一箭双雕的21厘米森林探针

21-cm forest as a simultaneous probe of dark matter and cosmic heating history

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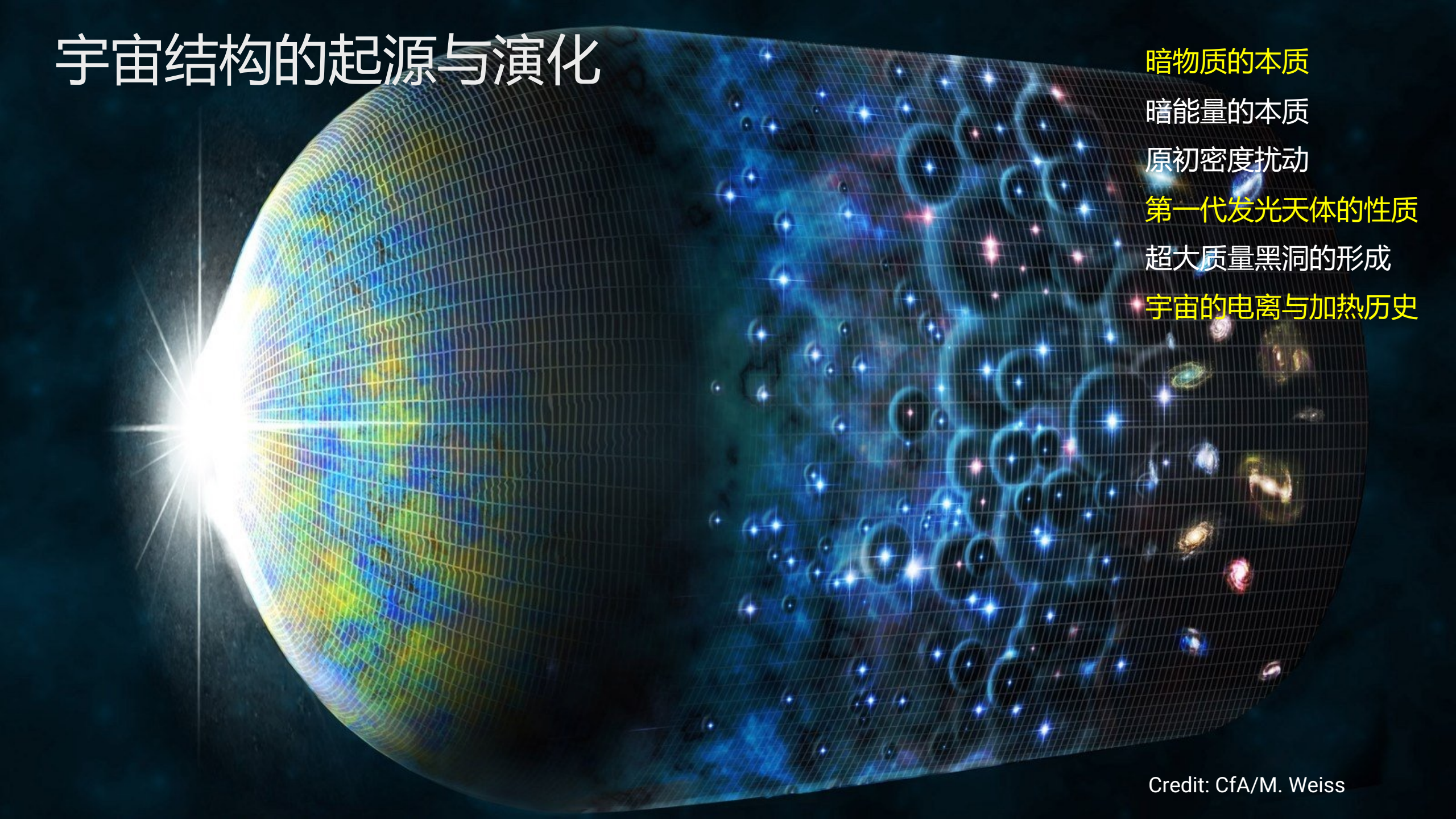
合作者：邵悦、王有刚、杨文秀、李然、张鑫、陈学雷

