2019/02/19 Cosmological challenges to dark matter, dark energy, and galaxy formation
@Sao Paulo, Brazil

Cosmology and Dark Energy with future *HI* galaxy surveys

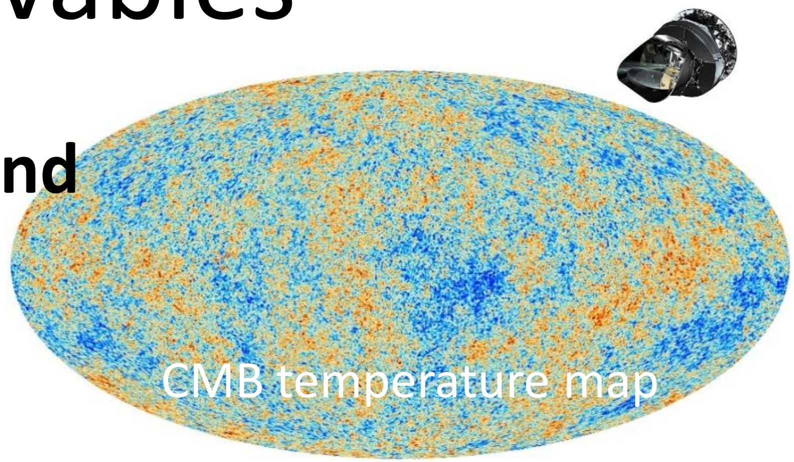
SQUARE KILOMETRE ARRAY

SKA-JP
日本百万平米電波干渉計計画協会

Daisuke Yamauchi
Kanagawa University

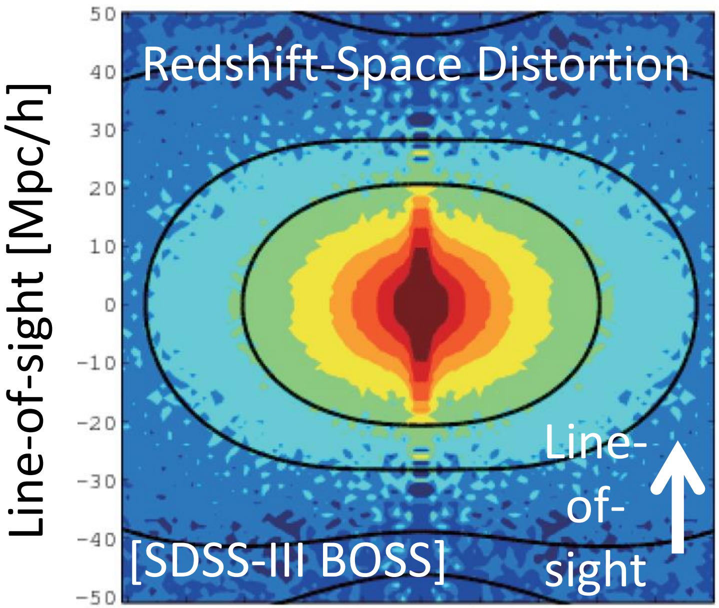
Cosmological observables

- **Cosmic Microwave Background**
  - → radio



- **Large-Scale Structure**
  - ◆ Baryon Acoustic Oscillation
  - ◆ Redshift-Space Distortion
  - ◆ Gravitational Lensing
  - → optical **+ Radio (New!)**

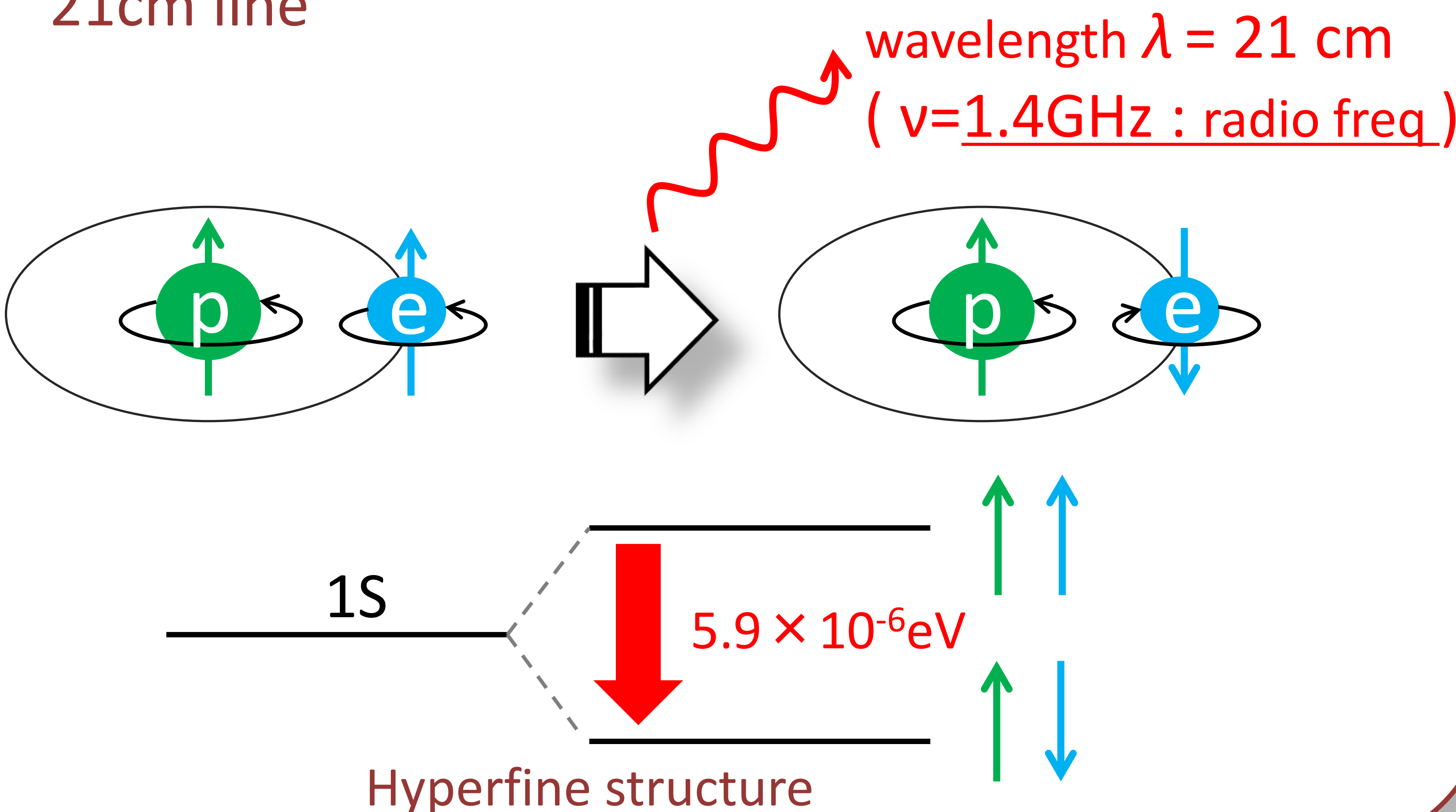
complementary



Takahashi and de Souza’s talk (yesterday)

Why “radio” frequency?

