2022/07/14 JGRG webinar

# Signature of **primordial non-Gaussianity** on **21-cm power spectrum** from ***dark ages***

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**DY**, PTEP ptac095 (2022)
review: Minoda+**DY**+, PASJ psac015(2022)

# Take-Home Message

**Dark Ages (z=30-200)**

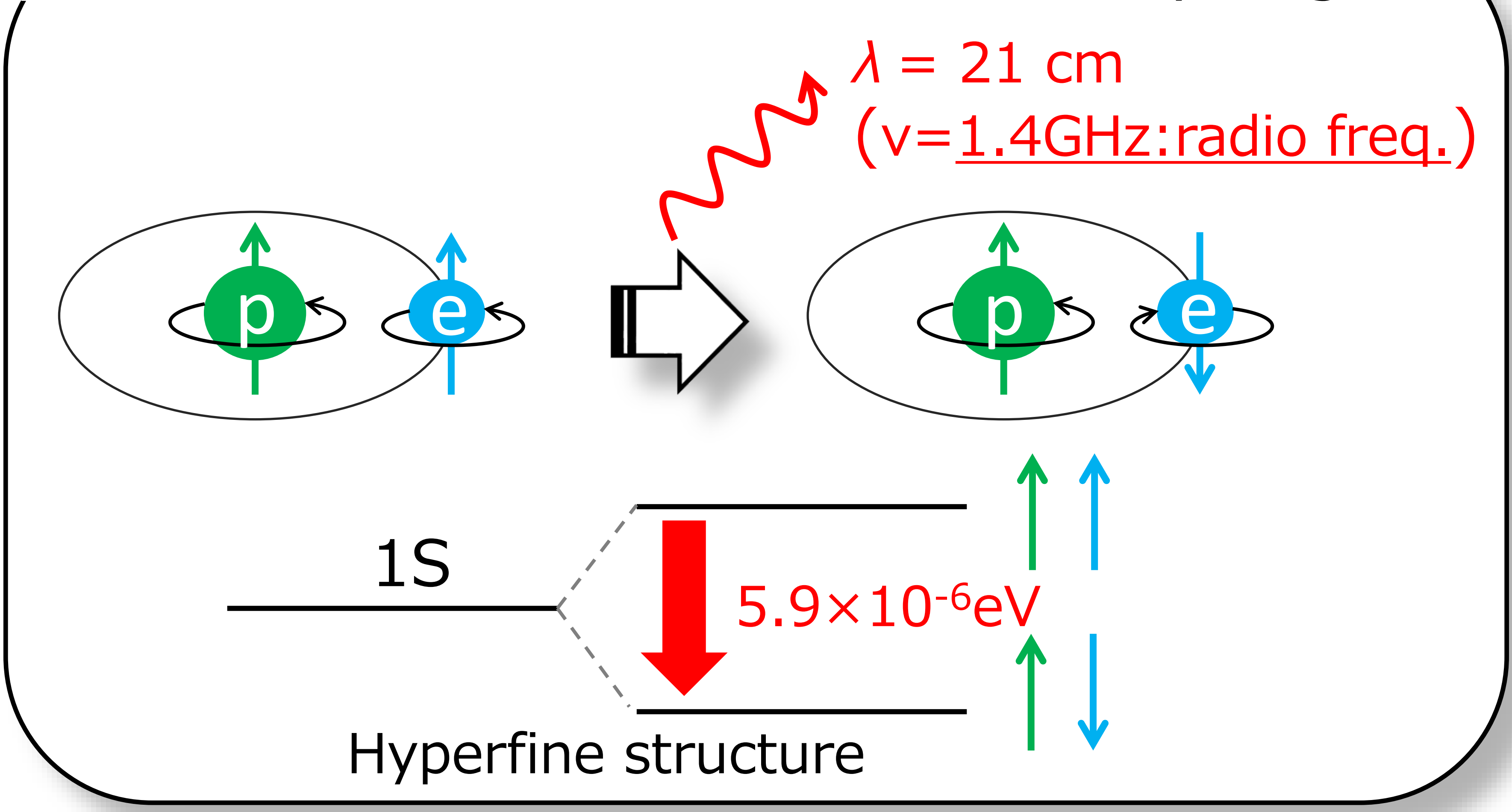
- We can easily obtain predictable **21-cm line** signals since most scales remain linear.
- Radio observations on/around the Moon is needed to avoid the Earth's ionosphere.

**In our work,** we derive…

- One-loop 21-cm power spectrum and
- Novel method to constrain primordial non-Gaussianity by using 21-cm power spectrum.

