名古屋大学 NAGOYA UNIVERSITY

華中師範大學 CENTRAL CHINA NORMAL UNIVERSITY

TOWARDS A COMPLETE SCENARIO OF THE EARLY UNIVERSE

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還暦

花甲 [huā jiǎ]

野尻さん
60歳のお誕生日
おめでとうございます！

Outline

- ❑ **PART I: TOWARDS A COMPLETE SCENARIO OF THE EARLY UNIVERSE**

  -Standard Cosmology

  -Singularity Problem

  -Non-singular scenario of the early universe

  -Problems and their solutions

- ❑ **PART II: BRIEF INTRODUCTION OF ALICPT (CHINESE GRAVITATIONAL WAVE TELESCOPE)**

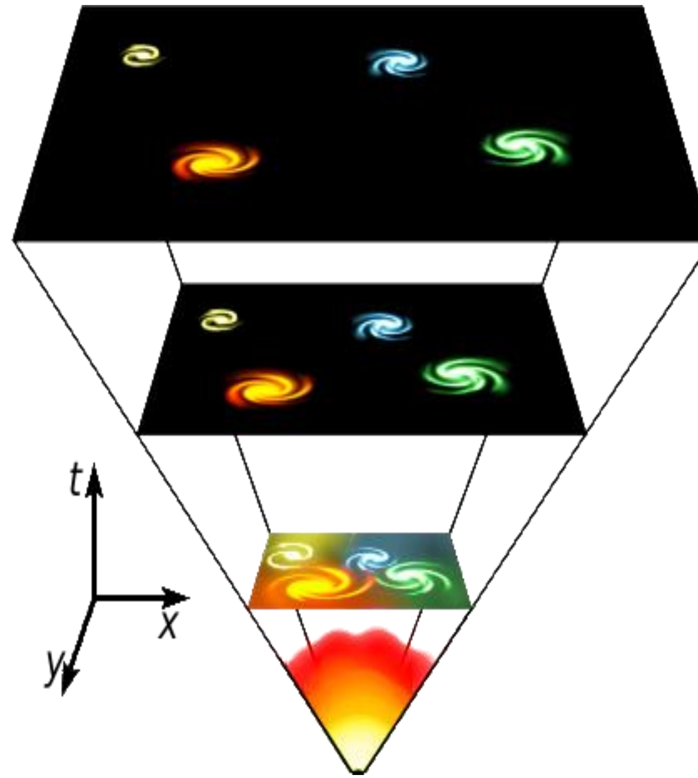
PART I: TOWARDS A COMPLETE SCENARIO OF THE EARLY UNIVERSE

The Big Bang theory

Ralph Alpher
(α)

Hans Bethe
(β)

George Gamow
(γ)



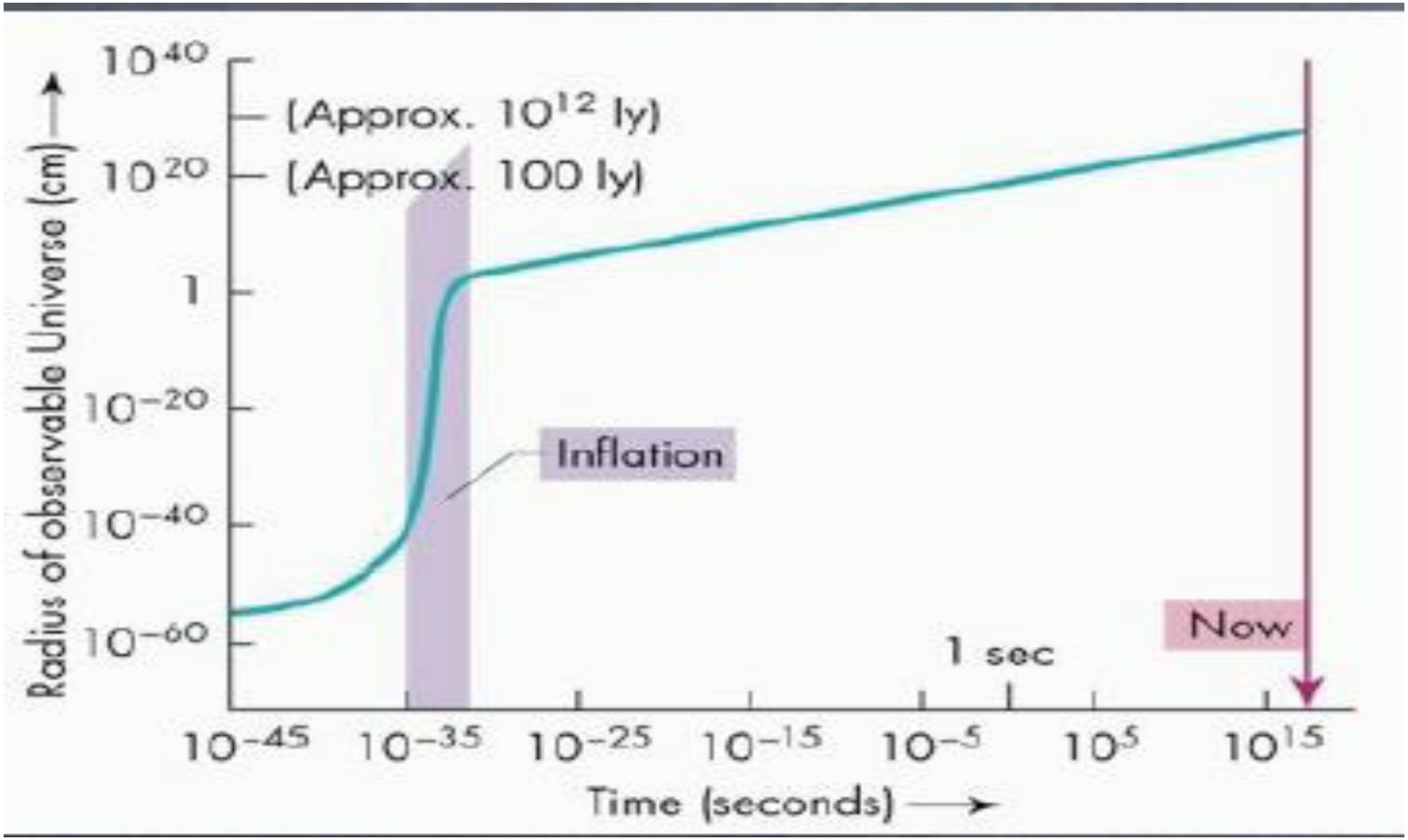
The Big Bang theory

The Big-Bang theory is both successful and non-successful!

- ✓ The age of galaxies
- ✓ The redshift of the galactic spectrum
- ✓ The He abundance
- ✓ The prediction of CMB temperature

- ❖ Flatness problem
- ❖ Horizon problem
- ❖ Unwanted relics problem
- ❖ Singularity problem

Inflation



Radius of observable Universe (cm)
10^{40}
(Approx. 10^{12} ly)
10^{20}
(Approx. 100 ly)
1
10^{-20}
10^{-40}
10^{-60}
Inflation
Now
1 sec
10^{-45}
10^{-35}
10^{-25}
10^{-15}
10^{-5}
10^{5}
10^{15}
Time (seconds)

Inflation

By assuming a rapid expansion that can:

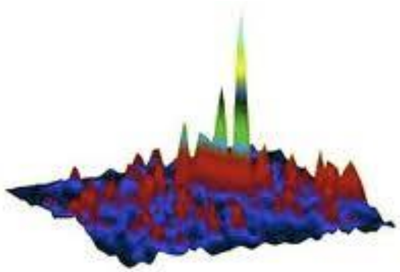
solve the horizon problem by stretching the space-time to a scale about 10^{30} *times the initial value, which means the* 10^{90} *casually disconnected regions are from one casual region. The stretch is faster than light but carries no information, so casuality is not violated.*

solve the Flatness problem by enlarging the curvature radius, and dissipating all the matter and curvature to amount of about 10^{-60} *. Since at the end of inflation the curvature perturbation is so small, even after the long period of successive evolution, it can still be within the range of* 10^{-5} *given by the current data. Therefore there is no need to finely tune the initial conditions.*

Also the Unwanted relics problem can be solved by inflation dissipation. As long as inflation happens after the Grand Unification is broken (below 10^{16} *GeV), the number density of unwanted relics such as monopoles can be dissipated to below the amount of* 10^{-30} *times that of baryons, within the observational constraints.*

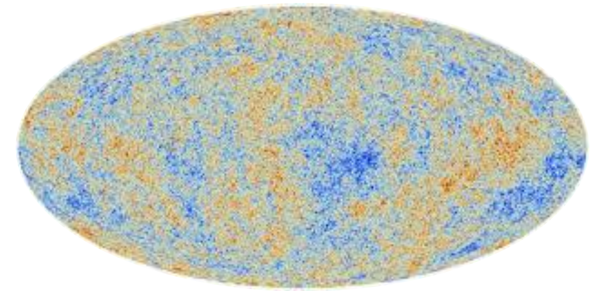
However, inflation can shed no light on the singularity problem because it took place after the initial point.

Observational tests

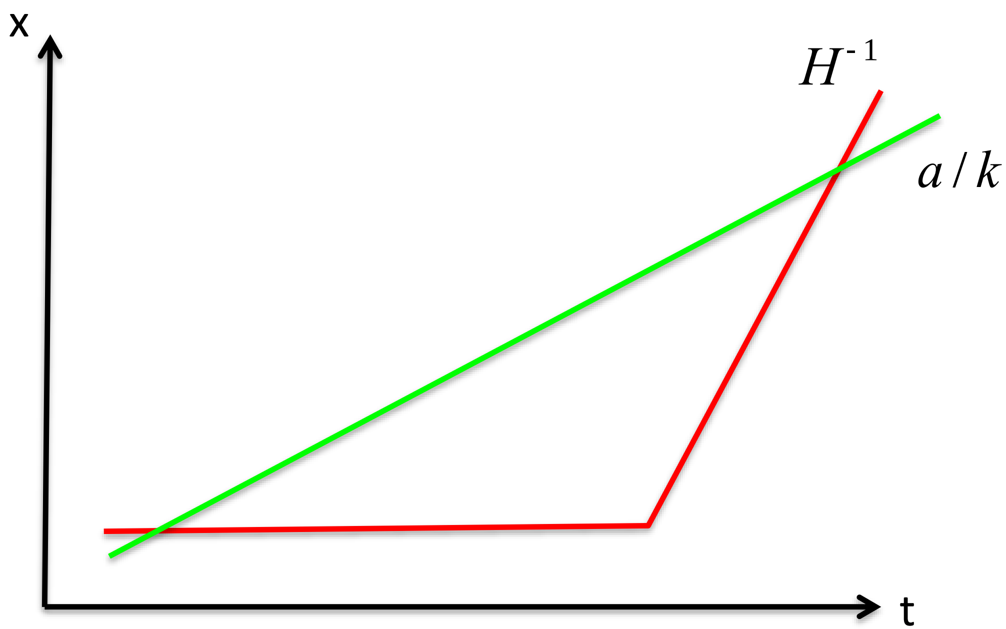


quantum fluctuations
(vacuum)

classical perturbations
(primordial)



Temperature fluctuations (CMB)



Initial value provided by quantum effect:

$$df = \frac{H}{2p}$$

Decohere into classical perturbations:

$$\zeta = \frac{H}{\dot{\phi}}\delta\phi$$

Observational tests

Power Spectrum:

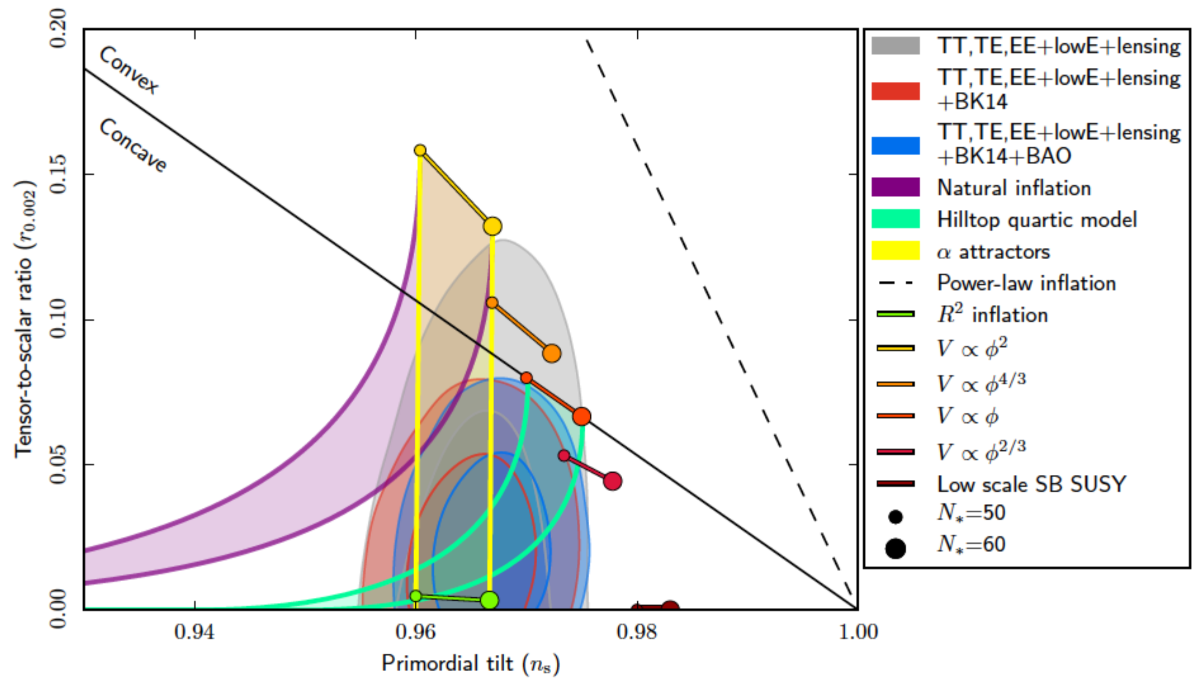
$$P_z \ \text{o}\ \frac{k^3}{2p^2}|z|^2$$

The typical prediction of inflation:

$$n_s \ \text{o}\ 1+\frac{d\ln P_z}{d\ln k}=1+6e-2h$$

$$r\ \text{o}\ \frac{P_T}{P_z}=16e$$

Observations from PLANCK 2018



(Planck collaboration, 2018)

The Singularity Problem

Theorem: the universe will meet a singularity when

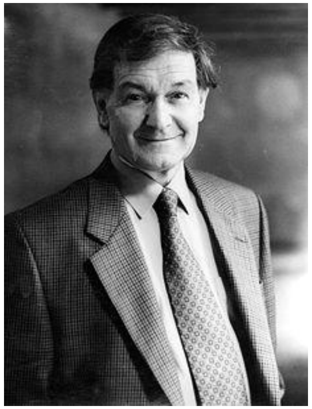
(1) it is described by General Relativity;

$$S=\int d^4x\sqrt{-g}[\frac{R}{16\pi G}+L_m]$$

(2) it satisfies Null Energy Condition;

$$T_{\mu\nu}n^\mu n^\nu=[(\rho+P)u_\mu u_\nu+g_{\mu\nu}P]n^\mu n^\nu$$
$$=(\rho+P)(u_\mu n^\mu)^2+Pn_\mu n^\mu$$
$$=(\rho+P)\geq 0$$

S. Hawking



R. Penrose

for any null vector n^μ: $u_\mu n^\mu=1$, $n_\mu n^\mu=0$

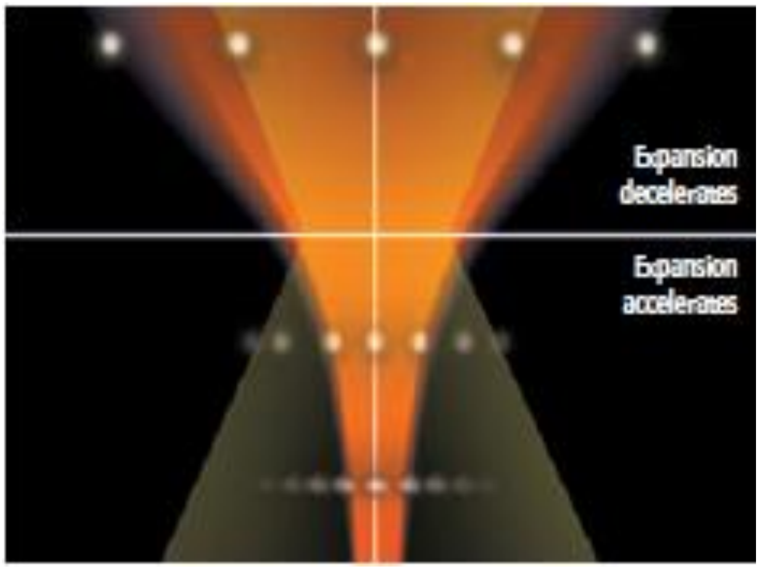
Where at finite time point

$$a_u(t)\to 0,\quad r_u(t)\to\infty$$

(S.W. Hawking, G.F.R. Ellis, 1973; Borde and Vilenkin, 1994.)

Non-Singular Cosmology

String-based scenarios



Pre-Big-Bang (Veneziano et al, 1991)

Ekpyrosis (Khoury et al, 1999)

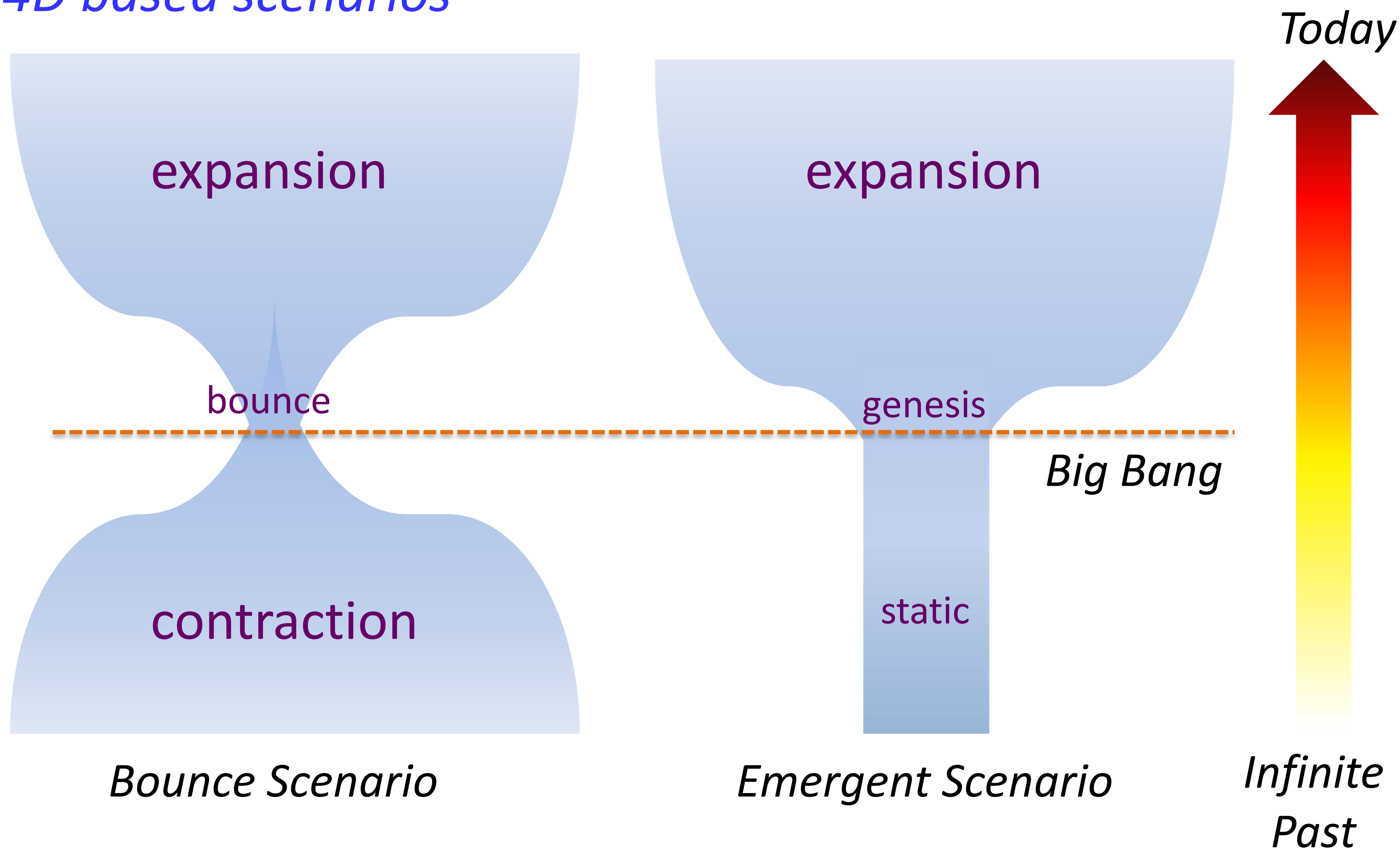
Characteristics:

1) extra dimensions needed

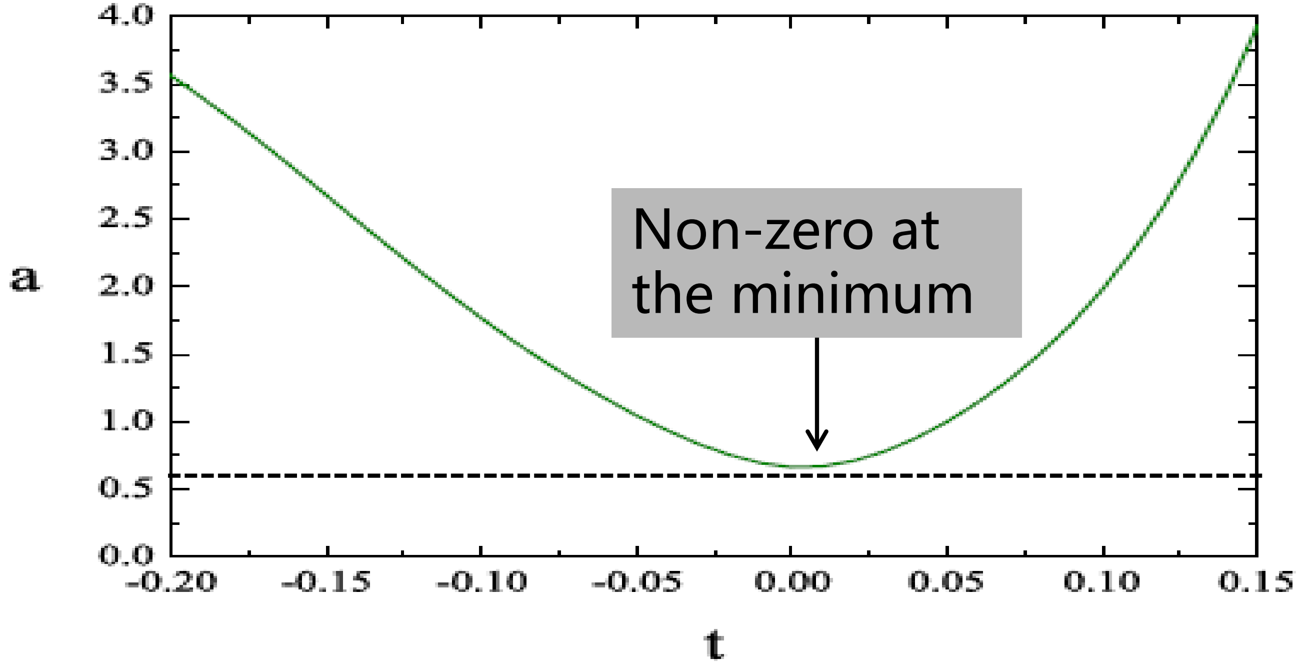
2) high energy scale: quantum effects may be robust

Non-Singular Cosmology

4D based scenarios



Bounce Cosmology



<u>*Contraction:*</u> $H < 0$ <u>*Expansion:*</u> $H > 0$

<u>*Bouncing Point*</u>*:* $\dot{H} > 0$ $\rho + p < 0$

Violating the Null Energy Condition (NEC)!

