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

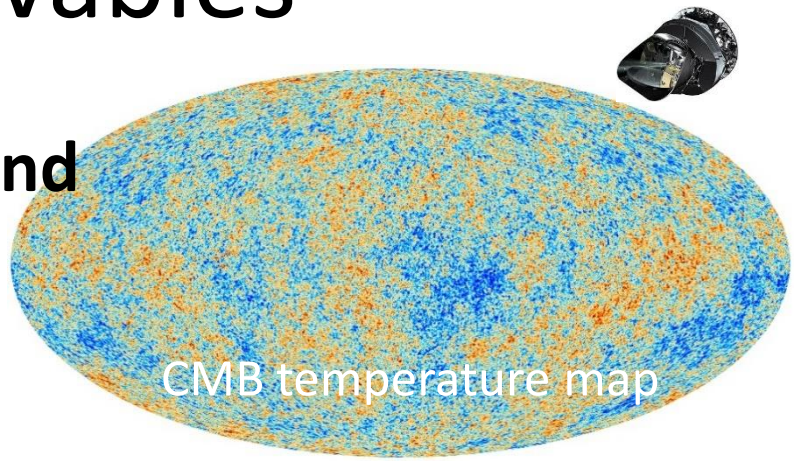
Cosmology and Dark Energy with future *HI* galaxy surveys

Daisuke Yamauchi

Kanagawa University

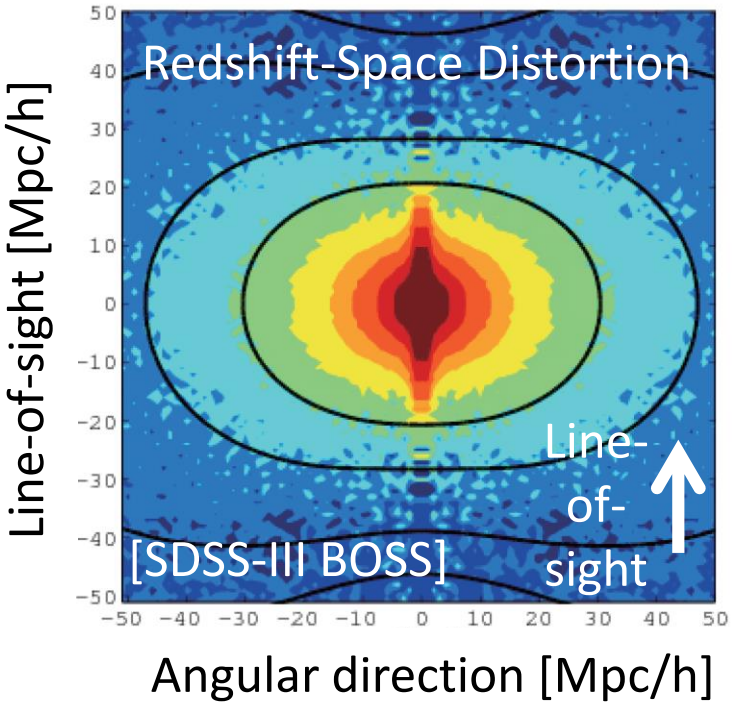
Cosmological observables

- **Cosmic Microwave Background**
  - → radio



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

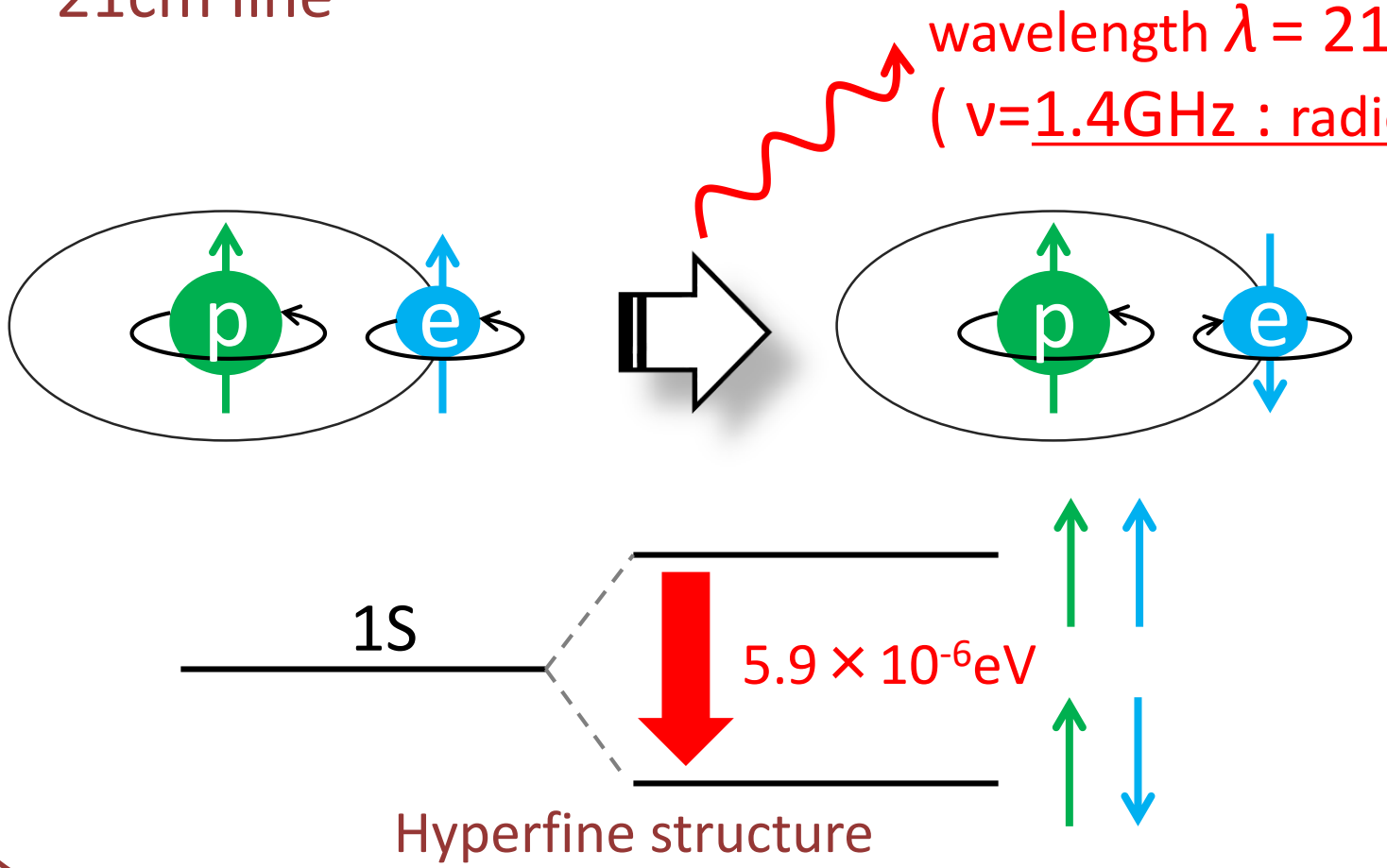
complementary



Takahashi and de Souza's talk (yesterday)

Why "radio" frequency?

- Hyperfine transition radiation of neutral hydrogen : 21cm line

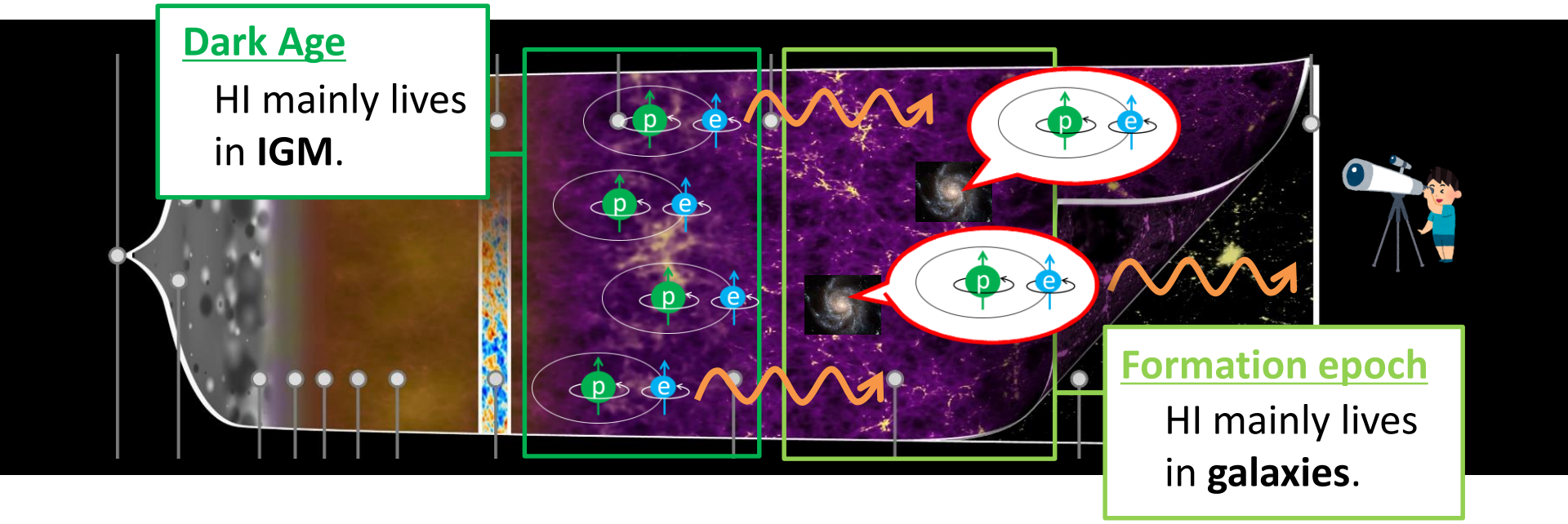


Why "radio" frequency?

