New insights
on neutrino interactions with dark matter from CMB data

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Theory of Particle Physics and Cosmology seminar

Faculty of Physics, University of Warsaw
March 26, 2024

P. Brax, C.v.d. Bruck, E. Di Valentino, W. Giare, ST, 2303.16895 (MNRAS:Letters)
2305.01383 (Phys. Dark Univ.)

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OUTLINE

Cosmology

♦ Cosmic Microwave Background (CMB) radiation
– the role of dark matter & neutrinos

Data analysis

♦ Dark matter – neutrino (DM-ν) interactions & CMB data

♦ High-multipole CMB data in the presence of DM-ν interactions
& confronting current data

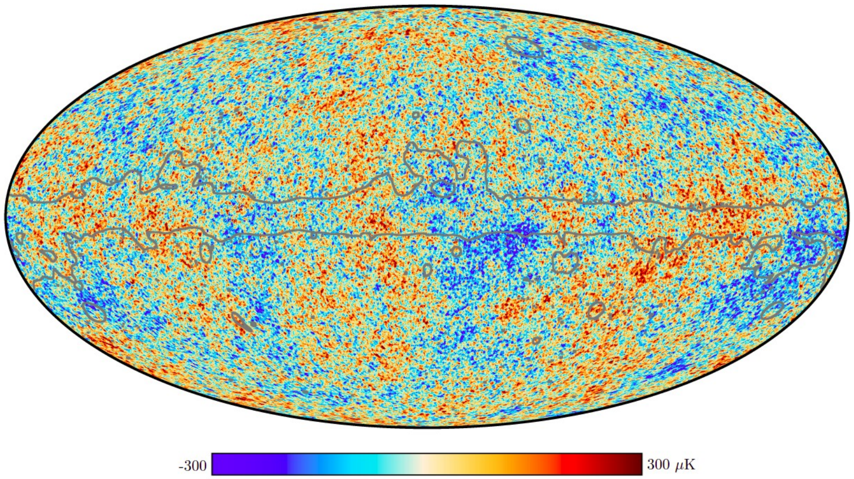
Particle physics

♦ Sample BSM model

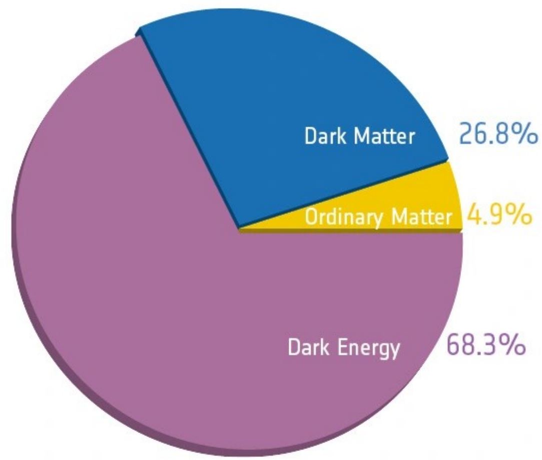
COSMIC MICROWAVE BACKGROUND – EXTREMELY POWERFUL TOOL

