Probing Early Universe with PBHs and SIGWs

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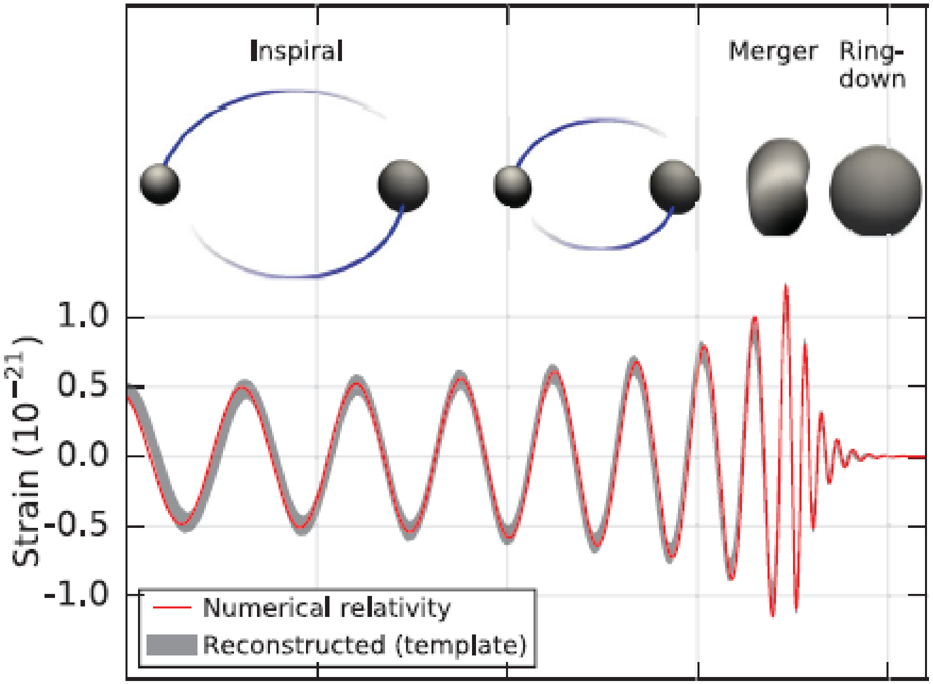
Outline

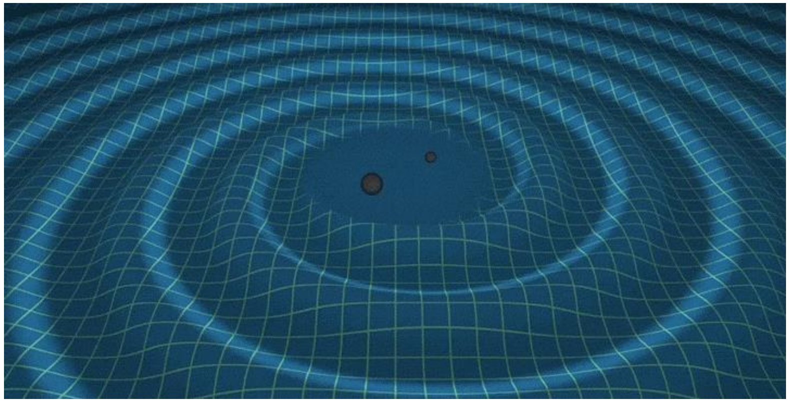
- Gravitational Waves (GWs) and Gravitational Universe
- Inflation and GWs in early Universe
- Higgs inflation
- The new enhancement mechanism
- Conclusions

Gao, Gong and Li, 1405.6451 (PRD); Di and Gong, 1707.09578 (JCAP); Yi and Gong, 1712.07478 (JCAP); Lu etal., 1907.11896 (JCAP); Lin etal, 2001.05909 (PRD); Lu etal., 2006.03450 (PRD); Yi etal., 2007.09957 (PRD); Arshad etal., 2009.11081 (PRD); Yi etal., 2011.10606 (PRD); Zhang etal., 2012.06960 (JCAP); Gao etal., 2012.03856

Motivation

- The discovery of Gravitational Waves (GWs)

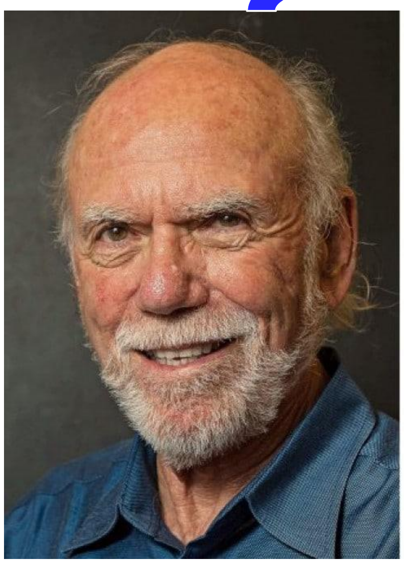




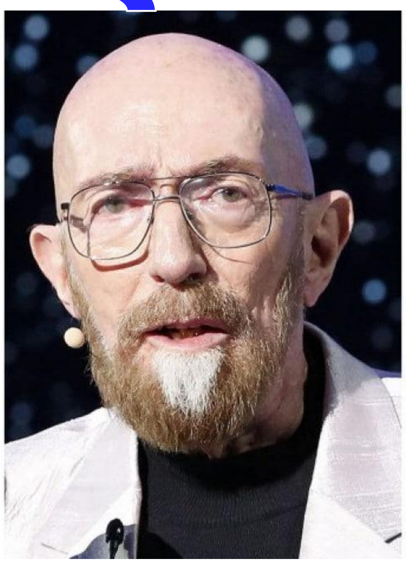
GW150914: PRL 116 (16) 061102

The discovery of GWs

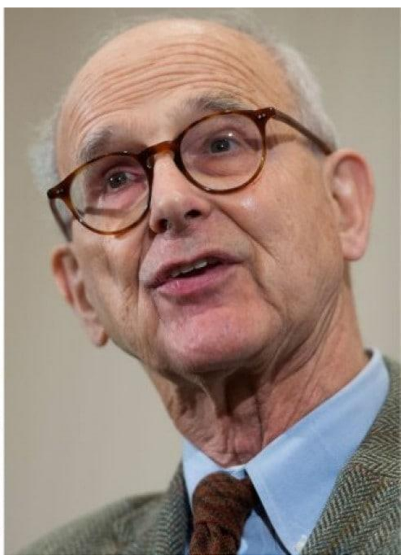
2017 Nobel Prize



Barry C. Barish



Kip S. Thorne

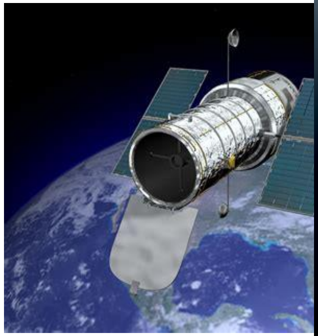


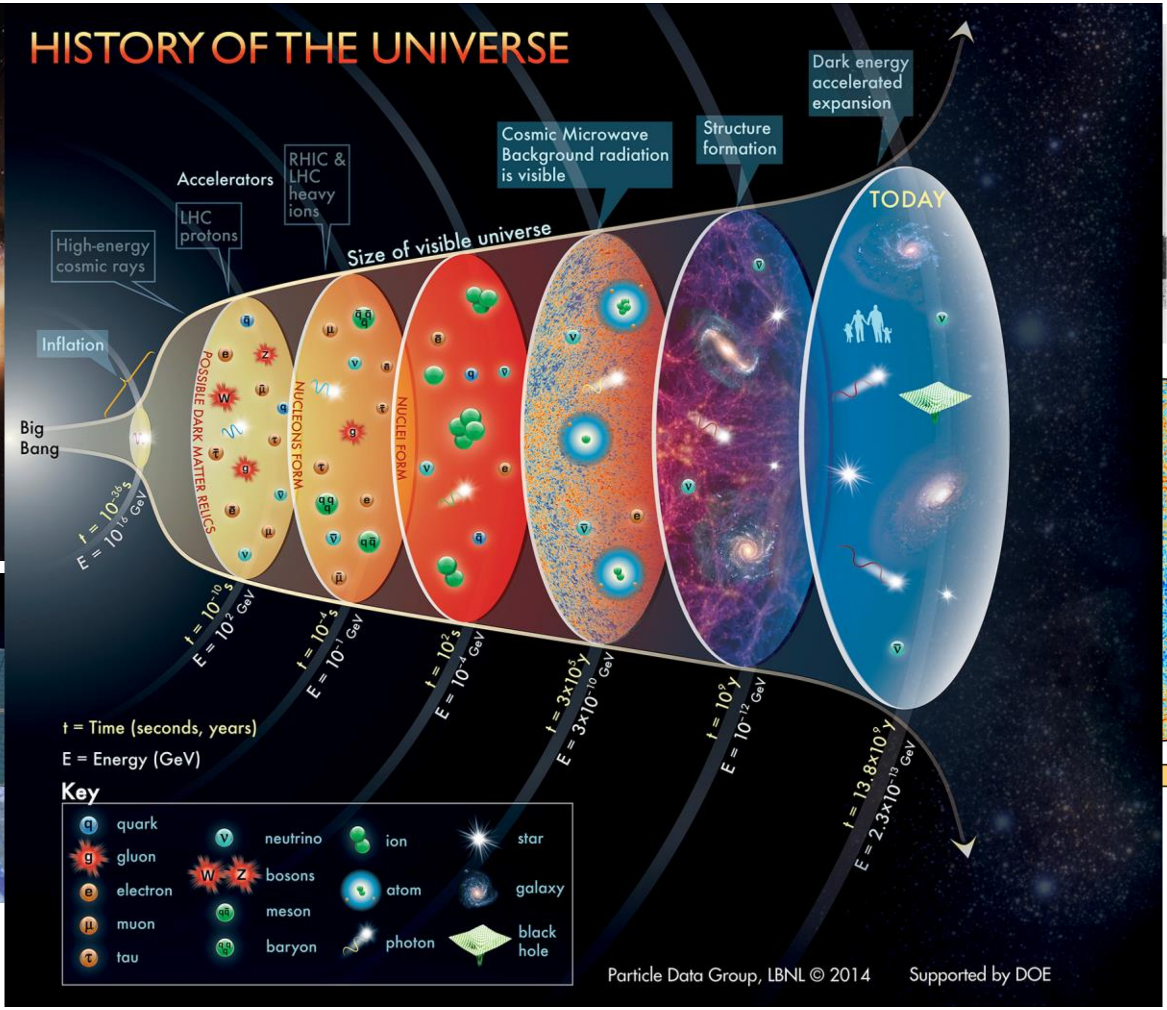
Rainer Weiss

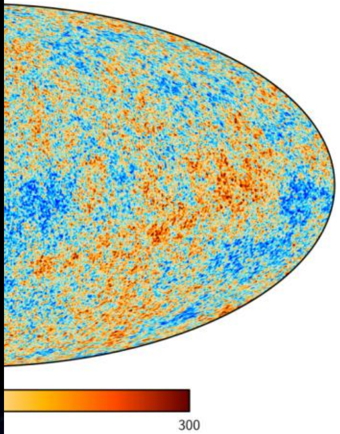
For decisive contributions to the LIGO detector and the observation of gravitational waves

Seeing the Universe

- Electromagnetic method







Gravitational Universe

- Opens a new window to uncover the Universe

- The dawn of multi-band/multi-messenger astronomy

eLISA, 1305.5720

GW tools

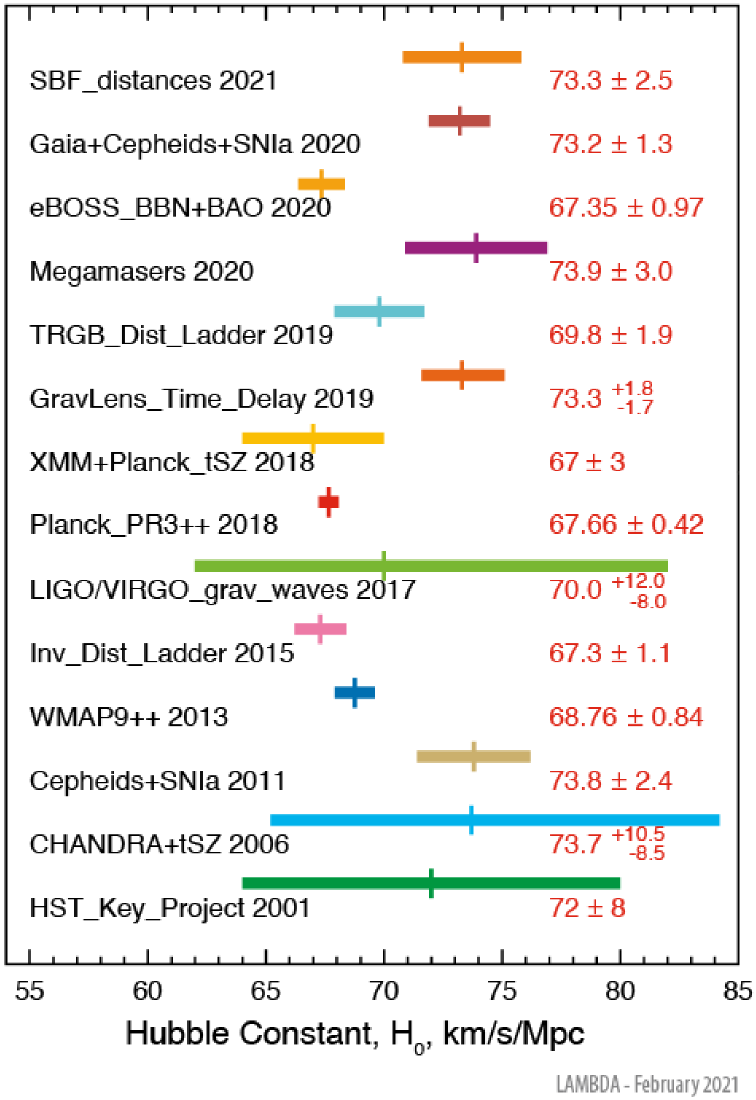
- Test of gravity in strong field and nonlinear regimes
- Provides model independent measurement of distance

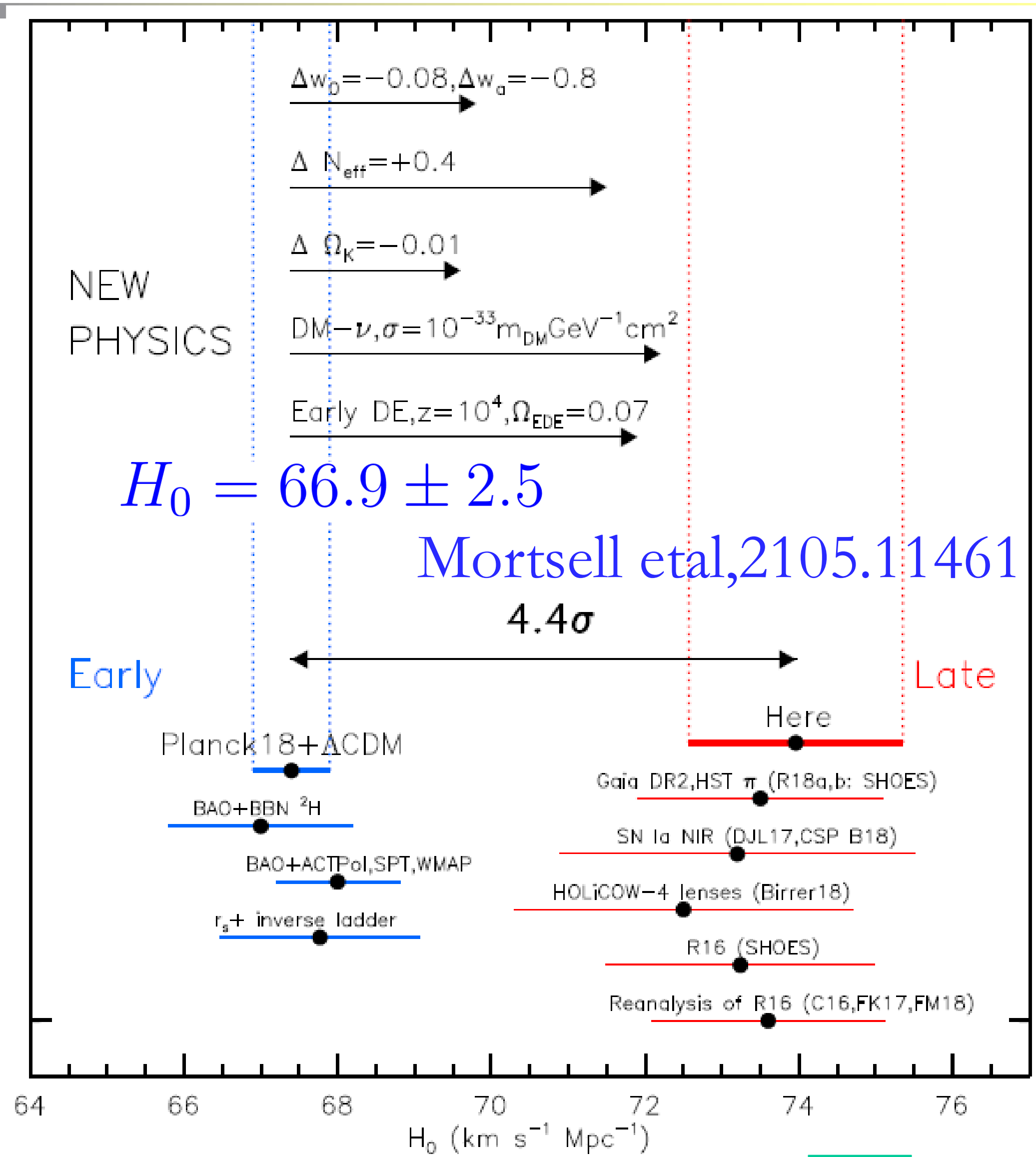
GW170817/GRB170817A

- Ground-based detectors: source localization
  - 10-1000Hz frequency band
  - A few seconds of signals
  - Stellar mass black holes and neutron stars