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

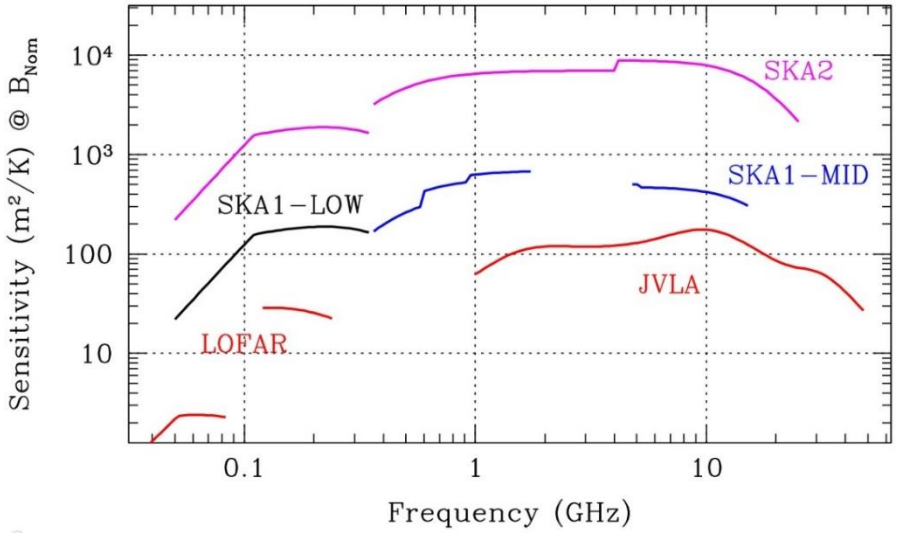
✓ **High sensitivity**

collecting area : 1km^2

✓ **Wide sky coverage**

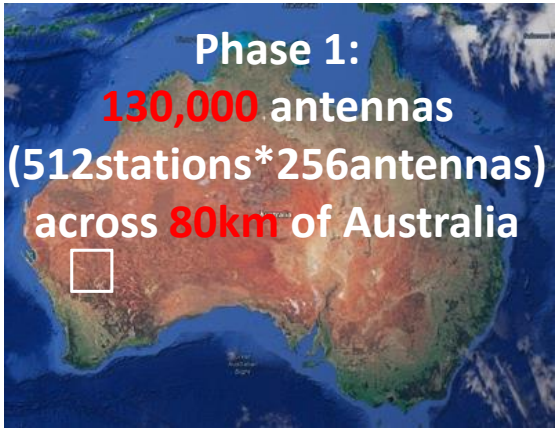
available full-sky

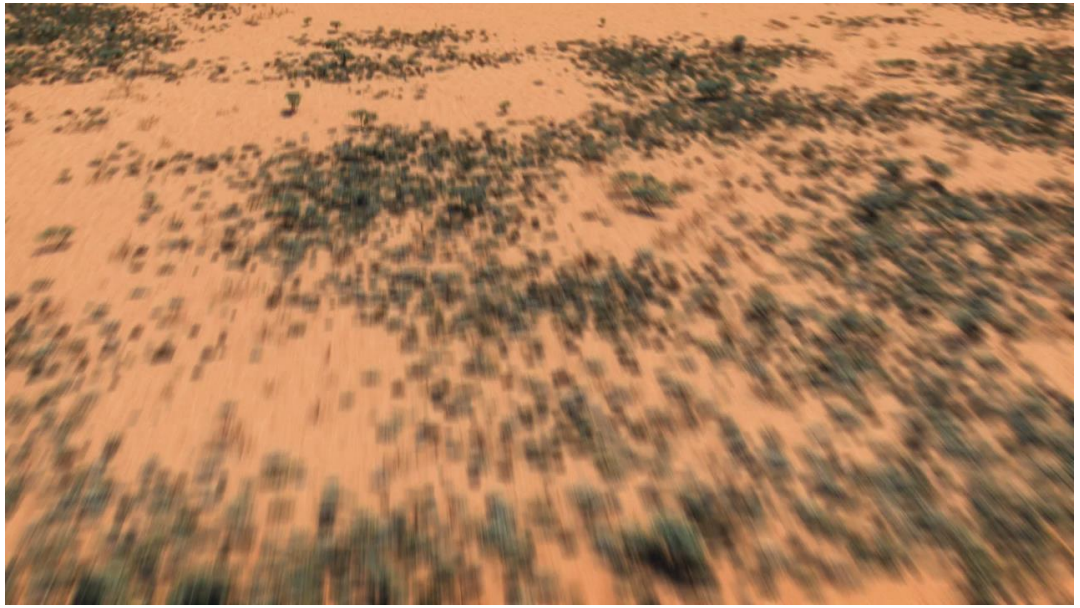
✓ **High angular resolution**



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

SKA Phase 1 (2019 – 2028)



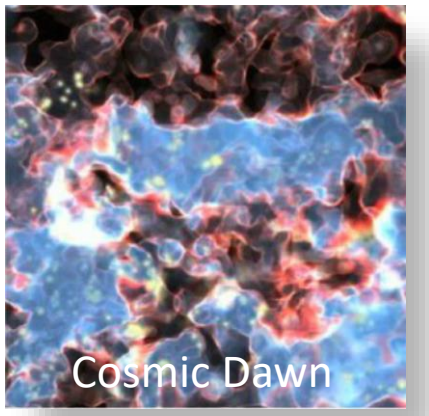


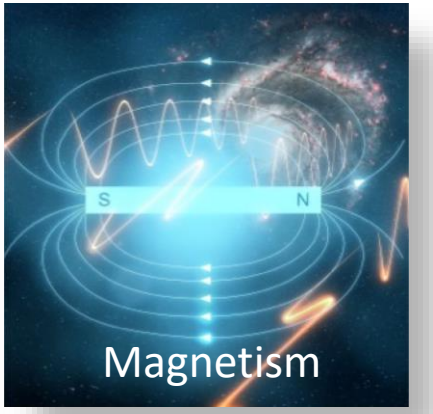
Construction will start soon!

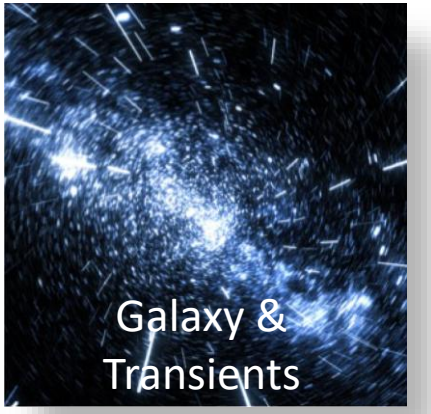
Scientific goals of SKA

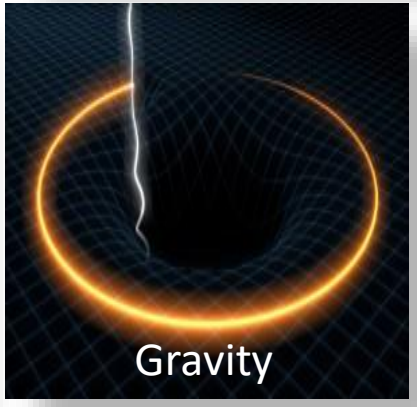
The SKA aims to solve some of the biggest questions.

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



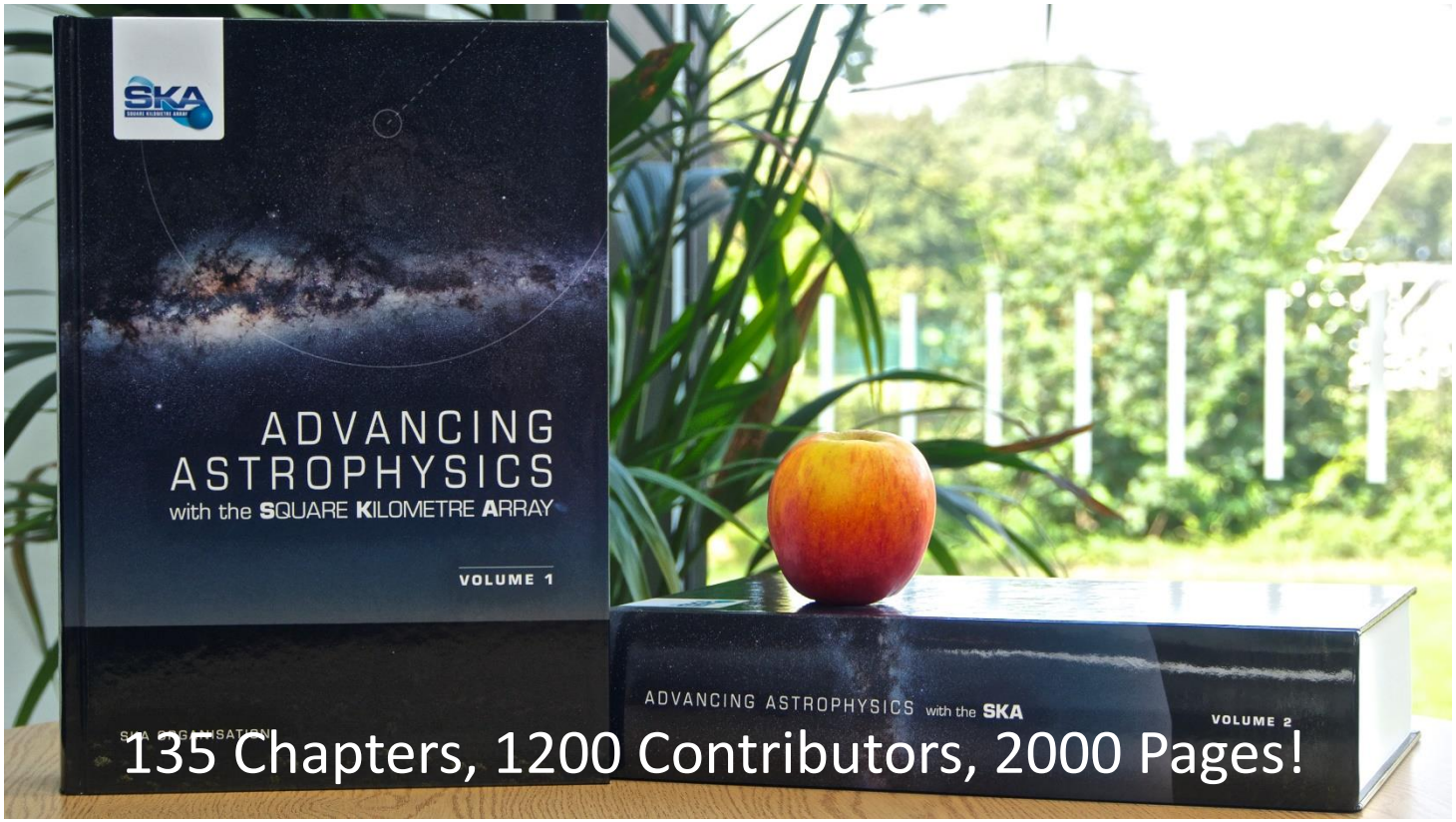






SKA Science Book/Red Book

- 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-JP
日本百万平米電波
干渉計計画協会

➢ 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

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]

