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# Mirror Twin Higgs Cosmology


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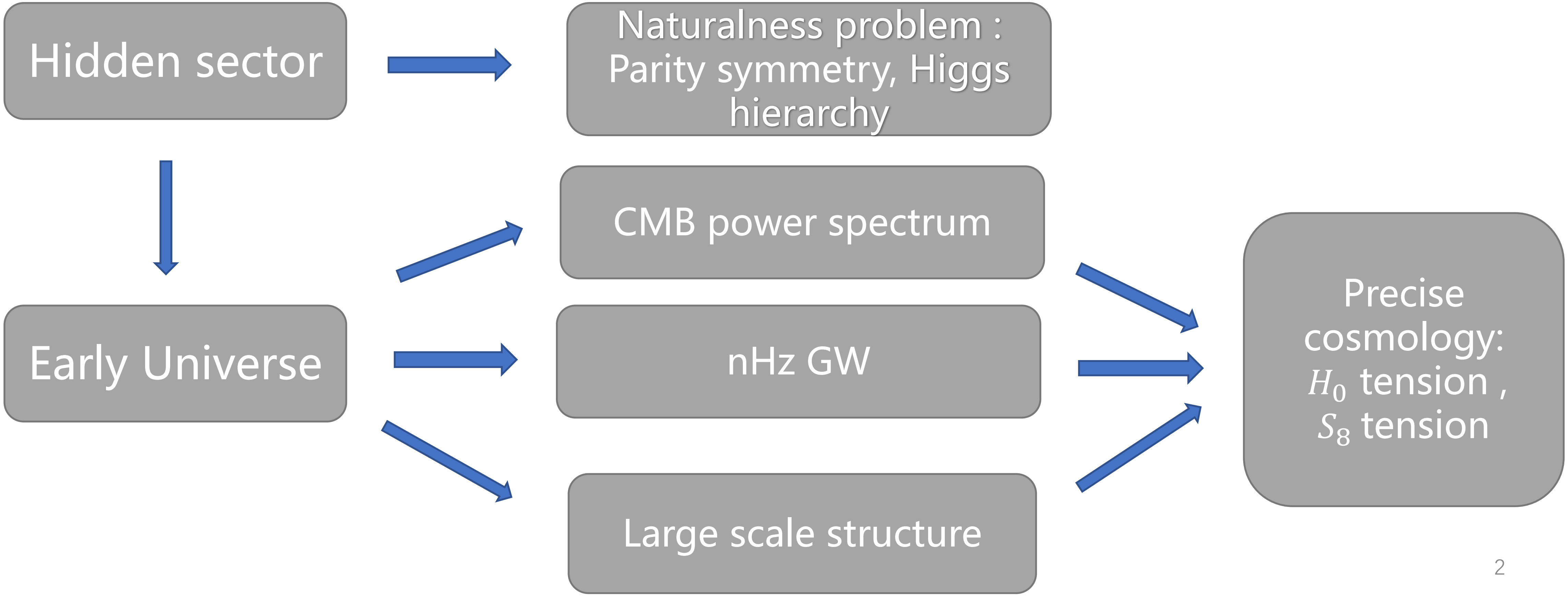
arXiv: 2304.06308, 2306.16769

# Cosmology as a particle lab

- **Early Universe Conditions:** high energy, extreme conditions for the clues about the fundamental particles and forces.
- **Neutrinos:** three generations, the number and properties of neutrinos in the early universe.
- **Dark Matter and Dark Energy:** the nature of dark matter and dark energy is a major challenge in particle physics.
- **Cosmology is a powerful tool for exploring particle physics**.

# Story we will talk today :



# Hidden sector

Dark matter evidences: cosmology, galaxy rotation curve, velocity dispersion and so on.

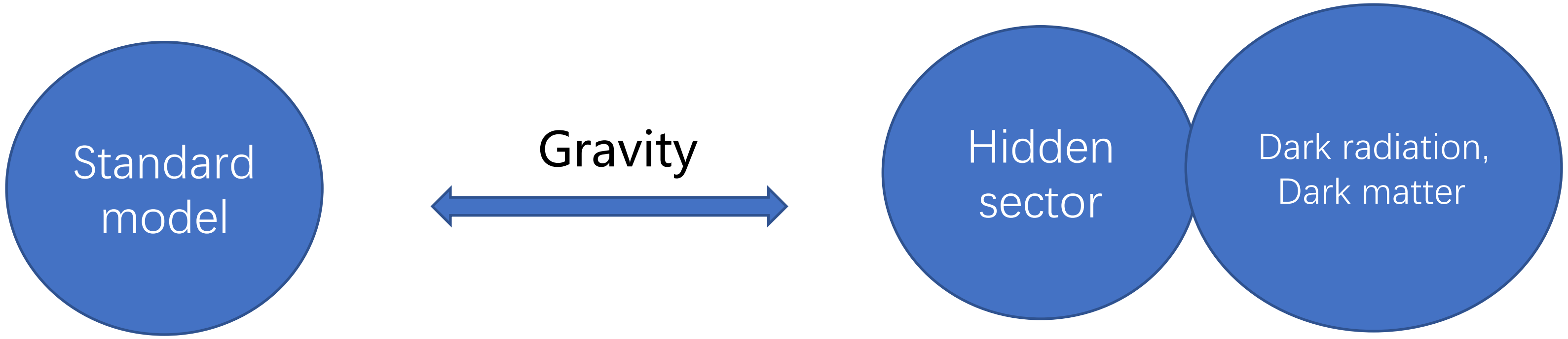
*Standard model ：*
*Lepton, quark, neutrino …*
*U(1),SU(2),SU(3)*

*How about hidden sector?*
*Hidden particles, Hidden interaction?*

# Hidden sector

The interaction between two sectors is strongly constrained.
But how about the interaction within hidden sector?

One way to explore this interaction: cosmology



# Mirror twin higgs

## Parity symmetry: mirror sector will help to restore the symmetry

PHYSICAL REVIEW VOLUME 104, NUMBER 1 OCTOBER 1, 1956

**Question of Parity Conservation in Weak Interactions***

T. D. LEE, *Columbia University, New York, New York*

AND

C. N. YANG,† *Brookhaven National Laboratory, Upton, New York*

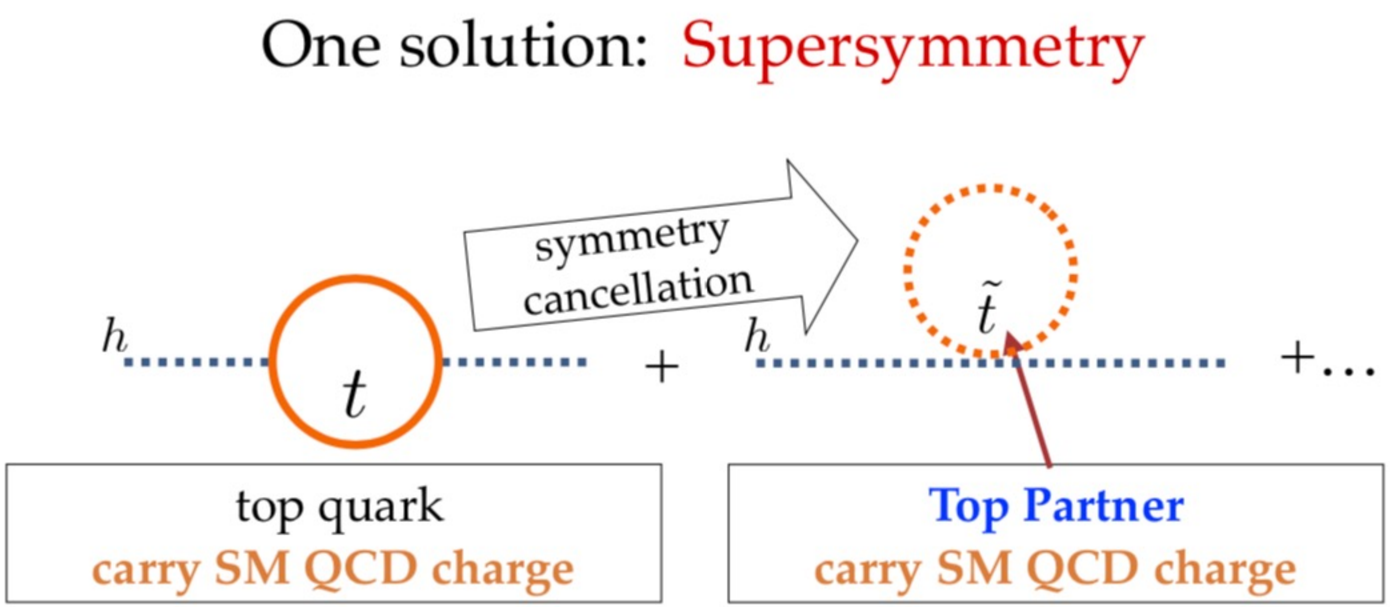
(Received June 22, 1956)

The question of parity conservation in $\beta$ decays and in hyperon and meson decays is examined. Possible experiments are suggested which might test parity conservation in these interactions.

# Mirror twin higgs

higgs hierarchy problem: why the weak force is $10^{24}$times as strong as gravity ?

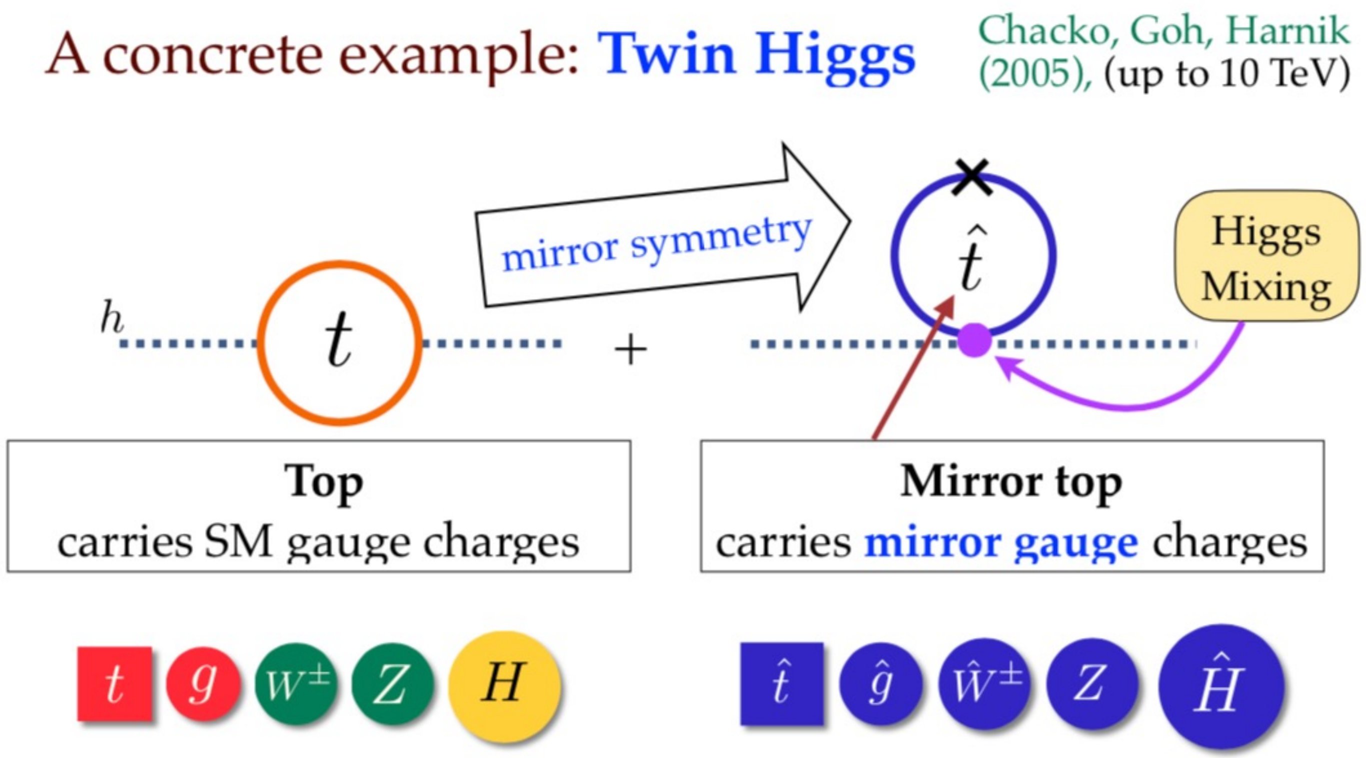
i.e. why higgs mass is so small compared to $m_{pl}$ ?




