宇宙論の諸問題(仮)

Inflation, dark energy, dark matter, …

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「第５回銀河進化と遠方宇宙」2019

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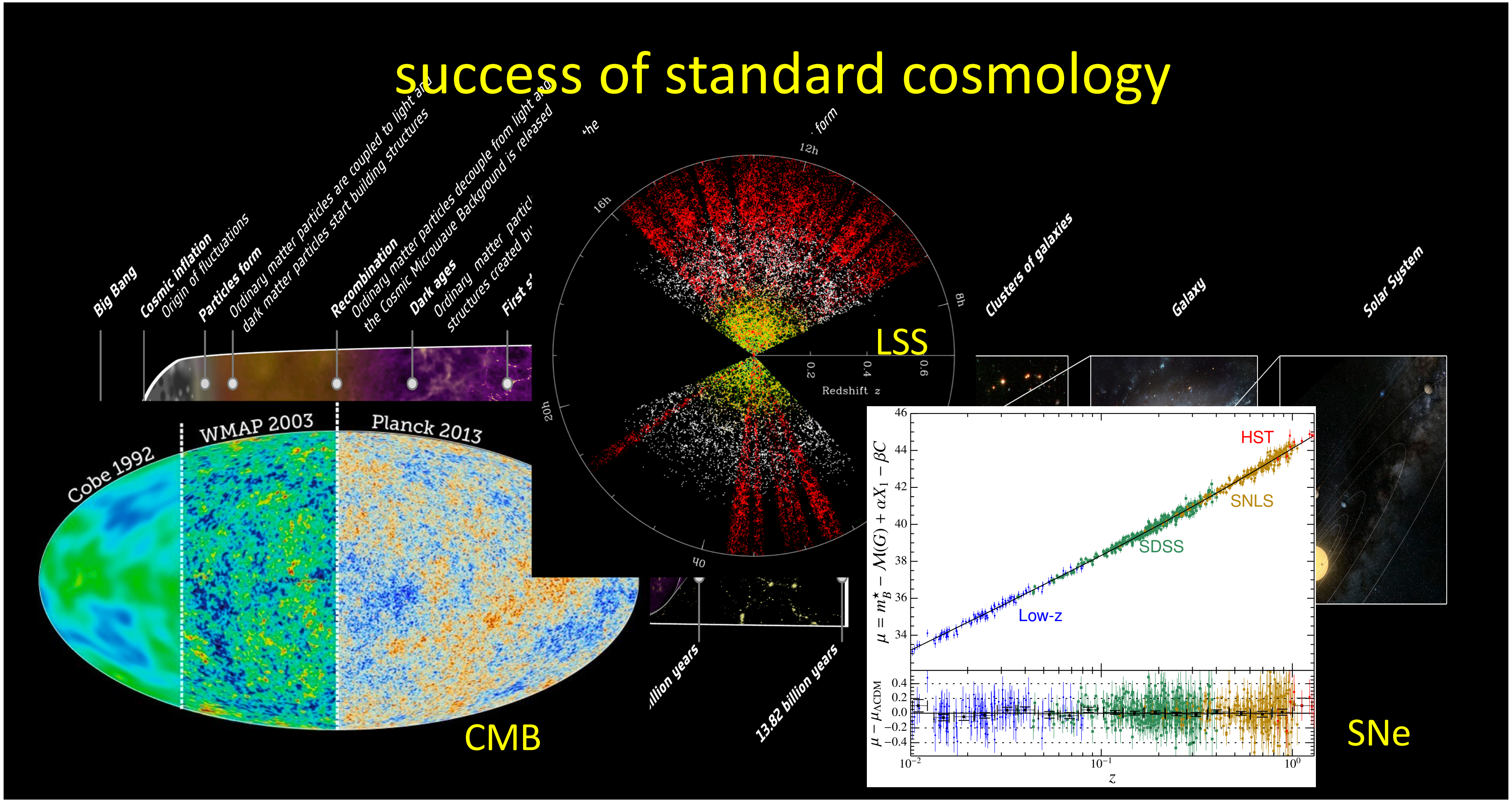
- Dark energy
- Dark matter
- Summary

Overview



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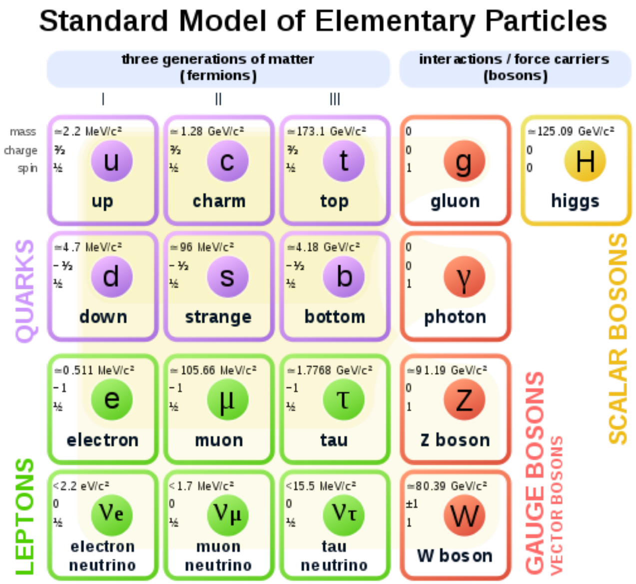
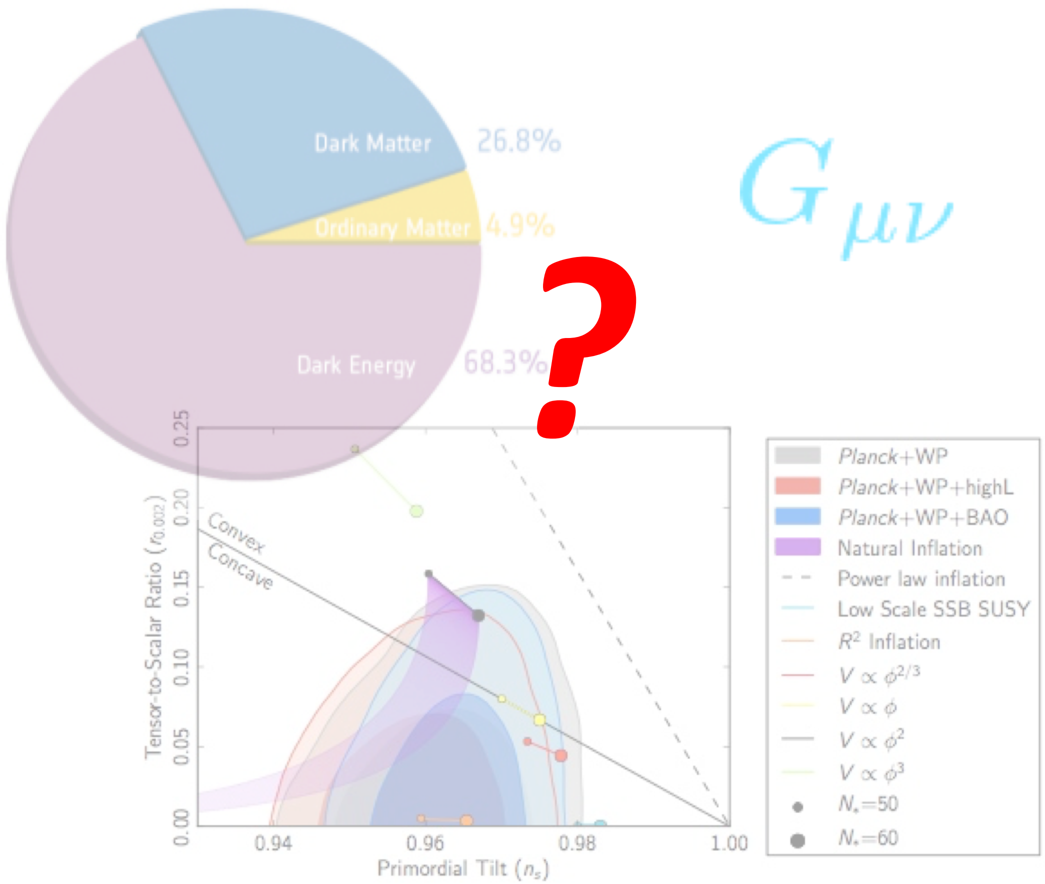
Overview

- Standard component in cosmology

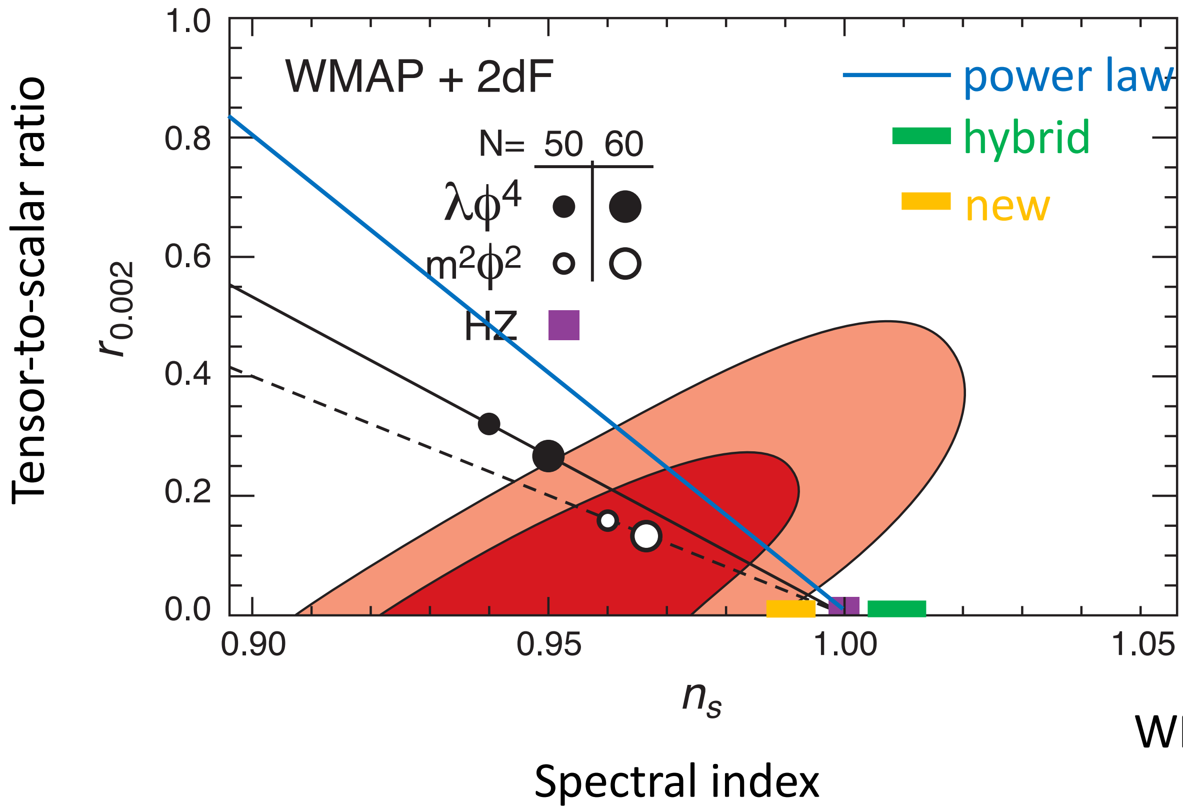




Any others?

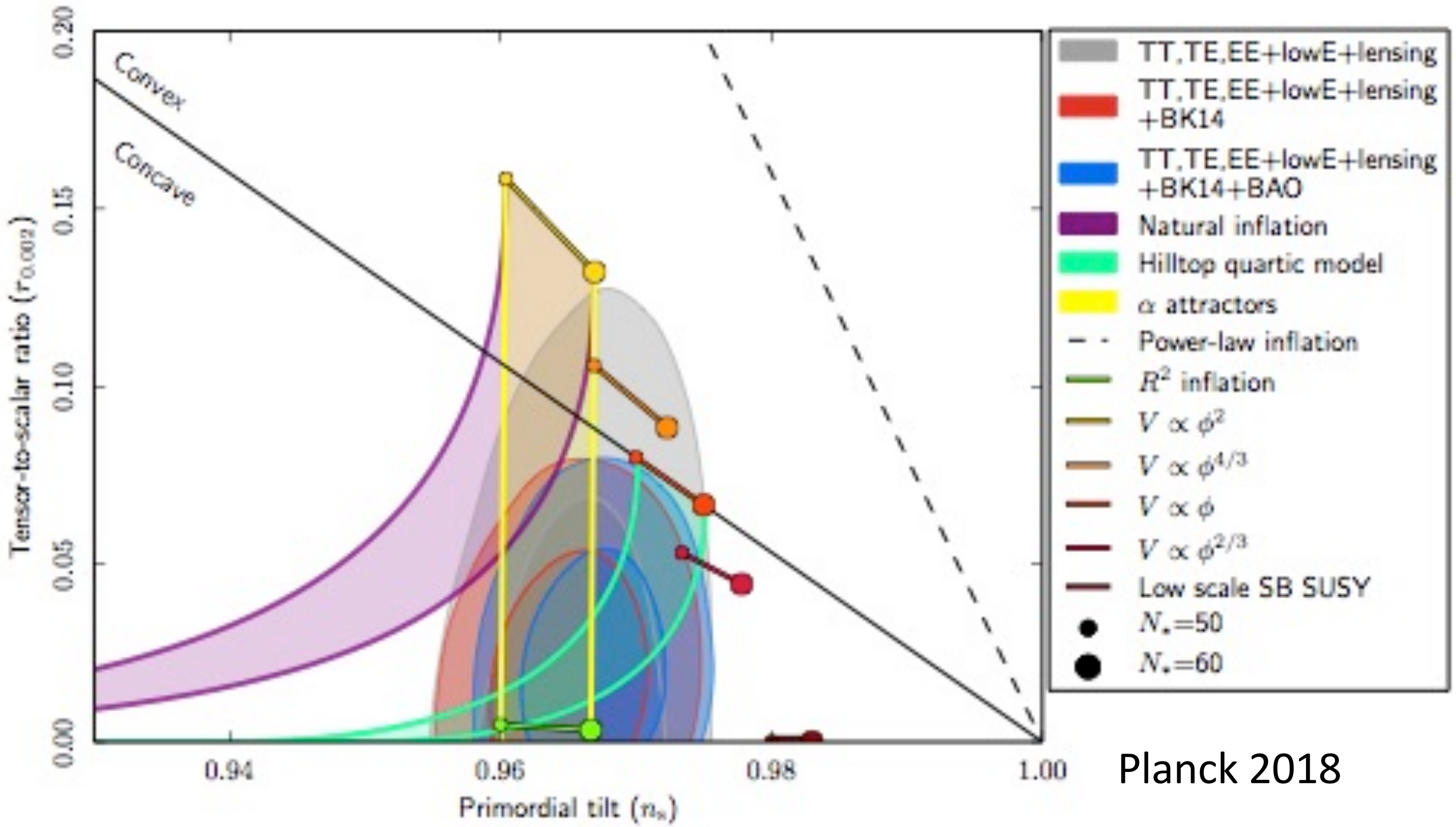
inflation

Constraint on CMB



WMAP 2007

Constraint on CMB

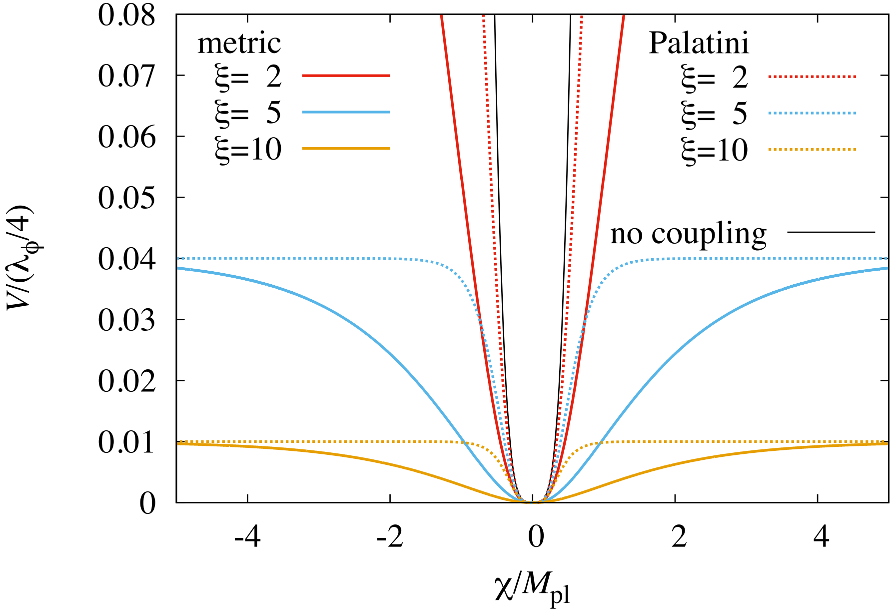


Planck 2018

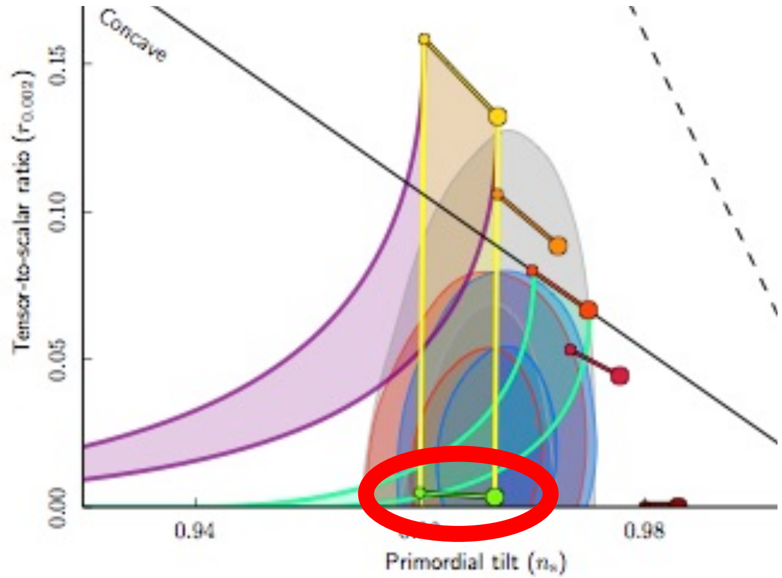
Beyond standard??

Inflaton with a non-minimal coupling

$\lambda\phi^4$ with $\xi\phi^2 R$



Takahashi, Tenkanen(2018)



Best model?