Shao Y., **XuYD***, et al. 2023 accepted in principle by **Nature Astronomy**

宇宙结构的起源与演化



暗物质的本质

暗能量的本质

原初密度扰动

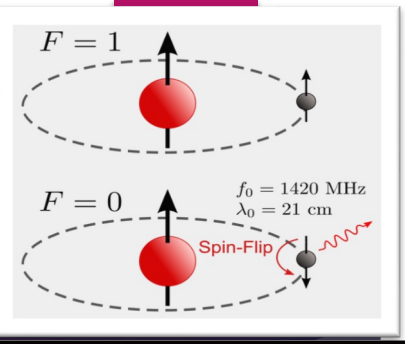
第一代发光天体的性质

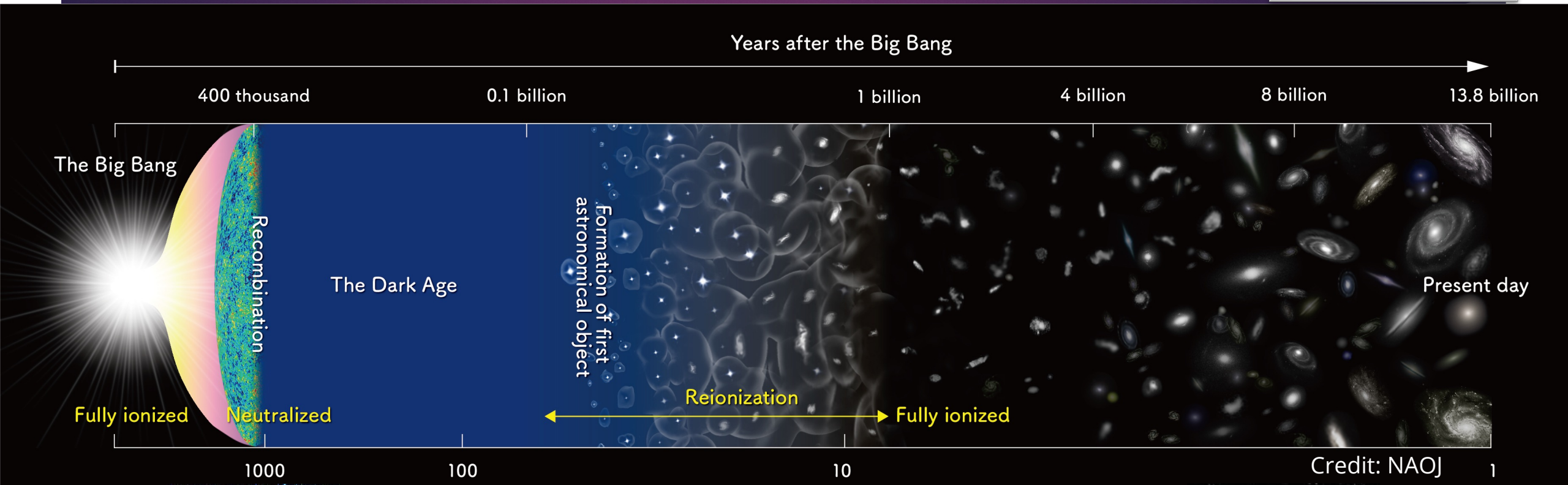
超大质量黑洞的形成

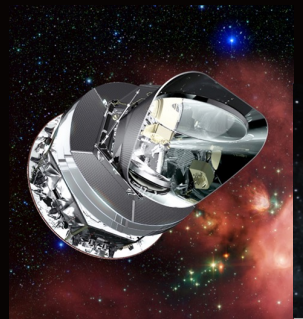
宇宙的电离与加热历史

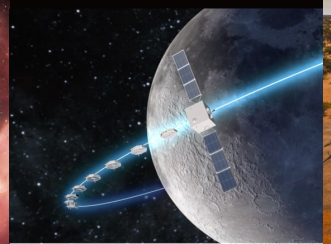
Credit: CfA/M. Weiss

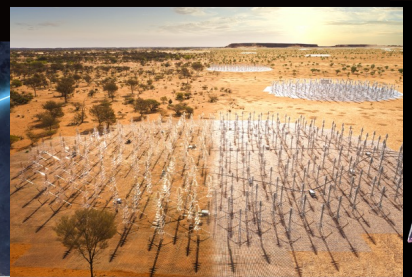
21厘米谱线——填补宇宙历史中的观测空白

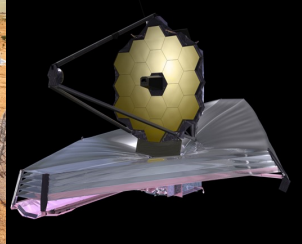


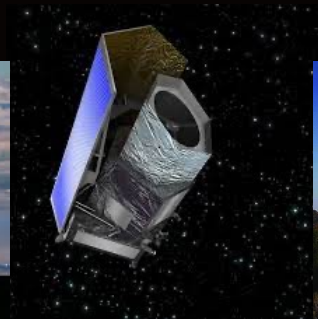


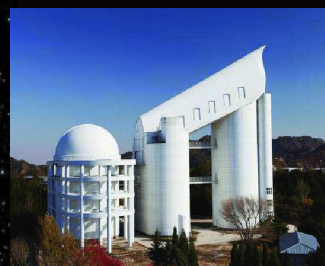












宇宙黎明的21厘米探测

- 以CMB为背景源

1. 21厘米全天平均频谱

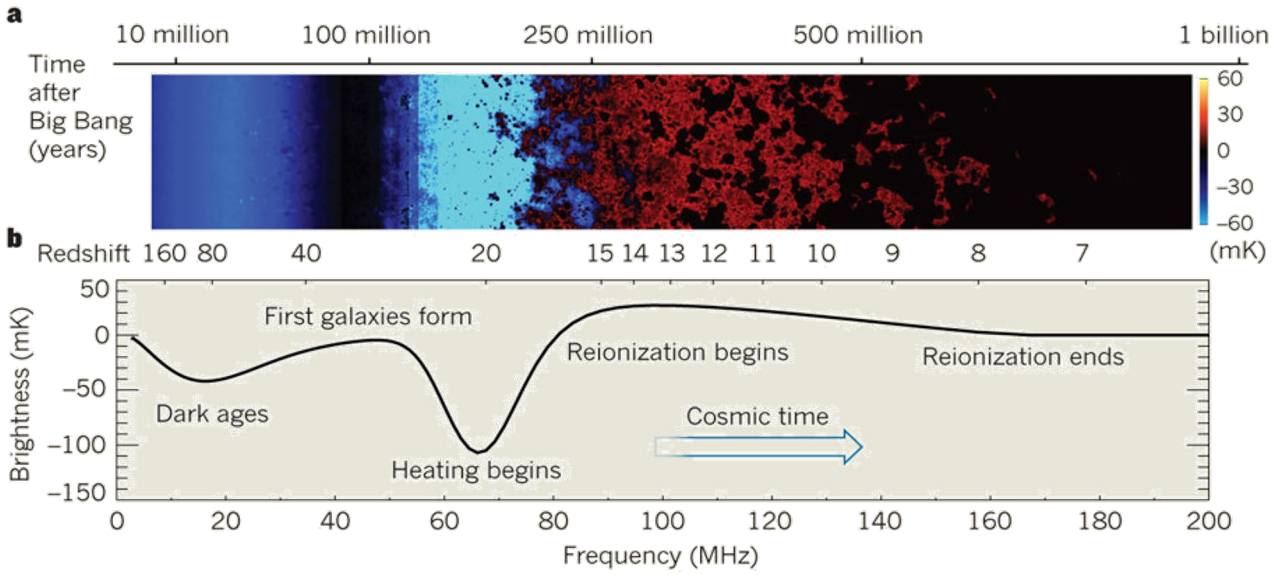
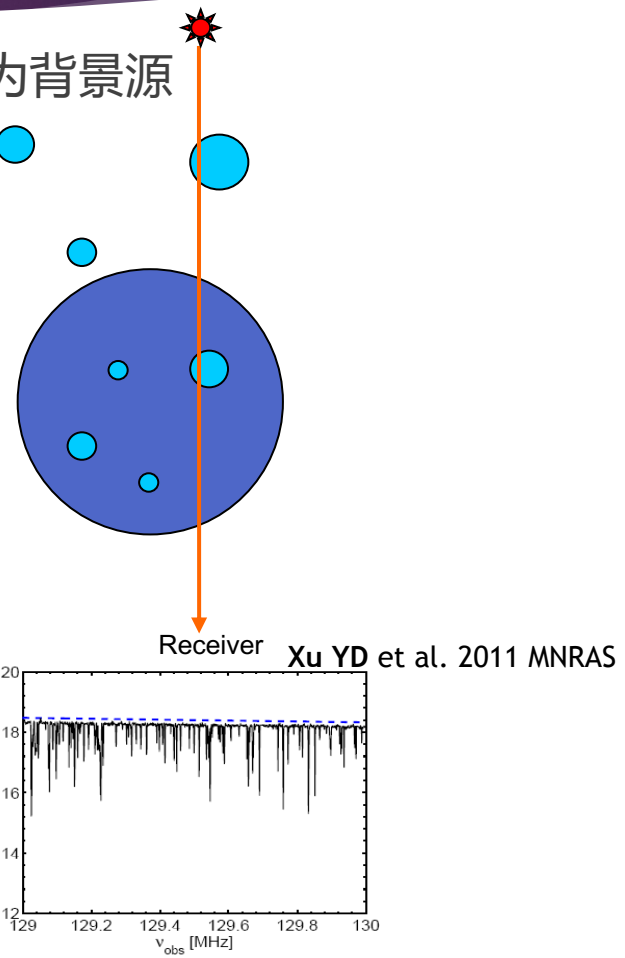