The hope for supersymmetry cancelling is fading since the LHC bounds are too strong ……

# Mirror twin higgs

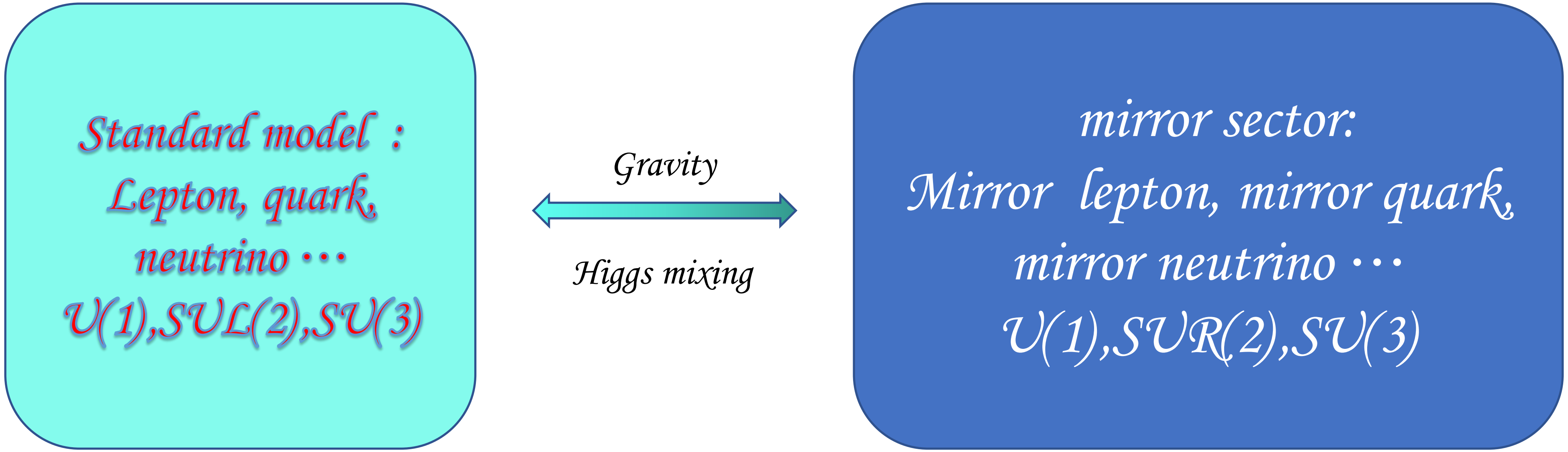
## Alternative method: cancelling partner through higgs mixing



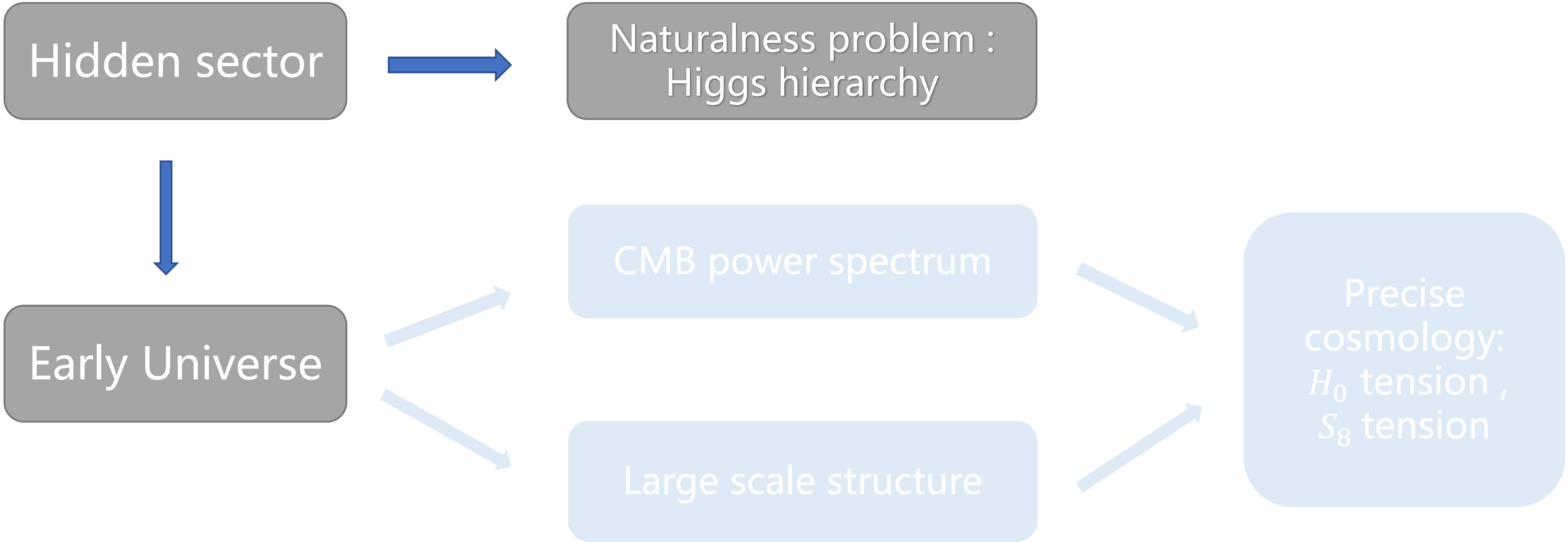

Avoid collider constraints compared to supersymmetry

# Mirror twin higgs

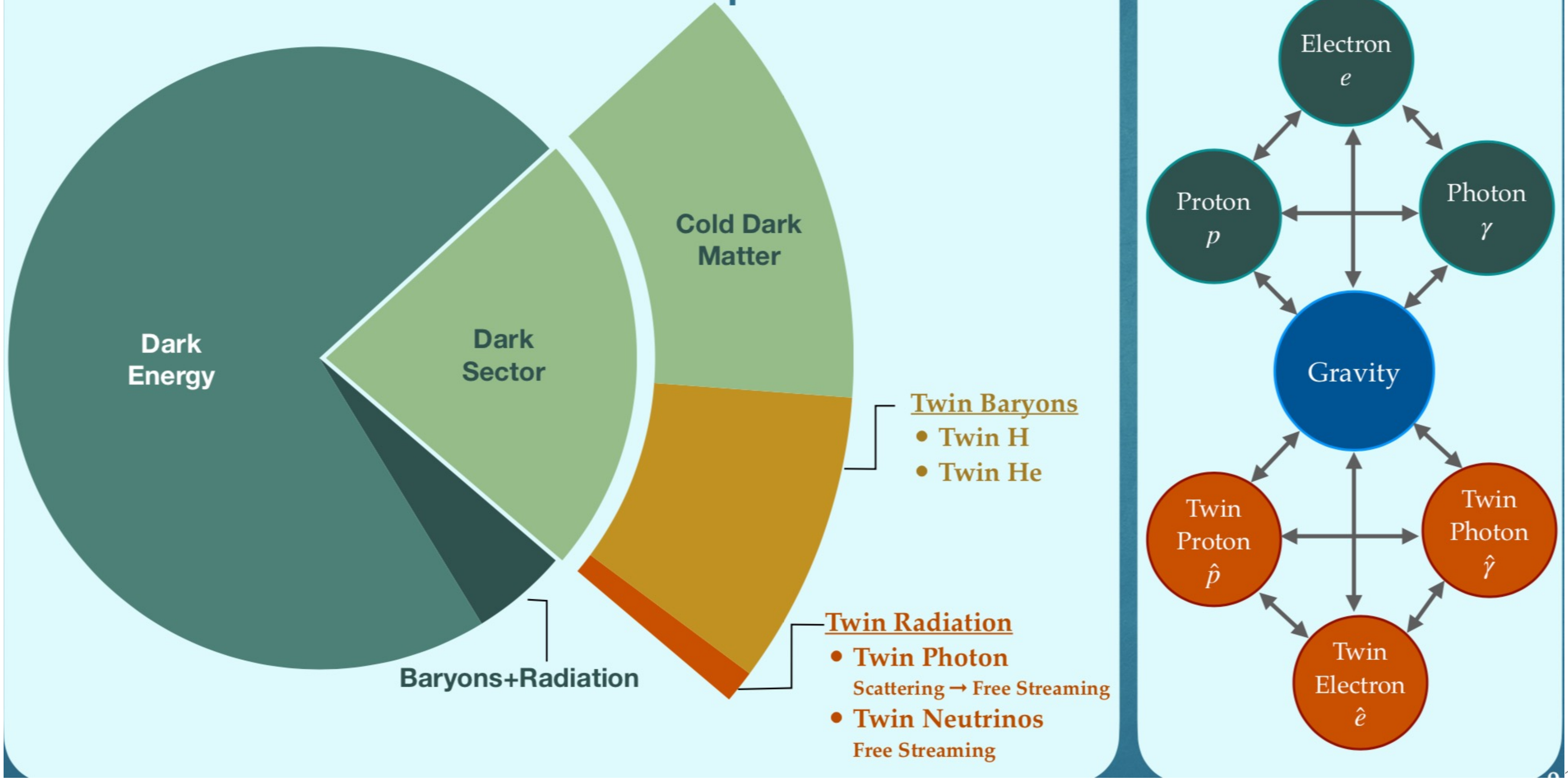
Just like supersymmetry, each particle in standard model has an exact counterpart in mirror sector



# Explore mirror sector with cosmology



# The Universe with MTH particles



# MTH cosmology

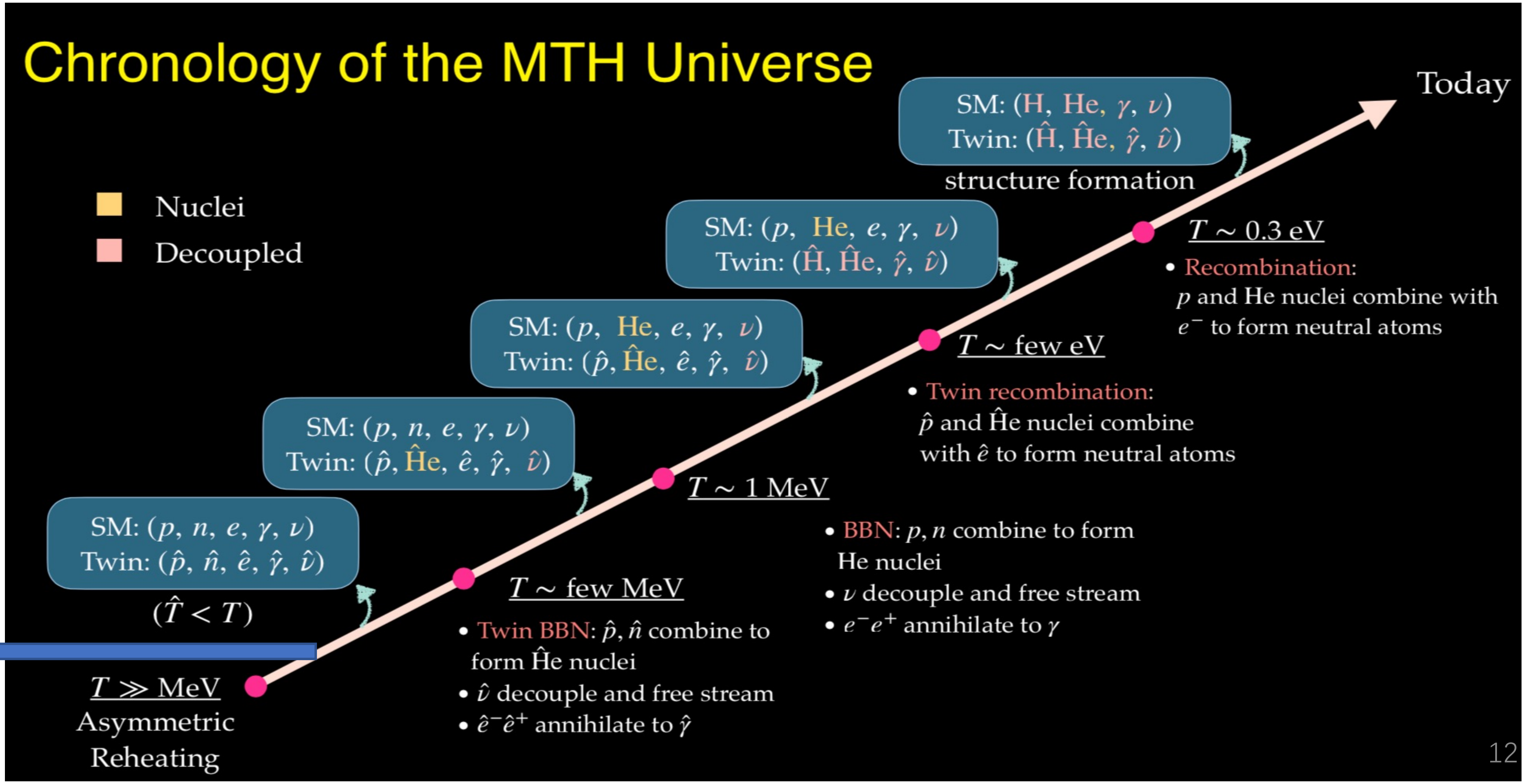
3 extra parameters:

- $\hat{r} = \frac{\Omega_{mb}}{\Omega_{cdm}}$ : Amount of twin baryons compared to the DM density
- $\Delta N_{eff}$ : Twin radiation energy , effective neutrino numbers
- $\hat{v}/v$ : Ratio of the twin and SM electroweak symmetry breaking

$\Delta N_{eff}$ depend on the temperature of twin recombination and $\Delta N_{eff}$ , $\hat{v}/v$ determines the time of the twin recombination.

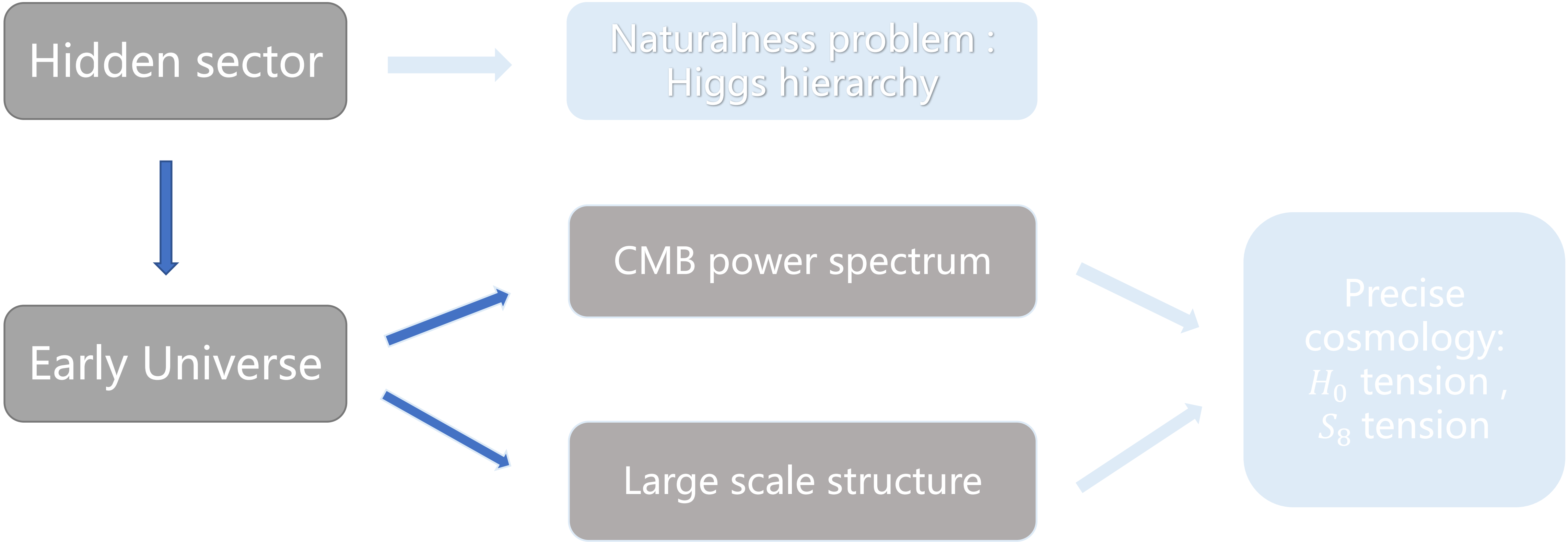
# MTH cosmology

One possible method to explain the different temperature between two sectors : asymmetric post-inflationary reheating .



