2019/12/16 Observational Cosmology Workshop@Tohoku U.

SKA Cosmology

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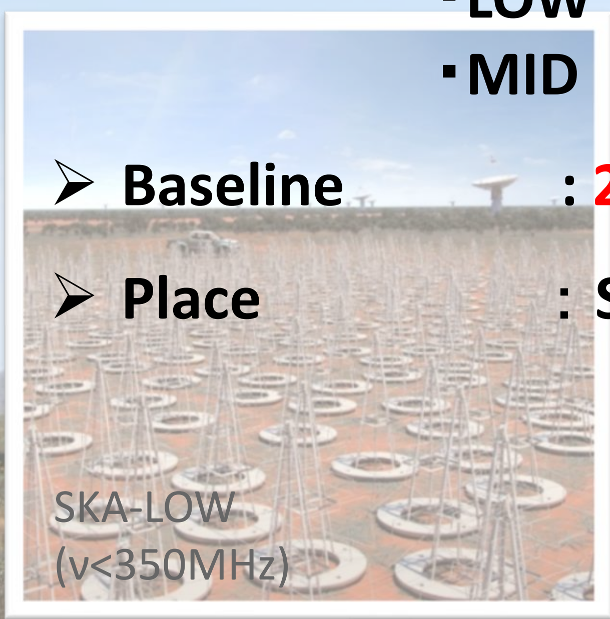
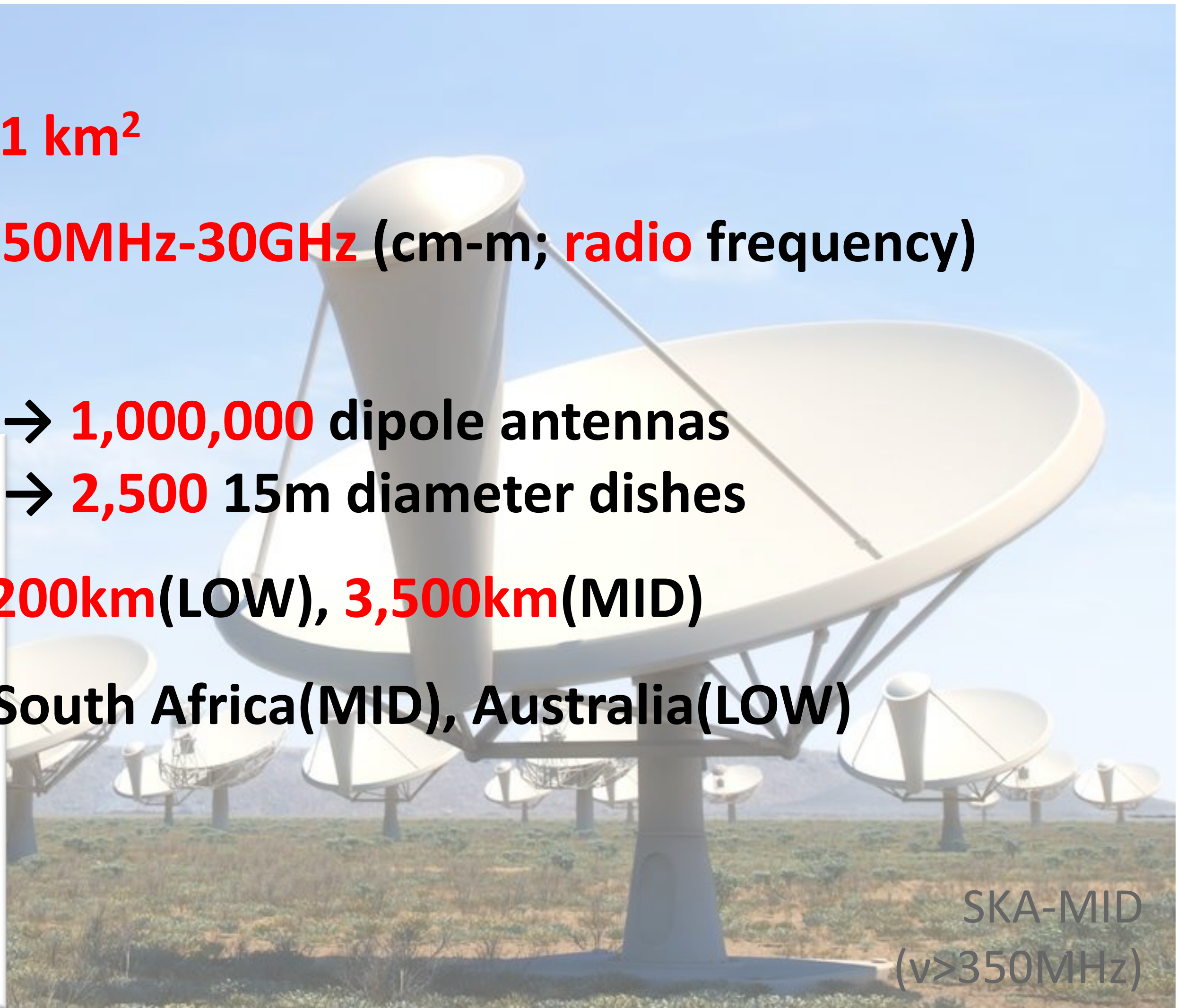
SQUARE KILOMETRE ARRAY

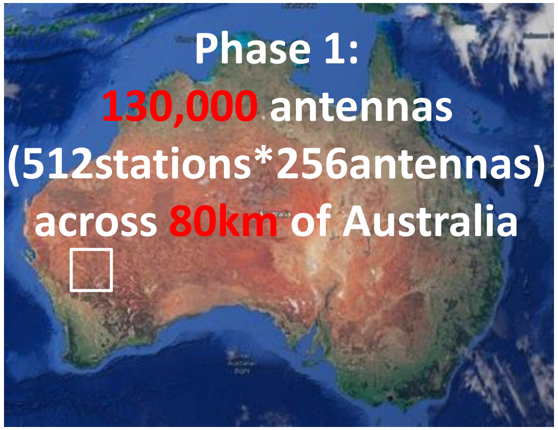
- **Collecting area : 1 km^2**
- **Frequency range : 50MHz-30GHz (cm-m; radio frequency)**
- **Instrument :**
  - **LOW → 1,000,000 dipole antennas**
  - **MID → 2,500 15m diameter dishes**
- **Baseline : 200km(LOW), 3,500km(MID)**
- **Place : South Africa(MID), Australia(LOW)**





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

SKA Phase 1
(2019 – 2028)

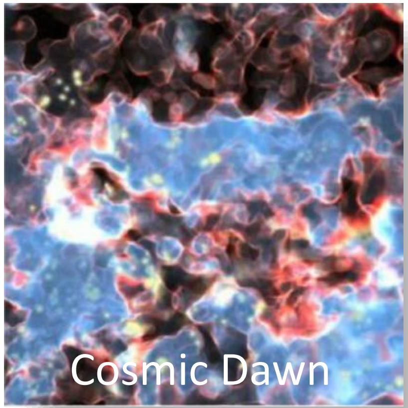


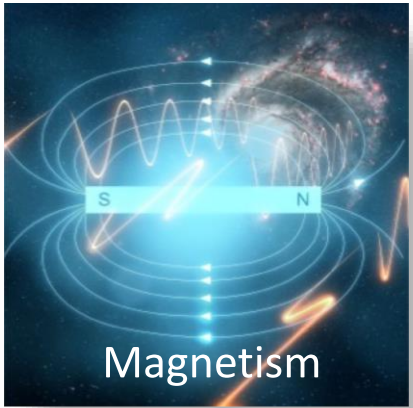
Scientific goals of SKA

The SKA aims to solve some of the biggest questions.

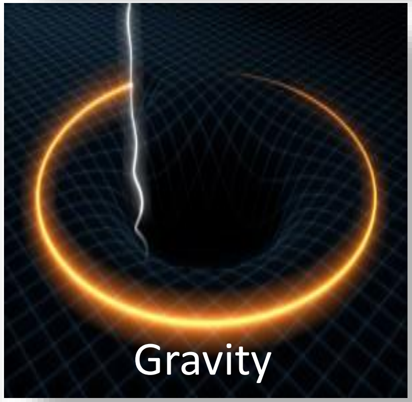
- Fundamental physics : **Gravity**, **Dark Energy**, Cosmic Magnetism
- Astrophysics : Cosmic Dawn, First galaxies, galaxy assembly and evolution, +...
- The unknowns : transients + ...


