2015/12/14 Dark Side of the Universe 2015 @YITP

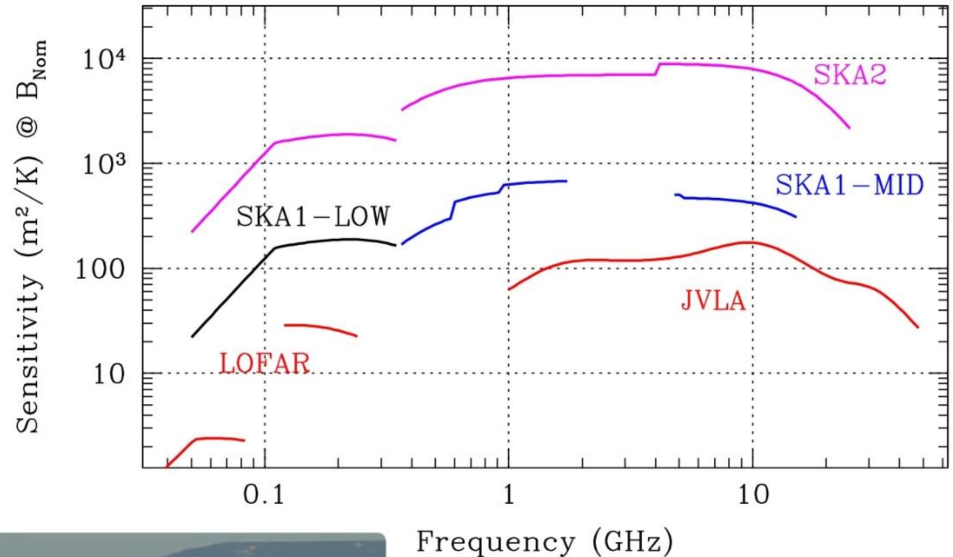
Cosmology with the Square Kilometre Array (by SKA-Japan)

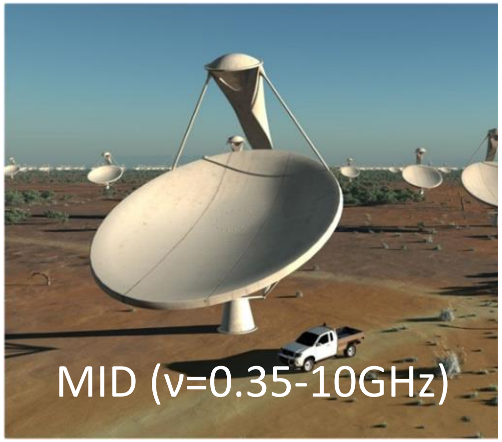
Daisuke YAMAUCHI

Research Center for the Early Universe,
The University of Tokyo,
On behalf of SKA-Japan Consortium (SKA-JP)
Cosmology SWG

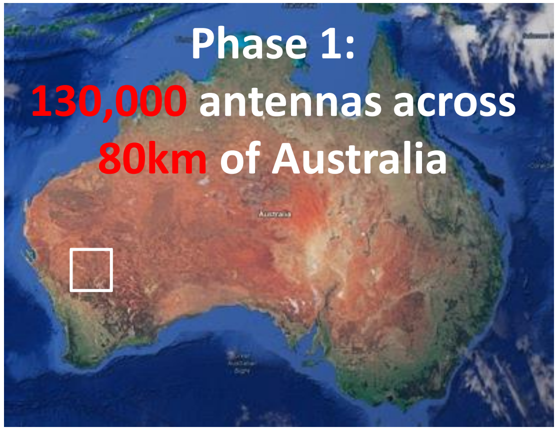
Square Kilometre Array

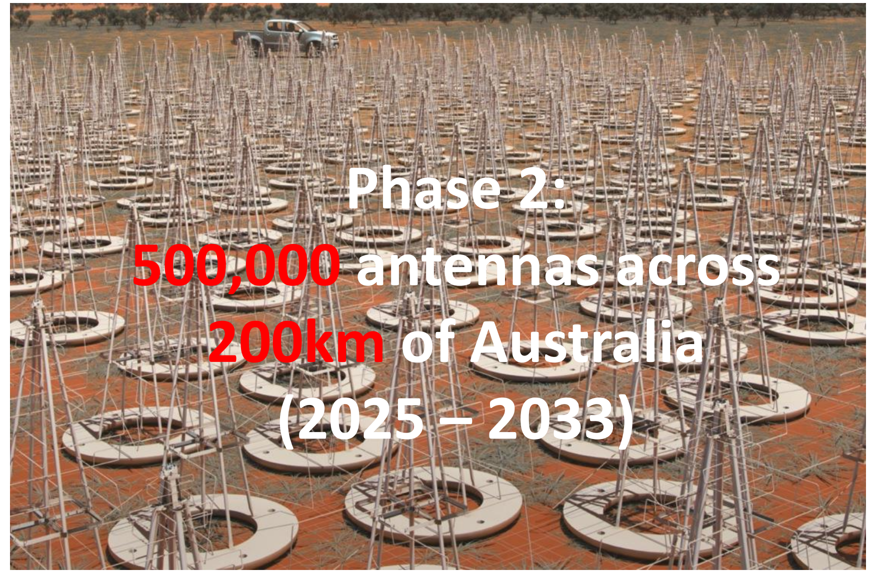
- ➢ Open a new window for Astronomy
  - ✓ New frequency regime
  - ✓ Wide sky coverage
  - ✓ high angular resolution
  - ✓ High sensitivity

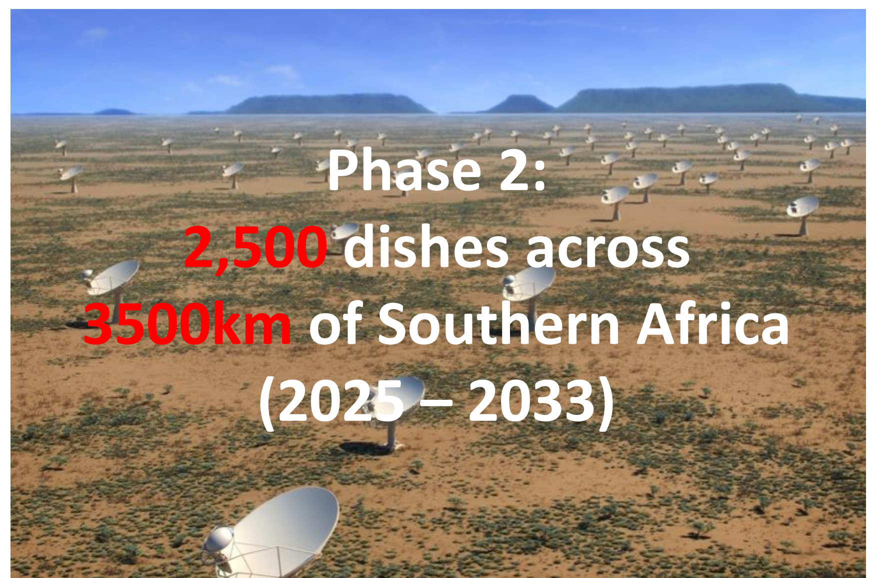




SKA Phase 1
(2018 – 2023)