However, there may be new problems…

Problems in background

Anisotropy → Ekpyrotic Bounce (Cai et al., 2012; Qiu et al, 2013) | Bounce Inflation (Qiu et al, 2015)

Problems in perturbations

Scale Invariant Spectrum → Matter Bounce (Wands, 1999; Finelli et al, 2002) | Bounce Inflation (Piao et al, 2003)

↓

Ghost Instability → Galileon Bounce (Qiu et al, 2011)

↓

Scale Invariant Tensor Spectrum → Bounce Inflation (Qiu et al, 2015) | Anamorphic (Ijjas et al, 2015)

↓

Gradient Instability → Bounce Inflation (Qiu et al, 2015) | Effective field theory (Cai et al., 2016, 2017; Creminelli et al, 2016)

I. Cosmic Anisotropy

If the initial metric is not exact isotropic:

$$ds^2 = -dt^2 + a^2(t)\sum_{i=1}^{3} e^{2\beta_i(t)} dx^{i2}$$

Friedmann Equation:

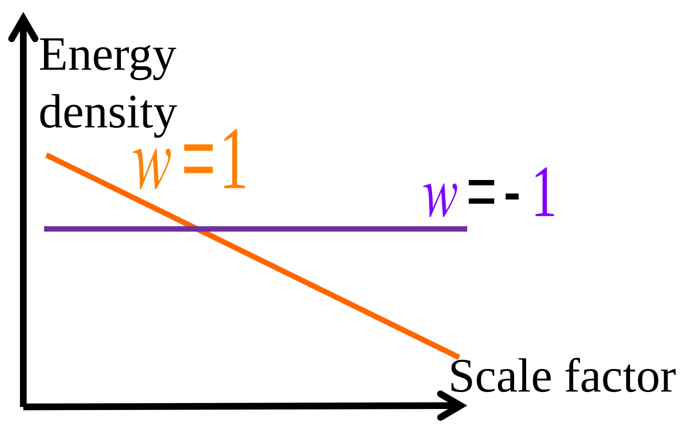
$$3H^2 = \rho_{bg} + \frac{1}{2}\sum_{i=1}^{3}\dot{\beta}_i^2$$

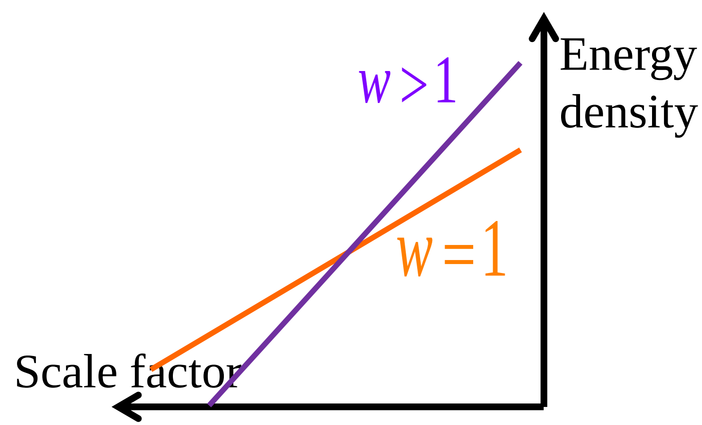
↑ *Matter* ↑ *Anisotropy*

EoM for anisotropy:

$$\ddot{\beta}_i + 3H\dot{\beta}_i = 0 \;\Rightarrow\; w_{ani} = 1$$

$$\rho_{ani} \propto a^{-3(1+w)} = a^{-6}$$

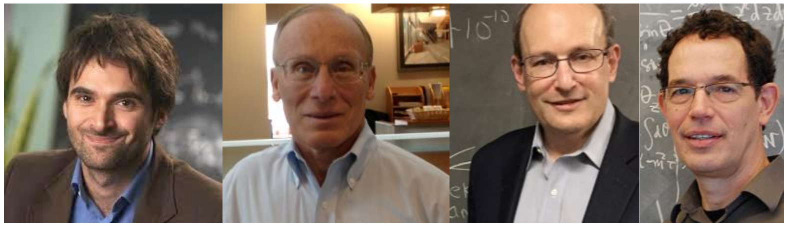




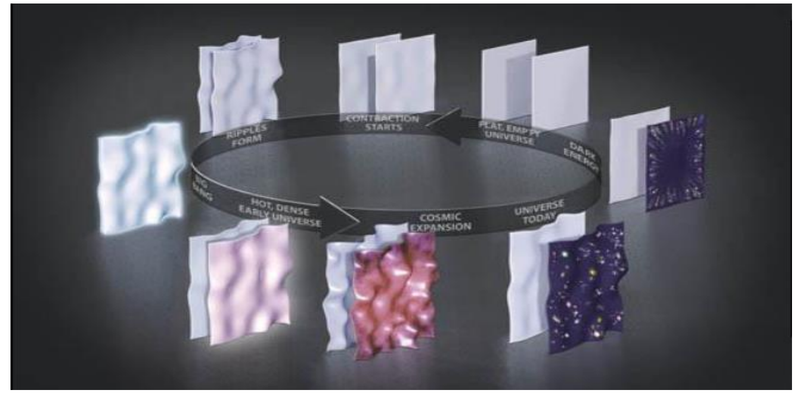
So we need contracting phase with w>1!

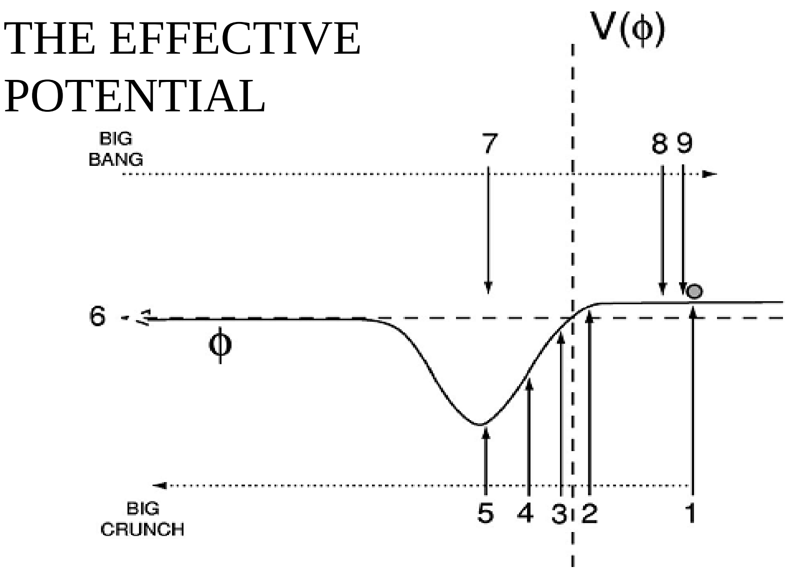
(J. Erickson, D. Wesley, P. Steinhardt, N. Turok, 2004.)

One of the Solutions: Ekpyrosis



(Khoury, Ovrut, Steinhardt & Turok, 2001)





The effective potential (Ekpyrotic phase):

$$V(\phi) = -V_0 \exp\left(-\sqrt{\frac{2}{p}}\frac{\phi}{M_p}\right) < 0$$

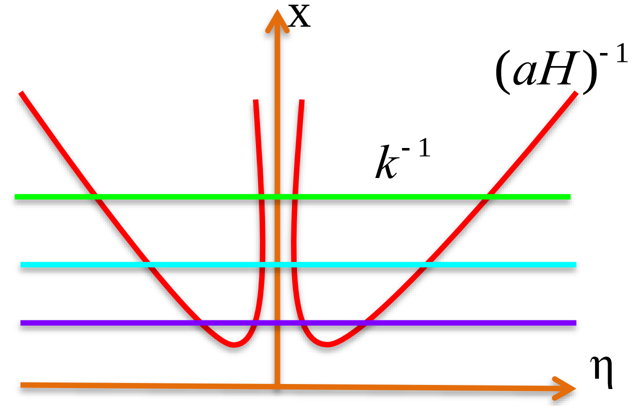
In order to make $w_{eff} = \frac{\dot{\phi}^2 - 2V}{\dot{\phi}^2 + 2V} > 1$

1 DE domination; 2 decelerated expansion; 3 turnaround; 4 Ekpyrotic contraction; 5 before big crunch; 6 a singular bounce in 4D; 7 after big bang; 8 radiation domination; 9 matter domination

2. Scale Invariance of Power Spectrum

<u>*The perturbation equation:*</u>

$$(z\zeta)'' + \left(c_s^2 k^2 - \frac{z''}{z}\right)(z\zeta) = 0$$



sketch plot of perturbations during the bounce

<u>*Solution:*</u>

$$\zeta \sim (c_s k)^{\frac{3}{2}\frac{1-w}{1+3w}} \eta^0, \quad (c_s k)^{-\frac{3}{2}\frac{1-w}{1+3w}} \eta^{-\frac{3}{2}\frac{1-w}{1+3w}}$$

constant — *growing for viable bounce models*

<u>*Power spectrum:*</u>

$$P_\zeta \equiv \frac{k^3}{2\pi^2}|\zeta|^2 \sim k^{3-\frac{3(1-w)}{1+3w}} \eta^{-\frac{1-w}{1+3w}}$$

$$n_s - 1 = 3 - \frac{3(1-w)}{1+3w} \approx 0 \quad \Rightarrow \quad w \approx 0$$

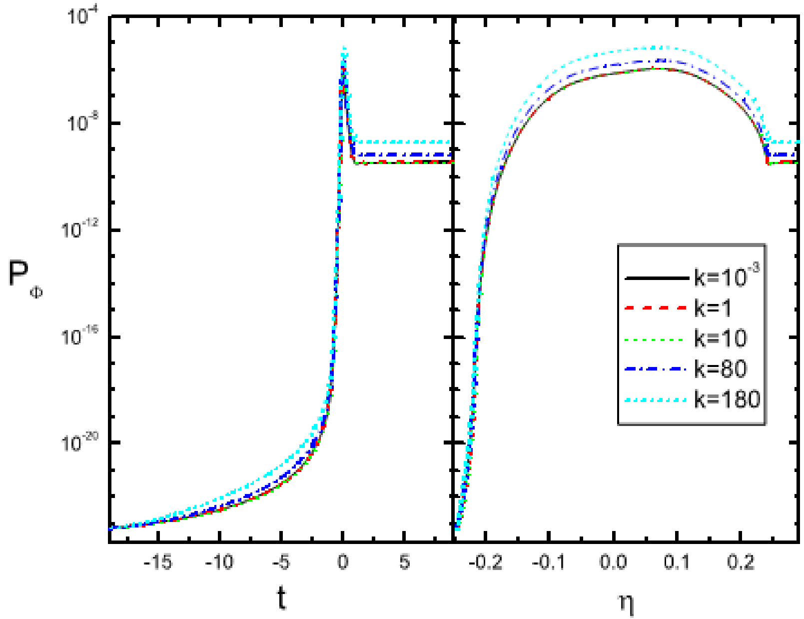
(D. Wands, 1999;
F. Finelli and R. Brandenberger, 2002.)

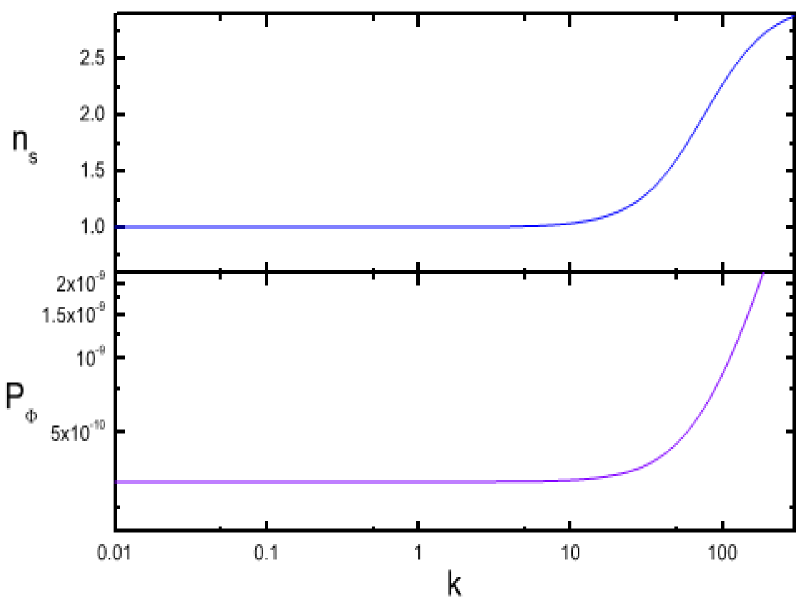

David Wands


Robert Brandenberger

2. Scale Invariance of Power Spectrum

The numerical plots of the power spectrum and spectral index:





(Y. F. Cai, **TQ,** R. Brandenberger, X. M. Zhang, 2009)

To Be Large or Not To Be Large? Is it a Problem?

Isotropy: $w>1$

Scale Invariance: $w=0$

Possible Solutions:

1) *To have another field in contracting phase to generate power spectrum (Entropic Mechanism);*

   F. Finelli, PLB 2002;

   K. Koyama and D. Wands, JCAP 2007;

   K. Koyama, S. Mizuno, D. Wands, CQG 2007;

   TQ, X. Gao and E. N. Saridakis, PRD 2014… …

2) *To have inflationary period following the bounce (Bounce Inflation).*

   Y. S. Piao, B. Feng and X. M. Zhang, PRD 2004;

   Z. G. Liu, Z. Guo and Y. S. Piao, PRD 2013;

   J. Q. Xia, Y. F. Cai, H. Li and X. M. Zhang, PRL 2014;

   TQ and Y. T. Wang, JHEP 2015……

3. Ghost Instability

NEC violation will generally cause ghost mode!

