Cosmological and Gravitational Wave Probes of Beyond the Standard Model Physics

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Based on:
I.Allali, AN, F.Rompineve 2404.15220
R. Z. Ferreira, AN, O. Pujolàs, F. Rompineve, JCAP 06 (2024) 020
R. Z. Ferreira, AN, O. Pujolàs, F. Rompineve, JCAP 02 (2023), 001

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Primordial Black Holes from Domain Walls

Cosmology and Fundamental Physics

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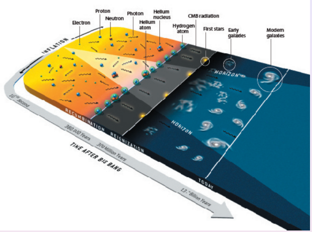
- Opportunity to discover new physics from cosmological data (Dark Matter, Dark energy, or... other Dark relic light particles?)
- Opportunity to discover new Physics from relic Gravitational Waves (e.g. theories with discrete broken symmetries)

Relics from expanding Universe



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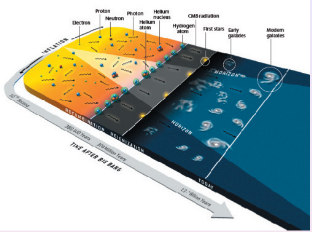

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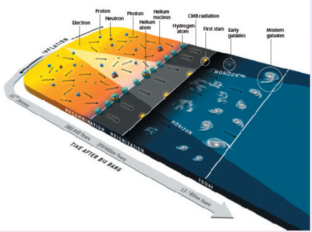

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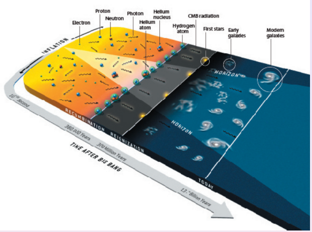

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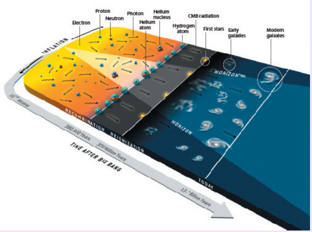

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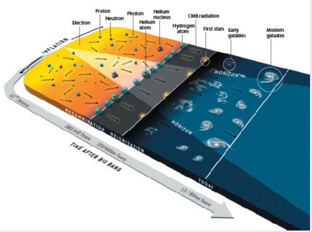

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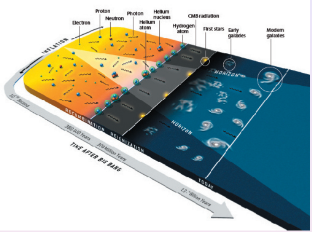

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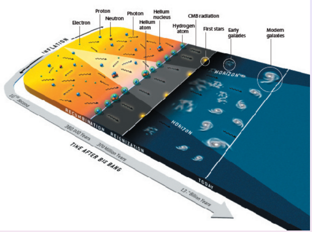

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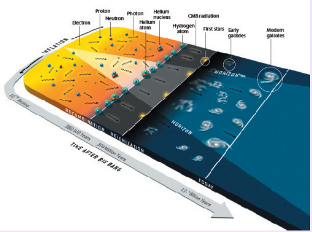

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- Relic primordial Gravitational Waves ?

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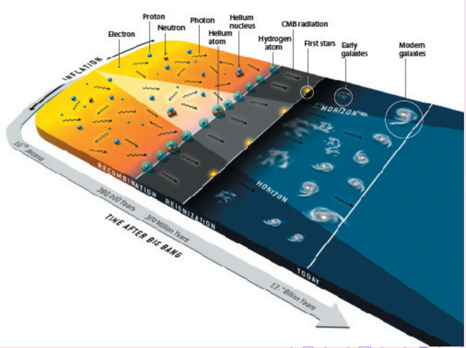
- Oscillations are frozen in when hydrogen forms (recombination): CMB photons emitted



CMB fluctuations

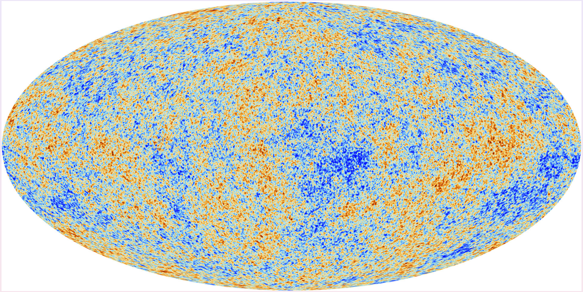


Figure: Credit: ESA and the Planck Collaboration

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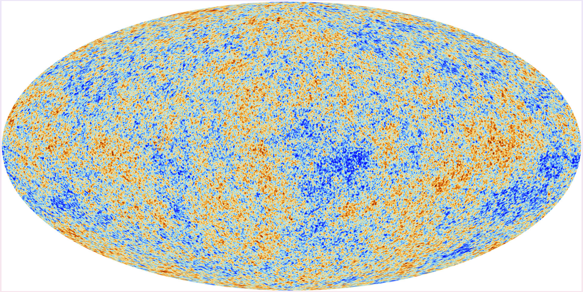

Figure: Credit: ESA and the Planck Collaboration

- Preferred angular scale of $\theta_{\text{peak}} \approx 1^\circ$

Sound horizon at CMB

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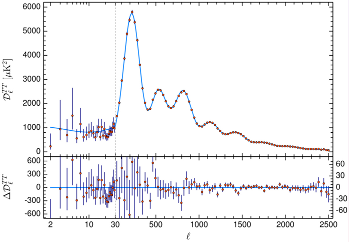
- Sound horizon at decoupling r_d: length scale imprinted in CMB
- "Standard ruler" of early universe, stretched to ~ 150 Mpc today
- r_d: the distance sound can travel from big bang until decoupling:

$$r_d = \int_{z_d}^{\infty} \frac{c_s(z)}{H(z)} dz$$

($H =$ Hubble parameter, $c_s \approx 1/3$ plasma sound speed)

Sound horizon in CMB

- Length scale r_d corresponds to angular scale in CMB $\theta_{\text{peak}} \sim 1/\ell_{\text{peak}}$