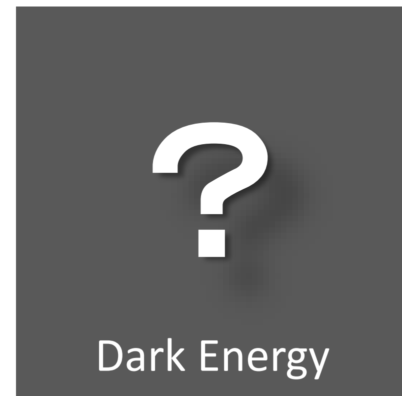


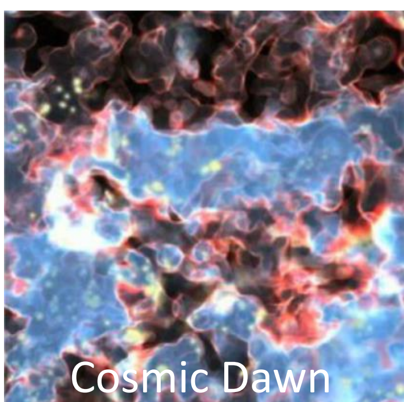


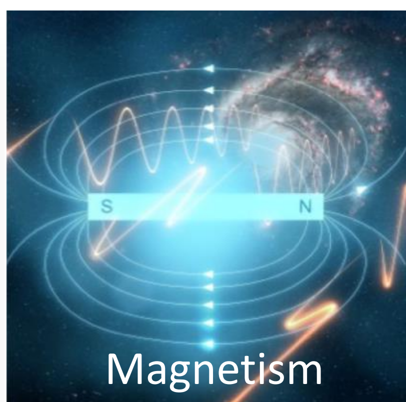
Scientific goals of SKA

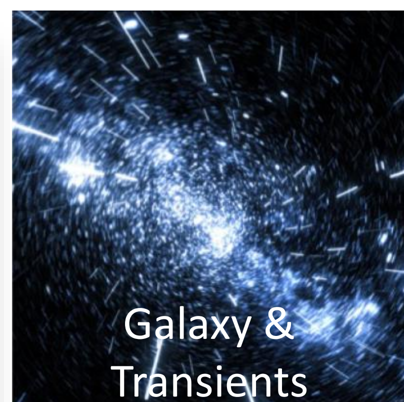
The SKA aims to solve some of the biggest questions.

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



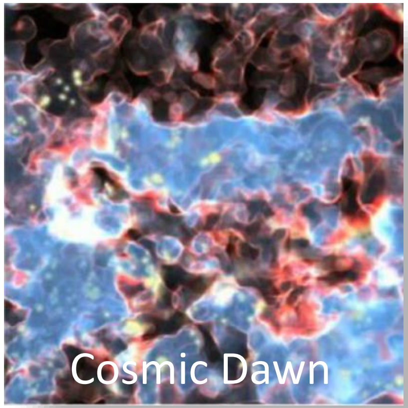


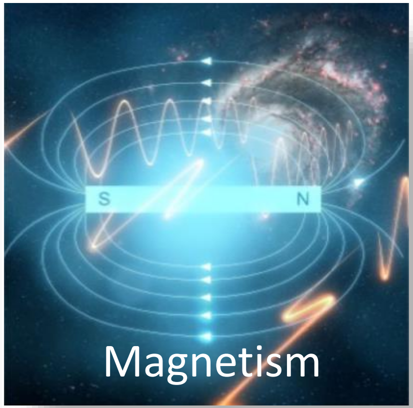


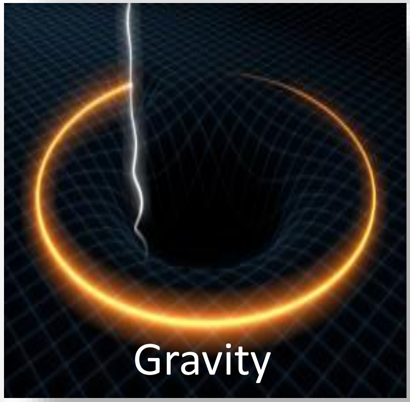


Science WG of global SKA

- (Global) Science working group
  - ✓ Epoch of Reionization
  - ✓ Continuum
  - ✓ Cosmology
  - ✓ Cradle of life
  - ✓ HI galaxy science
  - ✓ Magnetism
  - ✓ Pulsars
  - ✓ Transients
- Focus group Our galaxy, Spectral lines, VLBI







SKA-Japan Consortium

[187 members (Sep.2015)]

SKA-JP
日本百万平米電波
干渉計計画協会

Chair :
Sugiyama Nagoya U

Advisors :
Kobayashi NAOJ Honma NAOJ

Vice Chair :
Akahori* Kagoshima U
Takahashi* Kumamoto U

Publicity :
Nakanishi* Kagoshima U

Funding :
Imai* Kagoshima U

(*)global SKA SWG

Engineering WG :
Aoki* Waseda U

- **Software :** Kurayama Teikyo
- **Feed :** Ujihara NICT
- **Signal process :** Nakanishi* Kagoshima U
- **Industry forum :** Kumazawa Toyo corp.

Industry

Science WG :
Ichiki* Nagoya

- **High-z galaxies :** Hirashita ASIAA
- **Cosmology :** Yamauchi* U Tokyo
- **Reionization :** Hasegawa* Nagoya U
- **Galaxy evolution :** Takeuchi* Nagoya U
- **Pulsars :** Takahashi* Kumamoto U
- **Astrometry :** Imai* Kagoshima U
- **Interstellar medium :** Tachihara* Nagoya U
- **Transients :** Aoki* Waseda U
- **Magnetism :** Machida Kyushu U

SKA-Jn Consortium

[187 members (Sep.2015)]

