Dark energy

\- related activities

in observational cosmology group, Nagoya Univ. -

Shuichiro Yokoyama (KMI, Nagoya Univ.)

KMI2019

Contents

- Introduction
  - Why?
  - What?
- Light in the darkness
  - theoretical side
  - observational side
  - activities in our group
- Summary

In this talk, we use $c = 1$ units

Speed of light

Contents

- Introduction
    - Why?
    - What?

Previous Nishizawa-san's talk

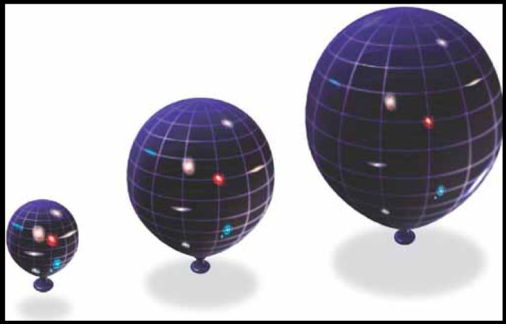
- Light in the darkness
    - theoretical side
    - observational side
    - activities in our group
- Summary

In this talk, we use $c = 1$ units

Speed of light

Why dark energy?

why



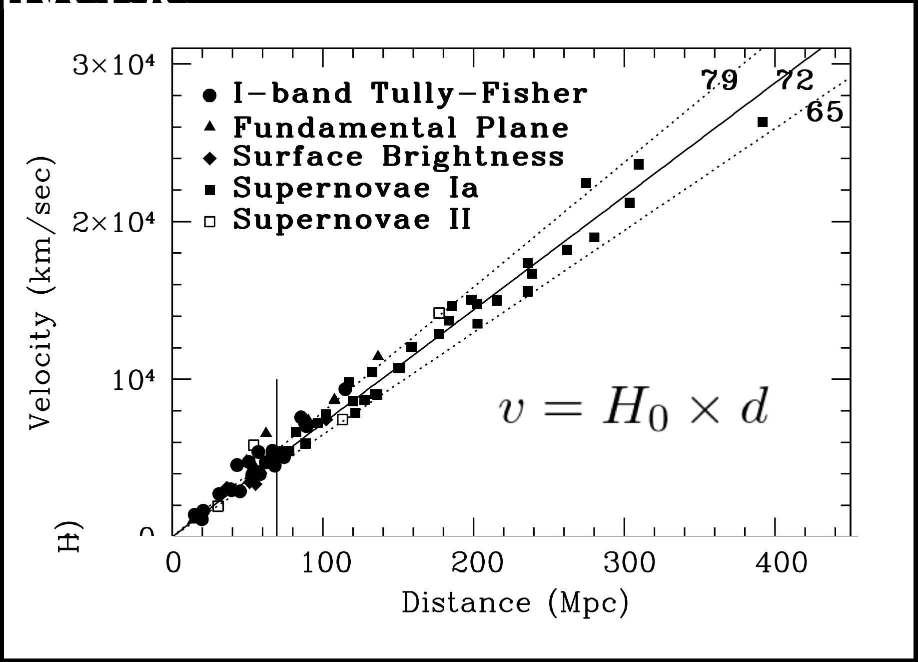
- Expanding Universe

Taylor expansion of
the size of our Universe;

$$a = a_0 + \dot{a}\,\Delta t + $$

$$\left.\frac{\dot{a}}{a}\right|_{t=t_0} =: H_0$$

Hubble parameter



Freedman et al. (2001)

Galaxies tend to go away from us, and it's isotropic.

➔ not intrinsic velocity of each galaxy..

➔ expansion of ``space", Our Universe!

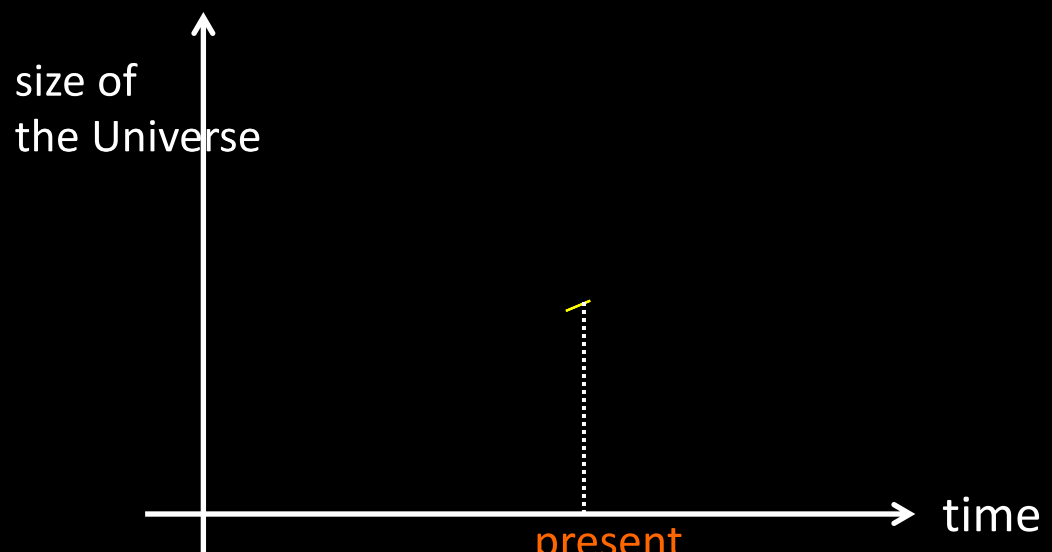
why

- Accelerating or decelerating?

$$a = a_0 + \dot{a}\,\Delta t + \boxed{\frac{\ddot{a}}{2}\,\Delta t^2} + \cdots$$

or $\dot{H}$

In cosmology, distant = past



why

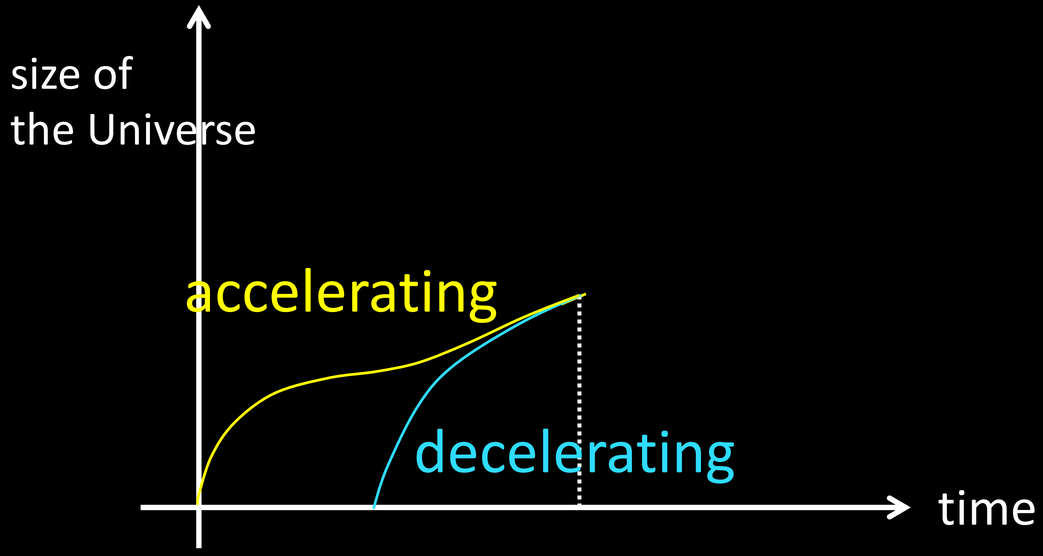
- Accelerating or decelerating?

$$a = a_0 + \dot{a}\,\Delta t + \boxed{\frac{\ddot{a}}{2}\,\Delta t^2} + \cdots$$

or $\dot{H}$

In cosmology, distant = past → Observing more distant objects,

→ earlier stage of the Universe!



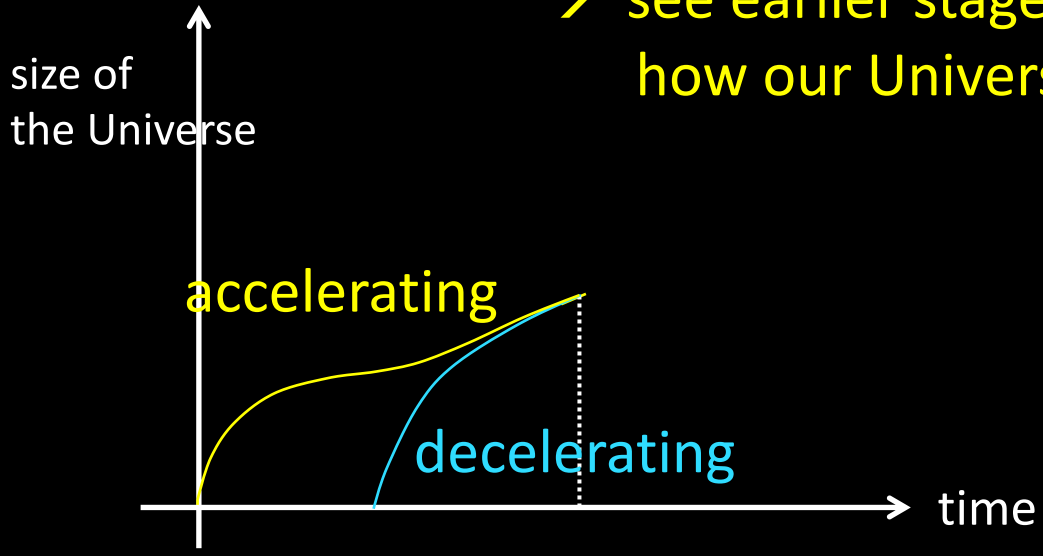
why

- Accelerating or decelerating?

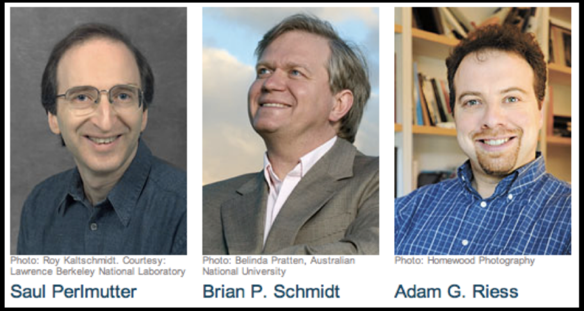
$$a = a_0 + \dot{a}\,\Delta t + \boxed{\frac{\ddot{a}}{2}\,\Delta t^2} + \cdots$$

or $\dot{H}$

In cosmology, distant = past ➔ Observing more distant objects,
→ see earlier stage of the Universe,
how our Universe evolves !



Dark energy



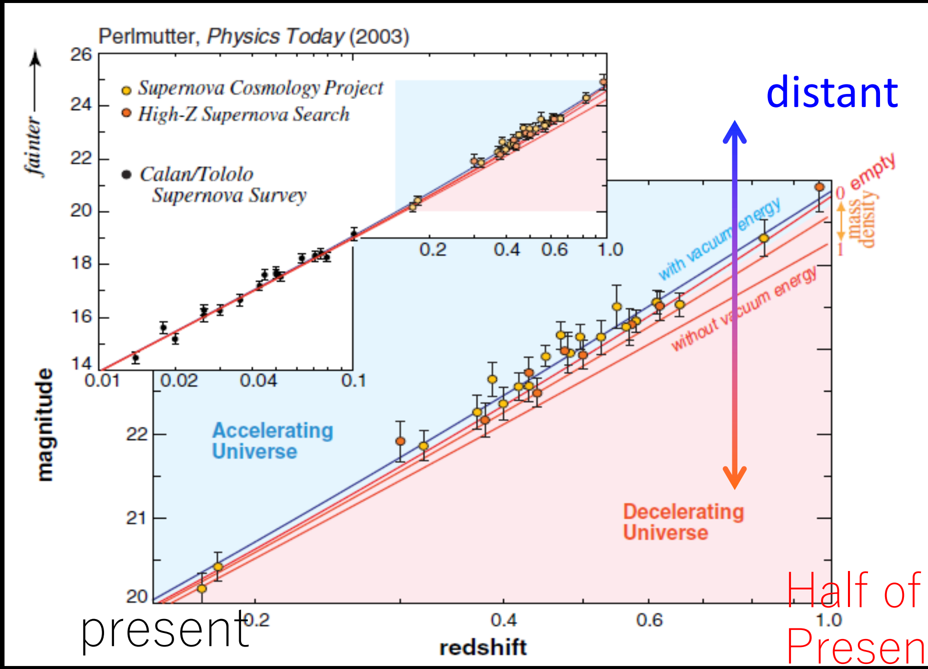
- Discovery of accelerating expansion

2011 nobel prize in physics

Observations of distant SNe

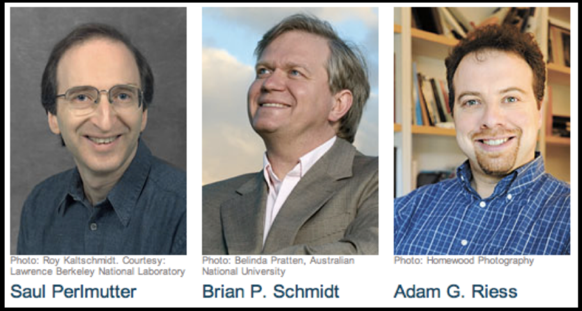
; one of the brightest objects (standard candle)

observed brightness
←→ distance from us



size of the Universe

Dark energy



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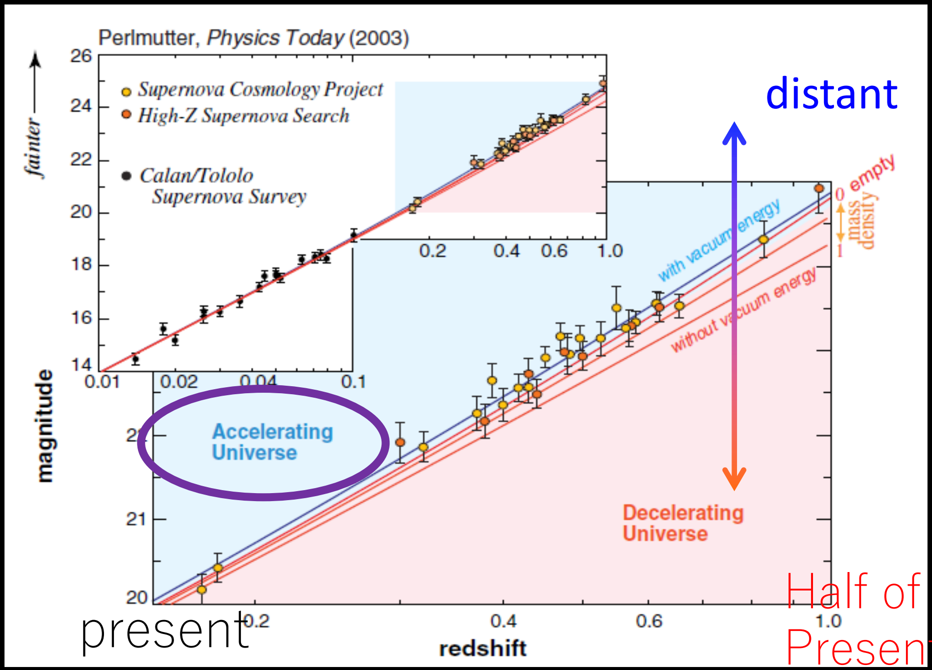


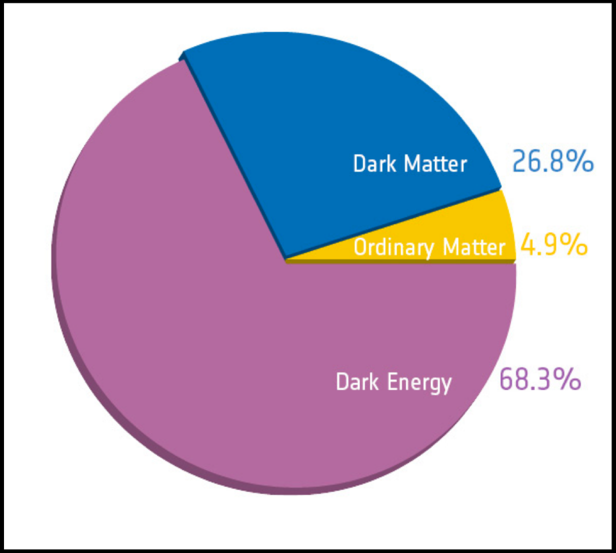
Half of
Present size

size of the Universe

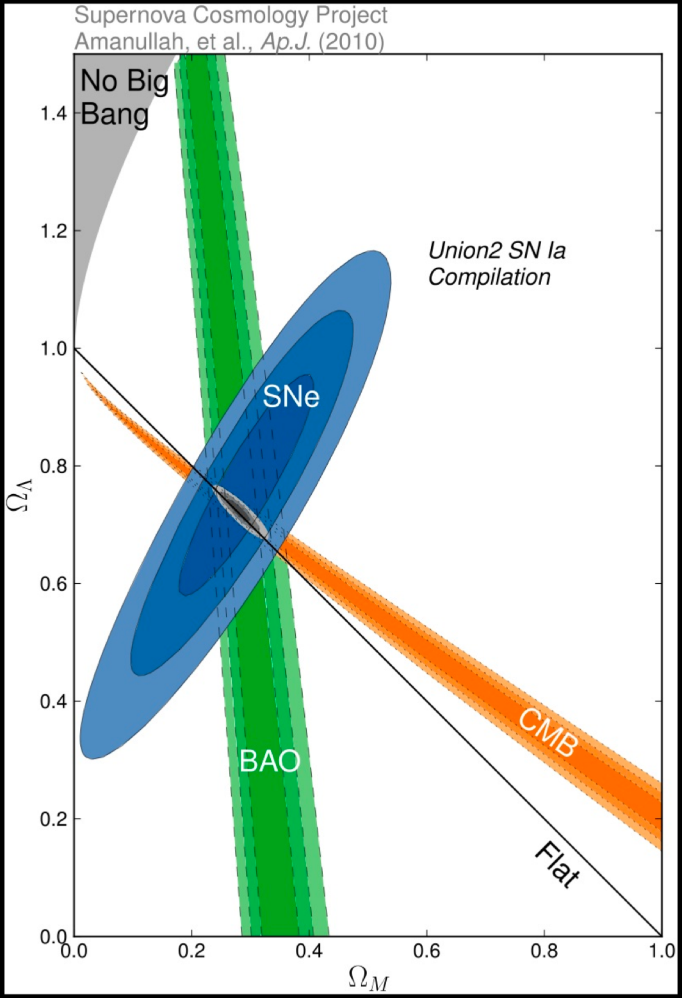
Dark energy

- Lots of evidence ..

