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Detecting Non-Gravitational interaction of Dark Matter in Cosmology: A Case Study of Mirror Dark Matter

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Talk@Jeju Workshop

Exploring Mirror Twin Higgs Cosmology with Present and Future Weak Lensing Surveys

JCAP 08 (2023) 023

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Mirror QCD phase transition as the origin of the nanohertz Stochastic Gravitational-Wave Background

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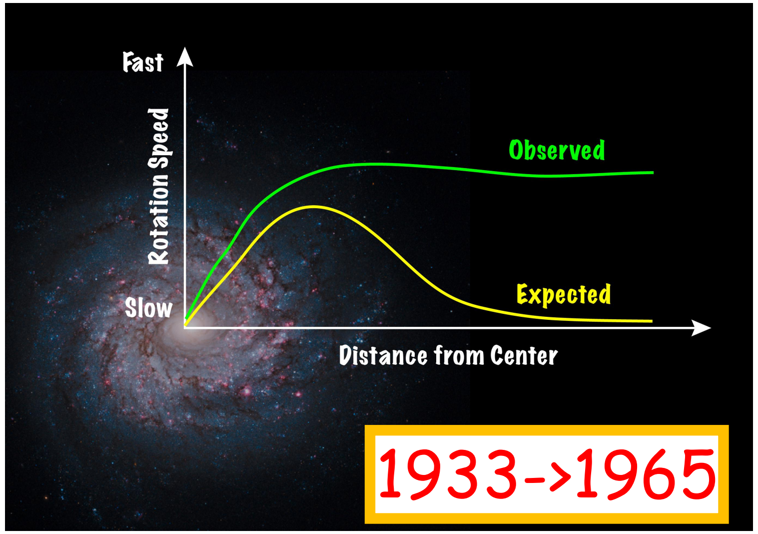
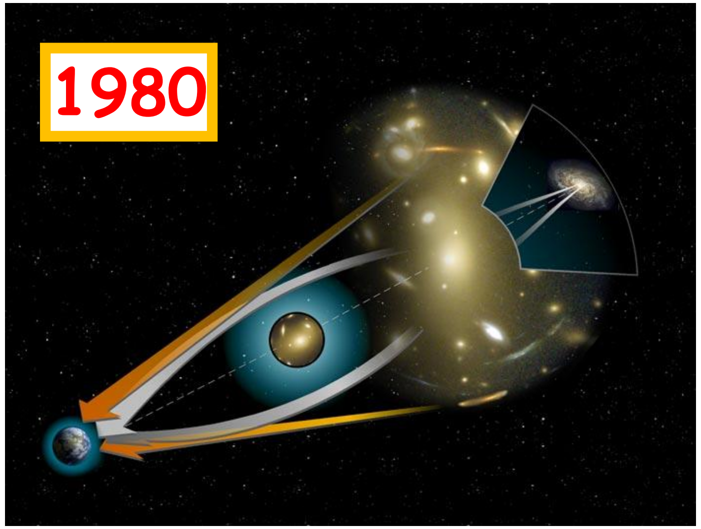
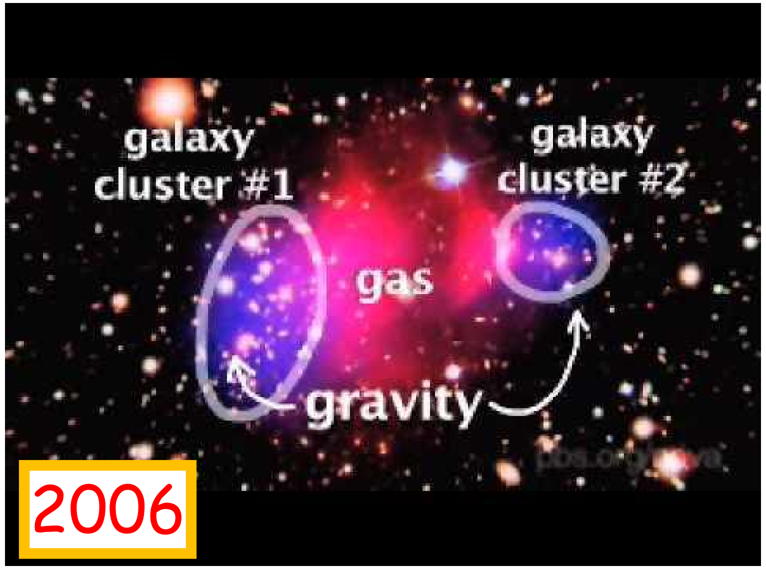
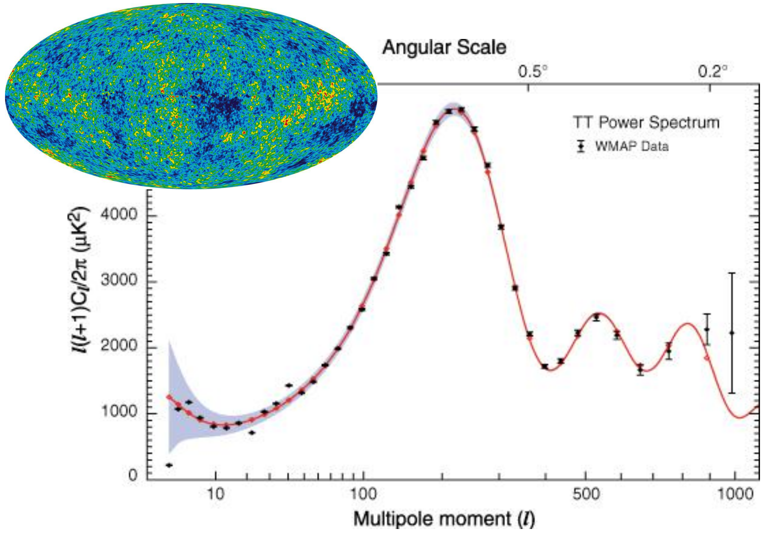
Dark Matter Problems

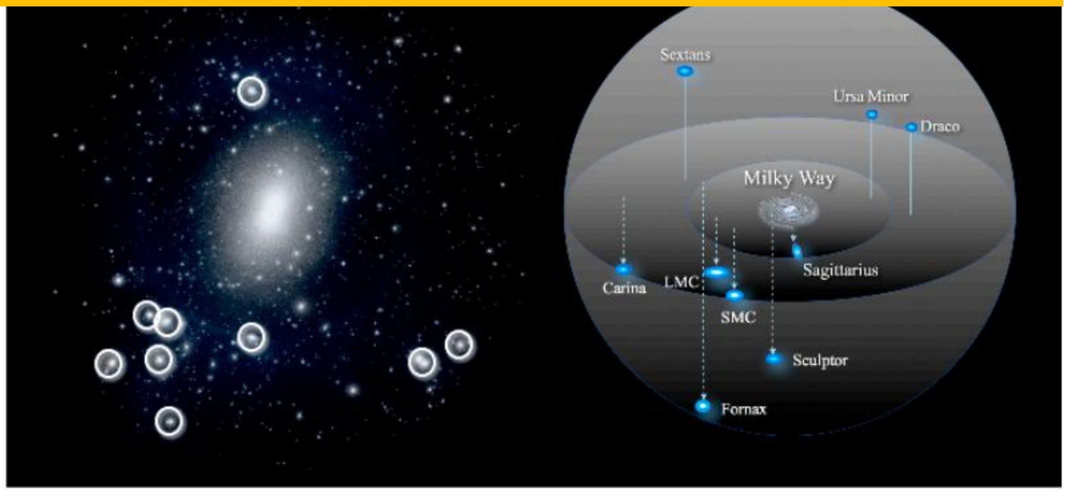




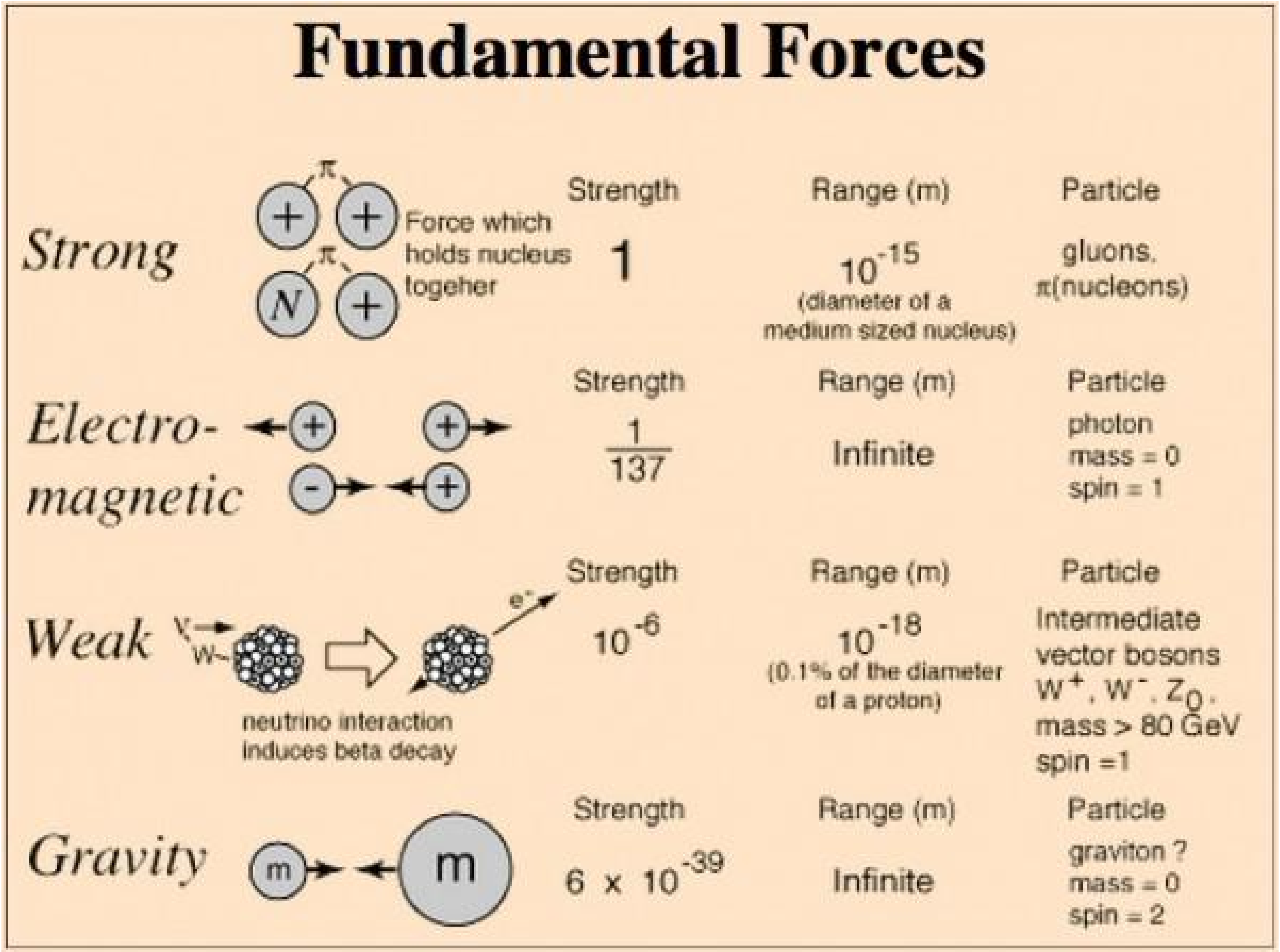




More and more dSphs were found!



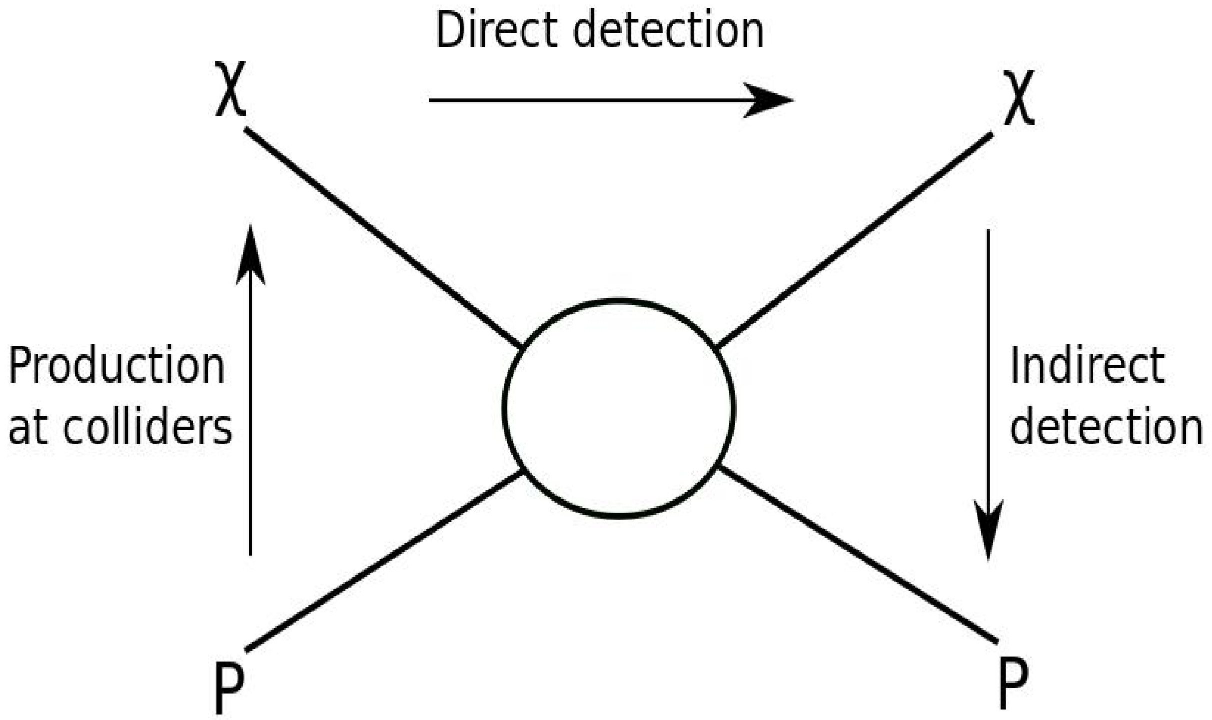
IF GR is correct, it will be difficult to explain the universe without DM assumption.

