Constraining Late-Time Cosmology with DESI DR2: BAO, Power Spectrum, and Bispectrum

PhD Prelim Talk

Prakhar Bansal
2nd Year PhD Sudent
Committee: Dragan Huterer (Chair), Gus Evrard, Scott Haselschwardt

About Me

- Second Year PhD student
- Graduated from Indian Institute of Technology Bombay, with a major in Electrical Engg. and a minor in Physics
- Started working with Dragan in May 2024
- Joined DESI in October 2024, contributed to the DR2 BAO analysis
- Recipient of the Peter Franken Departmental Award 2025
- Currently working on understanding Dark Energy in light of new DESI data

And these are some of the special people who put up with a cosmologist friend 🙂

Dark Energy

- The Universe's expansion is accelerating!!
  Reason: Dark Energy

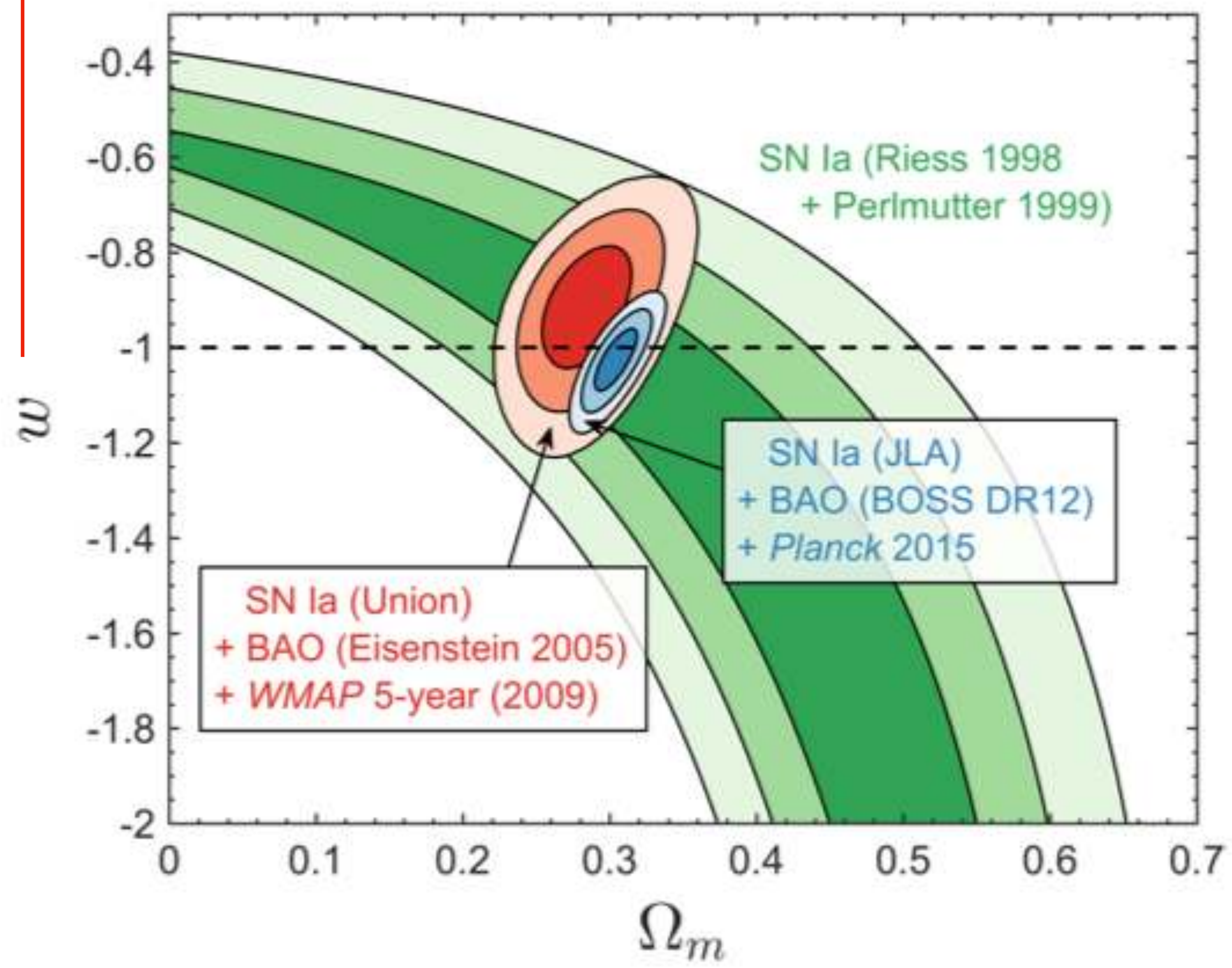
- Confirmed in 1998. Nobel Prize in 2011!

- Experiments so far have revealed

  - DE makes up ~70% of the energy budget of the Universe

  - A constant energy density (ΛCDM) DE model ($w \simeq -1$)

EOS Parameter for DE



$$\dot{\rho} \propto (1 + w)\rho$$

Huterer & Shafer 2018

DESI: Dark Energy Spectroscopic Instrument

- 4th Generation Spectroscopic Survey
- 4M Mayall Telescope at Kitt Peak (Tuscon, AZ)
- International Collaboration ~900 Scientists, ~70 institutions
- Mapping the distribution of the galaxies in the Universe by precisely measuring their redshifts

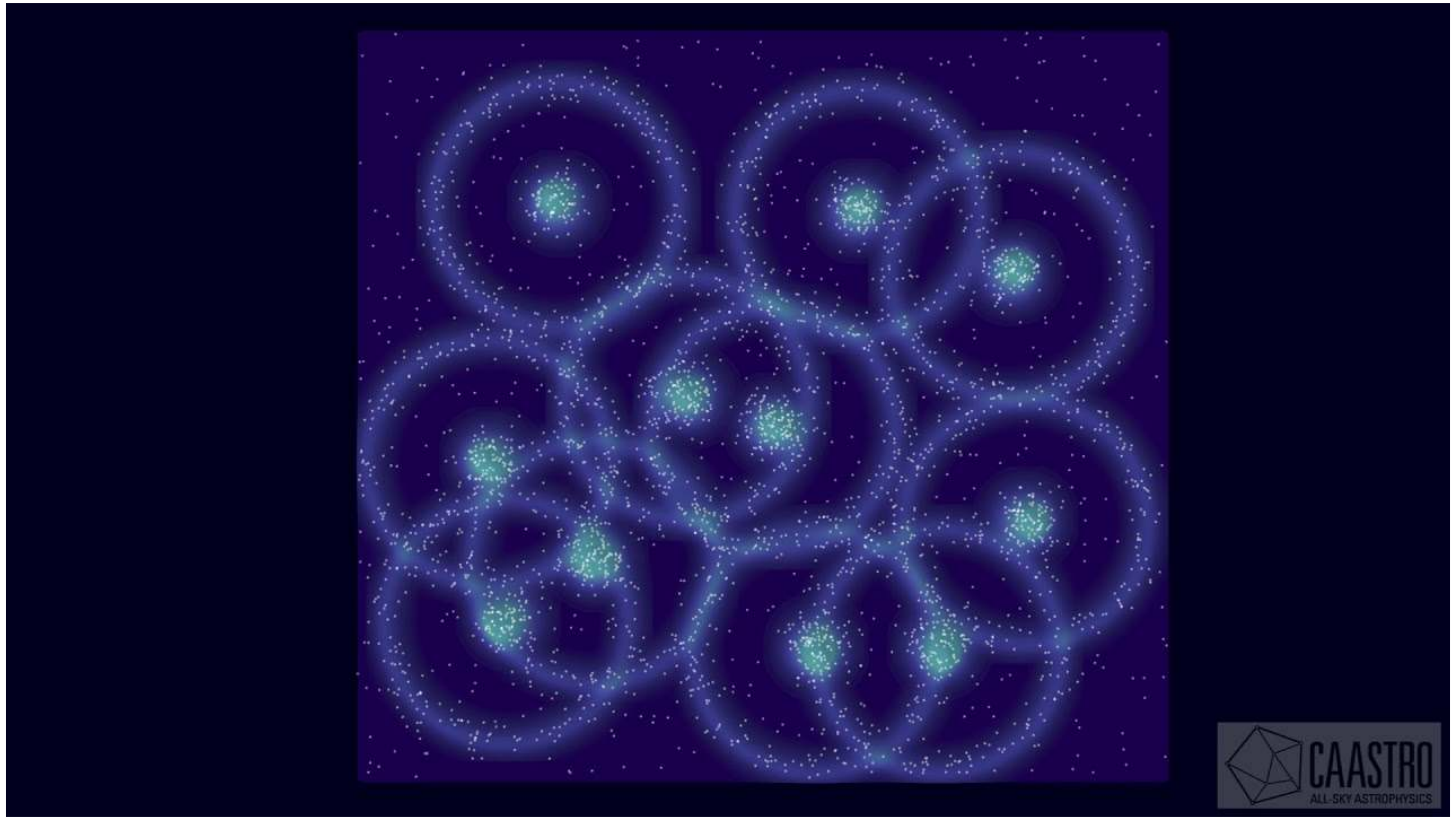
But how does this map of galaxies help??

Fig. Credits: NOIR LAB

1. Baryon Acoustic Oscillations

- Tightly coupled photons & baryons act as a single fluid plasma

- Overdensity $\longrightarrow$ Collapse $\downarrow$ Outwards travelling pressure wave

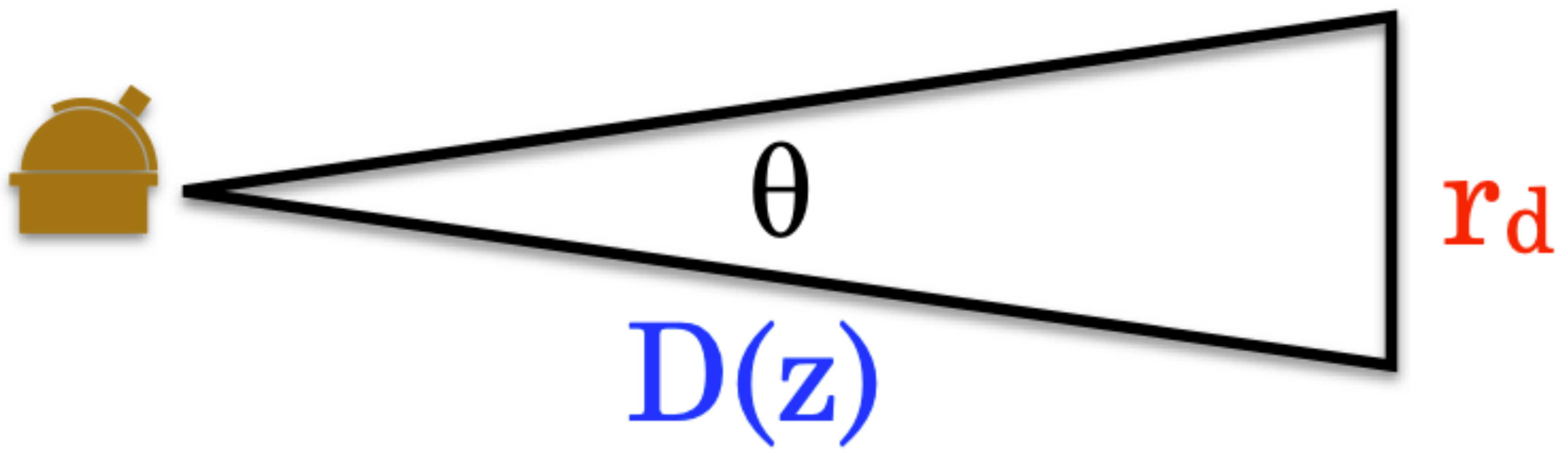


- At decoupling, $z_d \sim 1060$, the pressure wave stops and the distance this pressure wave travels from big bang ($r_d \sim 150$ Mpc) gets locked in

Movie Credits: CAASTRO

How does BAO help understand DE?