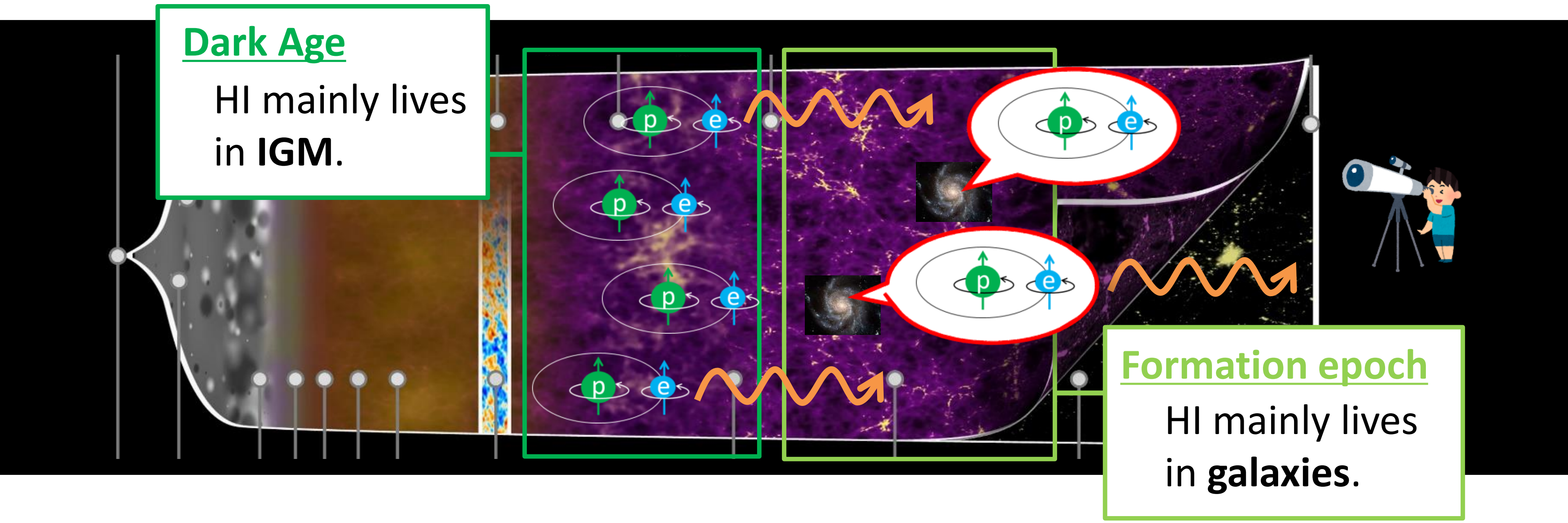
- Hyperfine transition radiation of neutral hydrogen : 21cm line



Why "radio" frequency?

21cm line observations ⇨ **Spatial distribution of IGM/galaxies in dark age/structure formation**

= Information of growth!

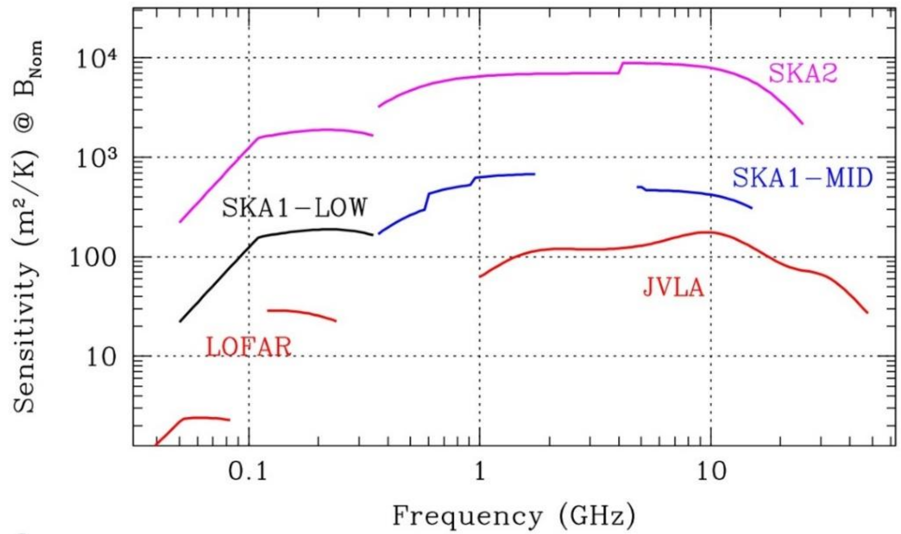


Brief Review of

Square Kilometre Array

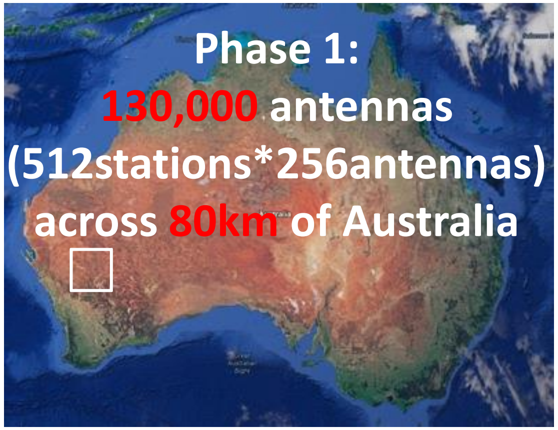
SQUARE KILOMETRE ARRAY

- Open a new window for Astronomy
  - ✓ **New frequency regime**
    50MHz -- 10^4MHz
  - ✓ **High sensitivity**
    collecting area : $1km^2$
  - ✓ **Wide sky coverage**
    available full-sky
  - ✓ **High angular resolution**



Movies from presentation by R. Brown (Science Director, SKAO)

SKA Phase 1 (2019 – 2028)

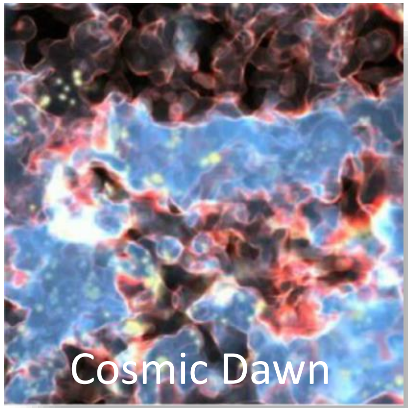


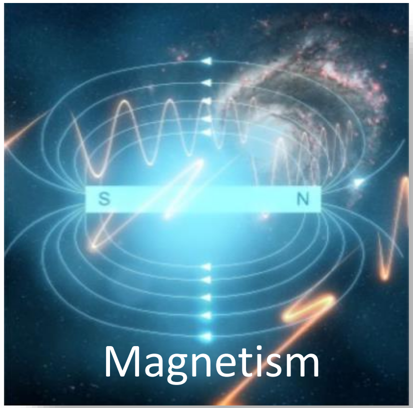
Construction will start soon!

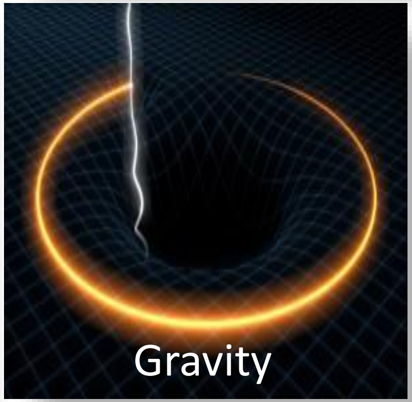
Scientific goals of SKA

The SKA aims to solve some of the biggest questions.