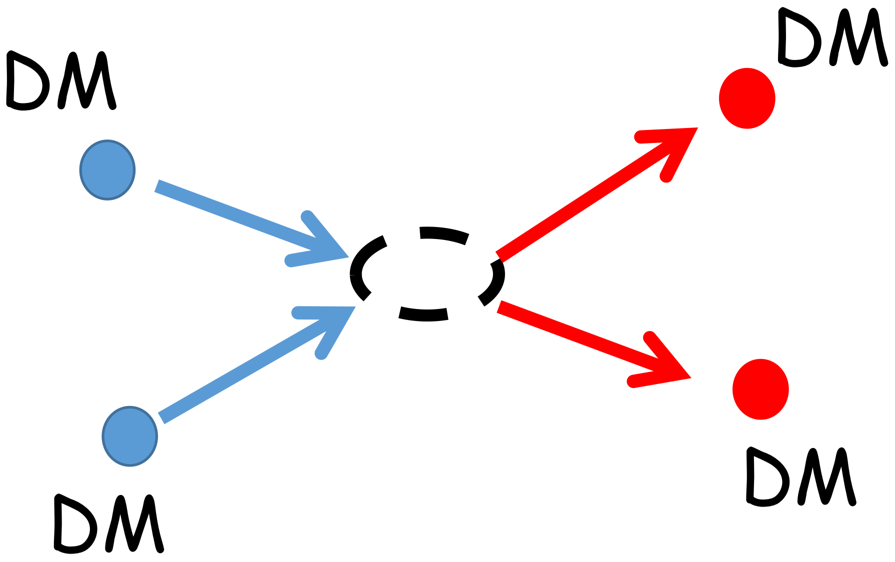


What is the DM-SM interaction strength?

How is possible that no interaction between 1e-6 and 1e-39?

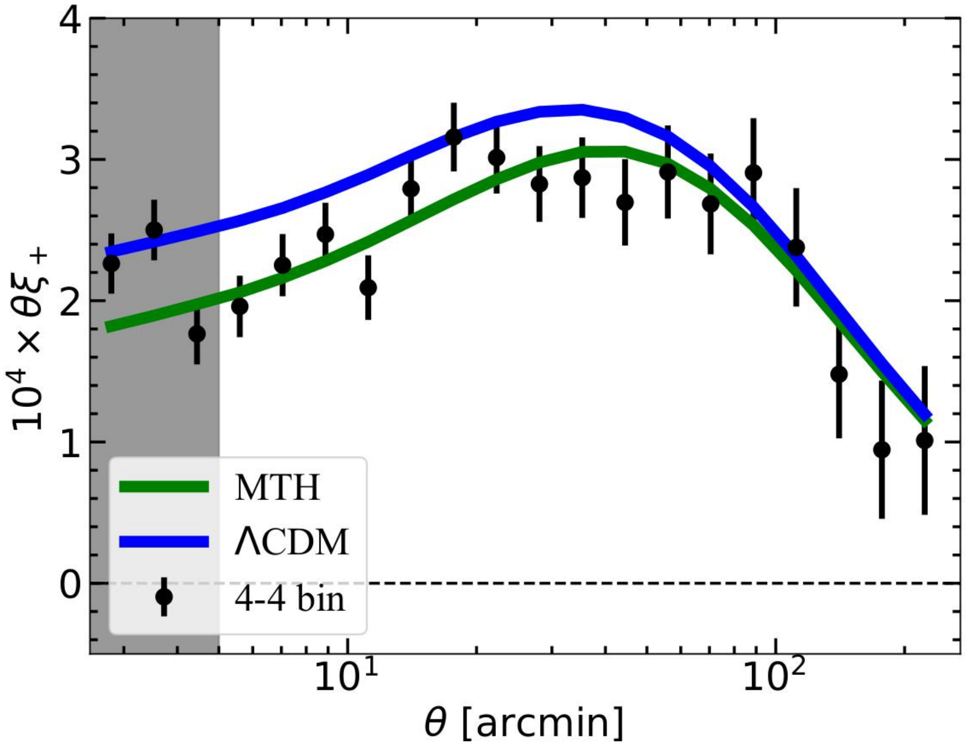
Unless, Gravity is not the fundamental force...

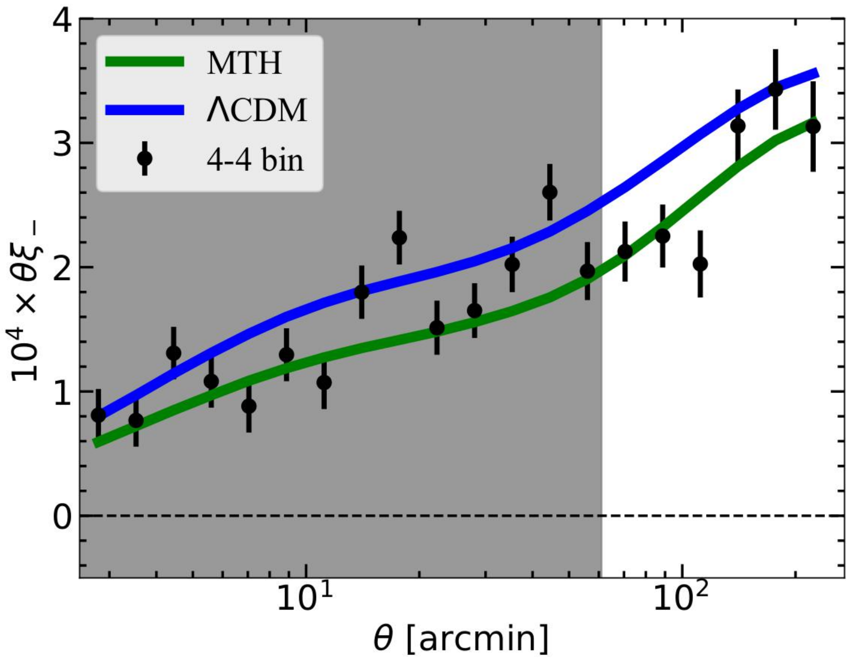




However, all the evidence are all based on gravitational interaction.
Can we see any non-gravitational interaction from gravitational evidence?

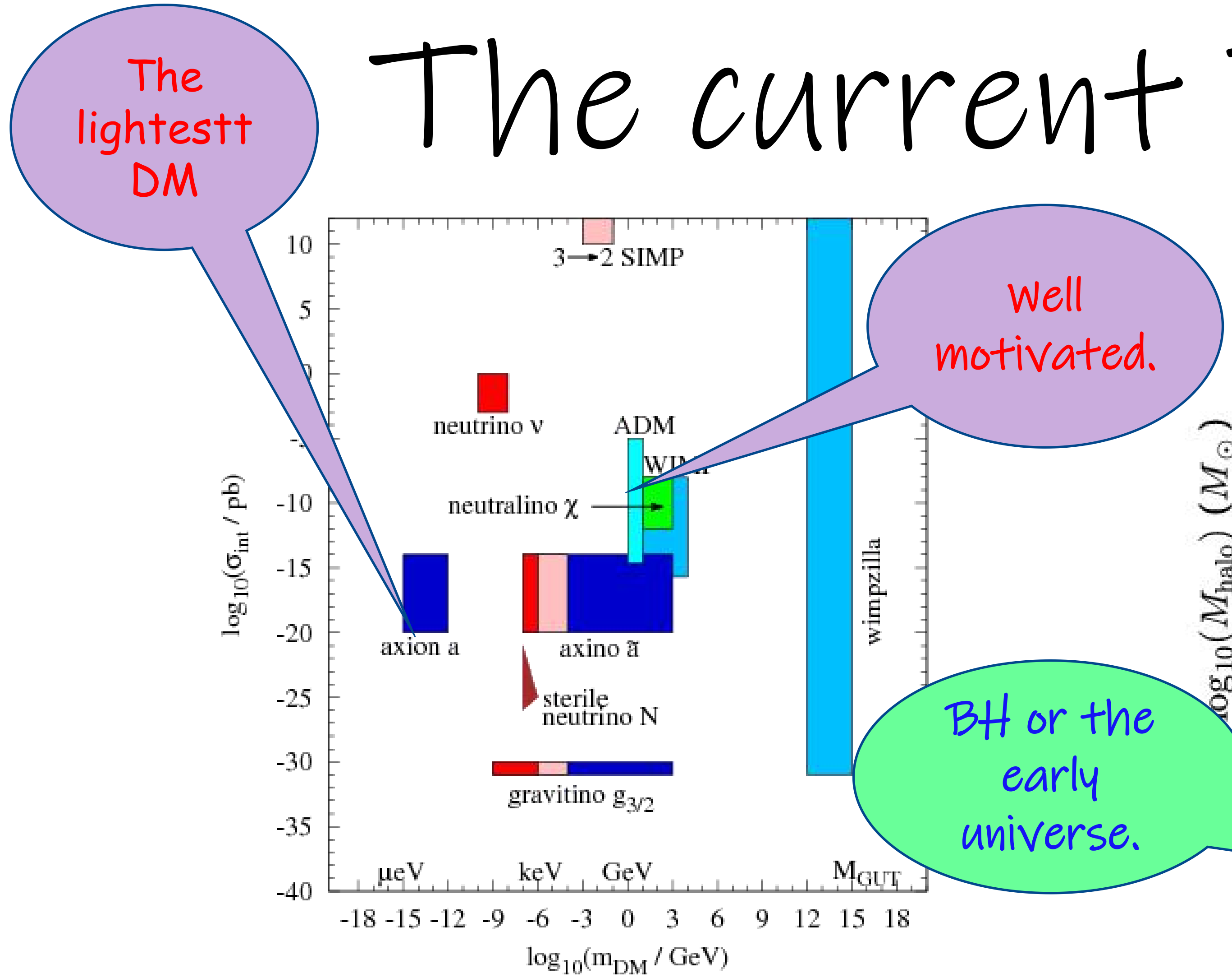
Only gravitational interaction?

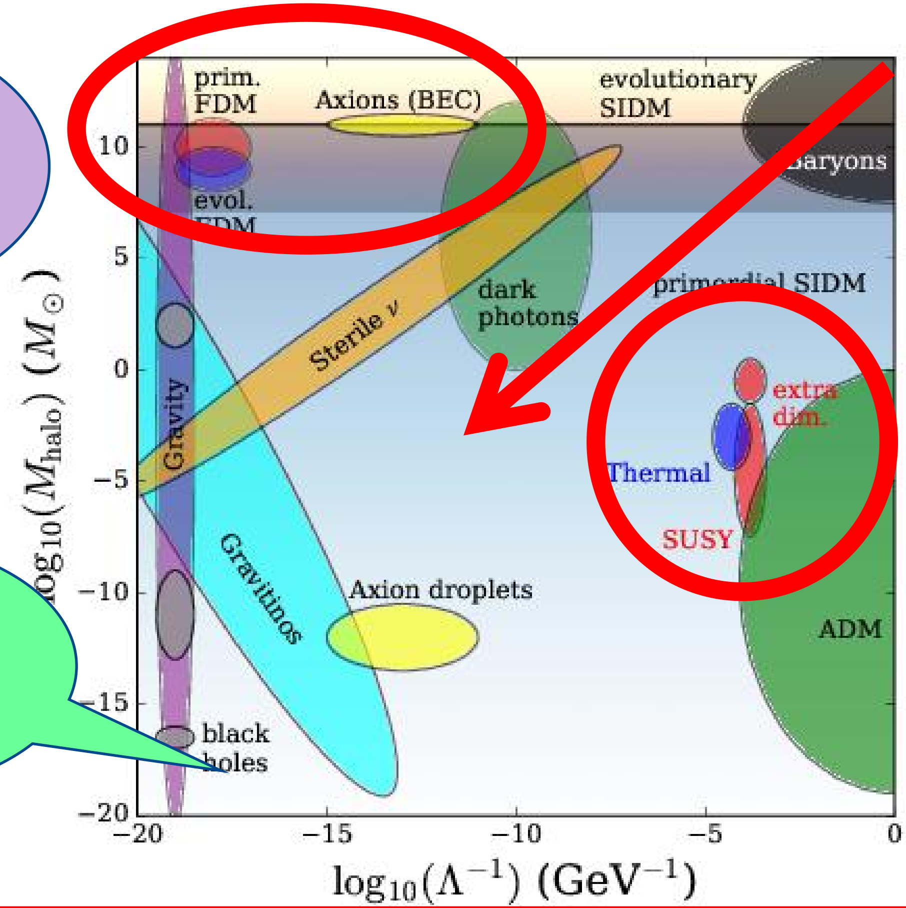




We shall be able to see non-gravitational interactions from precise cosmological measurements.

