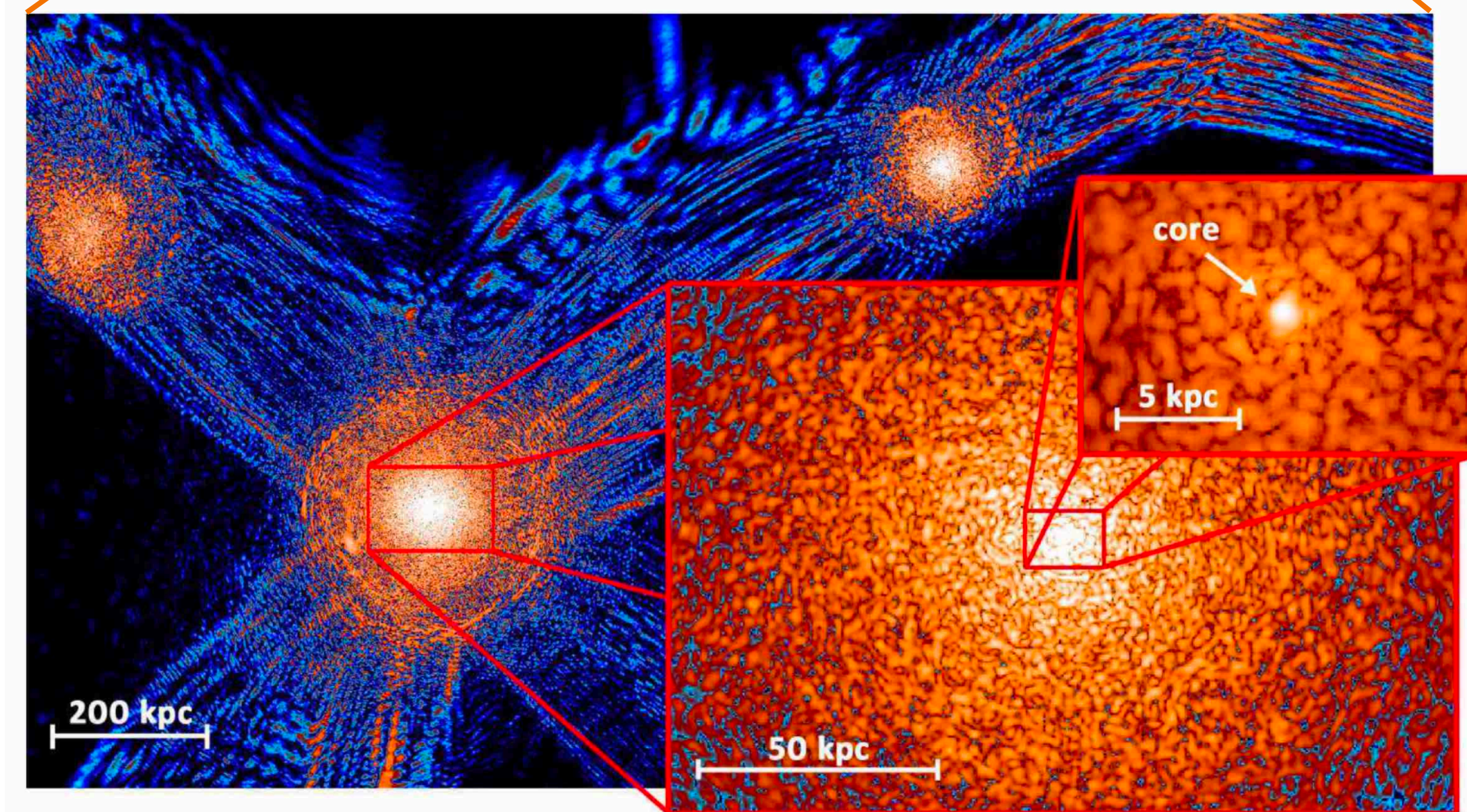
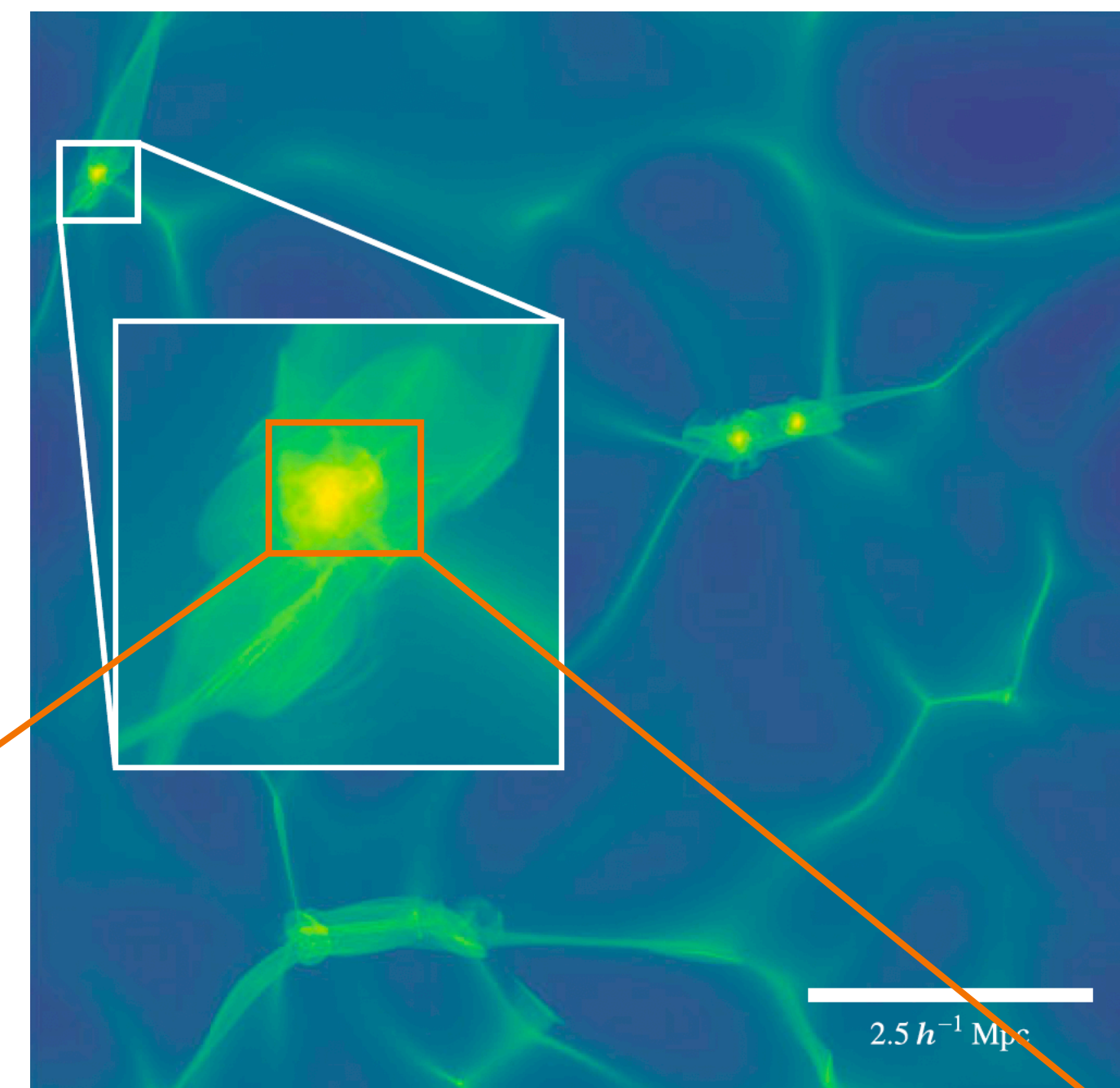


21-cm and gravitational-wave probes of ultralight dark matter

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广西相对论天体物理重点实验室



Outline

- Brief review of **ultralight scalar field dark matter (SFDM)**

- **New cosmological probes** of ultralight SFDM:

(1) 21-cm tomography of the Cosmic Dawn (CD)
and the Epoch of Reionization (EoR)

Liu, ..., Li*, Mao 2025, arXiv: [2508.10176](#),
PRD, 112, 103534

Li et al. 2026, SSPMA in press,
available online

(2) Inflationary stochastic gravitational-wave background (SGWB)

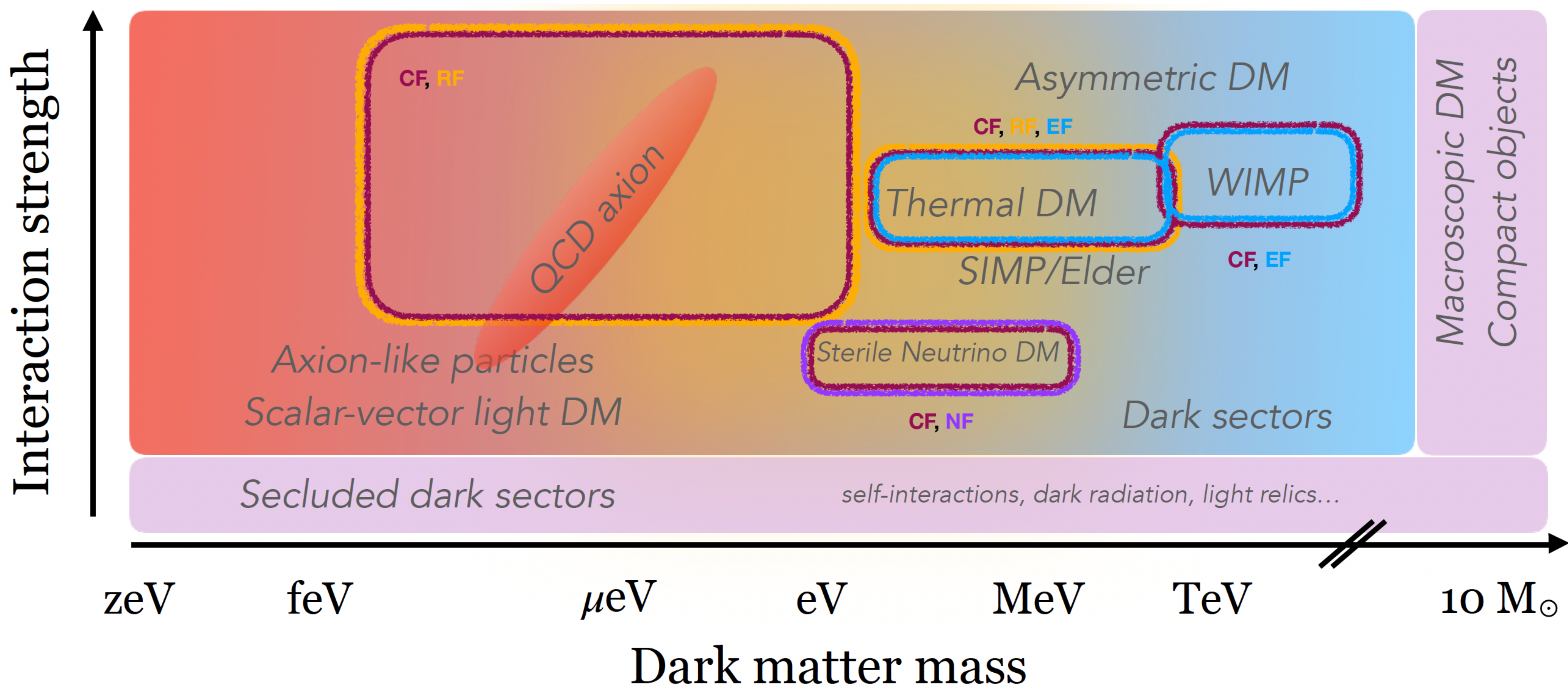
Li*, Meyers & Shapiro 2025, arXiv: [2503.18937](#), ApJ, 985, 117

Zhang, Luo, Li* et al. 2025, arXiv: [2504.04054](#), ApJS, 279, 44

- **Take-home message:**

Upcoming 21-cm and SGWB observations (e.g., **SKAO** and )
will be powerful probes of ultralight dark matter.

Dark matter complementarity



Ultralight scalar field dark matter (SFDM)

- 超轻标量场暗物质； various names/types in the literature:

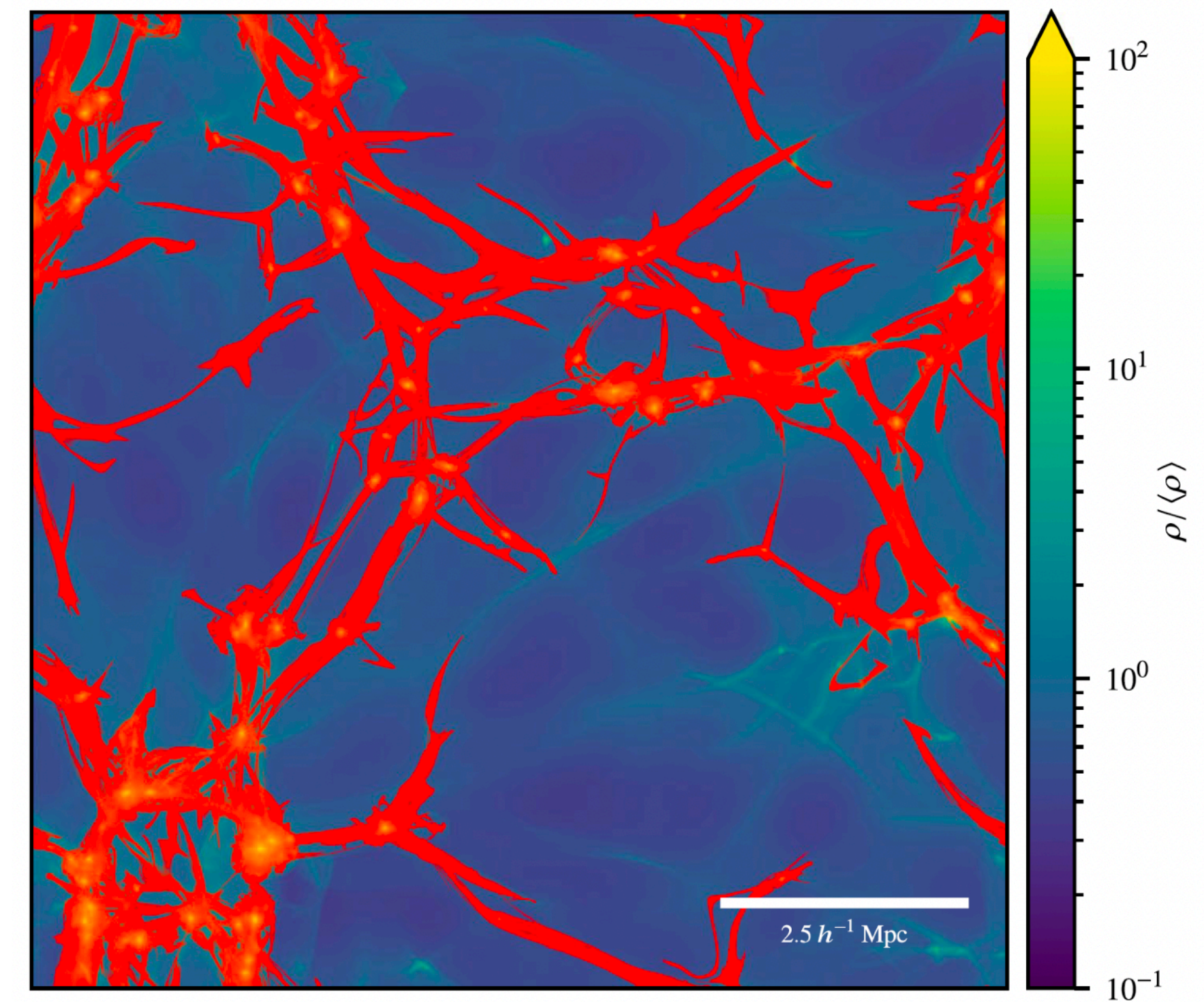
Ultralight axion dark matter, fuzzy dark matter (FDM), wave dark matter, Bose-Einstein condensate (BEC) dark matter, ...

- Commonalities:

Non-Standard-Model spin-0 scalar **boson**,
tiny mass ($\sim 10^{-22}$ eV),
Effectively described by **classical field/wave**

$$S = \int \frac{d^4x}{\hbar c^2} \sqrt{-g} \left[\frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - \frac{1}{2} \frac{m^2 c^2}{\hbar^2} \phi^2 \right]$$