Planck 2018 temperature anisotropy map

source: https://www.cosmos.esa.int/web/planck/picture-gallery

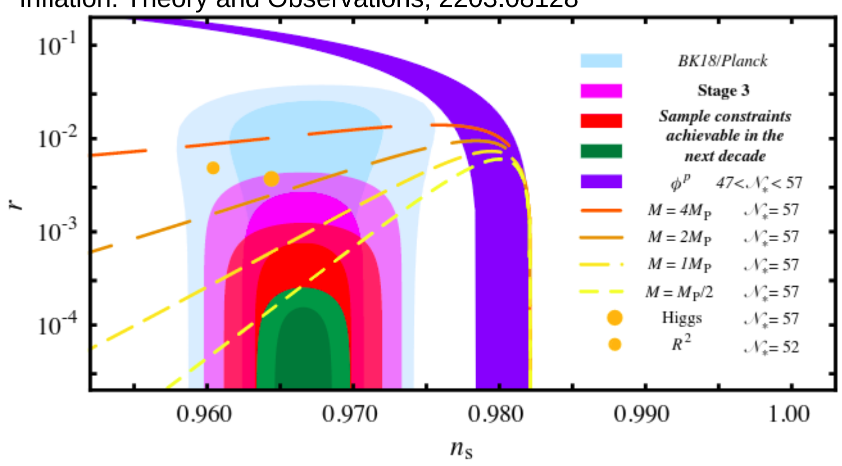


Matter-energy content of the Universe



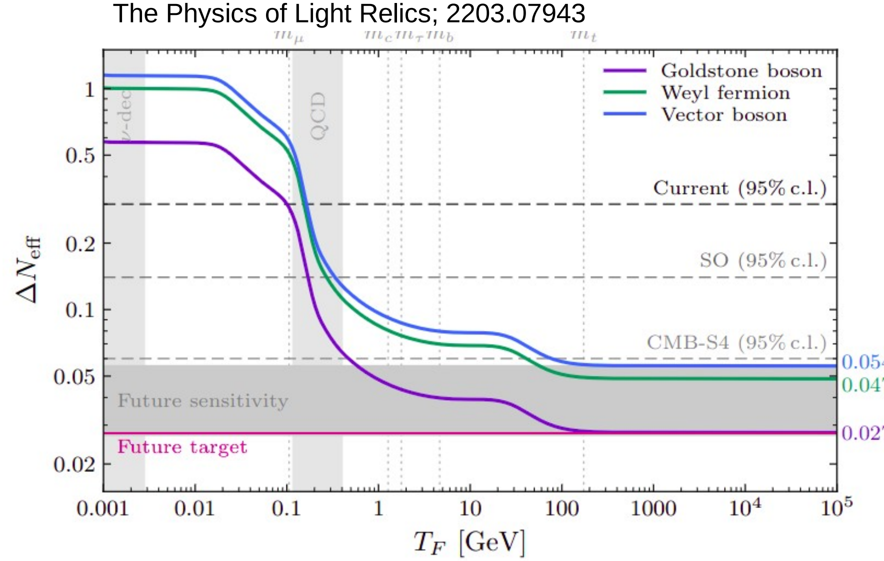
Signatures of cosmological inflation

Inflation: Theory and Observations; 2203.08128



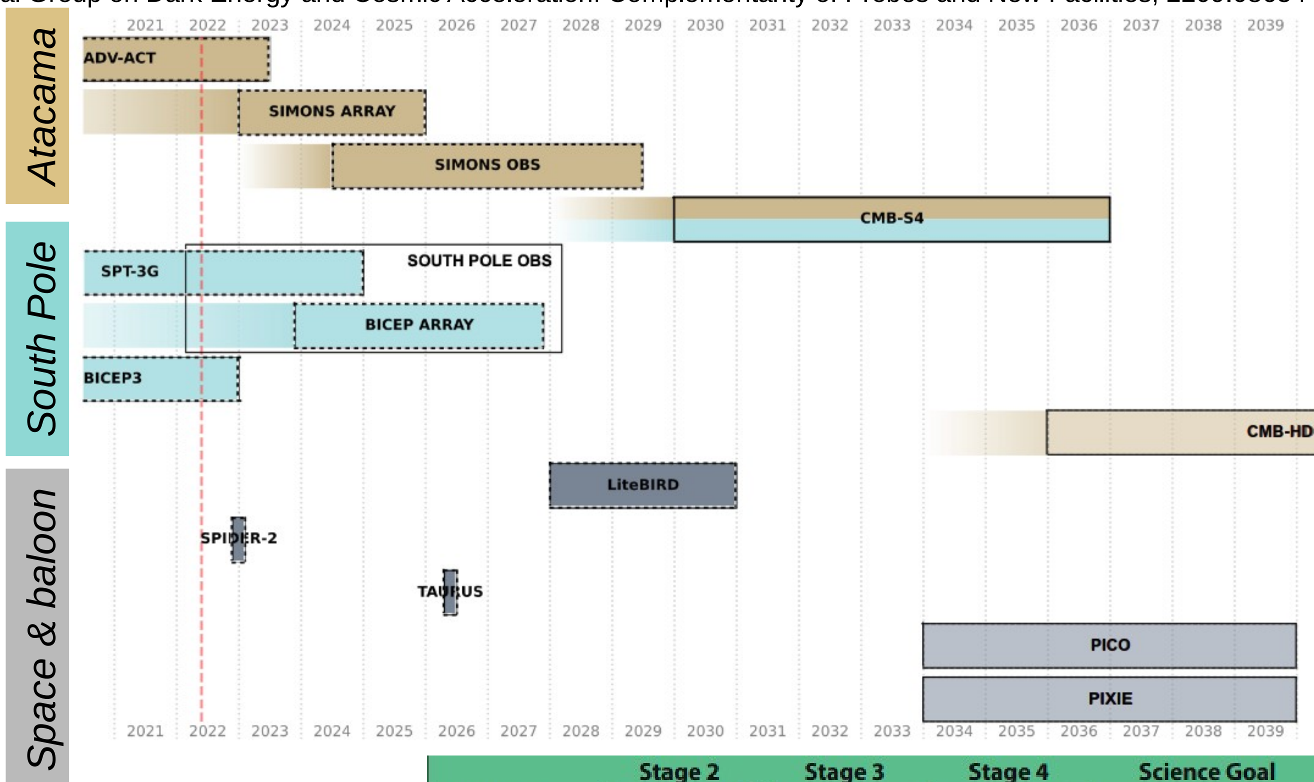
Probing light relics

The Physics of Light Relics; 2203.07943

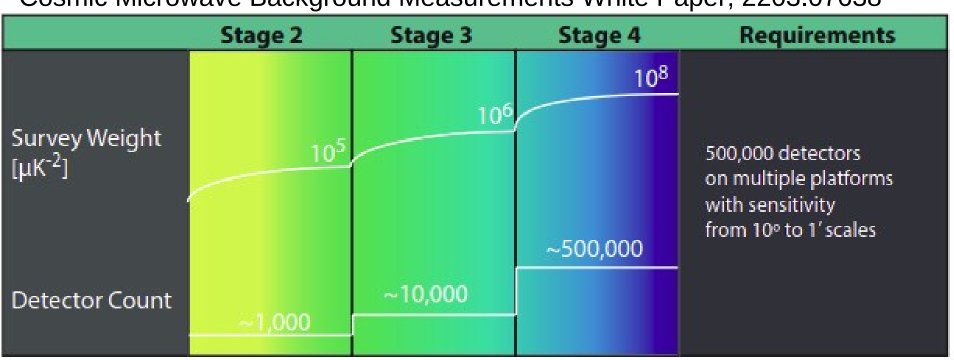


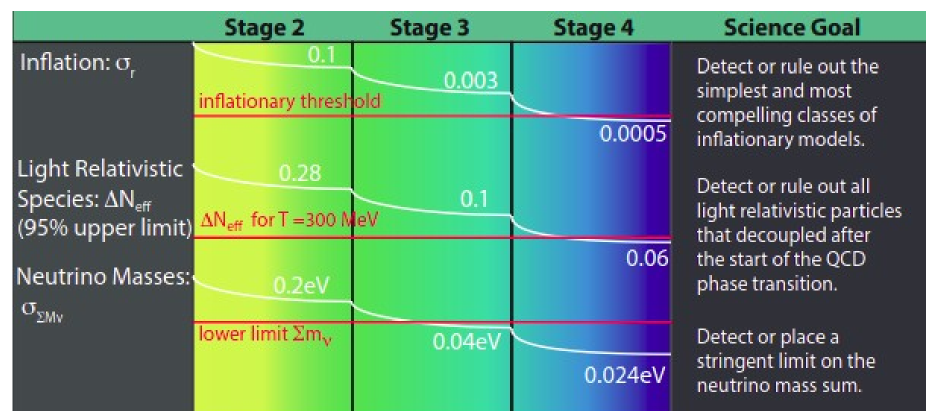
CMB
– ONGOING & FUTURE EXPERIMENTAL PROGRAM

Report of the Topical Group on Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities; 2209.08654



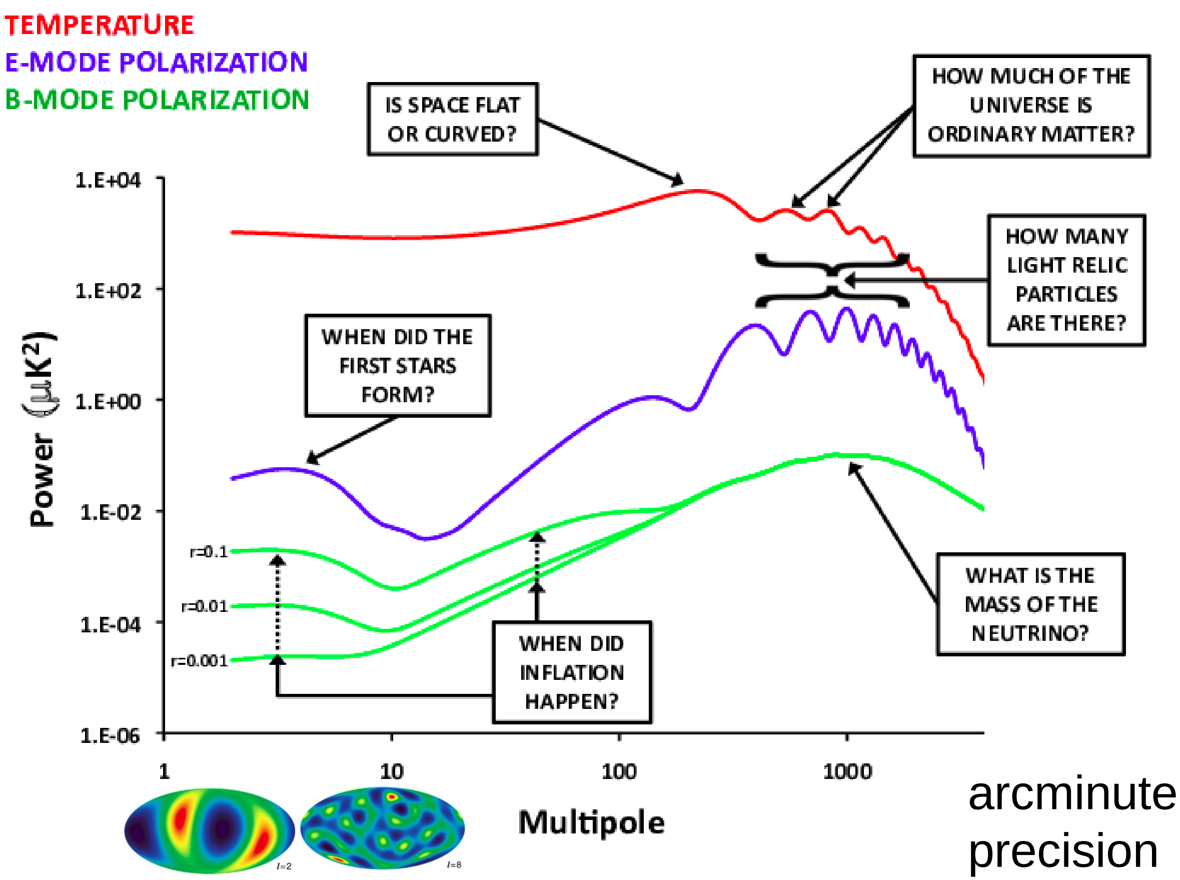
Snowmass2021 Cosmic Frontier:
Cosmic Microwave Background Measurements White Paper; 2203.07638





CMB POWER SPECTRUM

Snowmass2021 Cosmic Frontier: Cosmic Microwave Background Measurements White Paper; 2203.07638



arcminute precision

$$\Theta \equiv \frac{\delta T}{T}$$

$$\Theta(\eta, \mathbf{x}, \hat{\mathbf{p}}) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m}(\eta, \mathbf{x}) Y_{\ell m}(\hat{\mathbf{p}})$$

$$\langle a^*_{\ell m} a_{\ell' m'} \rangle = \delta_{\ell \ell'} \delta_{m m'} C_\ell$$

$$C_\ell^{\mathrm{obs}} \equiv \frac{1}{2\ell+1} \sum_m (a_{\ell m}^{\mathrm{obs}})^* a_{\ell m}^{\mathrm{obs}}$$