# Why radio frequency?

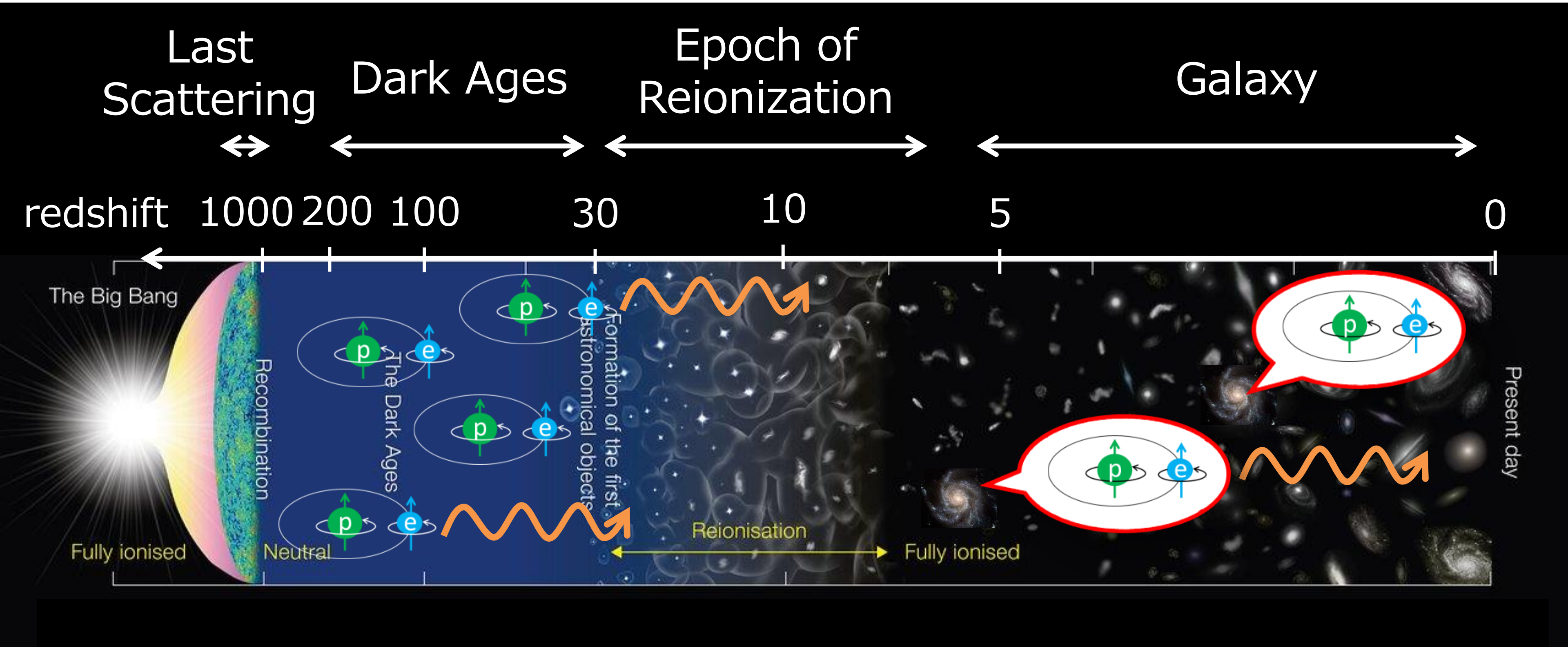
◆**21-cm line**: hyperfine transition radio emission of neutral hydrogen

