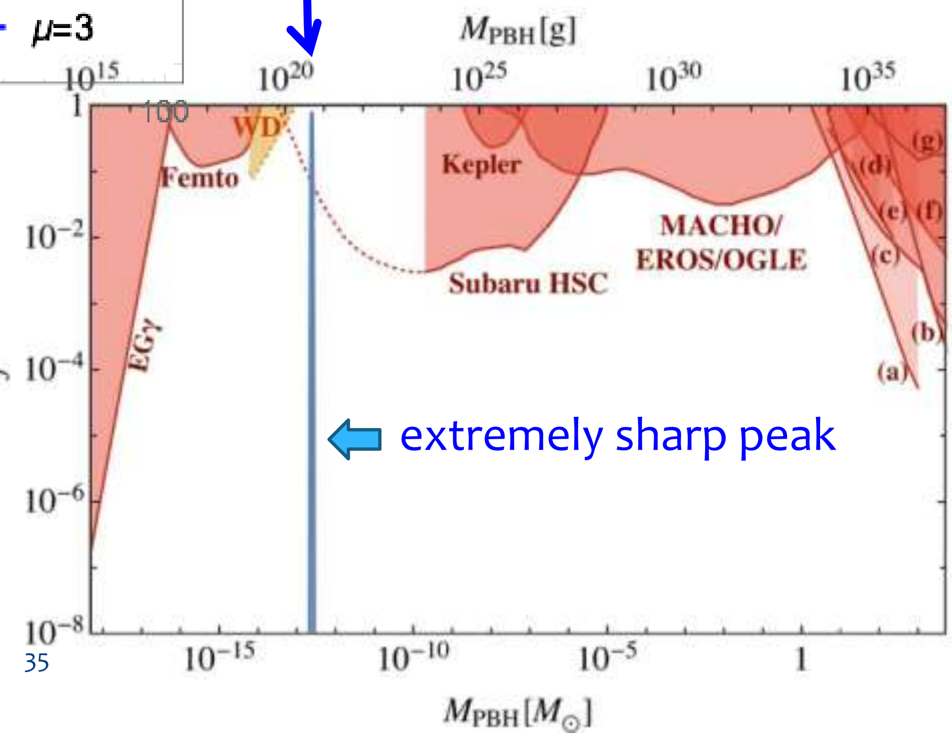
PBH as CDM from the transition stage



$$M_{PBH} = \gamma M_H \sim \frac{M_{Pl}^2}{H_*} e^{2(60-\Delta N_1)}$$

$H_* = k_* a_*$ during inflation

monocromatic PBH mass spectrum



critical amplitude

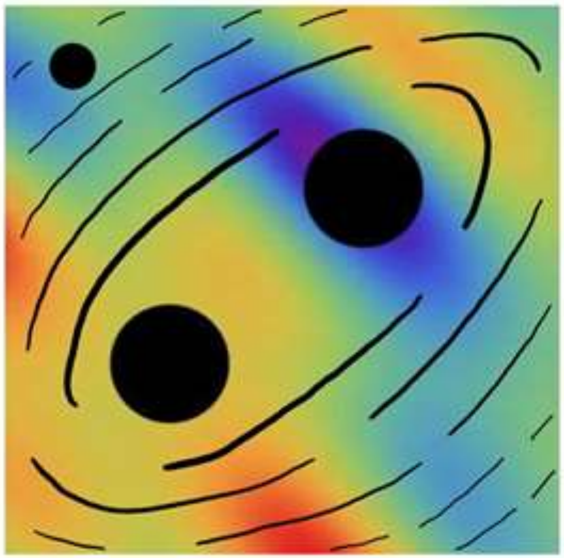
$$f(M_{PBH}) \propto \exp\left(-\frac{\delta_c}{\sqrt{2}\sigma(M_H)}\right)$$

