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KAVLI INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

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YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

Inflation, Primordial Black holes and Gravitational Waves

-- Dawn of Gravitational Wave Astronomy --

Misao Sasaki

Yukawa Institute for Theoretical Physics, Kyoto University

IPMU colloquium
24 January, 2018

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 $t\sim10^{-36}$ 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)

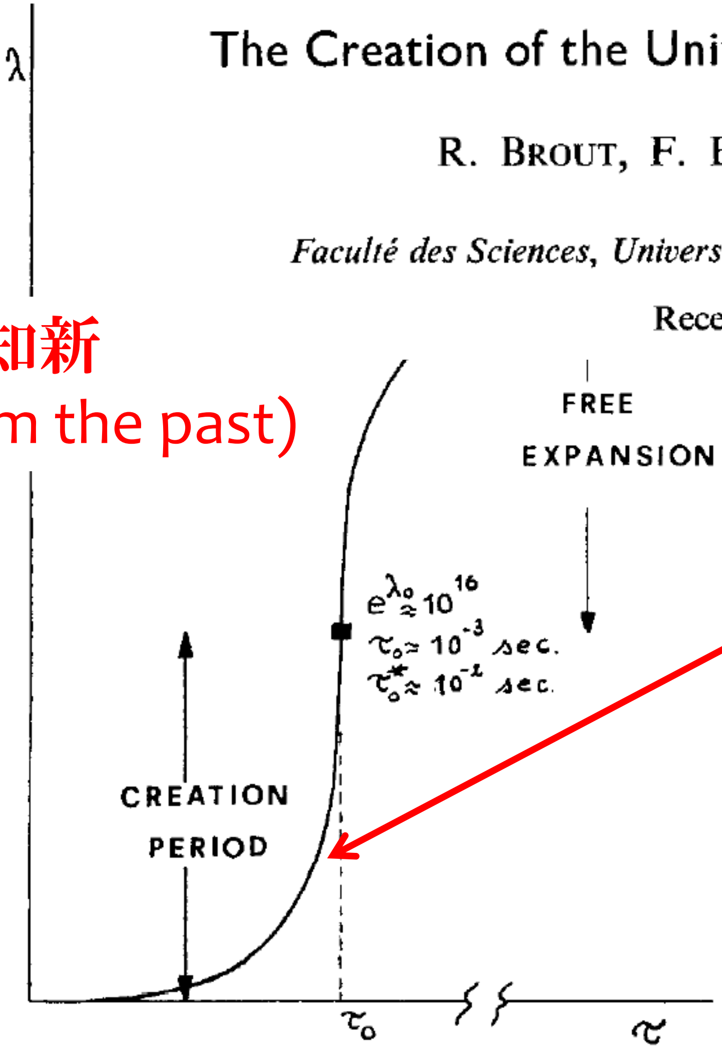


FIG. 1. λ as a function of kinematical time τ for $\delta = 0$. Time scales are calculated for $m = 1$ GeV.

$$ds^2 = -dt^2 + a^2(t)\,dH_{(3)}^2;$$

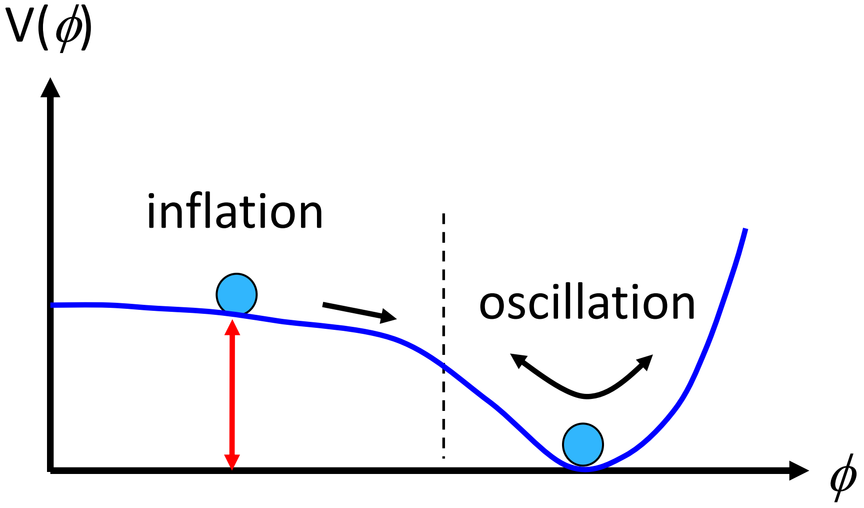
$$a(t) \simeq H^{-1} \sinh Ht$$

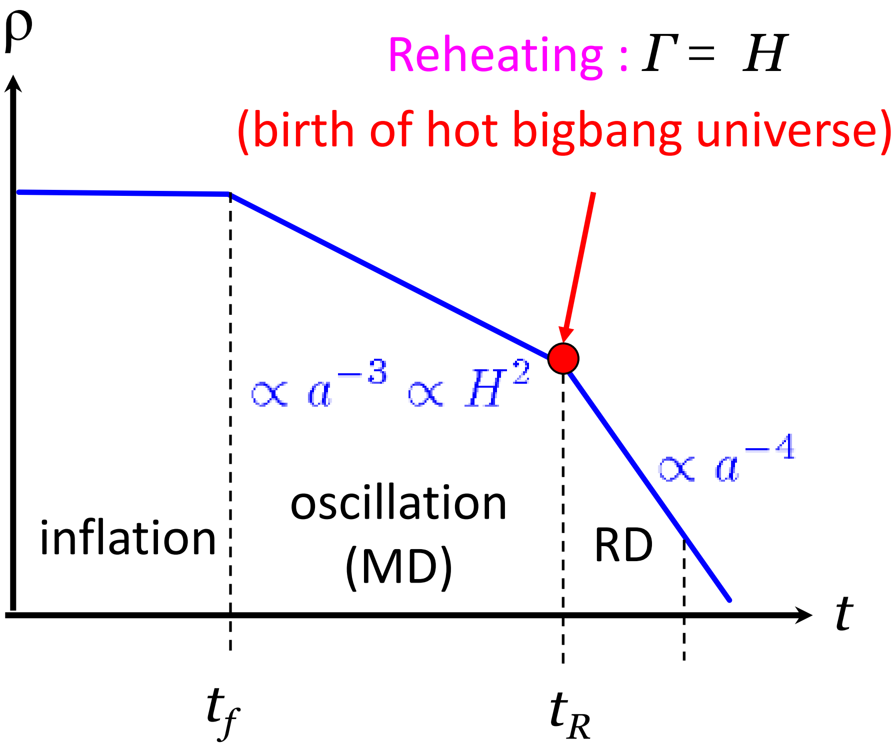
Creation of
Open Universe!

Now in the context of
String Landscape

From inflation to bigbang

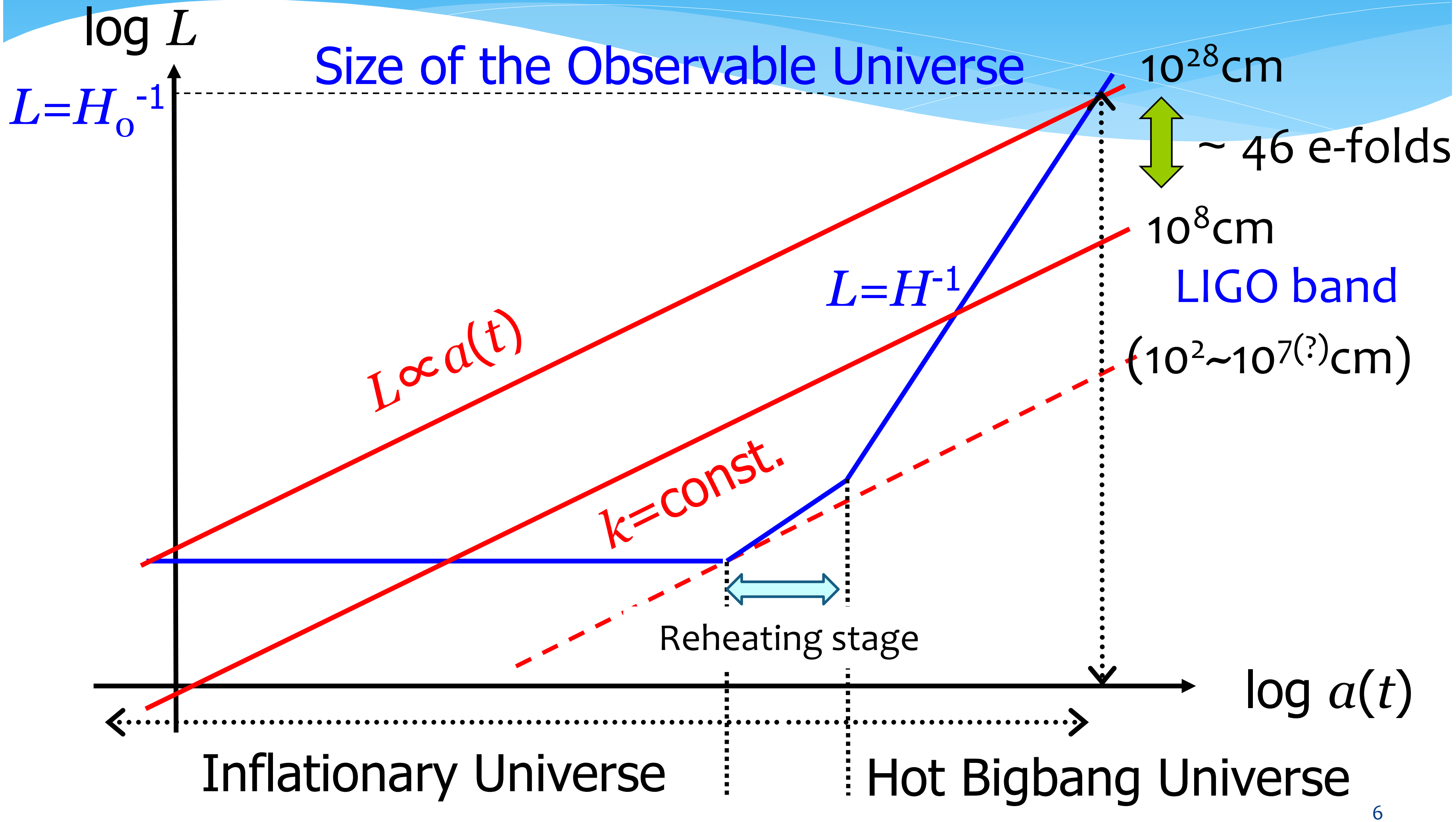
After inflation, vacuum energy is converted to thermal energy (called "re"heating) and hot Bigbang Universe is realized.