←→ Starobinsky model (R^2 inflation)

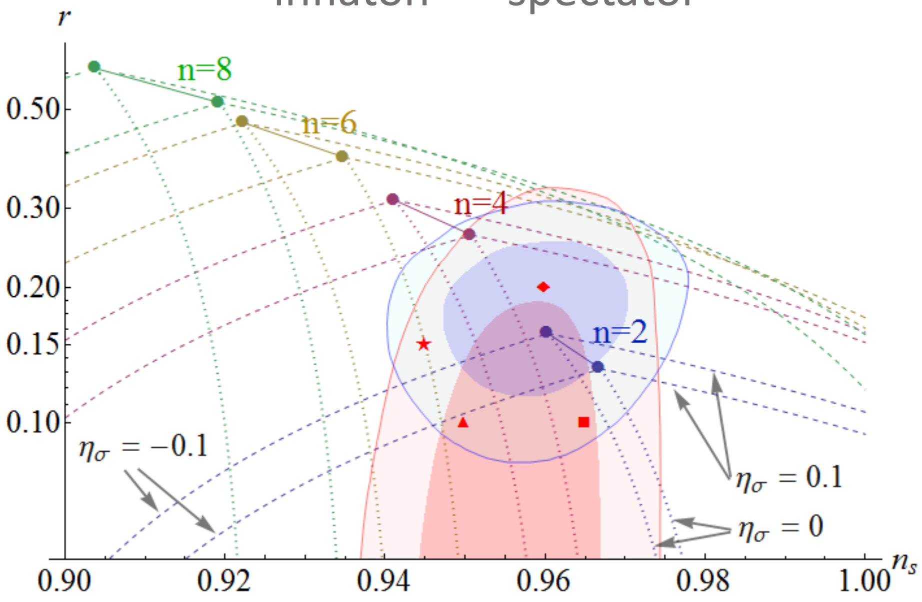
$\delta T/T \sim 10^{-5} \quad \Longrightarrow \quad \frac{\xi}{\sqrt{\lambda}} \simeq 47000$

(Higgs inflation, Bezrukov, Shaposhnikov (2008))

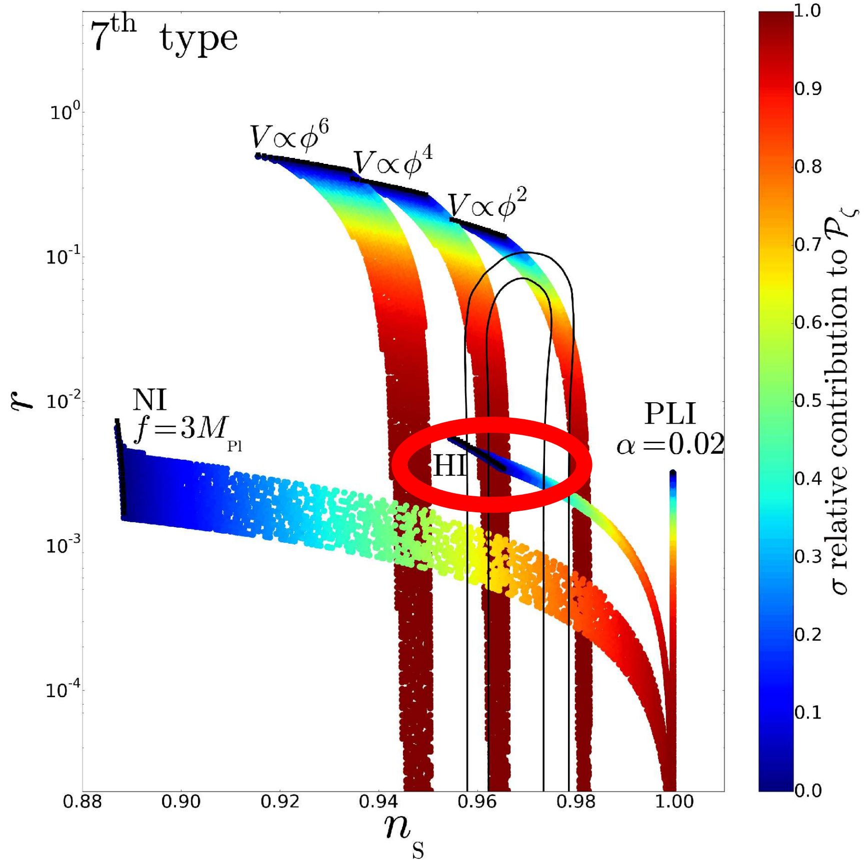
Inflaton with a spectator field
- extention to multi-field case -

$$\mathcal{P}_s(k) = \mathcal{P}_s^{(\phi)}(k) + \mathcal{P}_s^{(\chi)}(k),$$

inflaton spectator



Fujita, Kawasaki, SY (2014)



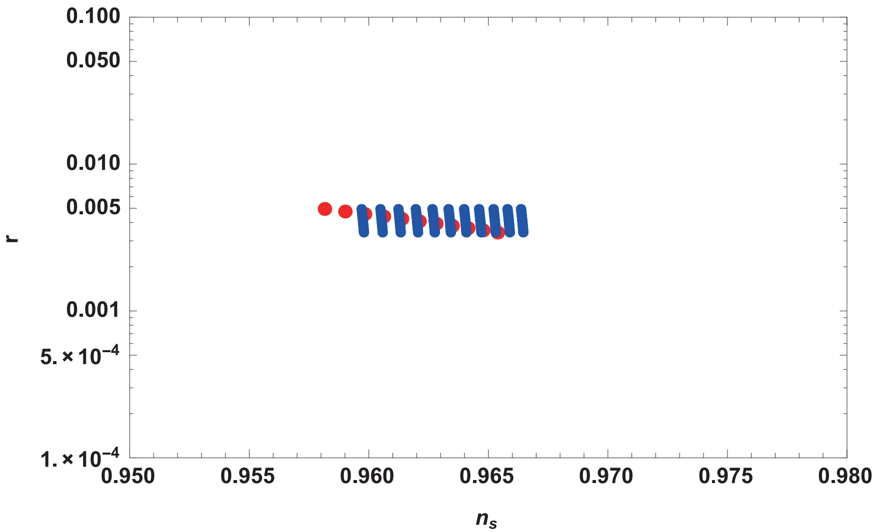
"Encyclopædia curvatonis"
Vennin, Koyama, Wands (2015)

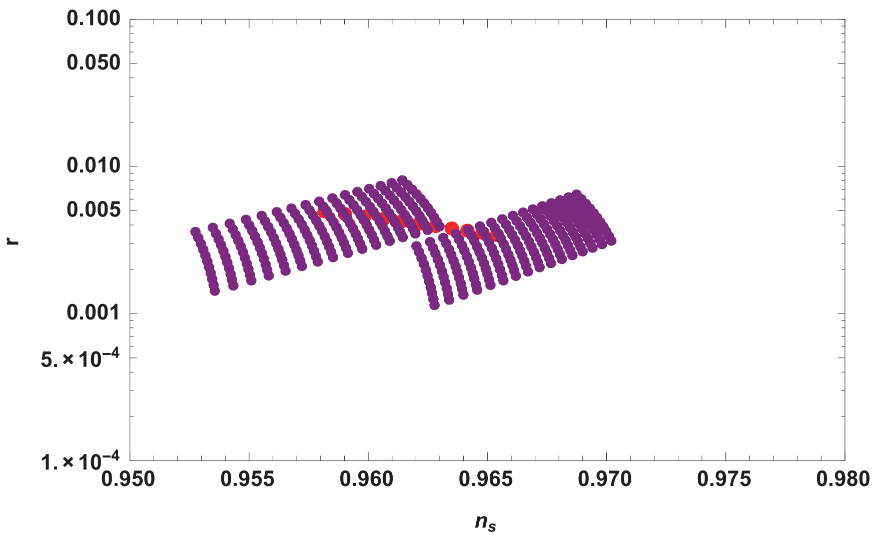
Not only tensor-to-scalar ratio, but also spectral index should change

➔ degenerate ?

R^2 inflation and …

Nariai and Tomita (1971), Starobinsky (1980), …





R^2 inflation (N = 50 - 60)

phi^4-inflation with a massless spectator (N = 50 – 60)

natural inflation with a massless spectator (N = 50 – 60, $Q_\chi = 0.5,\ 0.6$, $f = 3.3 - 3.75\ M_{\rm pl}$)

$r = (1 - Q_\chi)16\epsilon$; tensor-to-scalar ratio

$$Q_\chi \equiv \frac{\mathcal{P}_s^{(\chi)}(k_0)}{\mathcal{P}_s^{(\phi)}(k_0) + \mathcal{P}_s^{(\chi)}(k_0)}$$

$$V(\phi) = \Lambda^4 \left[1 - \cos\frac{\phi}{f}\right]$$

Sekiguchi, Takahashi, Tashiro, SY in preparation

How to discriminate?

- Higher order ?

Local type non-Gaussianity in multi-scalar inflation

$$\zeta = \zeta_{\rm G} + \frac{3}{5} f_{\rm NL} \left(\zeta_{\rm G}^2 - \langle \zeta_{\rm G}^2 \rangle \right) + \cdots$$

Linear perturbation (free propagation) ←→ Gaussian

➔ through the non-linear interaction
➔ non-zero higher order perturbations
➔ non-Gaussianity!!
➔ observed by higher order correlation functions!

Standard single slow-roll case; $\zeta \sim \frac{V}{V_\phi}\delta\phi + \left(\frac{V_\phi^2}{V^2} - \frac{V_{\phi\phi}}{V} \right) \left(\frac{V}{V_\phi}\delta\phi \right)^2$

slow-roll suppressed!!

Spectator case; $\zeta \sim F \frac{\delta\rho_\sigma}{\rho_\sigma} \sim F \frac{\delta\sigma}{\sigma} + \frac{1}{F} \left(F \frac{\delta\sigma}{\sigma} \right)^2$

$(\rho_\sigma \propto \sigma^2)$

transfer from spectator to curvature perturbations

Distinguishing models by Local type NG

- Single inflation vs spectator (curvaton, …)

Critical value; $f_{\rm NL}^{\rm local} = O(0.1-1)$

Spectator (curvaton) scenario ➔ $f_{\rm NL}^{\rm local} > O(1)$

due to the transfer from spectator to adiabatic curvature pert.

Single scalar inflation ➔ $f_{\rm NL}^{\rm local} \lesssim O(0.01)$

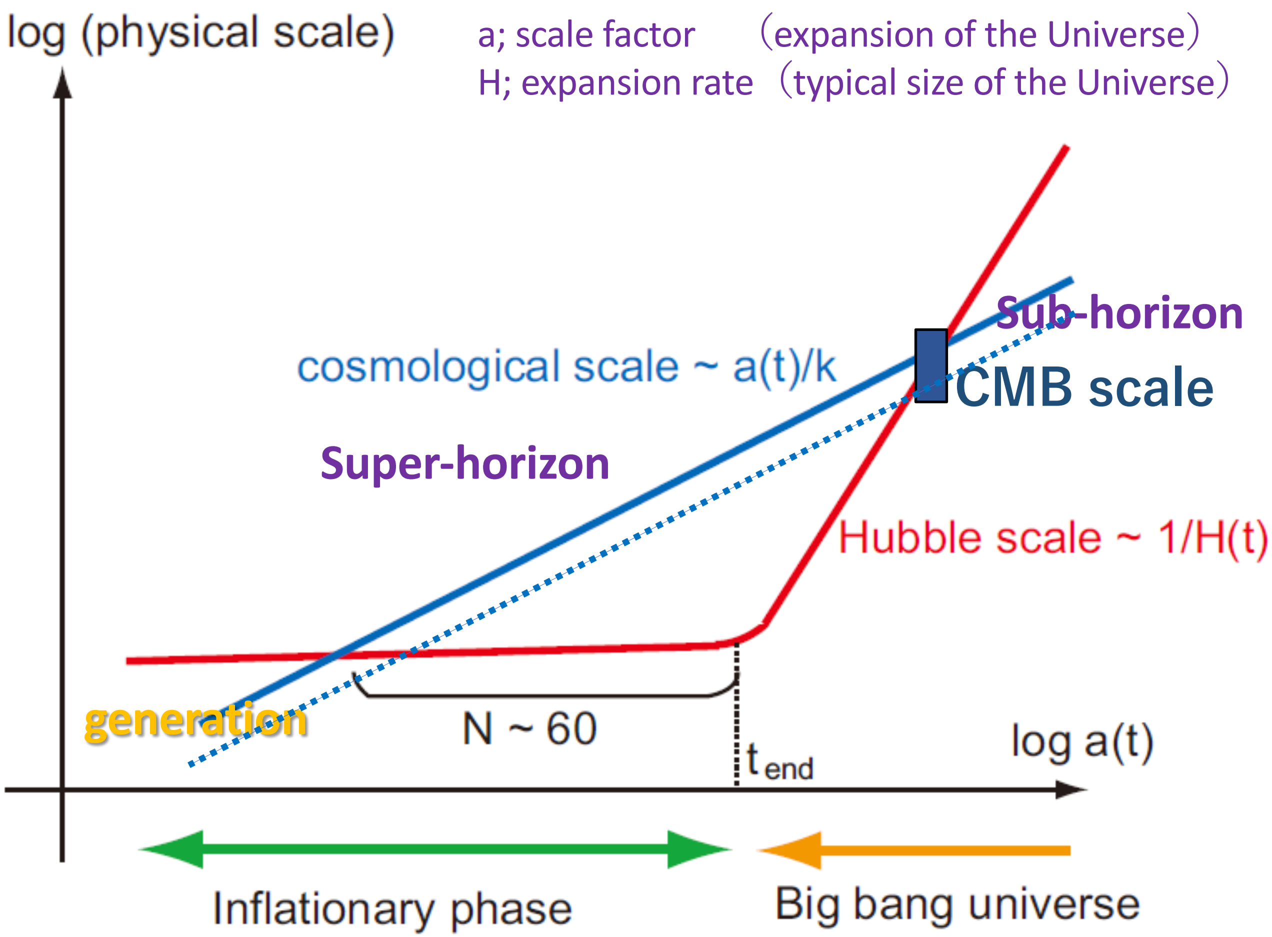
slow-roll suppression

How to discriminate?

- Higher order ?

- Smaller scales?

Primordial fluctuations from inflation



Quantum fluctuations (causal) are stretched by inflationary expansion

➔

"classical" super-horizon (acausal) fluctuations

(basically determined at the horizon exit)

➔

primordial fluctuations with different scales (wavenumber) would bring us the information of different stages of inflation !!

Runnings of spectral index as a perturbative approach

Spectral index

$$\mathcal{P}_s(k) = A_s \left(\frac{k}{k_0}\right)^{n_s - 1 + \frac{1}{2}\alpha_s \ln(k/k_0) + \frac{1}{3!}\beta_s \ln^2(k/k_0) + \cdots},$$

Taylor series of scale dependence of spectral index

For the slow-roll inflation, these parameters can be expressed w.r.t. slow-roll parameters as

$$\begin{aligned} n_s - 1 &= -6\epsilon + 2\eta, \\ \alpha_s &= -24\epsilon^2 + 16\epsilon\eta - 2\xi^{(2)}, \\ \beta_s &= -192\epsilon^3 + 192\epsilon^2\eta - 32\epsilon\eta^2 - 24\epsilon\xi^{(2)} + 2\eta\xi^{(2)} + 2\sigma^{(3)}, \end{aligned}$$

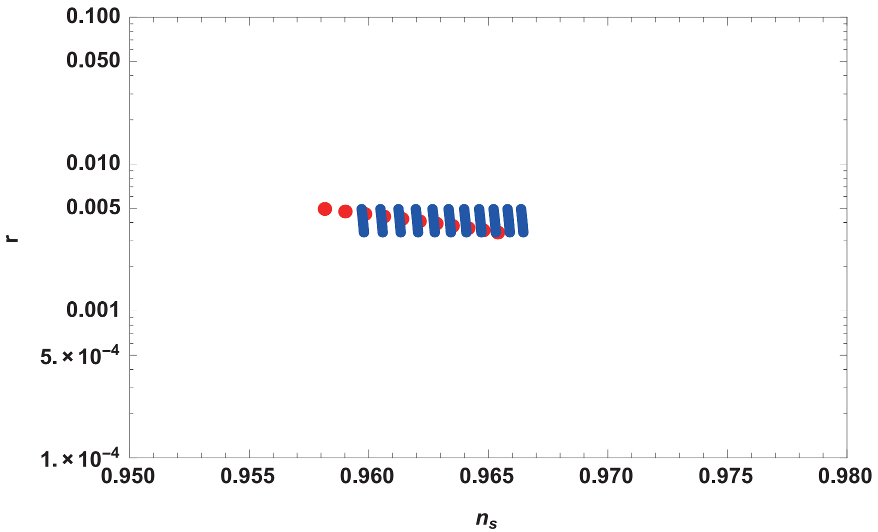
$$\xi^{(2)} \equiv M_{\rm pl}^4 \frac{V'V'''}{V^2}, \quad \sigma^{(3)} \equiv M_{\rm pl}^6 \frac{(V')^2 V^{(4)}}{V^3},$$

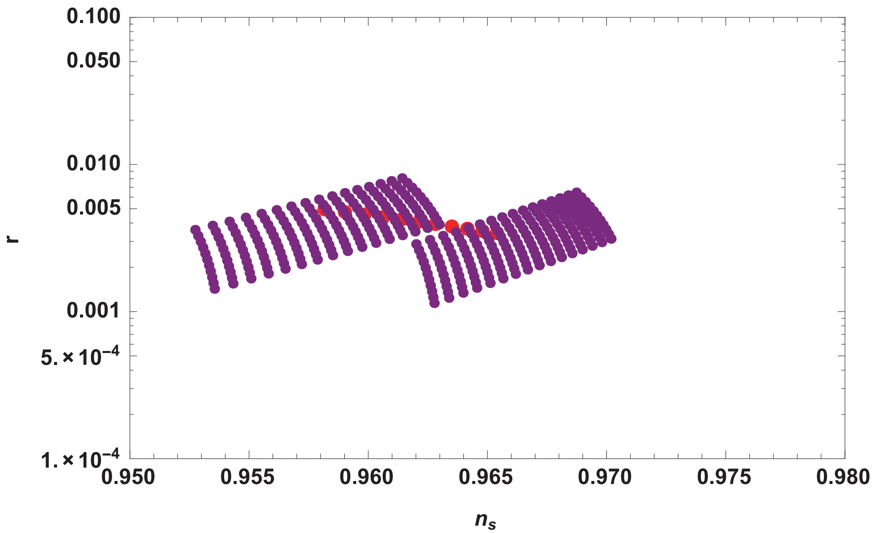
V; inflaton’s potential

depend on higher order slow-roll parameters which do not appear in “r” and “n_s”

As examples

r – n_s plane





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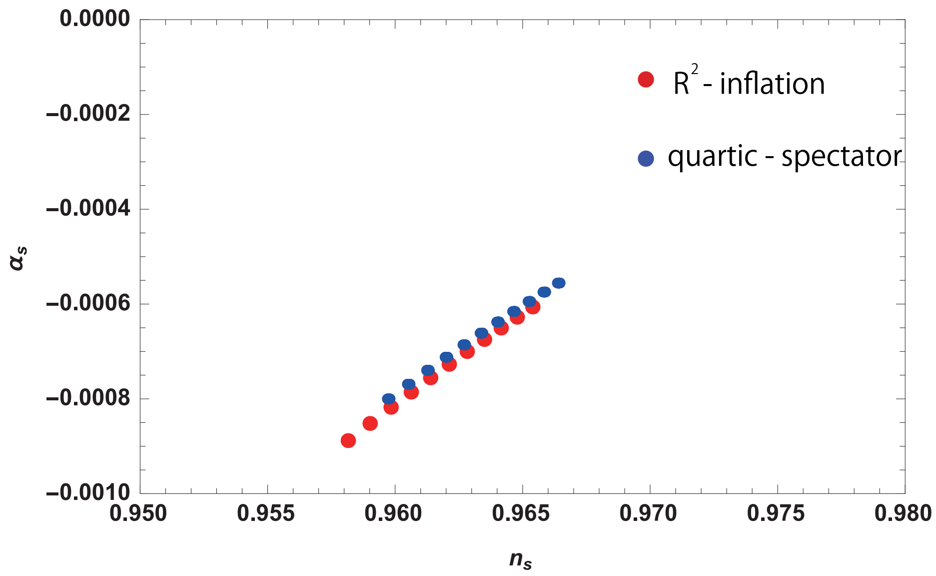
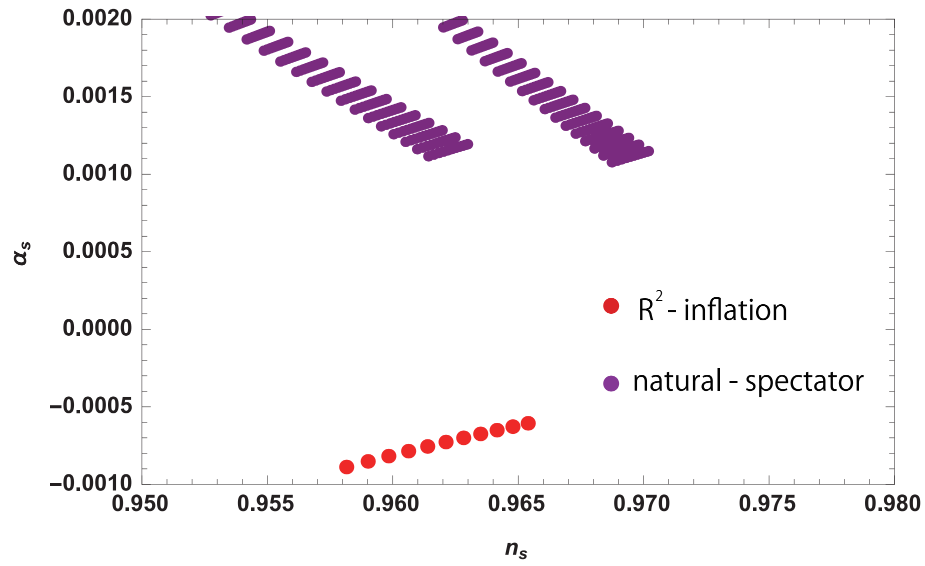
$$V(\phi) = \Lambda^4 \left[1 - \cos\frac{\phi}{f}\right]$$

