Astroparticle physics and cosmology working group summary (Cosmology part)

Jan Hamann

The University of New South Wales

WIN 2017

24th June 2017

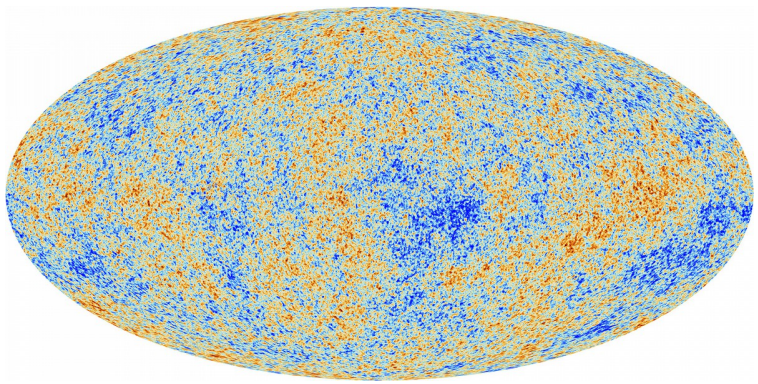
Irvine, CA

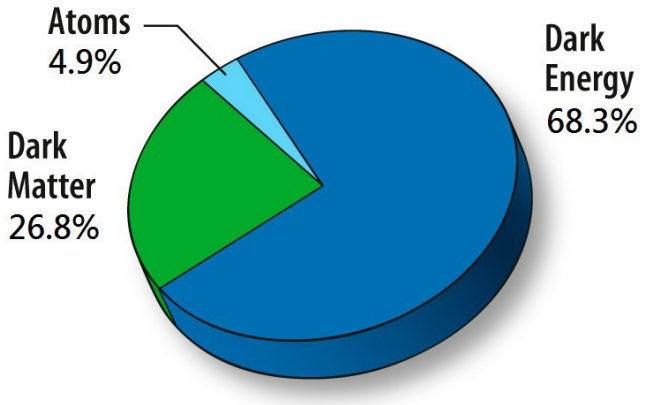
UNSW SYDNEY Australia's Global University

Australian Government
Australian Research Council

ΛCDM: the "standard model" of cosmology

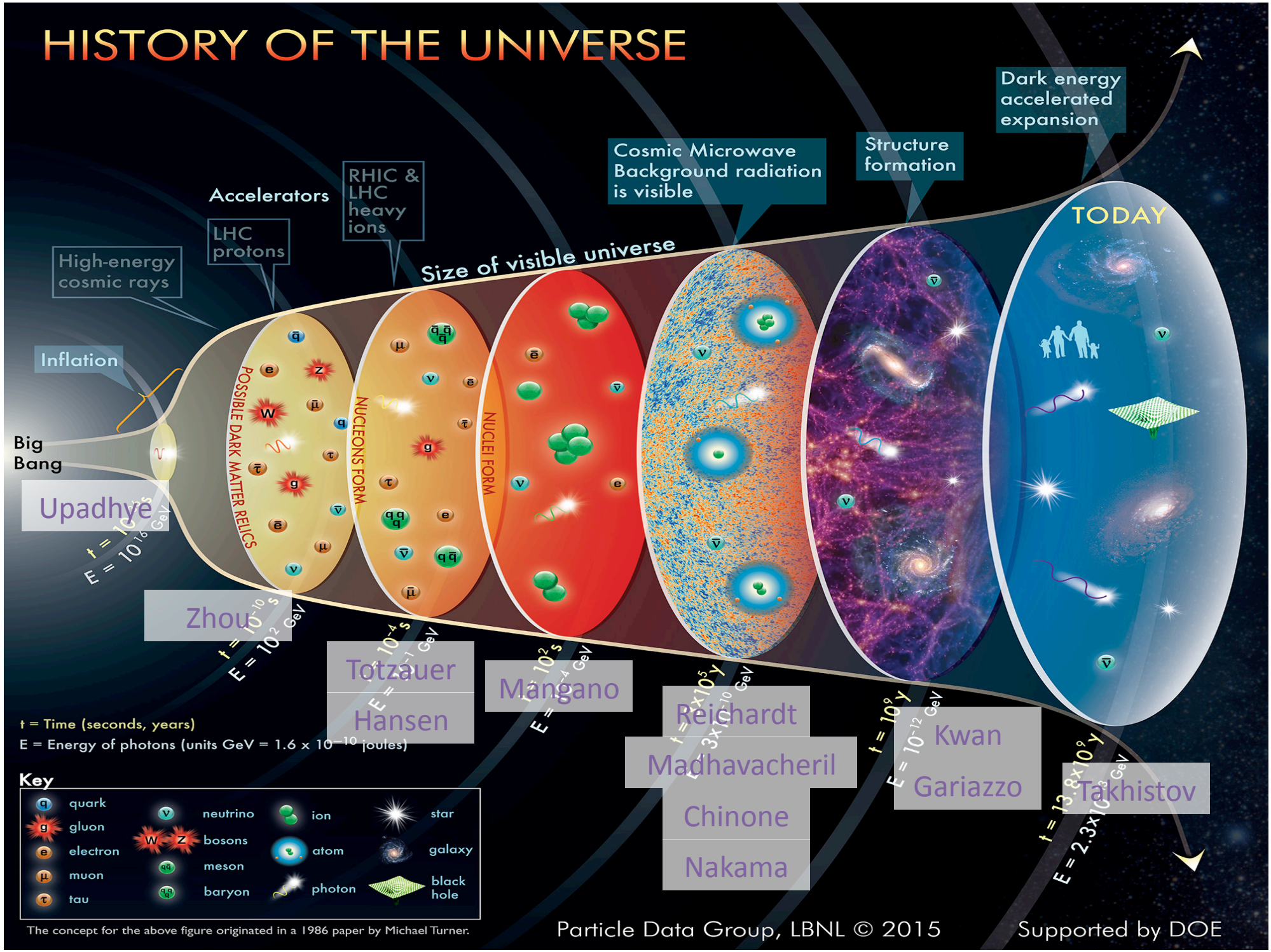
The simplest model consistent with current cosmological observations is the ΛCDM model.