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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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

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

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

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

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

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

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

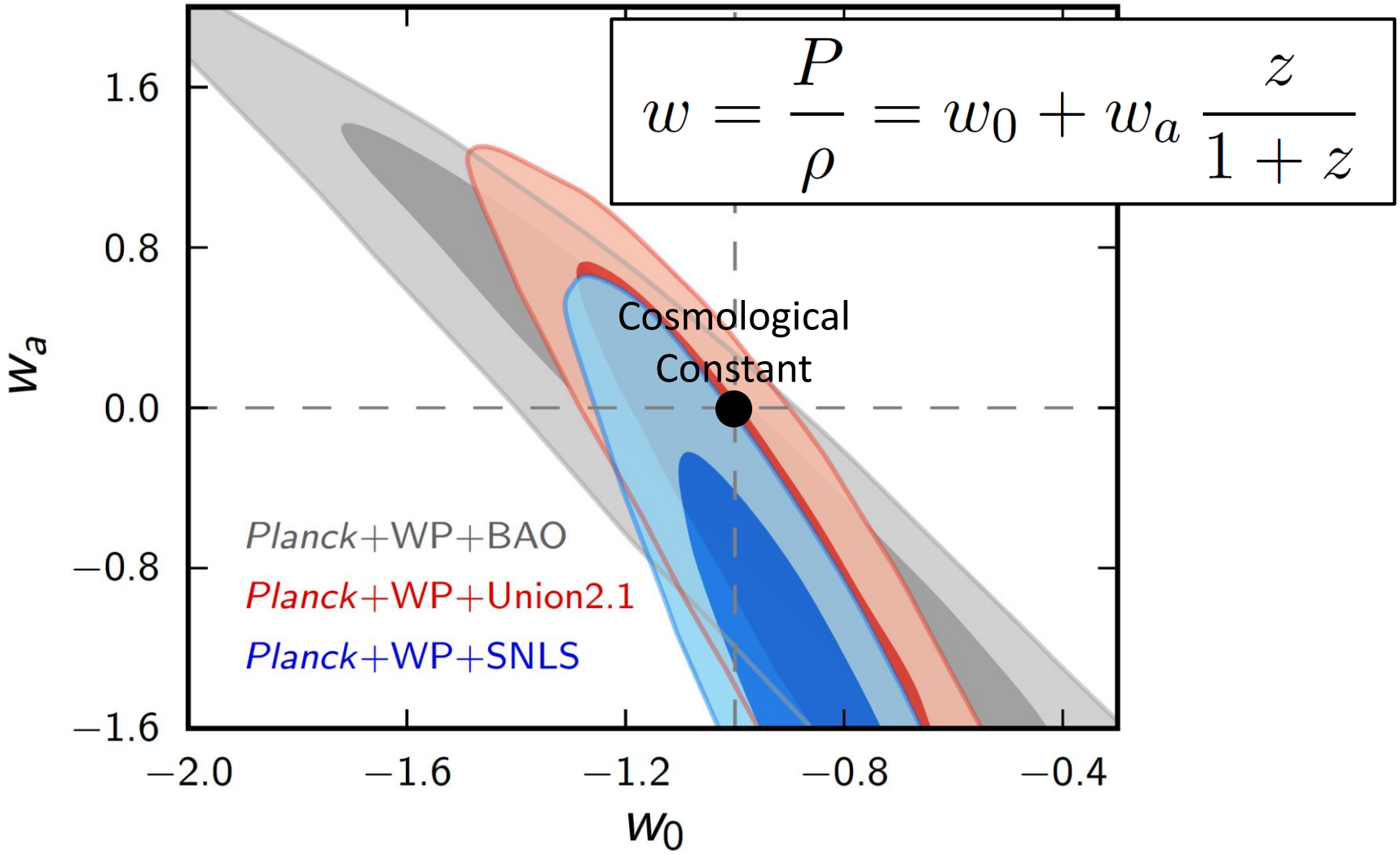
Growth index

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

[Planck XIV(2013)]