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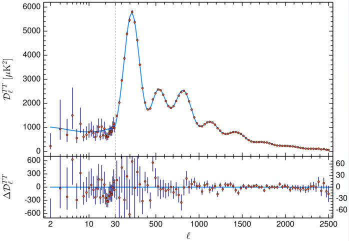

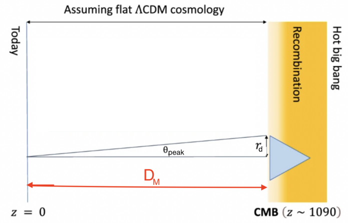

- Angular scale $\theta_{\rm peak} \approx 1^\circ \propto \dfrac{r_d}{D_M(z_{\rm decoupling})}$

  ($D_M(z) \equiv \int_0^z \frac{dz'}{H(z')}$ "transverse distance" from observer to decoupling)

Sound horizon in matter distribution

- The same sound horizion scale r_d is imprinted also in the galaxy distribution at late times

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- "Standard ruler" of early universe, stretched to ~ 150 Mpc at late-time: visible in galaxy correlations
- Baryon Acoustic Oscillations (BAO)

Measuring BAO

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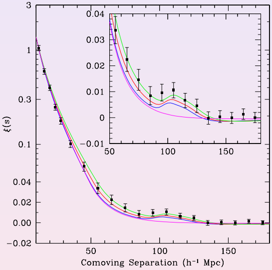

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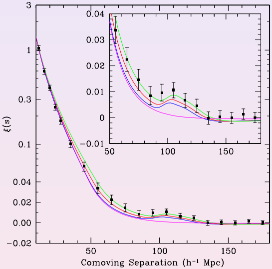

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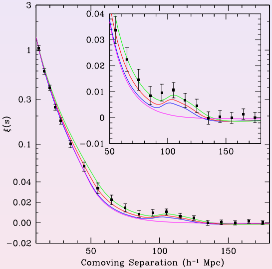

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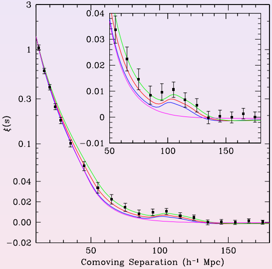

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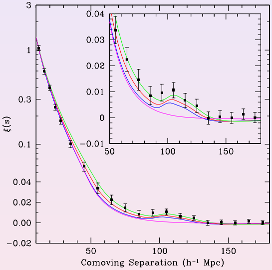
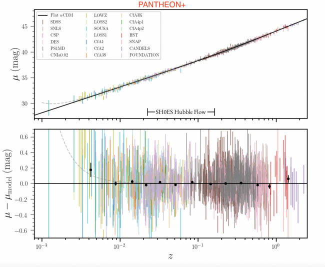


- $$\boxed{\Delta\theta = r_d / D_M(z)}$$
- Transverse comoving distance $D_M(z) = \int_0^z \frac{dz'}{H(z')}$
- Given a cosmological model $\implies r_d$

  $\implies$ BAO+CMB measure Distance D_M vs Redshift (z)

Supernovae



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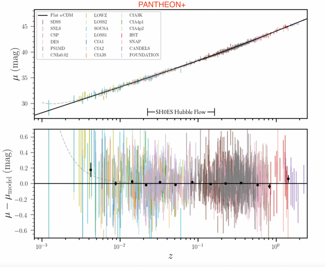

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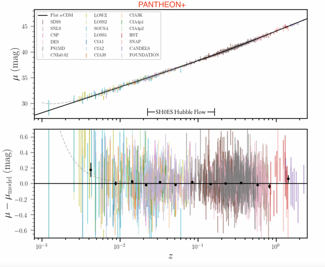

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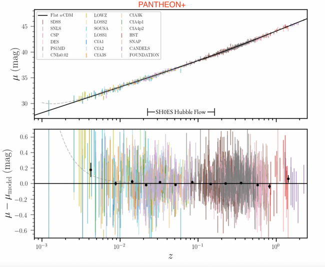

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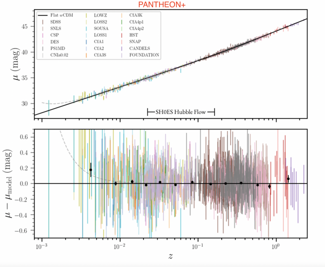

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- Only if Intrinsic luminosity known (calibration) $\rightarrow$ H_0 is measured

ΛCDM Concordance Model

BAO + CMB + uncalibrated Supernovae: establish the "Standard" ΛCDM cosmological model:

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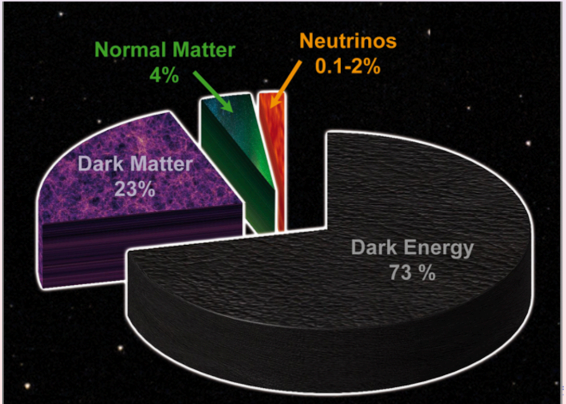

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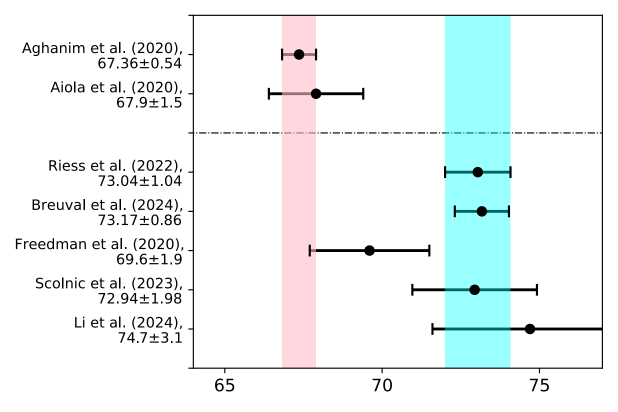
- Two groups:
  - SH0ES (Riess et al.), smallest statistical error
  - Carnegie-Chicago Hubble Project "CCHP" (Freedman et al.)