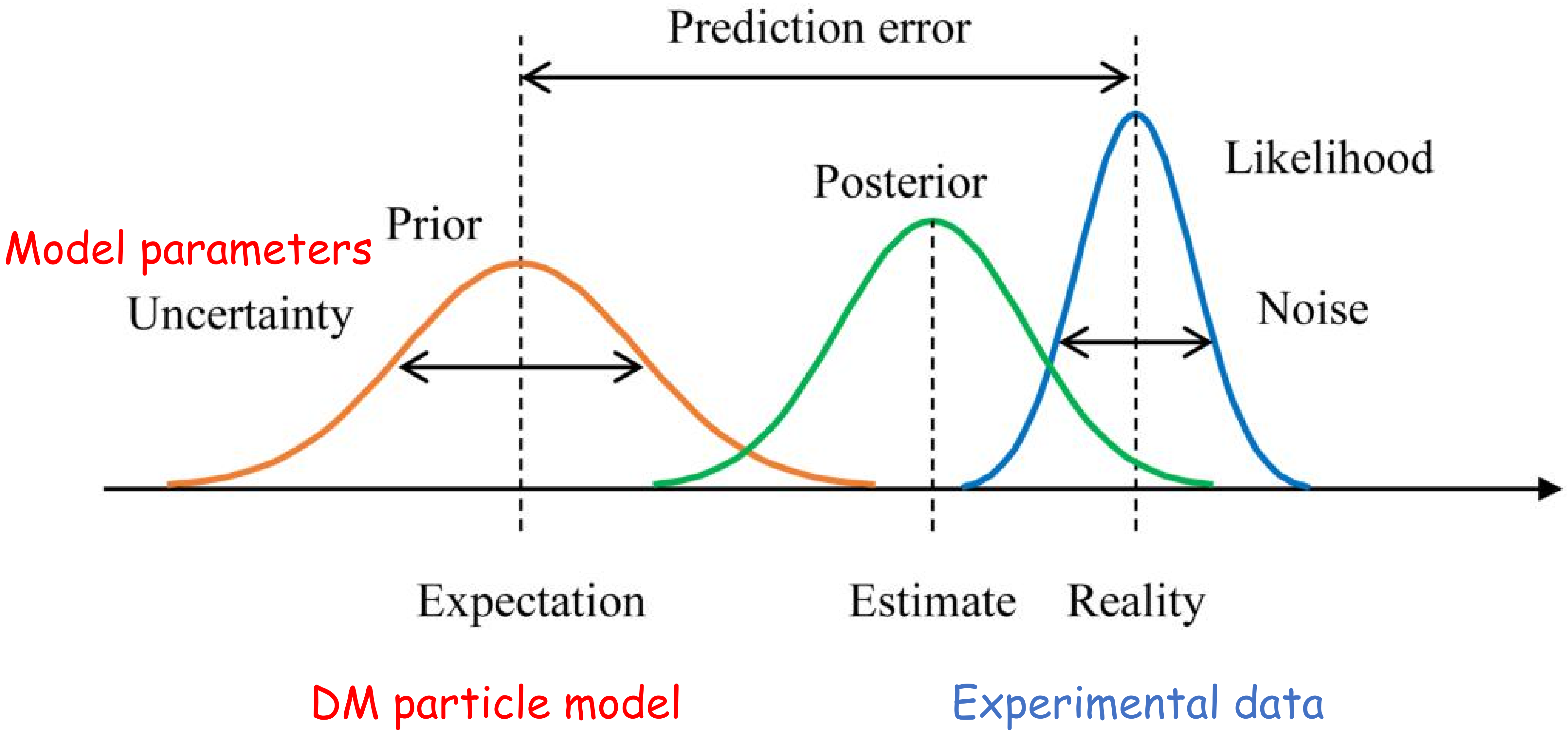
The current DM search

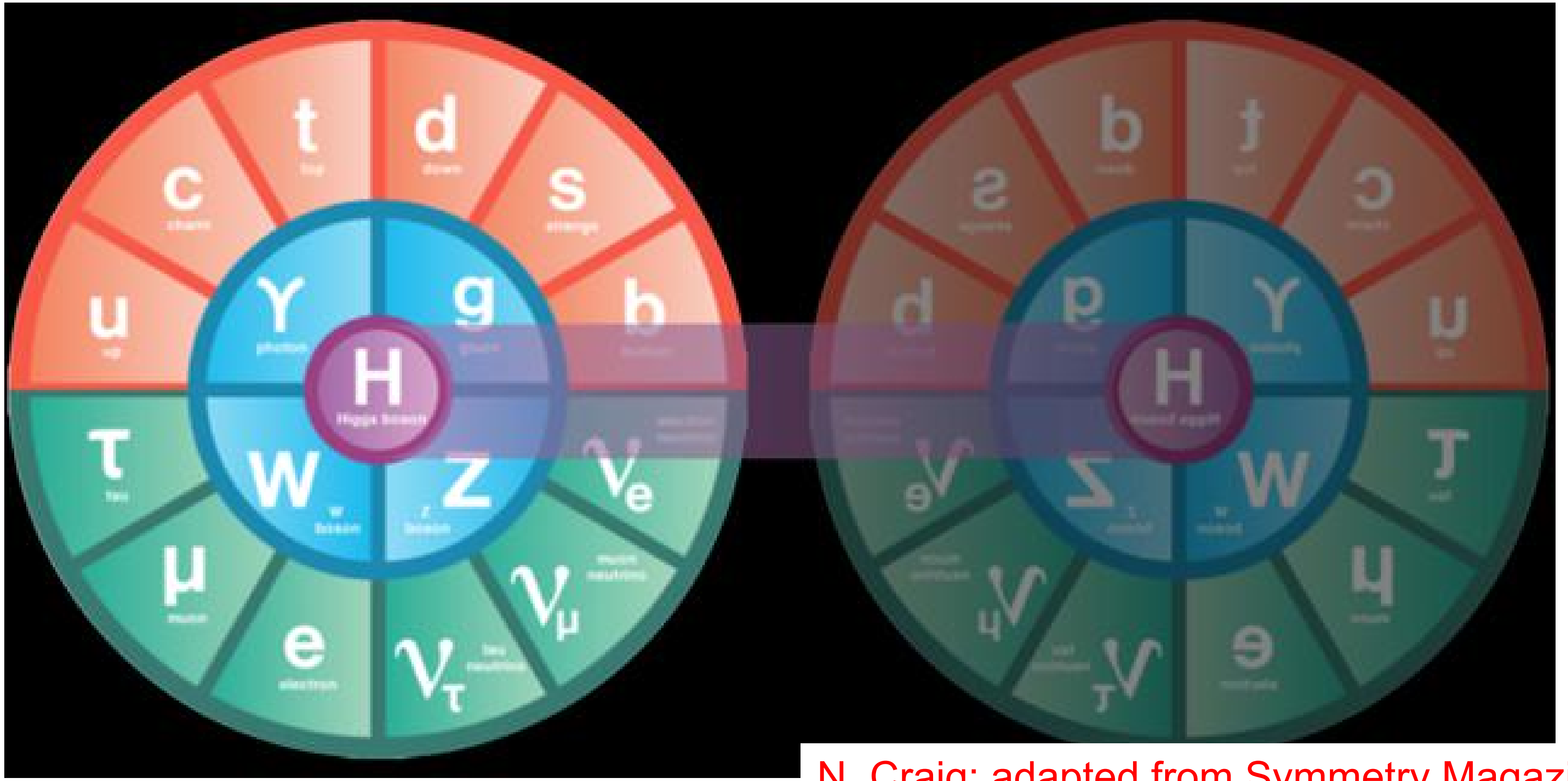




Over more than 40 orders of magnitudes.

Similarity to Bayesian theory





N. Craig; adapted from Symmetry Magazine

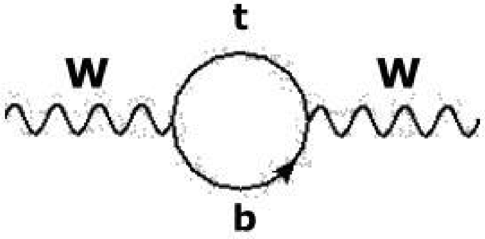
Mirror Twin Higgs

A solution of the Higgs hierarchy problem.

The hierarchy problem in the SM

- Success of radiative corr. in the SM:

	predicted	observed
top quark	179^{+12}_{-9}	172.7 ± 2.9
Higgs boson	91^{+45}_{-32}	?



- Failure of radiative corr. in Higgs sector:

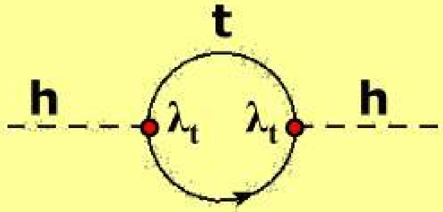
$$m_h = m_{h_{bare}} + \delta m_{h,top} + \ldots$$

150 = 135429433658723515**0**
−135429433658723500**0**

Hierarchy problem:

→ 'Conspiracy' to get $m_h \sim M_{EW}$ ($\ll M_{PL}$)
→ Biggest troublemaker is the top quark!

Radiative corrections from top quark



$$\delta m^2_{h,top} = -\frac{3}{8\pi^2}\lambda_t^2 \, \Lambda^2$$

Popular solutions of the Higgs hierarchy problem: SUSY, Mirror Twin Higgs, and so on.

The Hidden Naturalness solution

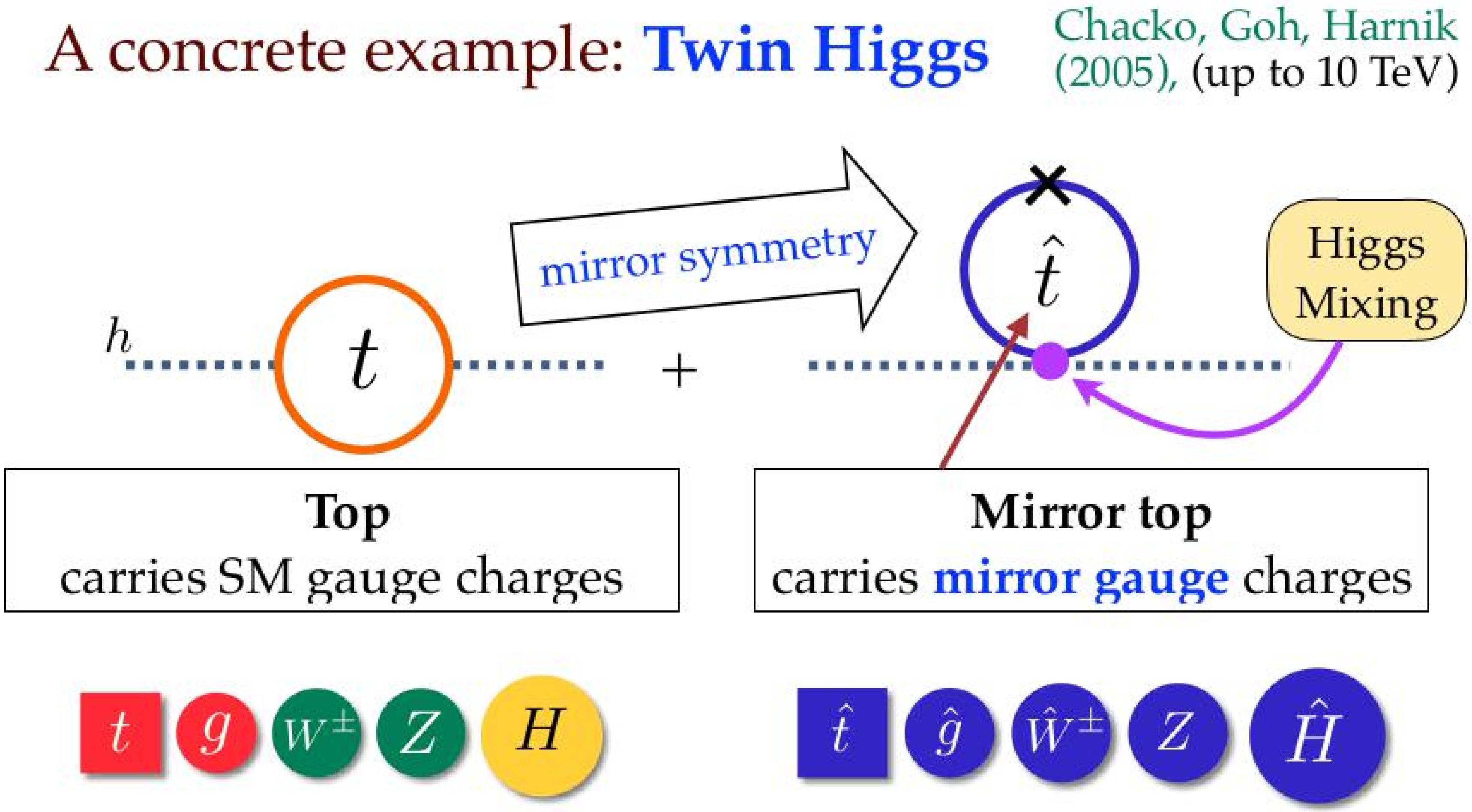
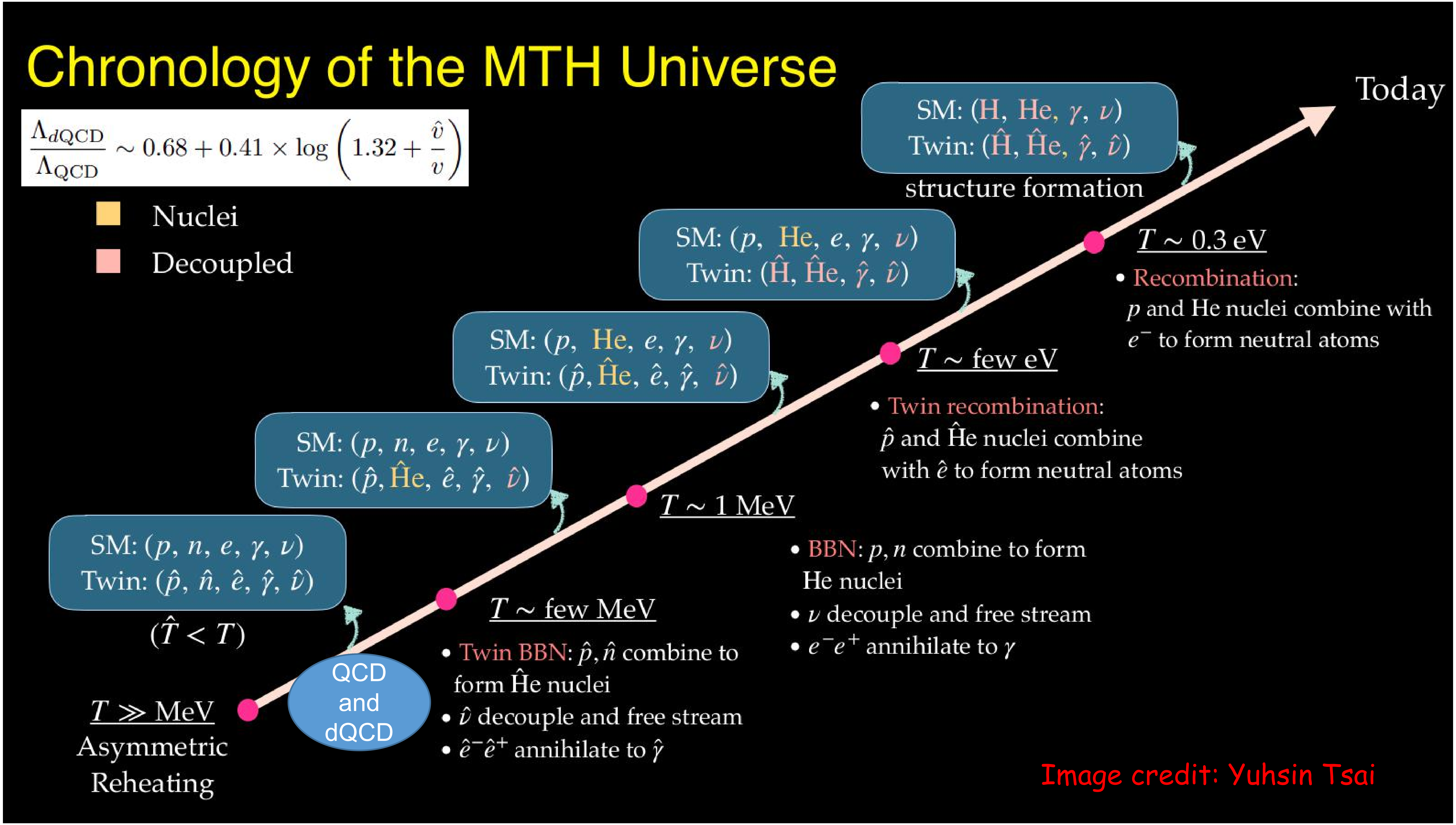