Power

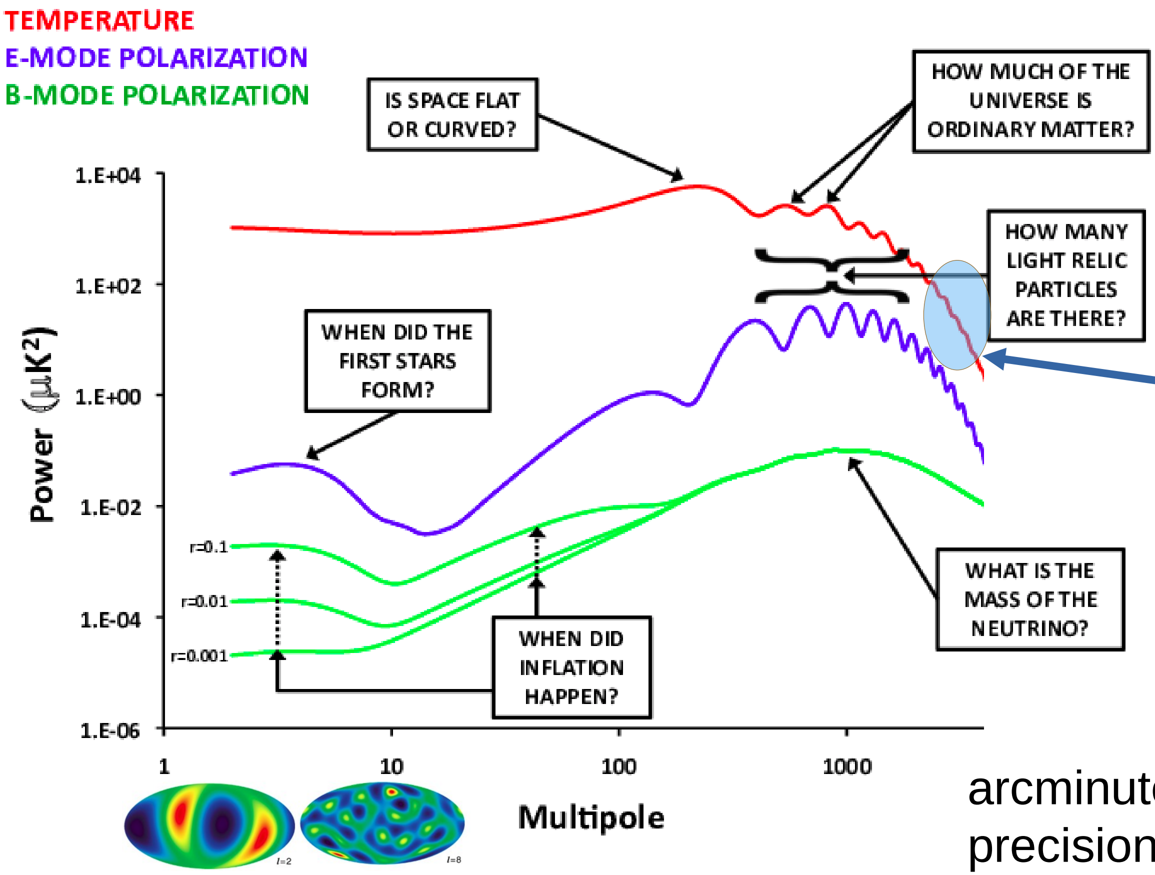
to be additionally multiplied by T^2_{av}

$$\frac{\ell(\ell+1)}{2\pi} C_\ell \approx \Delta_T^2$$

very early Universe (inflation)

thermal history (dark matter, neutrinos, ...)

CMB POWER SPECTRUM



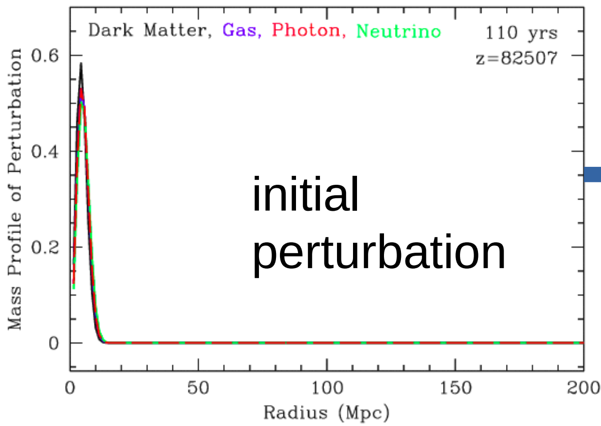
This talk
Damping tail
of the distribution

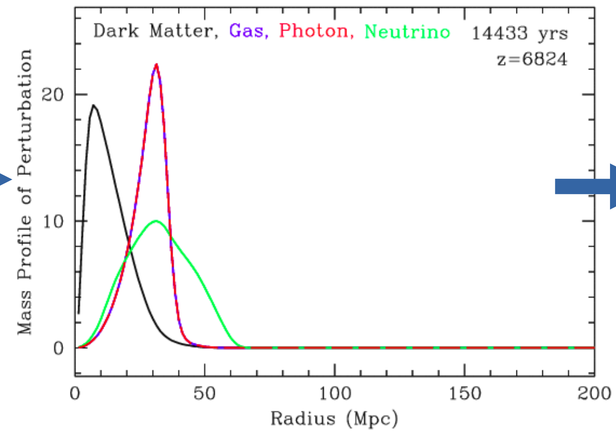
arcminute
precision

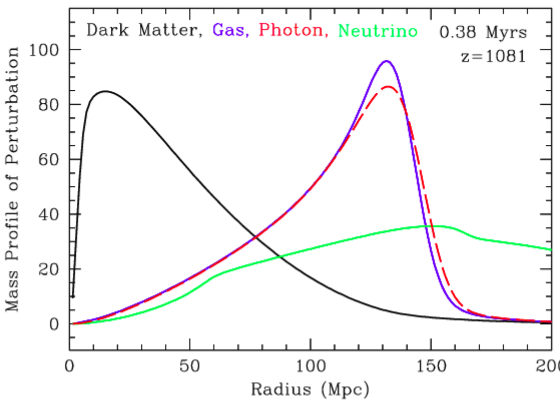
CAN WE LEARN MORE FROM THE DAMPING TAIL?

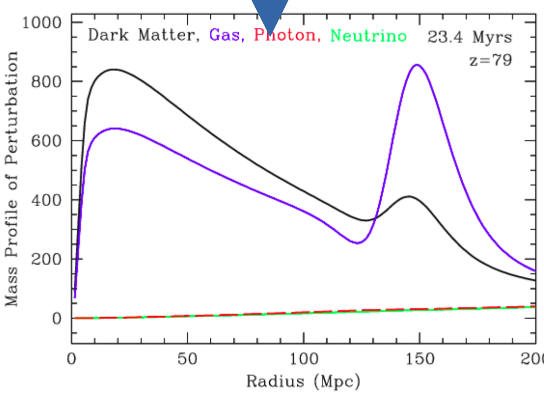
Credit: Daniel Eisenstein
also CMBfast code

BASICS OF ACOUSTIC OSCILLATIONS

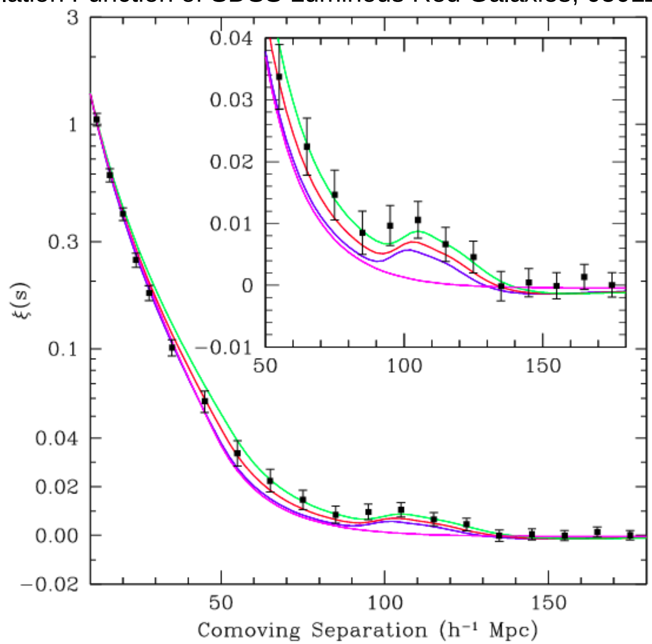






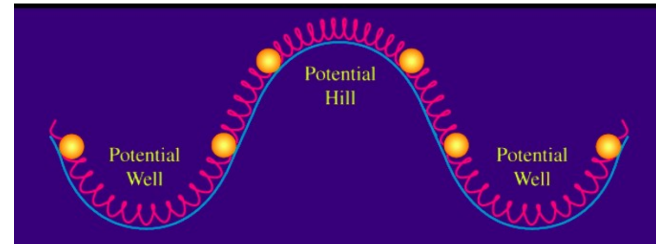


Detection of the Baryon Acoustic Peak in the Large-Scale Correlation Function of SDSS Luminous Red Galaxies; 0501171