Hui+ 2017 PRD

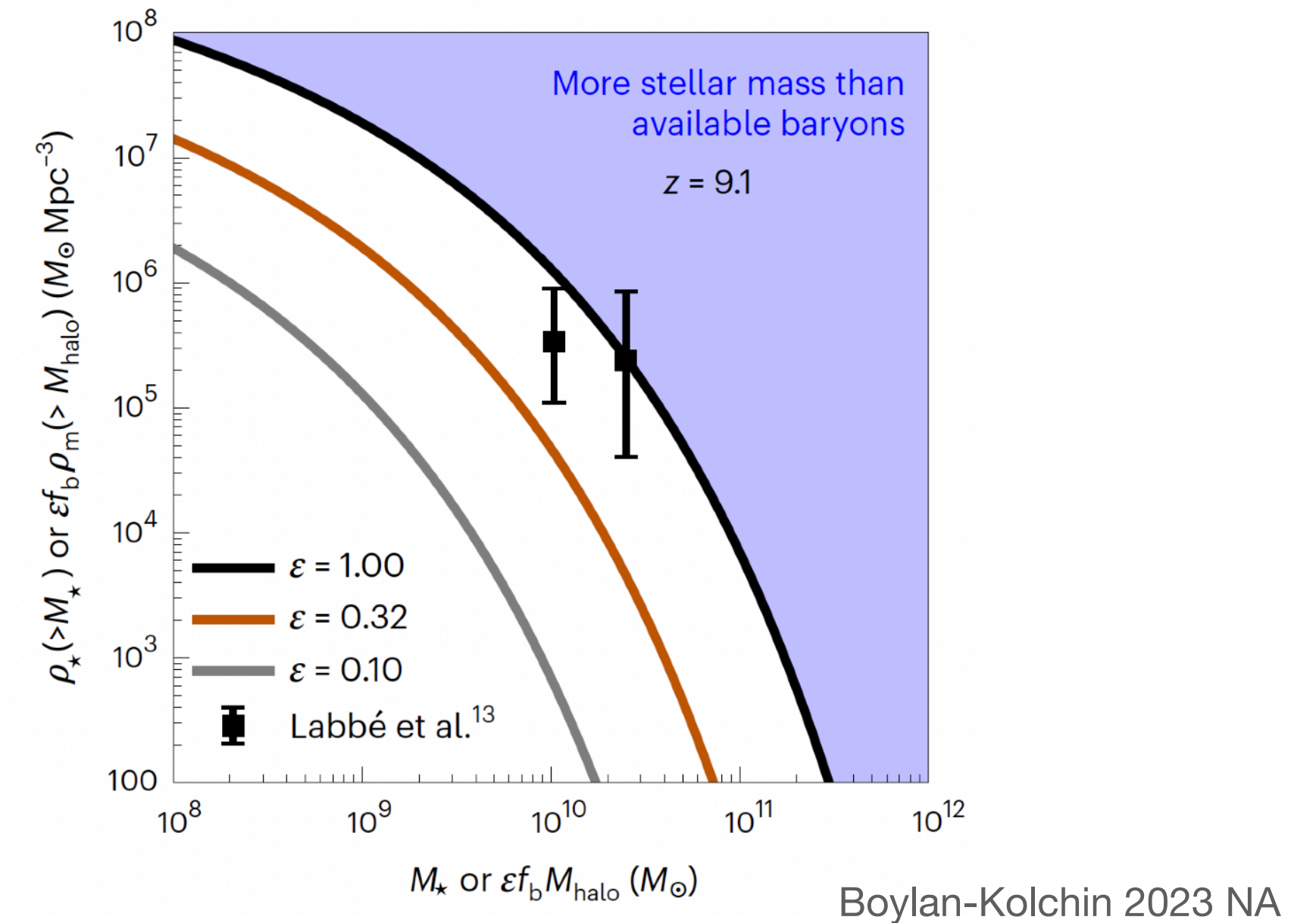


May & Springel 2023

Motivations for ultralight boson dark matter

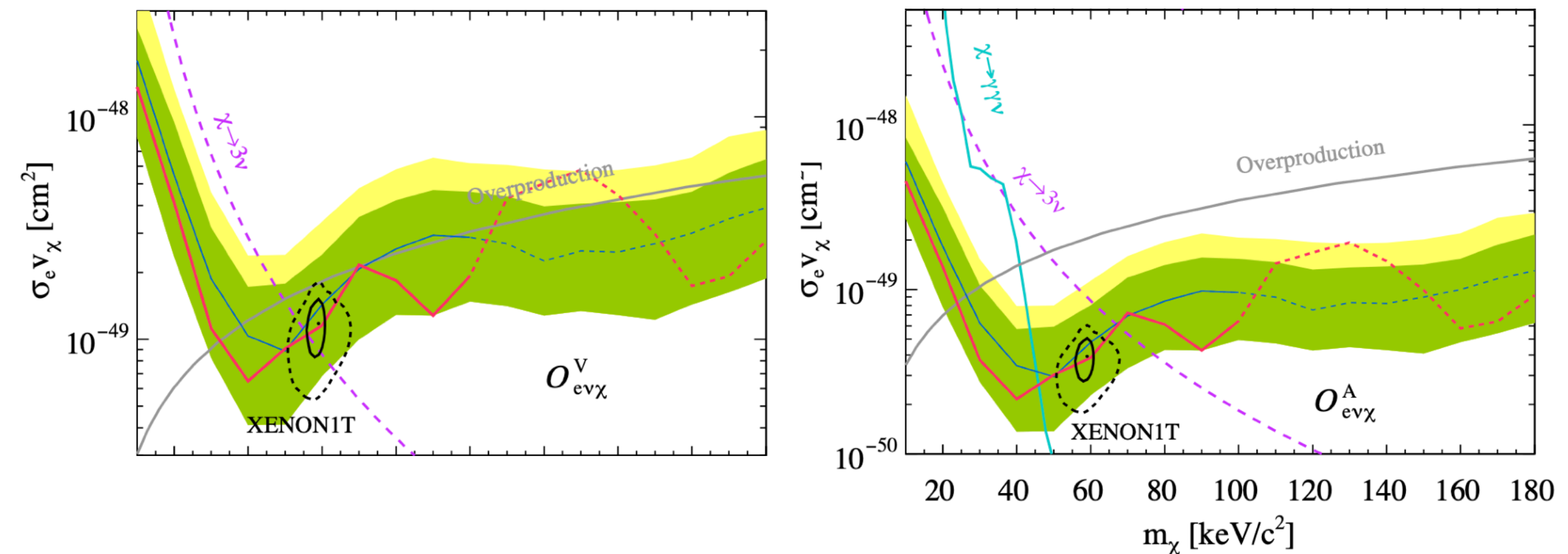
Small-scale challenges to CDM:

- “missing satellite” problem; “cusp-core” problem; “too-big-to-fail” problem; etc.
- High- z galaxies/AGNs observed by **JWST**



Non-WIMP candidate for CDM:

- If CDM is correct, what is it (if not WIMPs)?



Suppression of structure formation on small scales

- In nonrelativistic limit, SFDM is a fluid with “quantum potential”

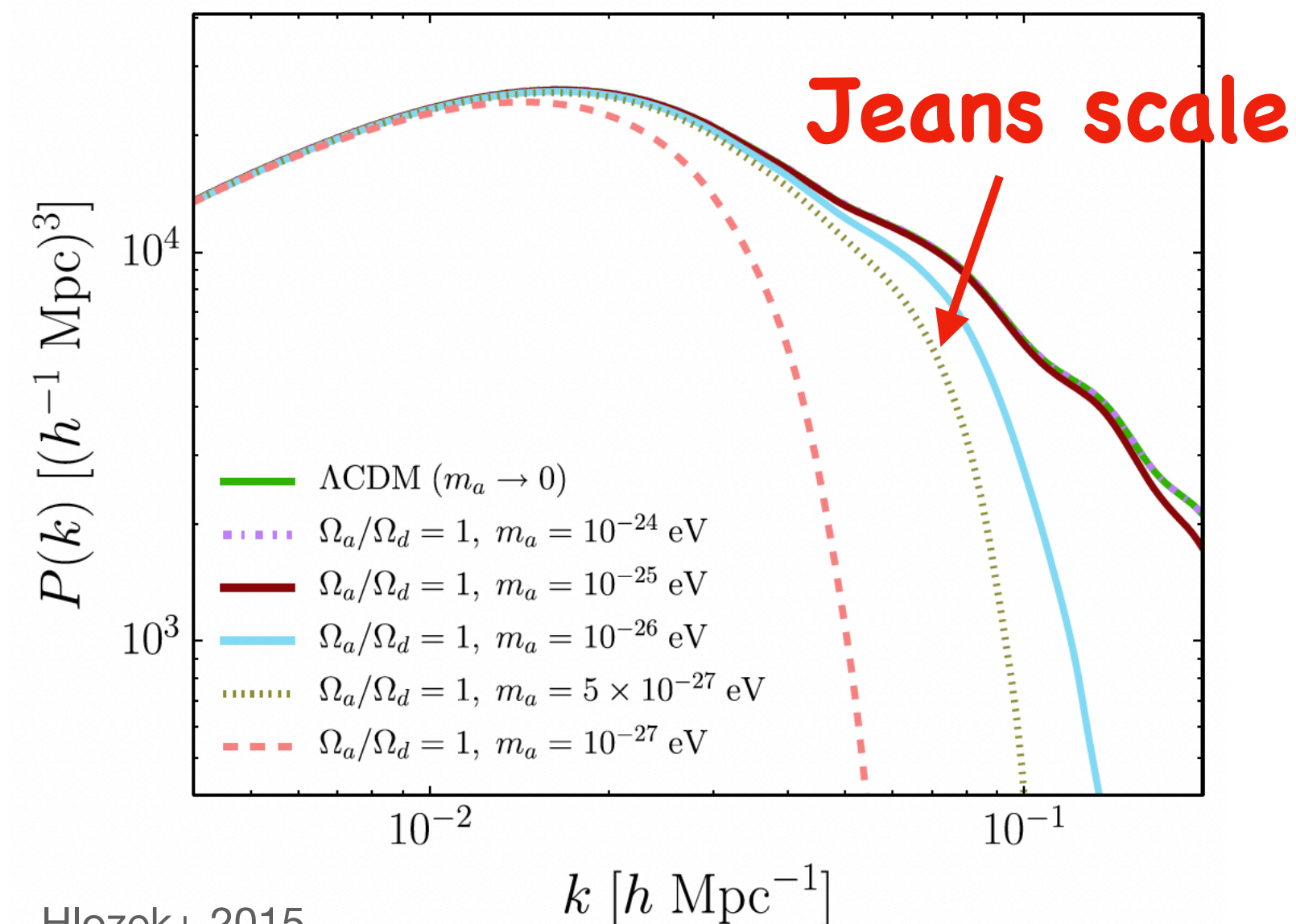
$$\begin{cases} \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0, \\ \frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{u} = -\frac{1}{m} \nabla (Q + V), \end{cases}$$

$$Q = -\frac{\hbar^2}{2m} \frac{\nabla^2 \sqrt{\rho}}{\sqrt{\rho}}.$$

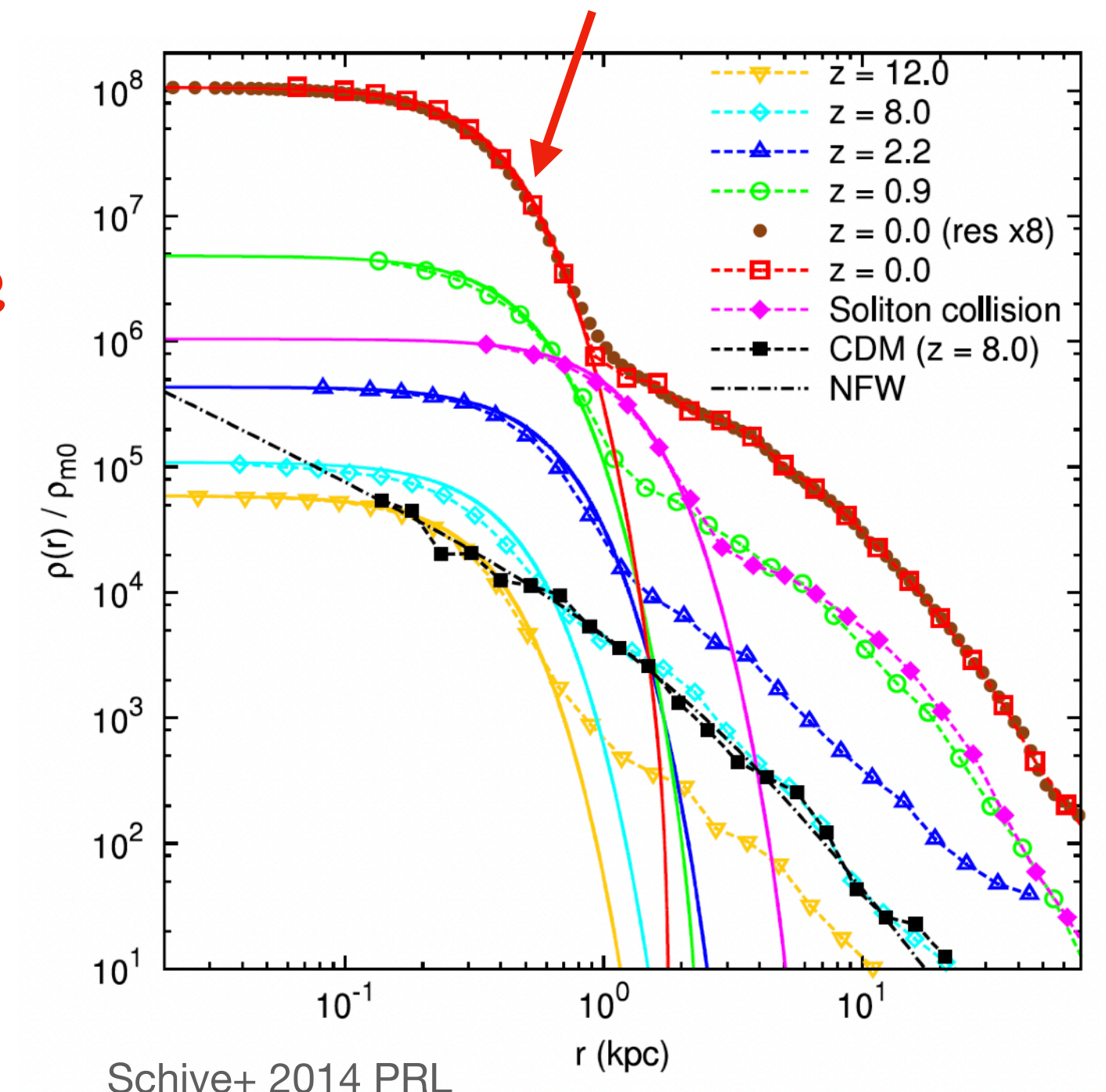
Mocz et al. 2017

- Can potentially resolve current small-scale challenges to CDM

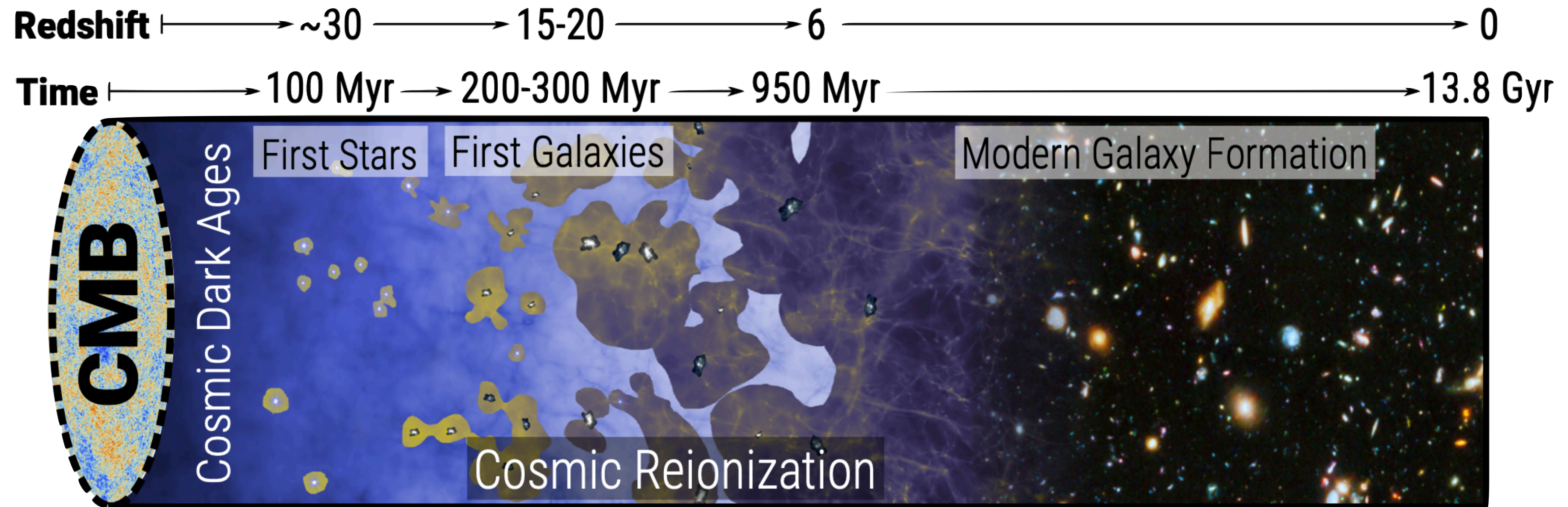
For linear theory of complex SFDM, see Yang, Li* & Shapiro 2025 SCPMA, arXiv: 2503.16773



The “soliton” core



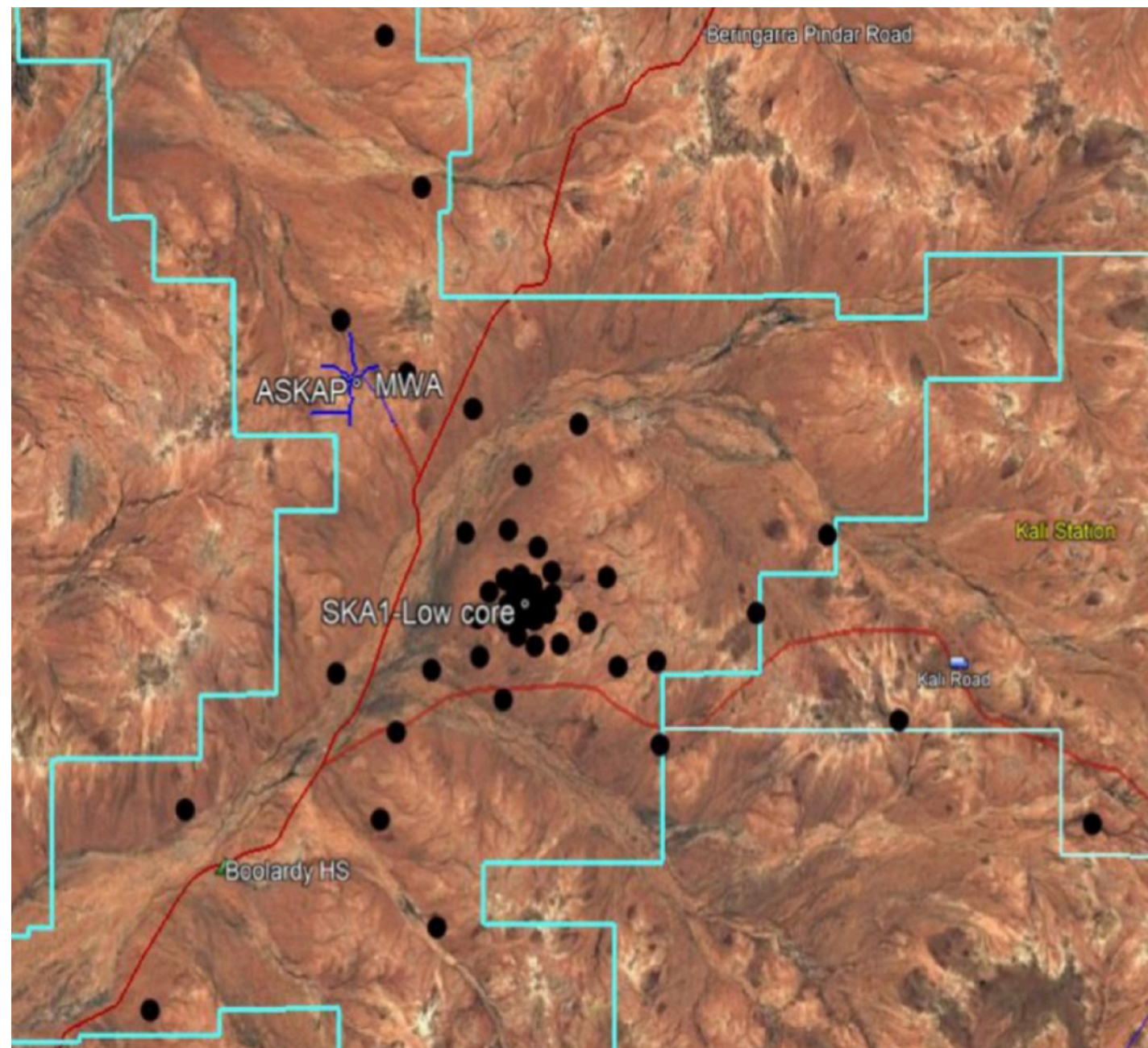
III. 21-cm tomography of the CD/EoR



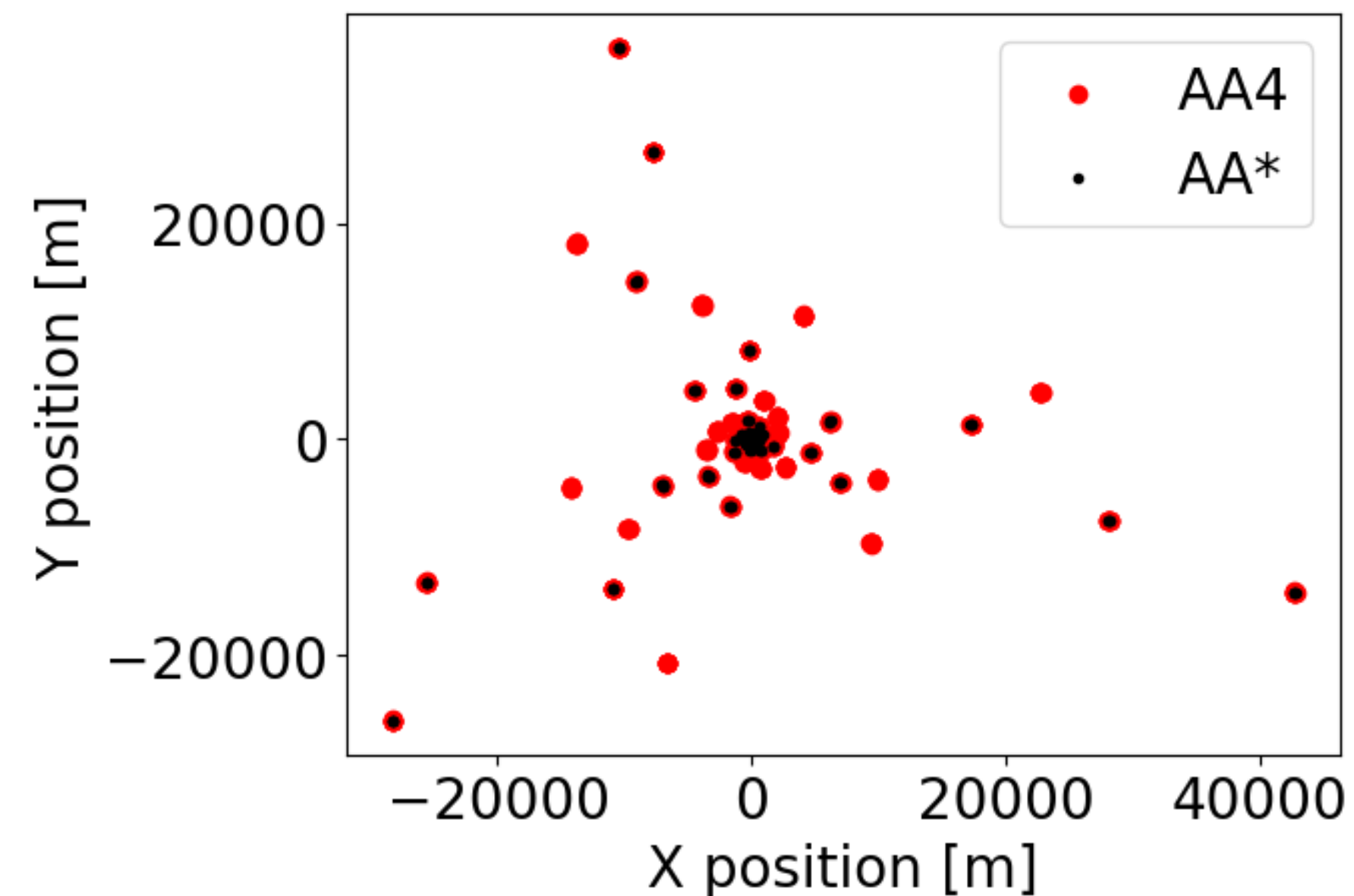
Credit: John Wise

Observational 21-cm cosmology

- Mapping **neutral hydrogen** by its **21-cm signal**: brightness temperature, polarization (Li, Tan & Mao* 2021, ApJ, 2101.11543)
- 21-cm power spectrum from the **CD/EoR**: SKA-Low, HERA, ...