- Due to this feature, two galaxies have a preferential probability of being separated by a distance r_d
- Excessive clustering at a preferred scale - “Standard Ruler”
- What we actually observe is the angle to the Standard Ruler



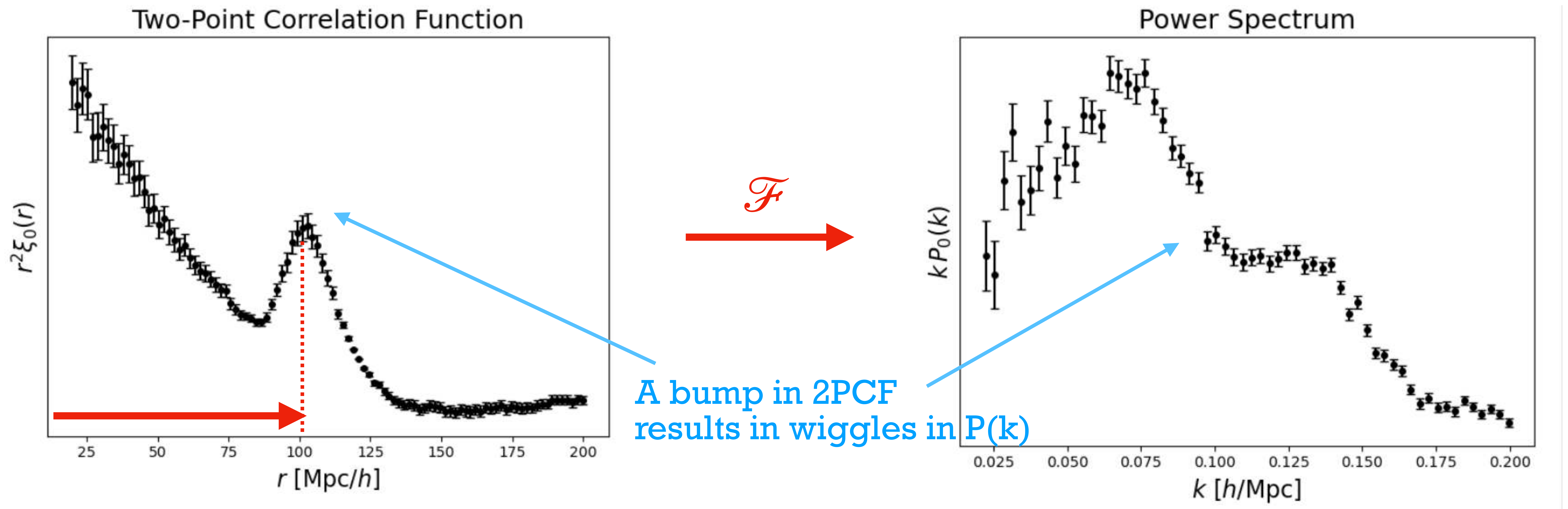
$$\theta = r_d / D$$

Sensitive to DE equation of state &
energy density

Fig. Credits: Dragan

2. Full Shape Analysis

- BAO measurement is the most important measurement of DESI for cosmology
- But it's not the only measurement!



DESI DE Results (DR1 BAO)

DESI 2024 VI: Cosmological Constraints from the Measurements of Baryon Acoustic Oscillations

- Came out in April 2024
- > 400 unique articles!!

A Tantalizing 'Hint' That Astronomers Got Dark Energy All Wrong

DESI DE Results (DR1 BAO)

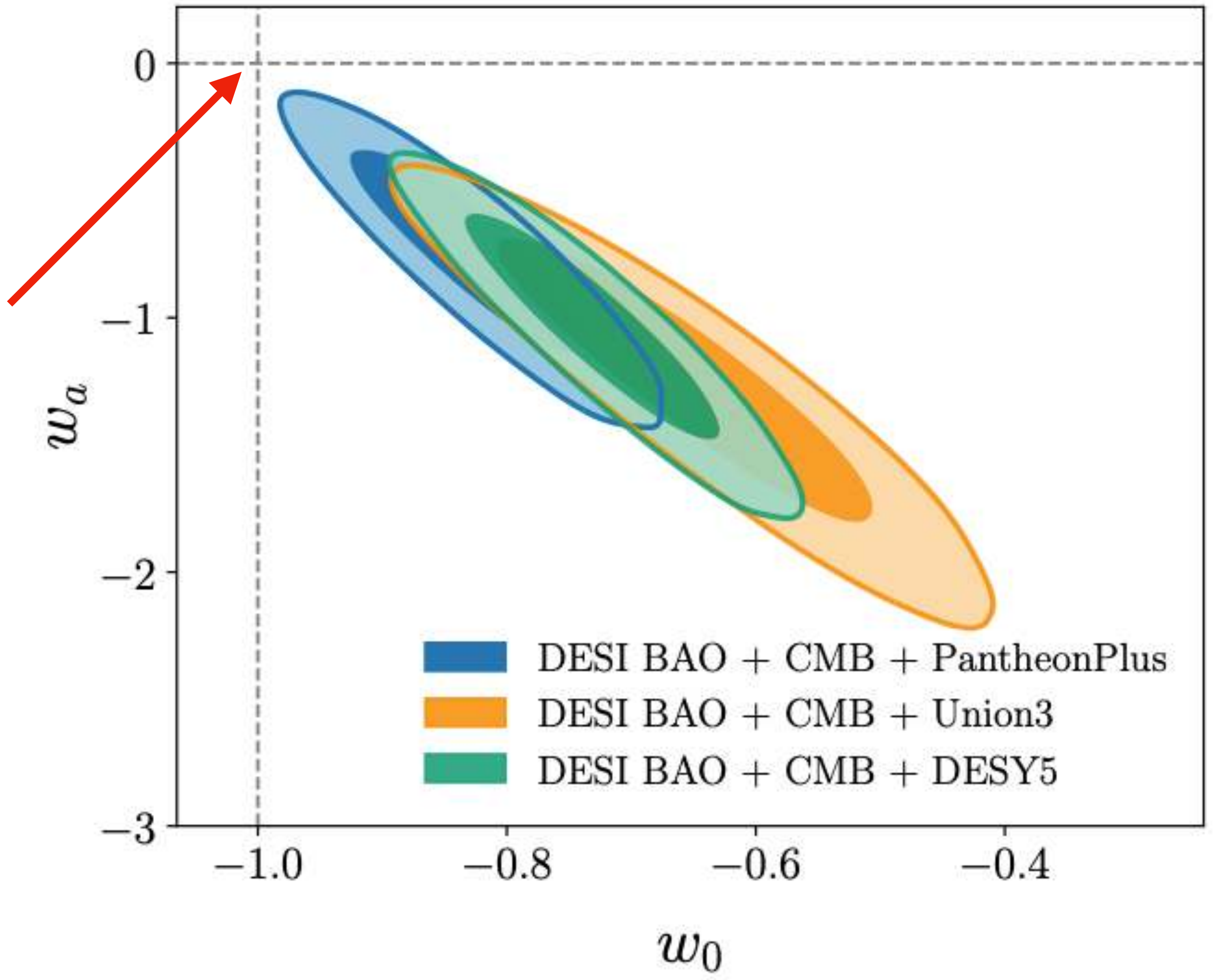
$w_0 w_a$ Parametrization

$$w = \frac{p_{\rm DE}}{\rho_{\rm DE}} = w_0 + (1-a)w_a$$

As $w_0 \to -1, w_a \to 0$

ΛCDM is recovered

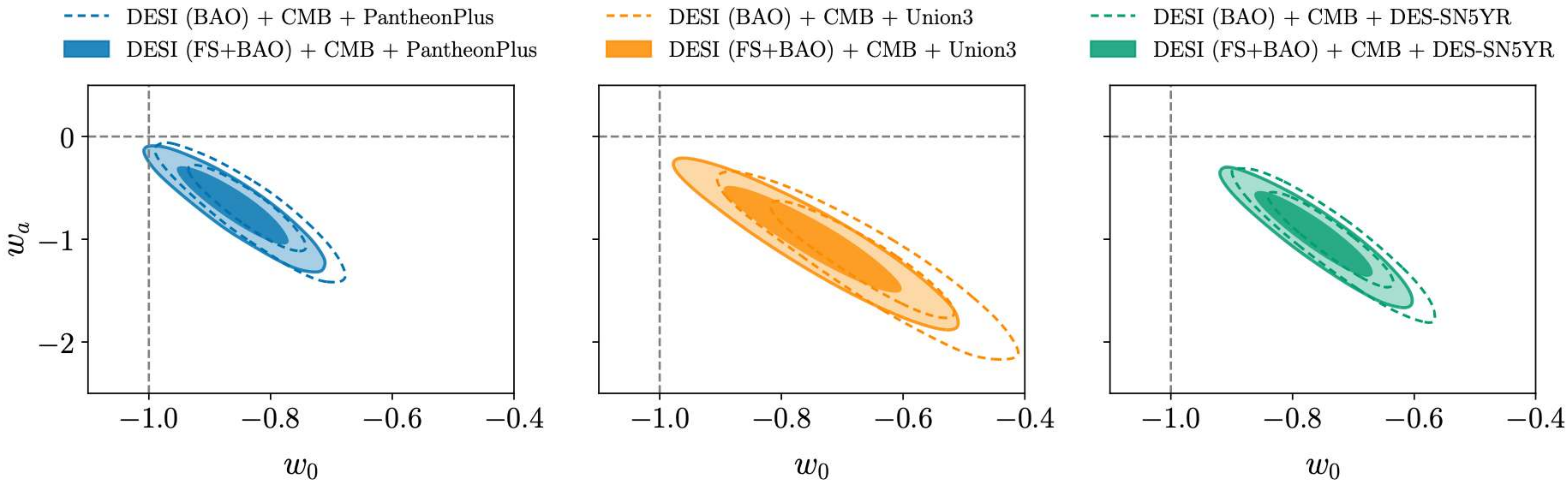
ΛCDM Point



2.5σ, 3.5σ, 3.9σ deviation from ΛCDM!!

DESI VI: 2024

DESI DE Results (DR1 Full Shape)



Contours shrink by ~ 20% on adding FS information

In total 42 Nuisance Parameters!

2.5σ, 3.4σ, 3.8σ deviation from ΛCDM!!

DESI VII: 2024

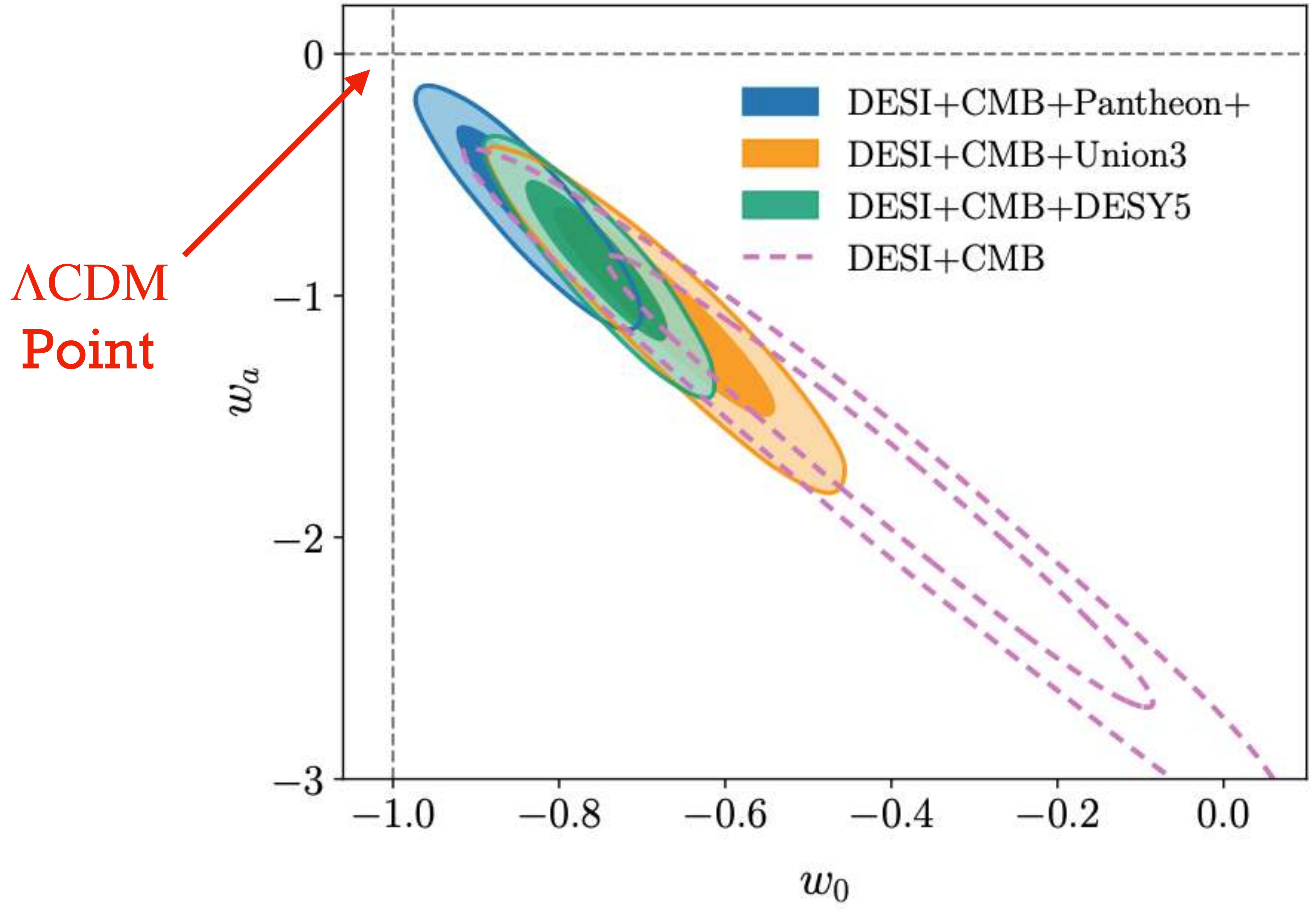
DESI DE Results (DR2 BAO)

DESI DR2 Results II: Measurements of Baryon Acoustic Oscillations and Cosmological Constraints