ACOUSTIC OSCILLATIONS & CMB

♦ Photon-baryon fluid: balance between pressure and gravity
→ **oscillations**

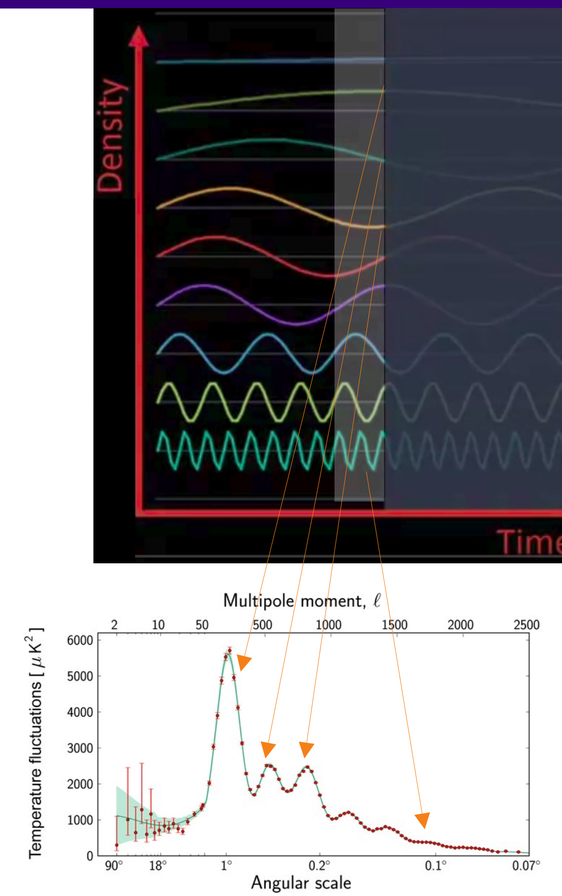


♦ Propagation with the speed of sound, $c_s \sim 57\%$ c

♦ Decomposition into standing waves

♦ Pattern of overdensities frozen around recombination,
it translates into photon temperatures

♦ Finite-time recombination: damping of small structures



♦ Modeling:

- small perturbations in density, velocity, and gravitational potential

$$\rho(\vec{r},t) = \rho_0(t) + \delta\rho(\vec{r},t) \cdots$$

- apply continuity, Euler, and Poisson equations

- standing wave solution for $\delta := \frac{\delta\rho}{\rho_0}$

$$\delta(x,\tau) = \delta_0 \cos(kx+\varphi)\cos\left(\frac{c}{\sqrt{3}}k[\tau - \tau_{\text{start}}(k)]\right)$$

C.-P. Ma, E. Bertschinger; 9506072
I.M. Oldengott, etal; 1409.1577
J. Stadler, etal; 1903.00540
M.R. Mosbech, etal, 2011.04206

HOW DO WE MODEL THIS?

- Neutrino distribution function

$$f(\mathbf{x}, \mathbf{P}, \tau) dx^1 dx^2 dx^3 dP^1 dP^2 dP^3 = dN \,,$$

- Boltzmann equation

$$\frac{d}{dt} f(\mathbf{x}, \mathbf{p}, t) = C\left[f(\mathbf{x}, \mathbf{p}, t)\right].$$

- Collision term

$$C(p) = \frac{1}{E_\nu(\mathbf{p})} \int \frac{d^3\mathbf{p}'}{(2\pi)^3 \, 2E_\nu(\mathbf{p}')} \frac{d^3\mathbf{q}}{(2\pi)^3 \, 2E_\chi(\mathbf{q})} \frac{d^3\mathbf{q}'}{(2\pi)^3 \, 2E_\chi(\mathbf{q}')} (2\pi)^4 |M|^2 \times \delta^4(q + p - q' - p') \left[g(\mathbf{q}') f(\mathbf{p}') (1 - f(\mathbf{p})) - g(\mathbf{q}) f(\mathbf{p}) (1 - f(\mathbf{p}'))\right]$$

- Assumptions: non-relativistic DM, Thomson-like scattering amplitude

$$C(p) = \frac{\sigma_0 n_\chi p^2}{E_\nu^2(p)} \left[\cdots \right] \qquad C_\chi = a \, u_{\nu\chi} \frac{\sigma_{\rm Th} \rho_\chi}{100 \text{ GeV}} \frac{p^2}{E_\nu^2}$$

$$u_{\nu\chi} = \frac{\sigma_0}{\sigma_{\rm Th}} \left(\frac{m_\chi}{100 \text{ GeV}} \right)^{-1}$$

- Constant (energy-independent) scattering cross section;

  Other examples include σ ~ E²/m^4

HOW DO WE MODEL THIS? (2)

- This is used to derive the Boltzmann hierarchy

$$f(\mathbf{x},\mathbf{p},\tau) = f_0(p)\left[1+\Psi(\mathbf{x},\mathbf{p},\tau)\right].$$

$$\Psi(\mathbf{k},\hat{\mathbf{n}},p,\tau) = \sum_{l=0}^{\infty}(-i)^l\,(2l+1)\,\Psi_l(\mathbf{k},p,\tau)\,P_l\left(\hat{\mathbf{k}}\cdot\hat{\mathbf{n}}\right)$$

$$\left\{\begin{aligned} \frac{\partial\Psi_0}{\partial\tau} &= -\frac{pk}{E_\nu(p)}\Psi_1(p) + \frac{1}{6}\dot{h}\frac{d\ln f^{(0)}(p)}{d\ln p} \\ \frac{\partial\Psi_1}{\partial\tau} &= \frac{1}{3}\frac{pk}{E_\nu(p)}\left(\Psi_0(p) - 2\Psi_2(p)\right) - C_\chi(p)\frac{v_\chi E_\nu(p)}{3f^{(0)}(p)}\frac{df^{(0)}(p)}{dp} - C_\chi(p)\Psi_1(p). \\ &\ldots. \end{aligned}\right.$$

- Numerical Boltzmann solver (CLASS)

- Challenge: regimes of the fluid approximation, expected error on the CMB power spectrum ~ 0.01%

M.R. Mosbech, etal, 2011.04206

DM-ν INTERACTIONS & CMB

♦ Standard cosmology: neutrinos free stream
& can "drag" baryon photon fluid

♦ In the presence of DM-neutrino interactions:

– DM can take part in oscillations → gravitational boost & enhanced CMB peaks
R.J. Wilkinson, etal, 1401.7597

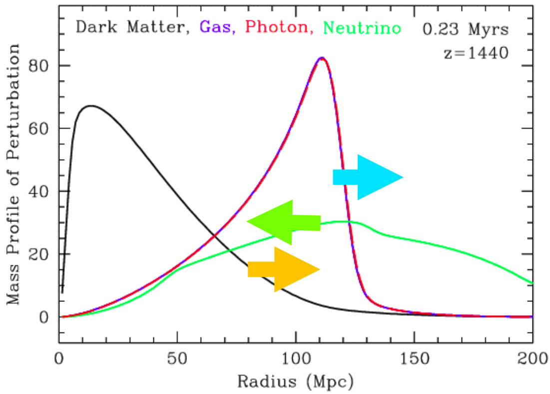
– DM-ν interactions can affect ν free streaming
→ stronger clustering & enhanced CMB peaks >1
G. Magano, etal 0606190

– DM-neutrino fluid has a lower sound speed → drag effect, CMB peaks shifted
and more…
P. Serra, etal, 0911.4411

♦ CMB peaks can be significantly affected
→ bounds on DM-ν interactions

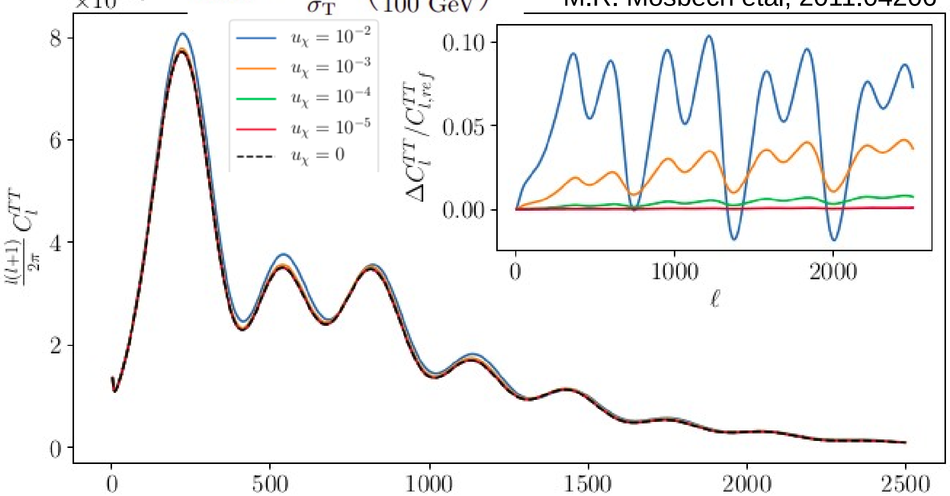
♦ **Focus of this talk is on more subtle effects**