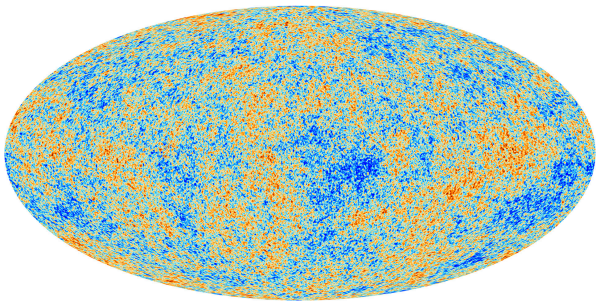
[Y. Wong's talk, see also A. Melchiorri's talk]

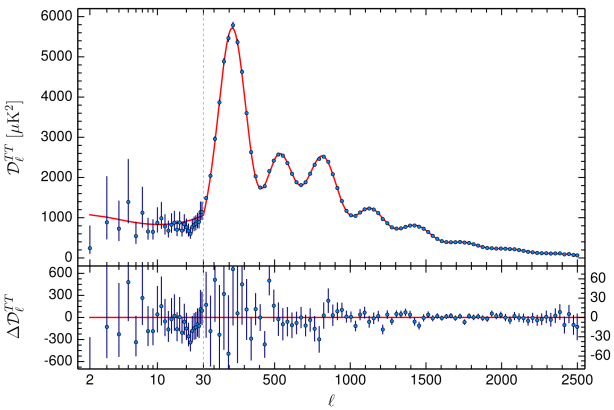
ΛCDM = General relativity
+ Standard Model of particle physics
+ empirical ingredients (DM, cosmological constant, primordial perturbations)


HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Cosmic Microwave Background radiation is visible
Structure formation
TODAY
Accelerators
RHIC & LHC heavy ions
LHC protons
High-energy cosmic rays
Size of visible universe
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
Upadhye
Zhou
Totzauer
Hansen
Mangano
Reichardt
Madhavacheril
Chinone
Nakama
Kwan
Gariazzo
Takhistov
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6 x 10−10 joules)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
The concept for the above figure originated in a 1986 paper by Michael Turner.
Particle Data Group, LBNL © 2015
Supported by DOE

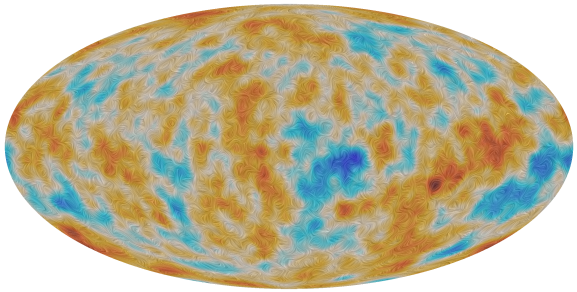
Cosmic microwave background anisotropies: observables

