From Cosmic Tensions to Fundamental Physics: A New Phase Transition in the Early Universe

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Cosmo-26
Leiden
24 August 2026

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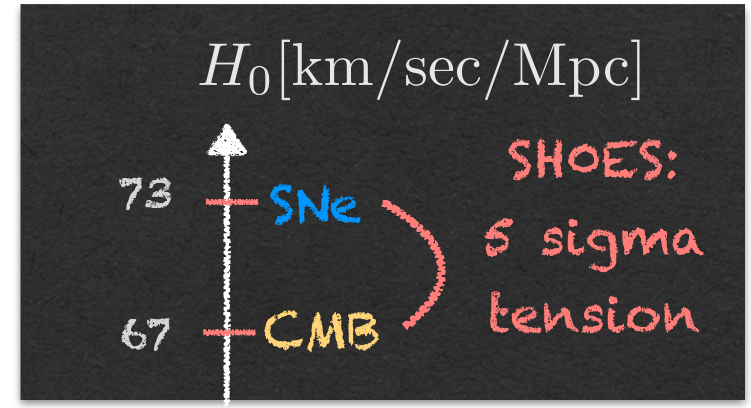
Vetenskapsrådet
Swedish Research Council

New physics, why?

- **Concurrence** of observational puzzles and more precise data should compel us to go beyond LCDM.
- **Hubble tension:** discrepancy between CMB (early Universe) and Type Ia supernovae as standard candles (late universe). A lot of important on-going work to solidify/clarify tension!



- **DESI puzzle:**
  - DESI spectroscopic survey maps the large-scale structure of the Universe; two puzzling aspects:

aspect A: " evolving DE"

2.8-4.2 sigma evidence

DESI constrains $H(z \lesssim 2)$

$$H^2 \simeq \frac{8\pi G}{3}\left[\rho_{\rm DE}(t) + \rho_m(t)\right]$$

$\rho_m(t) \propto a(t)^{-3}$ $\longrightarrow$ $\dot{\rho}_{\rm DE}(t) \neq 0$

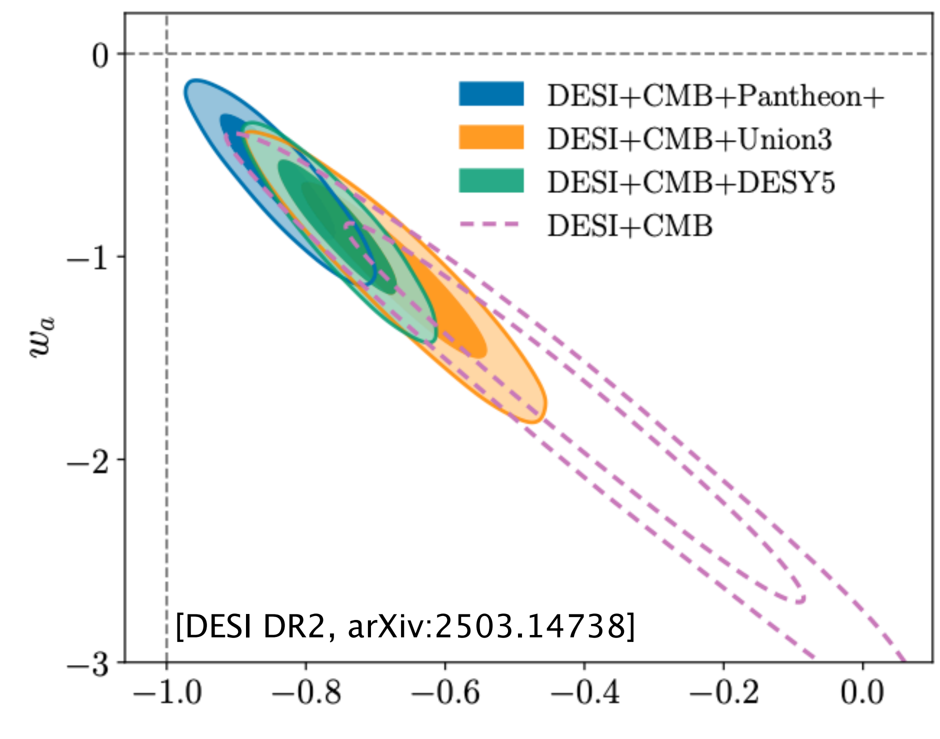
however:

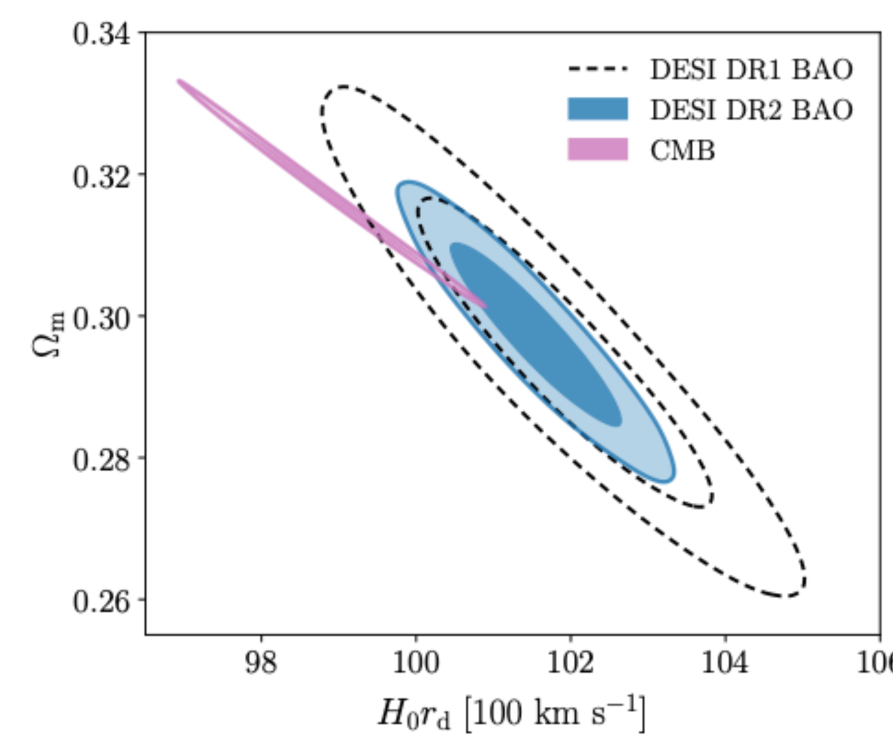
$$(\dot{\rho}_{\rm DE}/\rho_{\rm DE})|_{t<t_c} > 0$$

$\longrightarrow$ phantom regime

aspect B: (mild) CMB/BAO tension $\longrightarrow$ 2.3 sigma

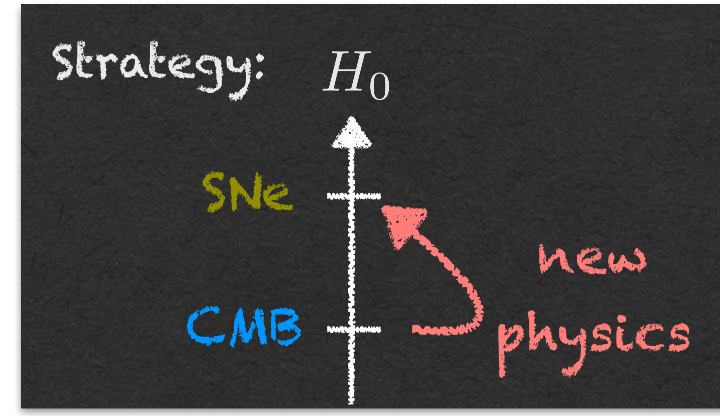
- \+ milder tensions and anomalies.
- **Opportunity** to learn about the dark sector — what are the fundamental principles governing it?



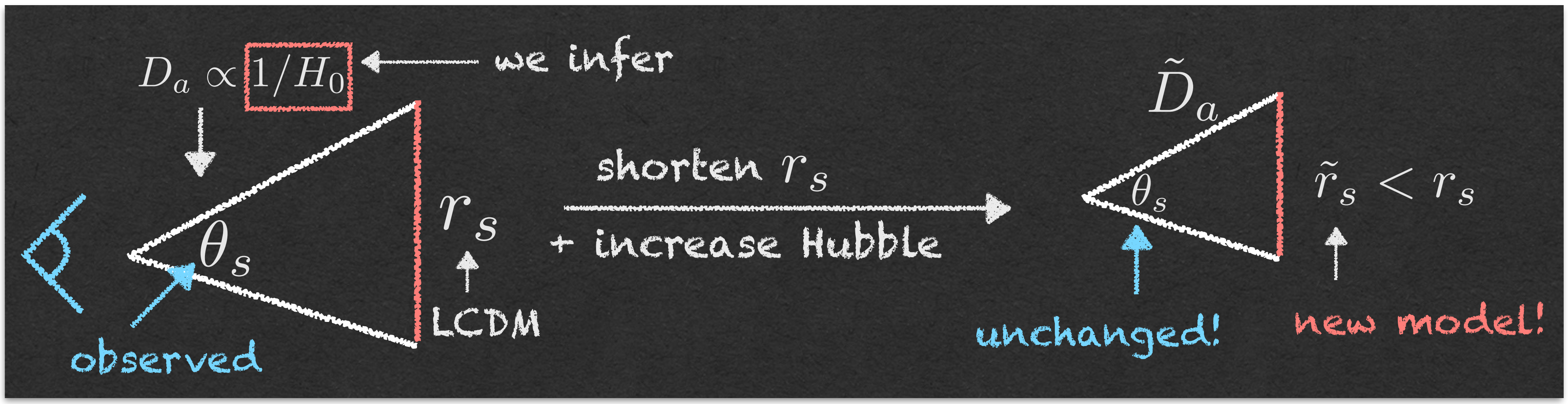


[DESI DR2, arXiv:2503.14738]

New physics, how?