Three or more detectors needed: Timing Triangulation

Hubble constant measurements





https://lambda.gsfc.nasa.gov/education/graphic_history/hubb_const.cfm

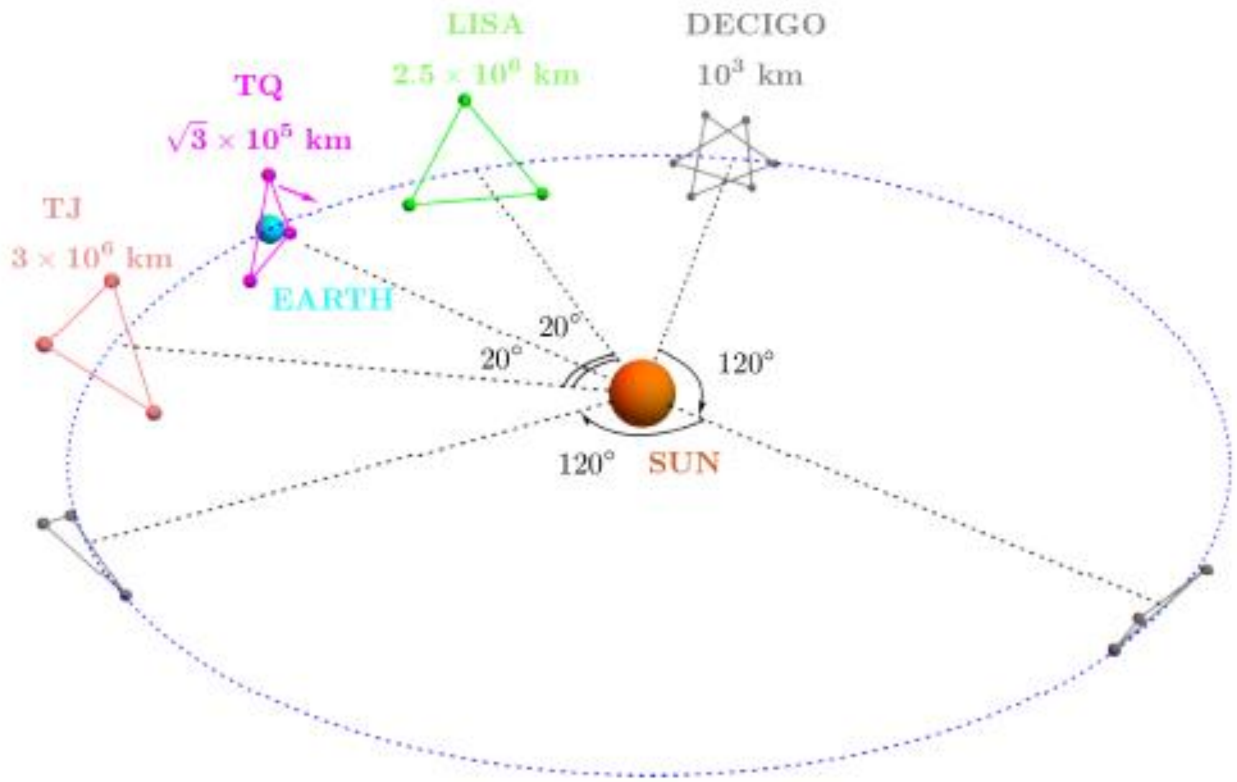
Spaceborne detectors

- Space-based detectors
  - mHz band
  - Last several years
  - Early inspiral signals (monochromatic): months to years before merger
  - Inspiral, merger and ringdown signals
  - Massive and Supermassive BHs
  - Extreme mass ratio inspiral (EMRI)
  - Sky localization and polarization measurement

The motion of detectors: Doppler modulation

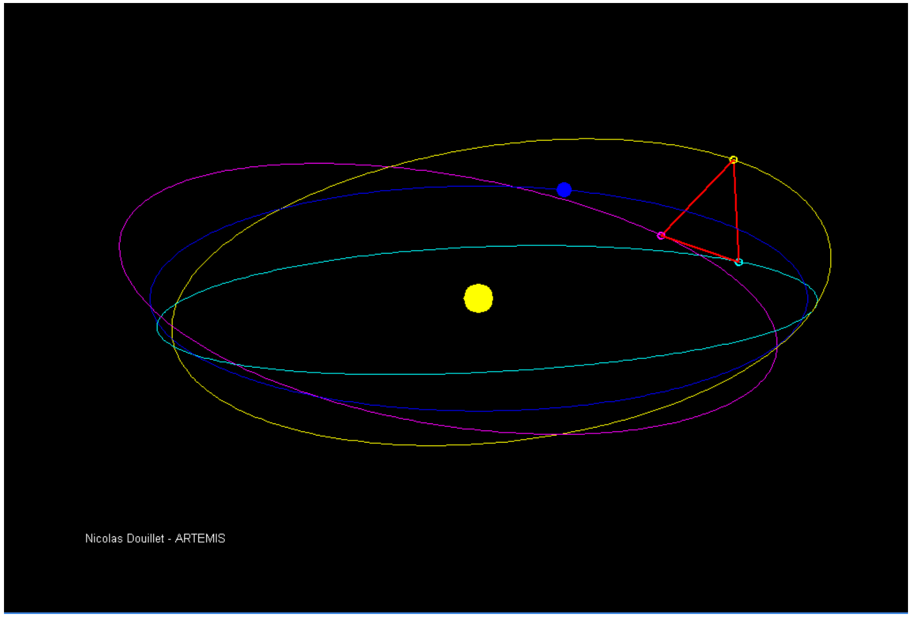
Space-based GW detectors

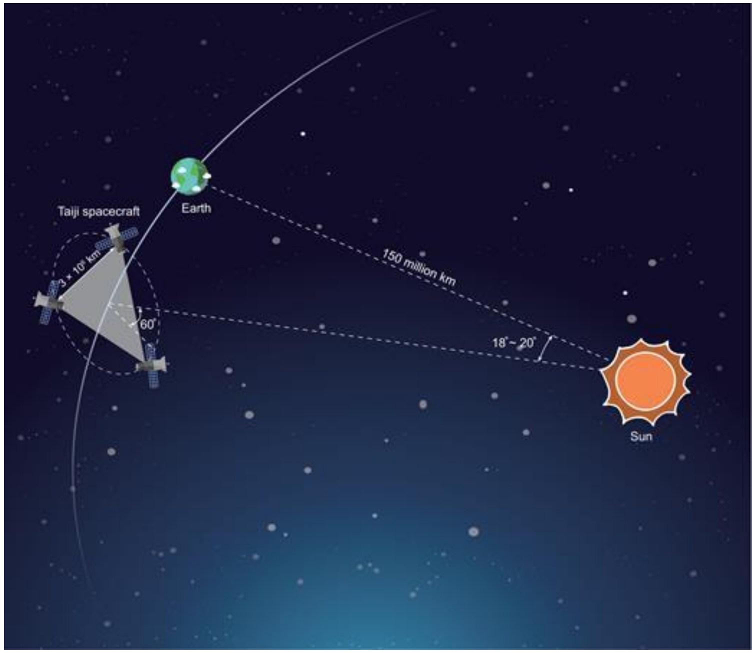
- LISA/Taiji/TianQin/DECIGO (OMEGA)