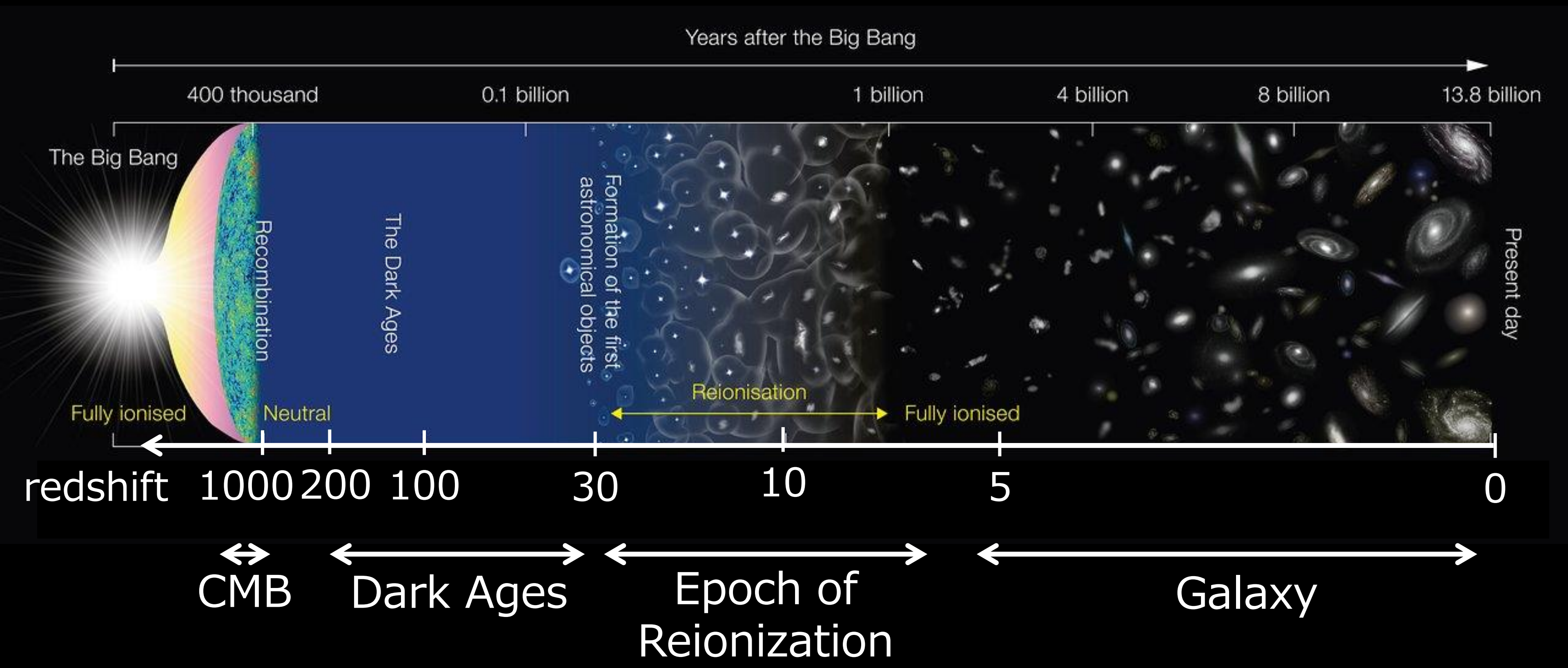


# Why 21-cm line?

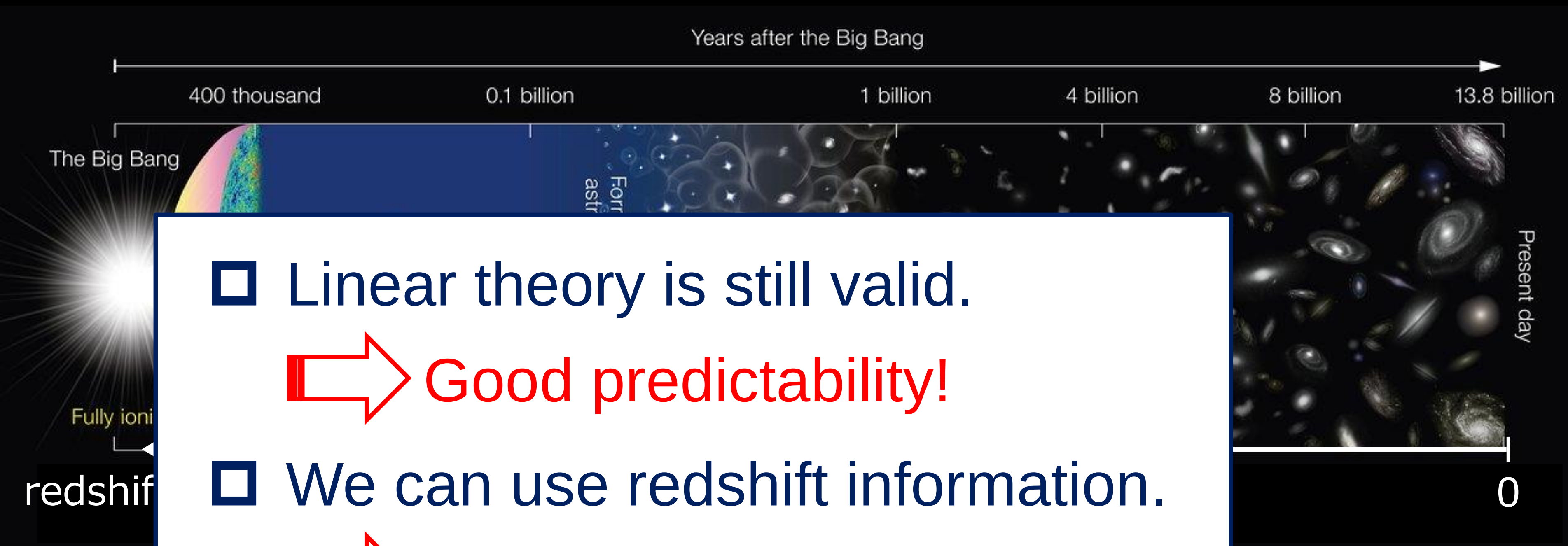
- Neutral hydrogen (HI) is the most **ubiquitous** baryonic matter in the high-redshift Universe.

  ⇨ HI is a good tracer of underlying field!






| | CMB | DA (21cm) | EoR (21cm) | Galaxy |
|---|---|---|---|---|
| redshift | 1100 | **30--200** | **6--30** | <5 |
| physics | simple | **simple** | **complicated** | complicated |
| information | 2D | **3D** | **3D** | 3D |
| observation | ongoing | **very hard** | **hard** | ongoing |




- Linear theory is still valid.
  - ⇨ Good predictability!
- We can use redshift information.
  - ⇨ Large number of modes!

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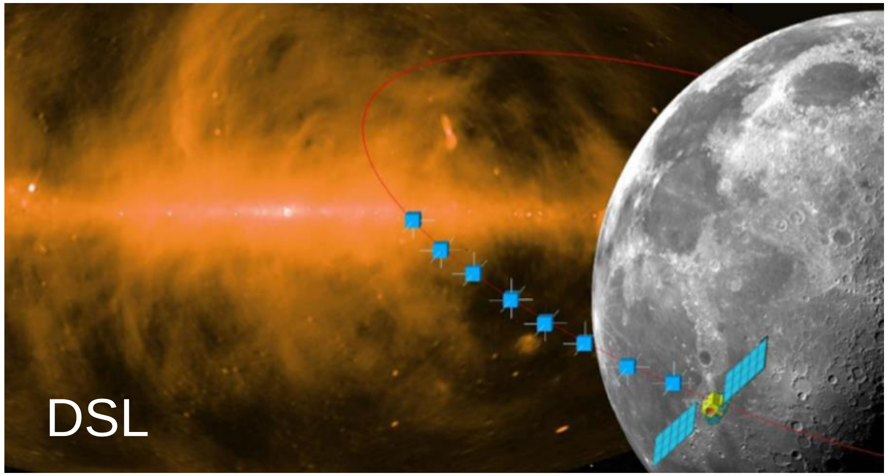
# Moon-based observations

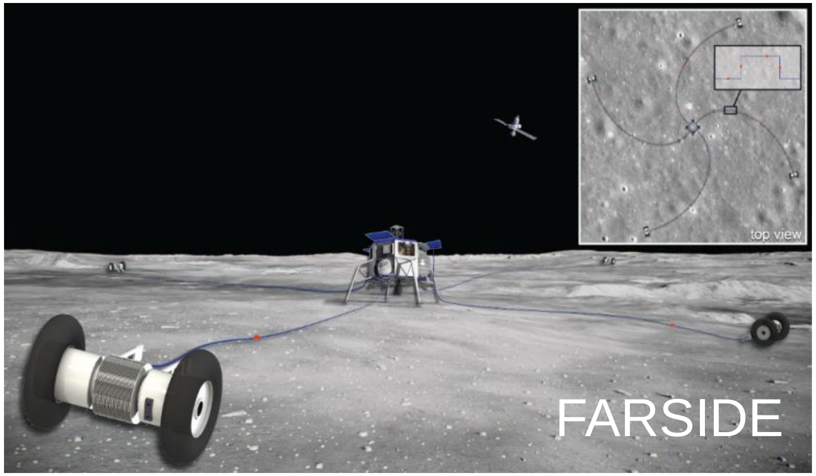
## ◻ Lunar orbit

- DARE/DAPPER (NASA)
- DSL (China)
- NCLE (Netherland+China)
- CoDex (ESA)

## ◻ Farside of the Moon

- FARSIDE (NASA)
- LCRT (NASA)
- New project??? (JAXA)
  [Feasibility study runs this year.]



# 21-cm line brightness temperature

- We observe 21-cm line brightness temperature with CMB as background light.