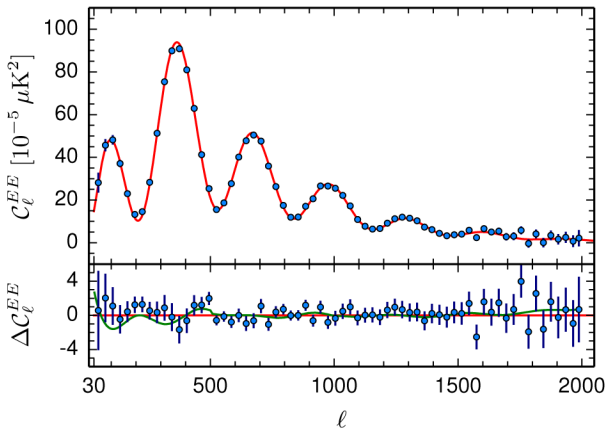
Temperature



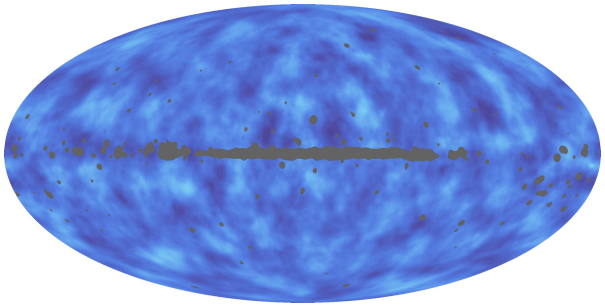


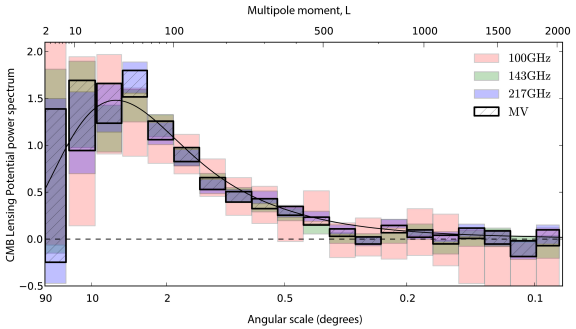
Polarisation



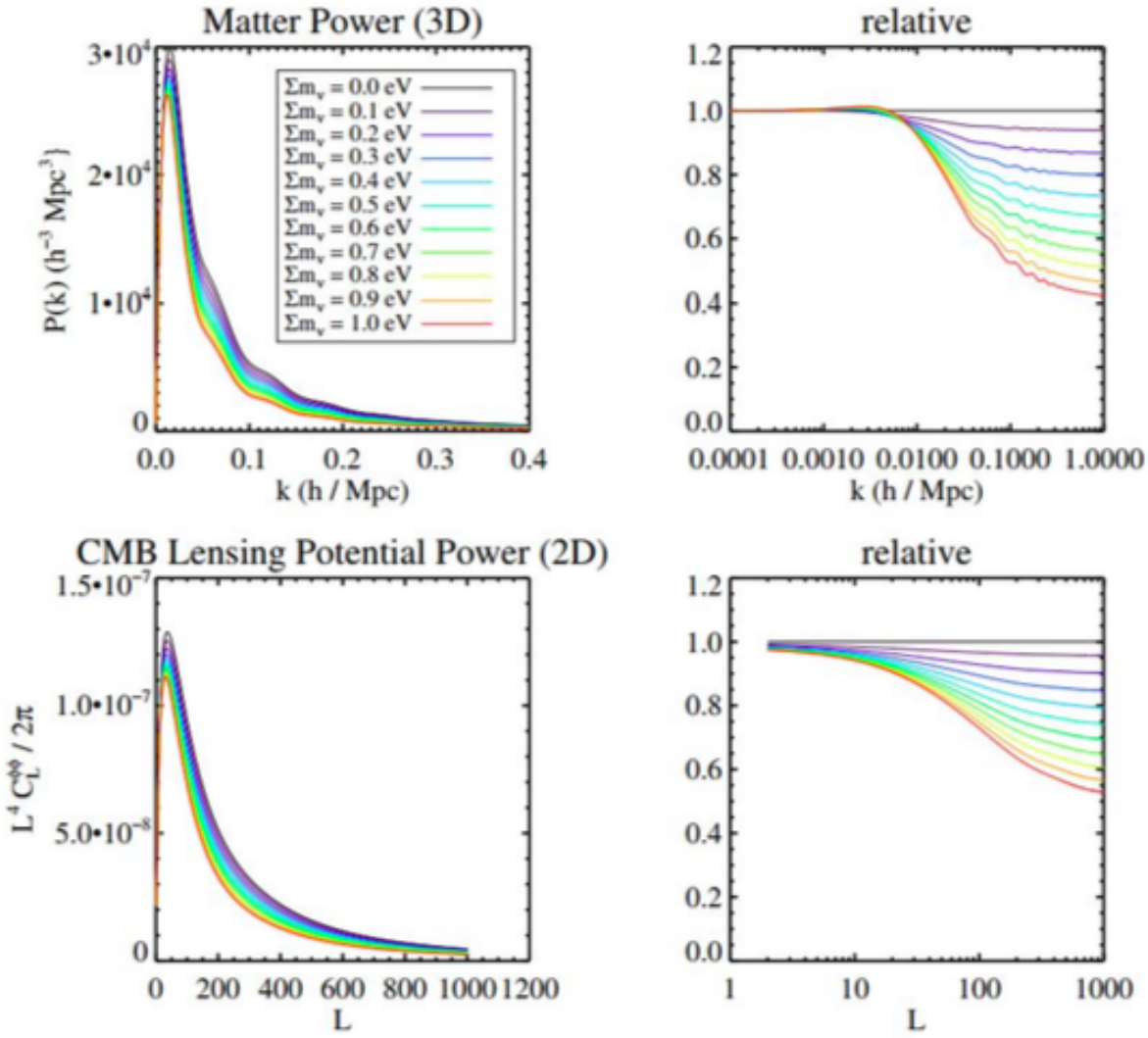


CMB lensing