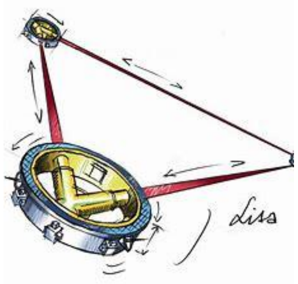


Space born GW detector

- LISA/Taiji/TianQin: Polarization

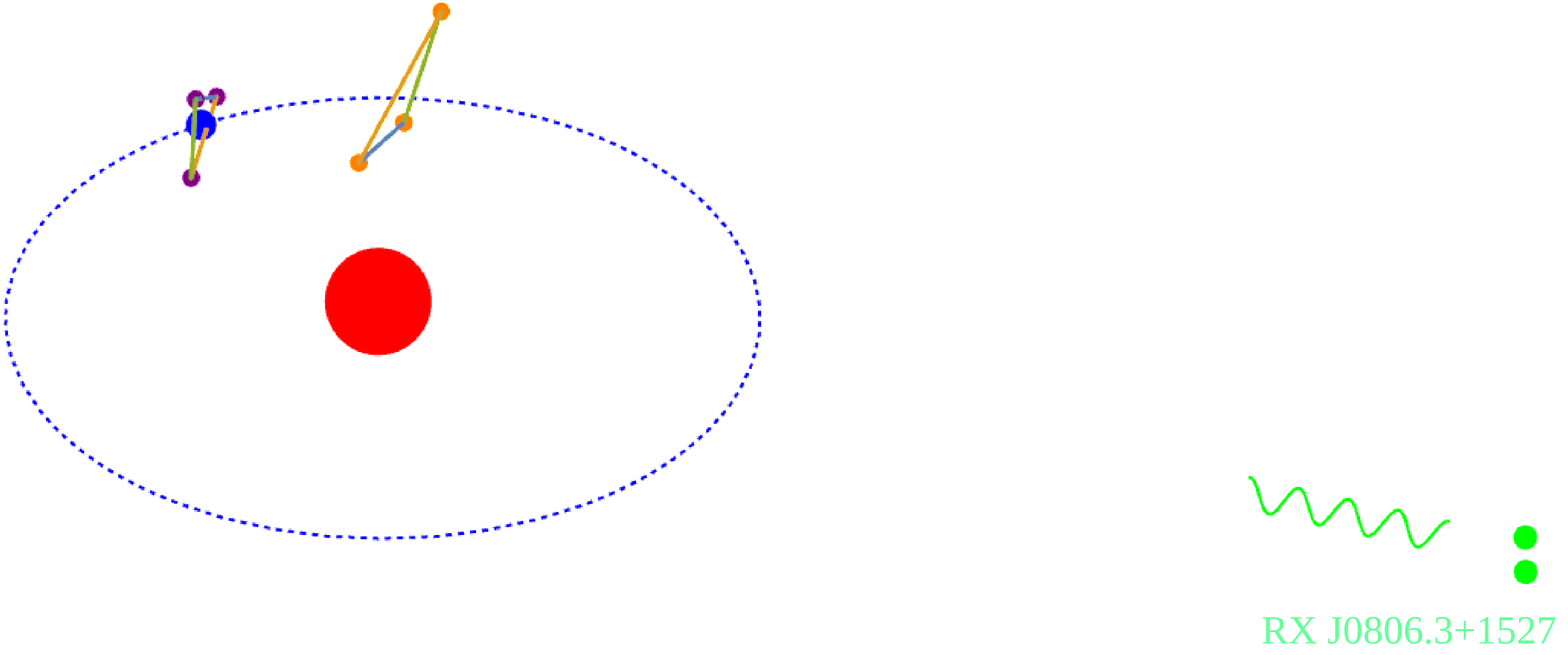






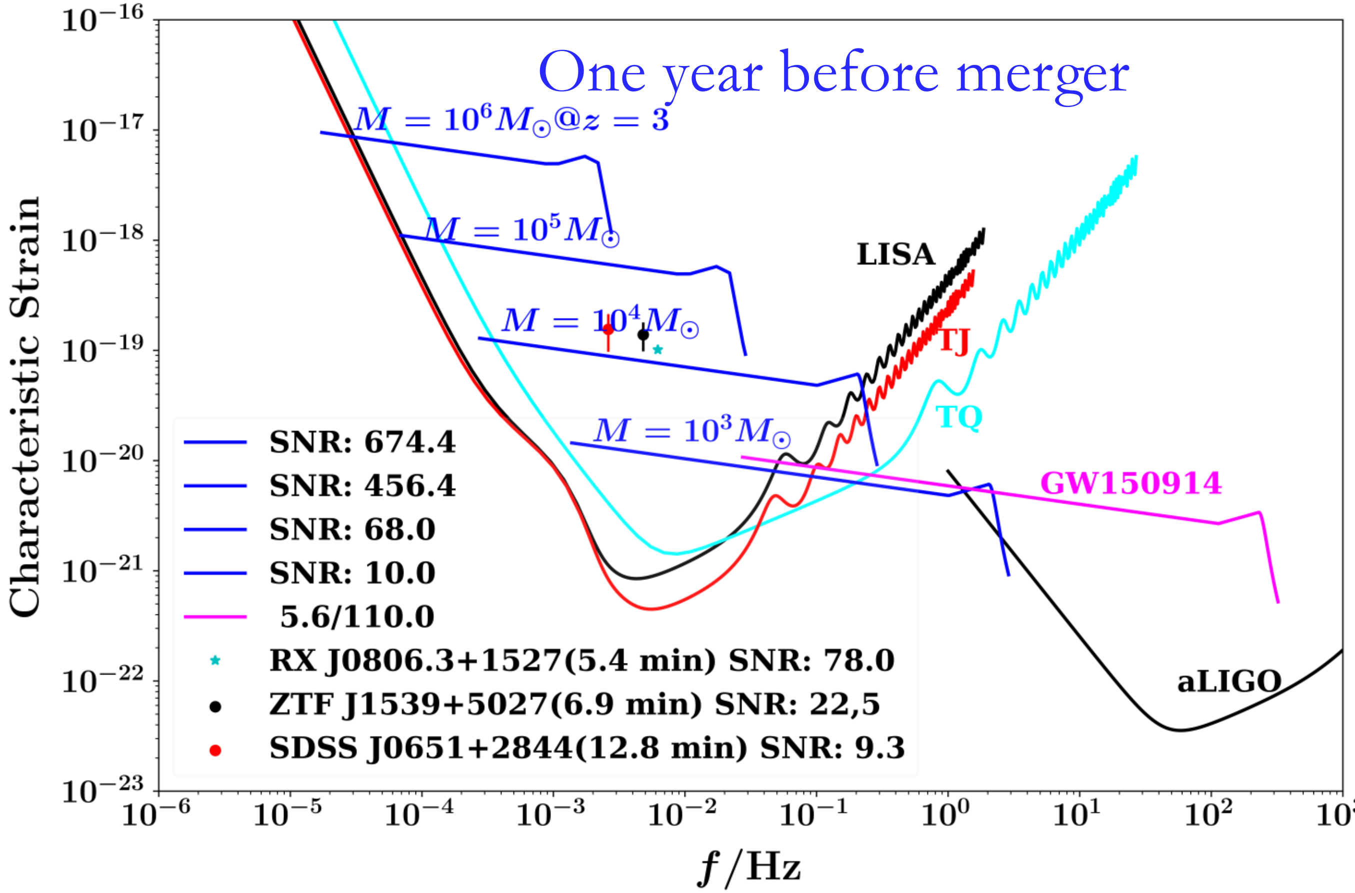
LISA/Taiji/TianQin

- TianQin



LISA/Taiji/TianQin

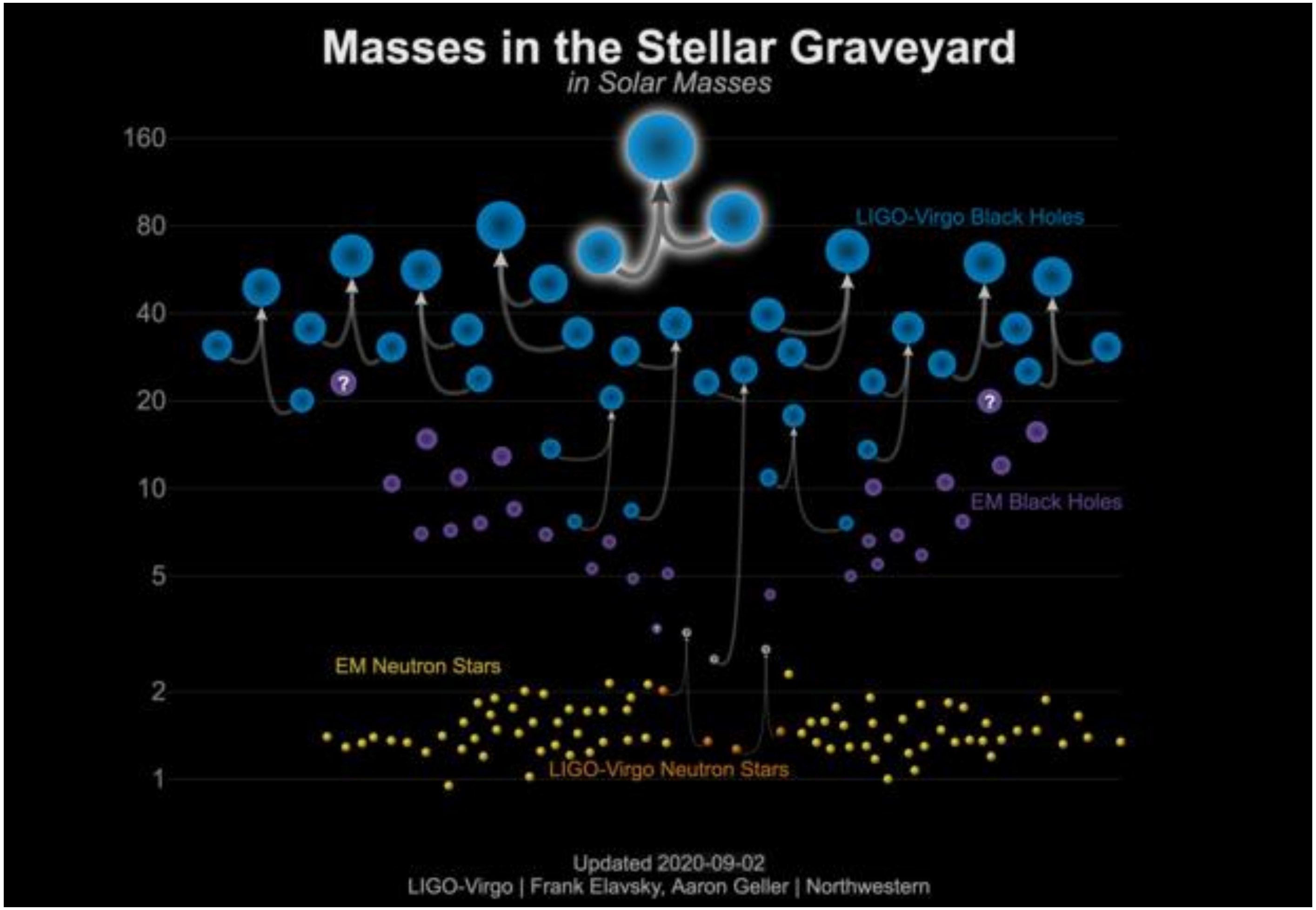
- Noise Curve



LIGO/Virgo Results

- Tens of GWs

GWTC-1: 1811.12907
GWTC-2: 2010.14527



LIGO/Virgo Results

- GW170817: first BNS with EM counterparts, Standard Siren
- GW190425: BNS? 1.6/1.46 solar mass NS?
- GW190412: 30/8 BBH with asymmetric mass, higher multipoles
- GW190814: 23/2.6 solar mass, heaviest NS or lightest BH?
- GW190521: Intermediate mass BH, about 150 solar mass BH

GWTC2: 2010.14527

Primordial black holes (PBHs)

- PBHs: PBH forms in the radiation era as a result of gravitational collapse of density perturbations generated during inflation

Hawking, MNRAS 152 (1971) 75;
Carr & Hawking, MNRAS 168 (1974) 399

- PBHs: LIGO/Virgo BHs are PBHs?

PRL **116,** 201301 (2016) PHYSICAL REVIEW LETTERS week ending 20 MAY 2016

Did LIGO Detect Dark Matter?

Simeon Bird,* Ilias Cholis, Julian B. Muñoz, Yacine Ali-Haïmoud, Marc Kamionkowski, Ely D. Kovetz, Alvise Raccanelli, and Adam G. Riess

PRL **117,** 061101 (2016) PHYSICAL REVIEW LETTERS week ending 5 AUGUST 2016

Primordial Black Hole Scenario for the Gravitational-Wave Event GW150914

Misao Sasaki,[1] Teruaki Suyama,[2] Takahiro Tanaka,[3,1] and Shuichiro Yokoyama[4]

PBHs from LIGO/Virgo

- LIGO/Virgo

PHYSICAL REVIEW LETTERS **126**, 051101 (2021)

GW190521 Mass Gap Event and the Primordial Black Hole Scenario

V. De Luca,[1] V. Desjacques,[2] G. Franciolini,[1] P. Pani,[3,4] and A. Riotto[1]

PHYSICAL REVIEW LETTERS **126**, 071101 (2021)

GW190425; GW190814

Test for the Origin of Solar Mass Black Holes

Volodymyr Takhistov,[1,2,*] George M. Fuller,[3,4,†] and Alexander Kusenko[1,2]

Evidence from GWTC-2 data: 2102.03809; 2105.03349→30% PBHs

Evidence for PBH DM

- Planet 9

PHYSICAL REVIEW LETTERS **125,** 051103 (2020)

Editors' Suggestion   Featured in Physics

What If Planet 9 Is a Primordial Black Hole?

Jakub Scholtz[1] and James Unwin[2]

- NANOGrav

PHYSICAL REVIEW LETTERS **126,** 041303 (2021)

Editors' Suggestion

NANOGrav Data Hints at Primordial Black Holes as Dark Matter

V. De Luca,[1,*] G. Franciolini,[1,†] and A. Riotto[1,2,‡]

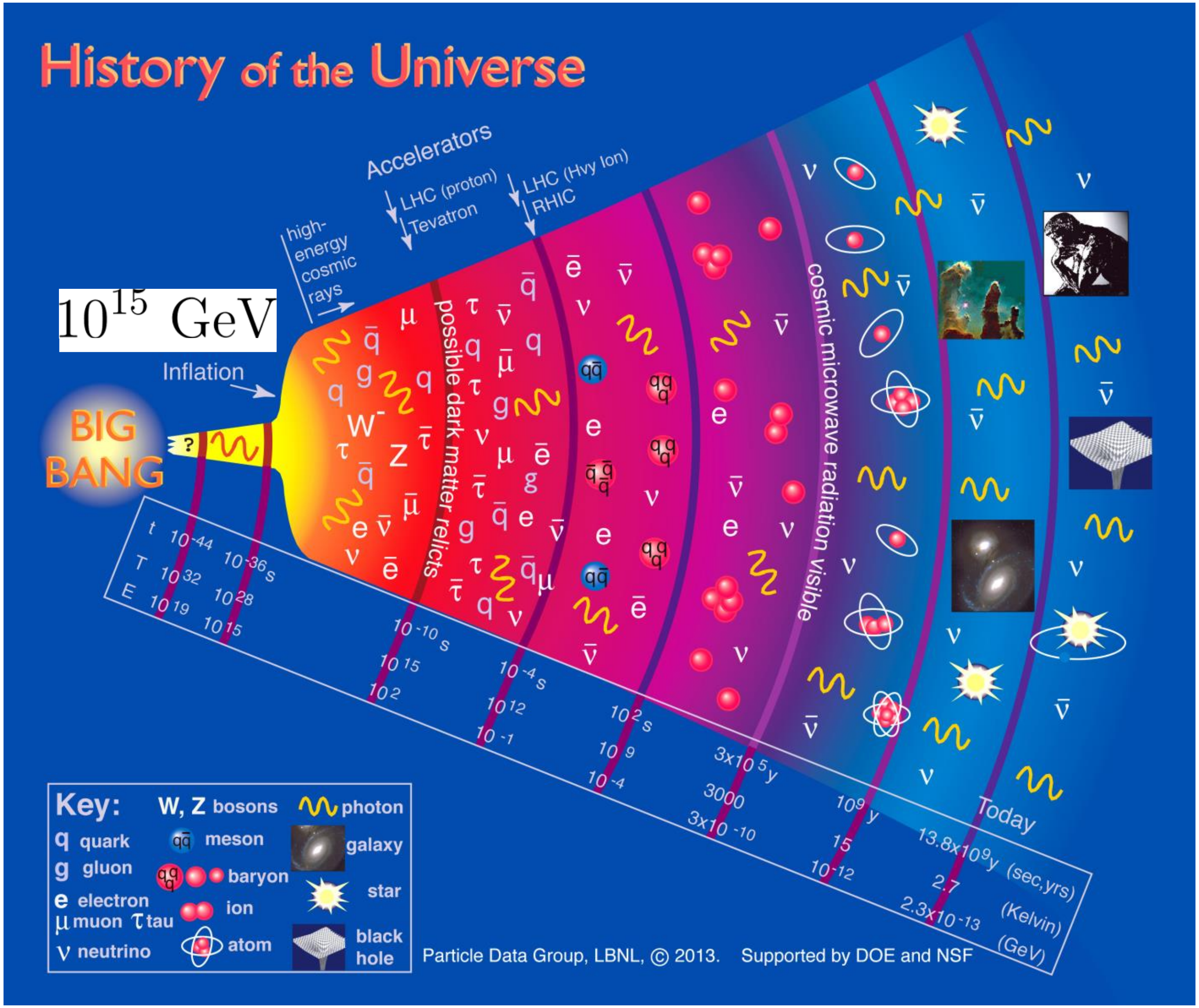
PHYSICAL REVIEW LETTERS **126,** 051303 (2021)

Editors' Suggestion

Did NANOGrav See a Signal from Primordial Black Hole Formation?

Ville Vaskonen[1,*] and Hardi Veermäe[2,†]

Early Universe



Inflationary models

- The power spectrum is parameterized

$$\mathscr{P}_{\mathscr{R}} = \frac{k^3}{2\pi^2}|\mathscr{R}_k|^2 = A_{\mathscr{R}}(k_*)\left(\frac{k}{k_*}\right)^{n_s-1+\frac{1}{2}n_s'\ln(k/k_*)+\cdots}$$

order of 10^{-9}

$$\mathscr{P}_T = A_T(k_*)\left(\frac{k}{k_*}\right)^{n_t+\frac{1}{2}n_t'\ln(k/k_*)+\cdots} \approx 64\pi G\left(\frac{H}{2\pi}\right)^2$$

$$n_s - 1 = \left.\frac{d\ln\mathscr{P}_{\mathscr{R}}}{d\ln k}\right|_{k=aH} = 3 - 2\nu = 2\eta_H - 4\epsilon_H \approx 2\eta - 6\epsilon$$

$$r = \frac{A_T}{A_{\mathscr{R}}} = 16\epsilon_H = 16\epsilon = -8n_T \qquad A_T = rA_{\mathscr{R}} \sim H^2 \sim V(\phi)$$

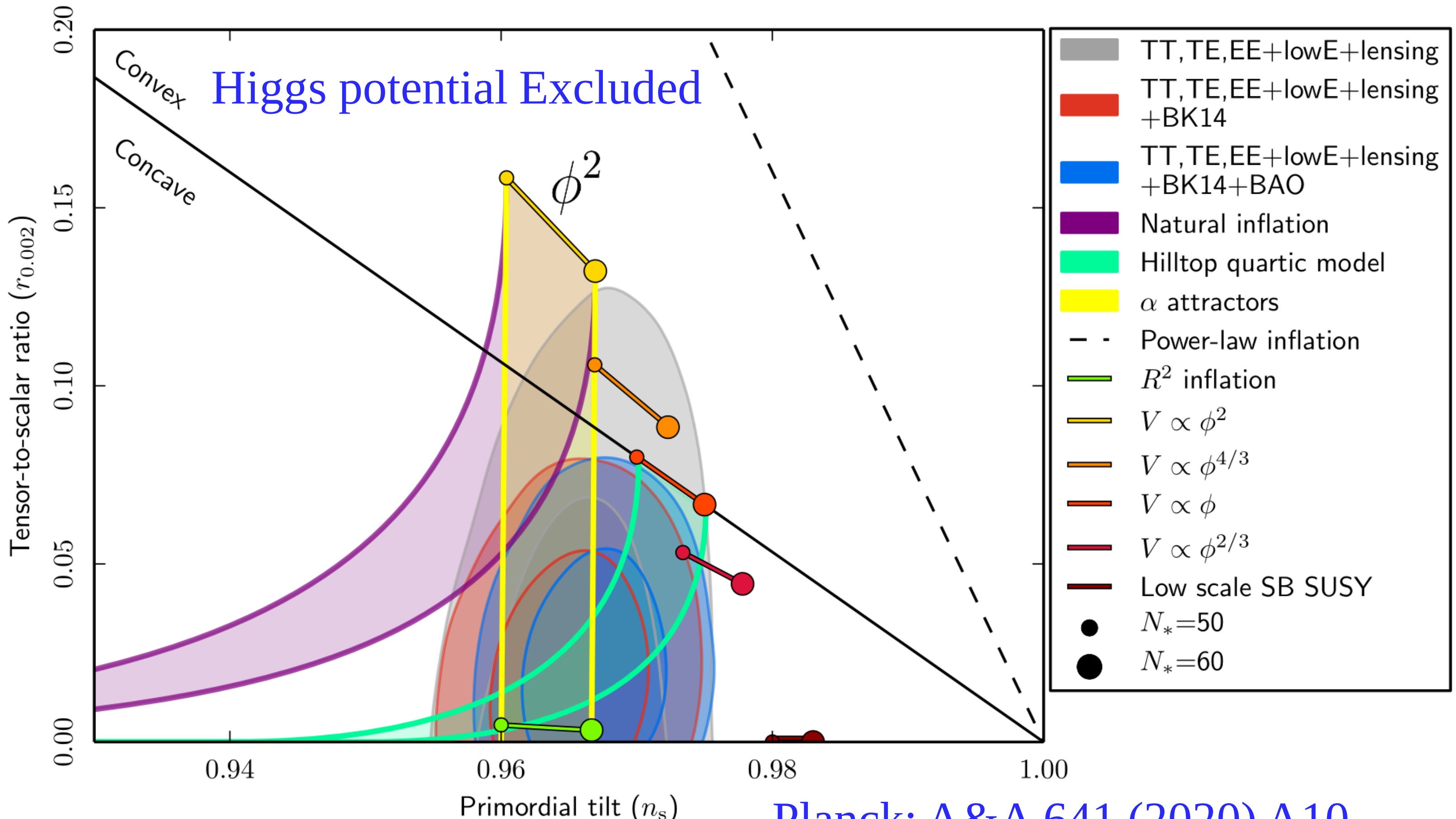
- Energy scale of inflation: measurement of r