Dark Energy

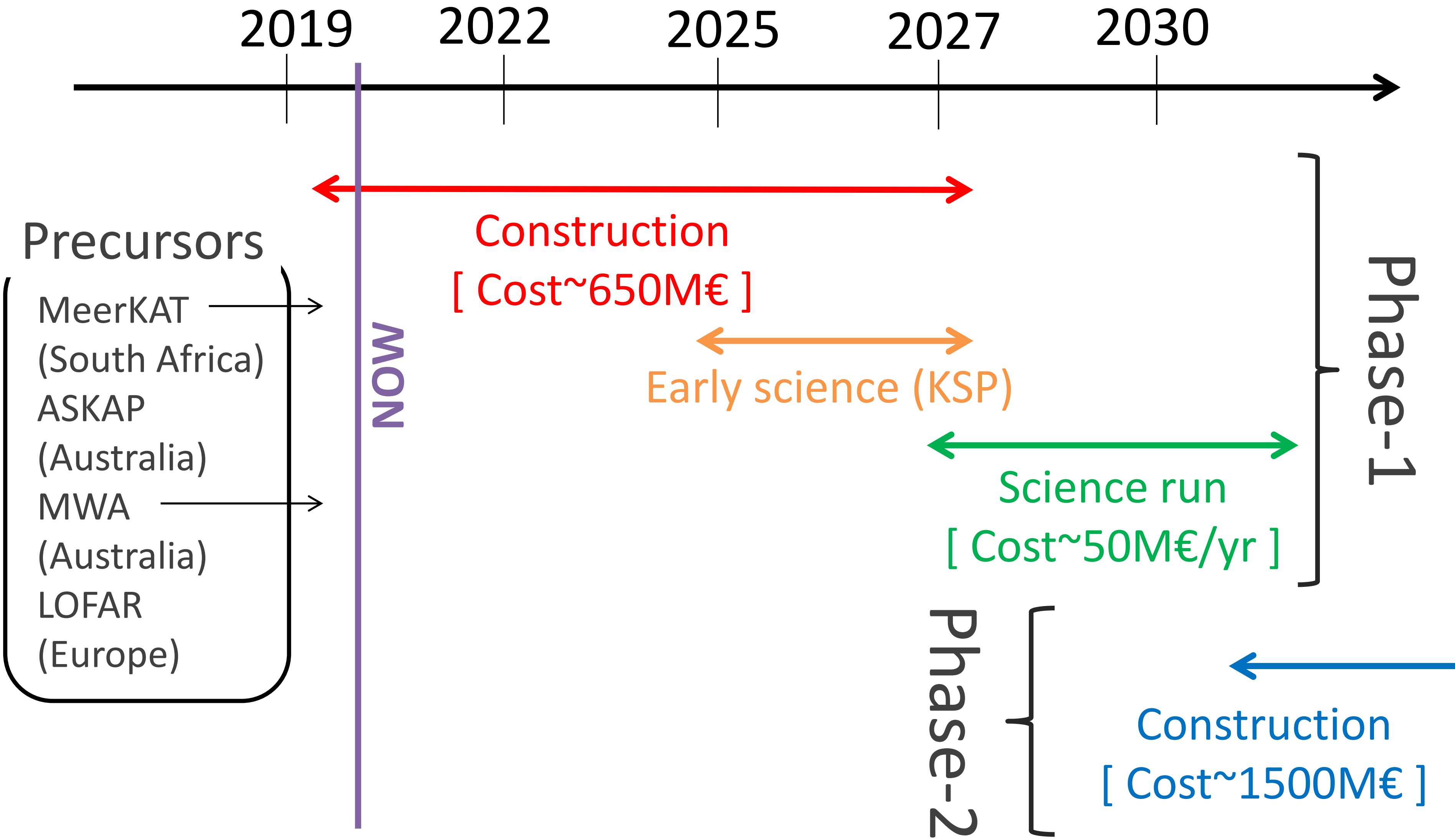

Cosmic Dawn


Magnetism


Galaxy & Transients

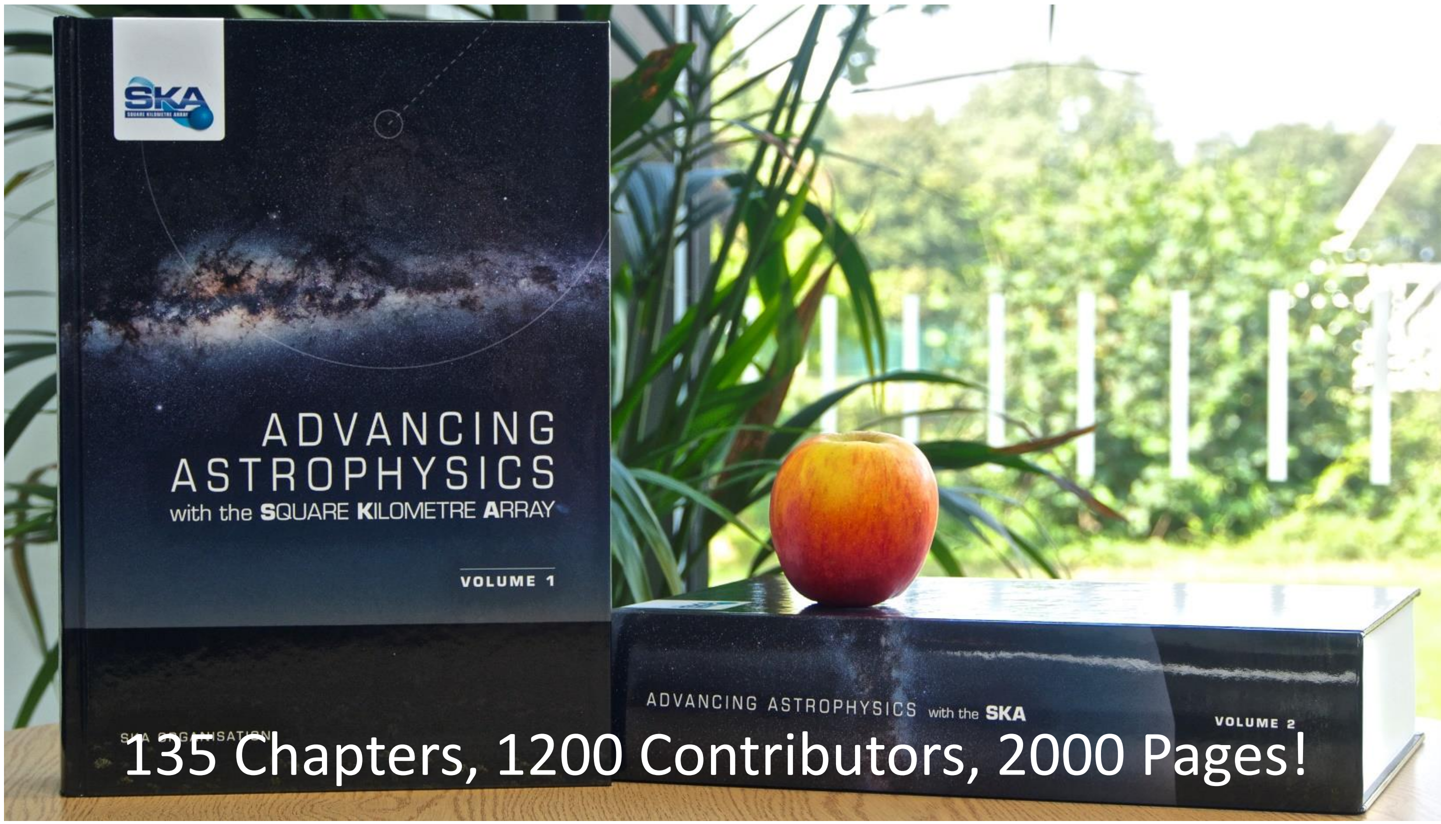

Gravity

SKA schedule



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, **2020(in prep!)**]

- 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

Plan

1. Introduction

2. **SKA Cosmological Surveys**

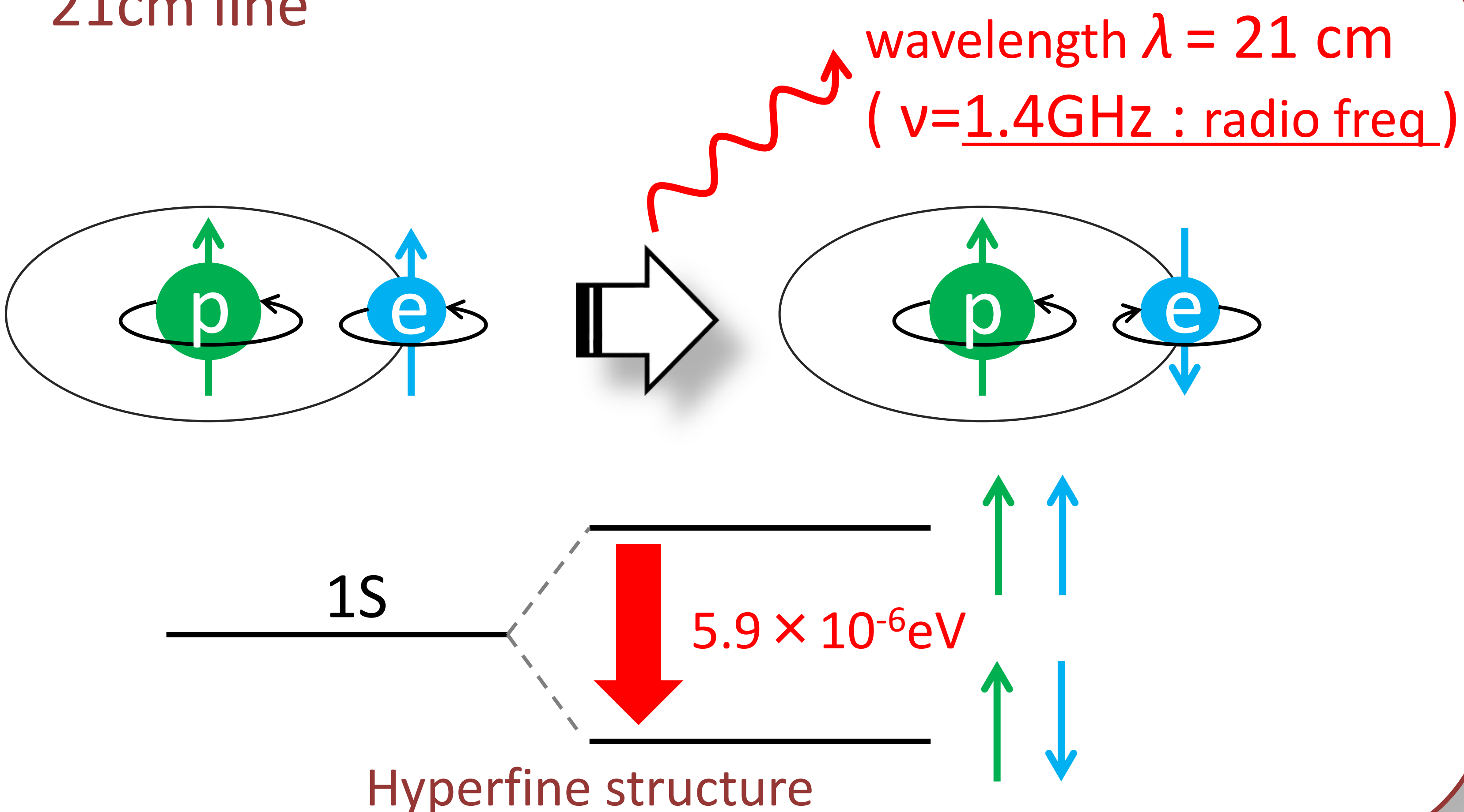
3. SKA Cosmology

    3.1 Dark Energy

    3.2 Inflation

Why "radio" frequency?

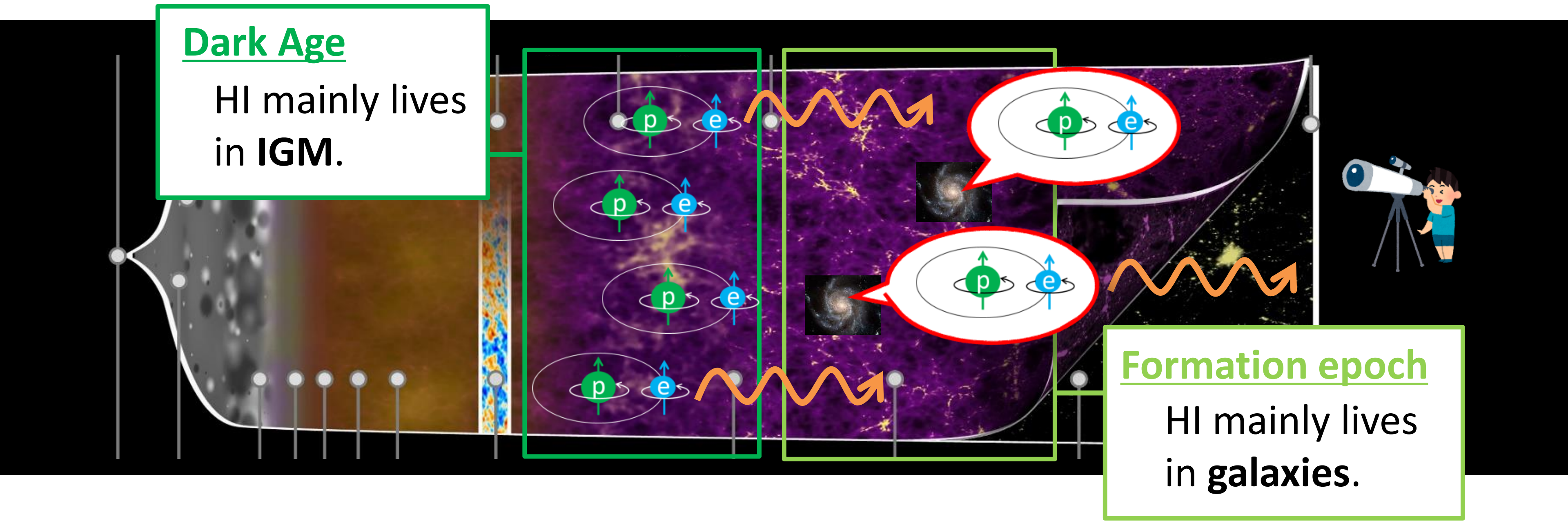
- Hyperfine transition radiation of neutral hydrogen :
  21cm line



Why "radio" frequency?