Disagreement in H_0 [km/s/Mpc]

Inferences from CMB+BAO+Uncalibrated SNe in the ΛCDM model disagree with the distance ladder measurement from SH0ES



(adapted from Di Valentino et al 21)

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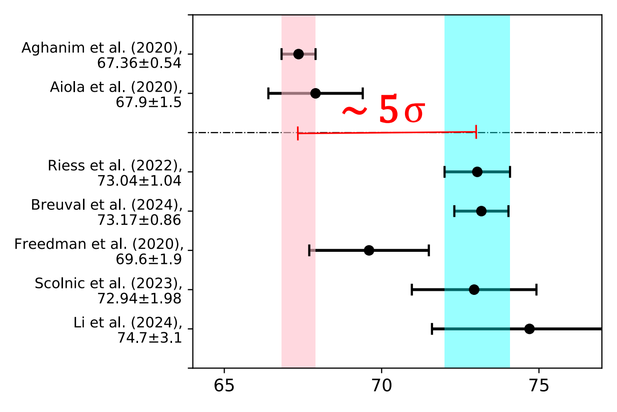

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  - More complex models, like "EDE", did better but lack simple embedding in particle physics (Kamionkowski et al 22, Qu et al 24)
- In light of new BAO data (DESI 2024), the status of tensions must be reassessed

Dark Energy Spectroscopic Instrument (DESI)

- Measures BAO in galaxies, quasars, and Lyman-α forest
- Redshift range $\boxed{0.1 < z < 4.2}$
- $\rightarrow$ Measure expansion history at highest precision yet

(Adame et al 24 (DESI III, VI), Abareshi et al 22)

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With respect to previous BAO measurements (6dFGS, BOSS, eBOSS, WiggleZ)

- 40 million target galaxies and quasars (vs. $\sim 3-4$ million)
- Aim to increase precision on distance $5-10\times$
- Extended redshift range $(0,1) \rightarrow (0,2.1)$
    - $(2,4) \rightarrow (1.77,4.16)$ for Lyα

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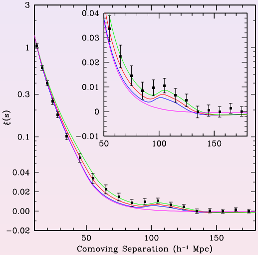
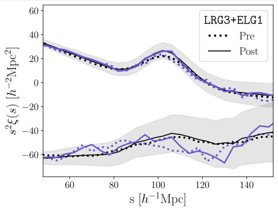
BAO from DESI

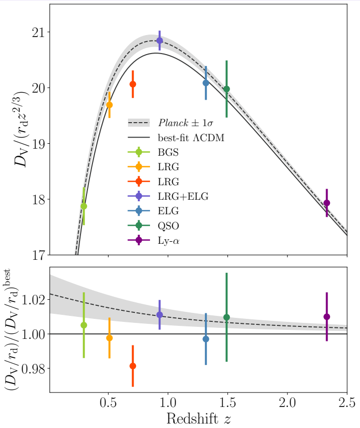


(from SDSS, Eisenstein et al 05)



(from DESI, Adame et al 24 (III))

Distance-redshift from DESI



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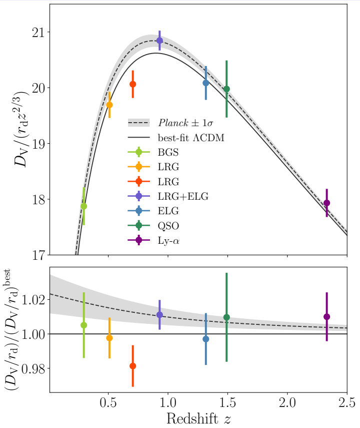

- Data point at $z \sim 0.7$ low.
- Discrepancy at $\sim 3\sigma$ level with old BAO (SDSS+6DFGS)

(from DESI, Adame et al 24)

Extract Cosmological Parameters

Datasets considered:

- **Planck18**: CMB (and CMB lensing) from *Planck* (Aghanim et al 18)
- **Pantheon+** (Scolnic et al 22) or **DESYR5** Uncalibrated Supernovae
- **DESI**: BAO from DESI 2024 DR1 (Adame et al (DESI VI) 24)

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- Cosmologies computed with Einstein-Boltzmann code `CLASS` (Blas + Lesgourgues + Tram 11)
- MCMC analysis: `MontePython` (Audren et al 12, Brinckmann + Lesgourgues 18)

With or without SH0ES?

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- With SH0ES: which model does best?
  - New physics at Early Time: Dark Radiation (Allali, AN, Rompineve arXiv:2404.15220)

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Dark Radiation (DR): extra light degrees of freedom

- Extra radiation increases H in the Early universe $\rightarrow$ changes $\boxed{r_d = \int_{z_d}^{\infty} \frac{c_s(z)}{H(z)} dz}$
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- Almost negligible today
- Can be fermionic, bosonic, low mass, massless, interacting, non-interacting . . .
- Examples: axions, gravitational waves, etc....

Dark Radiation (DR): extra light degrees of freedom

DR parameterized as an "effective number of extra neutrino species"

$$N_{\text{eff}} \equiv (\rho_\nu + \rho_{\text{DR}})/\rho_{\nu,1}$$

ΛCDM includes $N_{\text{eff}} = 3.044$ for 3 (massive) SM neutrinos

- The 0.044 is a SM correction (spectrum not exactly thermal)

Dark Radiation (DR): extra light degrees of freedom

DR parameterized as an "effective number of extra neutrino species"

$$N_{\text{eff}} \equiv (\rho_\nu + \rho_{\text{DR}})/\rho_{\nu,1}$$

ΛCDM includes $N_{\text{eff}} = 3.044$ for 3 (massive) SM neutrinos

- The 0.044 is a SM correction (spectrum not exactly thermal)
- Extra light degrees of freedom contribute as $N_{\text{eff}} = 3.044 + \Delta N_{\text{eff}}$