CMB constraints

- Planck 18

$$\ln(10^{10} A_s) = 3.044 \pm 0.014$$ order of 10^{-9}

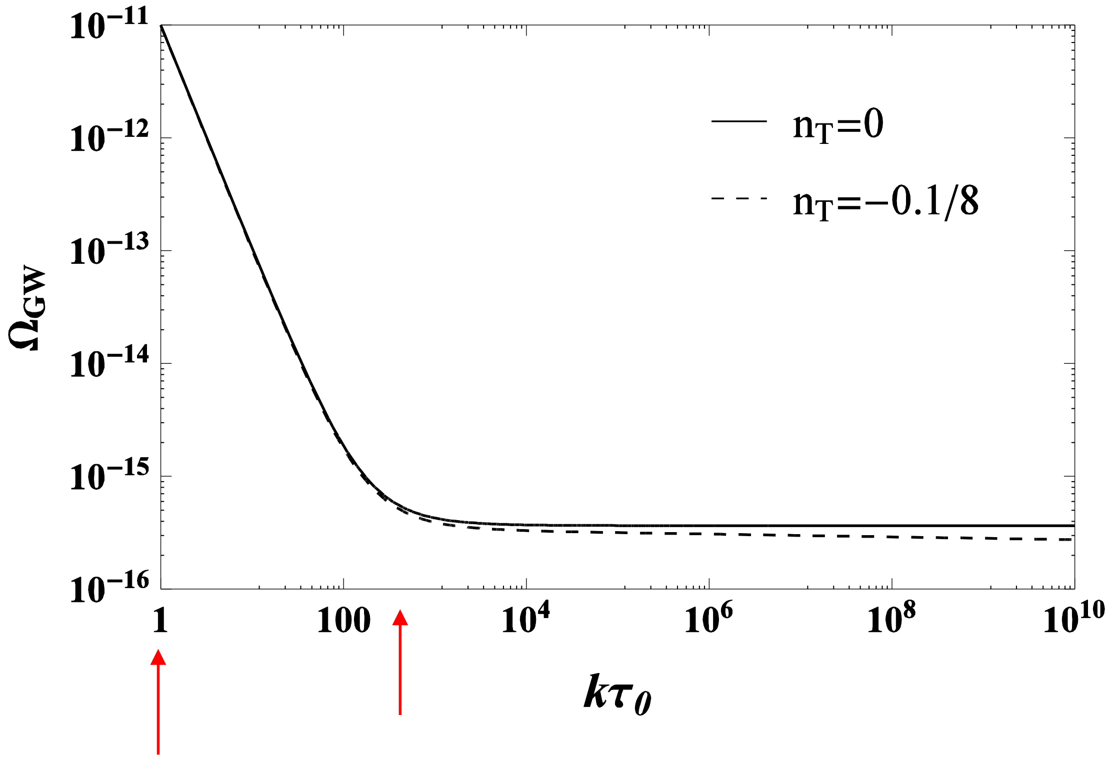
$$r_{0.05} < 0.06, \quad 95\%$$



Planck: A&A 641 (2020) A10

BICEP: PRL 121 (2018) 221301

Primordial GWs



arXiv: 1502.02114
1502.01589

$\Omega_{m0} = 0.3156$

$H_0 = 67.27$ km/s/Mpc

$T_{\gamma 0} = 2.725$ K

$r = 0.1$

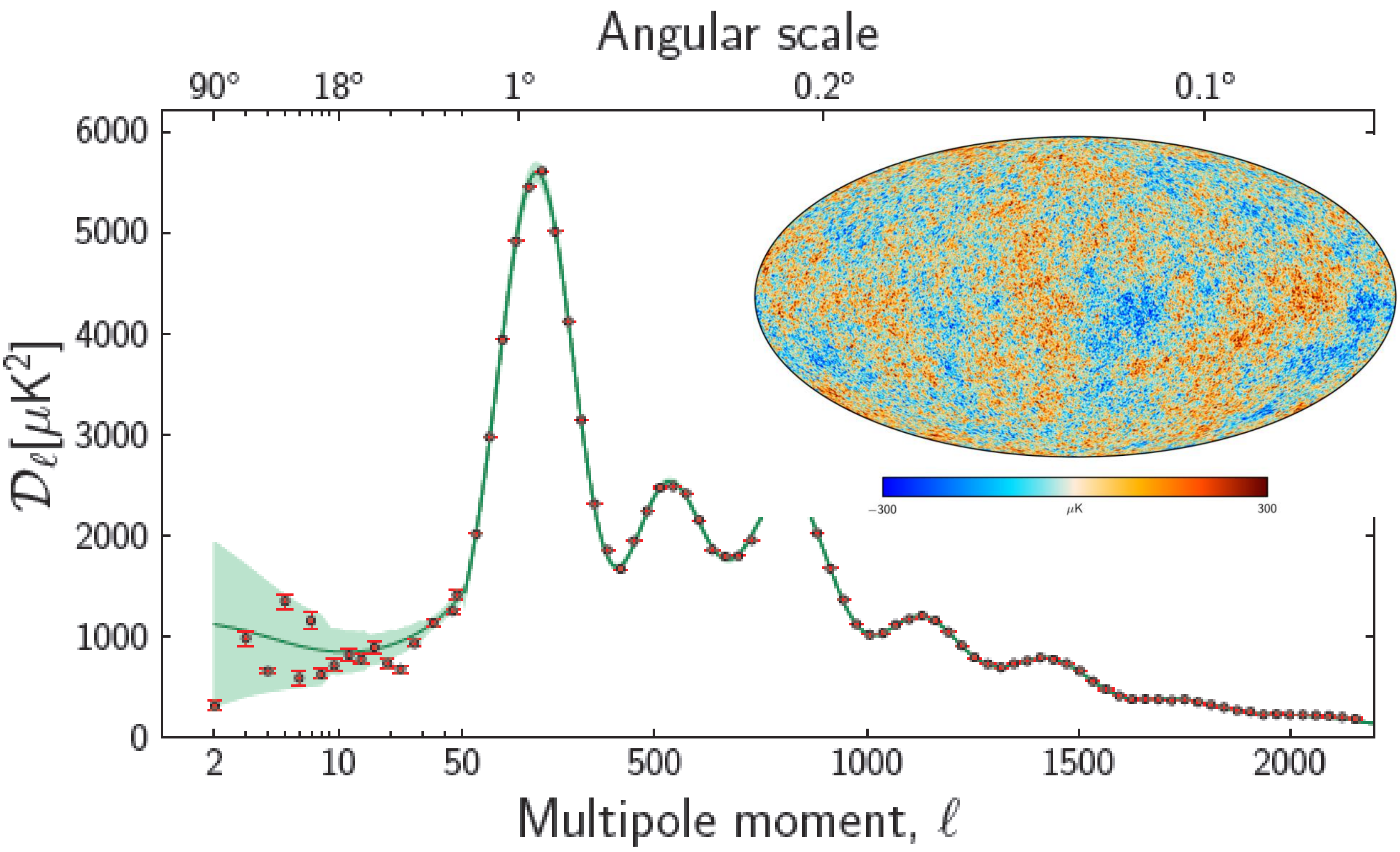
$A_s = 2.2 \times 10^{-9}$

Size of universe
14161.5Mpc
$2.2*10^{-18}$ Hz

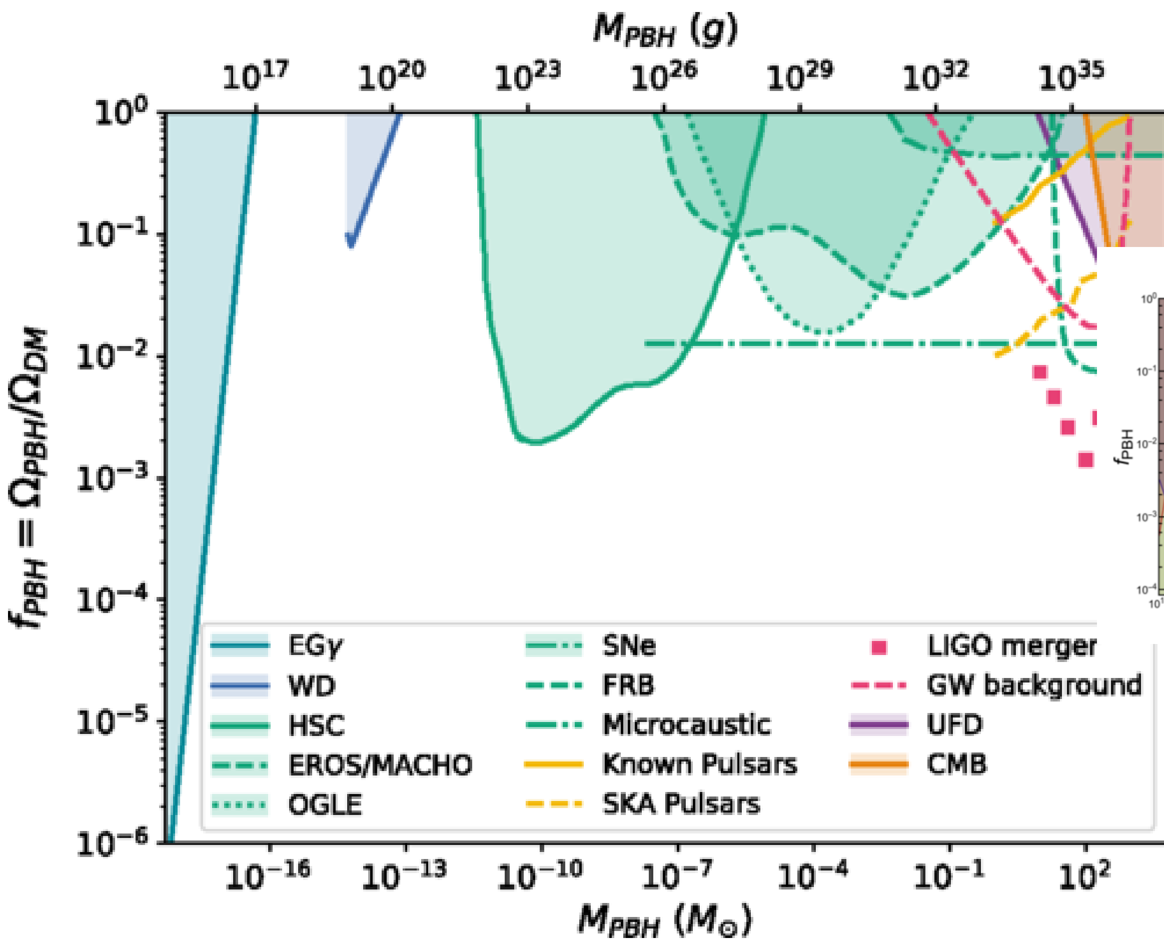
Equality
112.1Mpc
$1.0*10^{-16}$ Hz

End of inflation~10^{15}GeV
$8.9*10^{7}$Hz

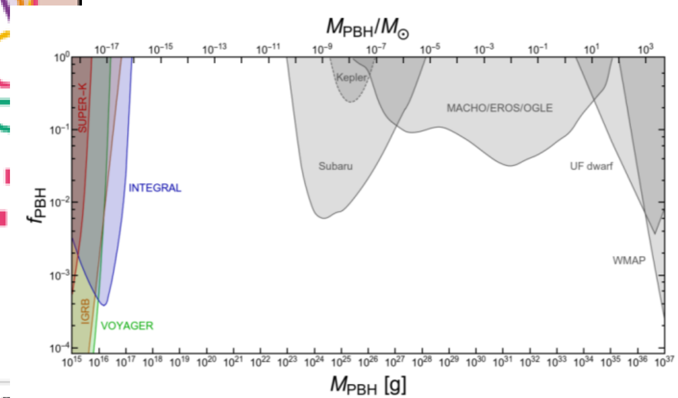
Primordial temperature spectrum



PBH constraints



Spinning PBHs



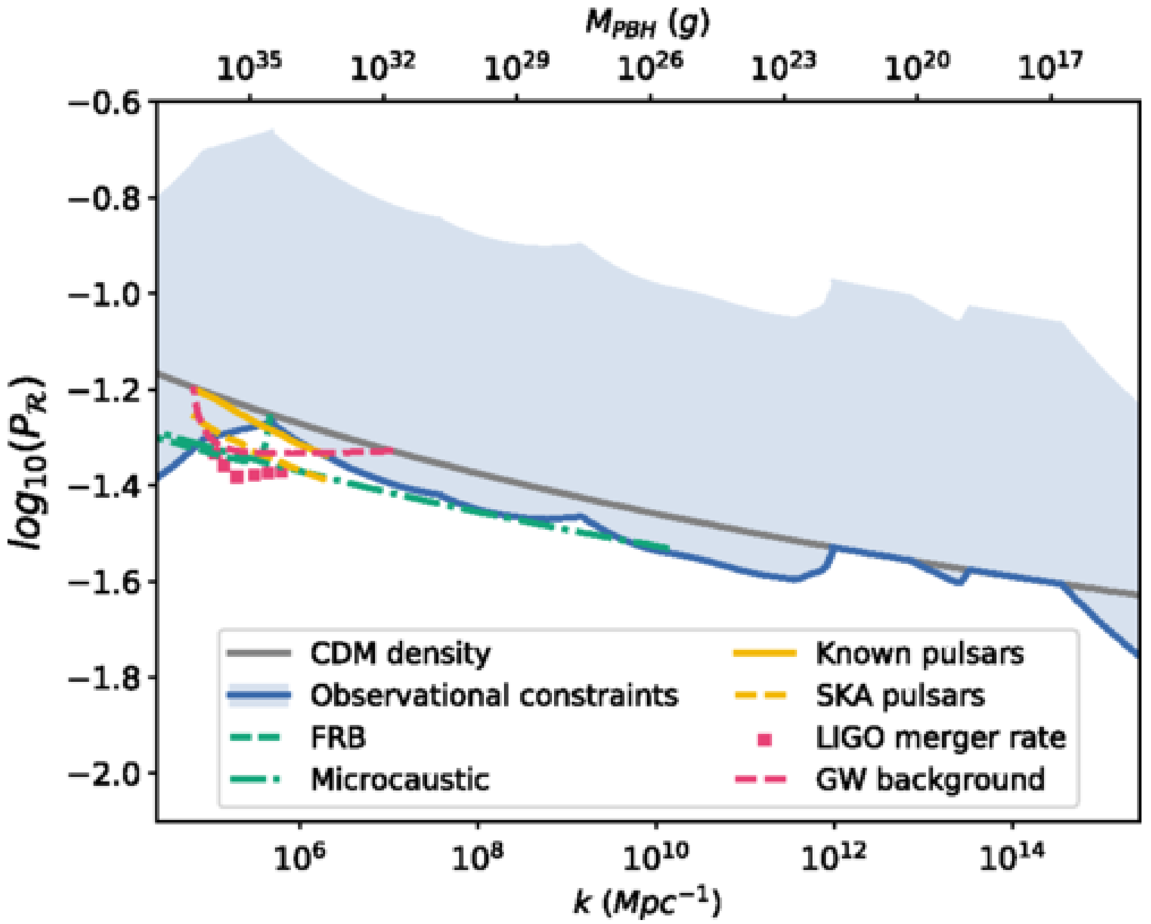
Dasgupta, Laha and Ray, PRL 125 (2020) 101101

Sato-Polito, Kovetz, Kamionkowski, PRD 100 (19) 063521

Observational constraints

- PBH fraction $f_{\rm PBH} \Rightarrow \mathcal{P}_\zeta$

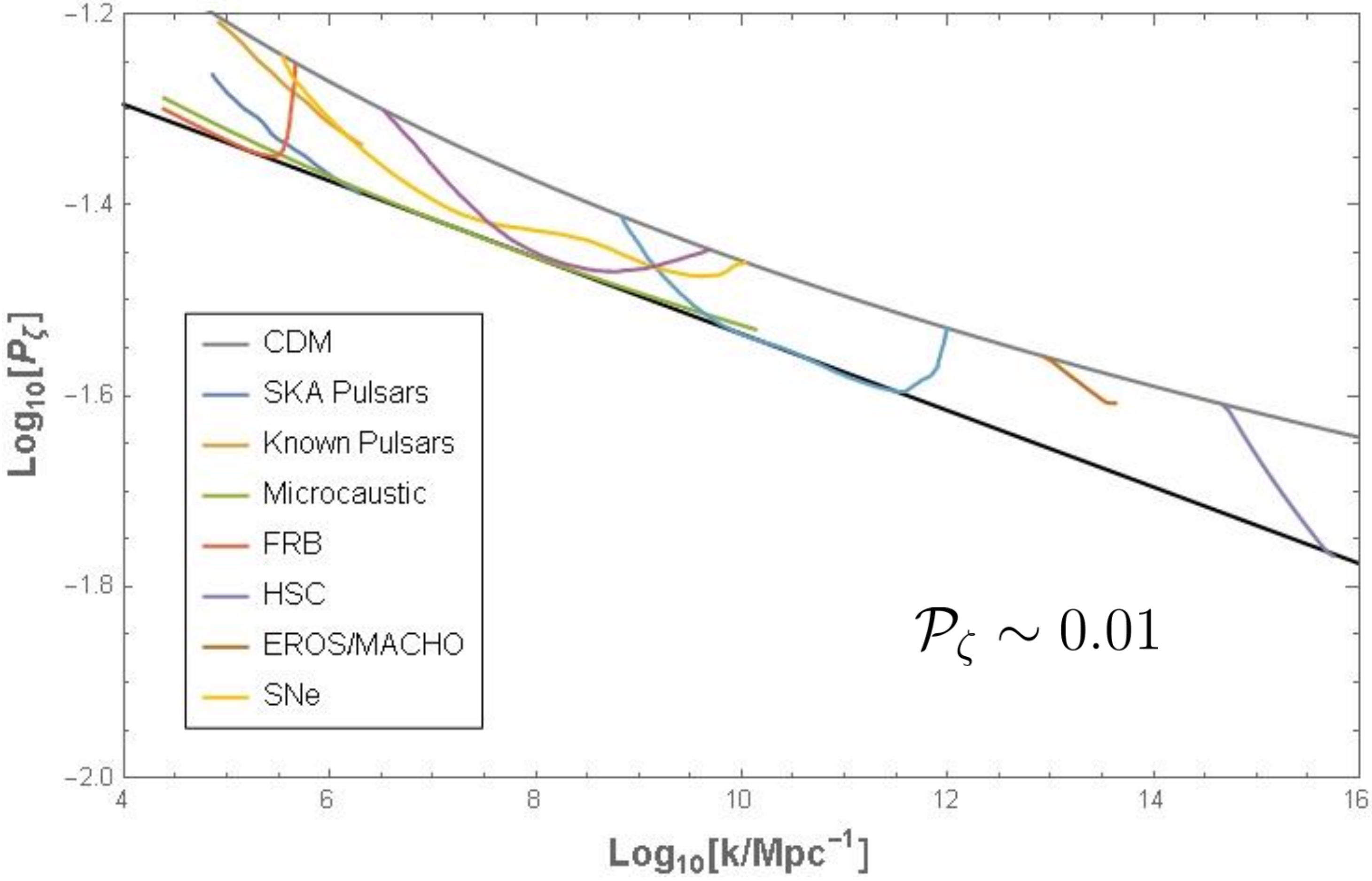
$$\beta = \frac{\rho_{\rm PBH}}{\rho_{\rm tot}} \approx {\rm erfc}\left(\frac{\delta_c}{\sqrt{2\mathcal{P}_\delta}}\right) = {\rm erfc}\left(\frac{9\delta_c}{4\sqrt{\mathcal{P}_\zeta}}\right)$$



