2019/05/29 East Asia SKA Science Workshop @Shanghai Astronomical Observatory

Cosmology and Dark Energy with future HI galaxy surveys

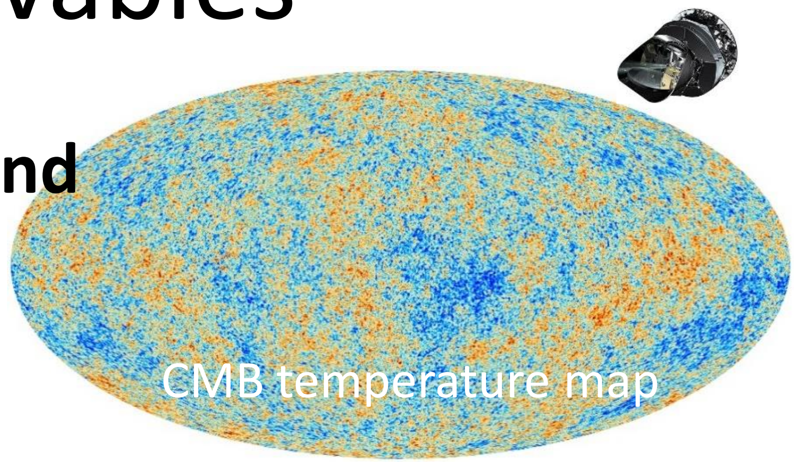
SKA
SQUARE KILOMETRE ARRAY

SKA-JP
日本百万平米電波干渉計計画協会

Daisuke Yamauchi

Kanagawa University

Cosmological observables



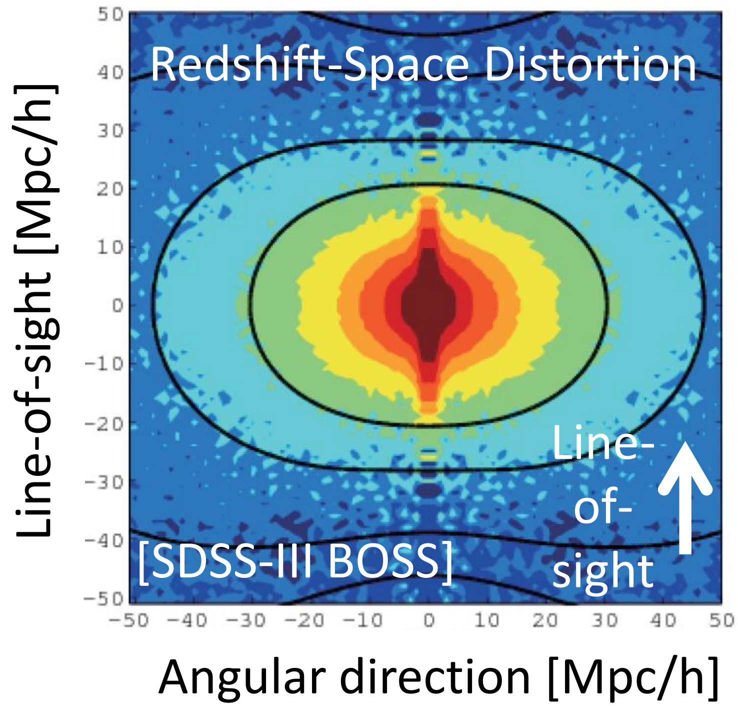
- **Cosmic Microwave Background**

  → radio

- **Large-Scale Structure**
  - Baryon Acoustic Oscillation
  - Redshift-Space Distortion
  - Gravitational Lensing