Relic light particle abundance ($\Delta N_{\rm eff}$) from decoupling

- Relic abundance $\Delta N_{\rm eff} \propto \frac{\rho_a}{\rho_\gamma}\Big|_{\rm CMB} \propto \frac{1}{g_{*,DEC}^{4/3}}$ at DECOUPLING

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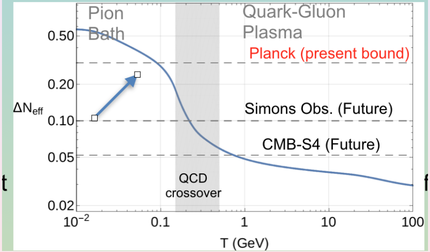

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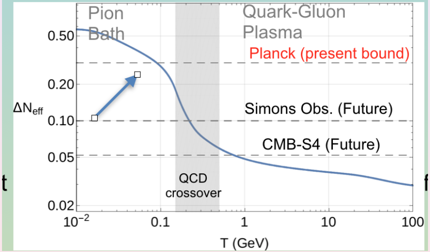

- Example: axions via Scattering with pions $\pi\pi \to \pi a$ below $T \lesssim 150$ MeV (QCD PT) (AN, F. Rompineve, G. Villadoro, PRL 2023)

DR: One-parameter extensions to ΛCDM

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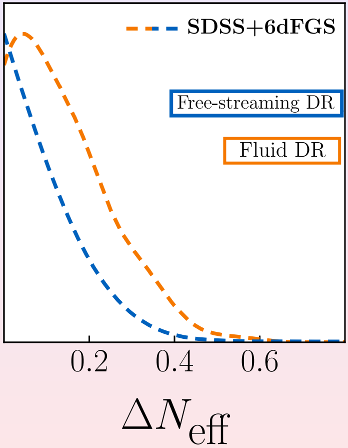
- Freestreaming (FS) dark radiation $\implies$ phase shift of the higher CMB peaks position

DR Constraints before DESI (without SH0ES)

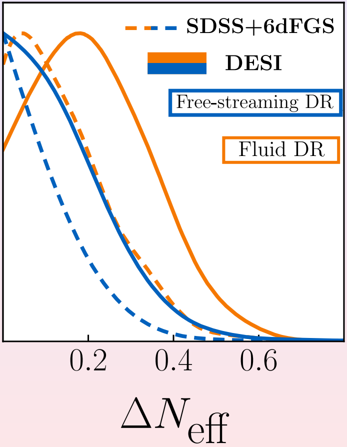


Combination of:

- CMB from **Planck18**
- Supernovae from **Pantheon+**
- BAO from **SDSS+6DFGS**

(Allali + AN + Rompineve 24)

Updated Constraints from DESI (without SH0ES)



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Light Element Abundance Constraints (BBN)

Primordial element abundances are sensitive to the amount of radiation present during Big Bang Nucleosynthesis (BBN)

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$\rightarrow$ Constraints on $\Delta N_{\rm eff}$ with and without these data*

(Aver et al 15, Cooke et al 18, Marcucci et al 16)

	Planck+DESI+Pantheon+	$+\mathbf{Y_{He}},\mathbf{D/H}$
Free-streaming	< 0.386	< 0.295
Fluid	$0.221^{+0.088}_{-0.18}$ (< 0.461)	< 0.365

(Allali + AN + Rompineve 24)

*Constraints sensitive to the choice of data for, e.g. the Y_{He} measurement (e.g. Aver et al 15 vs. Izotov et al 14)

DR produced before or after BBN?

DR could be produced after BBN

Example: decay of a massive particle at $\boxed{10\,\mathrm{eV} \ll T \ll \mathrm{MeV}}$.

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We have 4 cases:

- Free-Streaming DR:
  1. present before BBN
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- Fluid DR:
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DESI alleviates the H_0 tension

(Allali + AN + Rompineve 24)

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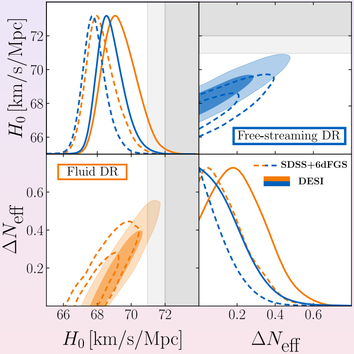

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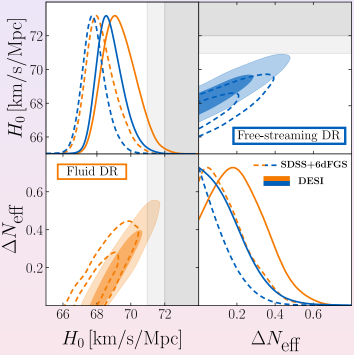

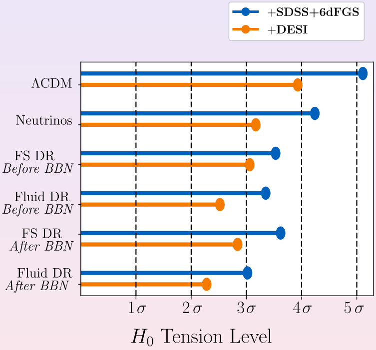

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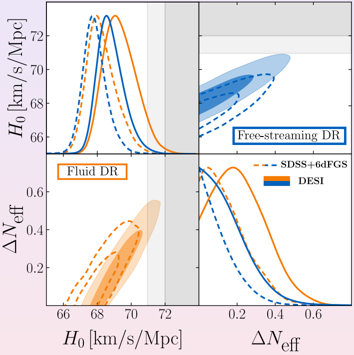
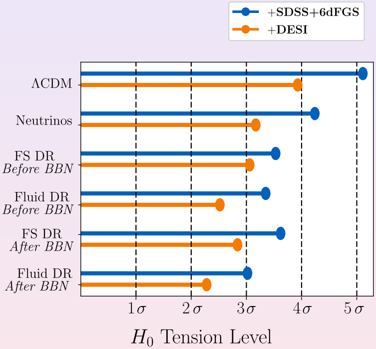