M. Abdul Karim,[1] J. Aguilar,[2] S. Ahlen,[3] S. Alam,[4] L. Allen,[5] C. Allende Prieto,[6,7] O. Alves,[8] A. Anand,[2] U. Andrade,[9,8] E. Armengaud,[1] A. Aviles,[10,11] S. Bailey,[2] C. Baltay,[12] P. Bansal,[9,8] A. Bault,[2] J. Behera,[13] S. BenZvi,[14] D. Bianchi,[15,16] C. Blake,[17] S. Brieden,[18] A. Brodzeller,[2] D. Brooks,[19] E. Buckley-Geer,[20,21] E. Burtin,[1] R. Calderon,[22] R. Canning,[23] A. Carnero Rosell,[6,7] P. Carrilho,[18] L. Casas,[24] M. Charles,[25] E. Chaussidon,[2] J. Chaves-Montero,[24] D. Chebat,[1] X. Chen,[12] T. Claybaugh,[2] S. Cole,[26] A. P. Cooper,[27] A. Cuceu,[2,28] K. S. Dawson,[29] A. de la Macorra,[30] A. de Mattia,[1] N. Deiosso,[31] J. Della Costa,[32,5] R. Demina,[14] A. Dey,[5] B. Dey,[33,34] Z. Ding,[35] P. Doel,[19] J. Edelstein,[36,37] D. J. Eisenstein,[38] W. Elbers,[26] P. Fagrelius,[5] K. Fanning,[39,40] E. Fernández-García,[41] S. Ferraro,[2,37] A. Font-Ribera,[24] J. E. Forero-Romero,[42,43] C. S. Frenk,[26] C. Garcia-Quintero,[38,28] L. H. Garrison,[44,45] E. Gaztañaga,[46,23,47] H. Gil-Marín,[48,46,49] S. Gontcho A Gontcho,[2] D. Gonzalez,[50] A. X. Gonzalez-Morales,[50] C. Gordon,[24] D. Green,[51] G. Gutierrez,[21] J. Guy,[2] B. Hadzhiyska,[52,2,37] C. Hahn,[53] S. He,[54] M. Herbold,[25] H. K. Herrera-Alcantar,[55,1] M.-F. Ho,[9,8] K. Honscheid,[56,57,25] C. Howlett,[58] D. Huterer,[8] M. Ishak,[59] S. Juneau,[5] N. V. Kamble,[59] N. G. Karaçaylı,[56,60,57,25] R. Kehoe,[61] S. Kent,[20,21] A. G. Kim,[2] D. Kirkby,[51] T. Kisner,[2] S. E. Koposov,[18,52] A. Kremin,[2] A. Krolewski,[62,63,64] O. Lahav,[19] C. Lamman,[38] M. Landriau,[2] D. Lang,[63] J. Lasker,[65] J.M. Le Goff,[1] L. Le Guillou,[66] A. Leauthaud,[67,68] M. E. Levi,[2] Q. Li,[29] T. S. Li,[33] K. Lodha,[69,70] M. Lokken,[24] F. Lozano-Rodríguez,[50] C. Magneville,[1] M. Manera,[71,24] P. Martini,[56,60,25] W. L. Matthewson,[69] A. Meisner,[5] J. Mena-Fernández,[72] A. Menegas,[26] T. Mergulhão,[18] R. Miquel,[73,24] J. Moustakas,[74] A. Muñoz-Gutiérrez,[30] D. Muñoz-Santos,[75] A. D. Myers,[76] S. Nadathur,[23] K. Naidoo,[23] L. Napolitano,[76] J. A. Newman,[34] G. Niz,[50,11] H. E. Noriega,[10,30] E. Paillas,[77] N. Palanque-Delabrouille,[1,2] J. Pan,[8] J. A. Peacock,[18] M. P. Ibanez,[18] W. J. Percival,[62,63,64] A. Pérez-Fernández,[78] I. Pérez-Ràfols,[79] M. M. Pieri,[75] C. Poppett,[2,36,37] F. Prada,[41] D. Rabinowitz,[12] A. Raichoor,[2] C. Ramírez-Pérez,[24] M. Rashkovetskyi,[38] C. Ravoux,[80] J. Rich,[1,66] A. Rocher,[54,1] C. Rockosi,[67,68,81] J. Rohlf,[3] J. O. Román-Herrera,[50] A. J. Ross,[56,60,25] G. Rossi,[82] R. Ruggeri,[83] V. Ruhlmann-Kleider,[1] L. Samushia,[84,13,85] E. Sanchez,[31] N. Sanders,[86] D. Schlegel,[2] M. Schubnell,[8] H. Seo,[86] A. Shafieloo,[69,70] R. Sharples,[87,26] J. Silber,[2] F. Sinigaglia,[6,7] D. Sprayberry,[5] T. Tan,[1] G. Tarlé,[8] P. Taylor,[25] W. Turner,[56,60,25] L. A. Ureña-López,[50] R. Vaisakh,[61] F. Valdes,[5] G. Valogiannis,[20,21] M. Vargas-Magaña,[30] L. Verde,[73,49] M. Walther,[88,89] B. A. Weaver,[5] D. H. Weinberg,[60,25] M. White,[90,37] M. Wolfson,[25] C. Yèche,[1] J. Yu,[54] E. A. Zaborowski,[56,57,25] P. Zarrouk,[66] Z. Zhai,[91] H. Zhang,[62,64] C. Zhao,[92] G. B. Zhao,[93,94] R. Zhou,[2] and H. Zou[93]

- Came out in March 2025
- 2.4x more galaxies than DR1
- ~20 - 40% improvement in the BAO distances

DESI DE Results (DR2 BAO)



3.1σ, 2.8σ, 3.8σ, 4.2σ deviation from ΛCDM!!

Upcoming: DR2 Full Shape!!!

DESI DR2: 2025

Outline

Individual Projects

1\. Expansion History Prefs. Of DESI DR2

(Bansal & Huterer) (Phys. Rev. D 112, 023528)

2\. The challenges with late time solutions of Hubble Tension

(Bansal & Huterer) (In Prep)

Collab. Projects

3\. DESI DR2 BAO P4 validation test

(Andrade et. al.) (arXiV: 2503.14742)

5.Inclusion of FOLPS PS and BS in desilike

(Infra Task) (FOLPSD paper in prerp)

4\. DESI DR2 Comp. CMB validation

(DR2 BAO KP) (arXiV: 2503.14738)

6.Testing Alternate Bases for Full shape analysis

(with M. White and A. Avilles)

Undergrad Projects

7.SARAS3 Constraints on Coulomb-like DM interactions

Main Paper (In Prep)

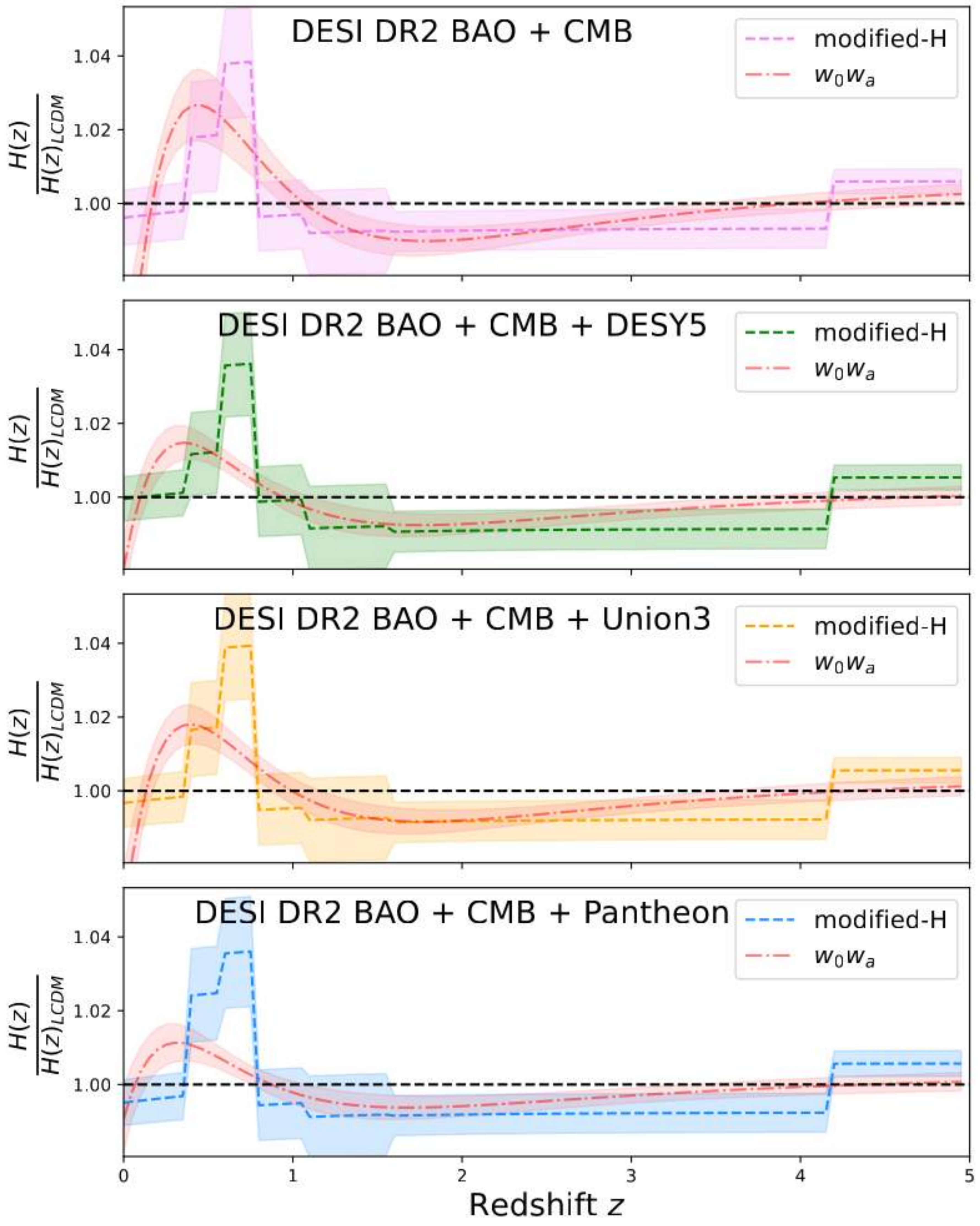
Pipeline Paper ECHO21 (arXiv: 2503.11762)

1. Expansion History Preferences of DESI DR2 and external data

Phys. Rev. D 112, 023528

16 citations so far….

Results



Modified-H Model

$$H(z) = H(z)^{LCDM}(1 + \alpha_i)$$

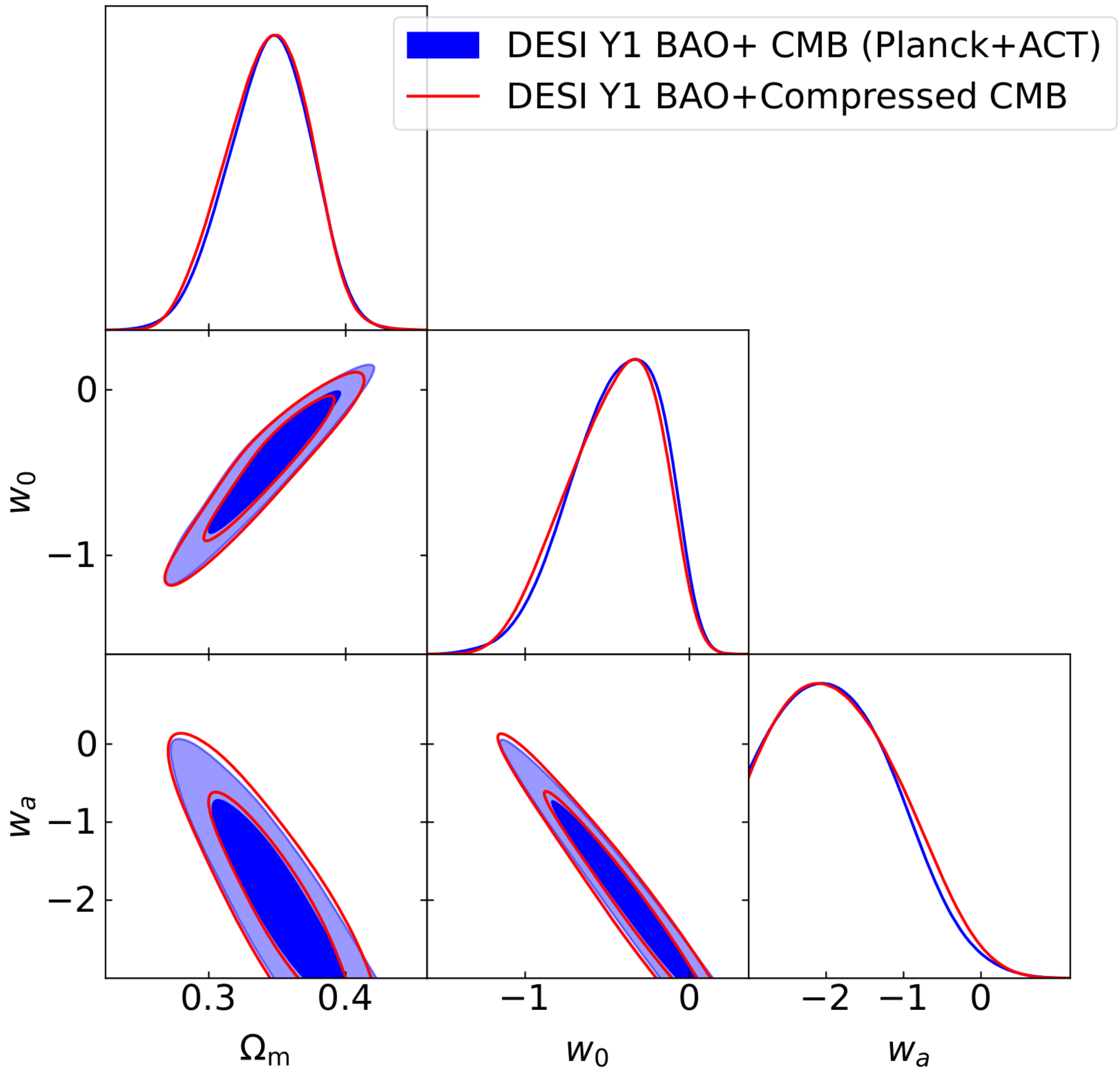
6 free parameters
(as opposed to 2 in $w_0 w_A$)

$w_0 w_a$ parametrization is flexible enough to model the DESI data favoured expansion history!!