- Fundamental physics : **Gravity, Dark Energy**, Cosmic Magnetism
- Astrophysics : Cosmic Dawn, First galaxies, galaxy assembly and evolution, +...
- The unknowns : transients + ...

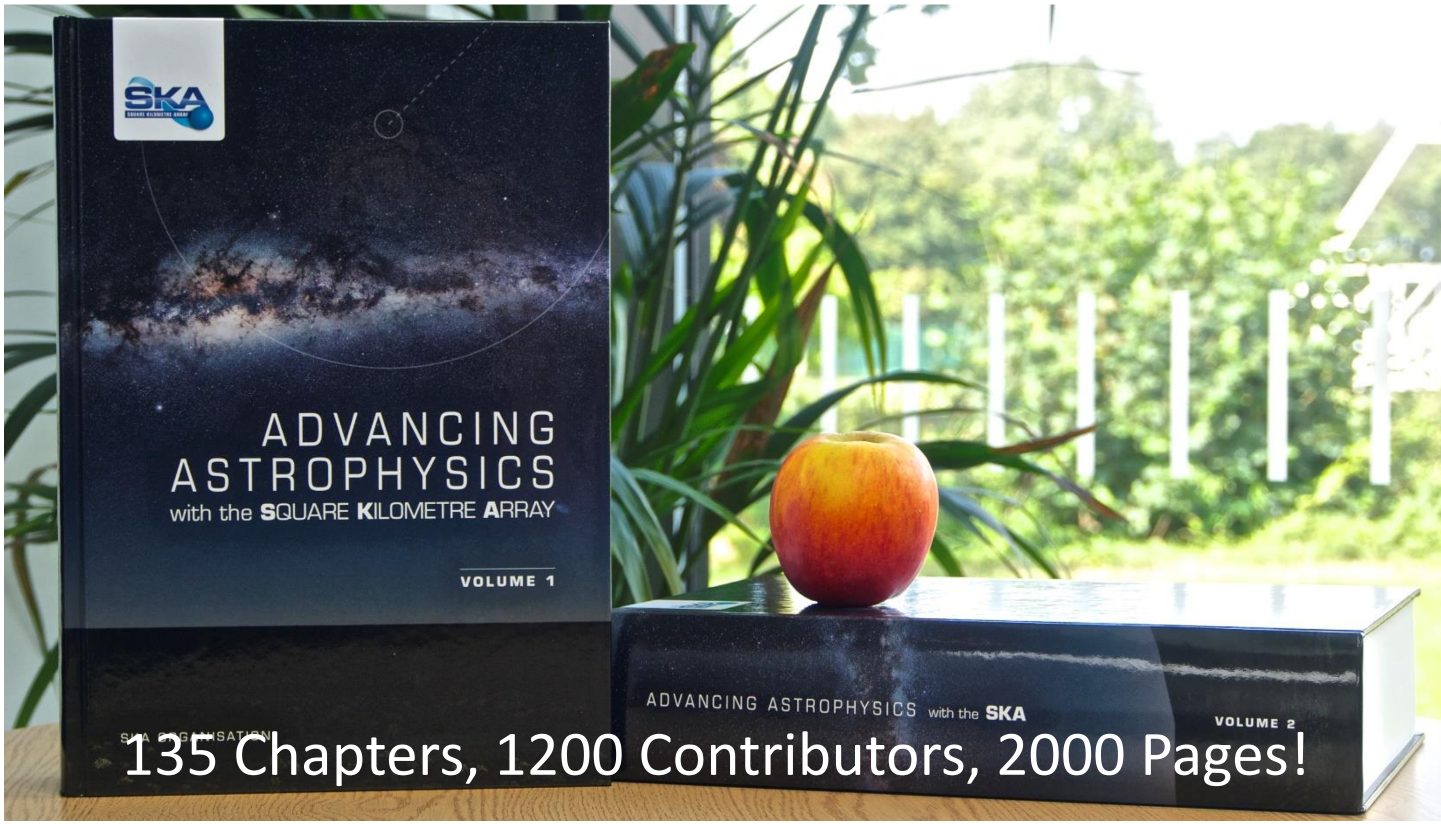






SKA Science Book/Red Book

- SKA Science Book [2015] https://www.skatelescope.org/books/



- Red Book [Bacon+**DY**+(2018)]

Cosmology with Phase 1 of the Square Kilometre Array

Red Book 2018: Technical specifications and performance forecasts

Contributions from Japanese community

- **SKA-Japan Consortium**
  - SKA-Japan SKA Science Book [2015, in Japanese(sorry!)]
  - Review (in English) [**DY**+(2016)]

Review

Cosmology with the Square Kilometre Array by SKA-Japan

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日本版
Square Kilometre Array
サイエンスブック
日本SKAコンソーシアム
科学検討班
2015

http://ska-jp.org/ws2015/SKA-JP/talks/SKAJP_Science_Book_2015.pdf


Brief review of
SKA Cosmological Surveys

➢ *HI [21-cm] line survey*

◆ The redshifting of HI-line provides the **redshift information.**

✓ HI galaxy redshift survey

- The 3D matter distributions can be reconstructed.

✓ *Mid-freq* HI intensity mapping [*after* CD/EoR]

- The detection of individual galaxies is not required.
- The integrated HI intensity of several galaxies in one pixel is measured.

de Souza's talk (yesterday)

✓ *Low-freq* HI intensity mapping [*before* CD/EoR]

- Measure the large-scale distributions of the HI inside the IGM via the brightness temperature. **Takahashi's talk (yesterday)**

➢ *Radio continuum survey*

- Measures galaxy synchrotron radiation radio emissions, which is advantageous in detecting high-z galaxies.
- Provides a featureless spectrum → **The redshift info is not available.**

Observable	Survey	SKA Phase	redshift	Sky coverage	Galaxy number
HI [21cm line]	HI galaxy survey (gal)	Phase-1	z<0.8	1/8	~ 10^7
		Phase-2	**z<2**	**3/4**	**~ 10^9**
HI [21cm line]	HI intensity mapping survey (MID-IM)	**Phase-1**	**z<3**	**3/4**	**--**
		Phase-2	z<3.7	3/4	--
HI [21cm line]	HI intensity mapping survey (LOW-IM)	Phase-1	3<z<27	1/40	--
		Phase-2	3<z<27	3/4	--
Synchrotron radiation	Continuum survey (conti)	**Phase-1**	**z<6**	**3/4**	**~ 10^8**
		Phase-2	z<6	3/4	~ 10^9
Optical	e.g. Euclid		z<2	3/8	~ 10^8

S = 70(SKA1gal), 5(SKA2gal), 1(SKA1cont), 0.1(SKA2cont) [μJy]
$\Delta\theta$ = 1(SKA1), 0.1(SKA2) [arcsec], $t_{int} = 10^4$ [hr]

Even phase-1 IM and RC surveys will cover
the extremely large survey volume
(available full sky out to very high-z)!