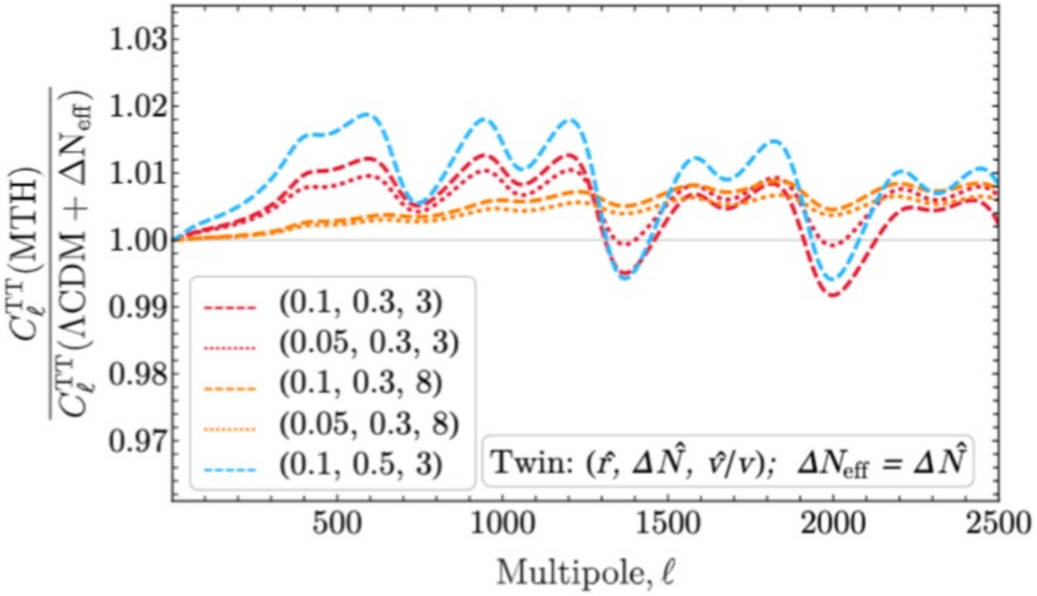

Twin QCD phase transition ~ few 100 MeV

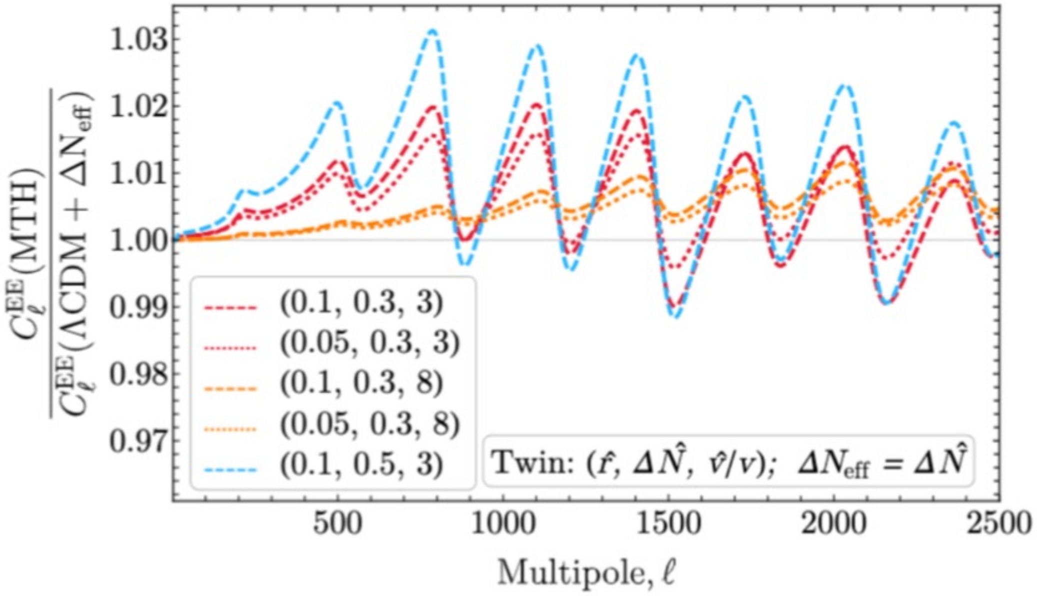
# Cosmology signals



# CMB power spectrum

Twin BAOs suppress the gravity perturbation and generate different phase.

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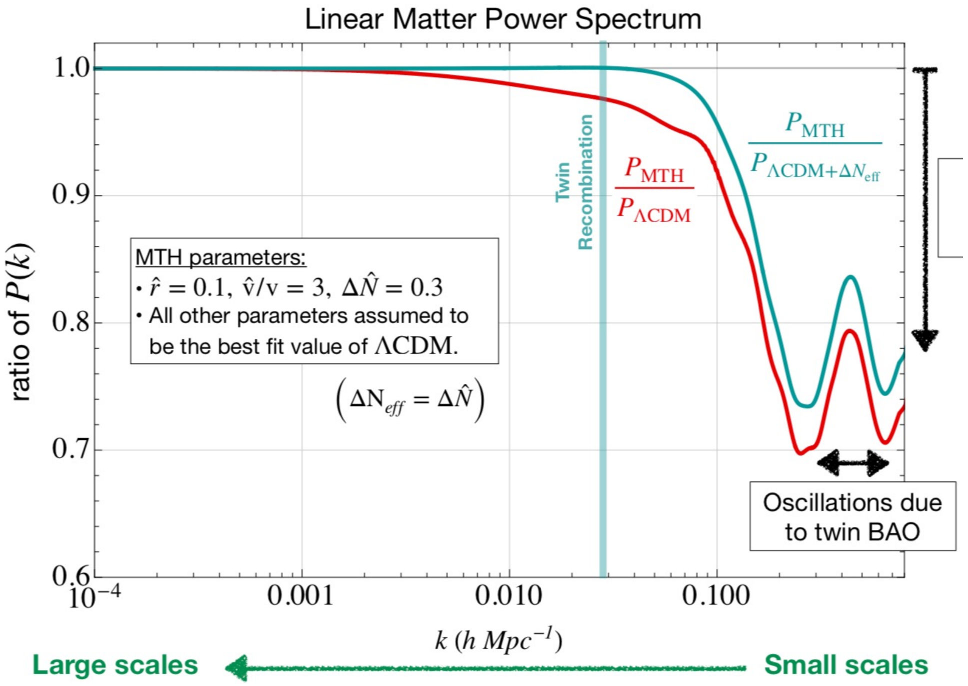
# Large scale structure

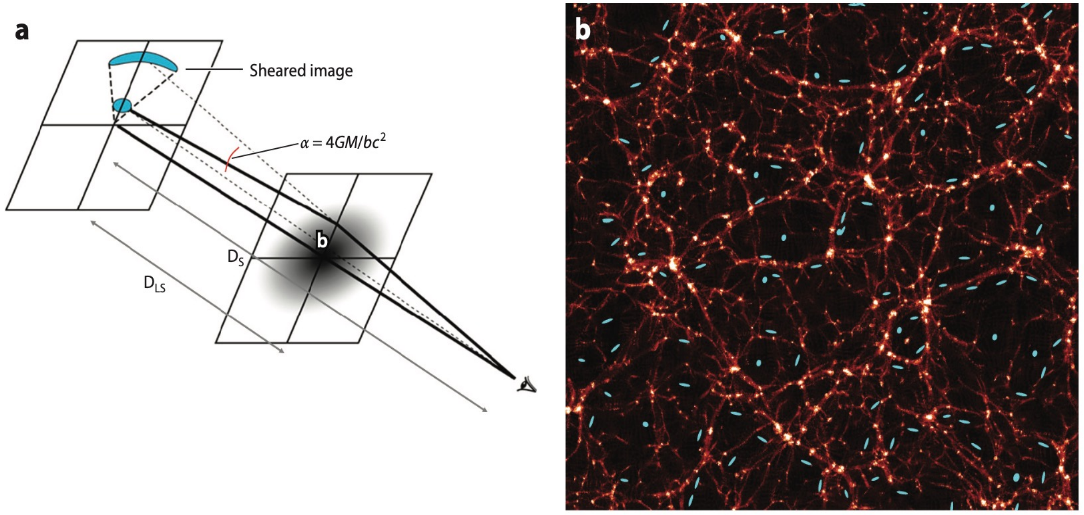
Compared to $\Lambda CDM$: Oscillations and suppression due to twin BAO, additional radiation for delay of $a_{eq}$ and ISW effects.




The diversity between MTH cosmology and $\Lambda CDM$ is mainly at models that enter horizon before twin recombination , i.e. nonlinear scale for the parameter range of the interest. (k > 0.1 h/Mpc)

# How to test this scale?

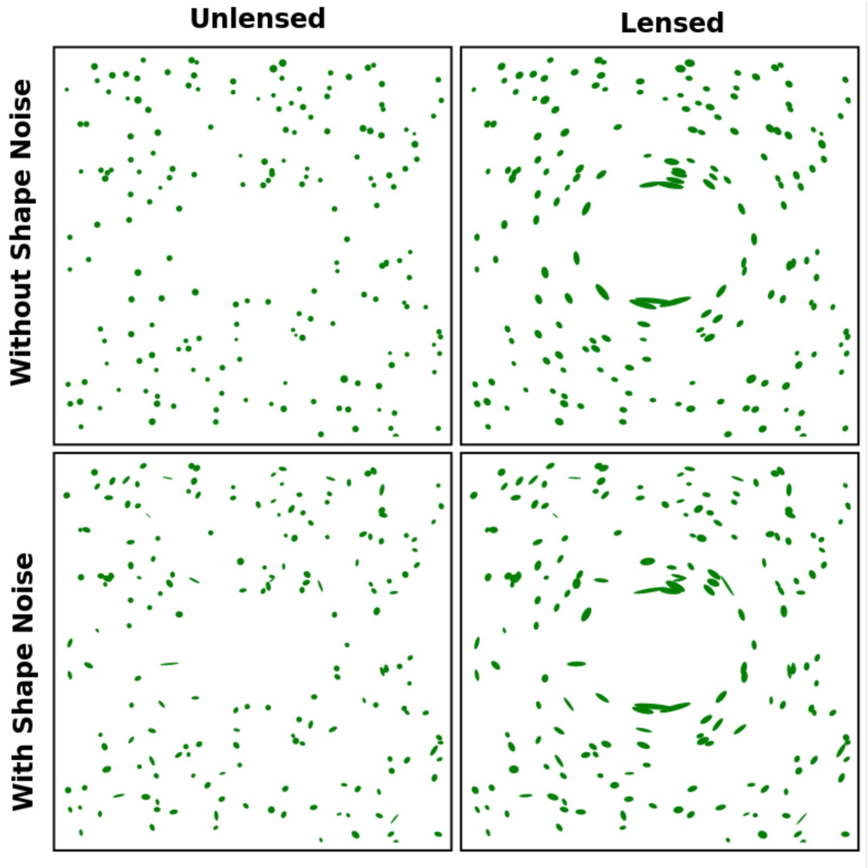
To probe the matter power spectrum P(k) at k > 0.1 h/Mpc (and k < 10 h/Mpc to avoid the baryonic effects): weak lensing survey

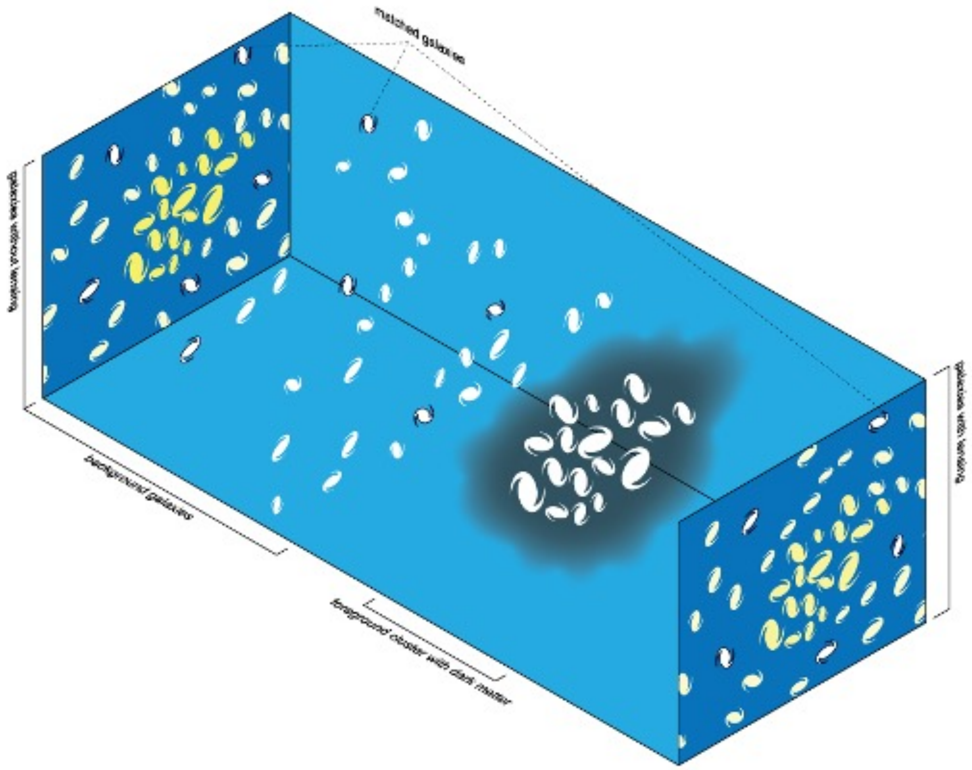



- Correspond to three set of correlation, respectively:
- position-position within foreground lens galaxies;
- position- shape of foreground lens galaxies with background source;
- shape-shape of background source due to LSS.

Cosmic gravitational lensing!