$$\sigma(M_H) = \sqrt{\mathcal{P}(k_*)}$$

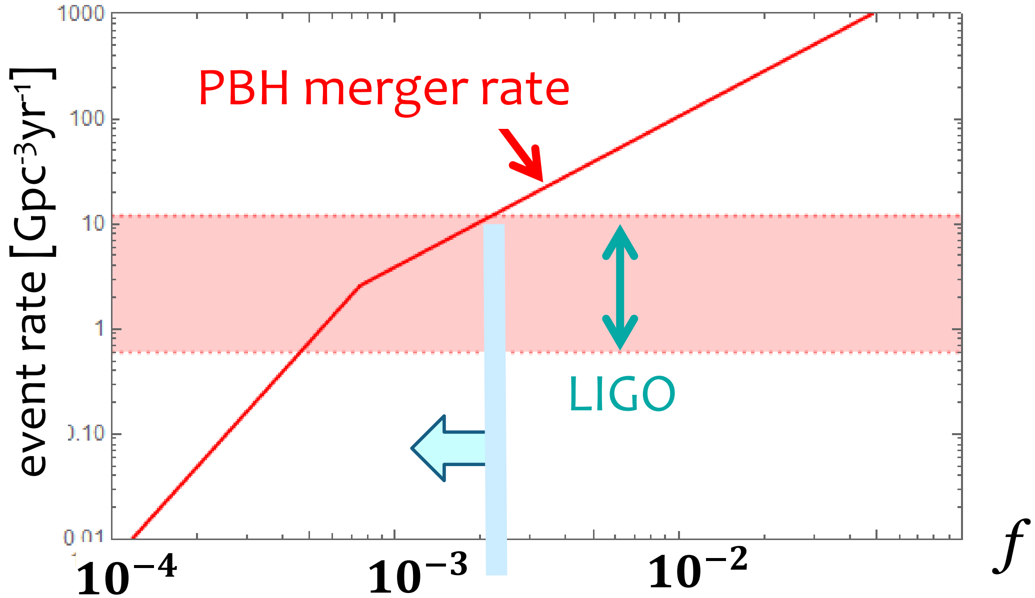
LIGO BHs = PBHs?