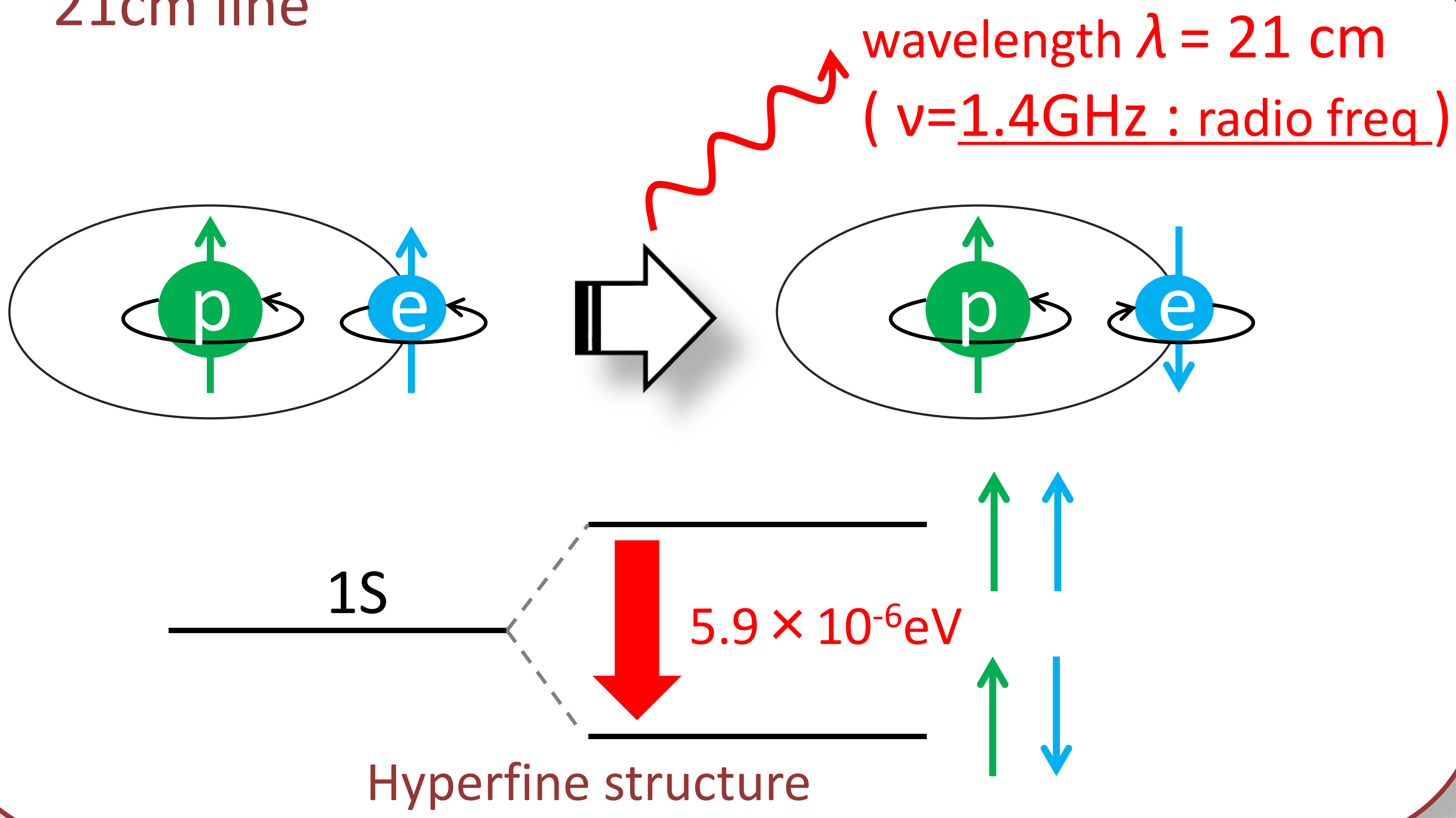
  → optical **+ Radio (New!)**

  complementary



Why "radio" frequency?

◆Hyperfine transition radiation of neutral hydrogen : 21cm line



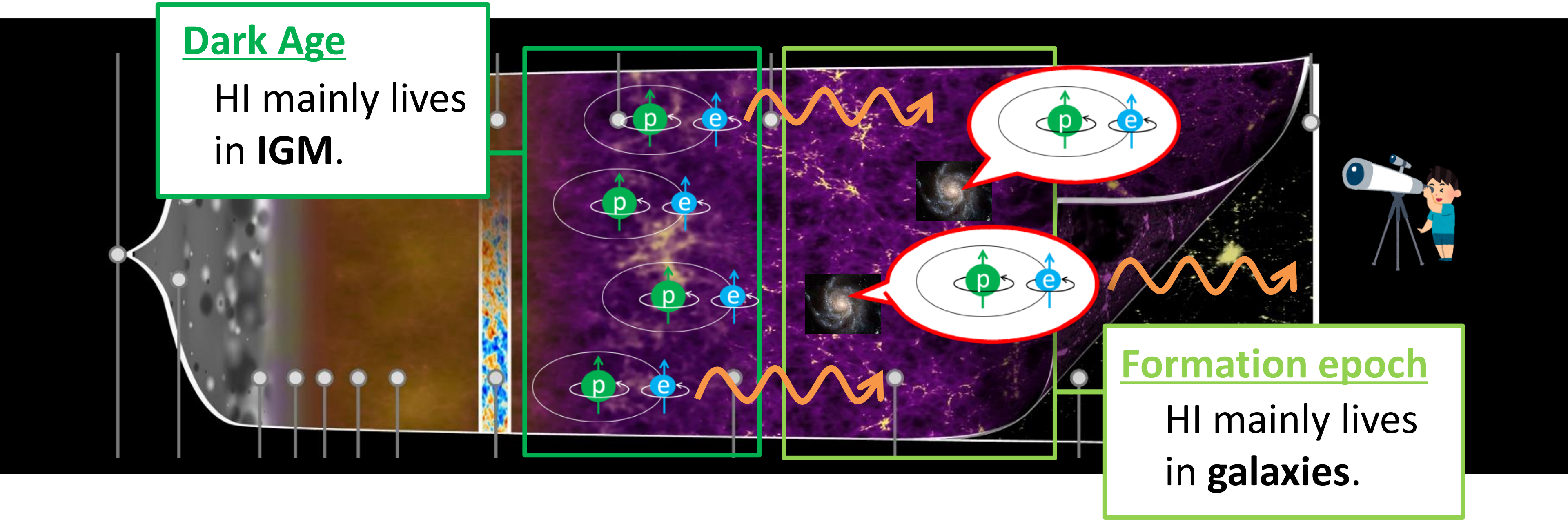
Why "radio" frequency?