# Weak lensing



# Cosmic shear

Two components for a galaxy : $\gamma = \gamma_1 + i\gamma_2$. $\xi_+ \equiv \langle \gamma\gamma^* \rangle$ $\xi_- \equiv \langle \gamma\gamma \rangle$

$$\xi_\pm^{ij}(\theta) = \langle \hat{\epsilon}_t \hat{\epsilon}_t \pm \hat{\epsilon}_\times \hat{\epsilon}_\times \rangle(\theta)$$

(i) Insensitive to galaxy bias, trace the matter directly;

(ii) Sensitive to detect the growth of structure and redshift evolution, constrain cosmological parameters $S_8$;

(iii) Well describe the geometry of the universe through the lensing kernel.

# Nonlinear correction

Nonlinear gravity effects on the scale k > 1h/Mpc , when perturbation theory fails.

$\Lambda CDM$ : HMcode and Halofit (analytic method based on the simulation)

How about MTH cosmology? If we use the HMcode and Halofit to do the nonlinear correct, how much errors we will get?

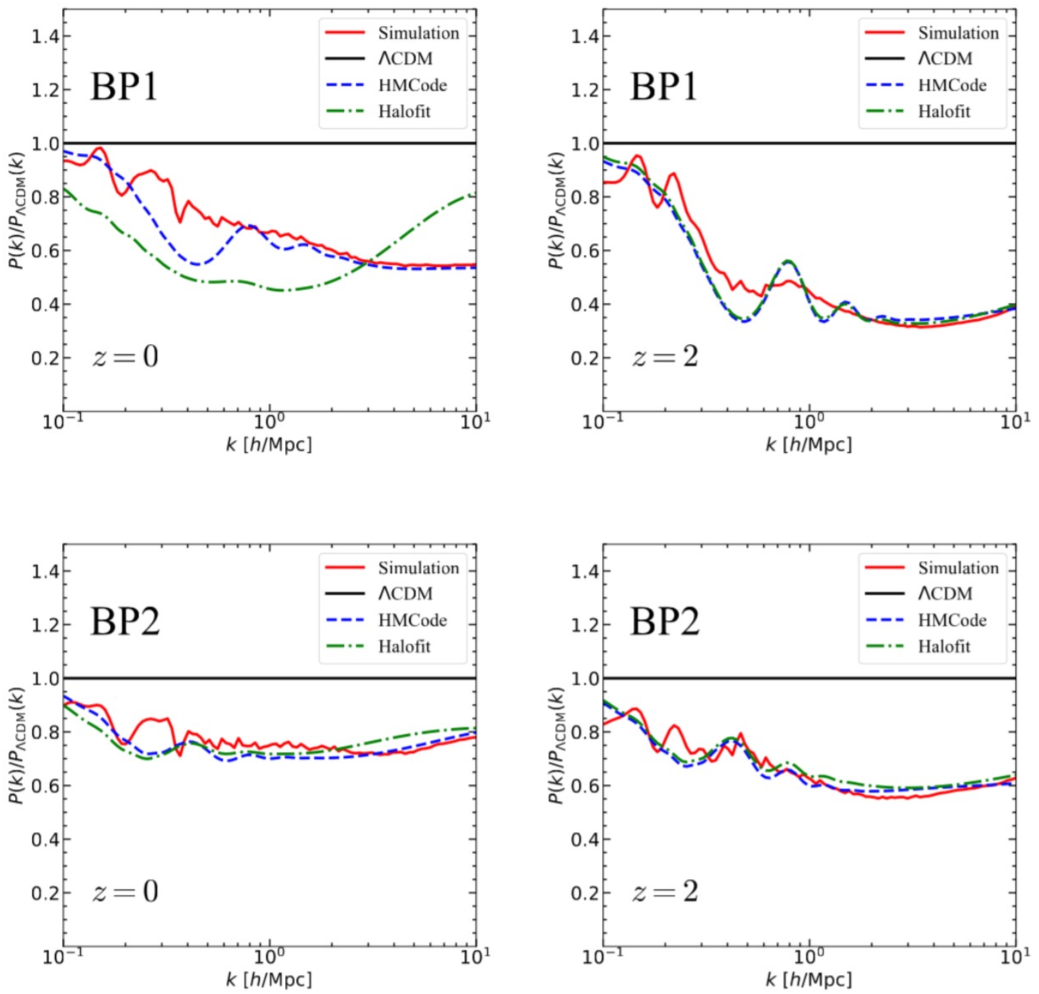
# simulation

Gravity-only simulation with P-Gadget3

$N_0 = 512^3$ particles in a periodic box of volume $(200 Mpc/h)^3$, The mass of a simulation particle is $4.733\times10^9 M_{\odot}/h$

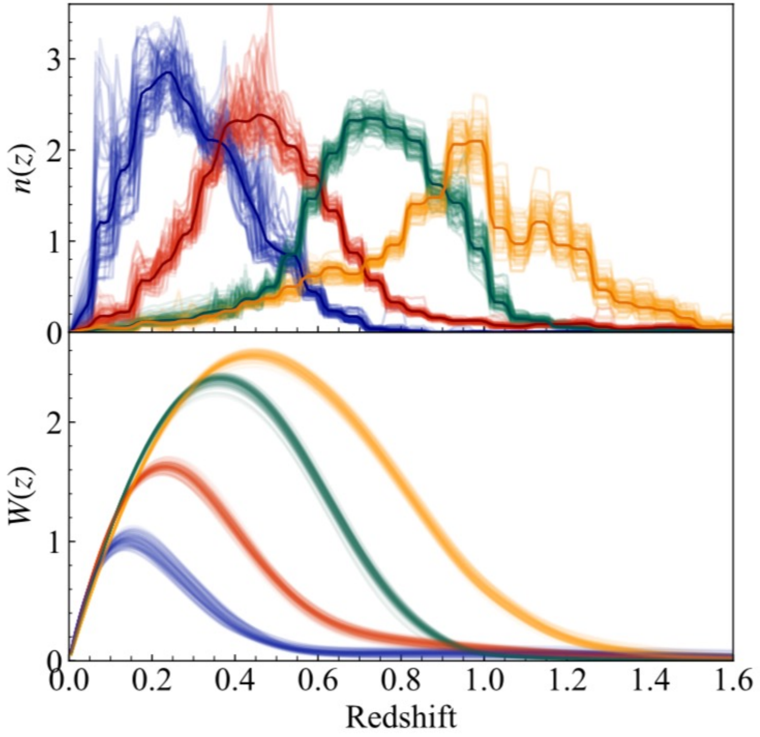
$$\mathbf{BP1}:\ \{\Omega_m = 0.2936,\ \Omega_\Lambda = 0.7064,\ h = 0.7084,\ n_s = 0.9727,\ \sigma_8 = 0.7599\},$$

$$\mathbf{BP2}:\ \{\Omega_m = 0.3254,\ \Omega_\Lambda = 0.6746,\ h = 0.6756,\ n_s = 0.9727,\ \sigma_8 = 0.7648\}.$$

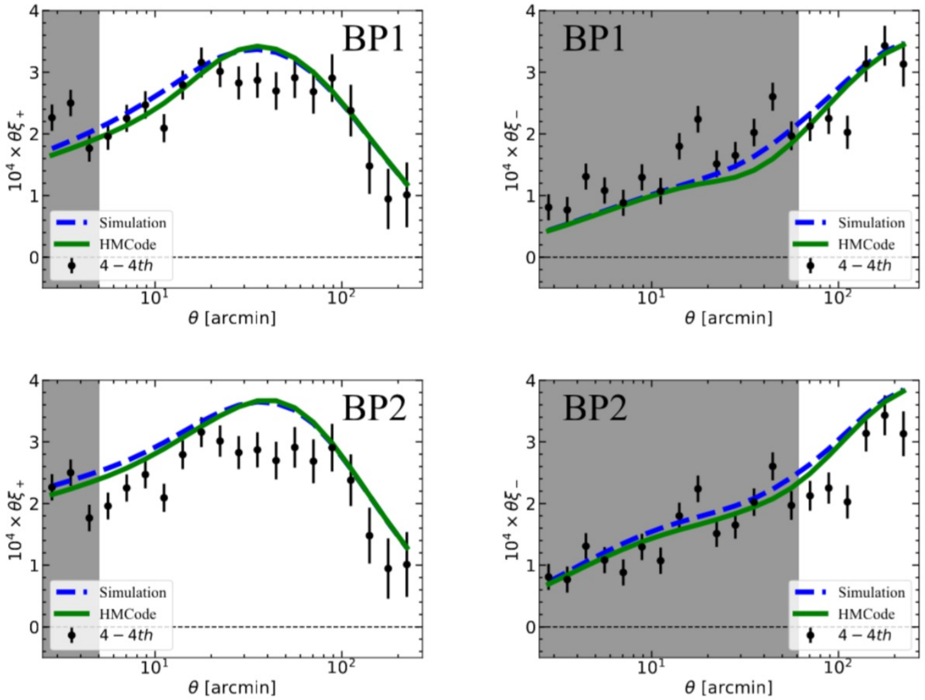


# Cosmic shear

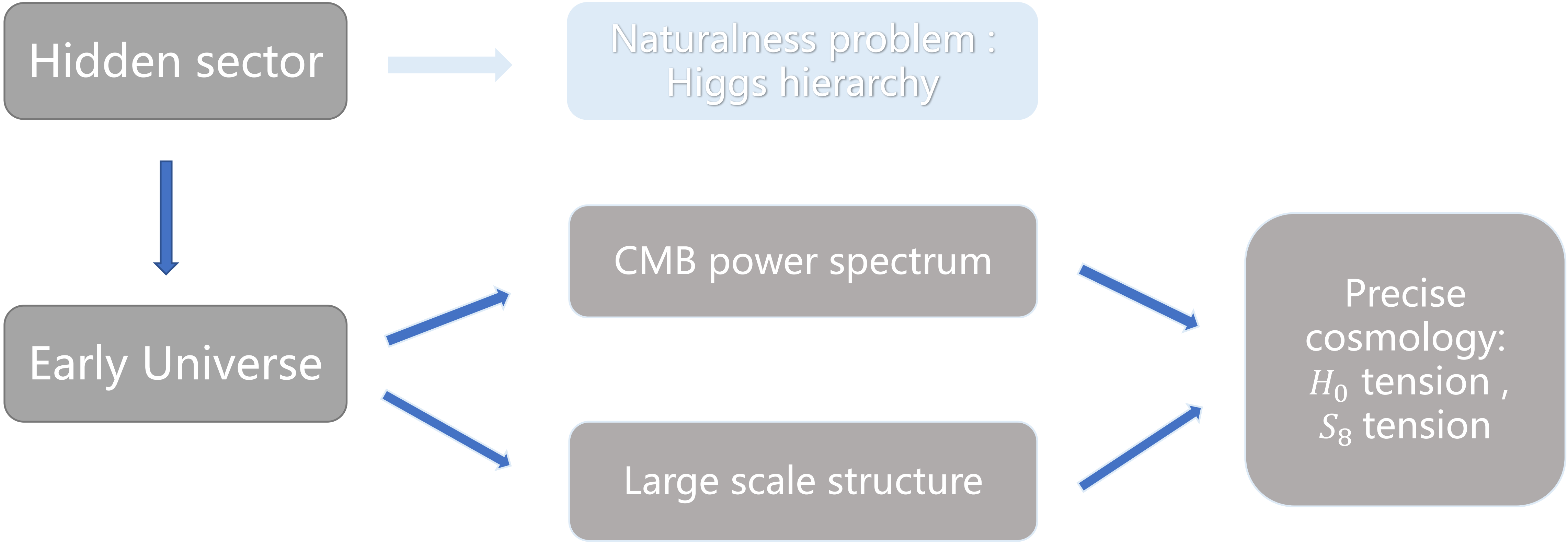
4 redshift bins :




Deviation mainly on small scale, and the $\Delta\chi^2/\mathrm{d.o.f}$ ~0.1
$\hat{r}$ ~ 0.25 →0.21 for BP1 and 0.1 → 0.065 for BP2
We use HMcode for nonlinear correction in our MCMC scan



# Precise Cosmology

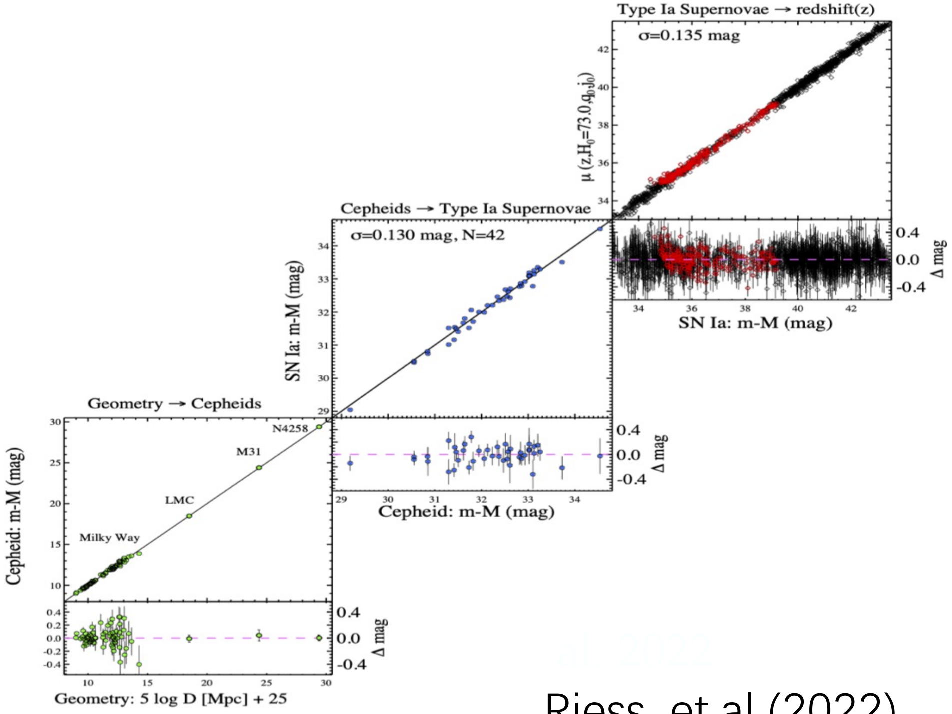


# Precise cosmology beyond $\Lambda CDM$

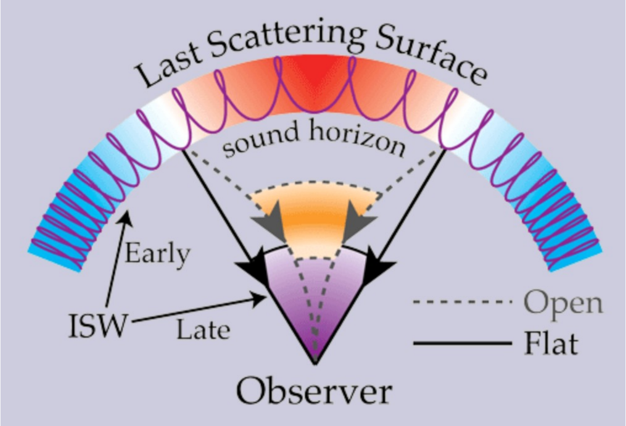
$H_0$ measurement:

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

Indirect : $H_0 = 67.4 \pm 0.5 \text{ km s}^{-1} \text{ Mpc}^{-1}$



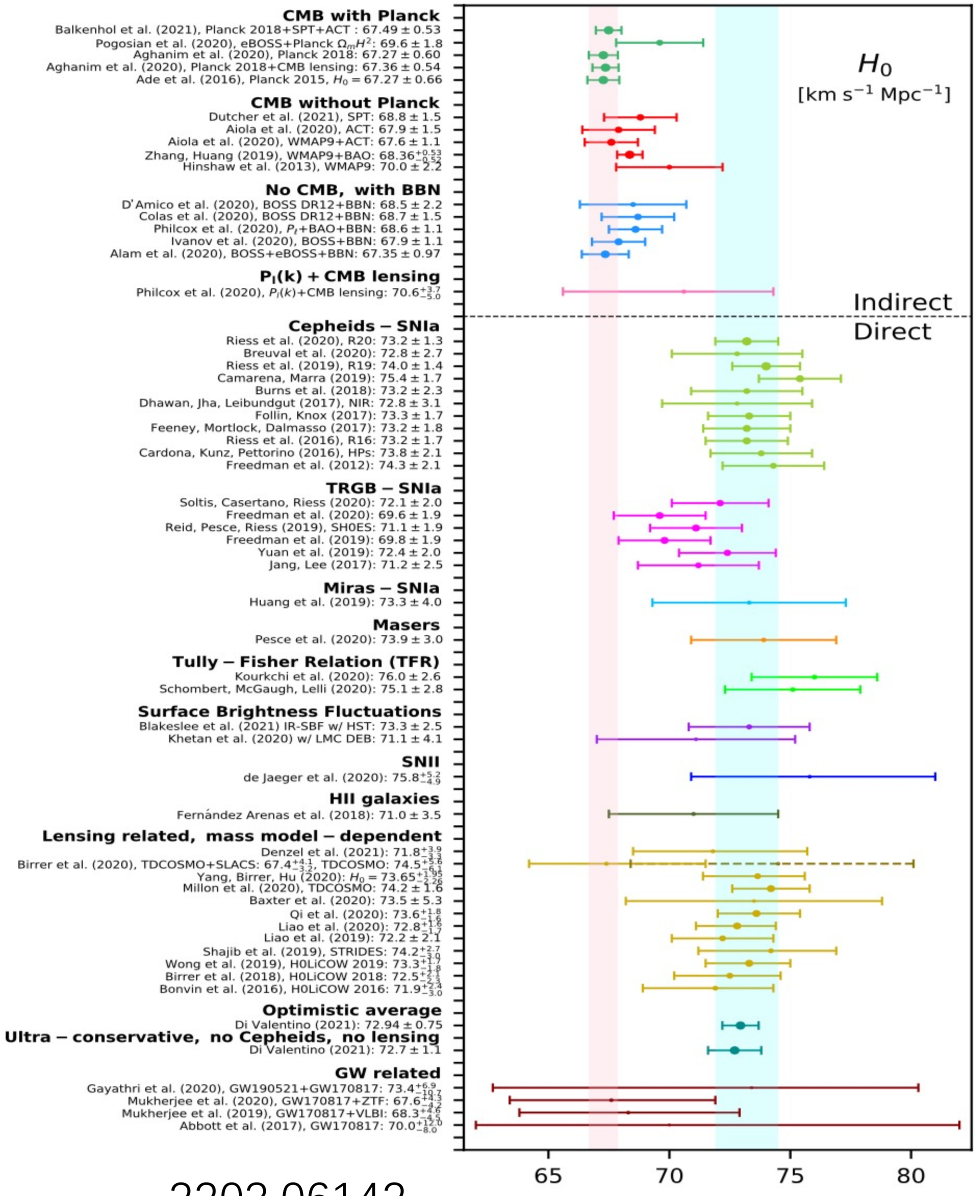

Riess .et.al (2022)




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

# $H_0$ *tension*

$\sim 4.8\,\sigma$ *tension*

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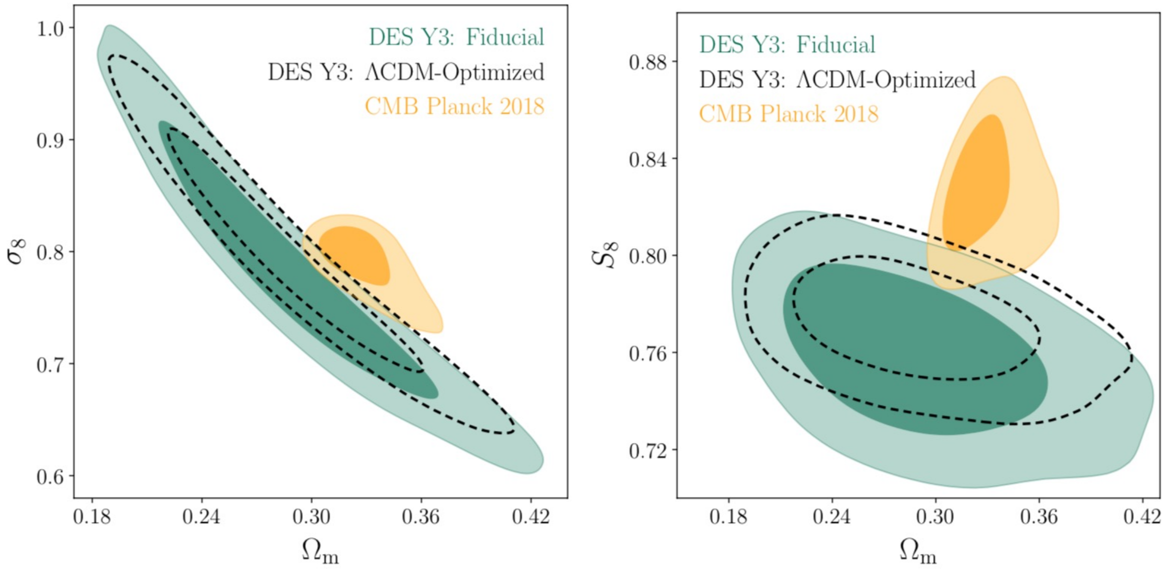
# $S_8$ *tension*

Amplitude of the matter perturbation within 8Mpc size of the structure

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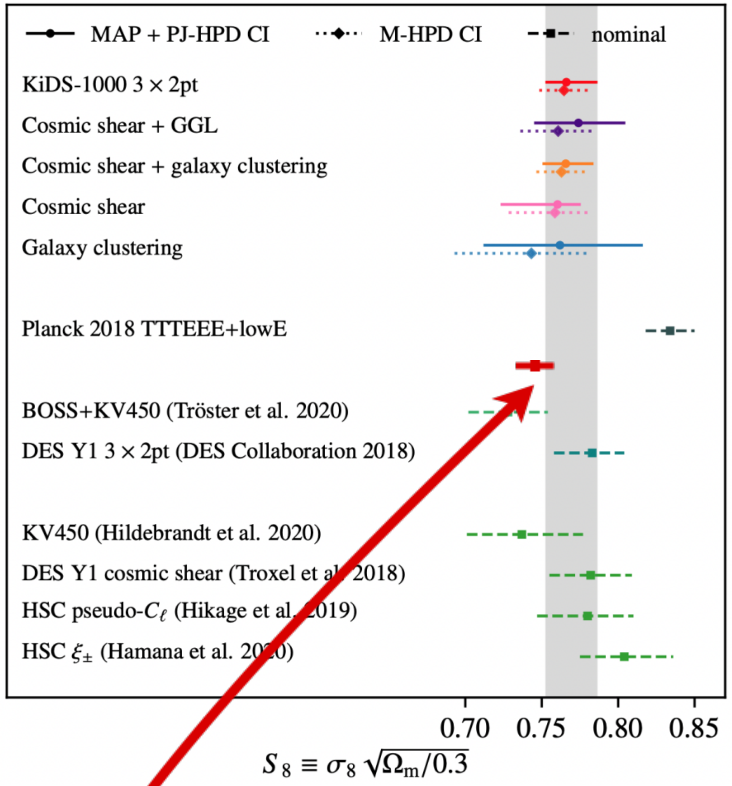



2007.15632

Planck 2013 SZ : $S_8^{SZ} \equiv \sigma_8\,(\Omega_m/0.27)^{0.3} = 0.782 \pm 0.010$

The tension is about 2-3 $\sigma$. The significance may grow if the systematic uncertainty gets improved in the future

# Models that solve the $H_0$ tension usually worse the $S_8$ tension

Additional fluid or free-streaming radiation (2003.28382):

| | $\Lambda$CDM | $N_{\rm eff}$ | $N_{\rm eff}=3.046,\ N_{\rm fld}$ | $N_{\rm tot},\ f_{\rm fs}$ |
|---|---|---|---|---|
| $100\theta_s$ | $1.042^{+0.00029}_{-0.00028}$ | $1.0414^{+0.00043}_{-0.00049}$ | $1.0423^{+0.0003}_{-0.00032}$ | $1.0427^{+0.00074}_{-0.00088}$ |
| $100\Omega_b h^2$ | $2.249^{+0.013}_{-0.015}$ | $2.265^{+0.017}_{-0.016}$ | $2.275^{+0.016}_{-0.018}$ | $2.275^{+0.018}_{-0.017}$ |
| $\Omega_c h^2$ | $0.11861^{+0.00093}_{-0.00092}$ | $0.1229^{+0.0026}_{-0.0026}$ | $0.1248^{+0.0026}_{-0.0029}$ | $0.1244^{+0.0029}_{-0.0029}$ |
| $\ln 10^{10} A_s$ | $3.049^{+0.014}_{-0.015}$ | $3.058^{+0.015}_{-0.016}$ | $3.043^{+0.014}_{-0.016}$ | $3.036^{+0.021}_{-0.019}$ |
| $n_s$ | $0.9681^{+0.0035}_{-0.004}$ | $0.9761^{+0.0061}_{-0.0057}$ | $0.9704^{+0.004}_{-0.0038}$ | $0.9669^{+0.0082}_{-0.0075}$ |
| $\tau$ | $0.0576^{+0.007}_{-0.0078}$ | $0.0575^{+0.007}_{-0.0076}$ | $0.0574^{+0.0066}_{-0.0082}$ | $0.0575^{+0.007}_{-0.0074}$ |
| $N_{\rm tot}$ | 3.046 | $3.3^{+0.15}_{-0.15}$ | $3.38^{+0.13}_{-0.15}$ | $3.35^{+0.16}_{-0.15}$ |
| $f_{\rm fs}$ | 1 | 1 | $0.901^{+0.039}_{-0.036}$ | $0.87^{+0.08}_{-0.06}$ |
| $H_0$ [km/s/Mpc] | $68.55^{+0.46}_{-0.41}$ | $70.0^{+0.93}_{-0.9}$ | $70.64^{+0.93}_{-1.0}$ | $70.5^{+1.0}_{-1.0}$ |
| $r_s^{\rm drag}$ [Mpc] | $147.34^{+0.22}_{-0.23}$ | $144.8^{+1.4}_{-1.5}$ | $143.9^{+1.5}_{-1.3}$ | $144.1^{+1.5}_{-1.6}$ |
| $\sigma_8$ | $0.8216^{+0.0061}_{-0.0062}$ | $0.8335^{+0.0089}_{-0.0093}$ | $0.8299^{+0.0068}_{-0.0078}$ | $0.826^{+0.011}_{-0.01}$ |
| $\chi^2_{\rm tot}$ | 2797.46 | 2795.16 | 2793.65 | 2793.44 |

early dark energy (1811.04083):

| 1.04149 Parameter | $\Lambda$CDM | $n=2$ | $n=3$ | $n=\infty$ |
|---|---|---|---|---|
| $100\ \theta_s$ | $1.04198\ (1.04213) \pm 0.0003$ | $1.04175\ (1.0414)^{+0.00046}_{-0.00064}$ | $1.04138\ (1.0414) \pm 0.0004$ | $1.04159\ (1.04149) \pm 0.00035$ |
| $100\ \omega_b$ | $2.238\ (2.239) \pm 0.014$ | $2.244\ (2.228)^{+0.019}_{-0.022}$ | $2.255\ (0.258) \pm 0.022$ | $2.257\ (2.277) \pm 0.024$ |
| $\omega_{\rm cdm}$ | $0.1179\ (0.1177) \pm 0.0012$ | $0.1248\ (0.1281)^{+0.003}_{-0.0041}$ | $0.1272\ (0.1299)_{\pm}0.0045$ | $0.1248\ (0.1249) \pm 0.0041$ |
| $10^9 A_s$ | $2.176\ (2.14) \pm 0.051$ | $2.185\ (2.230) \pm 0.056$ | $2.176\ (2.177) \pm 0.054$ | $2.151\ (2.177) \pm 0.051$ |
| $n_s$ | $0.9686\ (0.9687) \pm 0.0044$ | $0.9768\ (0.9828)^{+0.0065}_{-0.0072}$ | $0.9812\ (0.9880) \pm 0.0080$ | $0.9764\ (0.9795) \pm 0.0073$ |
| $\tau_{\rm reio}$ | $0.075\ (0.068) \pm 0.013$ | $0.075\ (0.083) \pm 0.013$ | $0.068\ (0.068) \pm 0.013$ | $0.062\ (0.066) \pm 0.014$ |
| $\mathrm{Log}_{10}(a_c)$ | – | $-4.136\ (-3.728)^{+0.57}_{-0.013}$ | $-3.737\ (-3.696)^{+0.110}_{-0.094}$ | $-3.449\ (-3.509)^{+0.047}_{-0.11}$ |
| $f_{\rm EDE}(a_c)$ | – | $0.028\ (0.044)^{+0.011}_{-0.016}$ | $0.050\ (0.058)^{+0.024}_{-0.019}$ | $0.054\ (0.057)^{+0.031}_{-0.027}$ |
| $r_s(z_{\rm rec})$ | $145.05\ (145.1) \pm 0.26$ | $141.4\ (139.8)^{+2}_{-1.5}$ | $140.3\ (138.9)^{+1.9}_{-2.3}$ | $141.6\ (141.3)^{+1.8}_{-2.1}$ |
| $S_8$ | $0.824\ (0.814) \pm 0.012$ | $0.826\ (0.836) \pm 0.014$ | $0.838\ (0.842) \pm 0.015$ | $0.836\ (0.839) \pm 0.015$ |
| $H_0$ | $68.18\ (68.33) \pm 0.54$ | $70.3\ (71.1) \pm 1.2$ | $70.6\ (71.6) \pm 1.3$ | $69.9\ (70) \pm 1.1$ |