Dark Energy Equation-of-State

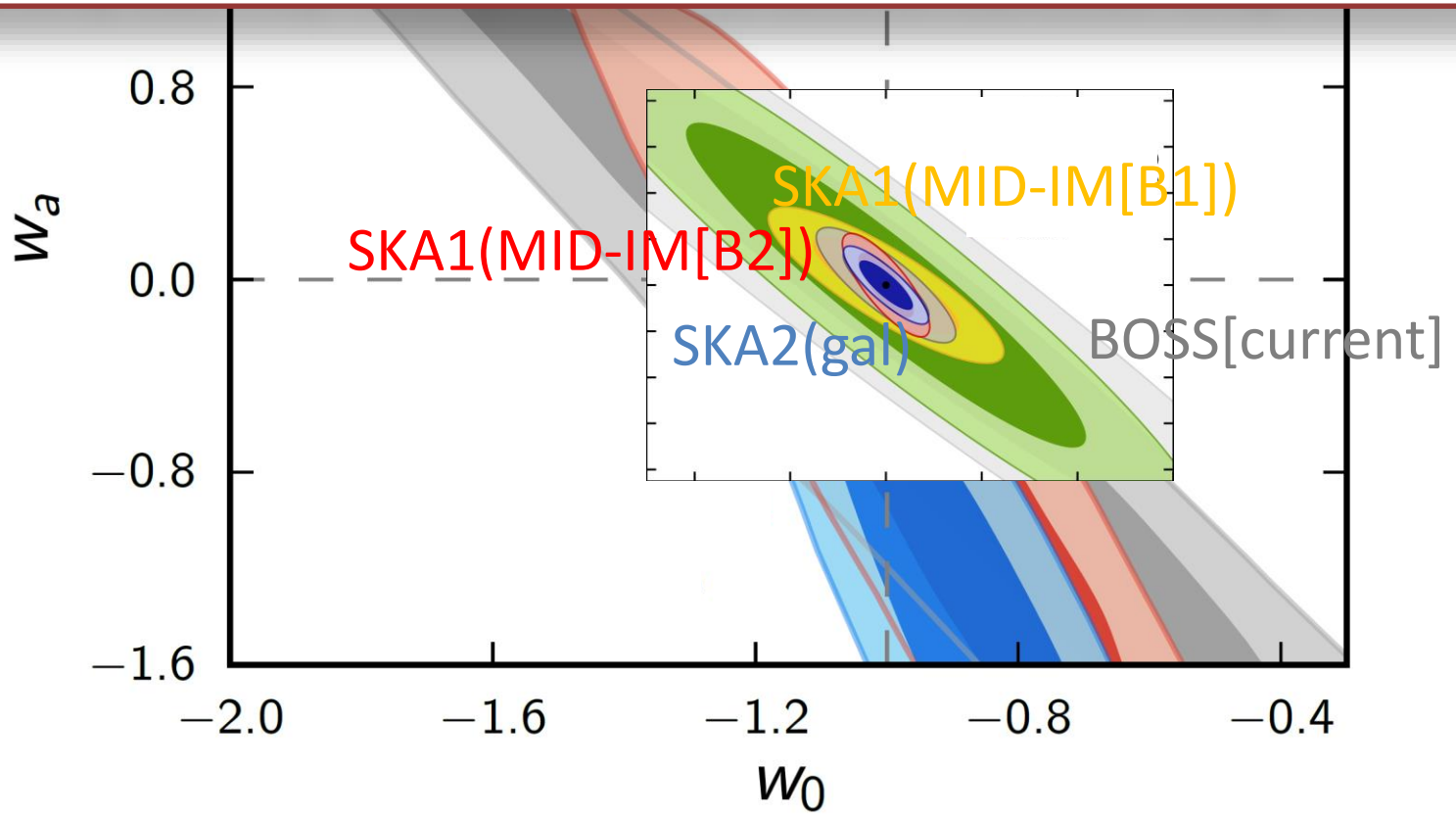
Yamaguchi's talk



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

Dark Energy **Equation-of-State**

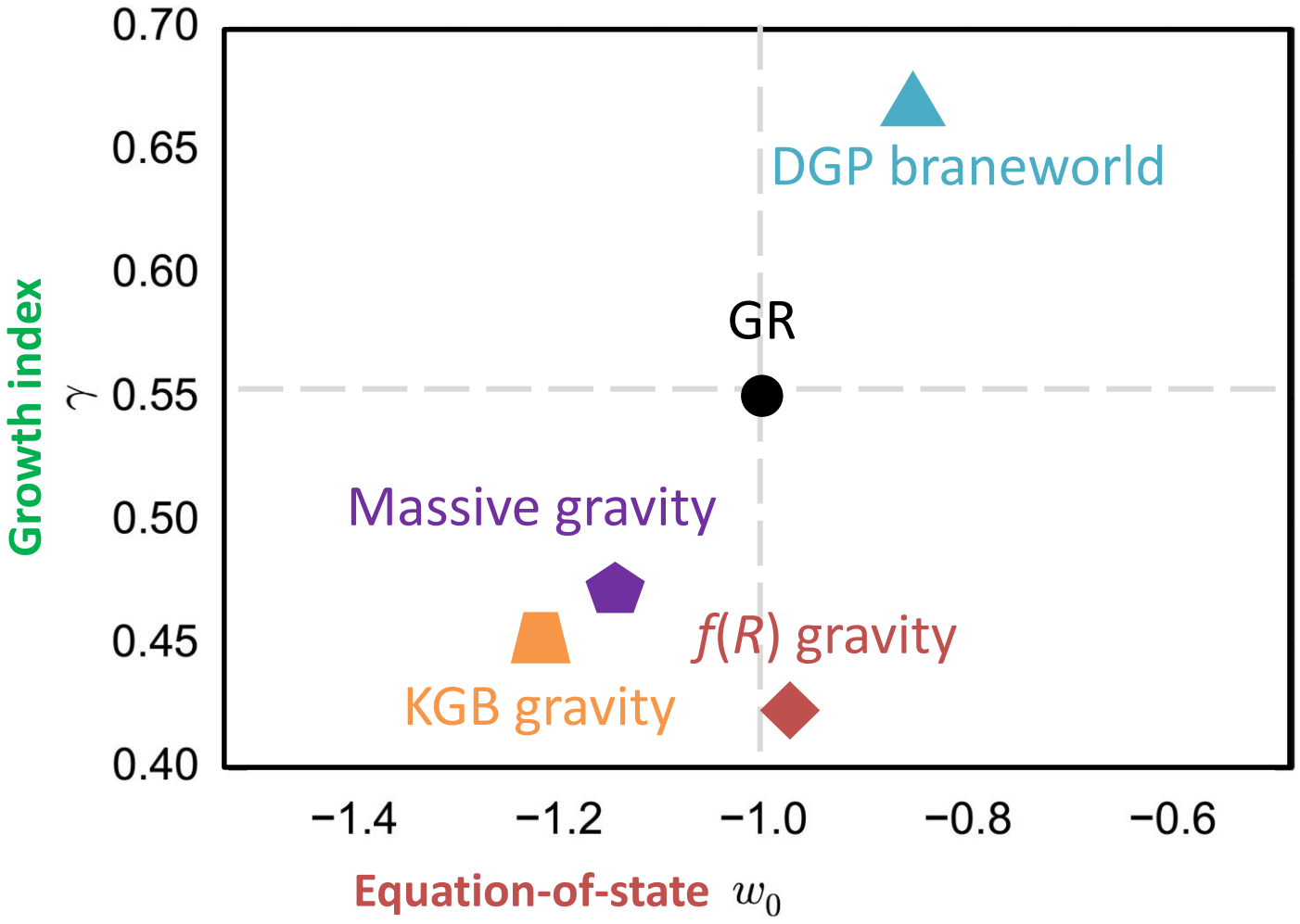
The SKA1 MID-IM survey will be able to provide comparable constraints with e.g. Euclid, and the SKA2 HI galaxy survey is expected to allow further improvements.



[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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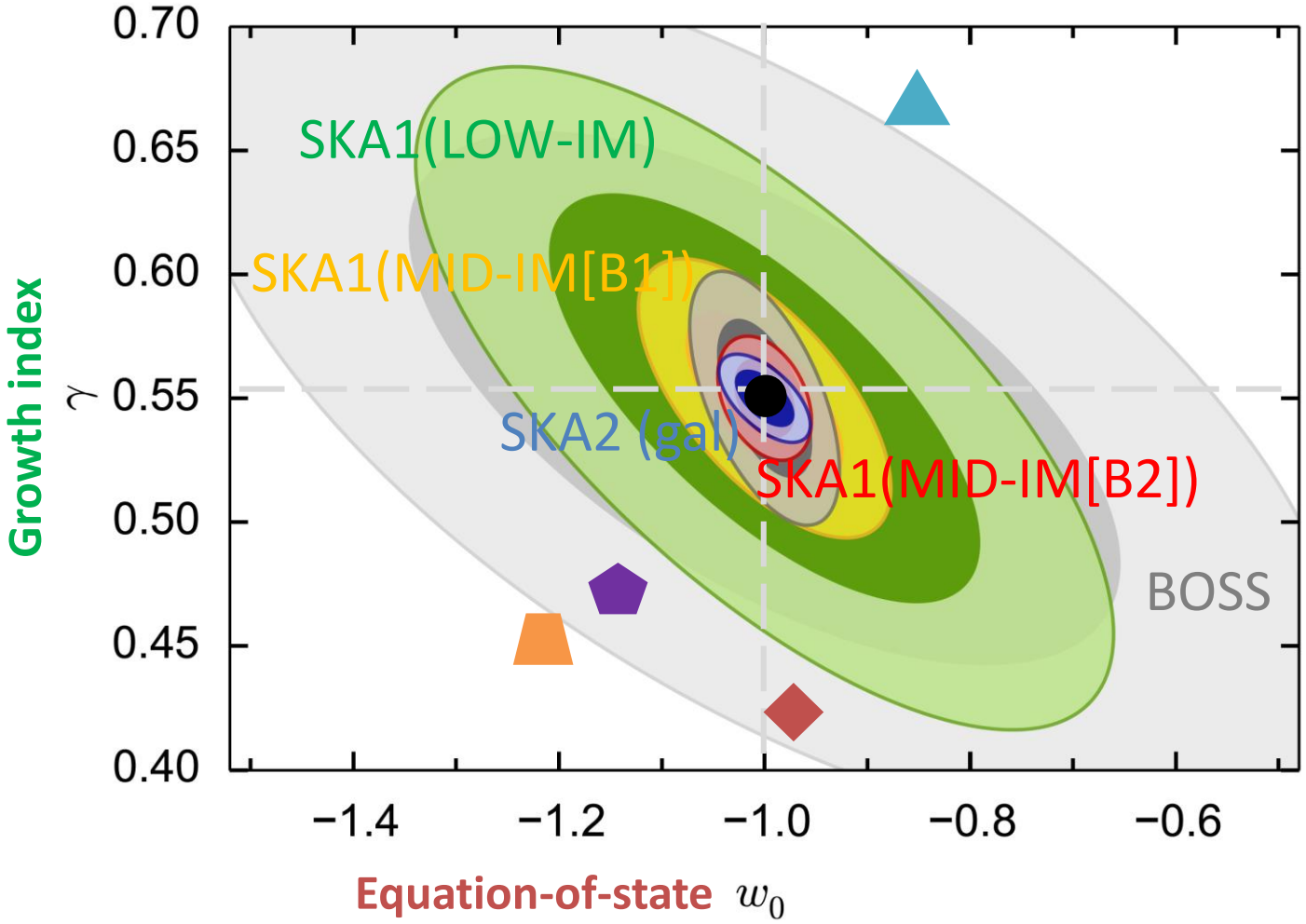


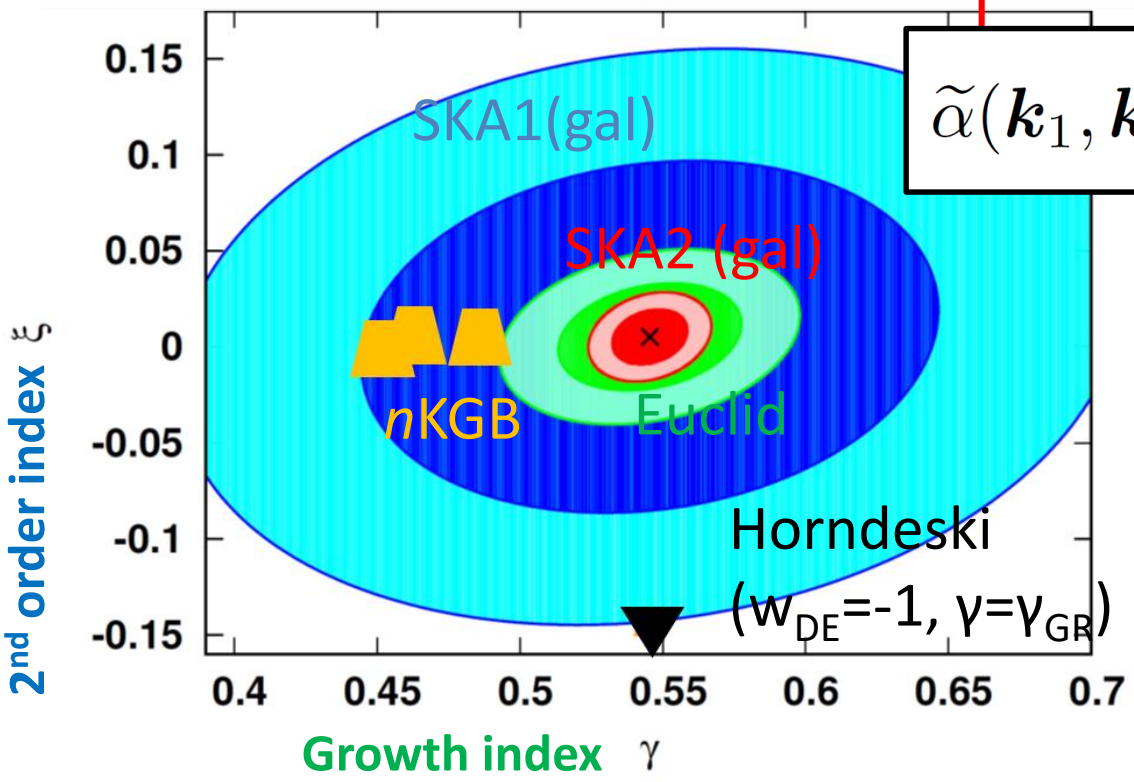
[DY+Yokoyama+Tashiro (2017)]

*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!