CMBS4 Science Book arXiv:1610.02743 (including **MM**)

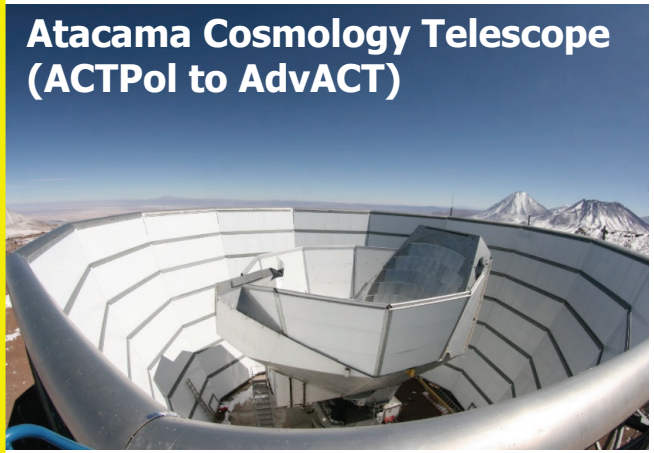


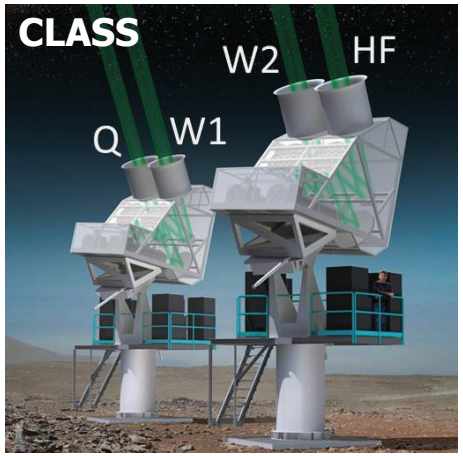
- CMB lensing probes late-time matter perturbations
  ➔ very useful for constraining neutrino masses

[M. Madhavacheril's talk]