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

= Information of growth!



➢ *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.

✓ *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	~ 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**	**--**
		Phase-2	z<3.7	3/4	--
HI [21cm line]	***HI intensity mapping survey (LOW-IM)***	Phase-1	3<z<27	1/40	--
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Synchrotron radiation	***Continuum survey (conti)***	**Phase-1**	**z<6**	**3/4**	**~ 10^8**
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S = 70(SKA1gal), 5(SKA2gal), 1(SKA1cont), 0.1(SKA2cont) [μJy]
$\Delta\theta$ = 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**
HI [21cm line]	***HI intensity mapping survey*** *(MID-IM)*	**Phase-1**	**z<3**	**3/4**	**--**
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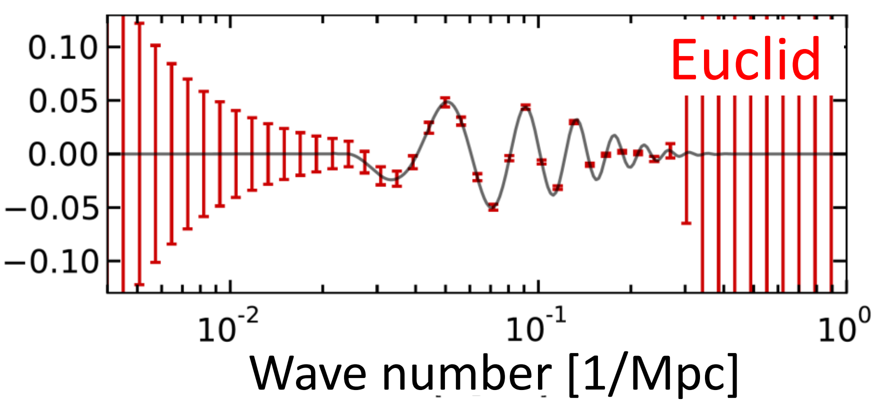
S = 70(SKA1gal), 5(SKA2gal), 1(SKA1cont), 0.1(SKA2cont) [μJy]

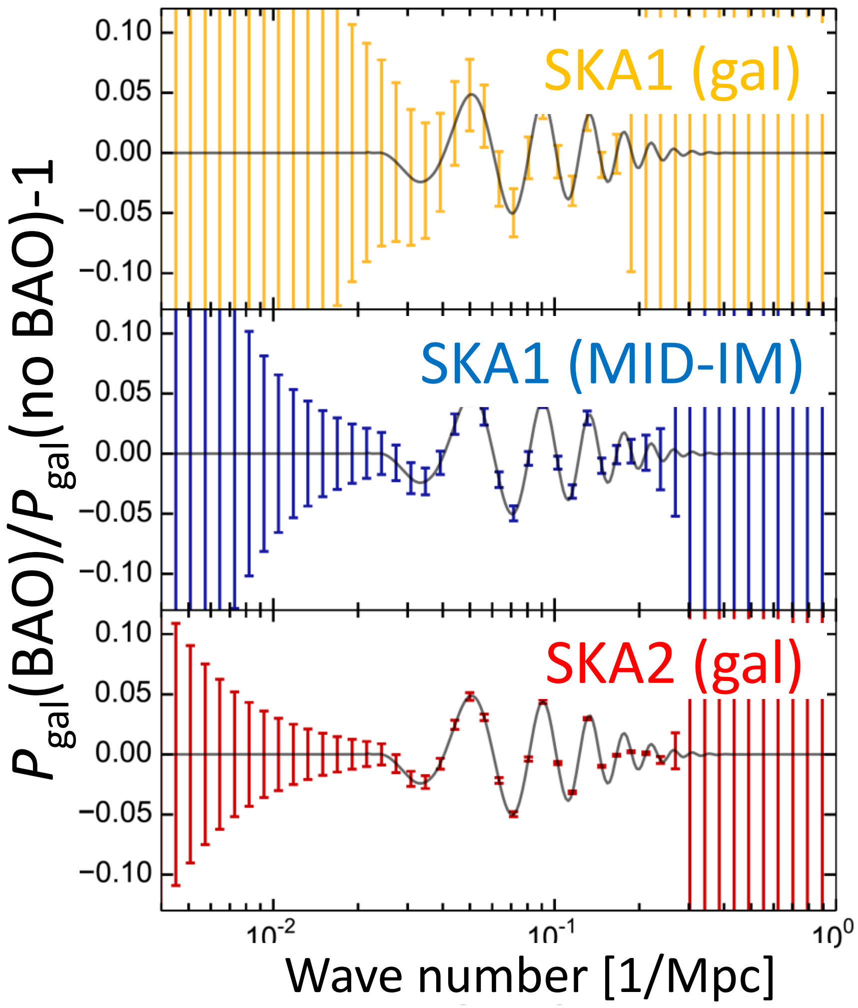
$\Delta\theta$ = 1(SKA1), 0.1(SKA2) [arcsec], $t_{int} = 10^4$ [hr]

[Bull+ 1405.1452,SKA Science Book(BAO) (2015)]

SKA constraining power

- ✓ **gal, MID-IM** : high-precision measurement of BAO and RSD
- ✓ **conti** : No redshift info, but possible to detect high-z gal
- ✓ **LOW-IM** : fluc remains linear-order even on small scales





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"

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    3.1 Dark Energy

    3.2 Inflation

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

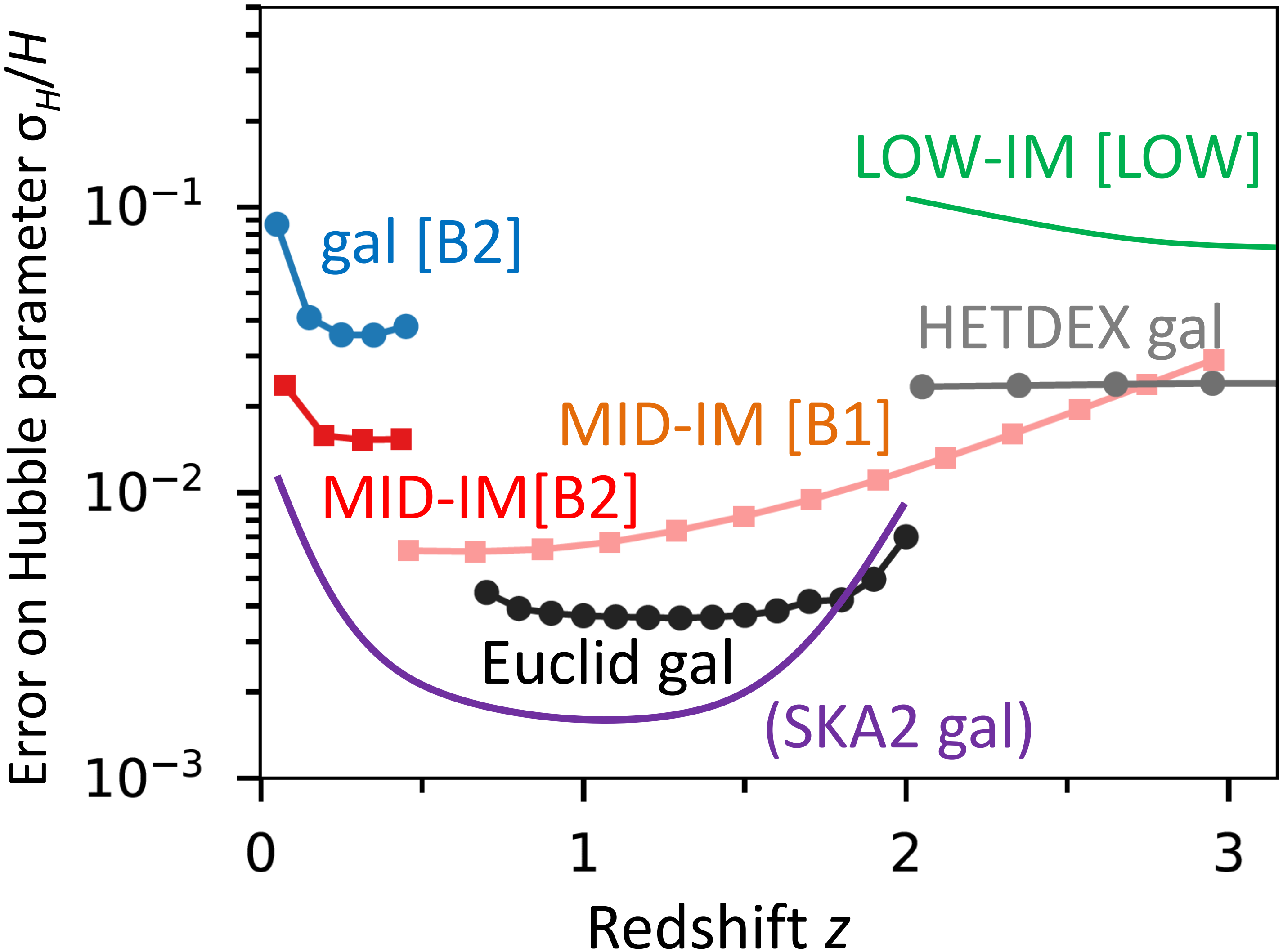
$$\delta(a,\boldsymbol{k}) = \delta_\mathrm{L}(a,\boldsymbol{k}) + \left[F_2(\boldsymbol{k}_1,\boldsymbol{k}_2;a)\,\delta_\mathrm{L}(a,\boldsymbol{k}_1)\star\delta_\mathrm{L}(a,\boldsymbol{k}_2)\right]_{\boldsymbol{k}} + \cdots$$