Sekiguchi, Takahashi, Tashiro, SY (2018)

As examples

n_s – alpha_s plane





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Sekiguchi, Takahashi, Tashiro, SY (2018)

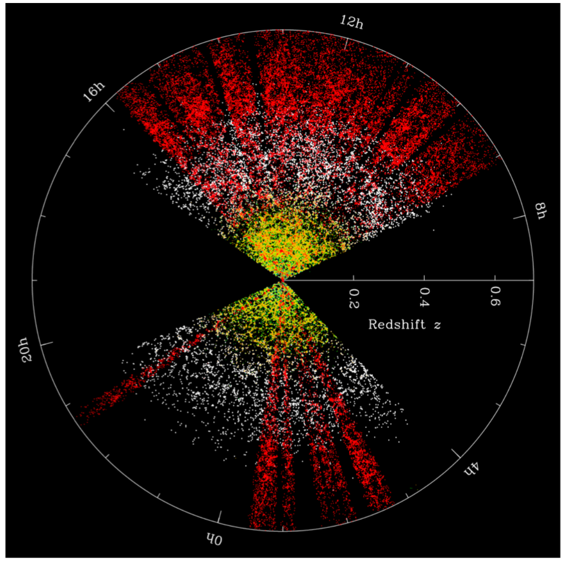
How to discriminate?

- Higher order ?

- Smaller scales?

SKA ??

Primordial NG in LSS



$$\zeta = \zeta_{\rm G} + \frac{3}{5} f_{\rm NL} \left(\zeta_{\rm G}^2 - \langle \zeta_{\rm G}^2 \rangle \right) + \cdots$$

- higher order correlation functions (bispectrum, …)

$$\langle \delta_{\rm L}(\mathbf{k}_1)\delta_{\rm L}(\mathbf{k}_2)\delta_{\rm L}(\mathbf{k}_3)\rangle \; = \; (2\pi)^3 \delta(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3) B_{\rm L}(k_1, k_2, k_3), \propto f_{\rm NL}$$

- Scale-dependent bias

$$P_{hh}(k) = \left(b^E_{eff}\right)^2 P_{mm}(k)$$

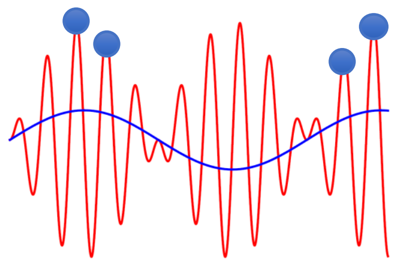
$$b^E_{eff}(k, z, f_{\rm NL}) = b^E_G + 3 f_{\rm NL} (b^E_G - 1) \frac{H_0^2 \Omega_m \delta_c(z)}{c^2 T(k) k^2}$$

1/k^2 dependence !!

Galaxies, minihalos !!!

$$\zeta \sim \delta / k^2$$

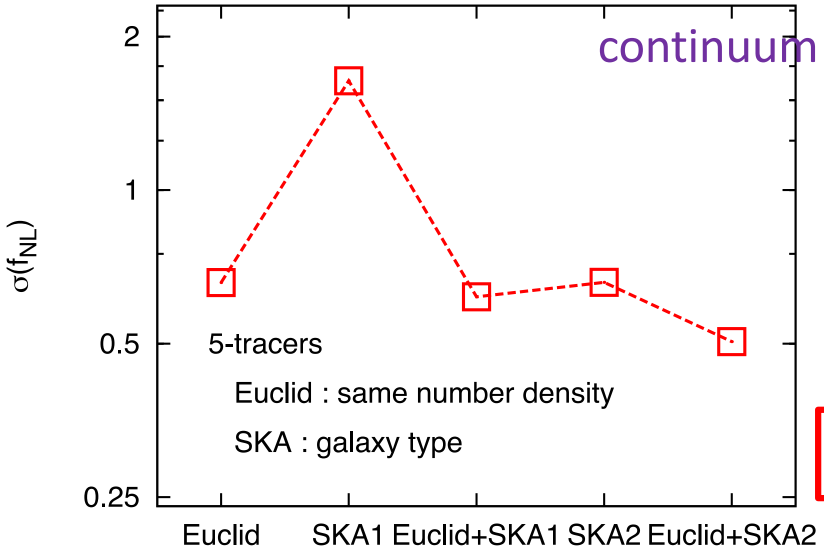
$$\delta \sim (1 + f_{\rm NL} \zeta) \delta$$



non-Gaussian

SKA as a galaxy survey

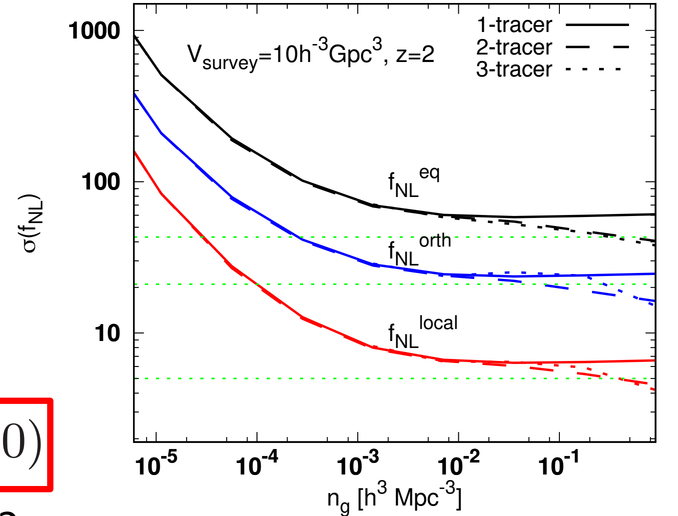
continuum survey



$\sigma(f_{\rm NL}) = 0.61\ (0.50)$

SKA1 (2) ?

Yamauchi, Takahashi, Oguri (2014)

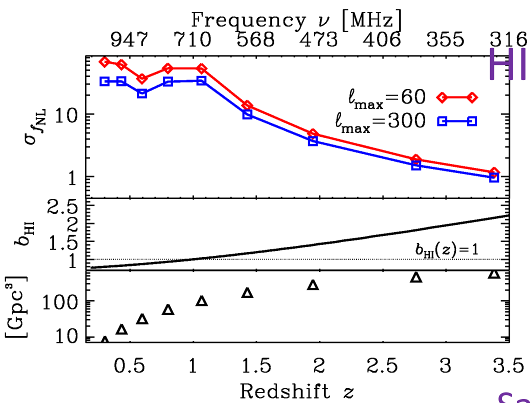


Yamauchi, SY, Takahashi (2016)

➔ Other types of NG ?

factor 2 improvement compared with Planck

HI IM



$\sigma_{f_{\rm NL}} = 2.3$

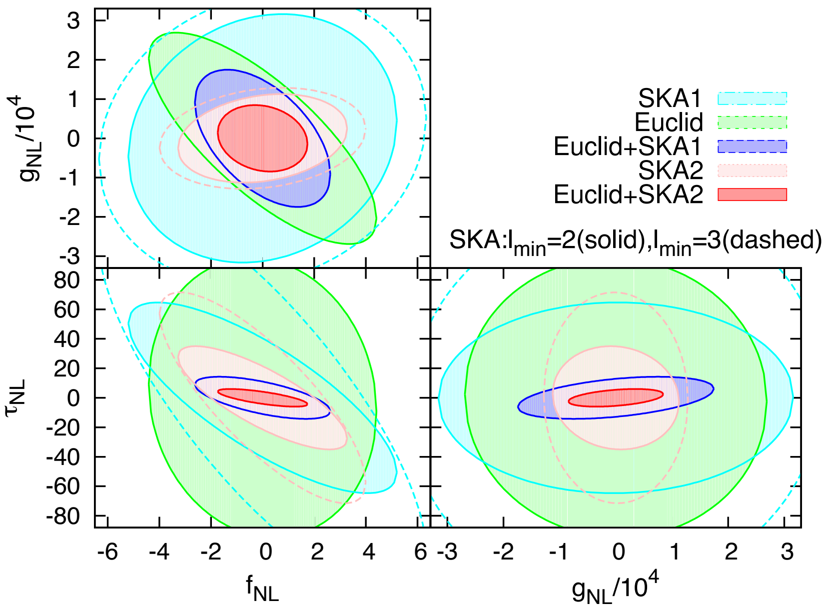
Santos, et. al. (2015)

SKA as a galaxy survey

Higher order non-Gaussianities?

$f_{\rm NL}$; a parameter related with the primordial bispectrum (3-pt. func.)

$g_{\rm NL}$
$\tau_{\rm NL}$; parameters related with the primordial trispectrum (4-pt. func.)



Yamauchi, Takahashi (2015)

SKA as a probe of EoR

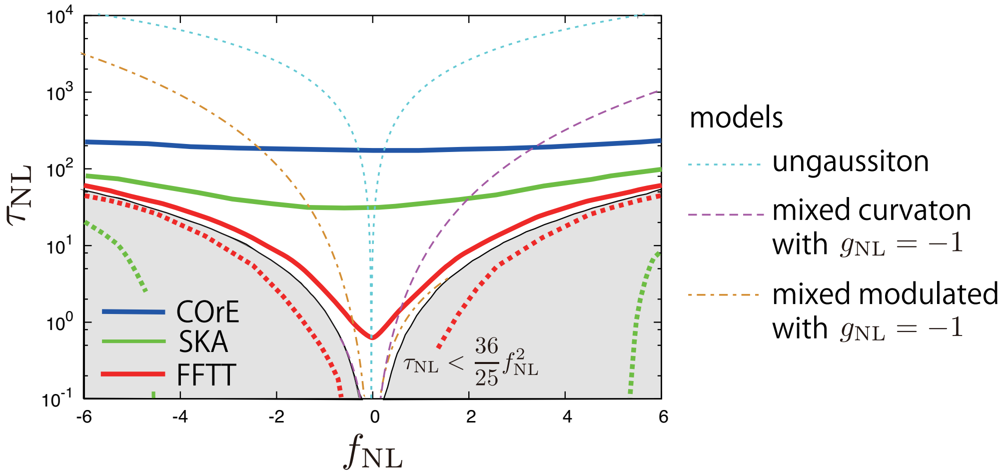
Sekiguchi, Takahashi, Tashiro, SY (2018)

Minihalos as biased tracers (lots of works, ...)

✓ virialized objects with the virial temperature $T < 10^4$ K

too low to cause the star formation

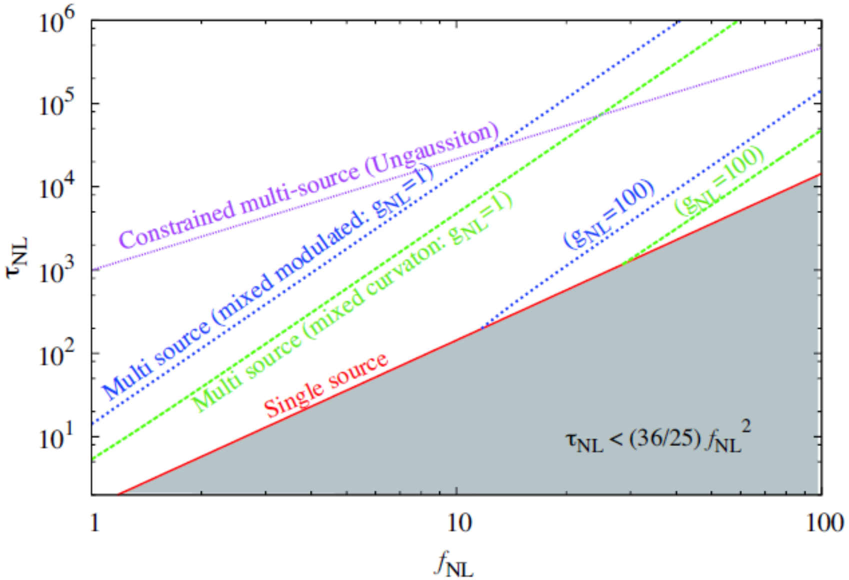
✓ filled neutral gas

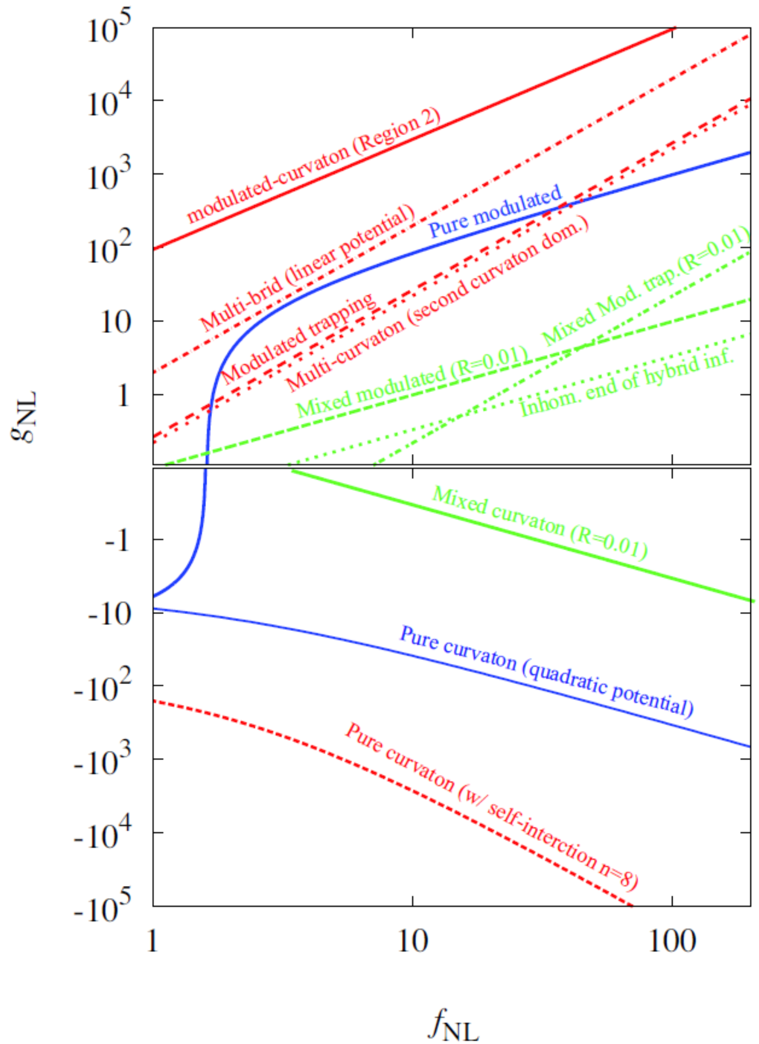


dataset	$\Delta f_{\rm NL}$	$\Delta g_{\rm NL}/10^3$	$\Delta \tau_{\rm NL}$
CMB alone			
Planck	4.0	41	610
COrE	2.0	18	160
SKA	1.4	2.3	28
+Planck	1.3	2.3	28
+COrE	1.1	2.2	27
FFTT	0.51	0.79	0.59
+Planck	0.50	0.78	0.58
+COrE	0.48	0.75	0.58

Powerful to discriminate large NG models (multi-inflation) !!!

Higher NGs in multi-scalar inf.





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Sekiguchi, Takahashi, Tashiro, SY (2018)

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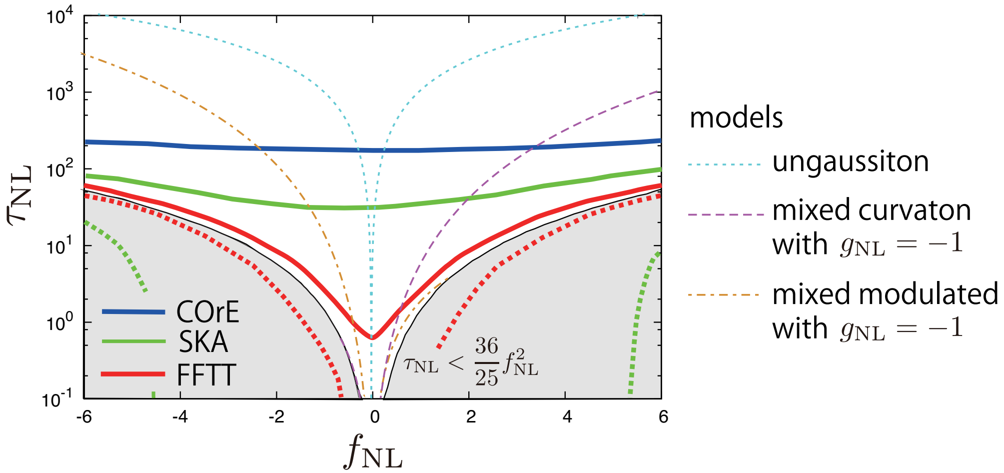

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Powerful to discriminate large NG models (multi-inflation) !!!

How to discriminate?

- Higher order ?
- Smaller scales?

SKA ??