Example: "Phantom" Energy

<u>*Lagrangian:*</u>

$$L_{phantom} = -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi)$$

↑ Ghost mode!

<u>*Hamiltonian (density):*</u>

$$H_{phantom} = \Pi\dot{\phi} - L = -\omega\int d^3k(a_k^\dagger a_k + \frac{1}{2})$$

unbounded energy!

S. Carroll, M. Hoffman, M. Trodden, 2003; J. Cline, S. Jeon, G. Moore, 2004.

Solution: Galileon Theories

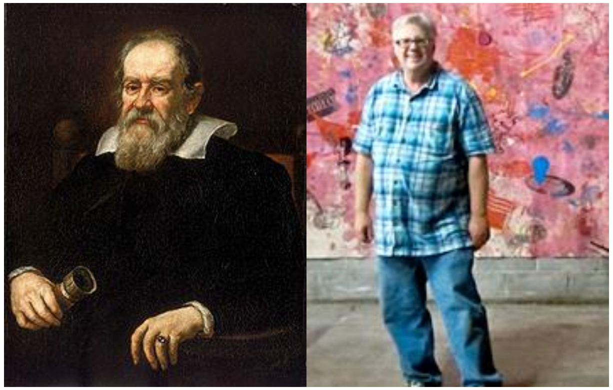
Galileon/Horndeski theories (2008/1974)

$$L_2 = K(\phi, X)$$

$$L_3 = -G_3(\phi, X)\Box\phi$$

$$L_4 = G_4(\phi, X)R + G_{4,X}[(\Box\phi)^2 - (\nabla_\mu\nabla_\nu\phi)^2]$$

$$L_5 = G_5(\phi, X)G_{\mu\nu}\nabla^\mu\nabla^\nu\phi - G_{5,X}[(\Box\phi)^3 - 3\Box\phi(\nabla_\mu\nabla_\nu\phi)^2 + 2(\nabla_\mu\nabla_\nu\phi)^3]/6$$



1) Higher derivative in lagrangian but 2nd order in equation of motion

2) Multi-degrees of freedom but only one is dynamical

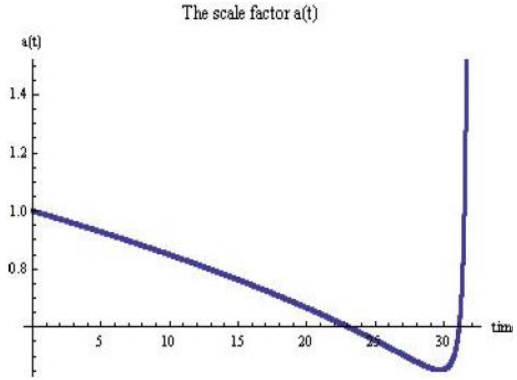
3) violating NEC free of ghosts.

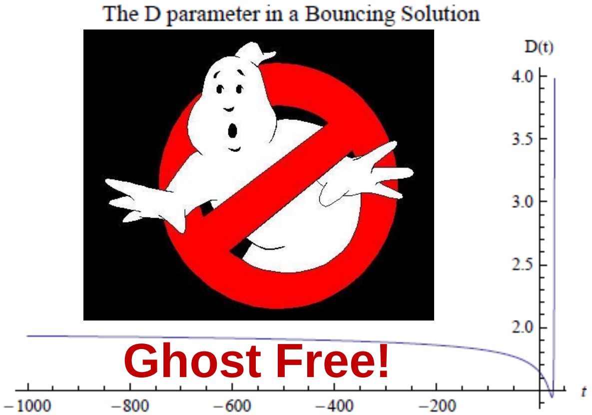
e. g. (**TQ** et al., 2011)

$$L = F^2 e^{2\phi}(\partial\phi)^2 + \frac{F^3}{2M^3}(\partial\phi)^4 + \frac{F^3}{M^3}(\partial\phi)^2\Box\phi$$

Perturbation action:

$$\delta^{(2)}S = 3\int dt d^3x D M_P^2\left[\dot{\zeta}^2 - \frac{c_s^2}{a^2}(\partial\zeta)^2\right]$$



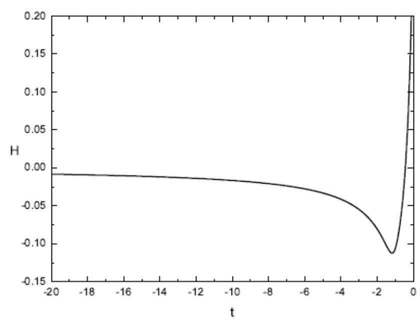


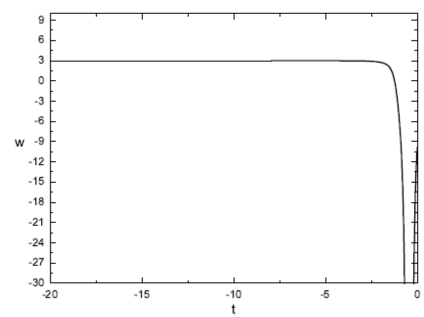
Solution: Galileon Theories

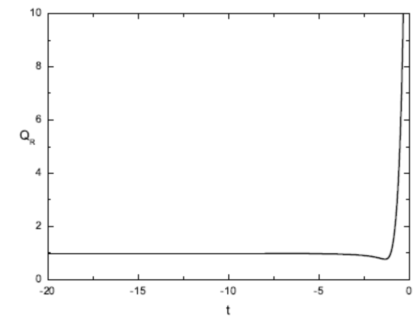
Taking into account the anisotropic and scale invariance issues, one can get more improved models:

1) multi-field bounce model ***(TQ**, X. Gao and E. N. Saridakis, 2013):*

$$S = \int d^4x\sqrt{-g}\left[\frac{R}{16\pi G} + X - V(\phi) - gX\Box\phi\right] \qquad V(f) = -V_0 e^{cf}$$

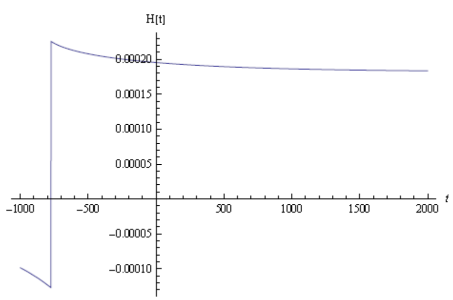


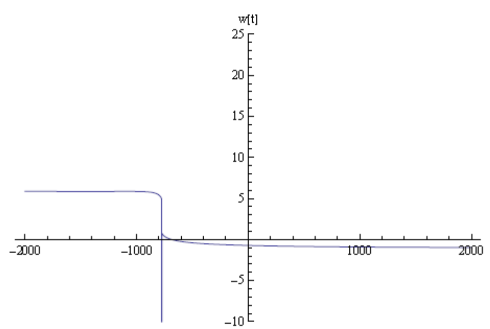


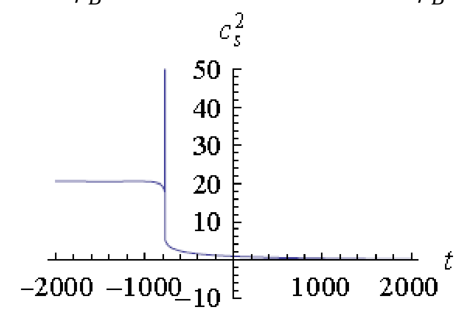


2) bounce inflation model ***(TQ,** Y. T. Wang, 2015):*

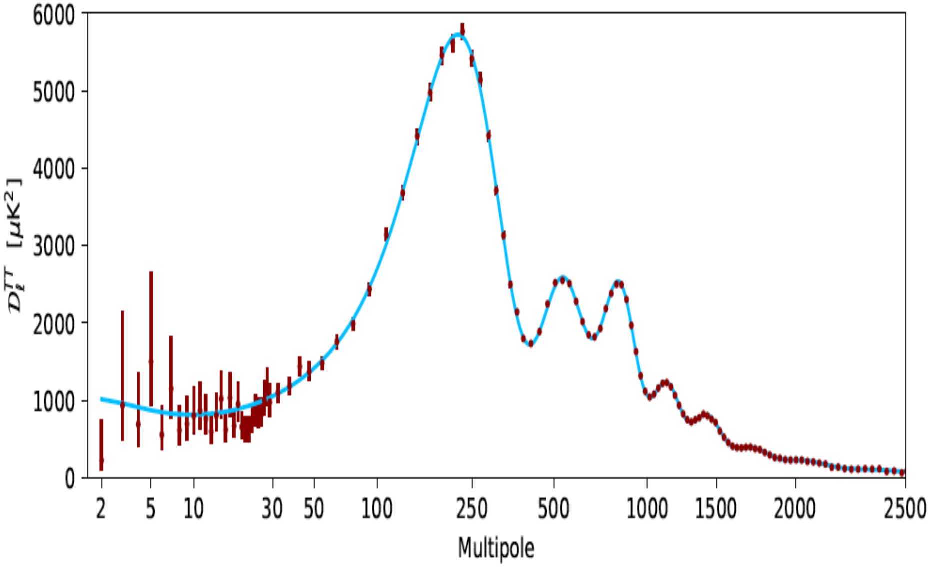
$$S = \int d^4x\sqrt{-g}\left[\frac{R}{16\pi G} + k(\phi)X + t(\phi)X^2 - V(\phi) - G(\phi, X)\Box\phi\right] \qquad V(\phi) = -V_0\left[1 - \tanh\left(\lambda_1\frac{\phi}{\phi_B}\right)\right]e^{c\phi} + \Lambda^4\left[1 + \tanh\left(\lambda_2\frac{\phi}{\phi_B}\right)\right]\left(1 - \frac{\phi^2}{v^2}\right)^2$$



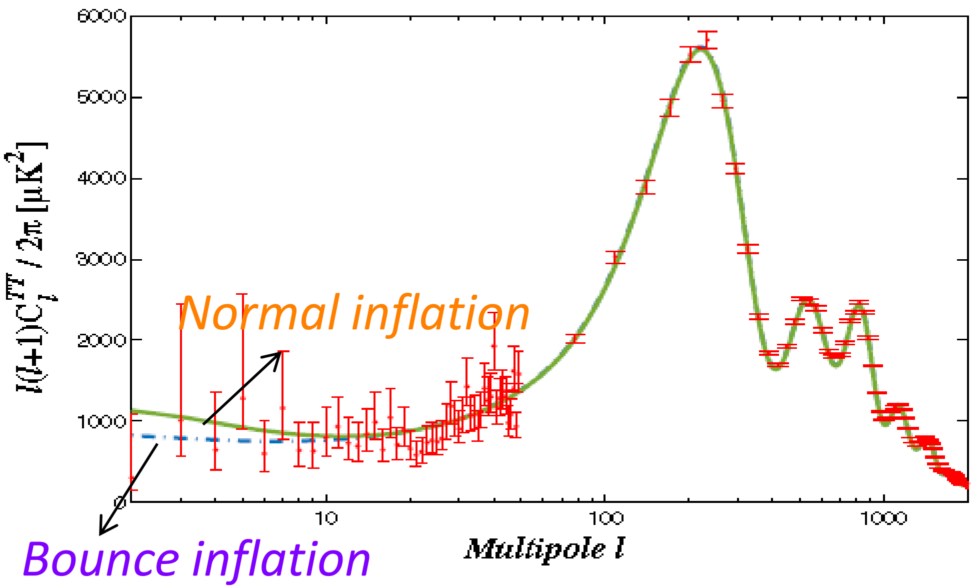




Bonus: Small-l suppression



Observations from PLANCK 2018



TQ, Y. T. Wang, JHEP 2015

4. Gradient Instability

In our model building, we found that it is difficult to also have the sound speed squared to be positive all the time.