Sato-Polito, Kovetz, Kamionkowski, PRD 100 (19) 063521

Constraints on power spectrum

- Result



Lu, Gong, Yi, Zhang, 1907.11896, JCAP 1912, 031

Scalar induced GWs (SIGWs)

- Tensor-scalar mixing

First order scalar perturbations as the source of the second order tensor perturbation $\Phi, \Psi \sim 0.1$

$$h''_{ij} + 2\mathcal{H}h'_{ij} - \nabla^2 h_{ij} = -4S_{ij}$$

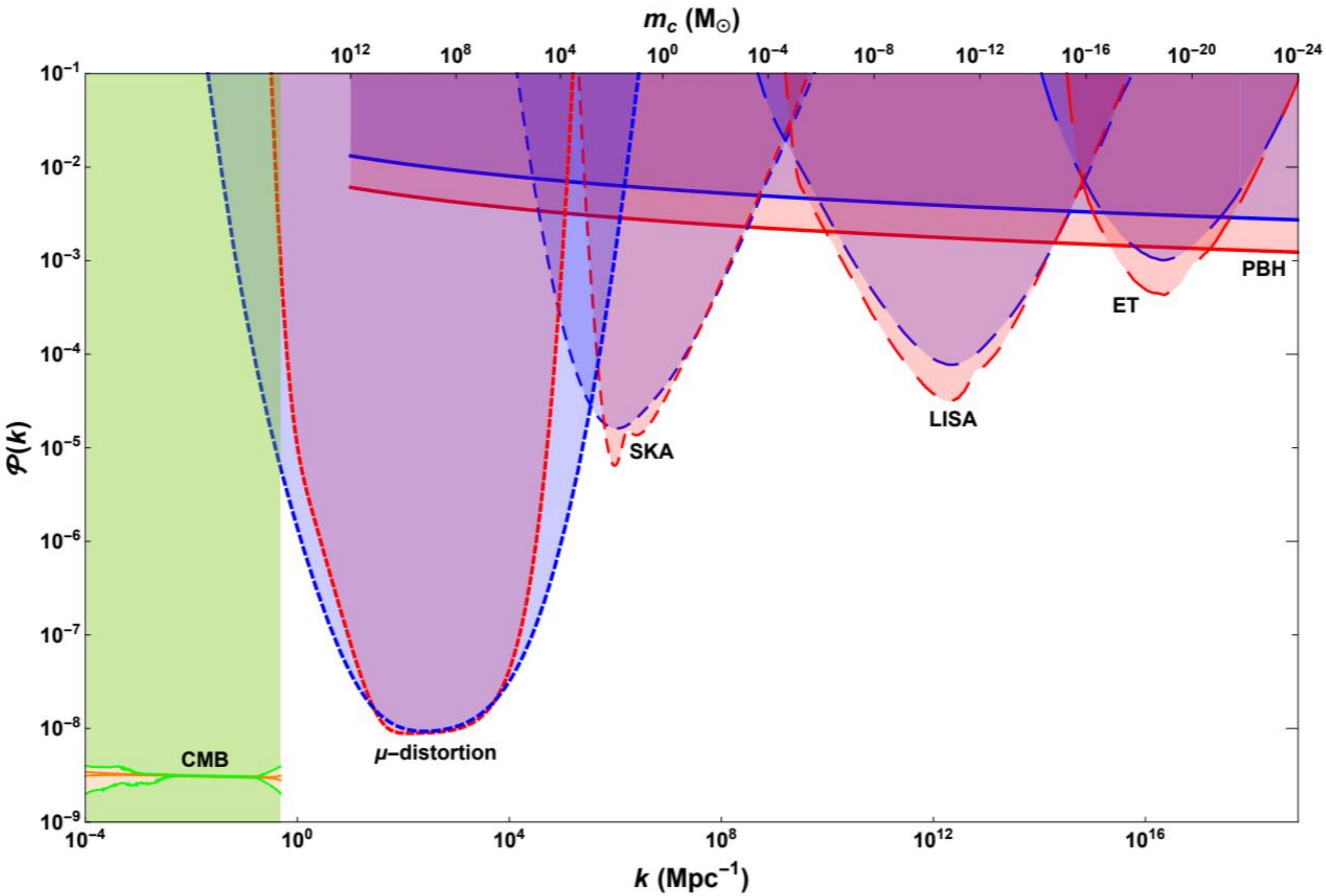
$$S_{ij} = 2\Phi\Phi_{,ij} + 2\Psi\Psi_{,ij} + \Phi_{,i}\Phi_{,j} + 3\Psi_{,i}\Psi_{,j} - \Psi_{,i}\Phi_{,j} - \Phi_{,i}\Psi_{,j} - \frac{4}{3(1+w)\mathcal{H}^2}(\Psi' + \mathcal{H}\Phi)_{,i}(\Psi' + \mathcal{H}\Phi)_{,j}$$

$$h_{ij}(\boldsymbol{x}, \eta) = \frac{1}{(2\pi)^{3/2}} \int d^3k e^{i\boldsymbol{k}\cdot\boldsymbol{x}} [h_{\boldsymbol{k}}(\eta) e_{ij}(\boldsymbol{k}) + \tilde{h}_{\boldsymbol{k}}(\eta) \tilde{e}_{ij}(\boldsymbol{k})]$$

$$\langle h_{\boldsymbol{k}}(\eta) h_{\tilde{\boldsymbol{k}}}(\eta) \rangle = \frac{2\pi^2}{k^3} \delta^{(3)}(\boldsymbol{k} + \tilde{\boldsymbol{k}}) \mathcal{P}_h(k, \eta)$$

$$\Omega_{\mathrm{GW}}(k, \eta) = \frac{1}{24} \left(\frac{k}{aH} \right)^2 \overline{\mathcal{P}_h(k, \eta)}$$

GW Constraints



Gow, Byrnes, Cole, Young, JCAP 02 (2021) 002

Enhancement: generic feature

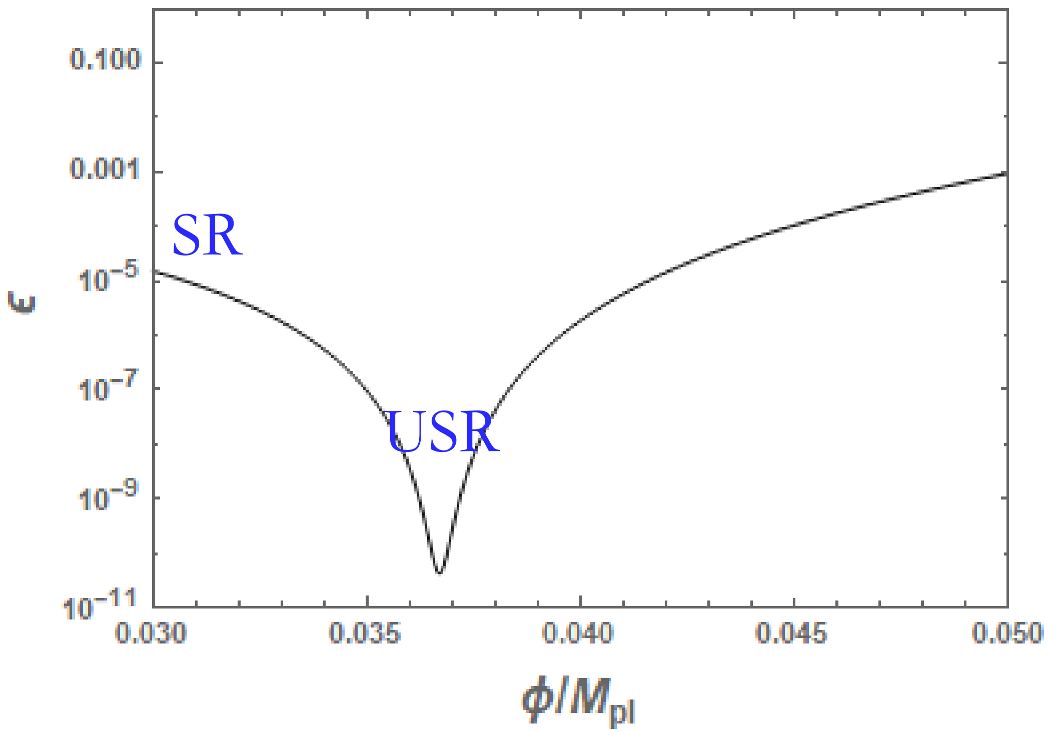
- Very small ϵ at small scales

Slow-roll inflation $\mathcal{P}_\zeta = \frac{H^2}{8\pi^2\epsilon}$

$\mathcal{P}_\zeta \sim 10^{-9}$ Larges scales

?

$\mathcal{P}_\zeta \sim 0.01$ Small scales



$$\epsilon = \frac{1}{2}\left(\frac{V_\phi}{V}\right)^2 \sim 0$$

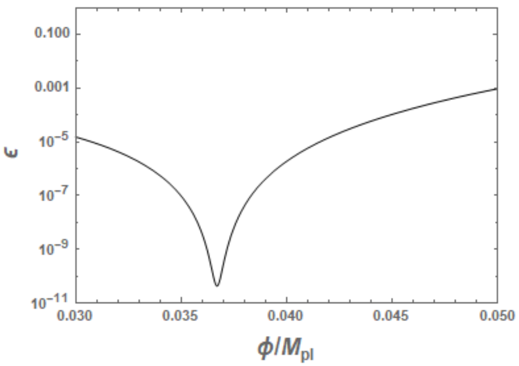
Motivation and Goal: Decrease by 7 orders of magnitude

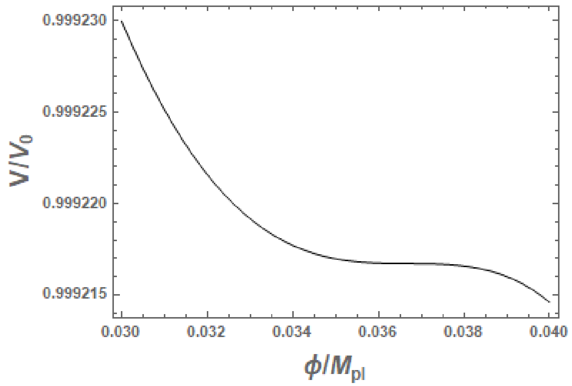
Slow-roll parameter ϵ cannot increase monotonically

Inflection point inflation

- Small ϵ requires very flat potential: inflection point

$$\mathcal{P}_\zeta = \frac{H^2}{8\pi^2\epsilon}$$





- Ultra-slow-roll inflation

Slow-roll

$$3H\dot{\phi} \approx -V_\phi(\phi) = 0$$

$$\ddot{\phi} + 3H\dot{\phi} + V_\phi(\phi) = 0$$

$$V_\phi(\phi) = 0$$

$$\eta_H = -\frac{\ddot{\phi}}{H\dot{\phi}} = 3$$ constant-roll

Break-down of slow-roll

Tsamis, Woodard, PRD 69 (04) 084005;
Motohashi, Starobinsky, Yokoyama, JCAP 1509, 018

Ultra-slow-roll inflation

- The field rolls faster $\dot{\phi} \propto a^{-3}$ $\rho_\phi^{KE} \propto a^{-6}$

$$N = \int_{\phi}^{\phi_e} \frac{d\phi}{\sqrt{2\epsilon(\phi)}}$$

N can be much larger than 60

Breakdown of Lyth bound

USR helps to reduce N

The contribution to N during ultra-slow-roll inflation (inflection point) becomes smaller

$$\eta_H = -\frac{\ddot{\phi}}{H\dot{\phi}} = 3$$

- Constant roll η_H constant

$$n_s - 1 = 3 - 2\nu \qquad \nu = \left|\frac{3}{2} - \eta_H\right| + \frac{\left(6 - 5\eta_H - 4\eta_H^2\right)\epsilon_H}{|3 - 2\eta_H|\,(1 + 2\eta_H)}$$

- How to enhance the power spectrum at the power spectrum while keeping the number of e-folds to be around 60

Yi and Gong, 1712.07478 (JCAP)

Modified model

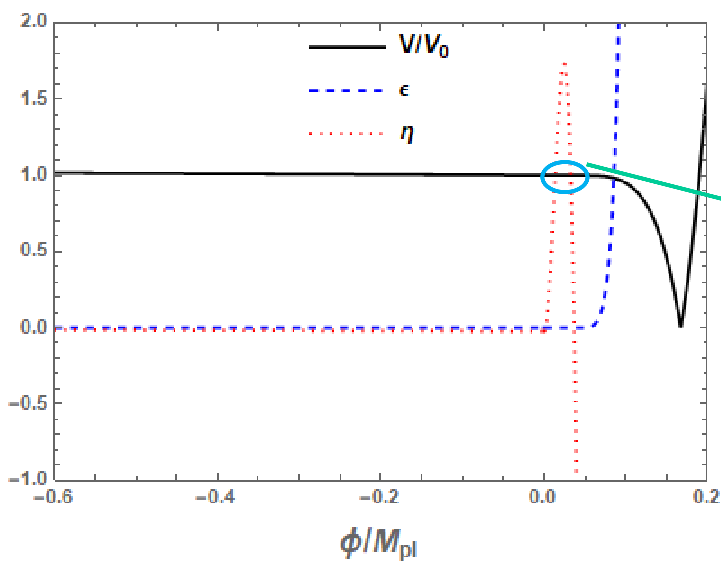
- Polynomial potential Di & Gong, JCAP 07 (18) 007

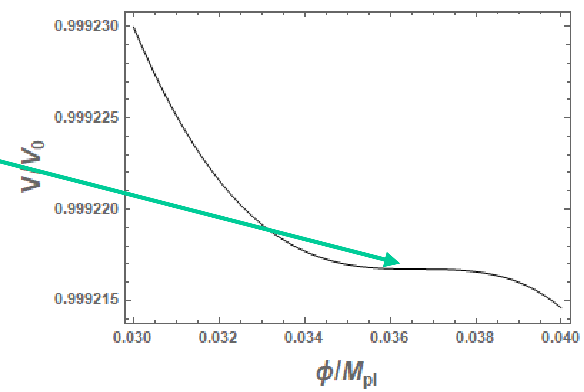
$$V(\phi) = \begin{cases} V_0 \left| 1 + \sum_{m=1}^{m=5} \lambda_m \left(\frac{\phi}{M_{\rm Pl}} \right)^m \right|, & \phi \geq 0, \\ V_0 \left[1 + \sum_{m=1}^{m=3} \lambda_m \left(\frac{\phi}{M_{\rm Pl}} \right)^m \right], & \phi < 0, \end{cases}$$

fine-tuning

$$\lambda_1 = -0.0353553, \quad \lambda_2 = -0.0115783, \quad \lambda_3 = -0.00235702,$$

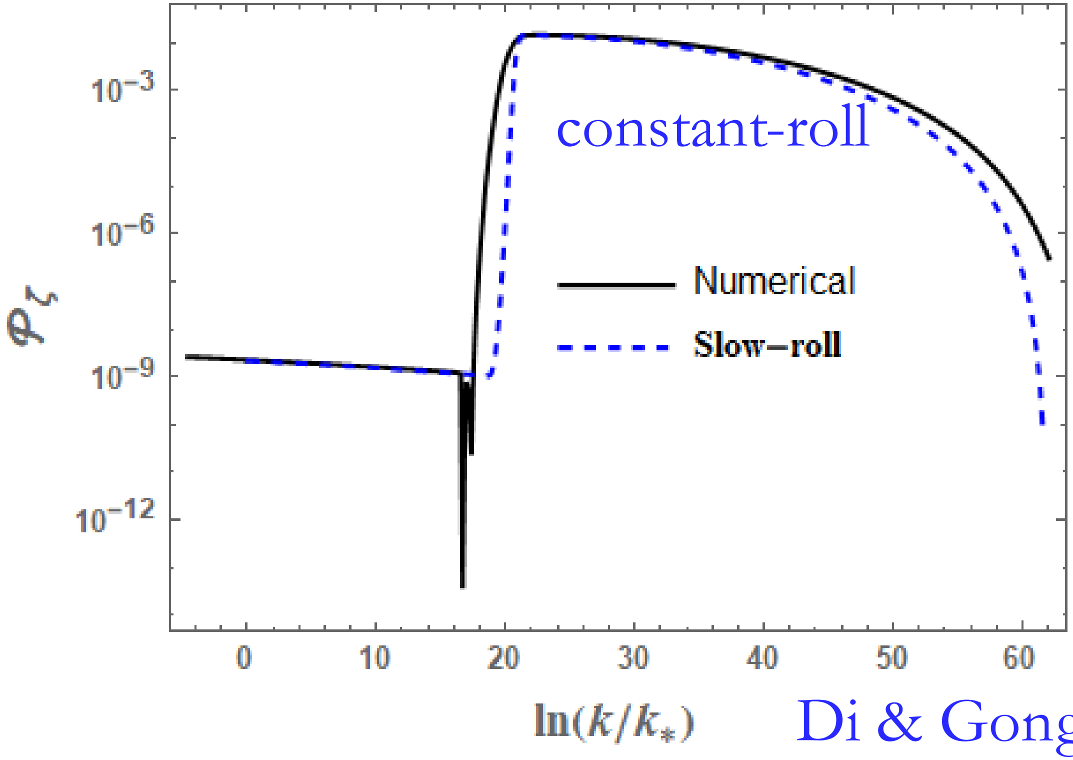
$$\lambda_4 = 728.239, \lambda_5 = -11882.9$$