Growth index

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

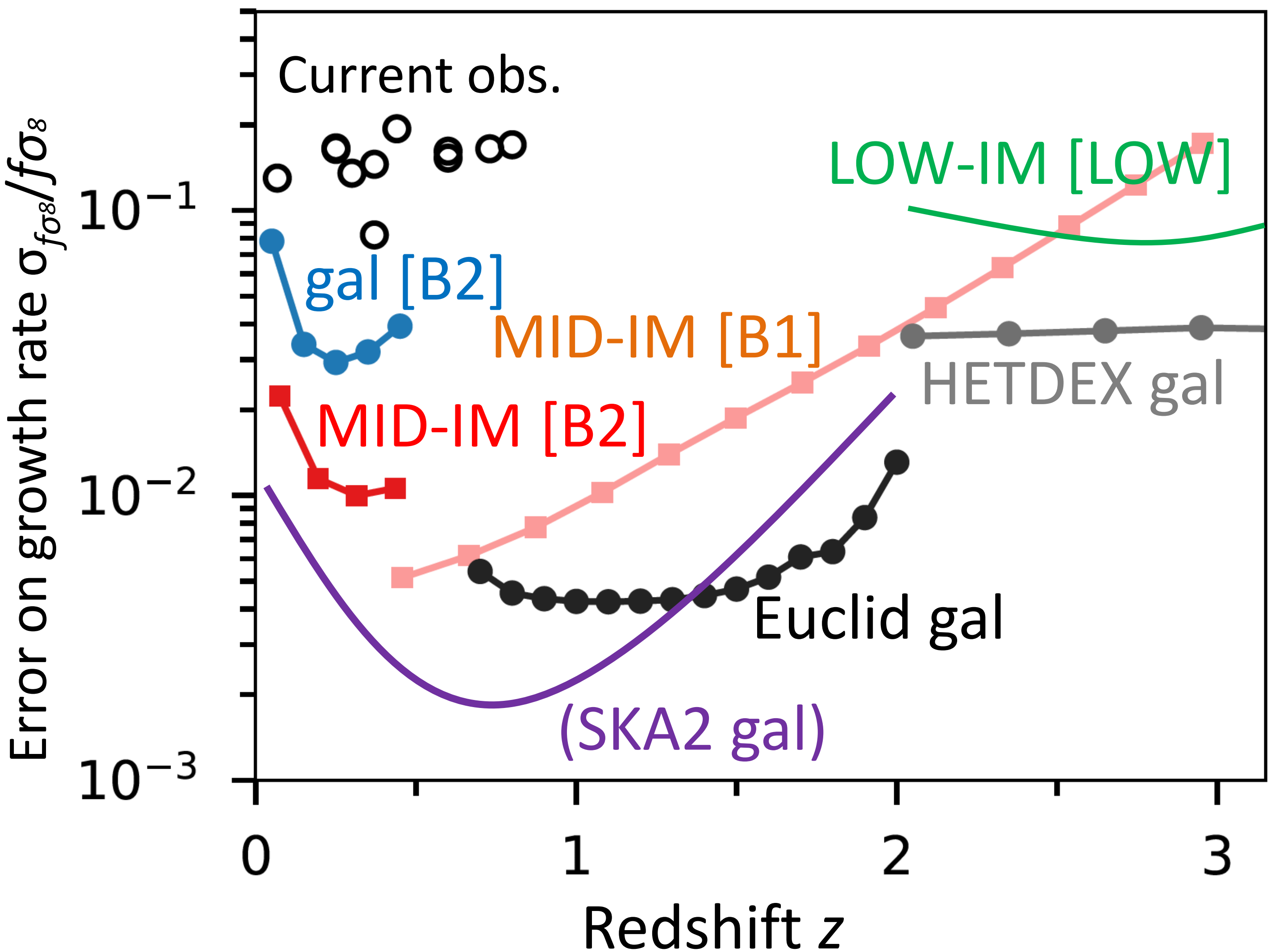
[SKA Cosmology Red Book(2018), Bull(2016)]

Cosmic expansion rate [BAO]



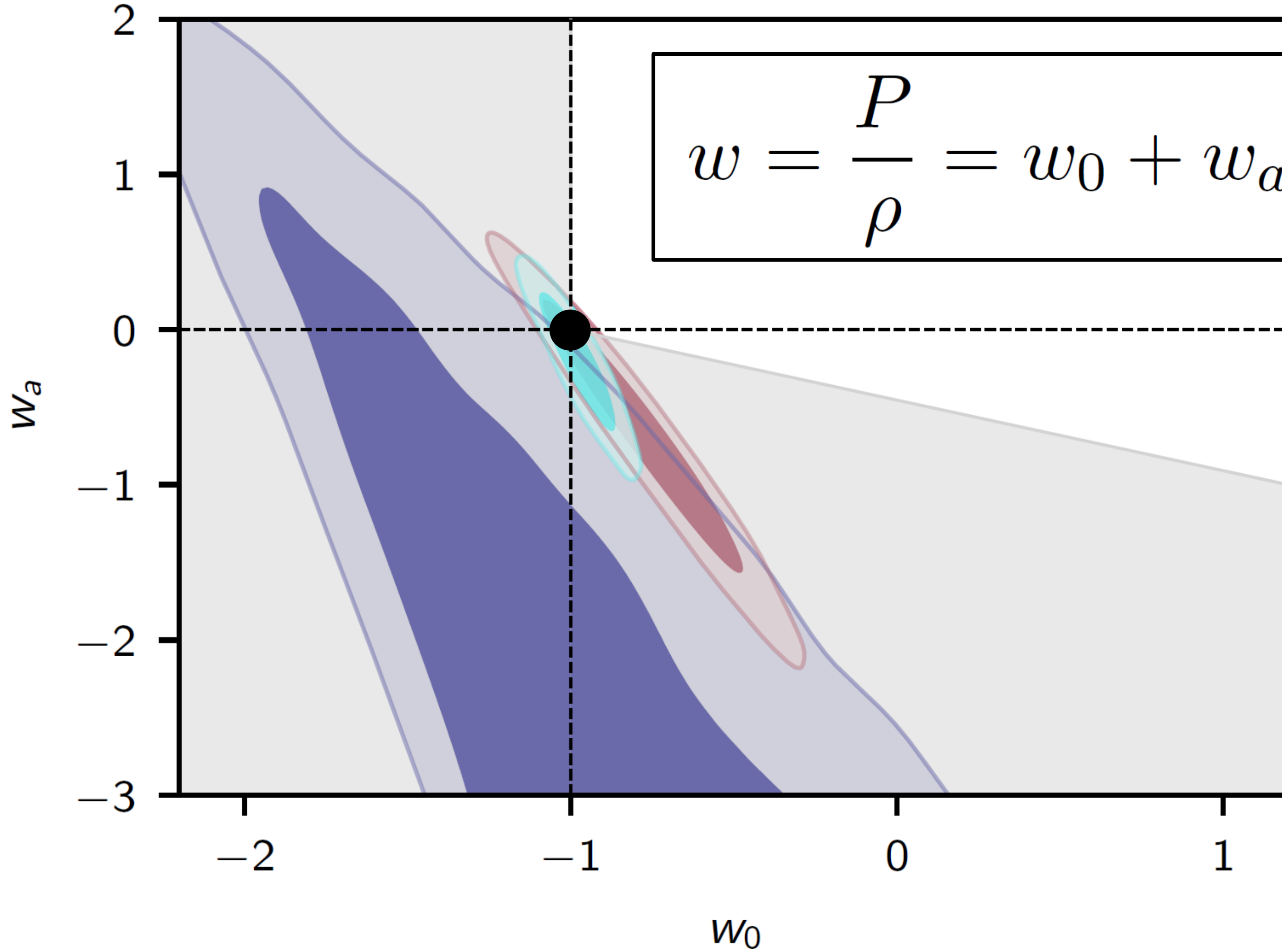
[SKA Cosmology Red Book(2018), Bull(2016)]

Growth rate [RSD]



[Planck XIV(2013)]

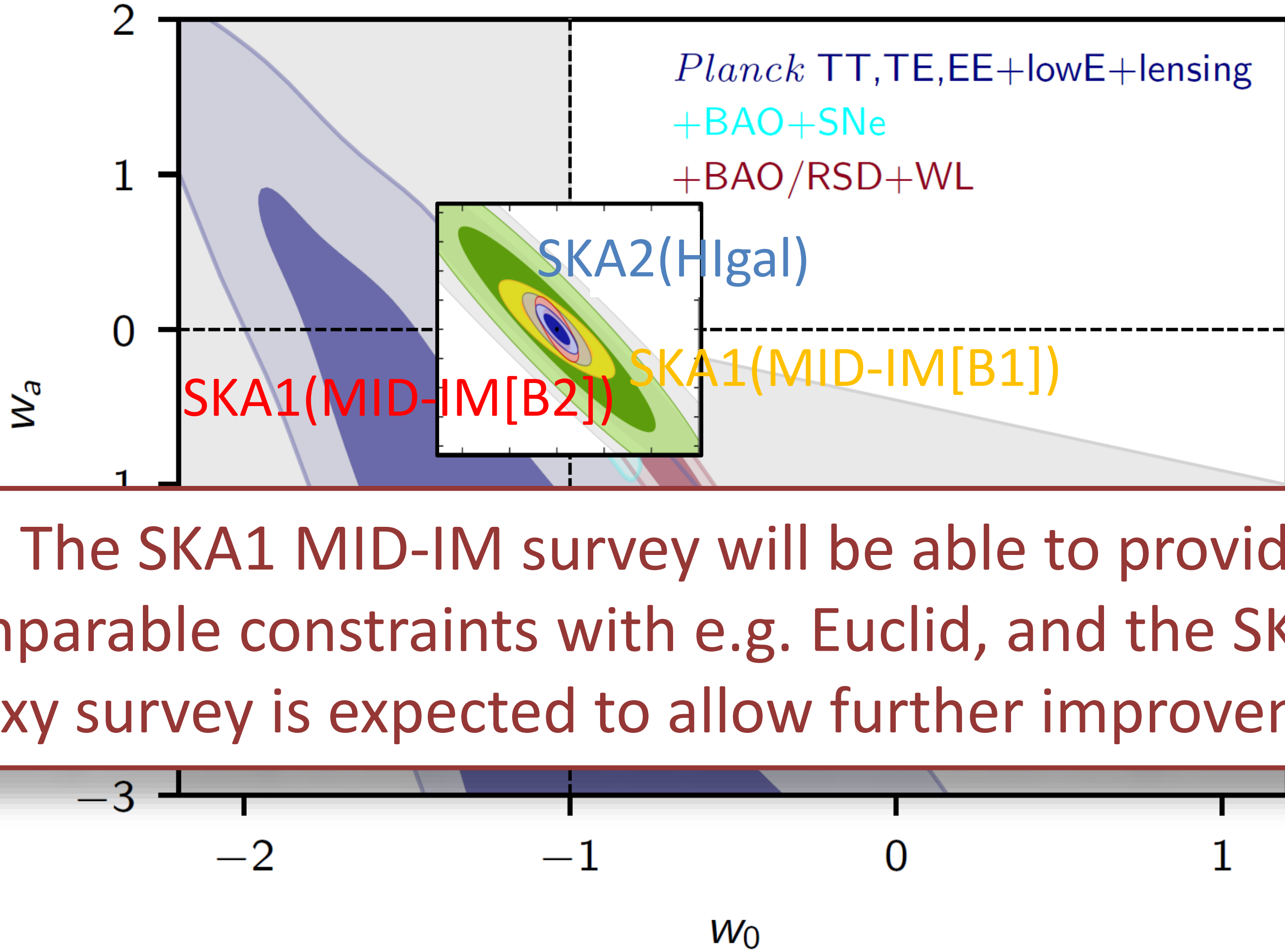
Dark Energy **Equation-of-State**



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

[Planck XIV(2013)]