- **First:** Use Hubble tension as guide to new physics.
- **Then:** Test new physics against other tensions because simultaneity of puzzles asks for unified solution.
- Important observable: primordial sound horizon (standard ruler)



Resolving the tension requires lowering the sound horizon by 5–10 %.

$$r_s = \int_{\mathrm{BB}}^{\mathrm{CMB}} \mathrm{d}\eta \, c_s(\eta) = \int_{z_{\mathrm{CMB}}}^{\infty} \mathrm{d}z \, \frac{c_s(z)}{H(z)}$$

⟶ increases $H(z)$ prior to recombination

$$H^2 = \frac{8\pi G}{3} \left[\rho_{\Lambda\mathrm{CDM}} + \boxed{\rho_{\mathrm{DR}}}\right]$$

⟵ new 10–15% component

- **Idea:** Dark radiation increases total energy before equality (and thus before recombination).
- **Challenge:** Highly constrained as expansion history is modified during the CMB epoch (1eV—10eV)
- **Alternative** energy injection models: early phase of dark energy (e.g. AxiEDE, cold NEDE).

dark radiation:

$$\Delta N_{\mathrm{eff}} = \rho_{\mathrm{DR}}/\rho_{1,\nu}$$

" additional neutrinos"

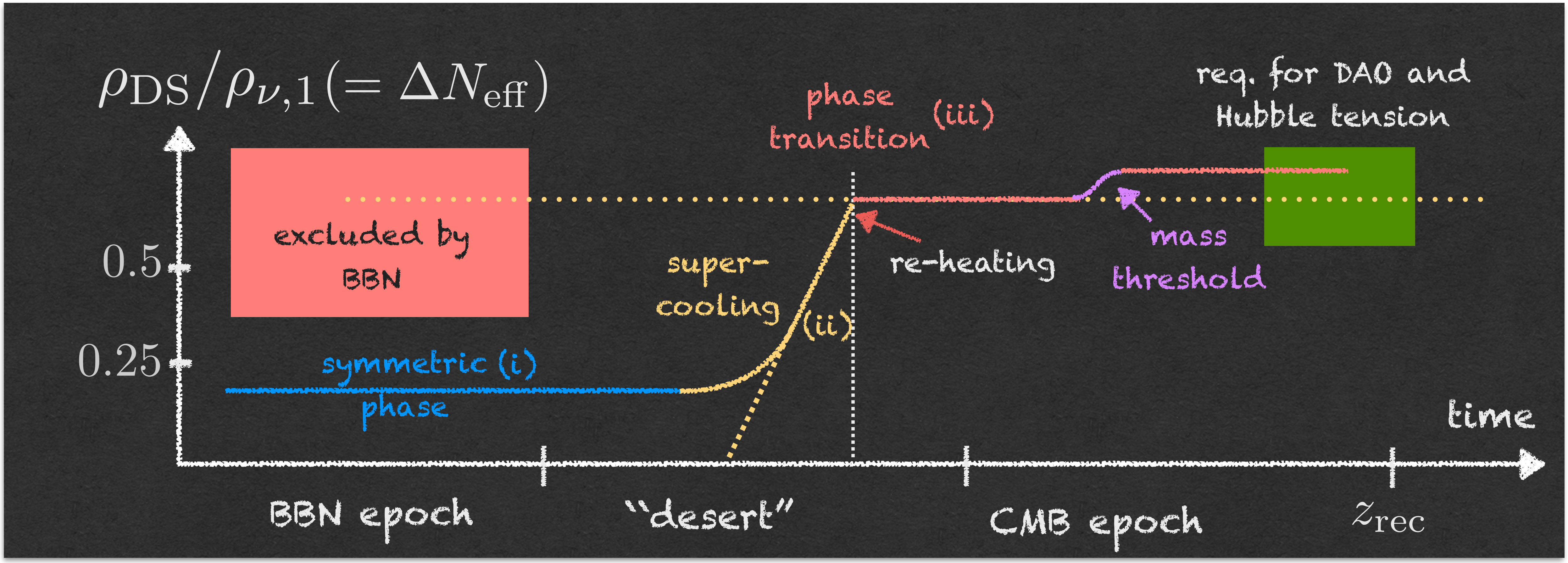
here: massless gauge bosons of dark SU(N), implying gauge interactions ⟶ $\lambda_{\mathrm{mfp}} \ll$ [size of the universe]

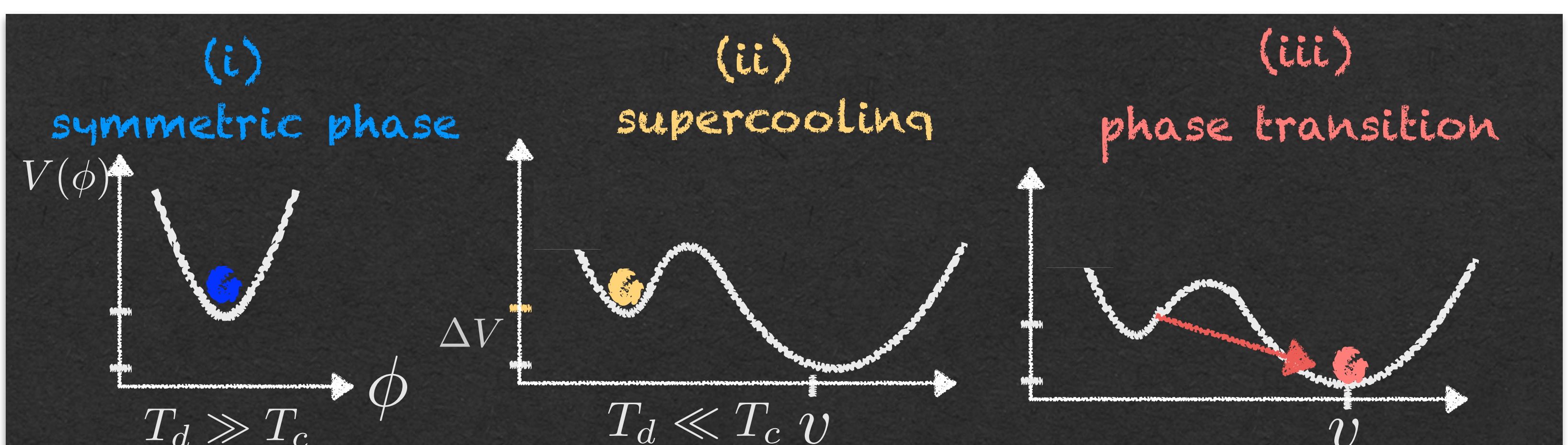
(i) self-interacting DR (SIDR) acts as perturbed fluid (not free-streaming!)

(ii) no phase shift in CMB

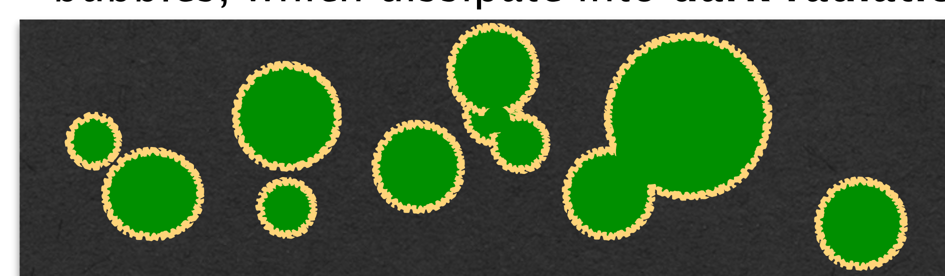
Dark radiation from supercooling

[arXiv: 2404.07256]





- **Supercooled** phase transition with quick re-heating of dark sector.
- Latent heat converted into expanding bubbles, which dissipate into **dark radiation.**



- **Microscopic model / Hot New Early Dark Energy**

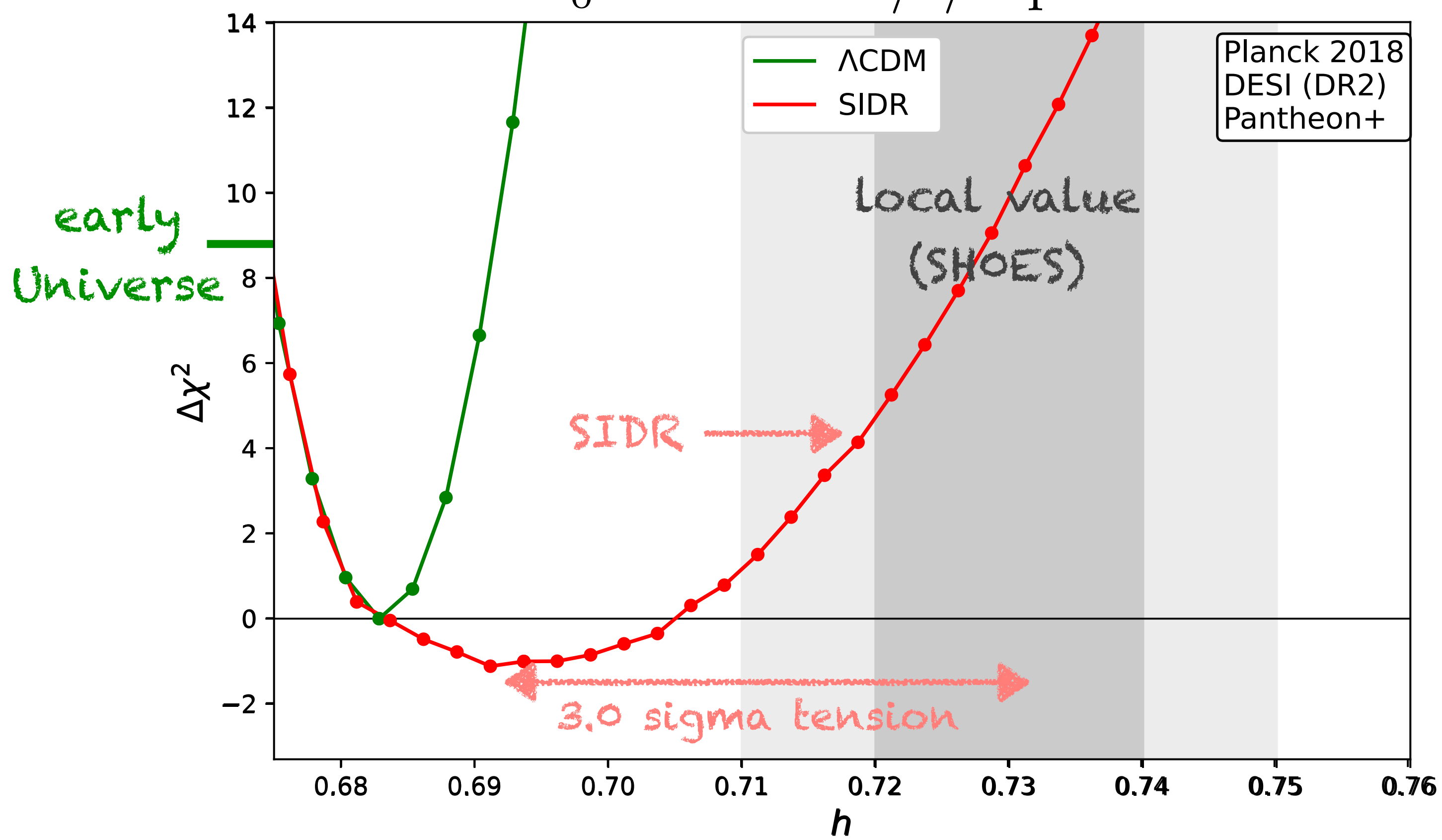
visible sector:	$SU(2)_L \times U(1)_Y \to U(1)_{\rm EW}$	'Higgs mechanism'	250 GeV	crossover
dark sector: (weakly coupled)	$SU(N) \to SU(N-1)$	'dark Higgs + softly broken classical conformal symmetry'	< MeV	supercooled first order

How well does it work?