Image credit: Pritchard & Loeb 2012

2. 21厘米层析观测

- 以射电点源为背景源

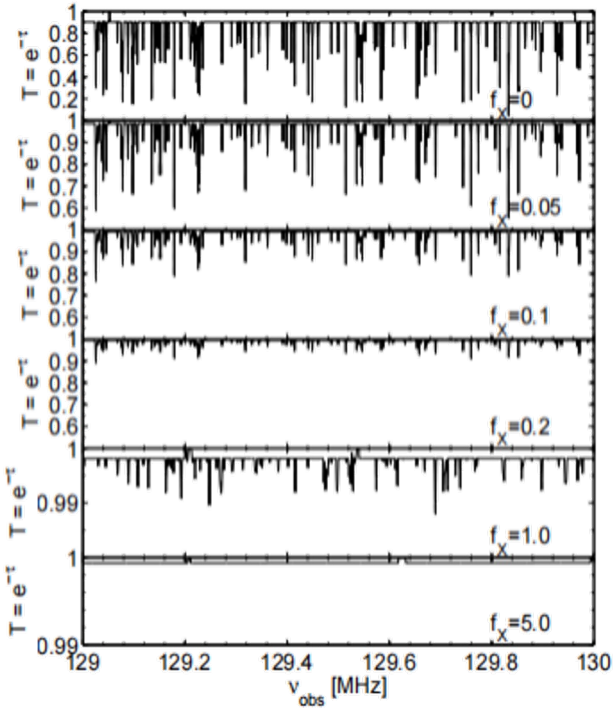
3. 21厘米森林



21厘米森林

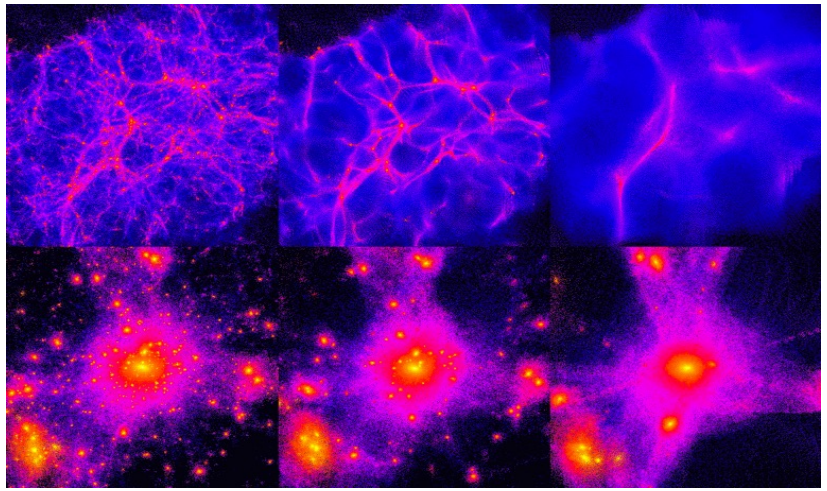
- 星系际介质温度的灵敏探针

$$\tau \propto \frac{1}{T_S}$$



Xu YD et al. 2009, 2010, 2011

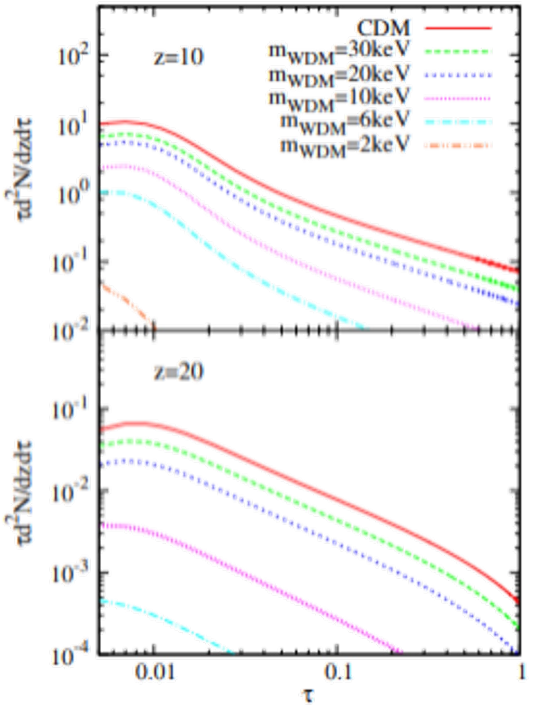
- 小尺度结构——暗物质粒子质量的高红移探针



冷暗物质
WIMP/AXION

温暗物质
Sterile
Neutrino

热暗物质
3 Neutrinos

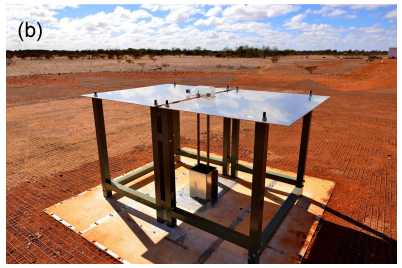


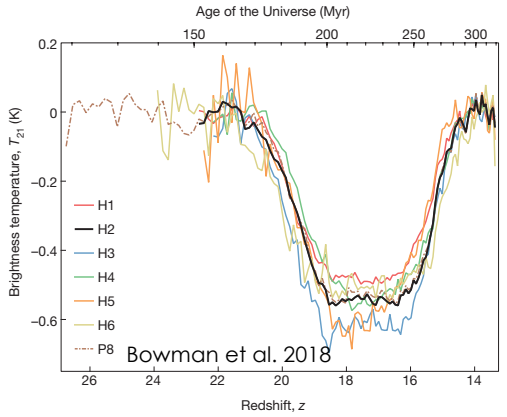
Shimabukuro et al. 2014

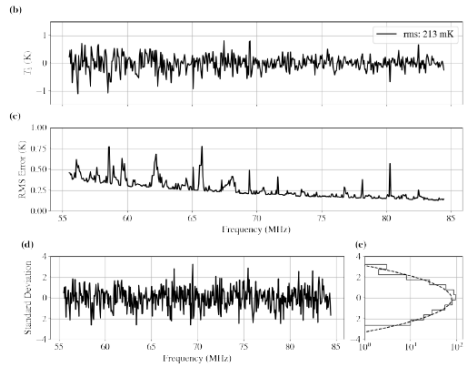
21厘米探测——唯独21厘米森林尚未尝试！？

1. 21厘米全天平均频谱

EDGES-Low-band



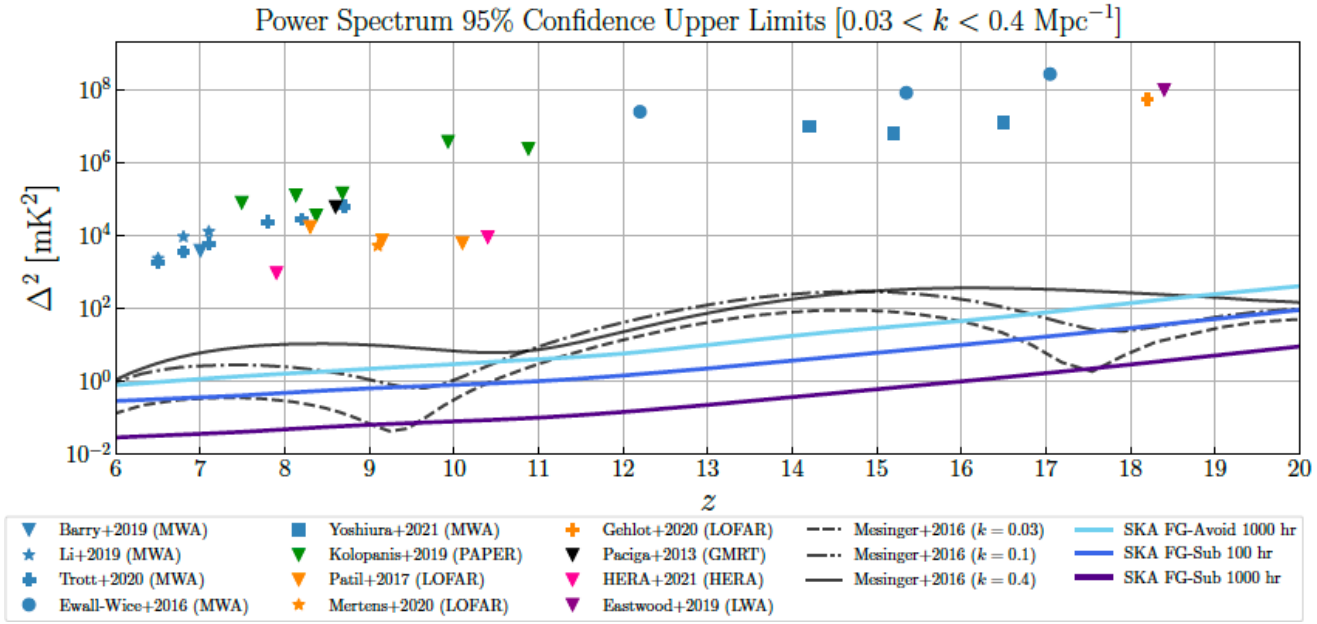




Singh et al. 2112.06778

2. 21厘米层析观测

Interferometers

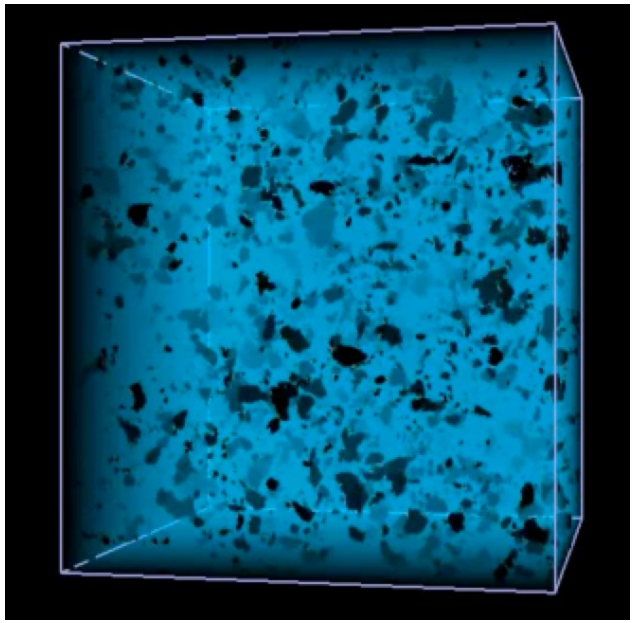


Barry et al. arXiv:2110.06173

21厘米森林理论难题

- 影响环境：宇宙大尺度电离场 & 温度场

1 Gpc

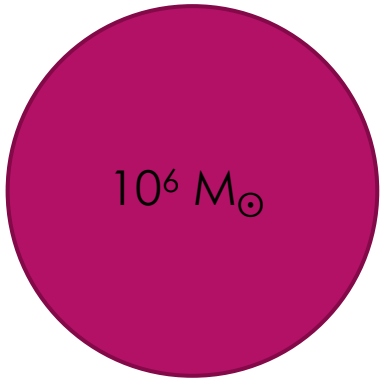


islandFAST, **XuYD** et al. 2017

2×10^5

- 信号主要贡献者：小暗晕（minihalos）及周边中性介质

6 kpc @ z=9



密度轮廓

温度轮廓

电离&复合

自旋温度耦合机制

（碰撞、Lyα、CMB）

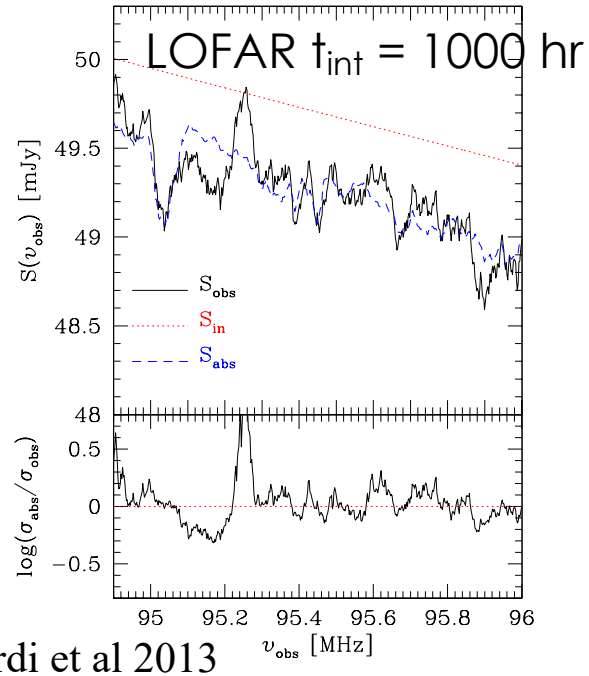