21cm line observation

⇨

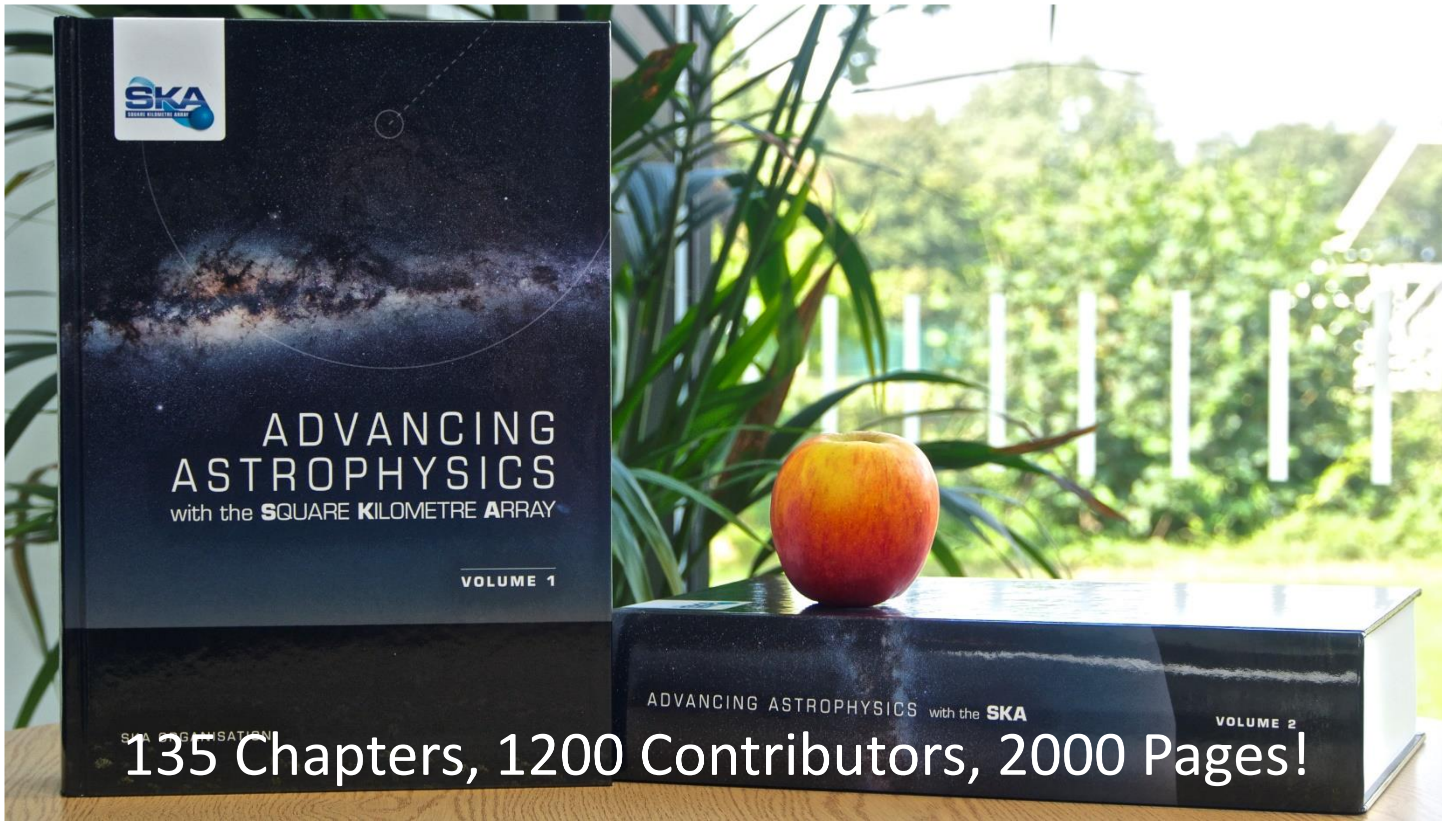
traces spatial distribution of IGM/galaxies in dark age/structure formation

= Information of growth!



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-JP
日本百万平米電波干渉計画協会

➢ 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

Daisuke Yamauchi,[1,*,†] Kiyotomo Ichiki,[2,3] Kazunori Kohri,[4,5] Toshiya Namikawa,[6,7] Yoshihiko Oyama,[8] Toyokazu Sekiguchi,[9] Hayato Shimabukuro,[2,10] Keitaro Takahashi,[10] Tomo Takahashi,[11] Shuichiro Yokoyama,[12] and Kohji Yoshikawa[13]

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

SKA-Japan

SKA-Japan Cosmology SWG

D. Yamauchi (Kanagawa, Chair)
R. Ando (Nagoya) → today's talk!
K. Ichiki（Nagoya）
K. Kohri (KEK, Sokendai)
T. Minoda (Nagoya)
A. Nishizawa (Nagoya)
S. Saga (Kyoto)
T. Sekiguchi (Tokyo)
H. Shimabukuro (Tsinghua) → today's talk!
K. Takahashi (Kumamoto) → tomorrow's talk!
T. Takahashi (Saga)
S. Tanaka (Kumamoto) → today's talk!
S. Yokoyama (Nagoya)
K. Yoshikawa (Tsukuba)
S. Yoshiura (Melbourne)

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.
- Measure the peculiar velocity field → info on how structure grows.

✓ *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.

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

- Measure the large-scale distributions of the HI inside the IGM via the brightness temperature.

➢ *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	$\sim 10^7$
		Phase-2	$z<2$	**3/4**	$\sim 10^9$
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**	$\sim 10^8$
		Phase-2	$z<6$	3/4	$\sim 10^9$
Optical	**e.g. *Euclid***		$z<2$	3/8	$\sim 10^8$

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**	**--**
		Phase-2	z<3.7	3/4	--
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Optical	**e.g. *Euclid***		z<2	3/8	~ 10^8

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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**
HI [21cm line]	***HI intensity mapping survey** (MID-IM)*	**Phase-1**	**z<3**	**3/4**	**--**
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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"

= *"Inflation & Dark Energy"*

Cosmology and Dark Energy with HI galaxy surveys

How do we characterize **Dark Energy**?