The perturbation EoM:

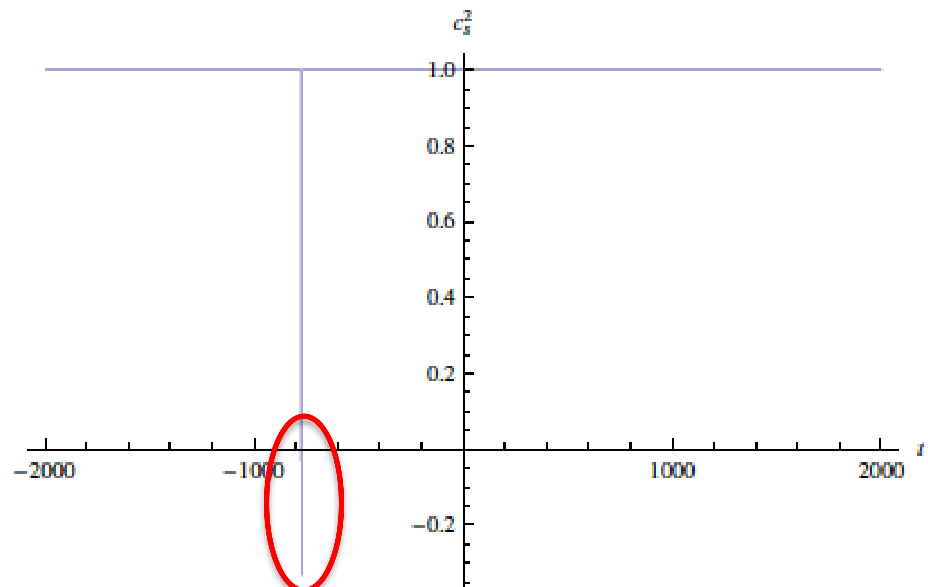
$$u_k'' + \left(c_s^2 k^2 - \frac{z''}{z} \right) u_k = 0$$

↑ sound speed squared

For $c_s^2 < 0$

$$u_k \sim e^{i\sqrt{c_s^2}kh} \sim e^{\pm|c_s|kh}$$

for large k modes.



Gradient Instability

(**TQ,** J. Evslin, Y. F. Cai, M. Z. Li, X. M. Zhang, 2011/Y. F. Cai, D. A. Easson, R. Brandenberger, 2012/**TQ,** X. Gao, E. Saridakis, 2013/M. Koehn, J. L. Lehners and B. A. Ovrut, 2014/L. Battara, M. Koehn, J. L. Lehners and B. A. Ovrut, 2014/**TQ** and Y. T. Wang, 2015……)

No-go Theorem

It has been proved that gradient instability is inevitable in cubic Galileon theories!

Abstract. We study spatially flat bouncing cosmologies and models with the early-time Genesis epoch in a popular class of generalized Galileon theories. We ask whether there exist solutions of these types which are free of gradient and ghost instabilities. We find that irrespectively of the forms of the Lagrangian functions, the bouncing models either are plagued with these instabilities or have singularities. The same result holds for the original Genesis model and its variants in which the scale factor tends to a constant as $t \to -\infty$. The result remains valid in theories with additional matter that obeys the Null Energy Condition and interacts with the Galileon only gravitationally. We propose a modified Genesis model which evades our no-go argument and give an explicit example of healthy cosmology that connects the modified Genesis epoch with kination (the epoch still driven by the Galileon field, which is a conventional massless scalar field at that stage).

Contents

It is this set of issues we address in this paper. We consider the simplest and best studied generalized Galileon theory interacting with gravity. The Lagrangian is (mostly negative signature; $\kappa = 8\pi G$)

$$L = -\frac{1}{2\kappa}R + F(\pi, X) + K(\pi, X)\Box\pi \,, \qquad (1.1)$$

Although linear perturbation theory suggests that, for some constructions, cubic Galileon theories can avoid pathologies during a period of NEC violation, it has been unclear until now whether this is possible when the NEC violating period includes a non-singular bounce. In fact, the recent arguments suggest that either the speed of sound of co-moving curvature modes becomes imaginary (*i.e.*, ghost or gradient instability) for some wavelengths during the NEC violating phase [6, 7] or the evolution must reach a singularity [8].

M. Libanov, S. Mironov, V. Rubakov, 2016; Anna Ijjas, Paul J. Steinhardt, 2016.

Solution: one must consider theories beyond cubic Galileon!

Solution: Effective Field Theory Description

The Effective field theory lagrangian (Cheung et al., 2007; Gleyzes et al., 2013; Kase et al., 2014)

$$
\begin{aligned}
S = \int d^4x\sqrt{-g}\Big[& \frac{M_p^2}{2} f(t)R - \Lambda(t) - c(t)g^{00} \\
& + \frac{M_2^4(t)}{2}(\delta g^{00})^2 - \frac{m_3^3(t)}{2}\delta K \delta g^{00} - m_4^2(t)\left(\delta K^2 - \delta K_{\mu\nu}\delta K^{\mu\nu}\right) + \frac{\tilde{m}_4^2(t)}{2} R^{(3)}\delta g^{00} \\
& - \bar{m}_4^2(t)\delta K^2 + \frac{\bar{m}_5(t)}{2} R^{(3)}\delta K + \frac{\bar{\lambda}(t)}{2}(R^{(3)})^2 + \ldots \\
& - \frac{\tilde{\lambda}(t)}{M_p^2}\nabla_i R^{(3)} \nabla^i R^{(3)} + \ldots \Big],
\end{aligned}
$$

Cubic Galileon: $f = 1 \qquad m_4^2 = \tilde{m}_4^2 = \bar{m}_4^2 = \bar{m}_5 = \bar{\lambda} = \tilde{\lambda} = 0$

Horndeski: $m_4^2 = \tilde{m}_4^2 \qquad \bar{m}_4^2 = \bar{m}_5 = \bar{\lambda} = \tilde{\lambda} = 0$

Beyond Horndeski (high order space derivative): every coefficient can be non-zero!

Eliminating The Gradient Instability

According to the No-Go Theorem proved using EFT approach (Y. Cai, Y. Wan, H. Li, **TQ,** Y. S. Piao, JHEP (2017); Y. Cai, H. Li, **TQ,** Y. S. Piao, EPJC (2017))

	$g_i < 0$	$g_i > 0$
Cubic Galileon	*No way*	*No way*
Beyond cubic galileon (in EFT language)	$Q_T = 0$: $g \sim (t - t_g)^p, Q_T \sim (t - t_g)^n$, n ³ $2p$	$Q_T = 0$: $Q_T \sim (-t)^{-p}, g \sim (-t)^{-n}$, $p > n > 1$ Kobayashi's work
	$Q_{\tilde{m}_4} = 0$	$Q_{\tilde{m}_4} = 0$

where $\gamma = HQ_T - \frac{m_3^3}{2M_p^2} + \frac{1}{2}\dot{f}$ $\qquad Q_{\tilde{m}_4} = f + \frac{2\tilde{m}_4^2}{M_p^2}$

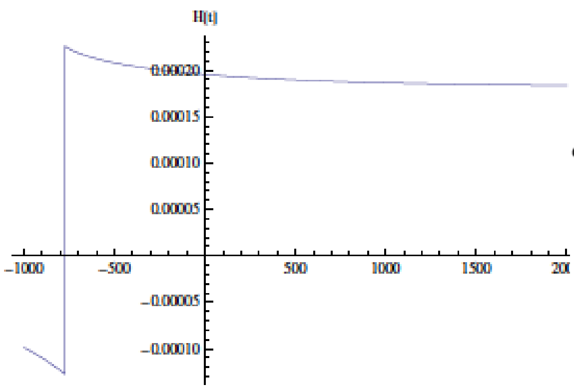
Q_T is the coefficient in front of kinetic term of tensor perturbation action.

Model Construction

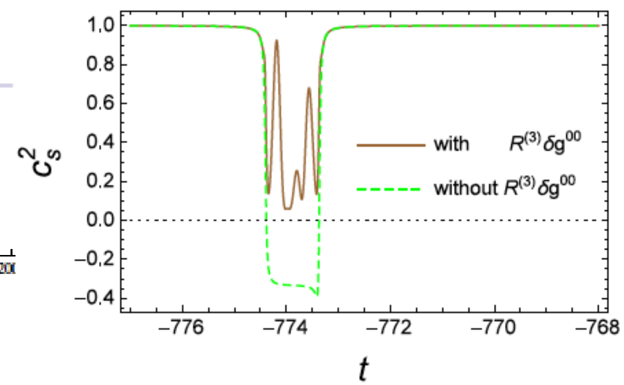
According to this conclusion, we can construct models free of gradient instability!

Action of a New Bounce Inflation Model:

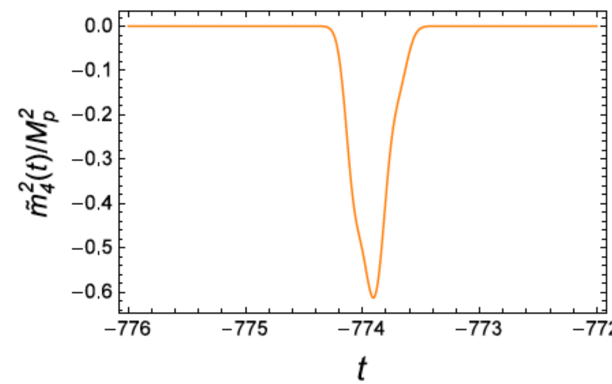
$$S = \int d^4x\sqrt{-g}\left[\frac{M_p^2}{2}R + \mathcal{K}(\phi)X - G_3(\phi,X)\Box\phi + T(\phi)X^2 - V(\phi) + \underline{\frac{\tilde{m}_4^2(t)}{2}R^{(3)}\delta g^{00}}\right]$$



Background



c_s^2 with/without the $\frac{\tilde{m}_4^2(t)}{2}R^{(3)}\delta g^{00}$ erm (green/brown)



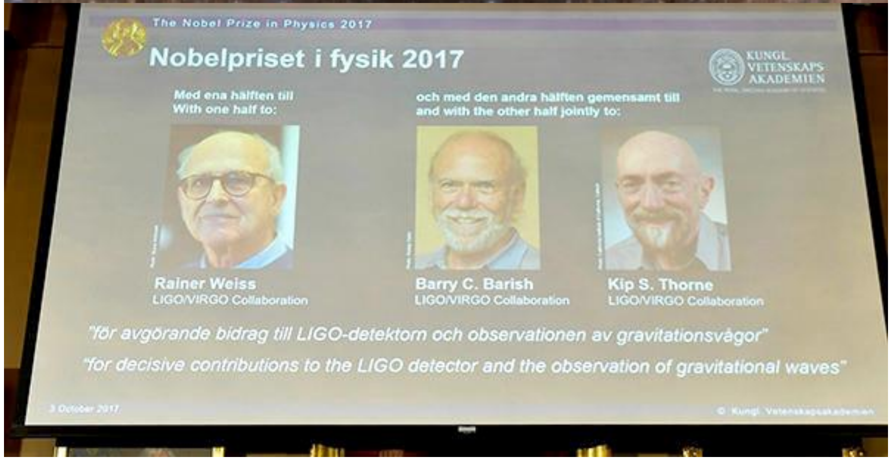
Evolution of $\tilde{m}_4^2(t)$

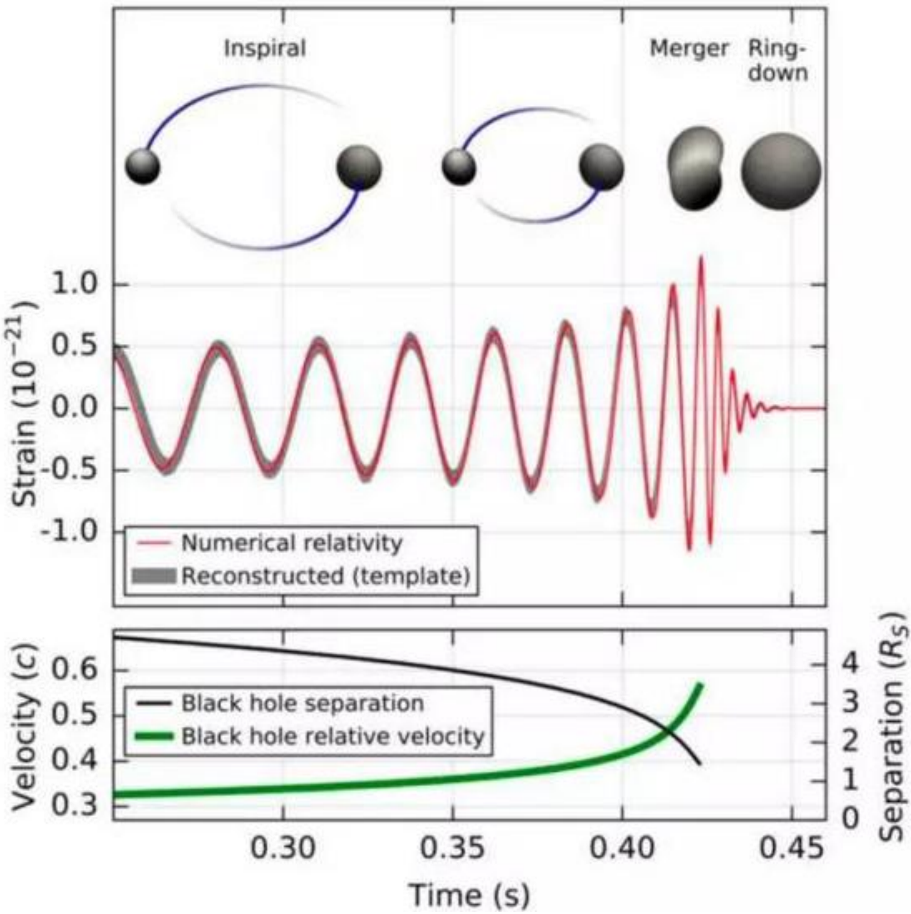
For covariant models, see Y. Cai and Y. S. Piao, JHEP 2017;
Y. Cai, Y. T. Wang, J. Y. Zhao and Y. S. Piao, 1709.07464;
Y. F. Cai, X. Gao, **TQ** et al., in preparation.