Obser…		SKA…		Sky …age	Galaxy number
H… [21cm…				…3	~ 10^7
				…4	**~ 10^9**
HI [21cm line]	***HI intensity mapping survey*** *(MID-IM)*	**Phase-1**	**z<3**	**3/4**	**--**
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$\Delta\theta$ = 1(SKA1), 0.1(SKA2) [arcsec], $t_{int} = 10^4$ [hr]

When the Phase-2 is constructed, the flux threshold will be drastically improved (~5μJy), providing ***the spectropic survey of 1 billion (!) HI galaxies*** can be delivered.

Observab					
HI [21cm line]	***HI galaxy survey*** *(gal)*	-1	z<0.8	1/8	~ 10^7
		Phase-2	**z<2**	**3/4**	**~ 10^9**
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A Key Science with SKA

- List of highest priority SKA1 science

Science Goal	SWG	Objective	SWG Rank
1	*CD/EoR*	Physics of the early universe IGM - I. Imaging	1/3
2	*CD/EoR*	Physics of the early universe IGM - II. Power spectrum	2/3
4	*Pulsars*	Reveal pulsar population and MSPs for gravity tests and Gravitational Wave detection	1/3
5	*Pulsars*	High precision timing for testing gravity and GW detection	1/3
13	*HI*	Resolved HI kinematics and morphology of ~10^10 M_sol mass galaxies out to z~0.8	1/5
14	*HI*	High spatial resolution studies of the ISM in the nearby Universe.	2/5
15	*HI*	Multi-resolution mapping studies of the ISM in our Galaxy	3/5
18	*Transients*	Solve missing baryon problem at z~2 and determine the Dark Energy Equation of State	=1/4
22	*Cradle of Life*	Map dust grain growth in the terrestrial planet forming zones at a distance of 100 pc	1/5
27	*Magnetism*	The resolved all-Sky characterisation of the interstellar and intergalactic magnetic fields	1/5
32	*Cosmology*	Constraints on primordial non-Gaussianity and tests of gravity on super-horizon scales.	1/5
33	*Cosmology*	Angular correlation functions to probe non-Gaussianity and the matter dipole	2/5
37 + 38	*Continuum*	Star formation history of the Universe (SFHU) – I+II. Non-thermal & Thermal processes	1+2/8

"Constraints on primordial non-Gaussianity and tests of gravity on super-horizon scales"

Cosmology and Dark Energy with HI galaxy surveys

How do we characterize **Dark Energy**?

◆ **Expansion history**

Equation-of-state

$$\frac{H^2(a)}{H_0^2} = \frac{\Omega_\mathrm{m}}{a^3} + \frac{\Omega_\mathrm{r}}{a^4} + \frac{\Omega_\mathrm{K}}{a^2} + \Omega_\mathrm{DE} e^{-3\int_1^a (1+w_\mathrm{DE}(a'))\mathrm{d}\ln a'}$$

◆ **Growth of large-scale structure** : δ=δρ/ρ

$$\delta(a,\boldsymbol{k}) = \delta_\mathrm{L}(a,\boldsymbol{k}) + \left[F_2(\boldsymbol{k}_1,\boldsymbol{k}_2;a)\,\delta_\mathrm{L}(a,\boldsymbol{k}_1)\star\delta_\mathrm{L}(a,\boldsymbol{k}_2)\right]_{\boldsymbol{k}} + \cdots$$

Growth index

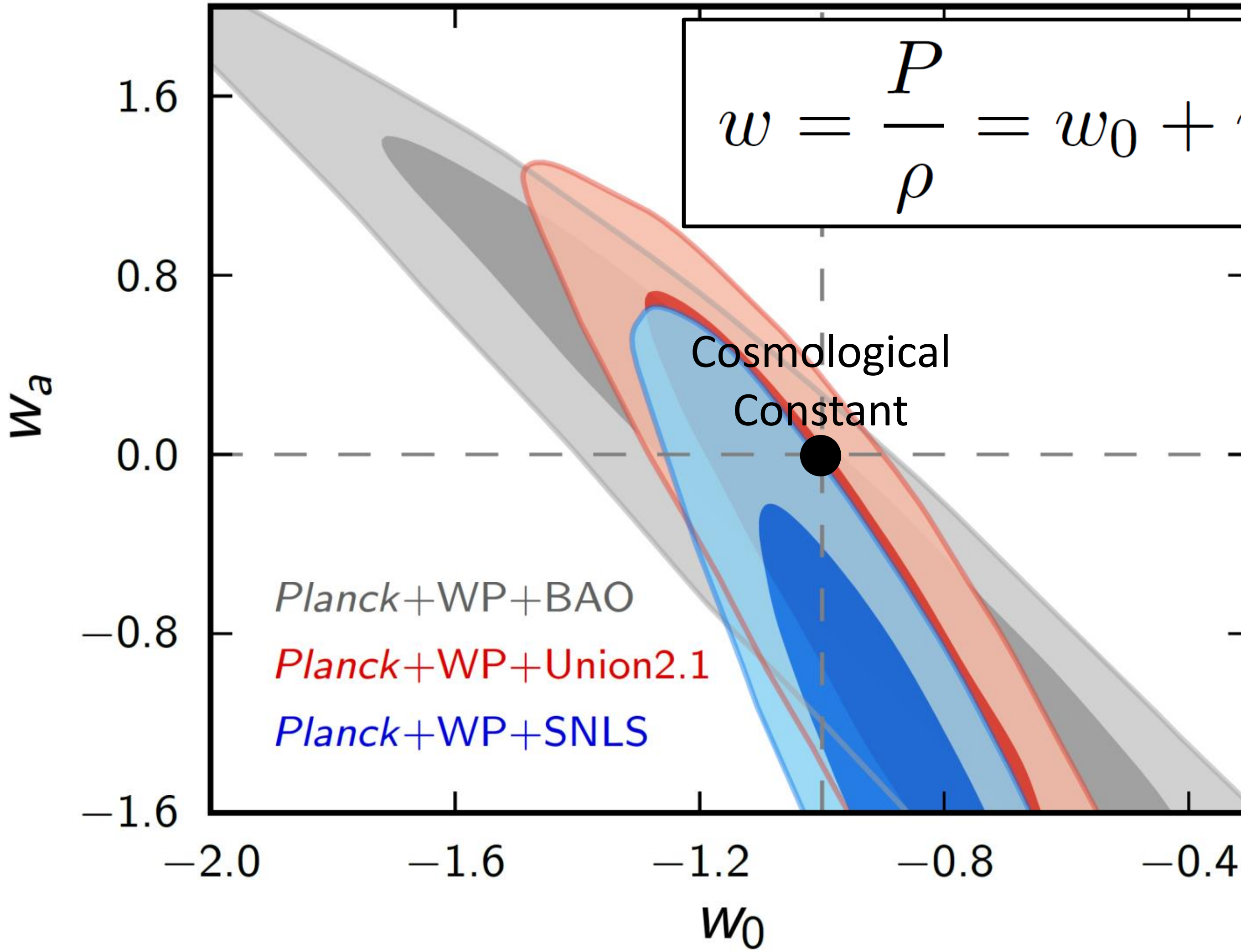
$$\frac{\mathrm{d}\ln\delta_\mathrm{L}}{\mathrm{d}\ln a} = \Omega_\mathrm{m}(a)^\gamma$$