SKA-JP
日本百万平米電波干渉計計画協会

Chai
Sugiyama

Advisors:
Kobayashi NAOJ Honma NA

Vice
Akahori*
Takahashi

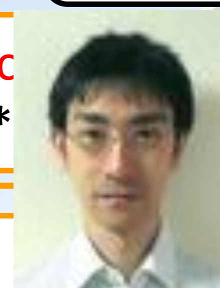
Publi
Nakanishi* U

Fund
Imai* Kag

(*)global
SKA SWG

Engineering WG:
Aoki* Waseda U

Scienc
Ichiki*



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Machida Kyushu U

SKA-Japan Science Book

SKA-JP
日本百万平米電波干渉計計画協会

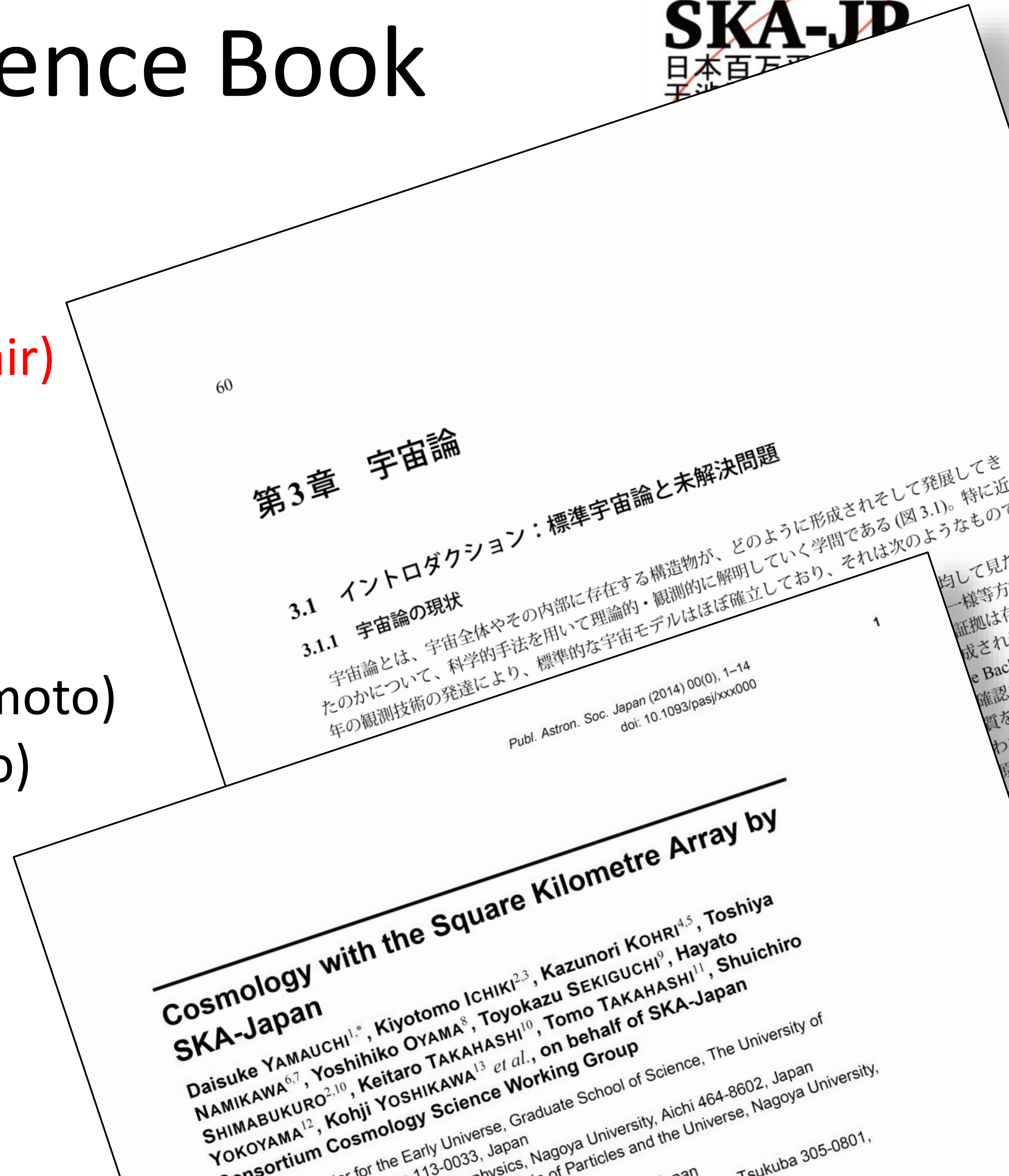
- In Japanese (published; 316 pages)
    1. Introduction
    2. Reionization
    3. Cosmology
    4. Galaxy Evolution
    5. Pulsars
    6. Cosmic Magnetism
    7. Astrometry
    8. Interstellar Medium
    9. Transients
    10. Summary
- Now being translated in English

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

SKA-Japan Science Book

- SKA-JP Cosmology SWG

  D. Yamauchi (Tokyo, Chair)
  K. Ichiki（Nagoya）
  K. Kohri (KEK, Sokendai)
  Y. Oyama (ICRR)
  T. Sekiguchi (Helsinki)
  H. Shimabukuro (Kumamoto)
  K. Takahashi (Kumamoto)
  T. Takahashi (Saga)
  S. Yokoyama (Rikkyo)
  K. Yoshikawa (Tsukuba)



Plan

1. Introduction

2. **Cosmology with the SKA**
   : brief review

3. **Cosmology with the SKA**
   by SKA-JP Cosmology SWG

4. **Summary**

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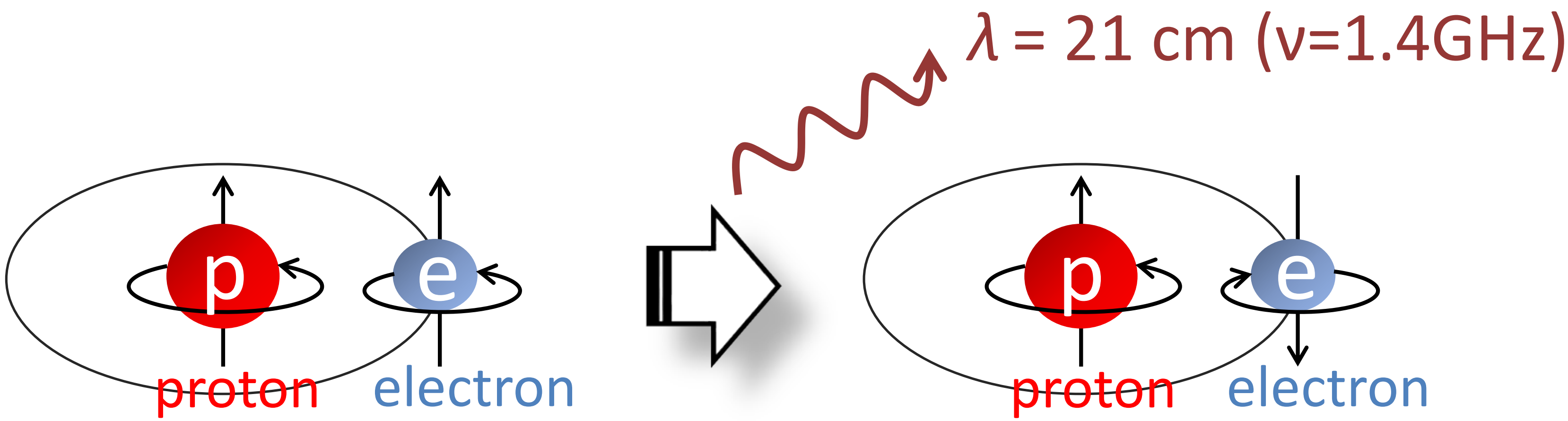
Hydrogen 21cm-line



- Hyperfine transition of neutral hydrogen (HI)
- Characteristic line emission with λ=21cm
- HI mainly lives inside galaxies (after the Universe has reionized)

⇨ Can be used as a (biased) tracer of the 3D structure of the Universe

➢ *HI survey*

✓ HI galaxy redshift survey

- The redshifting of HI-line provides the redshift info of galaxies.
- The 3D matter distributions can be reconstructed.

✓ HI intensity mapping survey [*after* CD/EoR]

- A novel technique to prove the large-scale structure. [Chang+(2010)]
- The detection of individual galaxies is not required.
- The integrated HI intensity of several galaxies in one pixel is measured.

✓ HI intensity mapping survey [*during* CD/EoR]

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

➢ *Radio continuum survey*

- Measure galaxy synchrotron radiation radio emissions, which is also treated as a tracer of the large-scale structure.
- In the SKA era, the sufficient number source density will be expected.

Observables	Surveys	SKA Phase	Redshifts	Coverage (deg^2)	Galaxy number
HI 21cm line	HI galaxy redshift survey	Phase-1	$z<0.8$	5,000	$\sim 10^7$
		Phase-2	$z<2$	**30,000**	$\sim 10^9$
HI 21cm line	HI intensity mapping	**Phase-1**	$z<3$	**30,000**	--
		Phase-2	$z<3.7$	30,000	--
synchrotron rad.	Radio continuum	**Phase-1**	$z<6$	**30,000**	$\sim 10^8$
		Phase-2	$z<6$	30,000	$\sim 10^9$
synchrotron rad.	Weak lensing	Phase-1	$z<3$	5,000	3 [$arcmin^{-2}$]
		Phase-2	$z<6$	30,000	10 [$arcmin^{-2}$]
optical/IR	e.g. Euclid		$z<2$	15,000	$\sim 10^8$

$\Delta\nu/\nu = 0.3$ @ 0.8-1.7[GHz], $\Delta\theta = 1$ [arcsec], $t_{int} = 10^4$ [hour]

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HI 21cm line	***HI intensity mapping***	**Phase-1**	$\mathbf{z<3}$	**30,000**	**--**
		Phase-2	$z<3.7$	30,000	--
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synchrot rad.					3 [$arcmin^{-2}$]
					10 [$arcmin^{-2}$]
optical/IR	**e.g. *Euclid***		$z<2$	15,000	$\sim 10^8$

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

$\Delta\nu/\nu = 0.3$ @ 0.8-1.7[GHz], $\Delta\theta = 1$ [arcsec], $t_{int} = 10^4$ [hour]

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.