length scales of the inflationary universe

⟺ targets for multi-frequency GW astronomy

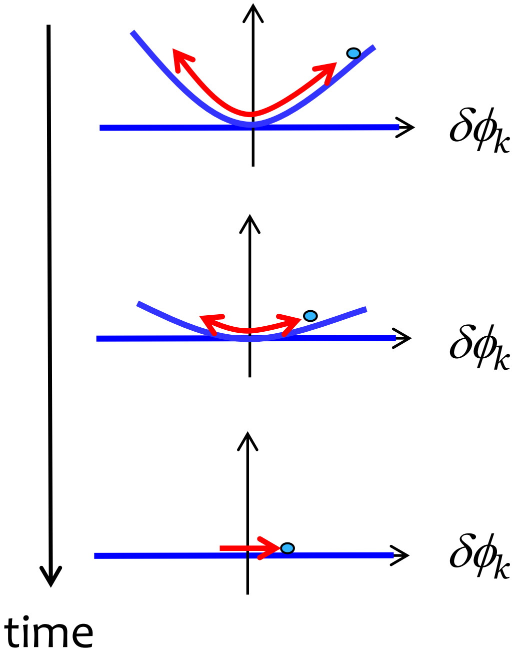


Quantum fluctuations during inflation

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

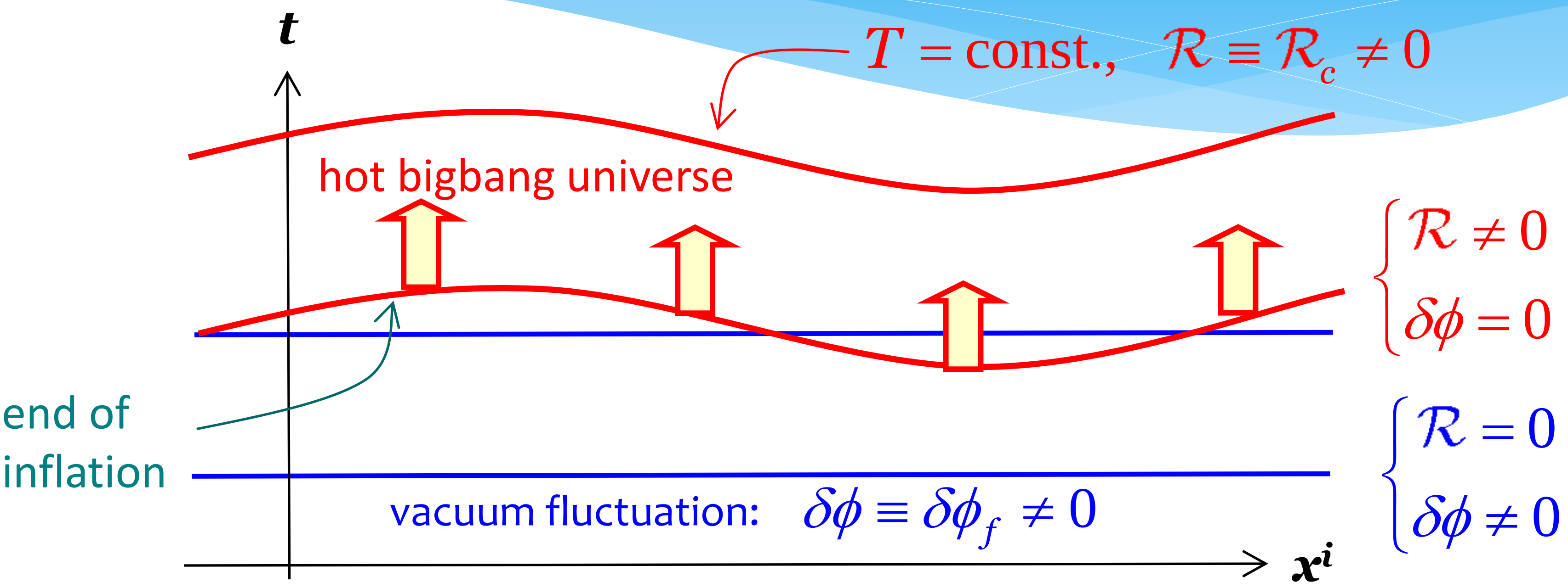
$$\delta\phi_k \to \text{const.}$$

… 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.



t

$T = \text{const.}, \quad \mathcal{R} \equiv \mathcal{R}_c \neq 0$

hot bigbang universe

$\begin{cases} \mathcal{R} \neq 0 \\ \delta\phi = 0 \end{cases}$

end of inflation

$\begin{cases} \mathcal{R} = 0 \\ \delta\phi \neq 0 \end{cases}$

vacuum fluctuation: $\delta\phi \equiv \delta\phi_f \neq 0$

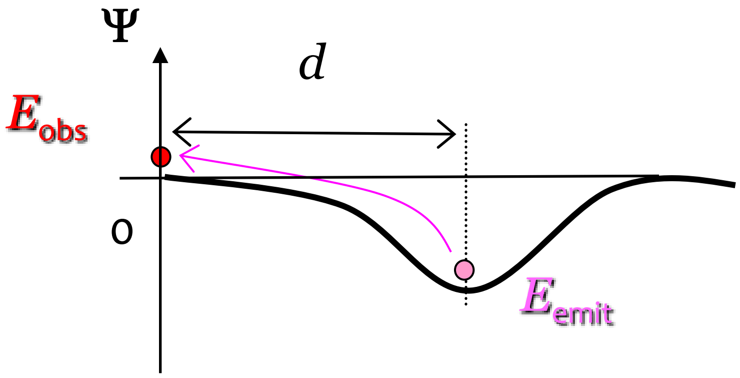
x^i

- 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,

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

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

c=1 units

- In an expanding universe, this is modified to be

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

Sachs-Wolfe effect

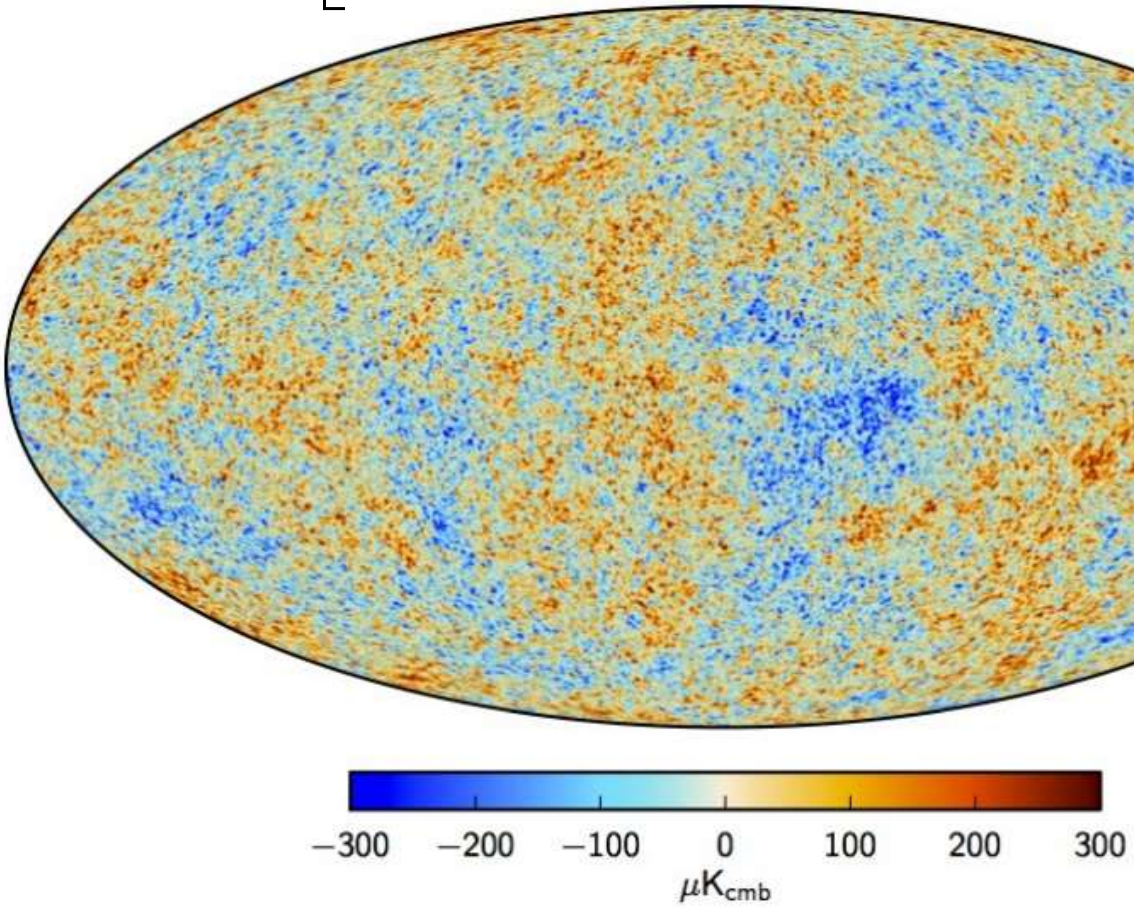
- There is also the standard Doppler effect:

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

Planck CMB map

Planck 2013

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



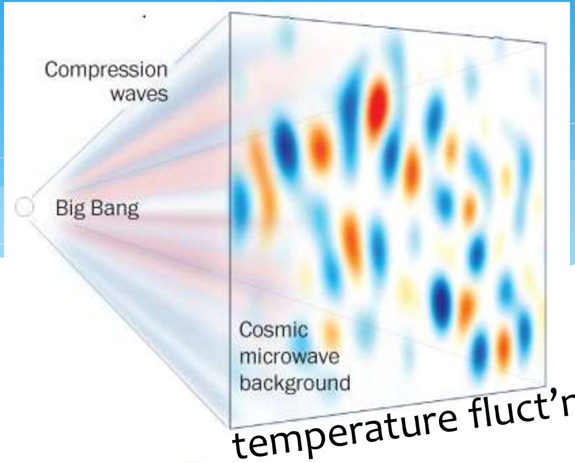
$T_0 = 2.73K$

Gravitational Waves from Inflation

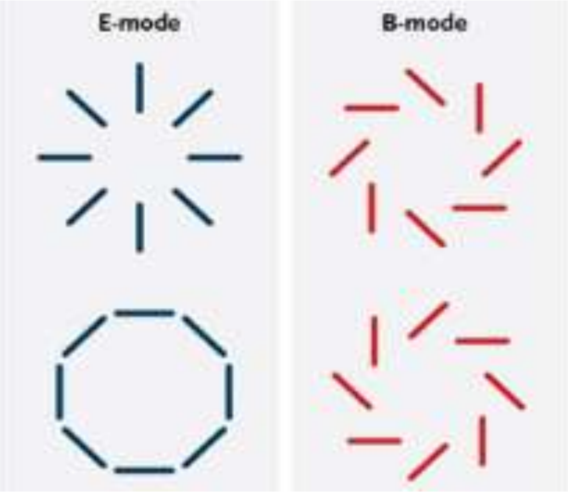
Cosmological GWs

- 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

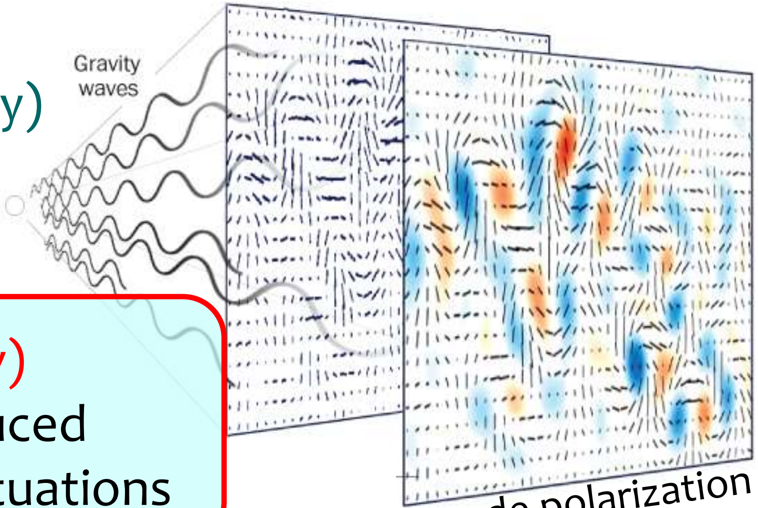


http://www.skyandtelescope.com/

E-mode (even parity)