- Implement self-interacting dark radiation (SIDR) in CLASS to simulate modified expansion history.

$$\boxed{\mathrm{SIDR} = \Lambda\mathrm{CDM} + \Delta N_{\mathrm{eff}}}$$

$H_0 \equiv h\,100\mathrm{km/s/Mpc}$

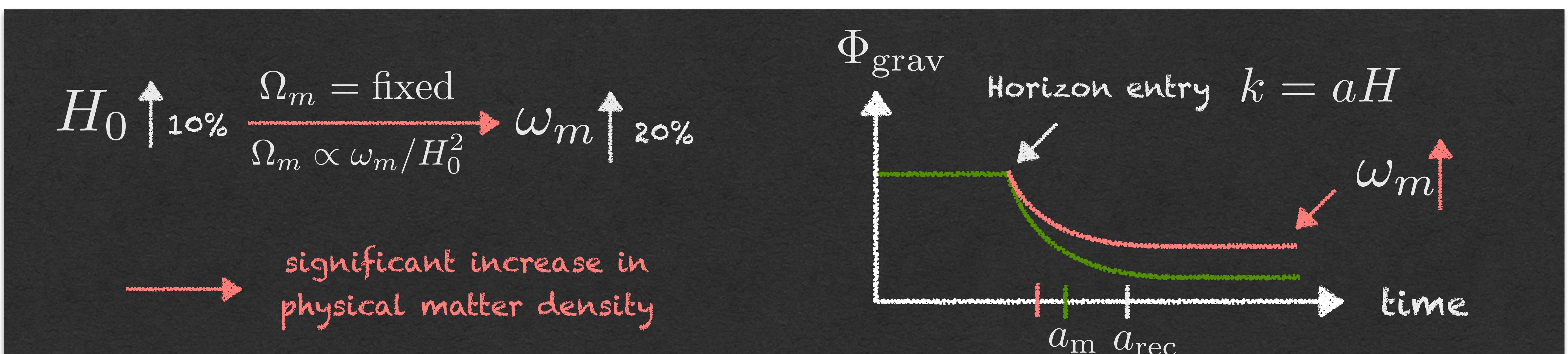


- **LCDM:** The early universe value is incompatible with the local value.
- **SIDR from supercooled phase transition:** The tension is weakened but not resolved.

$$\Delta N_{\mathrm{eff}}^{(\mathrm{SIDR})} < 0.525\,(95\%\,\mathrm{CL})$$

`[arXiv:2508.03795], see also [Schöneberg++,2306.12469] and [Allali++,2305.14166]`

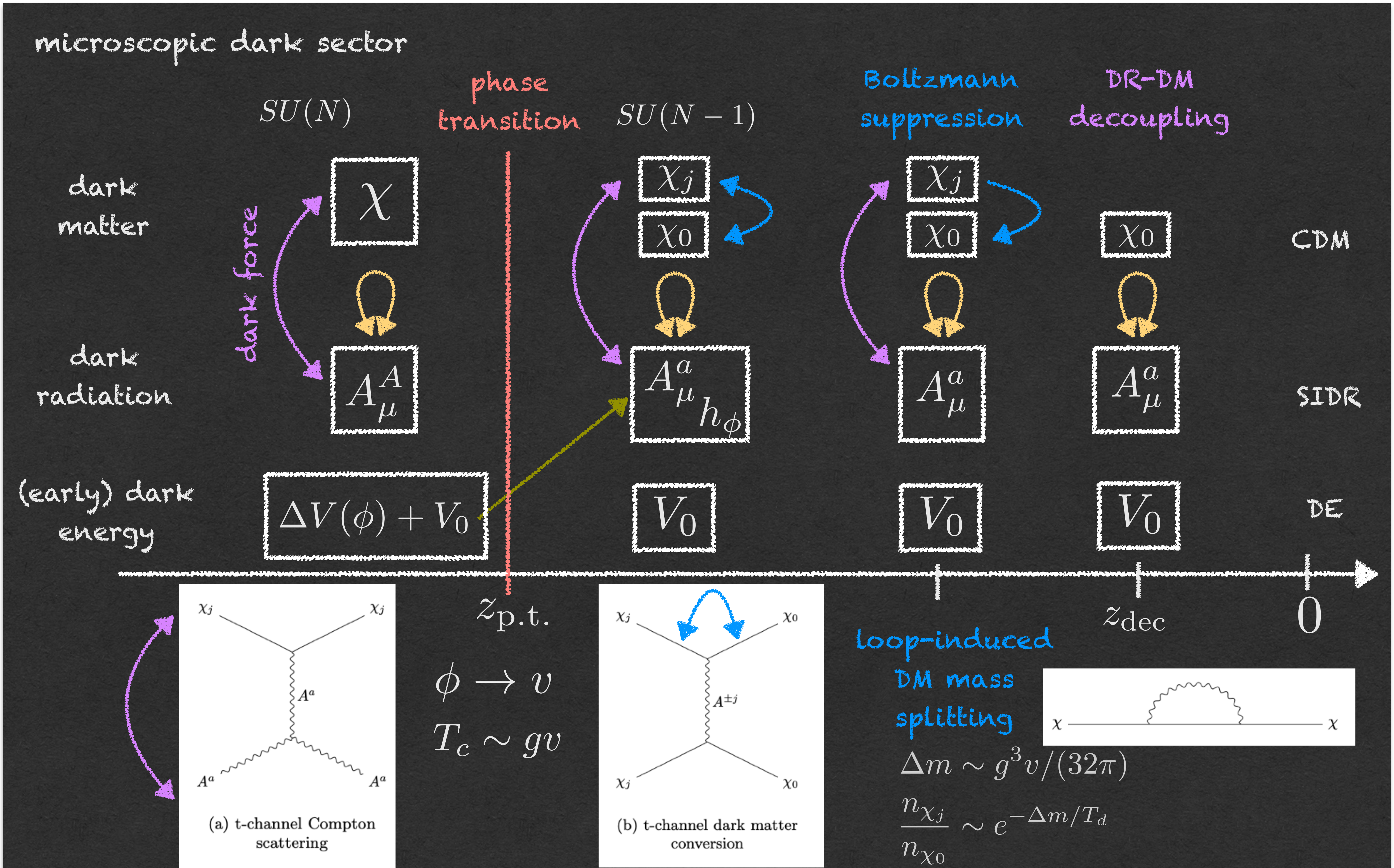
- **Problem:** Too strong gravitational potential for pre-equality modes.



- **Idea:** Prevent dark matter from clumping too much by introducing a radiation drag force.

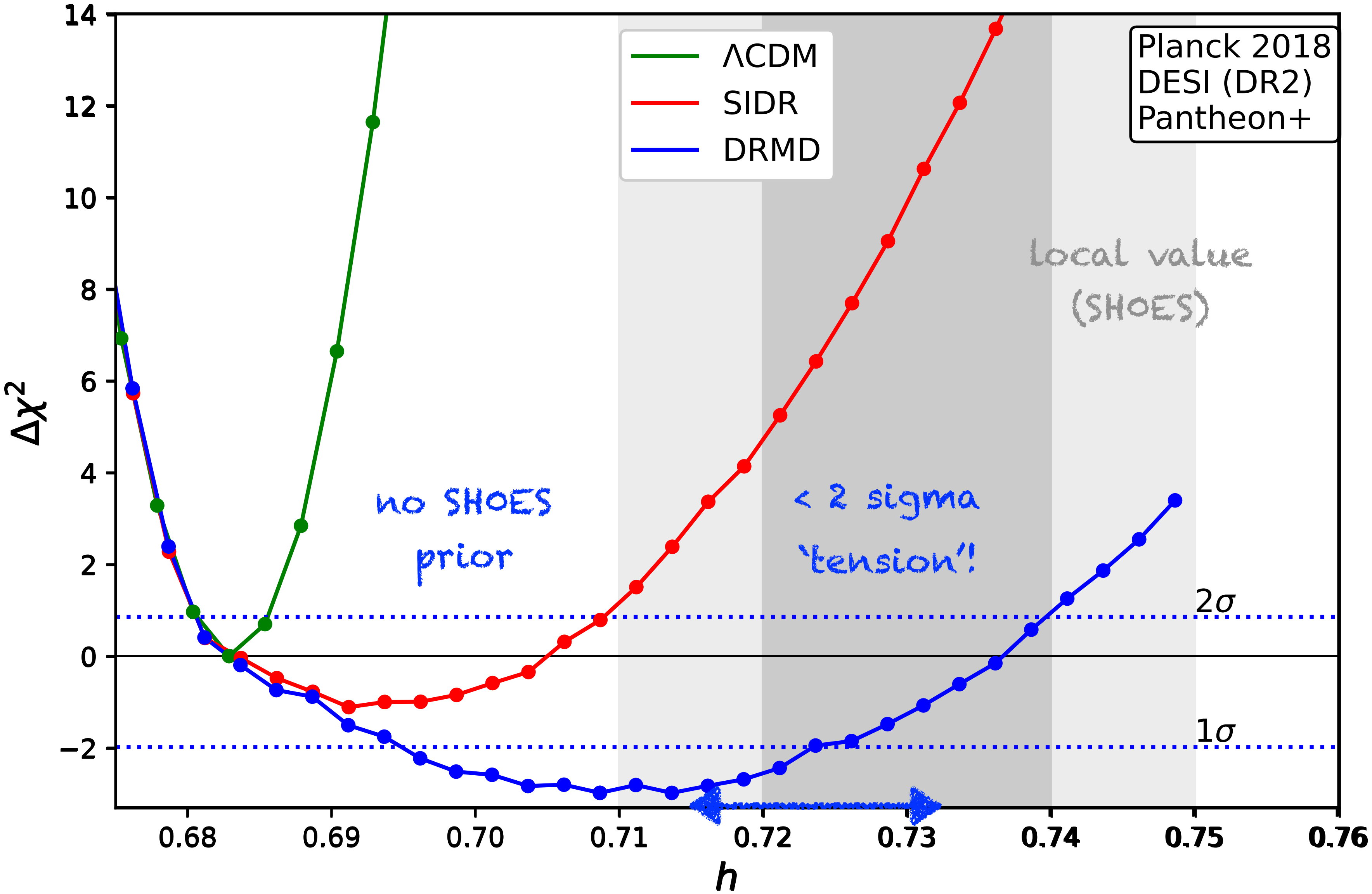
Dark Radiation–Matter Decoupling

- **Idea:** A fraction of dark matter is a heavy fermion in the fundamental of SU(N), i.e. carries dark charge [arXiv:2508.03795].