……

$$\tau_{\nu_0}(\hat{\boldsymbol{s}},z)\approx 0.0085\,[1+\delta(\hat{\boldsymbol{s}},z)]\,(1+z)^{3/2}\left[\frac{x_{\rm HI}(\hat{\boldsymbol{s}},z)}{T_{\rm S}(\hat{\boldsymbol{s}},z)}\right]\left[\frac{H(z)/(1+z)}{{\rm d}v_\parallel/{\rm d}r_\parallel}\right]\left(\frac{\Omega_{\rm b}h^2}{0.022}\right)\left(\frac{0.14}{\Omega_{\rm m}h^2}\right)$$

21厘米森林探测难题

- 探测热历史——双刃剑

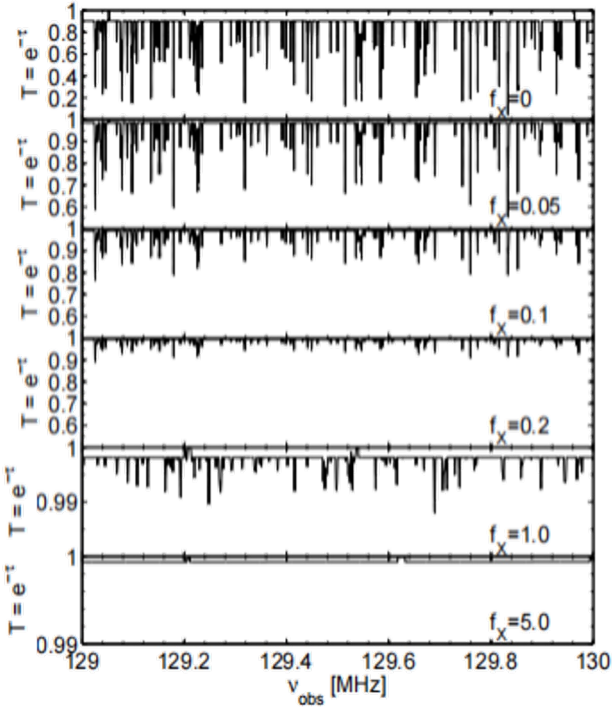
$$\tau \propto \frac{1}{T_S}$$



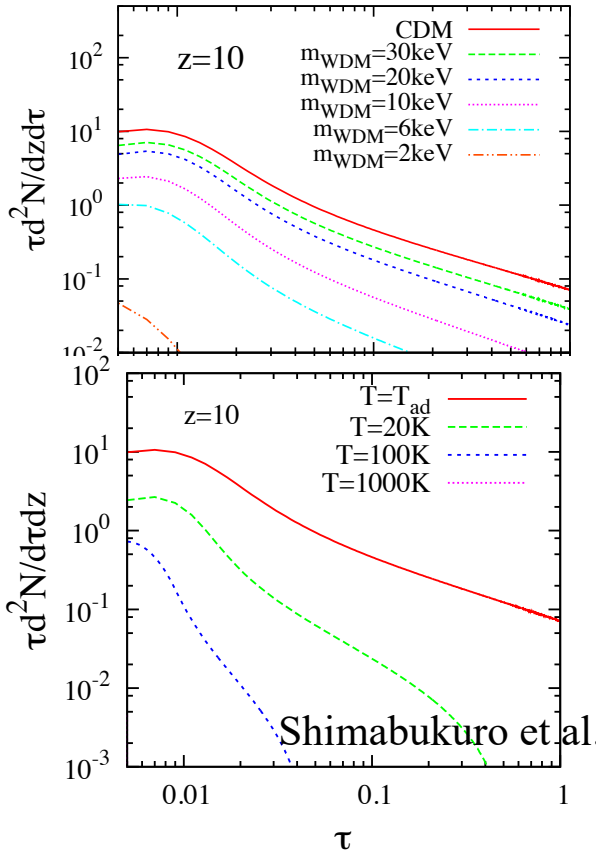
Ciardi et al 2013

Figure 13. *Upper panel:* Spectrum of a source positioned at $z = 14$ (i.e. $\nu \sim 95$ MHz), with an index of the power-law $\alpha = 1.05$ and a flux density $S_{\rm in}(z_s) = 50$ mJy. The lines are the same as those in Figure 10. Here we have assumed the noise σ_n given in eq. 3, a bandwidth $\Delta\nu = 20$ kHz, smoothing over a scale $s = 20$ kHz, and an integration time $t_{int} = 1000$ h. The IGM absorption is calculated from the reference simulation $\mathcal{L}4.39$.