SKA1-Low: 512 stations, 40 m diameter



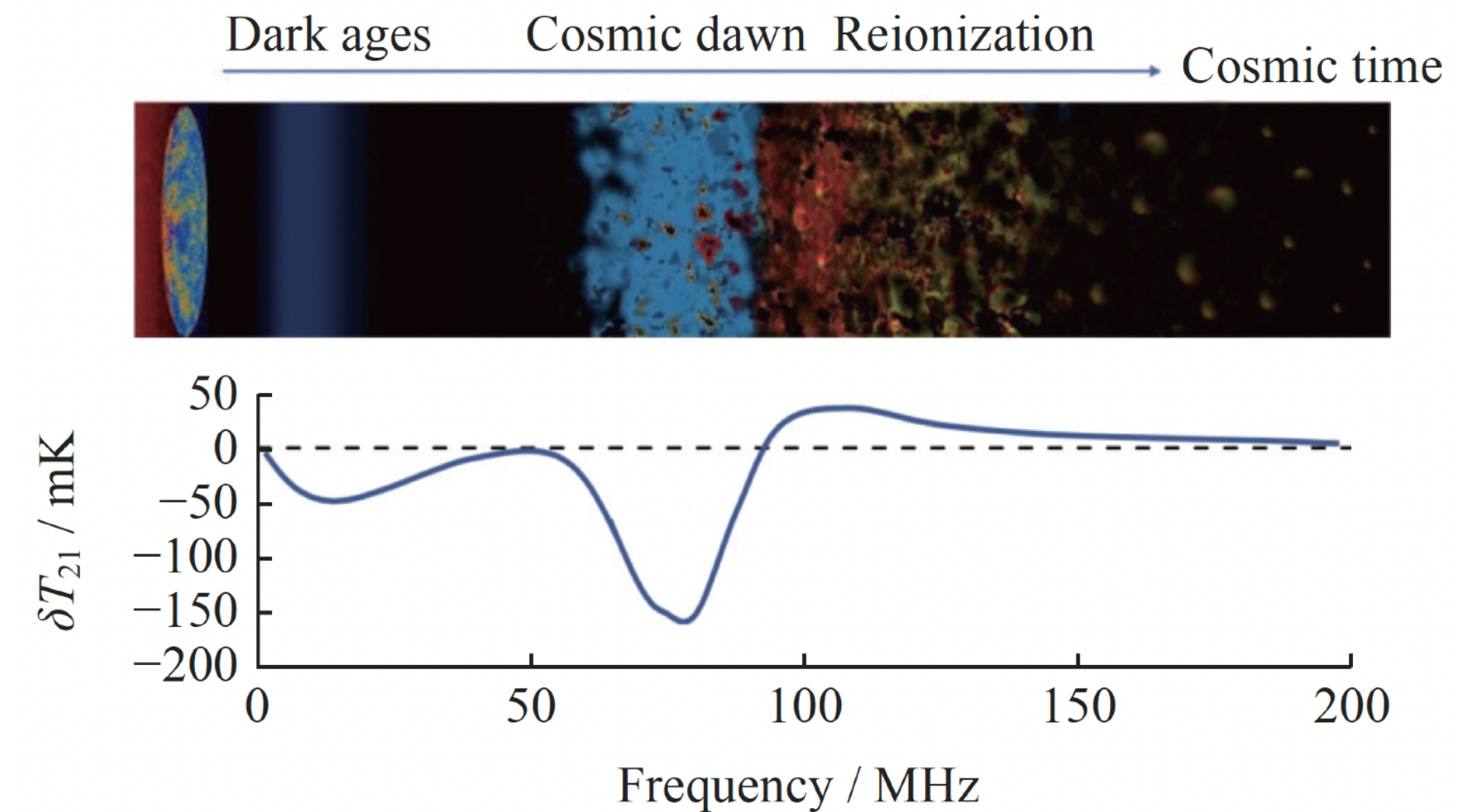
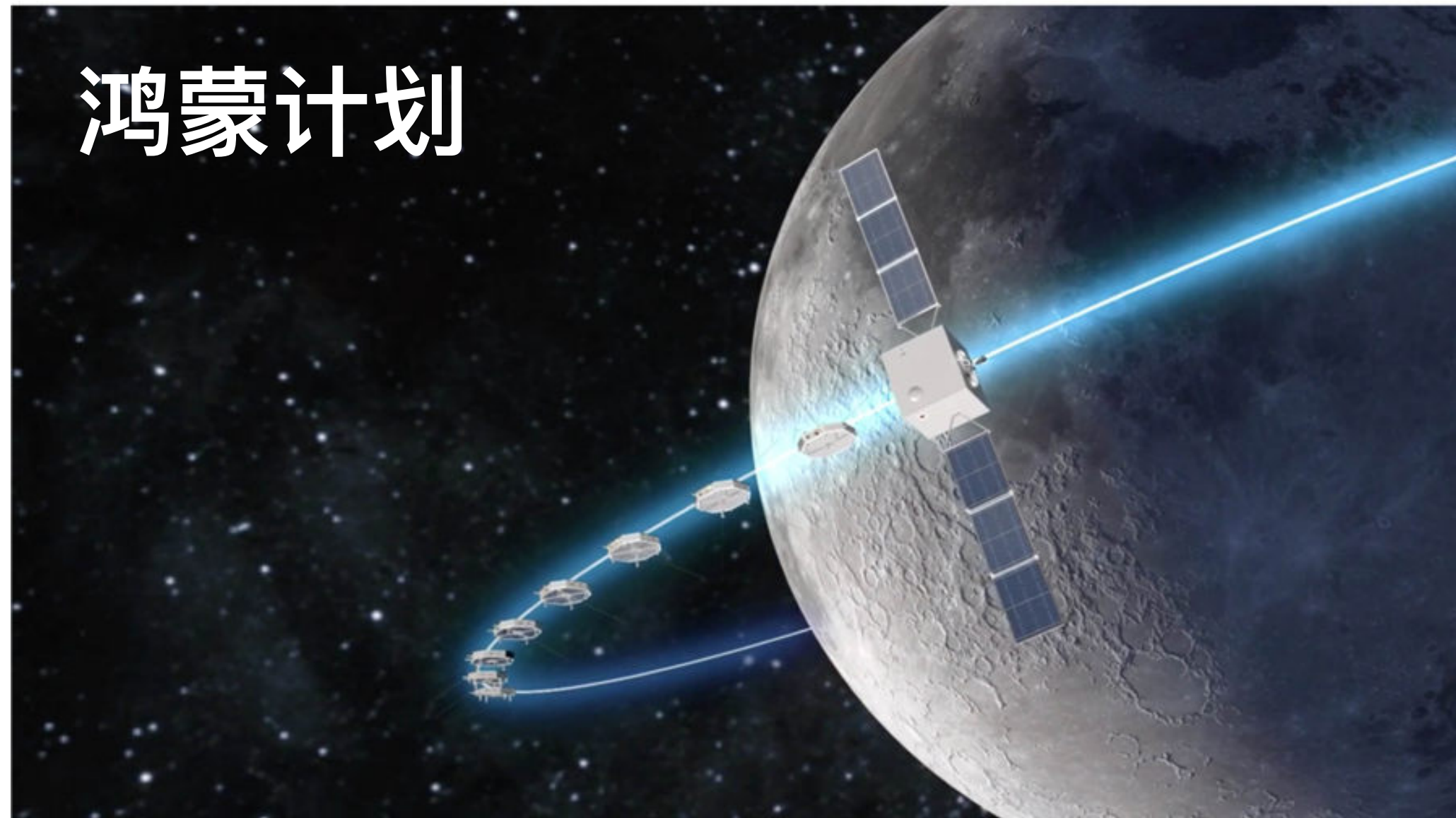
SKA1-Low AA*: 307 stations



256 antennae per station, 50-350 MHz

Observational 21-cm cosmology

- Global (sky-averaged) 21-cm spectrum from the **Dark Ages & CD/EoR**



EDGES



SARAS 3

EDGES implications

Possible interaction between baryons and dark-matter particles revealed by the first stars

Rennan Barkana¹

Nature, 555 (2018)

A small amount of mini-charged dark matter could cool the baryons in the early Universe

Julian B. Muñoz^{1*} & Abraham Loeb²

Nature, 557 (2018)

Probing the effects of FDM on structure formation

- Seminumerical simulations of the CD/EoR with the **21cmFAST** code

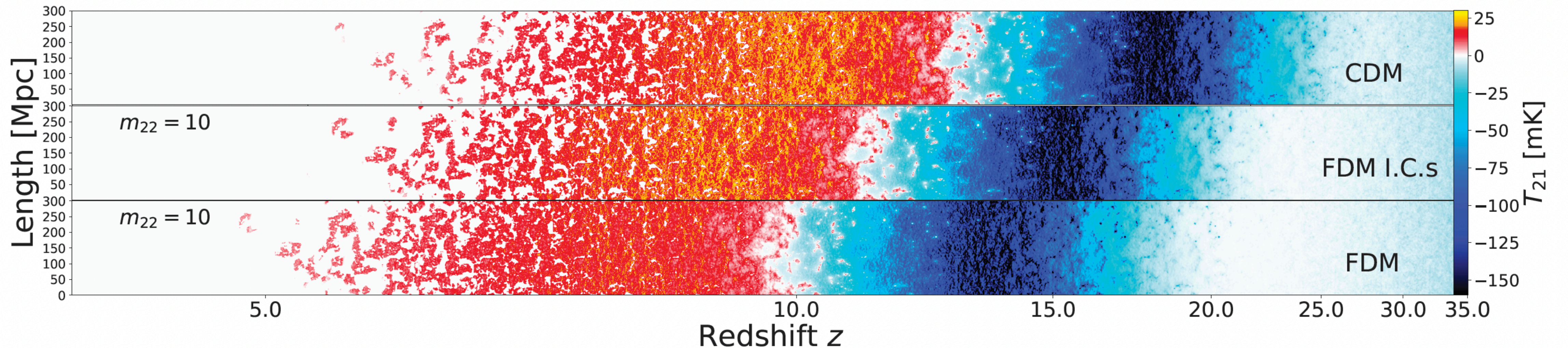
- Cosmology: the halo mass function (HMF) determined by the dark matter model, in this case, **fuzzy dark matter (FDM)**

- **Astrophysics**: counts of ionizing photons

$$\dot{n}_{\text{ion/b}} = \frac{d}{dt} \left[\bar{\rho}_m^{-1} \int_{M_{\text{min}}}^{\infty} dM_h \frac{dn}{d \ln M_h} f_b f_* N_{\gamma/b} f_{\text{esc}} \right]$$

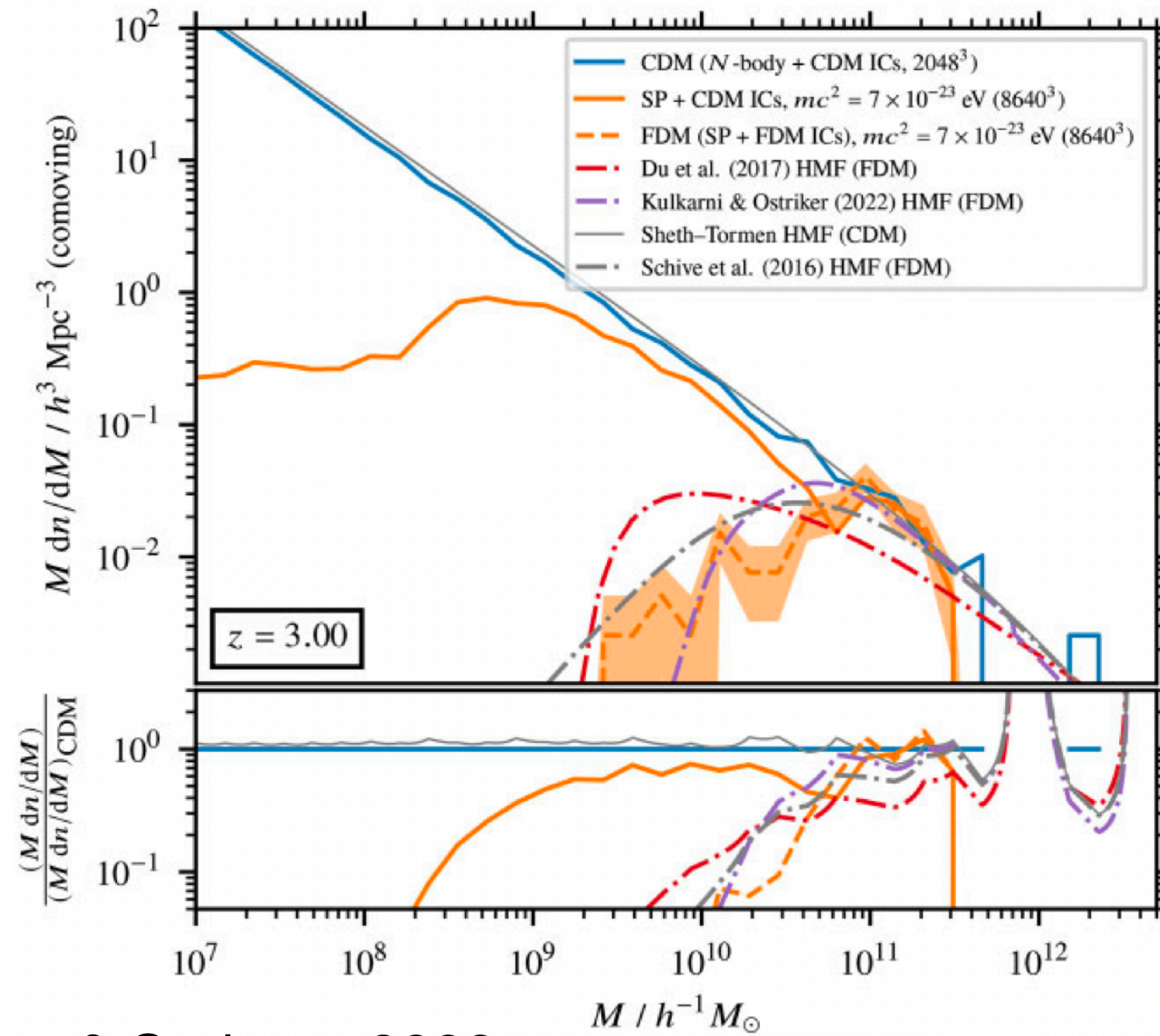
$$\zeta = 20 \left(\frac{N_{\gamma}}{4000} \right) \left(\frac{f_{\text{esc}}}{0.1} \right) \left(\frac{f_*}{0.05} \right) \left(\frac{f_b}{1} \right)$$

$$T_{\text{vir}} = \frac{\mu m_p V_c^2}{2k_B} = 1.98 \times 10^4 \left(\frac{\mu}{0.6} \right) \left(\frac{M}{10^8 h^{-1} M_{\odot}} \right)^{2/3} \left[\frac{\Omega_m}{\Omega_m^z} \frac{\Delta_c}{18\pi^2} \right]^{1/3} \left(\frac{1+z}{10} \right) \text{ K}$$

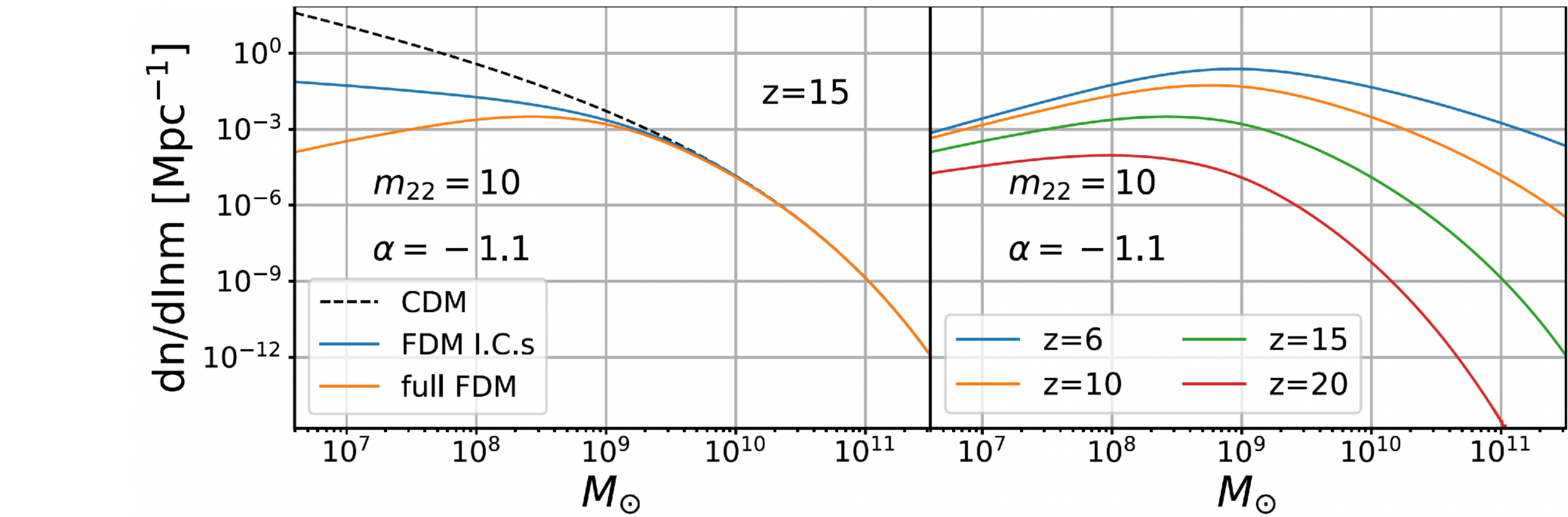


Halo mass function: the FDM case

- Existing efforts using excursion set formalism is inaccurate for FDM!