Significant progress

- Implement decoupling feature in CLASS code. $\boxed{\mathrm{DRMD} = \Lambda\mathrm{CDM} + \Delta N_{\mathrm{eff}} + f_{\mathrm{idm}} + z_{\mathrm{dec}}}$
- Leave fine-grained features (phase transition imprints, mass thresholds) for future.

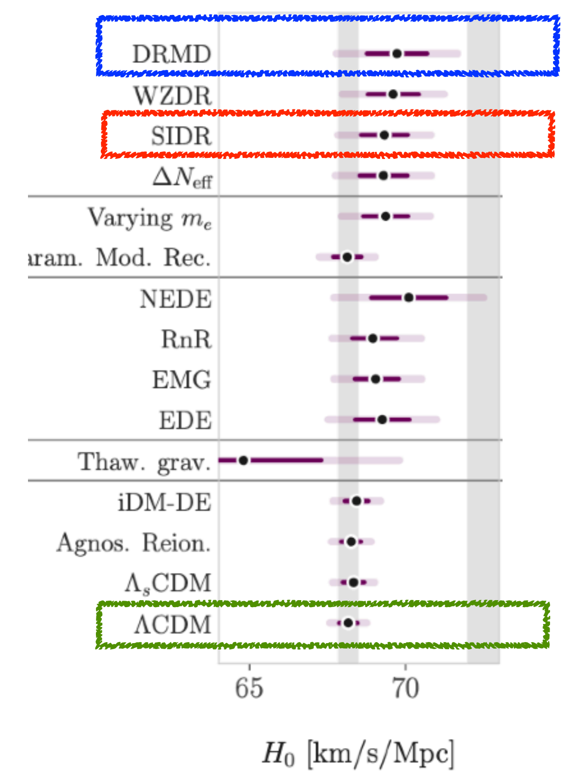


$\Delta N_{\mathrm{eff}}^{(\mathrm{SIDR})} < 0.525\ (95\%\ \mathrm{CL})$

$\Delta N_{\mathrm{eff}}^{(\mathrm{DRMD})} < 0.811\ (95\%\ \mathrm{CL})$

The H_0 world cup II:

[Schöneberg++,2607.13283]



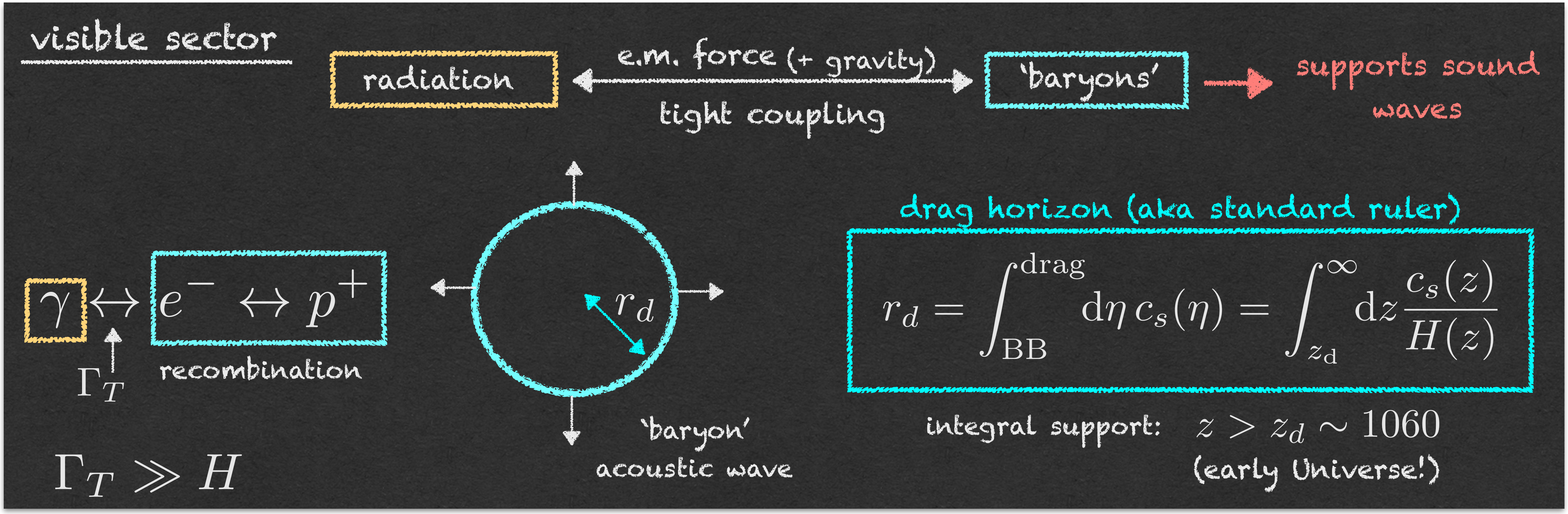
[Fig.17, Planck+SPT, DESI (DR2), Pantheon+ but no ACT DR6]

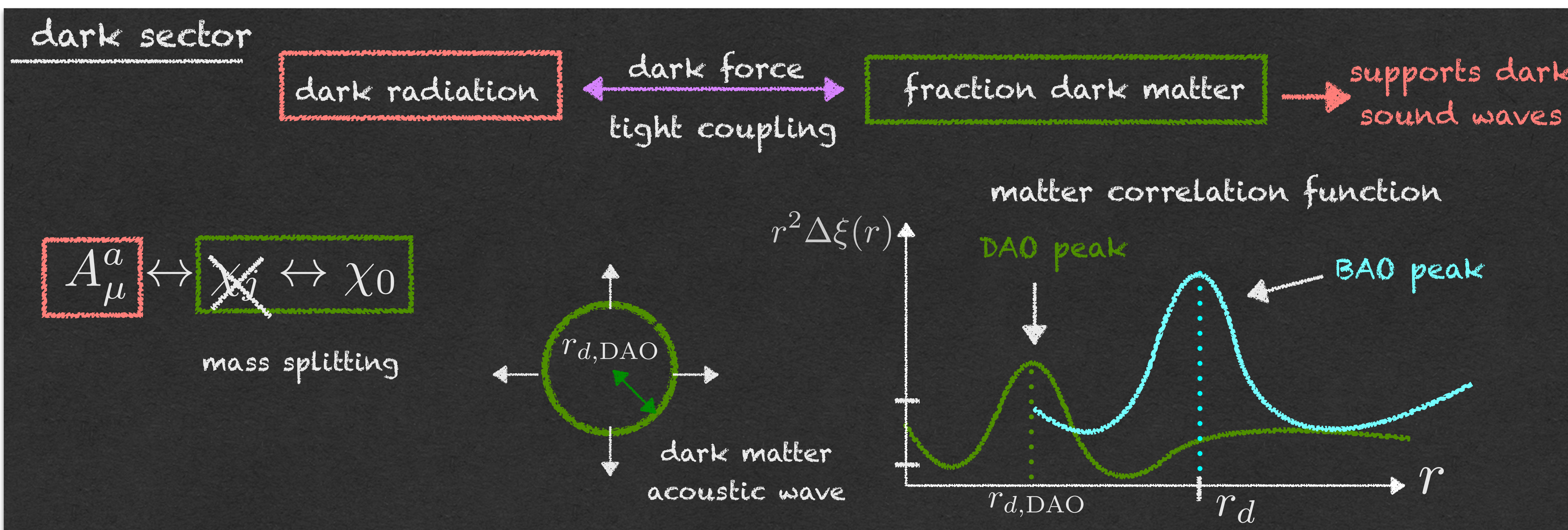
- **DRMD:** Resolves the Hubble tension with standard datasets (no SH0ES input; more about ACT later).
- Having a fundamental principle (gauge symmetry + spontaneous symmetry breaking) was crucial to getting this far. This is a promising start!
- **Next:** Are there any distinct signatures / motivations beyond the Hubble tension?

Dark Acoustic Oscillations (DAO)

- Consequence and distinct signature of dark sector decoupling scenario.

e.g. [F. Cyr-Racine, K. Sigurdson, 2012]