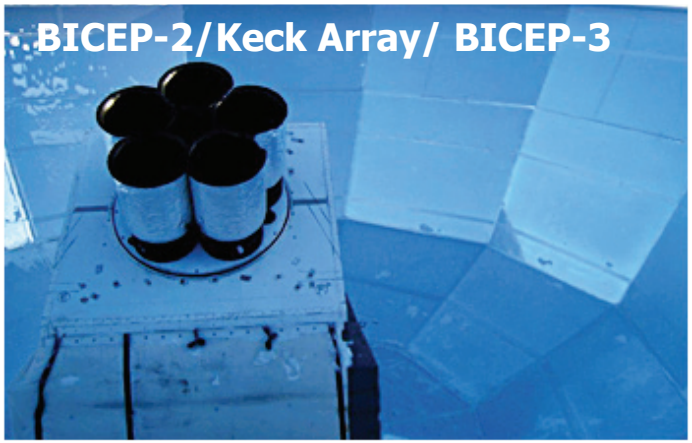
Current Ground-Based Experiments

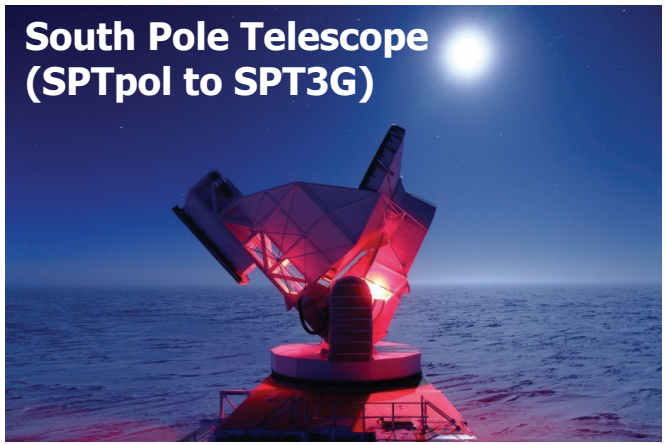
Chile, Atacama