Energy fraction
of ``dark energy”



Planck

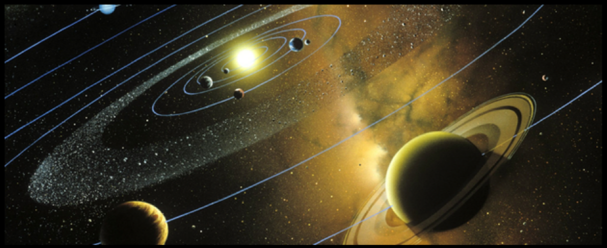


Note that all of the evidences are obtained by cosmological observations

Dark energy is what?

Learning from the past..

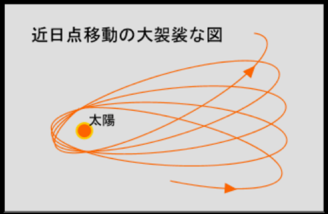
Dark planet



- Kepler motion of planets in solar system

In early 19th, ..

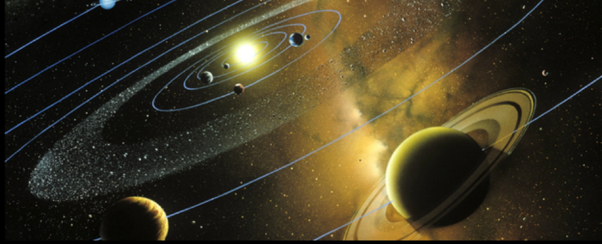
1. Small deviation in the Kepler motion of Uranus
2. Precession of the perihelion of Mercury



Existence of dark planets??

Based on Newtonian gravity in a system of observed objects

Dark planet



- How to resolve?

two way;
- New undetected object?
- New theory?

1. Small deviation in the Kepler motion of Uranus
   → Discovery of Neptune (1846)
2. Precession of the perihelion of Mercury
   → Newton gravity → general relativity (in 20th century)

What?

- Come back to dark energy

Based on the General Relativity,

$$G_{\mu\nu} = T_{\mu\nu}$$

Expansion of the Universe

Unknown components ?

Neptune case

What?

- Come back to dark energy

Based on the General Relativity,

$$G_{\mu\nu} = T_{\mu\nu}$$

Expansion of the Universe

Extension of gravity theory ?

Mercury case

Dark energy is …

What?

- Unknown ``component" ?
  - Cosmological constant (vacuum energy)

$$G_{\mu\nu} = T_{\mu\nu} - \Lambda g_{\mu\nu}$$

What?

- Unknown ``component" ?
  - Cosmological constant (vacuum energy)

$$G_{\mu\nu} = T_{\mu\nu} - \Lambda g_{\mu\nu}$$

  - Scalar field? ← idea of cosmic inflation

$$T_{\mu\nu} = \partial_\mu \phi \partial_\nu \phi + g_{\mu\nu} \left(-\frac{1}{2} \partial^\alpha \phi \partial_\alpha \phi - V(\phi) \right)$$

How?

- How to realize accelerating?

Equation for acceleration of the Universe,

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P) + \frac{\Lambda}{3}$$

``Accelerating" can be realized when the right hand side is positive!

With introducing ``equation of state " parameter, w, $P = w\,\rho$
Necessary condition for accelerating for the component is

$$w < -1/3$$

How?

- Scalar field with $w < -1/3$

For scalar field (assuming homogeneity and isotropy)

$$\rho(\phi) = \frac{1}{2}\dot{\phi}^2 + V(\phi)$$ (kinetic term + potential term)

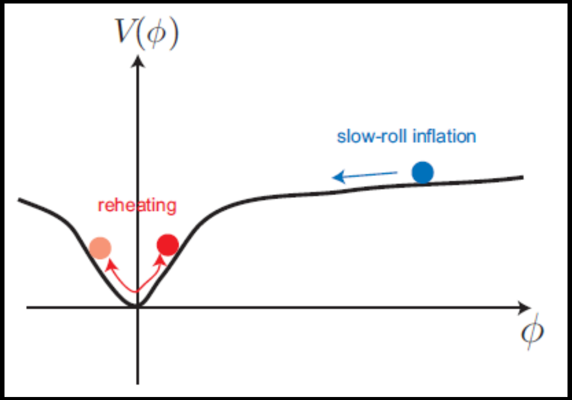
$$P(\phi) = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

➔ when, $\frac{1}{2}\dot{\phi}^2 \ll V(\phi)$, effectively $w \simeq -1$

``slowly-rolling" scalar field ➔ accelerating !!

``quintessence"

Basically characterized by the potential



Cf. standard slow-roll inflation

How?

- Scalar field with $w < -1/3$

As an extended class of scalar dark energy,

Kinetically driven quintessence, called ``k-essence”

See, e.g., Chiba, Okabe, Yamaguchi (2000)

$$\mathcal{L} = P(X,\, \phi)$$

General function of kinetic term

$$X := -\frac{1}{2}\partial^{\mu}\phi\partial_{\mu}\phi$$

For the simplest case: $P(X) = -X + X^2$

Energy density; $\rho = 2X\dfrac{\partial P}{\partial X} - P$

→ On the point with $\dfrac{\partial P}{\partial X} \simeq 0$

→ $w \simeq -1$

What?

- Modification of gravity ?

  - General relativity

    - consistent with`` local” gravity test (and weak gravity regime)
    - theory of massless spin-2 degree of freedom (2-tensor d.o.f)

⇩ How modified or extended?

What?

- Modification of gravity ?

  - General relativity

    - consistent with`` local" gravity test (and weak gravity regime)
    - theory of massless spin-2 degree of freedom (2-tensor d.o.f)

How modified or extended?

Massive spin-2? → massive gravity theory

Adding additional degree of freedom? → scalar-tensor theory,
vector-tensor theory

How?

- Modification of gravity ?

  - Massive gravity theory

Fierz, Pauli (1939)
de Rham, Gabadadze, Tolley(2010), …

Change the gravitational law at the mass scale of graviton

c.f. fifth force

Effectively, the mass of graviton behaves like a cosmological constant

$$G_{\mu\nu} = 8\pi G T_{\mu\nu} - m^2 g_{\mu\nu}$$

mass of the graviton

see, e.g. Kobayashi et al. (2012)

How?

- Modification of gravity ?
  - Scalar tensor theory
    - GR (theory of massless spin-2 degree of freedom (2-tensor d.o.f)) adding a scalar d. o. f.

In some sense, scalar tensor theory is just GR + scalar field (as a matter)

Here (at least), scalar d.o.f. in scalar tensor theory is in the gravity sector, that is, scalar d. o. f. would be non-minimally coupled with the gravity.

A famous example; (Jordan) Brans/Dicke theory (1961) (extension of GR with $1/G \to \phi$)

$$S = \frac{1}{16\pi}\int d^4x\sqrt{-g}\left(\underbrace{\phi R}_{\text{non-minimal coupling}} - \frac{\omega}{\phi}\partial^\mu\phi\partial_\nu\phi\right)$$

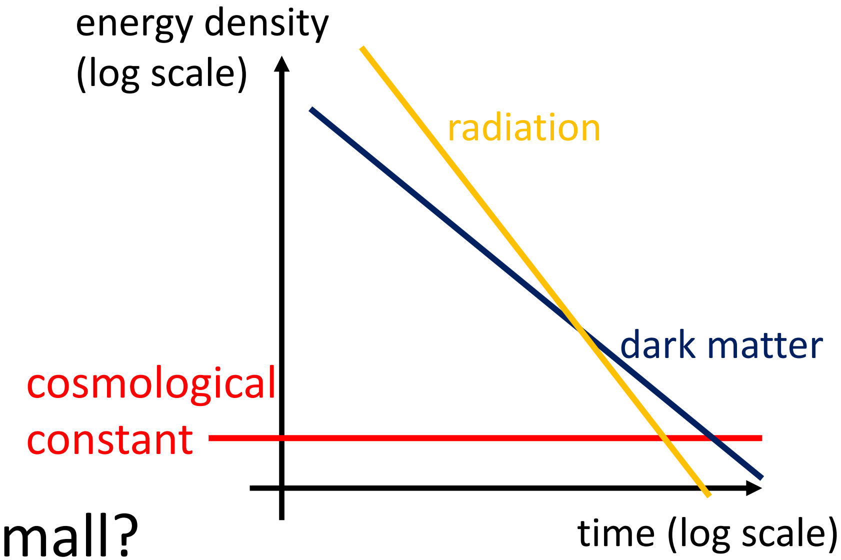
Shedding light on the darkness..

Many attempts

- Construction of successful model (theoretical side)
- Probe from observations (observational side)

(main part of this talk)
activities in observational cosmology group, Nagoya

Theoretical side



- Cosmological constant

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

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

related with the string theory ?

not allowed by swampland conjecture ??

Obied, Ooguri, Spodyneiko, Vafa (2018)

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

Theoretical side

- 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 $w = \dfrac{2XP_X - P}{P}$

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

Theoretical side

- Quintessence (potential driven)

Lots of models … motivated by SUGRA, …

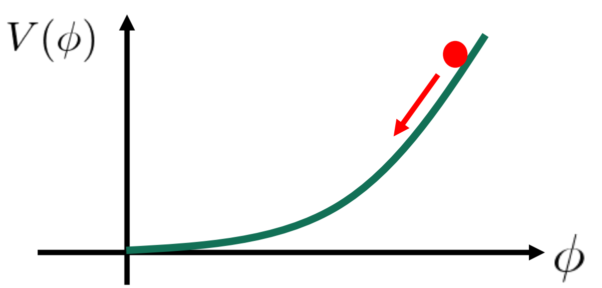
(like an inflation zoo …)

Basically, two types of quintessence model

See, e.g., Caldwell and Linder (2005), …

Thawing model

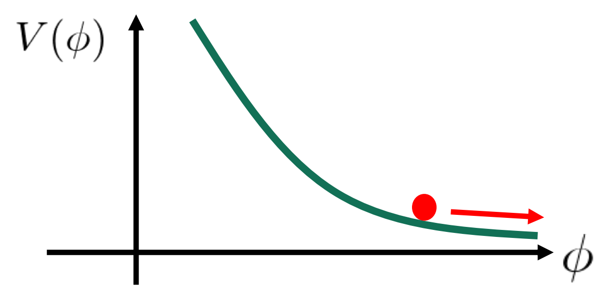
e.g., $V \propto \phi^n \ (n > 0)$



starts slow-rolling (thawing)
around the present time

Freezing model (tracker)

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



fast rolling →slow rolling (freezing)

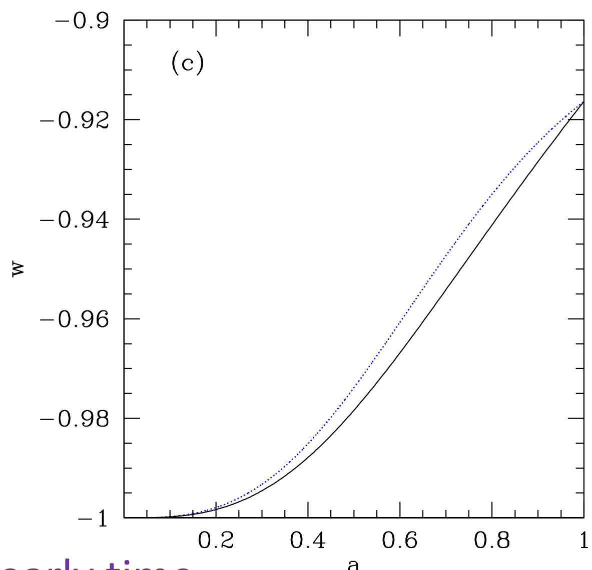
Theoretical side

- Quintessence (potential driven)

Evolution of equation of state

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

Chiba (2009)

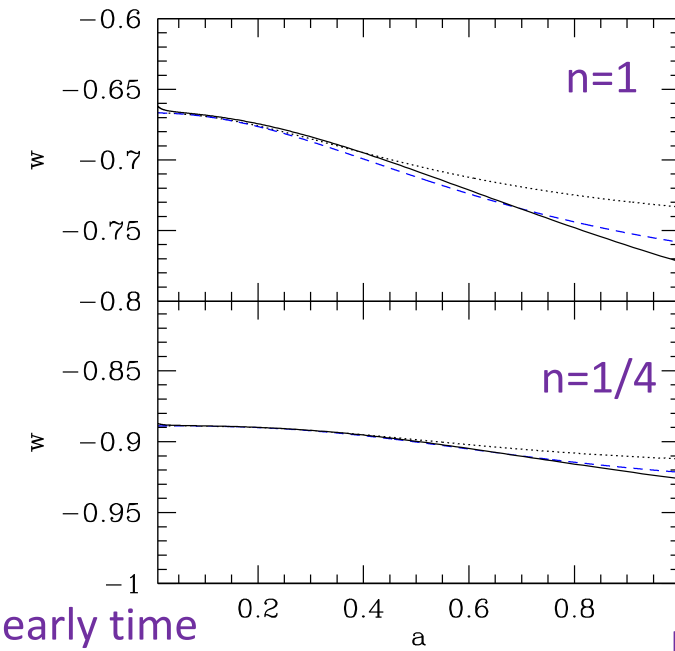


early time

present

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

Chiba (2010)



early time

present

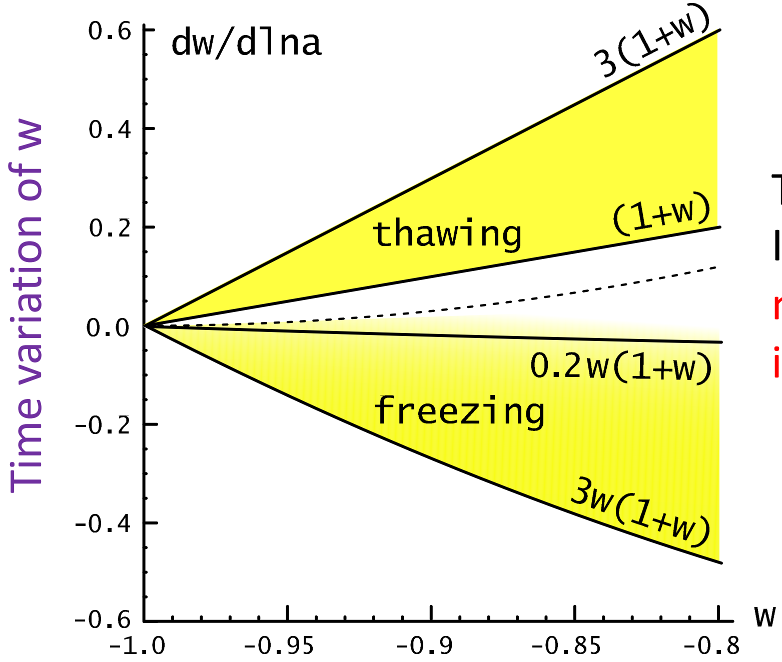
Theoretical side

- 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 variation !