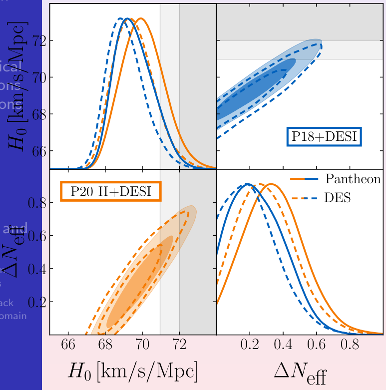


Lowest tension when DR is fluid, and when produced after BBN
→ justifies a combined fit with SH0ES

(Allali + AN + Rompineve 24)

More recent Planck '20 Likelihood

We also use a more recent Planck '20 Likelihood:



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- Larger sky fraction
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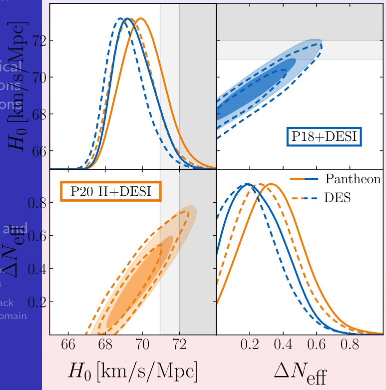
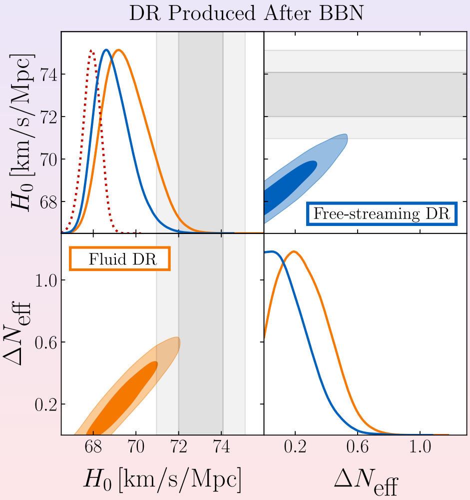


- Hillipop+Lollipop 2020 likelihoods
- Larger sky fraction
- Resolves an inconsistency ("A_L anomaly") in CMB lensing
- Lower H_0 tension (down to 1.87 σ)
- Stronger evidence for dark radiation

(Allali + AN + Rompineve 24)

Increased H_0: adding SH0ES



	H_0 (Tension)
ΛCDM	$67.93^{+0.44}_{-0.38}$ (3.9σ)
Fluid	$69.56^{+0.85}_{-1.2}$ (2.3σ)
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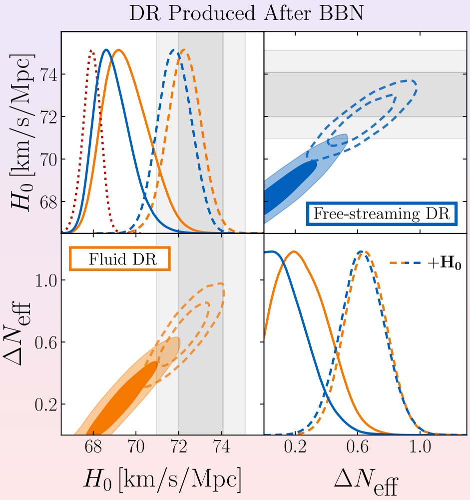

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ΛCDM	$67.93^{+0.44}_{-0.38}$ (3.9σ)
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Fluid	$69.56^{+0.85}_{-1.2}$ (2.3σ)
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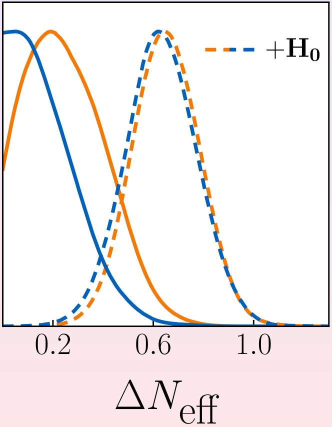
	72.25 ± 0.79 (0.6σ)
FS	$68.94^{+0.63}_{-0.99}$ (2.8σ)
	$\downarrow$
	$71.82^{+0.78}_{-0.77}$ (0.9σ)

(Allali + AN + Rompineve 24)

$\sim 5\sigma$ Evidence for $\Delta N_{\rm eff}$



	$\Delta N_{\rm eff}$ (w.r.t zero)
Fluid	0.65 ± 0.13 ($\sim 5\sigma$)
FS	0.63 ± 0.14 ($\sim 4.5\sigma$)

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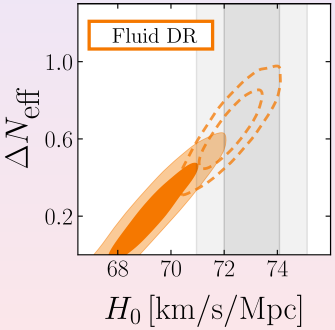

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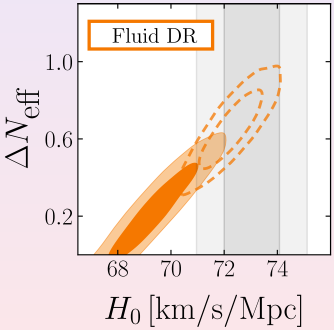

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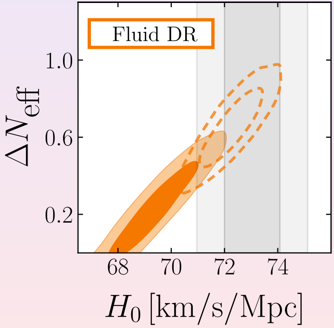

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- Much better fit than ΛCDM

$$\Delta\chi^2 = -24.7\,, \quad \Delta{\rm AIC} = -22.7$$

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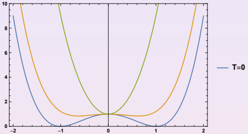
Table of Contents

Discrete symmetry broken

- Simple example: scalar field with Z_2 symmetry
  $V(\phi) = \frac{\lambda}{4}(\phi^2 - v^2)^2$



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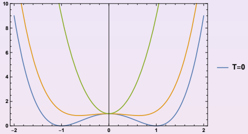

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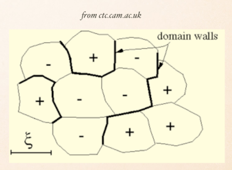
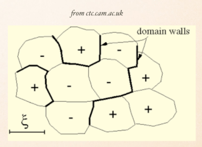
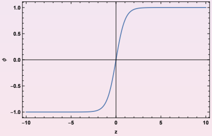
- ϕ goes to $\pm v$ randomly (uncorrelated in different Hubble patches)



Topological Defects: Domain Walls



- Domain walls produced at T_{PT} , interpolating $+v$ and $-v$, $\phi(z) = v \tanh(\sqrt{\lambda/2}vz)$.