◆ **Expansion history**

Equation-of-state

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

◆ **Fluctuation of galaxy number count**: δ=δn/n

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

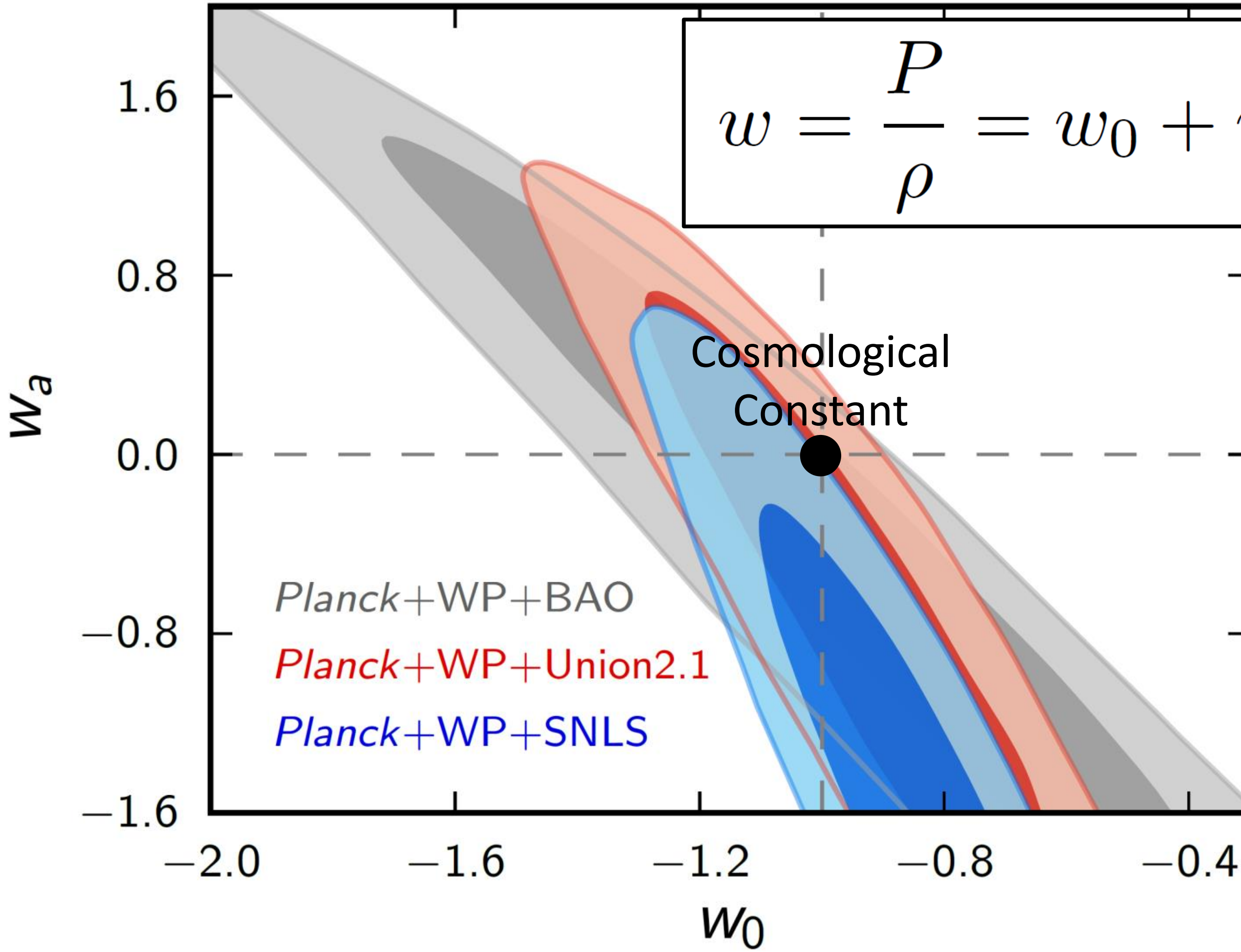
Growth index

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

[Planck XIV(2013)]

Dark Energy **Equation-of-State**

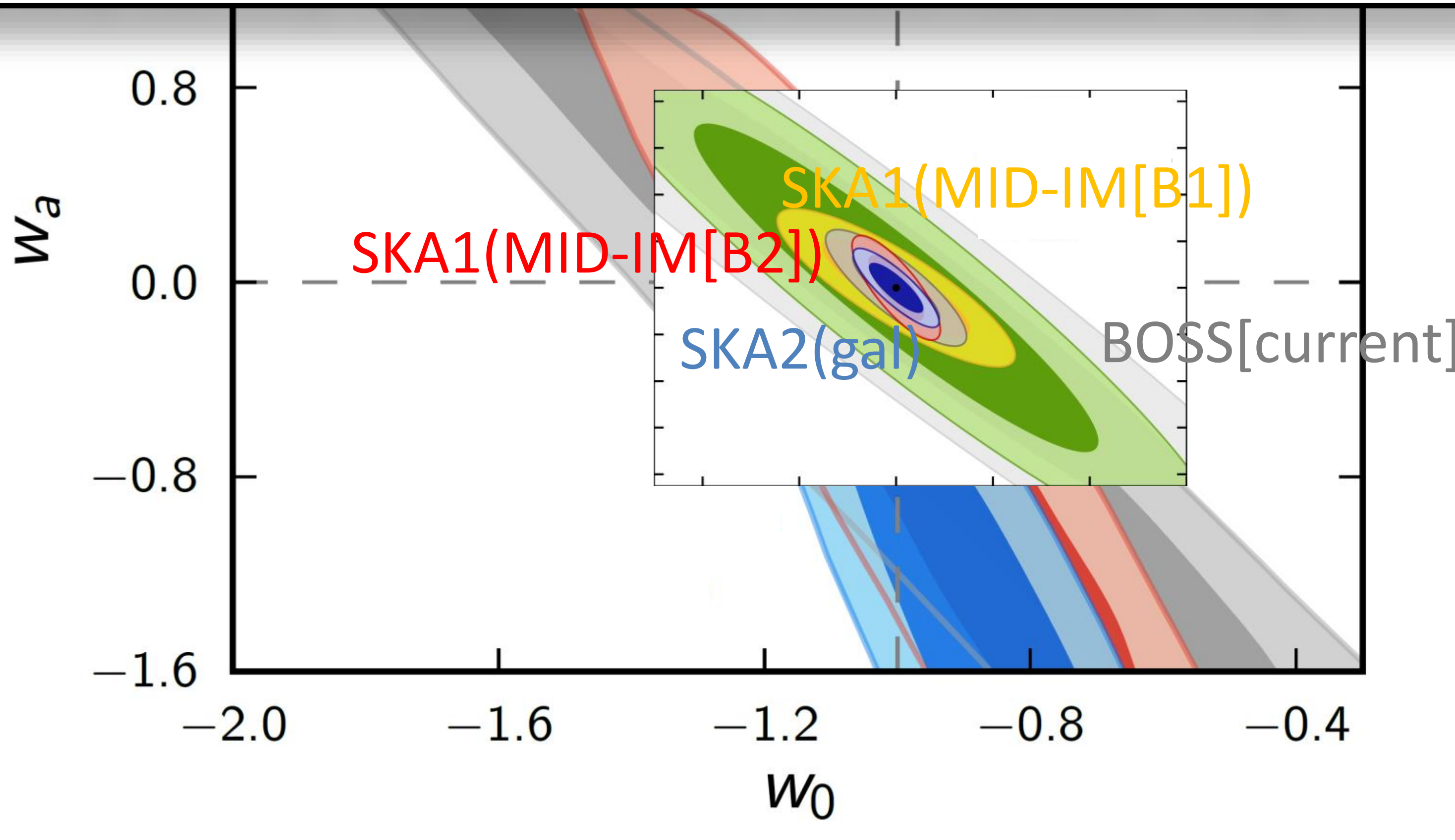
$$w = \frac{P}{\rho} = w_0 + w_a \frac{z}{1+z}$$



[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.