Image credit: Yusin Tsai

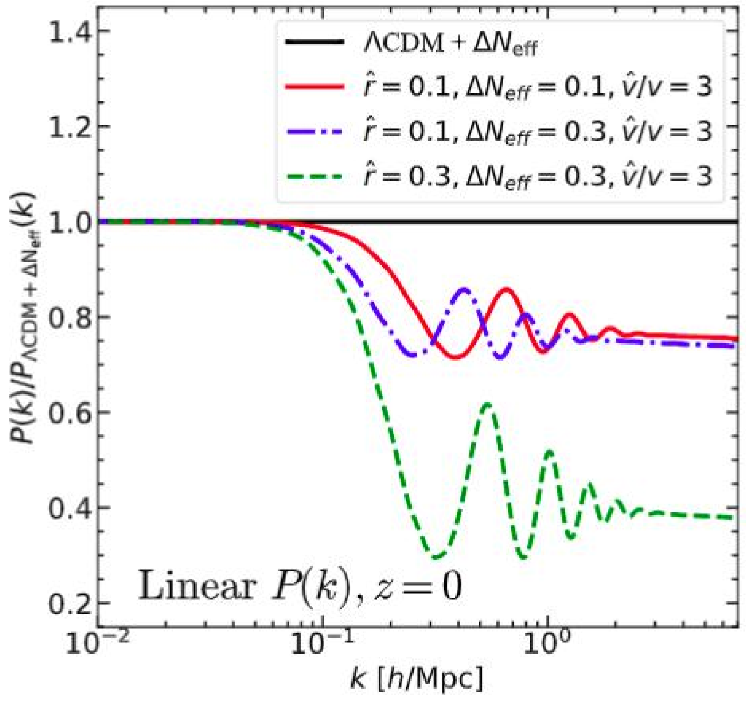
Mirror twin Higgs		
$\hat{r}$	Flat	$[10^{-3}, 1]$
$\hat{v}/v$	Flat	[2, 15]
$\Delta\hat{N}$	Flat	$[10^{-3}, 1]$

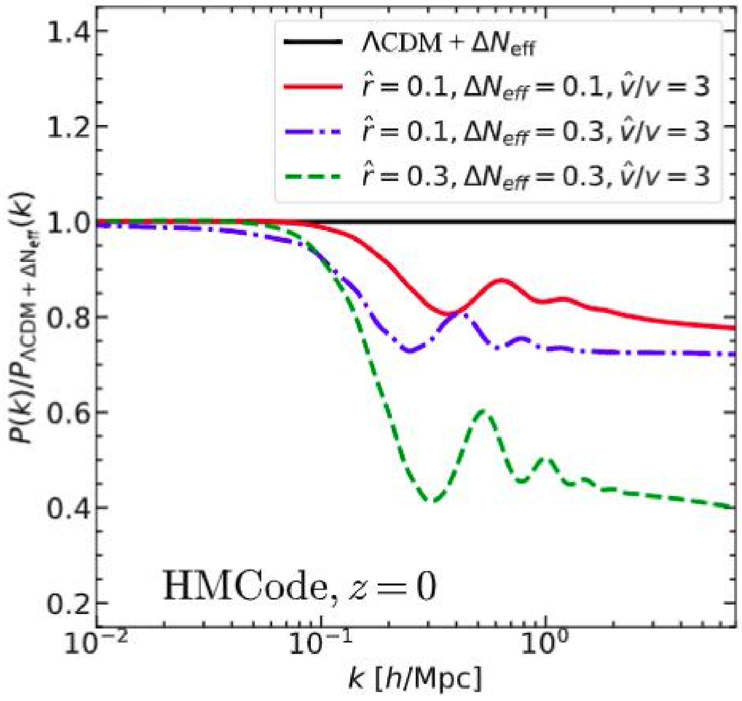
- We only introduce three parameters for a cosmological study.
- DR includes twin neutrinos and photons.
- Higgs mixing correlates to vhat



Chronology of the MTH Universe
$\frac{\Lambda_{dQCD}}{\Lambda_{QCD}} \sim 0.68 + 0.41 \times \log\left(1.32 + \frac{\hat{v}}{v}\right)$
Nuclei
Decoupled
$T \gg$ MeV
Asymmetric Reheating
QCD and dQCD
SM: (p, n, e, γ, ν)
Twin: $(\hat{p}, \hat{n}, \hat{e}, \hat{\gamma}, \hat{\nu})$
$(\hat{T} < T)$
$T \sim$ few MeV
• Twin BBN: $\hat{p}, \hat{n}$ combine to form $\hat{\mathrm{H}}$e nuclei
• $\hat{\nu}$ decouple and free stream
• $\hat{e}^-\hat{e}^+$ annihilate to $\hat{\gamma}$
SM: (p, n, e, γ, ν)
Twin: $(\hat{p}, \hat{\mathrm{H}}\mathrm{e}, \hat{e}, \hat{\gamma}, \hat{\nu})$
$T \sim 1$ MeV
• BBN: p, n combine to form He nuclei
• ν decouple and free stream
• e^-e^+ annihilate to γ
SM: $(p, \mathrm{He}, e, \gamma, \nu)$
Twin: $(\hat{p}, \hat{\mathrm{H}}\mathrm{e}, \hat{e}, \hat{\gamma}, \hat{\nu})$
$T \sim$ few eV
• Twin recombination: $\hat{p}$ and $\hat{\mathrm{H}}$e nuclei combine with $\hat{e}$ to form neutral atoms
SM: $(p, \mathrm{He}, e, \gamma, \nu)$
Twin: $(\hat{\mathrm{H}}, \hat{\mathrm{H}}\mathrm{e}, \hat{\gamma}, \hat{\nu})$
$T \sim 0.3$ eV
• Recombination: p and He nuclei combine with e^- to form neutral atoms
SM: $(\mathrm{H}, \mathrm{He}, \gamma, \nu)$
Twin: $(\hat{\mathrm{H}}, \hat{\mathrm{H}}\mathrm{e}, \hat{\gamma}, \hat{\nu})$
structure formation
Today
Image credit: Yuhsin Tsai

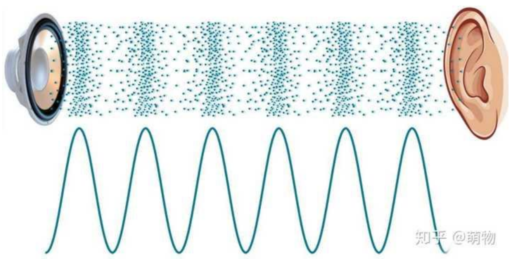
The Mirror Twin Higgs

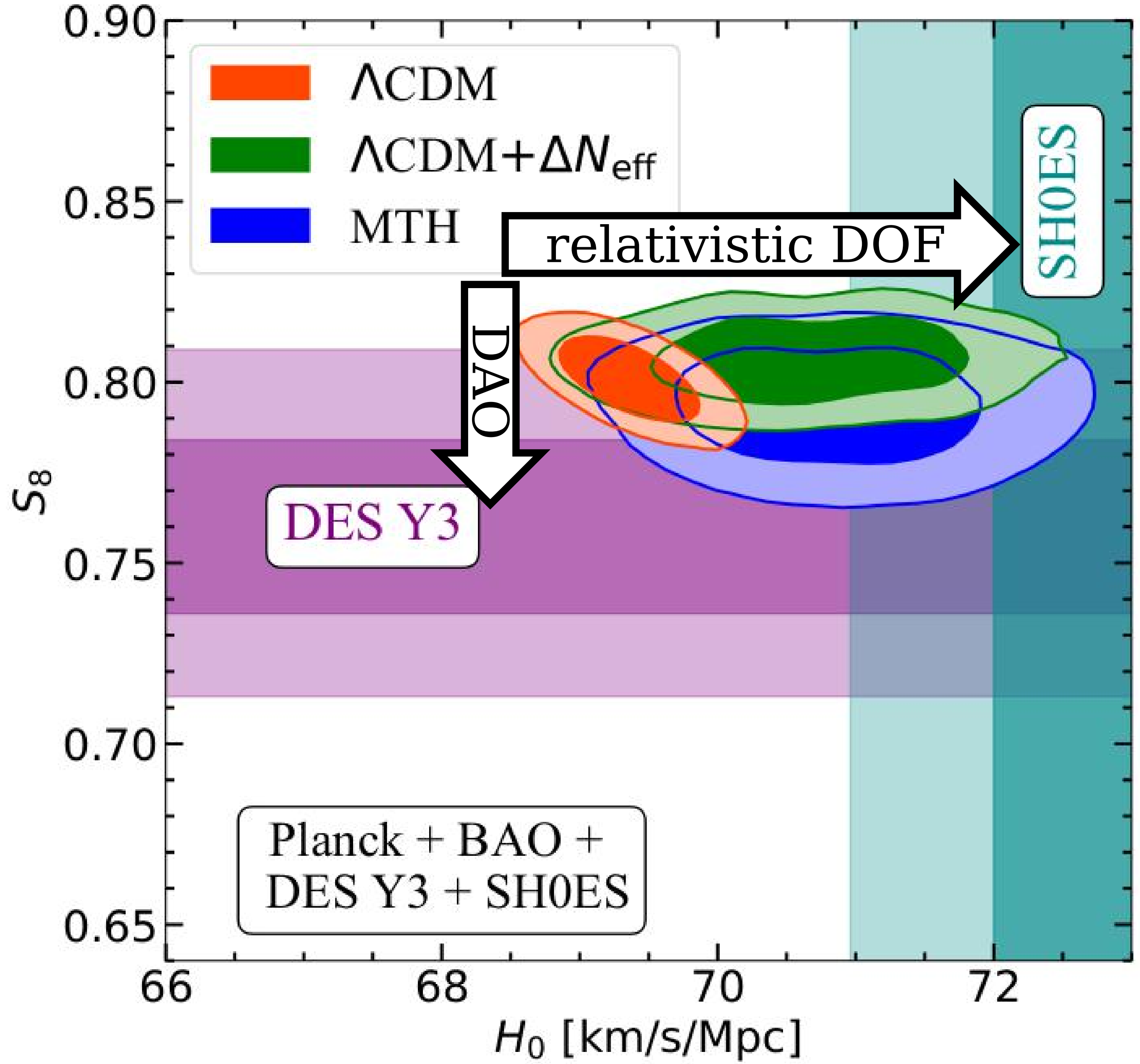




Parameter	Prior distribution	Prior range
Cosmology		
$\Omega_b h^2$	Flat	[0.022, 0.023]
$\Omega_{cdm} h^2$	Flat	[0.112, 0.128]
$100 \cdot \theta_s$	Flat	[1.039, 1.043]
$\ln(A_s \times 10^{10})$	Flat	[2.955, 3.135]
n_s	Flat	[0.941, 0.991]
τ_{reio}	Flat	[10^{-2}, 0.7]
Mirror twin Higgs		
$\hat{r}$	Flat	[10^{-3}, 1]
$\hat{v}/v$	Flat	[2, 15]
$\Delta\hat{N}$	Flat	[10^{-3}, 1]
Intrinsic alignment		
A_{IA}	Flat	[-6, 6]
η	Flat	[-6, 6]