[Planck XIV(2013)]

Dark Energy **Equation-of-State**

Yamaguchi's talk

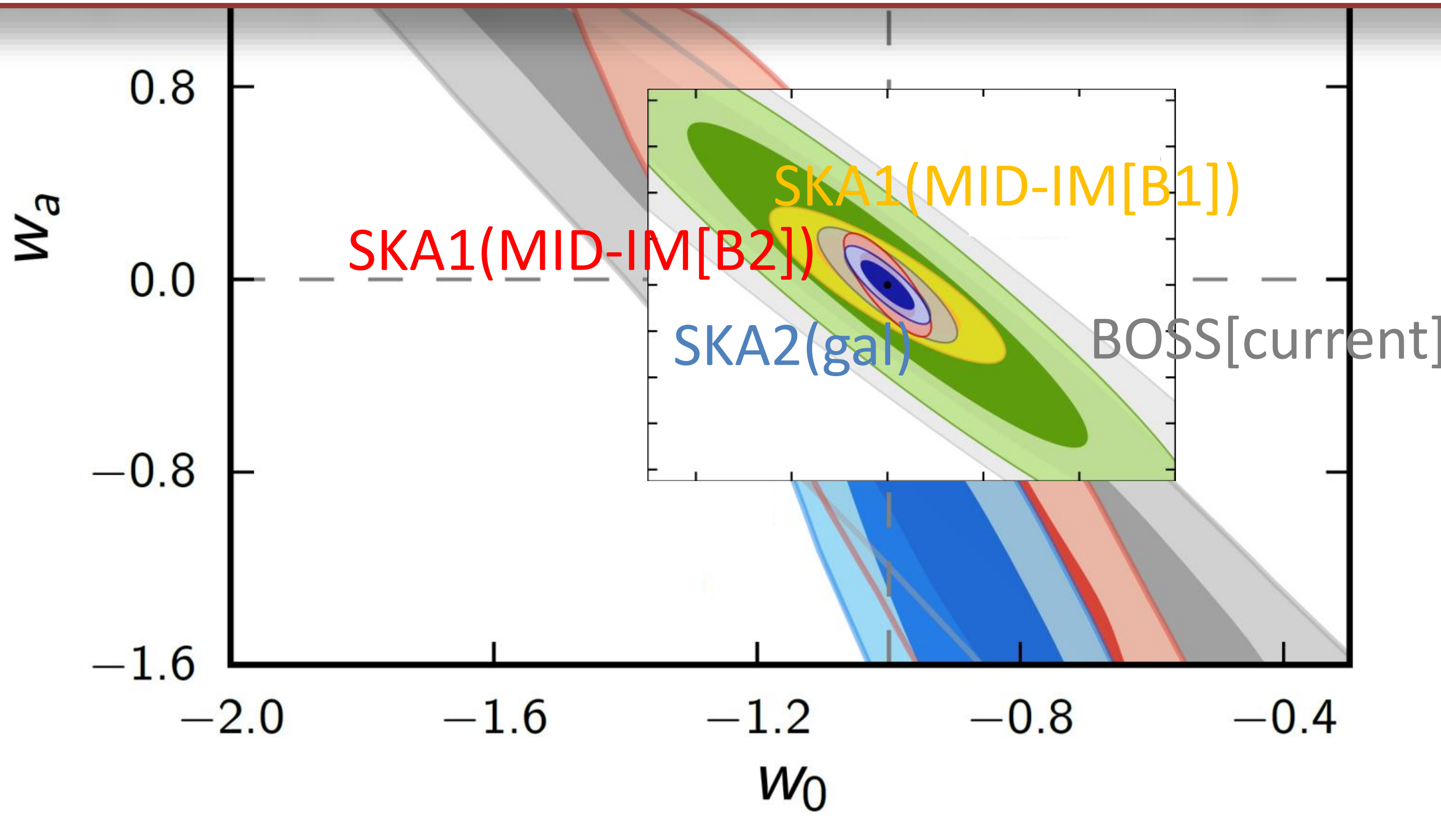
$$w = \frac{P}{\rho} = w_0 + w_a \frac{z}{1+z}$$



[Planck XIV(2013), SKA Science Book(BAO) (2015), Bull (2016)]

Dark Energy **Equation-of-State**

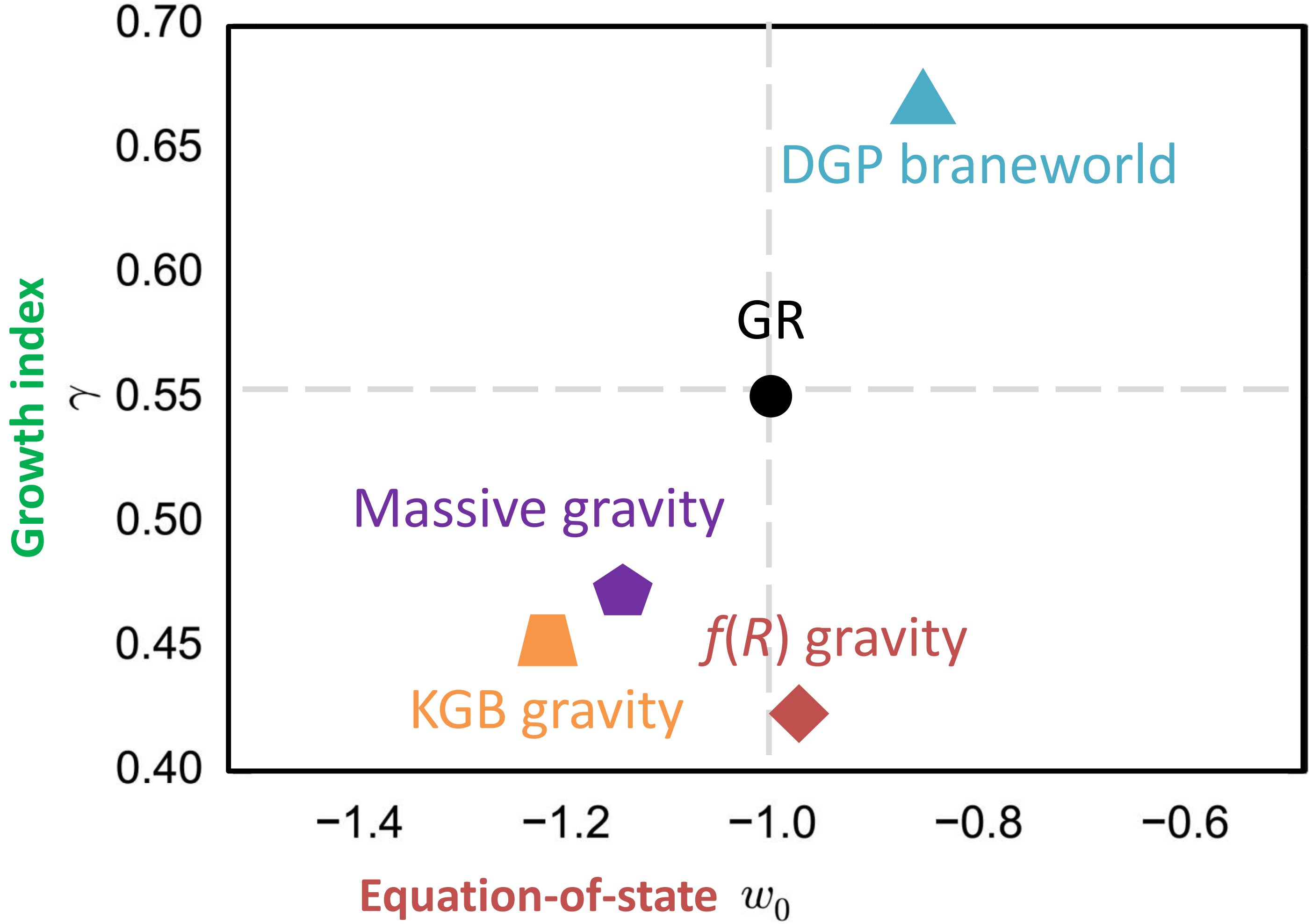
The SKA1 MID-IM survey will be able to provide comparable constraints with e.g. Euclid, and the SKA2 HI galaxy survey is expected to allow further improvements.