⇕

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



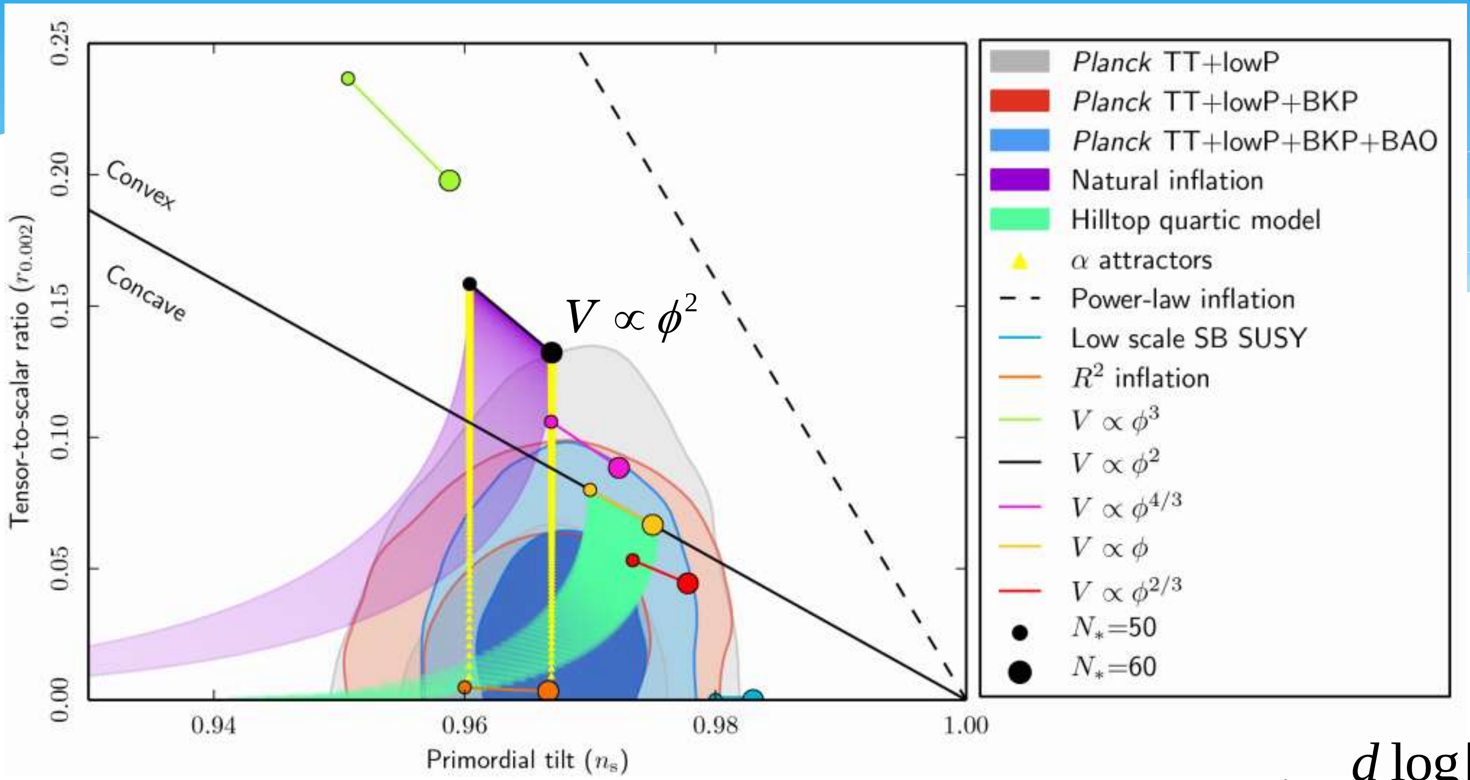
B-mode polarization

Source: Harvard-Smithsonian Center for Astrophysics

CMB B-mode=cosmological GW detector

Planck constraints on inflation

Planck 2015 XX



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

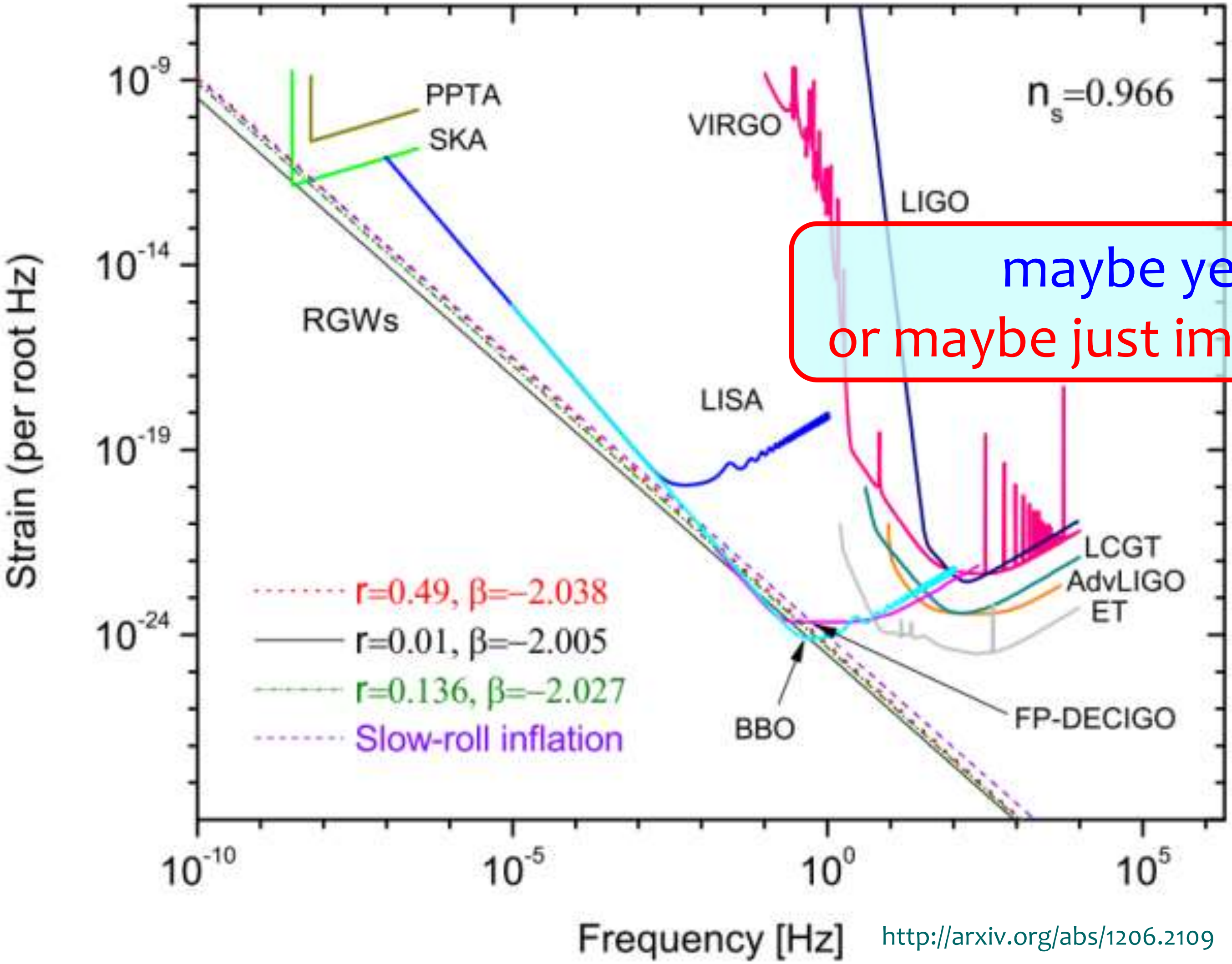
$$r \equiv \frac{P_T(k)}{P_S(k)}$$

- 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 needed

GWs from "Standard" Inflation

could direct detection by GW observatories possible?



maybe yes…

or maybe just impossible…

http://arxiv.org/abs/1206.2109

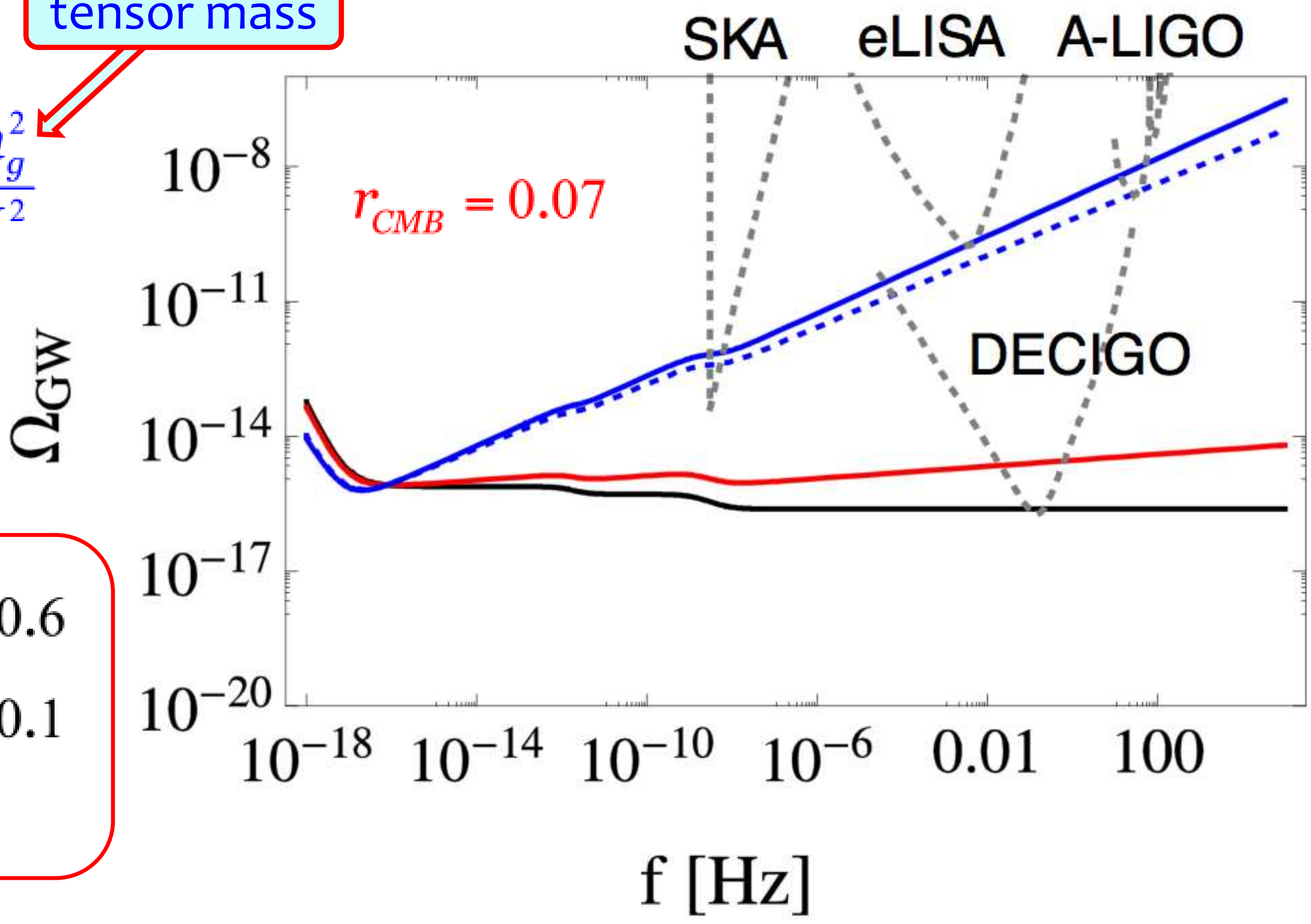
blue-tilted GW spectrum?