May & Springer 2023



- Adopt fitting formula from full FDM simulations

$$\left. \frac{dn}{dm} \right|_{\text{FDM}}(m, z) = \left. \frac{dn}{dm} \right|_{\text{CDM}}(m, z) \left[1 + \left(\frac{m}{M_0} \right)^\alpha \right]^{-2.2}$$

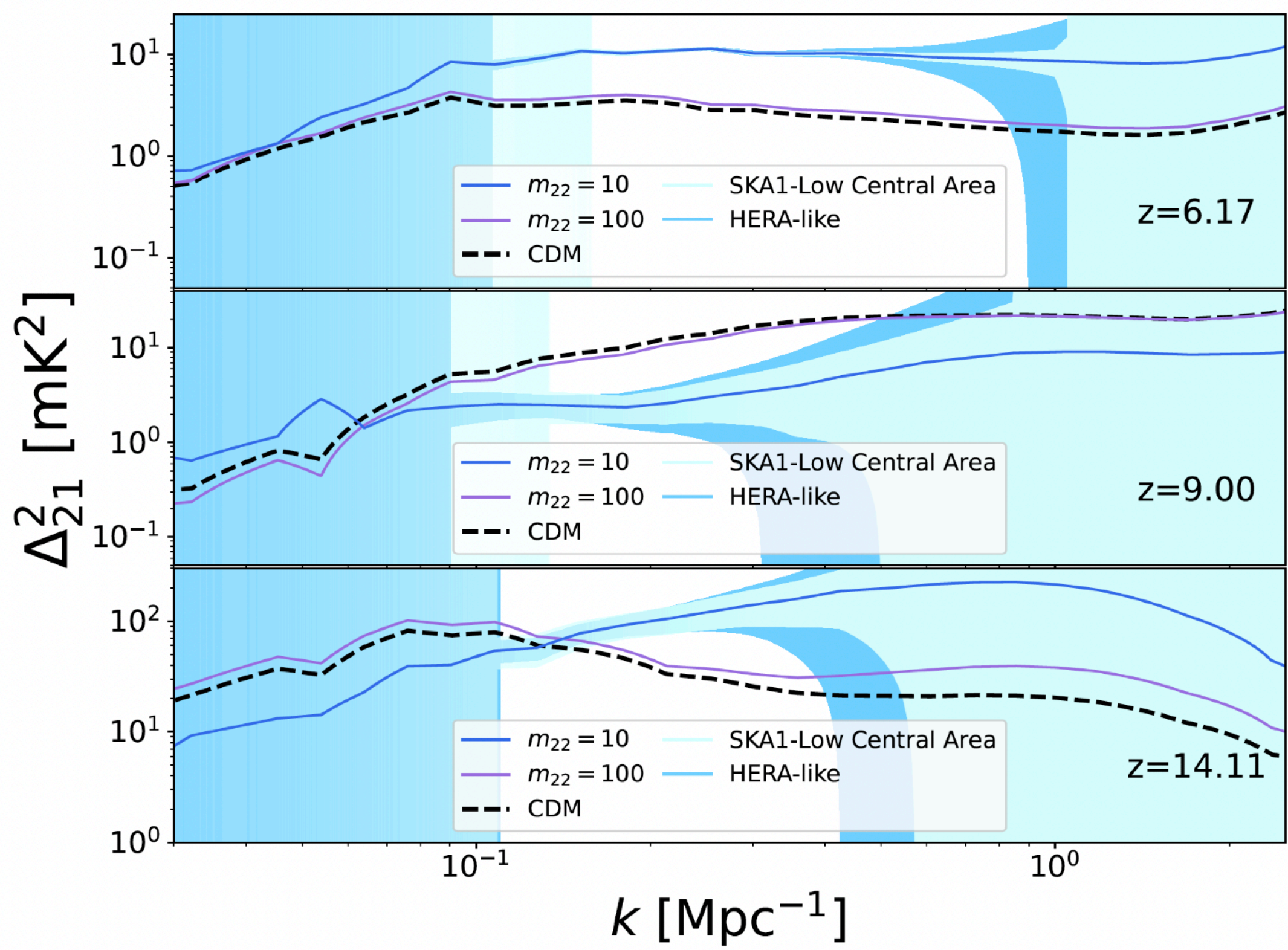
- Density-modulation ansatz:

$$\left. \frac{dn}{dm} \right|_{\text{CDM}}(m, z) = -\frac{\bar{\rho}_m}{m} f(\nu) \frac{d \ln \sigma}{dm}$$

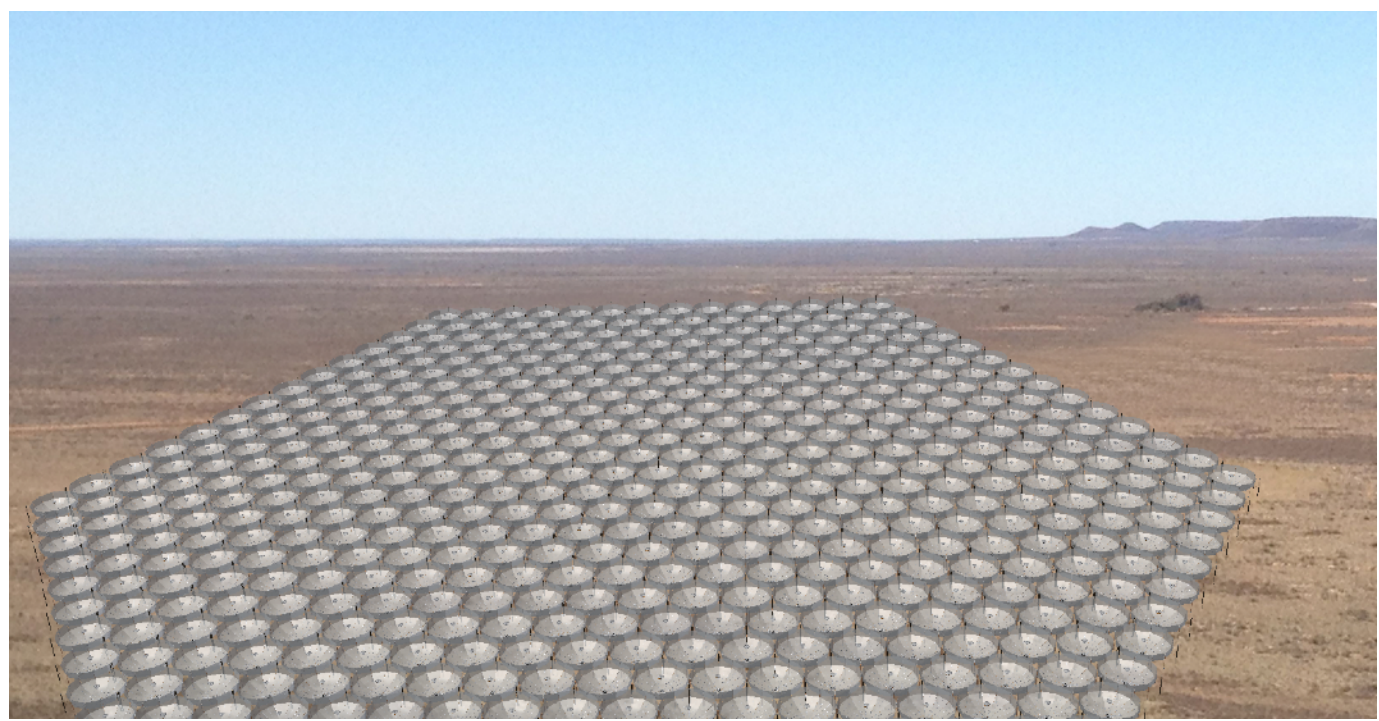
$$\nu^2 = \frac{[\delta_c (1+z) - \delta_{\text{FDM}}]^2}{\sigma_{\text{CDM}}^2(m) - \sigma_{\text{FDM}}^2(M)}$$

Forecast: detecting FDM by 21-cm power spectrum

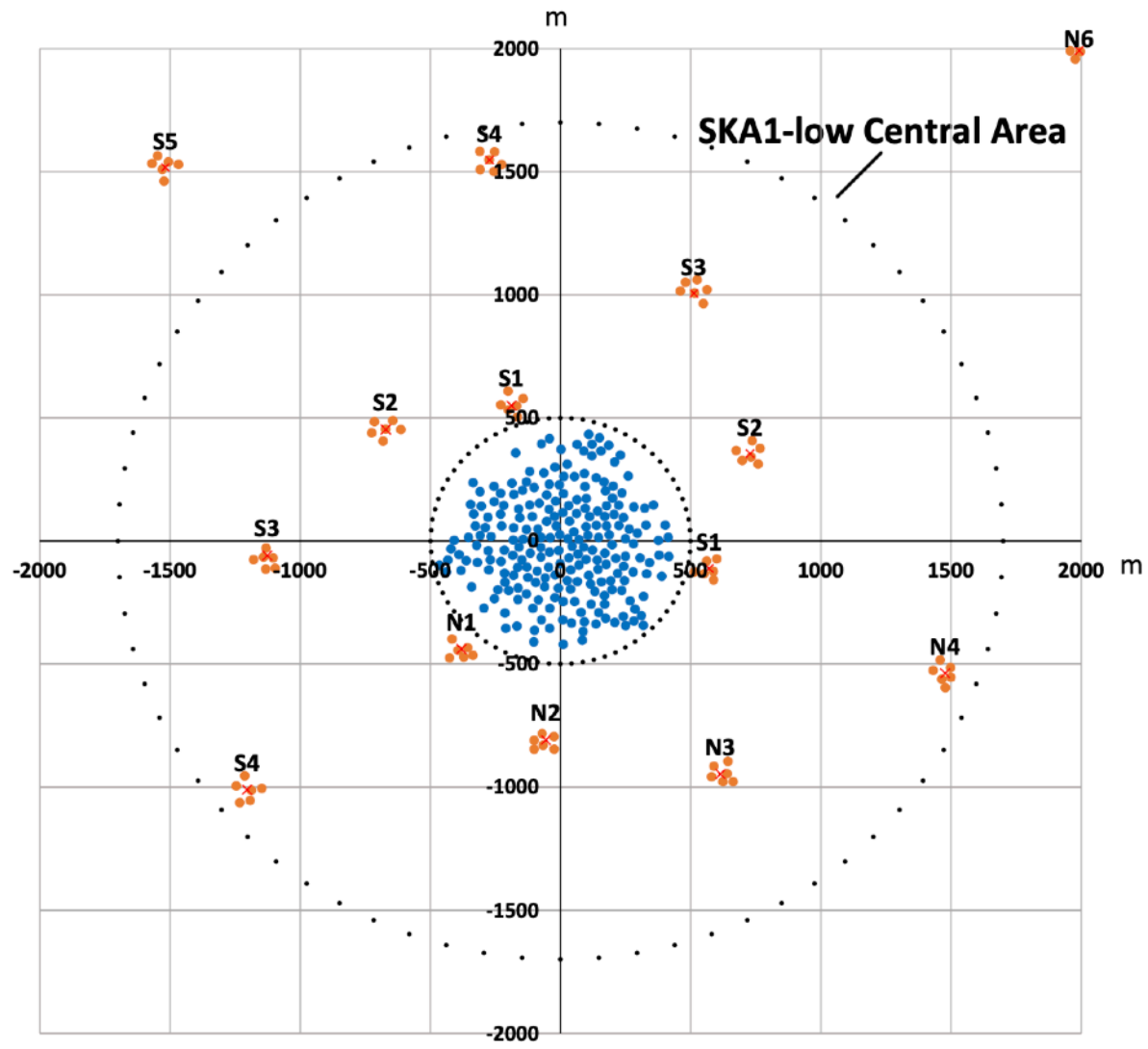
- Sensitivity of 21-cm power spectrum measurements, estimated by the 21cmSense code



Parameters	HERA	SKA1-Low (central area)
Number of dishes/stations	331	296 ^a
Sky temperature T_{sky} [K]	$60 (\nu/300 \text{ MHz})^{-2.55}$	$20 (\nu/408 \text{ MHz})^{-2.75}$ ^b
Receiver temperature T_{rev} [K]	100	30 (Ref. [65])
Dish size [m]	14	40 ^b
Frequency resolution [kHz]	97.65	5.4 ^c
Bandwidth [MHz]	8	8
Observing time [h]	1080	1080



HERA



SKA1-Low (central area)

Liu, ..., Li* & Mao 2025, PRD, arXiv: 2508.10176

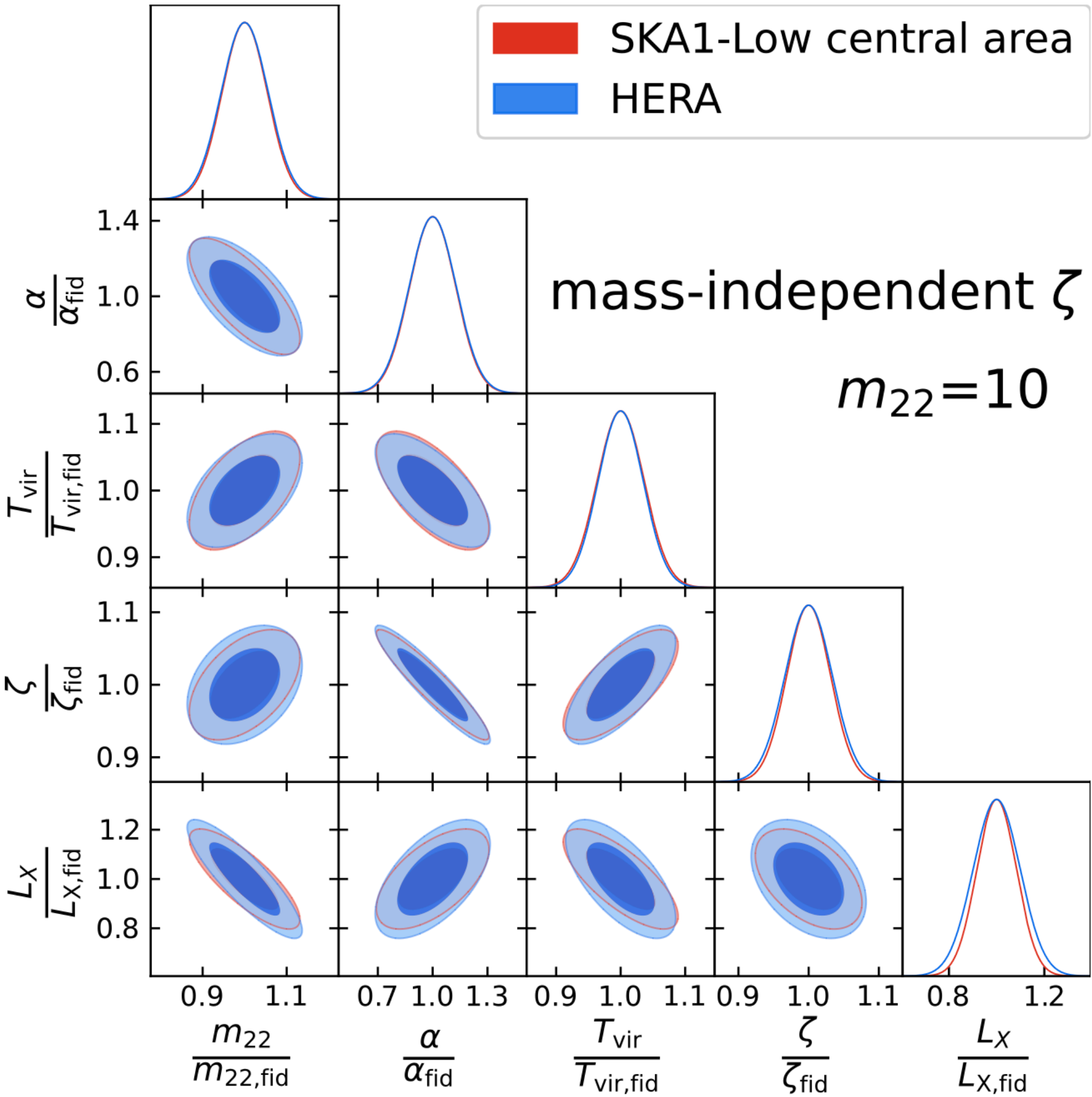
Forecast: detecting FDM by 21-cm power spectrum

● Fisher matrix forecast for the fiducial model

$$F_{ij} = \sum_{k,z} \frac{\partial \Delta_{21}^2(k,z)}{\partial p_i} \frac{\partial \Delta_{21}^2(k,z)}{\partial p_j} \frac{1}{\text{var} [\Delta_{21}^2(k,z)]}$$

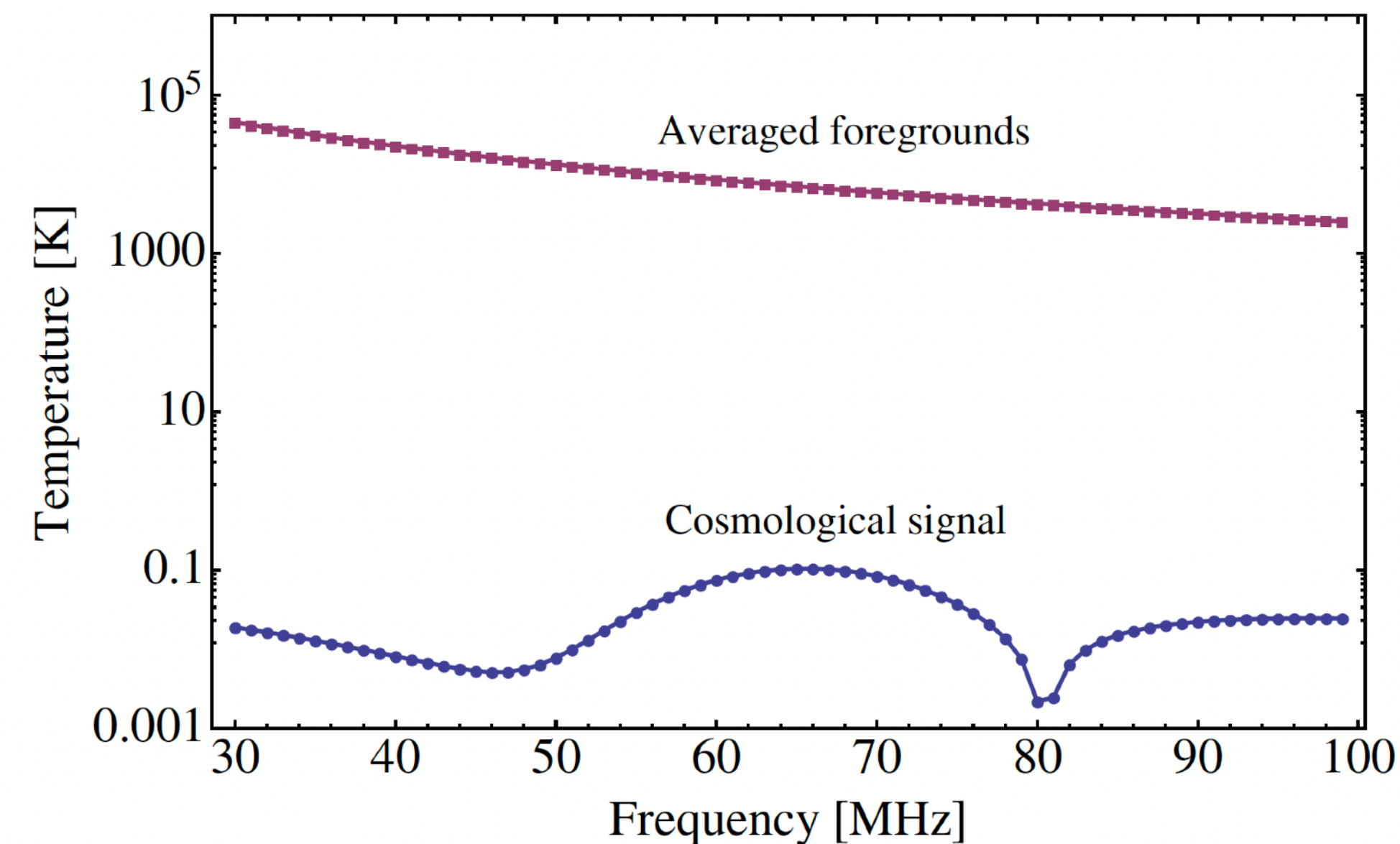
Parameter	value	SKA1-Low central area (1σ)	HERA (1σ)
m_{22}	10	5.37%	5.59%
α	-1.1	12.59%	12.86%
ζ	20	3.10%	3.35%
T_{vir}	2×10^4	3.64%	3.48%
L_{X}/SFR	10^{40}	8.30%	9.85%