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

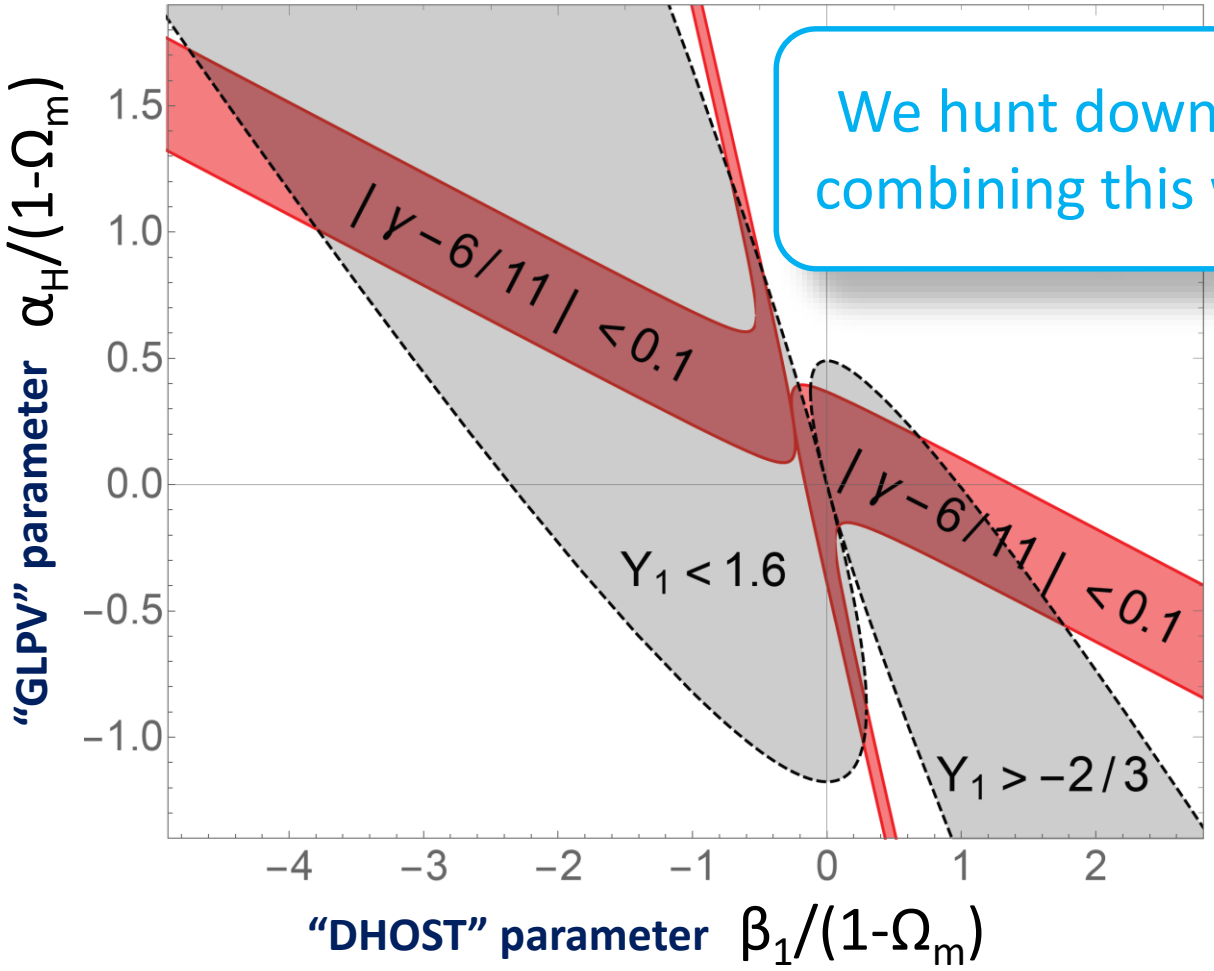
$$\mathcal{L} = F(\phi, X)\, R + A_3(\phi, X)\, \Box\phi \nabla^\mu \phi \nabla^\nu \phi \nabla_\mu \nabla_\nu \phi$$
$$+ \frac{1}{8F}\left[48F_X^2 - 8(F - XF_X)A_3 - X^2 A_3^2\right] \nabla^\mu \phi \nabla_\mu \nabla_\rho \phi \nabla^\rho \nabla^\nu \phi \nabla_\nu \phi$$
$$+ \frac{1}{2F}(4F_X + XA_3)\,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

[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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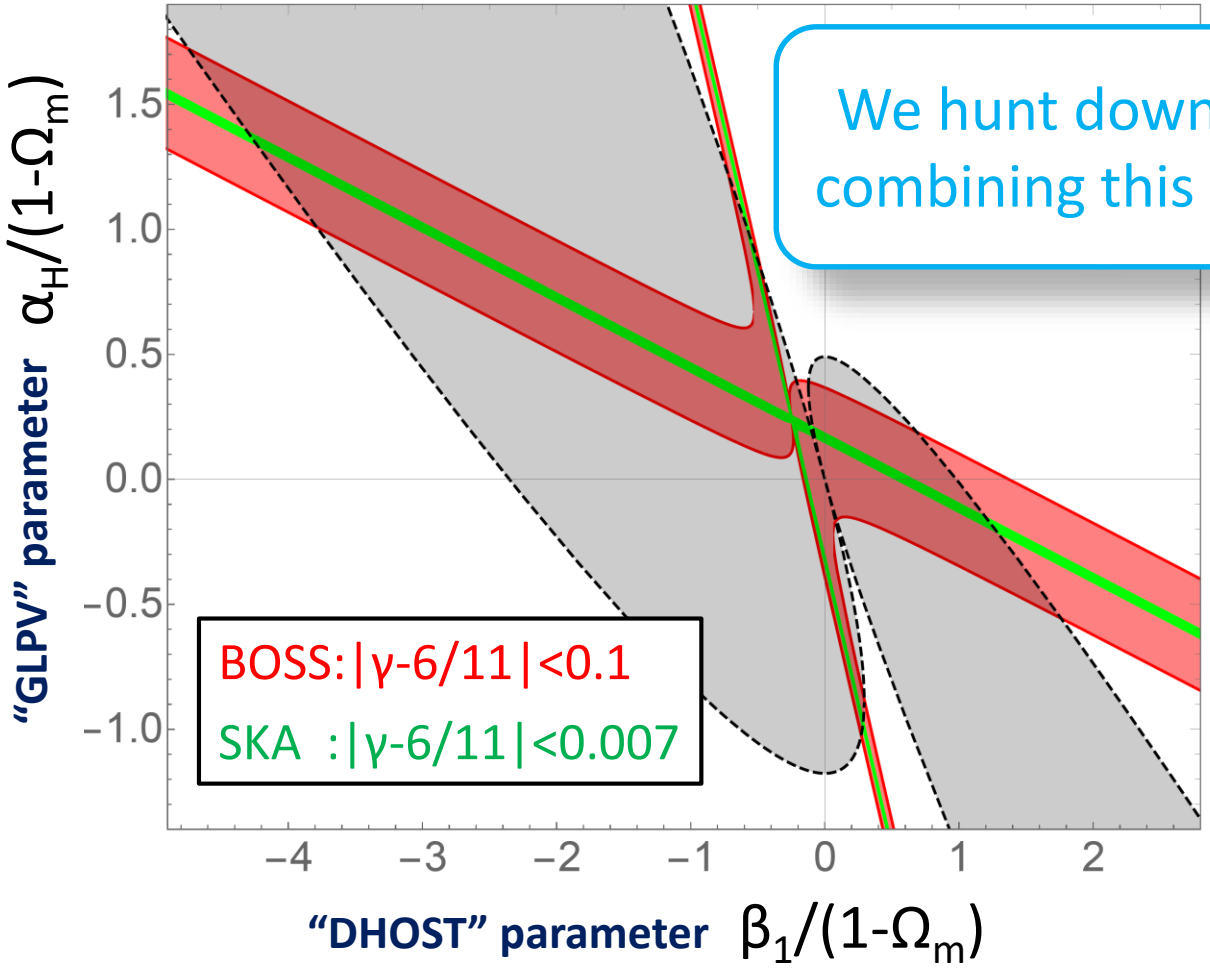

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[Gray(stellar structure): Kobayashi+**DY**+(2015), Saito+**DY**+(2015), Sakstein+(2015)]