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

tensor (=GW) spectral index:

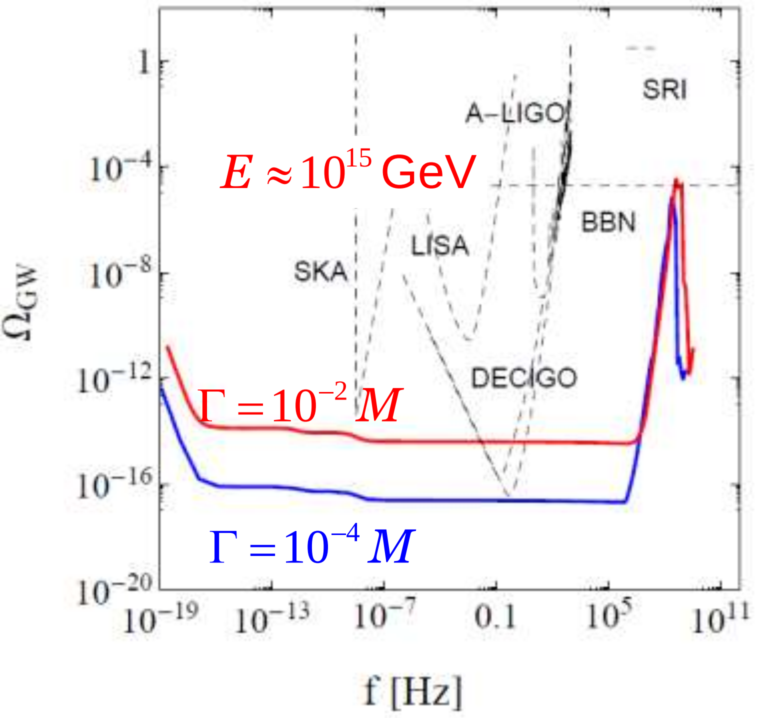
tensor mass

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



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

quantitative examples



$E \approx 10^{15}$ GeV

$\Gamma = 10^{-2} M$

$\Gamma = 10^{-4} M$

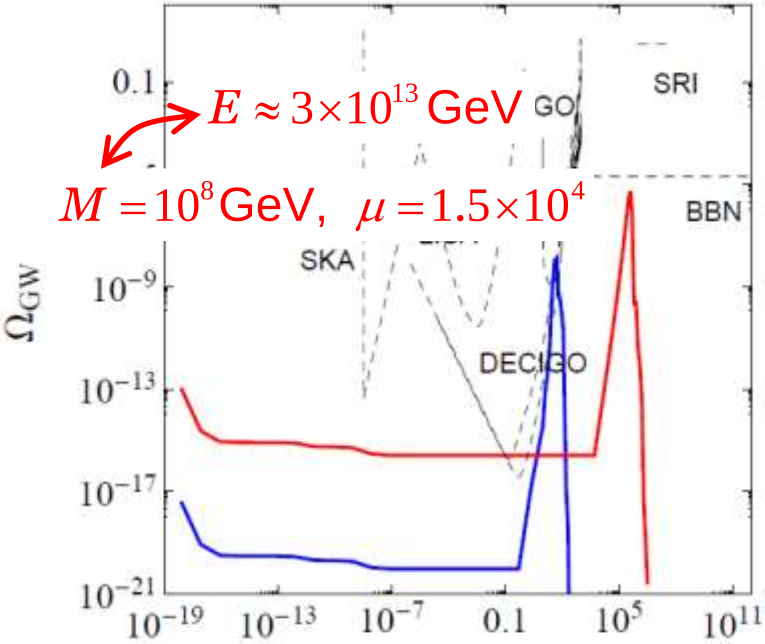
Starobinsky model $\left(\varepsilon_{\rm inf} = -\frac{H}{H^2} \simeq 2.5\times10^{-4}\right)$

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

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

$\lambda = 4.8\times10^{-7}$

Kuroyanagi, Lin, MS & Tsujikawa ’17



$E \approx 3\times10^{13}$ GeV

$M = 10^8$ GeV, $\mu = 1.5\times10^4$

$M = 1$GeV, $\mu = 4.8\times10^4$ $E \approx 3\times10^9$ GeV

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

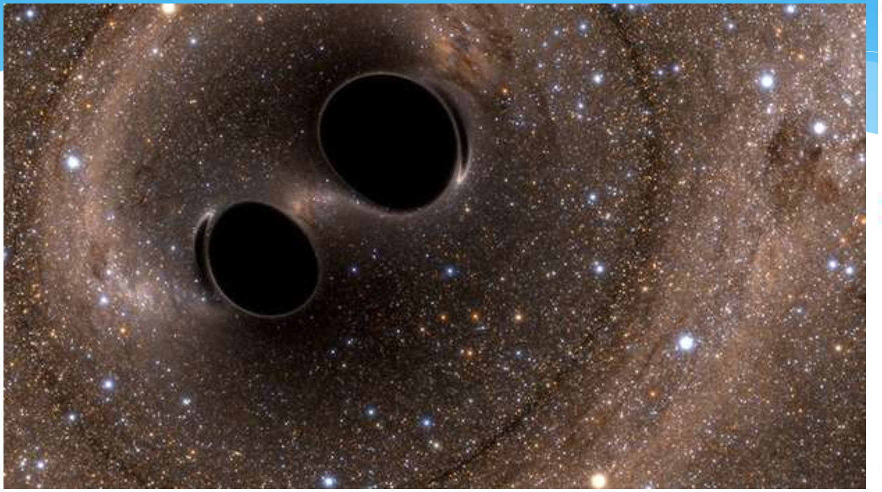
$$V = \frac{1}{2} M^2 \phi^2, \quad H_{\rm end} = \frac{2}{3} M, \quad \Gamma = 10^{-3} M$$

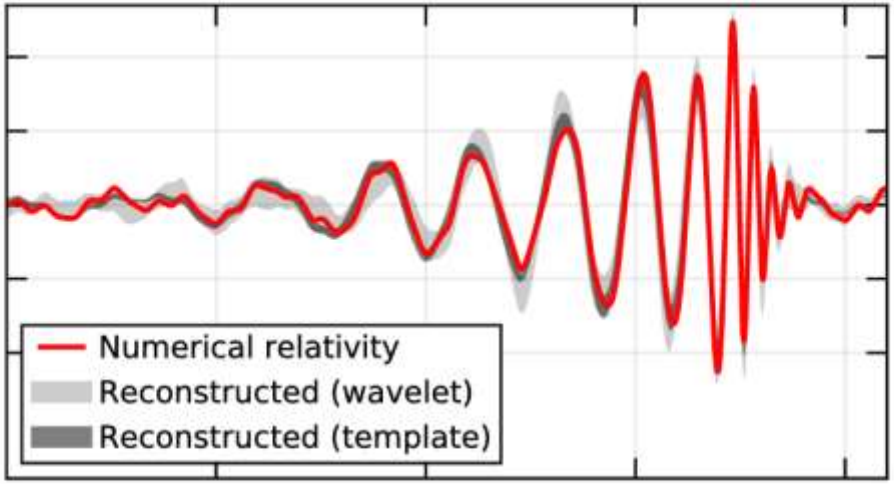
with $m_g^2 = \mu \frac{\dot{\phi}^2}{M_{pl}^2}$

Big-Bang Nucleosynthesis (BBN) gives stringent constraints

Gravitational Wave Physics/Astronomy

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: $0.6\text{-}12\ /\mathrm{Gpc}^3\ /\mathrm{yr}$

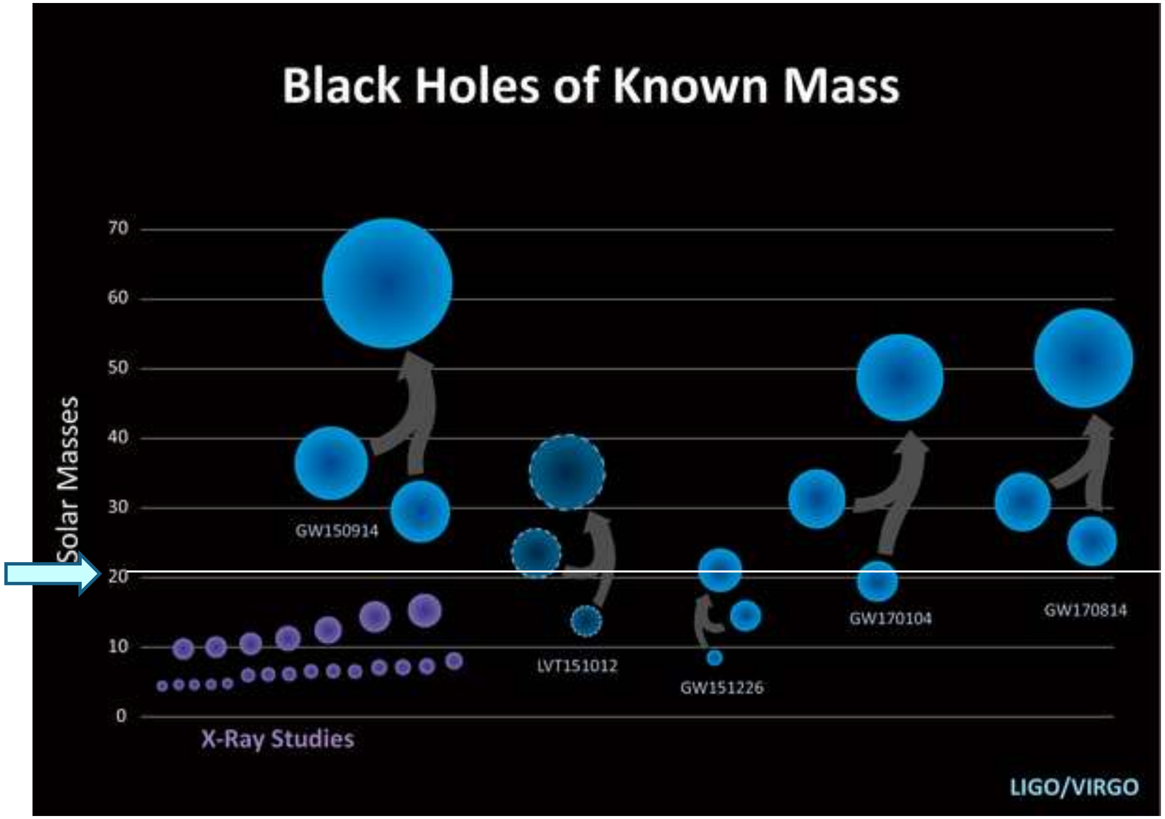
Unusual properties of LIGO BHs

LIGO has detected 4BBH mergers (+1 candidate) so far.

Any implications ?

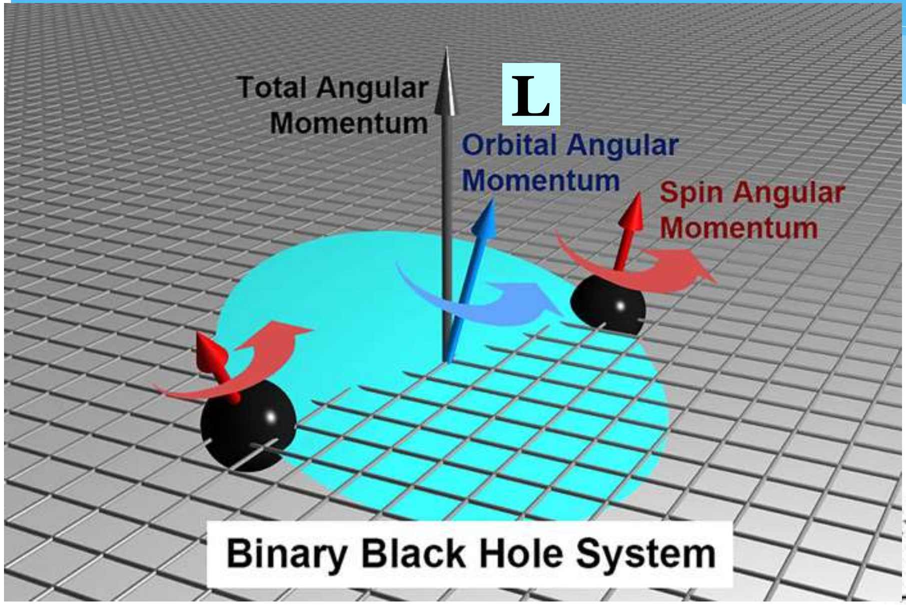
- They seem to be unusually heavy! (exc. GW151226)
- Their spins seem to be be unusually small!