$T_{\mathrm{CMB}}$

- optical depth $\tau_{21}$
- spin temperature $T_{\mathrm{s}}$

$T_{\mathrm{CMB}} + T_{21}$

$$T_{21} = \frac{T_{\mathrm{s}} - T_{\mathrm{CMB}}}{1+z}\left(1 - e^{-\tau_{21}}\right)$$

# 21-cm fluctuations

HI fraction

Baryon fluctuation

$$T_{21} = 27\,[\mathrm{mK}] \left(\frac{1+z}{10}\right)^{1/2} x_{\mathrm{HI}} \frac{1+\delta_{\mathrm{b}}}{1-\delta_v} \left(1 - \frac{T_{\mathrm{CMB}}}{T_{\mathrm{s}}}\right)$$

Peculiar velocity along LoS

Spin temperature

$$= \overline{T}_{21}(z) + \left[\alpha(z)\delta_{\mathrm{b}} + \overline{T}_{21}(z)\delta_v\right] + \cdots$$

Global signals

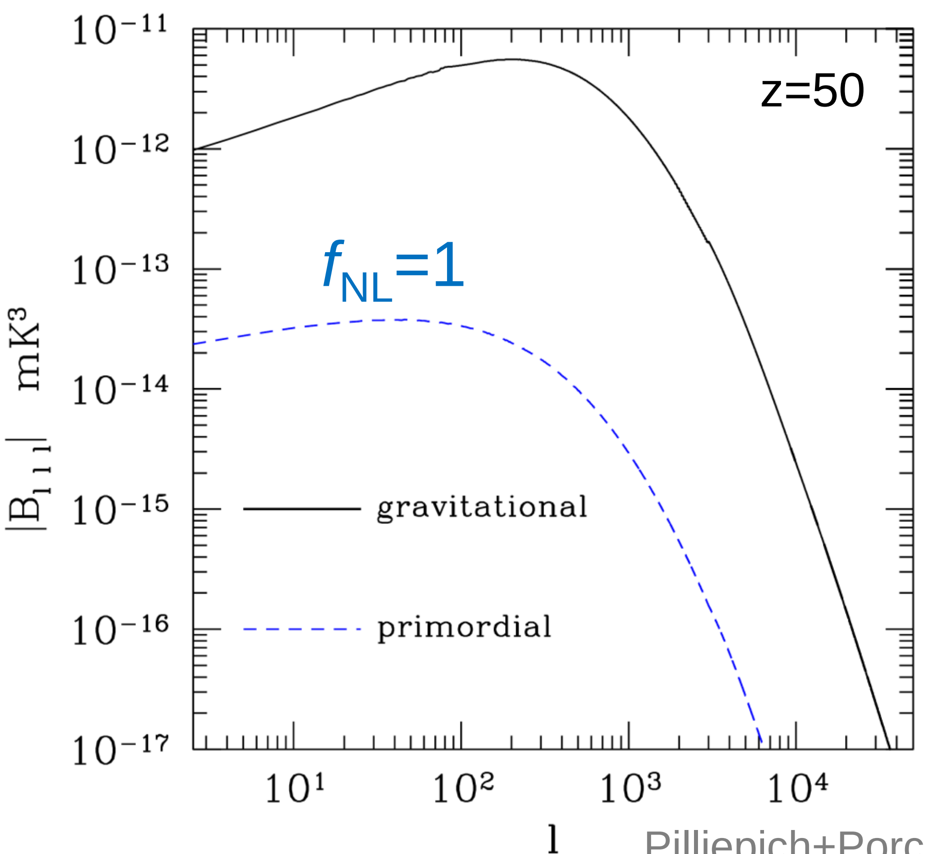
Linear 21-cm perturbation

Higher-order terms

# [Previous studies] 21-cm bispectrum

## --to constrain primordial non-Gaussianity

$$\langle \delta T_{21}(\boldsymbol{k}_1)\delta T_{21}(\boldsymbol{k}_2)\delta T_{21}(\boldsymbol{k}_3)\rangle' = \prod_{i=1}^{3}\left(\alpha(z) + \overline{T}_{21}(z)\mu_i^2\right) B_\delta(k_1, k_2, k_3)$$




Pilliepich+Porciani+Matarrese, ApJ662(2007)1-14

- Previous studies focus only on 21-cm bispectrum to probe $f_{NL}$.
- Secondary (gravitational) contributions give several order of magnitude larger than primordial one.

# **One-loop** and **primordial non-Gaussianity** contributions from 21cm fluctuations

**DY**, PTEP ptac095 (2022), 2203.15599

See e.g., Taruya+Koyama+Matsubara, PRD78(2008)123534

# One-loop matter power spectrum
## --Warm up [**NOT** 21cm!]

- Let us expand matter fluctuation as

$$\delta_{\rm m} = \delta_1 + \boxed{\delta_2 + \delta_3 + \cdots} \qquad \delta_n = [\delta_1]^n$$

→ Nonlinear clustering due to gravity

- Nonlinear growth induces one-loop

…and bispectrum contrib.

$$P_{\rm m} = \langle \delta_{\rm m}^2 \rangle'$$

$$= \langle [\delta_1]^2 \rangle' + 2 \langle \delta_1 \delta_3 \rangle' + \langle [\delta_2]^2 \rangle' + \cdots$$