Caldwell and Linder (2005)

Theoretical side

- Massive gravity

Historically, constructing consistent massive gravity has been suffering from ``ghost" (pathological d. o. f.) problem.

Fierz-Pauli theory (1939)

$$m^2\left(h_{\mu\nu}h^{\mu\nu}-h^2\right)$$

Massive graviton
without ghost
but at linear order

$$g_{\mu\nu}=\eta_{\mu\nu}+h_{\mu\nu}$$

perturbation
around Minkowski background

nonlinear theory?

appear ghost d. o. f.

Boulware,Deser (1972)

FP theory in massless limit
does not coincide with GR..
non-linear term should be necessary.

van Dam , Veltman (1970) , Zakharov (1970)

Theoretical side

- Massive gravity

Historically, constructing consistent massive gravity has been suffering from ``ghost” (pathological d. o. f.) problem.

de Rham, Gabadadze, Tolley (2010)

non-linear massive gravity
without ghost

$$S = \frac{M_{\rm Pl}^2}{2}\int \mathrm{d}^4x\sqrt{-g}\,(R + m^2\mathcal{U})$$

$$\mathcal{U} := \mathcal{U}_2 + \alpha_3\mathcal{U}_3 + \alpha_4\mathcal{U}_4,$$

$$\begin{aligned}\mathcal{U}_2 &:= [\mathcal{K}]^2 - [\mathcal{K}^2],\\ \mathcal{U}_3 &:= [\mathcal{K}]^3 - 3[\mathcal{K}][\mathcal{K}^2] + 2[\mathcal{K}^3],\\ \mathcal{U}_4 &:= [\mathcal{K}]^4 - 6[\mathcal{K}^2][\mathcal{K}]^2 + 8[\mathcal{K}^3][\mathcal{K}] + 3[\mathcal{K}^2]^2 - 6[\mathcal{K}^4].\end{aligned}$$

$$\mathcal{K}_\mu^{\ \nu} := \delta_\mu^{\ \nu} - (\sqrt{g^{-1}\Sigma})_\mu^{\ \nu}, \qquad \Sigma_{\mu\nu} = \partial_\mu\phi^a\partial_\nu\phi^b\eta_{ab}, \qquad \eta_{ab} = \mathrm{diag}(-1,1,1,1)$$

Theoretical side

- Massive gravity

Historically, constructing consistent massive gravity has been suffering from ``ghost" (pathological d. o. f.) problem.

de Rham, Gabadadze, Tolley (2010)

non-linear massive gravity without ghost

$$S = \frac{M_{\rm Pl}^2}{2}\int d^4x\sqrt{-g}\left(R + m^2\mathcal{U}\right)$$

$$\mathcal{U} := \mathcal{U}_2 + \alpha_3\mathcal{U}_3 + \alpha_4\mathcal{U}_4,$$

$$\begin{aligned}
\mathcal{U}_2 &:= [\mathcal{K}]^2 - [\mathcal{K}^2], \\
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$$\mathcal{K}_\mu^{\ \nu} := \delta_\mu^{\ \nu} - (\sqrt{g^{-1}\Sigma})_\mu^{\ \nu}, \qquad \Sigma_{\mu\nu} = \partial_\mu\phi^a\partial_\nu\phi^b\eta_{ab}, \qquad \eta_{ab} = \mathrm{diag}(-1,1,1,1)$$

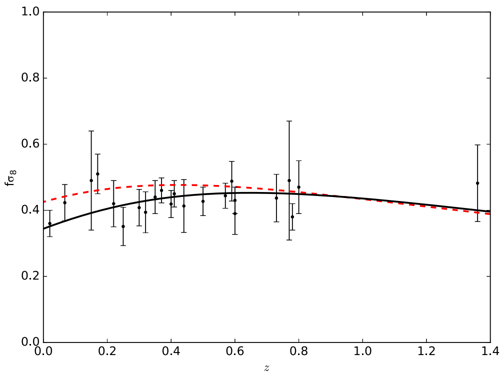
D'Amico, et al. (2011)

It might be difficult to obtain stable cosmological solution in this theory..

need some fine-tuning …

Theoretical side

De Fellice and Mukohyama (2016)



- Massive gravity

There are lots of works.

(In my ``biased” opinion,)

- Not so many about obtaining cosmological observational constraints (related with dark energy) on massive gravity theory …

- Many attempts to construct consistent massive gravity theory

De Felice and Mukohyama (2016), Naruko, Kimura, Yamauchi (2018), …

- Graviton mass bounds from other experiments, such as GW experiments, … see, e.g., de Rham et al. (2016)

Roughly, $m_g < 10^{-20} - 10^{-30}\,\mathrm{eV}$

($H_0 \simeq 10^{-33}\,\mathrm{eV}$)

Theoretical side

- Scalar tensor theory

also in Nishizawa-san's talk

➔ 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 !!

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 <u>second-order field equations</u> in 4D

free from ghost instabilities associated with the higher derivative terms

could have extra d.o.f.

Theoretical side

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

- time varying gravitational constant
- effect on the propagation of gravitational waves, … (in Nishizawa-san's talk)
- BH solutions?

In some sense, can be tested not only by cosmological observations
but also by local gravity test, GW experiments, and more..

Theoretical side

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?

Theoretical side

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)

$$\mathcal{L} = f(\phi, X)R + \sum_{I=1}^{5} A_I(\phi, X)L_I, \qquad \begin{aligned} &L_1 = \phi_{\mu\nu}\phi^{\mu\nu}, \quad L_2 = (\Box\phi)^2, \quad L_3 = \Box\phi\phi^\mu\phi^\nu\phi_{\mu\nu} \\ &L_4 = \phi^\mu\phi_{\mu\alpha}\phi^{\alpha\nu}\phi_\nu, \quad L_5 = (\phi^\mu\phi^\nu\phi_{\mu\nu})^2. \end{aligned}$$

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

Theoretical side

- Scalar-tensor theory

  should affect gravitational law :

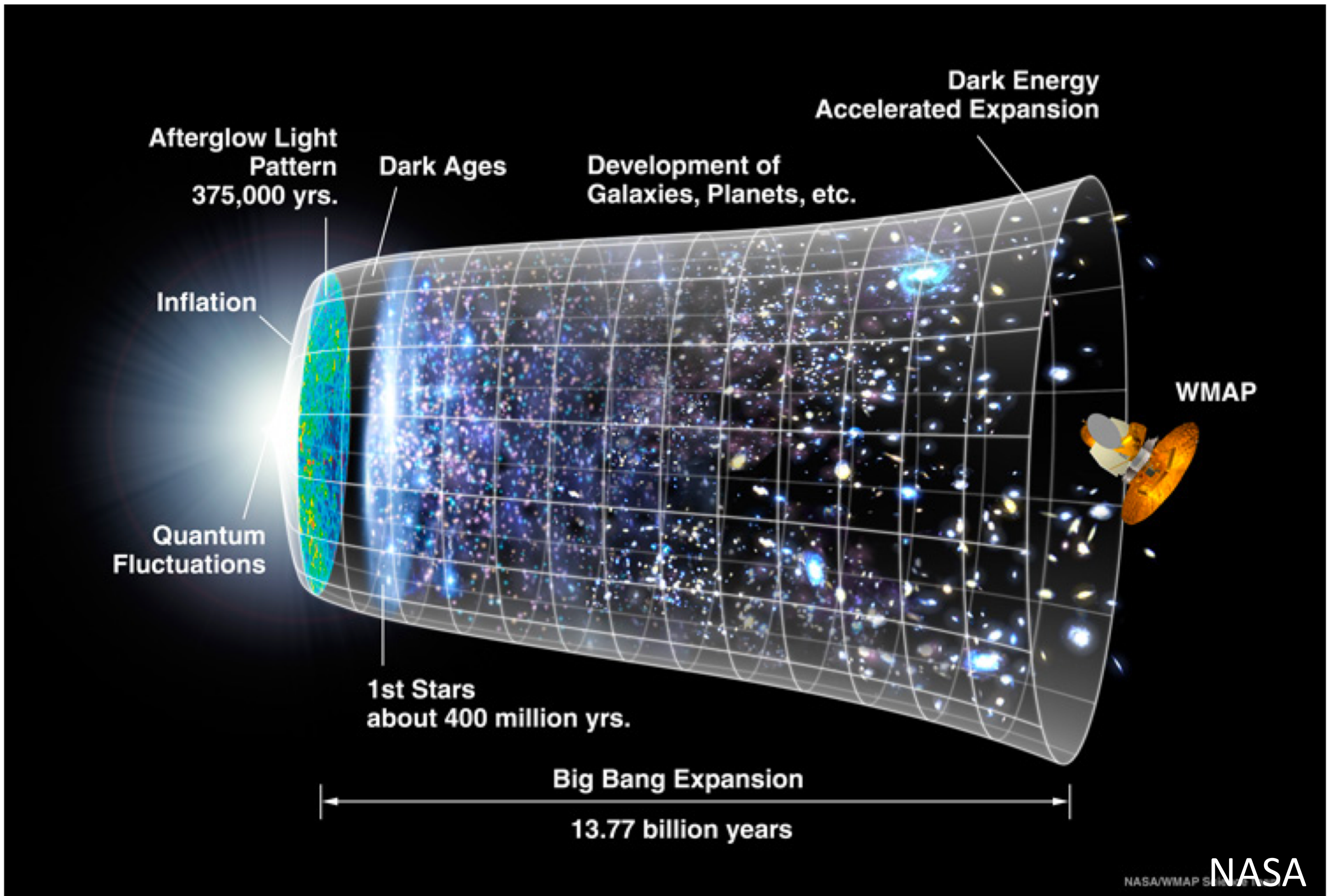
  - time varying gravitational constant
  - effect on the propagation of gravitational waves, … (in Nishizawa-san's talk)
  - BH solutions?
  - Fifth force?
  - …

Of course, would give various effects in cosmology
➔ Various cosmological tests for scalar tensor theory!

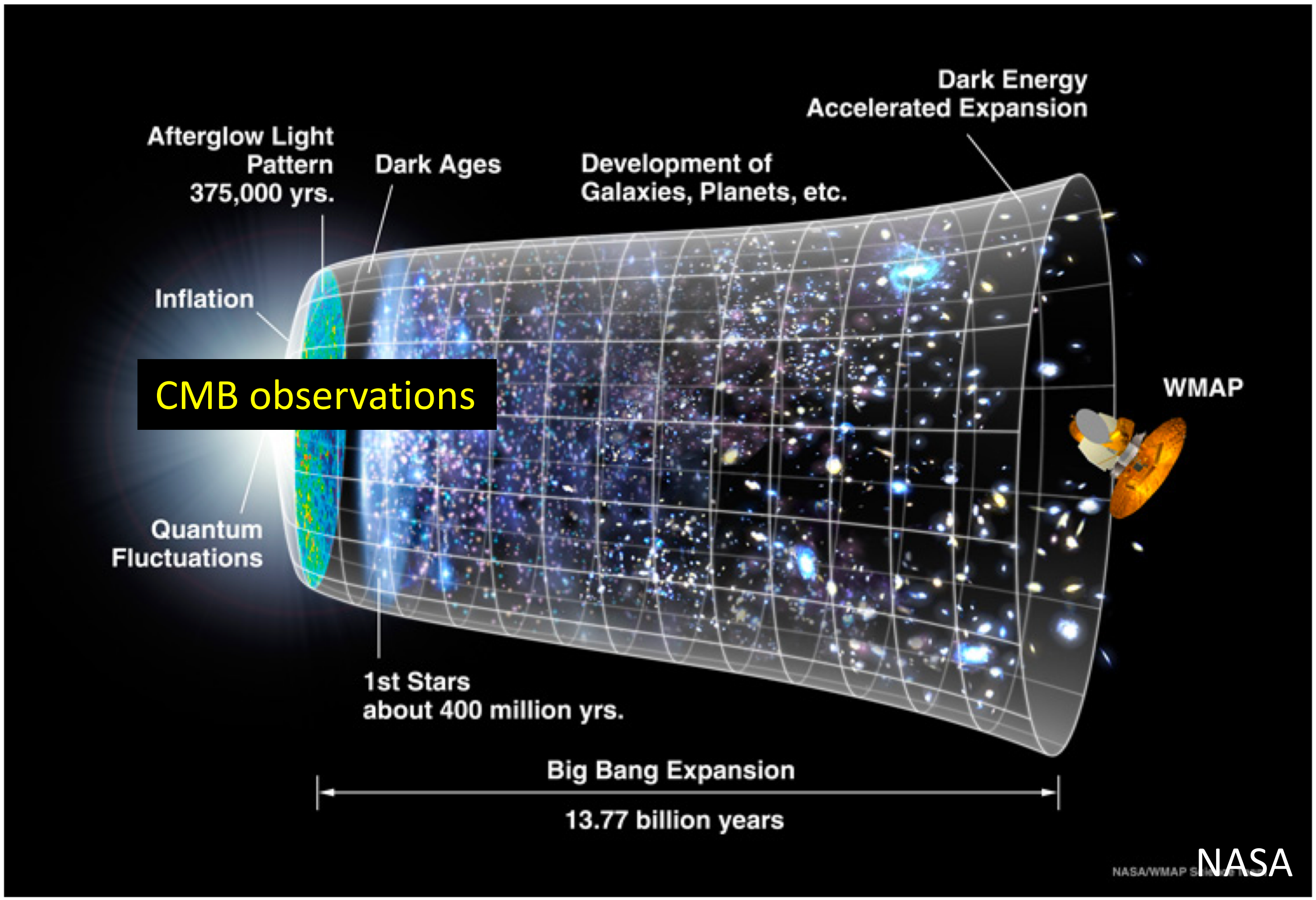
Cosmological observations

current status and future prospects to probe the dark energy

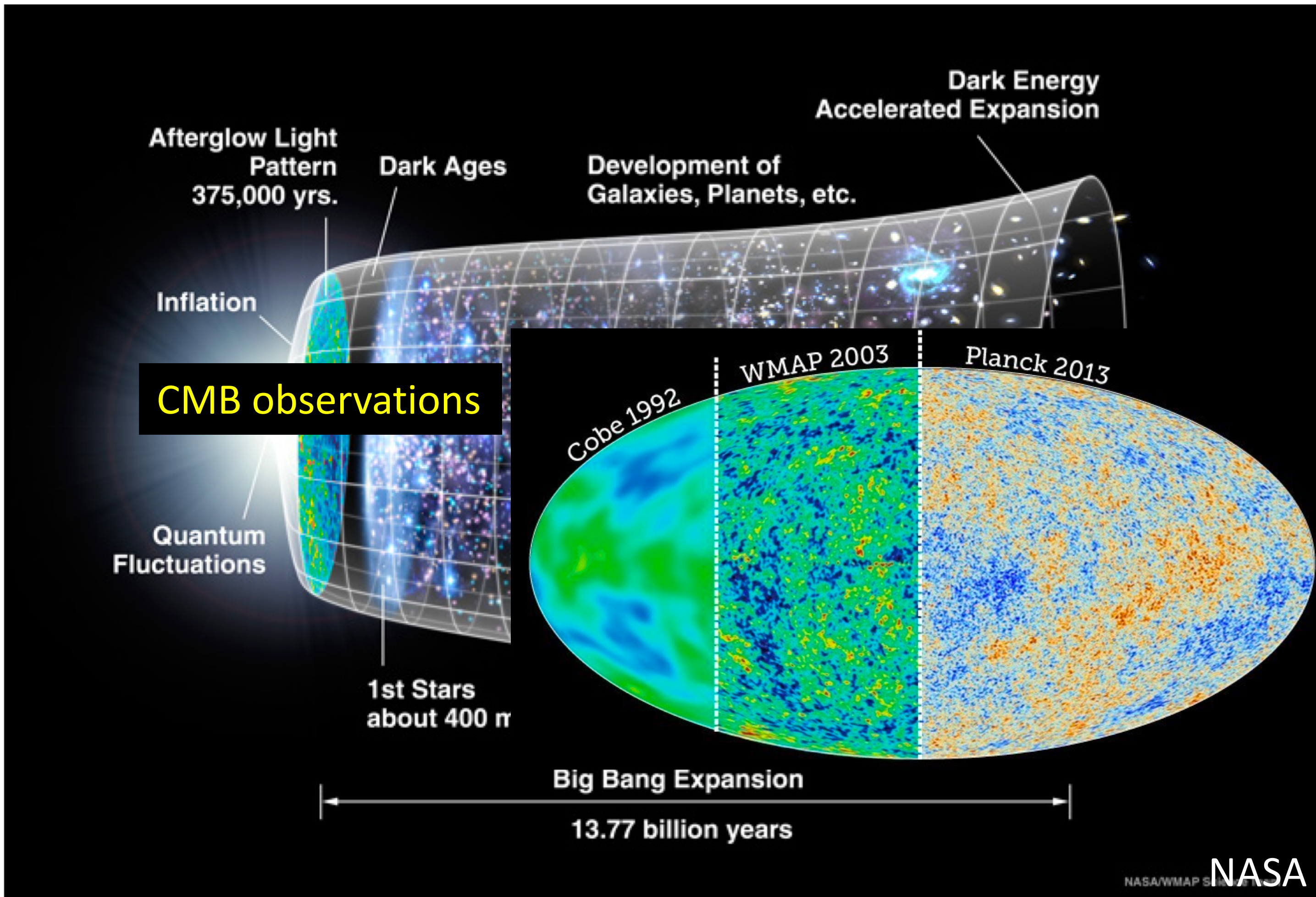
Remarkable progress of cosmological observations