20 $M_\odot$



LIGO BH spins

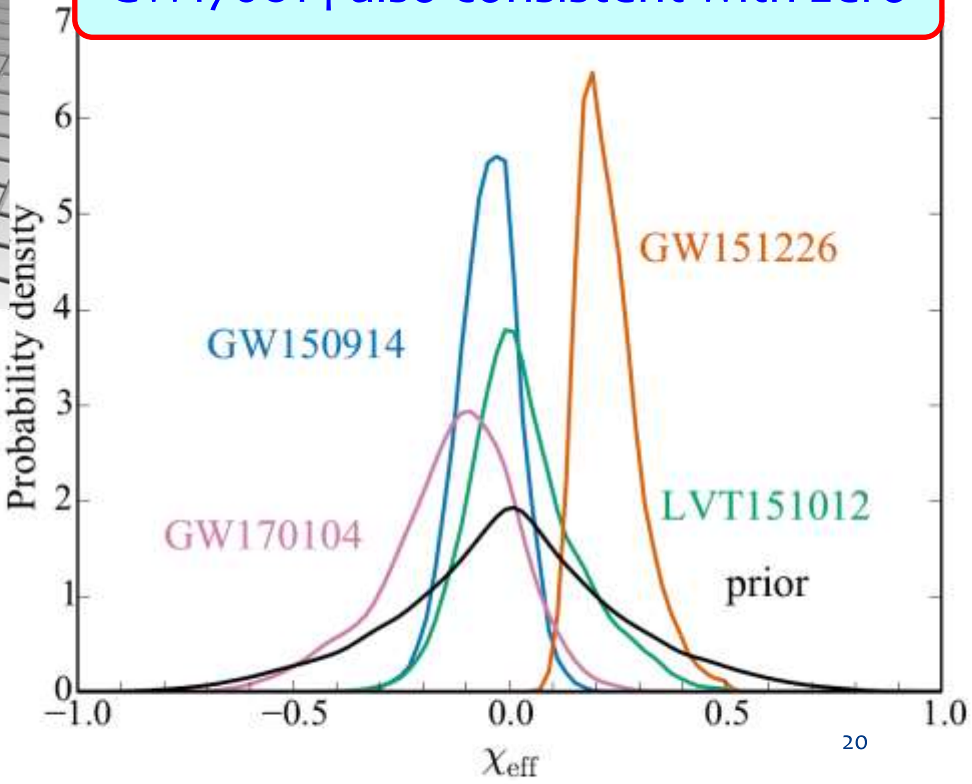
$$\chi_{\rm eff} = (m_1\mathbf{s}_1 + m_2\mathbf{s}_2)\cdot\mathbf{n}_L/(m_1+m_2): \quad \mathbf{n}_L = \mathbf{L}/L$$



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

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

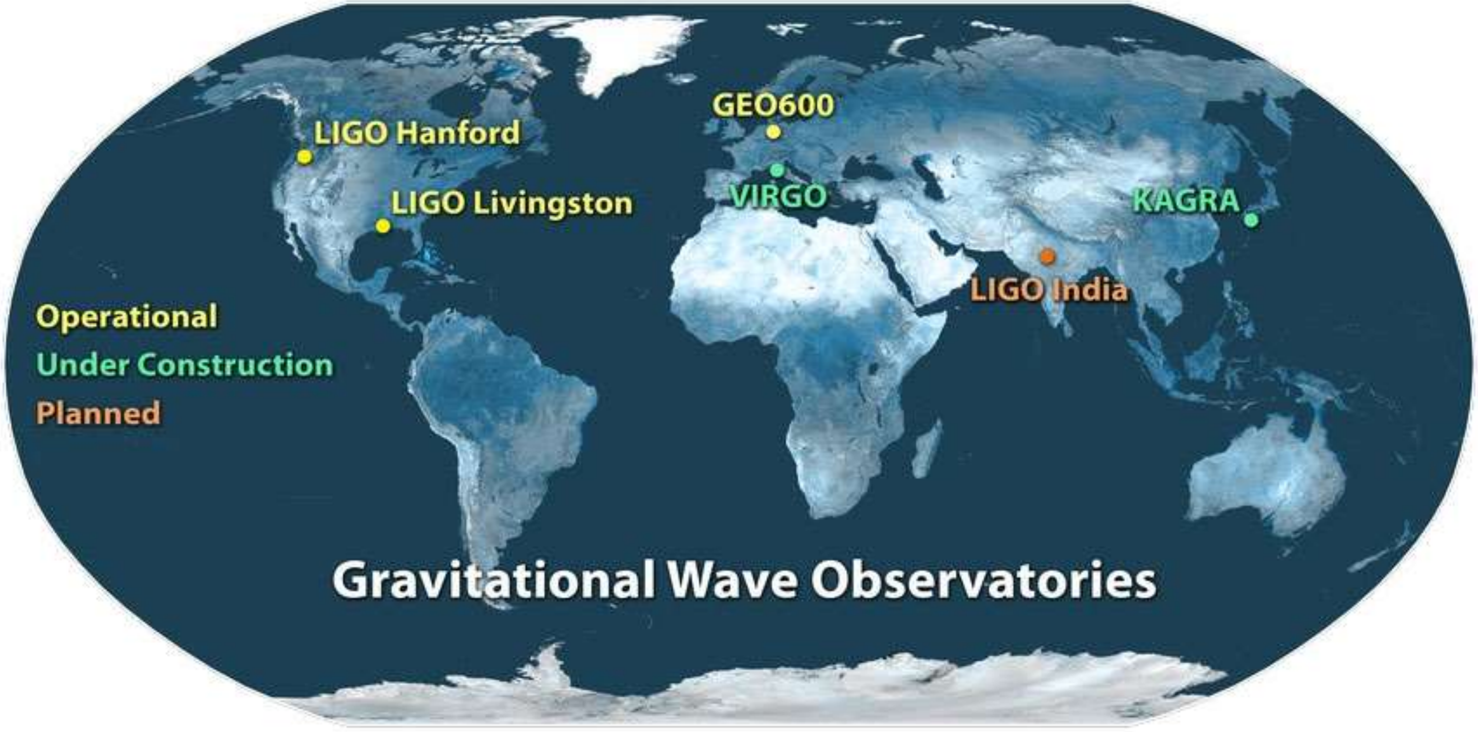
GW170814 also consistent with zero



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

Future
Network of GW Observatories

VIRGO started to operate on 1st Aug. 2017
KAGRA will start operation by 2020-2021 (iKAGRA has started!)
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=15 (LIGO), 4.4 (Virgo) ⇨ S/N=18.3 (LIGO+Virgo)