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

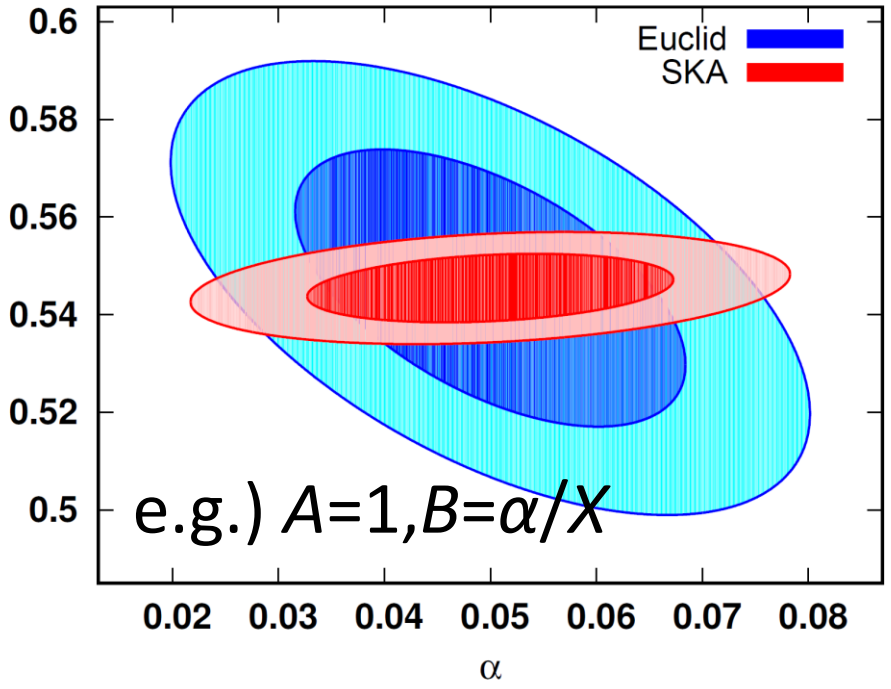
RSD and coupling between DE and DM

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

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

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

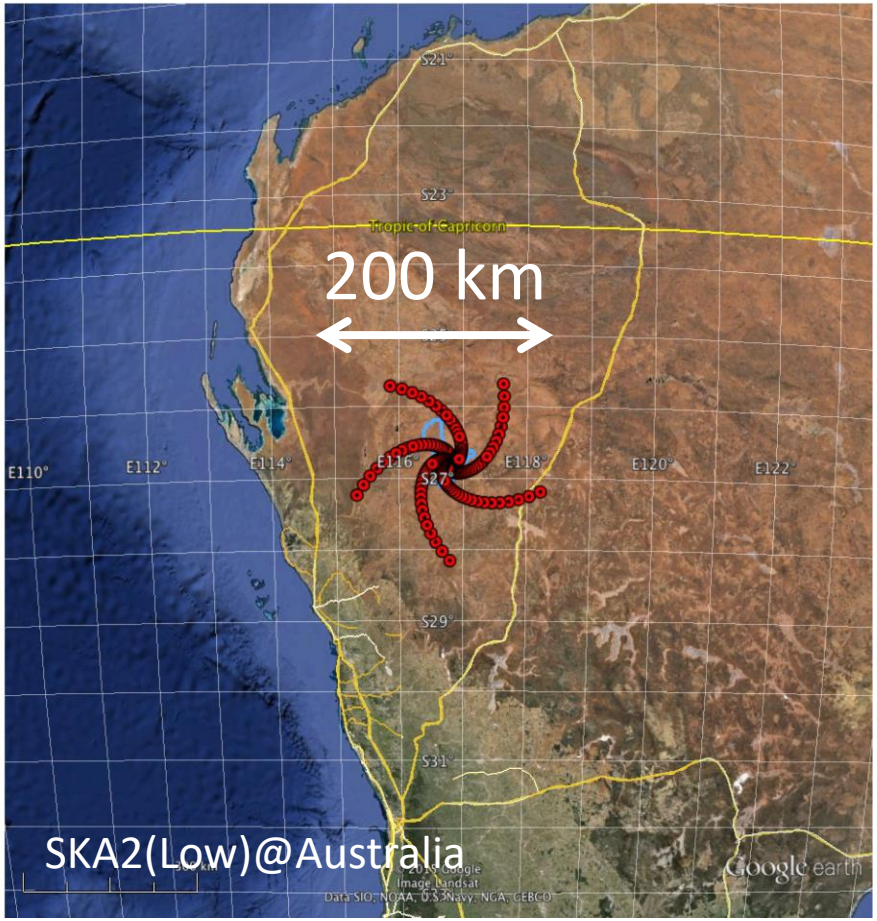
    [Namikawa+**DY**+Sherwin+Nagata (2015)]
  - With optical galaxy survey : Multitracer

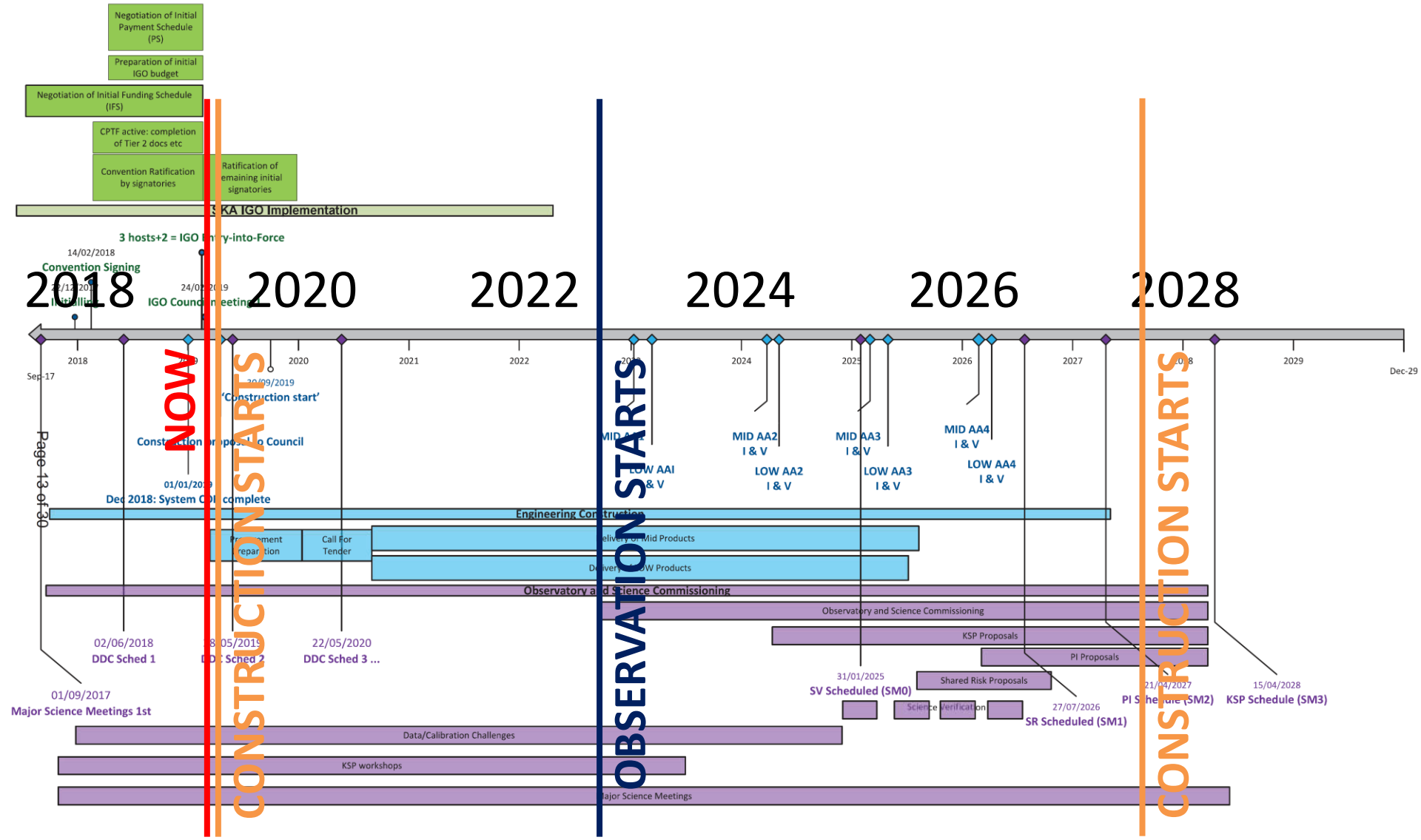
    [**DY**+ (2014), **DY**+K.Takahashi(2015), DY+Yokoyama+K.Takahashi(2016)]
  - With particle physics : Lepton asymmetry, ν,…

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

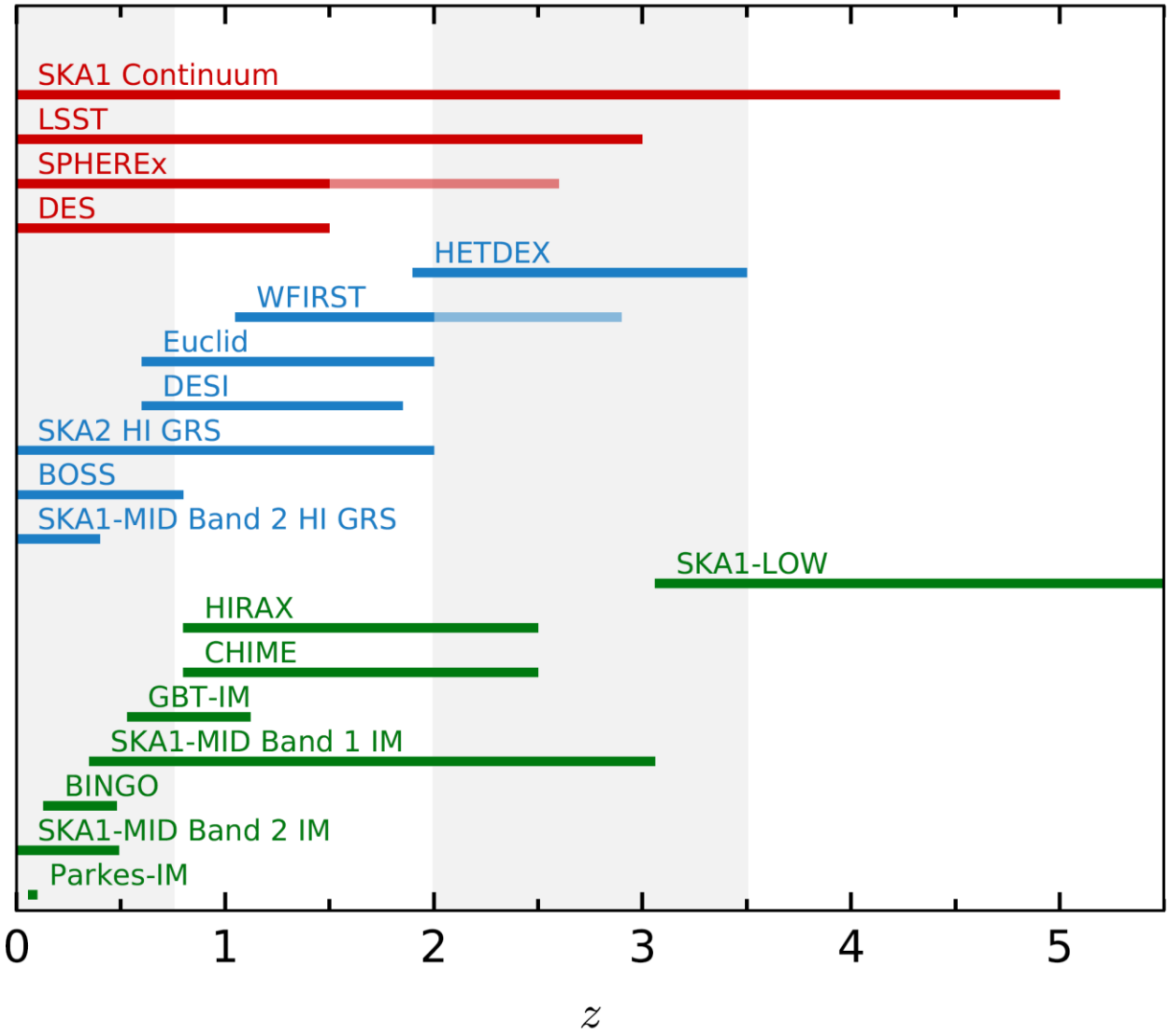
Thank you!