PART II: BRIEF INTRODUCTION OF ALICPT (CHINESE GRAVITATIONAL WAVE TELESCOPE)

Gravitational Waves

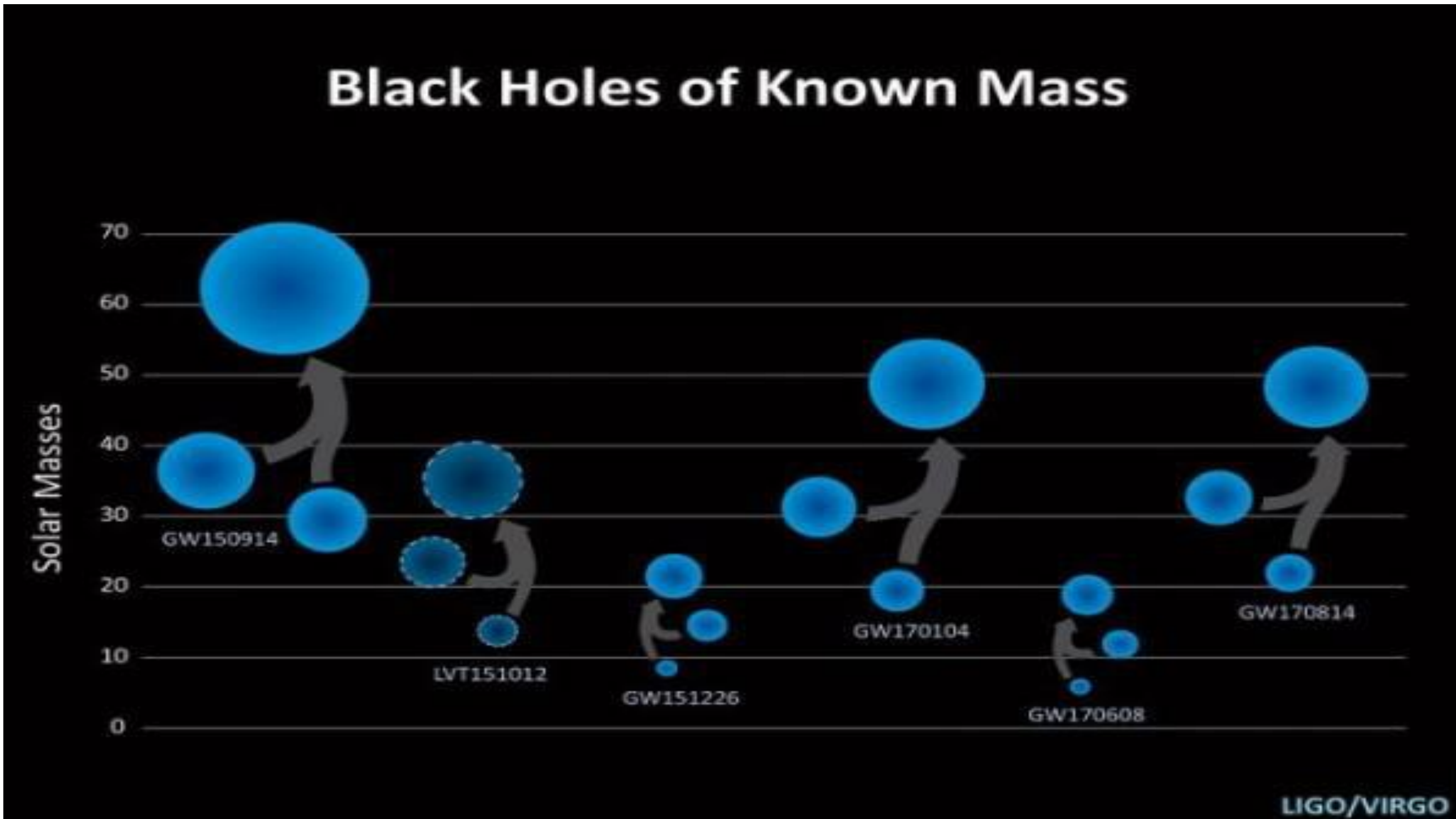
The first Big news about GW: GW150914



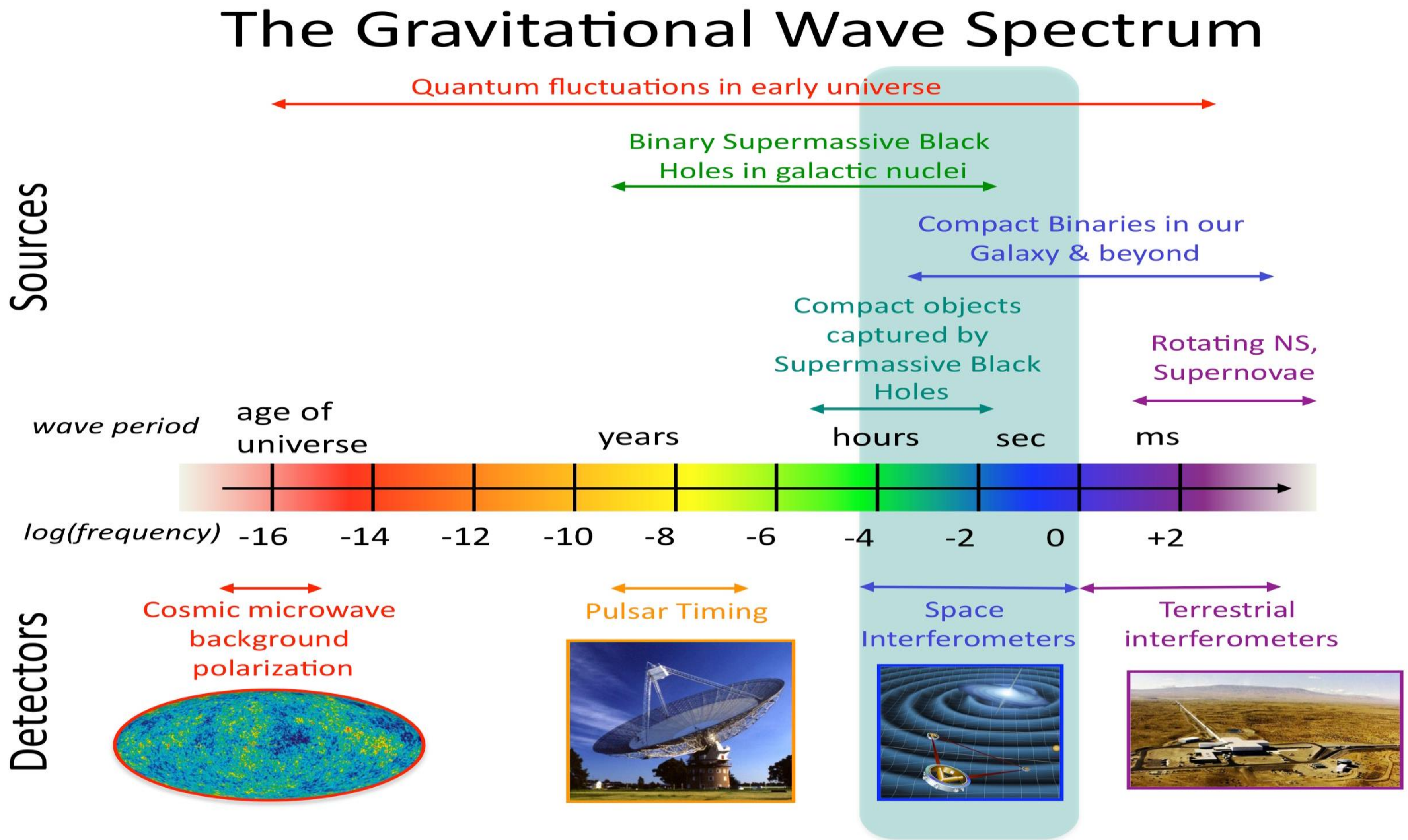


Gravitational Waves

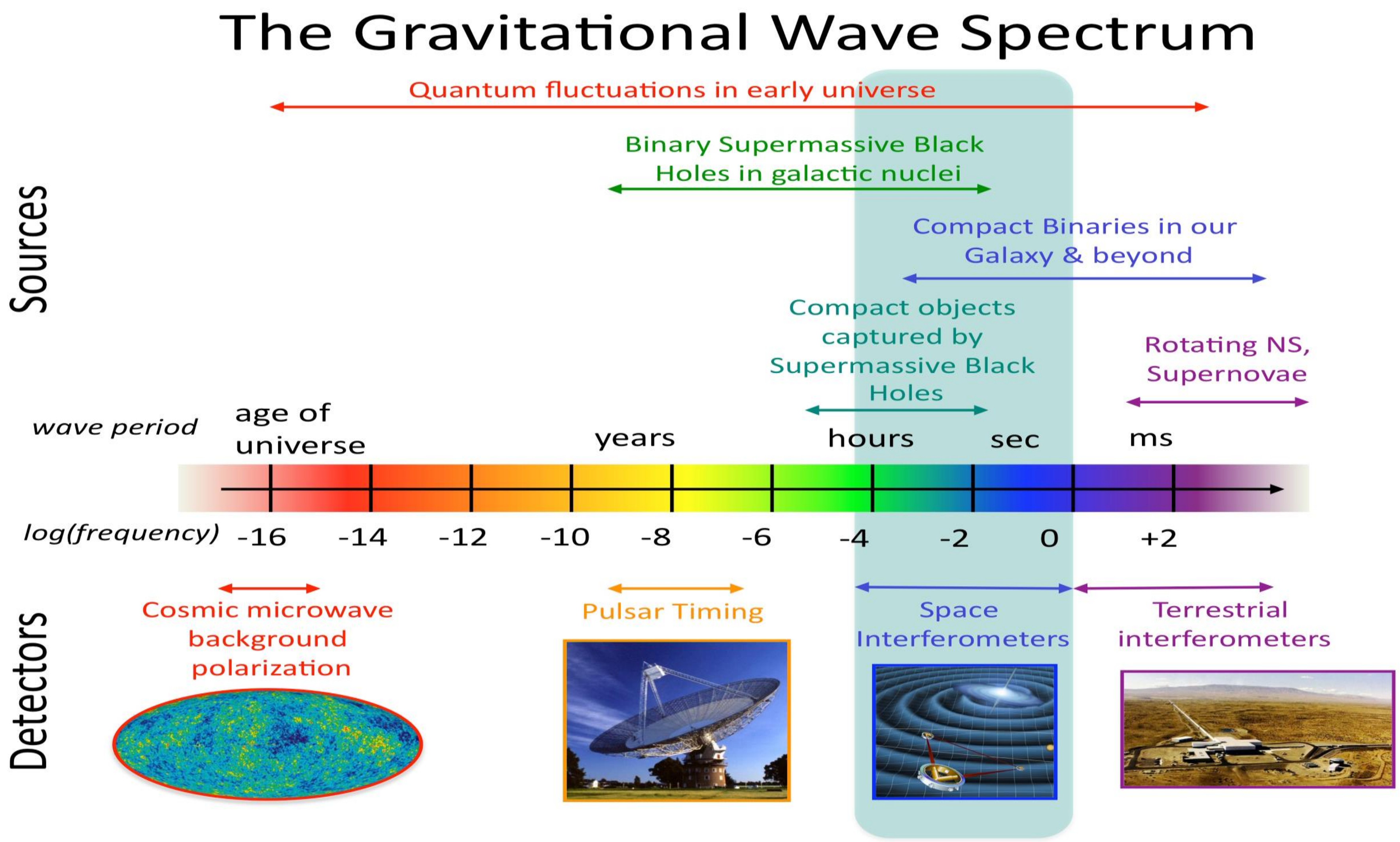
Then……



AliCPT: The next (primordial) GW detector



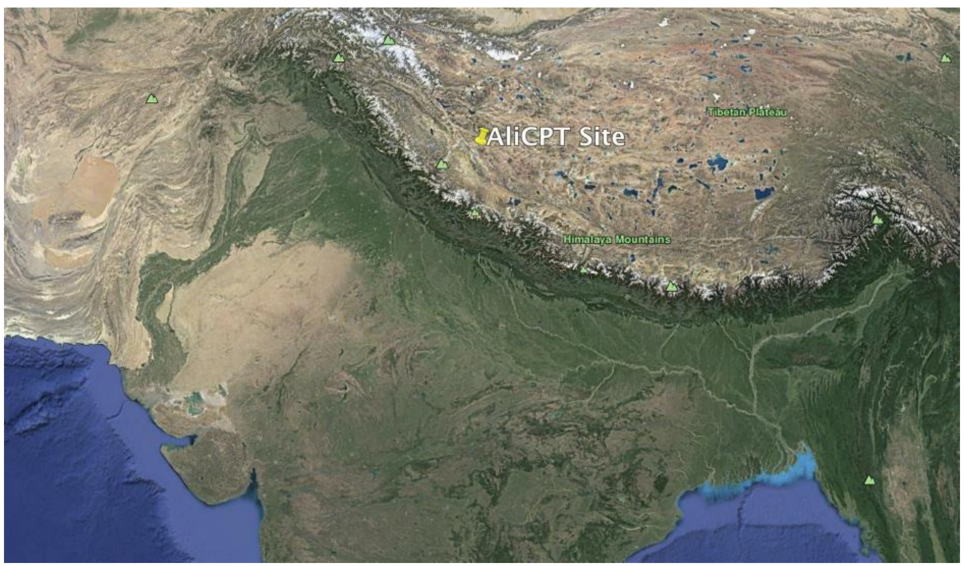
AliCPT: The next (primordial) GW detector