Observabl					
HI 21cm line	*HI galaxy redshift survey*	1	z<0.8	5,000	10
		Phase-2	**z<2**	**30,000**	**~ 10^9**
HI 21cm line	*HI intensity mapping*	**Phase-1**	**z<3**	**30,000**	**--**
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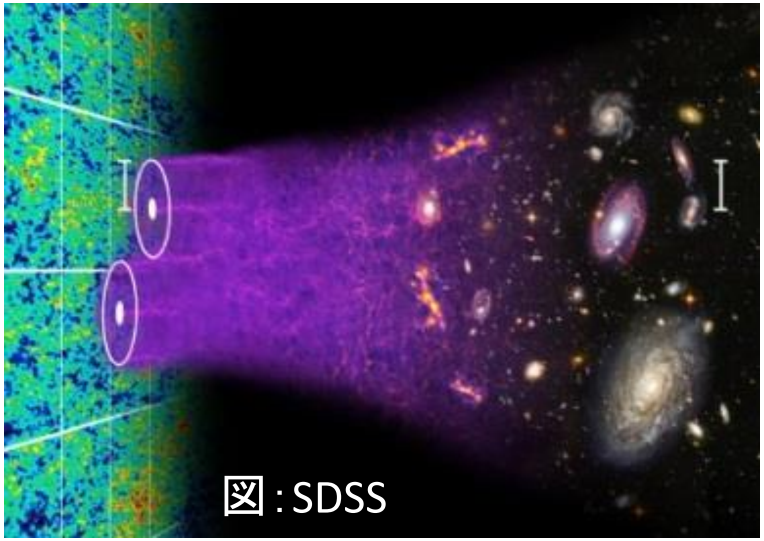
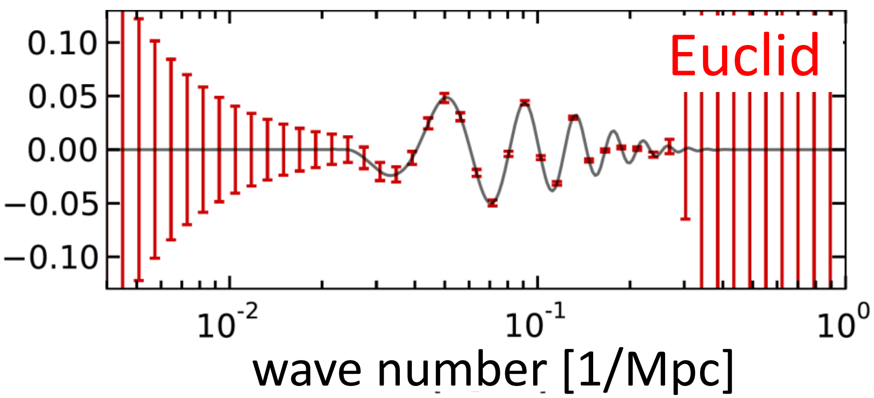
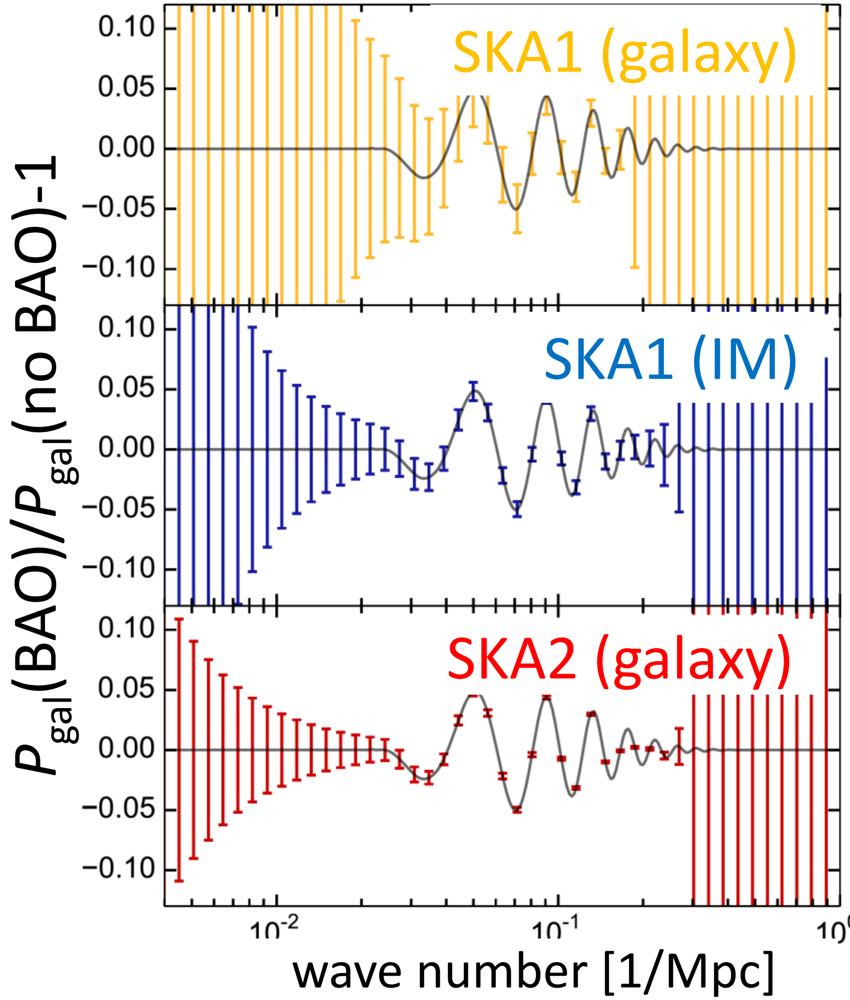
$\Delta\nu/\nu = 0.3$ @ 0.8-1.7[GHz], $\Delta\theta = 1$ [arcsec], $t_{int} = 10^4$ [hour]