Dark Energy **Equation-of-State**

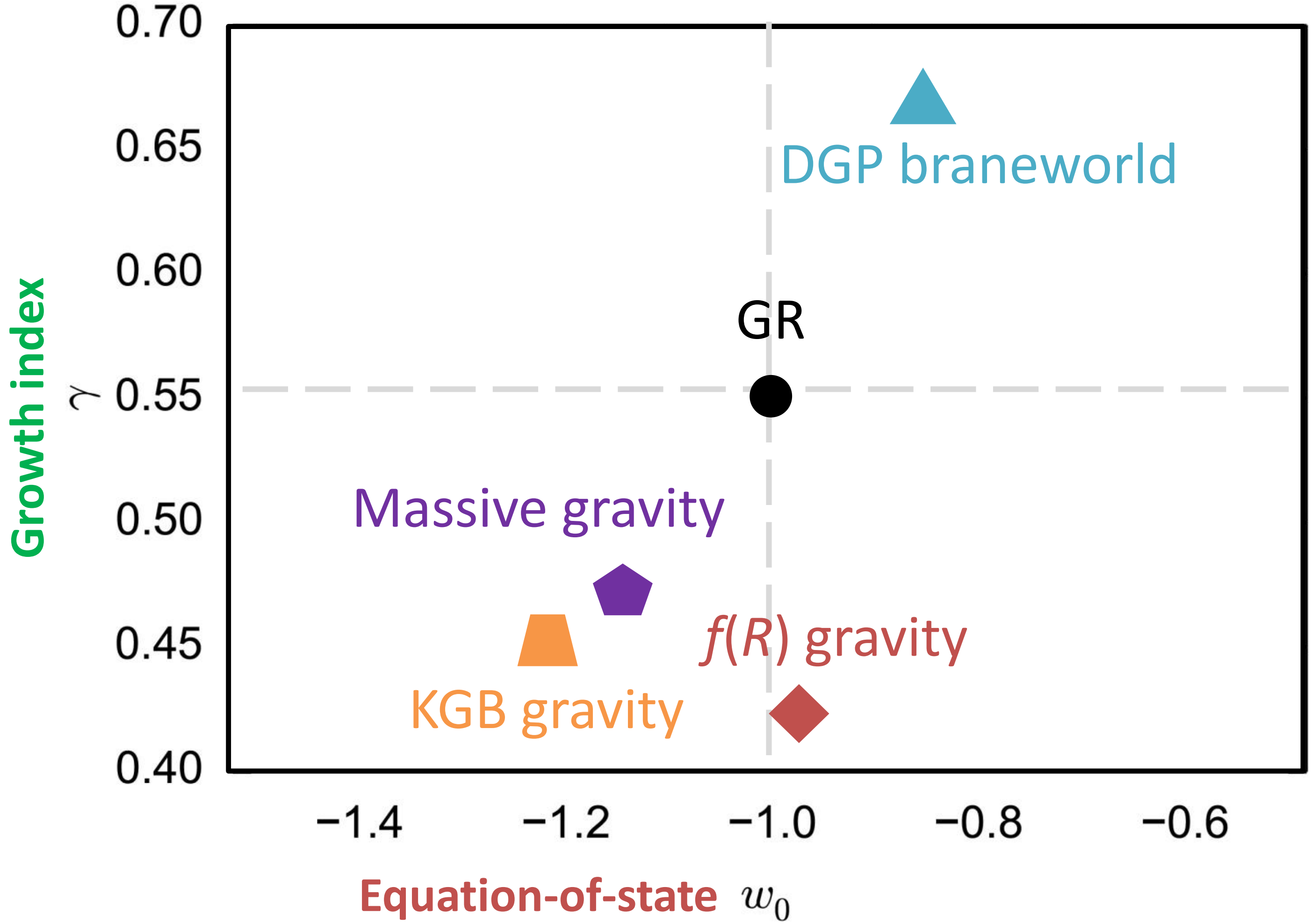


The SKA1 MID-IM survey will be able to provide comparable constraints with e.g. Euclid, and the SKA2 HI galaxy survey is expected to allow further improvements.

[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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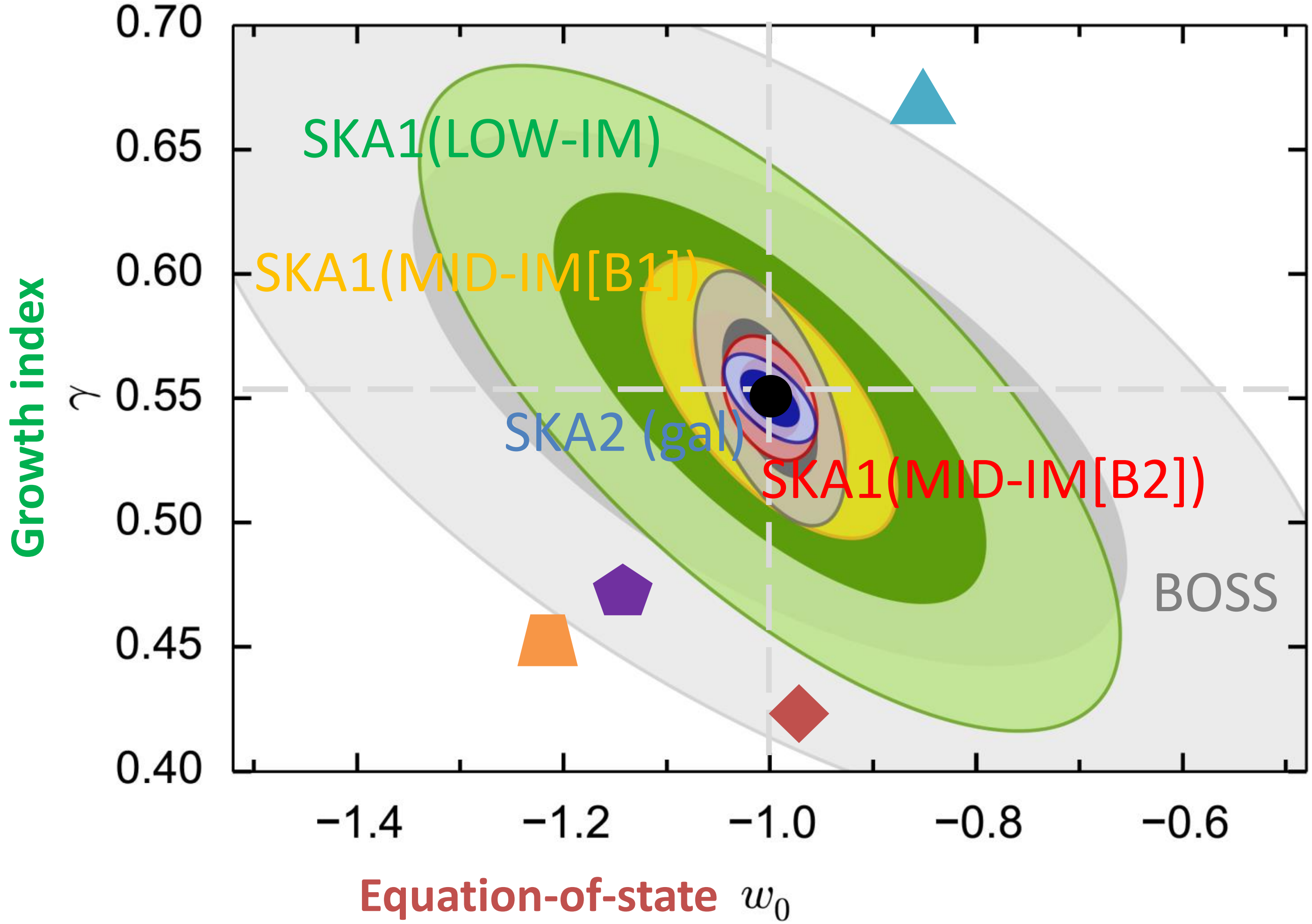


Dark Energy and Scalar-Tensor Theories

- **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

$$\mathcal{L} = F(\phi, X) R + A_3(\phi, X) \Box\phi \nabla^\mu \phi \nabla^\nu \phi \nabla_\mu \nabla_\nu \phi$$

$$+ \frac{1}{8F}\left[48F_X^2 - 8(F - XF_X)A_3 - X^2 A_3^2\right] \nabla^\mu \phi \nabla_\mu \nabla_\rho \phi \nabla^\rho \nabla^\nu \phi \nabla_\nu \phi$$

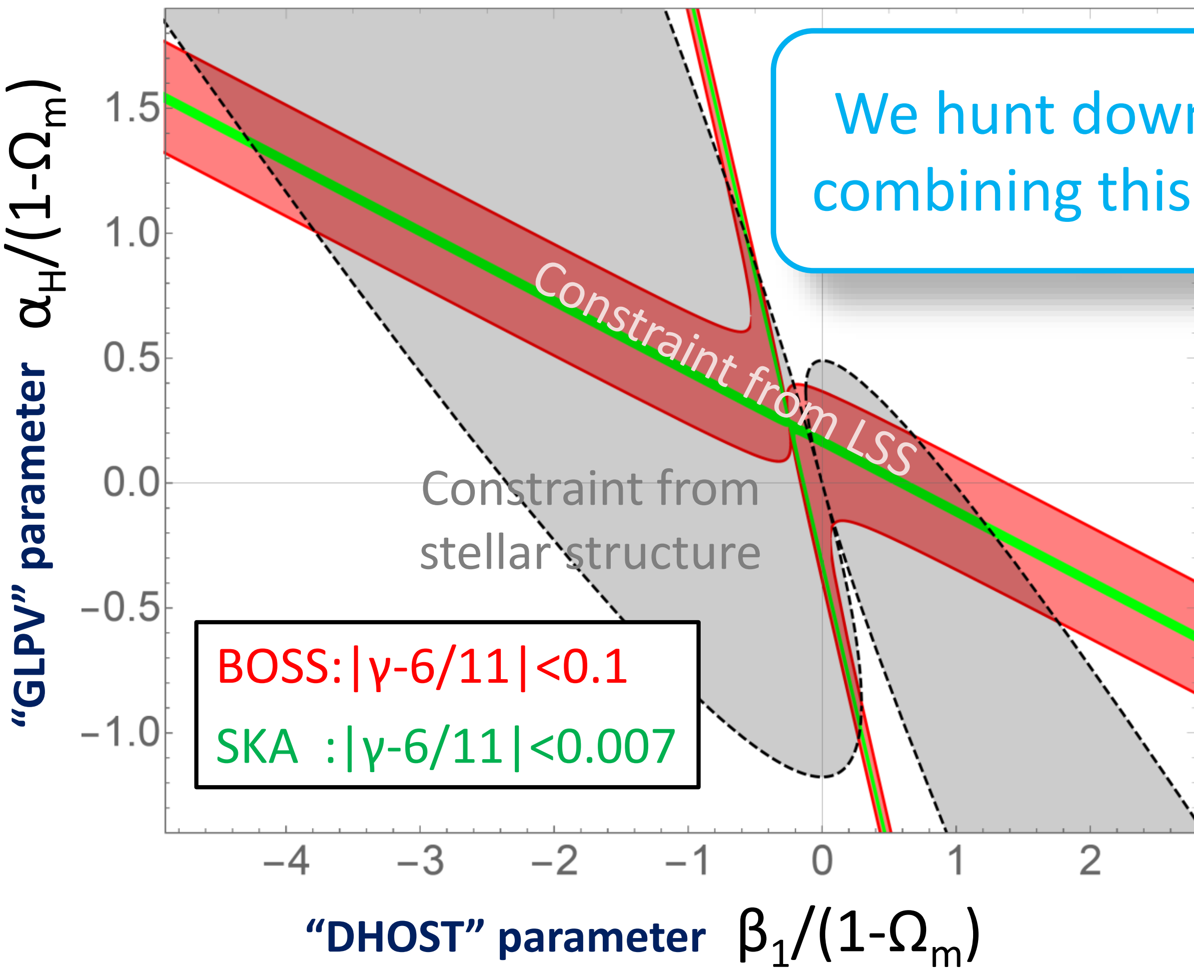
$$+ \frac{1}{2F}(4F_X + XA_3) A_3 (\nabla^\mu \phi \nabla_\mu \nabla_\nu \phi \nabla^\nu \phi)^2$$