Liu, ..., Li* & Mao 2025, PRD, arXiv: 2508.10176



Global 21-cm spectrum: data analysis

- **Data model:** $\mathbf{T}_D = \mathbf{T}_{21} + \mathbf{T}_{fg} + \mathbf{n}$
over frequency bins in [30, 120] MHz
- **Typical foreground (FG) model:**
logarithmic polynomial fit
based on the assumption/notion of
smooth frequency dependence



Liu et al. 2013

In the case of SARAS 3: $\log_{10} \mathbf{T}_{fg} = \sum_{i=0}^6 a_i \left[\mathcal{R}(\log_{10} \nu) \right]^i$

Bevins et al. 2022 NA

- **Likelihood:**

$$\ln \mathcal{L} = -\frac{1}{2} \left(\mathbf{T}_D - \mathbf{T}_{21} - \mathbf{T}_{fg} \right)^T \mathbf{\Sigma}^{-1} \left(\mathbf{T}_D - \mathbf{T}_{21} - \mathbf{T}_{fg} \right) + \text{const}$$

Hybrid approach (Frequentist + Bayesian)

- Assuming FG removal is done with **an optimal/unbiased estimator of FG** (e.g., an ultralong-wavelength sky model) with residual uncertainties

$$\ln \mathcal{L} = -\frac{1}{2} (\mathbf{T}_D - \mathbf{T}_{21})^T \mathbf{\Sigma}^{-1} (\mathbf{T}_D - \mathbf{T}_{21}) + \text{const}$$

- Total estimated error:**

$$\sqrt{(\mathbf{\Sigma}^{-1})_{\alpha\alpha}} = \left(T_{\text{eff}}(\nu_\alpha) \sqrt{f_{\text{noise}}} \right)^{-1} \quad T_{\text{eff}}(\nu_\alpha) : \text{effective FG temperature at } \nu_\alpha$$

$$f_{\text{noise}} = \boxed{\frac{\epsilon_0^2 \theta_{\text{fg}}^2}{4\pi f_{\text{sky}}}} + \boxed{\frac{1}{t_{\text{int}} B}}$$

Residual FG contribution

$$\left\{ \begin{array}{l} \text{Pessimistic: } \epsilon_0 = 0.1 \\ \text{Moderate: } \epsilon_0 = 10^{-4} \\ \text{Optimistic: } \epsilon_0 = 0 \end{array} \right.$$

Instrumental noise contribution

Forecast: detecting FDM by **global 21-cm spectrum**

- **Total estimated error:**

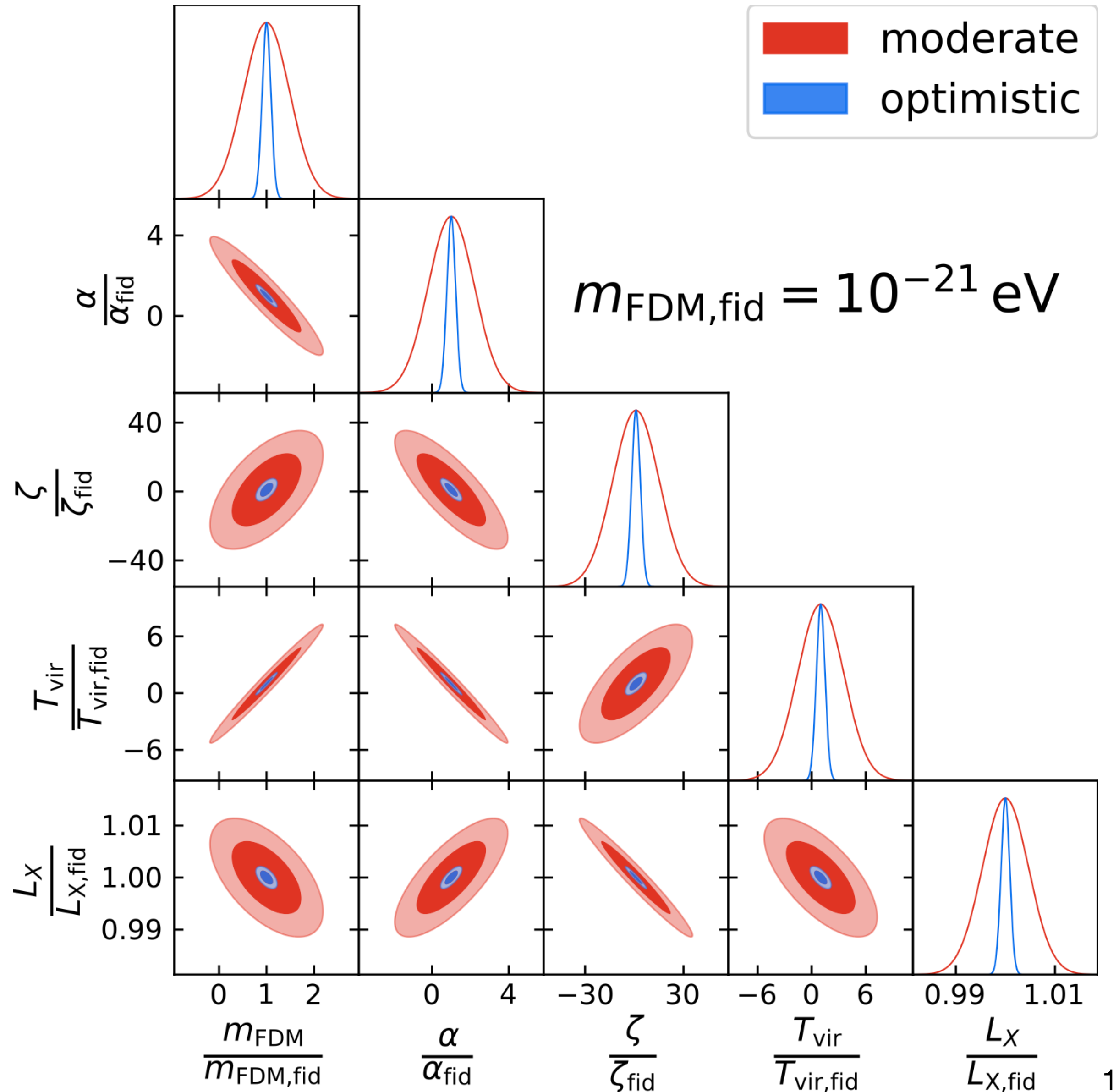
$$\sqrt{(\Sigma^{-1})_{\alpha\alpha}} = \left(T_{\text{eff}}(\nu_{\alpha}) \sqrt{f_{\text{noise}}} \right)^{-1}$$

$$f_{\text{noise}} = \frac{\epsilon_0^2 \theta_{\text{fg}}^2}{4\pi f_{\text{sky}}} + \frac{1}{t_{\text{int}} B} \quad \begin{cases} t_{\text{int}} = 1000 \text{ hrs} \\ B = 1 \text{ MHz} \end{cases}$$

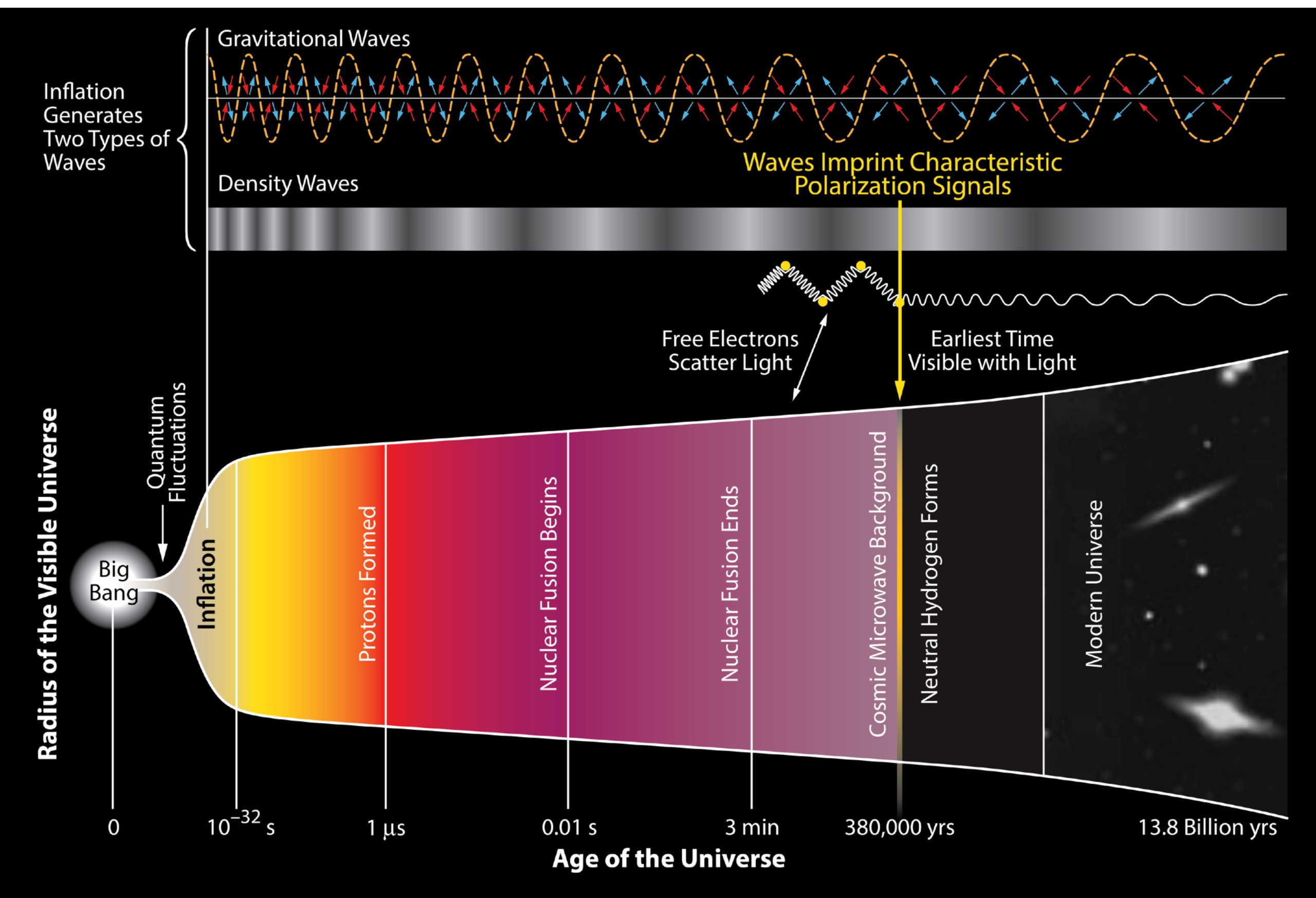
$\theta_{\text{fg}} \simeq 5^\circ$: angular resolution of the FG model

$\left\{ \begin{array}{l} \text{Pessimistic: } \epsilon_0 = 0.1 \\ \text{Moderate: } \epsilon_0 = 10^{-4} \\ \text{Optimistic: } \epsilon_0 = 0 \end{array} \right.$

- **Fisher matrix forecast w.r.t. the fiducial signal model**



II. **Kination-amplified** inflationary gravitational-wave background



Ultralight SFDM has an early **kination** phase

- A special phase in the cosmic history in which

Energy density of the Universe **dominated by** Kinetic energy of a scalar field

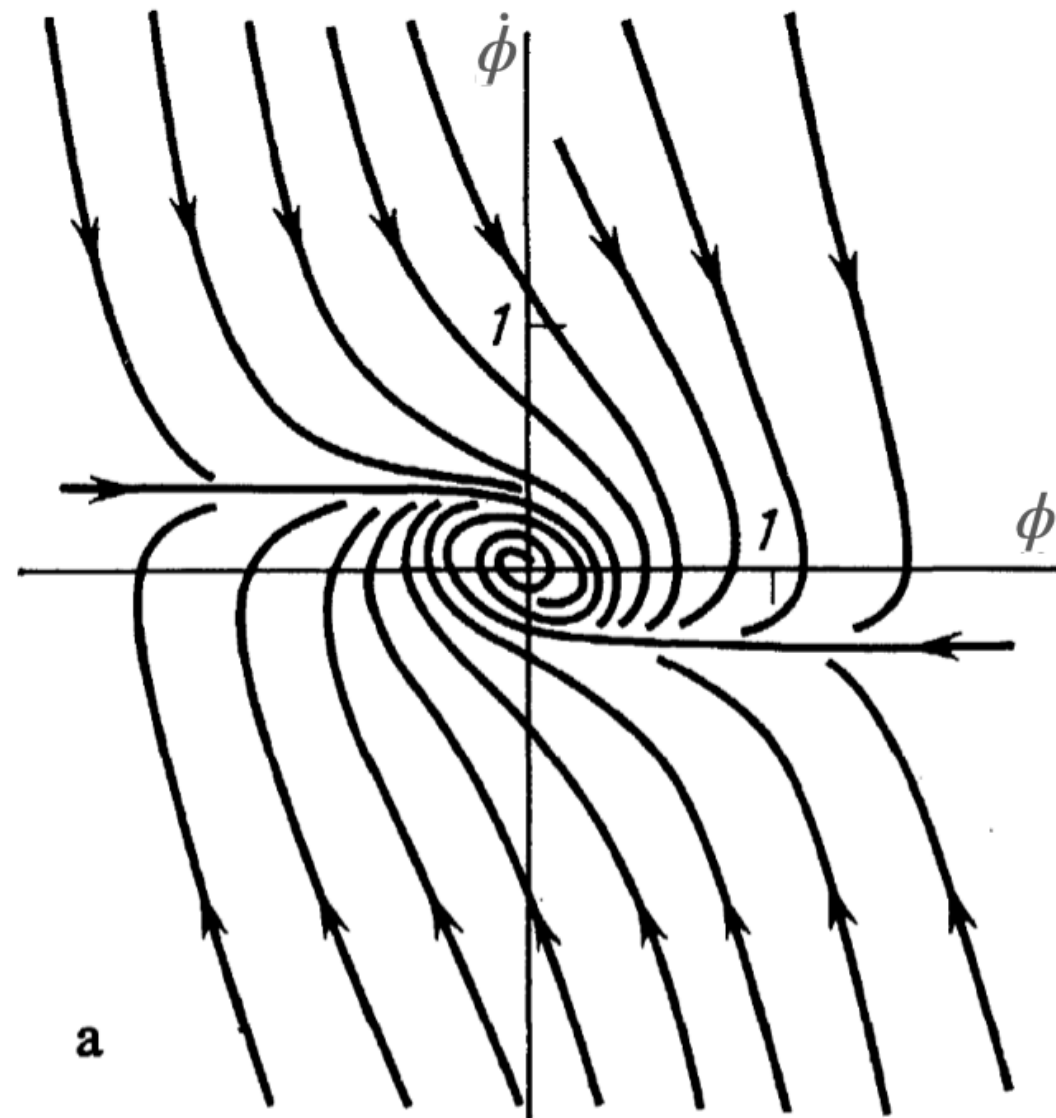
Joyce 1997

$$\mathcal{L} = K - V = \frac{1}{2}\dot{\phi}^2 - \frac{1}{2}m^2\phi^2$$

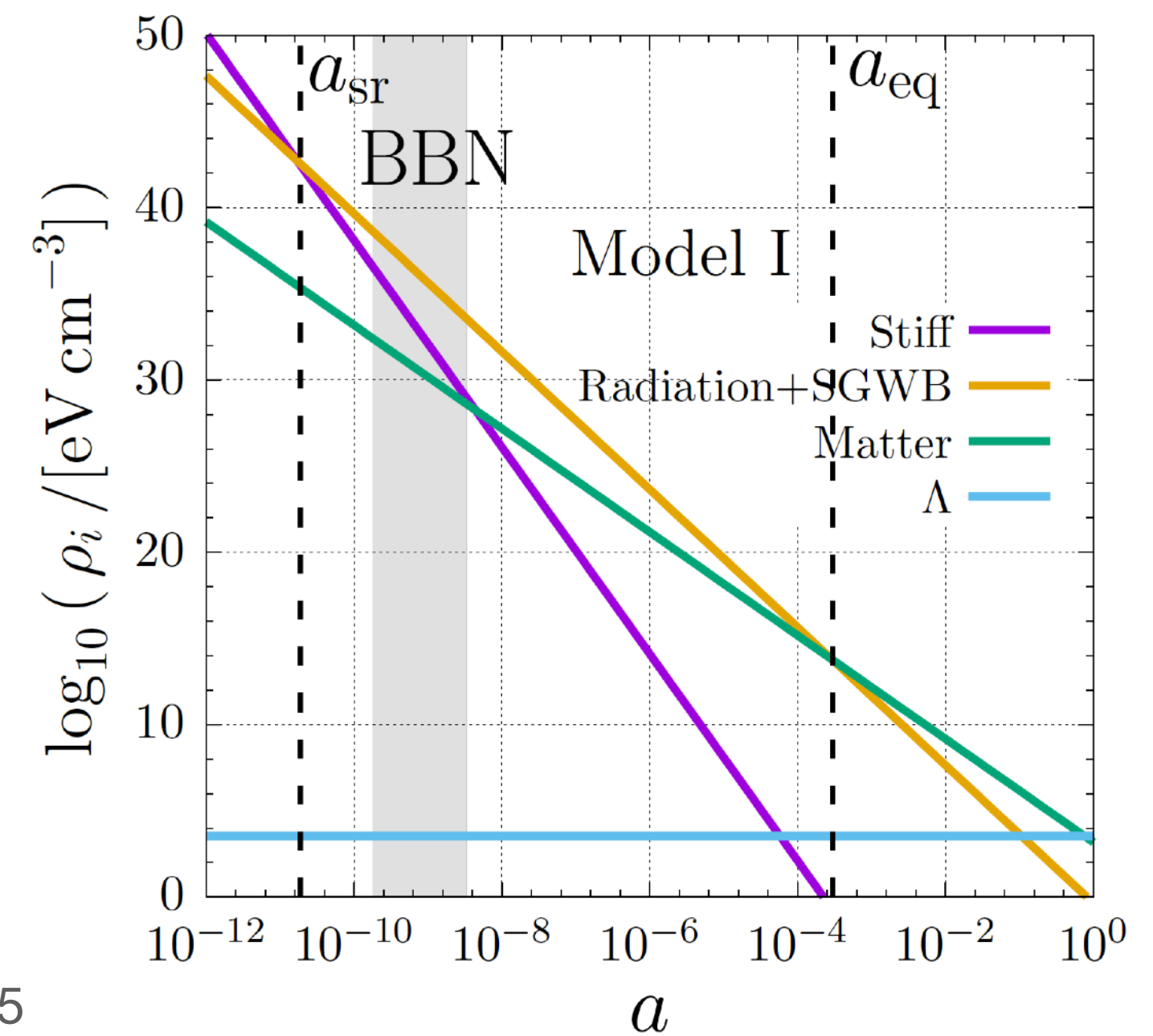
$$\Rightarrow \rho_\phi \simeq \frac{1}{2}\dot{\phi}^2 \propto a^{-6}$$

$$w_\phi = p_\phi/\rho_\phi \simeq 1$$

“stiff matter”