KAGRA

KAmioka GRAvitational wave detector

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

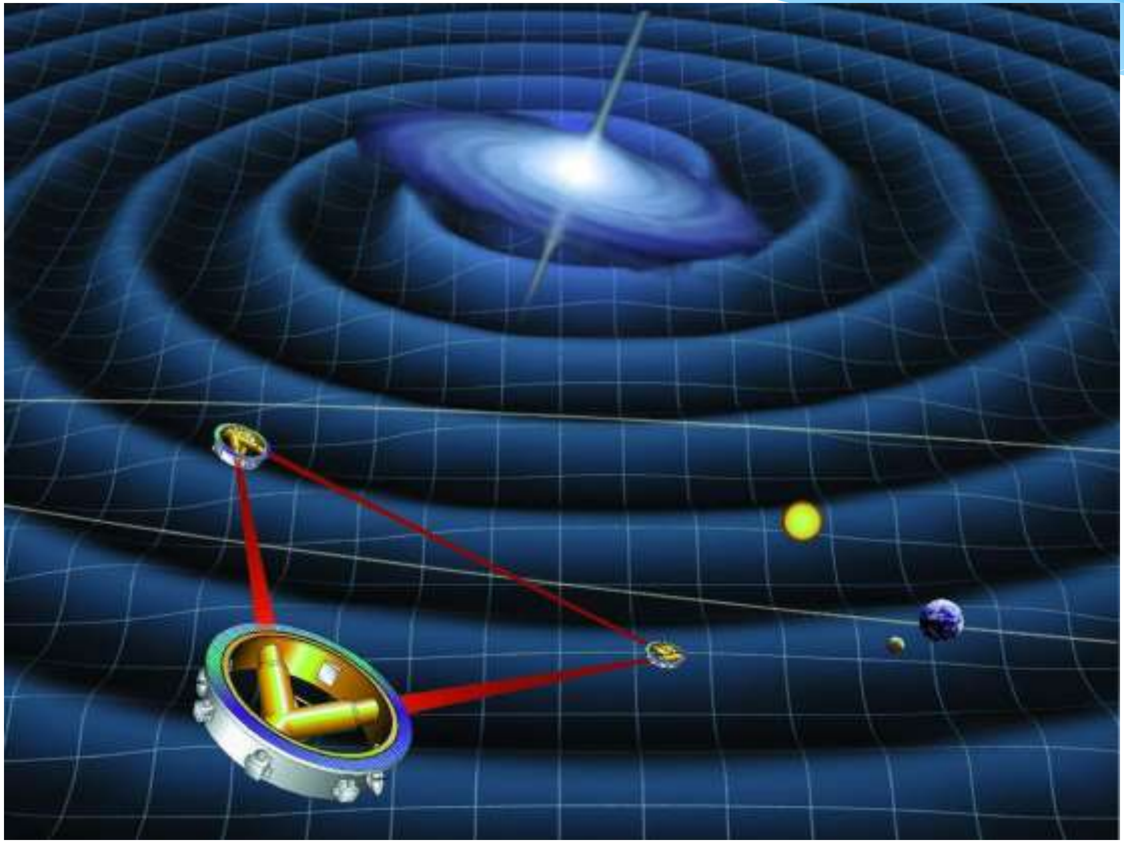
http://gwcenter.icrr.u-tokyo.ac.jp/en/

Previously called LCGT

Large Cryogenic
Gravitational wave Telescope

Arm length 3km
Cooled to 20K

Space-based Future Projects



http://lisa.nasa.gov/

Arm Length

⇩

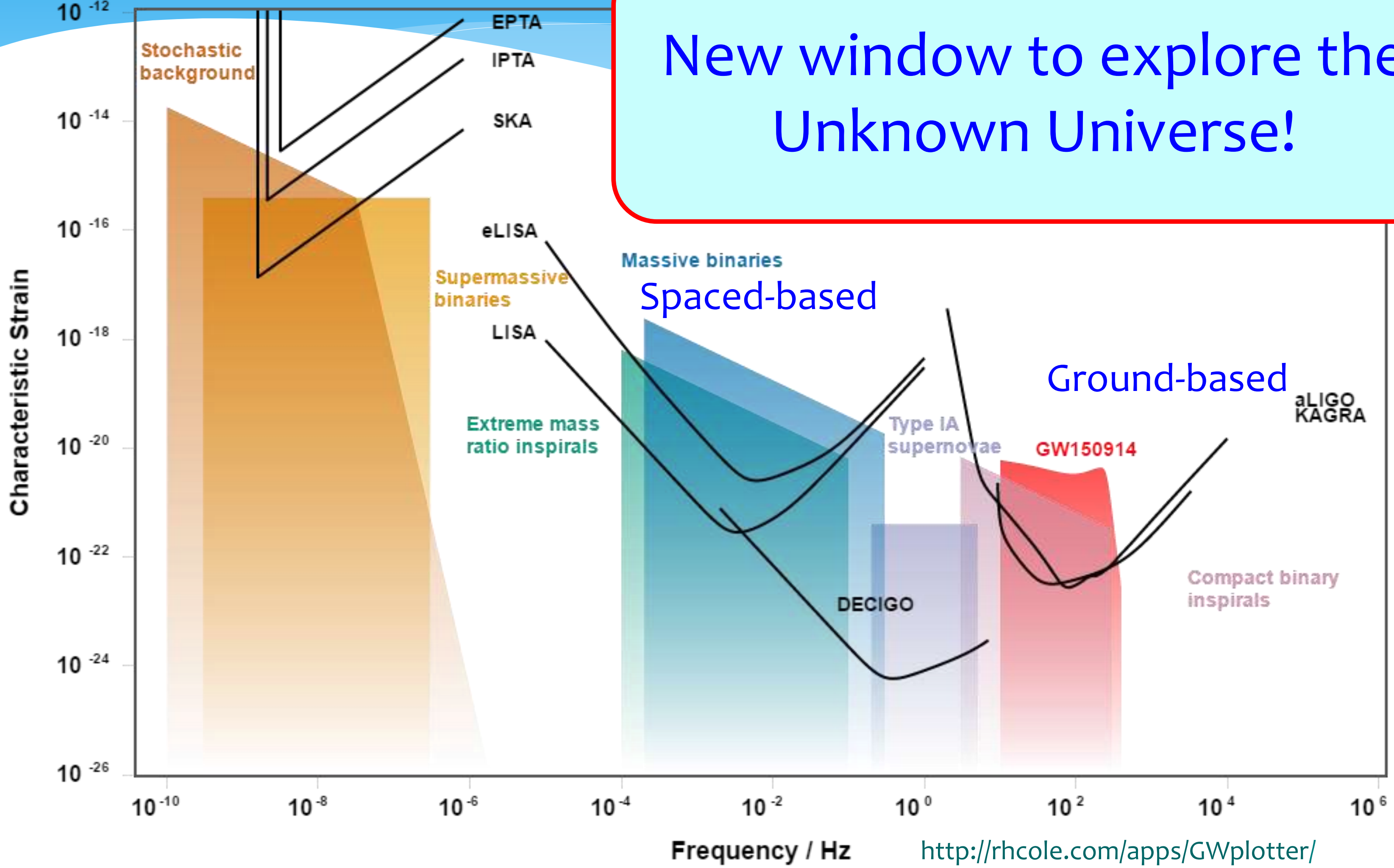
DECIGO: 1,000 km
launched by ~2030?
target freq: ~ 0.1 Hz

Deci-hertz Interferometer
Gravitational wave Observatory

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

Laser Interferometer Space Antenna

Multi-frequency GW Astronomy



Pulsar Timing Array

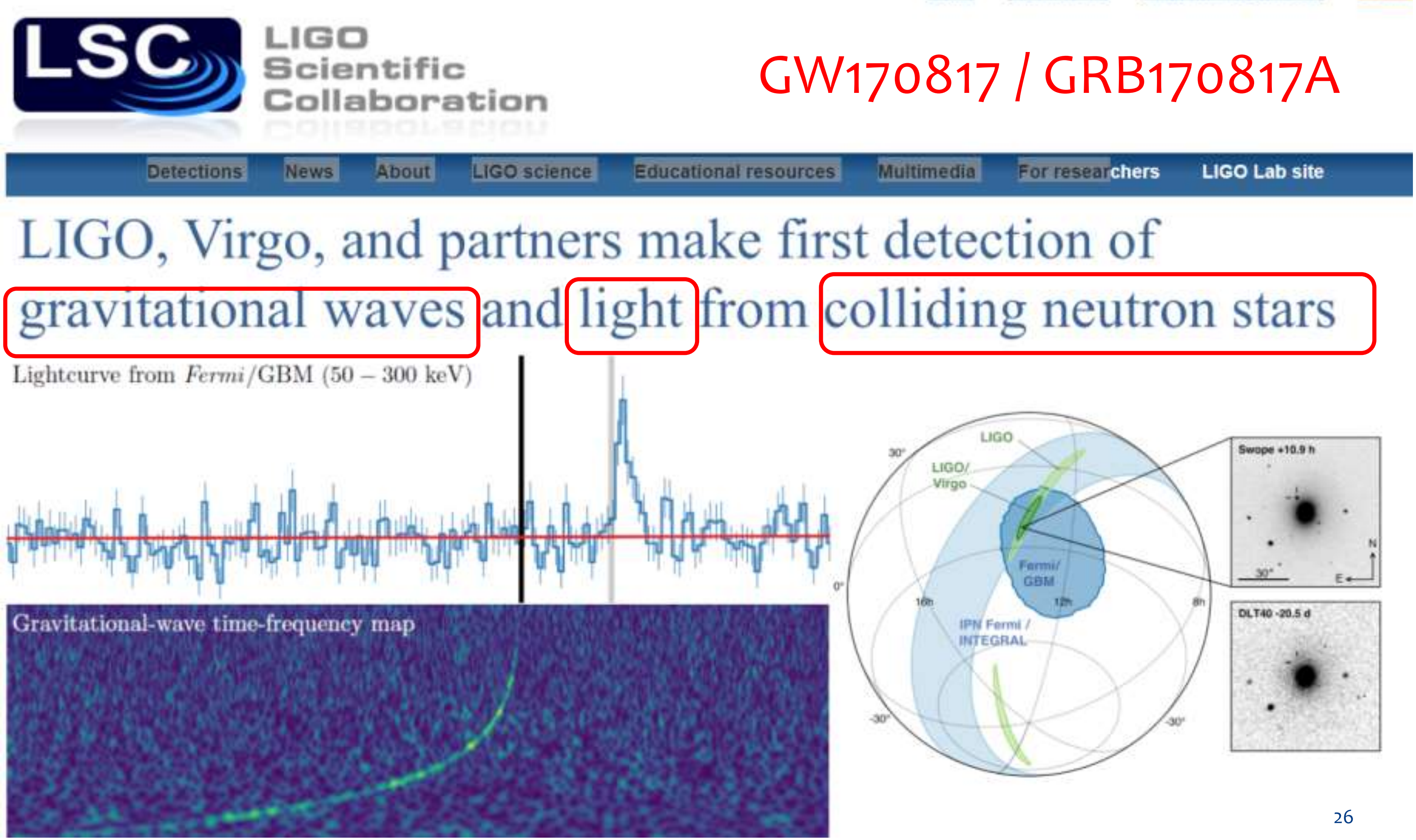
New window to explore the Unknown Universe!

Spaced-based

Ground-based

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

Binary Neutron Star merger found!

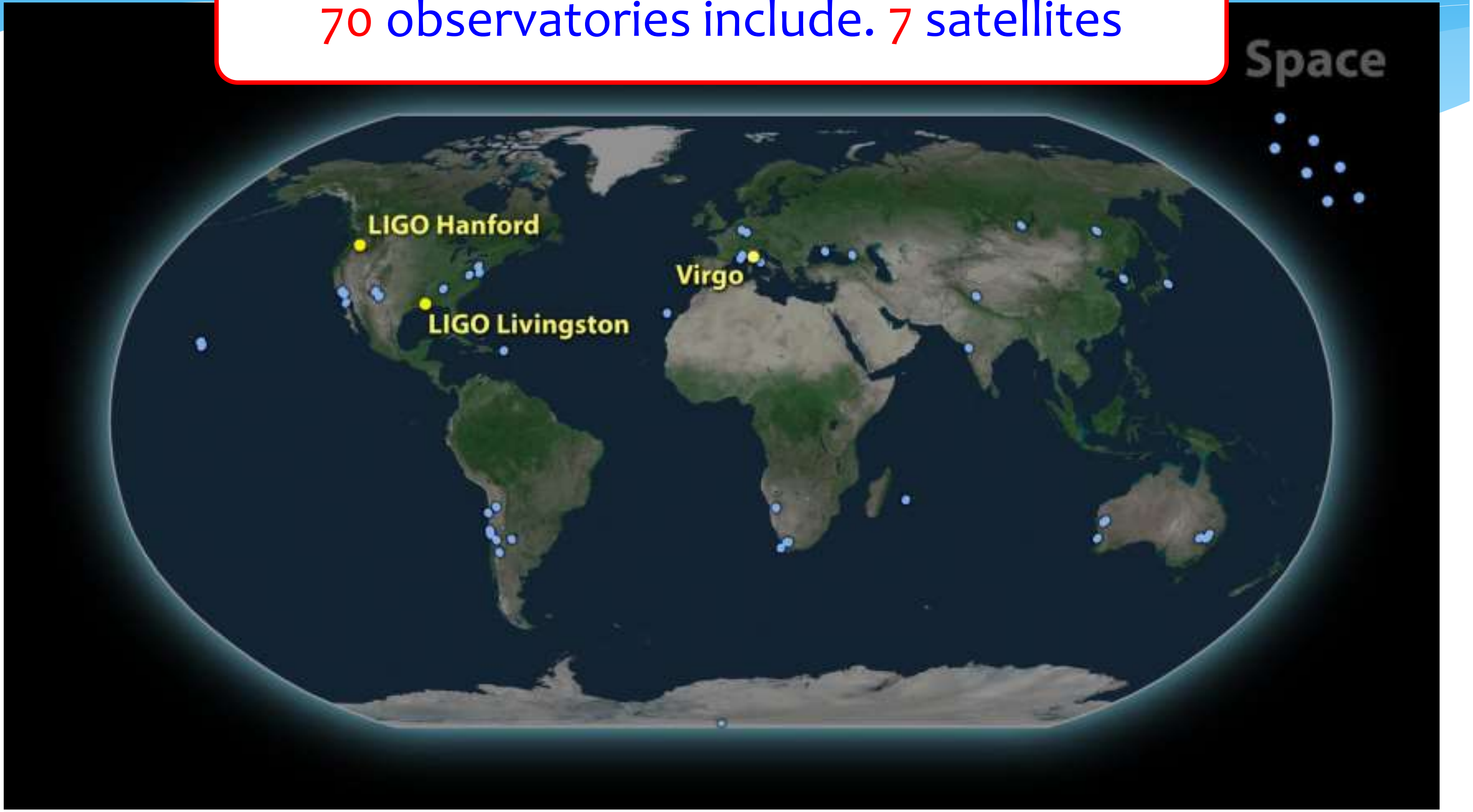


GW170817 / GRB170817A

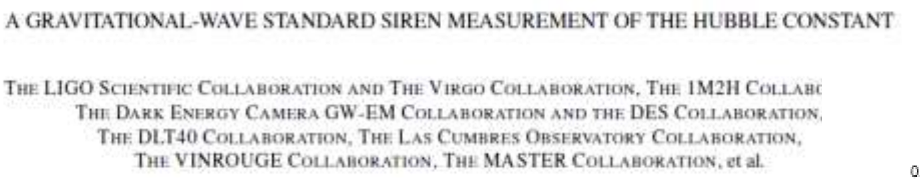
LIGO, Virgo, and partners make first detection of gravitational waves and light from colliding neutron stars

multi-messenger astronomy!