The power spectrum

- Numerical solution



Di & Gong, JCAP 07 (18) 007

$$k_* = 0.05\text{Mpc}^{-1},\ n_s = 0.9674,\ r = 0.005,\ n_s' = -0.0008$$

Peak value $\mathcal{P}_\zeta = 0.0175$

Ultra-slow-roll to SR

- USR to SR transition

$$V(\phi) = V_0 + \frac{\beta}{2}\left[\phi + \delta_1 \log\left\{\cosh\left(\frac{\phi - \phi_1}{\delta_1}\right)\right\}\right] + \frac{\gamma}{2}\left[\phi - \delta_2 \log\left\{\cosh\left(\frac{\phi_2 - \phi}{\delta_2}\right)\right\}\right]$$

$$\{\beta,\ \phi_1,\ \delta_1\} = \{10^{-14},\ 0,\ 10^{-2}\} \qquad \gamma = 6 \times 10^{-21}$$

fine-tuning

Fast transition $\quad \phi_2 = -0.1580281699,\ \delta_2 = 2.12 \times 10^{-10}$

Slow transition $\quad \phi_2 = -0.1580282187,\ \delta_2 = 3.6 \times 10^{-8}$

S. Passaglia, W. Hu, H. Motohashi, PRD 99 (2019) 043536

Ultra-slow-roll models

- String inflation

$$V_{\rm inf} = \frac{W_0^2}{\mathcal{V}^3}\left[\frac{C_{\rm up}}{\mathcal{V}^{1/3}} - \frac{C_{\rm W}}{\sqrt{\tau_{\rm K3}}} + \frac{A_{\rm W}}{\sqrt{\tau_{\rm K3}} - B_{\rm W}} + \frac{\tau_{\rm K3}}{\mathcal{V}}\left(D_{\rm W} - \frac{G_{\rm W}}{1 + R_{\rm W}\frac{\tau_{\rm K3}^{3/2}}{\mathcal{V}}}\right)\right]$$

fine-tuning

	C_W	A_W	B_W	$G_W/\langle\mathcal{V}\rangle$	$R_W/\langle\mathcal{V}\rangle$	$\langle\tau_{K3}\rangle$	$\langle\mathcal{V}\rangle$
$\mathcal{P}_1$	$1/10$	$2/100$	1	1.303386×10^{-3}	6.58724×10^{-3}	3.89	107.3
$\mathcal{P}_2$	$4/100$	$2/100$	1	3.080548×10^{-5}	7.071067×10^{-4}	14.30	1000
$\mathcal{P}_3$	$1.978/100$	$1.65/100$	1.01	9.257715×10^{-8}	1.414×10^{-5}	168.03	5×10^4

M. Cicoli, V.A. Diaz, F.G. Pedro, JCAP 1806, 034

- SUGRA $W = a_0(1 + a_1 e^{-b_1\Phi} + a_2 e^{-b_2\Phi} + a_3 e^{-b_3\Phi}).$

	a_0	a_3	b_1	b_2	b_3	c
1	4.35×10^{-6}	7×10^{-8}	3.05	6.3868164	-4.4	2.8
2	4.06×10^{-6}	1×10^{-6}	2.89	7.251197	-3.2	2.85

T.J. Gao, Z.K. Guo, PRD 98, 063526

Higgs field

- Higgs particle

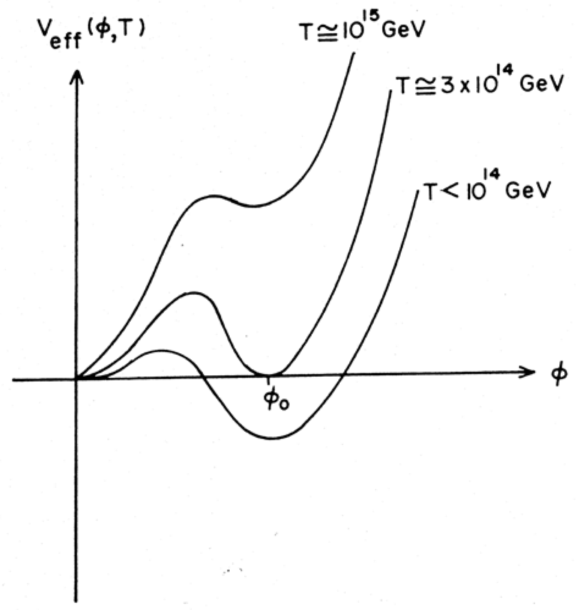
$m = 125\ \text{GeV}$ 2012

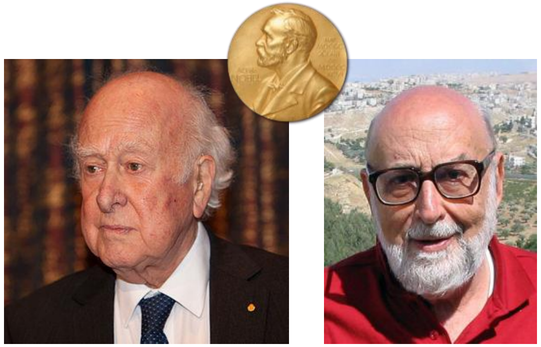
- 2013 Nobel prize

$$V(\phi) = \frac{\lambda}{4}(\phi^2 - v^2)^2 + bT^2\phi^2$$

$$V(\phi) = \frac{\lambda}{4}\phi^4, \quad T \gg T_{crt}$$

A. Linde, 80s





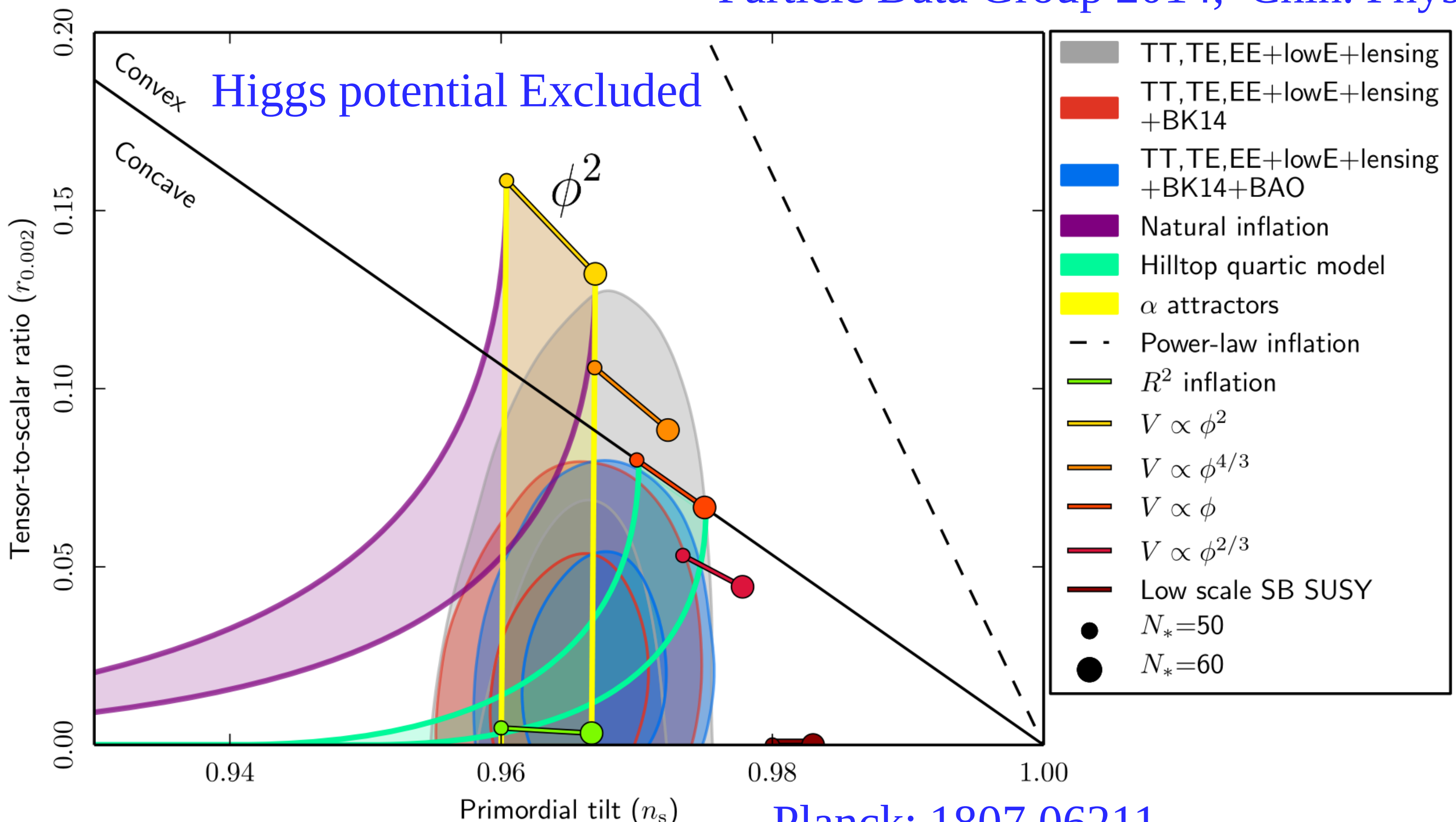
Higgs Englert

CMB constraints

- Planck 18

$$V(h_c) = \frac{1}{4}\lambda h_c^4 \qquad \lambda = 0.13$$

Particle Data Group 2014, Chin. Phys. C



Planck: 1807.06211

BICEP: PRL 121 (2018) 221301

Higgs inflation

- Nonminimal coupling

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2}(1+\xi\phi^2)R - \frac{1}{2}g^{\mu\nu}\nabla_\mu\phi\nabla_\nu\phi - \frac{1}{4}\lambda\phi^4\right]$$

Strong coupling attractors $n_s \approx 1 - \frac{2}{N}, \quad r \approx \frac{12}{N^2}$

Kaiser, PRD 52 (95) 4295
Bezrukov and Shaposhnikov, PLB 659 (08) 703

- Critical inflation

RG running of coupling constant $\lambda = 0, \quad \beta_\lambda = 0$

$$\lambda(\phi) = \lambda_0 + b_\lambda \ln^2(\phi/\mu) \qquad \xi(\phi) = \xi_0 + b_\xi \ln(\phi/\mu)$$

Hamada, Kawai, Oda and Park, PRL 112, 241301
Bezrukov and Shaposhnikov, PLB 734 (14) 249

Critical Higgs Inflation

- The Higgs inflation (nonminimal coupling)

$$S=\int d^4x\sqrt{-g}\left[\frac{1}{2}(1+\xi\phi^2)R-\frac{1}{2}g^{\mu\nu}\nabla_\mu\phi\nabla_\nu\phi-\frac{1}{4}\lambda(\phi)\phi^4\right]$$

$$\lambda(\phi)=\lambda_0+b_\lambda\ln^2(\phi/\mu) \qquad \xi(\phi)=\xi_0+b_\xi\ln(\phi/\mu)$$

$$S=\int dx^4\sqrt{-g}\left[\frac{1}{2}R-\frac{1+\xi\phi^2+6(\xi\phi+\xi_\phi\phi^2/2)^2}{(1+\xi\phi^2)^2}\frac{1}{2}g_{\mu\nu}\nabla^\mu\phi\nabla^\nu\phi-V(\phi)\right]$$

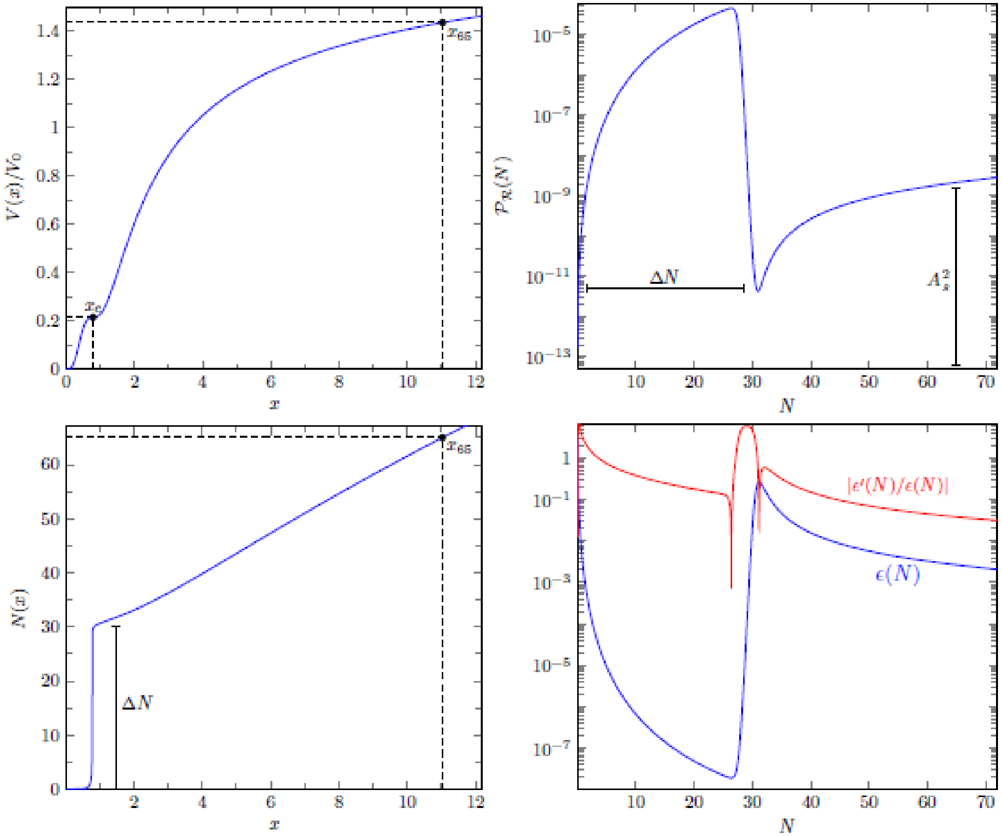
$$V(x)=\frac{V_0(1+a\ln^2 x)x^4}{[1+c(1+b\ln x)x^2]^2},$$

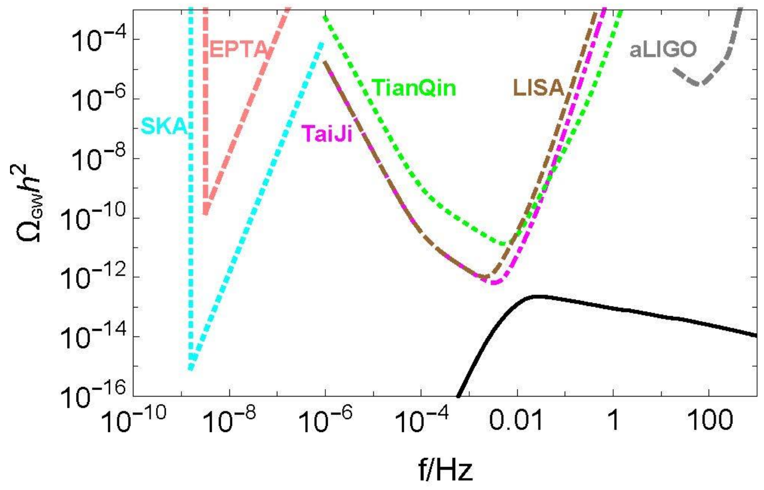
$$x=\phi/\mu,\ V_0=\lambda_0\mu^4/4,\ a=\lambda_1/\lambda_0,\ b=\xi_1/\xi_0 \text{ and } c=\xi_0\mu^2.$$