SKA configuration




Negotiation of Initial Payment Schedule (PS)
Preparation of initial IGO budget
Negotiation of Initial Funding Schedule (IFS)
CPTF active: completion of Tier 2 docs etc
Convention Ratification by signatories
Ratification of remaining initial signatories
SKA IGO Implementation
3 hosts+2 = IGO Entry-into-Force
14/02/2018
Convention Signing
IGO Council meeting
2018
2020
2022
2024
2026
2028
NOW
CONSTRUCTION STARTS
OBSERVATION STARTS
CONSTRUCTION STARTS
2018
2019
2020
2021
2022
2024
2025
2026
2027
2029
Sep-17
Dec-29
30/09/2019
'Construction start'
Construction proposal to Council
01/01/2019
Dec 2018: System CDR complete
MID AA2 I & V
LOW AA2 I & V
MID AA3 I & V
LOW AA3 I & V
MID AA4 I & V
LOW AA4 I & V
Engineering Construction
Call for Tender
Delivery of Mid Products
Delivery of LOW Products
Observatory and Science Commissioning
KSP Proposals
PI Proposals
Shared Risk Proposals
02/06/2018
DDC Sched 1
22/05/2020
DDC Sched 3 ...
31/01/2025
SV Scheduled (SM0)
27/07/2026
SR Scheduled (SM1)
15/04/2028
KSP Schedule (SM3)
01/09/2017
Major Science Meetings 1st
Data/Calibration Challenges
KSP workshops
Major Science Meetings

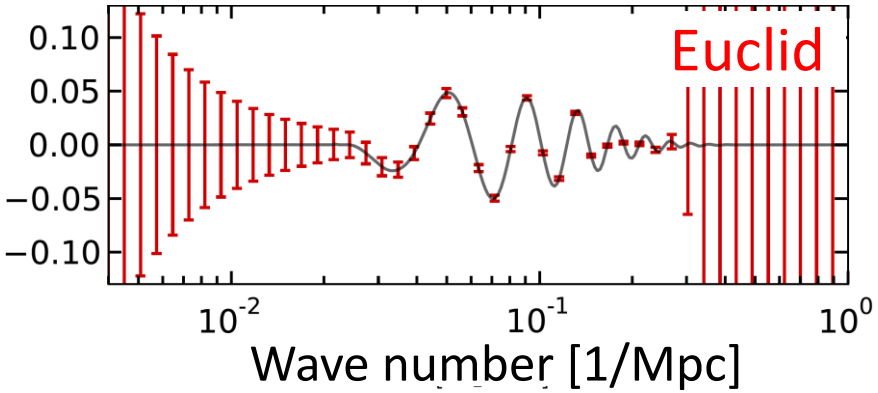
[Bull+(2018)]

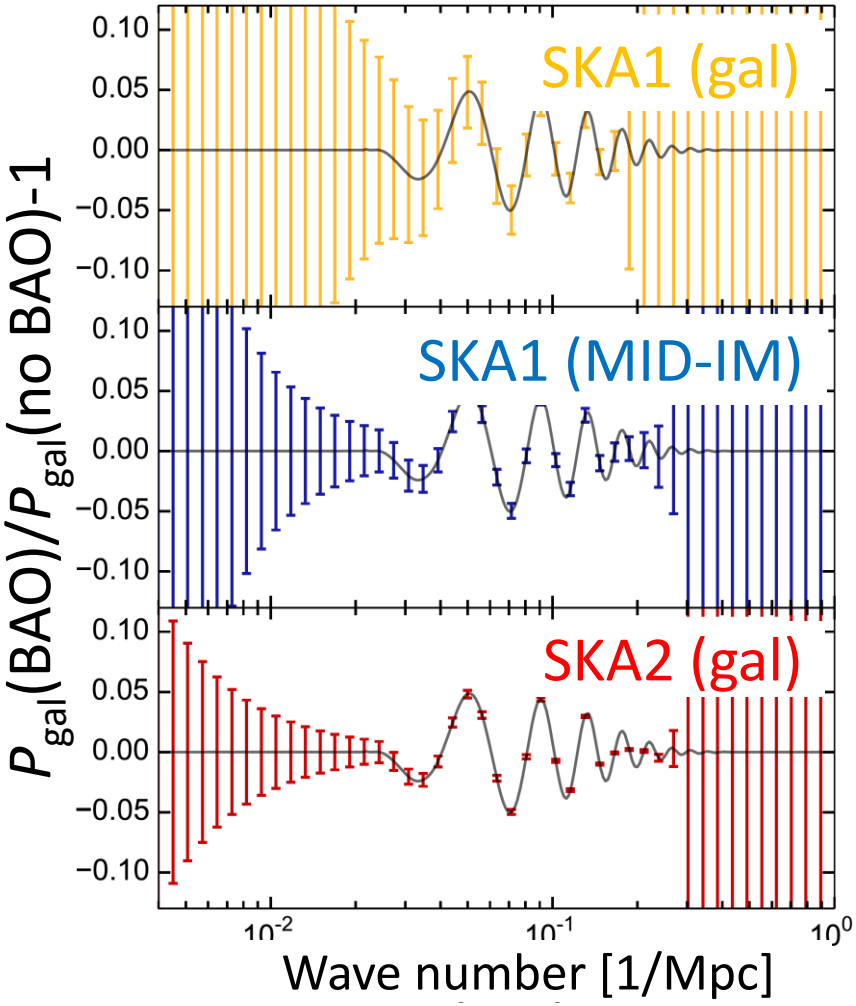

SKA1 Continuum
LSST
SPHEREx
DES
HETDEX
WFIRST
Euclid
DESI
SKA2 HI GRS
BOSS
SKA1-MID Band 2 HI GRS
SKA1-LOW
HIRAX
CHIME
GBT-IM
SKA1-MID Band 1 IM
BINGO
SKA1-MID Band 2 IM
Parkes-IM
0
1
2
3
4
5
z