70 observatories include. 7 satellites

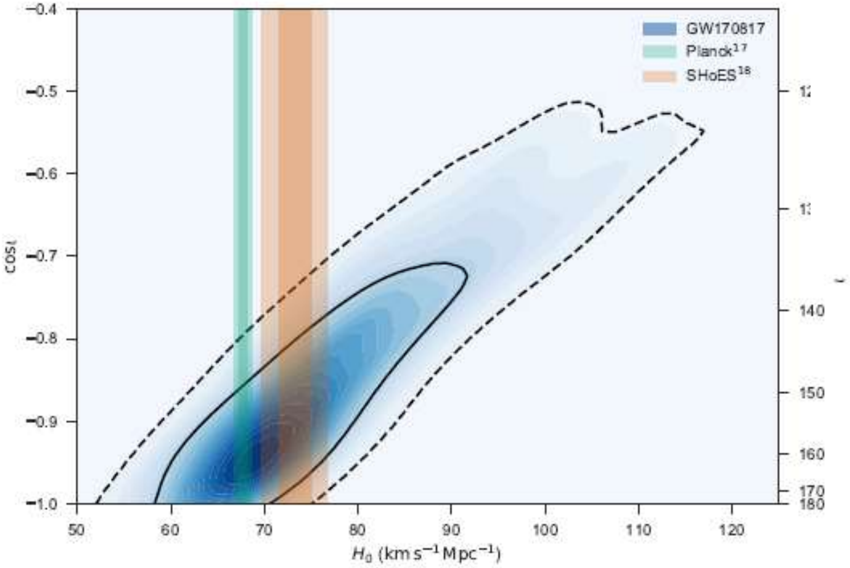


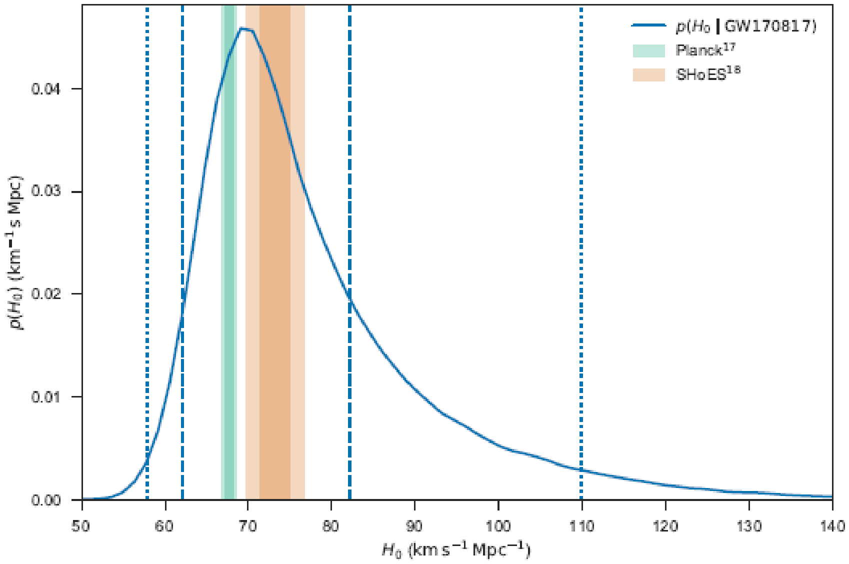
Cosmological Implication!



A GRAVITATIONAL-WAVE STANDARD SIREN MEASUREMENT OF THE HUBBLE CONSTANT

THE LIGO SCIENTIFIC COLLABORATION AND THE VIRGO COLLABORATION, THE 1M2H COLLABO
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 δρ/ρ=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.

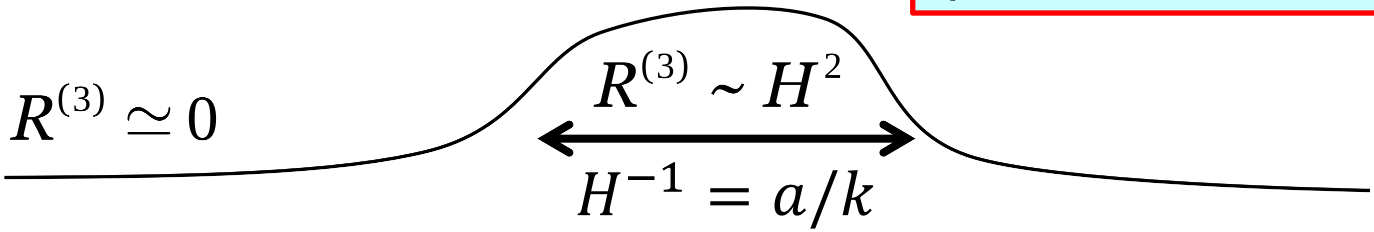
Curvature perturbation to PBH

- gradient expansion/separate universe approach

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

Hamiltonian constraint
(Friedmann eq.)

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



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

Young, Byrnes & MS '14

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

- Spins of PBHs are expected to be very small

examples

hybrid-type inflation

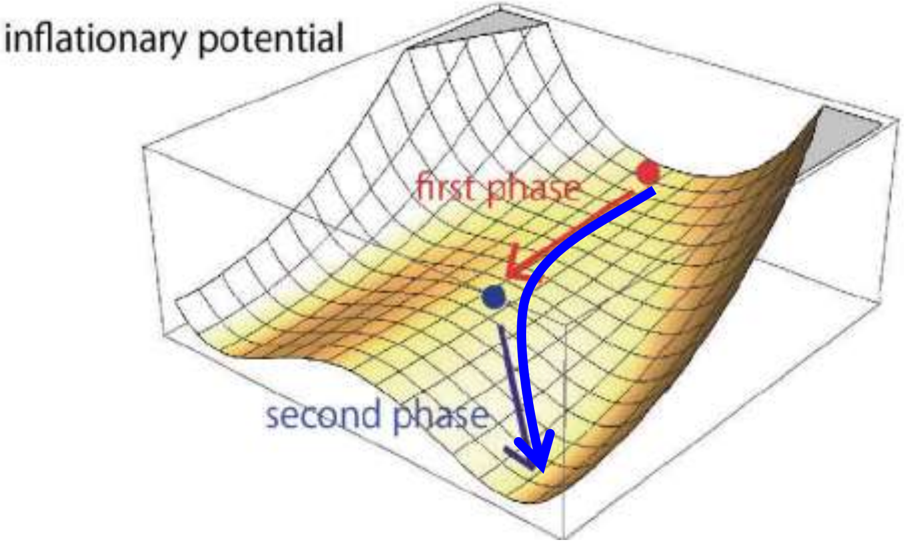
Garcia-Bellido, Linde & Wands ‘96, …

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

non-Gauss may become large

Abolhasani, Firouzjahi & MS ’11,..

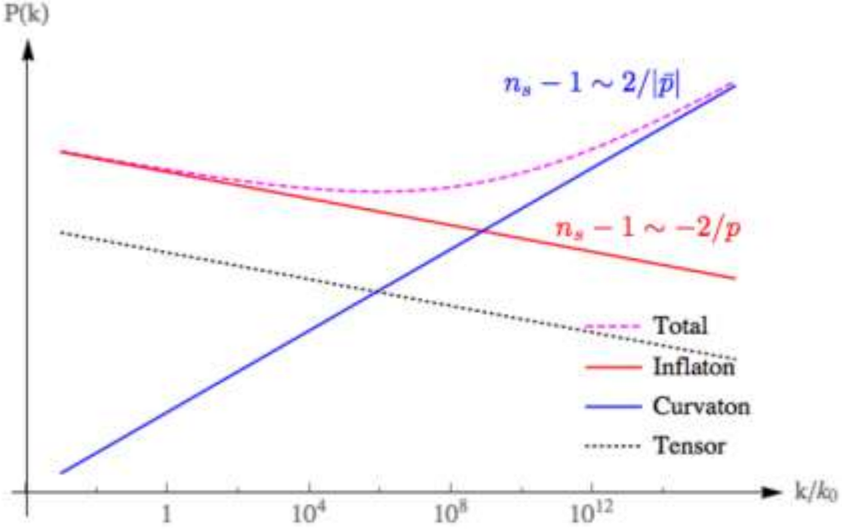
Pattison et al. 1707.00537



non-minimal curvaton

Domenech & MS ‘16

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



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

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

horizon size at the time of PBH formation

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

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

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

- energy output/Hubble time

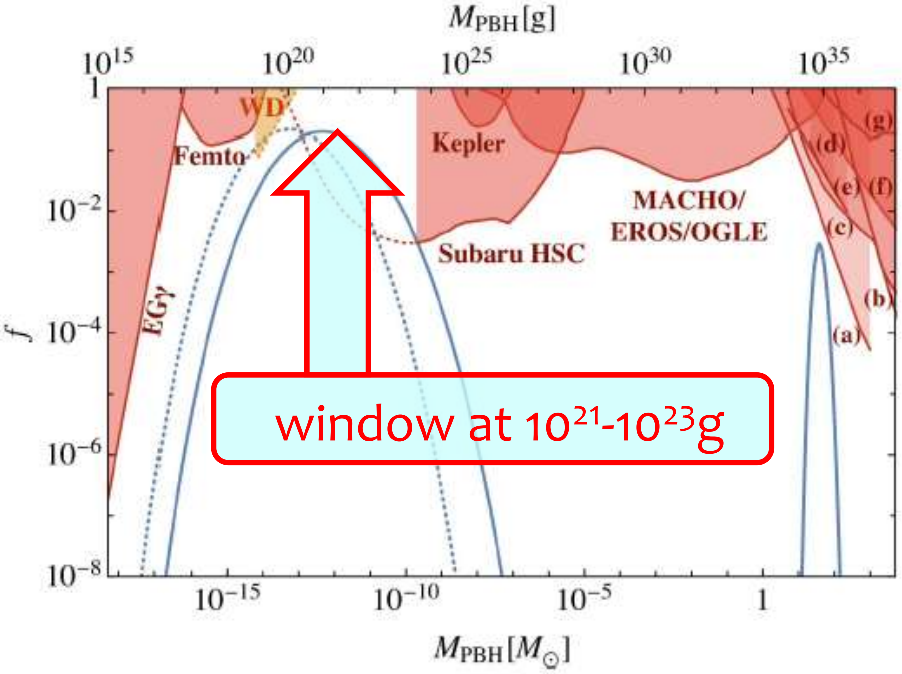
$$\frac{\dot{\rho}_R}{H\rho_R} = \varepsilon \frac{n_{PBH} L_{\text{edd}}}{H\rho_R} = \varepsilon \frac{\rho_{PBH}}{\rho_R} \frac{4\pi G m_p}{\sigma_T H} = \varepsilon f_{PBH} \left(\frac{a}{a_{eq}}\right)^3 \frac{4\pi G m_p}{\sigma_T H_{eq}}$$

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

small, but may not be entirely negligible…

Constraints on PBHs

Can DM be PBHs?