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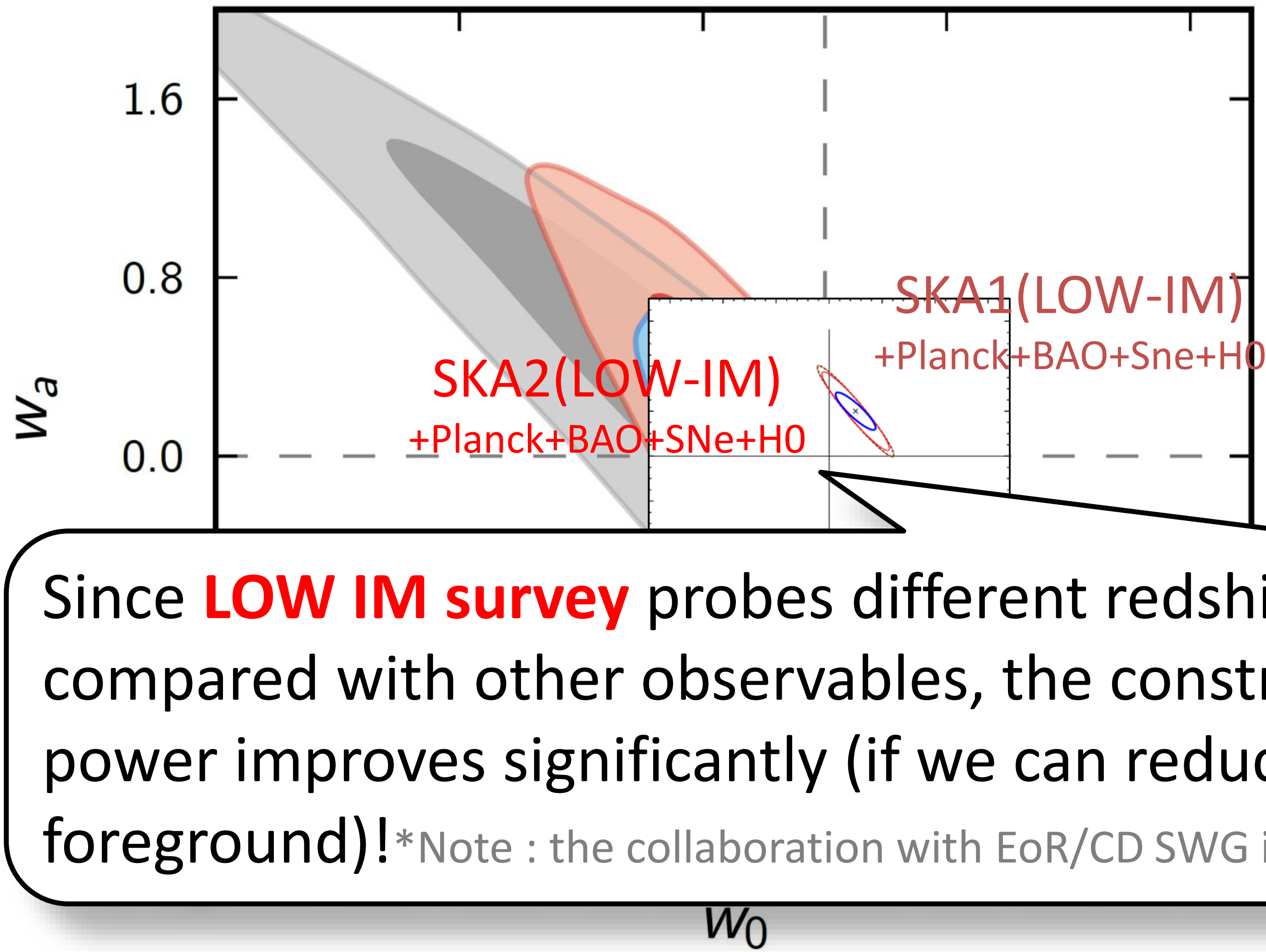
[Planck XIV(2013), **Kohri+Oyama+Sekiguchi+T.Takahashi**(2016)]

Dark Energy Equation-of-State



Since **LOW IM survey** probes different redshift epoch compared with other observables, the constraining power improves significantly (if we can reduce the foreground)! *Note : the collaboration with EoR/CD SWG is essential!]

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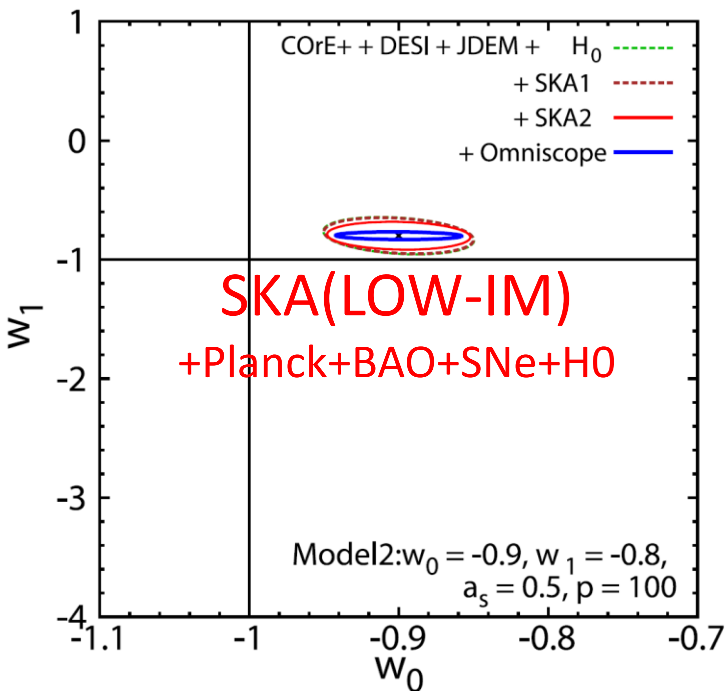
[Kohri+Oyama+Sekiguchi+T.Takahashi(2016)]