MS, Suyama, Tanaka & Yokoyama '16

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



3-body interaction leads to formation of BH binaries

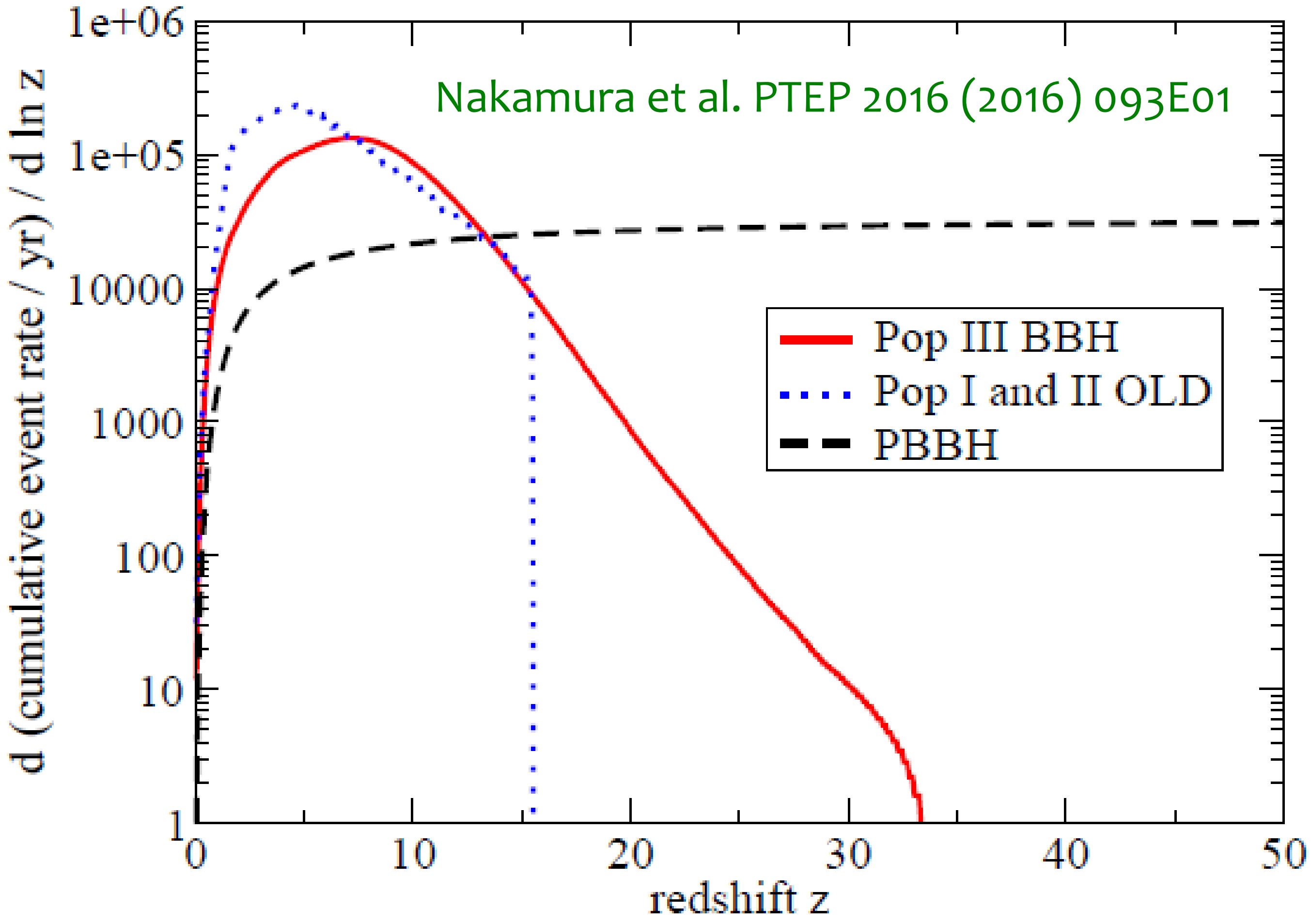


f = fraction of PBH in dark matter

tightest constraint at $M \sim 10 M_{\odot}$

(cf. Ali-Haïmoud et al., 1709.06576)

testing PBH hypothesis



testing PBH hypothesis 2

Kocsis, Suyama, Tanaka, Yokoyama, arXiv:1709.09007

BBH Merger Rate at time *t*:

mass function

$$\mathcal{R}(m_1,m_2,t) = \frac{n_{\rm BH}}{2} f(m_1) f(m_2) P_{\rm intr}(m_1,m_2,t)$$

intrinsic probability

$$P_{\rm intr}(m_1,m_2,t) \propto g(m_1)g(m_2)m_t^{\alpha} : \quad m_t = m_1 + m_2$$

$$\Leftrightarrow \quad \alpha(m_1,m_2,t) \equiv -m_t^{\,2} \frac{\partial^2}{\partial m_1 \partial m_2} \ln \mathcal{R}(m_1,m_2,t)$$