[Bull(2016), SKA Science Book(RSD) (2015)]

Growth index and Dark Energy

- can trace the (linear) growth history.
- can distinguish and hopefully exclude the dark energy models.



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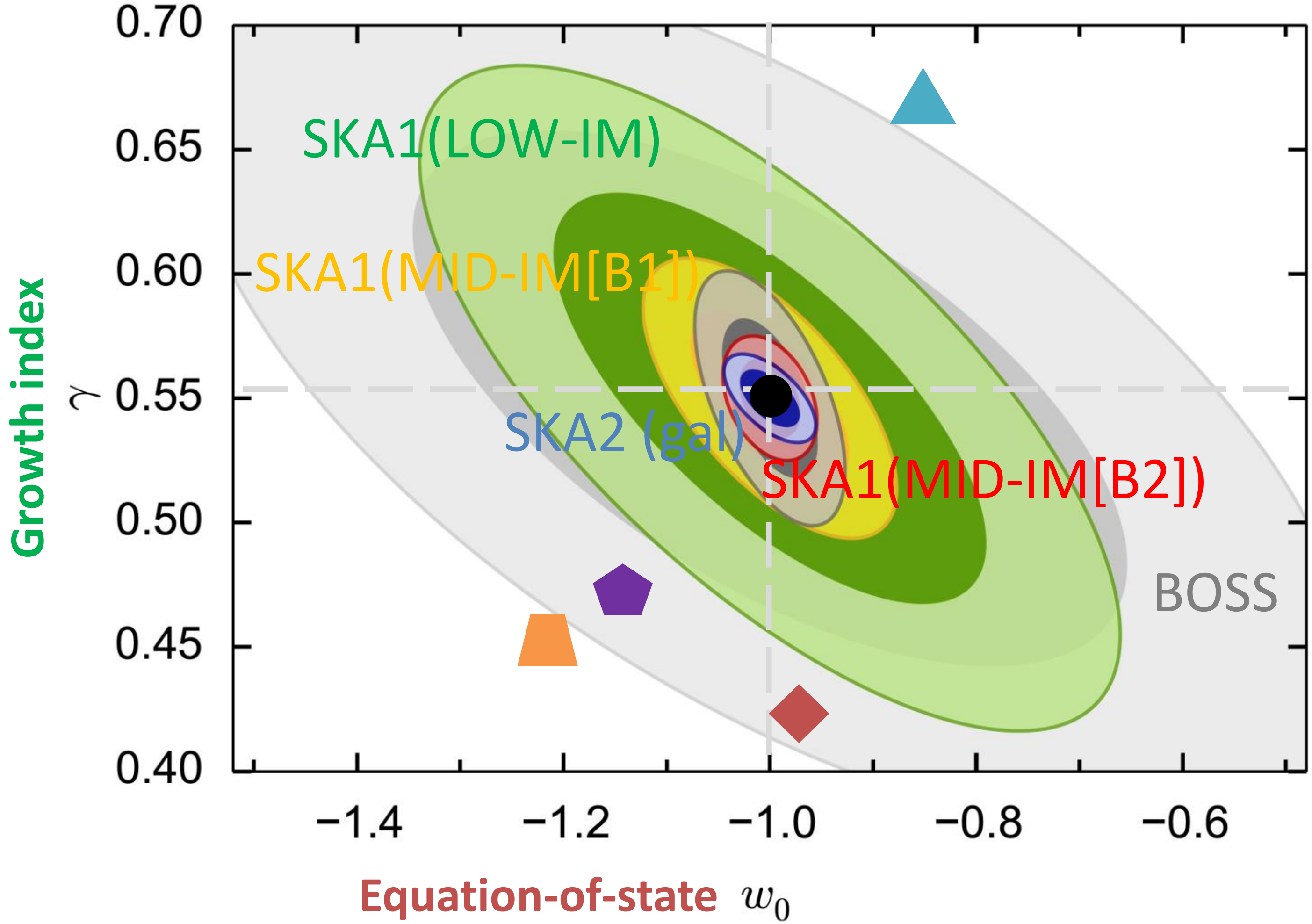
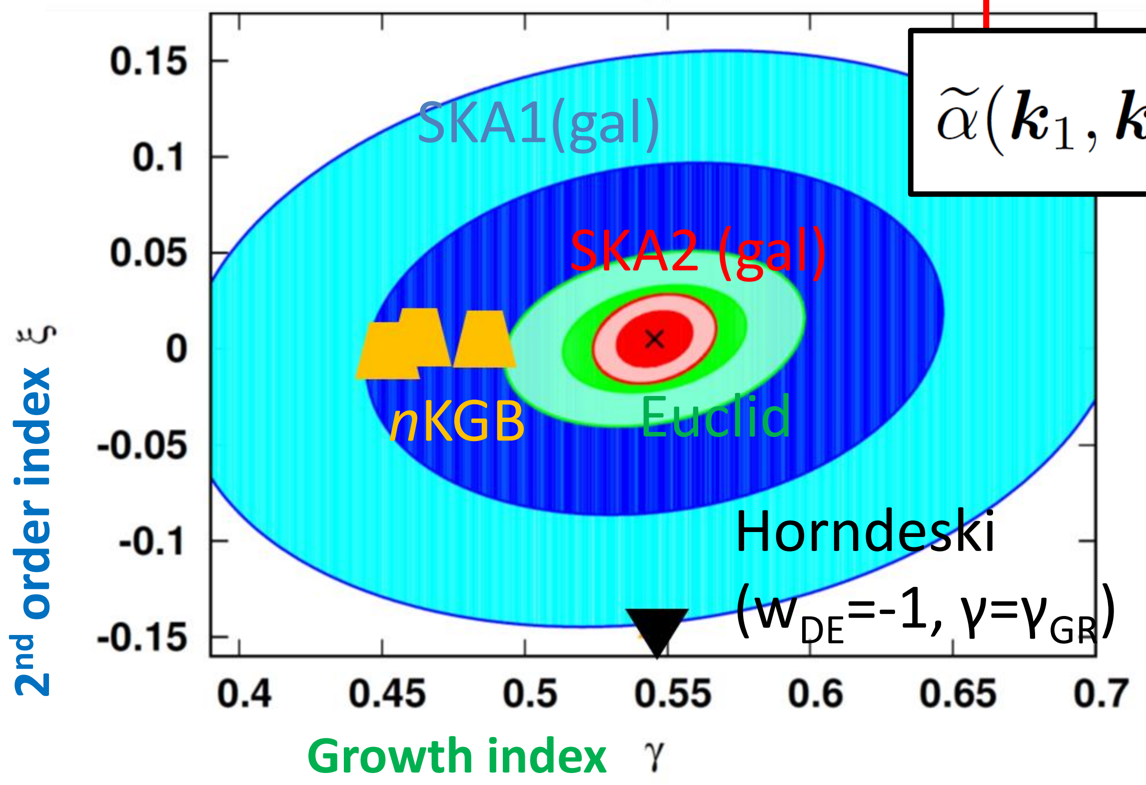