$$+2 \langle \delta_1 \delta_2 \rangle' + \cdots$$

See e.g., Taruya+Koyama+Matsubara, PRD78(2008)123534

# One-loop matter power spectrum
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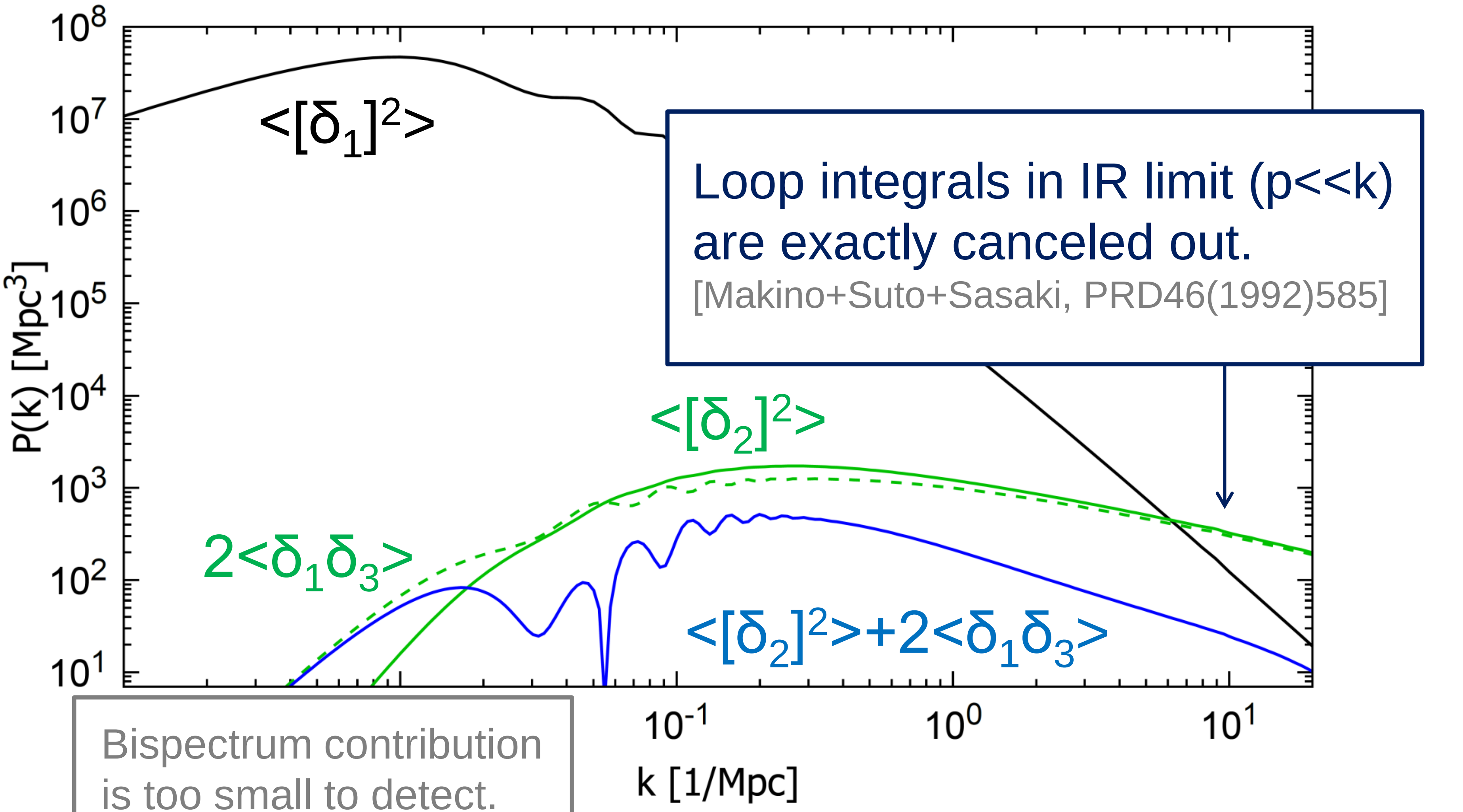


Bispectrum contribution is too small to detect.

**DY**, PTEP ptac095 (2022), 2203.15599

# One-loop **21-cm** power spectrum

## --Expansion

- Let us expand 21-cm fluctuation as

$$\delta T_{21} = \alpha_1 \delta_{\rm b}^{(1)} + \overline{T}_{21}\delta_v^{(1)} + \alpha_2^{(2)}\delta_{\rm b}^{(2)} + \alpha_2^{(1)}[\delta_{\rm b}^{(1)}]^2 + \alpha_1 \delta_{\rm b}^{(1)}\delta_v^{(1)} + \cdots + \alpha_3^{(3)}\delta_{\rm b}^{(3)} + \alpha_3^{(2)}\delta_{\rm b}^{(1)}\delta_{\rm b}^{(2)} + \alpha_3^{(1)}[\delta_{\rm b}^{(1)}]^3 + \cdots$$

(Almost) standard matter contribution

Correction terms

⇨ There appear **nontrivial** one-loop terms, e.g., $\langle\delta_{\rm b}^{(2)}[\delta_{\rm b}^{(1)}]^2\rangle$, $\langle\delta_{\rm b}^{(1)}[\delta_{\rm b}^{(1)}]^3\rangle\cdots$.