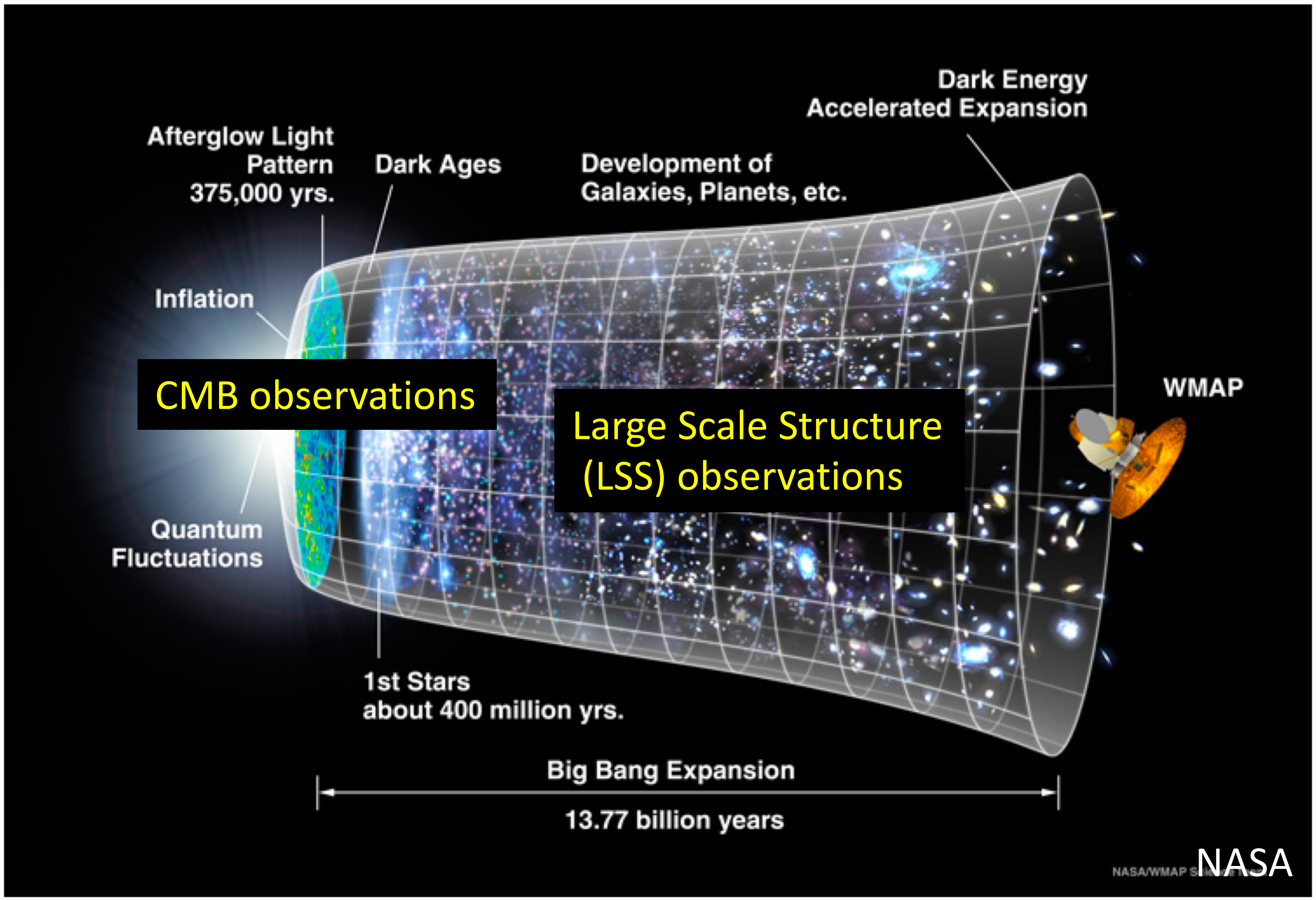
Remarkable progress of cosmological observations



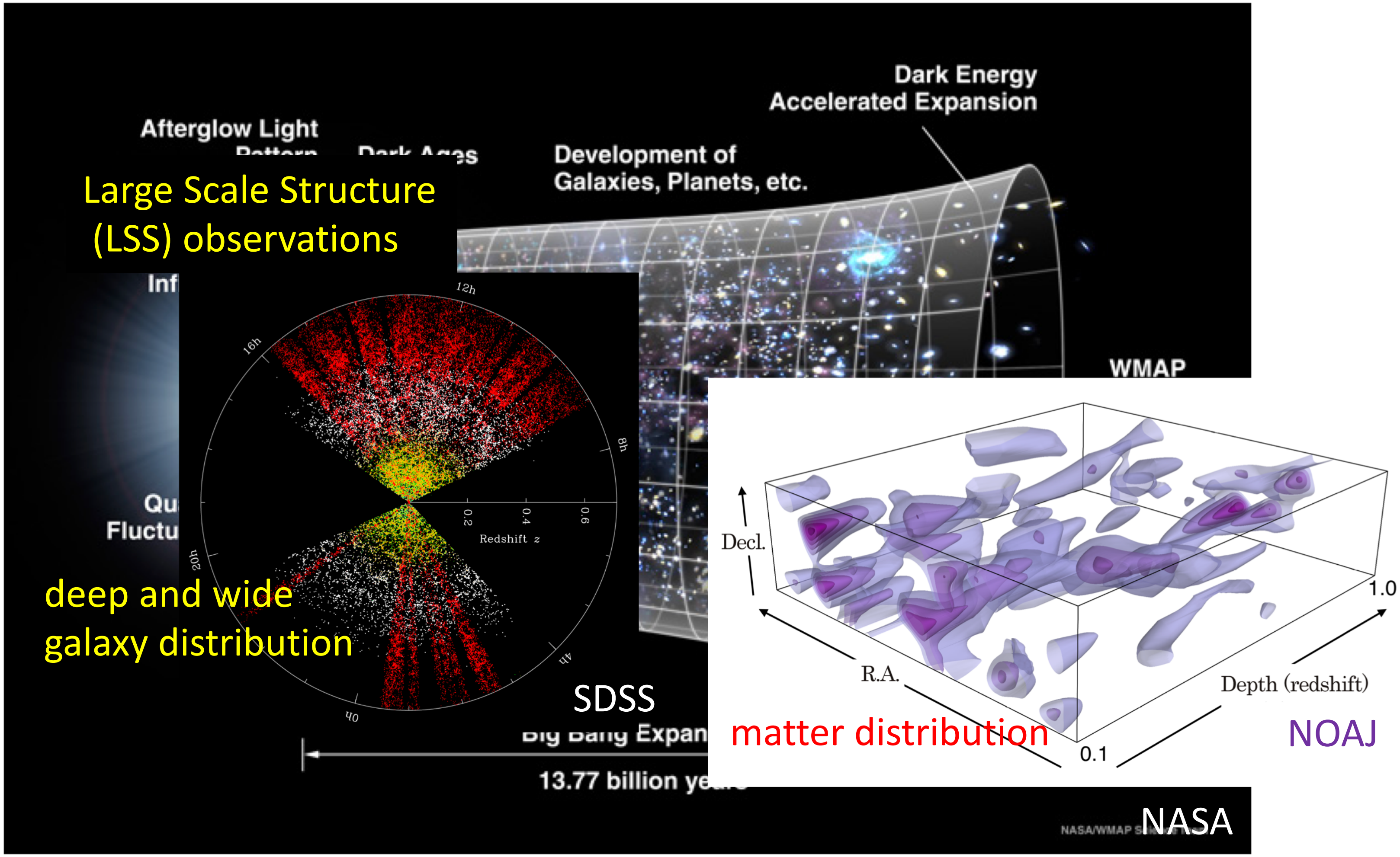
Remarkable progress of cosmological observations



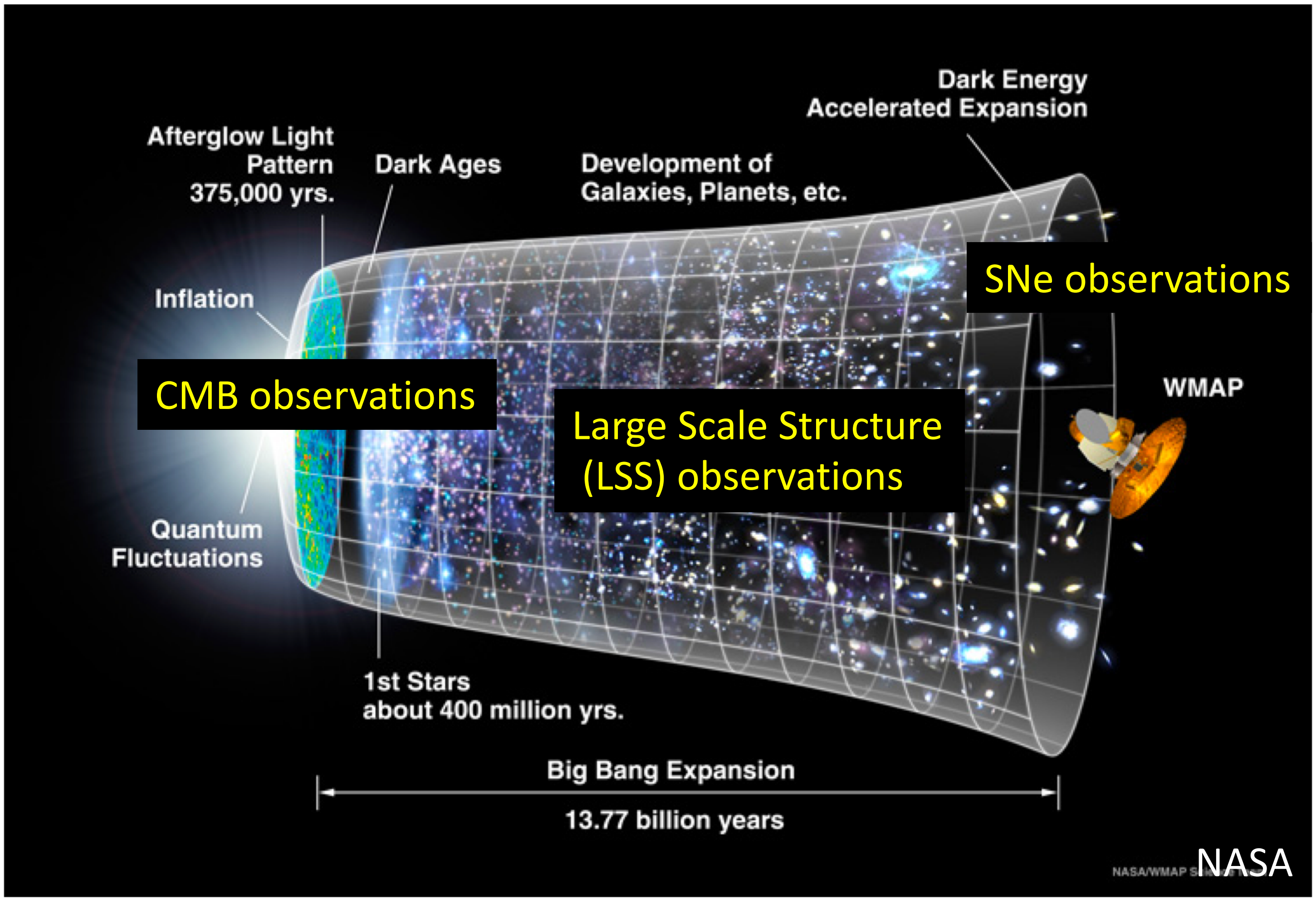
Remarkable progress of cosmological observations



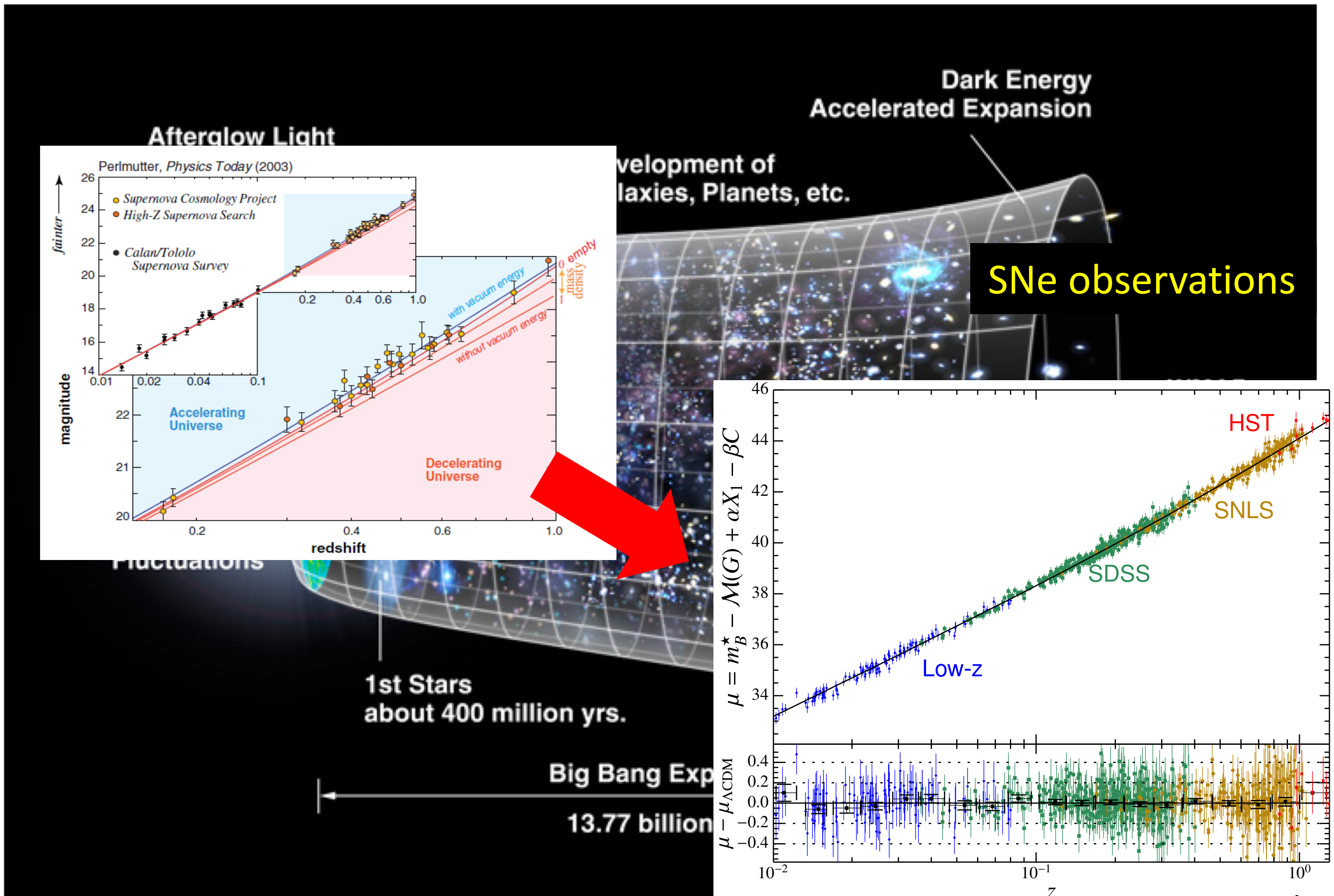
Remarkable progress of cosmological observations