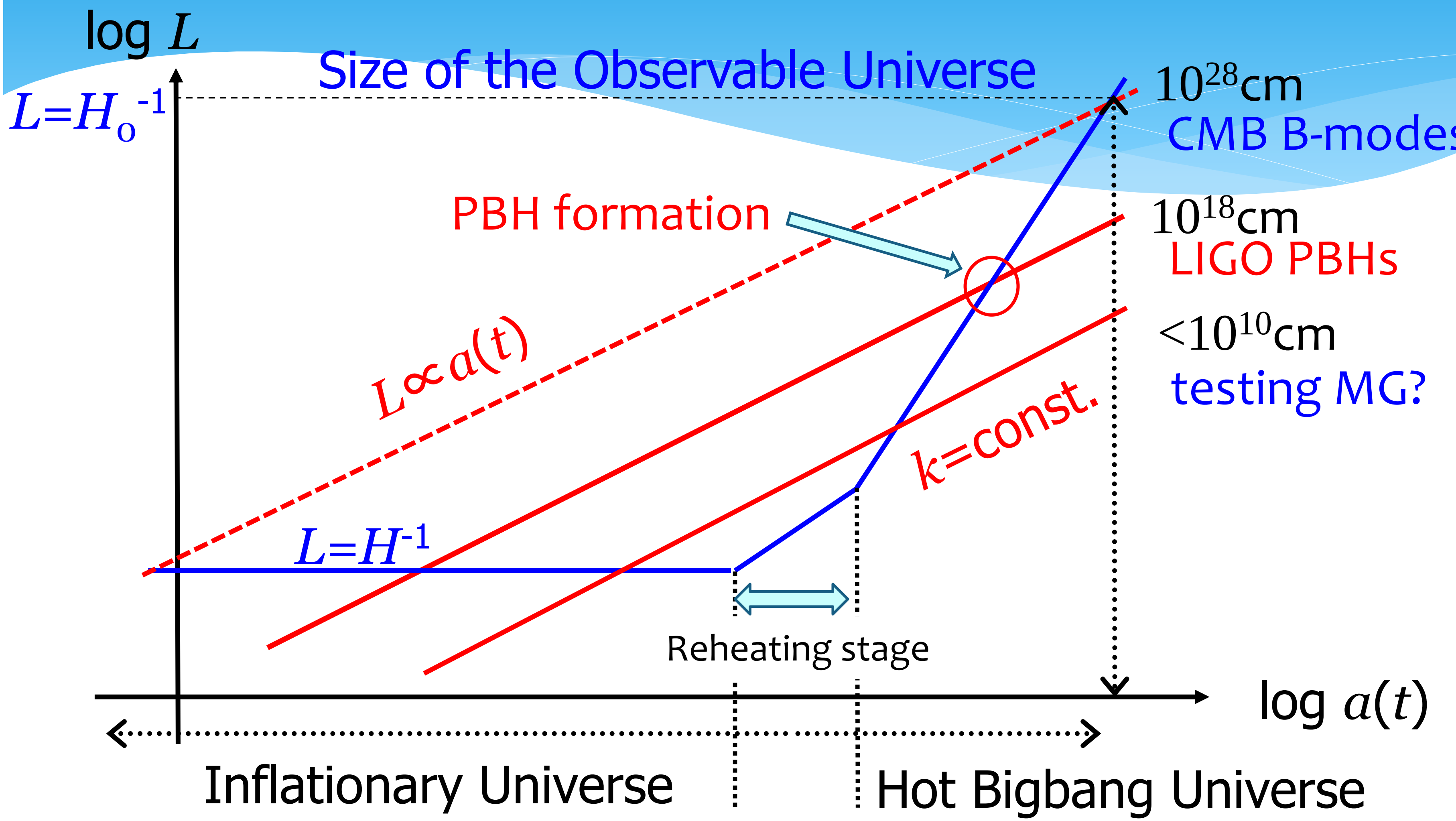
- PBH binary scenario $\frac{36}{37} < \alpha < \frac{22}{21}$
- Dynamical formation in dense stellar systems $\alpha \approx 4$

$\Updownarrow$

clearly distinguishable!

O'Leary et al (2016)

testing inflation by GW cosmology



Summary

* Inflation has become the standard model of the Universe

  further tests are needed to confirm inflation.

* Cosmological GWs are the key to confirmation of inflation

* LIGO-Virgo marked the 1st milestone in GW astronomy

  The dawn has arrived!

CDM may be PBHs!

observational test?

* LIGO BHs may be primordial

  advanced GW detectors will prove/disprove the scenario.

* Multi-band GW astronomy/cosmology has begun!

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

So live long and prosper !

from ***STAR TREK***