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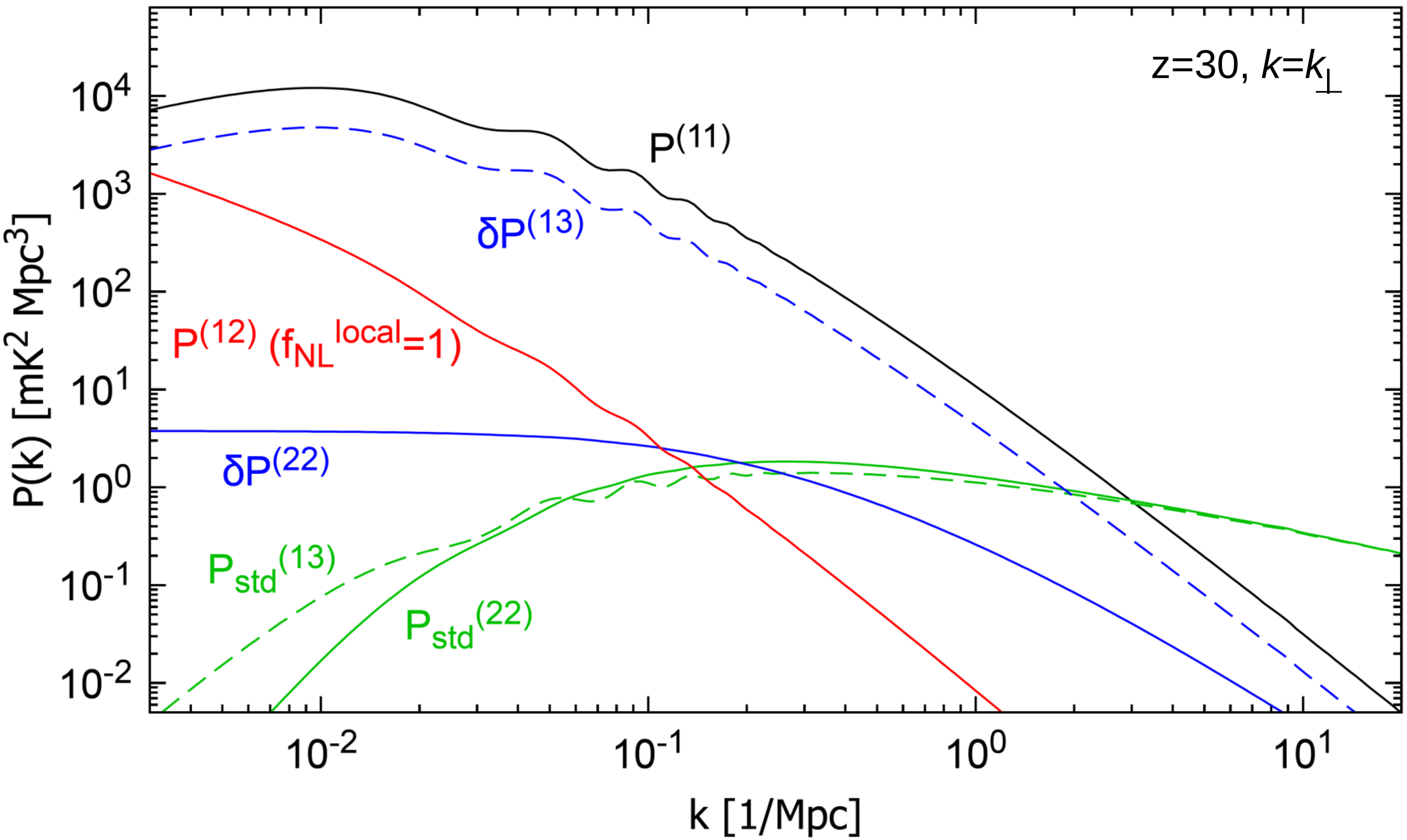
# One-loop **21-cm** power spectrum

## --Nontrivial one-loop contributions



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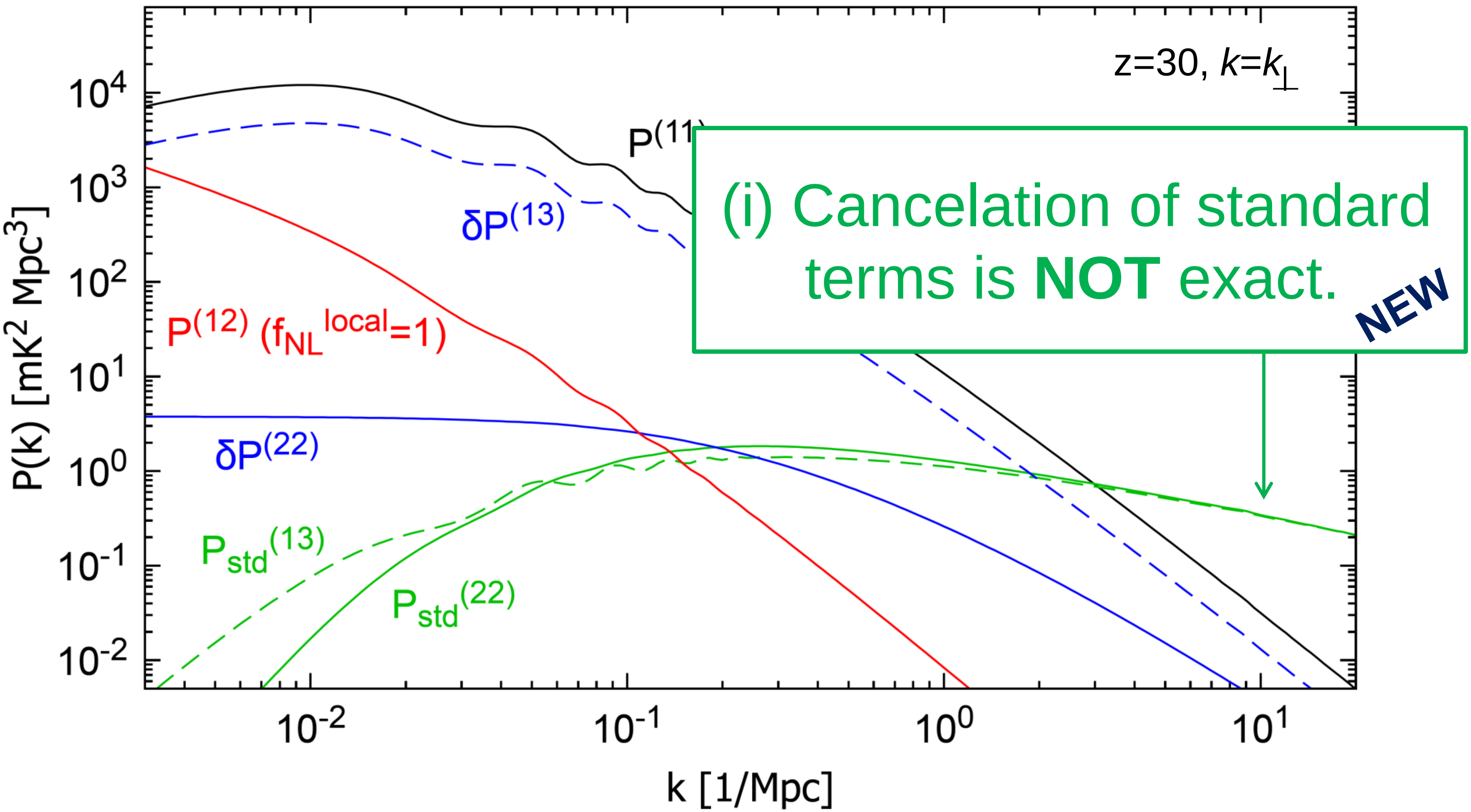