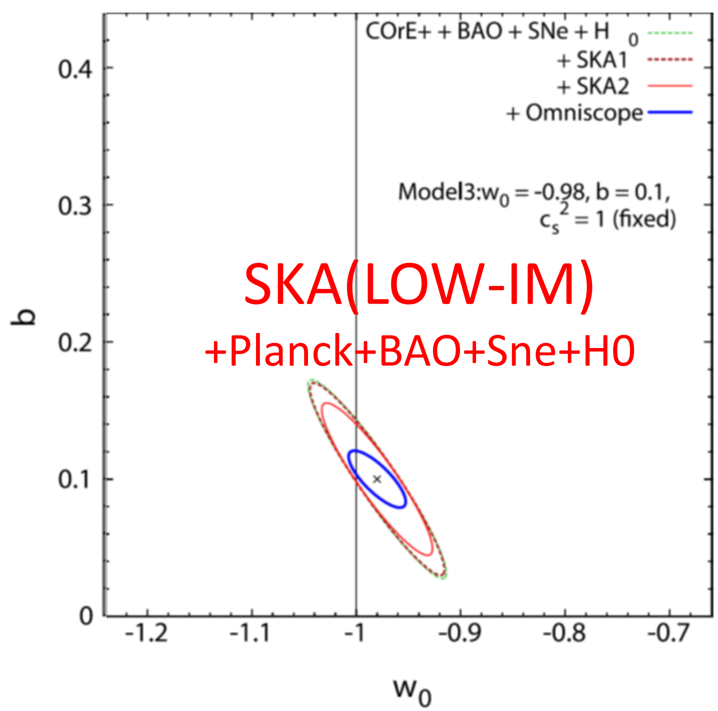
DE **EoS z-dependence** from LOW-IM

- The z-dependence of EoS is highly model-dependent.
- SKA constrains the model in which the EoS changes at high-z.

$$w = w_0 w_1 \frac{1 + \left(\frac{a_s}{a}\right)^p}{w_1 + w_0 \left(\frac{a_s}{a}\right)^p}$$