Remarkable progress of cosmological observations

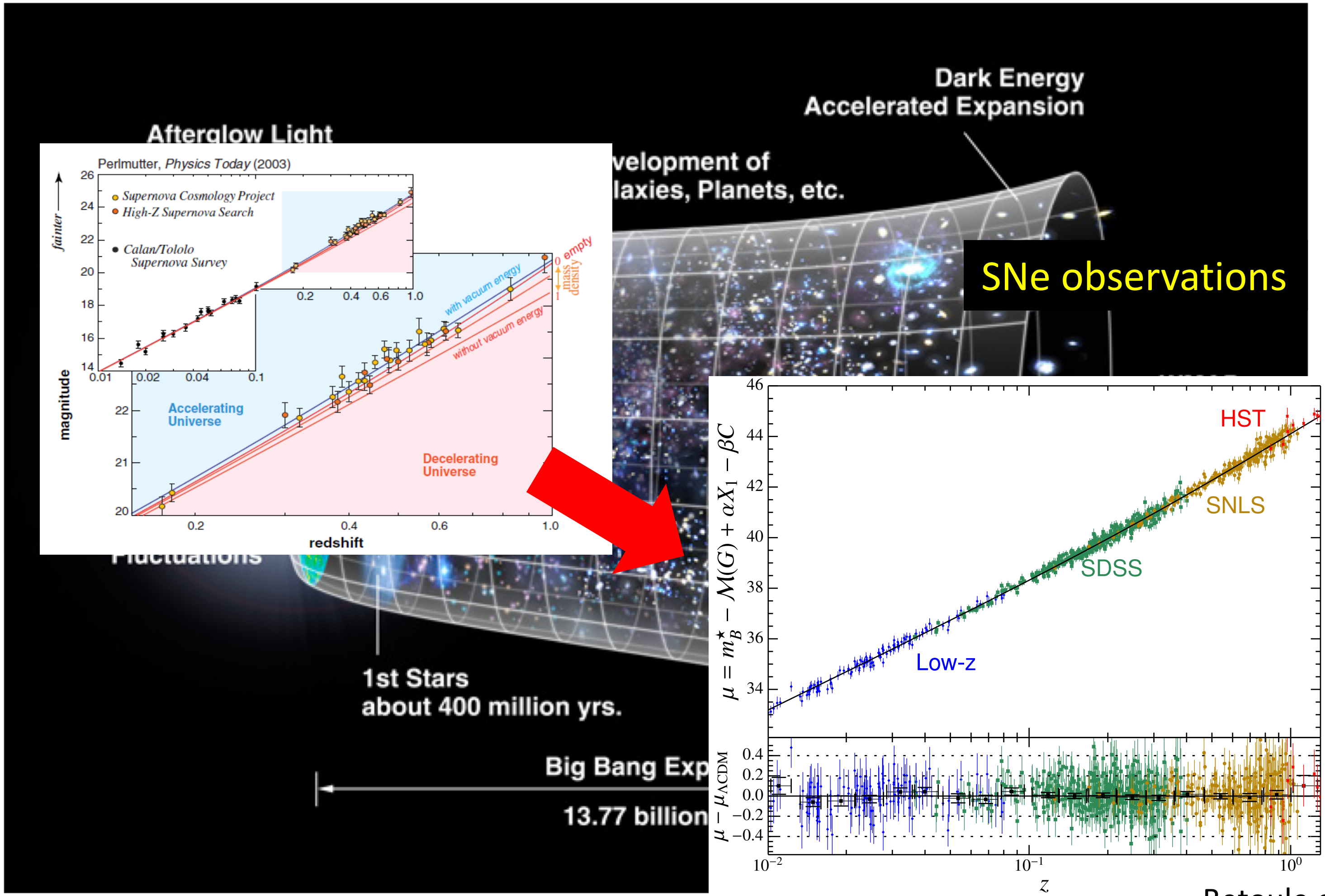


Remarkable progress of cosmological observations



Betoule et al. (2014)

Remarkable progress of cosmological observations

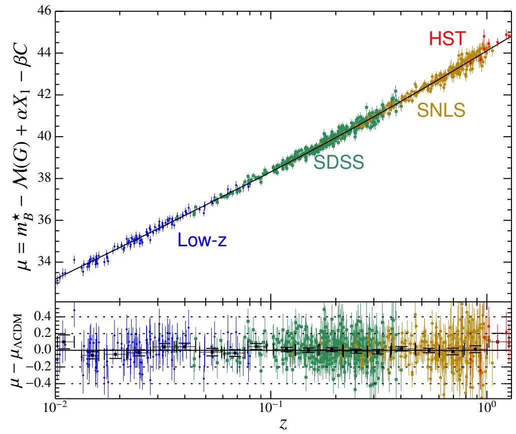


Betoule et al. (2014)

What we observe?

- Expansion of the Universe

➔ SNe observations



$$a(t) = a_0 + \dot{a}_0\,\Delta t + \frac{1}{2}\frac{\ddot{a}}{a}\Big|_0\,\Delta t^2 + \cdots$$

$$H_0 \qquad \dot{H}_0$$

Friedmann equations;

$$H^2 = \frac{8\pi G}{3}\left(\rho_m + \rho_{\rm DE}\right)$$

energy density of ``Dark energy" component

$$\dot{H} = -4\pi G\left(\rho_m + (1+w)\rho_{\rm DE}\right)$$

``effective" equation of state of DE component

What we observe?

- 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”.

What we observe?

- 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”.

CMB/LSS observations!

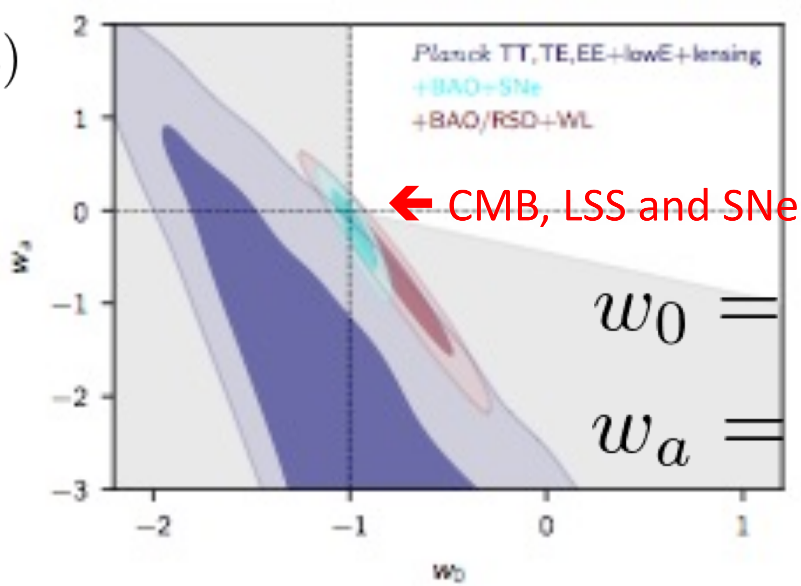
What we observe?

- 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)

What we can learn?

- Comparing theoretical implication with this result

$$w_0 = -0.961 \pm 0.077$$
$$w_a = -0.28^{+0.31}_{-0.27}$$

still consistent with $w = -1$; cosmological constant

If we take the best-fit values
of these parameters,

What we can learn?

- Comparing theoretical implication with this result

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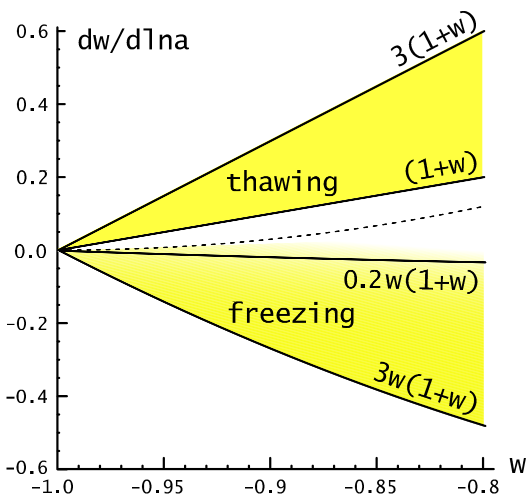

For quintessence model,

Caldwell and Linder (2005)

What we can learn?

- Comparing theoretical implication with this result

$$w_0 = -0.961 \pm 0.077$$
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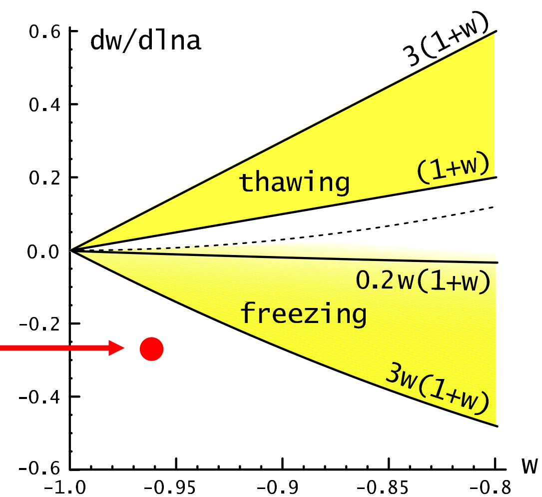
If we take the best-fit values of these parameters,

Freezing model might be favored??
but,..



For quintessence model,

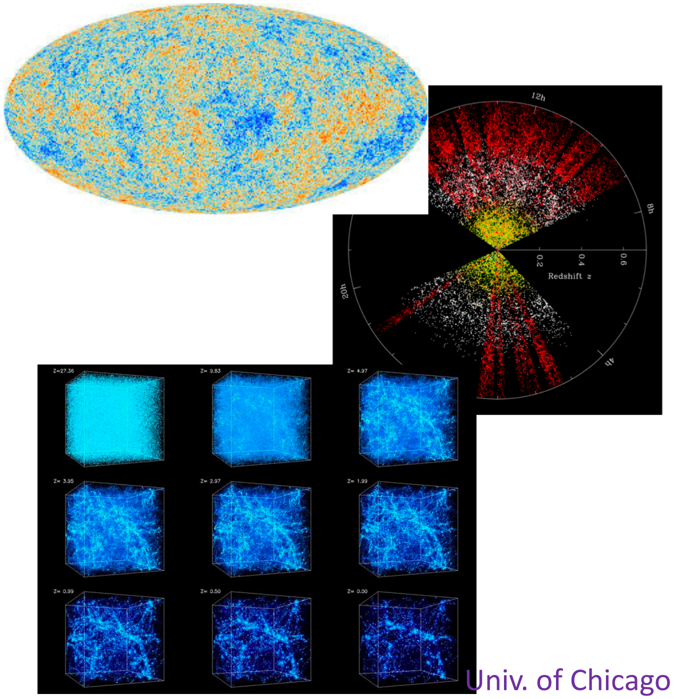
Caldwell and Linder (2005)

Any other?

- 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).

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



Such a matter inhomogeneity evolves through the gravitational interaction!

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

Univ. of Chicago

Any other?

- Evolution of matter inhomogeneities in the Universe

Basic equations (fluid approximation);

$$\dot{\delta} + \frac{1}{a}\partial_i[(1+\delta)u^i] = 0,$$; continuity equation

$$\dot{u}^i + Hu^i + \frac{1}{a}u^j\partial_j u^i = -\underline{\frac{1}{a}\partial^i\Phi}.$$; Euler equation

gravitational potential

➔ Linearized evolution equation (in Fourie space);

$$\delta(t, \boldsymbol{x}) = \int \frac{d^3k}{(2\pi)^3}\delta(t)e^{i\boldsymbol{k}\cdot\boldsymbol{x}}$$

$$\ddot{\delta} + 2H\dot{\delta} + \frac{k^2}{a^2}\Phi = 0$$

In GR (Newtonian), Poisson equation for gravitational potential;

$$-\frac{k^2}{a^2}\Phi = 4\pi G\rho_m\,\delta$$; gravitational law

Any other?

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

- Evolution of matter inhomogeneities in the Universe

However, in scalar-tensor theory (even in Horndeski theory),

$$-\frac{k^2}{a^2}\Phi = 4\pi G\rho_m\,\delta$$

$\Downarrow$ would be changed

$$-\frac{k^2}{a^2 H^2}\Phi = \kappa_\Phi \delta$$

$\kappa_\Phi = \kappa_\Phi(t)$; non-trivial time dependence!!

e.g., time-dependent gravitational constant, …

Any other?

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

- Evolution of matter inhomogeneities in the Universe

However, in scalar-tensor theory (even in Horndeski theory),

$$-\frac{k^2}{a^2}\Phi = 4\pi G\rho_m\,\delta$$

would be changed

Furthermore, in DHOST theories,

$$-\frac{k^2}{a^2H^2}\Phi = \kappa_\Phi\delta + \underline{\nu_\Phi\frac{\dot{\delta}}{H} + \mu_\Phi\frac{\ddot{\delta}}{H^2}}$$

New contribution coming from the time derivatives of density contrast would appear ..

Any other?

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

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

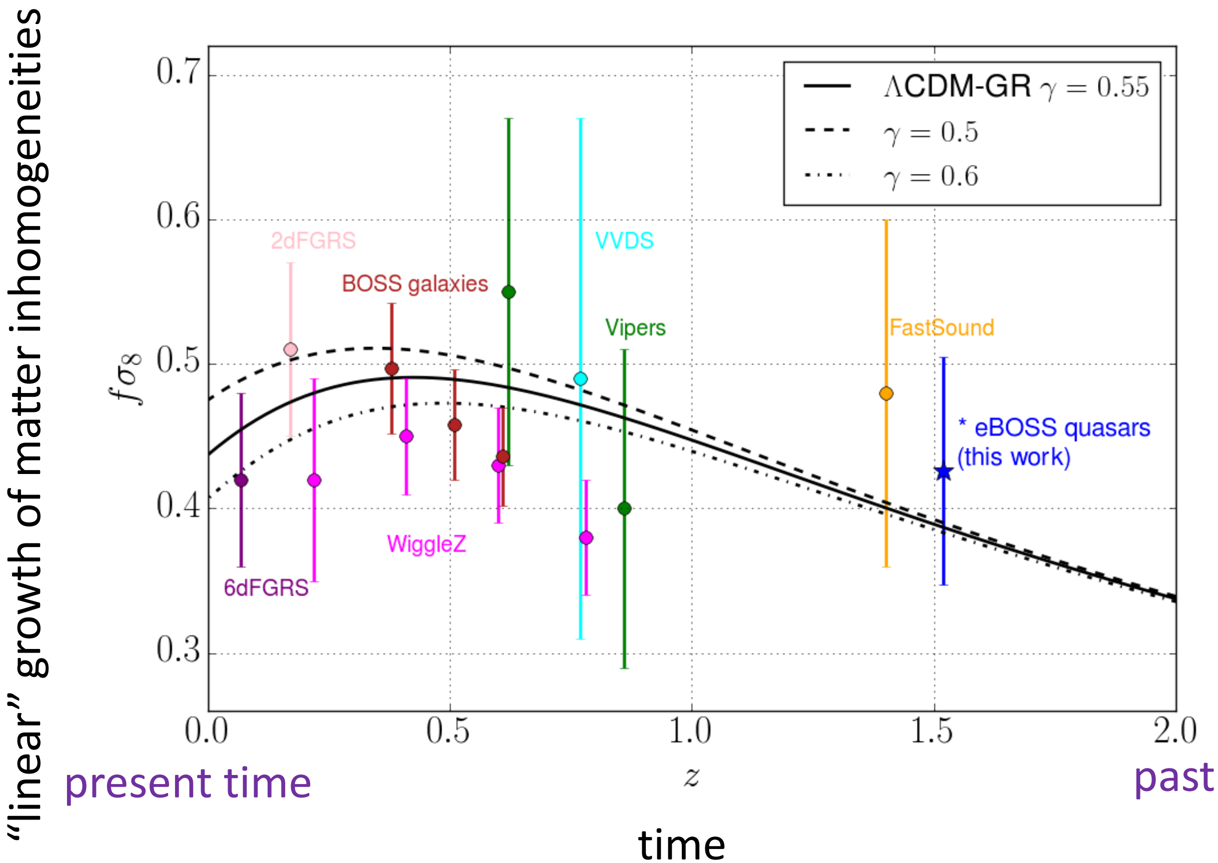
In GR,

$$\gamma = 0.55$$

a is a scale factor (time coordinate)

What we observe?