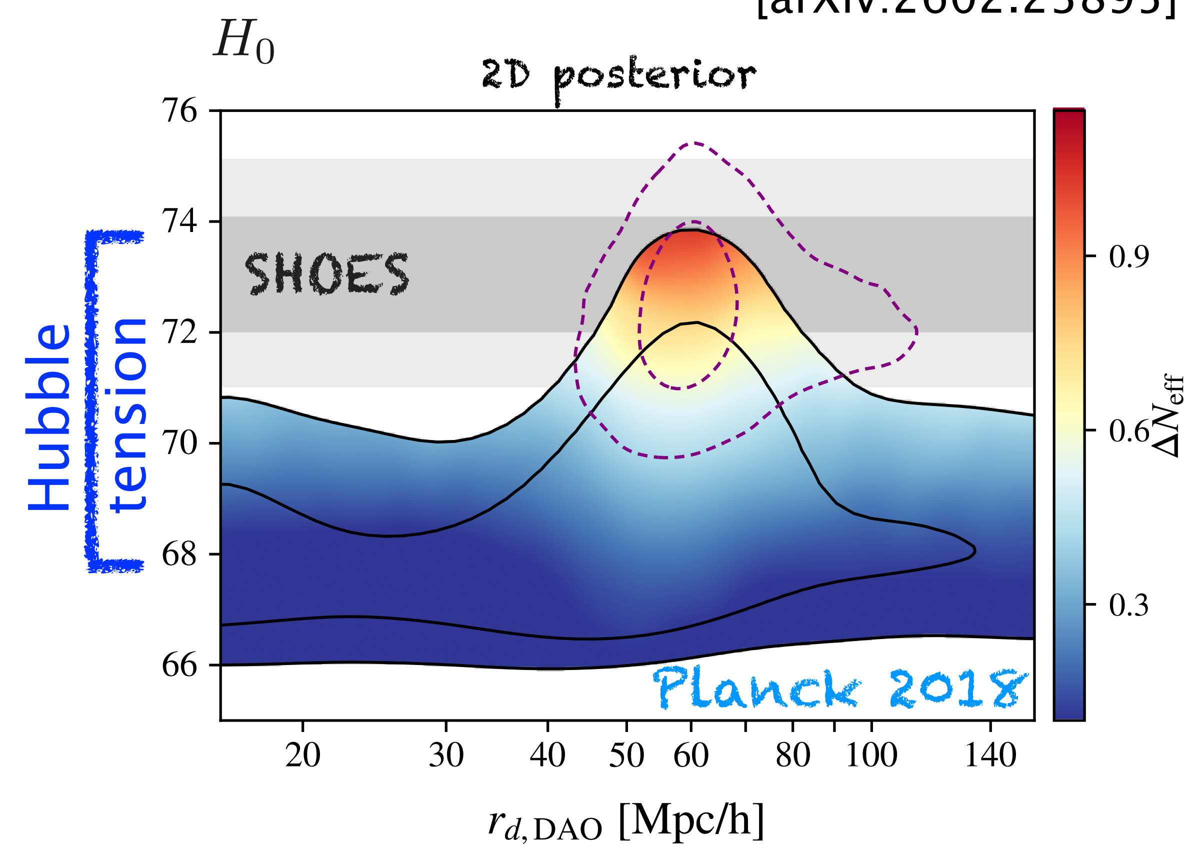
DAO as a smoking gun

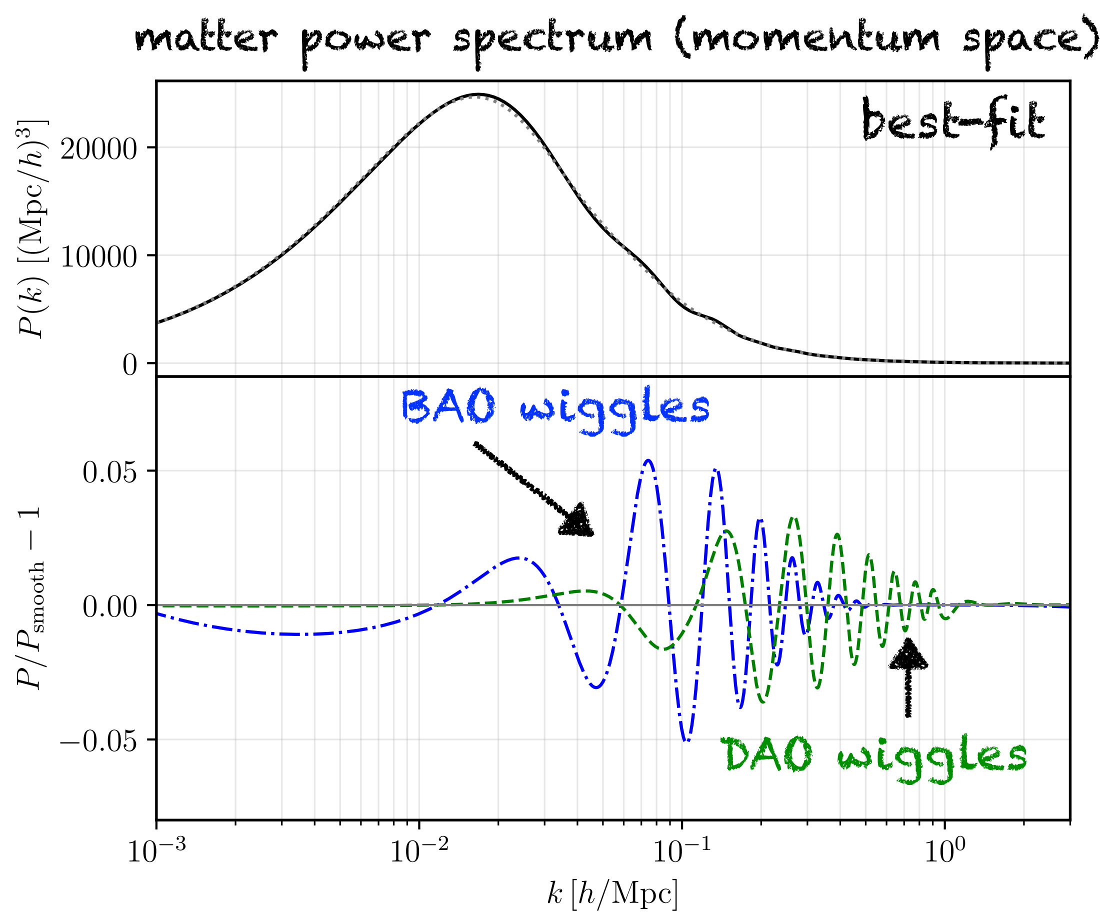
[arXiv:2602.23895]

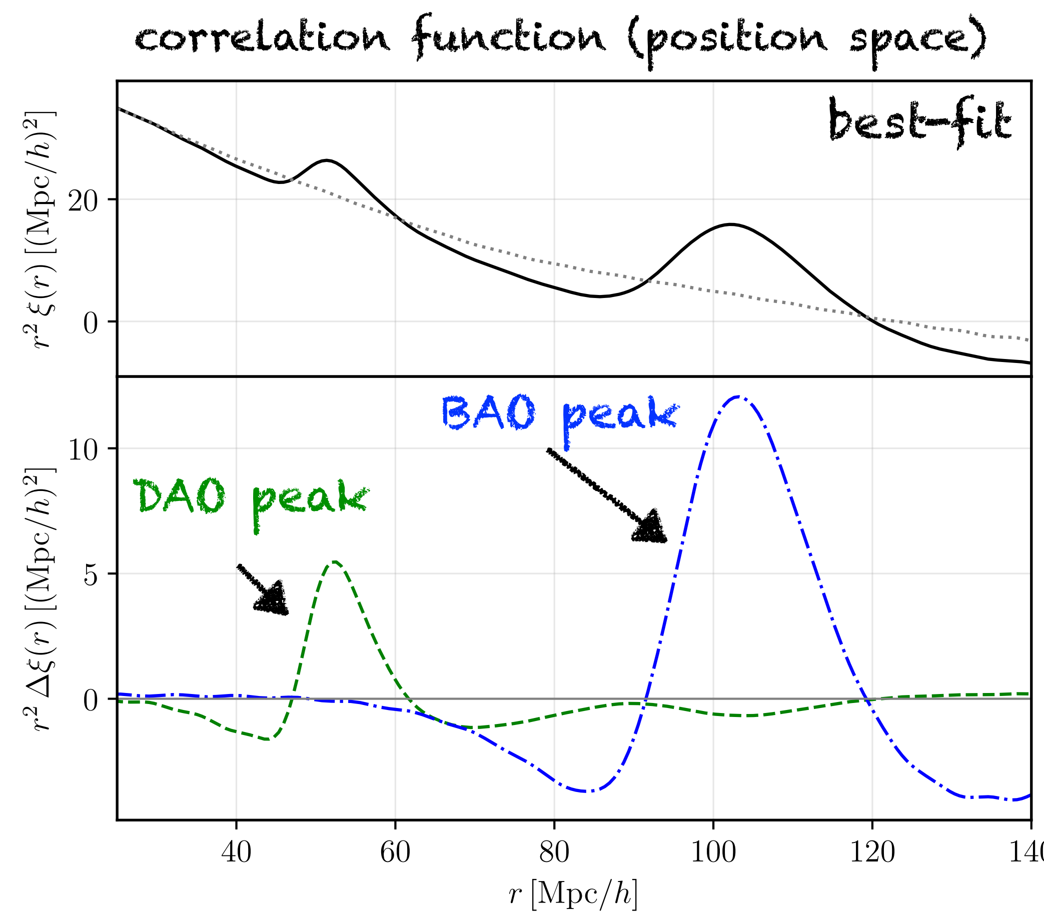
- Planck data compatible with SHOES for DAO around 60 Mpc/h -> natural resolution of H0 tension.
- Turn into prediction by including SH0ES-calibrated supernova data (purple dashed):

$$54\,\mathrm{Mpc}/h < r_{d,\mathrm{DAO}} < 65\,\mathrm{Mpc}/h\;(68\%\ \mathrm{C.I.})$$

$$0.02 < A_{\mathrm{DAO}} < 0.05$$ ← amplitude





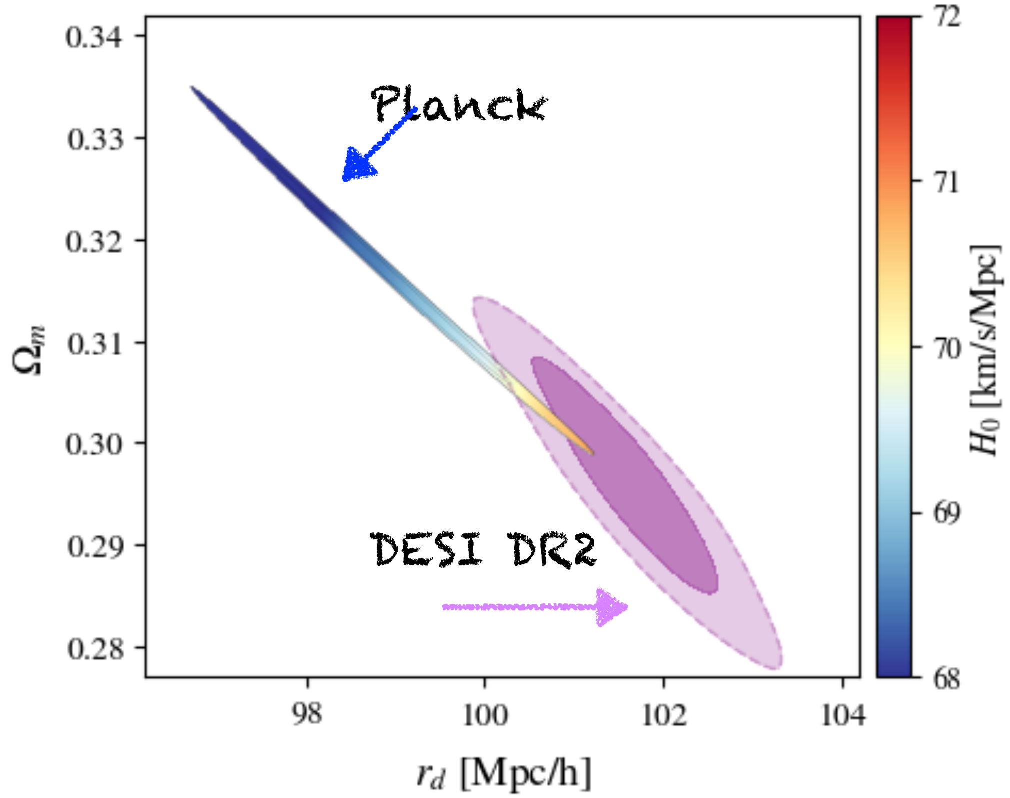


- **On-going work**: Search for DAOs in full-shape data (requires non-linear power spectrum).