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

[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)]

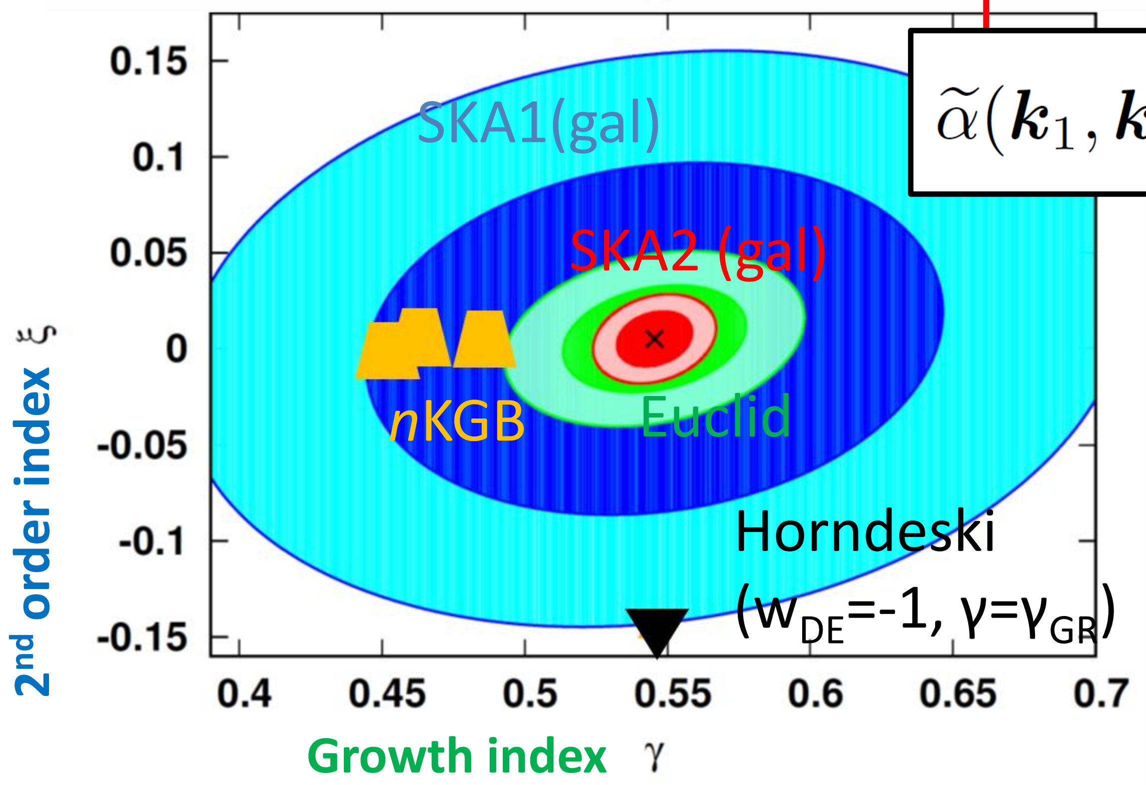
[DY+Yokoyama+Tashiro (2017)]

*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!

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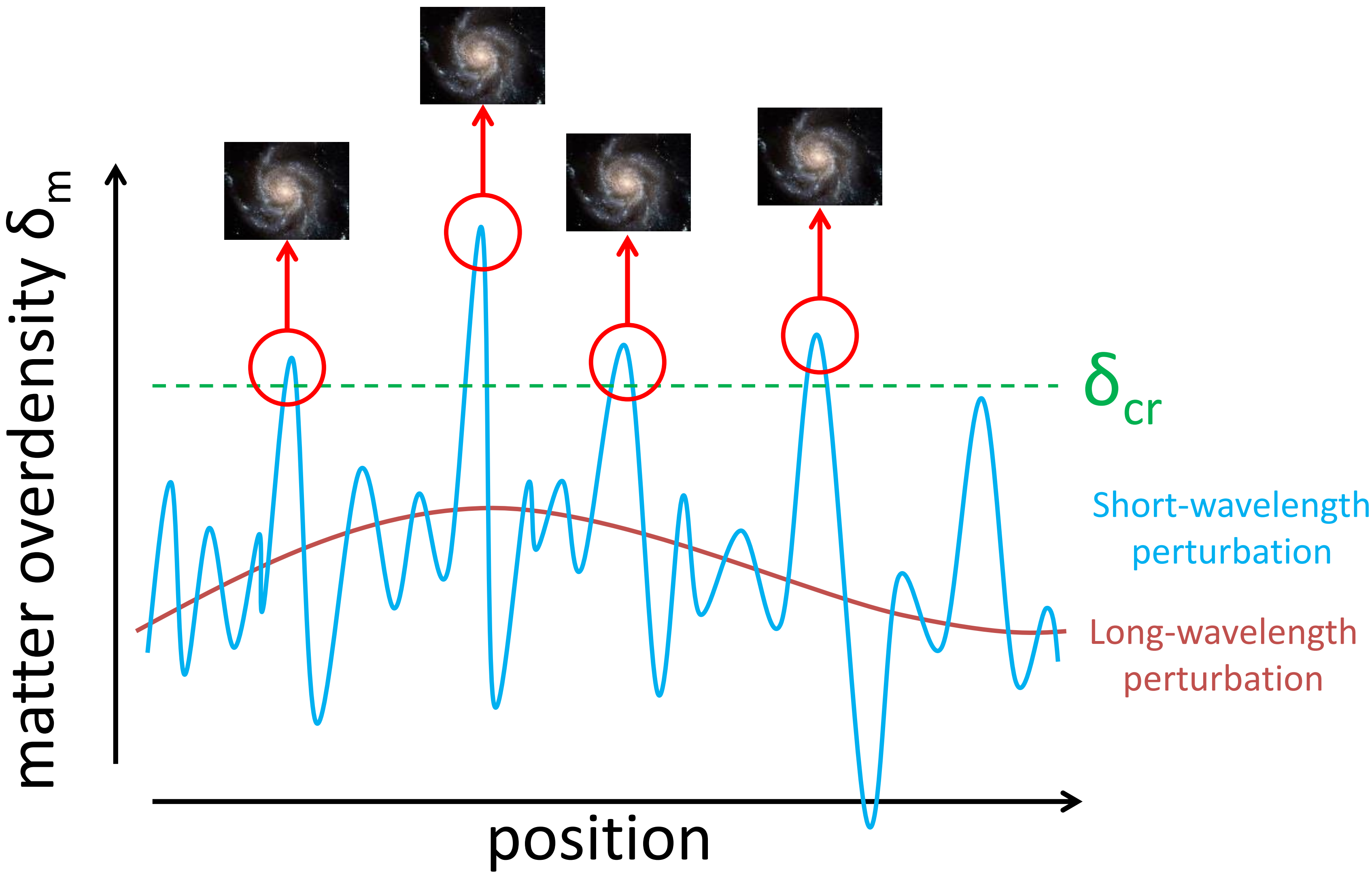
Galaxy bias

Luminous sources should be treated as **biased** tracer of LSS.



f_{NL}^{local} induces scale-dependence

[Dalal+Dore+Huterer+Shirokov(2008)]

◆"Rough" estimation

$$\Phi_{NG} = \phi_G + f_{NL}(\phi_G)^2$$

⇓ Acting the Laplacian on Φ_{NG}…

$$\underbrace{\nabla^2\Phi_{NG}}_{\propto\, \delta_{NG}} = \underbrace{\nabla^2\phi_G}_{\propto\, \delta} + 2f_{NL}\underbrace{\phi_G}_{\propto\, \delta/k^2}\underbrace{\nabla^2\phi_G}_{\propto\, \delta} + \cdots$$

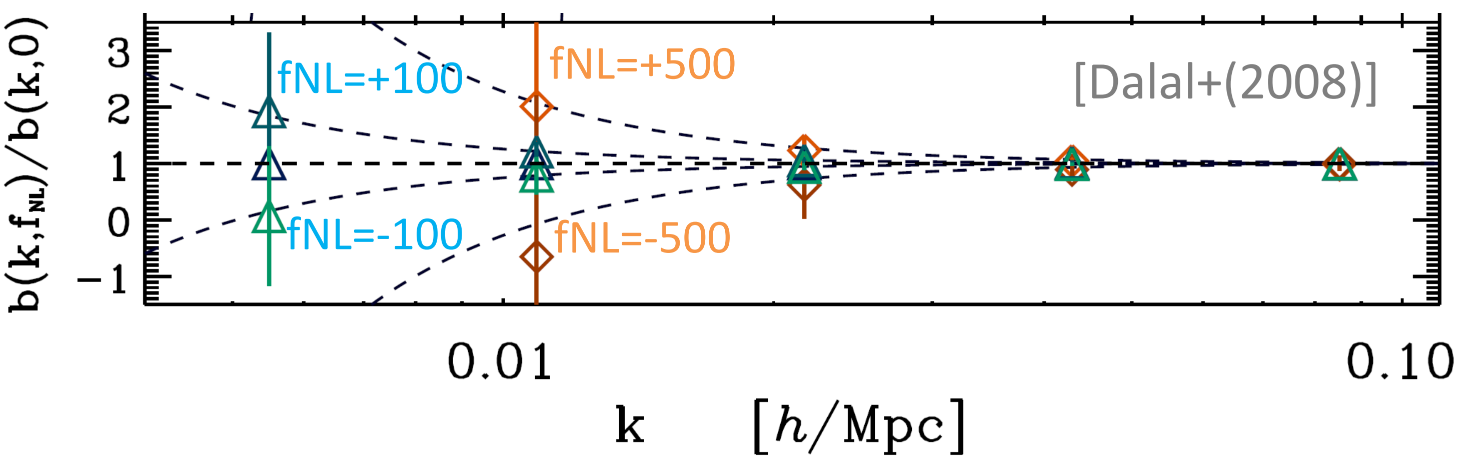
$$\Rightarrow \quad \delta_{NG} \simeq (1 + 2f_{NL}\phi_G)\delta$$

f_{NL}^{local} induces scale-dependence

- Local-type PNG induces $\Delta b \propto 1/k^2$ dependence such that the effect dominates at very large scales:

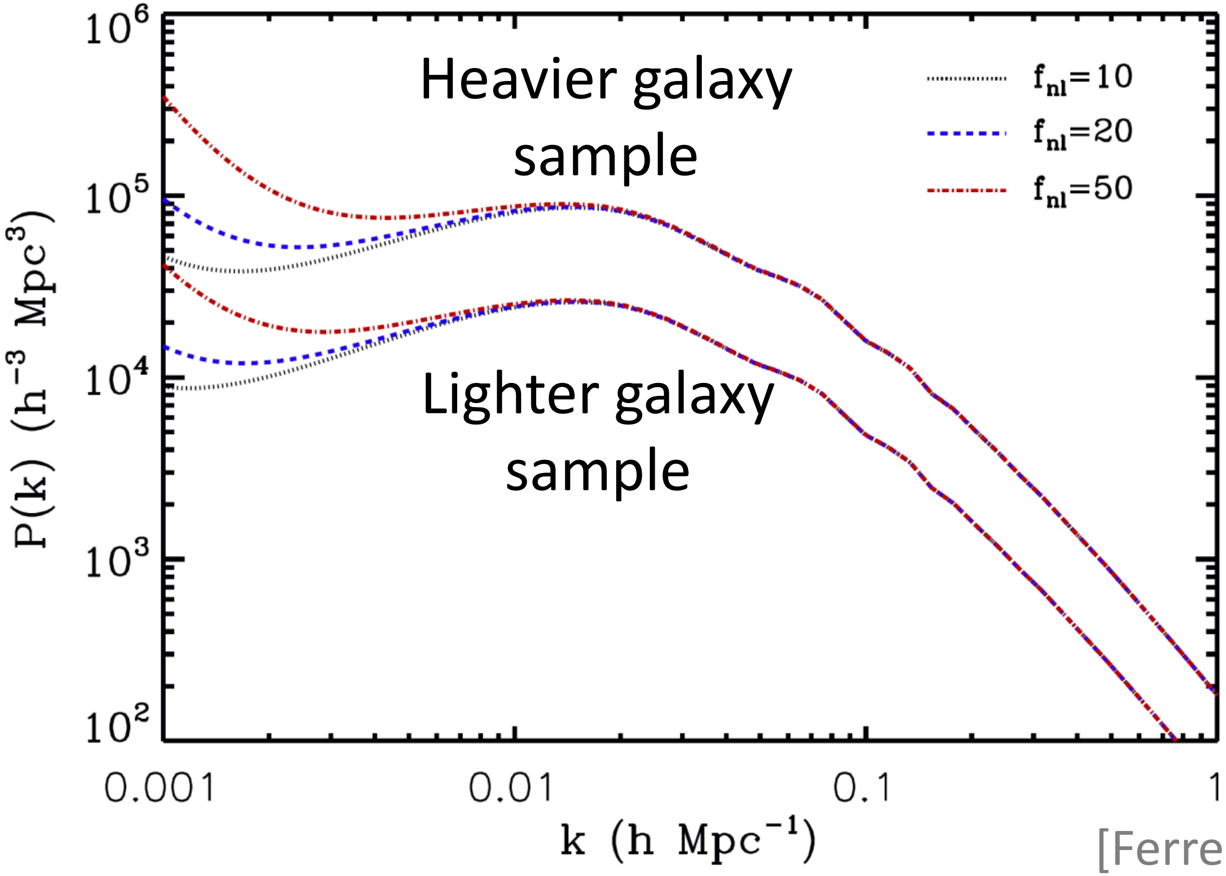
[Dalal+(2008), Desjacques+(2009)]

$$\Delta b = \frac{3 H_0^2 \Omega_{m,0} \delta_c (b_G - 1)}{k^2 T(k) D_+(z)} f_{NL}$$



f_{NL}^{local} induces scale-dependence

$$P_{gg} = (b_1 + b_{NG}^{(f)} f_{NL}^{local}/k^2)^2 P_{mm}$$



[Ferremacho+(2014)]

Multi-tracer cosmology

Cosmic variance: fundamental limit to large-scale obs.

- Only a finite number of Fourier modes in our Hubble volume
- Biased populations probe the **same** DM field → **deterministic**
- Tracer-dependent quantities are no CV-limited [Seljak(2008)]

Tracer1 $\delta_1 = (b_1 + f\mu^2)\,\delta_{DM}$

Tracer2 $\delta_2 = (b_2 + f\mu^2)\,\delta_{DM}$

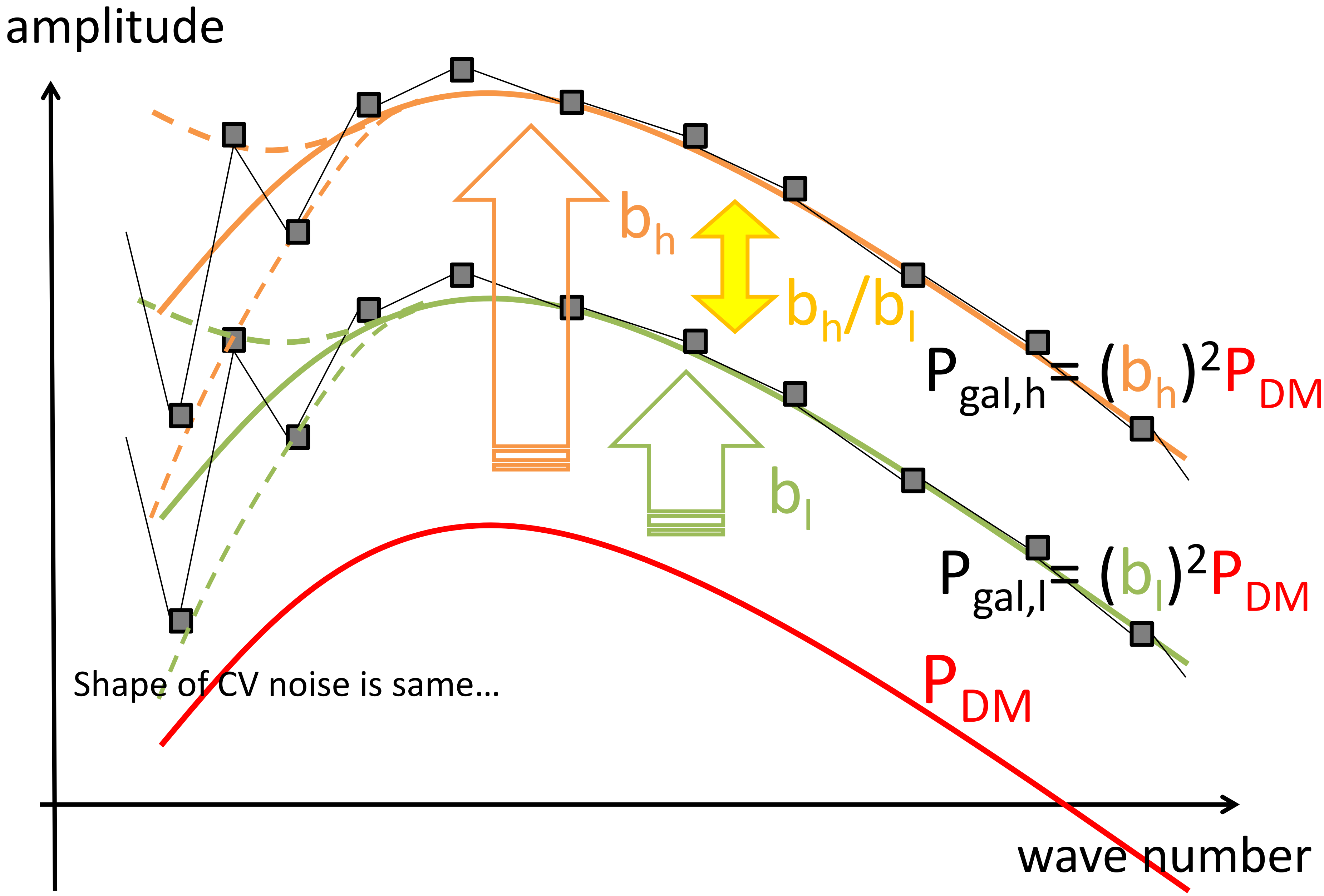
Tracers are **stochastic**

$$\delta_1/\delta_2 = (b_1 + f\mu^2)/(b_2 + f\mu^2)$$

Ratio is **deterministic**

Noise on MT quantities scales like shot noise

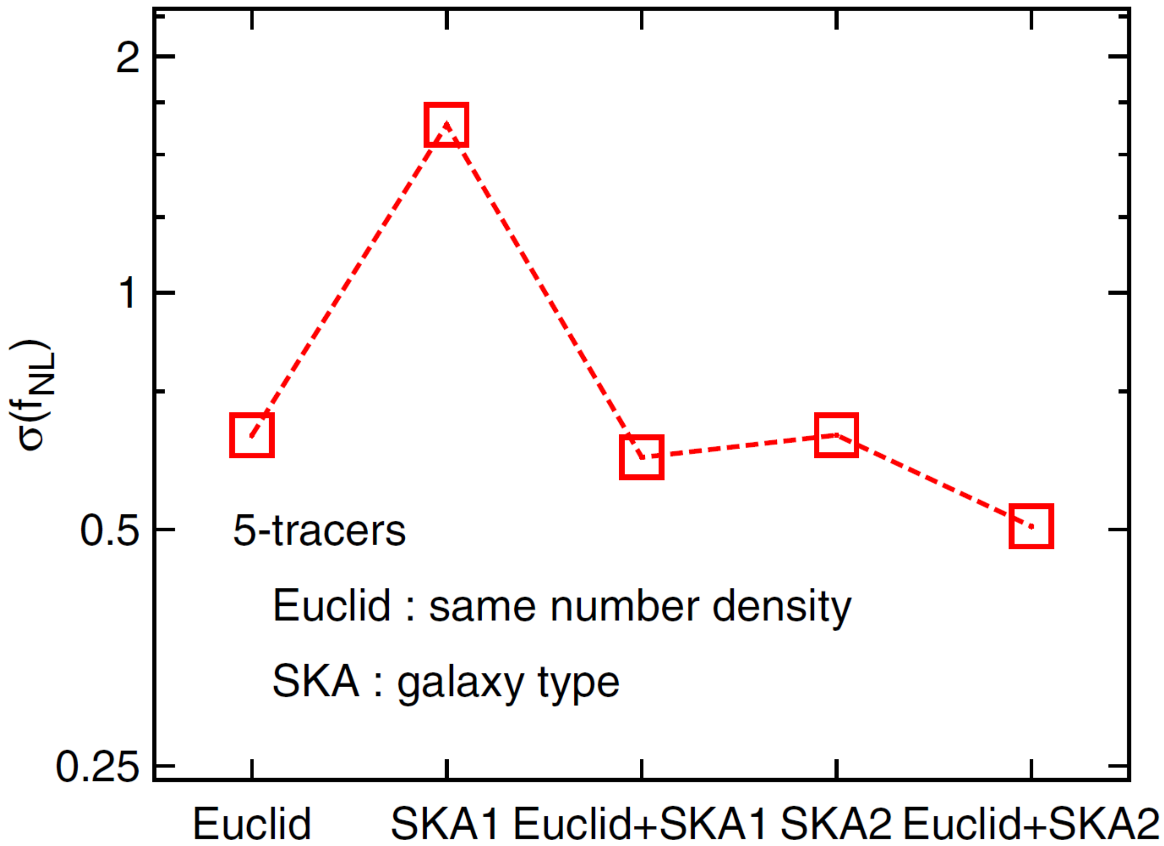
→ Need high source density & large bias ratio



amplitude
b_h
b_h/b_l
$P_{gal,h} = (b_h)^2 P_{DM}$
b_l
$P_{gal,l} = (b_l)^2 P_{DM}$
P_{DM}
Shape of CV noise is same...
wave number

Constraining $f_{\rm NL}^{\rm local}$ with SKA+Euclid

[**DY**+Takahashi+Oguri(2014)]