$$w = \frac{w_0}{[1 + b\log(1+z)]^2}$$

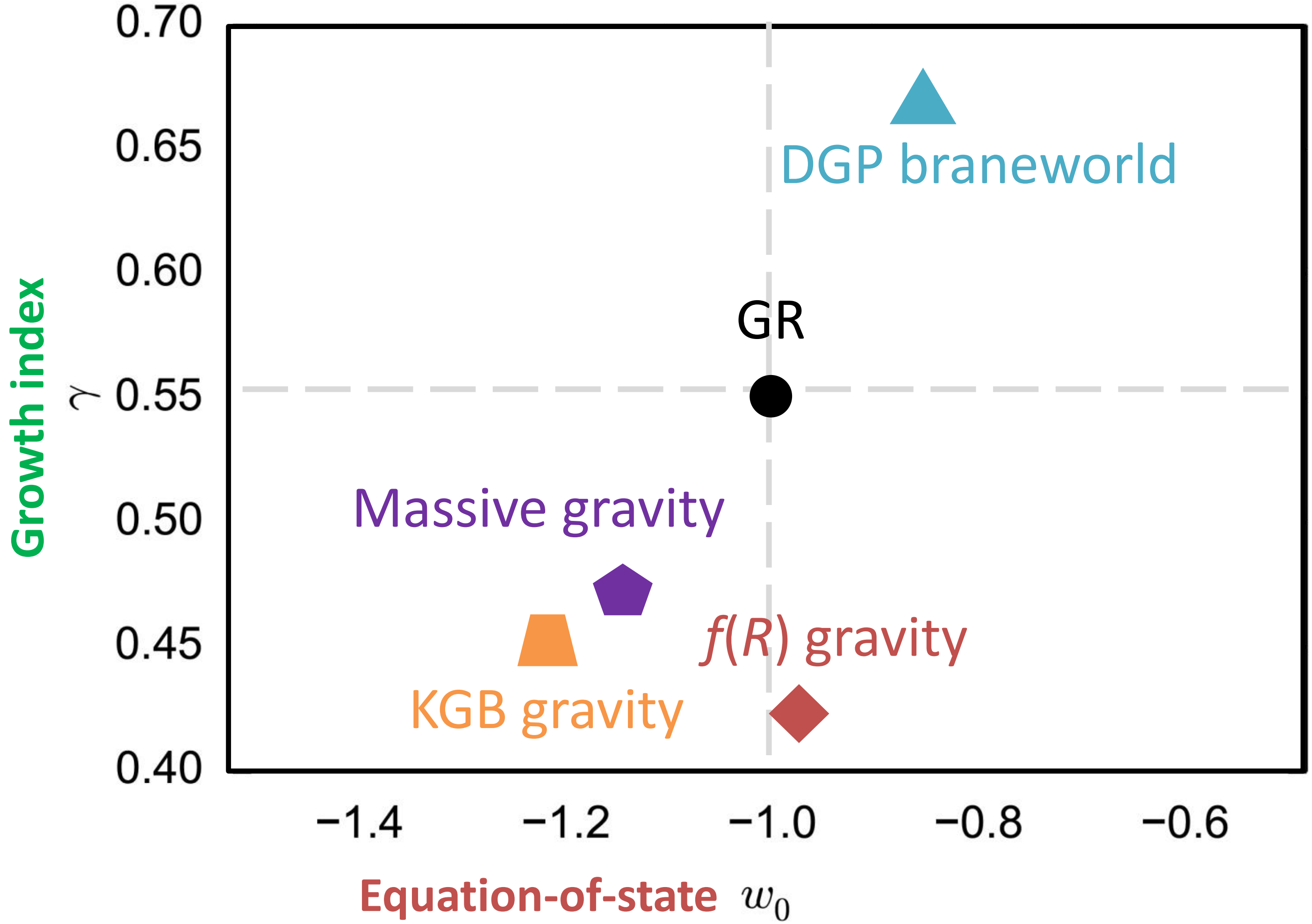




[Bull(2016), SKA Science Book(RSD) (2015)]

Growth index and Dark Energy

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



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

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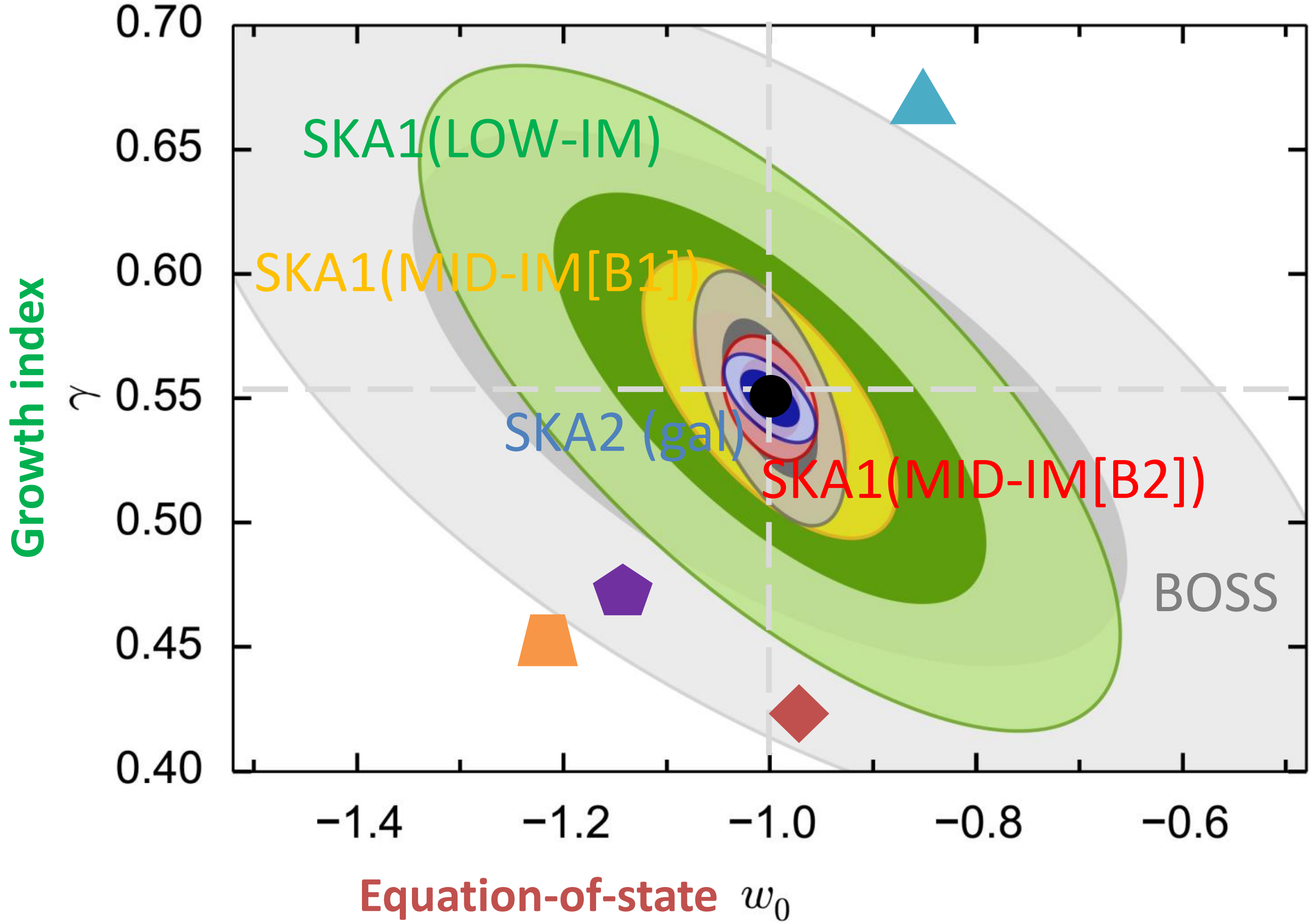