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

BAO with the SKA





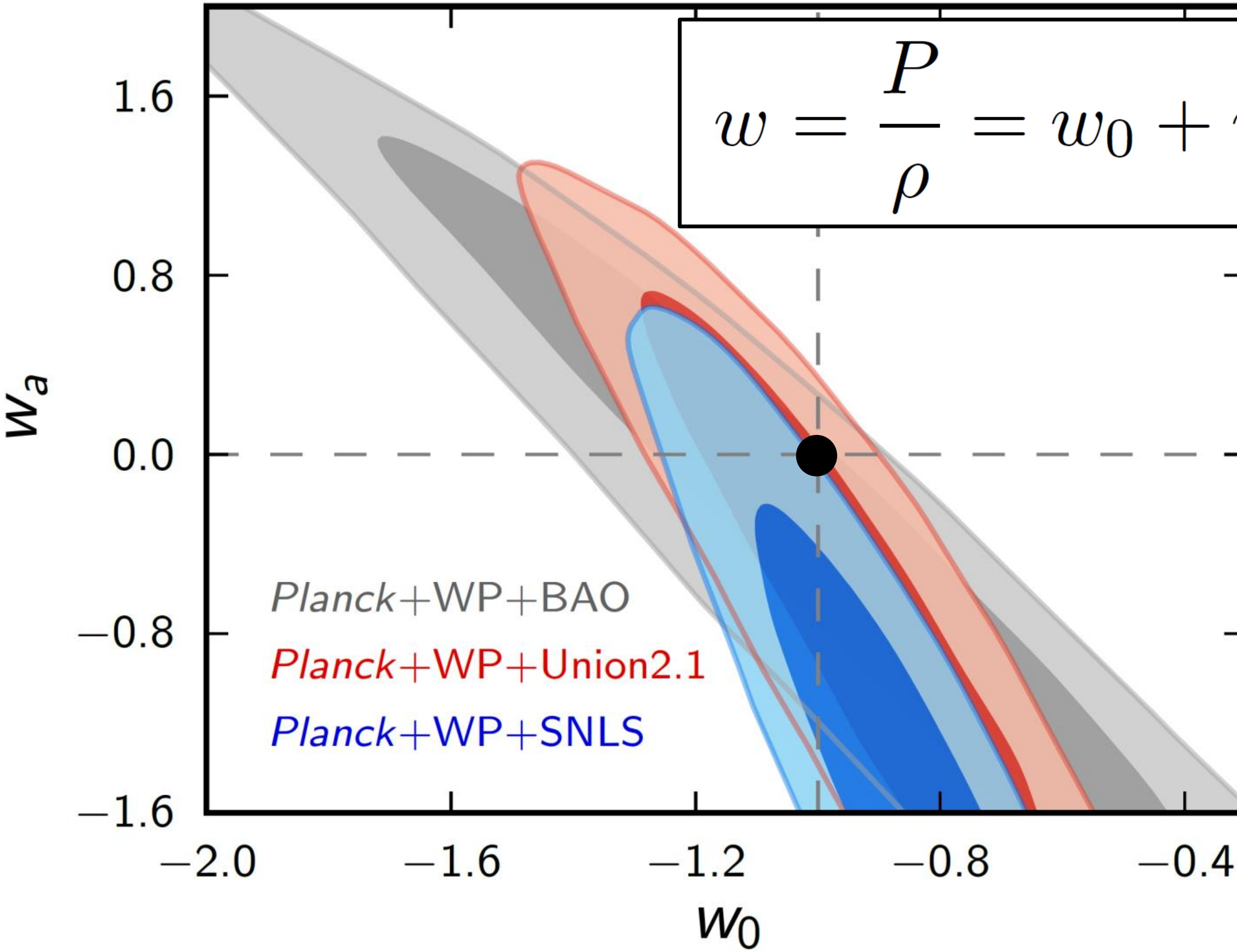


The HI galaxy and IM surveys will provide very accurate measurements for BAO/RSD of the large scale structure in its both phases.

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

Dark Energy with the SKA

Constraints on dark energy EOS

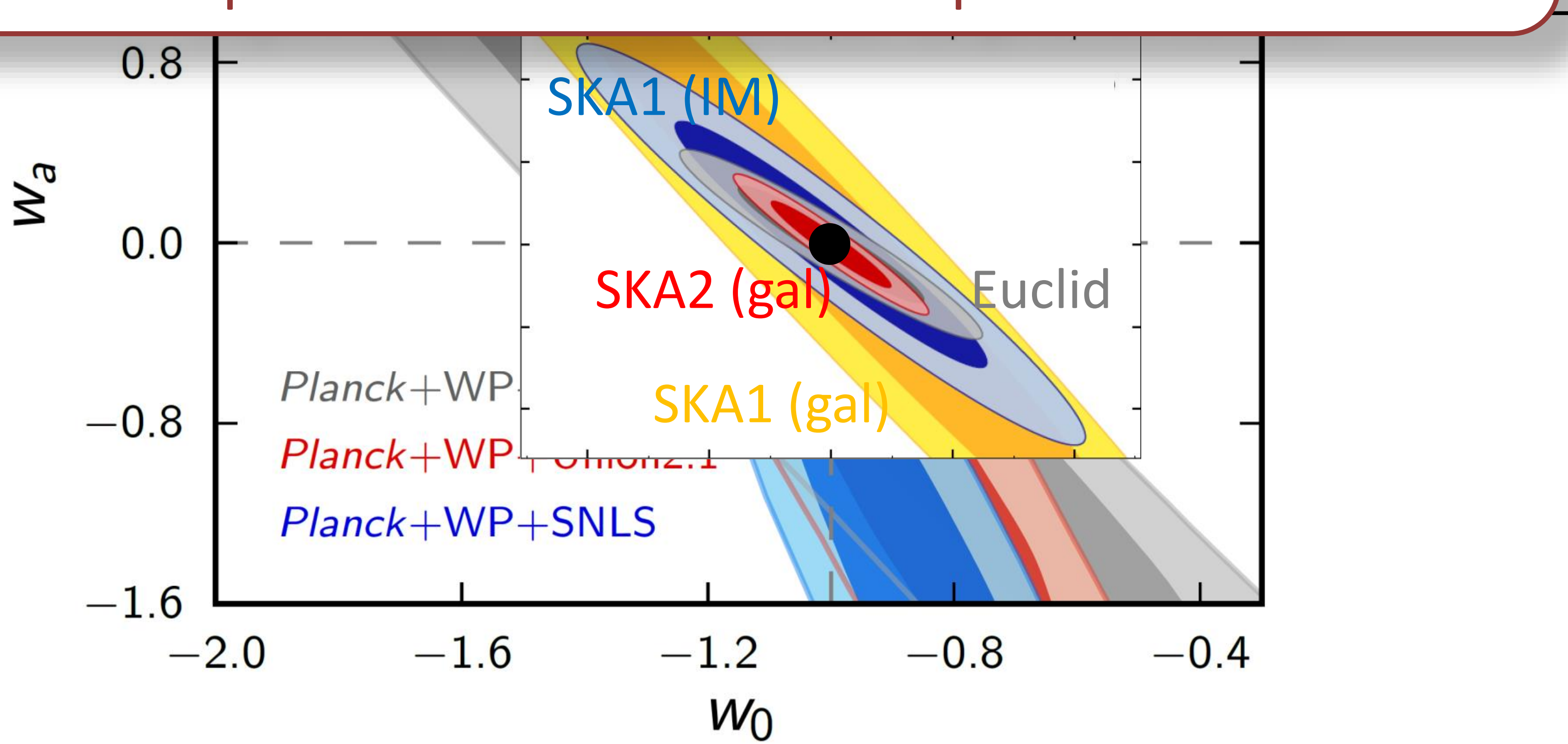


$$w = \frac{P}{\rho} = w_0 + w_a \frac{z}{1+z}$$

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

Dark Energy with the SKA

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



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SKA-JP Cosmology SWG

SKA-JP
日本百万平米電波干渉計計画協会

- Cosmological scientific challenges in which we have a deep interest.

◆ Ultra-large scale cosmology with multitracer technique

D. Yamauchi, S. Yokoyama, K. Takahashi, M. Oguri

- ✓ Density perturbations fully remains within the linear regime.
- ✓ Baryonic feedback are sufficiently suppressed.
- ✓ Clustering analysis is limited due to cosmic variance.