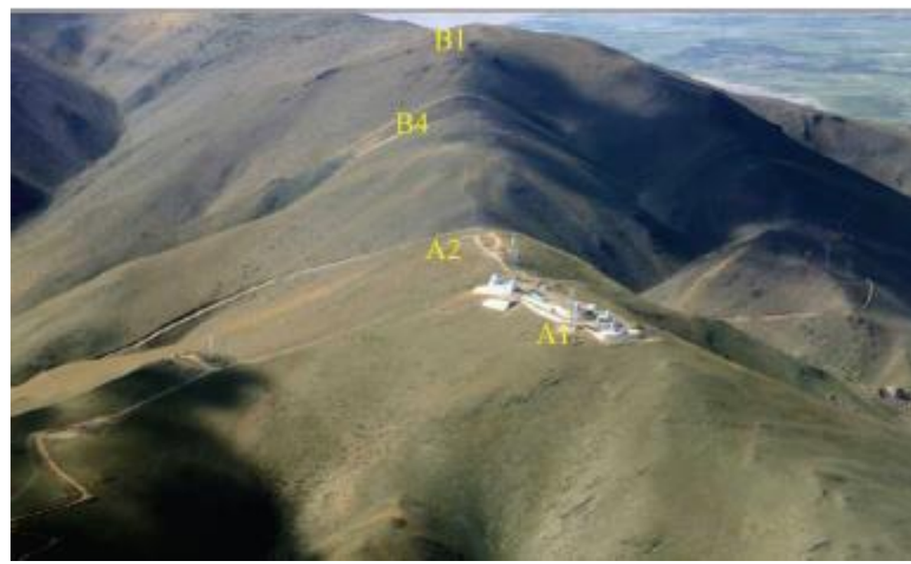


AliCPT: The next (primordial) GW detector

Ali CMB Polarization Telescope

Location: on a hilltop of 32° 18’38”N, 80° 01’50’’E, in the Ngari (Ali) Prefecture of Tibet,at an altitude of 5250 meters.
AliCPT (B1, 5250m) is only about 1km to Ali observatory, A1 station (5100m).



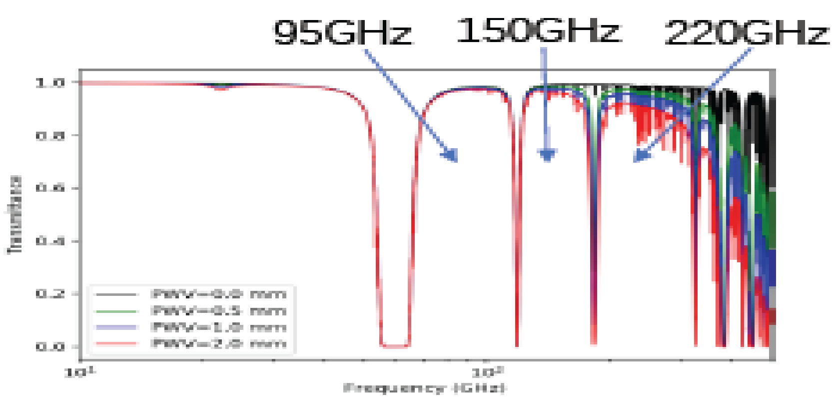


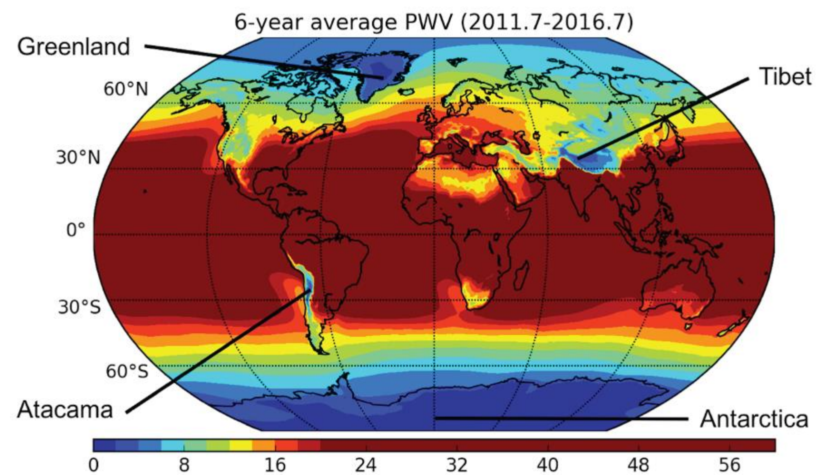
(Hong Li et al., 2018)

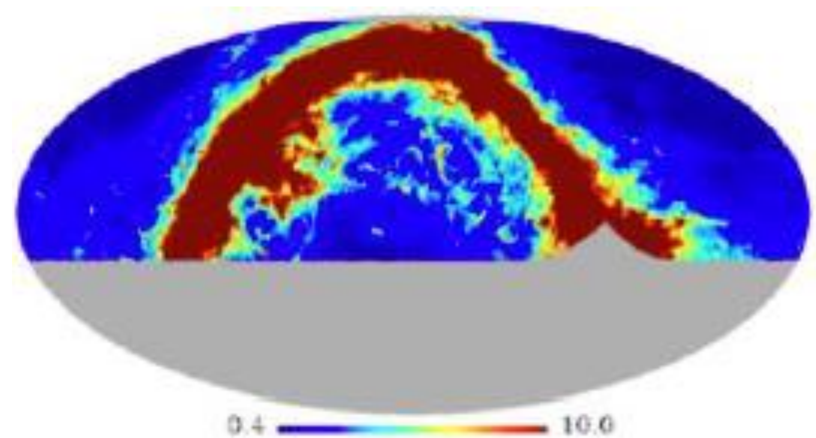
AliCPT: The next (primordial) GW detector

Why Ali?

- ✓ Ali is one of the 4 major sites with lowest Precipitable Water Vapor.
- ✓ For those 4, Ali is one of the two that is located in Northern hemisphere (the other is Greenland), which could provide a cross-check to those in Southern hemisphere (Antarctica & Actama, Chile).
- ✓ Ali can cover up to 65% of the sky region (Greenland: 30%).







(Y. P. Li et al., 1709.09053)

AliCPT: The next (primordial) GW detector

Science goals:

• to probe the primordial gravitational waves (PGWs) with BB spectra, and constrain the Early Universe with primordial GWs;

• to study on statistical properties of each component in B-mode polarization;

• to measuring the rotation angle, testing CPT symmetry with TB and EB spectra;

• to investigate the CMB polarization large-scale anomalies such as hemispherical asymmetry;

• to studying the galactic foreground and searching for the cleanest region with lowest foreground for deep survey;

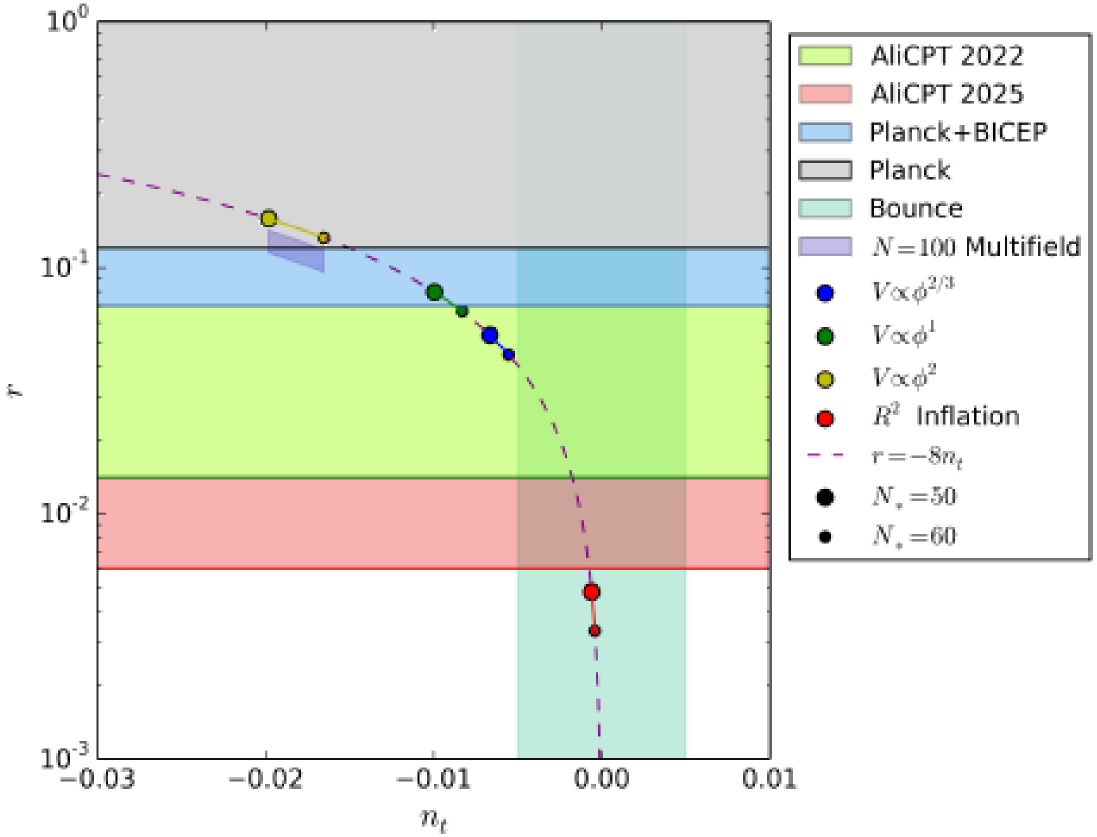
• to studying the weak-lensing effect, and the cross-correlation between CMB and LSS;

• to studying the dark energy property, neutrino masses；

…… ……

AliCPT: The next (primordial) GW detector

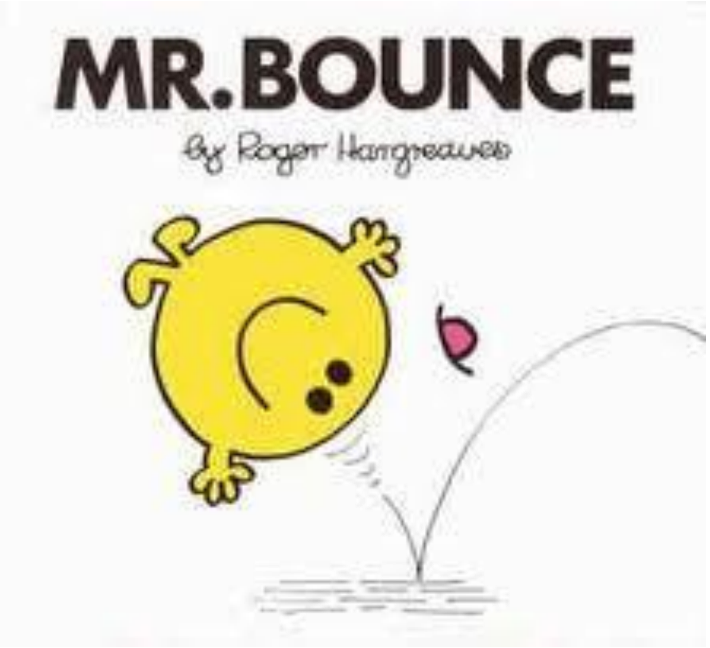
Estimated constraint on amplitude of primordial GW (in terms of tensor/scalar ratio r)