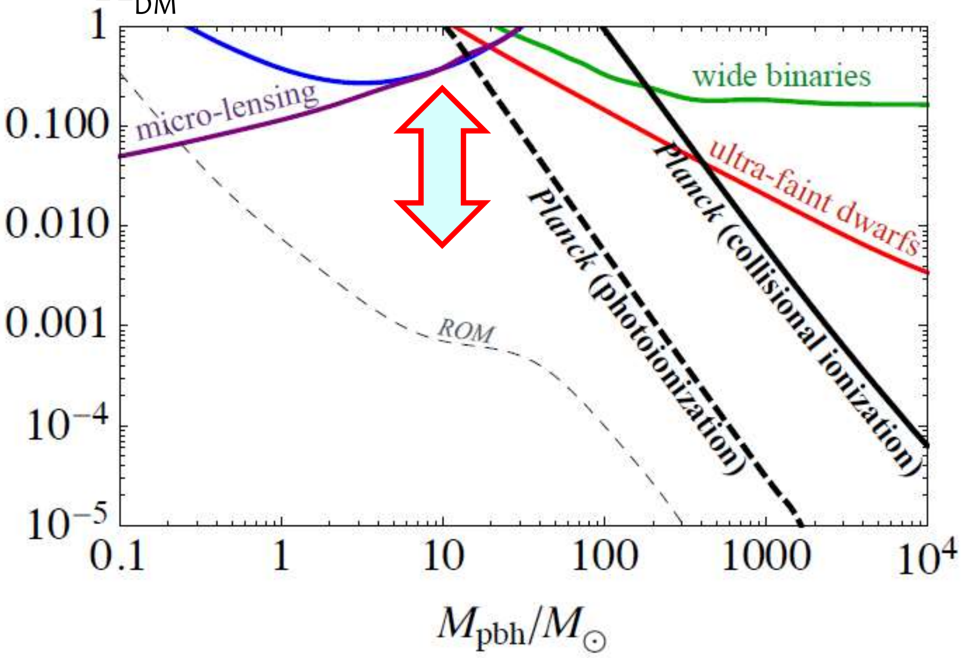


window at 10^{21}-10^{23}g

Inomata et al., 1711.06129

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

LIGO BBHs may occupy ~10% of DM



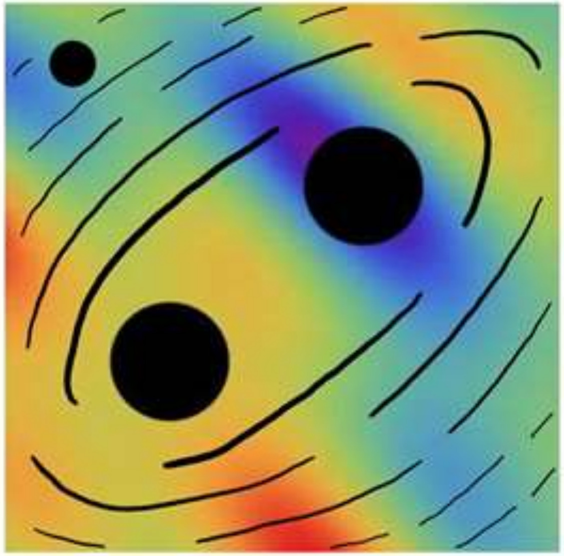
Ali-Haimoud & Kamionkowski, 1612.05644

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

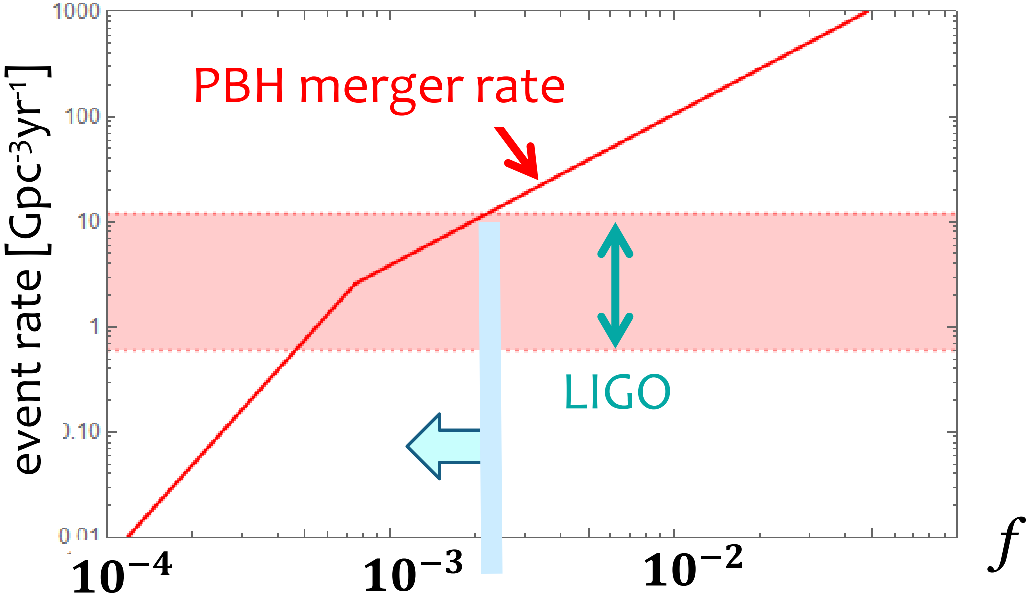
LIGO BHs = PBHs?

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

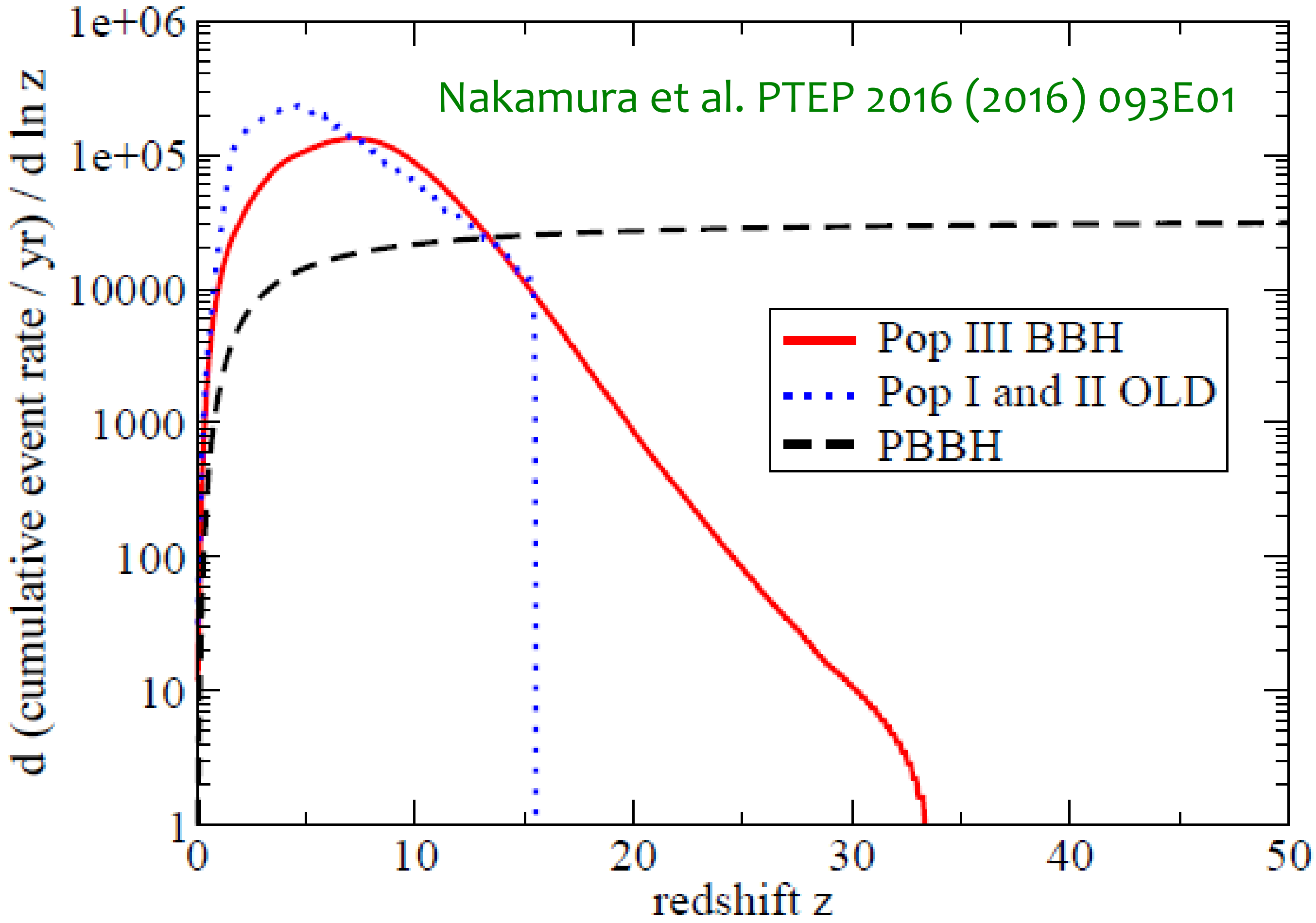


f = fraction of PBH in dark matter

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

(cf. Ali-Haïmoud et al., 1709.06576)

testing PBH hypothesis



Nakamura et al. PTEP 2016 (2016) 093E01

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

$$\boxed{\frac{36}{37} < \alpha < \frac{22}{21}}$$

$$\Updownarrow$$

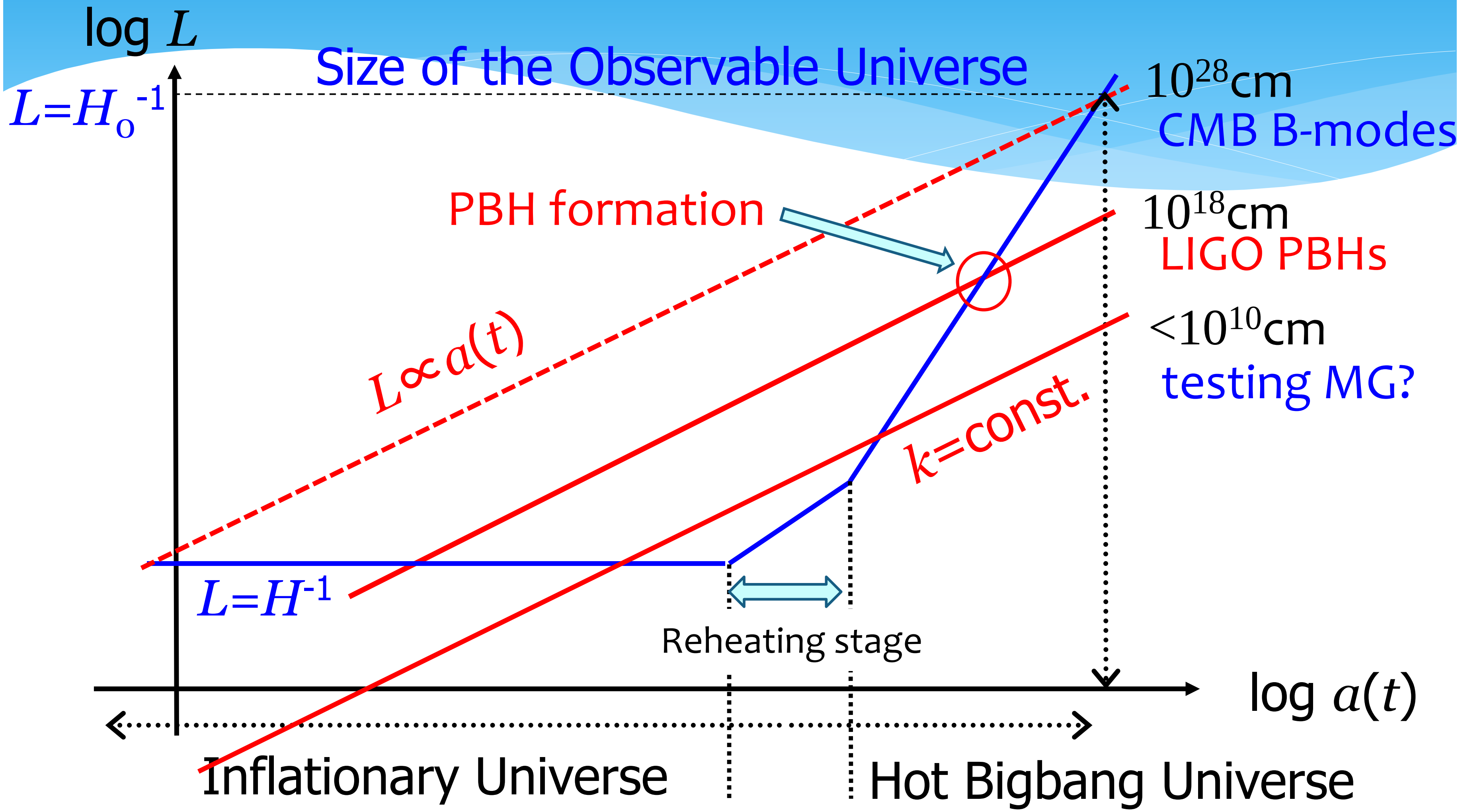
- Dynamical formation in dense stellar systems

$$\boxed{\alpha \approx 4}$$

clearly distinguishable!

O'Leary et al (2016)

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 has begun.

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