- 限制暗物质——参数简并



Xu YD et al. 2011



Shimabukuro et al. 2014

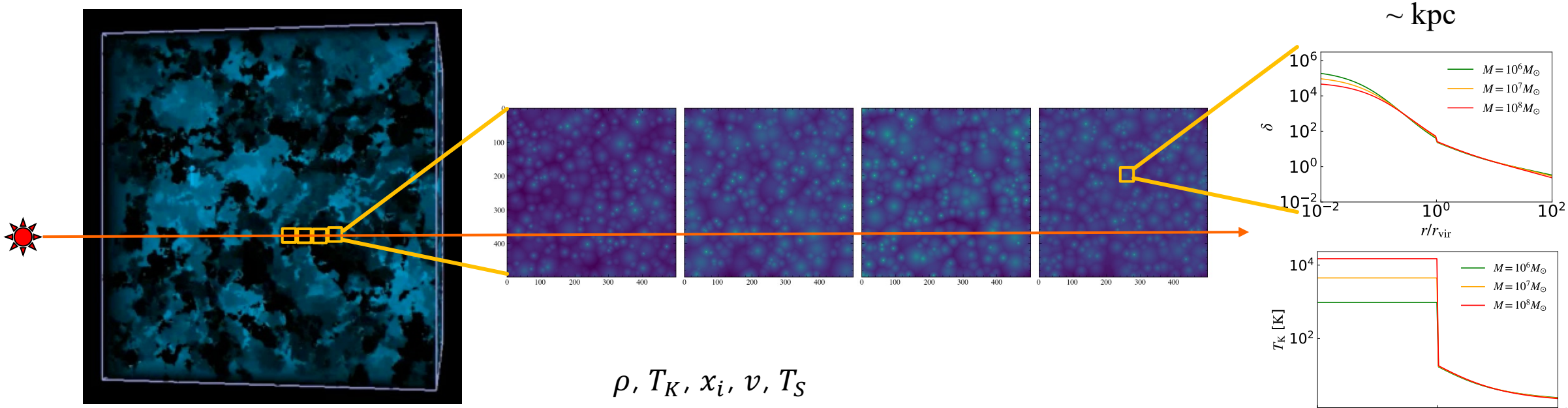
破局1——跨尺度混合建模

- 大尺度：准数值模拟
- 小尺度：精细解析建模

Box 1 Gpc → 500^3 Grids

2 Mpc → 500^3 Voxels

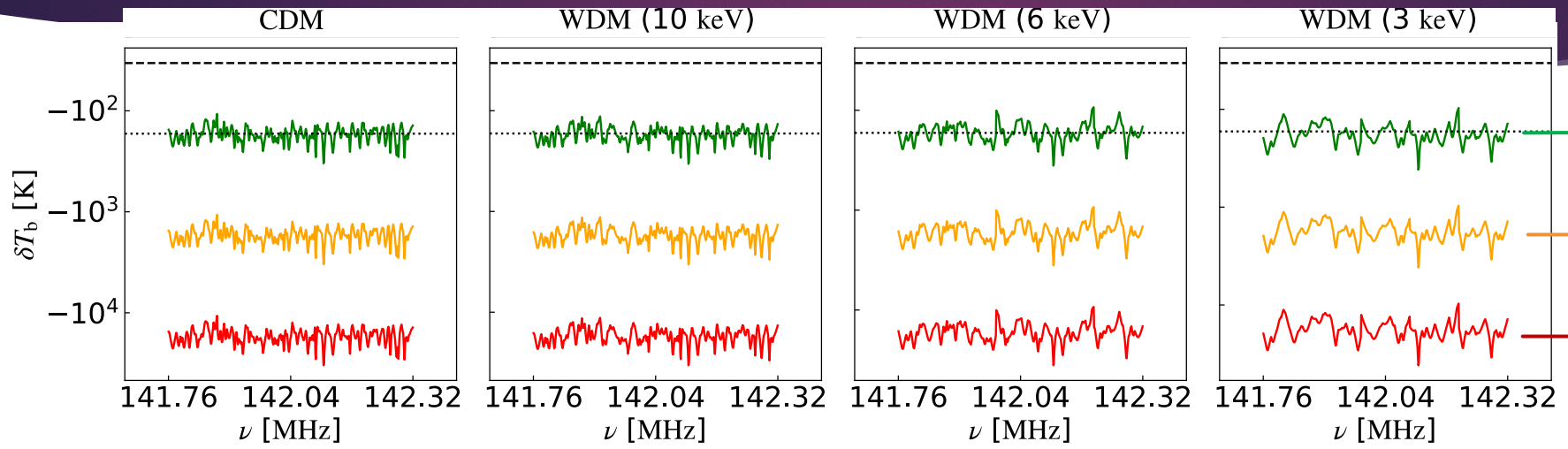
~ kpc



21cmFAST/islandFAST

XuYD et al. 2017

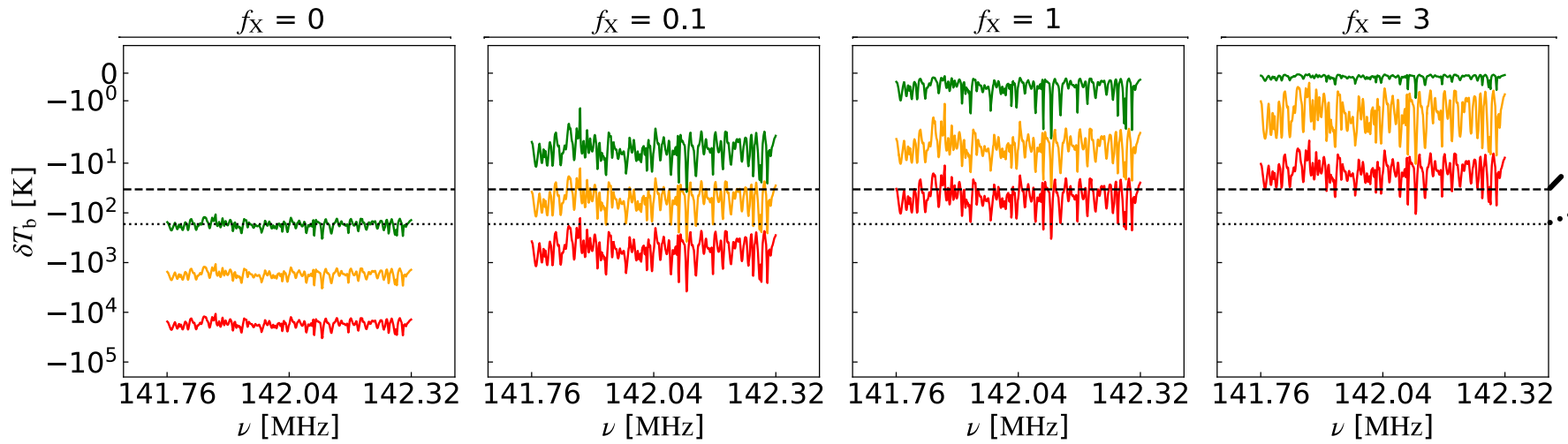
21厘米森林信号



S_{150} = 1 mJy

S_{150} = 10 mJy

S_{150} = 100 mJy



A_{eff}/T_{sys} =

SKA2-Low 4000 m^2 K^{-1}

SKA1-Low 800 m^2 K^{-1}

100 hr, 1 kHz

$$\delta T^{\mathrm{N}} = \delta S^{\mathrm{N}} \left(\frac{\lambda_z^2}{2k_{\mathrm{B}}\Omega} \right) \approx \frac{\lambda_z^2 T_{\mathrm{sys}}}{A_{\mathrm{eff}}\Omega\sqrt{2\delta\nu\delta t}},$$