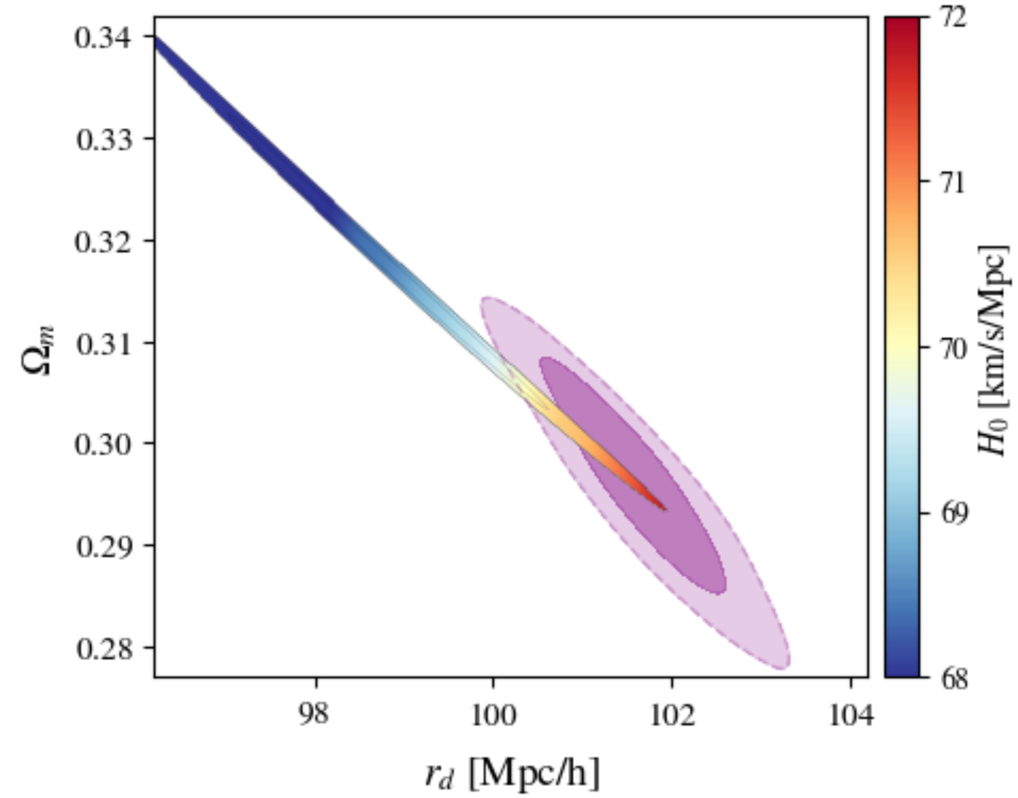
BAO–CMB tension (DESI puzzle B)

- Mild tension between DESI and CMB data for the LCDM model (2.3 sigma).
- **Our finding:** (i) DRMD resolves the tension, (ii) pulls in same direction as Hubble tension.

LCDM



DRMD [arXiv:2512.15870]



- What about evolving dark energy (DESI puzzle A)?

Deus ex H_0 – Is evidence for dynamical dark energy conditioned on early cosmology?

Nils Schöneberg[1,2] Rodrigo Calderón[3] and Julien Lesgourgues[4]

[arXiv:2608.07654]

→ lowers evidence for evolving dark energy!

DRMD: in addition DAO also bias the BAO extraction providing another early-Universe handle on evolving DE.

$$r_{d,\mathrm{DAO}} = 58^{+8}_{-10}\ \mathrm{Mpc/h}$$

[paper from April, arXiv:2604.26541

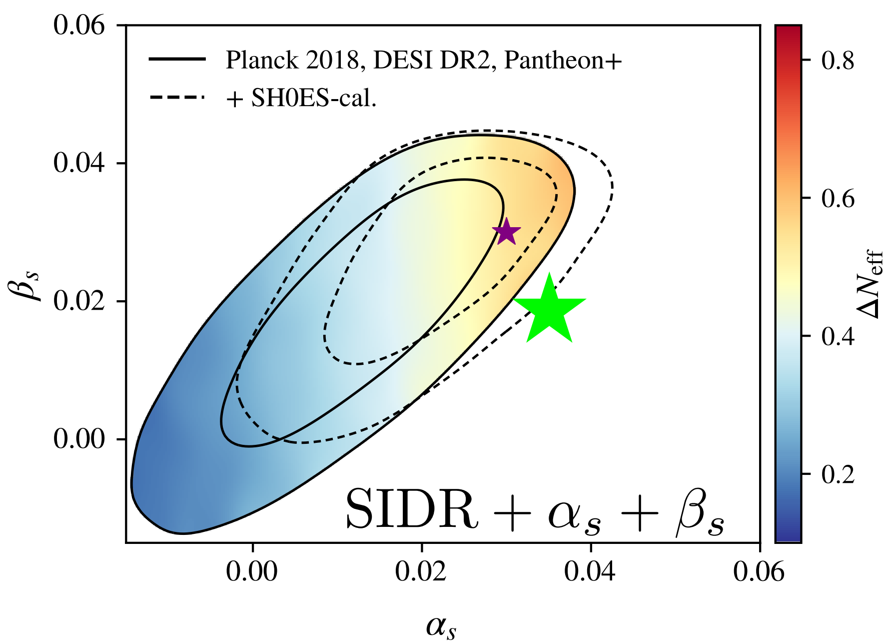
ACT DR6 and spectral running

- ACT DR6 small-scale CMB data constrains fluid-like DR (SIDR) significantly.
- **However**: This conclusion is very dependent on initial conditions from inflation.
- Bounds are relaxed if we allow for running and running-of-running of the spectral tilt.

$$\Delta N_{\rm eff}^{\rm (SIDR)} < 0.13\,(95\%\,{\rm CL})$$

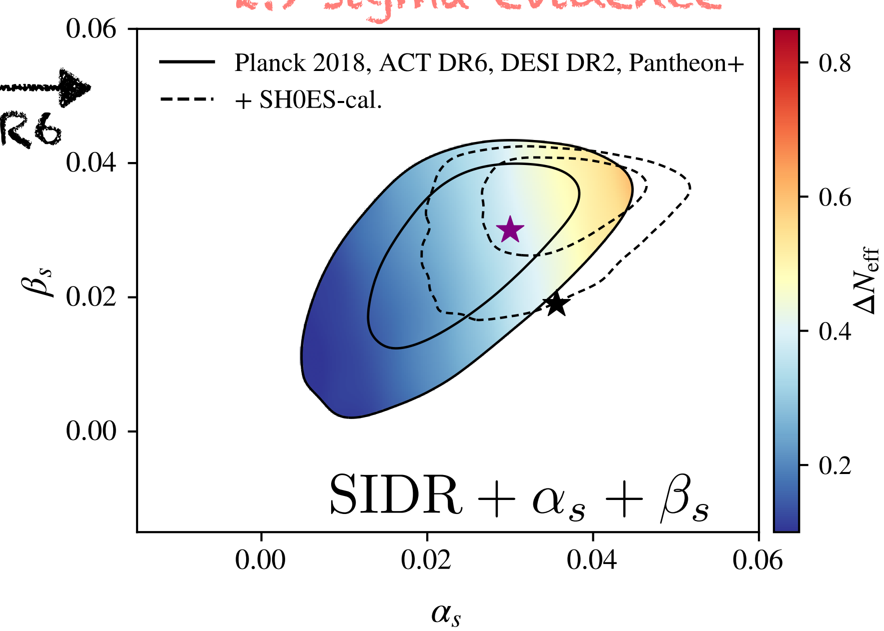
[ACT DR6, arXiv:2503.14454]

$$\mathcal{P}_{\mathcal{R}}(k) = A_s \exp\left[(n_s - 1)\ln\left(\frac{k}{k_*}\right) + \frac{1}{2}\boxed{\alpha_s}\ln^2\left(\frac{k}{k_*}\right) + \frac{1}{6}\boxed{\beta_s}\ln^3\left(\frac{k}{k_*}\right) + \ldots\right]$$



add ACT DR6

2.9 sigma evidence



Our key results:

$$\Delta N_{\rm eff}^{\rm (SIDR)} < 0.58\,(95\%\,{\rm CL})$$

$$n_s = 0.970 \pm 0.004$$

$$H_0 \text{ tension} : 2.2\sigma$$

The H_0 world cup II:

[Schöneberg++,2607.13283]

→ confirmation of caveat!

- **Mechanism:** Running compensates small-scale suppression due to DR excess damping.
- **Important:** Running and running-of-running need to be of same order!
- Possible inflationary **explanation**: ACT probes the end of the first act of inflation when resonant gauge field production kicks in.
- **Upshot:** Both SIDR and DRMD are still possible resolutions.

e.g. axion inflation

$$\mathcal{L}_{\rm int} = -\frac{\phi}{4 f_\phi} F^a_{\mu\nu}\tilde{F}^{a\mu\nu}$$

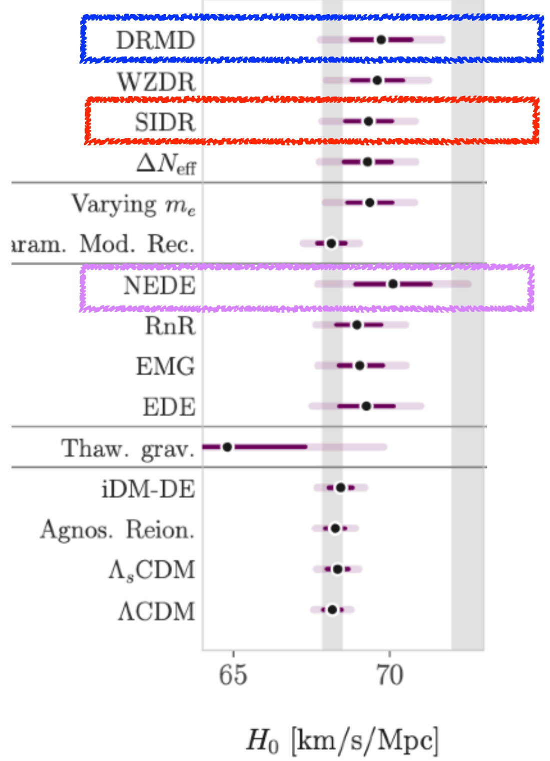
★ $V(\phi) \propto \phi^2$

$$f_\phi/M_{\rm pl} = 0.04 \qquad \dot{\phi}/(2 f_\phi H)|_{\rm pivot} = 2.5$$

Summary

- The Hubble tension **and** the BAO anomaly might be the signature of a supercooled phase transition that produces fluid-like dark radiation (SIDR) after BBN, with a possible dark matter decoupling feature (DRMD).
- **Falsifiable signature** of DRMD model: DAO between 50 and 70 Mpc/h.
- Such a dark radiation resolution to the Hubble tension seems to require **spectral running** at high significance (lesson from ACT DR6 data).
- Resolving the tensions is an on-going process based on **both** new data and fundamental principles.
- Alternative model I did not talk about today (insensitive to ACT issue): **Cold NEDE** (based on a non-thermal phase transition).