Bansal & Huterer, Phys. Rev. D 112, 023528

Corollary: CMB Compression

- Full CMB likelihood: ~7K data points
- Compressed CMB: 3 data points
- Useful for non-physical models for which the CMB power spectrum cannot be evaluated



One of the most accurate compressions as of now!!
Also adopted in DESI DR2 BAO Key Paper*

Bansal & Huterer, Phys. Rev. D 112, 023528

2. The challenges with Late Time solutions for the Hubble Tension

(In Prep)

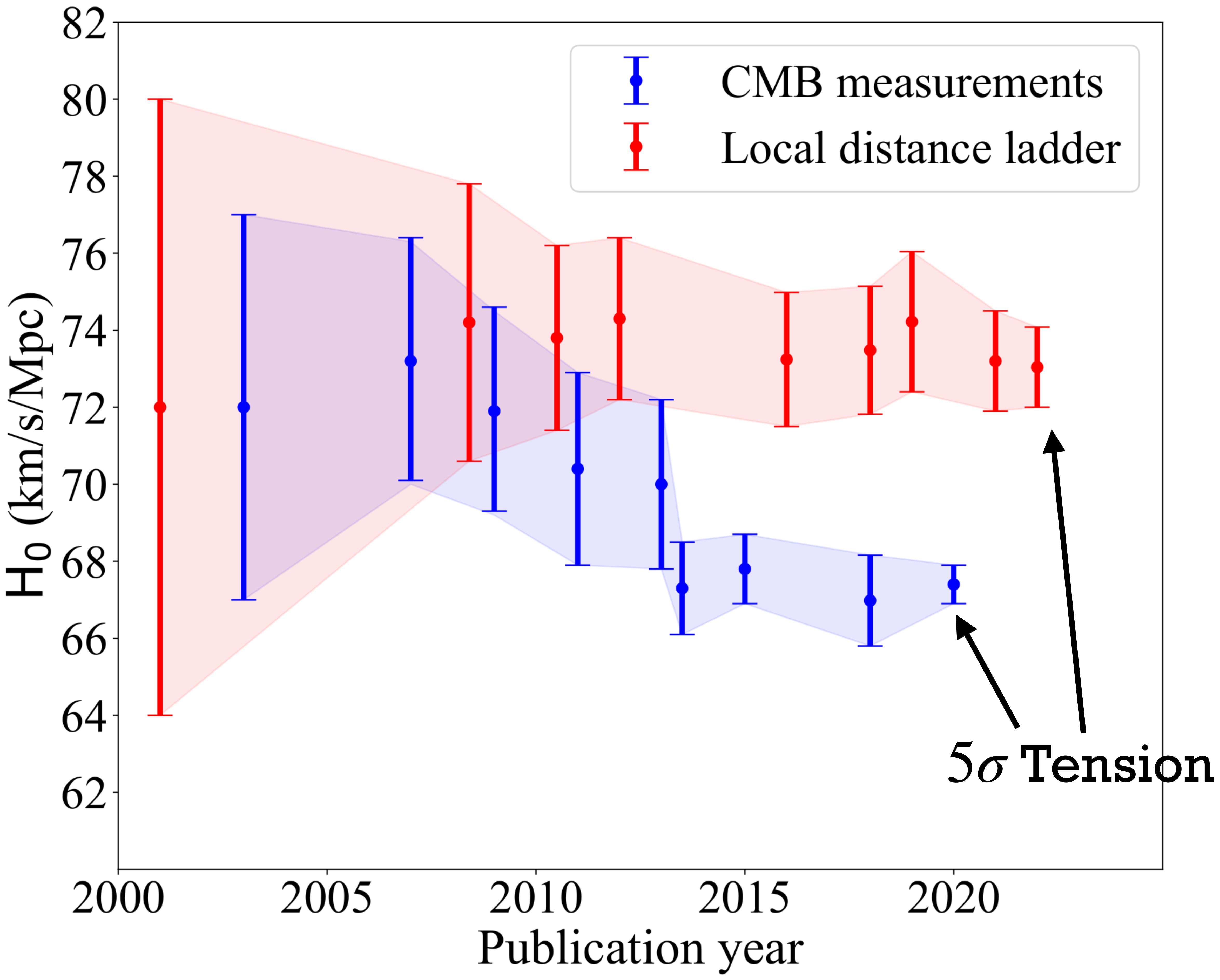
The Hubble Tension

H_0

Hubble Constant: Measure of the expansion rate today

Two ways to measure H_0

- CMB: Early Time Probe (z~ 1100)
- SNIa Distance Ladder: Late Time Probe (z~0.001-0.15)



Hu & Wang 2023

Late Time Solutions

It might be tempting to think of a solution, in which the Universe went through a phase of exotic expansion at late times!!

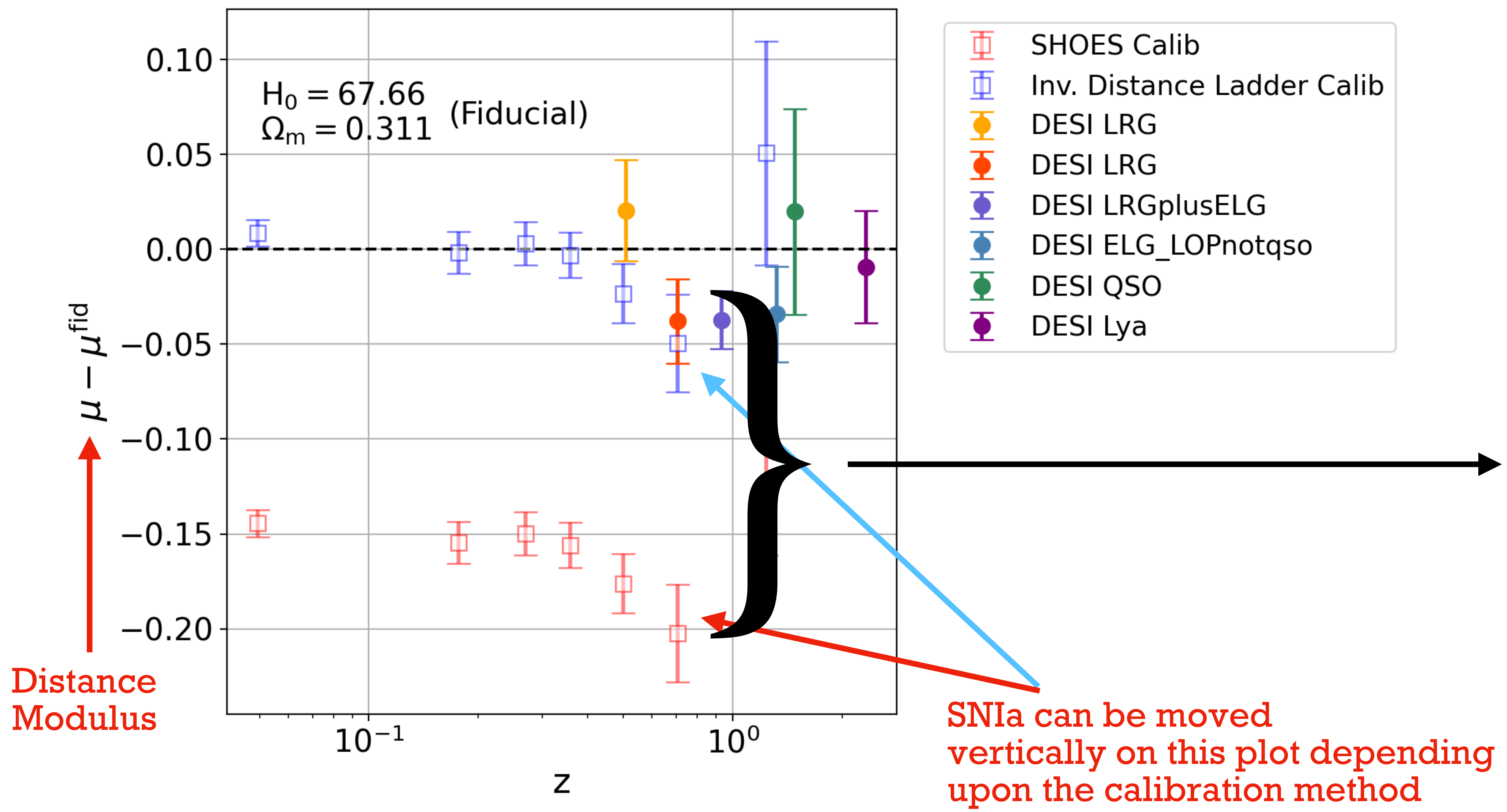
Late time solutions!!

In this work, we show that…..

Late time modifications to expansion history cannot resolve Hubble Tension!!*

Late Time Solutions

- SNIa measure relative distances
- They need to be “anchored” by some calibration method



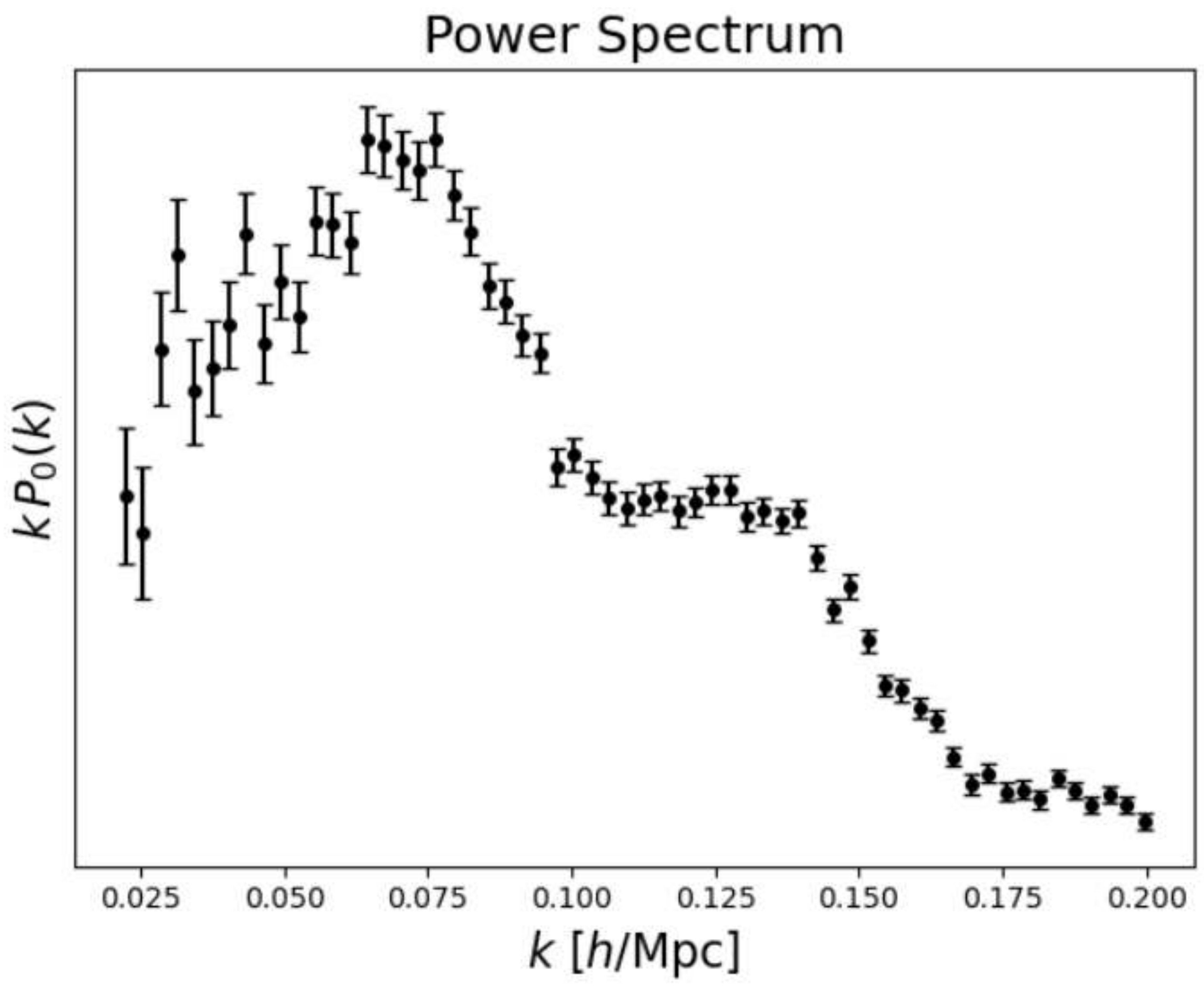
Any modification to expansion history cannot bring these points in agreement unless