破局2——一维交叉功率谱测量

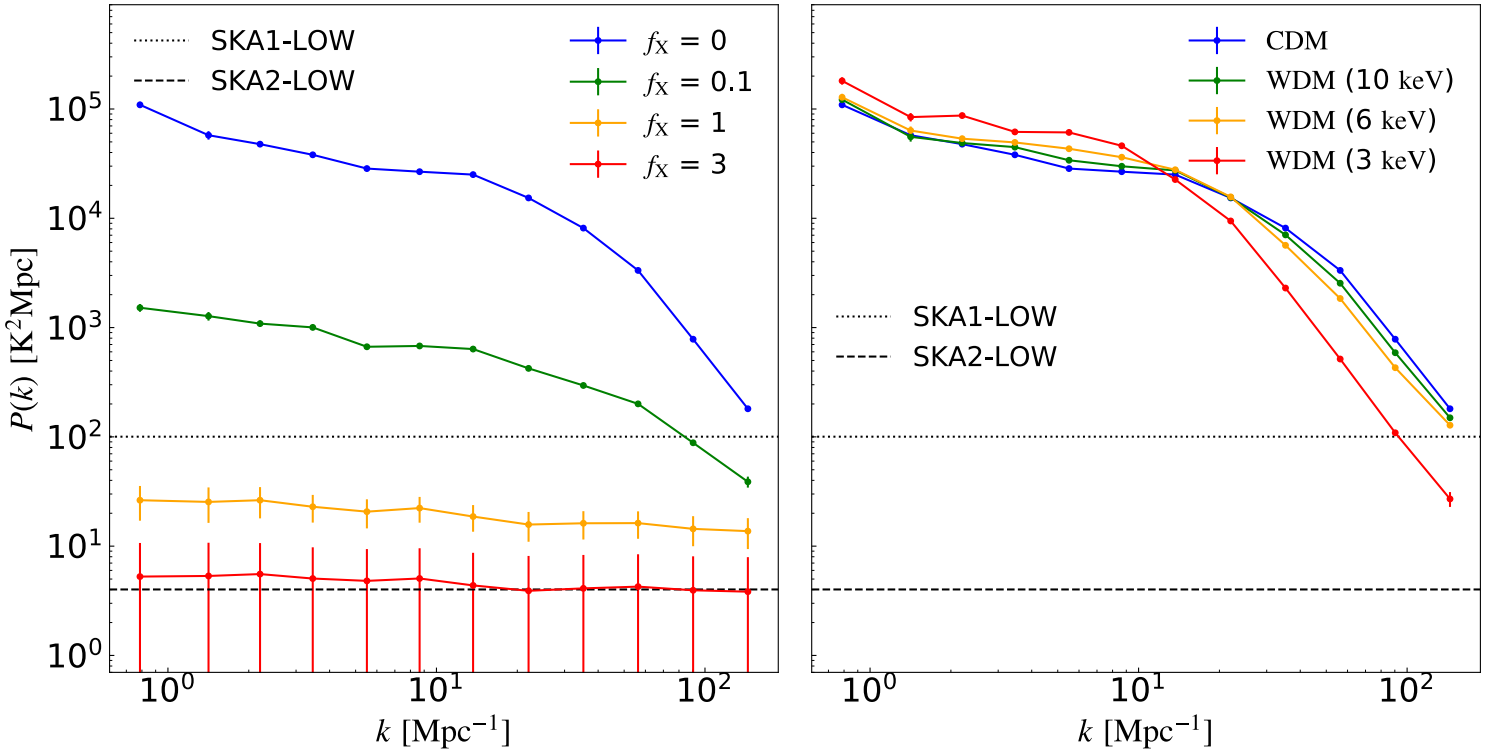
- 两次观测/观测时间分两段，交叉相关抑制噪声　　~ 10 sources with S_{150} = 10 mJy at z = 9

$$P\left(\hat{\boldsymbol{s}}, k_{\parallel}\right) = \left|\delta\widetilde{T}'\left(\hat{\boldsymbol{s}}, k_{\parallel}\right)\right|^2 \left(\frac{1}{\Delta r_z}\right)$$

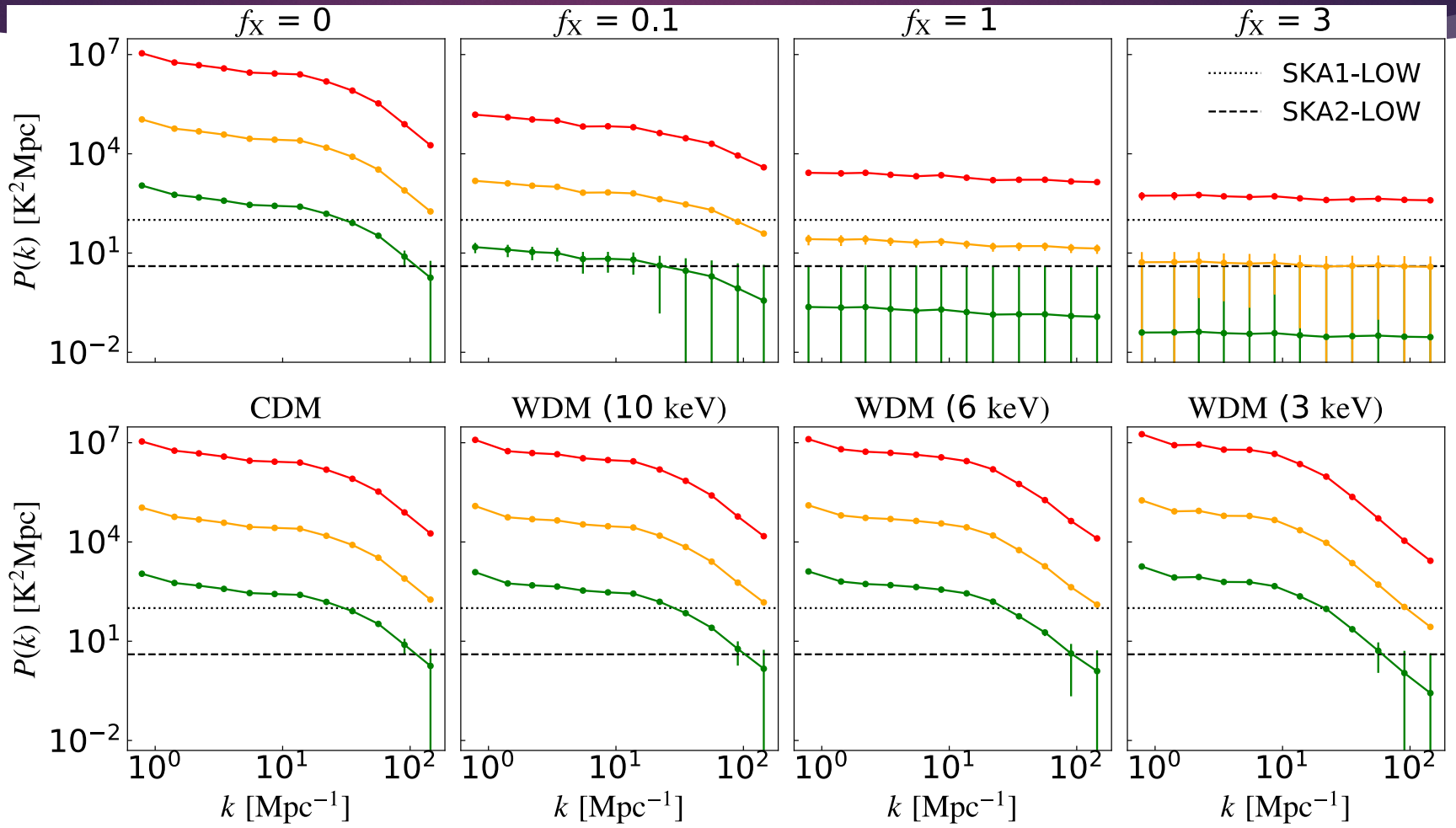
$$P^S = \sigma_P(k)/\sqrt{N_s \cdot N_m}$$