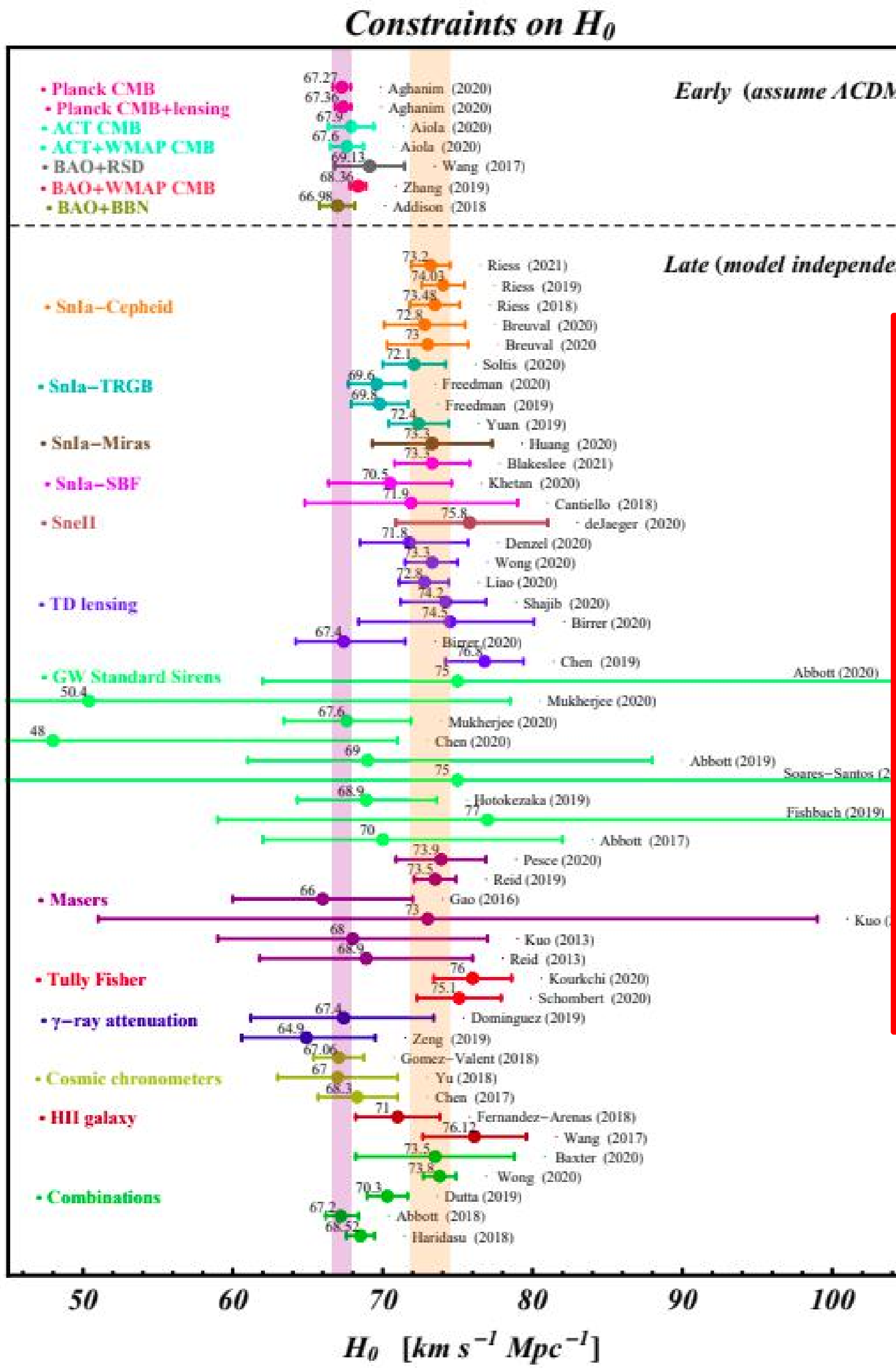
- Matter power spectra are suppressed at a large k region (small scale).
- Non-linear effects wash out the DAO features.

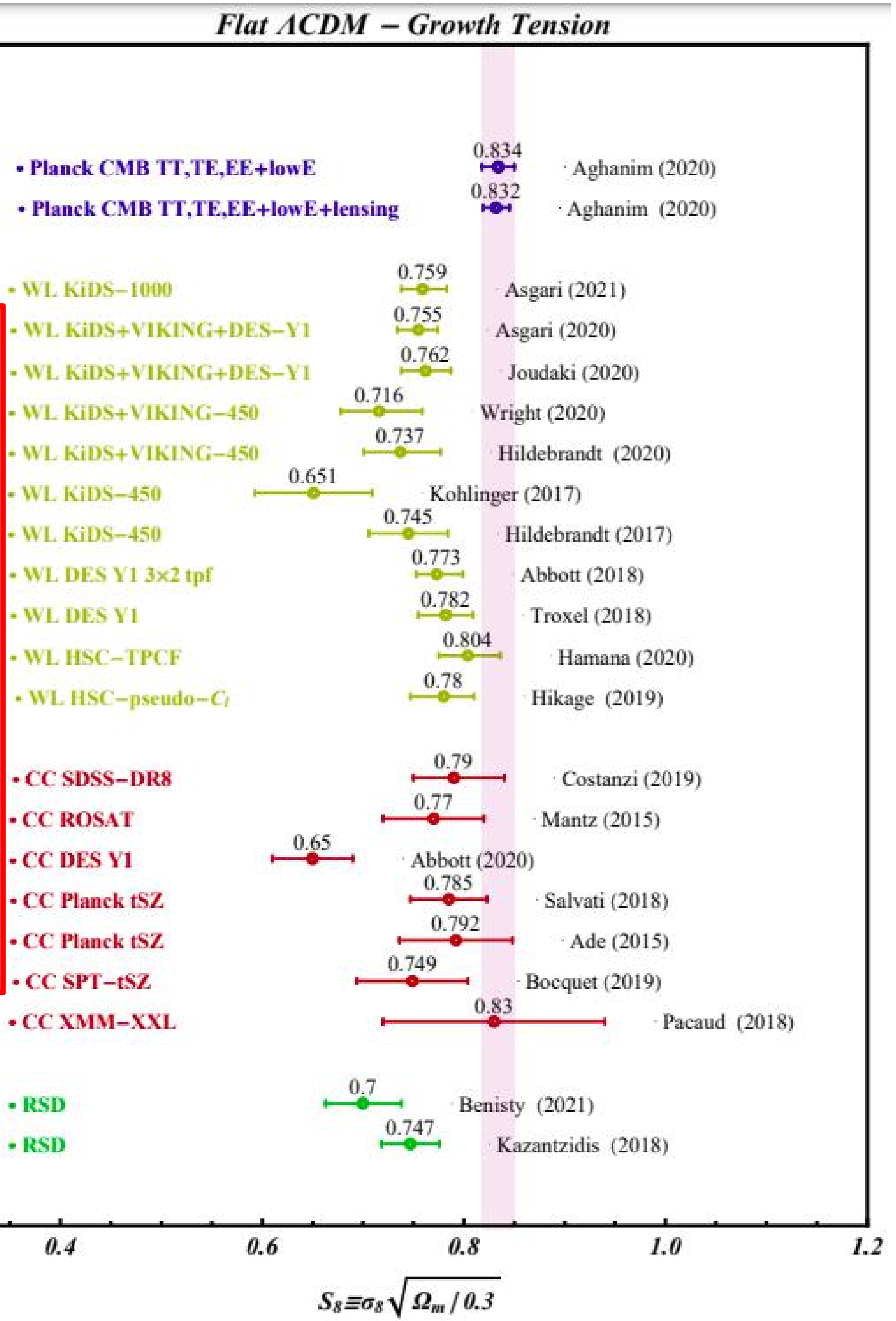




Small Ho but large S8?

If adding a dark radiation component to the Universe, H0 can be increased while S8 is still large!

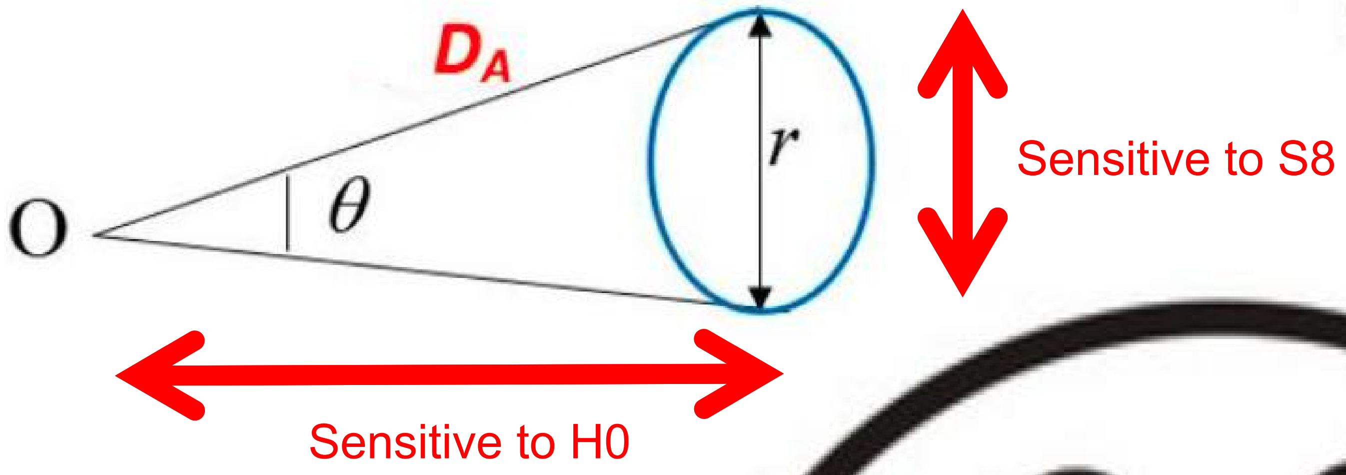


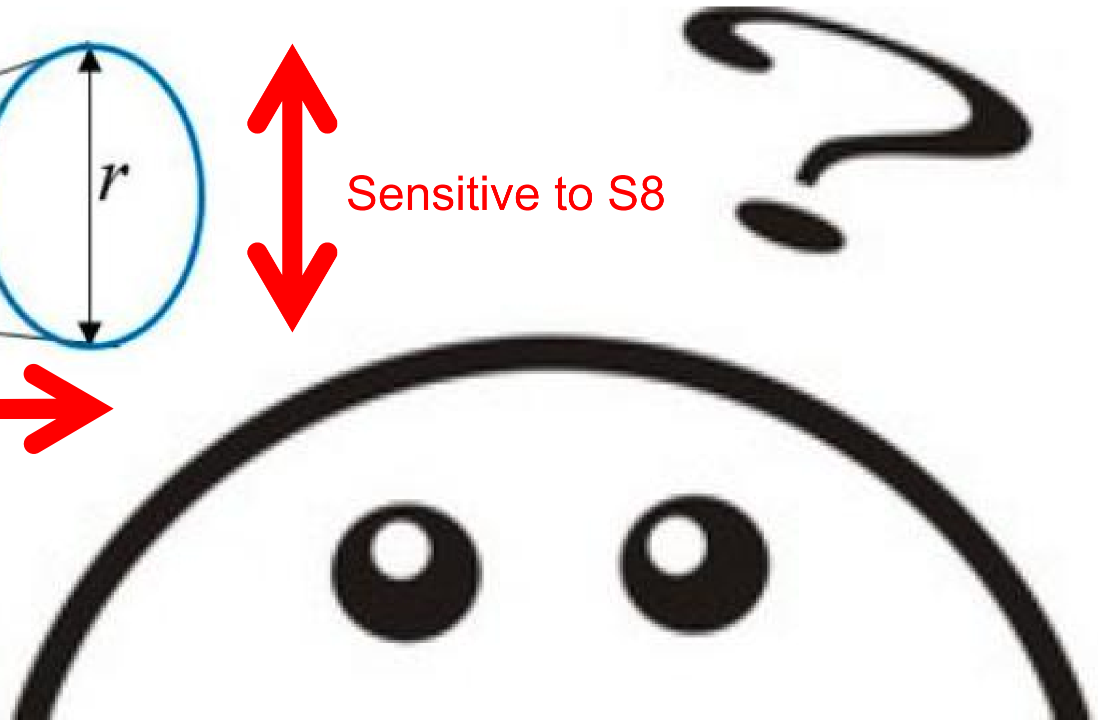


The LCDM large sclae results are smaller Ho but larger S8 than the small scale measurements.

This coincides with to MTH.