Credit: Daniel Eisenstein



$$u_{\nu \rm DM} = \frac{\sigma_{\nu \rm DM}}{\sigma_{\rm T}} \left(\frac{m_{\rm DM}}{100\ \rm GeV}\right)^{-1}$$

M.R. Mosbech etal; 2011.04206



C. Boehm, R. Schaeffer, 0410591
J. Stadler, C. Boehm, O. Mena, 1903.00540

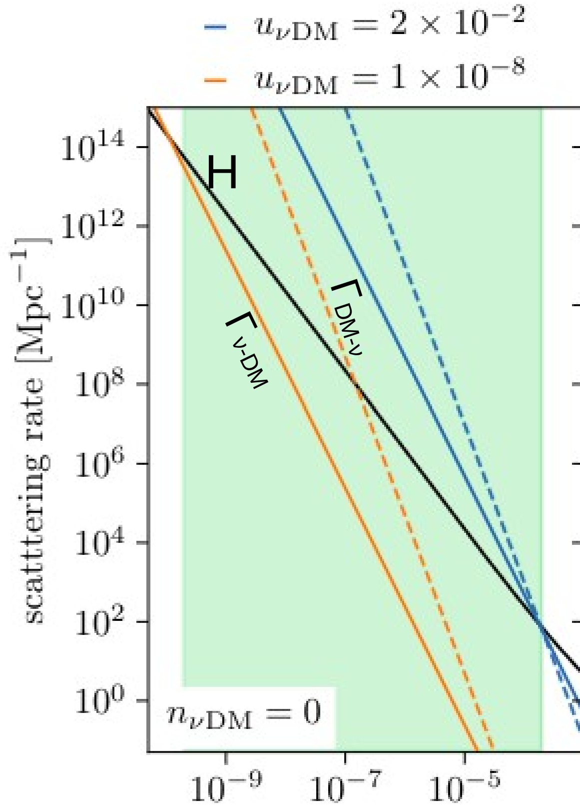
MIXED DAMPING

♦ Mixed damping: DM is coupled to a relativistic fluid which is itself free streaming

$$\Gamma_{\rm DM-\nu} > H > (\Gamma_{\nu} \equiv \Gamma_{\nu-e} + \Gamma_{\nu-\rm DM}),$$

♦ The difference in the individual interaction rates is
due to the difference in the (target) number densities

$$\Gamma_{\nu-\rm DM} = n_{\rm DM}\, \sigma_{\nu \rm DM}\,,$$
$$\Gamma_{\rm DM-\nu} = \frac{4\rho_{\nu}}{3\rho_{\rm DM}}\, \Gamma_{\nu-\rm DM}$$



♦ Neutrinos are free streaming while…

♦ ...DM is dragged by neutrino free streaming

♦ DM perturbation growth is slowed down

♦ For low interactions strength:

– effect to subtle to impact large scales (low-multiplicity)

– significantly more important for small-scale perturbations (h

SMALL-SCALE CMB & ν-DM INTERACTIONS

- DM-ν interactions:

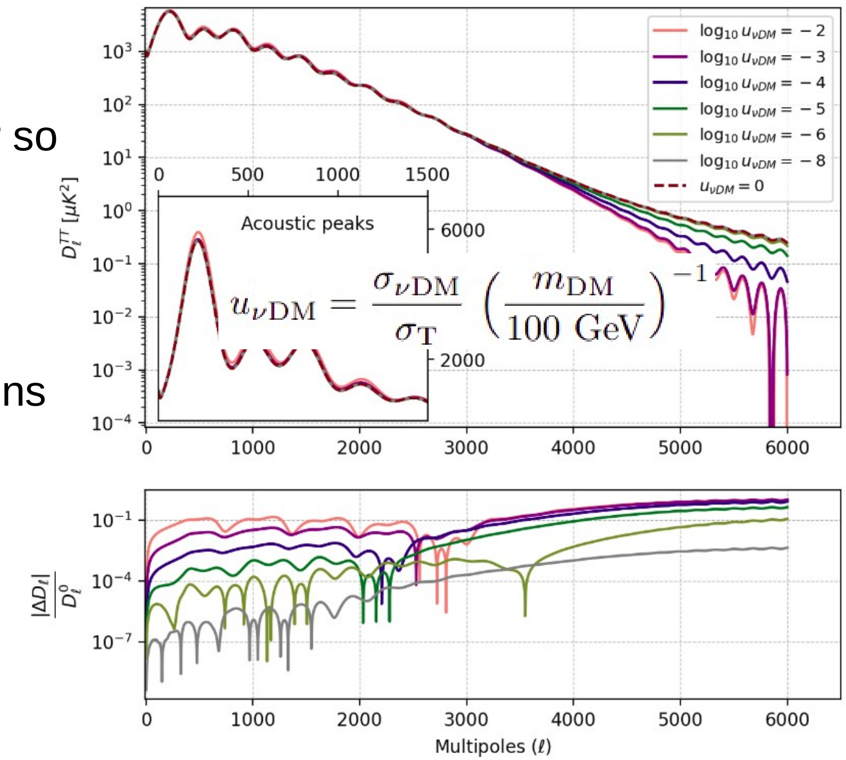
– suppression of high-multipole peaks at few % level or so

– negligible effect at low multipoles for $u_{\nu DM} < 10^{-5}$

- Similar effect in the temperature (TT) & polarization (EE) distributions

- Current data: Atacama Cosmology Telescope (ACT), South Pole Telescope (SPT)

- Future surveys can further improve: CMB-S4, ...



$$u_{\nu\mathrm{DM}} = \frac{\sigma_{\nu\mathrm{DM}}}{\sigma_\mathrm{T}} \left(\frac{m_\mathrm{DM}}{100\ \mathrm{GeV}}\right)^{-1}$$

High-multipole CMB data = new window to study DM-ν interactions

CURRENT DATA & ANALYSIS

DATA

● **Planck** 2018

temperature & polarization
1907.12875, 1807.06209, 1807.06205

lensing 1807.06210

● Atacama Cosmology Telescope (**ACT**)

temp. & polar. DR4 2007.07289

new confirmation: + ACT-DR6 & SPT W. Giare, etal, 2311.09116

● Baryon Acoustic Oscillations (**BAO**)
& Redshift Space Distortions

BOSS DR12 1208.0022

ANALYSIS

● (modified) CLASS + DM-ν
1104.2933, 1903.00540, 2011.04206

● Sampling:
COBAYA (with CosmoMC)
2005.05290, 0205436, 1304.4473

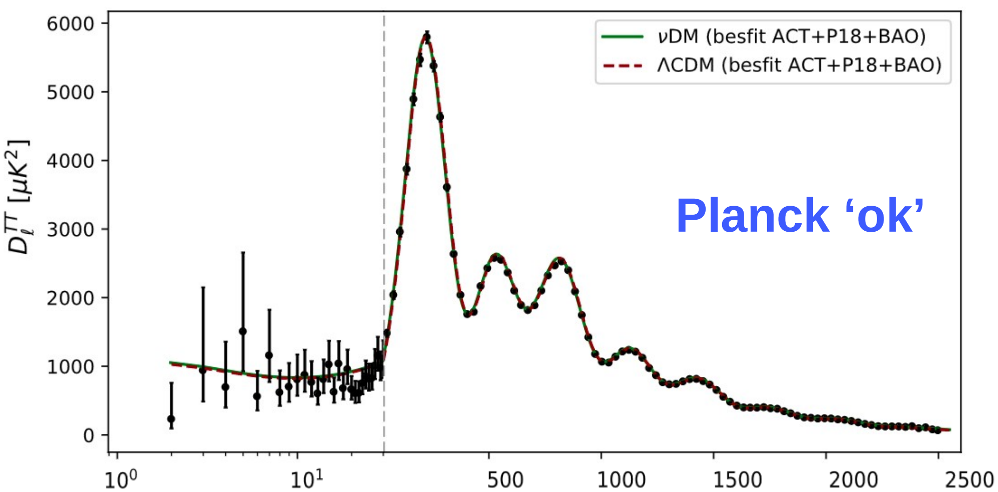
● Adding ACT:

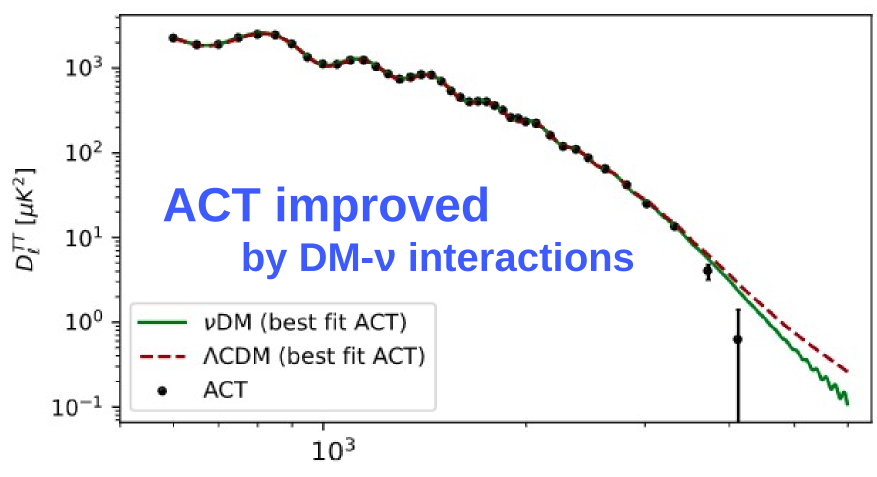
- weaker bounds on $u_{\nu DM}$
- non-zero coupling preferred

	Parameter	$\sigma_{\nu DM} \sim T^0$
	$\Omega_b h^2$	$[0.005\,,\,0.1]$
	$\Omega_c^{\nu DM} h^2$	$[0.005\,,\,0.1]$
	$100\,\theta_{MC}$	$[0.5\,,\,10]$
	τ	$[0.01\,,\,0.8]$
	$\log(10^{10} A_S)$	$[1.61\,,\,3.91]$
	n_s	$[0.8\,,\,1.2]$
	$N_{\rm eff}$	$[0\,,\,10]$
DM-ν	$\log_{10} u_{\nu DM}$	$[-8\,,\,-1]$

$$u_{\nu DM} = \frac{\sigma_{\nu DM}}{\sigma_T}\left(\frac{m_{DM}}{100\ \mathrm{GeV}}\right)^{-1}$$

σ_T – Thomson scat.





PREFERENCE: NON-ZERO DM-ν COUPLING

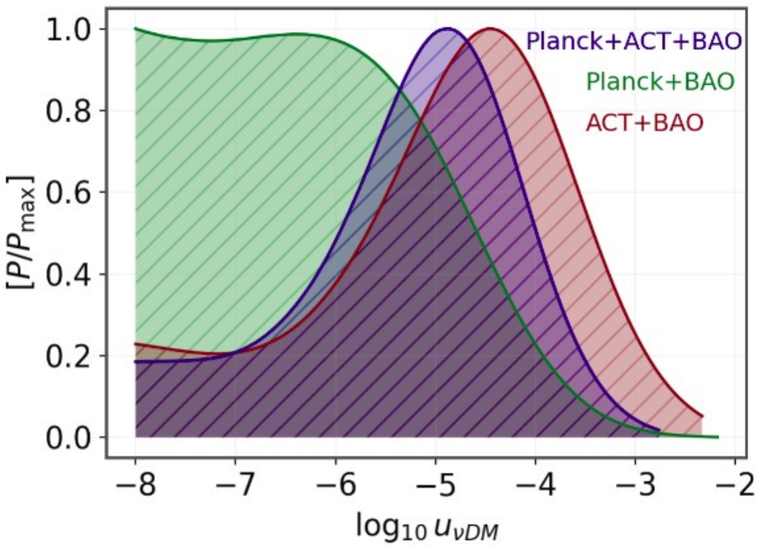
$\sigma_{\nu DM} \sim T^0$

CMB (this work)

Hints from Lyman-α

D.C. Hopper, M. Lucca, 2110.04024

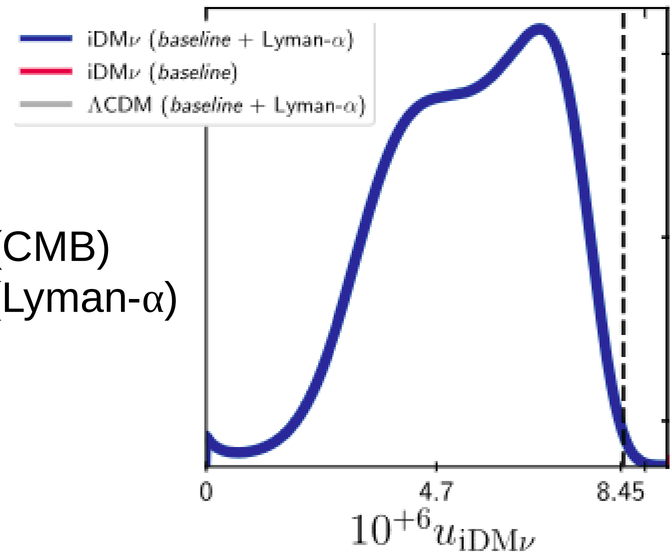
Posterior



$\log_{10} u_{\nu DM} = -5.20^{+1.20}_{-0.74}$ (CMB)

$-5.42^{+0.17}_{-0.08}$ (Lyman-α)

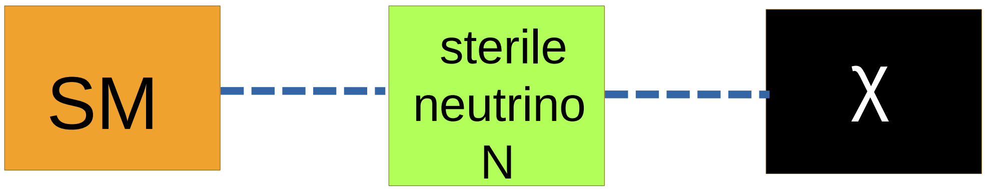
$$u_{\nu DM} = \frac{\sigma_{\nu DM}}{\sigma_T}\left(\frac{m_{DM}}{100\text{ GeV}}\right)^{-1}$$

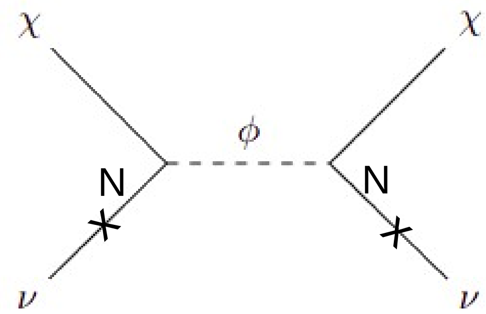


Parameter	Planck	Planck + BAO	ACT	ACT + BAO	ACT + Planck + BAO
$\Omega_b h^2$	0.02239 ± 0.00015	0.02239 ± 0.00013	0.02153 ± 0.00030	0.02154 ± 0.00030	0.02236 ± 0.00012
$\Omega_c^{\nu DM} h^2$	0.1196 ± 0.0012	0.11958 ± 0.00093	0.1185 ± 0.0039	0.1198 ± 0.0015	0.11975 ± 0.00097
$100\theta_s$	1.04193 ± 0.00030	1.04191 ± 0.00028	1.04337 ± 0.00069	1.04321 ± 0.00063	1.04206 ± 0.00026
τ_{reio}	0.0528 ± 0.0074	0.0524 ± 0.0072	0.064 ± 0.015	0.062 ± 0.014	0.0563 ± 0.0064
$\log(10^{10} A_s)$	3.039 ± 0.014	3.038 ± 0.014	3.049 ± 0.030	3.047 ± 0.030	3.053 ± 0.013
n_s	0.9642 ± 0.0044	0.9642 ± 0.0038	1.004 ± 0.016	1.001 ± 0.014	0.9678 ± 0.0036
$log_{10} u_{\nu DM}$	$< -4.42\ (< -3.95)$	$< -4.46\ (< -4.39)$	$-5.08^{+1.5}_{-0.98}\ (< -3.74)$	$-4.86^{+1.5}_{-0.83}\ (< -3.70)$	$-5.20^{+1.2}_{-0.74}\ (< -4.17)$
H_0	$68.03 \pm 0.55\ (68.0^{+1.1}_{-1.1})$	$68.05 \pm 0.42\ (68.05^{+0.81}_{-0.82})$	$68.2 \pm 1.6\ (68.2^{+3.3}_{-3.3})$	$67.66 \pm 0.58\ (67.7^{+1.1}_{-1.2})$	$68.01 \pm 0.43\ (68.01^{+0.83}_{-0.85})$
σ_8	$0.806^{+0.013}_{-0.0097}\ (0.806^{+0.024}_{-0.028})$	$0.807^{+0.011}_{-0.0084}\ (0.807^{+0.020}_{-0.021})$	$0.823^{+0.025}_{-0.021}\ (0.823^{+0.046}_{-0.050})$	$0.821^{+0.025}_{-0.020}\ (0.821^{+0.044}_{-0.050})$	$0.820^{+0.011}_{-0.0093}\ (0.820^{+0.021}_{-0.023})$
$\ln BF$	-3.74	-2.48	-0.194	-0.156	0.525