*Quasi-non*linear Growth and Dark Energy

- Even if w_{DE}=-1 and $\gamma=\gamma_{GR}$, it is **NOT** necessary that our Universe is described by ΛCDM with GR.
- Non-Gaussianity should be generated from nonlinear growth.

$$\delta(a,\boldsymbol{k}) = \delta_{\rm L}(a,\boldsymbol{k}) + \left[F_2(\boldsymbol{k}_1,\boldsymbol{k}_2;a)\,\delta_{\rm L}(a,\boldsymbol{k}_1)\star\delta_{\rm L}(a,\boldsymbol{k}_2)\right]_{\boldsymbol{k}} + \cdots$$

$$\widetilde{\alpha}(\boldsymbol{k}_1,\boldsymbol{k}_2) + \Omega_{\rm m}(a)^{\xi}\,\widetilde{\gamma}(\boldsymbol{k}_1,\boldsymbol{k}_2)$$



2nd order index

can carry new info that is not included in the linear-order!

Dark Energy and Scalar-Tensor Theories

- Scalar-Tensor Theories have been widely studied as an alternative to the dark energy.
- GW170817+GRB 170817A gave the stringent constraint on the speed of GW : $|c_{GW}/c_{EM}-1|<10^{-15}$, which rules out theories which predict a variable GW speed. **Yamaguchi's talk**

The most general framework that has been developed so far

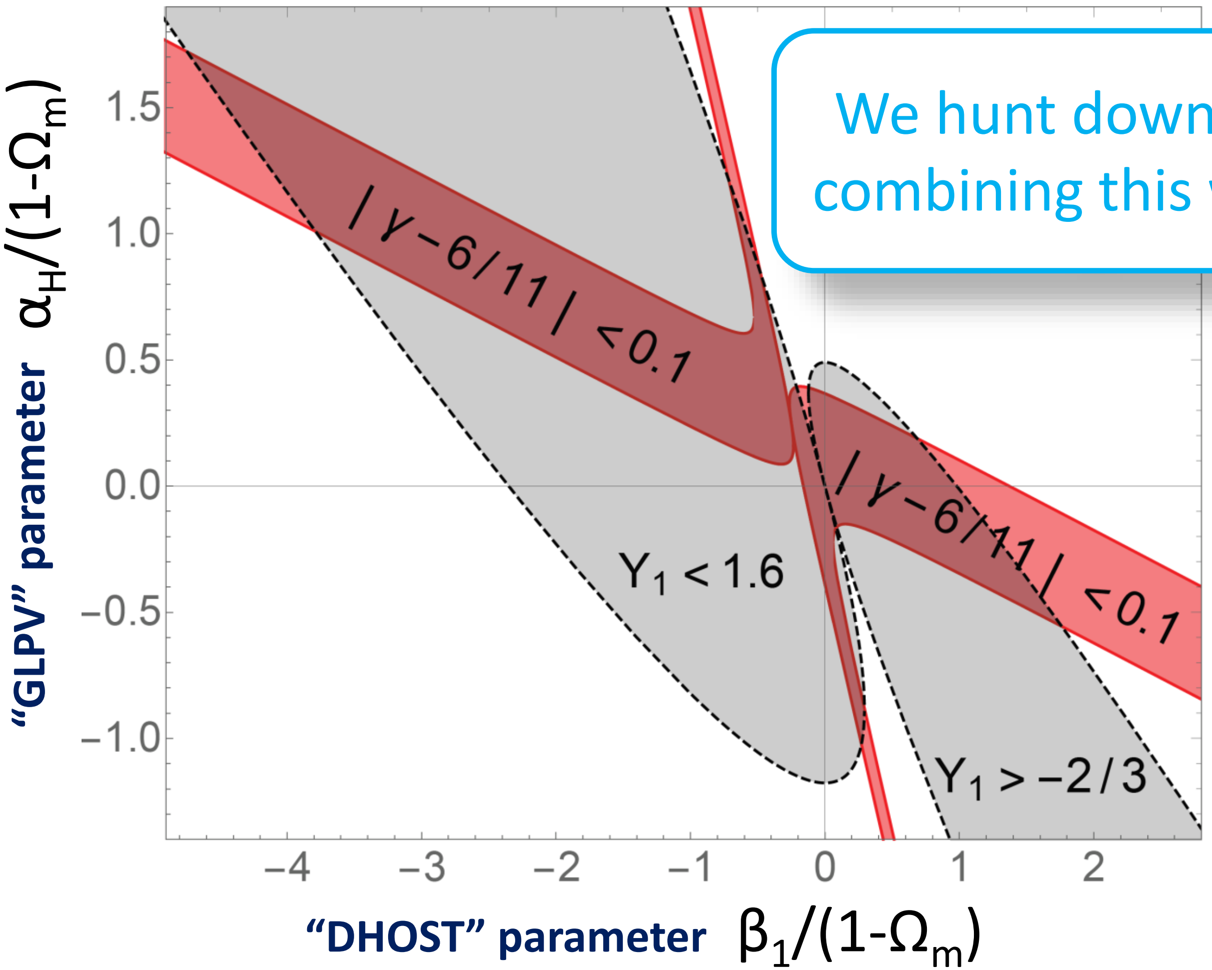
$$\mathcal{L} = F(\phi, X) R + A_3(\phi, X) \Box\phi \nabla^\mu \phi \nabla^\nu \phi \nabla_\mu \nabla_\nu \phi + \frac{1}{8F}\left[48F_X^2 - 8(F - XF_X)A_3 - X^2 A_3^2\right] \nabla^\mu \phi \nabla_\mu \nabla_\rho \phi \nabla^\rho \nabla^\nu \phi \nabla_\nu \phi + \frac{1}{2F}(4F_X + XA_3) A_3 (\nabla^\mu \phi \nabla_\mu \nabla_\nu \phi \nabla^\nu \phi)^2$$

[Langlois+Saito+**DY**+Noui (2018)]

[Hirano+Kobayashi+**DY**+Yokoyama (2019)]

Growth index and Scalar-Tensor Theories

- The precise measurement of growth of structure can provide the severe constraint on the wide class of modified gravity.