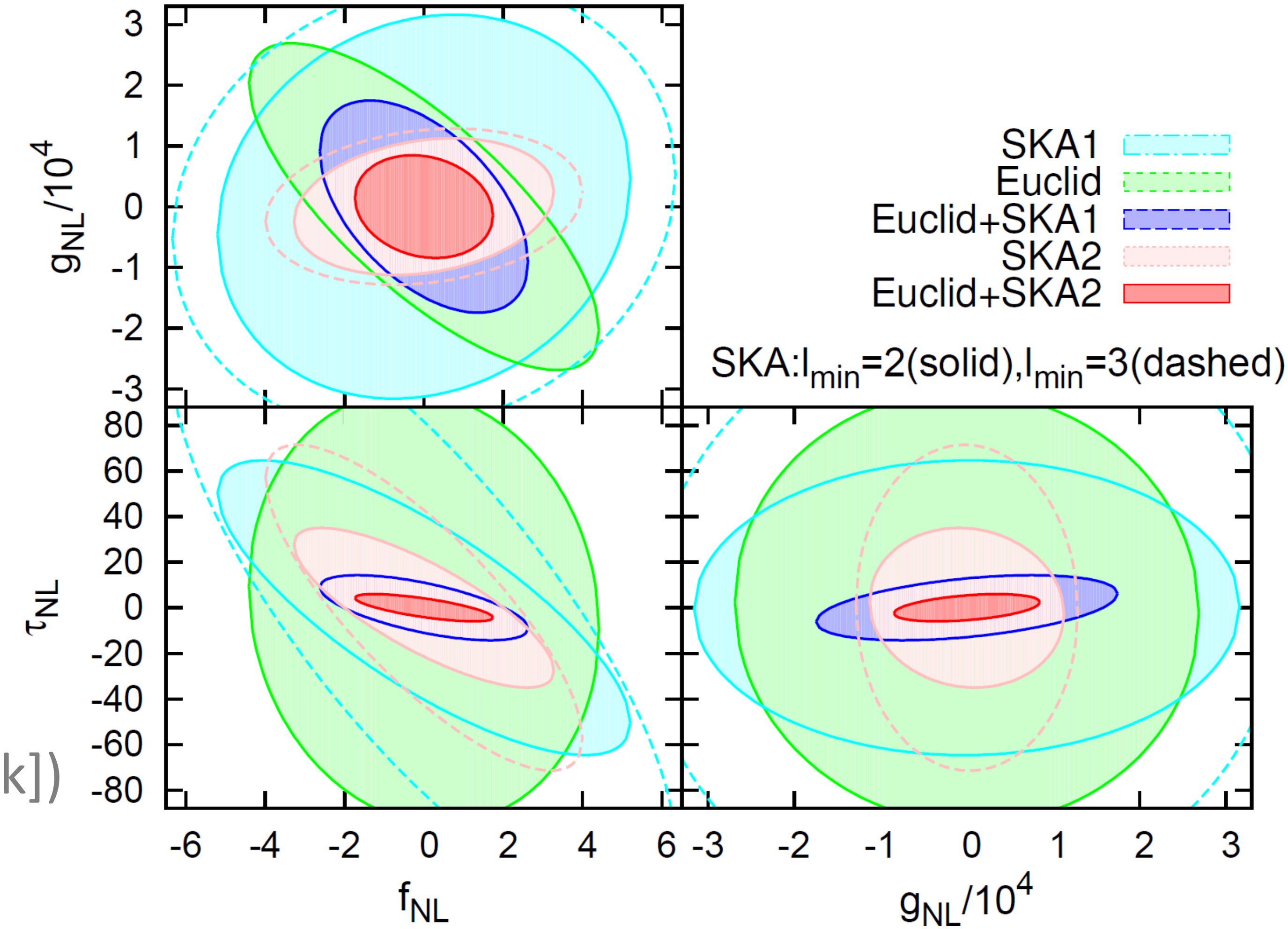


Constraining local PNG with SKA+Euclid

[**DY**+Takahashi(2015)]

$\sigma(g_{NL})/10^3$=
21 [SKA1]
7.4 [SKA2]
18 [Euclid]
(65 [Planck])

$\sigma(\tau_{NL})$=
43 [SKA1]
23 [SKA2]
62 [Euclid]
(2800 [Planck])

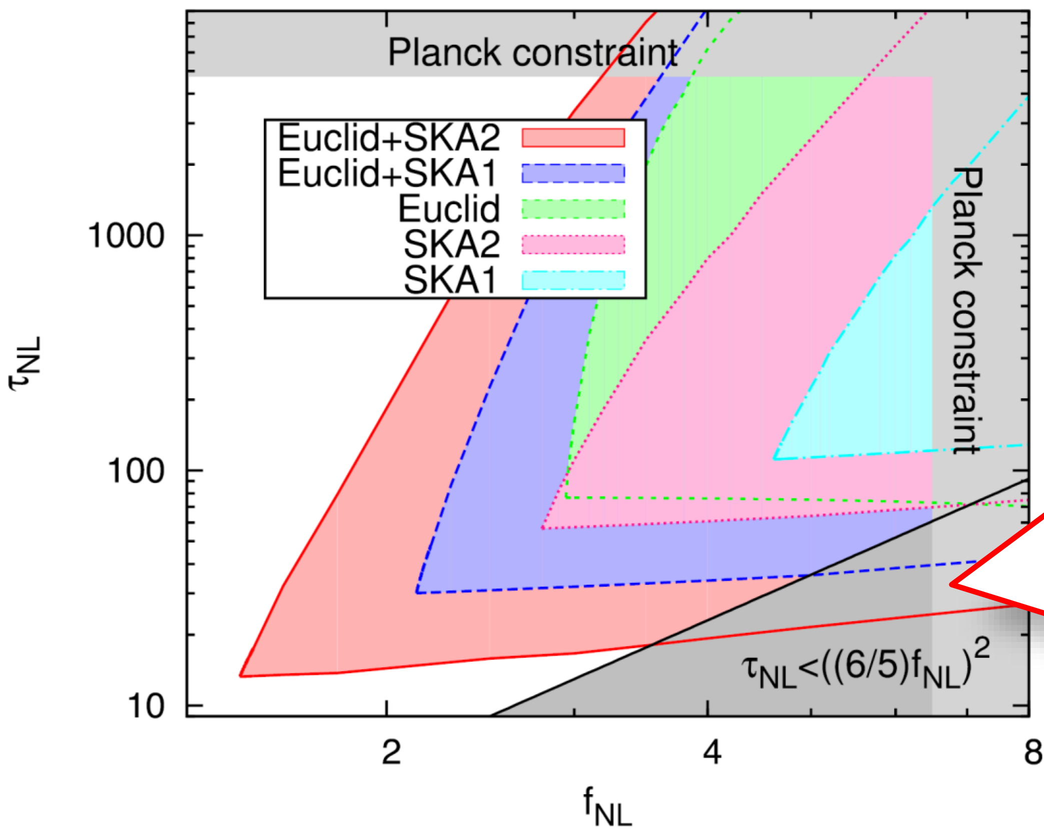


[DY+Takahashi(2015)]

Confirming Suyama-Yamaguchi ineq.

Consistency relation $\tau_{NL} \geqq ((6/5)f_{NL})^2$

[Suyama+T.Takahashi+S.Yokoyama+(2010), Suyama+Yamaguchi(2008),…]



It is possible to detect the region where the SY-inequality is **NOT** satisfied.

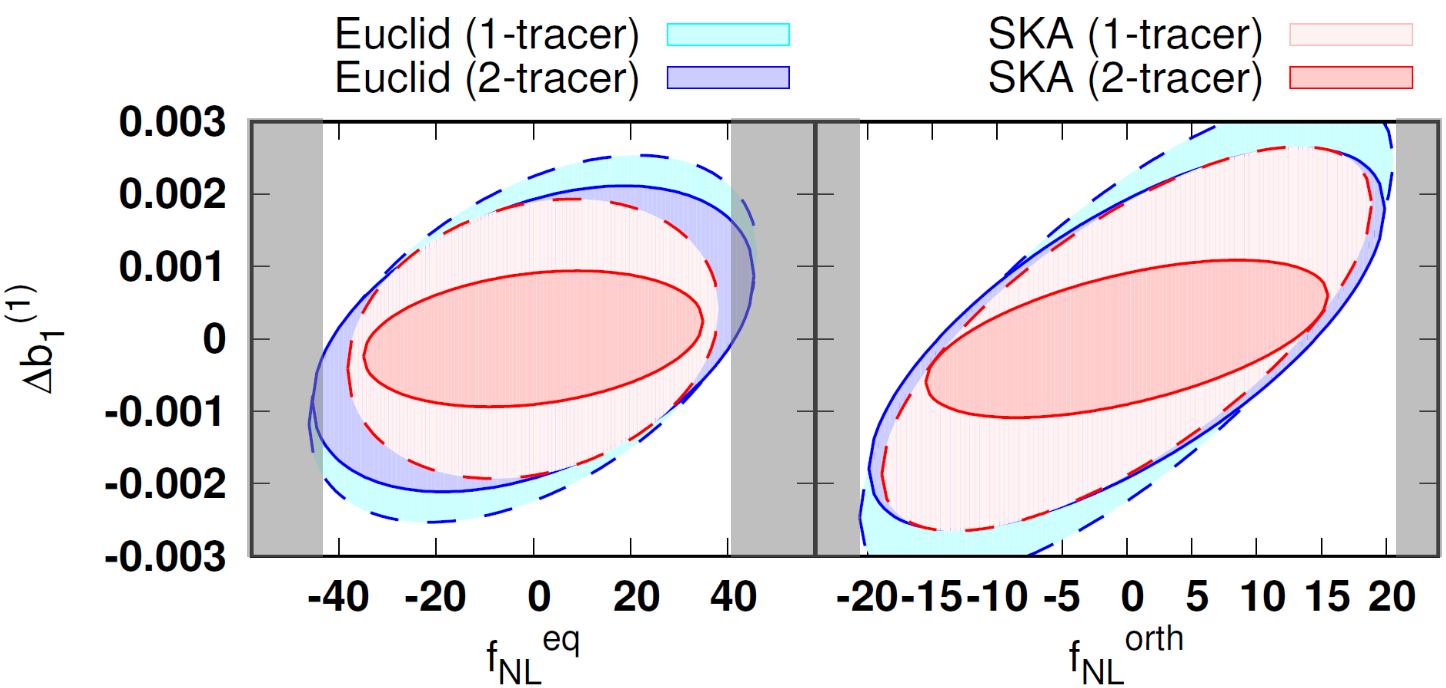
The region where **both** f_{NL} and τ_{NL} are detected at 1σ

[DY+S.Yokoyama+K.Takahashi (2016)]

Non-local f_{NL} with galaxy bispectrum

- SKA can provide the galaxy **higher-order** correlation.
- Galaxy bispectrum can constrain **non-local** PNG.

✓ **Equilateral → Sound speed** ✓ **Orthogonal → Vacuum state**



Summary

- **The SKA will be able to deliver competitive and transformational cosmology.**

- **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!

SKA1 Phase-1 Design Baselineにおける宇宙論サーベイ

サーベイ	観測時間[hr]	掃天[deg^2]	赤方偏移	サイエンス
Medium-Deep **Band2** Survey	10,000	5,000	<0.4	連続線弱重力レンズ HI銀河赤方偏移 [磁場SWGとcommensal]
Wide **Band1** Survey	10,000	20,000	0.35-3	連続線銀河サーベイ MID-HI強度マッピング [連続線SWGとcommensal]
Deep SKA1-**LOW** Survey	5,000	100	3-6	LOW-HI強度マッピング [LOW SWGとcommensal]