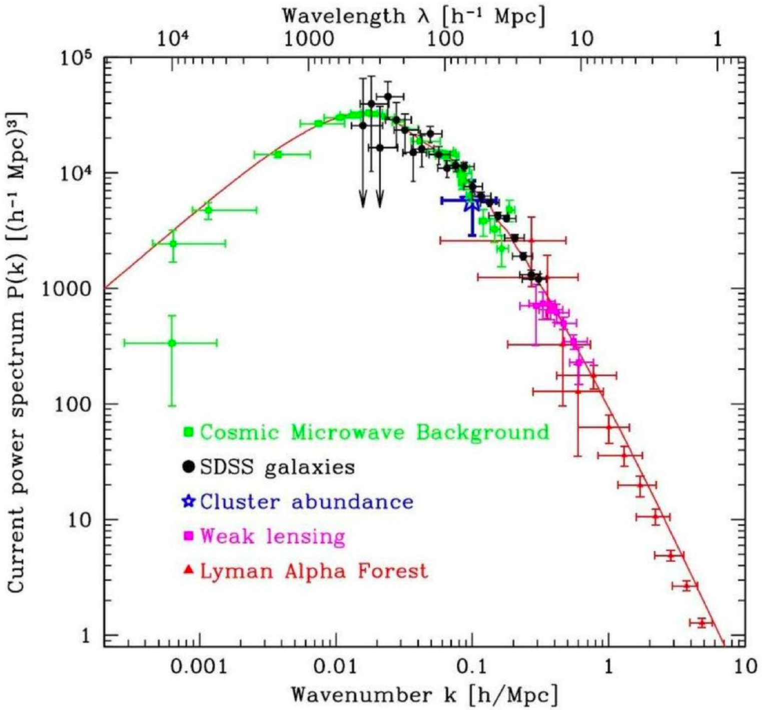
SKA as a probe of EoR

Kohri, et al. (2013)

Matter fluctuations in EoR

(lots of works, …)

- High-z ➔ “gravitational“ non-linearity is not so large (~1 Mpc?)



Tegmark et al. (2004)

	δn_s	$\delta \alpha_s$	$\delta \beta_s$
Planck	4.11×10^{-3}	6.59×10^{-3}	9.95×10^{-3}
Planck + SKA phase1	2.03×10^{-3}	2.90×10^{-3}	2.21×10^{-3}
Planck + SKA phase2	1.73×10^{-3}	2.36×10^{-3}	1.52×10^{-3}
Planck + Omniscope	6.04×10^{-4}	1.07×10^{-3}	7.31×10^{-4}
CMBpol	2.10×10^{-3}	2.36×10^{-3}	4.37×10^{-3}
CMBpol + SKA phase1	1.46×10^{-3}	2.07×10^{-3}	1.61×10^{-3}
CMBPol + SKA phase2	1.33×10^{-3}	1.84×10^{-3}	1.21×10^{-3}
CMBpol + Omniscope	5.53×10^{-4}	1.00×10^{-3}	6.86×10^{-4}
COrE	2.13×10^{-3}	2.43×10^{-3}	4.47×10^{-3}
COrE + SKA phase1	1.47×10^{-3}	2.09×10^{-3}	1.63×10^{-3}
COrE + SKA phase2	1.34×10^{-3}	1.85×10^{-3}	1.22×10^{-3}
COrE + Omniscope	5.54×10^{-4}	1.00×10^{-3}	6.87×10^{-4}

SKA as a probe of EoR

Sekiguchi, Takahashi, Tashiro, SY (2017)
Shimabukuro, Ichiki, Inoue, SY (2014), …

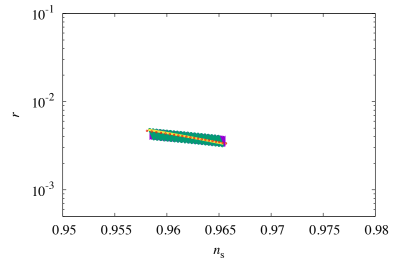
Minihalos as a probe of smaller scales

Iliev et al. (2002), …

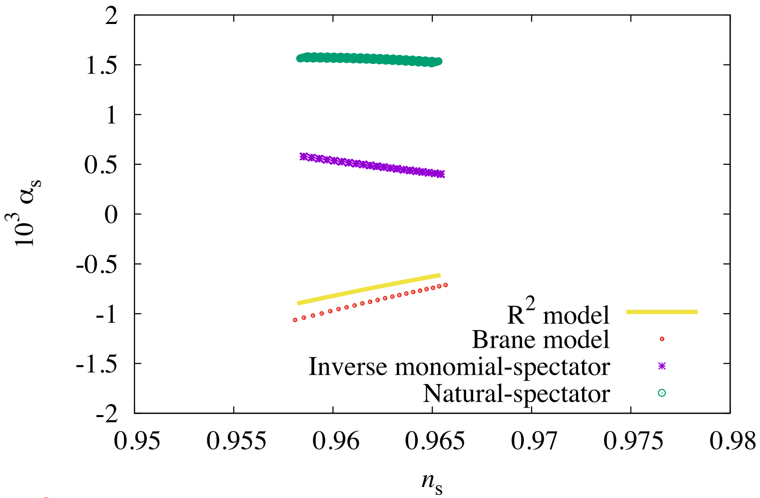
- ✓ virialized objects with the virial temperature $T < 10^4$ K

too low to cause the star formation

- ✓ filled neutral gas
- ✓ corresponding scales; $20\ \mathrm{Mpc}^{-1} < k < 500\ \mathrm{Mpc}^{-1}$



	$10^{-3}\Delta n_s$	$10^{-3}\Delta\alpha_s$	$10^{-3}\Delta\beta_s$
Planck	7.7	10.7	15.1
COrE	3.2	2.9	6.5
SKA	4.6	2.9	1.5
FFTT	2.4	1.6	0.79
Planck+SKA	1.7	2.0	0.63
Planck+FFTT	1.3	1.3	0.44
COrE+SKA	1.2	1.6	0.39
COrE+FFTT	0.95	1.1	0.28



We can distinguish !

Observational inflation cosmology

SKA

- Higher order

$$\sigma(f_{\rm NL}) = 0.61\ (0.50)$$

- Smaller scales

	$10^{-3}\Delta n_s$	$10^{-3}\Delta\alpha_s$	$10^{-3}\Delta\beta_s$
Planck	7.7	10.7	15.1
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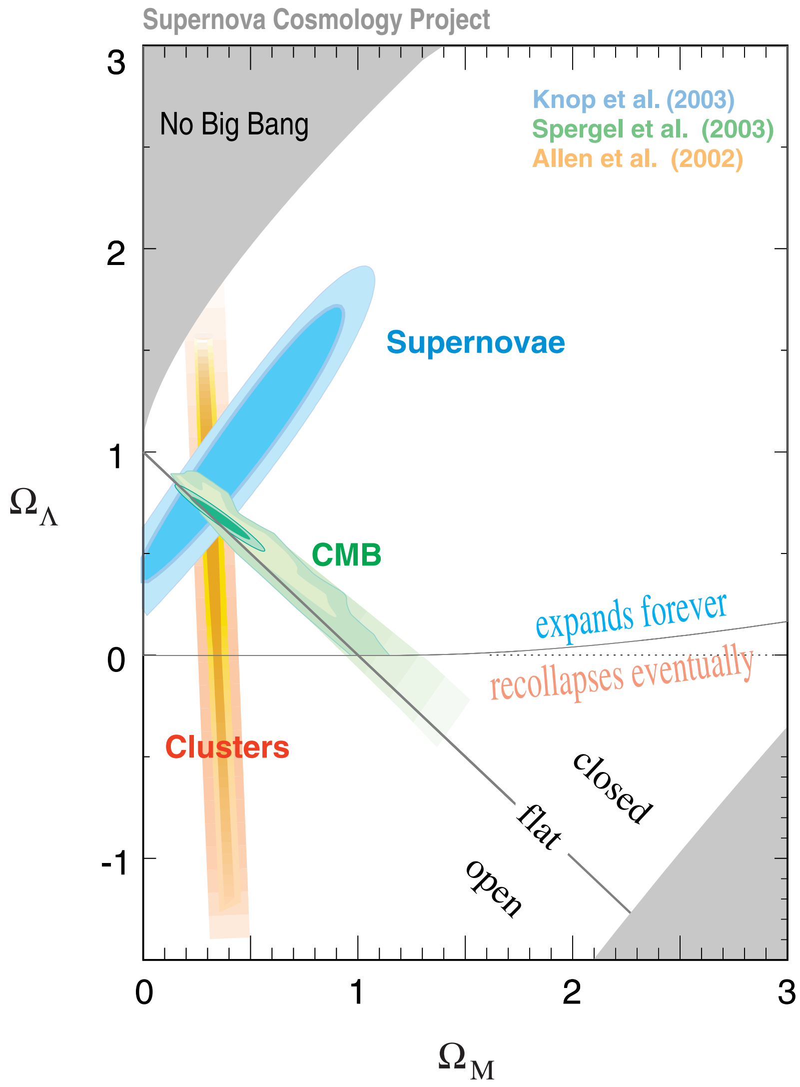
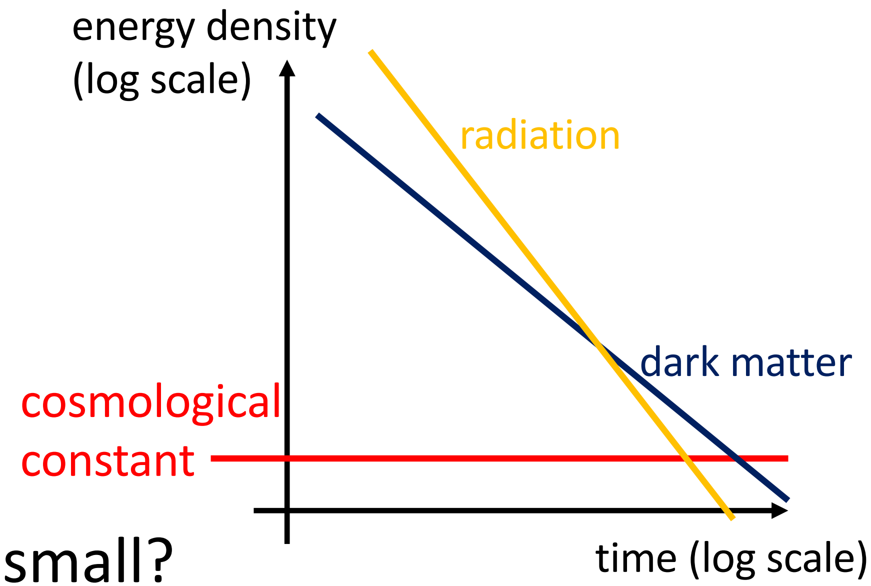
COrE+SKA	1.2	1.6	0.39
COrE+FFTT	0.95	1.1	0.28

Dark energy

Accelerated expansion of the Universe at present …



Most probable?



- Cosmological constant

➔should be resolved: why so small?
why now?

$$\rho_\Lambda \ll M_{\rm Pl}^4$$

resolved by string landscape picture?

Susskind, Weinberg, …

not allowed by swampland conjecture ??

Obied, Ooguri, Spodyneiko, Vafa (2018)

cosmological constant; w = -1

from https://www.kitp.ucsb.edu/activities/stringvacua20

Inflation like

- Quintessence (potential driven)

Lots of models …

(like an inflation zoo …)

equation of state parameter is

$$w = \frac{\frac{1}{2}\dot{\phi}^2 - V}{\frac{1}{2}\dot{\phi}^2 + V} > -1$$

c.f. cosmological constant; w = -1

k-essence $w = \frac{2XP_X - P}{P}$

would be smaller than -1 .. (violation of energy condition?)

Thawing and freezing

- Quintessence (potential driven)

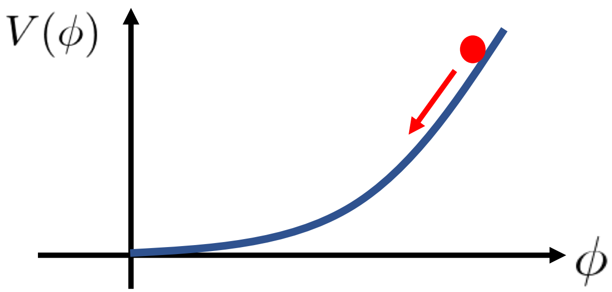
Lots of models … motivated by SUGRA, …

(like an inflation zoo …)

Basically, two types of quintessence model See, e.g., Caldwell and Linder (2005), …

Thawing model

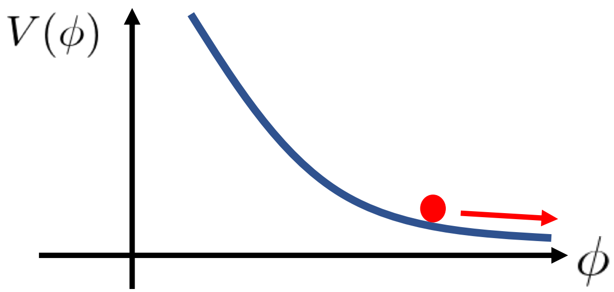
e.g., $V \propto \phi^n \ (n > 0)$



starts slow-rolling (thawing)
around the present time

Freezing model (tracker)

e.g., $V \propto \phi^{-n} \ (n > 0)$



fast rolling → slow rolling (freezing)

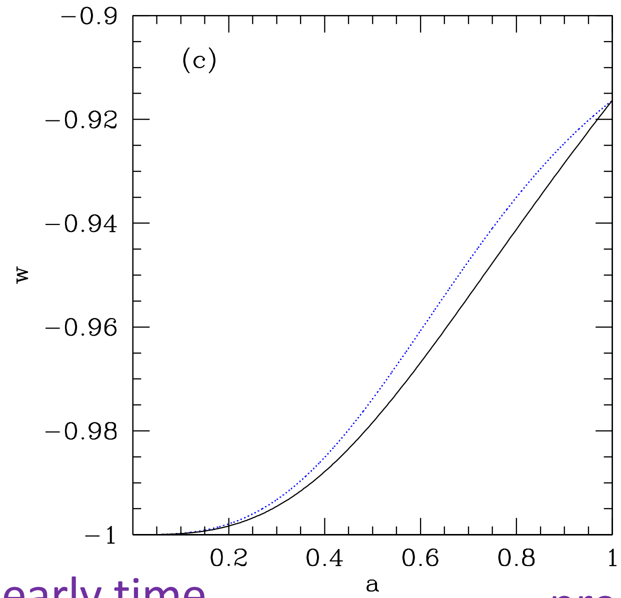
Thawing and freezing

- Quintessence (potential driven)

Evolution of equation of state

Thawing model $V = \frac{1}{2}m^2\phi^2$

Chiba (2009)

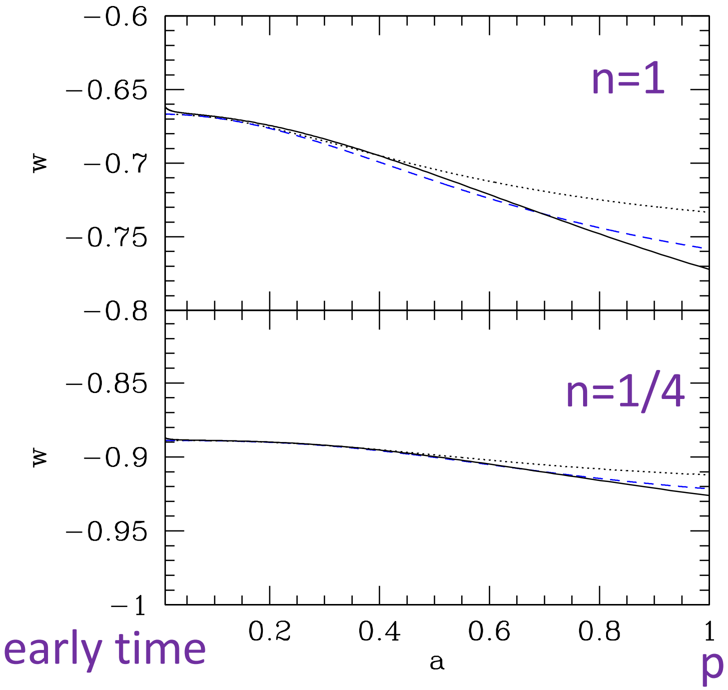


early time

present

Freezing model $V \propto \phi^{-n} \ (n > 0)$

Chiba (2010)



early time

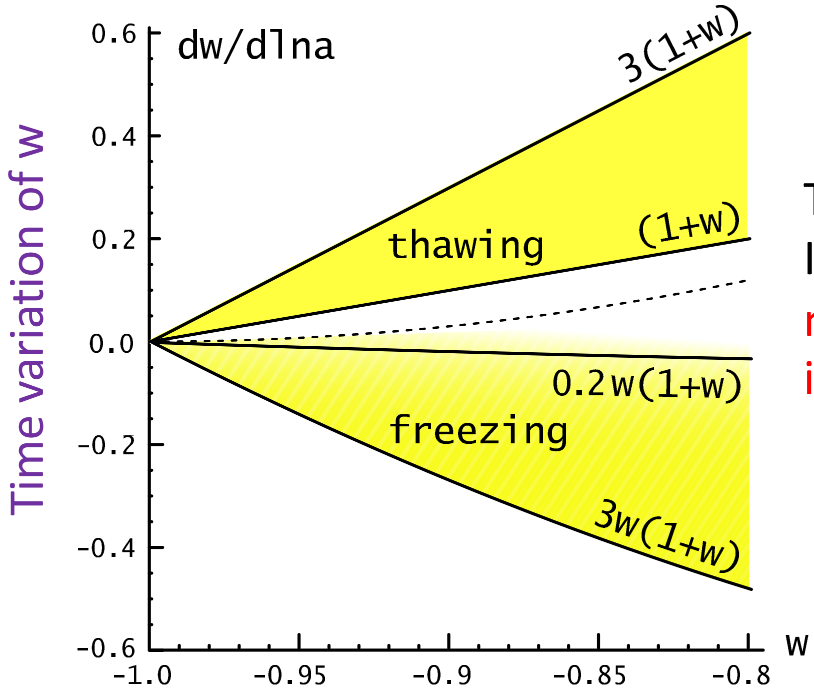
present

Thawing and freezing

- Quintessence (potential driven)

Evolution of equation of state

Thawing model $V = \frac{1}{2}m^2\phi^2$ Freezing model $V \propto \phi^{-n}\ (n > 0)$



To discriminate these models,
It should be important to observe
not only equation of state but also
its time dependence !

Caldwell and Linder (2005)

Modified gravity

- Scalar tensor theory

➔ non-minimally coupled scalar field $\supset \phi R$

could also include the derivative coupling $\supset G_{\mu\nu}\partial^{\mu}\phi\partial^{\nu}\phi$

In general, we can consider the Lagrangian
which has infinite terms with including higher order derivatives …

Infinite possible theories ?

Is there any guiding principles?

- from the first principle (string theory, or …?) (top-down)
- Based on some philosophy (respect some symmetry, stability condition, …)

➔ free from ghost instabilities !!

Modified gravity

see, e.g., Kobayashi, 1901.07183 (review paper)

- Horndeski theory

Lagrangian;

$$\mathcal{L} = G_2(\phi, X) - G_3(\phi, X)\Box\phi + G_4(\phi, X)R + G_{4X}\left[(\Box\phi)^2 - \phi^{\mu\nu}\phi_{\mu\nu}\right]$$
$$+ G_5(\phi, X)G^{\mu\nu}\phi_{\mu\nu} - \frac{G_{5X}}{6}\left[(\Box\phi)^3 - 3\Box\phi\phi^{\mu\nu}\phi_{\mu\nu} + 2\phi_{\mu\nu}\phi^{\nu\lambda}\phi^{\mu}_{\lambda}\right],$$

$G_i\ (i = 2, 3, 4, 5)$ are arbitrary functions of ϕ and X

$$f_X := \partial f/\partial X$$
$$X := -g^{\mu\nu}\phi_\mu\phi_\nu/2$$
$$\phi_\mu := \nabla_\mu\phi,$$

The most general scalar-tensor theory having second-order field equations in 4D

free from ghost instabilities associated with the higher derivative terms

could have extra d.o.f.