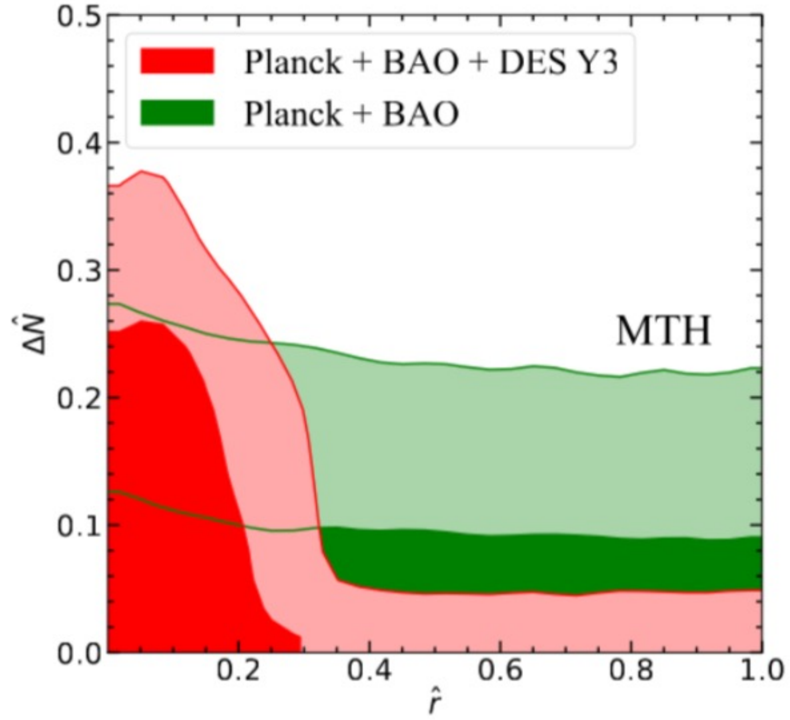
# MTH relax both tension

Dark radiation(twin photon and twin neutrinos) as additional radiation components to relax $H_0$ tension.

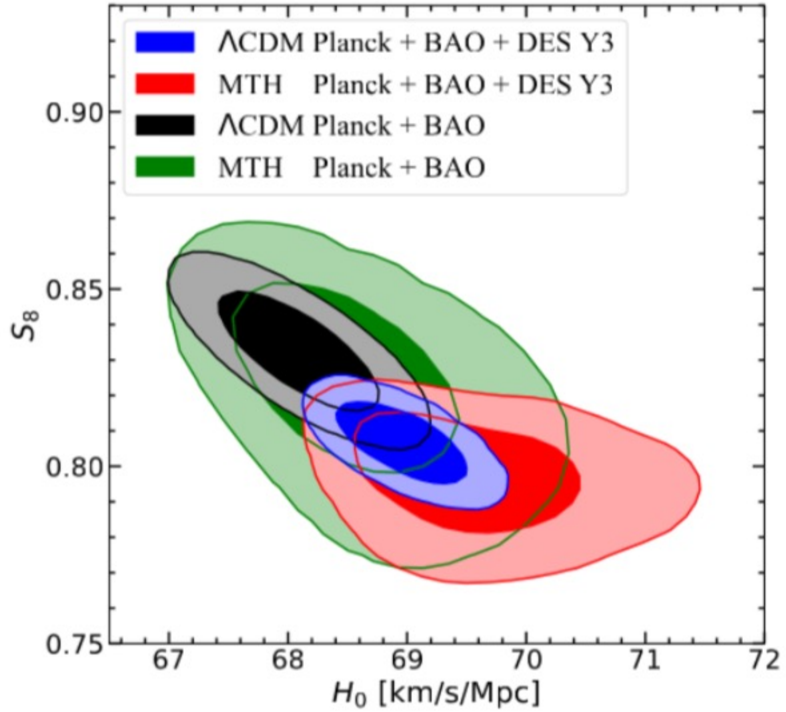
While twin BAOs suppress the mass perturbation at small scale, thus relax the $S_8$ tension.

Cosmology data we used in MCMC scans: Planck , BAO, SH0ES, DES Y3

# Planck+BAO+DES Y3

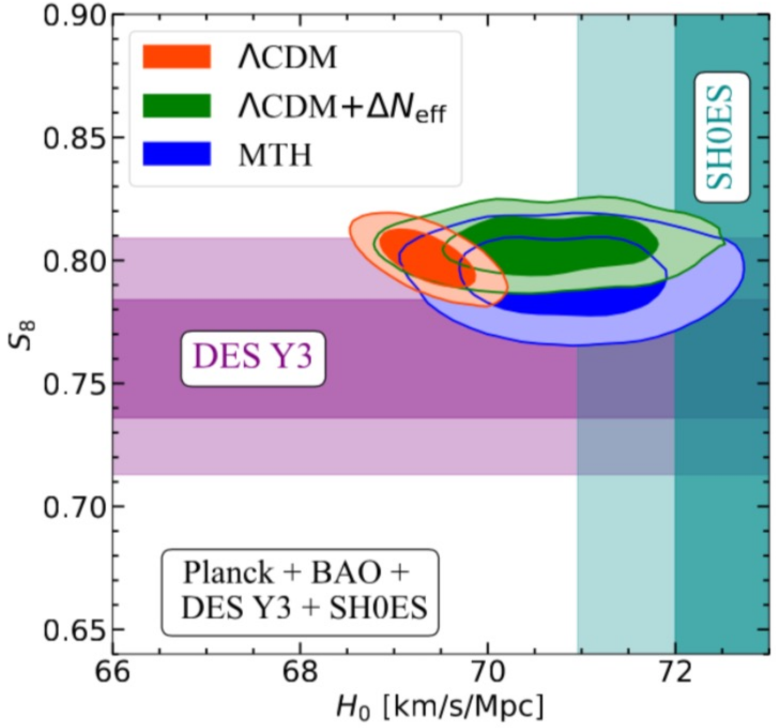



An up limits for fraction of MTH DM




More flexible for MTH cosmology

# Planck+BAO+DES Y3+SH0ES

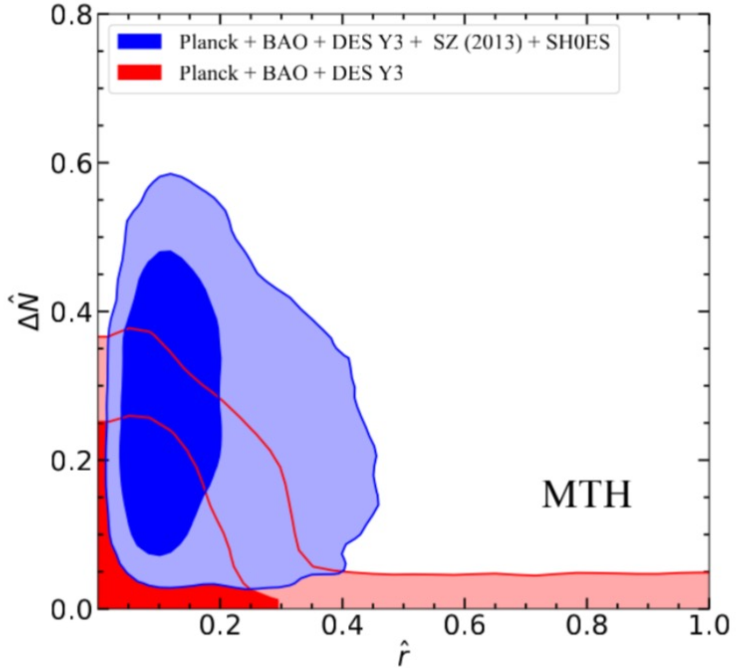


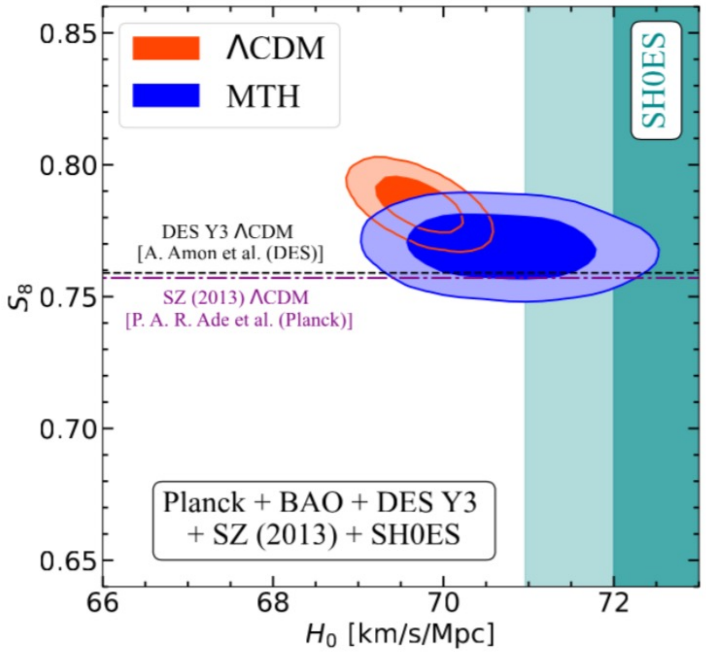

| | $\Lambda$CDM | | $\Lambda$CDM + $\Delta N_{\rm eff}$ | | MTH | |
|---|---|---|---|---|---|---|
| Parameters | best-fit | mean $\pm\sigma$ | best-fit | mean $\pm\sigma$ | best-fit | mean $\pm\sigma$ |
| $100\Omega_b h^2$ | 2.270 | $2.268^{+0.0099}_{-0.0148}$ | 2.275 | $2.282^{+0.0115}_{-0.0175}$ | 2.273 | $2.283^{+0.012}_{-0.017}$ |
| $\Omega_{dm} h^2$ | 0.1166 | $0.1167^{+0.0009}_{-0.0005}$ | 0.1204 | $0.1211^{+0.017}_{-0.0026}$ | 0.1210 | $0.1224^{+0.0021}_{-0.0028}$ |
| $100\theta_s$ | 1.042 | $1.042^{+0.0002}_{-0.0003}$ | 1.042 | $1.042^{+0.00046}_{-0.00032}$ | 1.042 | $1.042^{+0.00042}_{-0.00035}$ |
| $\ln(10^{10}A_s)$ | 3.048 | $3.044^{+0.012}_{-0.016}$ | 3.052 | $3.05^{+0.012}_{-0.016}$ | 3.054 | $3.051^{+0.013}_{-0.016}$ |
| $n_s$ | 0.9735 | $0.9736^{+0.0028}_{-0.0041}$ | 0.9803 | $0.9811^{+0.0038}_{-0.0062}$ | 0.9740 | $0.9795^{+0.0036}_{-0.0054}$ |
| $\tau_{\rm reio}$ | 0.0595 | $0.0572^{+0.0060}_{-0.0082}$ | 0.05784 | $0.0555^{+0.0067}_{-0.0074}$ | 0.05866 | $0.05566^{+0.0068}_{-0.0074}$ |
| $\hat{r}$ | – | – | – | – | 0.1144 | $0.1128^{+0.091}_{-0.076}$ |
| $\hat{v}/v$ | – | – | – | – | 9.62 | $8.98^{+3.76}_{-4.04}$ |
| $\Delta\hat{N}$ | – | – | 0.2071 | $0.2588^{+0.093}_{-0.1545}$ | 0.1979 | $0.3098^{+0.0950}_{-0.1520}$ |
| $\Omega_m$ | 0.2908 | $0.2901^{+0.0039}_{-0.0040}$ | 0.288 | $0.2873^{+0.0041}_{-0.0041}$ | 0.2915 | $0.2895^{+0.0046}_{-0.005}$ |
| $H_0$ | 69.51 | $69.48^{+0.21}_{-0.43}$ | 70.5 | $70.65^{+0.775}_{-0.732}$ | 70.22 | $71.04^{+0.52}_{-0.92}$ |
| $S_8$ | 0.8159 | $0.8145^{+0.0052}_{-0.0055}$ | 0.8086 | $0.8062^{+0.0078}_{-0.0078}$ | 0.8034 | $0.794^{+0.0117}_{-0.0099}$ |
| $-2\ln\mathcal{L}$ | 3046.49 | | 3042.76 | | 3042.21 | |
| Planck + BAO | 2794.87 | | 2794.27 | | 2792.9 | |
| DES Y3 | 240.09 | | 242.52 | | 241.81 | |
| SH0ES | 11.53 | | 5.966 | | 7.355 | |

Compared to $\Lambda CDM + \Delta N_{eff}$,
The fitting results are similar while
MTH is able to get a lower $S_8$.

# Future test (Planck SZ(2013))

If future observation provides a much more precise observation and the uncertainty of $S_8$ is comparable to Planck SZ (2013), MTH model could also give a good fit.