◆ Exploring the dark Universe with the 21-cm surveys

Y. Oyama, K. Kohri, T. Sekiguchi, H. Shimabukuro, K. Takahashi, T. Takahashi, S. Yokoyama, K. Yoshikawa

- ✓ Redshifted HI 21cm-line → 21cm tomography
- ✓ In high-z era, nonlinear growth is less effective than that in later era.
- ✓ Poor understanding of the astrophysical process during EoR

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A critical test of primordial Universe

➢ One of the most powerful tests of inflation

→ *Primordial non-Gaussianity*

= Possible departures from a purely Gaussian distribution of primordial density fluctuations

- Hint about a mechanism for generating primordial fluctuations
- More generally key to understanding the extreme high-energy physics

A Key Science with SKA1 and SKA2

- 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"

Nonlinear parameters : $f_{NL}, \tau_{NL}, g_{NL}, \ldots$

➢ Primordial bispectrum (3-pt. fn.)

$$\langle \Phi(\boldsymbol{k}_1)\Phi(\boldsymbol{k}_2)\Phi(\boldsymbol{k}_3)\rangle = (2\pi)^3 B_\Phi(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3)\, \delta^3(\boldsymbol{k}_1+\boldsymbol{k}_2+\boldsymbol{k}_3)$$

(amplitude) × (shape dependent fn)

f_{NL}

➢ Primordial trispectrum (4-pt. fn.)

$$\langle \Phi(\boldsymbol{k}_1)\Phi(\boldsymbol{k}_2)\Phi(\boldsymbol{k}_3)\Phi(\boldsymbol{k}_4)\rangle = (2\pi)^3 T_\Phi(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3)\, \delta^3(\boldsymbol{k}_1+\boldsymbol{k}_2+\boldsymbol{k}_3+\boldsymbol{k}_4)$$

(amplitude) × (shape dependent fn)

τ_{NL}, g_{NL}

PNG consistency relation

All inflationary models predict that (if $f_{NL} \neq 0$) the trispectrum must necessarily exist with

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

[Suyama+Yamaguchi (2010)]

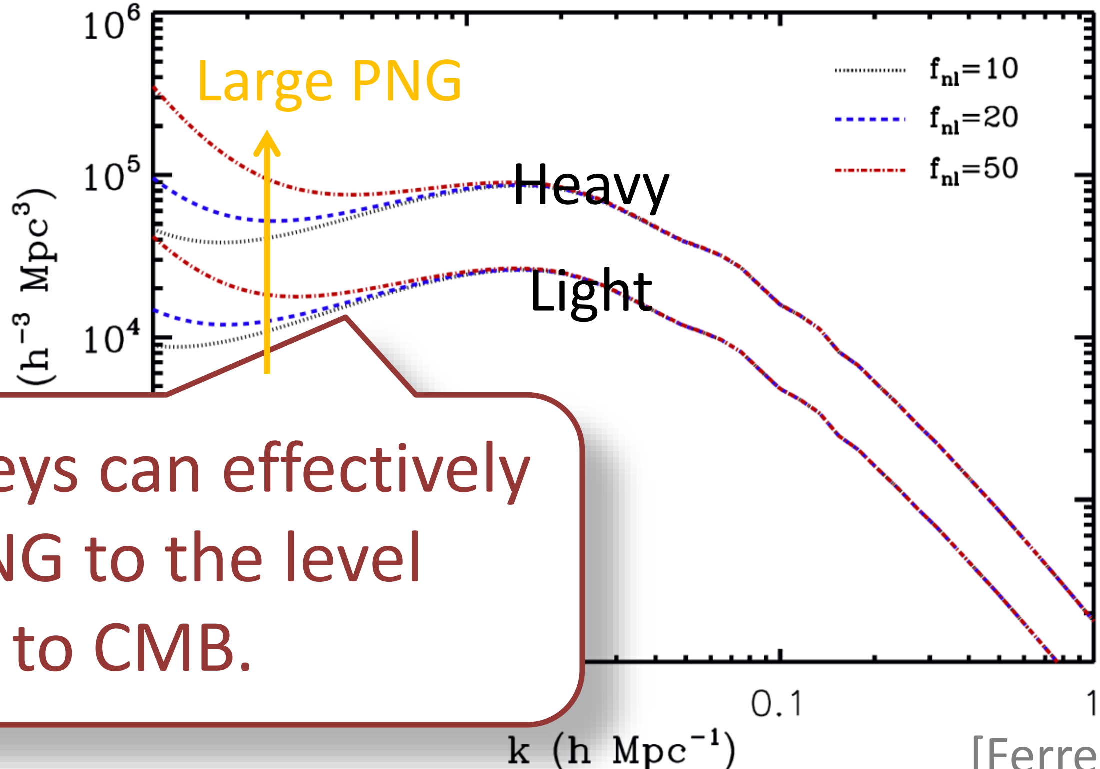
The confirmation of the inequality would indicate the presence of complicated dynamics in the primordial Universe.

It should be the target in future experiments!

PNG in large-scale structure

- PNG induces the scale dependent-bias such that the effect dominates at very large scales:

$$P_{gal} = [b_L(M,z) + f_{NL}\beta_f(M,z)/k^2 D_+(z)]^2 \, P_\delta$$



Galaxy surveys can effectively constrain PNG to the level comparable to CMB.

[Ferremacho+(2014)]

[Seljak (2009), Hamaus+Seljak+Desjacques(2011)]

Multitracer technique

- The availability of multiple tracers with the different biases allows significantly improved statistical error in the measurement of ratio of biases.

All galaxy samples

N_{tot}, $\delta_{gal} = b_{tot}\, \delta$

$$\sigma(\ln P_{gal}) = \text{const.} \quad (N_{tot} \to \infty)$$

Limited due to CV!