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

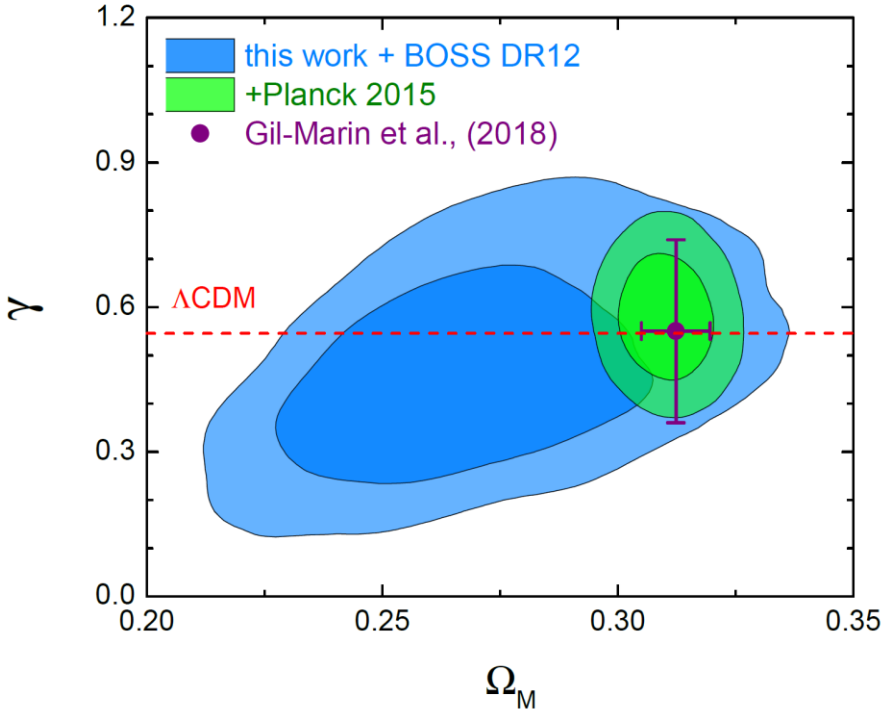
SKA constraining power

- ✓ 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

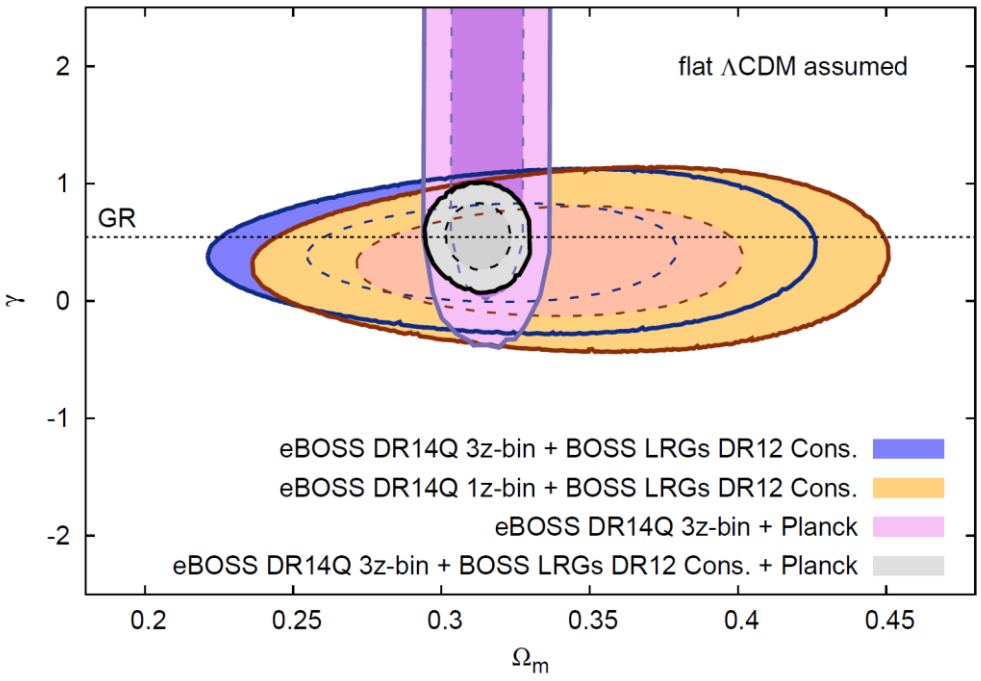




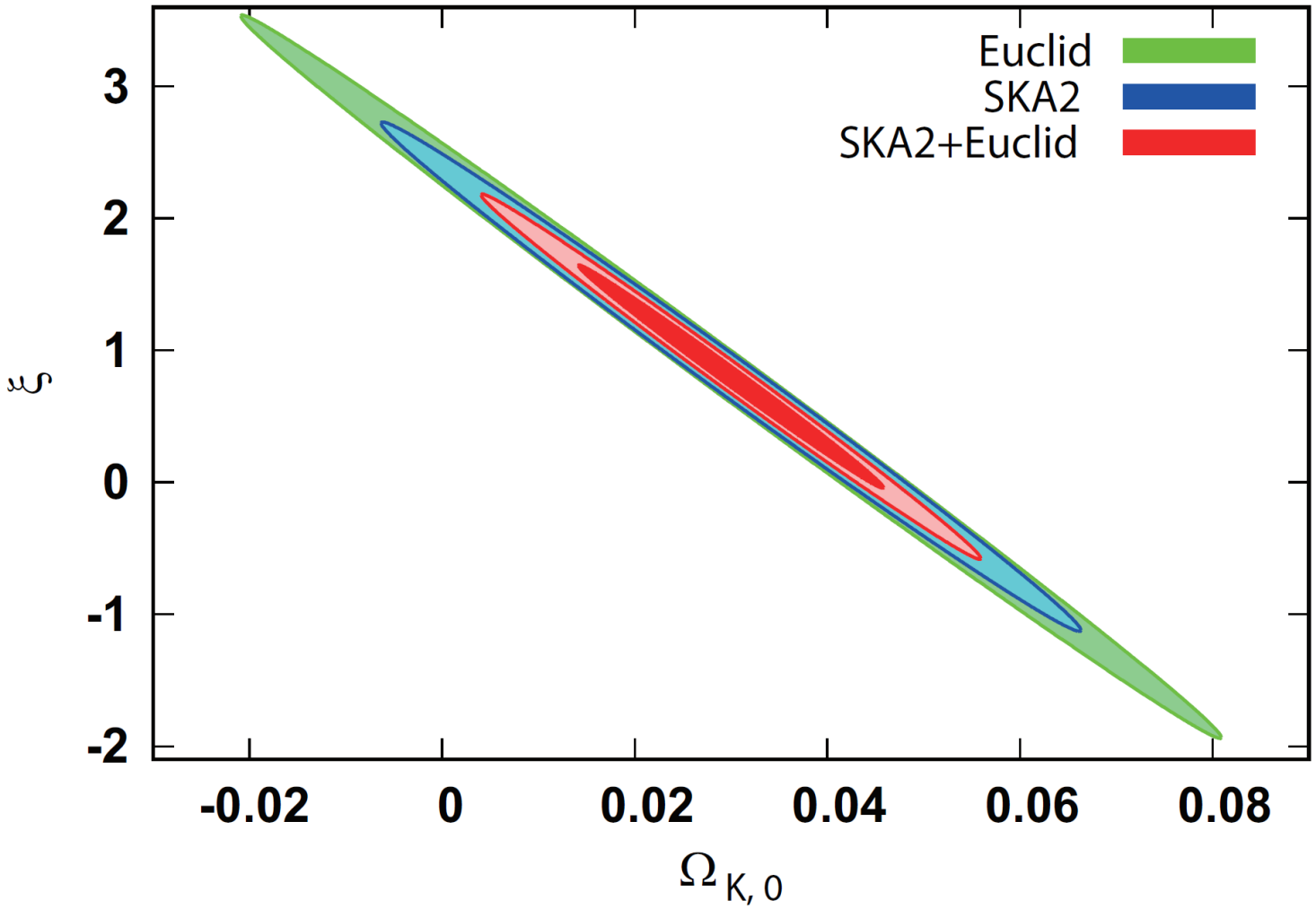
Current status : Ωm-γ plot

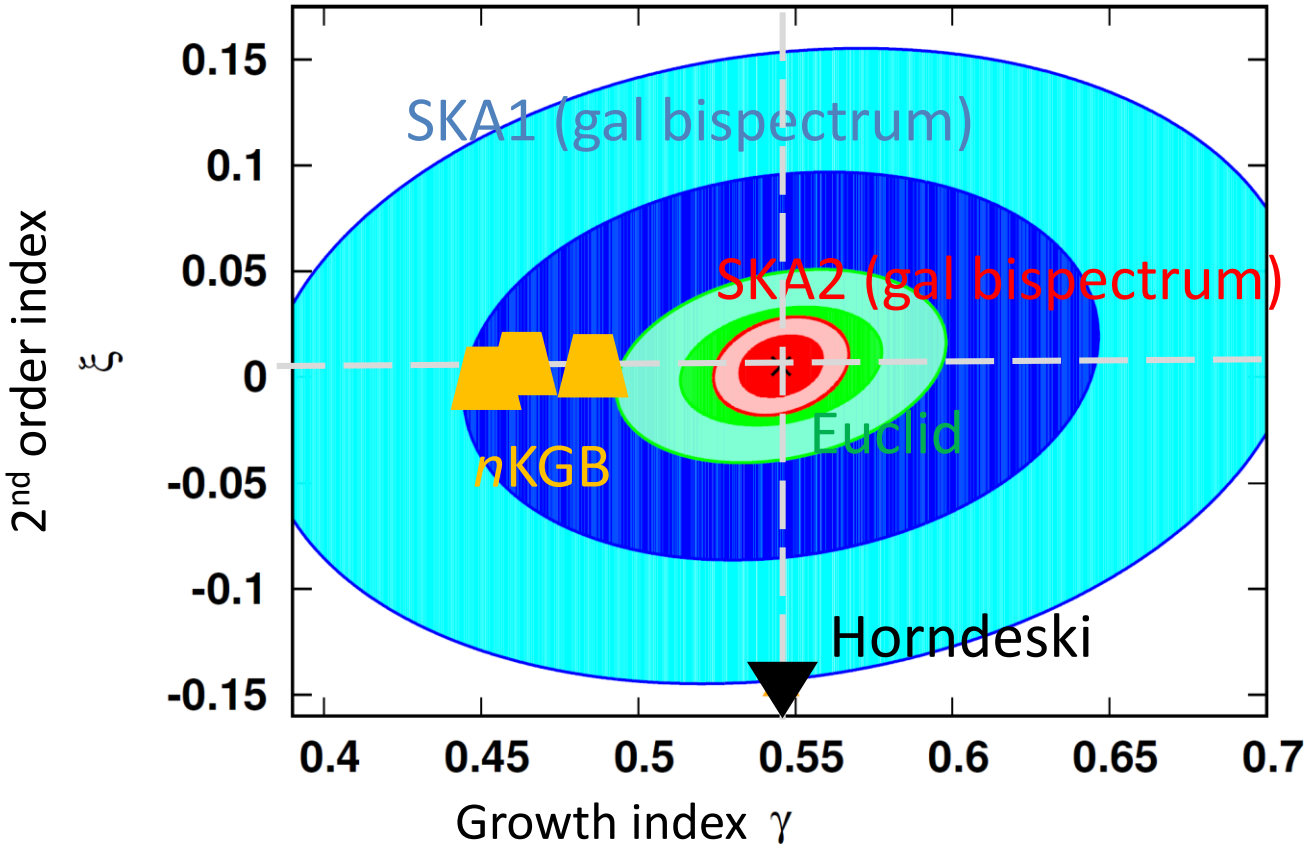


[Zhao et al.(2018)]



[Gil-Marin et al.(2018)]


Euclid
SKA2
SKA2+Euclid
3
2
1
0
-1
-2
ξ
-0.02
0
0.02
0.04
0.06
0.08
Ω K, 0


SKA1 (gal bispectrum)
SKA2 (gal bispectrum)
Euclid
nKGB
Horndeski
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
0.4
0.45
0.5
0.55
0.6
0.65
0.7
2nd order index ξ
Growth index γ