L. Perivolaropoulos, and F. Skara (2105.05208)





$$\theta_s = \frac{r_s(z^\star)}{D_A(z^\star)}$$

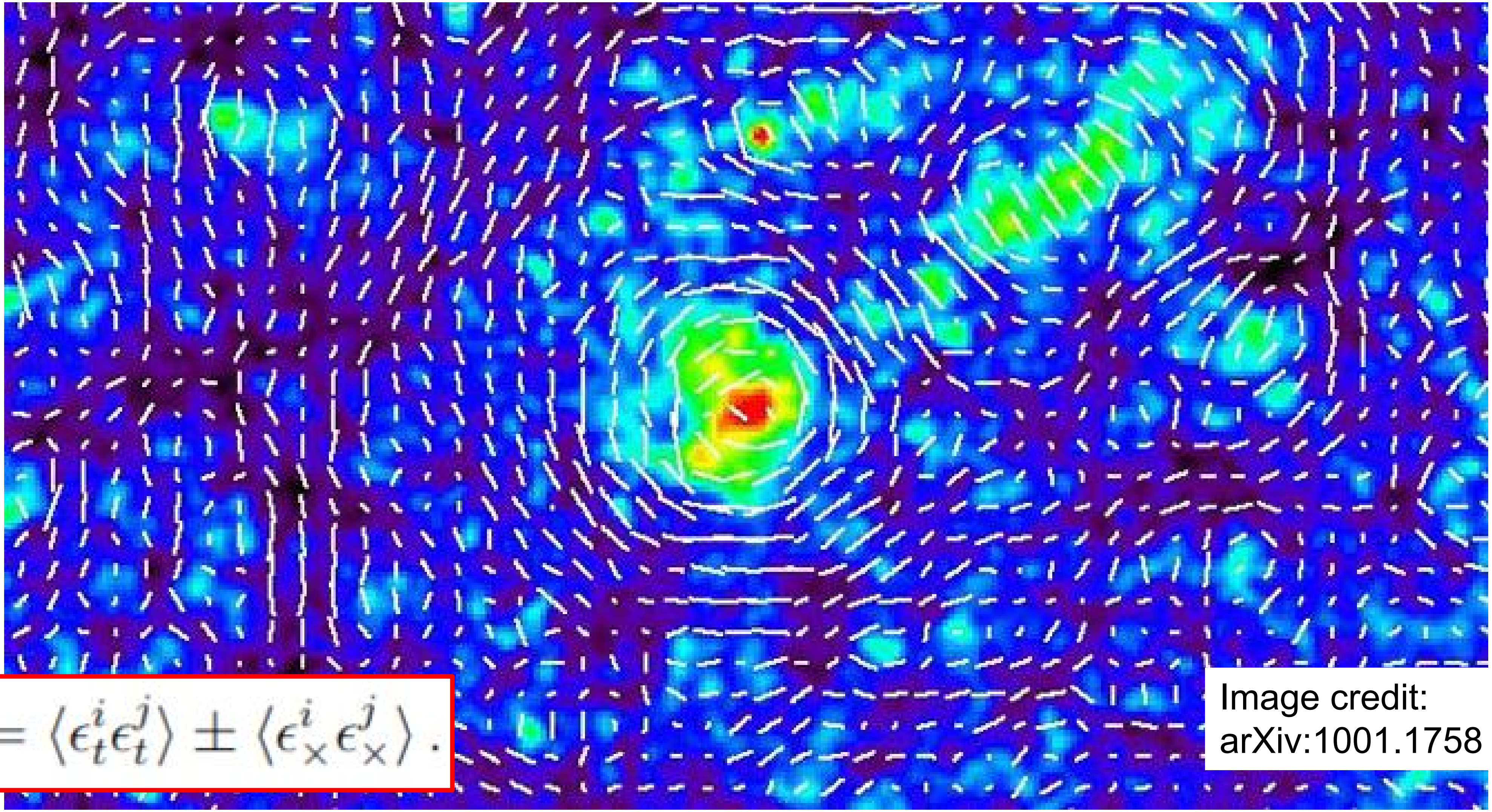
$$r_s(z^\star) = \int_{z^\star}^{\infty} \frac{dz}{H(z)} c_s(z)$$

where cs~dP/d\rho

$$D_A(z^\star) = \int_0^{z^\star} \frac{dz}{H(z)}$$

Cosmic Shear measurement

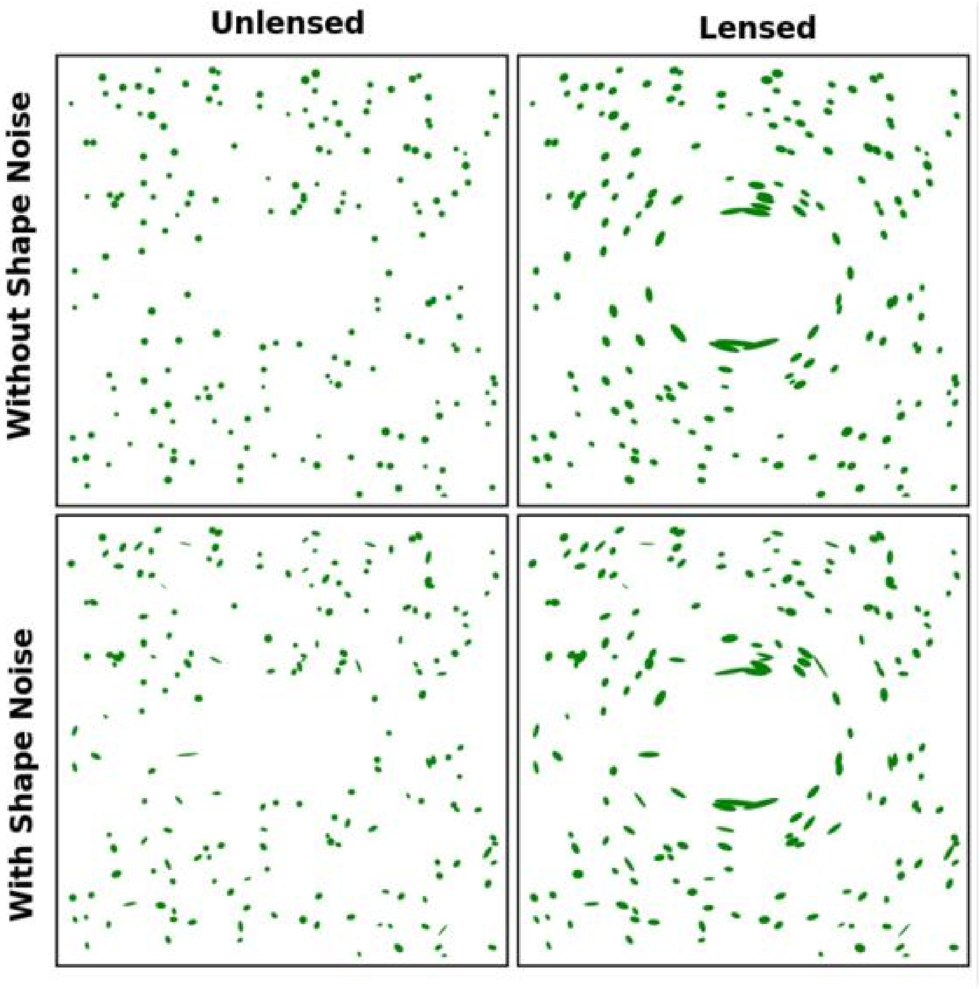
shape-shap 2 points-correlation: Cosmic Shear



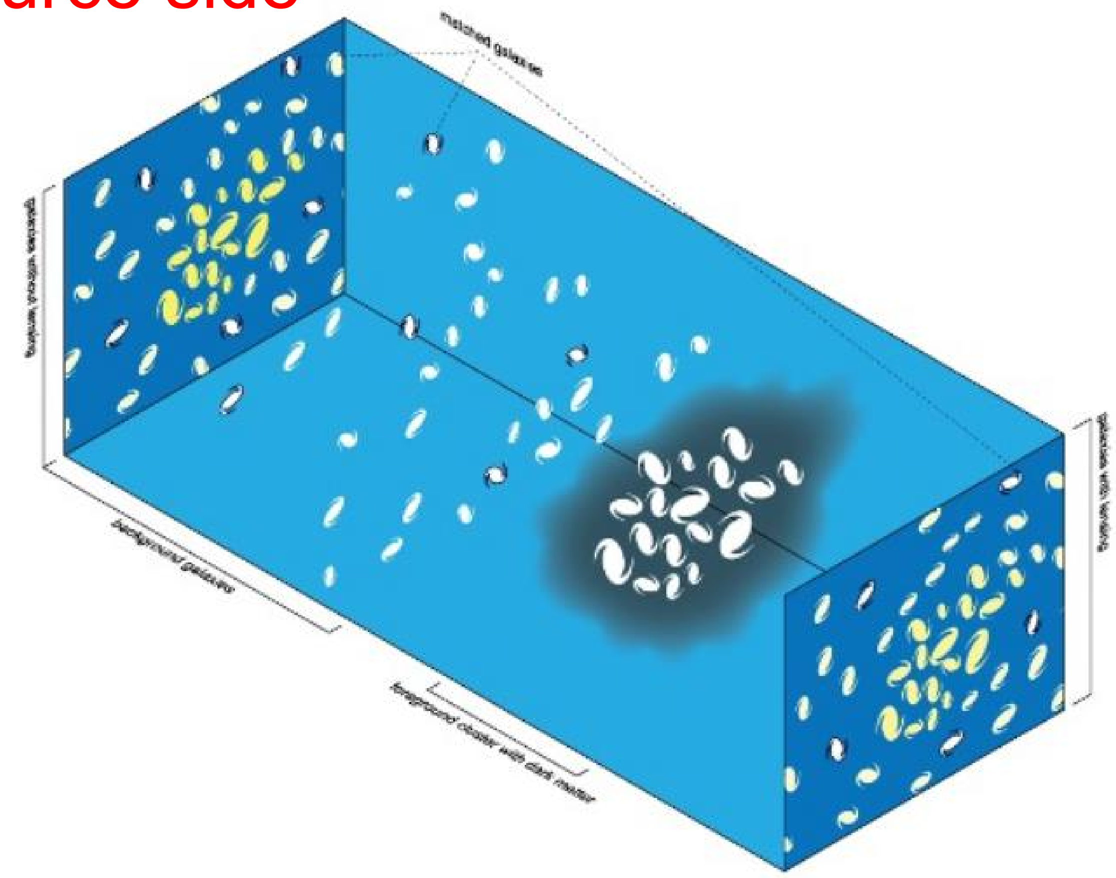
$$\xi_{\pm}^{ij}(\theta) = \langle \epsilon_t^i \epsilon_t^j \rangle \pm \langle \epsilon_\times^i \epsilon_\times^j \rangle \,.$$

Image credit: arXiv:1001.1758

Weak lensing

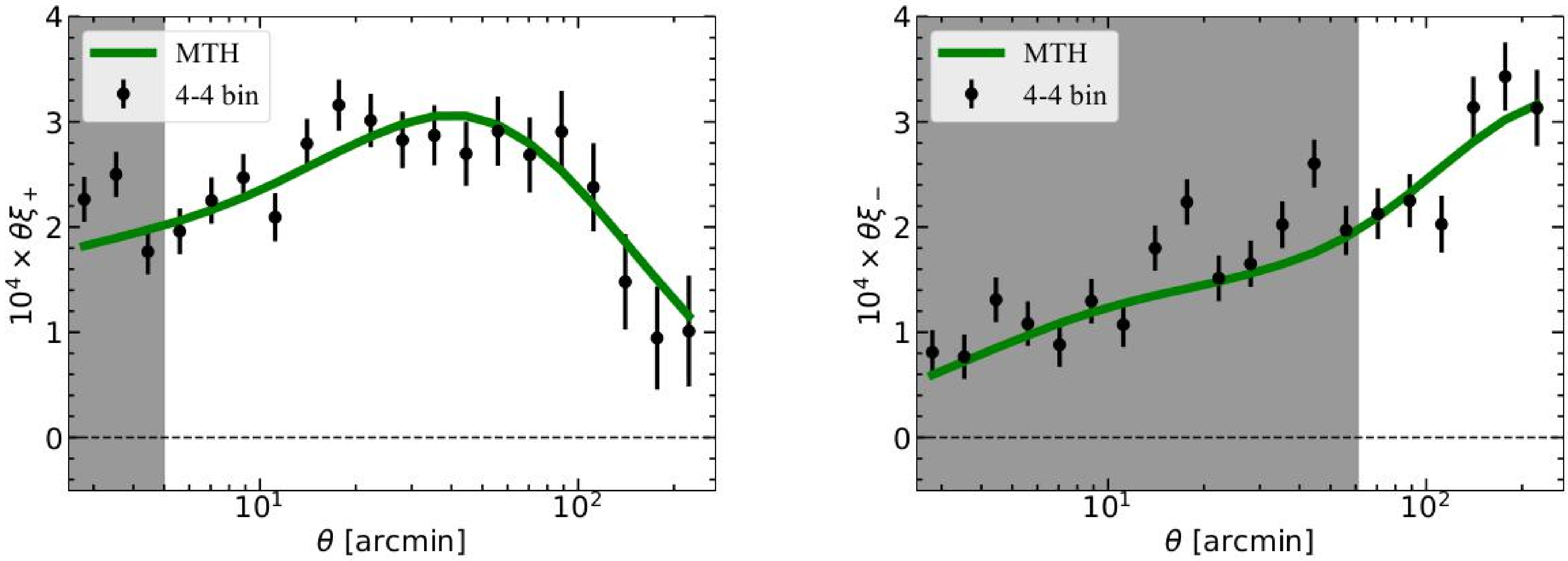


Source side



Our side.