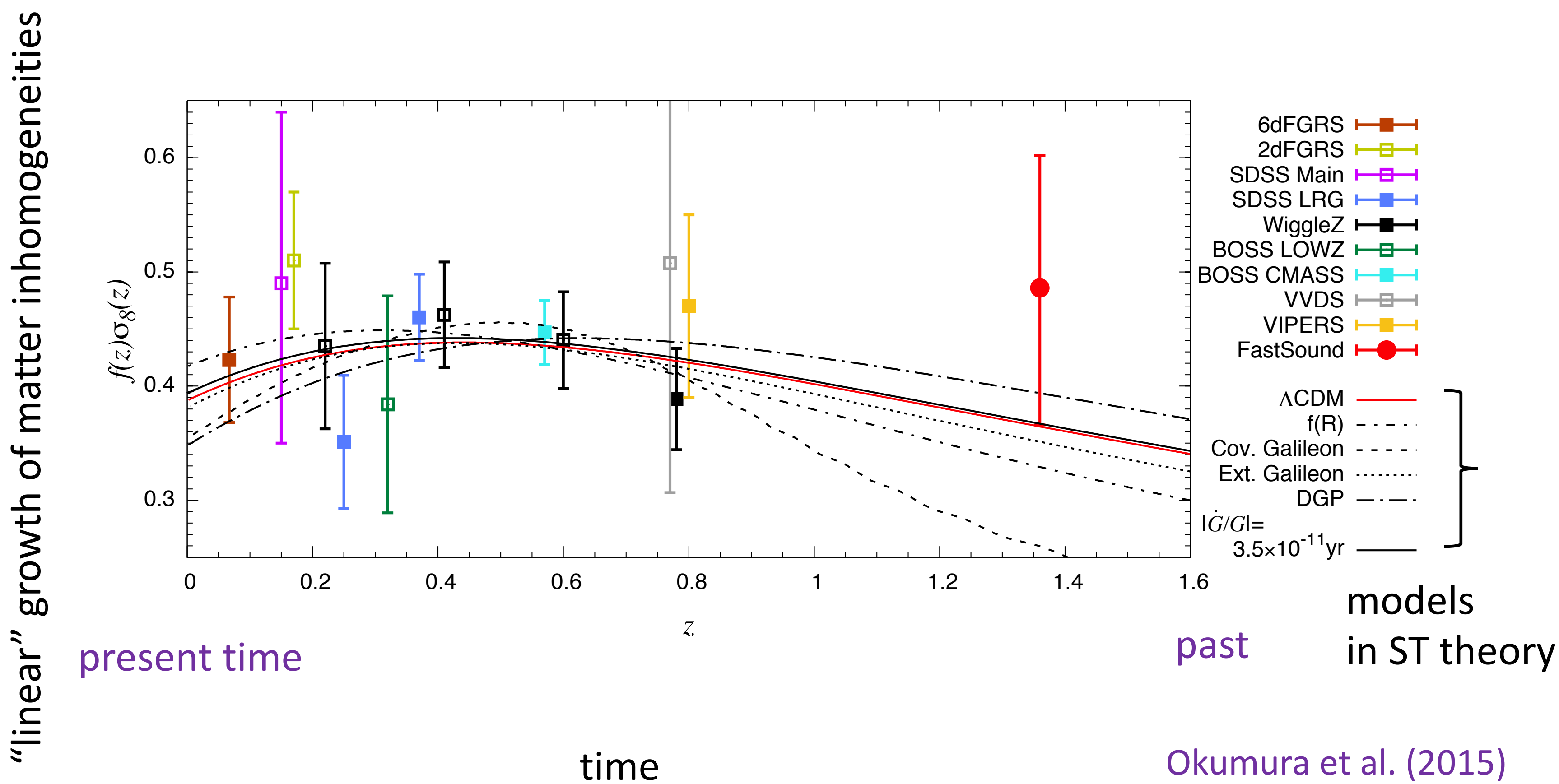
- Evolution of matter inhomogeneities in the Universe



Zarrouk et al. (2018)

What we learn?

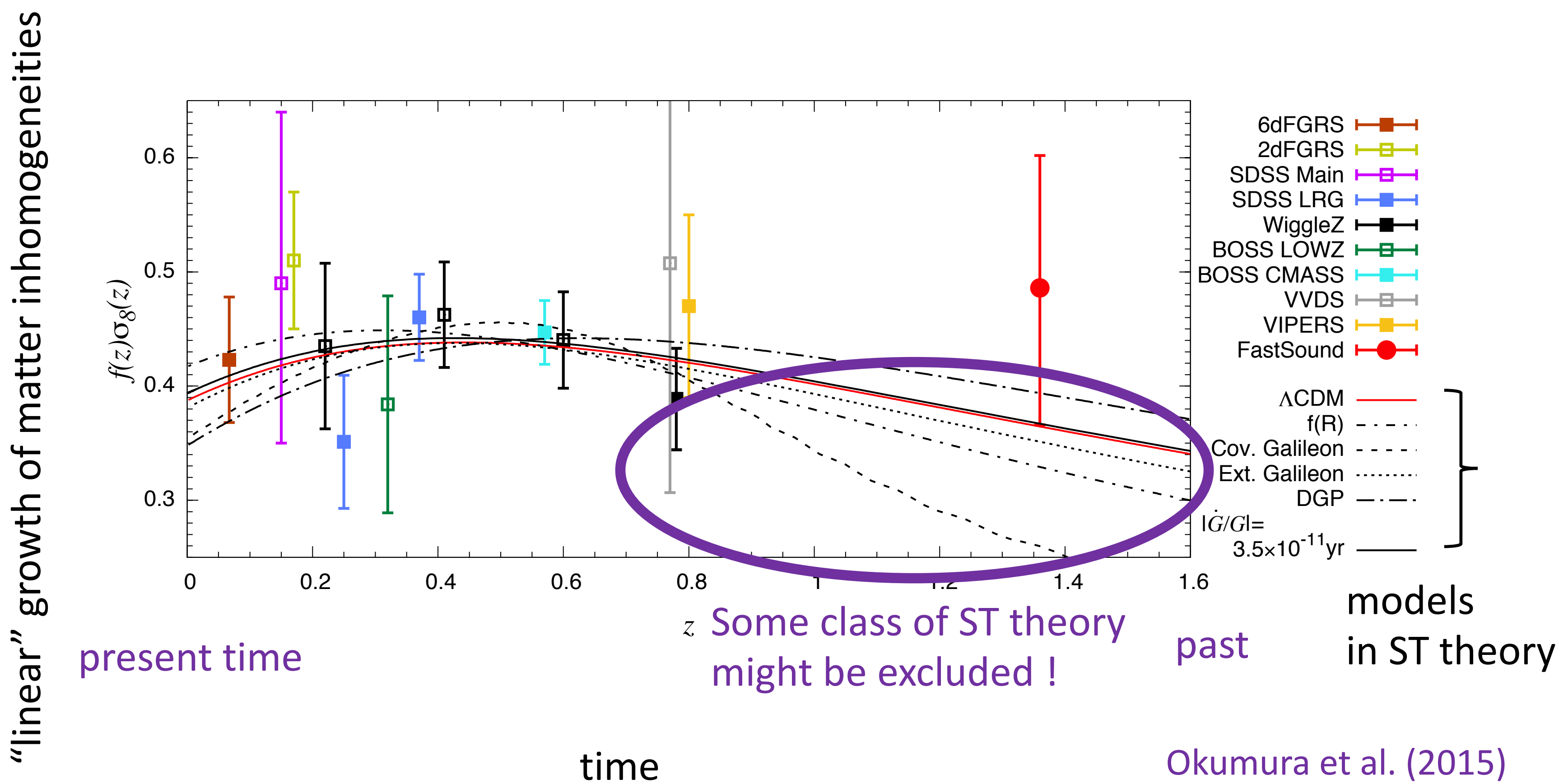
- Evolution of matter inhomogeneities in the Universe



Okumura et al. (2015)

What we learn?

- Evolution of matter inhomogeneities in the Universe



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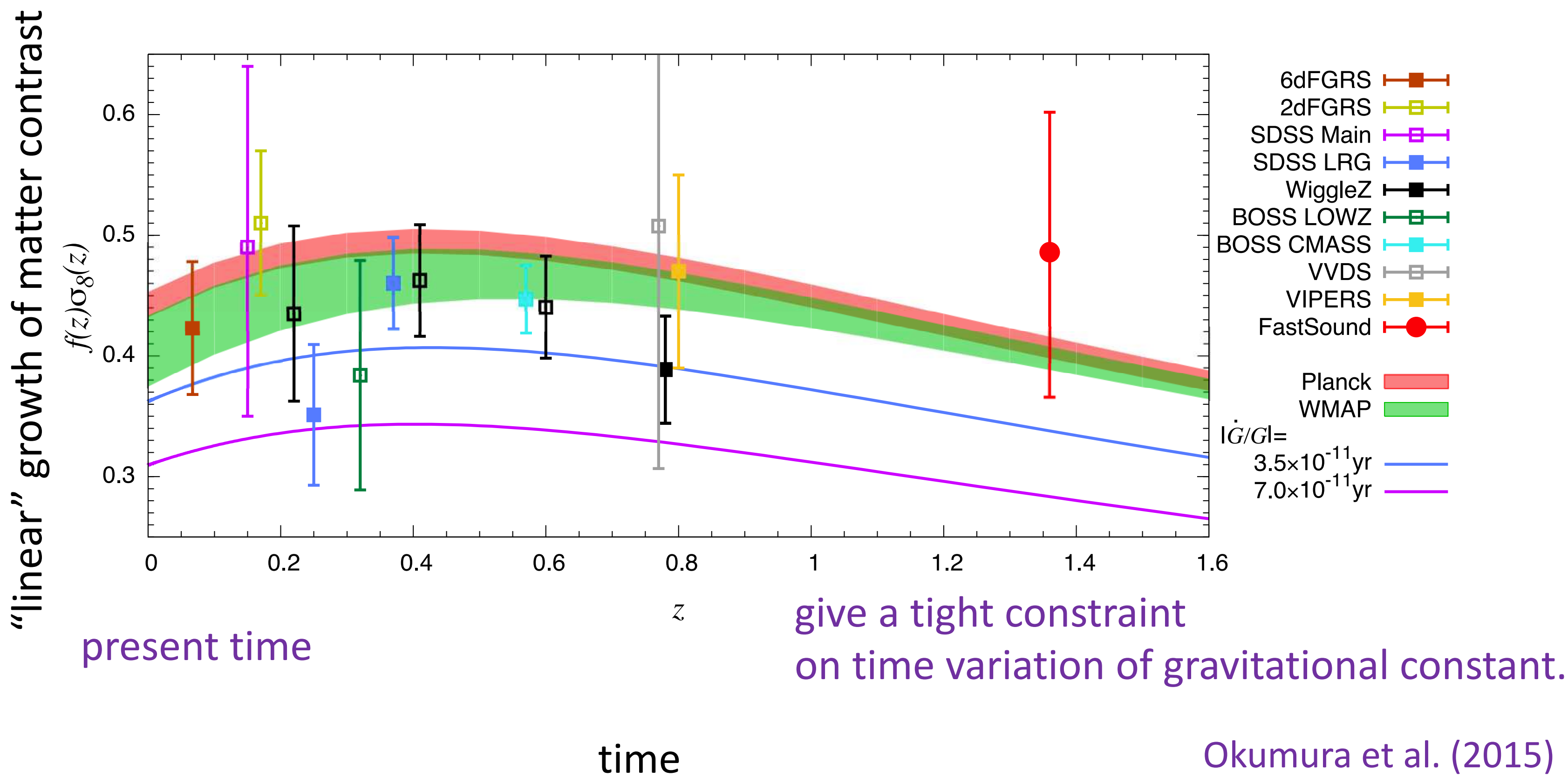
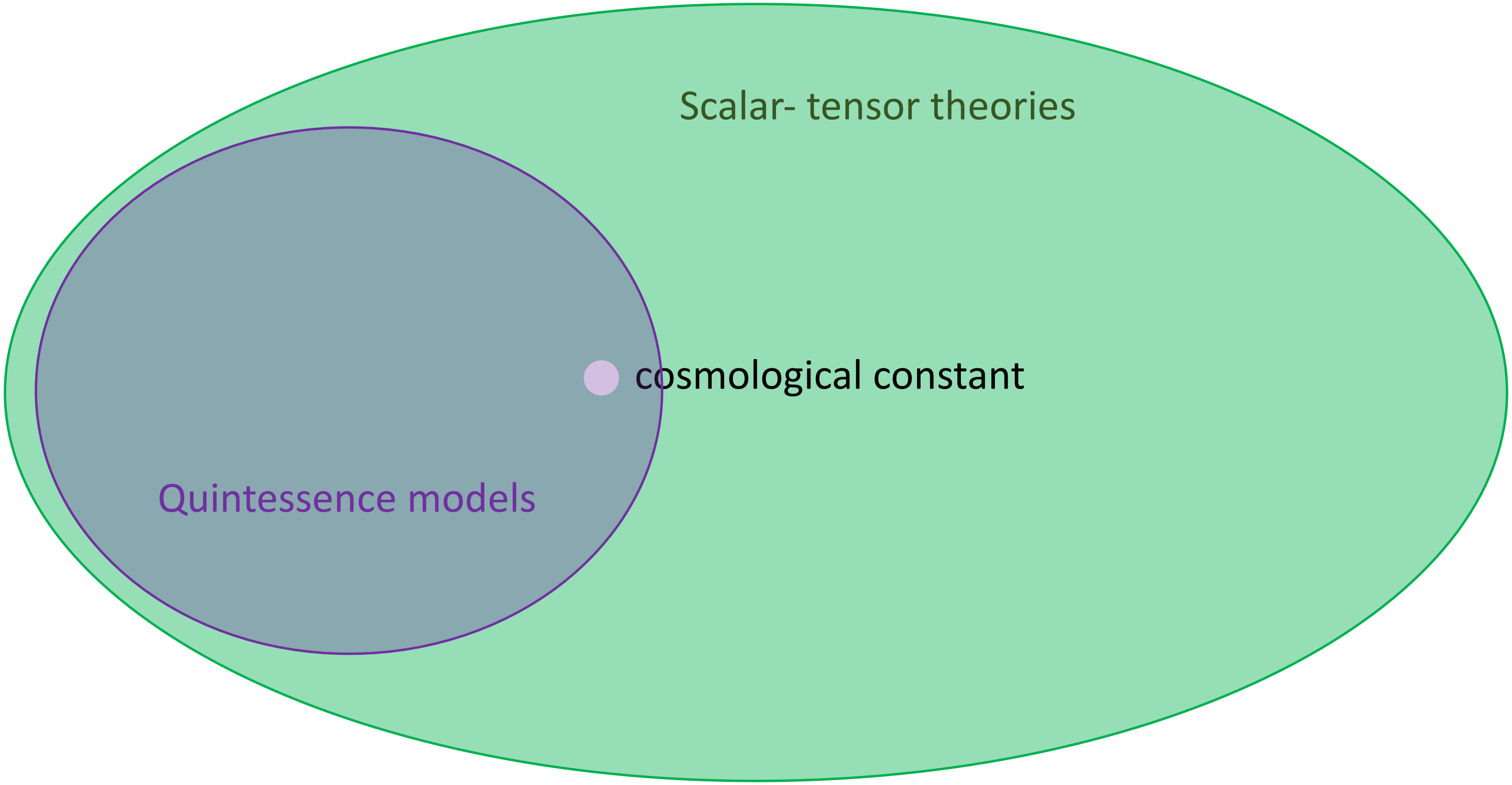


Okumura et al. (2015)