- Distance Duality relation is broken
- The absolute magnitude of the SNIa evolves with redshift

We quantify how much the fit to the data improves for some test cases

5. Implementation of FOLPSv2 Power Spectrum and Bispectrum in DESI pipeline (with U. Andrade, H. Noriega & A. Avilles)

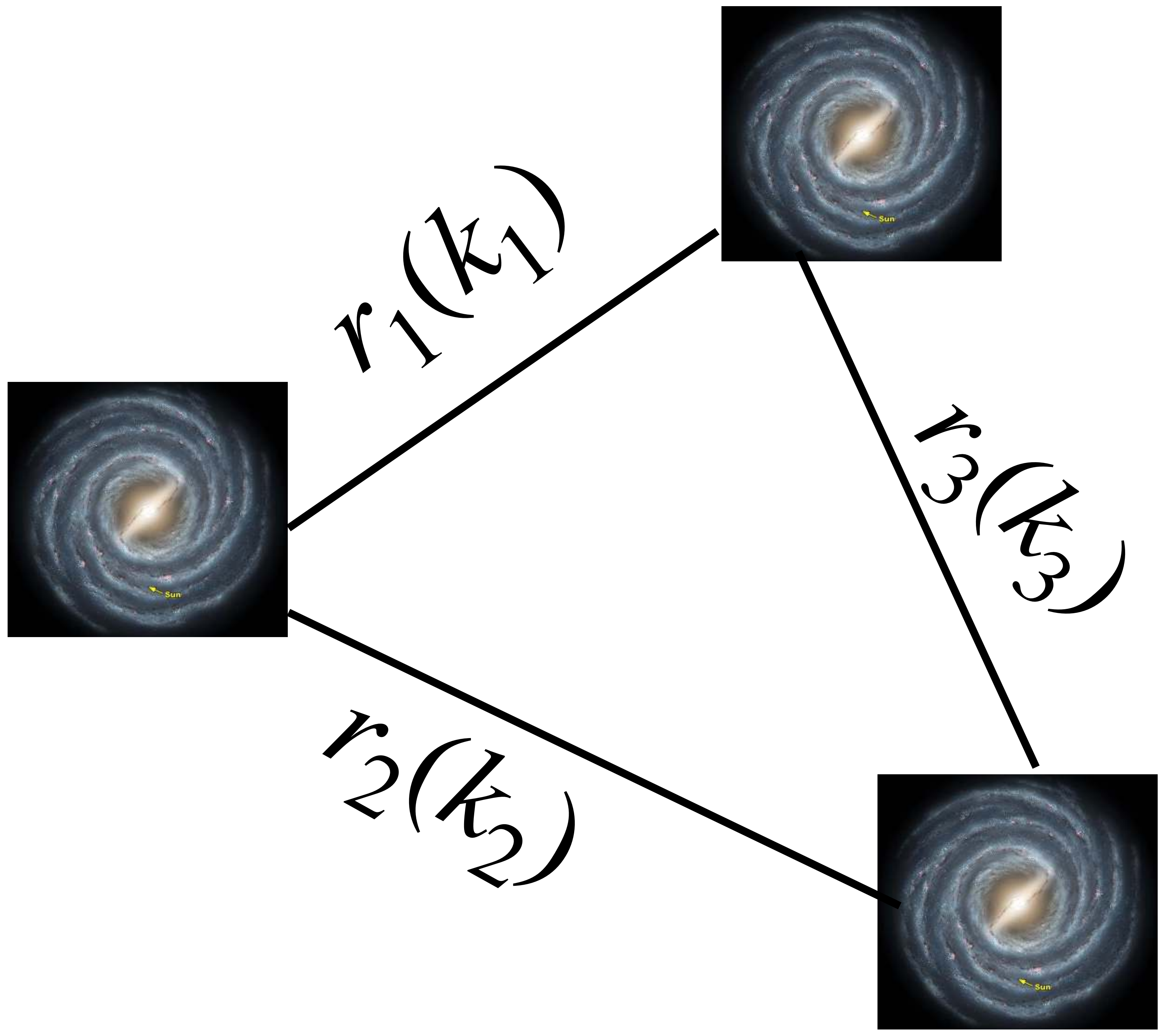
Power Spectrum



Fourier analogue of 2PCF

$P(k)$

Bispectrum



Fourier analogue of 3PCF

$B(k_1, k_2, k_3)$

FOLPS

Fast computation of non-linear power spectrum in cosmologies with massive neutrinos

Hernán E. Noriega,[a,b] Alejandro Aviles,[b,c,1] Sebastien Fromenteau,[d] Mariana Vargas-Magaña[a]

- EFT based code
- Massive ν and Modified gravity models
- Computationally very fast (~ 0.2s/ PS)

FOLPS-D

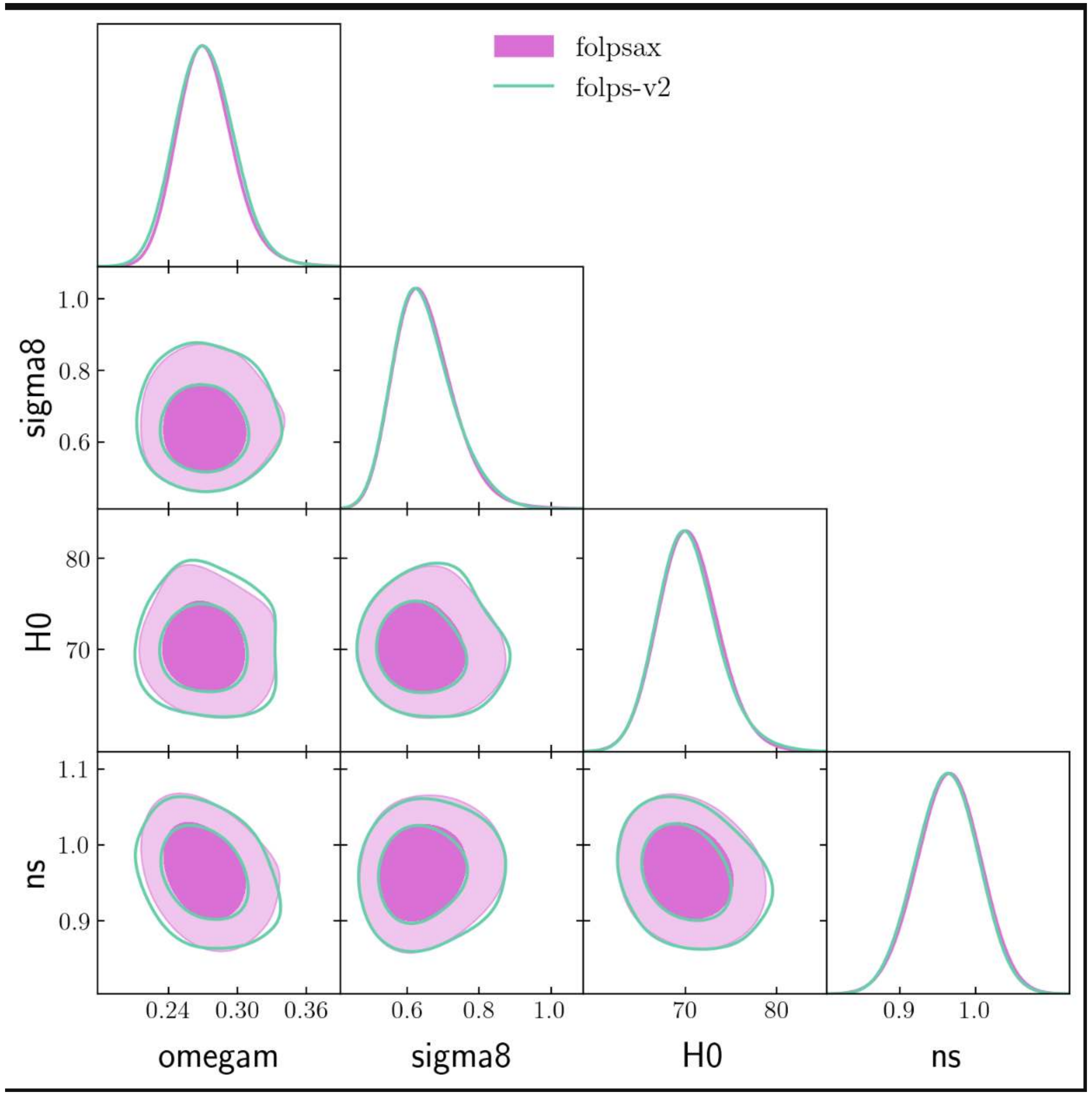
- Paper in preparation
- Bispectrum included
- EFT + a phenomenological damping term
- The pheno. damping term allows modelling upto higher k ($k_{max} \sim 0.3$ as opposed to 0.25 in EFT)
- Even faster (~ 0.1s/ PS, 0.02s/ BS)

Desilike implementation

Why do we care about desilike?

- Analytic marginalization
- Emulator for linear power spectrum
- Massive speedup
  Single PS chain
  (20 h $\longrightarrow$ 40 mins)

Stay Tuned
DESI DR1 PS + BS + DR2 BAO!!



SARAS3 Constraints on Millicharged DM particles

(with S. Mittal, V. Rentala, G. Kulkarni & S. Singh)

- ECHO21 (arXiv: 2502.07185)
- SARAS3 Constraints (In Prep)

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(Bansal & Huterer)
(Phys. Rev. D 112, 023528)

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(In Prep)

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Main Paper
(In Prep)

Pipeline Paper
ECHO21
(arXiv: 2503.11762)

Additional Slides

The Expanding Universe

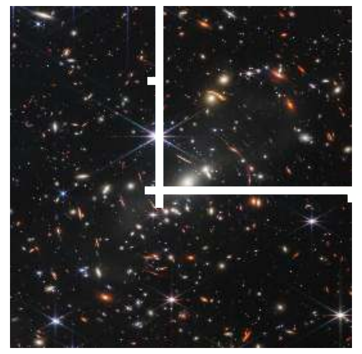


Image Credits: JWST

Compressed CMB

$$\mathbf{v}_{\rm CMB} \equiv \begin{pmatrix} R \\ \ell_a \\ \Omega_b h^2 \end{pmatrix} = \begin{pmatrix} 1.7504 \\ 301.77 \\ 0.022371 \end{pmatrix}$$

$$R = 100\sqrt{\Omega_b + \Omega_{cdm} + \Omega_{\nu,\rm m}}\, h D_{M*}/c$$

$$\ell_a = \pi D_{M*}/r_*,$$

$R \rightarrow$ Shift Parameter

$\ell \rightarrow$ Angular Accoustic Scale

- Useful for non-physical models for which the CMB power spectrum cannot be evaluated

- Means and Covariances calculated from Planck+ACT6 lensing LCDM chains

- Validated against LCDM and w0wa CDM full CMB constraints

So how does H0 measurement from SNIa work?

$$\mu = 5\log_{10}(d_L) + 25$$
$$m_{app} = \mu + M_{abs}$$
$$m_{app} = 5\log_{10}(d_L) + 25 + M_{abs}$$

$$d_L = (1+z)^2 d_A$$
$$d_A = \int_0^{z_s} \frac{dz}{H(z)} = \int_0^{z_s} \frac{dz}{H_0 E(z)}$$
$$\implies (H_0 d_L) \text{ is } \mathrm{H}_0 \text{ independent}$$

$$m_{app} = 5\log_{10}(H_0 d_L) - 5\log_{10} H_0 + 25 + M_{abs}$$
$$m_{app} = 5\log H_0 d_L + \mathscr{M}$$

$\{$SN Properties, $H_0\}$

$\{\Omega_M, \Omega_K, w_0, w_a \ldots\}$

What could we do at late times to fix this?

1. Violating Distance Duality Relation $(d_L = (1+z)^n d_A \; ; \; n \neq 2)$
2. A late time transition in SNIa absolute magnitude M
3. A late time transition in SNIa absolute magnitude M along with a modification in expansion history

So how does H0 measurement from SNIa work?