Modified gravity

see, e.g., Kobayashi, 1901.07183 (review paper)

- Horndeski theory

Lagrangian;

$$\mathcal{L} = G_2(\phi, X) - G_3(\phi, X)\Box\phi + G_4(\phi, X)R + G_{4X}\left[(\Box\phi)^2 - \phi^{\mu\nu}\phi_{\mu\nu}\right]$$
$$+ G_5(\phi, X)G^{\mu\nu}\phi_{\mu\nu} - \frac{G_{5X}}{6}\left[(\Box\phi)^3 - 3\Box\phi\phi^{\mu\nu}\phi_{\mu\nu} + 2\phi_{\mu\nu}\phi^{\nu\lambda}\phi^{\mu}_{\lambda}\right],$$

Due to the existence of non-minimal coupling between scalar d. o. f. and gravity,

in this theory, the gravitational law would be changed!

That is, we can test not only by cosmological observations
but also by local gravity test, GW experiments, and more..

Modified gravity

see, e.g., Kobayashi, 1901.07183 (review paper)

- Beyond ?

Horndeski theory: The most general scalar-tensor theory having second-order field equations in 4D

little bit strong?

Healthy extension

Degenerate Higher-Order Scalar-Tensor theories (DHOST theories)

see, e.g., Langlois, 1811.06271 (review paper)

$$\mathcal{L} = f(\phi, X)R + \sum_{I=1}^{5} A_I(\phi, X)L_I, \qquad L_1 = \phi_{\mu\nu}\phi^{\mu\nu}, \quad L_2 = (\Box\phi)^2, \quad L_3 = \Box\phi\phi^\mu\phi^\nu\phi_{\mu\nu}$$

$$L_4 = \phi^\mu\phi_{\mu\alpha}\phi^{\alpha\nu}\phi_\nu, \quad L_5 = (\phi^\mu\phi^\nu\phi_{\mu\nu})^2.$$

With so-called ``degeneracy conditions", pathological extra d. o. f. doesn't appear.

What is DE?

- Points for observations

  ✓ Cosmological constant $w = -1$

  ✓ Quintessence models – thawing type $dw/dt > 0$

  $w > -1$ -- freezing type $dw/dt < 0$

  ✓ Scalar-tensor theories – Horndeski, DHOST theories,…

measurement the gravitational law

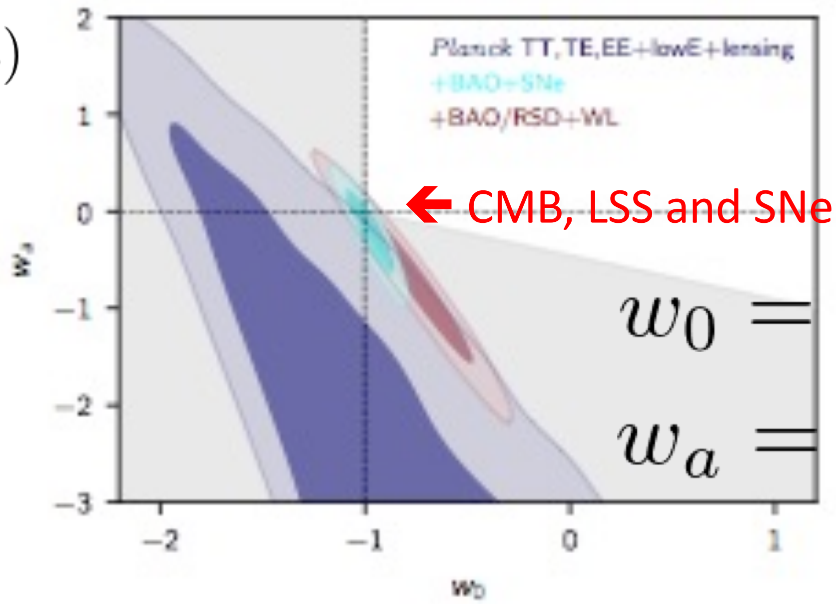
Equation of state

- Expansion of the Universe

In principle,
if we could measure the long time history of the expansion rate of the Universe,
we can also get the information about the evolution of the ``equation of state”.

$$w = w_0 + w_a(1-a)$$

Perturbative parameterization



← CMB, LSS and SNe

$$w_0 = -0.961 \pm 0.077$$

$$w_a = -0.28^{+0.31}_{-0.27}$$

Planck (2018)

Cosmological gravitational law

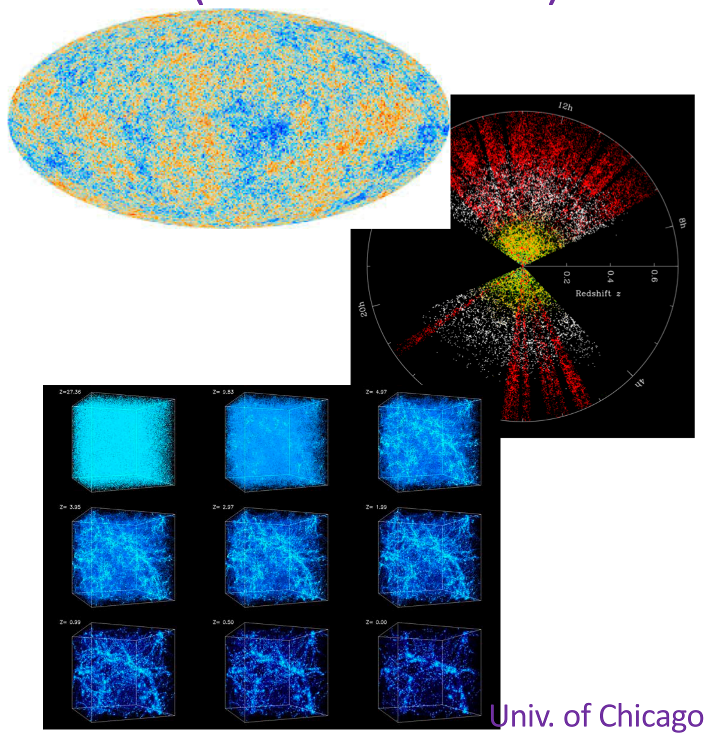
- Evolution of matter inhomogeneities in the Universe

In cosmology, we treat the spatial inhomogeneities of matter distributions, (including galaxy distributions on large scales), as perturbations on the background homogeneous and isotropic Universe (FLRW Universe).

$$\rho(t,\boldsymbol{x}) = \bar{\rho}_m(t)\,(1+\delta(t,\boldsymbol{x}))$$

Such a matter inhomogeneity evolves through the gravitational interaction!

valuable information about the ``cosmological" gravitational law!!



Univ. of Chicago

Linear growth

see, e.g., Kobayashi, 1901.07183 (review paper)

- Evolution of matter inhomogeneities in the Universe

Measure

the ``linear" growth of matter (DM) density contrast (inohomogeneities),

to find the cosmological gravitational law

and test the scalar-tensor theories !

usually, parameterized as

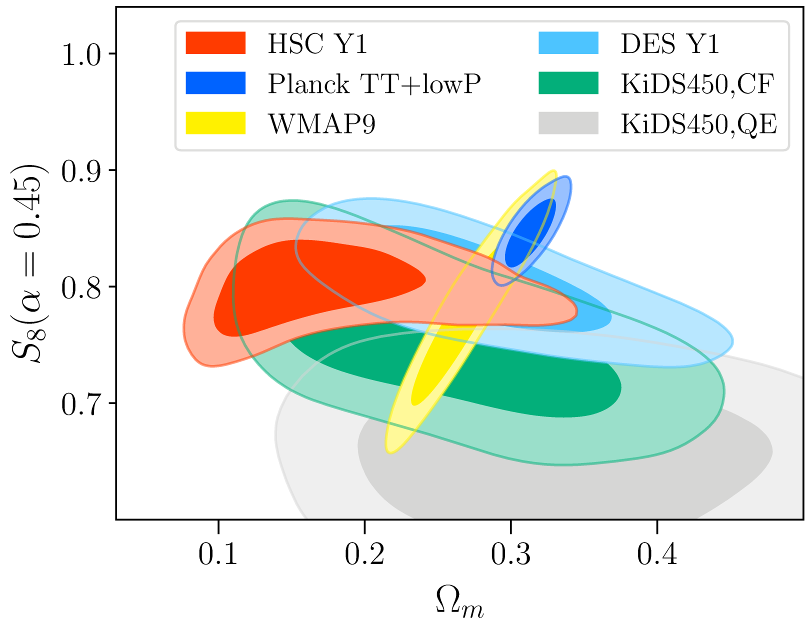
$$f := \frac{d \ln \delta(t)}{d \ln a} \quad \text{or} \quad f = \Omega_m^\gamma$$

In GR,

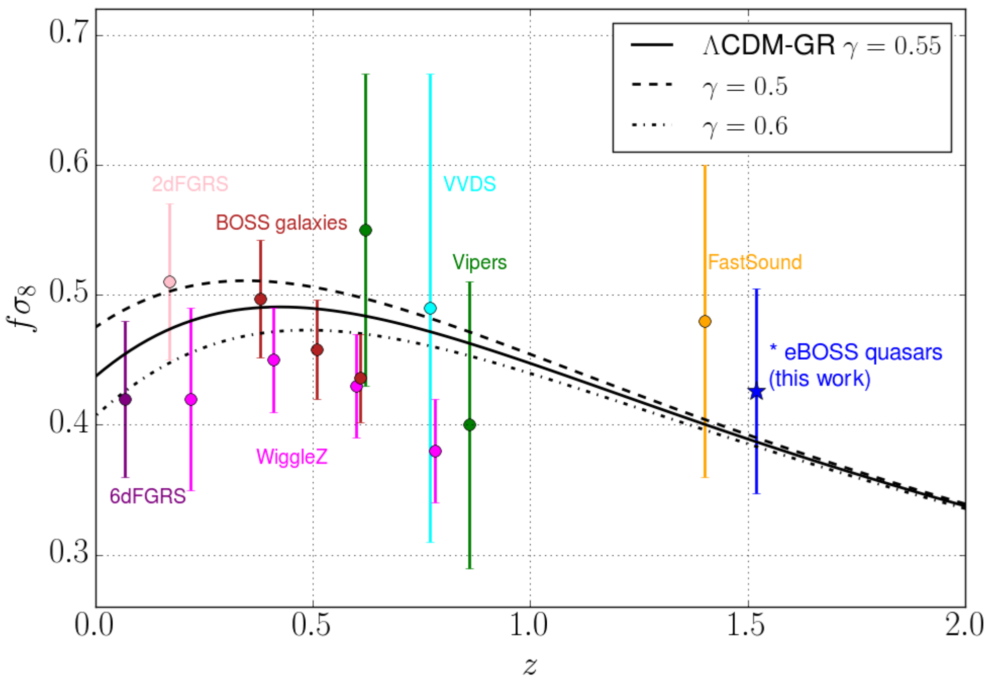
$$\gamma = 0.55$$

a is a scale factor (time coordinate)

Linear growth



arXiv:1809.09148v2



Zarrouk et al. (2018)

What is DE?

- Points for observations

  ✓ Cosmological constant $w = -1$

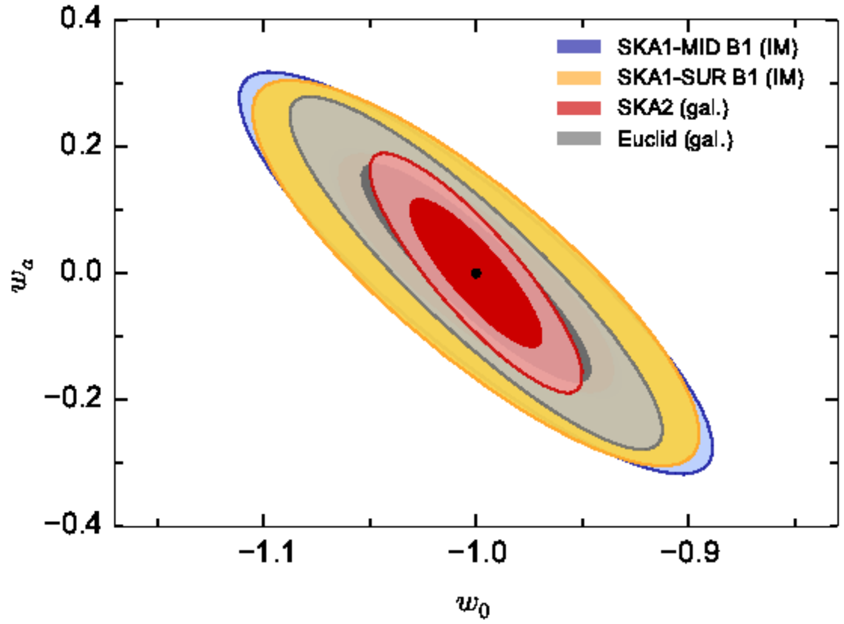
  ✓ Quintessence **SKA ??** :ype $dw/dt > 0$

  $w > -1$ -- freezing type $dw/dt < 0$

  ✓ Scalar-tensor theories – Horndeski, DHOST theories,...

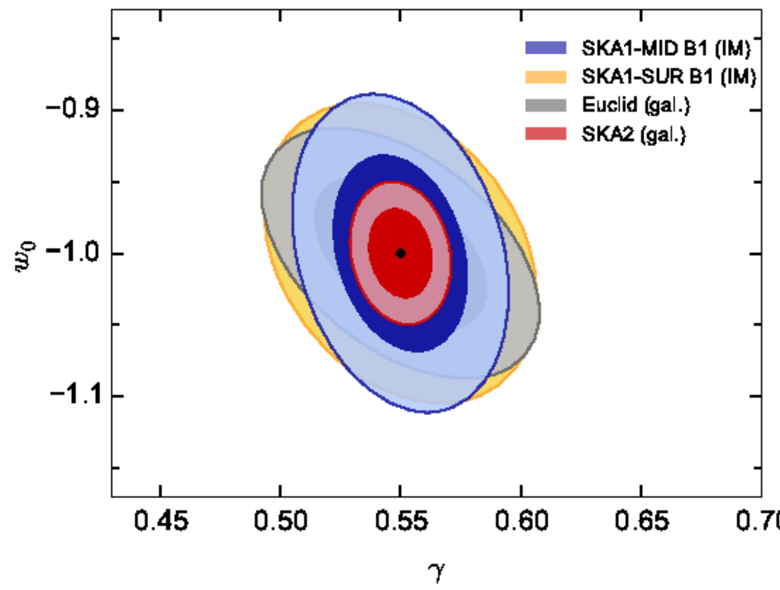
measurement the gravitational law

SKA as a galaxy survey / HI intensity mapping



Santos et al. (2015)

Bertolami, Gomes (2018)



Planck (2018)

$$w_0 = -0.961 \pm 0.077$$

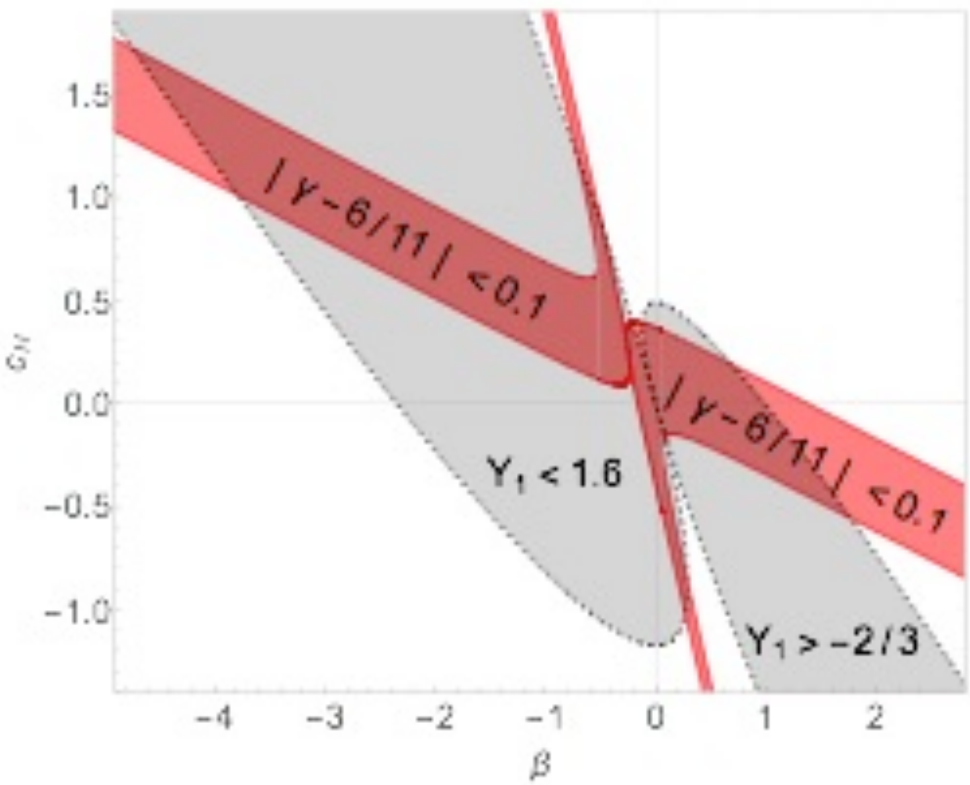
$$w_a = -0.28^{+0.31}_{-0.27}$$

BOSS DR14 (2018)

$$\gamma = 0.55 \pm 0.19$$

Implication for ST theories

Hirano, Kobayashi, Yamauchi, SY (2019)



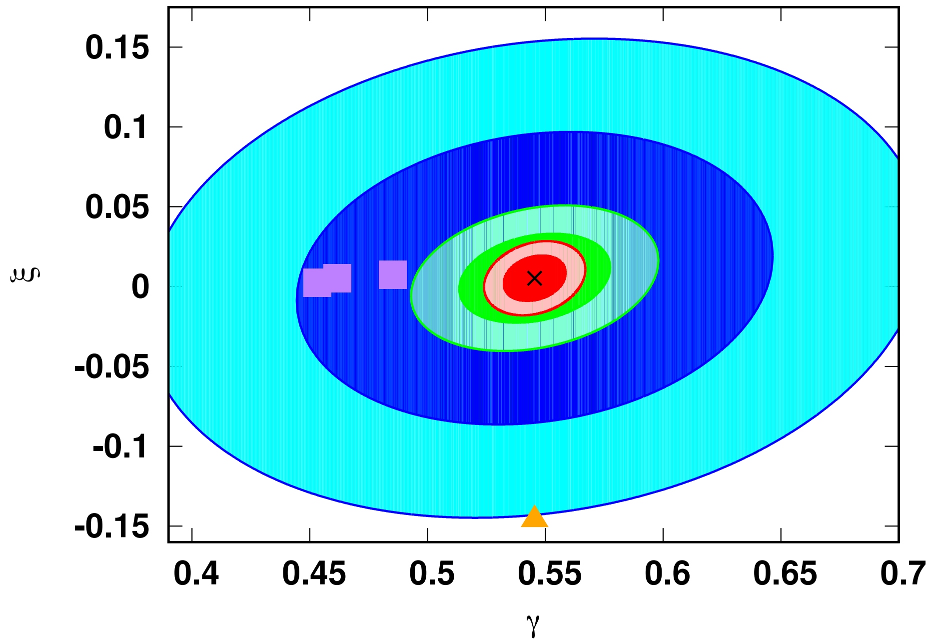
Modification of gravity
in astrophysical bodies;

$$\frac{\mathrm{d}\Phi}{\mathrm{d}r} = \frac{G_{\mathrm{N}} M(r)}{r^2} + \frac{\Upsilon_1 G_{\mathrm{N}}}{4} \frac{\mathrm{d}^2 M(r)}{\mathrm{d}r^2}$$

Growth in higher order ?

Yamauchi, Tashiro, SY (2017)

expected constraint from galaxy bispectrum



Second order growth

Linear growth

assuming · SKA1MID(blue), SKA2(red) and Euclid(green)

What is DE?