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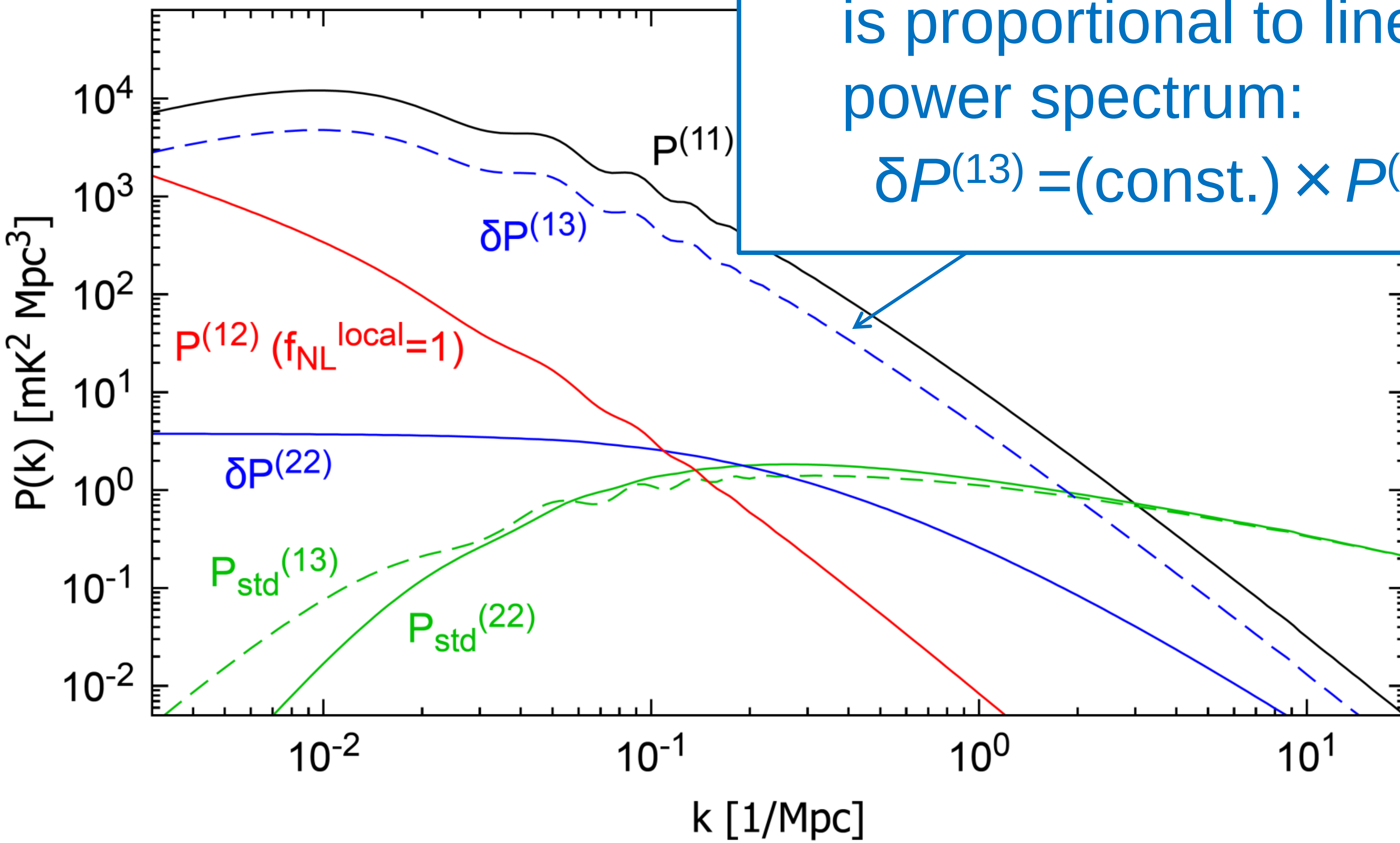


(ii) One of correction terms is proportional to linear power spectrum:

$\delta P^{(13)} = (\text{const.}) \times P^{(11)}$

**NEW**

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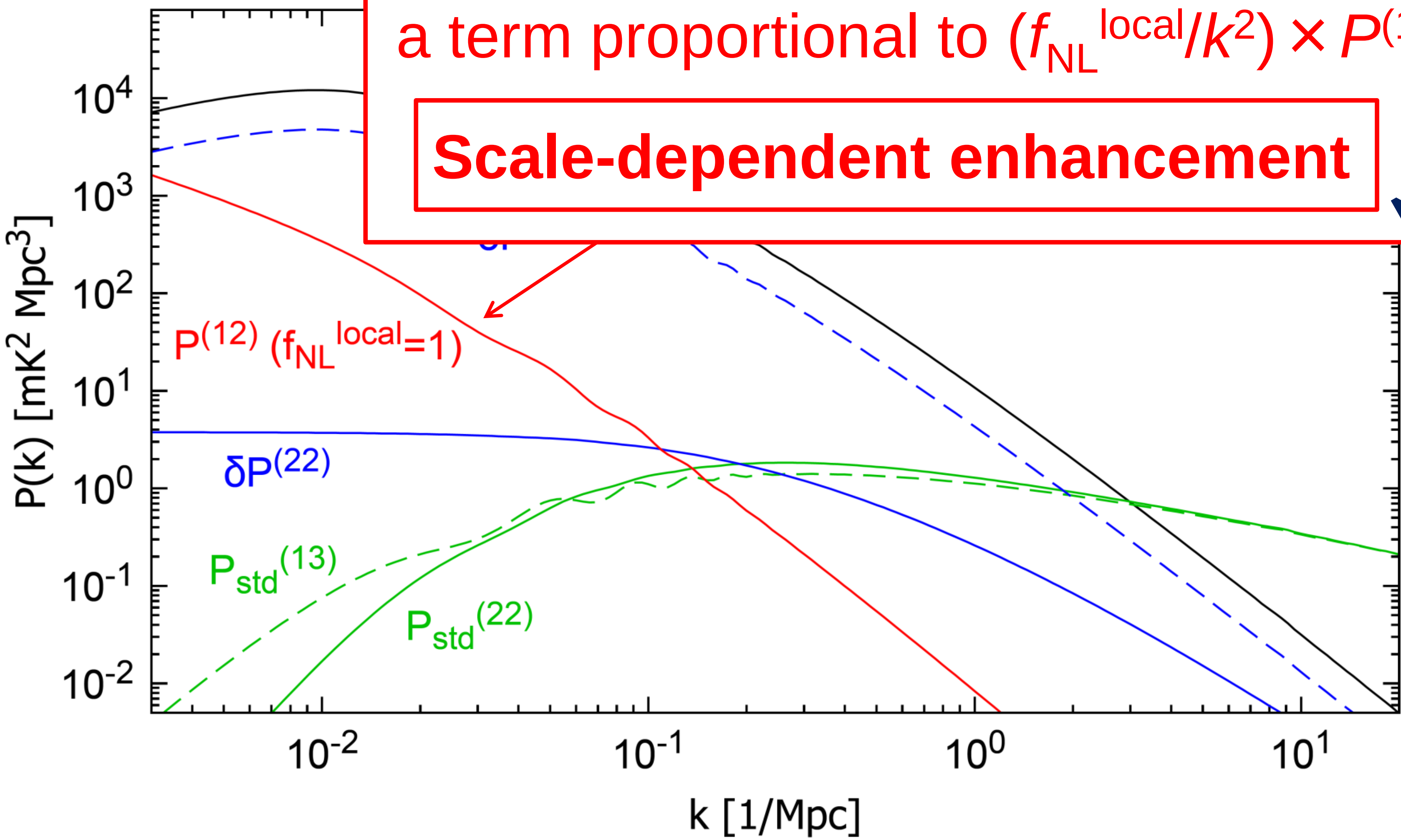
# One-loop **21-cm** power spectrum