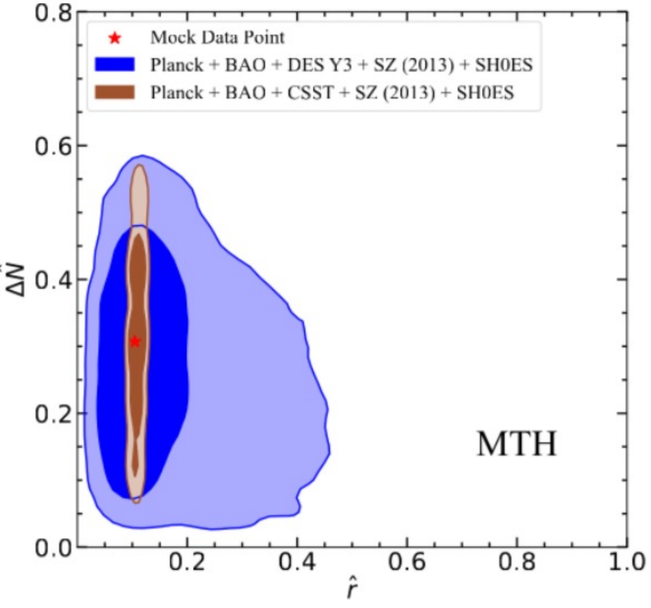


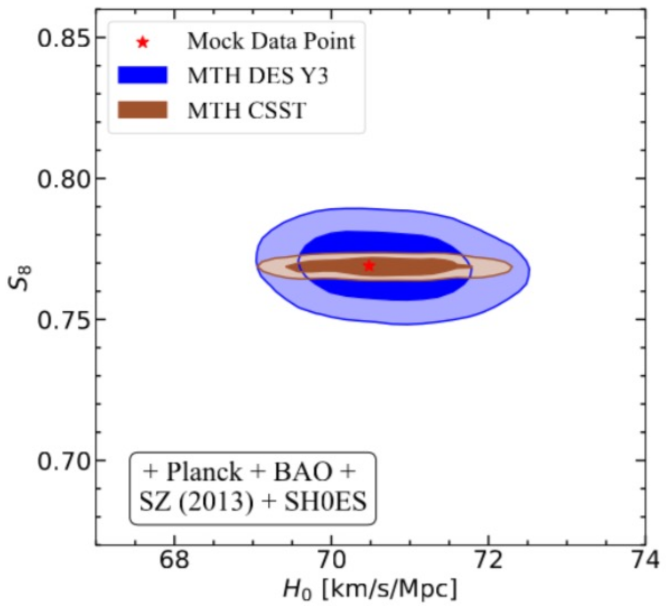



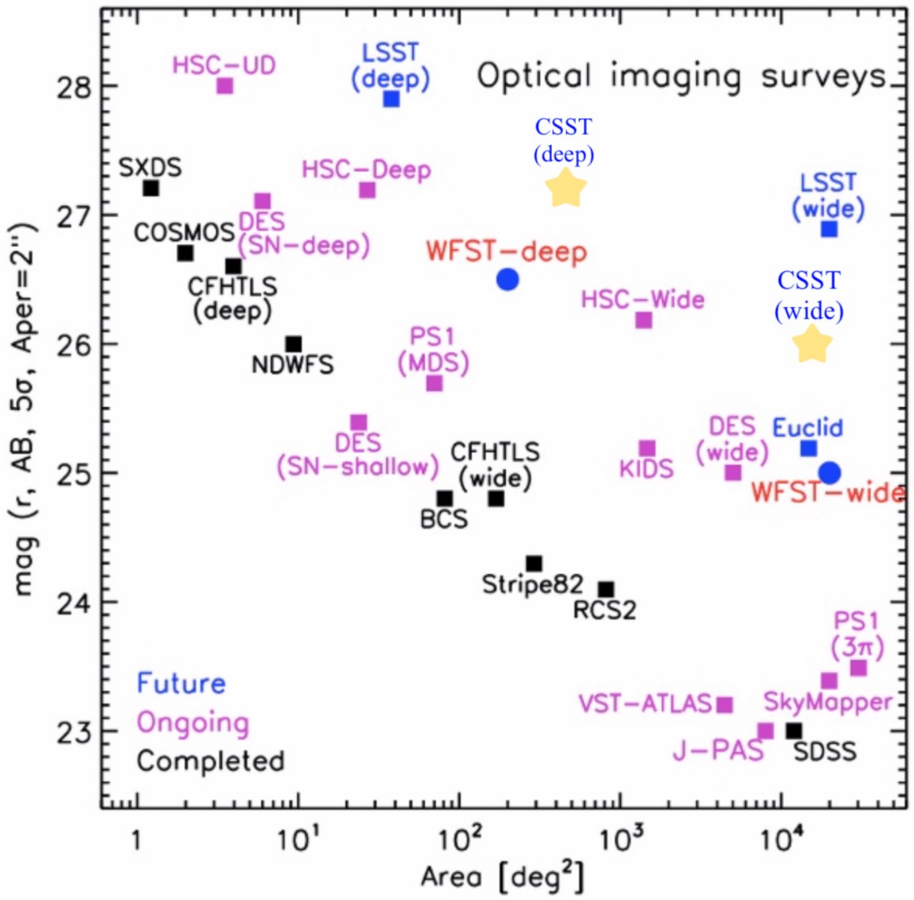

| | ΛCDM | | MTH | |
|---|---|---|---|---|
| Param | best-fit | mean $\pm\sigma$ | best-fit | mean $\pm\sigma$ |
| $100\Omega_b h^2$ | 2.272 | $2.273^{+0.011}_{-0.015}$ | 2.286 | $2.285^{+0.012}_{-0.018}$ |
| $\Omega_{dm} h^2$ | 0.1164 | $0.1159^{+0.00089}_{-0.00052}$ | 0.1205 | $0.1226^{+0.0020}_{-0.0028}$ |
| $100\theta_s$ | 1.042 | $1.042^{+0.00025}_{-0.00031}$ | 1.042 | $1.042^{+0.00040}_{-0.00034}$ |
| $\ln\left(10^{10} A_s\right)$ | 3.03 | $3.026^{+0.011}_{-0.016}$ | 3.034 | $3.046^{+0.013}_{-0.016}$ |
| $n_s$ | 0.9749 | $0.9744^{+0.0029}_{-0.0041}$ | 0.9747 | $0.9772^{+0.0034}_{-0.0051}$ |
| $\tau_{\mathrm{reio}}$ | 0.05286 | $0.05^{+0.0059}_{-0.0082}$ | 0.05058 | $0.05419^{+0.0068}_{-0.0076}$ |
| $\hat{r}$ | – | – | 0.06745 | $0.1537^{+0.087}_{-0.074}$ |
| $\hat{v}/v$ | – | – | 2.725 | $5.968^{+2.329}_{-2.513}$ |
| $\Delta\hat{N}$ | – | – | 0.1676 | $0.3002^{+0.0898}_{-0.1449}$ |
| $\Omega_m$ | 0.2867 | $0.2856^{+0.0040}_{-0.0039}$ | 0.2908 | $0.29^{+0.0051}_{-0.0050}$ |
| $H_0$ | 69.65 | $69.72^{+0.33}_{-0.34}$ | 70.23 | $70.71^{+0.70}_{-0.72}$ |
| $S_8$ | 0.7896 | $0.7847^{+0.0065}_{-0.0065}$ | 0.7631 | $0.769^{+0.0082}_{-0.0082}$ |
| $-2\ln\mathcal{L}$ | 3063.72 | | 3048.68 | |
| Planck + BAO | 2798.51 | | 2801.012 | |
| DES Y3 | 238.2 | | 239.3 | |
| SZ (2013) | 16.39 | | 1.068 | |
| SHOES | 10.625 | | 7.3 | |

# Future test (CSST)

CSST is much more powerful compared to DES.



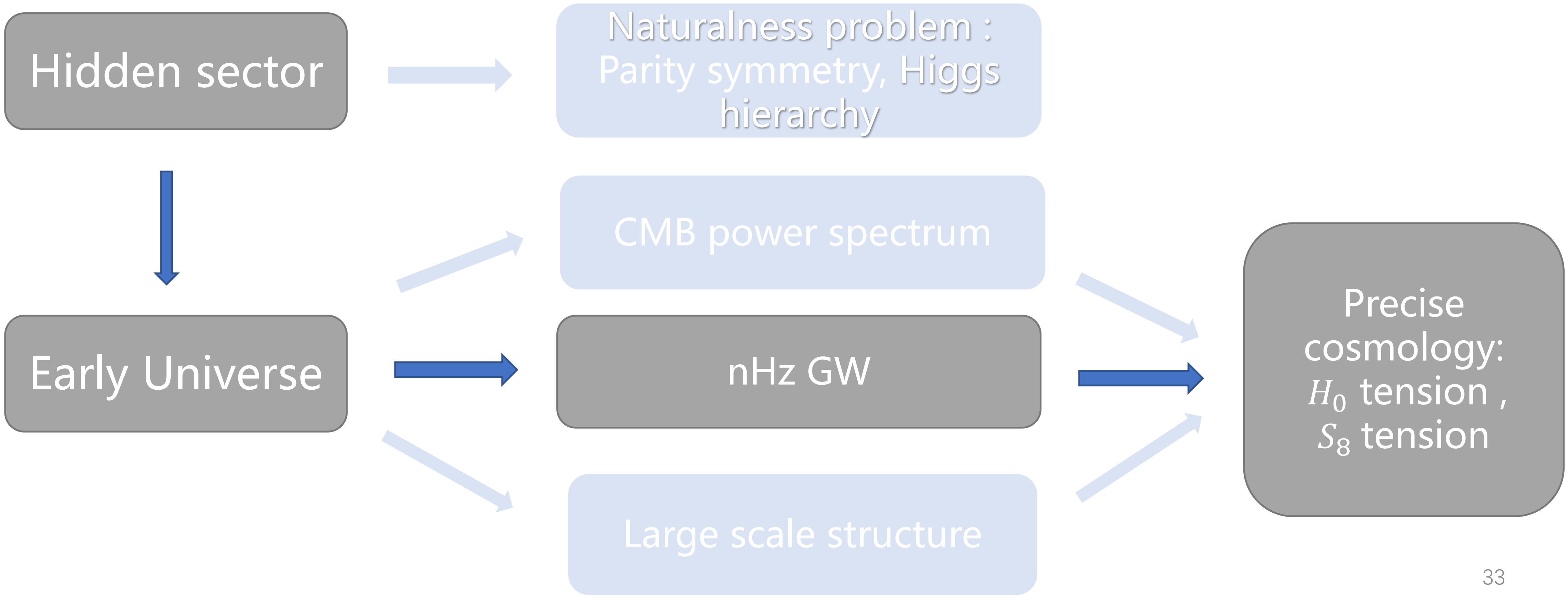



# Ongoing project

- True N-body Simulations: choose ~200 parameter points to run N-body simulations and interpolate the nonlinear results for what we need. (use machine learning method for the dimension of inputs)

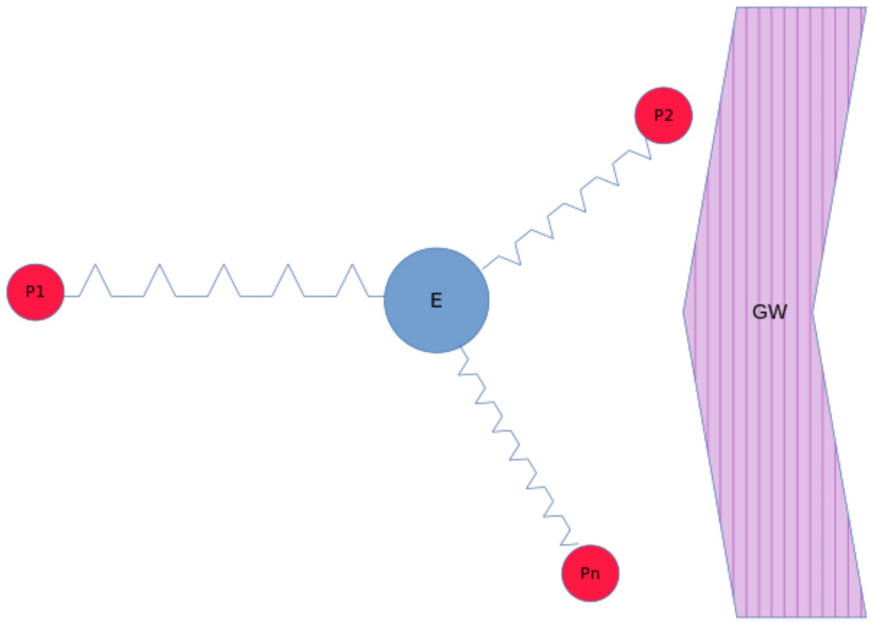
- Github montepython likelihood for the cosmic shear calculation (with true nonlinear correction) is in preparing.

# nHz gravitational wave



# Pulsar Timing Array

- The effect of a passing long-wavelength GW would be to perturb the galactic spacetime and cause a small change in the observed time of arrival of the pulses.




Five active pulsar timing array projects:

Parkes Pulsar Timing Array (PPTA), European Pulsar Timing Array (EPTA),

North American Nanohertz Observatory for Gravitational Waves (NANOGrav),

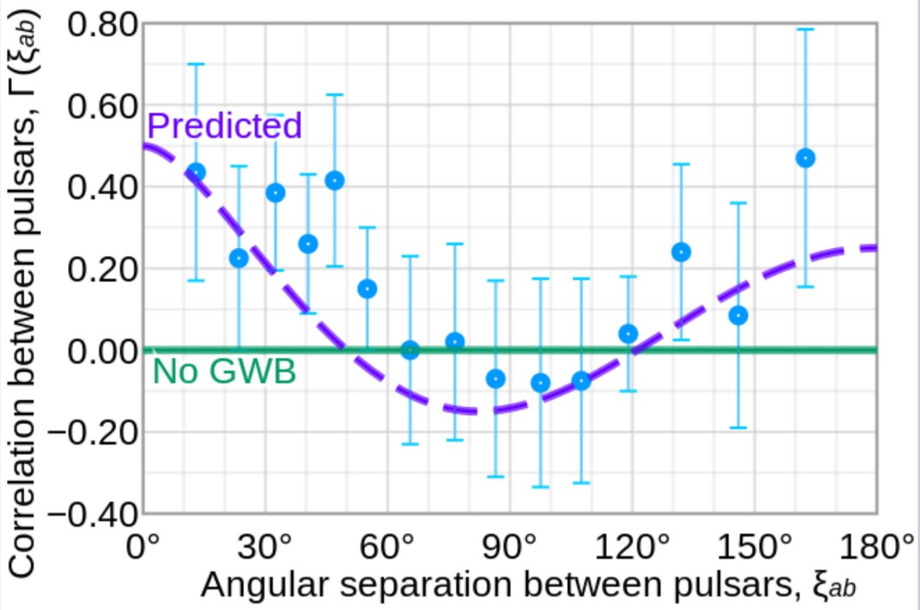
Chinese Pulsar Timing Array (CPTA), Indian Pulsar Timing Array (InPTA)

# Hellings-Downs correlation

- Hellings-Downs correlation: a quadrupolar spatial correlation between arrival times of pulses emitted by different millisecond pulsar pairings that depends only on the pairing's angular separation in the sky as viewed from Earth (actually the solar system barycenter).