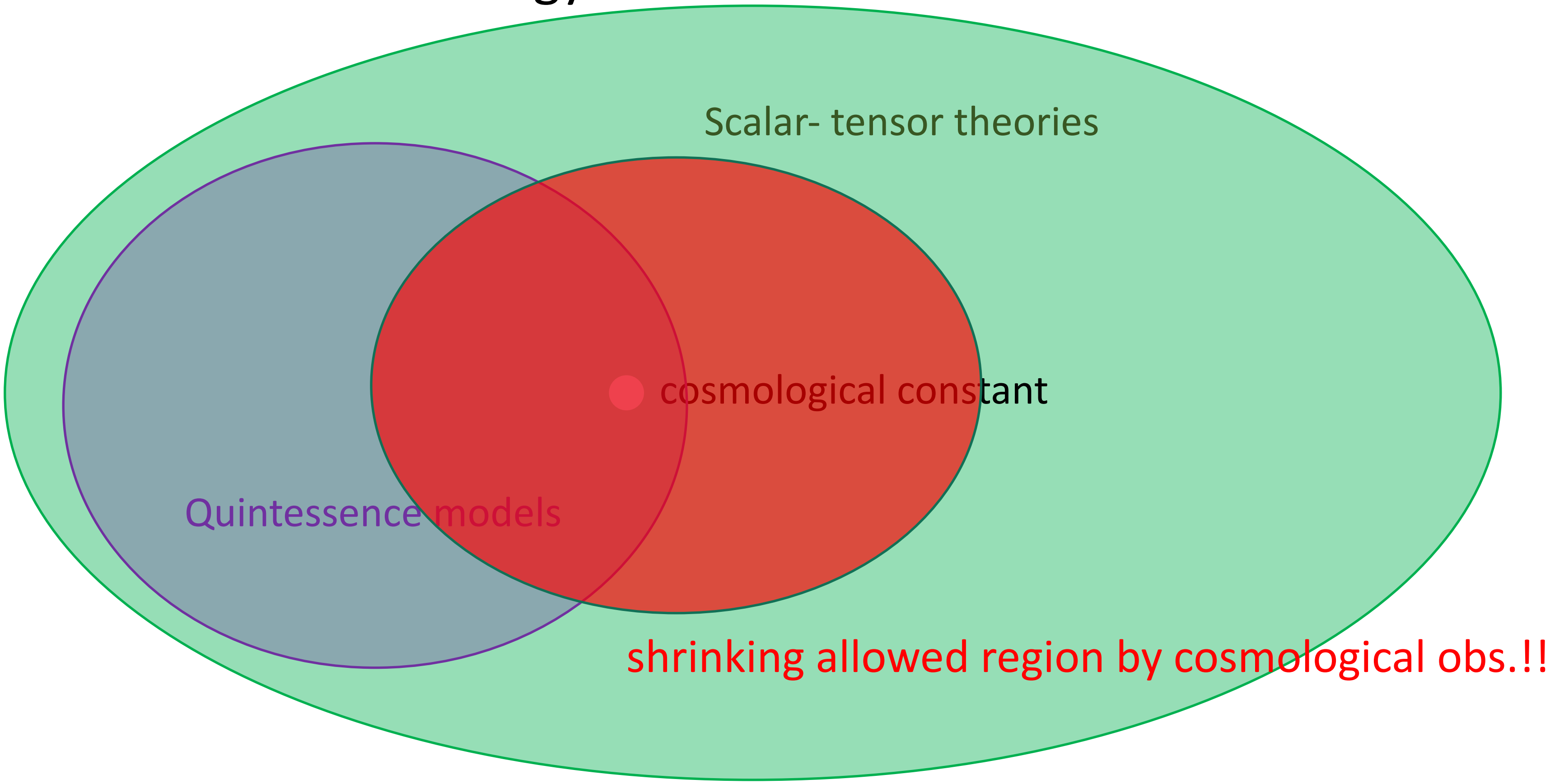
Thus...

- Bunch of dark energy models ..



Thus…

- Bunch of dark energy models ..



DE activities
in observational cosmology group, Nagoya

HSC (Subaru Hyper Suprime-Cam) collaboration

Cosmology from cosmic shear power spectra with Subaru Hyper Suprime-Cam first-year data

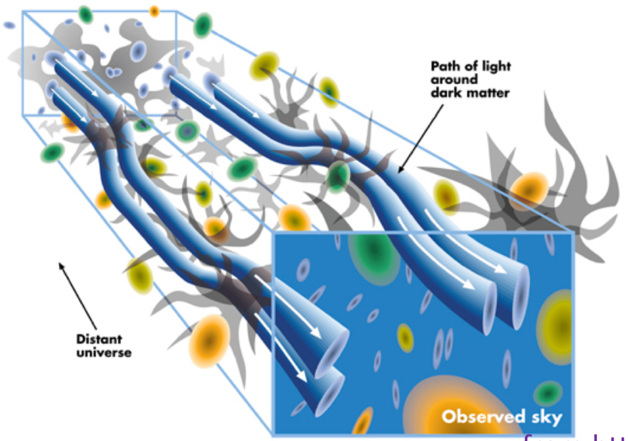
Chiaki Hikage[1], Masamune Oguri[2,3,1], Takashi Hamana[4], Surhud More[1,5], Rachel Mandelbaum[6], Masahiro Takada[1], Fabian Köhlinger[1], Hironao Miyatake[7,8,9,1], Atsushi J. Nishizawa[7,8], Hiroaki Aihara[3,1], Robert Armstrong[10], James Bosch[11], Jean Coupon[12], Anne Ducout[1], Paul Ho[13], Bau-Ching Hsieh[13], Yutaka Komiyama[4,14], François Lanusse[6], Alexie Leauthaud[15], Robert H. Lupton[11], Elinor Medezinski[11], Sogo Mineo[4], Shoken Miyama[4,16], Satoshi Miyazaki[4,14], Ryoma Murata[1,3], Hitoshi Murayama[1,17,18], Masato Shirasaki[4], Cristóbal Sifón[11], Melanie Simet[19,9], Joshua Speagle[20], David N. Spergel[11,21], Michael A. Strauss[11], Naoshi Sugiyama[8,22,1], Masayuki Tanaka[4], Yousuke Utsumi[23], Shiang-Yu Wang[13] and Yoshihiko Yamada[4]

arXiv:1809.09148v2

a member in our group

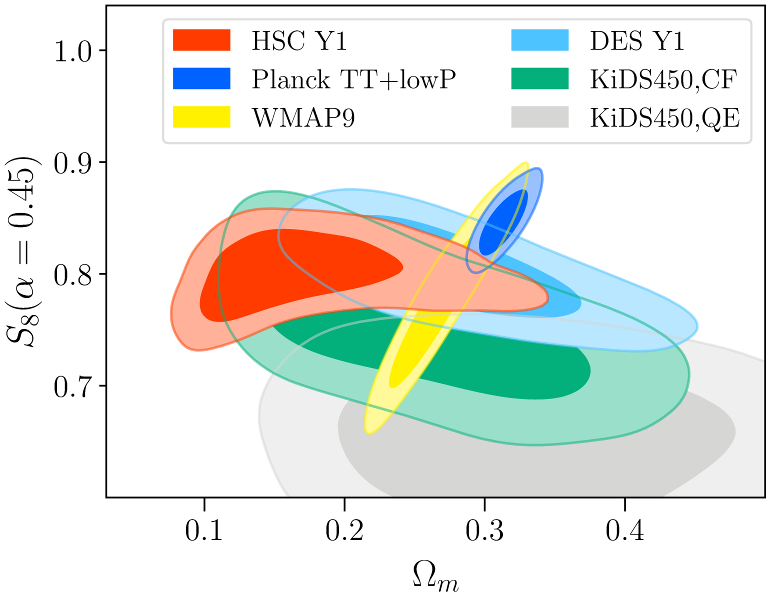
HSC collaboration

from NAOJ

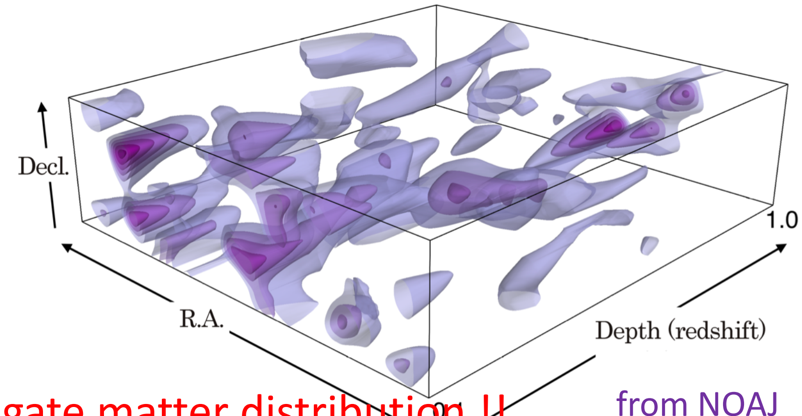


from https://www.nsf.gov/

measure the weak lensing signal



a new constraint on the growth !



investigate matter distribution !!

from NOAJ

arXiv:1809.09148v2

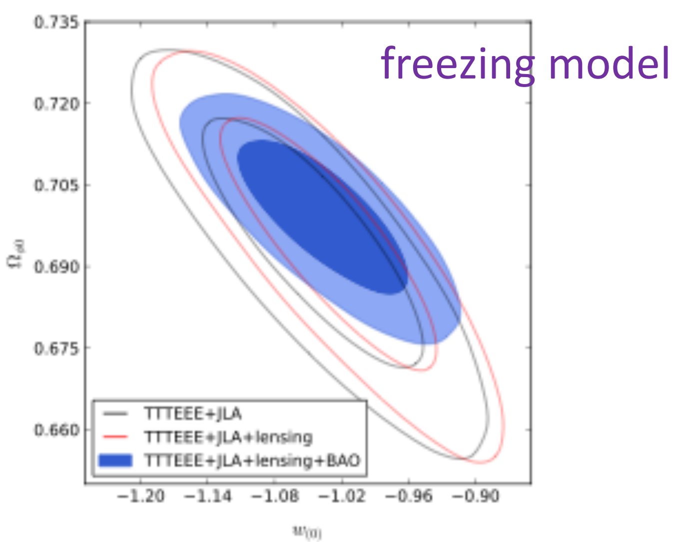
Constraints on quintessence scenarios

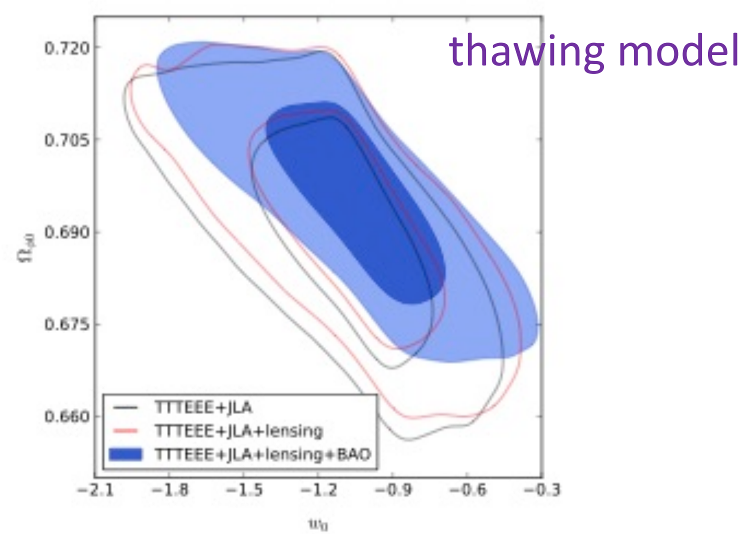
1801.09446

Updated observational constraints on quintessence dark energy models

Jean-Baptiste Durrive[1], Junpei Ooba[1], Kiyotomo Ichiki[1,2] and Naoshi Sugiyama[1,2,3]
[1] *Department of Physics and Astrophysics, Nagoya University, Nagoya 464-8602, Japan*
[2] *Kobayashi-Maskawa Institute for the Origin of Particles and the Universe, Nagoya University, Nagoya 464-8602, Japan*
[3] *Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU), The University of Tokyo, Chiba 277-8582, Japan* *
(Dated: January 30, 2018)

model-dependent analysis for a constraint on quintessence scenarios





Constraints seem to depend on models..

Cosmological constraints on scalar-tensor gravity and the variation of the gravitational constant

1702.00742

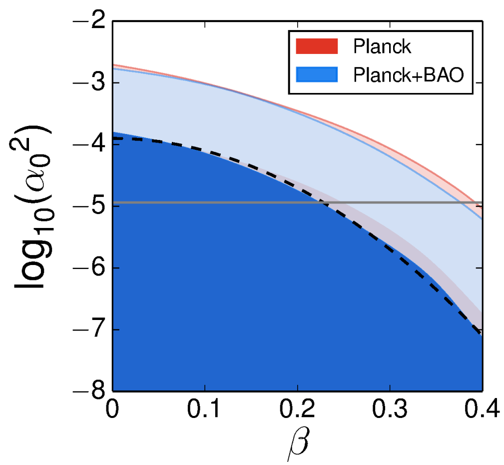
Junpei Ooba[1], Kiyotomo Ichiki[1,2], Takeshi Chiba[3], and Naoshi Sugiyama[1,2,4]

$$S = \frac{1}{16\pi G_0}\int d^4x\sqrt{-g}\left[\phi R - \frac{\omega(\phi)}{\phi}(\nabla\phi)^2\right]$$

$$2\,\omega(\phi) + 3 = \left\{{\alpha_0}^2 - \beta\ln(\phi/\phi_0)\right\}^{-1}$$

constraint on the deviation of
the gravitational constant between
at the present and the recombination time
from CMB observation;

$$G_{\rm rec}/G_0 - 1 < 1.9\times10^{-3}$$



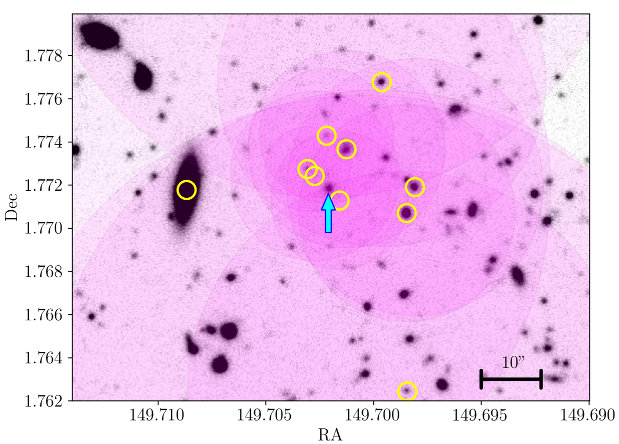
Constraint on BD parameter

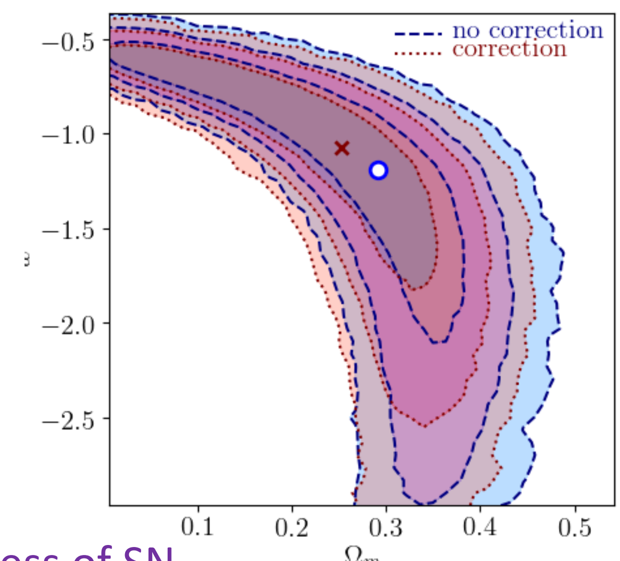
Correction to the brightness of SNe

1901.10129

Effect of lensing magnification on type Ia supernova cosmology

Hinako Sakakibara,[1★] Atsushi J. Nishizawa,[1,2†] Masamune Oguri,[3,4,5]
Masayuki Tanaka,[6] Bau-Ching Hsieh[7] and Kenneth C. Wong[5]





Due to the existence of matter between SN and us,
gravitational lensing effect might appear in the brightness of SN.

corrected constraint

should be important for more precise measurement of SNe !