## --Nontrivial one-loop contributions

(iii) Primordial bispectrum induces a term proportional to $(f_{\rm NL}^{\rm local}/k^2) \times P^{(11)}$.

**Scale-dependent enhancement**

**NEW**



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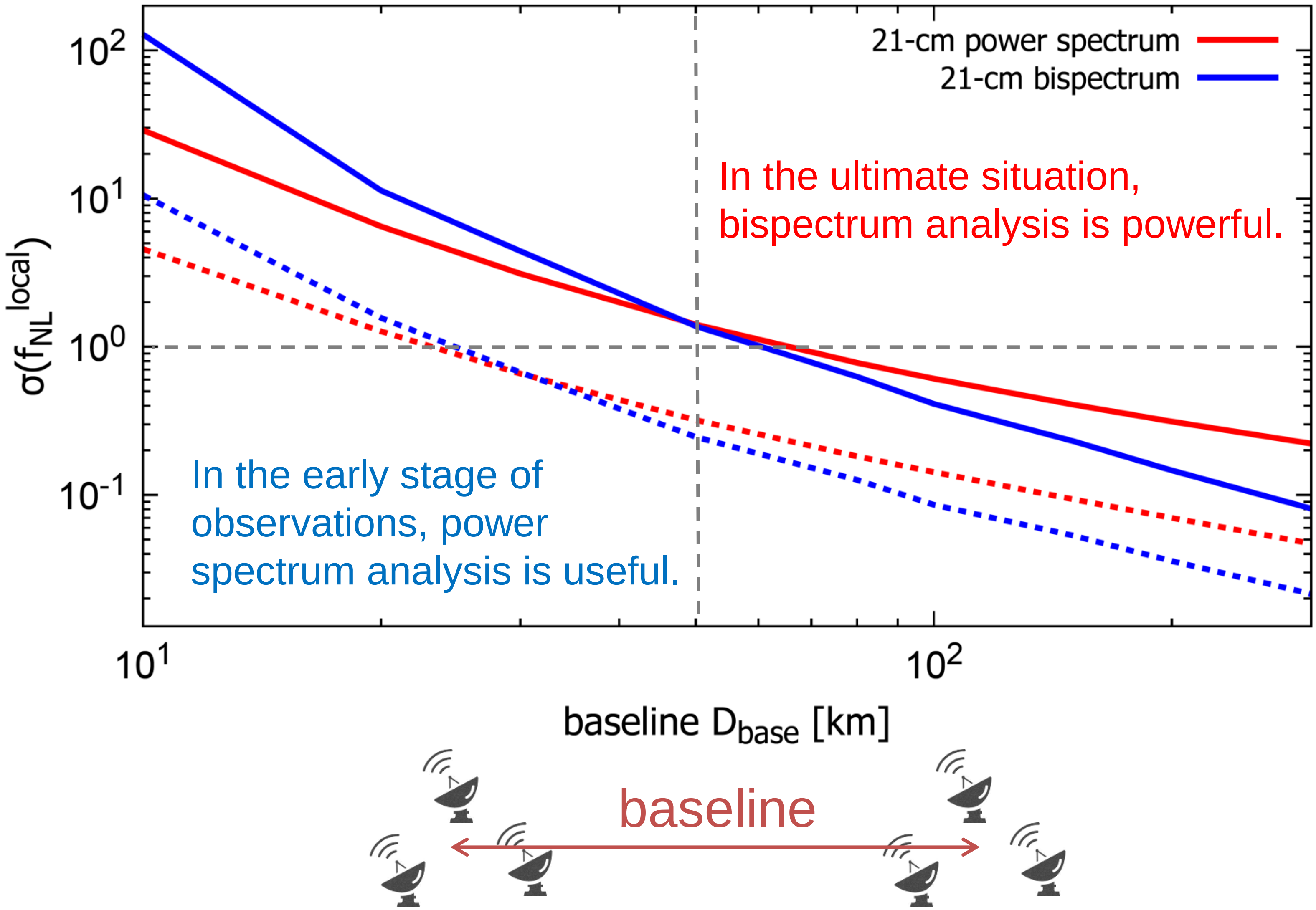
# Constraining power



# Summary

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