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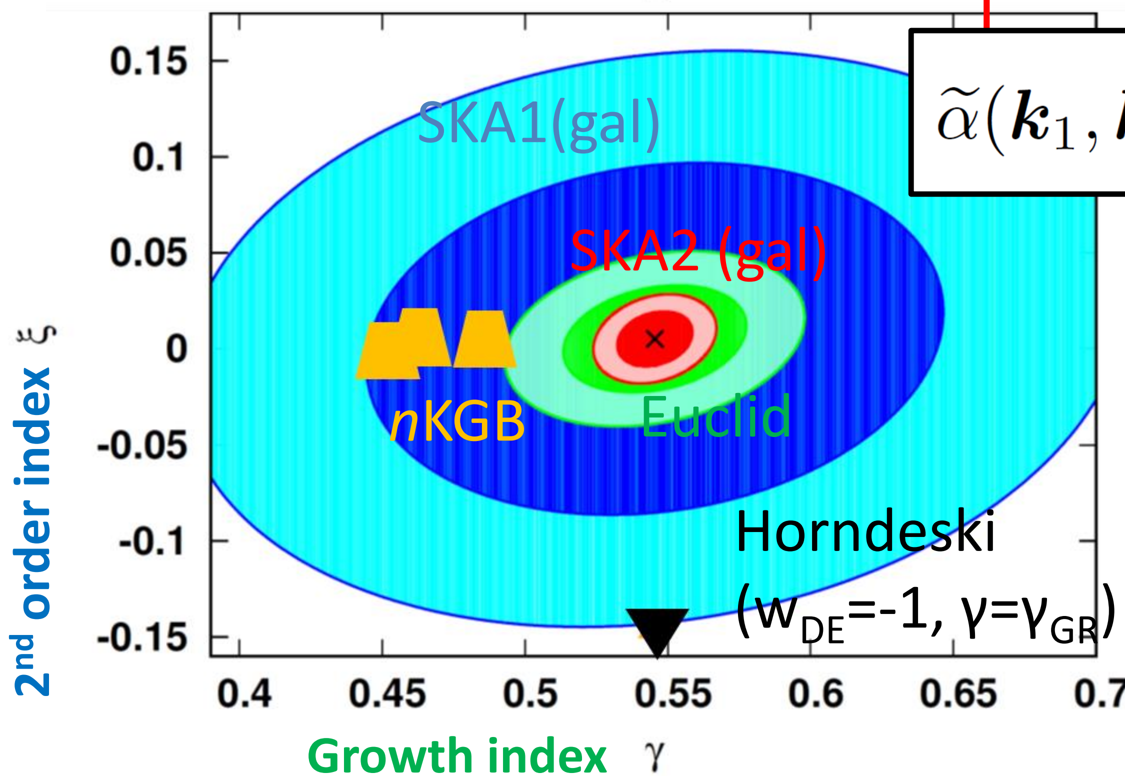
[DY+Yokoyama+Tashiro (2017)]

Nonlinear **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.

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

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



2^{nd} order index

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

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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.

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)]

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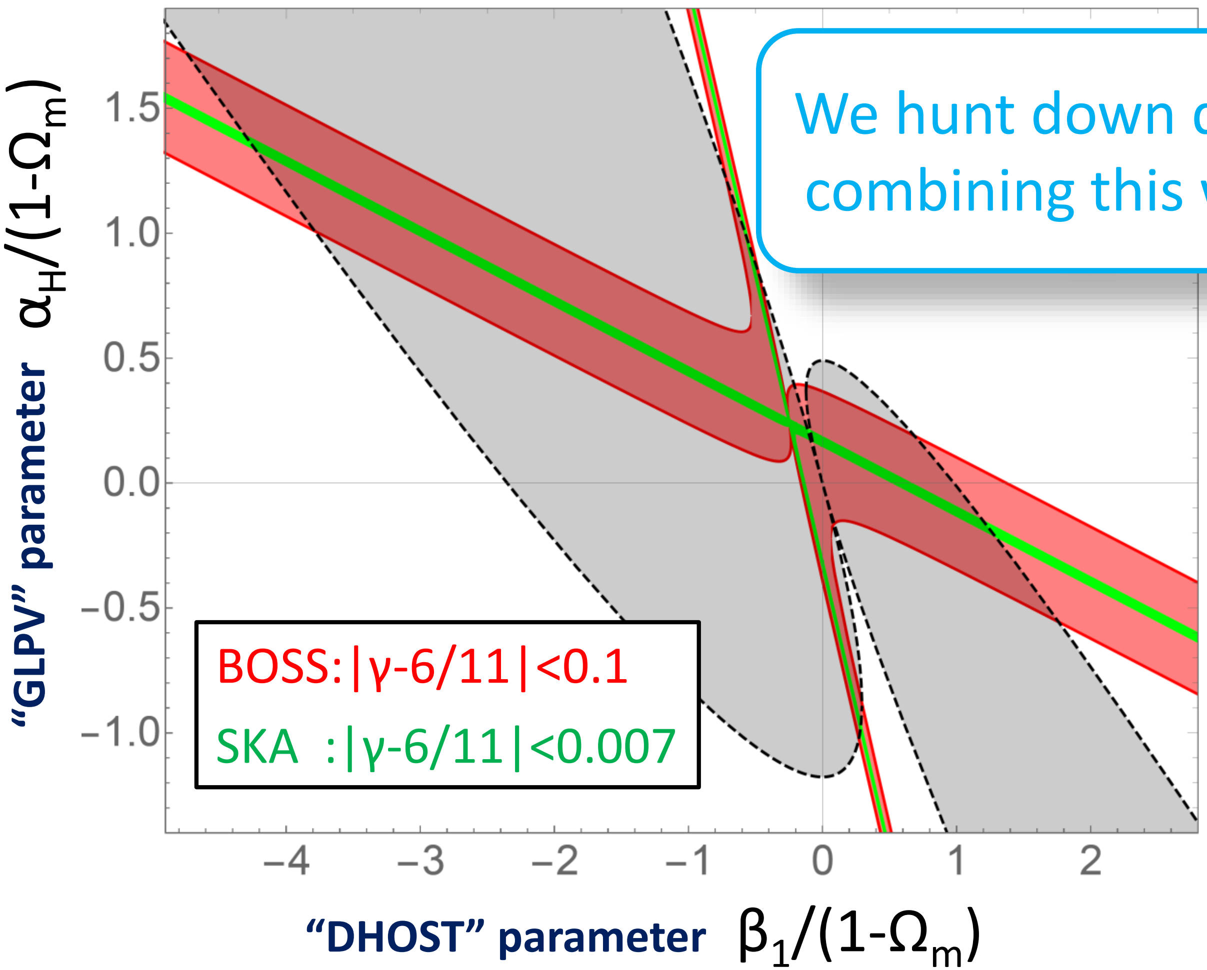
[Hirano+Kobayashi+**DY**+**Yokoyama** (2019)]

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 dark energy model 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)]

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 surveys : 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!