Usually in a cosmological analysis, we marginalize over $\mathscr{M}$ and thus the

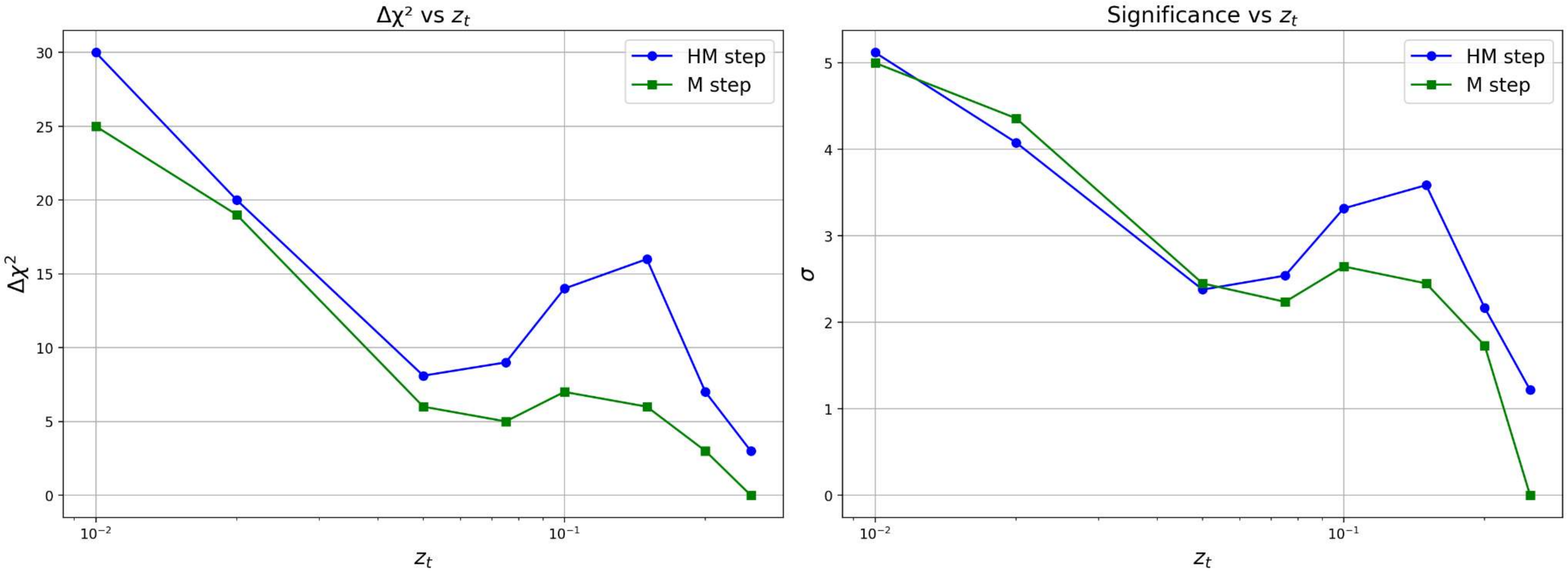
Statement, “SNIa alone cannot constraint H_0”

But, if we don’t marginalize, then we can get a very good constraint on $\mathscr{M}$

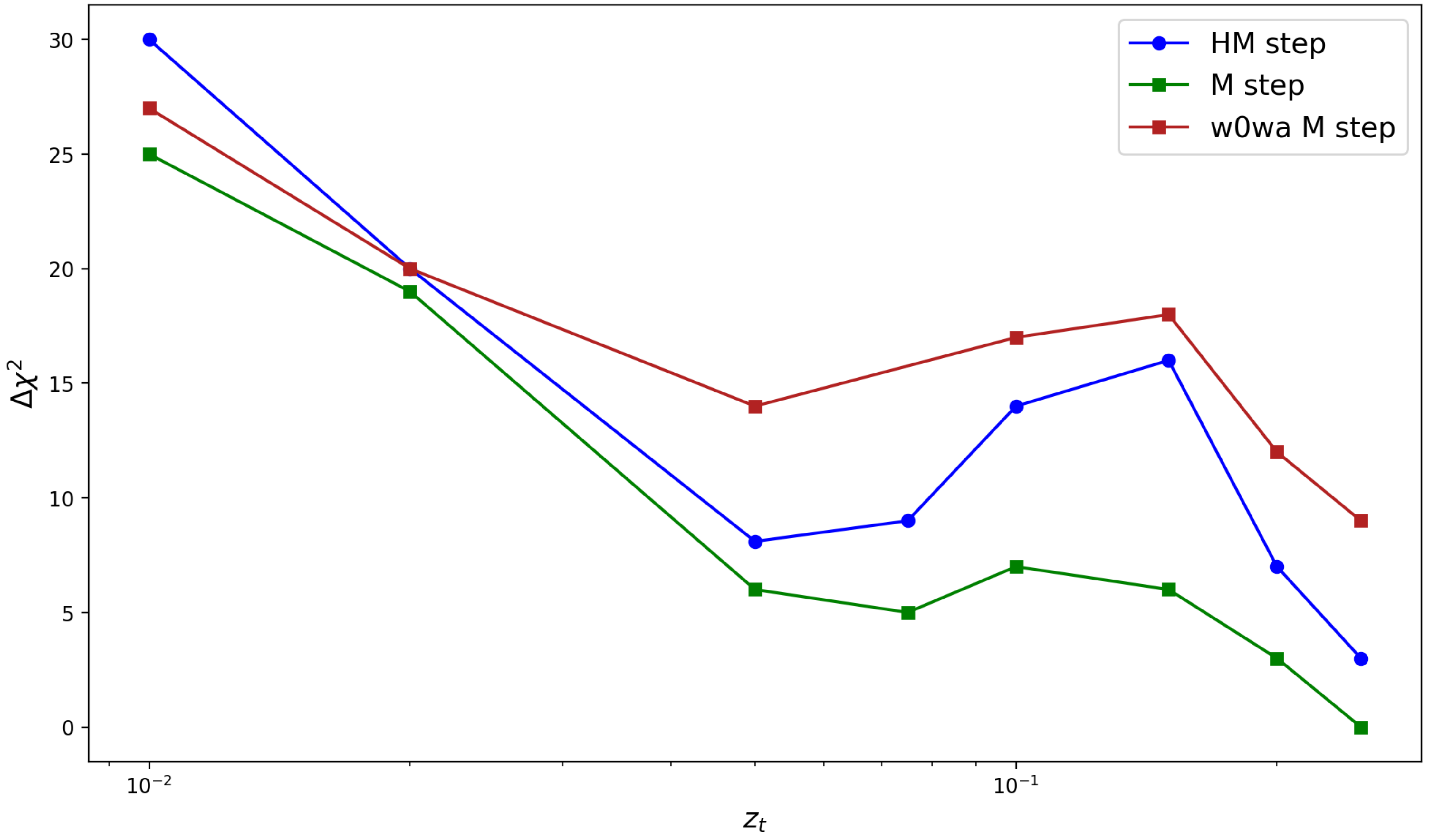
And then we need an independent measurement to break the degeneracy

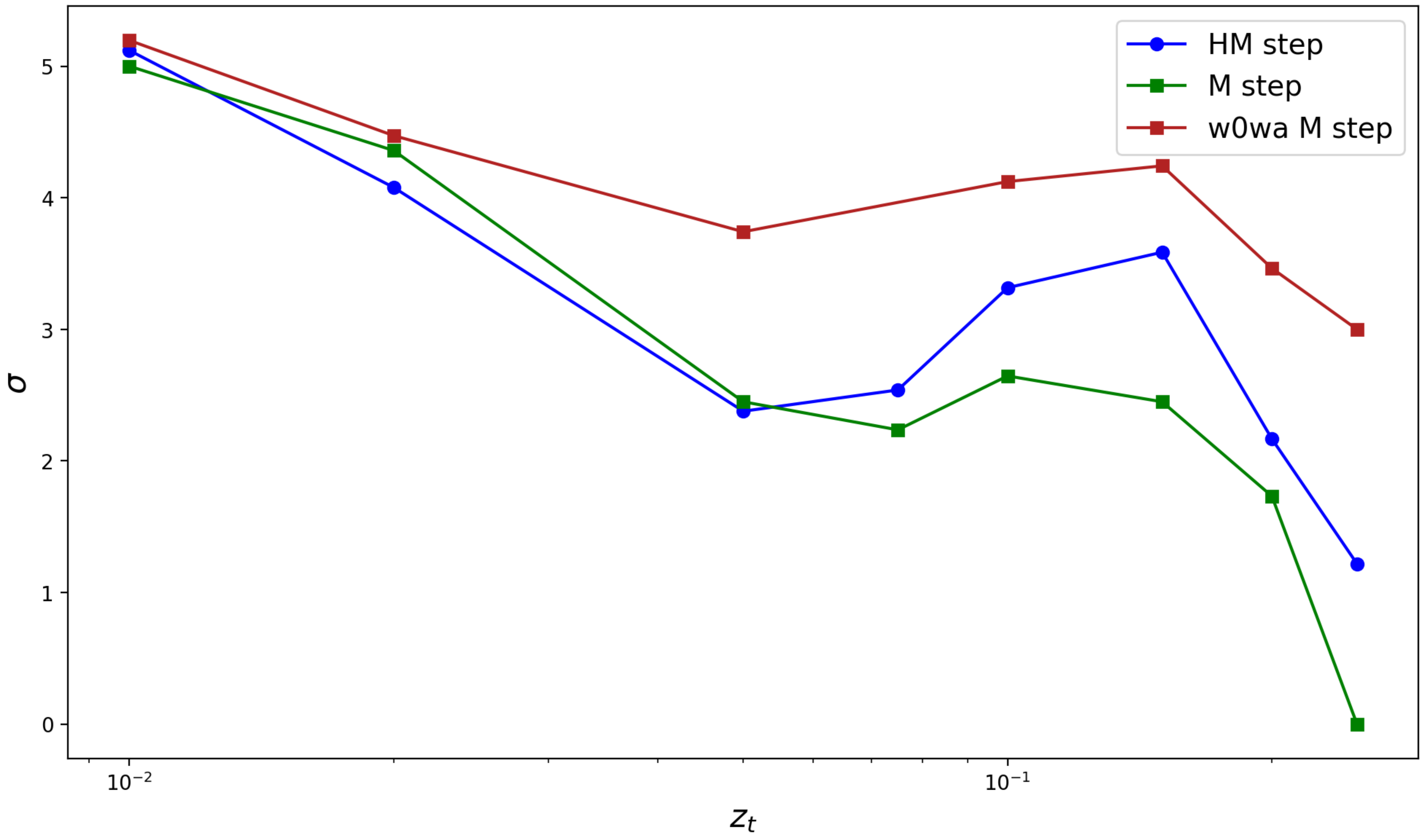
B/w H_0 and M_{abs}

What could we do at late times to fix this?



What could we do at late times to fix this?





The global 21-cm Signal

Observables

Low-z
(Late Universe)

BAO, SNIa
Weak & Strong Lensing

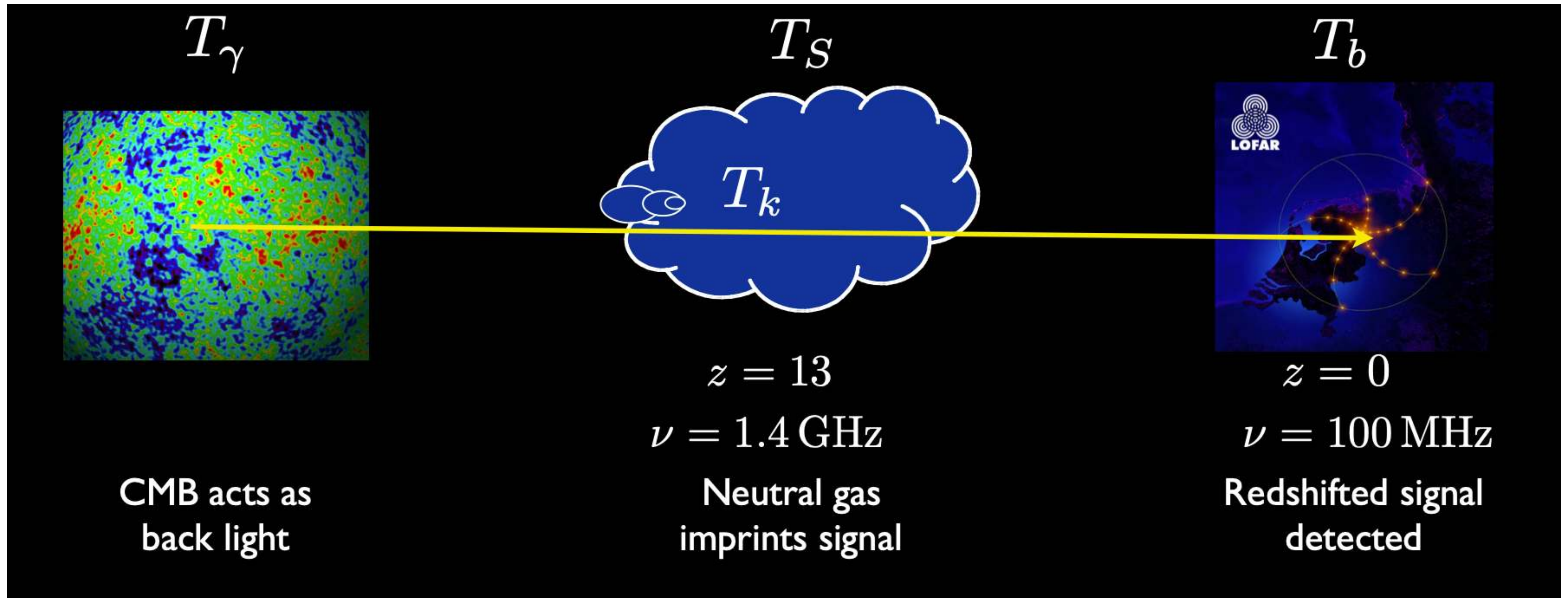
Z ~ 0.01 - 3

High-z
(Early Universe)