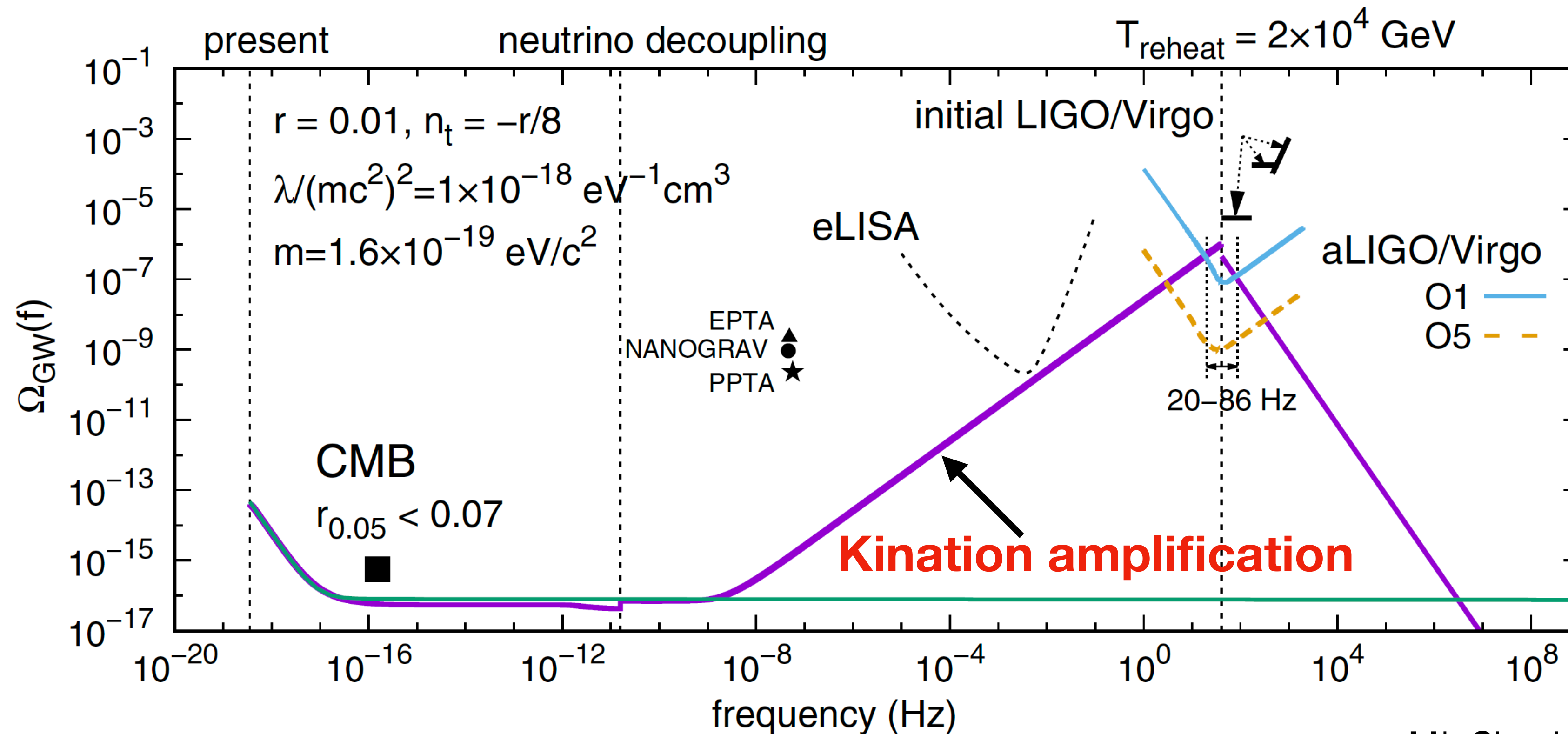
Belinsky, Grishchuk, Zel'dovich & Khalatnikov 1985



Li* & Shapiro 2021, JCAP
2107.12229

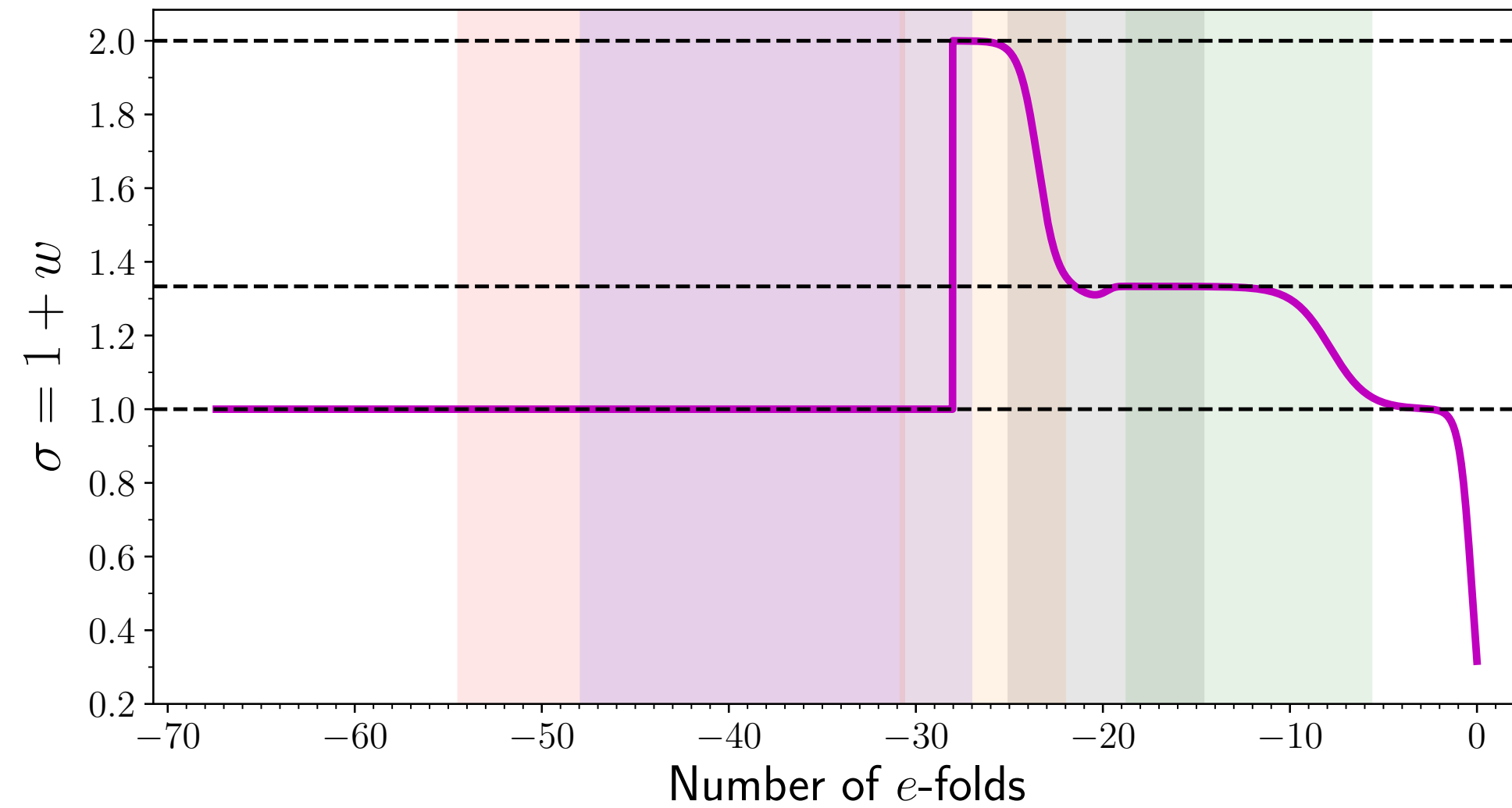
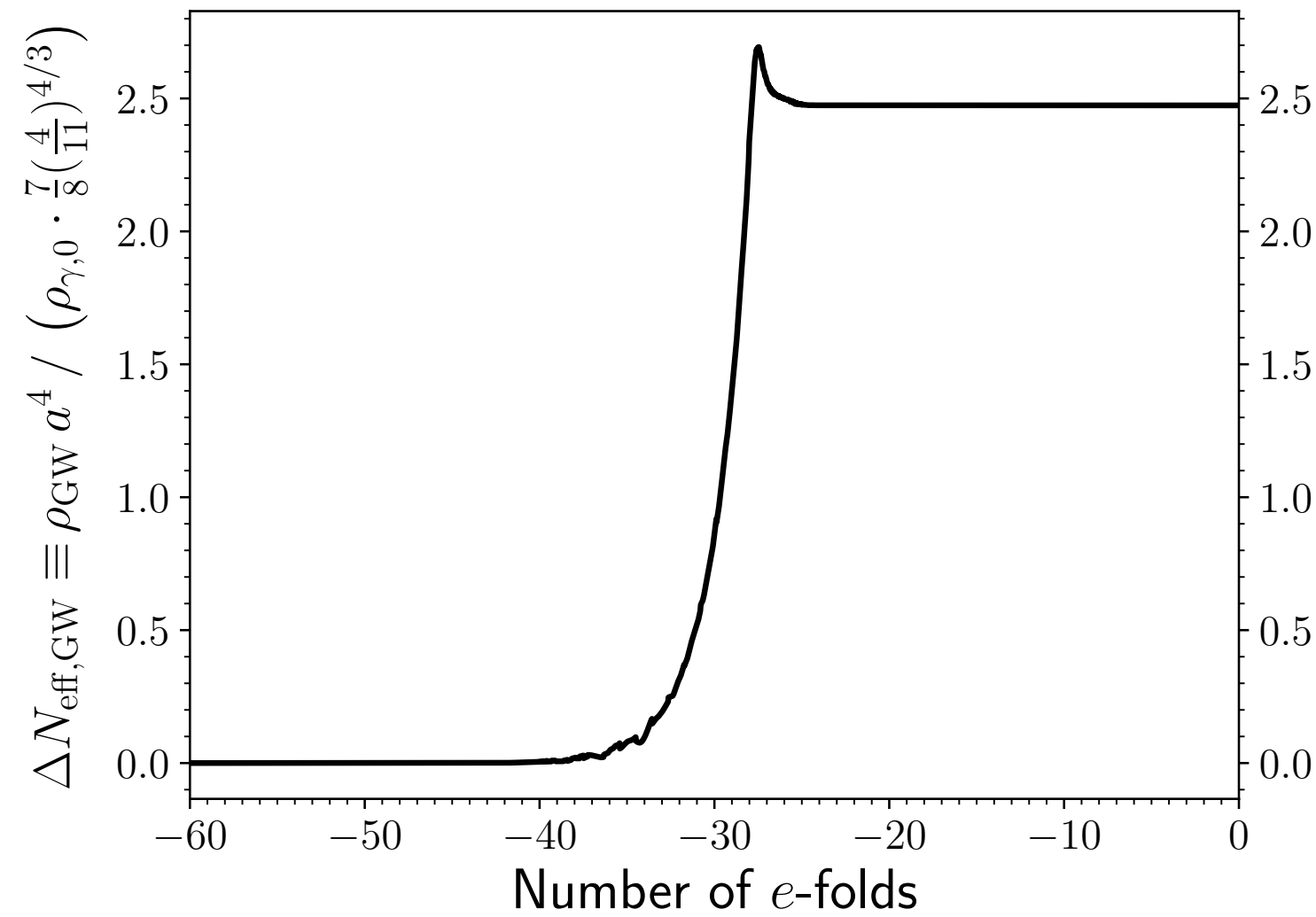
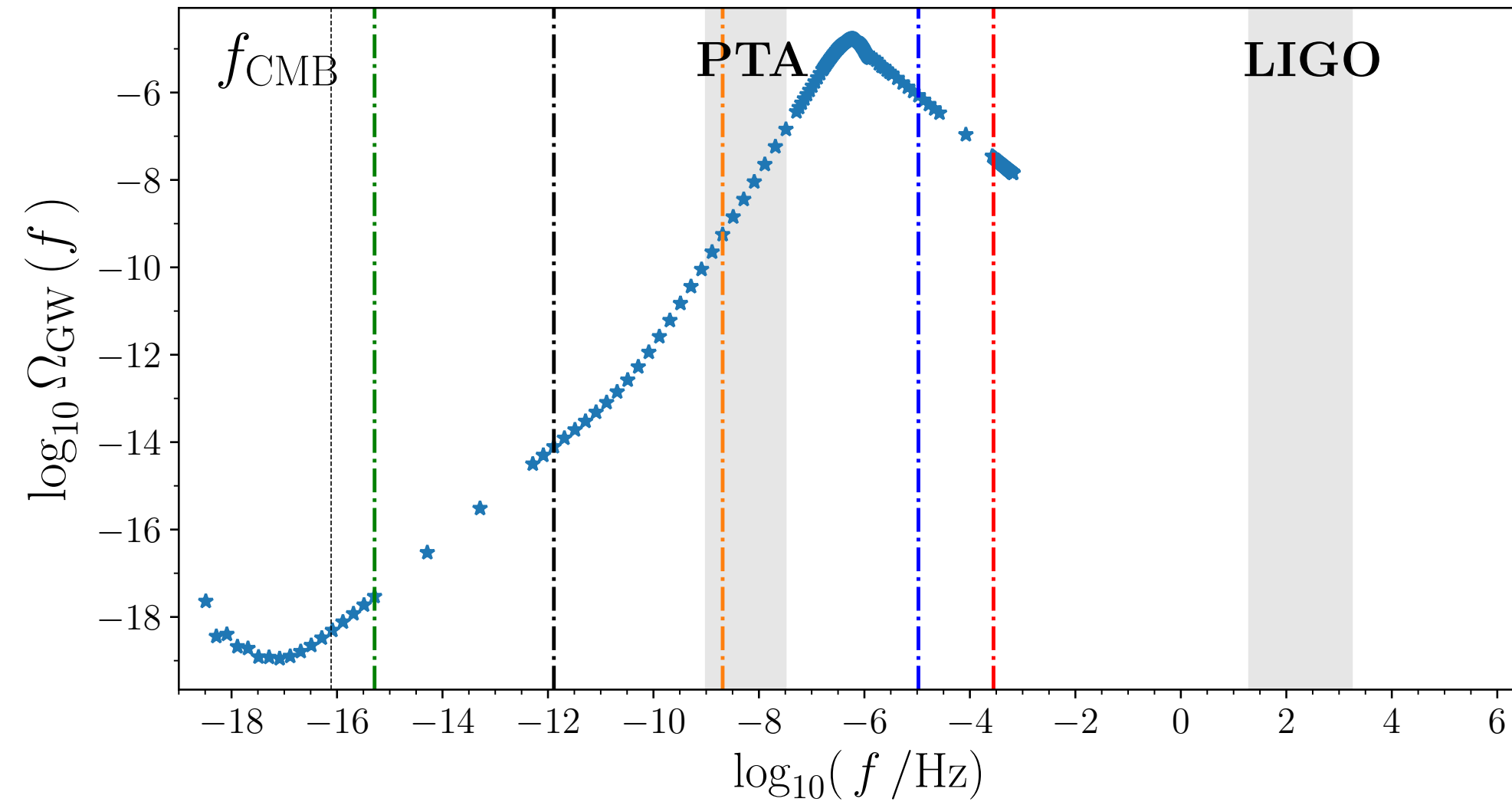
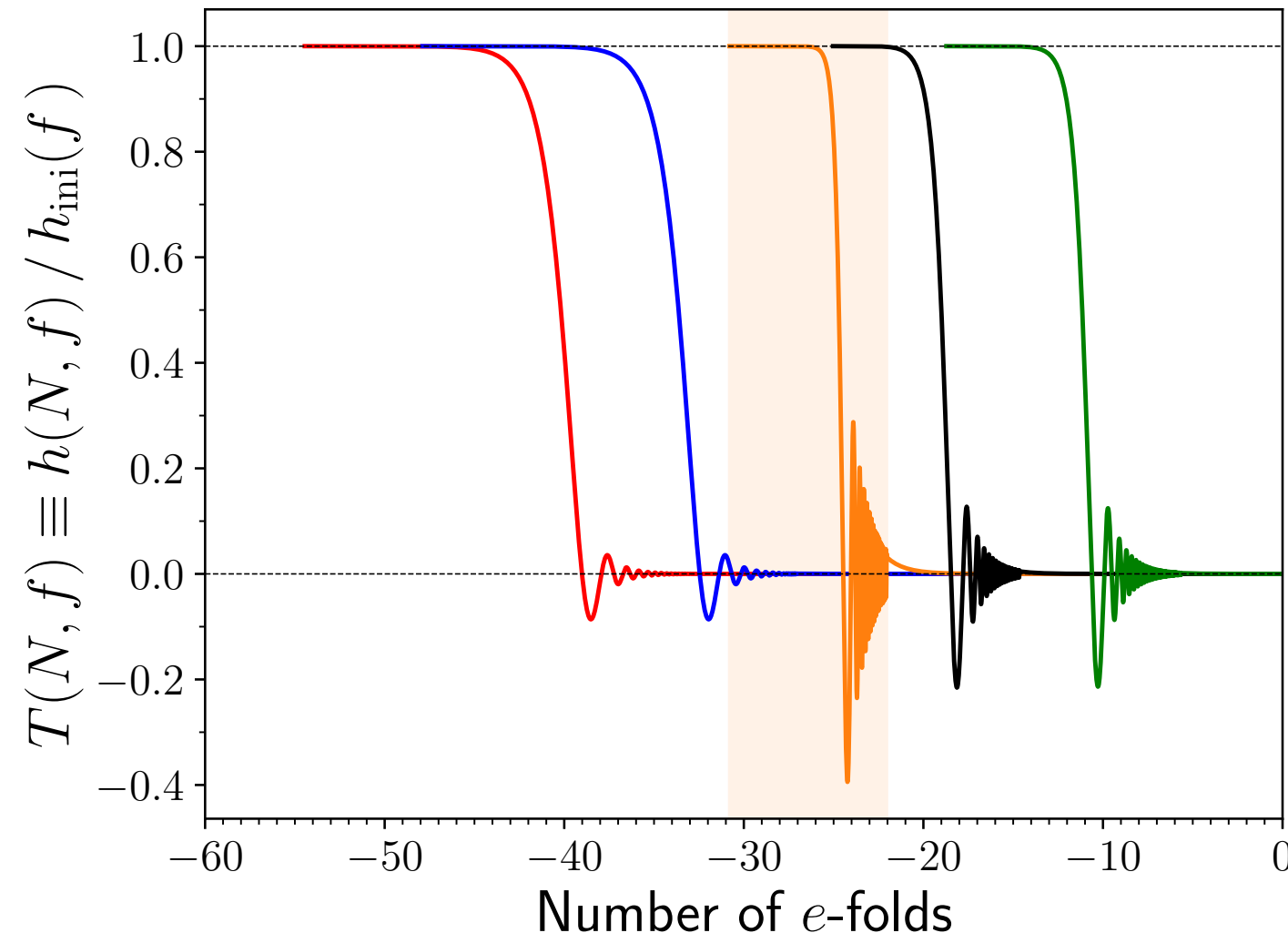
The “kination-amplified” primordial SGWB

- Tensor modes that reenter the horizon **during kination** get amplified.
- Results in a **blue tilt** signature in the GW energy spectrum today, $\Omega_{\text{GW}}(f) \propto f^{n_t+1}$