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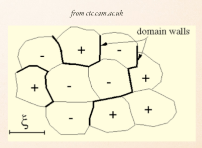

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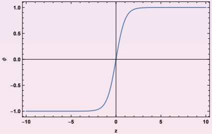

- Wall with energy per unit area (tension)

$$\sigma = 2 \int dz V(z) = \sqrt{\lambda} v^3$$

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- Initial complicated dynamics (need simulations)
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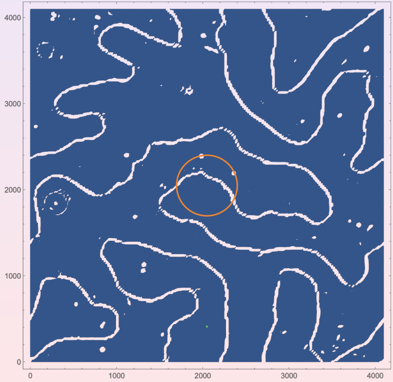

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- They can quickly dominate over radiation background, $\rho_{RAD} = 3H^2 M_{Pl}^2$
- $\implies$ Domain wall problem!
  (unless small $\sigma^{1/3} \lesssim 100$ MeV)

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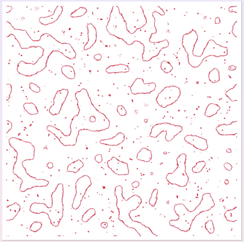

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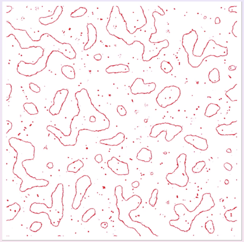
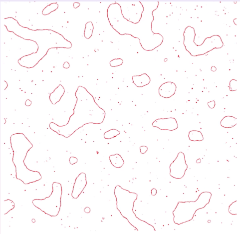

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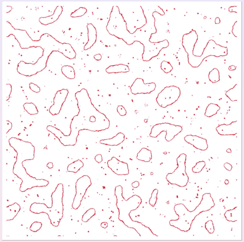

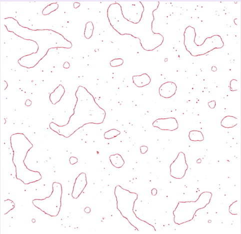

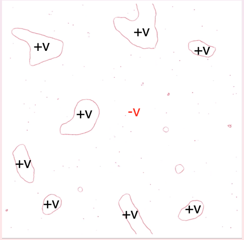

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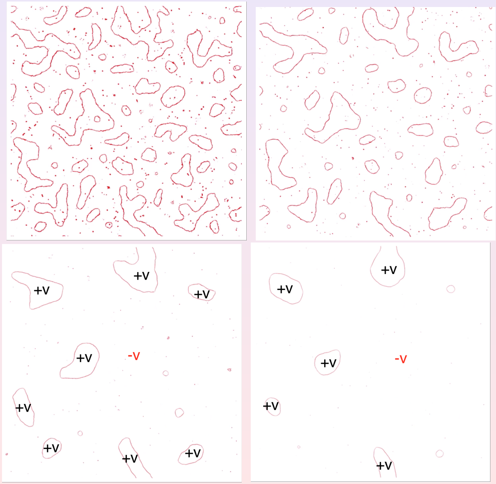

Simulations from R.Ferreira, A.N., O.Pujolas, F. Rompineve, JCAP 2024

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- Two free parameters σ (or α_*) and T_*

GW spectra

- GW spectrum $\rho_{\mathrm{GW}} \equiv \int \frac{d\rho_{\mathrm{GW}}}{d\log k}\frac{dk}{k}$:

$$\frac{d\rho_{GW}}{d\log k} = \begin{cases} f^3 \text{ for } f < f^0_{\text{peak}}, \text{ (causality)} \\ f^{-1} \text{ for } f > f^0_{\text{peak}} \text{ , (until cutoff given by DW width).} \end{cases}$$

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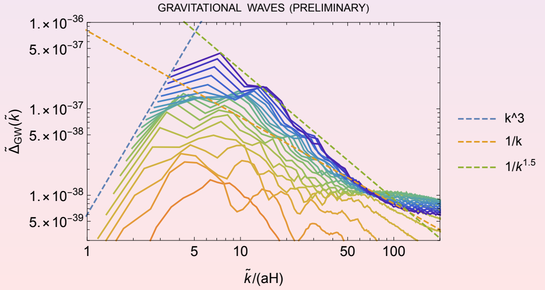
- Our simulations (2000^3 lattice sites) :



NANOGRAV 15-year announcement (2023)

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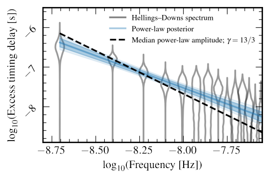

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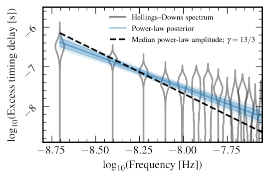
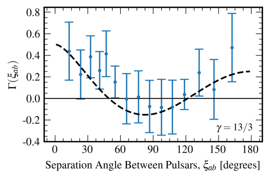


- First evidence $\sim 3\sigma$, Hellings-Downs angular correlation (signal from background of GWs?)