SKA ??

- Points for observations

✓ Cosmological constant

$$\Delta w < 0.05$$

✓ Quintessence models – thawing type

$$\Delta(dw/dt) < 0.1$$

-- freezing type

✓ Scalar-tensor theories – Horndeski, DHOST theories,…

$$\Delta\gamma < 0.02$$

Dark matter

Dark matter

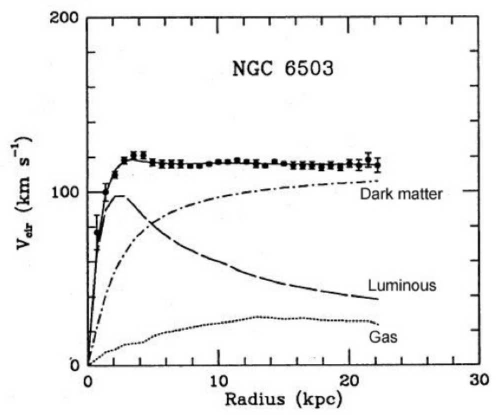
- Existence of dark matter
  - ✓ Lots of astro/cosmological observations (rotation curve, LSS, CMB)

Basically, gravitational interaction

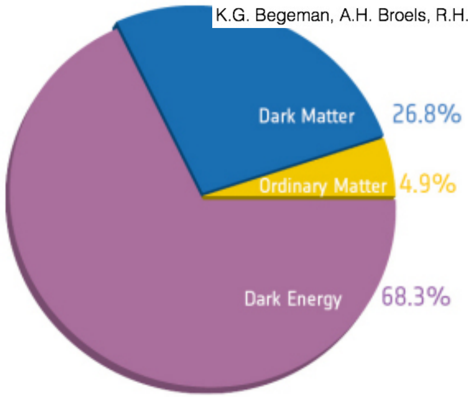
↓

Unknown ``weakly” interacting particles?

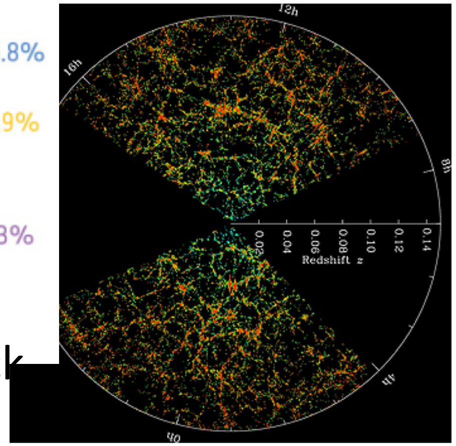
SUSY particles (WIMP LSP)、
QCD axion, sterile neutrino,
Axion Like Particles (string theory) …



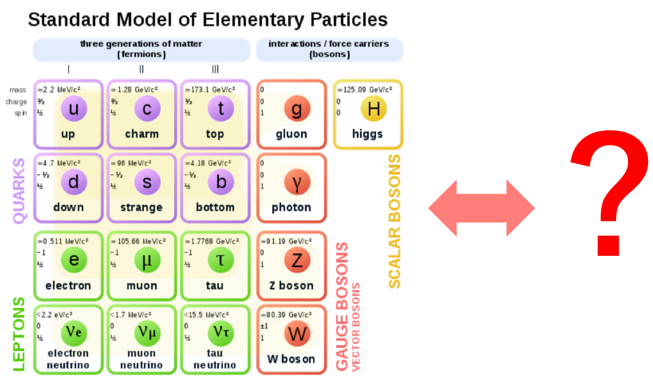
K.G. Begeman, A.H. Broels, R.H. Sanders. 1991. Mon.Not.RAS 249, 523.



©Planck

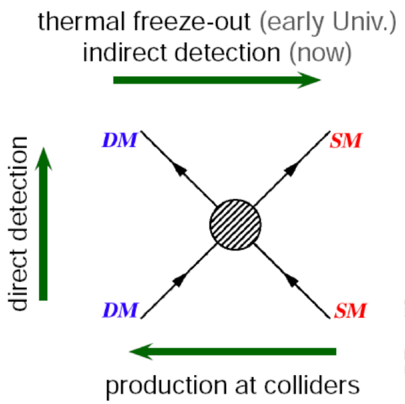


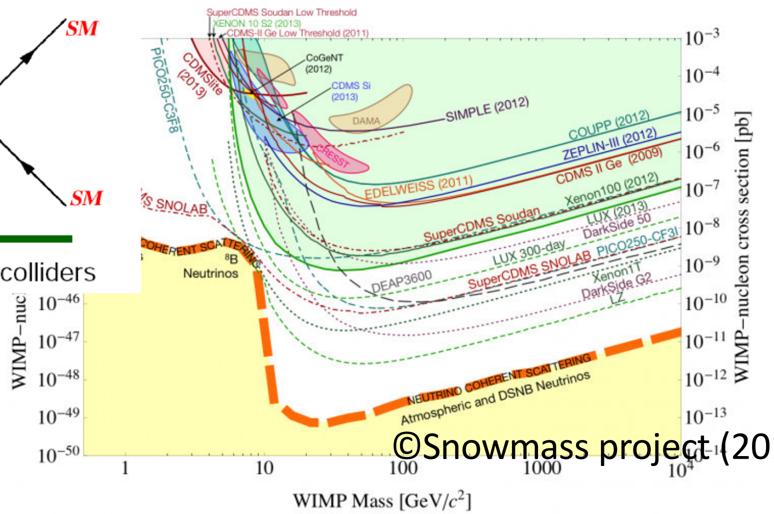
from SDSS



unknown particles?

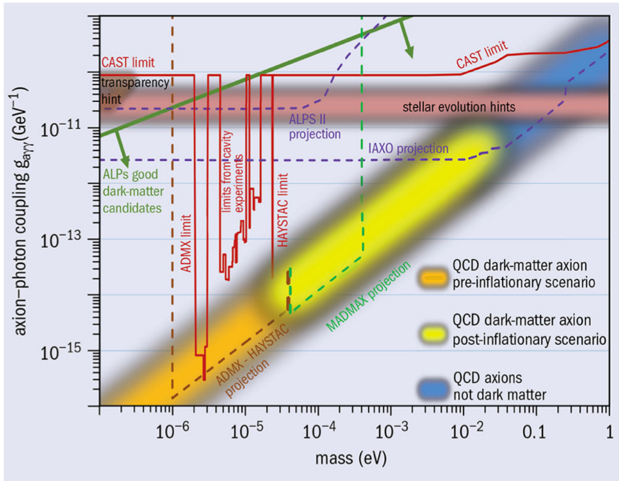
- lots of particle experiments





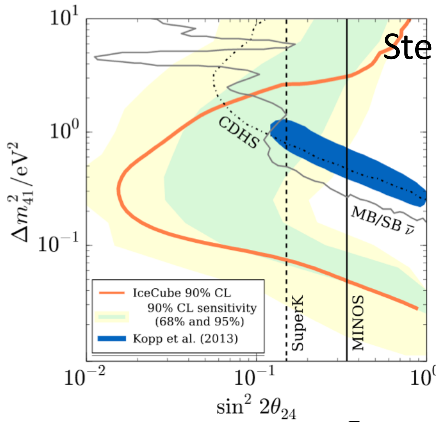
©Snowmass project (2013)

axion - photon coupling



©Majorovits (MADMAX)

Sterile neutrino



©IceCube collabo.

➔ No evidence …

➔ Beyond standard ``WIMP”?

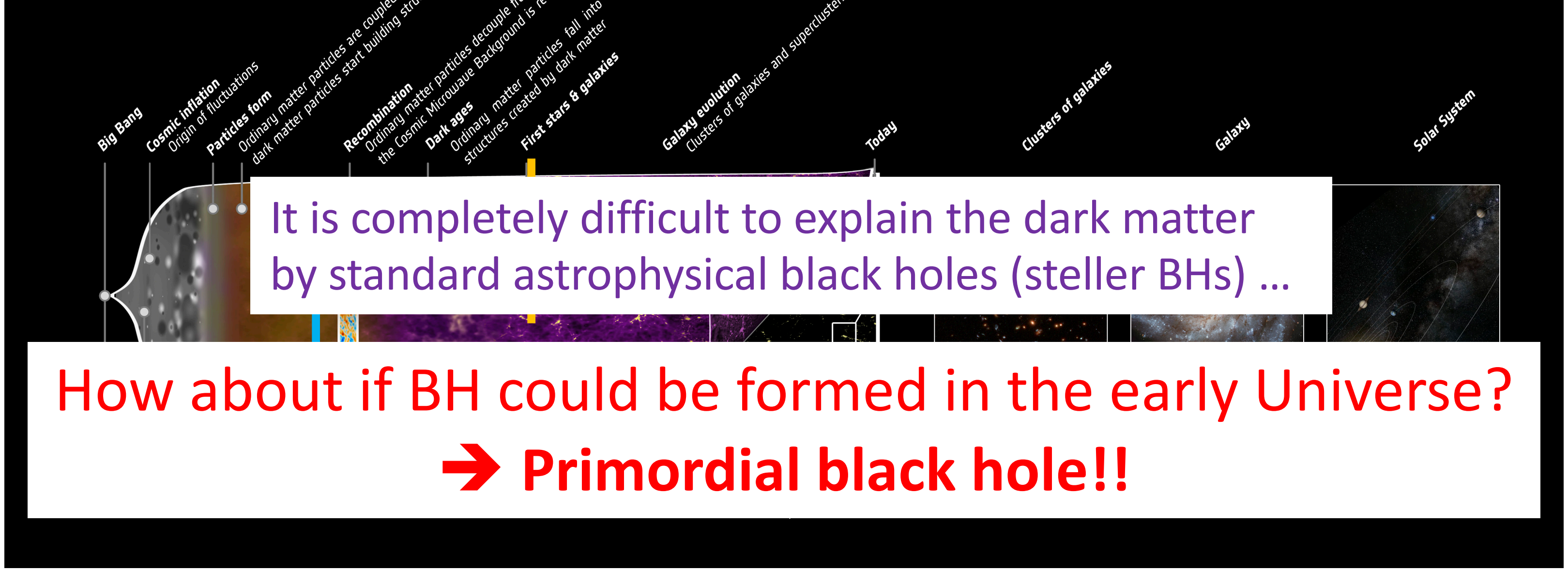
BHs as DM

- How about other candidates?

Basically, only gravitational interaction ➡ Black holes？？

However,

Success of standard big bang model



It is completely difficult to explain the dark matter by standard astrophysical black holes (steller BHs) …

How about if BH could be formed in the early Universe?

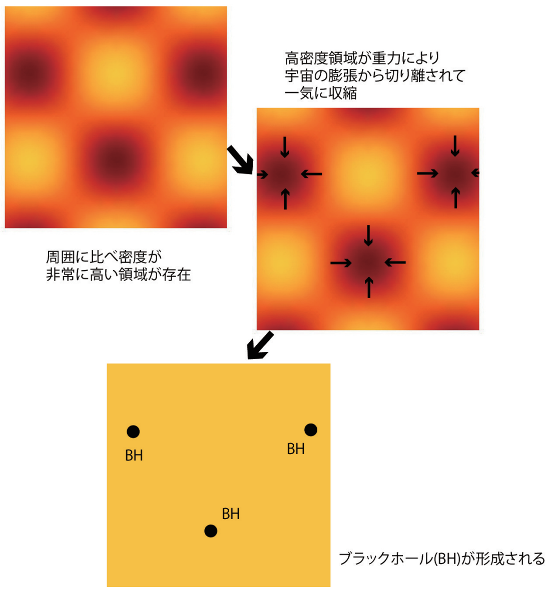
➔ **Primordial black hole!!**

Basics of PBH

Zeldovich and Novikov (1967)
Hawking (1971)
Carr and Hawking (1974), …

- Primordial Black Hole (PBH)
  - ✓ BHs formed in the early Universe (after inflation)
  - ✓ direct gravitational collapse of a overdense region (horizon scale)
  - ✓ mass of formed BH ~ Hubble horizon mass at the formation

especially for the PBH formed in the radiation-dominated era

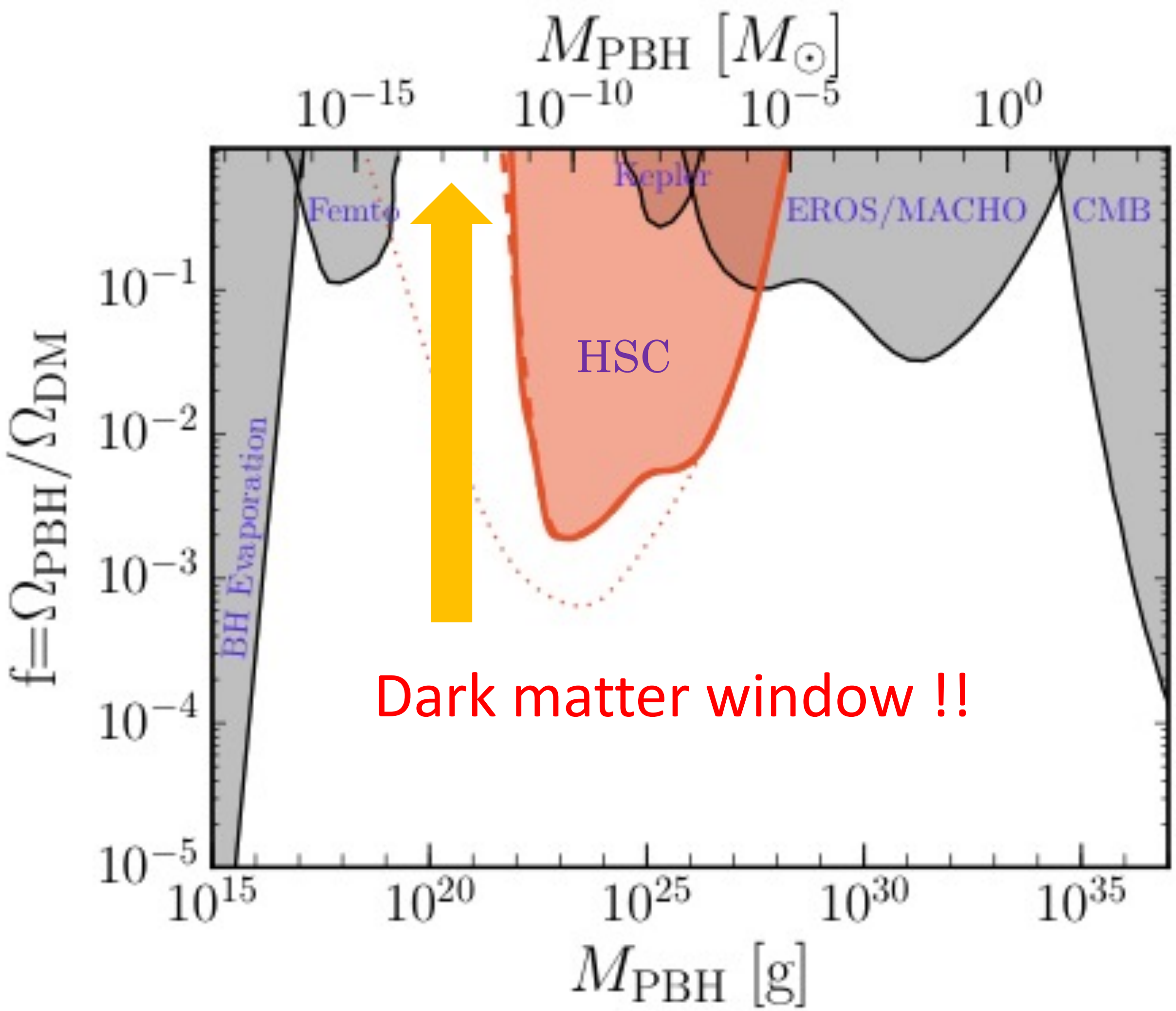


$$M = \gamma M_{\rm PH} = \frac{4\pi}{3}\gamma\rho H^{-3} \approx 2.03 \times 10^5 \gamma \left(\frac{t}{1\ {\rm s}}\right) M_\odot .$$

$$t \approx 0.738 \left(\frac{g_*}{10.75}\right)^{-1/2} \left(\frac{T}{1\ {\rm MeV}}\right)^{-2}\ {\rm s},$$

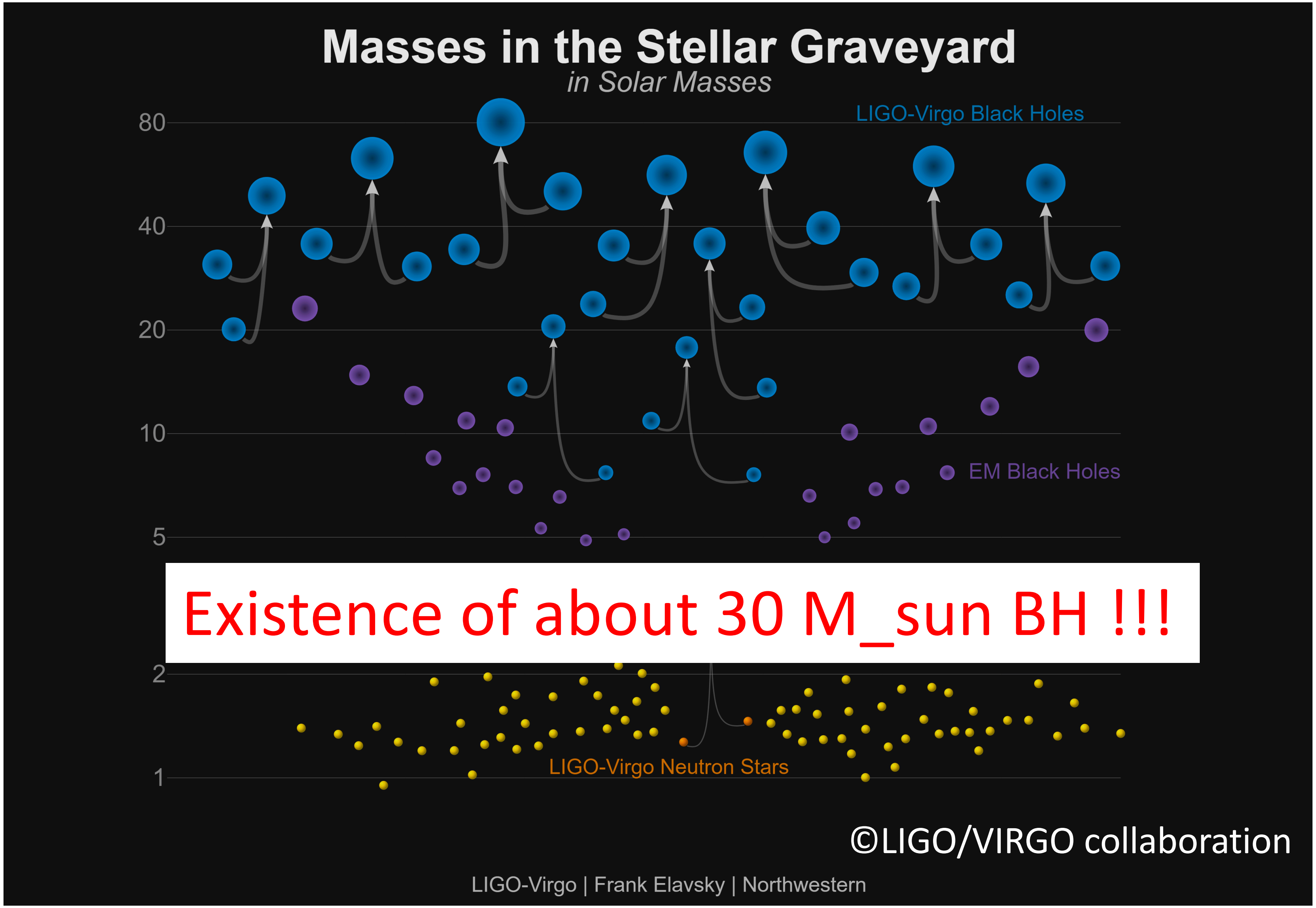
$$30\ M_\odot \leftrightarrow 70\ {\rm MeV}$$