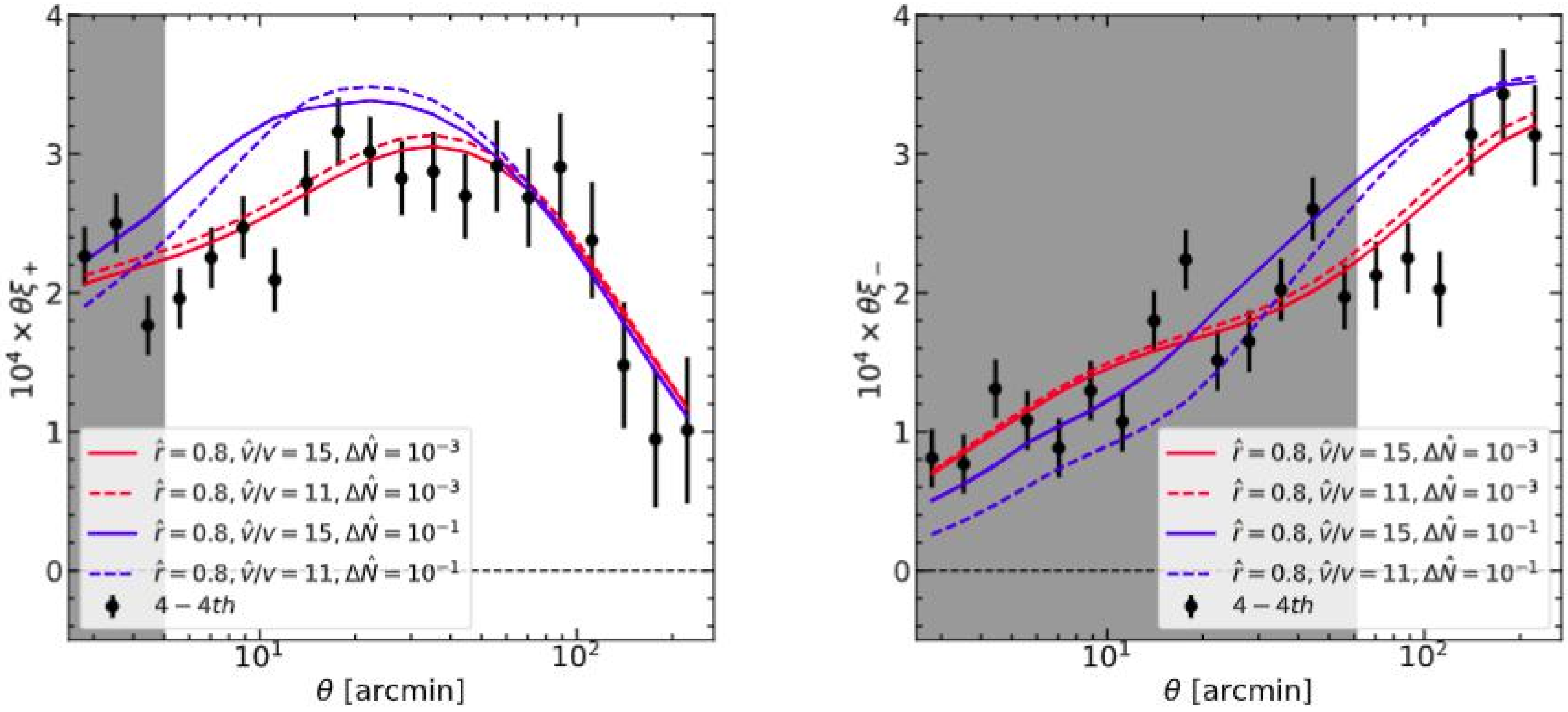
shape-shap 2 points-correlation: Cosmic Shear



$$\xi_{\pm}^{ij}(\theta) = \frac{1}{2\pi}\int_0^{\infty} C_{\mathrm{tot}}^{ij}(\ell) J_{0/4}(\ell \cdot \theta)\ell d\ell$$

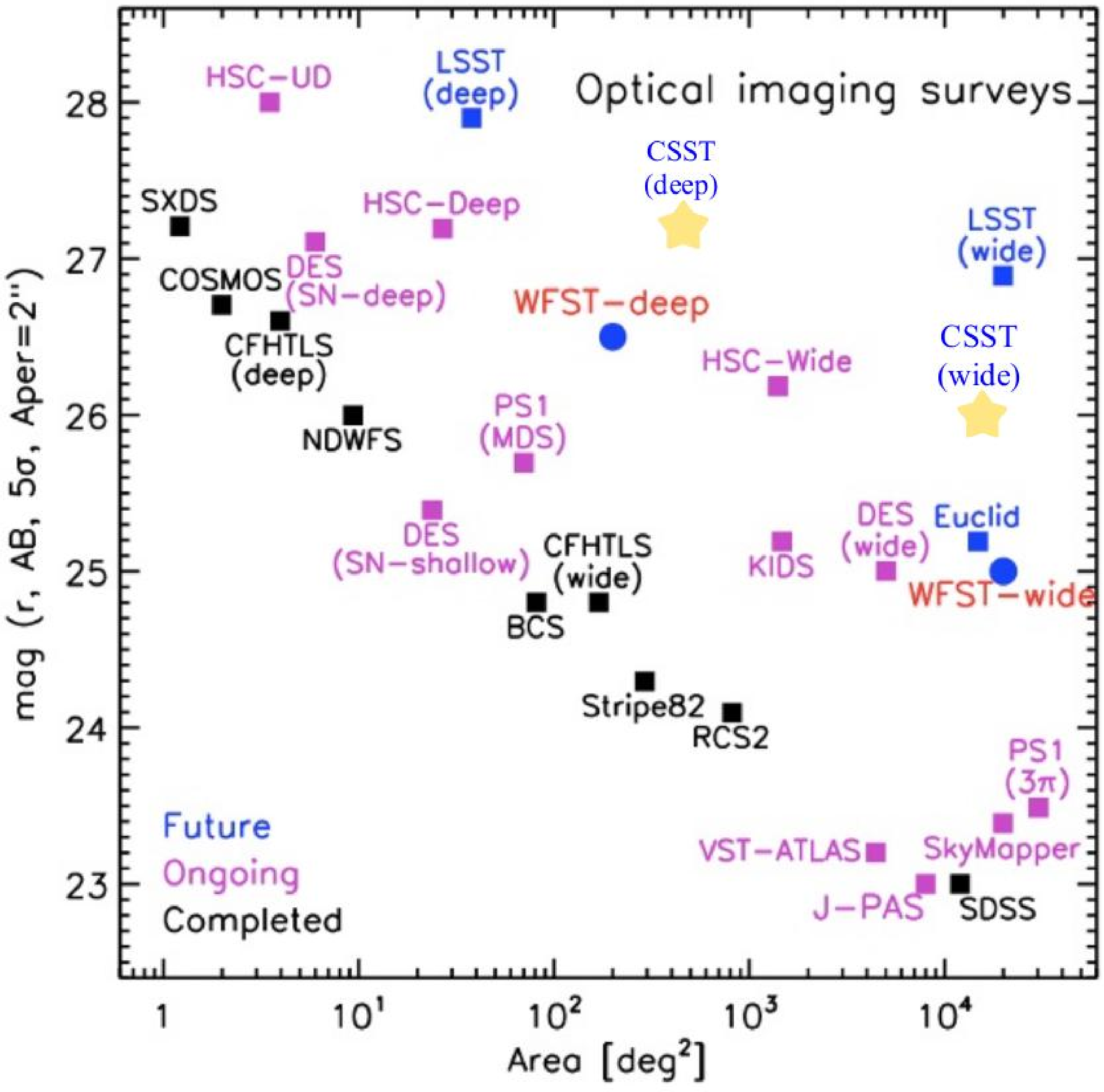
$$C_{GG}^{ij}(\ell) = \int_0^{\chi_{z_{\max}}} d\chi \frac{W^i(\chi)W^j(\chi)}{\chi^2} P_\delta\left(k = \frac{\ell + 1/2}{\chi}, z(\chi)\right)$$

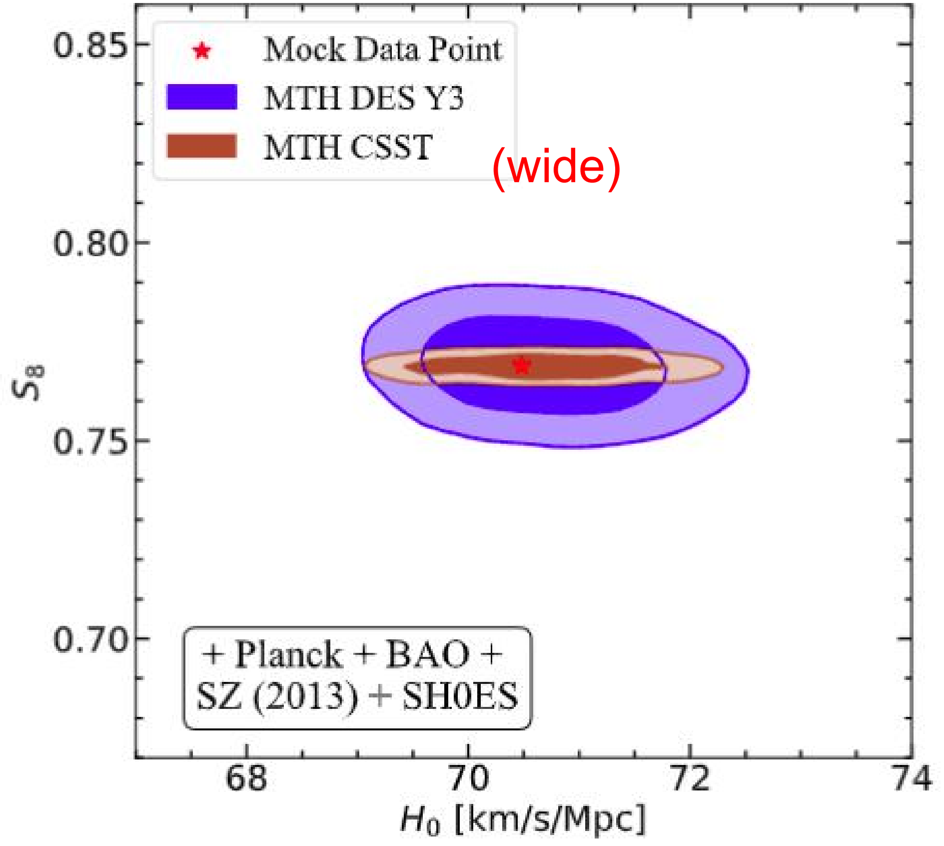
The impact of vev and Delta N



- DES Y3 cannot probe a small scale.
- A large v-hat and small Delta N (LCDM-like) can escape from DES due to mask.

Telescopes for Cosmic Shear





References: HSC website, Chi Zhang, [Chinese Science Bulletin 66, 1290 (2021)], and 2301.03068

Basic likelihoods:

1. Cosmic shear (DES Y3, shape-shape).
2. CMB (TT, TE, EE, lensing).
3. BAO (BOSS DR12).

When studying how MTH can relax the H_0 and S_8 tensions, we further include two datasets one by one

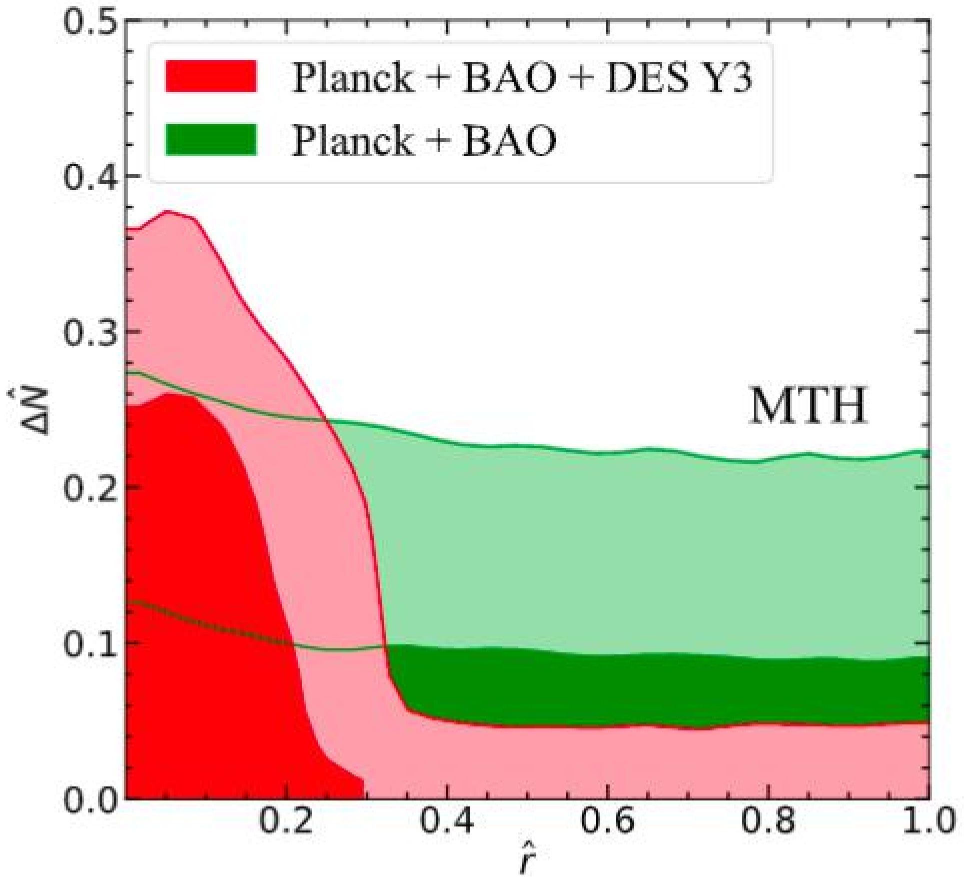
(iv) The SH0ES likelihood is also a Gaussian distribution with the measurement [74]