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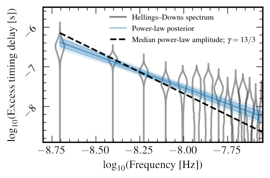

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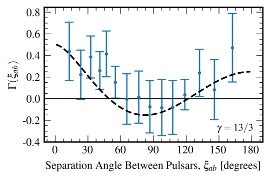

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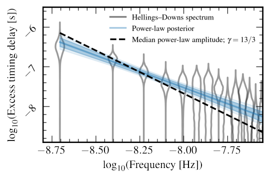

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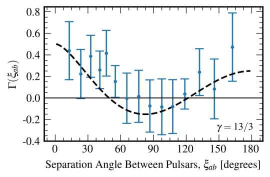

- Conservative: "Supermassive Black Holes mergers?"
- We interpreted it with GWs from Domain Walls

Decay of the network

- Assume DW decay into ϕ quanta and subsequently:
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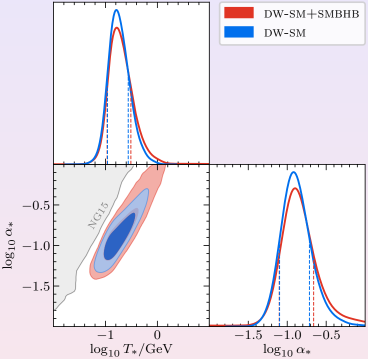

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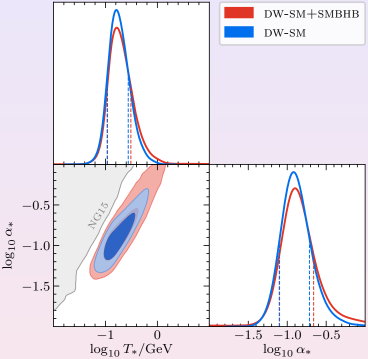

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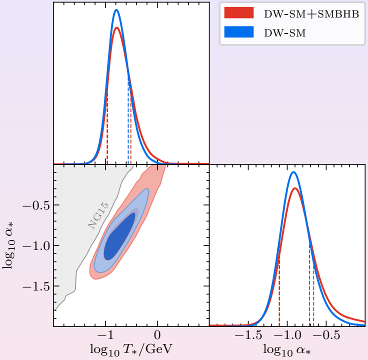

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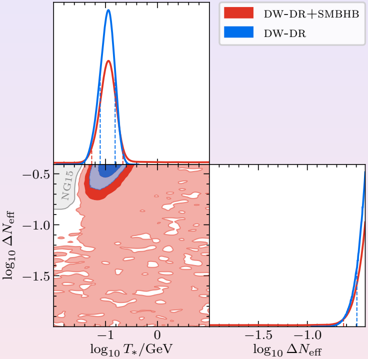

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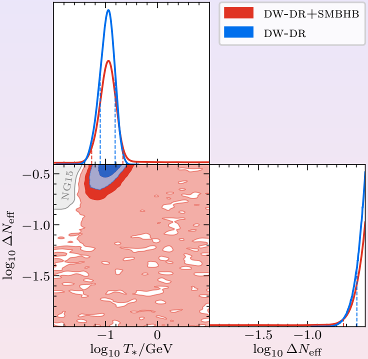

- Similar scales
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- Future Forecast: $\Delta N_{\rm eff} \gtrsim 0.16$ visible by forthcoming experiments (Simons Observatory, DESI, Euclid)

Overlap with LISA?

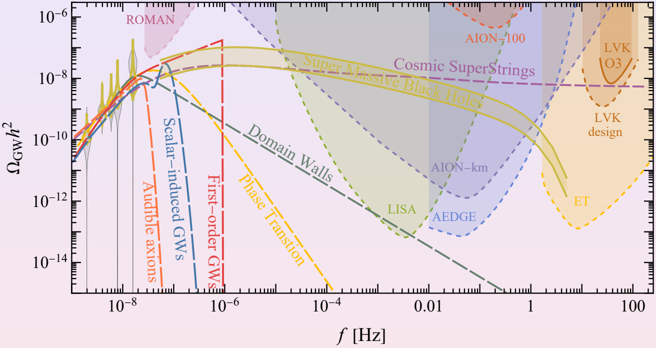

Figure: J.Ellis et al., PhysRevD.109.023522

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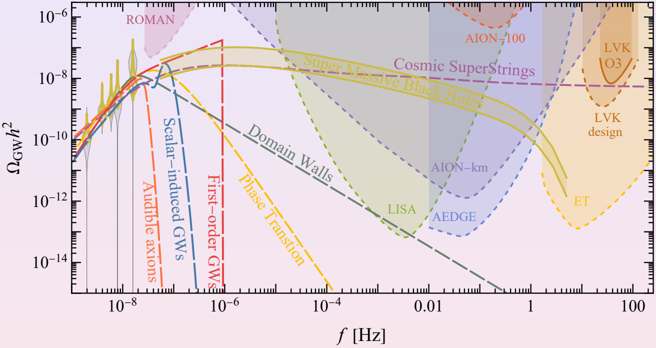

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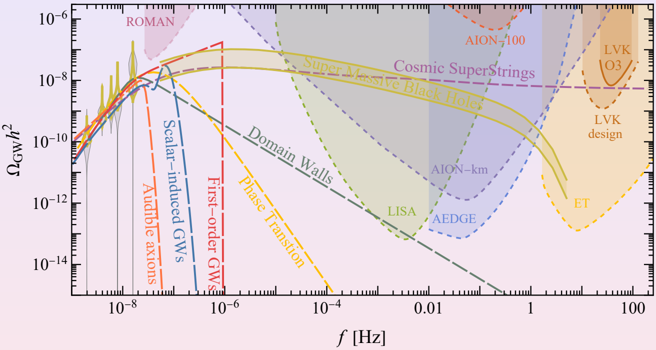

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- Depends on high k behavior: $1/k$?
- Work in progress...

Primordial Black Holes

- Primordial black holes from "False vacuum" pockets?