B. Bertoni, etal, 1412.3113
B. Batell, etal, 1709.07001
P. Brax, etal, 2305.01383

STERILE NEUTRINO PORTAL TO DARK MATTER





$$-\mathcal{L} \supset m_\phi^2 |\phi|^2 + m_\chi \bar{\chi}\chi + m_N \bar{N}N + \left[\lambda_\ell \bar{L}_\ell \hat{H} N_R + \phi\bar{\chi}\,(y_L N_L + y_R N_R) + \text{h.c.}\right]$$

- After EWSB and mass matrix diagonalization

$$\nu_4 = \begin{pmatrix} U^*_{N4} N_L + \sum_\ell U^*_{\ell 4}\nu_{\ell L} \\ N_R \end{pmatrix} \qquad m_4 = \sqrt{m_N^2 + \sum_\ell \lambda_\ell^2 v^2},$$

- Mixing angles:

$$U_{\ell 4} = \frac{\lambda_\ell v}{m_4}, \qquad |U_{N4}| = \frac{m_N}{m_4} = \sqrt{1 - \sum_\ell |U_{\ell 4}|^2}.$$

Assumption:

$$U_{\tau 4} \neq 0 = U_{e4} = U_{\mu 4}.$$

- Coupling between DM and active neutrinos

$$y_L\,\phi\,\bar{\chi}_R\,N_L + \text{h.c.}$$

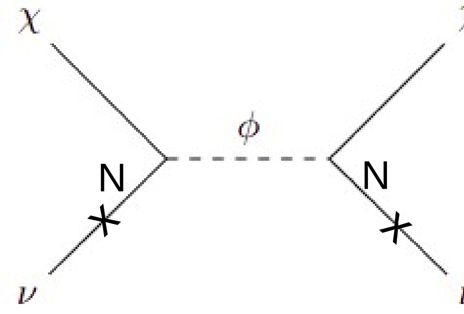
$$\rightarrow y_L\,|U_{N4}|\,\phi\,\bar{\chi}_R\,\nu_{4L} - y_L\sqrt{1-|U_{N4}|^2}\,\phi\,\bar{\chi}_R\,\nu_{lL} + \text{h.c.}$$

$$\nu_{lL} \rightarrow \frac{\sum_\ell U^*_{\ell 4}\nu_{\ell L}}{\sqrt{\sum_\ell |U_{\ell 4}|^2}}$$

DM-ν CROSS SECTION

$g = y_L \, |U_{\tau 4}|$

$$\frac{d\sigma_{\nu\chi}}{dE'_\nu} = \frac{g^4}{32\pi} m_\chi \left\{ \frac{1}{\left(m_\phi^2 - m_\chi^2 - 2m_\chi E_\nu\right)^2 + m_\phi^2 \Gamma_\phi^2} + \frac{E'^2_\nu / E_\nu^2}{\left(m_\phi^2 - m_\chi^2 + 2m_\chi E'_\nu\right)^2 + m_\phi^2 \Gamma_\phi^2} \right\}$$



temperature-independent $\sigma_{\nu DM}$ for $\delta = (m_\phi - m_\chi)/m_\chi$ << 1

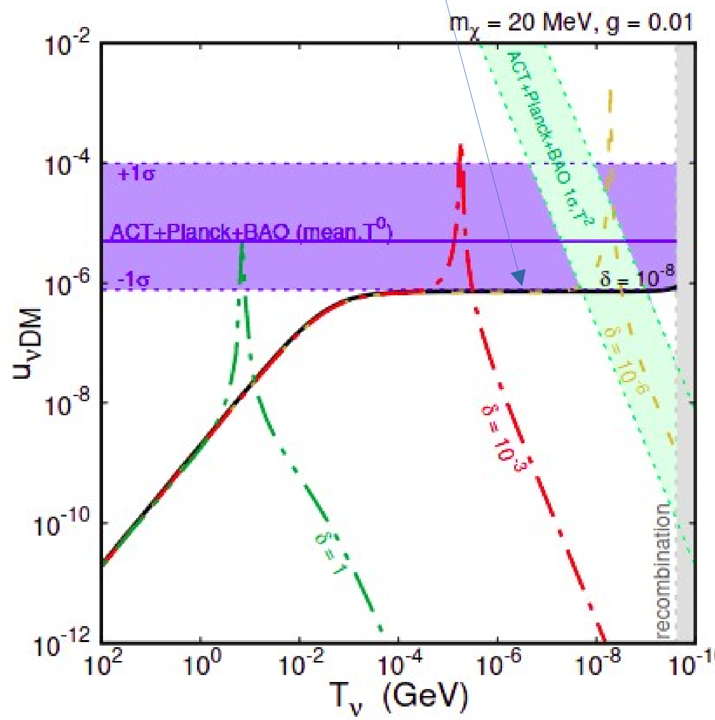
♦ Limiting cases:

a) Heavy mediator $m_\phi \gg m_\chi, E_\nu$,

$$\sigma_{\chi\nu} \simeq (10^{-52}\,\mathrm{cm}^2) \left(\frac{g}{0.1}\right)^4 \left(\frac{100\ \mathrm{MeV}}{m_\phi}\right)^4 \left(\frac{T}{T_0}\right)^2,$$

b) Small χ-ϕ mass splitting $(m_\phi - m_\chi) \ll E_\nu$,

$$\sigma_{\chi\nu} \simeq (10^{-34}\,\mathrm{cm}^2) \left(\frac{g}{0.01}\right)^4 \left(\frac{20\ \mathrm{MeV}}{m_\chi}\right)^2 \times \left[1 + 0.075 \left(\frac{m_\chi}{20\ \mathrm{MeV}}\right)^2 \left(\frac{T_{\mathrm{rec.}}}{T_\nu}\right)^2 \left(\frac{\delta}{10^{-8}}\right)^2\right]$$



OTHER PHENOMENOLOGY

♦ We assume the sterile neutrino N is heavier than both χ and ϕ (typically $m_N = 10\, m_\chi$)
It decays invisibly, $N \to \chi\phi$, and avoids bounds from searches for decaying HNLs

♦ $\phi \to \chi\nu$ decays are allowed and should happen before the BBN

$$\tau_\phi \simeq (0.1\ \text{sec}) \left(\frac{0.01}{g}\right)^2 \left(\frac{20\ \text{MeV}}{m_\phi}\right) \left(\frac{10^{-8}}{\delta}\right)$$