New way to measure the growth of matter inhomogeneities

Redshift Space Distortion of 21cm line at $1 < z < 5$ with Cosmological Hydrodynamic Simulations

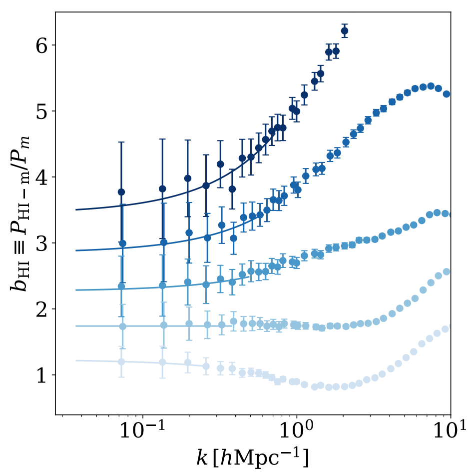
1808.01116

Rika Ando[1], ⋆ Atsushi J. Nishizawa[1,2], † Kenji Hasegawa[1], Ikkoh Shimizu[3] and Kentaro Nagamine[3,4,5]

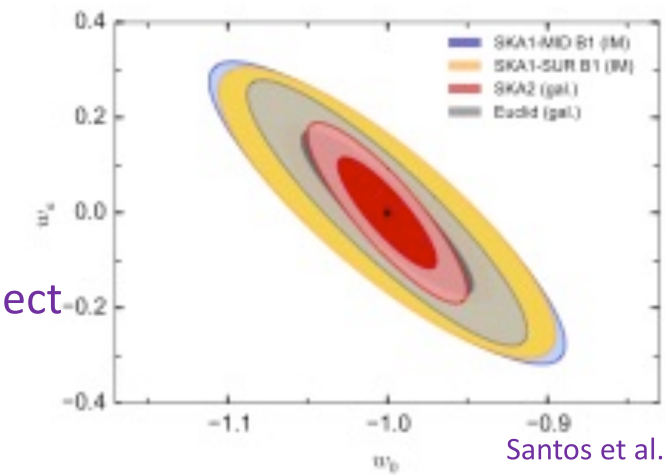
As a new ``tracer” of matter inhomogeneities, HI intensity distribution should be powerful !!

How to adapt HI distribution to total matter (DM) distribution?

$$b_{HI} = \delta_{HI}/\delta_m$$



We can expect



Santos et al. (2015)

Growth in higher order ?

1709.03243

Constraining modified theory of gravity with galaxy bispectrum

Daisuke Yamauchi,[1,*] Shuichiro Yokoyama,[2,3] and Hiroyuki Tashiro[4]

Basic equations (fluid approximation) for evolution of the matter density contrast;

$$\dot{\delta} + \frac{1}{a}\partial_i[(1+\delta)u^i] = 0,$$; continuity equation

$$\dot{u}^i + Hu^i + \frac{1}{a}u^j\partial_j u^i = \underline{-\frac{1}{a}\partial^i\Phi}.$$; Euler equation

gravitational potential

➔ Linearized evolution equation (in Fourie space);

$$\delta(t,\boldsymbol{x}) = \int \frac{d^3k}{(2\pi)^3}\delta(t)e^{i\boldsymbol{k}\cdot\boldsymbol{x}}$$

$$\ddot{\delta} + 2H\dot{\delta} + \frac{k^2}{a^2}\Phi = 0$$

In GR (Newtonian), Poisson equation for gravitational potential;

$$-\frac{k^2}{a^2}\Phi = 4\pi G\rho_m\,\delta$$; gravitational law

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Basic equations (fluid approximation) for evolution of the matter density contrast;

$$\dot{\delta} + \frac{1}{a}\partial_i[(1+\underline{\delta)u^i}] = 0, \qquad \text{; continuity equation}$$

$$\dot{u}^i + Hu^i + \frac{1}{a}u^j\underline{\partial_j u^i} = \underline{-\frac{1}{a}\partial^i\Phi}. \qquad \text{; Euler equation}$$

include non-linear terms!

gravitational potential

Furthermore, in general, in scalar-tensor theories, non-trivial non-linear terms would appear in the Poisson equation for gravitational potential

$$-\frac{k^2}{a^2H^2}\Phi = \kappa_\Phi\delta + \underline{\int \frac{\mathrm{d}^3\boldsymbol{k}_1\mathrm{d}^3\boldsymbol{k}_2}{(2\pi)^3}\delta^3_{\mathrm{D}}(\boldsymbol{k}_1+\boldsymbol{k}_2-\boldsymbol{k})\gamma_{2,\epsilon}(\boldsymbol{k}_1,\boldsymbol{k}_2;t)\delta(t,\boldsymbol{k}_1)\delta(t,\boldsymbol{k}_2)} + \cdots$$

e.g., second order in the perturbation

Growth in higher order ?

1709.03243

Constraining modified theory of gravity with galaxy bispectrum

Daisuke Yamauchi,[1,*] Shuichiro Yokoyama,[2,3] and Hiroyuki Tashiro[4]

Can we observe (perturbatively) second order effects ?

BY assuming the linear perturbation is a Gaussian,
second order effect should appear as non-Gaussianity!

Non-Gaussianity can be detected as higher order correlation function !

e.g., 3-point correlation function in real space ←→ bispectrum in Fourier space

Gaussianity of the linear perturbation is supported in the inflationary genesis scenario

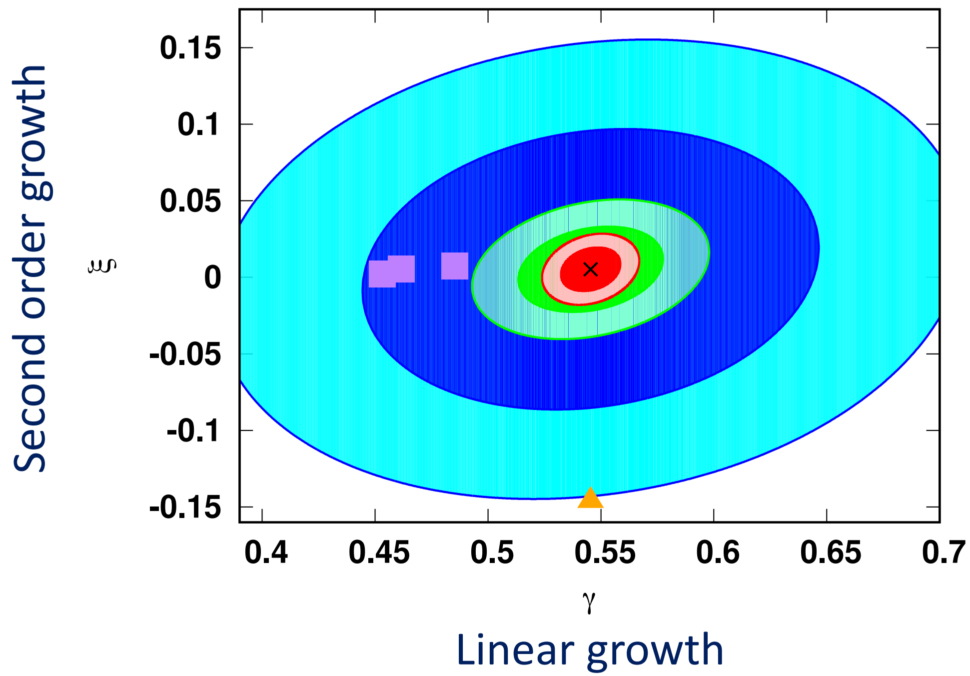
Growth in higher order ?

1709.03243

Constraining modified theory of gravity with galaxy bispectrum

Daisuke Yamauchi,[1,*] Shuichiro Yokoyama,[2,3] and Hiroyuki Tashiro[4]

expected constraint



assuming SKA1MID(blue), SKA2(red) and Euclid(green) as future galaxy surveys in 2020 – 2030?

Growth in higher order ?

1709.03243

Constraining modified theory of gravity with galaxy bispectrum

Daisuke Yamauchi,[1,*] Shuichiro Yokoyama,[2,3] and Hiroyuki Tashiro[4]

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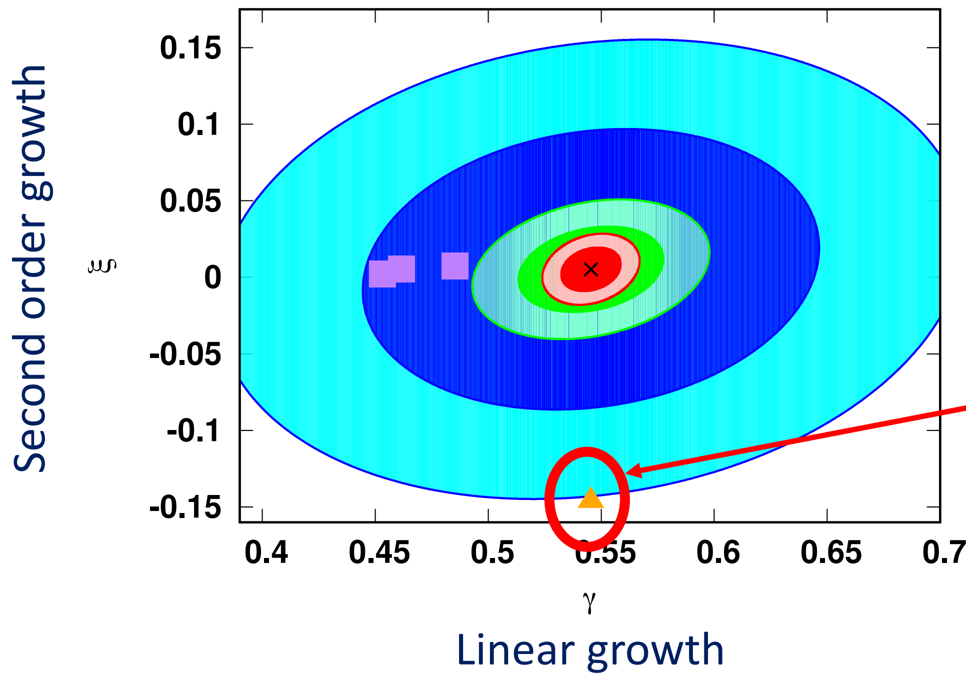


Some class of ST theories

assuming SKA1MID(blue), SKA2(red) and Euclid(green) as future galaxy surveys in 2020 – 2030?

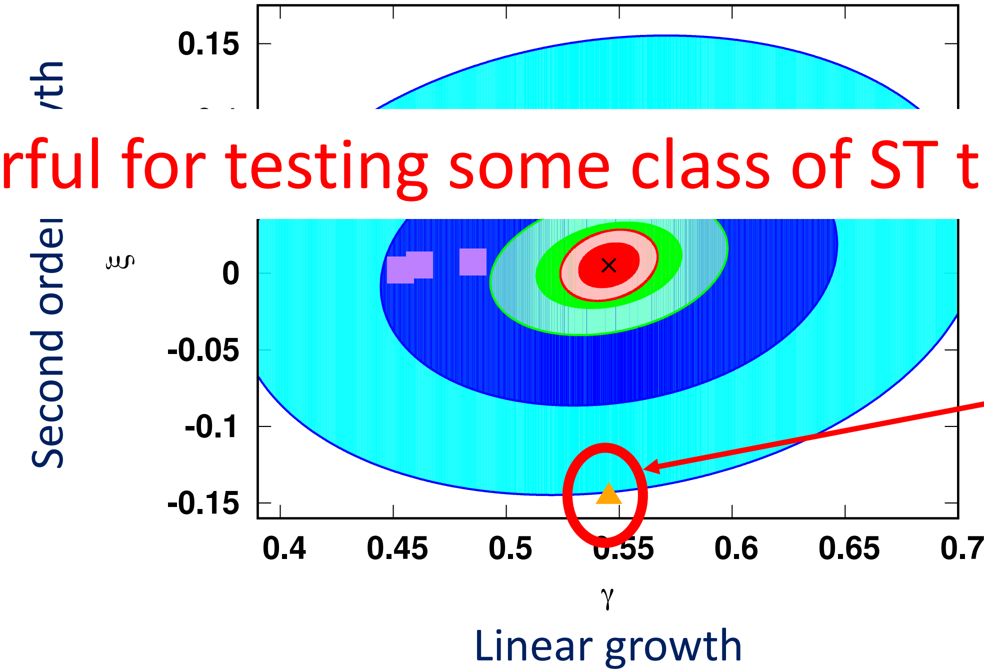
Growth in higher order ?

1709.03243

Constraining modified theory of gravity with galaxy bispectrum

Daisuke Yamauchi,[1,*] Shuichiro Yokoyama,[2,3] and Hiroyuki Tashiro[4]

expected constraint

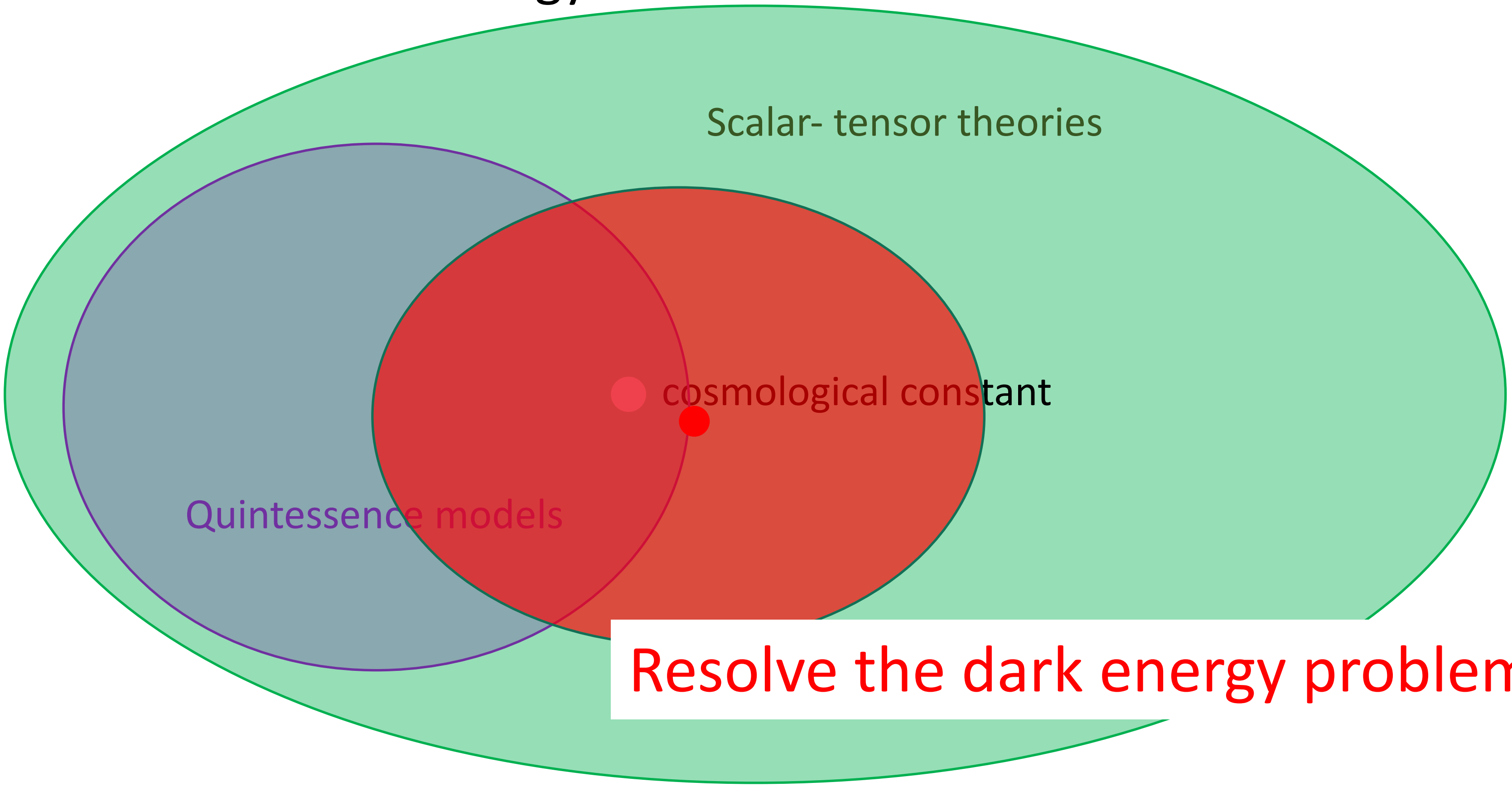


Powerful for testing some class of ST theories !!

assuming SKA1MID(blue), SKA2(red) and Euclid(green) as future galaxy surveys in 2020 – 2030?

Thus... (based on our efforts ..)

- Bunch of dark energy models ..



Resolve the dark energy problem !?

Summary

- Expansion of our Universe is now accelerating.
- There are many attempts to solve the problem;
 ``what is the source of this acceleration? - dark energy”
- Cosmological constant, quintessence, massive gravity, Scalar tensor theories, …
- In cosmological observations, measuring the expansion rate and also measuring the growth of matter density contrast should be important.
- Observational cosmology group in Nagoya gives important contributions in dark energy studies!