The H_0 world cup II:
[Schöneberg++,2607.13283]



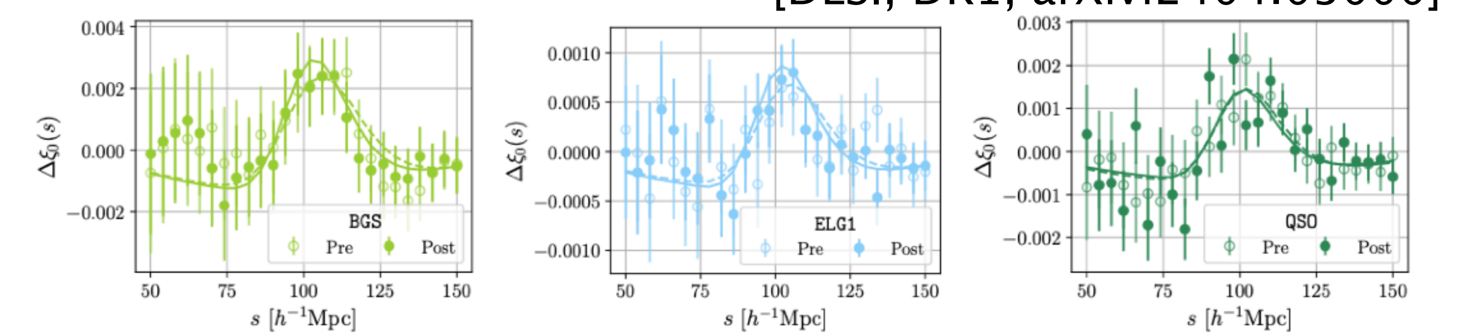
[Fig.17, Planck+SPT, DESI (DR2), Pantheon+ (no ACT DR6)]

On-going work:

How constraint are DAO with percent-level amplitude at these scales? Not obviously excluded!

What is future data telling us about the physics of the phase transition and the subsequent dark sector (threshold effects, p.t. parameters)?

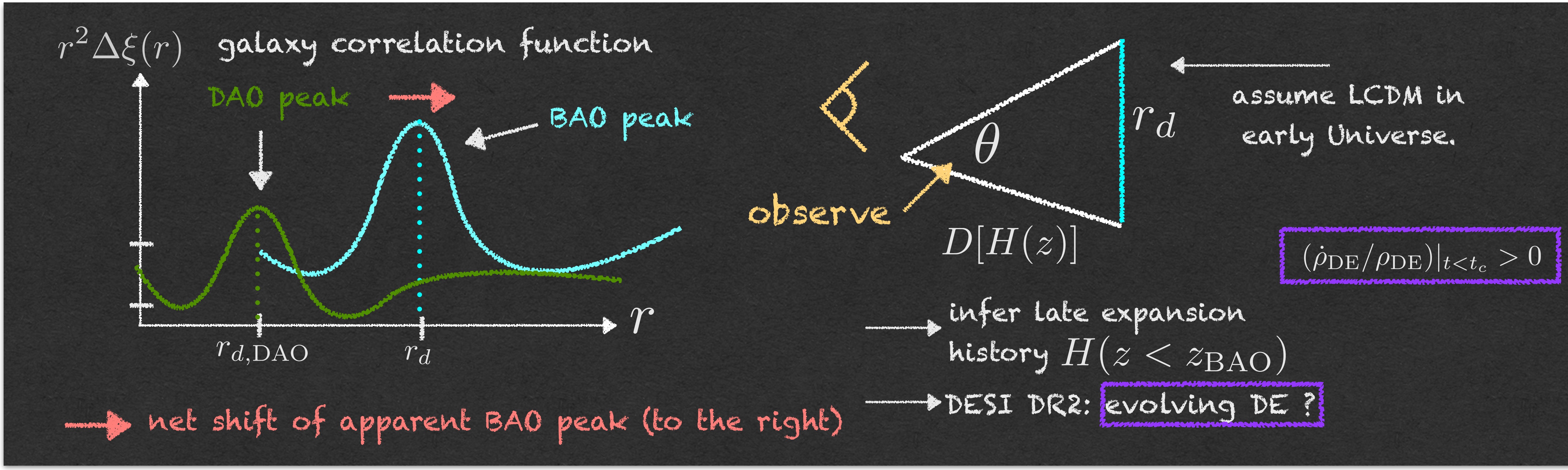
[DESI, DR1, arXiv:2404.03000]



Can we generate the neutrino masses in the same transition? Possibly through inverse seesaw.

An early-Universe alternative to evolving DE

- **Question**: Is the extraction of BAO from data reliable if there are DAO similar in scale?



- A reliable extraction of baryon drag horizon requires correcting for presence of DAO.

momentum space: $\xi(\mathbf{r}) = \int \frac{d^3\mathbf{k}}{(2\pi)^3} P_g(\mathbf{k})\, e^{i\mathbf{k}\cdot\mathbf{r}}$

galaxy power spectrum $P_g \to \tilde{P}_g = P_g + P_{\mathrm{DAO}}$

damped sinusoidal wave

$\theta[\tilde{P}_g] = \theta[P_g] + \Delta\theta(r_{d,\mathrm{DAO}}, A_{\mathrm{DAO}}, \Sigma)$

DAO bias correction: $\theta_{\mathrm{obs}} \to \theta_{\mathrm{obs}} - \Delta\theta(z)$

result:

$A_{\mathrm{DAO}}/A_{\mathrm{BAO}} \gtrsim 0.1$

$\boxed{r_{d,\mathrm{DAO}} = 58^{+8}_{-10}\ \mathrm{Mpc/h}}$

negative branch

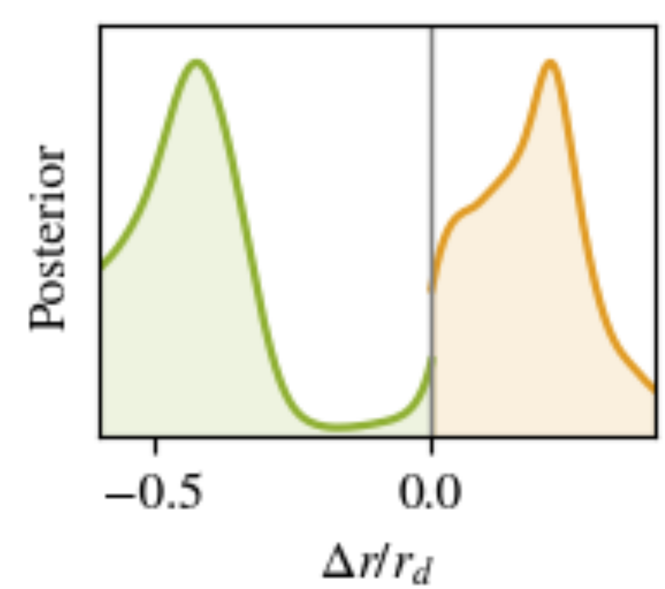
$\boxed{r_{d,\mathrm{DAO}} = 118^{+9}_{-14}\ \mathrm{Mpc/h}}$

positive branch

[DESI DR2, Panth+, Planck]

[arXiv:2512.15870]

$\Delta r = r_{d,\mathrm{DAO}} - r_d$



- Fit improvement of $(\Delta\chi^2)_{\mathrm{DAO}} \approx -5$ as compared to $(\Delta\chi^2)_{(w_0,w_a)} \approx -10$
- The negative branch is compatible with the scale inferred from CMB and supernova data.

Hot New Early Dark Energy

- Dark non-Abelian Higgs model with radiative breaking of classical conformal symmetry à la Coleman-Weinberg (CW).

$$\mathcal{L} = |\mathcal{D}\Phi|^2 - V(\Phi) - \frac{1}{2}\mathrm{tr}(F_{\mu\nu}F^{\mu\nu})$$

weak gauge coupling: $g \ll 1$

Φ dark Higgs; transforms in fundamental SU(N) rep.

$$V(\phi, T_d) = V_0 + \boxed{B\phi^4\left(\ln\frac{\phi^2}{v^2} - \frac{1}{2}\right)} - \boxed{\frac{\mu_{\rm eff}^2}{2}\phi^2\left(1 - \frac{\phi^2}{2v^2}\right)} + \boxed{\Delta V_{\rm thermal}(\phi, T_d)}$$

$\phi = \sqrt{2}|\Phi|$

$B \sim g^4$

CW 1-loop result → radiative symmetry breaking due to dim. transmutation $\xrightarrow{SU(N) \to SU(N-1)}$ $\phi \to v$

(i) $\mu_{\rm eff} \to 0$: $V'(0) = V''(0) = 0$ — nucleation inhibited for $T_d > T_d^*|_{\rm CW} (\ll v)$ → strong supercooling

(ii) $\mu_{\rm eff} > 0$: soft breaking of conformal symmetry — nucleation possible for $T_d \gg T_d^*|_{\rm CW}$ → ($\mu_{\rm eff}^2 \ll v^2 g^4$) controlled supercooling

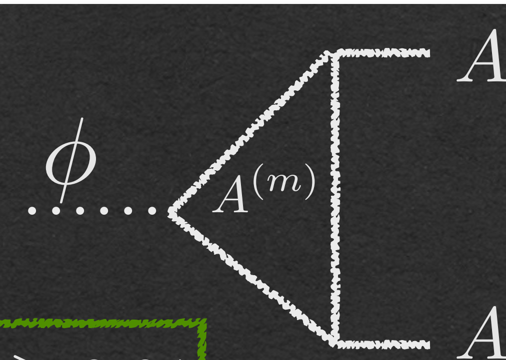
$$\frac{\Delta N_{\rm eff}|_{\rm after\ p.t.}}{\Delta N_{\rm eff}|_{\rm BBN}} \propto v^4/\mu_{\rm eff}^4$$ ← controls energy injection