♦ $\chi\chi \to \nu\nu$ annihilations are very efficient:

a) $m_\chi \gtrsim 10$ MeV to avoid BBN bounds

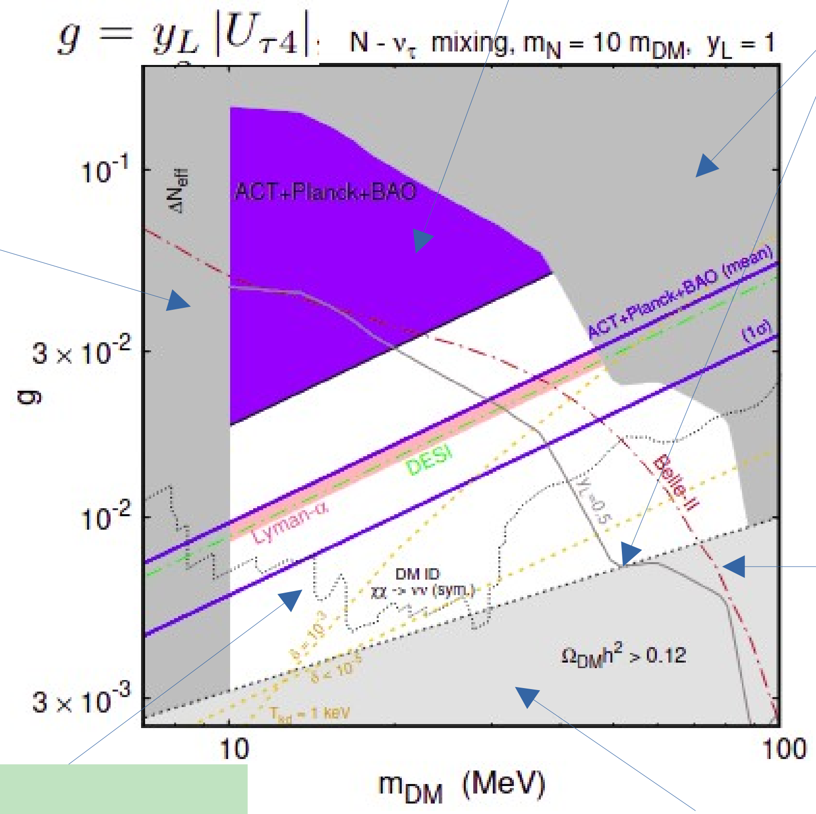
b) thermal χ relic density too low; need for additional mechanism, e.g., asymmetry

c) potential strong DM indirect detection (ID) bounds;
can be avoided, e.g., for asymmetric DM

♦ One could consider ϕ DM scenario ($m_\phi < m_\chi$);
here $\phi\phi \to \nu\nu$ annihilations p-wave suppressed

CURRENT BOUNDS

NEW RESULTS



too large N$_L$-ν$_\tau$ mixing:

- atmospheric neutrino oscillations
- τ lepton decays, e.g., $\tau \to \mu \bar{\nu} \nu$
- LFU in B meson decays

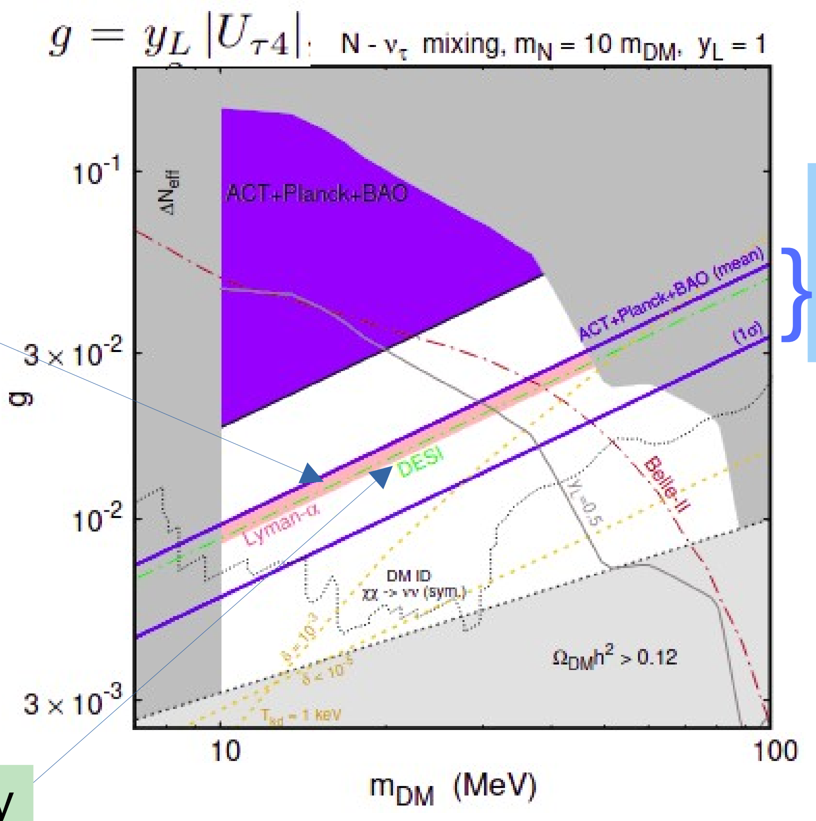
BBN
χχ → νν

Future Belle-II bounds

χ DM
indirect detection (symmetric)
χχ → νν

χ DM overabundance
χχ → νν

FITTING THE DATA



Lyman-α best fit

Future DESI survey

OUR RESULTS
Cosmologically preferred region (1σ, ACT+Planck+BAO)

CHALLENGES OF THE TOY MODEL

- Mass degeneracy requires fine-tuning
  & can be radiatively unstable via $\lambda_{\phi H}|\phi|^2|H|^2$

$$\lambda_{\phi H} \;\sim\; (y_L^2\lambda^2/16\pi^2)\,\log(\Lambda_{\rm UV}/m_N^2)$$

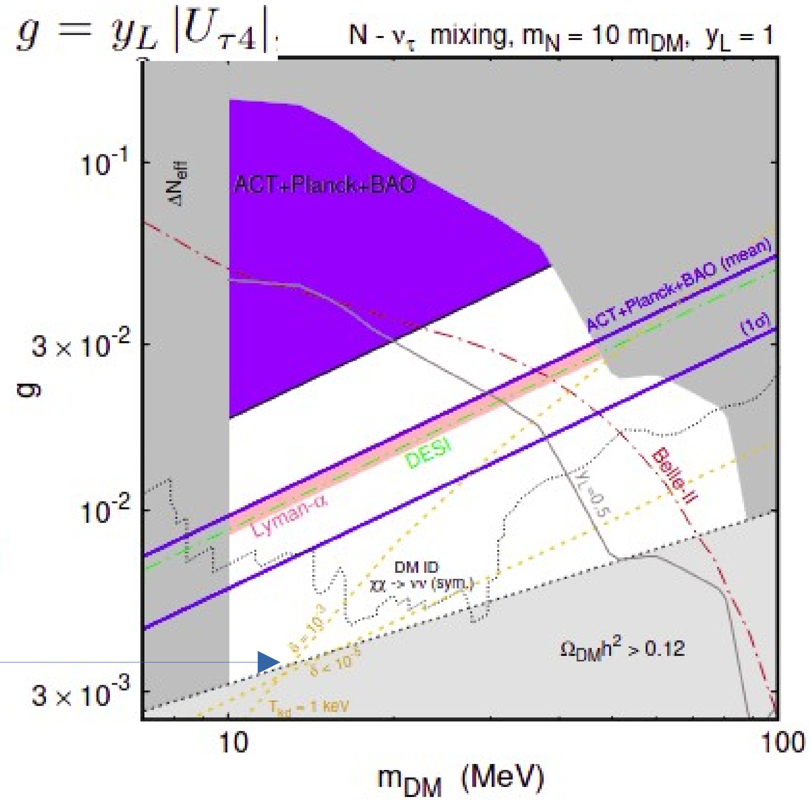
potential keV – MeV corrections

- Low neutrino kinetic decoupling temperature

$$T_{kd}\Big|_{m_\phi\simeq m_\chi} \simeq (0.12\ {\rm keV})\left(\frac{0.01}{g}\right)^2\left(\frac{m_\chi}{20\ {\rm MeV}}\right)^{3/2}.$$

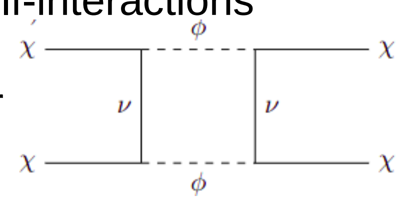
$$\rightarrow\quad M_{\rm cutoff} \sim 10^{11}\,M_\odot\,(0.1\ {\rm keV}/T_{kd})^3$$

It depends on the precise mass splitting



- Possible DM (too) strong self-interactions

upscattering $\chi\chi \to \phi\phi$, or



Upscattering rate (& environment) depends on the mass splitting.
Self $\chi\chi \to \chi\chi$ scattering can also be good (small-scale tensions of ΛCMD)

Y. Zhang; 2310.10743

CONCLUSIONS

- CMB observations are crucial for our understanding of dark matter

- **small-scale CMB measurements with few % accuracy open a new window to study DM interactions with neutrinos**

- **preference for non-zero DM-ν coupling in the high-multipole ACT data & agreement with low-multipole Planck data + BAO & RSD**

- Similar earlier hints from Lyman-α

- Toy model: sterile neutrino portal to DM

- Can accommodate the data but careful checking of other effects needed (cutoff scale, DM self-interactions...)

- Future data: ACT, CMB-S4, DESI, … + accelerator-based bounds on sterile neutrinos

T H A N K Y O U !

BACKUP