CMB

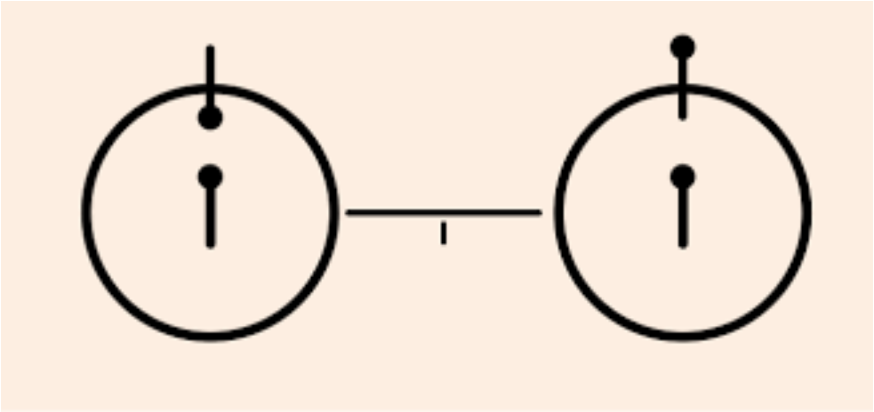
Z ~1100

Intermediate
Universe?



Intermediate Universe

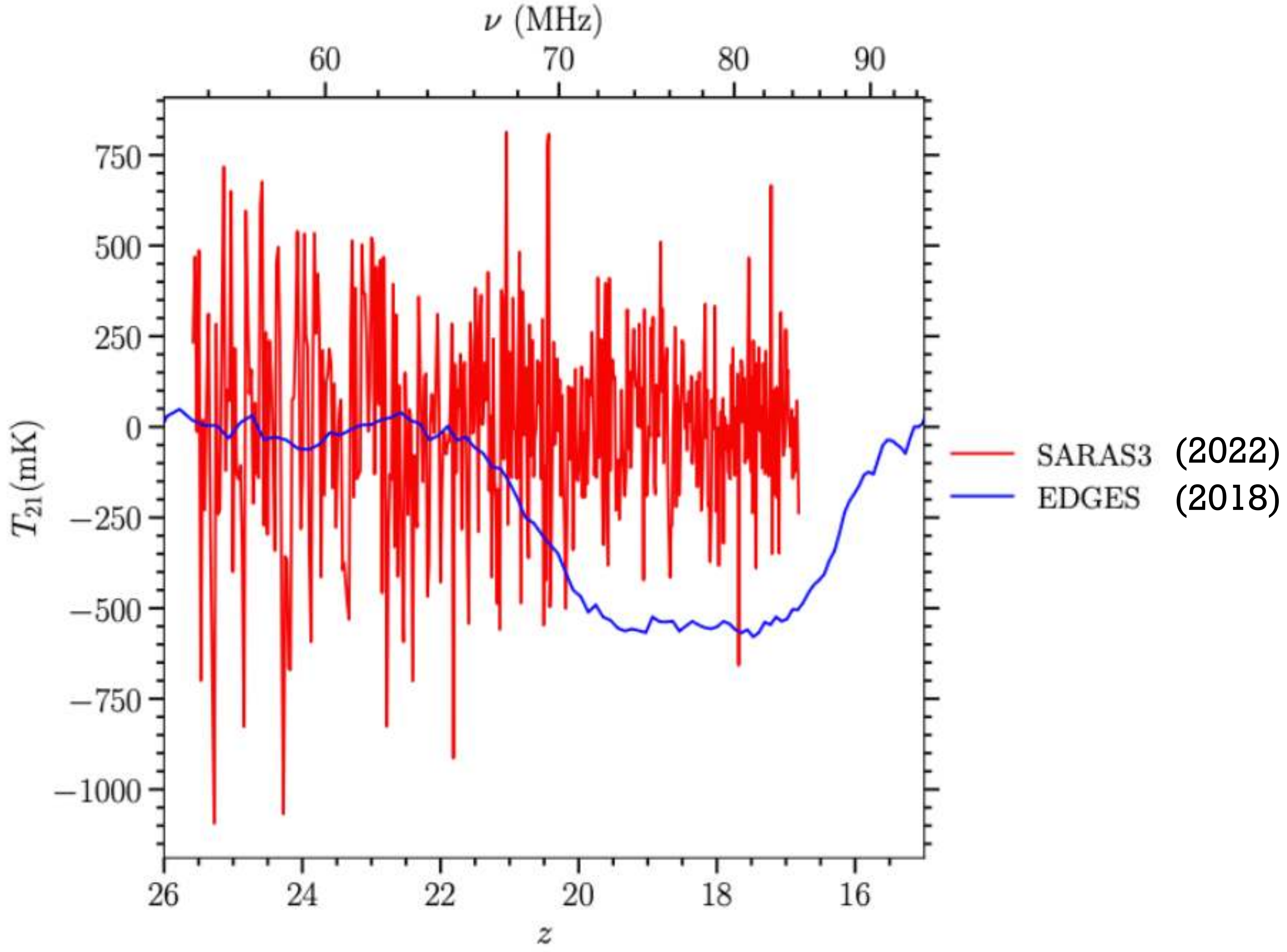
- Filled with clumps of Neutral H clouds

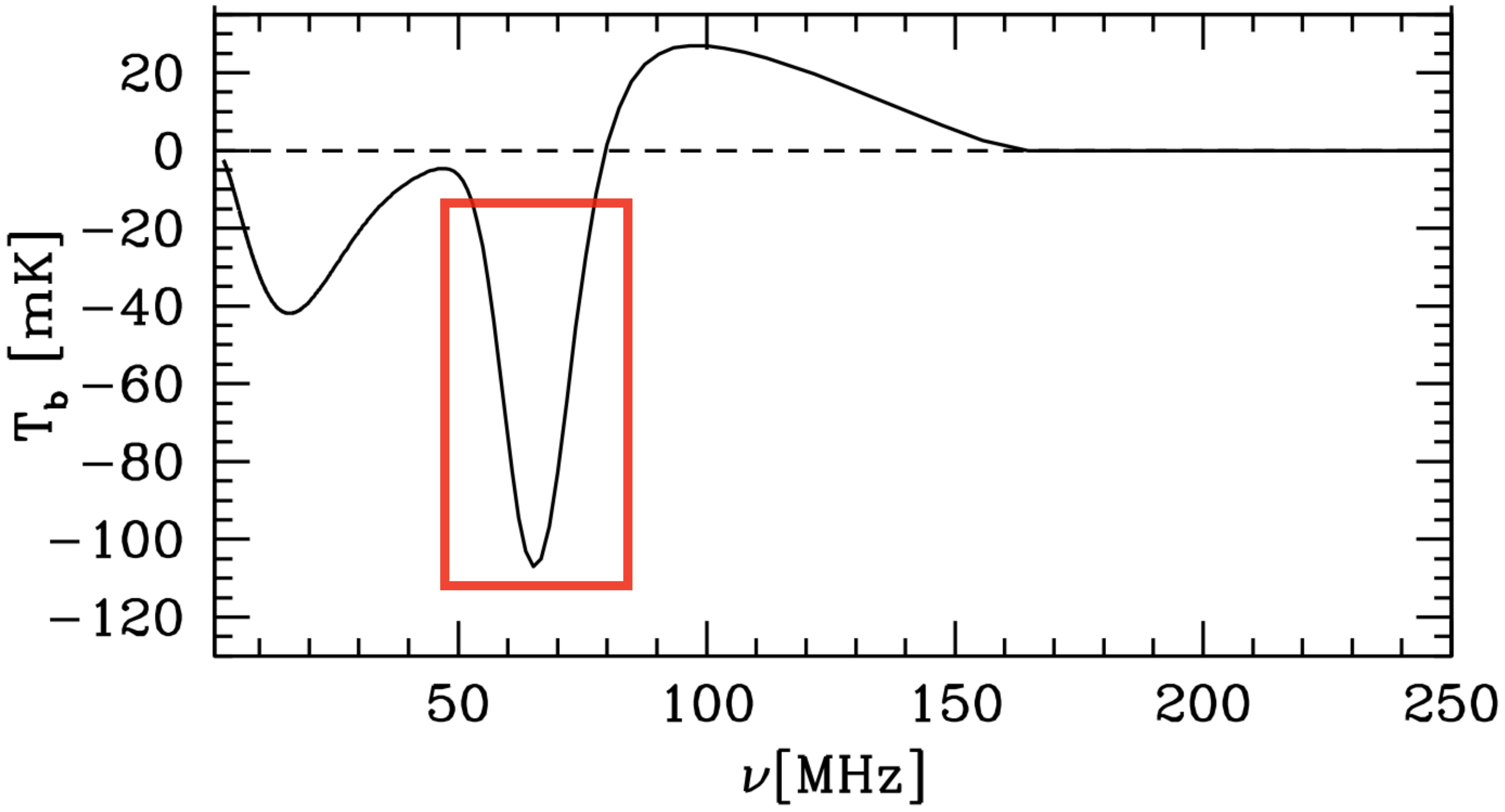


- Only possible transiton: Hyperfine Transition (21 cm)

Credits: Wikipedia, Jonathan Pritchard

SARAS3 vs EDGES





Some absorption dip
is expected in CDM model!!

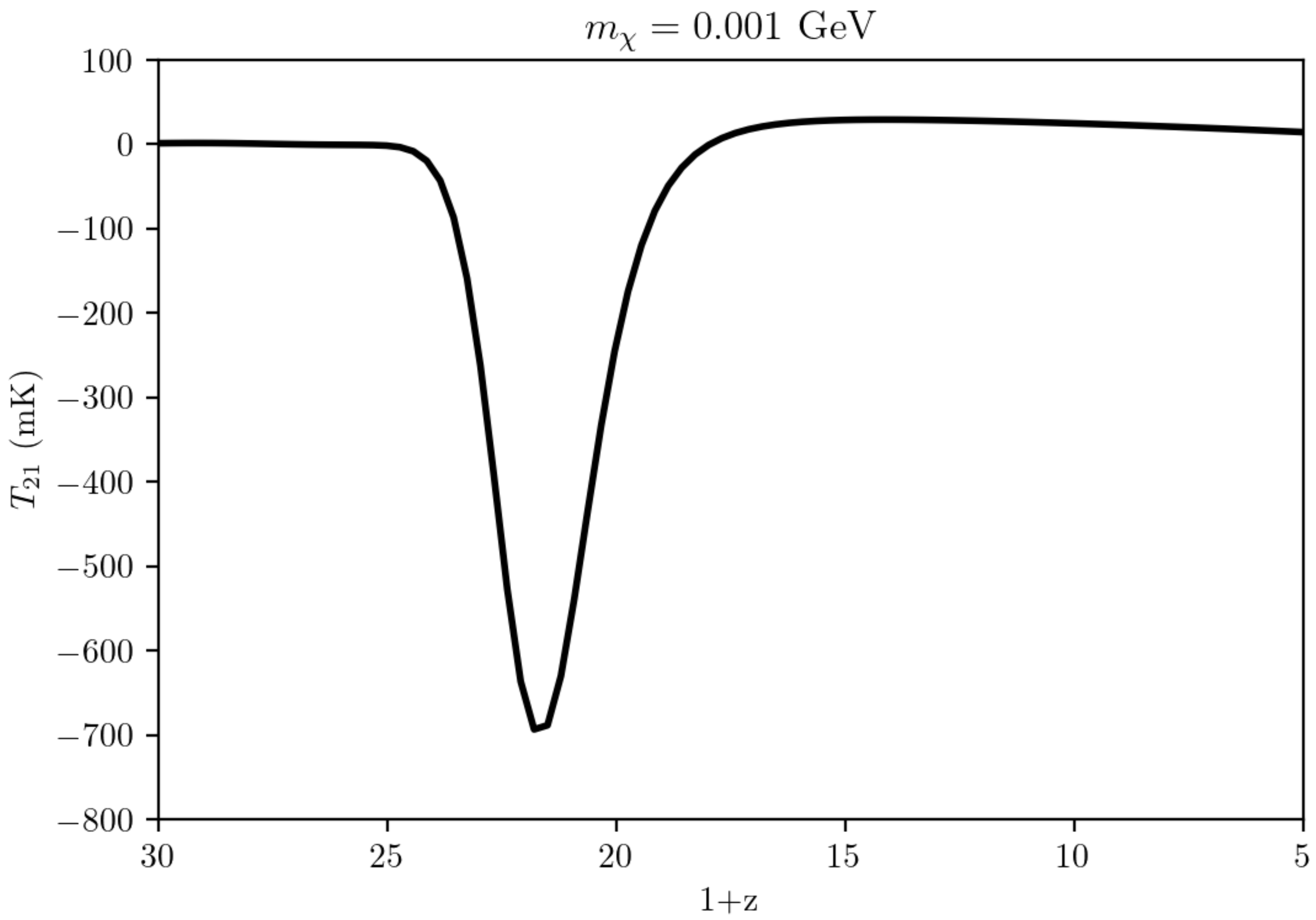
Signature of some exotic Physics!?