``Conservative" constraints



Niikura et al.; 1710.02151v3

10 BH-BH merger events and 1 NS-NS



OGLE-IV (data) results
-exoplanet search -

OGLE (Optical Gravitational Lensing Experiment) IV;

Udalski, Szymanski, Szymanski, 1504.05966

5-years monitoring observations of stars in the Galactic bulge

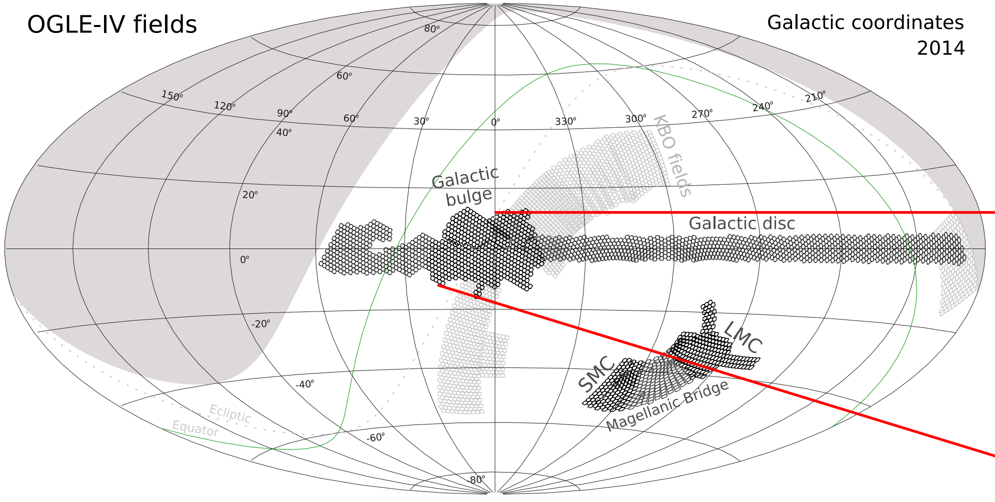
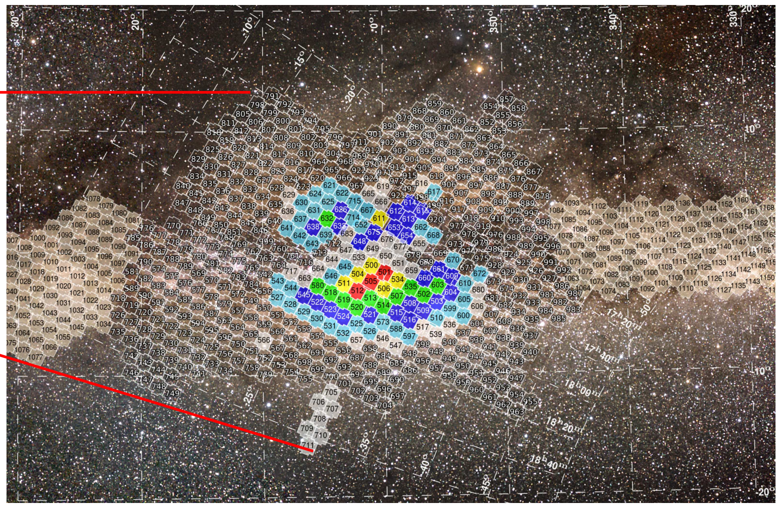
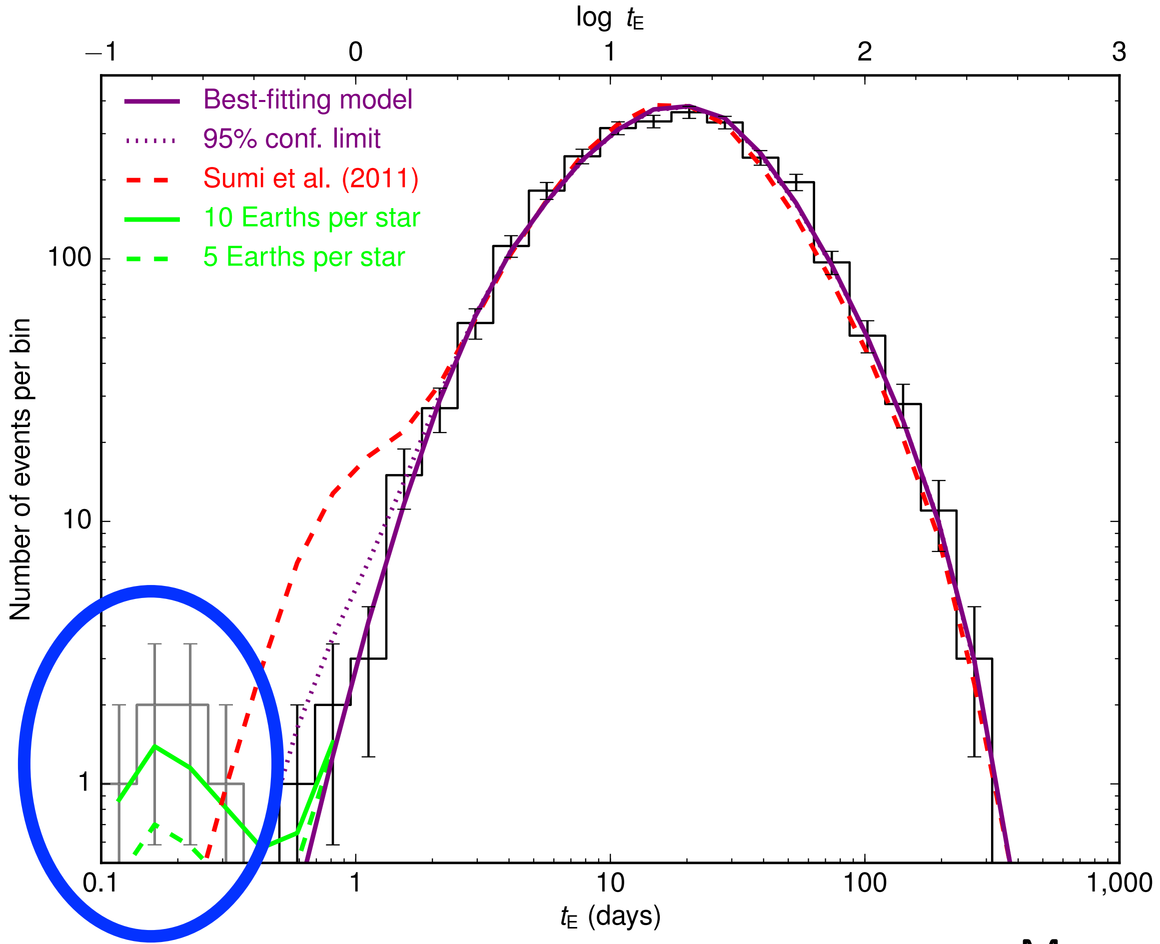


Fig. 13. OGLE-IV sky coverage in the Galactic coordinates. Credit: Jan Skowron.



Earth-mass PBHs???

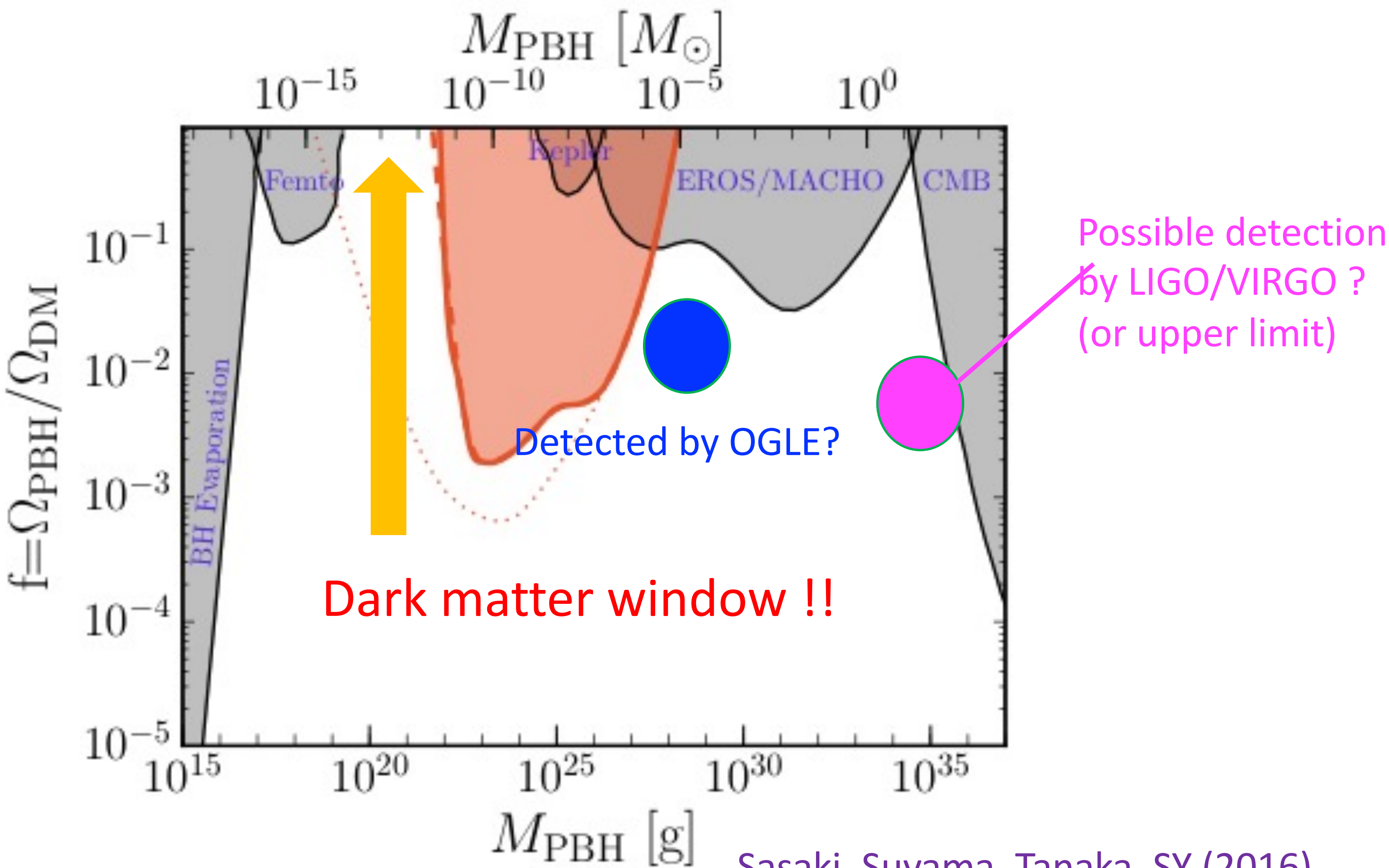


Mroz et al. arXiv:1707.07634

6 microlensing events with short-time scale

➔ detection of earth mass PBHs?

Earth mass BHs, LIGO BHs and DM

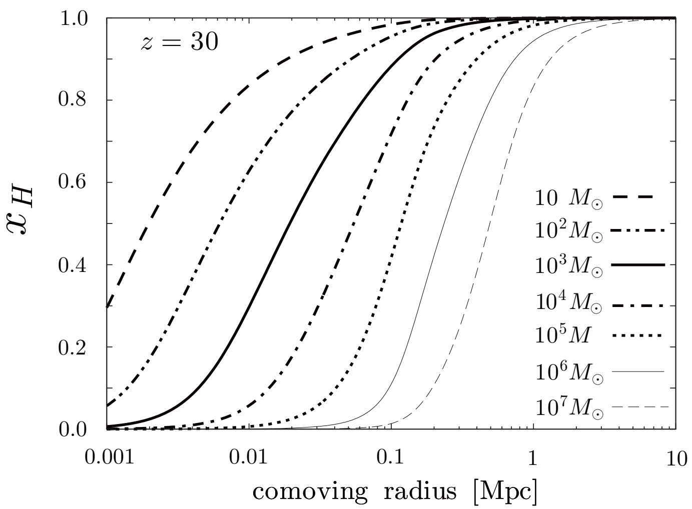


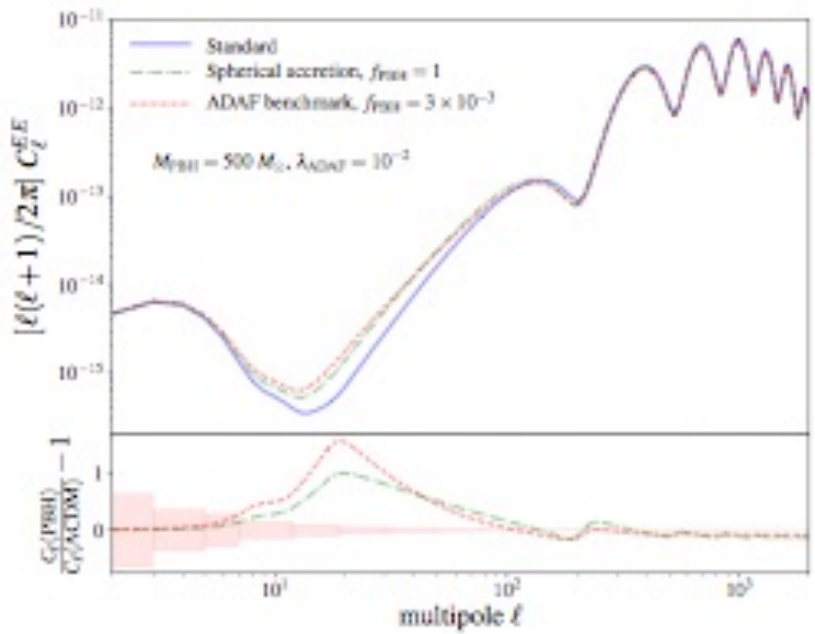
Sasaki, Suyama, Tanaka, SY (2016),
Niikura, Takada, SY, Sumi, Masaki (2019)

Can we probe PBH-DM by SKA?

- SKA as a probe of high redshift Universe
  - ➢ Tashiro and Sugiyama (2012), and more.. (e.g., Poulin et al. (2017), …)

    X-ray photons emitted by accretion of matter onto PBHs





change the optical depth

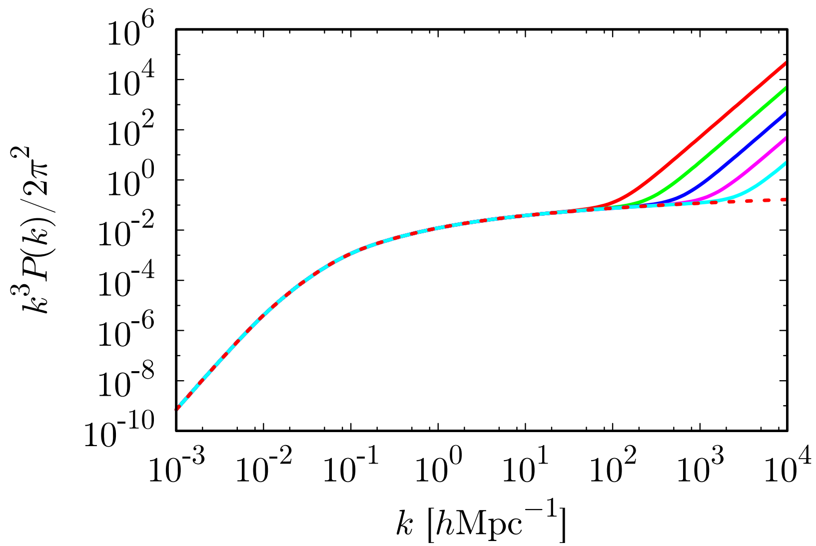
Can we probe PBH-DM by SKA?

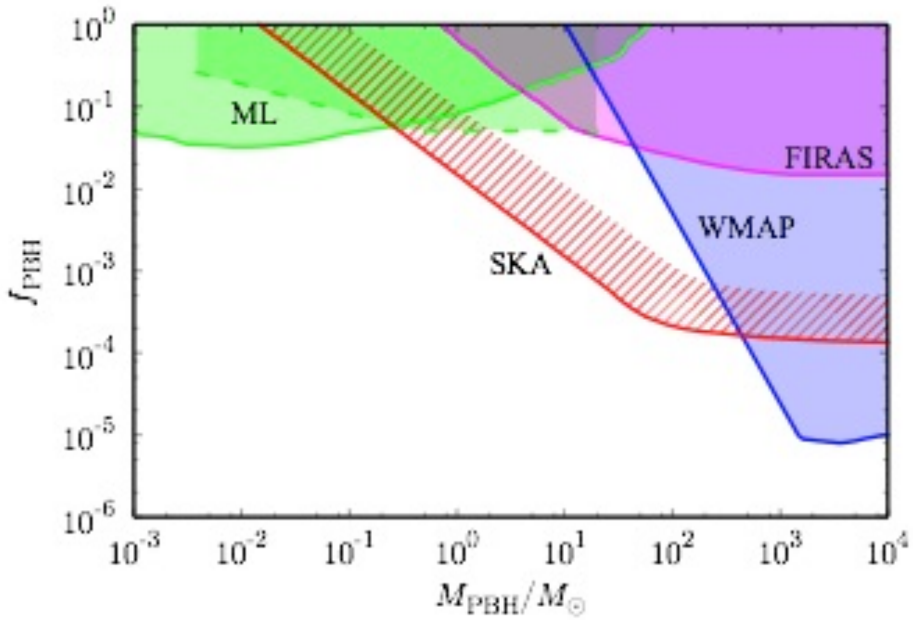
- SKA as a probe of high redshift Universe

  ➢ Gong and Kitajima (2017)

  Poisson like isocurvature fluctuations of PBHs

Matter power spectrum

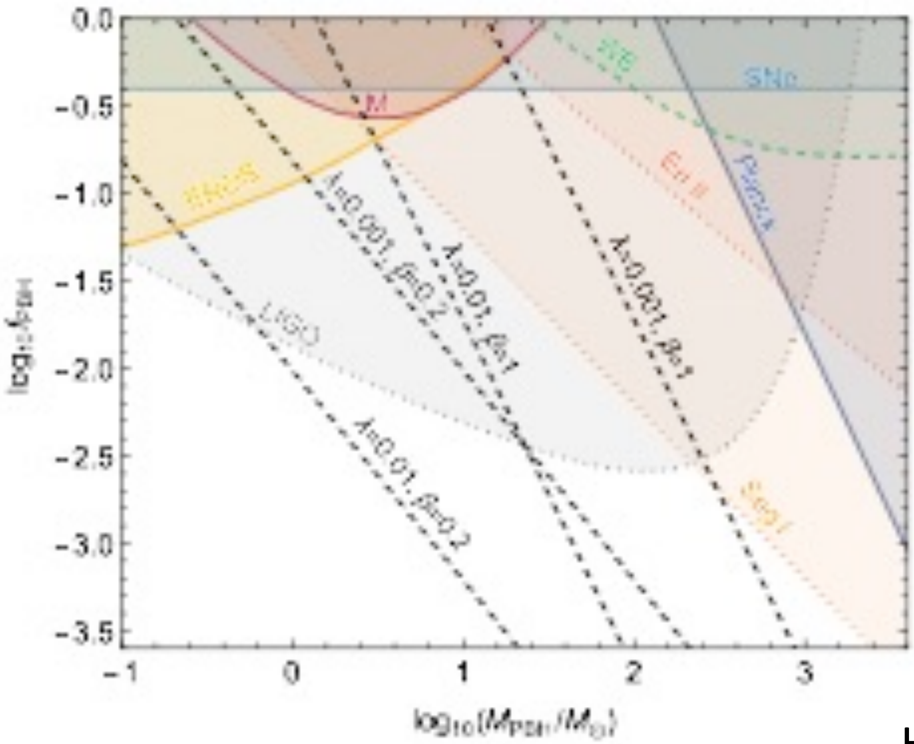




Can we probe PBH-DM by SKA?