Light galaxies

N_l

$\delta_{gal,l} = b_l\, \delta$

Heavy galaxies

N_h

$\delta_{gal,h} = b_h\, \delta$

$$\sigma(b_h/b_l) \sim (N_l^{-1} + N_h^{-1})^{1/2}$$

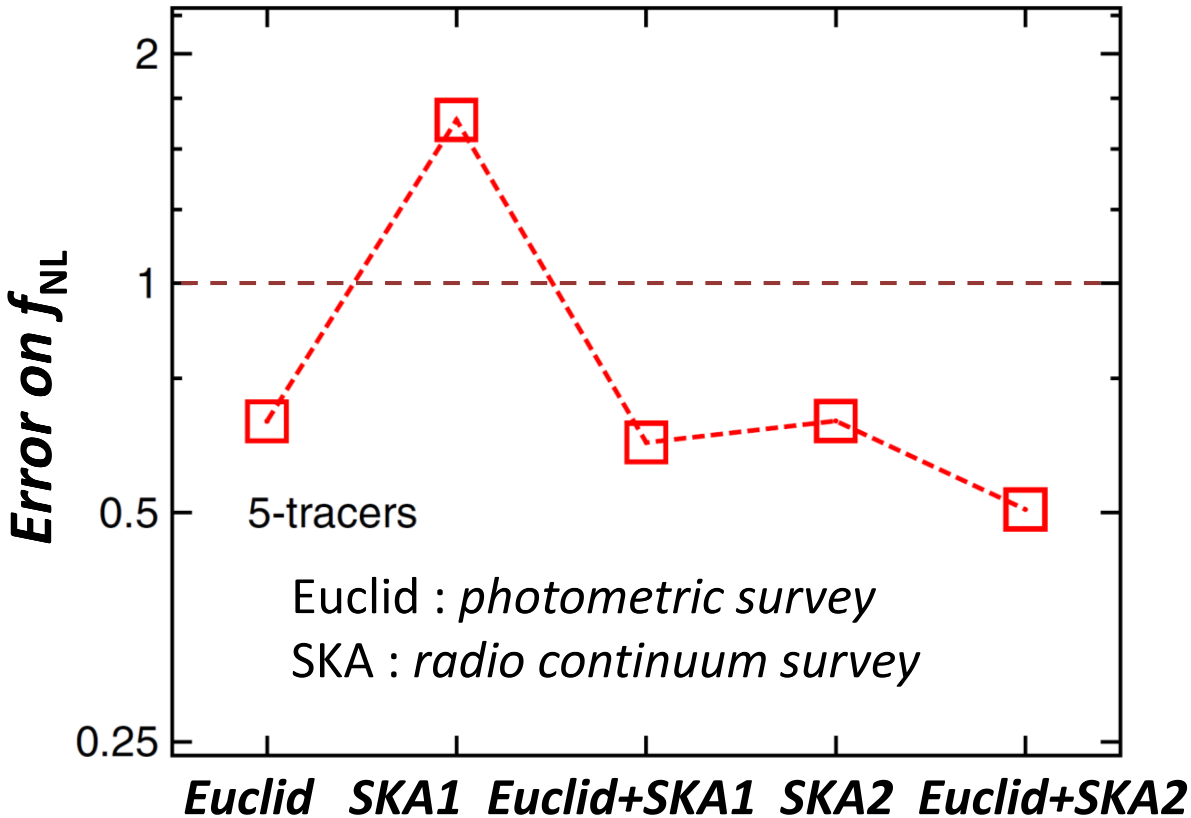
$$(N_l, N_h \to \infty)$$

There is no fundamental limit!

[**DY**+Takahashi+Oguri 1407.5453,SKA-JP Science Book]

Single-source case : $\tau_{NL} = ((6/5)f_{NL})^2$

The constraints of $\sigma(f_{NL})$=O(1) can be obtained even with a single survey. Combining Euclid and SKA, even stronger constraints of $\sigma(f_{NL})$=O(0.1) can be obtained.

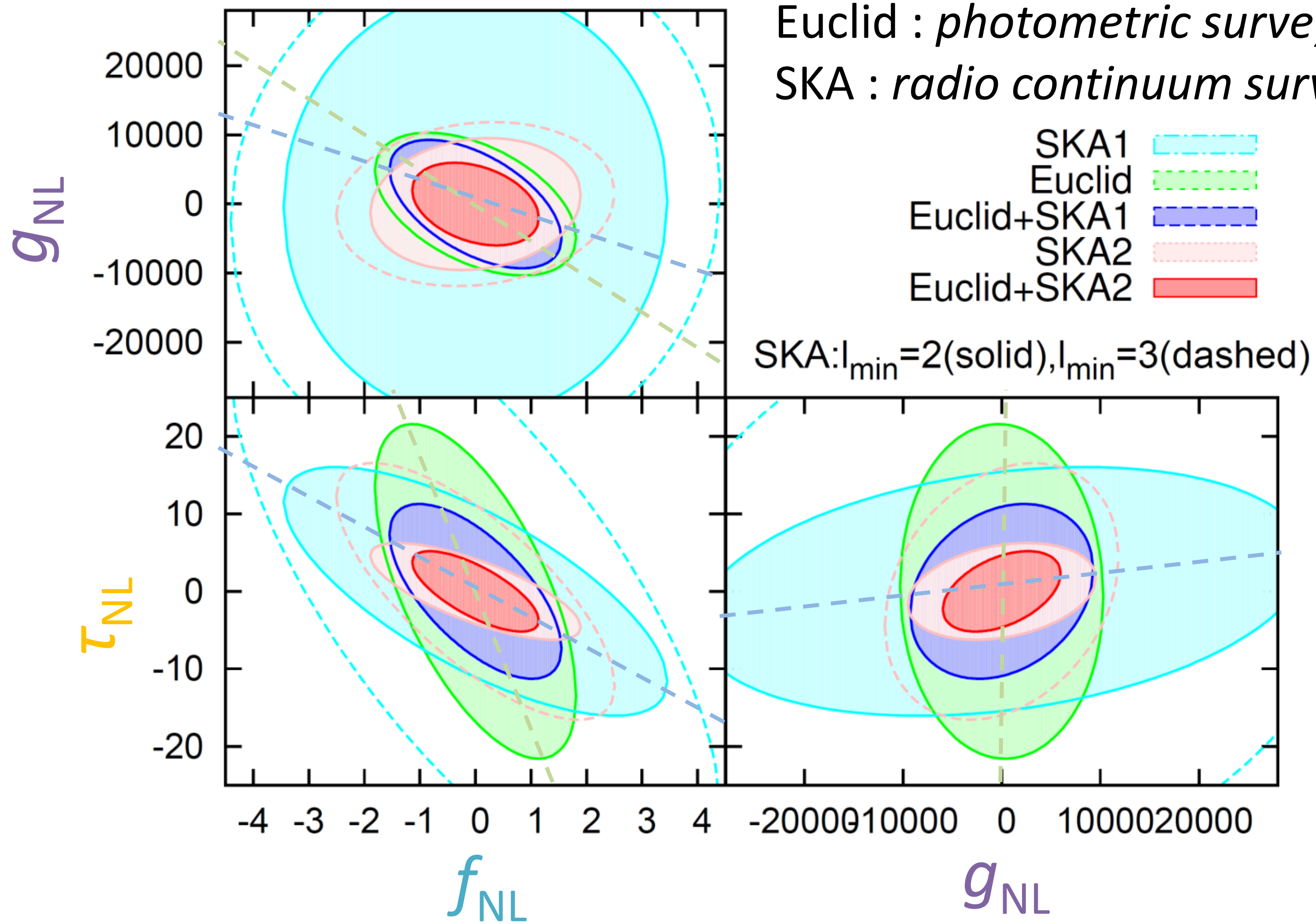


[**DY**+Takahashi 1509.07585,SKA-JP Science Book]