$$P^N = \frac{1}{\sqrt{N_s}} \left(\frac{\lambda_z^2 T_{\rm sys}}{A_{\rm eff}\Omega}\right)^2 \left(\frac{\Delta r_z}{2\Delta\nu_z \delta t_{0.5}}\right)$$

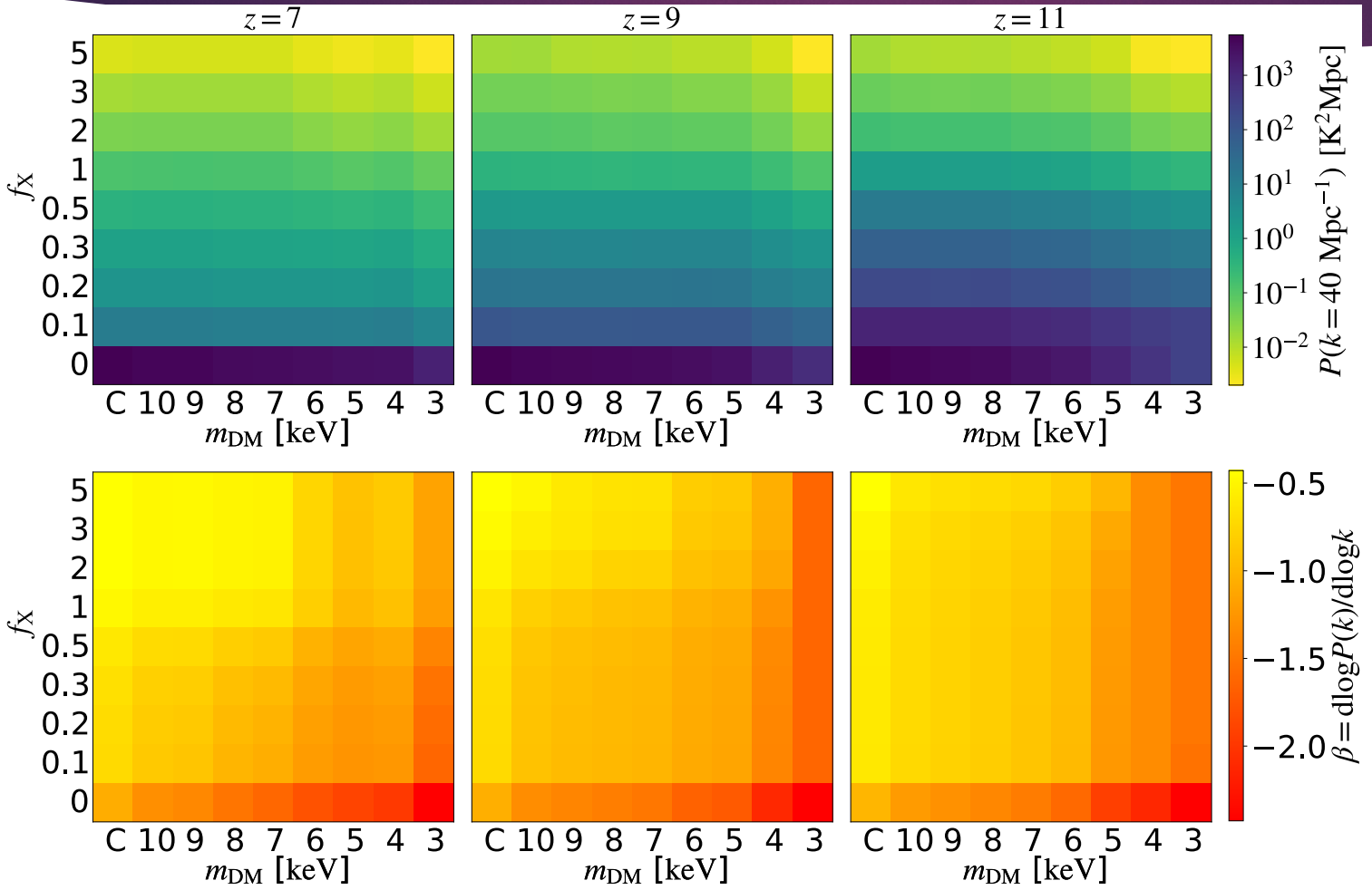
t_{int} = 2 * 50 hr



一维功率谱结果


f_X = 0
f_X = 0.1
f_X = 1
f_X = 3
SKA1-LOW
SKA2-LOW
CDM
WDM (10 keV)
WDM (6 keV)
WDM (3 keV)
$P(k)$ [K^{2}Mpc]
k [Mpc^{-1}]
10^7
10^4
10^1
10^{-2}
10^0
10^1
10^2