- SKA as a probe of high redshift Universe

From EDGES result …

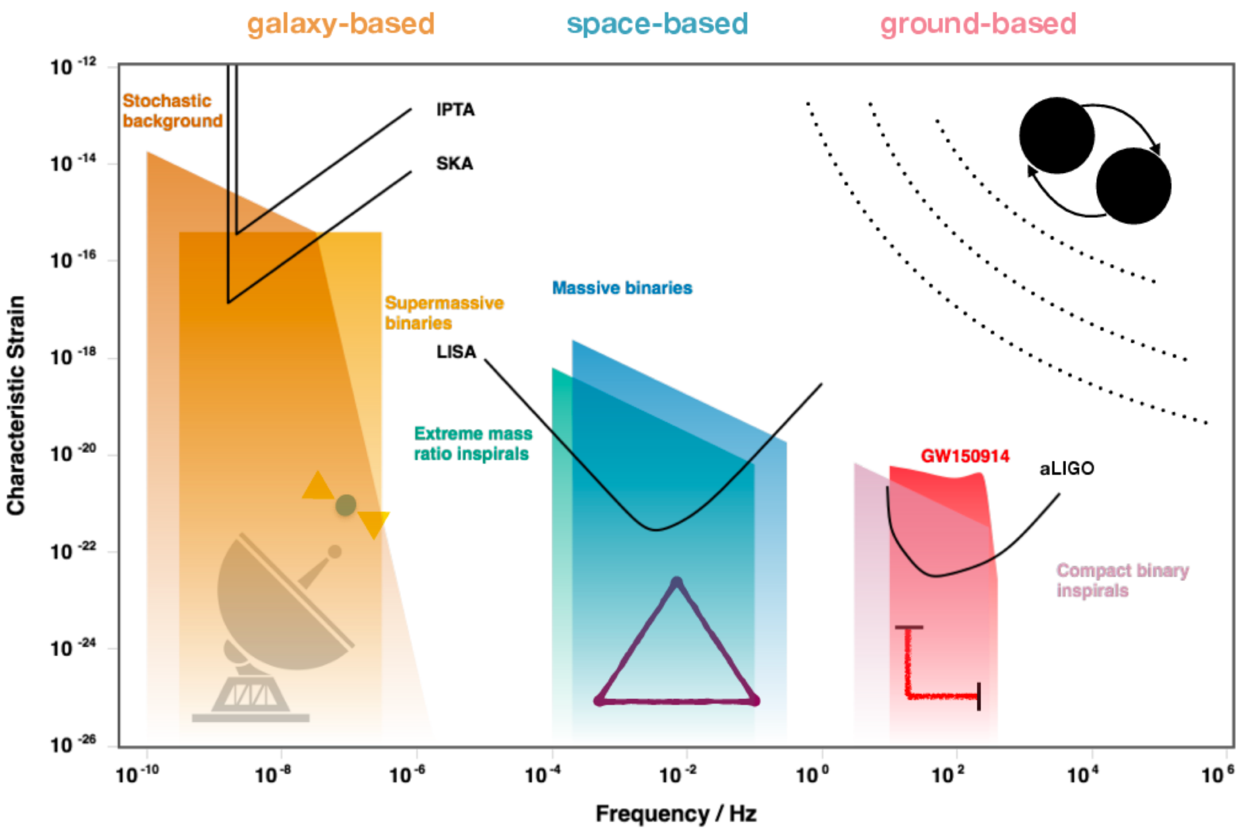


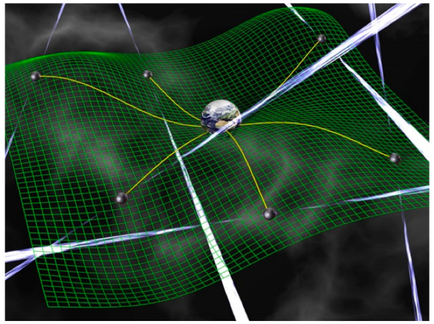
depending on
the astrophysical parameters
(accretion rate, …)..

Hektor et al. (2018)

Can we probe PBH-DM by SKA?

- SKA as a PTA





Pulsar Timing Array is known to be an GW detection experiment.

SKA can find lots of radio Pulsars!

Barak, et al. (2018)

Can we probe PBH-DM by SKA?

See, e.g. Saito and J. Yokoyama (2009)

Density fluctuations with large amplitude ➔ collapse ➔ PBH formation

Based on the cosmological perturbation up to the second order,

Density fluctuations would be source of the tensor modes, that is, gravitational waves!!

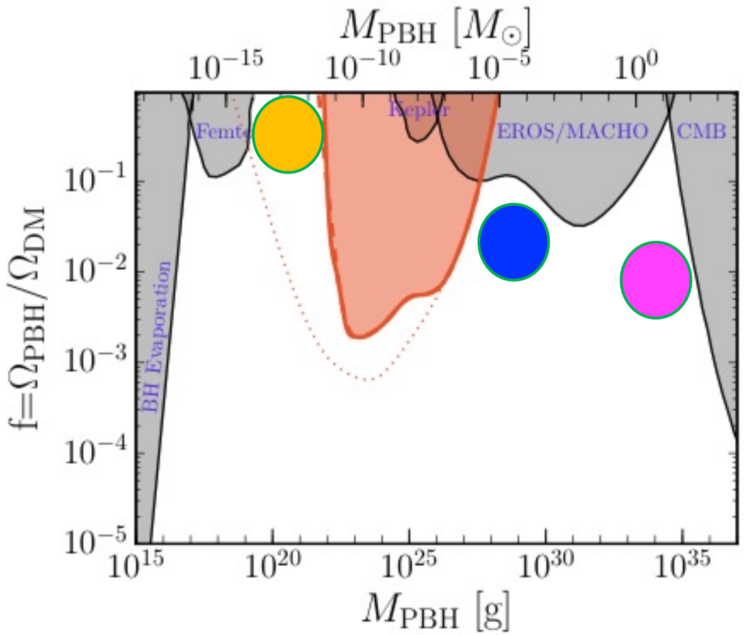
frequency (wave number) of induced GWs ～ horizon scale at the reenter

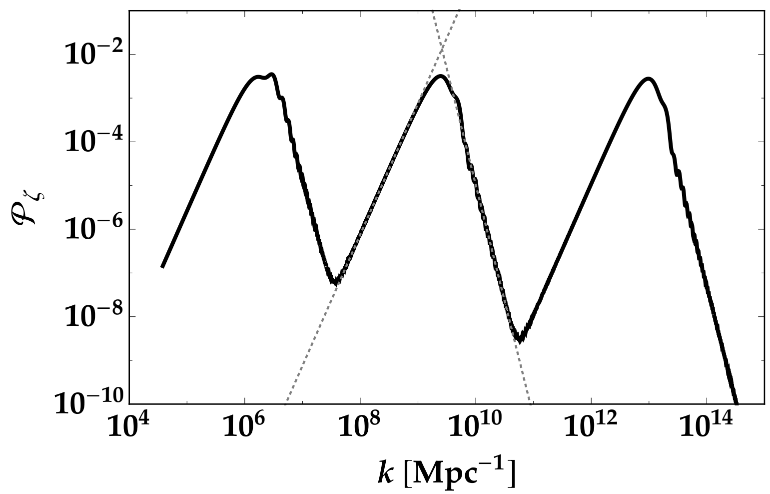
mass of PBH ～ horizon mass at the reenter

Can we probe PBH-DM by SKA?

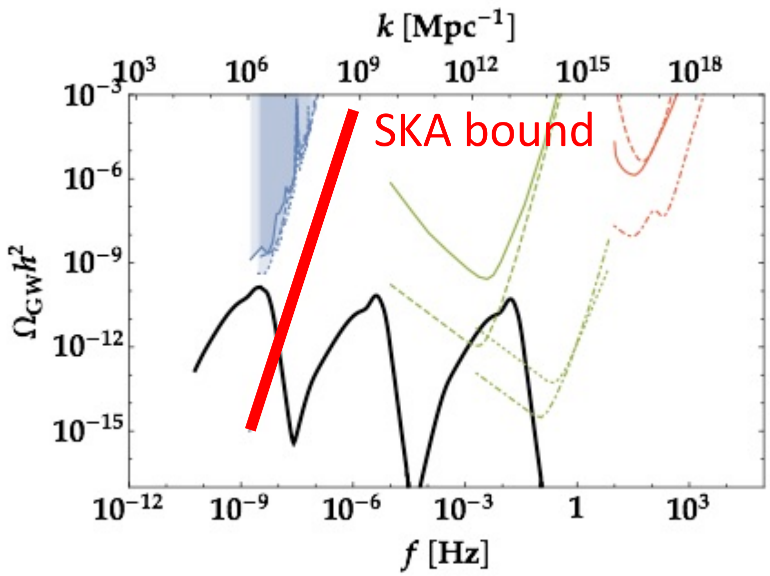
- SKA as a PTA

Primordial scalar power





induced GWB

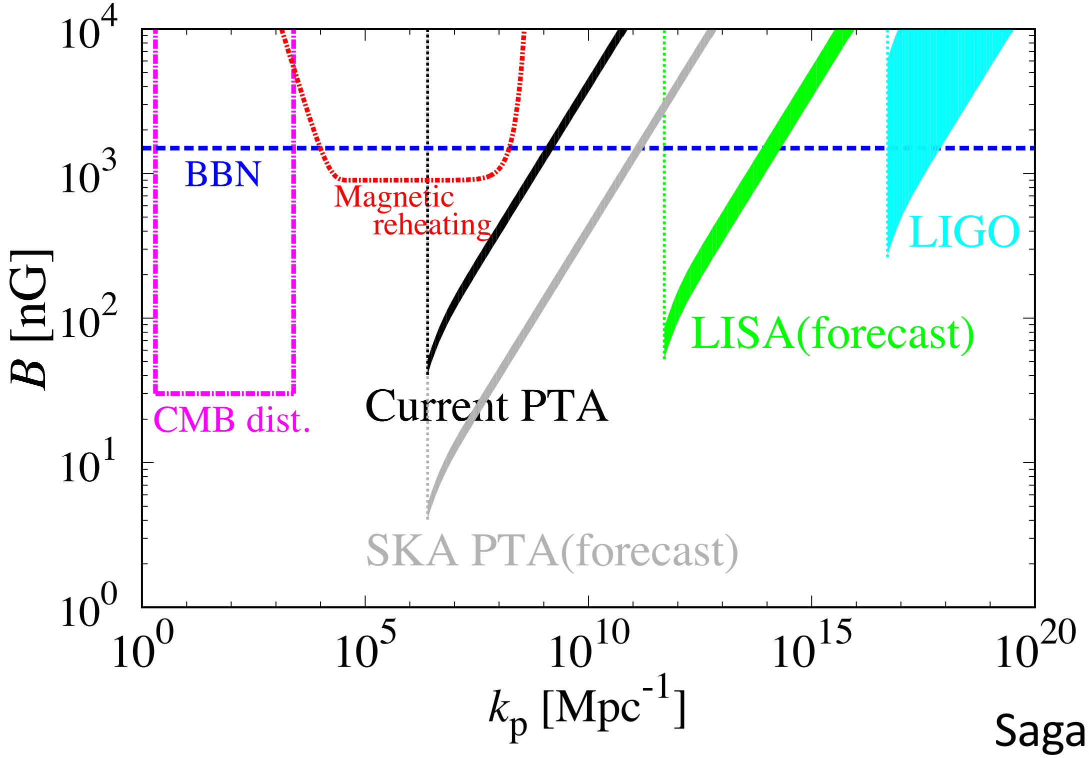


Tada, SY in prep.

byproduct

- SKA as a PTA

Primordial magnetic field x primordial magnetic field ➔ primoprrdial GWs



Saga, Tashiro, SY (2018)

summary

Observational inflation cosmology

SKA

- Higher order

$$\sigma(f_{\rm NL}) = 0.61\ (0.50)$$

- Smaller scales

	$10^{-3}\Delta n_s$	$10^{-3}\Delta \alpha_s$	$10^{-3}\Delta \beta_s$
Planck	7.7	10.7	15.1
COrE	3.2	2.9	6.5
SKA	4.6	2.9	1.5
FFTT	2.4	1.6	0.79
Planck+SKA	1.7	2.0	0.63
Planck+FFTT	1.3	1.3	0.44
COrE+SKA	1.2	1.6	0.39
COrE+FFTT	0.95	1.1	0.28

And more;

- ➢ 21cm global signal (small scale structure ➔ gas temp. evo., …) Yoshiura, Takahashi^2 (2018)
- ➢ 21cm lensing (detecting PGWs) Book, Kamionkowski, Schmidt (2011)

$$r \sim 10^{-9}$$

What is DE?

SKA

- Points for observations

  ✓ Cosmological constant

  $\Delta w < 0.05$

  ✓ Quintessence models – thawing type

  $\Delta(dw/dt) < 0.1$

  -- freezing type

  $\Delta\gamma < 0.02$

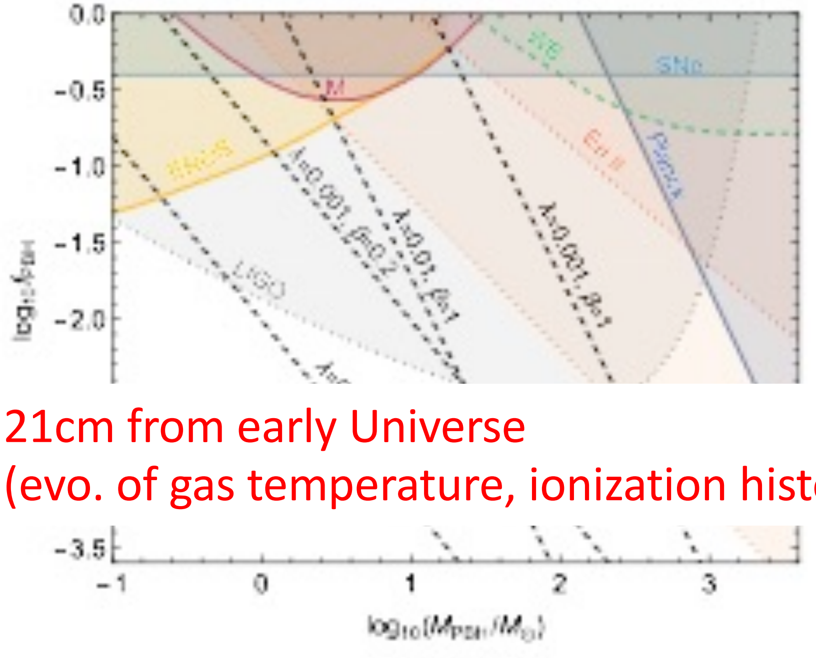
  ✓ Scalar-tensor theories – Horndeski, DHOST theories,…

And more;

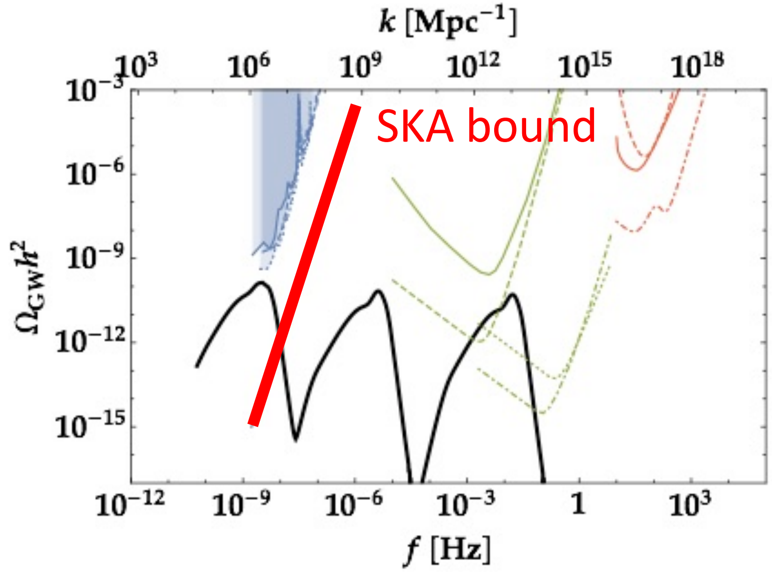
- DE constraints from early Universe Kohri et al. (2016)
- growth index, or MG in astrophysical bodies, in early Universe?

Can we probe DM by SKA?

- PBH-DM



21cm from early Universe
(evo. of gas temperature, ionization history, ..)

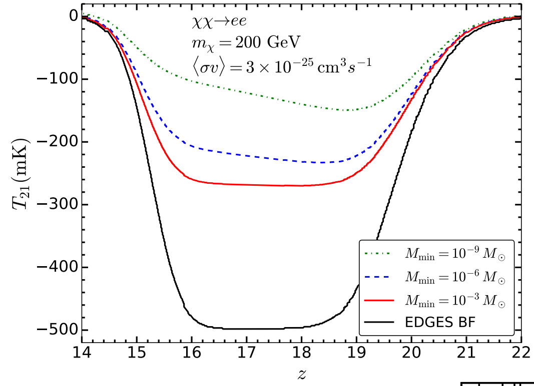


Induced Primordial Gravitational Waves

And more;

- small scale DM clumps with PTA Oguri, Kashiyama (2018)
- any other idea? microlensing, radio sources, …

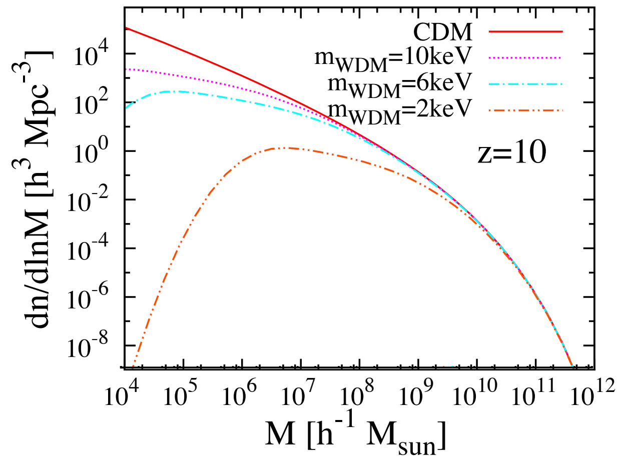
Can we probe other DM by SKA?



- **Baryon – DM interaction**

  evolution of gas temperature

  Fialkov, Barkana, Cohen (2018),
  Cheung et al. (2018),
  Kovetz et al. (2018), …



- **Warm DM**

  SKA as a probe of small scale structure

  Shimabukuro, Inoue, Ichiki, SY (2014),
  Sekiguchi, Tashiro (2014),

- **Axion DM** (Ultra light particles, ..)

  Axion-photon conversion search
  Kelley, Quinn (2017)

  Modulation of grav. potential
  Khmelnitsky, Rubakov (2014)