Li*, Shapiro & Rindler-Daller 2017, PRD
1611.07961

stiffGWpy: a dynamical system approach



- Model parameters:
 $\Omega_c h^2, \Omega_b h^2, H_0, A_s,$
 $r, n_t, \kappa_{10}, T_{\text{re}}, \Delta N_{\text{re}}$
- Tensor-to-scalar ratio
 & tensor index: r, n_t
- **Stiff matter:** $\rho_s \propto a^{-6}$,
 $\kappa_{10} \equiv (\rho_s / \rho_\gamma) |_{T=10 \text{ MeV}}$
 determines the kination-
 radiation transition
- Assume **matterlike**
 reheating: $T_{\text{re}}, \Delta N_{\text{re}}$

SageNet: a neural network emulator

- **Five-parameter model:** $\{r, n_t, \kappa_{10}, T_{\text{re}}, \Delta N_{\text{re}}\}$

Param	$\log_{10} r$	n_t	$\log_{10} \kappa_{10}$	$\log_{10}(T_{\text{re}}/\text{GeV})$	ΔN_{re}
Limits	$[-25, 0]$	$[-1, 6]$	$[-7, 3]$	$[-3, 7]$	$[0, 40]$
Prior	Uniform				

- **Architecture:** Encoder-Decoder Curve Generator

- **Long Short-Term Memory (LSTM)** feature extractor

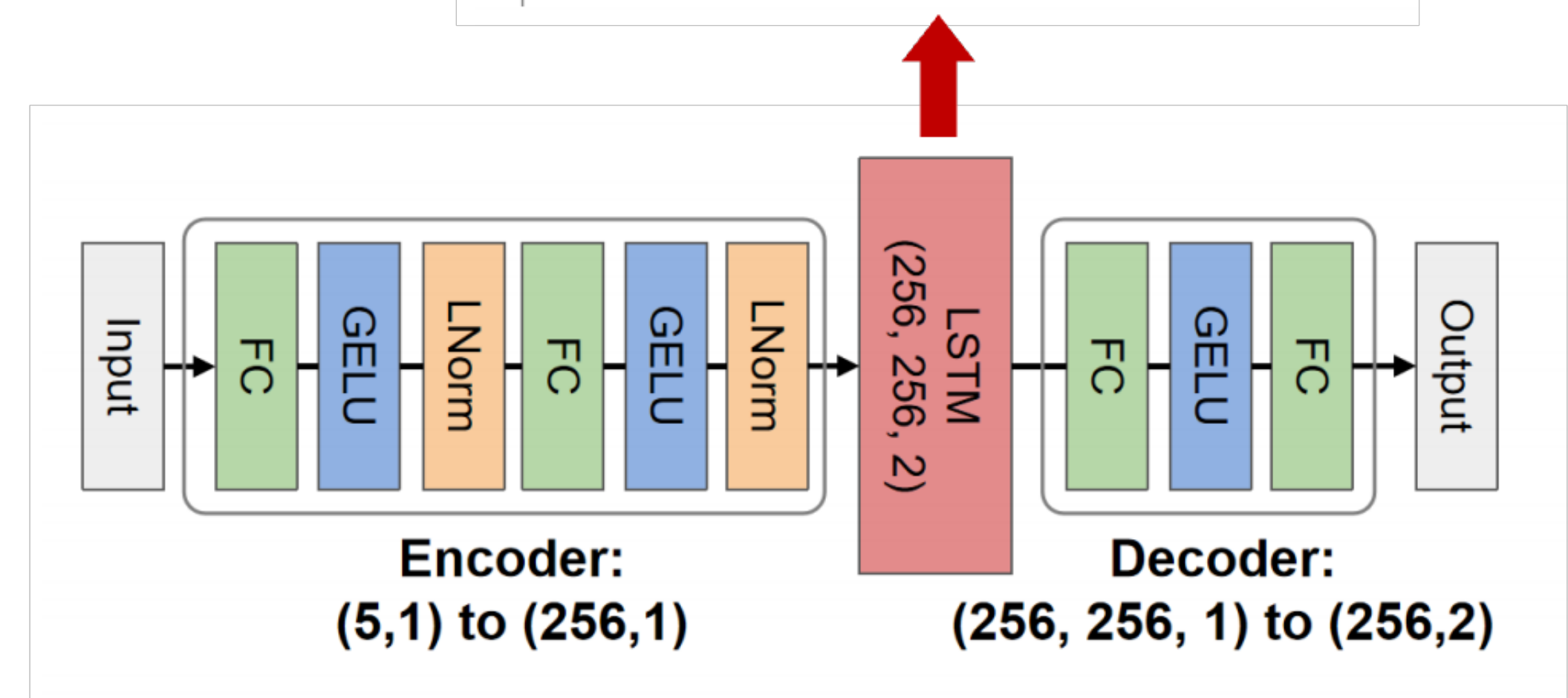
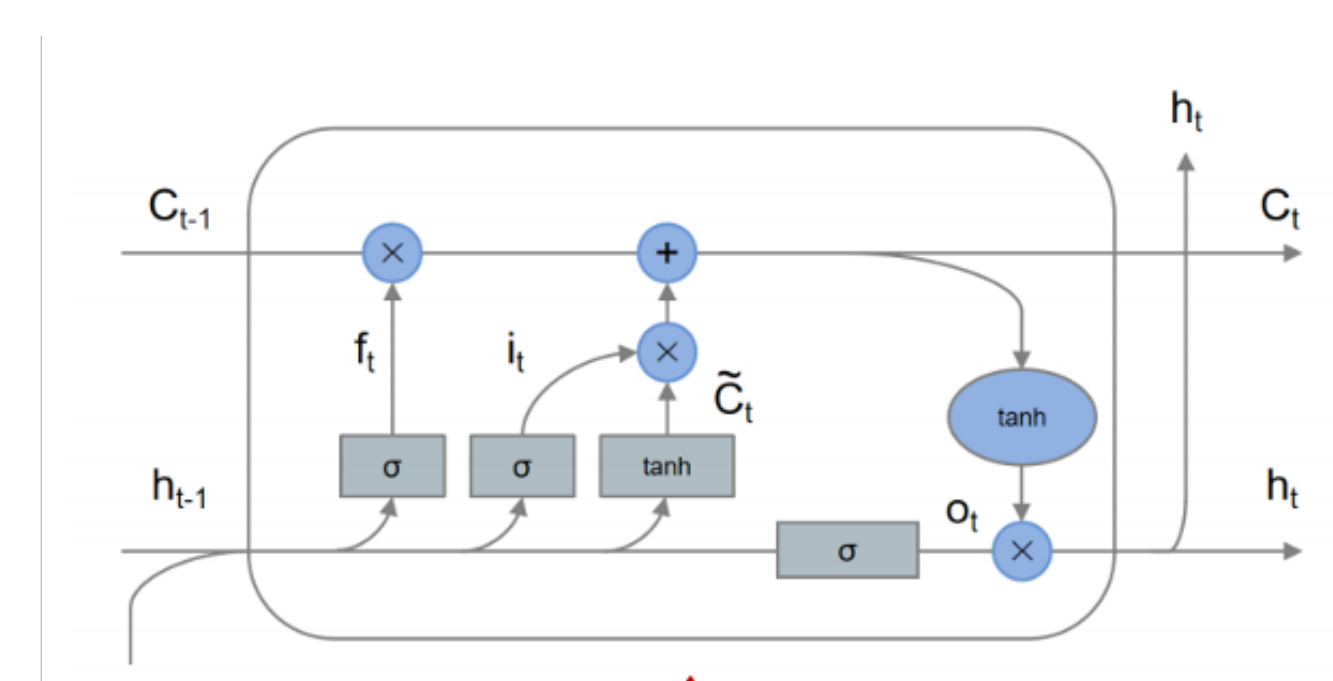
Modeling the sequentiality of points

- **Training data:** 25,000 samples of

$$\{f_i, \log_{10} \Omega_{\text{GW}}(f_i)\}$$

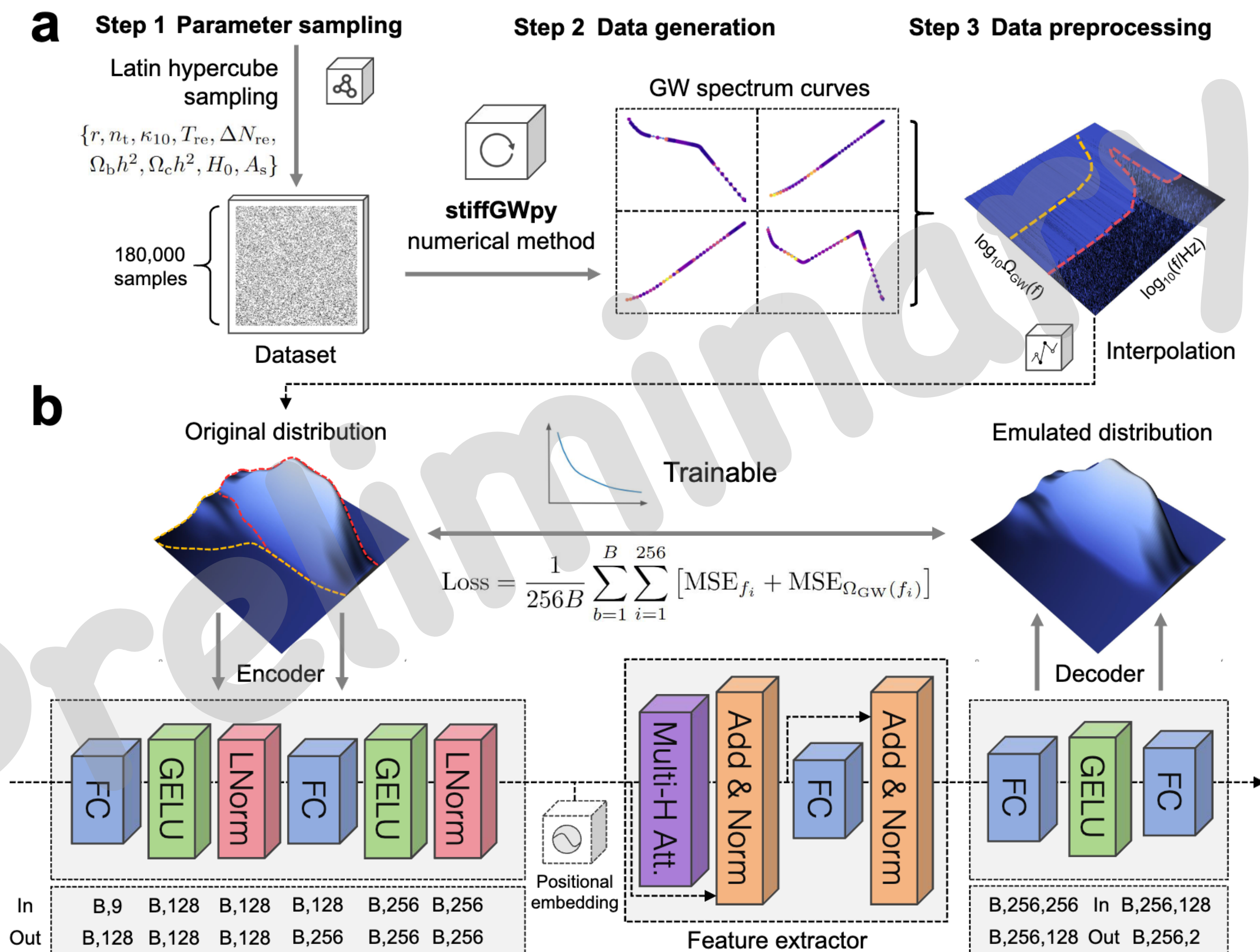
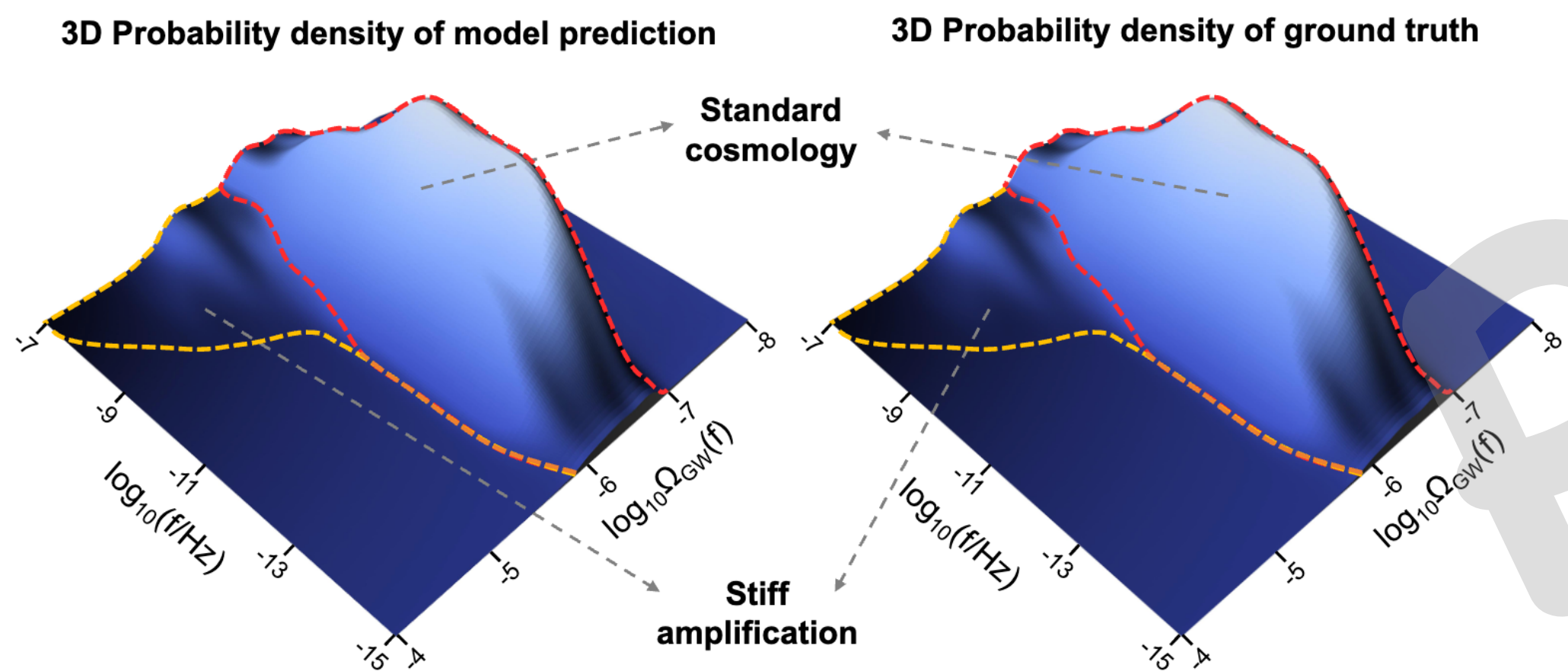
- **Precision** of the emulator: $\lesssim 3\%$ errors (SMAPE) for $\gtrsim 90\%$ test samples

- Achieves $\gtrsim 10^4$ **times acceleration** compared with first-principle calculations (**stiffGWpy**)



SageNet+: a neural network emulator

- Nine-parameter (full) model
- Architecture: **self-attention**-based
- Precision of the emulator:
 $\lesssim 1\%$ errors for $\gtrsim 99.85\%$ test samples



Zhang, Luo, Li* et al. 2026, CP under review, <https://github.com/YifangLuo/SageNet>

Application: interpreting pulsar timing data

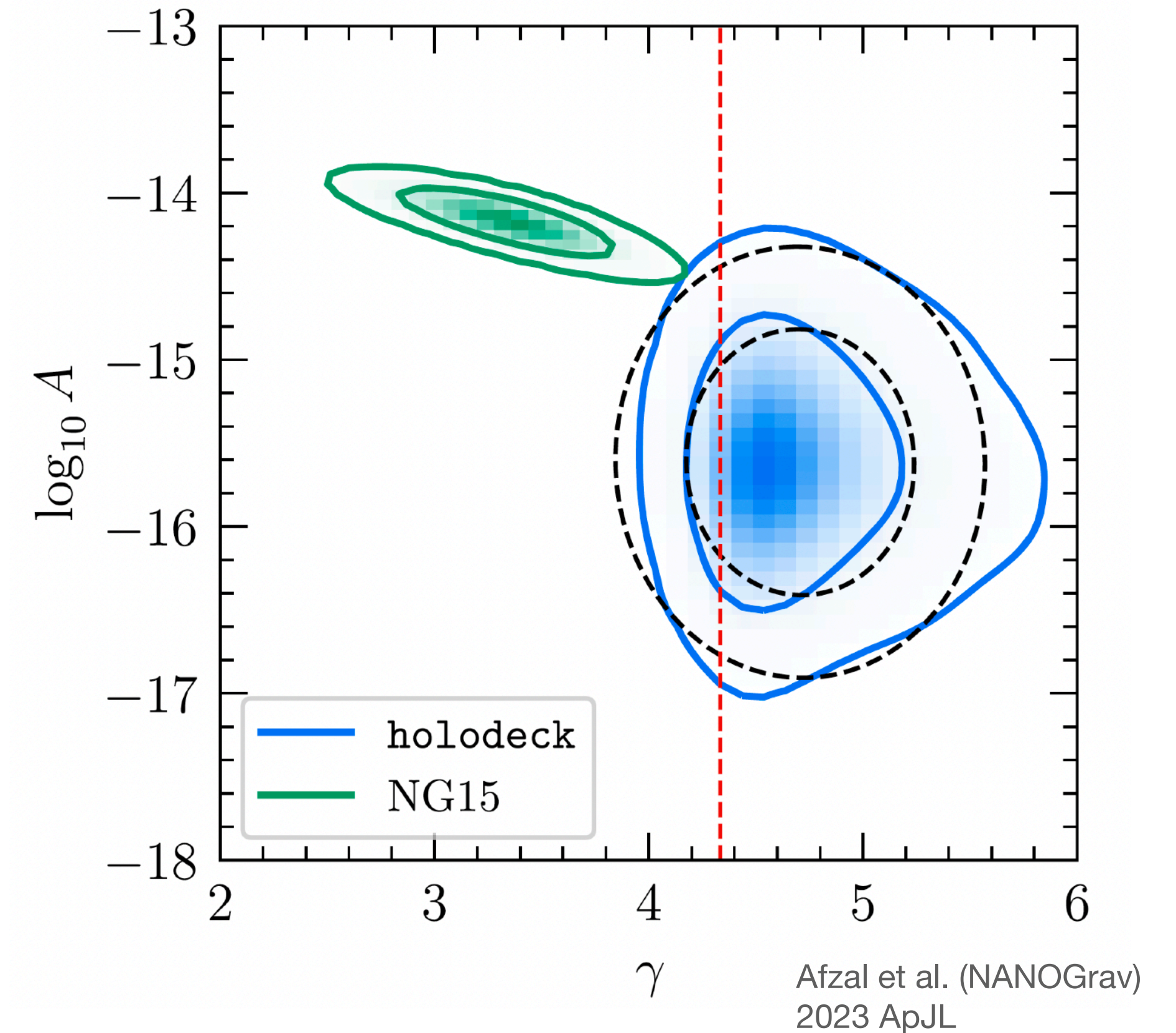


Xu et al. (CPTA) 2023 RAA

Agazie et al. (NANOGrav) 2023 ApJL

Antoniadis et al. (EPTA & InPTA) 2023 A&A

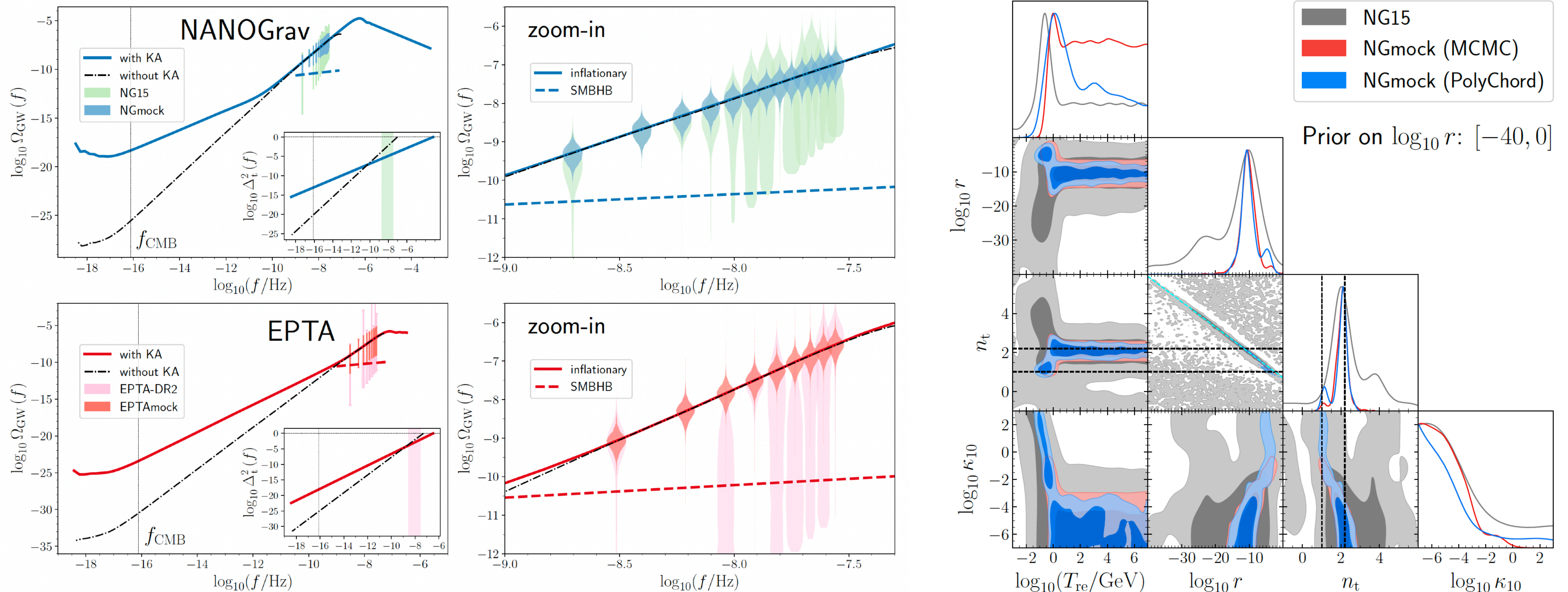
Reardon et al. (PPTA) 2023 ApJL



Opportunity for new physics!