参数简并方向不同 ➔ 一箭双雕



- 科学上

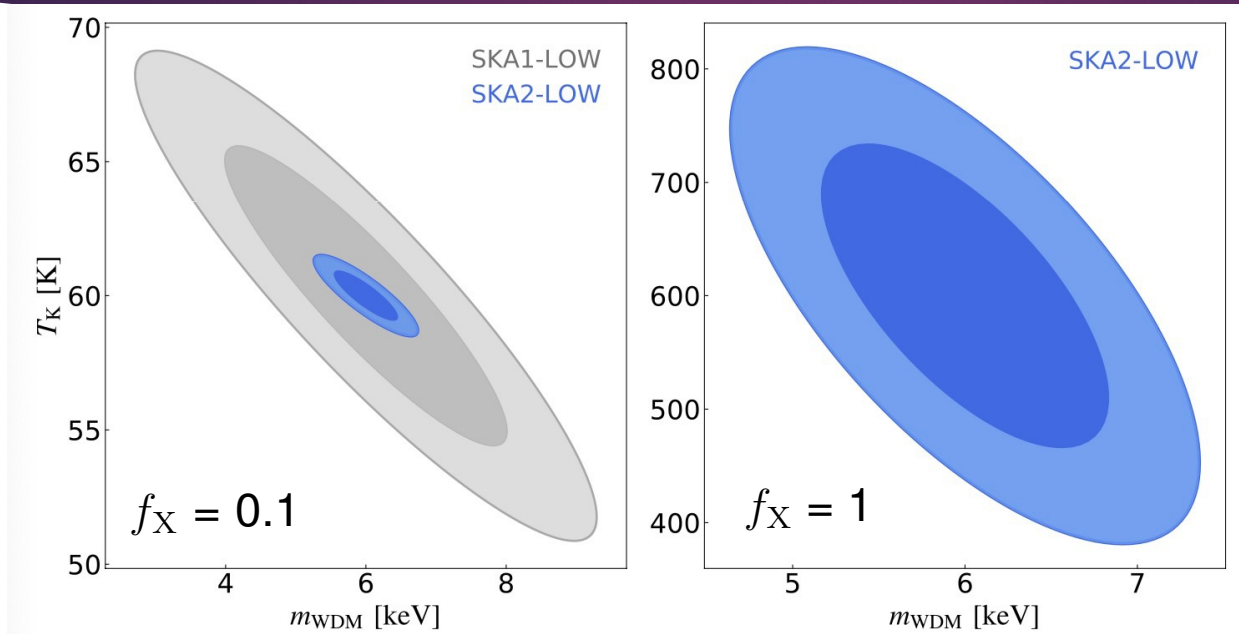
1. 暗物质粒子质量
2. 宇宙热演化历史

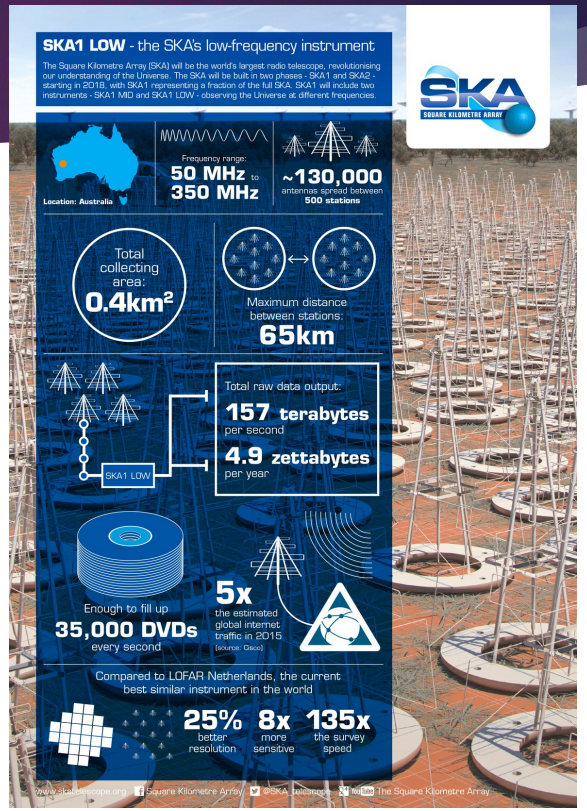
- 方法上

1. 提升灵敏度→探测切实可行
2. 打破参数简并→有效观测限制

SKA观测预研

Using ~ 10 sources with S_{150} = 10 mJy at z = 9





- **For SKA1-Low:**

$$\sigma_{m_{\mathrm{WDM}}} = 1.3\ \mathrm{keV} \ \text{ and } \ \sigma_{T_{\mathrm{IGM}}} = 3.7\ \mathrm{K}$$

- **For SKA2-Low:**

$$\sigma_{m_{\mathrm{WDM}}} = 0.3\ \mathrm{keV} \ \text{ and } \ \sigma_{T_{\mathrm{IGM}}} = 0.6\ \mathrm{K}$$

- **For SKA2-Low:**

$$\sigma_{m_{\mathrm{WDM}}} = 0.6\ \mathrm{keV} \ \text{ and } \ \sigma_{T_{\mathrm{IGM}}} = 88\ \mathrm{K}$$

高红移背景射电源？？——Yes！

- High-z radio-loud quasars
  - ~ 250 quasars discovered at redshift z≥6
  - ~ 12 radio-loud quasars at z > 6
  - J1427+3312 at z = 6.12 (McGreer et al. 2006); J1429+5447 at z = 6.18 (Willott et al. 2010); J2318−3113 at z = 6.44 (Decarli et al. 2018; Ighina et al. 2021); J0309+2717 at z = 6.10 (Belladitta et al. 2020, 2022); J172.3556+18.7734 at z = 6.82 (Bañados et al. 2021); J233153.20+112952.11 at z=6.57 (Koptelova & Hwang 2022); ILTJ1037+4033 at z = 6.07; ILTJ1133+4814 at z = 6.25; ILTJ1650+5457 at z = 6.06; ILTJ2336+1842 at z = 6.60 (Gloudemans+2022); DES J0320−35 at z = 6.13 ± 0.05 and DES J0322−18 at z = 6.09±0.05 (Ighina+2023);

➔ A few hundred radio quasars with > 8 mJy at z ∼ 6 are expected (Gloudemans+2021)

➔ **∼ 2000 sources with > 6 mJy at 8 < z < 12** (Haiman+2004)

- Radio afterglows of high-z GRBs
  - GRB090423 at z = 8.1 (Salvaterra+2009)
  - GRB090429B at z = 9.4 (Cucchiara+2011)

➔ The expected detection rate of luminous GRBs from Population III stars is **3 – 20 yr−1 at z > 8** (Kinugawa+2019)

21厘米森林——冷门探针的春天

- 跨尺度的混合建模
- 一维交叉功率谱测量 ➔

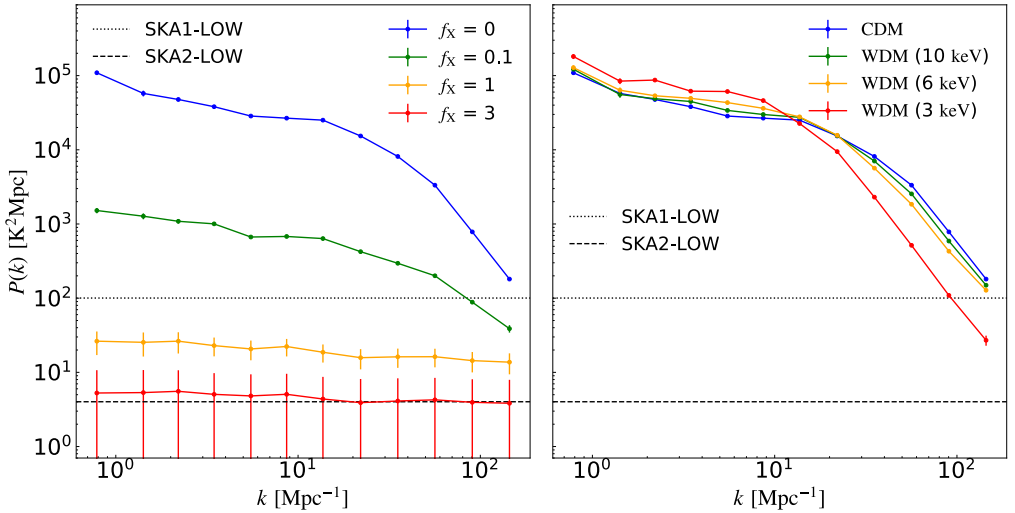
1. 提升灵敏度→探测切实可行;
2. 打破参数简并→有效观测限制

- 一箭双雕 ➔

1. 暗物质粒子质量：在宇宙黎明限制暗物质的性质，构建完整演化图景

2. 宇宙热演化历史：揭示第一代星系的性质

- 为SKA观测提供指导，交叉验证，联合限制。



谢谢！

21-cm forest as a simultaneous probe of dark matter and cosmic heating history