Conclusion

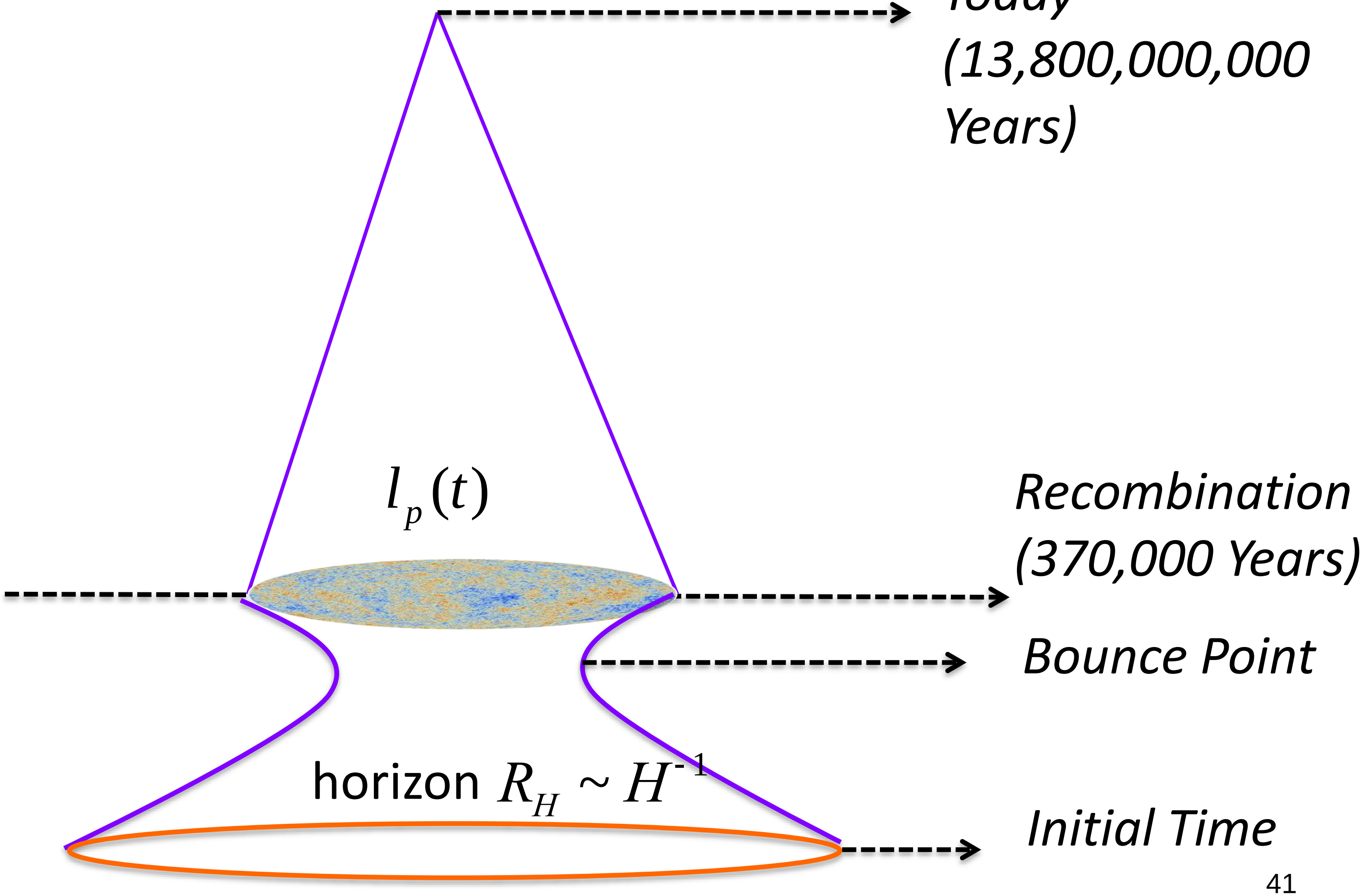
- Big-Bang/inflation scenarios suffers from singularity problem.
- Singularity problem can be solved by a bounce scenario, but there are new problems.
- Anisotropy problem---Ekpyrotic phase contraction;
- Scale invariance---Matter contraction/Multifield contraction/Bounce Inflation;
- Ghost instability---Galileon/Horndeski/Beyond H;
- Gradient instability---EFT approach;
- AliCPT: New GW detector and will achieve data soon! Can we constraint the non-singular models?

Thanks For Attention!



Non-Singular Cosmology

Solution to horizon problem



Non-Singular Cosmology

Solution to horizon problem

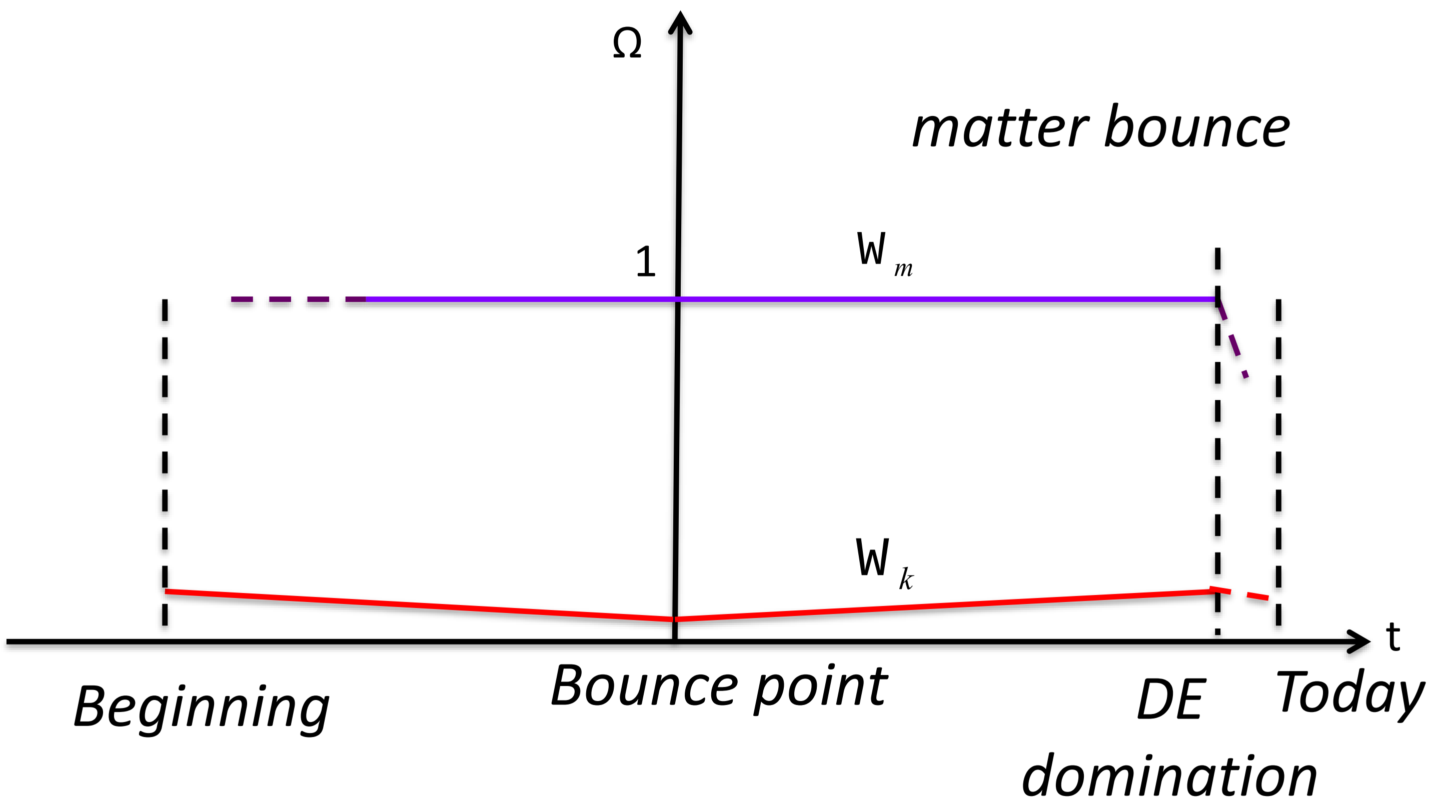
To solve the horizon problem, one requires $w<-1/3$ in expanding phase or $w>-1/3$ in contracting phase.

model	behavior	Equation of state	Horizon problem?
Big-Bang	*expanding*	$w>-1/3$	*Y*
Inflation	*expanding*	$w=-1$	*N*
Bounce	*when contracting*	*As long as* $w>-1/3$	*N*

Non-Singular Cosmology

Solution to flatness problem

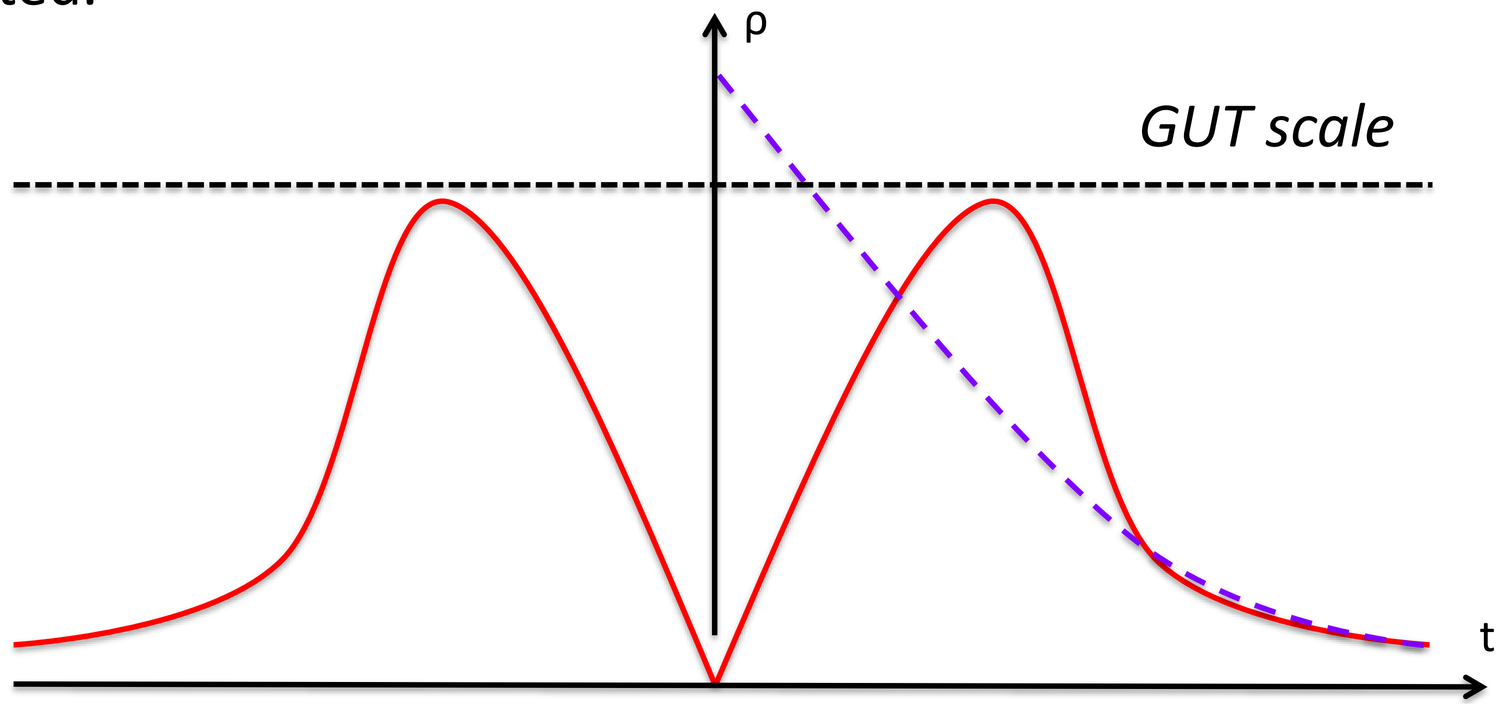
This problem can be avoided if the spatial curvature in the contracting phase when the temperature is comparable to today is not larger than the current value.



Non-Singular Cosmology

Solution to unwanted relics problem

This problem can be solved if the maximum value of the energy density during bounce doesn't exceed the $(GUT\ scale)^4$, so that there is no GUT symmetry breaking and no monopoles are created.



So-called "*Anti-gravitational effects*" during the bounce.