(i) small bubbles:

$$\beta/H_* \propto g^{-2} \gg 1$$

viable window → $\boxed{0.1 \gtrsim g \gtrsim 0.01}$

(ii)



efficient decay in massless gauge bosons

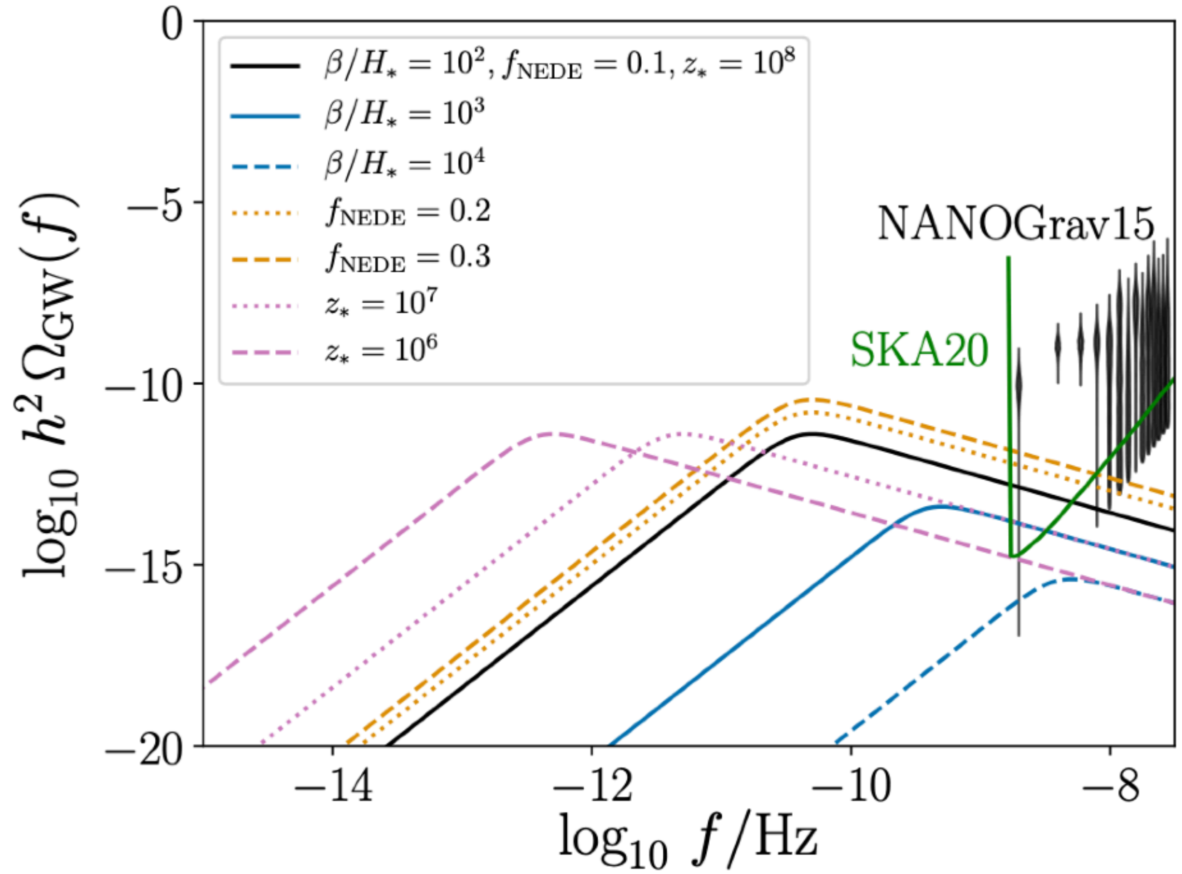
$$\frac{\Gamma^{\rm (cm)}_{\phi \to AA}}{H_*} = \mathcal{O}(1) \times \frac{g^9 f_{\rm NEDE}^{1/4}}{1 + z_*} 10^{24} \gg 1$$

Signatures I+II

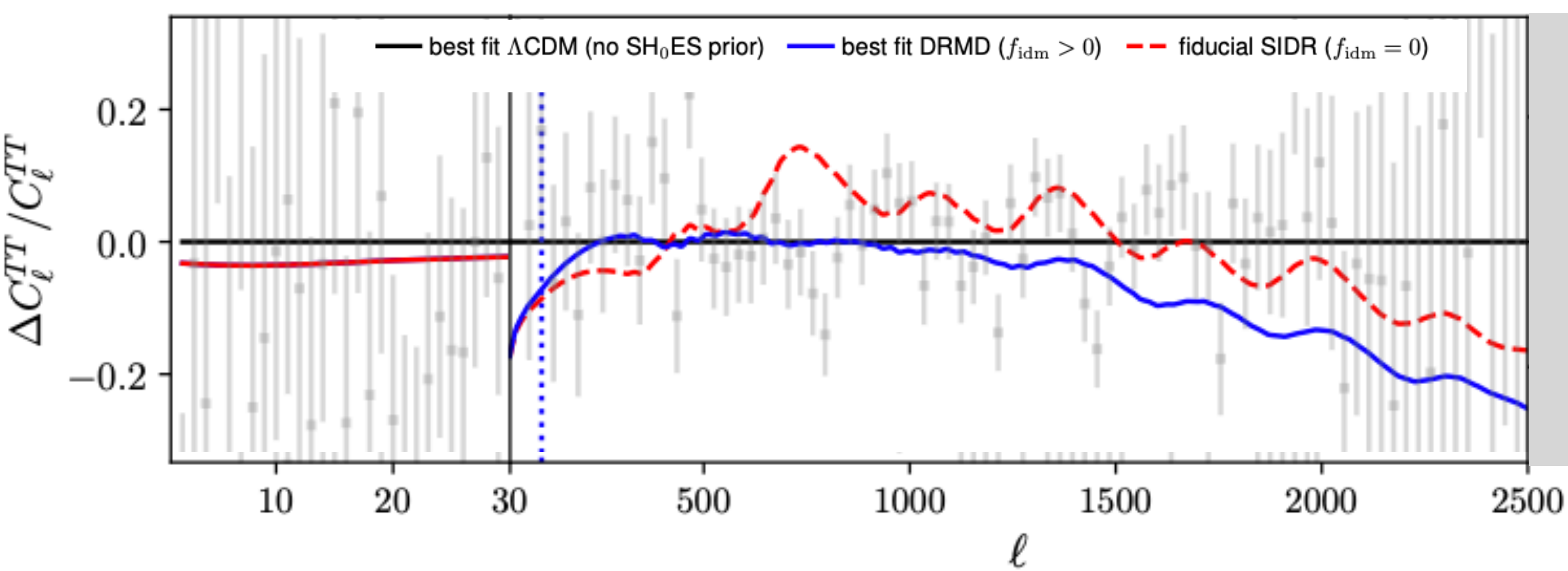
- Stochastic **gravitational wave** background
  - Overlap with PTAs for phase transitions that occur close to BBN and create large bubbles.

$$10^7 < z_* < 10^9$$

  - First estimate (envelope approximation, thin-wall, ...)

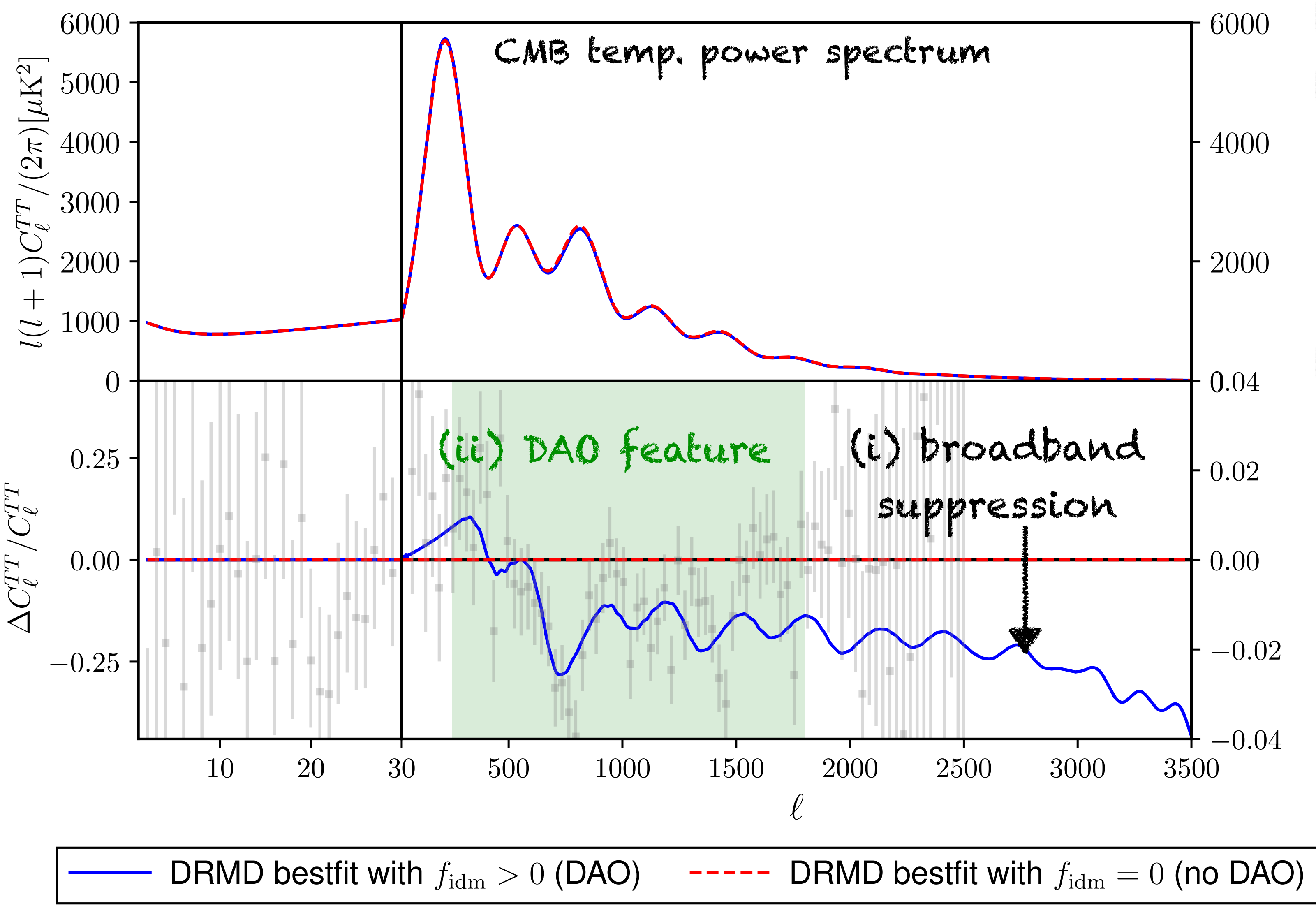


- **CMB anisotropies**
  - DM-DR coupling suppresses power on small scales.
  - Test against new ground based CMB data by **ACT and SPT**.
  - Higher angular moments probe features at earlier times.



ACT and SPT can probe earlier details of model: mass threshold, phase transition

DAO in CMB / Planck



- Comparison SIDR (red) vs DRMD (blue).
- (i) Broadband effect: DM-DR coupling suppresses power on small scales (blue vs red), countering the effect of increased matter density.
- (ii) Localised DAO feature: most pronounced around angular scales of l=600 (Planck regime).

- **Upshot**: Planck CMB data compatible with large H0 value in presence of a ~60 Mpc/h DAO feature.
- **Question 1**: Is there any additional evidence for DRMD/DAO? **Yes**, from recent DESI DR2 BAO data.
- **Question 2**: What about small-scale CMB data by ACT released last year?