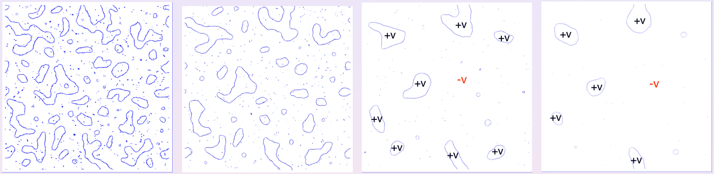

Figure: Simulations from: R. Z. Ferreira, A.N., O. Pujolas, F. Rompineve, e-Print: 2401.14331

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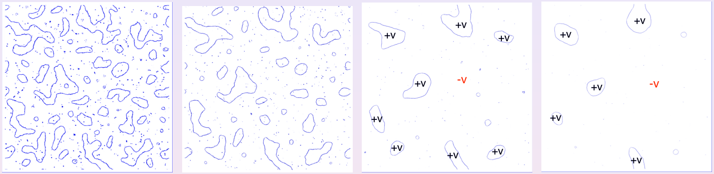

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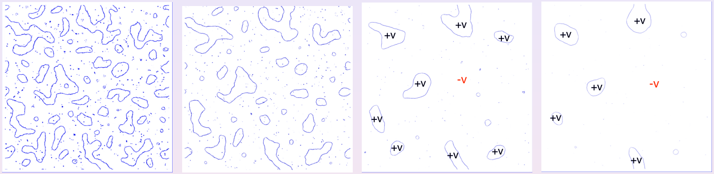

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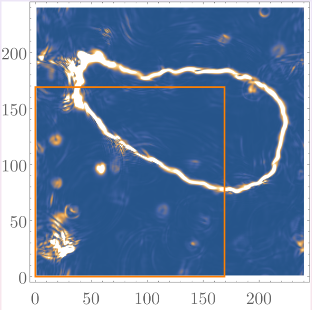
- A pocket may enter its Schwartzschild radius
- From our simulations (3240^3) we estimated fraction of volume in False Vacuum "pockets" that reach a density contrast $\alpha_c \approx \mathcal{O}(1)$ at horizon crossing $\implies$ collapse into PBH

Late birds entering the Hubble radius



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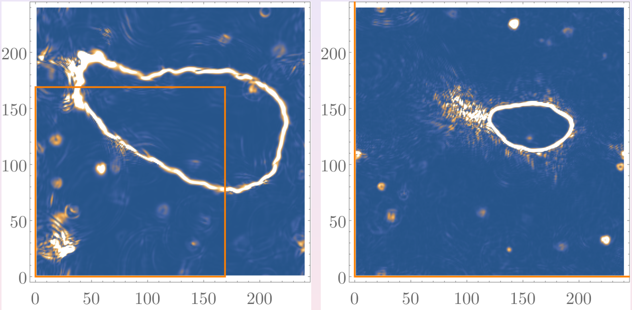

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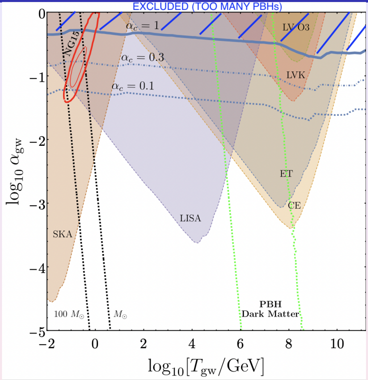
Phenomenology



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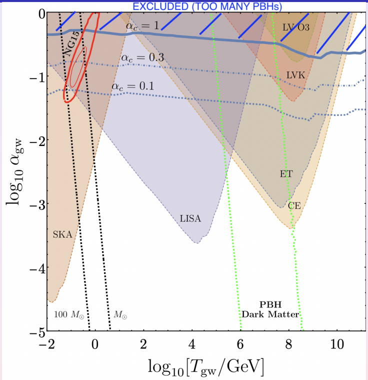

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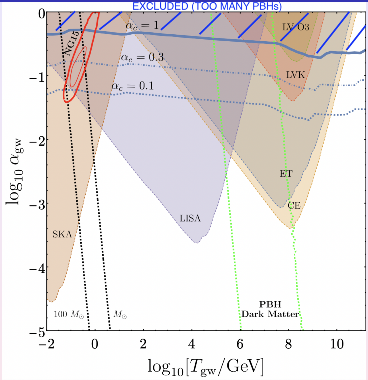

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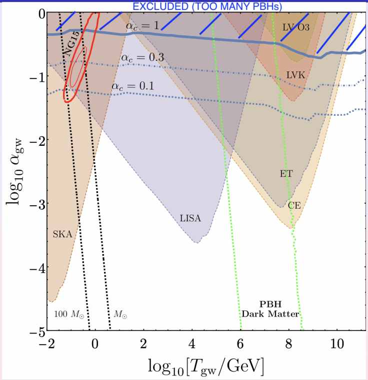

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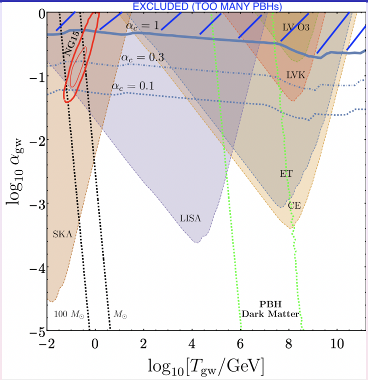

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- More work needed to understand subhorizon collapse of DWs

EXTRA SLIDES

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Figure: R.Ferreira, A.N., O.Pujolas, F. Rompineve, JCAP 06 (2024)

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with $L = \eta_{\Delta V}$ (correlation length = Hubble size at $\eta_{\Delta V}$)

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- PBH mass: horizon mass at collapse epoch ($T_{\mathrm{PBH}} \approx 10 \sim 100$ MeV)
- After collapse scales like matter, cannot exceed present abundance

NANOGRAV 15 year

- NANOGrav analysis for several new physics models:

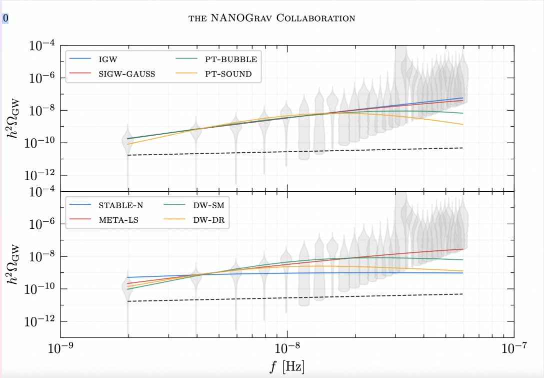

Figure: Afzal et al. Ap.J. Lett. (2023)