- Distinguish the signals from noises.

- 3~4$\sigma$ **HD correlation confirmed by all projects**




NANOGrav(2023)

# nHz GW

- Origins:

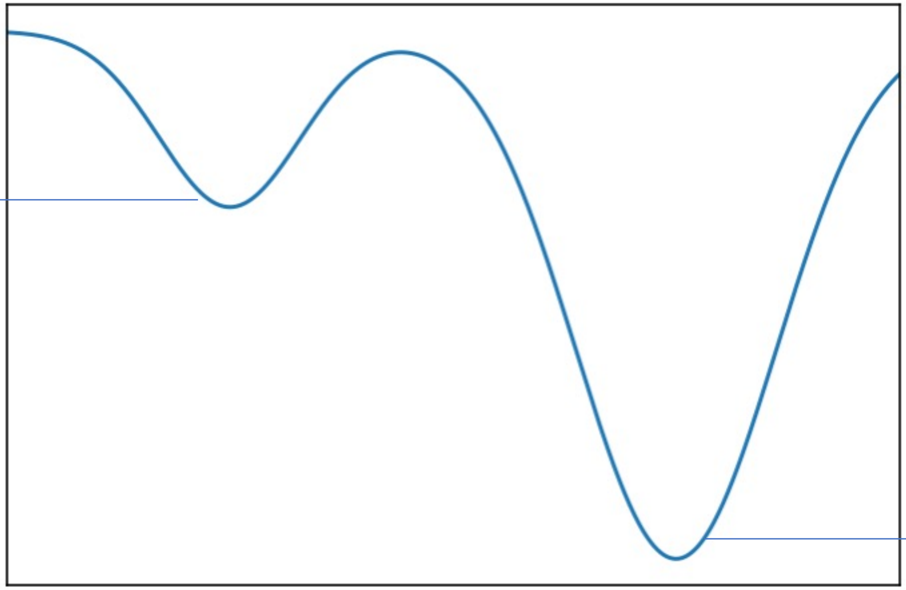
1. Supermassive black hole binaries (SMBHB)
2. **Phase transition**
3. cosmic strings, domain walls
4. curvature-induced GWs

# Phase transition

- If the cosmological phase transition is strongly first order and lasts sufficiently long during T~100 MeV, it generates a background of gravitational waves which can be detected via pulsar timing experiments.

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

False vacuum



True vacuum

# Phase transition bubble

- Quantum effects cause false-vacuum state decay to the true-vacuum state. This decay proceeds via the quantum nucleation and expansion of bubbles of the true-vacuum phase

- The energy difference between the true and false vacuum phases creates an effective outward pressure on the bubble wall, causing it to expand with constant acceleration.

the bubble wall : $\mathbf{x}_{\text{wall}}^2 - t^2 = R_0^2,$ stress-energy tensor: $T_{\mu\nu}(\mathbf{x}, t) = \partial_\mu \varphi \partial_\nu \varphi - g_{\mu\nu} \mathcal{L}.$

$$T_{ij}(\hat{\mathbf{k}}, \omega) = \frac{1}{2\pi} \int_0^\infty dt\, e^{i\omega t} \int d^3x \partial_i \varphi \partial_j \varphi e^{-i\omega \hat{\mathbf{k}} \cdot \mathbf{x}}$$

the Fourier transform of the spatial components of the scalar-field stress-energy tensor during colliding: GW

# Phase transition GW

- linearized gravity approximation :

$$\frac{dE}{d\omega d\Omega} = G\omega^2 \left| T_{zz}(\hat{\mathbf{k}},\omega)\sin^2\xi + T_{xx}(\hat{\mathbf{k}},\omega)\cos^2\xi - T_{yy}(\hat{\mathbf{k}},\omega) - 2T_{xz}(\hat{\mathbf{k}},\omega)\sin\xi\cos\xi \right|^2 .$$

- Numerical Methods : the bubble nucleation rate $\beta$ , the ratio of the vacuum and relativistic energy density at the time of the phase transition $\alpha_*$, the velocity of the bubble walls $v_w$.

$$h^2\Omega_{\rm GW}(f) = 7.69\times 10^{-5}\times g_{s*}^{-\frac{4}{3}} g_{\rho *}\times \left(\frac{\kappa_{\phi(sw)}\alpha_*}{1+\alpha_*}\right)^2 \times \begin{cases} \frac{0.48v_w^3}{1+5.3v_w^2+5v_w^4}\frac{H_*^2}{\beta^2} S_b\left(\frac{f}{f_{p,b}}\right) & \text{for bubble collision,} \\ 0.513 v_w \frac{H_*}{\beta} S_{sw}\left(\frac{f}{f_{p,sw}}\right)\Gamma(\tau_{sw}) & \text{for sound wave,} \end{cases}$$

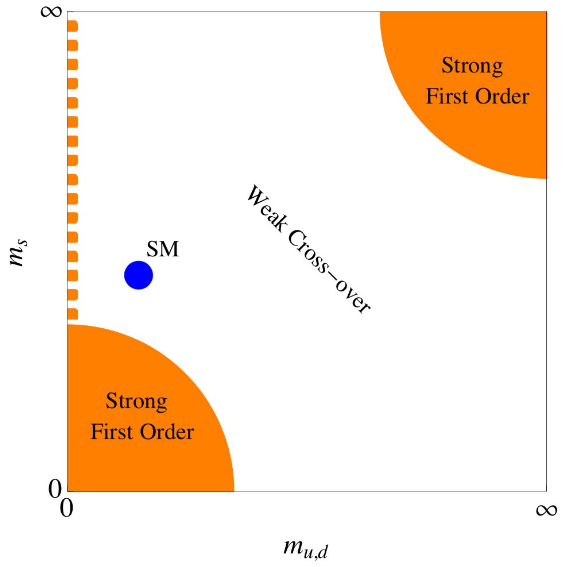
- In principle, these parameters can be calculated for a given model. While for the strongly coupled models considered here they can only be estimated using lattice simulations.

# Phase transition GW

- Gravitational waves will propagate undisturbed in the expanding universe, therefore their frequency $f$ will decrease as $a^{-1}$. Phase transition GW would be nHz if $T \sim 100$ MeV.

- QCD phase transition is at about $T \sim 100$ MeV($\Lambda_{QCD}$), while the lattice simulation tells us it is cross-over rather than first order.

- However this is not a generic result for QCD and similar theories, but more a consequence of the precise values of $m_u \approx m_d$ and $m_s$ in the SM.

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# Dark QCD phase transition in MTH

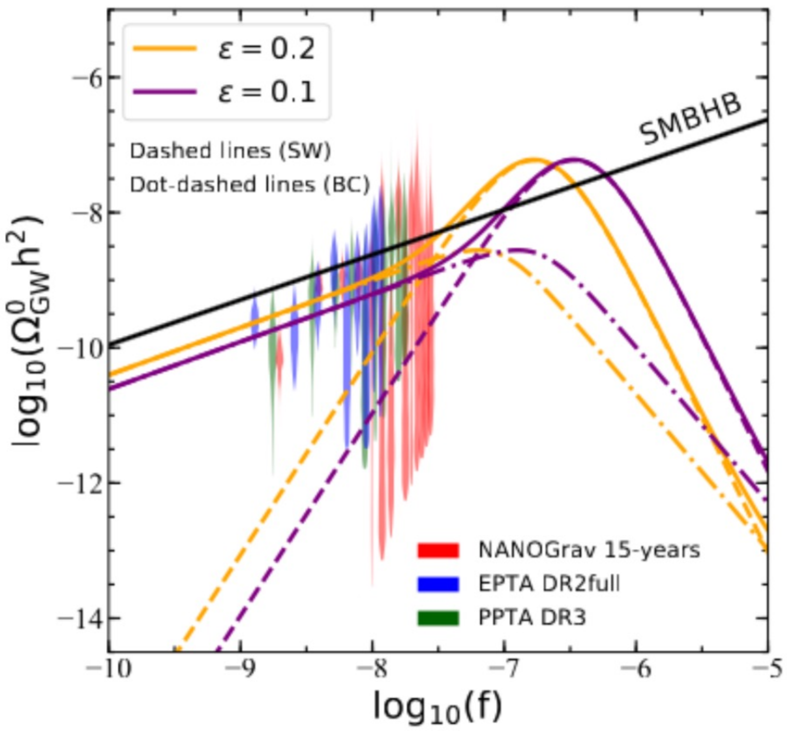
The phase transition is first order if either $N_f = 0$ or $3 \leq N_f < 4N_d$ , where $N_f$ is the total number of nearly massless fermions and $N_d$ is for $SU(N_d)$ gauge group.

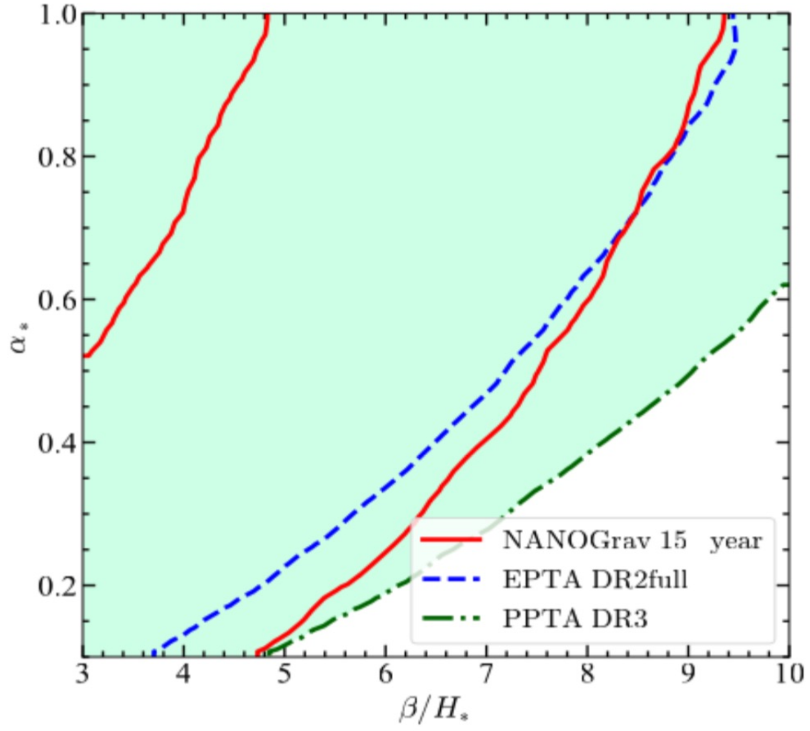
Case (i) : the minimal setup assuming only the presence of twin top and bottom quarks that are necessary for addressing the hierarchy problem.

Case (ii) :an extended scenario assuming two additional nearly massless flavours.

Parameters we used: $\beta/H_*$, $\epsilon, \frac{\hat{v}}{v}, \alpha_*$ where $\epsilon = T_{twin}/T_{SM}$

# Dark QCD phase transition in MTH



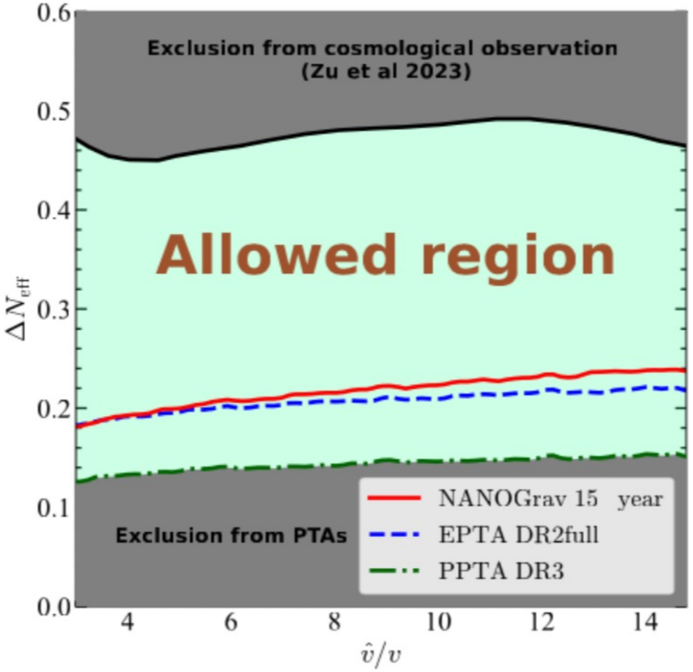
# Dark QCD phase transition in MTH

- For a given $\epsilon = T_{twin}/T_{SM}$ , we can calculate the $\Delta N_{eff}$ at twin recombination since :

$$\Delta N_{\rm eff} = \frac{7.4}{4.4}\left(\frac{\hat{T}_{\rm rec}}{T_{\rm rec}}\right)^4$$

- Although the true twin recombination need a further discussion at our two cases since the mirror symmetry is broken, the dark matter-dark radiation interaction still exists and the main results would not be changed.

Combine our previous results:



# Summary

MTH model is motivated by the naturalness problem while leads to a rich dark sector.

Dark radiation and self-interacting dark matter, Additional radiation components $\Delta N_{eff}$ and Dark BAOs.

The combined data provide an up limit for the fraction of MTH DM : $\hat{r} < 0.4$, unless the temperature of twin photons is low enough.

MTH model could explain the nHz GW.

MTH model could alleviate both the $H_0$ and $S_8$ tensions.

**Cosmology is a powerful tool for exploring particle physics**.