1σ marginalized contours for f_{NL}, τ_{NL}, g_{NL}

Euclid : *photometric survey*

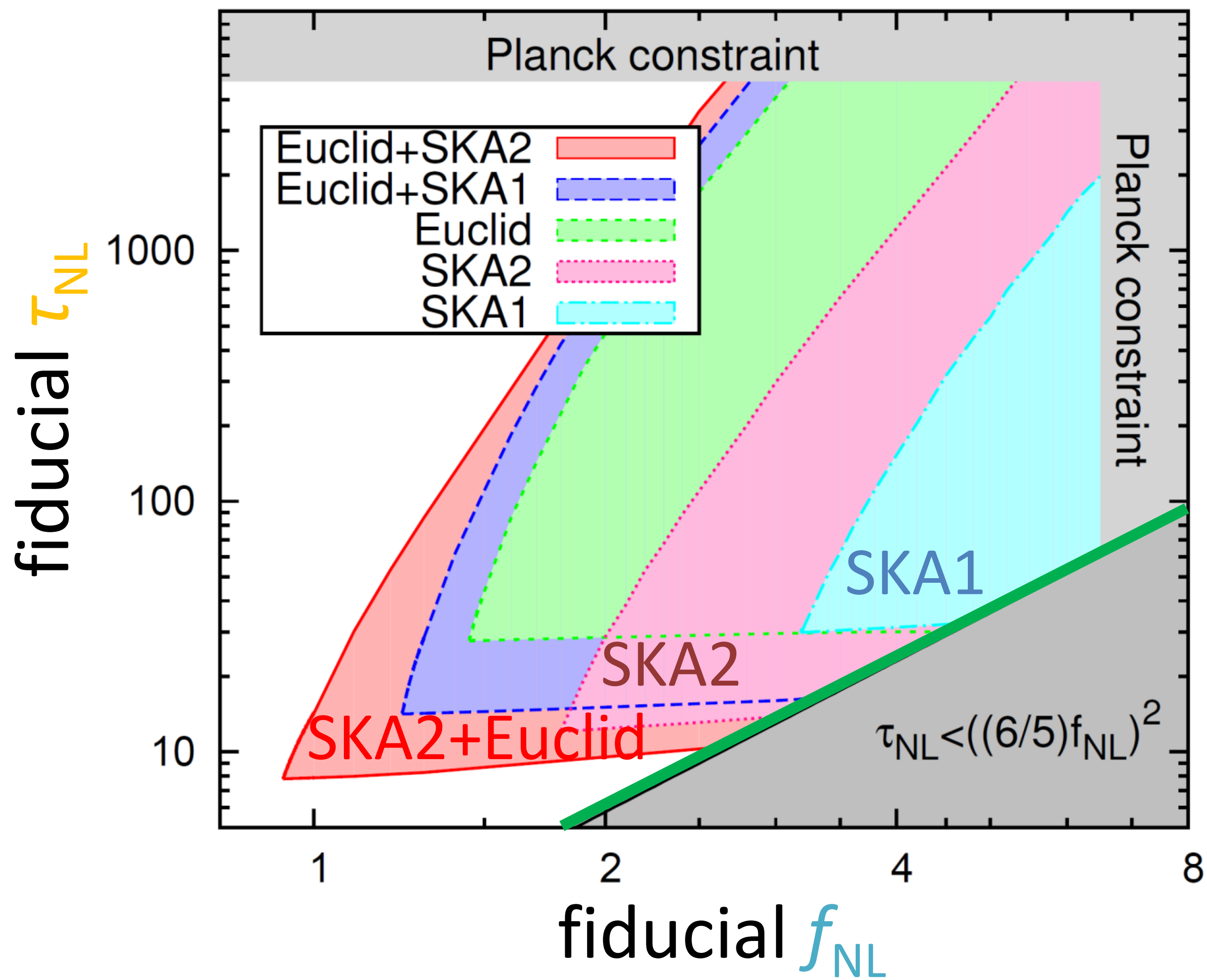
SKA : *radio continuum survey*



Complementary information from SKA and Euclid helps to break the parameter degeneracy between PNG.

[**DY**+Takahashi 1509.07585,SKA-JP Science Book]

Accessible region: $f_{NL}/\sigma(f_{NL})>1$&$\tau_{NL}/\sigma(\tau_{NL})>1$



[**DY**+Takahashi 1509.07585,SKA-JP Science Book]

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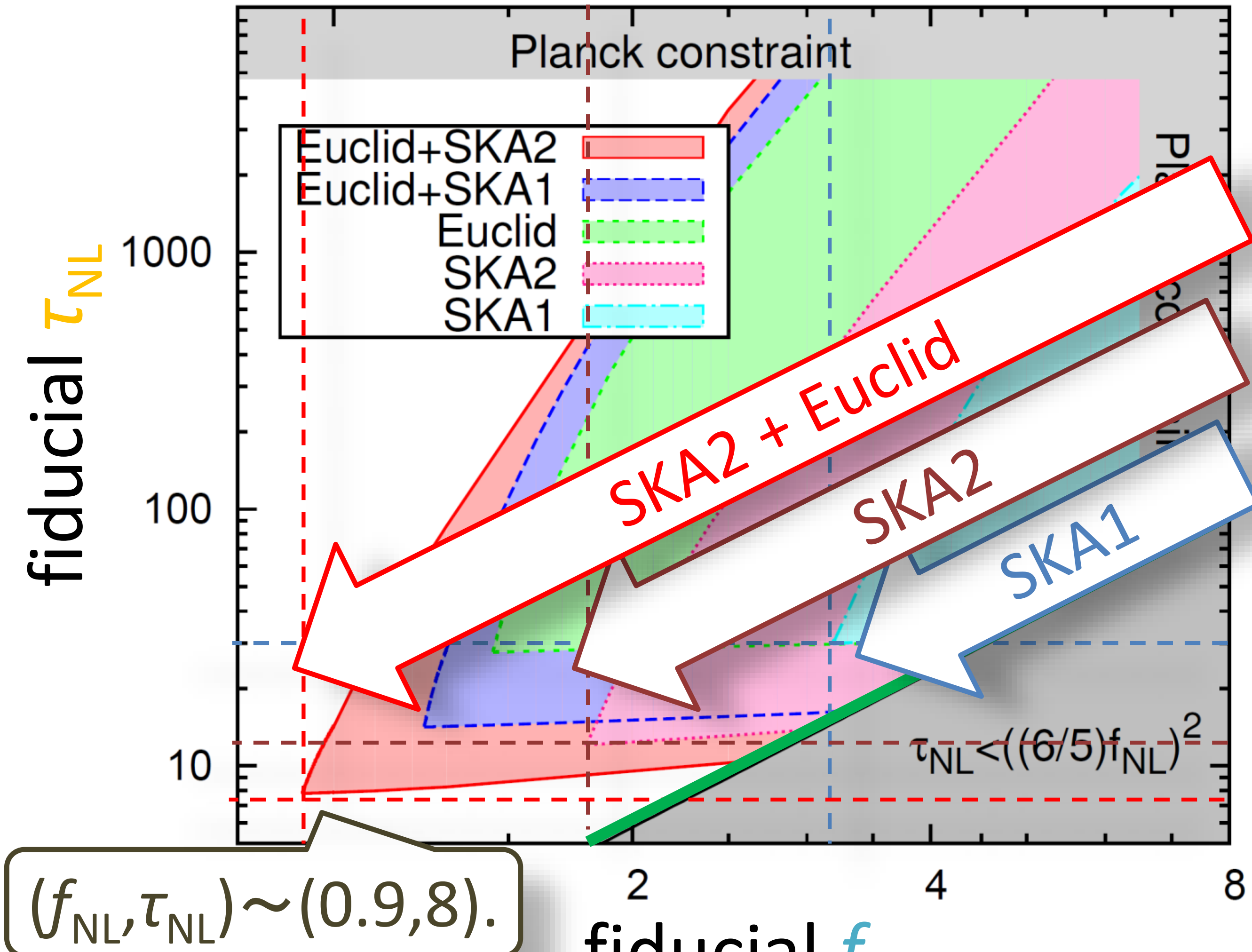

Summary

- The SKA will yield transformational science across a wide range of cosmology in the next decade.

- Other topics that is of great interests for SKA-JP:
  - ✓ Precise measurement of primordial fluctuations
    [Kohri+Oyama+Sekiguchi+T.Takahashi (2013)]
  - ✓ Constraint properties of neutrino; Σmν, its hierarchy
    [Oyama+Kohri+Hazumi (2015), Oyama+Shimizu+Kohri (2013)]
  - ✓ Weak lensing : Synergy between SKA and CMB
    [Namikawa+**DY**+Sherwin+Nagata (2015), Saga+**DY**+Ichiki(2015)]

- SKA-Japan Science Book (in English) will appear soon.

Thank you!