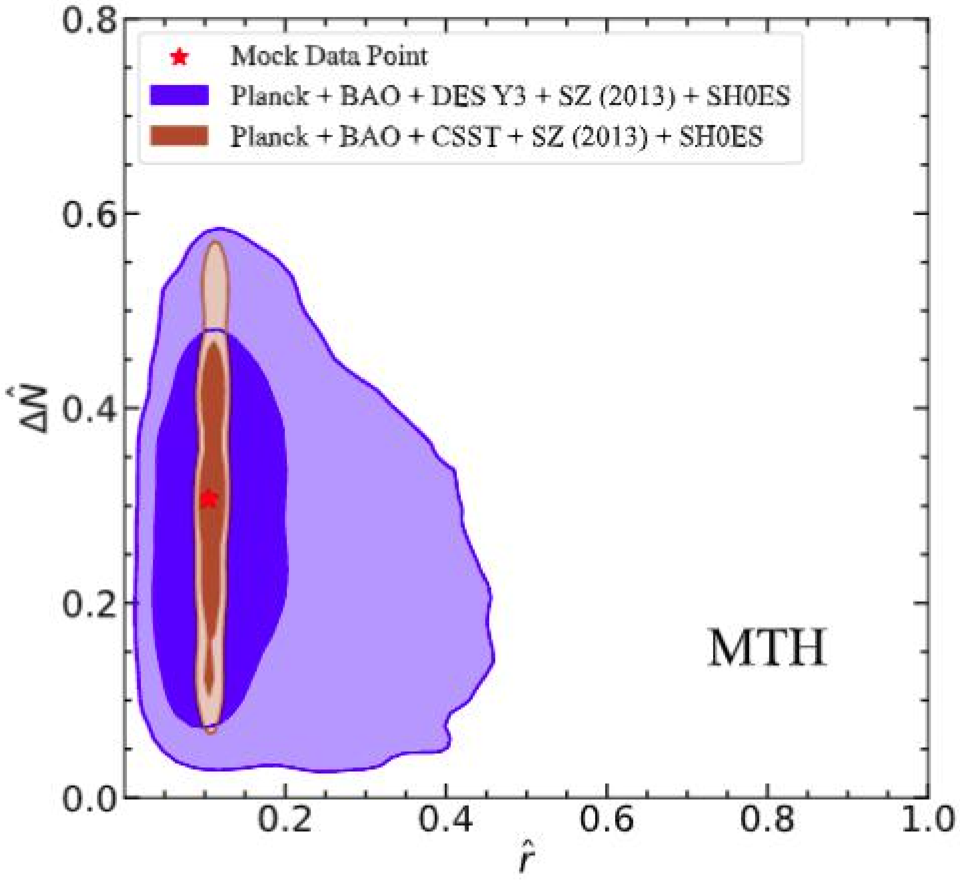
$$H_0 = 73.04 \pm 1.04 \text{ km s}^{-1}\text{Mpc}^{-1}.$$

(v) The Planck SZ (2013) likelihood[4] is described by a Gaussian distribution with the measurement [45]

$$S_8^{\rm SZ} \equiv \sigma_8 \left(\Omega_{\rm m}/0.27\right)^{0.3} = 0.782 \pm 0.010.$$

MTH with SZ (2013) and SHOES

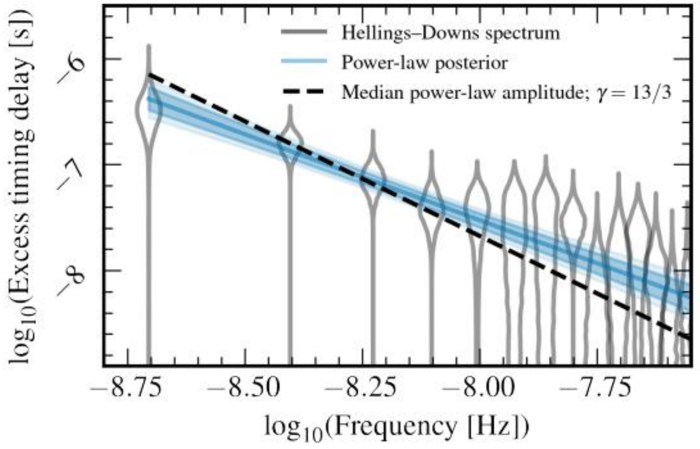




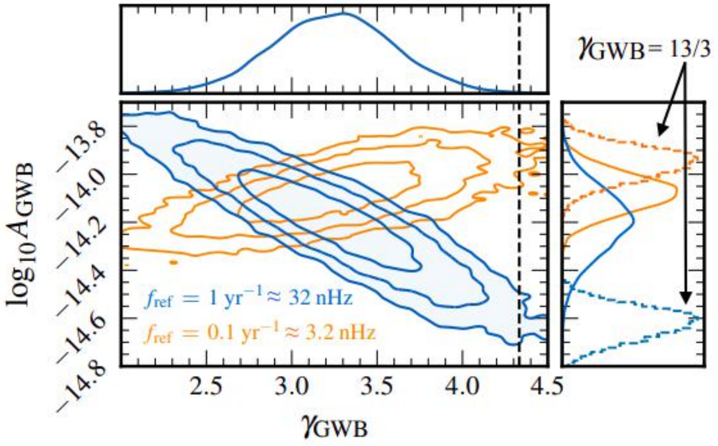
- DES Y3 strongly disfavour the region of large r-hat.
- The future telescopes like CSST can pin down the range of r-hat.

The nanohertz Stochastic Gravitational-Wave Background

NANOGrav (2306.16213)



(b)



$$\Omega_{\rm GW}(f) = \frac{2\pi^2}{3H_0^2} f^2 h_c^2(f), \qquad (6)$$

where H_0 is the Hubble constant and $h_c(f)$ is a power-law function for the GWB characteristic strain spectrum

$$h_c(f) = A_{\rm GWB}(\frac{f}{f_{yr}})^{\gamma}, \qquad (7)$$

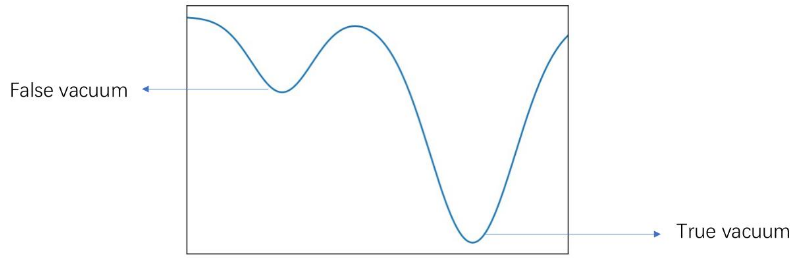
$A_{\rm GWB} = 6.4^{+4.2}_{-2.7} \times 10^{-15}$ and $\gamma = 3.2^{+0.6}_{-0.6}$ for NANOGrav, $\log_{10} A_{\rm GWB} = -14.54^{+0.28}_{-0.41}$ and $\gamma = 4.19^{+0.73}_{-0.63}$ for EPTA, $A_{\rm GWB} = 3.1^{+1.3}_{-0.9} \times 10^{-15}$ and $\alpha = -0.45^{+0.20}_{-0.20}$ ($\alpha = \frac{3-\gamma}{2}$) for PPTA, and $\log_{10} A_{\rm GWB} = -14.4^{+1.0}_{-2.8}$ with $\gamma < 6.6$ for CPTA.

The significance obtained from NANOGrav, EPTA, PPTA, and CPTA is approximately
3σ, 3σ, 2σ, and 4.6σ, respectively.

The nanohertz Stochastic Gravitational-Wave Background

$$\frac{m_{\hat{p}}}{m_p} \approx \frac{m_{\hat{n}}}{m_n} \approx \frac{\Lambda_{QCD_B}}{\Lambda_{QCD_A}} \approx 0.68 + 0.41\log(1.32 + v_B/v_A)$$

vacuum bubbles: $\mathcal{L} = \frac{1}{2}\partial^\mu\varphi\partial_\mu\varphi - V(\varphi).$



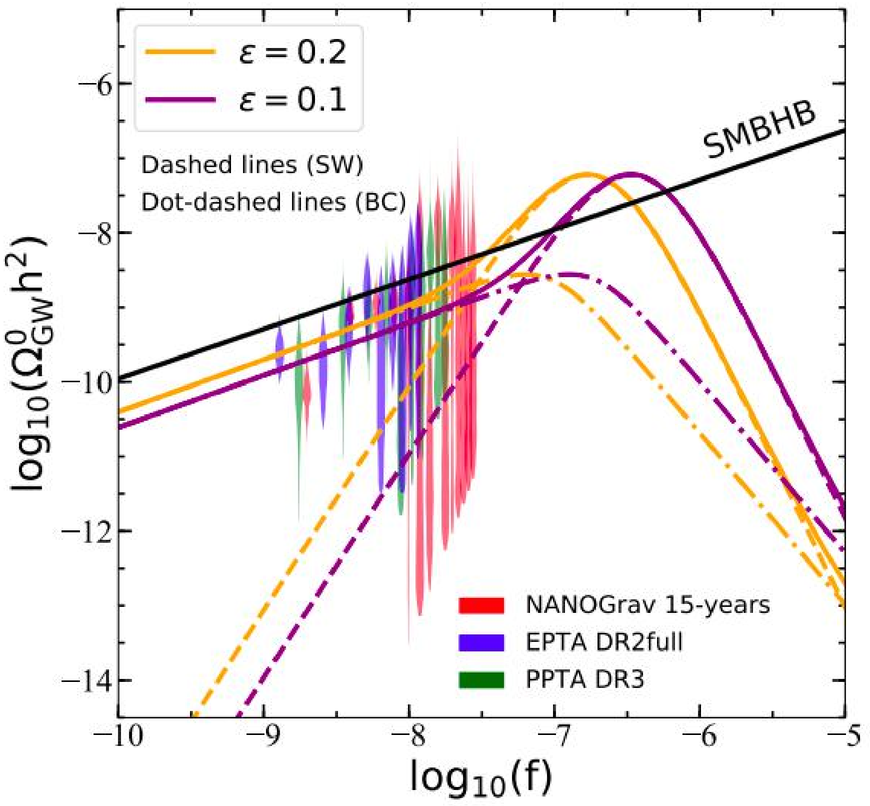
Two cases in this talk:

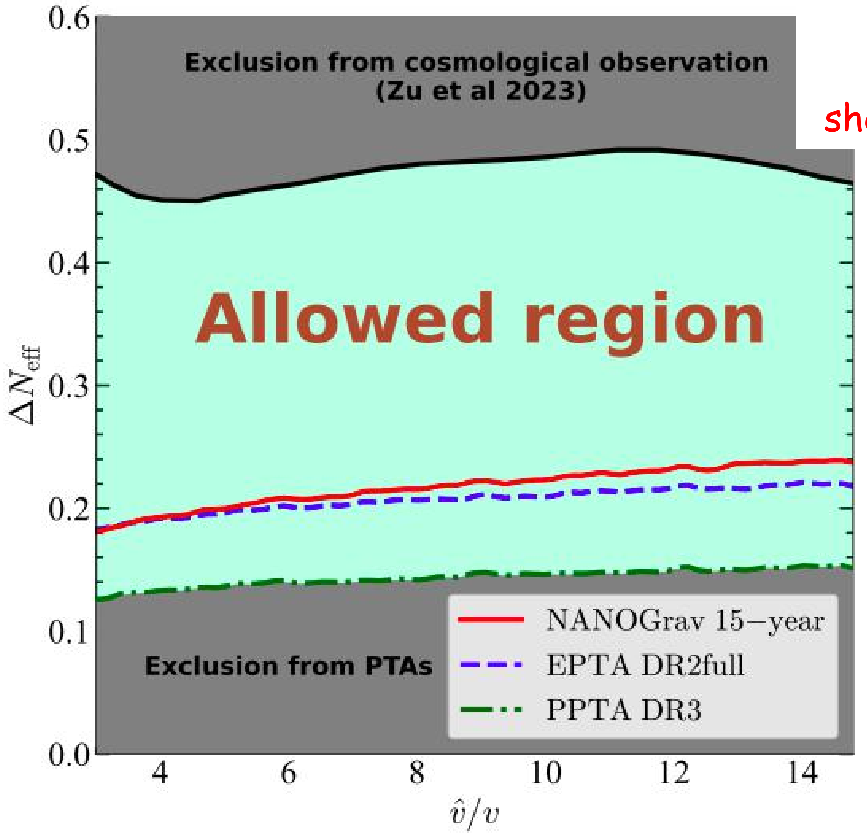
(i) Nf = 0, the minimal setup assuming only the presence of twin top and bottom quarks that are necessary for addressing the hierarchy problem.

(ii) Nf = 4, an extended scenario assuming two additional nearly massless flavours.

Nf is the dof of the color particles with mass "much lighter" than Lambda_QCD.

The nanohertz Stochastic Gravitational-Wave Background





Planck (CMB)+ DES Y3 (cosmic shear)+BAO+SH0ES

- Bubble Collision can contribute SGWB at PTA detected region, while Sound Wave contribution locates at higher frequency.
- Fitting PTA signal requires Delta Neff> 0.1.

Summary

- While the MTH model is presently not a superior solution to the observed H0 tension compared to the ΛCDM+ΔNeff model, we demonstrate that it has the potential to alleviate both the H0 and S8 tensions, especially if the S8 tension.

- The MTH model can relax the tensions while satisfying the DES power spectrum constraint up to k~10 h Mpc−1.

- We show that the future China Space Station Telescope (CSST) can determine the twin baryon abundance with a 10% level precision.

- Together with the current PTA excess, Delta Neff is required to be between 0.1 and 0.45.

Thank you for your attentions