Ezquiaga, Garcia-Bellido, Morales, PLB 776 (18) 345

Critical Higgs Inflation

- The Higgs inflation (nonminimal coupling)





$$n_s = 0.952, \ \ r = 0.043.$$

Ezquiaga, Garcia-Bellido, Morales, PLB 776 (18) 345

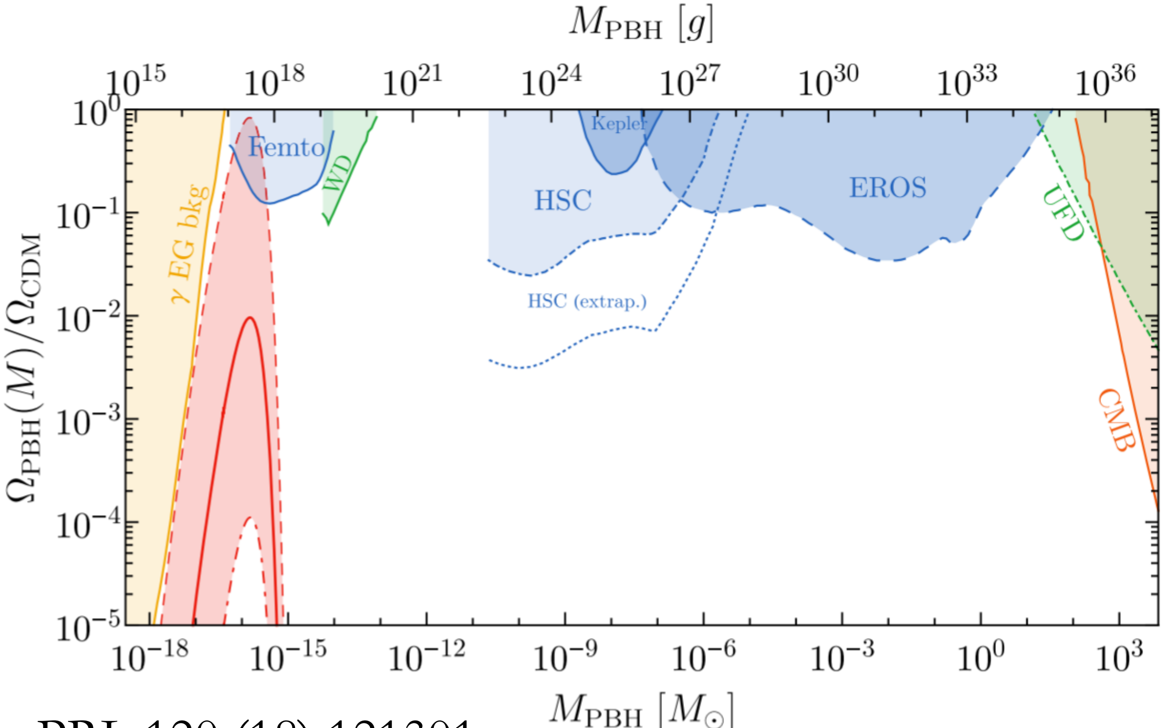
Spectator Higgs model

- Higgs field is not responsible for inflation, but its fluctuation generate large power

$$V(h_c) = -\frac{1}{4}\lambda h_c^4$$

RG running, coupling becomes negative

Higgs instability



Espinosa, Racco, Riotto, PRL 120 (18) 121301

Passaglia, Hu, Motohashi, PRD 101 (20) 123523

Nonminimal coupling and R+R^2 Gundhi & Steinwachs , 2011.09485

Horndeski Theory

- The most general scalar-tensor theory with 2nd order of EOMs

$$L_H = L_2 + L_3 + L_4 + L_5$$

$$L_2 = K(\phi, X), \quad X = -\frac{1}{2}\nabla_\mu\phi\nabla^\mu\phi$$

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

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

$$\begin{aligned} L_5 = & G_5(\phi, X)G_{\mu\nu}\nabla^\mu\nabla^\nu\phi - \frac{1}{6}G_{5,X}\left[(\Box\phi)^3\right. \\ & \left. -3(\Box\phi)(\nabla_\mu\nabla_\nu\phi)(\nabla^\mu\nabla^\nu\phi) + 2(\nabla^\mu\nabla_\alpha\phi)(\nabla^\alpha\nabla_\beta\phi)(\nabla^\beta\nabla_\mu\phi)\right] \end{aligned}$$

Horndeski Theory: Special cases

- Non-minimally coupling

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

$G_4(\phi, X) = f(\phi)$ Non-minimal coupling $f(\phi)R$

- Non-minimally derivative coupling

$$G_5(\phi, X)G_{\mu\nu}\nabla^\mu\nabla^\nu\phi \longrightarrow G^{\mu\nu}\partial_\mu\phi\partial_\nu\phi$$

$$G_5(\phi, X) = \phi$$

Non-minimal coupling
Gauss-Bonnet coupling
Derivative coupling

- New Higgs inflation

$$S = \frac{1}{2}\int d^4x\sqrt{-g}\left[M_{pl}^2 R - g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi + \frac{1}{M^2}G^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - 2V(\phi)\right]$$

Germani & Kehagias, PRL 105 (2010) 011302

k/G inflation

- Non-canonical field

$$S=\frac{1}{2}\int d^4x\sqrt{-g}\left[M_{pl}^2R-g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi+\frac{f(\phi)}{M^2}G^{\mu\nu}\partial_\mu\phi\partial_\nu\phi-2V(\phi)\right]$$

$$f(\phi)=\frac{d}{\sqrt{(\frac{\phi-\phi_r}{c})^2+1}} \qquad V(\phi)=\lambda\phi^{2/5}$$

Parameter needs to be fine tuned at least to six decimal digits

Fu, Wu & Yu, PRD 100 (19) 063532; PRD 101 (20) 023529

- G inflation

$$S=\int d^4x\sqrt{-g}\left[\frac{1}{2}R+K(\phi,X)-G_3(\phi,X)\Box\phi\right]$$

$$X=-g_{\mu\nu}\nabla^\mu\phi\nabla^\nu\phi/2$$

Lin, Gao & Gong etal., PRD 101 (20) 103515

k/G inflation

- G inflation

Special case: $$G_{3\phi} = dG_3(\phi)/d\phi$$

$$K(\phi, X) = X - V(\phi)$$

- k inflation

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2}R + X + G(\phi)X - V(\phi)\right]$$

$$\mathcal{P}_\zeta = \frac{H^2}{8\pi^2\epsilon}(1+G)$$

G used to generate a peak

At large scales, G is negligible, we recover standard SR result
At small scales, G is very big, the power spectrum is enhanced

Lin, Gao & Gong etal., PRD 101 (20) 103515

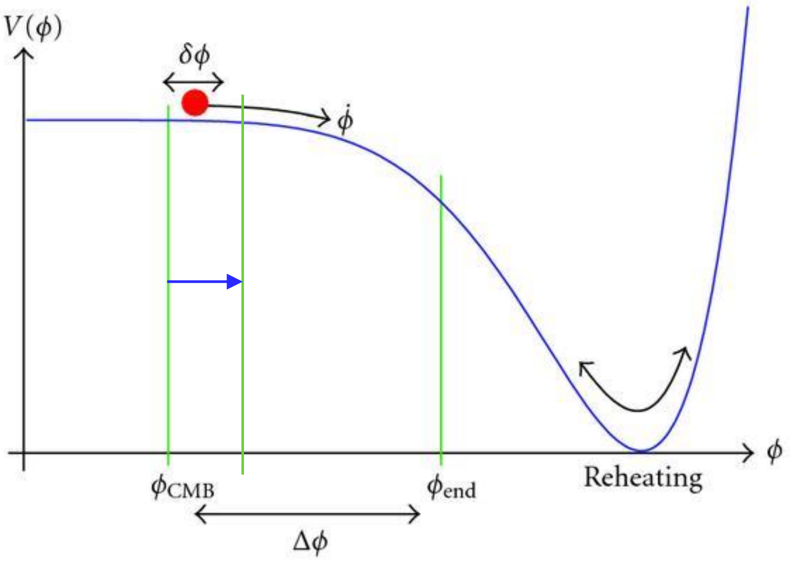
k/G inflation

- Number of e-folds around the peak

$$\Delta N = \int_{\phi_r - \Delta\phi}^{\phi_r + \Delta\phi} \frac{H}{\dot{\phi}} d\phi \simeq - \int_{\phi_r - \Delta\phi}^{\phi_r + \Delta\phi} \frac{V(1+G)}{V_\phi} d\phi$$

Peak width should be small

- The limit on the potential



$$\Delta N \sim 20$$

$$N_* \sim 60 \rightarrow N_* \sim 40$$

The possible potentials

- The power-law potential $V(\phi) = \lambda\phi^n$

$$n_s = 1 - \frac{n+2}{2N}$$

$$r = \frac{4n}{N}$$

Higgs potential $n = 4, N_* = 40$

$$n_s = 0.925$$

$$r = 0.4$$

$$n = 1/3,\ n_s = 0.971,\ r = 0.033$$

$$n = 2/3,\ n_s = 0.967,\ r = 0.067$$

k/G inflation

- Examples for peak functions

Peak function $G_a(\phi) = \frac{d}{1+\left|\frac{\phi-\phi_r}{c}\right|}$

Brans-Dicke theory: $\omega(\phi) = 1/\phi$

Around the peak $|\phi - \phi_r| \ll c,\ G_a(\phi) \sim d$

To get the enhancement, $d \sim 10^8$

To ensure enhancement at small scales, ϕ_r should away from ϕ_*

Away from the peak $|\phi - \phi_r| \gg c,\ G_a(\phi) \sim dc/|\phi - \phi_r|$

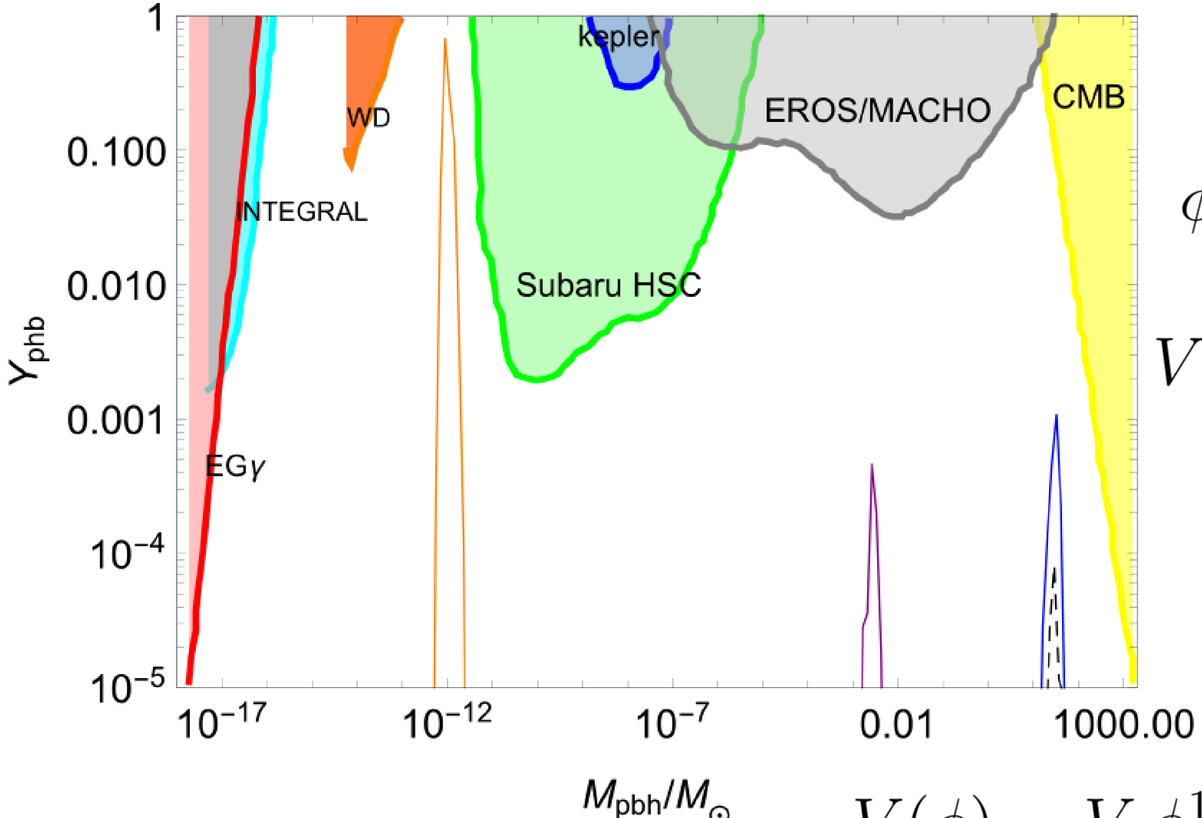
$\sim O(0.01)$ $\sim O(1)$

Small peak width $c \sim 10^{-10}$ at most

Lin, Gao & Gong etal., PRD 101 (20) 103515

PBH from k/G inflation

Sets	ϕ_r	c	n_s	$k_{\rm peak}/{\rm Mpc}^{-1}$	$P_{\zeta({\rm peak})}$	$M_{\rm pbh}^{\rm peak}/M_\odot$	$Y_{\rm PBH}^{\rm peak}$	$f_c/{\rm Hz}$
A	4.5	9.54×10^{-11}	0.9736	2.86×10^{5}	1.66×10^{-2}	28.9	7.7×10^{-5}	4.43×10^{-10}
B	4.5	9.568×10^{-11}	0.9737	2.7×10^{5}	1.86×10^{-2}	32.5	0.001	4.18×10^{-10}
C	4.1	1.05×10^{-10}	0.969	3×10^{7}	1.49×10^{-2}	0.0026	4.7×10^{-4}	4.6×10^{-8}
D	2.97	1.472×10^{-10}	0.967	1.63×10^{12}	1.32×10^{-2}	9×10^{-13}	0.73	2.5×10^{-3}



$$\phi_* = 5.21$$

$$V(\phi) = V_0\phi^{2/5}$$

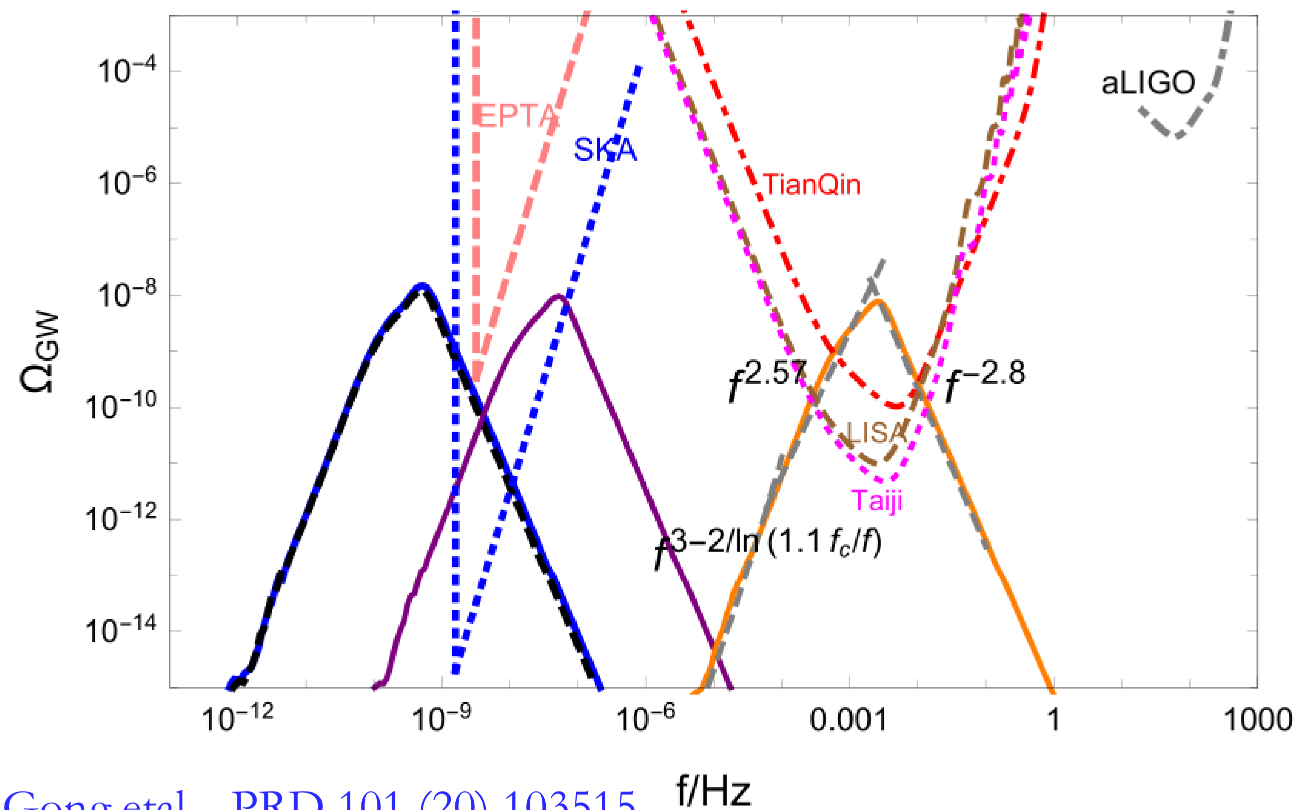
Gao, 2102.07369

$$V(\phi) = V_0\phi^{1/3}$$

Lin, Gao & Gong etal., PRD 101 (20) 103515

SIGWs from k/G inflation

Sets	ϕ_r	c	n_s	$k_{\rm peak}/{\rm Mpc}^{-1}$	$P_{\zeta({\rm peak})}$	$M_{\rm pbh}^{\rm peak}/M_\odot$	$Y_{\rm PBH}^{\rm peak}$	$f_c/{\rm Hz}$
A	4.5	9.54×10^{-11}	0.9736	2.86×10^5	1.66×10^{-2}	28.9	7.7×10^{-5}	4.43×10^{-10}
B	4.5	9.568×10^{-11}	0.9737	2.7×10^5	1.86×10^{-2}	32.5	0.001	4.18×10^{-10}
C	4.1	1.05×10^{-10}	0.969	3×10^7	1.49×10^{-2}	0.0026	4.7×10^{-4}	4.6×10^{-8}
D	2.97	1.472×10^{-10}	0.967	1.63×10^{12}	1.32×10^{-2}	9×10^{-13}	0.73	2.5×10^{-3}