Credits: Jonathan Pritchard

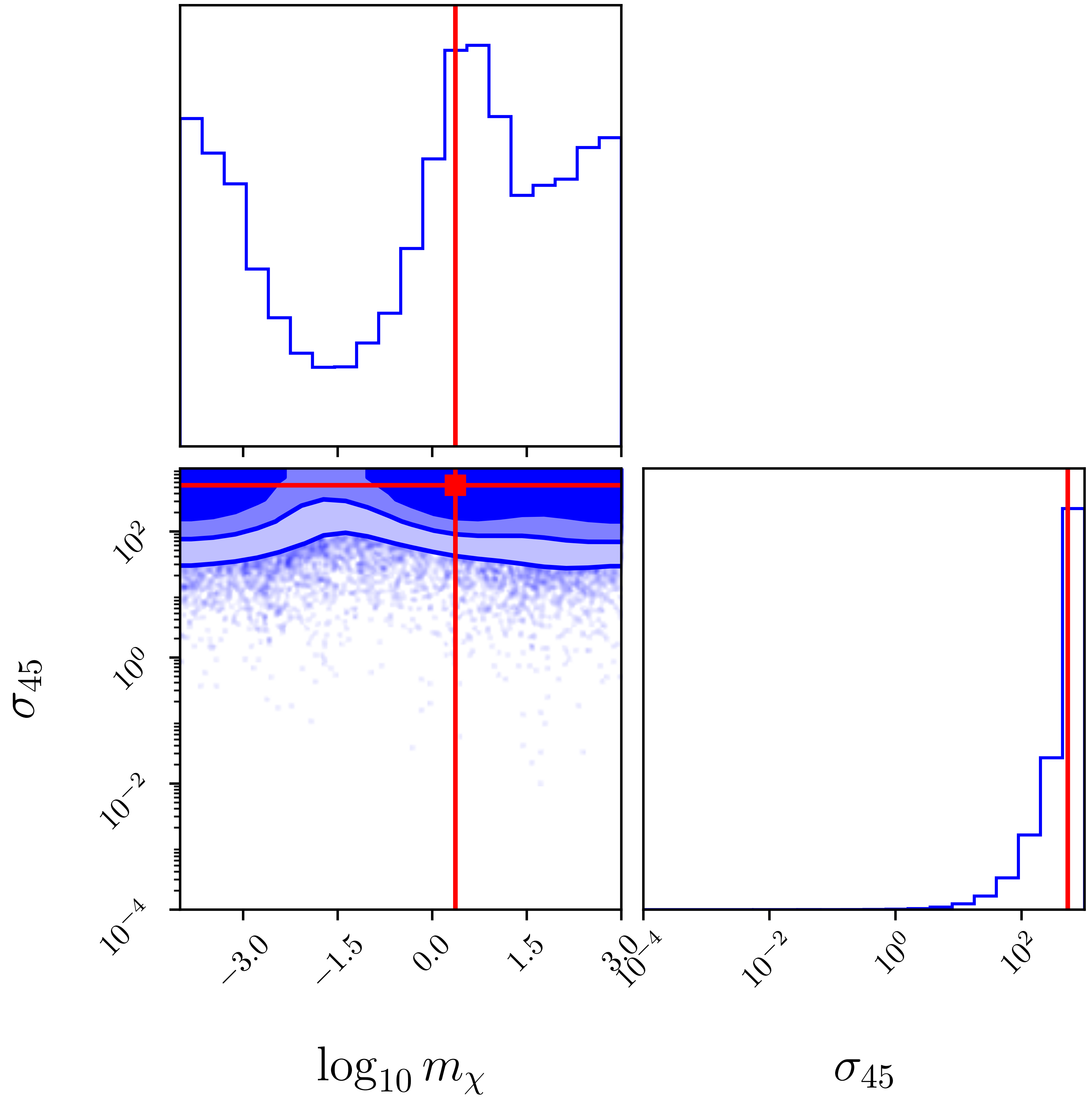
The IDM Model

- Interacting DM with Coulomb-like interactions
- Parametrized by DM Mass (m_χ) and Interaction Cross Section (σ_0)

$$\sigma = \sigma_0 v_{b\chi}^{-4}$$



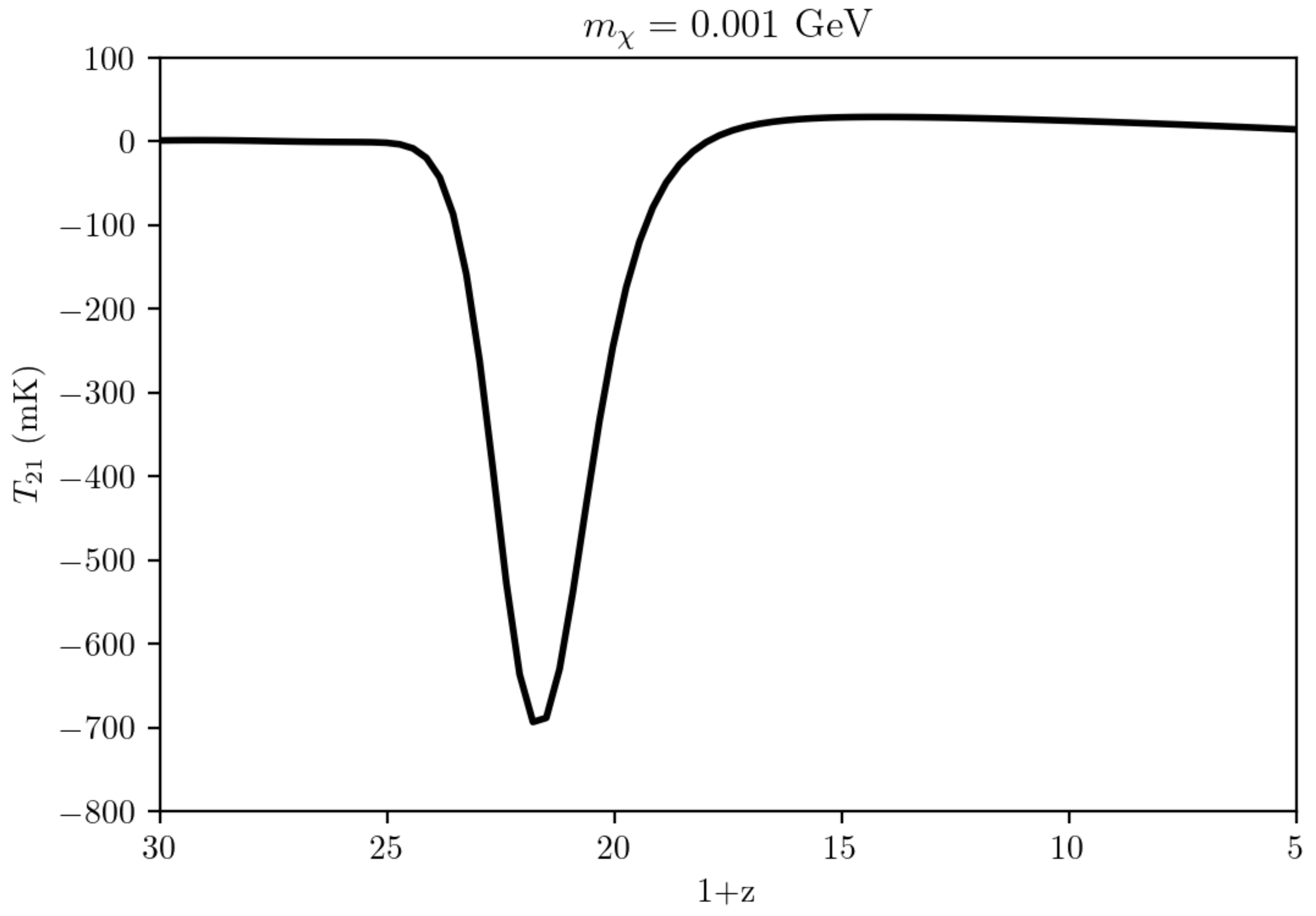
Results

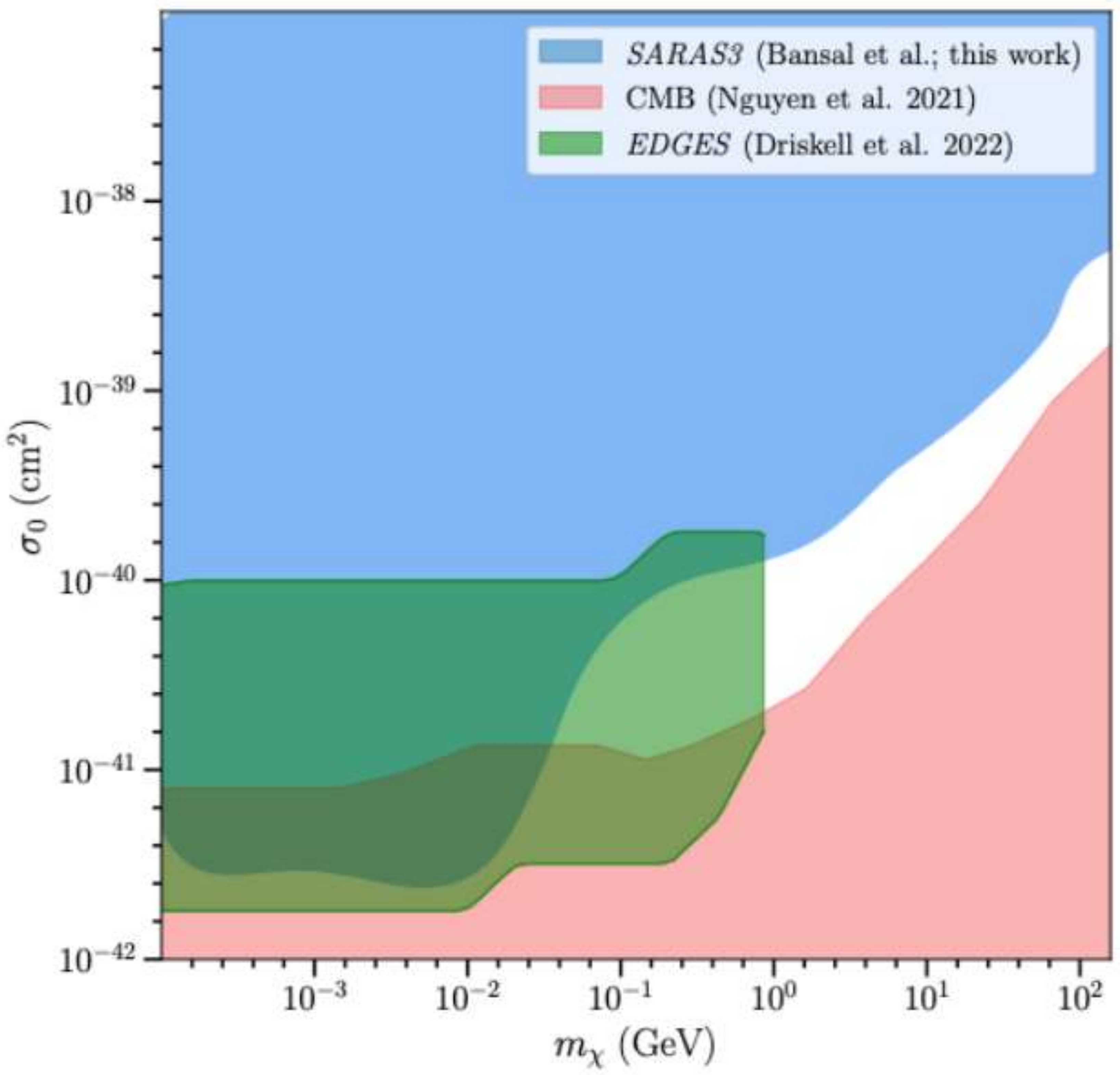


- The null signal in SARAS3 data favours high interaction cross sections
- Uncertainity in Astrophysical parameters prevent stronger bounds on DM params
- Combining with CMB can help putting an upper bound on σ_0

Code: Echo 21 (Mittal et al 2025)

Effect of IDM mass on global signal





SARAS3 (Bansal et al.; this work)
CMB (Nguyen et al. 2021)
EDGES (Driskell et al. 2022)
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
σ_0 (cm^2)
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
m_χ (GeV)