We hunt down modified gravity by combining this with local constraint!

$$\alpha_{\rm H} = -\frac{2XF_X}{F}$$

$$\beta_1 = \frac{X(F_X + XA_3)}{F}$$

[Gray(stellar structure): Kobayashi+**DY**+(2015), Saito+**DY**+(2015), Sakstein+(2015)]

[Hirano+Kobayashi+**DY**+Yokoyama (2019)]

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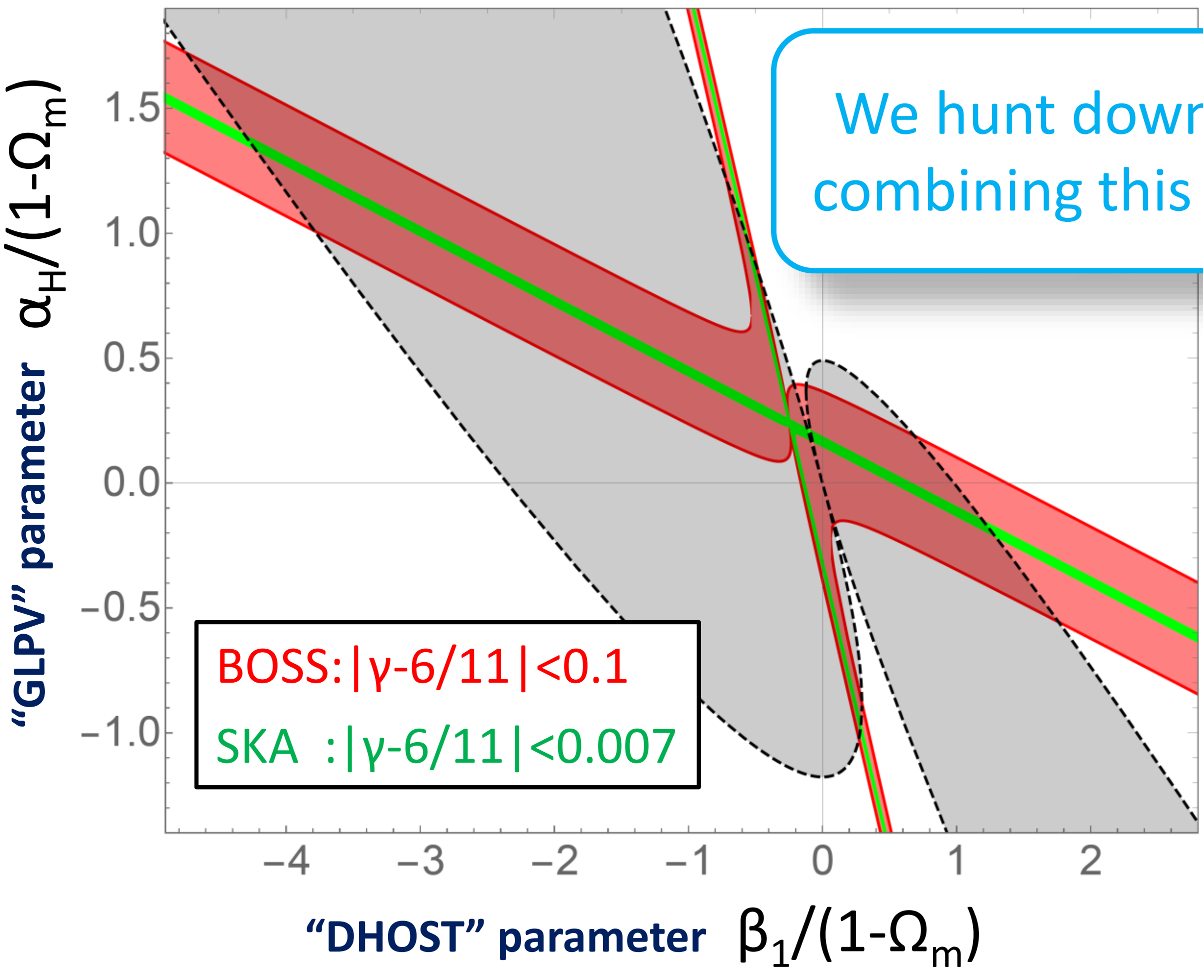

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[Gray(stellar structure):
Kobayashi+**DY**+(2015),
Saito+**DY**+(2015),
Sakstein+(2015)]

[Kimura+Suyama+Yamaguchi+**DY**+Yokoyama(2017)]

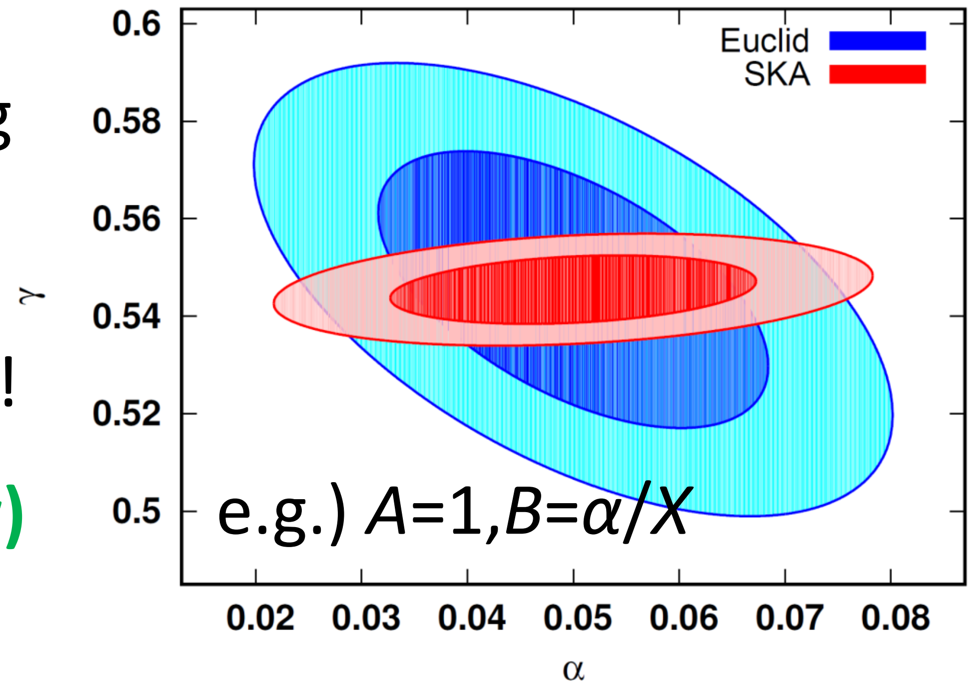
RSD and coupling between DE and DM

- In the presence of a coupling between DE and DM through the conformal-disformal metric:

$$\bar{g}_{\mu\nu} = A(\phi, X) g_{\mu\nu} + B(\phi, X) \partial_\mu \phi \partial_\nu \phi$$

The information of coupling is encoded in the peculiar velocity field
= Redshift-Space Distortion!

Chibana's talk (tomorrow)



Summary

- **The SKA will provide new information of DE and hopefully single out the true model of DE.**
- **Other topics :Various Synergies**
  - ☐ With CMB observations : Delensing

    [Namikawa+**DY**+Sherwin+Nagata (2015)]
  - ☐ With optical galaxy survey : Multitracer

    [**DY**+ (2014), **DY**+K.Takahashi(2015), DY+Yokoyama+K.Takahashi(2016)]
  - ☐ With particle physics : Lepton asymmetry, ν,…

    [Kohri+Oyama+Sekiguchi+T.Takahashi (2014),…]

Thank you!