Lin, Gao & Gong etal., PRD 101 (20) 103515

The new mechanism

- Combine slow roll with the peak

To generate peak

$$L = [1 + G_a(\phi)]X - U(\phi)$$

Transform non-canonical field to canonical field

$$L = [1 + G(\varphi)]X - V(\varphi)$$

$$G = G_a + f(\varphi)$$

Slow roll $L = f(\varphi)X - V(\varphi) \qquad V(\varphi) = \lambda\varphi^4, \ f(\varphi) = f_0\varphi^{22}$

$$d\phi = \sqrt{f(\varphi)}d\varphi, \ U(\phi) = V[\varphi(\phi)]$$

$$L = X - U(\phi) \qquad U(\phi) = \lambda\phi^{1/3}$$

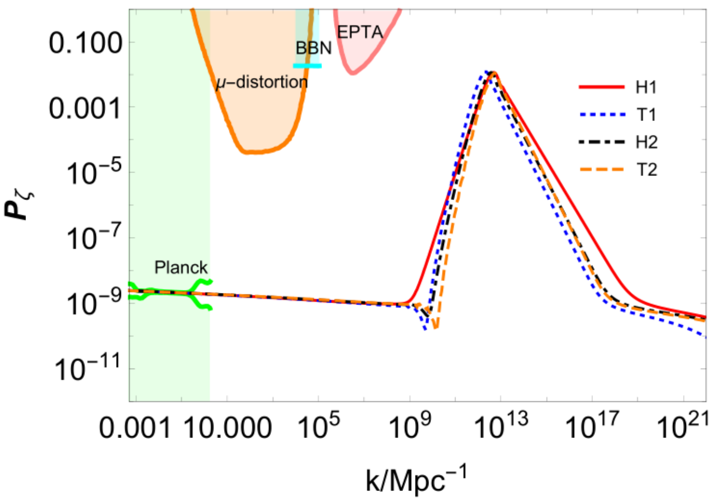
Yi, Gong, Wang, Zhu, 2007.09957

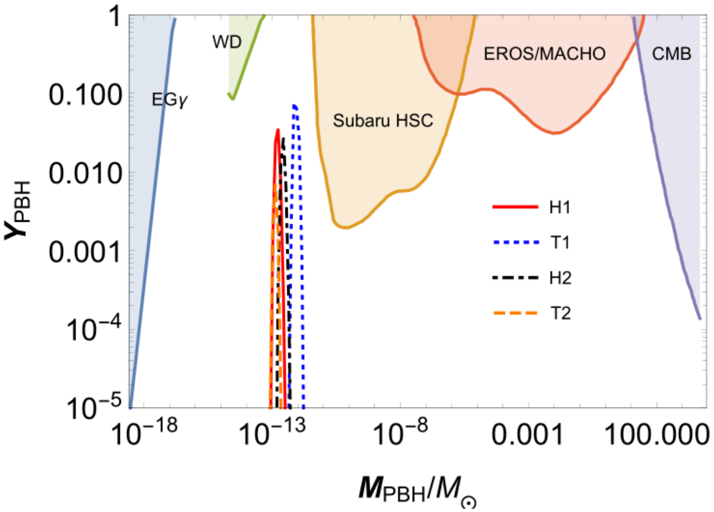
Higgs k/G inflation

Model	d	c	ϕ_p	ϕ_*	λ/V_0	f_0	N	n_s	r	$k_{\text{peak}}/\text{Mpc}^{-1}$
H1	1.05×10^{10}	2.04×10^{-10}	1.344	1.40	1.24×10^{-9}	1	62.3	0.9681	0.0383	4.66×10^{12}
T1	4.72×10^{9}	8.89×10^{-11}	0.451	0.81	1.68×10^{-9}	36	55.6	0.9686	0.0369	2.29×10^{12}
H2	7.13×10^{9}	1.94×10^{-10}	1.750	1.88	6.40×10^{-10}	1	64.2	0.9694	0.0641	3.67×10^{12}
T2	8.90×10^{9}	4.75×10^{-11}	0.835	1.35	2.95×10^{-9}	36	63.4	0.9704	0.0597	5.24×10^{12}

Model	$P_{\zeta(\text{peak})}$	$M_{\text{peak}}/M_\odot$	$Y_{\text{PBH}}^{\text{peak}}$	f_c/Hz
H1	1.16×10^{-2}	1.70×10^{-13}	3.57×10^{-2}	8.11×10^{-3}
T1	1.21×10^{-2}	7.05×10^{-13}	7.64×10^{-2}	3.54×10^{-3}
H2	1.15×10^{-2}	2.73×10^{-13}	2.64×10^{-2}	6.40×10^{-3}
T2	1.10×10^{-2}	1.34×10^{-13}	7.12×10^{-3}	9.13×10^{-3}

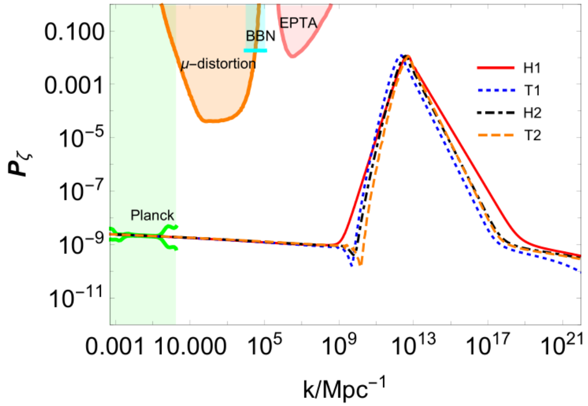
Yi, Gong, Wang, Zhu, 2007.09957

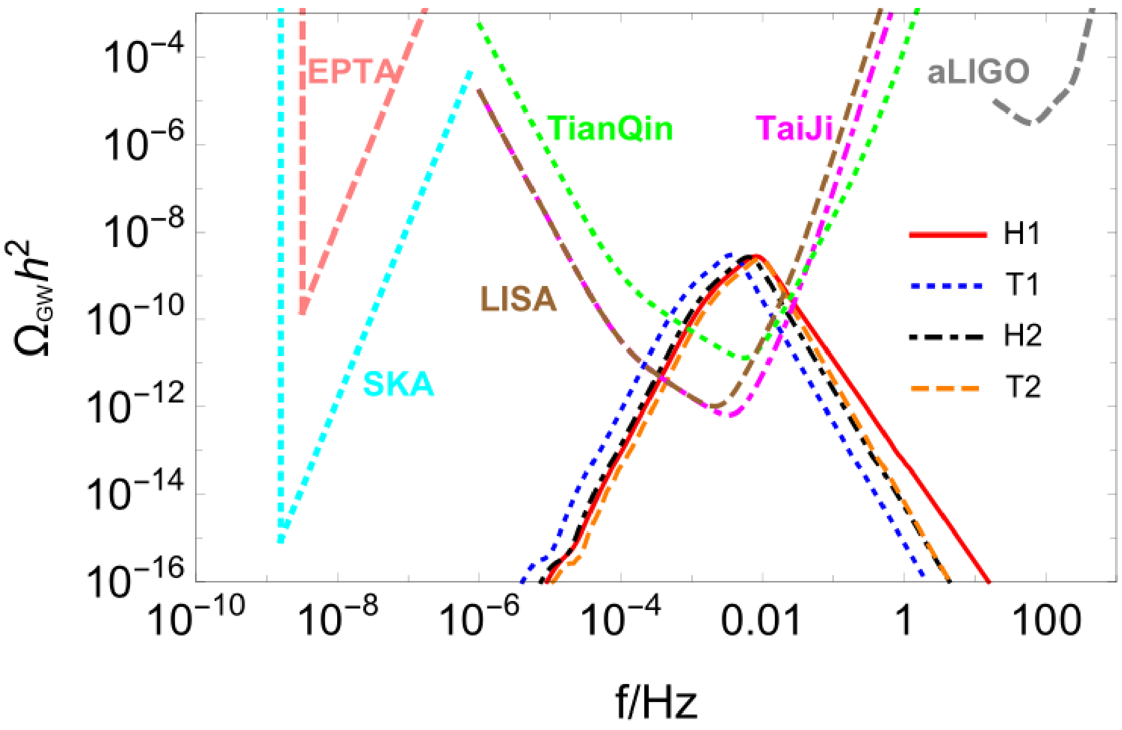




SIGWs from Higgs field

- Peak (broken power law form)





Yi, Gong, Wang, Zhu, 2007.09957

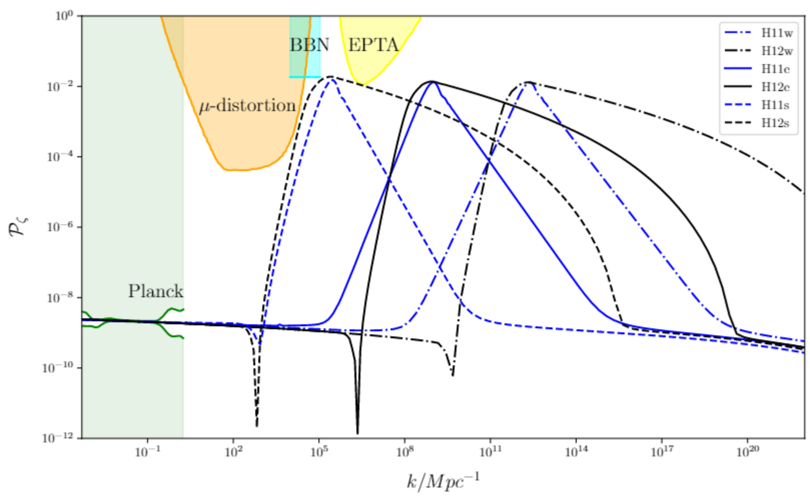
Broad Spectrum

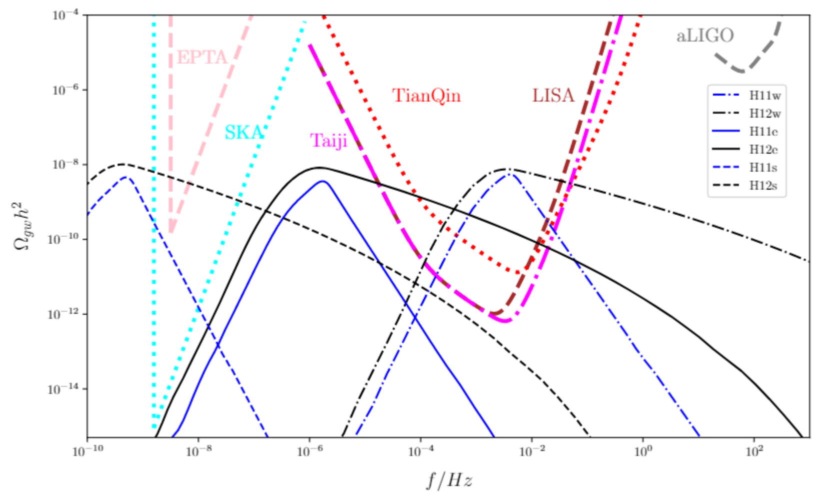
- Non-canonical kinetic

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2}R + X + G(\phi)X - V(\phi)\right]$$

$$G = G_a + f(\phi) \quad V(\phi) = \lambda\phi^4/4$$

$$G_a(\phi) = \frac{h}{1+(|\phi-\phi_p|/w)^q} \qquad q = 5/4 \qquad f(\phi) = \phi^{22}$$





Yi, Gong, Wang, Zhu, 2007.09957; 2011.10606

Non-Gaussianity

- Bispectrum

$$\left\langle \hat{\zeta}_{\boldsymbol{k}_1} \hat{\zeta}_{\boldsymbol{k}_2} \hat{\zeta}_{\boldsymbol{k}_3} \right\rangle = (2\pi)^3 \delta^3 \left(\boldsymbol{k}_1 + \boldsymbol{k}_2 + \boldsymbol{k}_3\right) B_\zeta \left(k_1, k_2, k_3\right)$$

$$f_{\rm NL}(k_1, k_2, k_3) = \frac{5}{6} \frac{B_\zeta(k_1, k_2, k_3)}{P_\zeta(k_1) P_\zeta(k_2) + P_\zeta(k_2) P_\zeta(k_3) + P_\zeta(k_3) P_\zeta(k_1)}$$

- PBH

$$\mathcal{J} = \frac{1}{6\sigma_R^3} \int \frac{\mathrm{d}^3 k_1}{(2\pi)^3} \int \frac{\mathrm{d}^3 k_2}{(2\pi)^3} \int \frac{\mathrm{d}^3 k_3}{(2\pi)^3} \mathrm{W}\left(k_1 R\right) \mathrm{W}\left(k_2 R\right) \mathrm{W}\left(k_3 R\right) \left\langle \hat{\zeta}_{k_1} \hat{\zeta}_{k_2} \hat{\zeta}_{k_3} \right\rangle$$

$$\mathcal{J}_{\rm peak} = \frac{3}{20\pi} f_{\rm NL}(k_{\rm peak}, k_{\rm peak}, k_{\rm peak}) \sqrt{\Delta_\zeta^2(k_{\rm peak})}$$

R. Saito, J. Yokoyama and R. Nagata, JCAP 06 (2008) 024

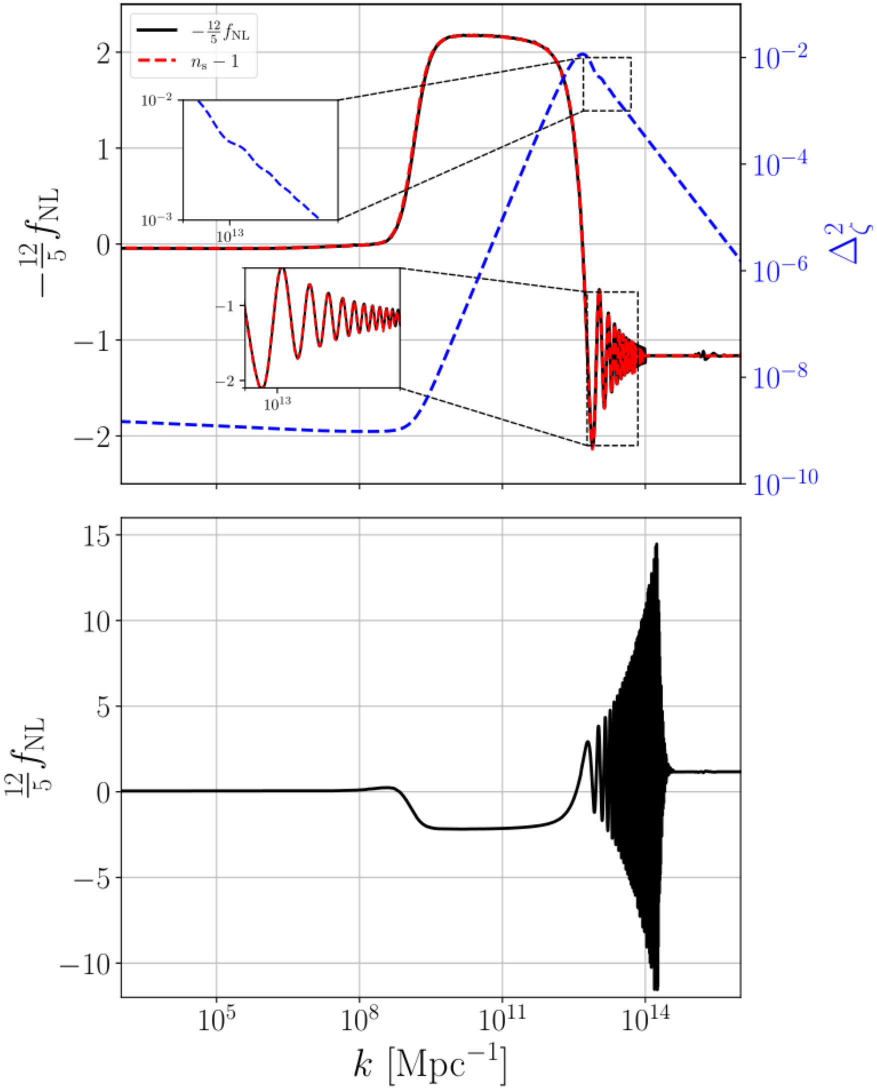
- SIGWs $\quad f_{\rm NL}^2 \Delta_\zeta^2 \gtrsim 1$

R.-G. Cai, S. Pi and M. Sasaki, PRL 122 (2019) 201101

Non-Gaussianity in k/G inflation

Squeezed limit

Equilateral



Conclusion

- Higgs field drives inflation, explains DM in the form of PBHs
- The mechanism works for more general scalar fields
- Different types of spectrum are also possible
- The observations of PBH and SIGWs can be used to probe early universe

2007.09957, 2011.10606, 2012.03856, 2102.07369

Thank You