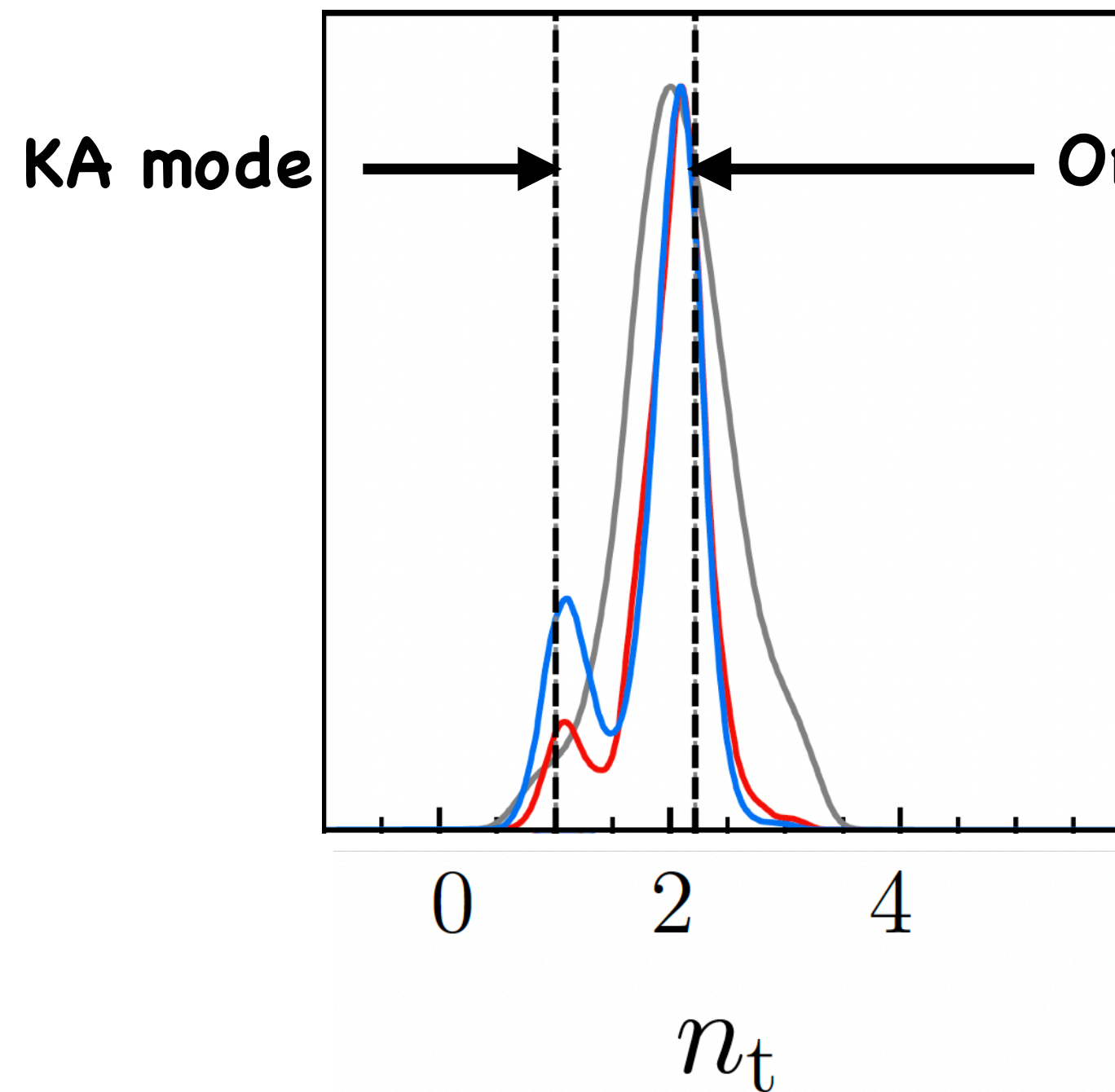
Bimodality in the inflationary SGWB model: KA vs. no-KA

- Mock PTA free spectra (“violins”) are constructed in consistence with the best-fit ones from the current measurements, NANOGrav 15yr & EPTA DR2



Bimodality in the inflationary SGWB model: KA vs. no-KA

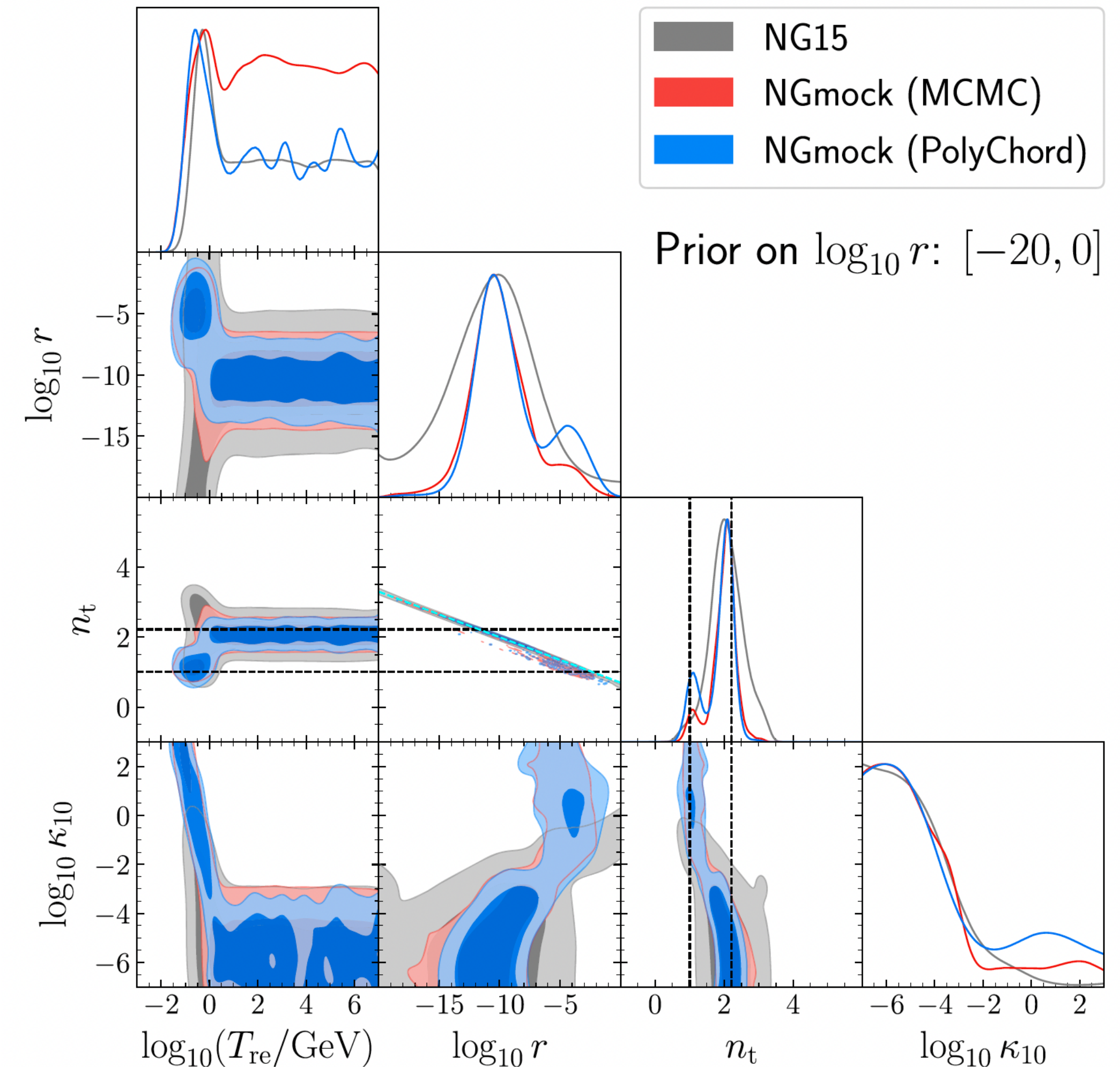
- The reason why the analysis of current NG15 data does not show the KA mode: “prior volume effect”



Bayes factor

$$\mathcal{B} \equiv \mathcal{I}_{\text{no-KA}} / \mathcal{I}_{\text{KA}} = 2.9 \pm 1.9$$

Li*, Meyers & Shapiro 2025, ApJ, arXiv: 2503.18937,
<https://github.com/bohuarolandli/stiffGWpy>

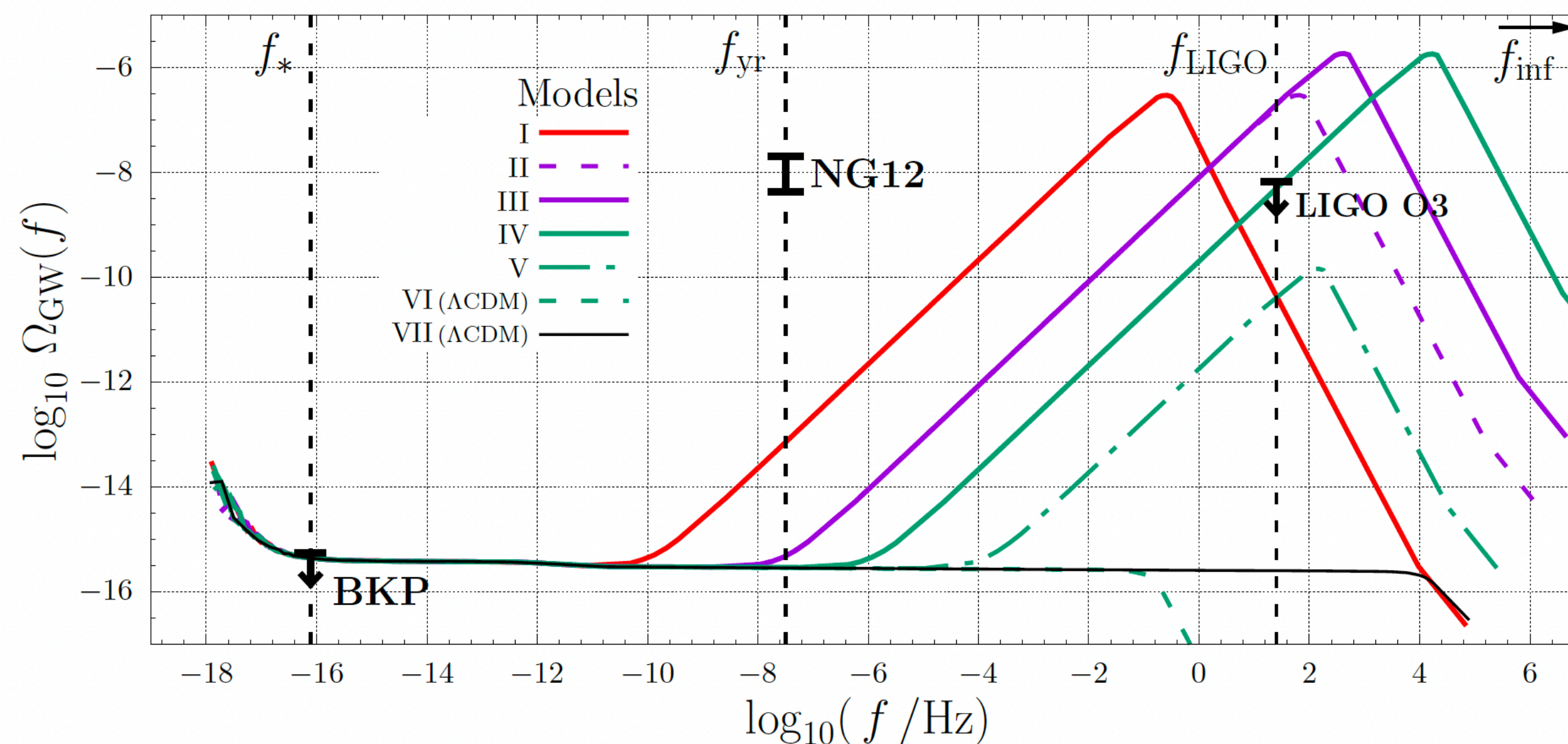
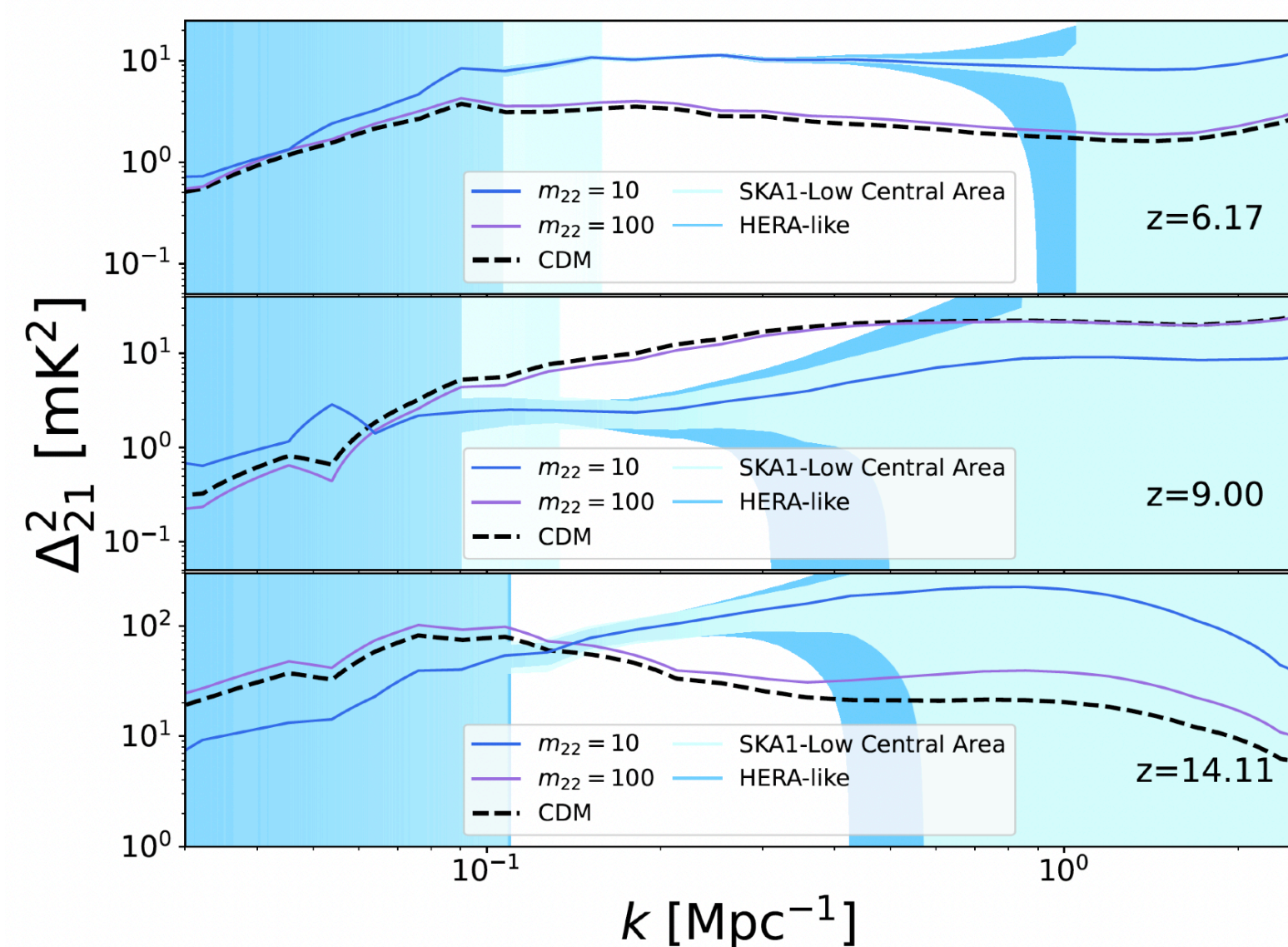


Summary

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- Upcoming 21-cm and SGWB observations (e.g., **SKA** and **LIGO**) will be powerful probes of ultralight dark matter.



arXiv: [2503.16773](#), [2503.18937](#), [2504.04054](#), [2508.10176](#)

stiffGWpy: <https://github.com/bohuarolandli/stiffGWpy>

SageNet: <https://github.com/YifangLuo/SageNet>

Thanks!

Scientific timeline of the SKA Observatory

Milestone Event	Mid Dishes	Mid Date	Low Stations	Low Date
AA0.5	4 (4 SKA + 0 MeerKAT)	2026 Q2	4	2025 Q3
AA1	8 (8+0)	2027 Q1	16	2026 Q1
AA2	64 (64+0)	2027 Q4	68	2026 Q4
Science Verification begins 2027				
AA*	144 (80+64)	2028 Q3	307	2028 Q2
Operations Readiness Review		2029 Q1		2028 Q3
End of Staged Delivery		2029 Q1		2029 Q1
Early Operations begin 2029 (shared risk)				
AA4 (Full Design Baseline SKA1)	197 (133+64)	TBD	512	TBD

Scientific timeline

*Calls will include available modes and capabilities