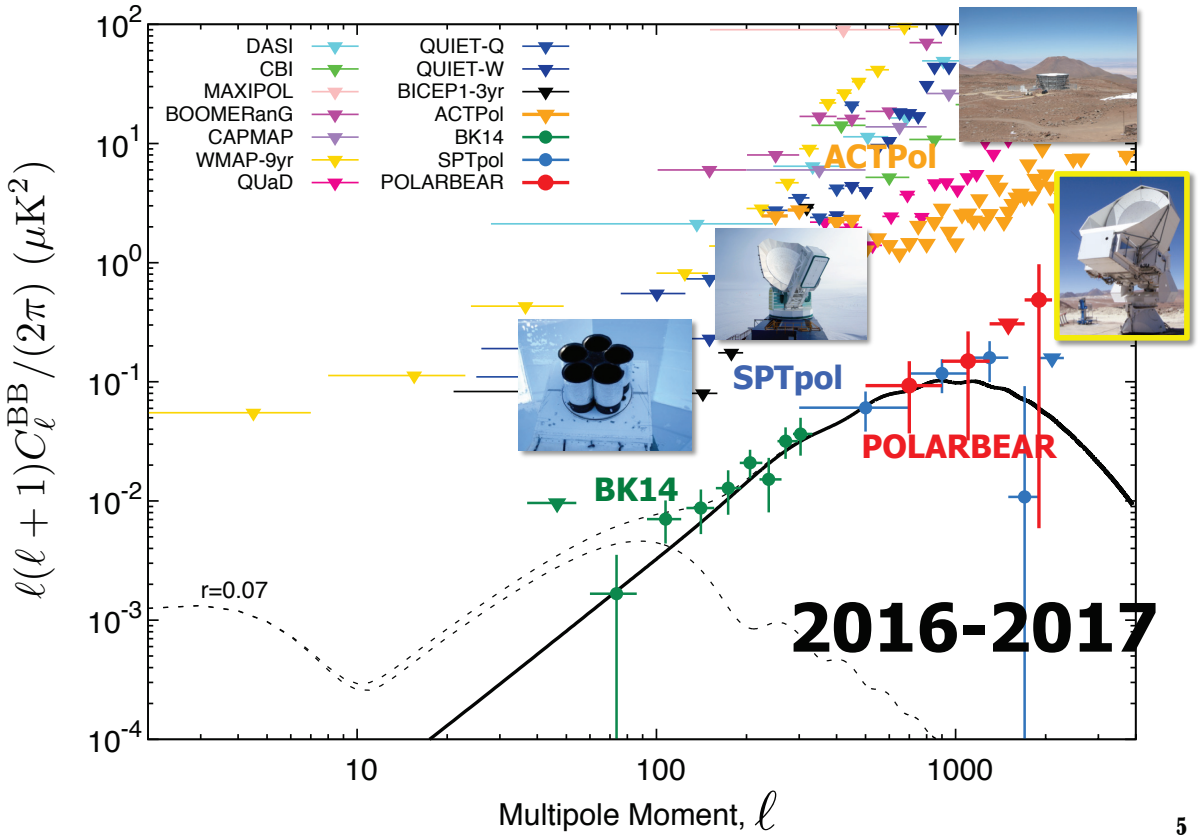


South Pole

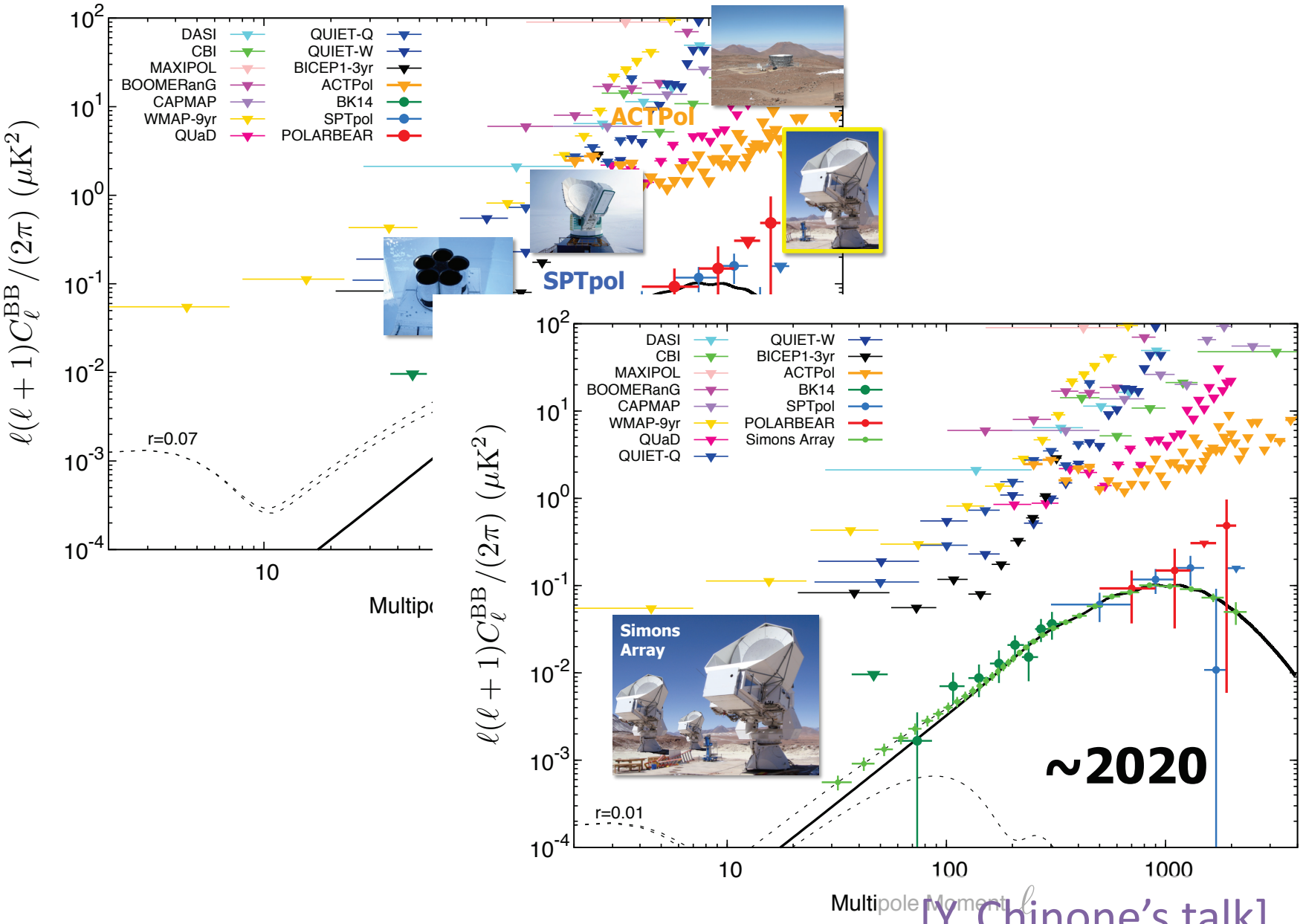




[Y. Chinone's talk]

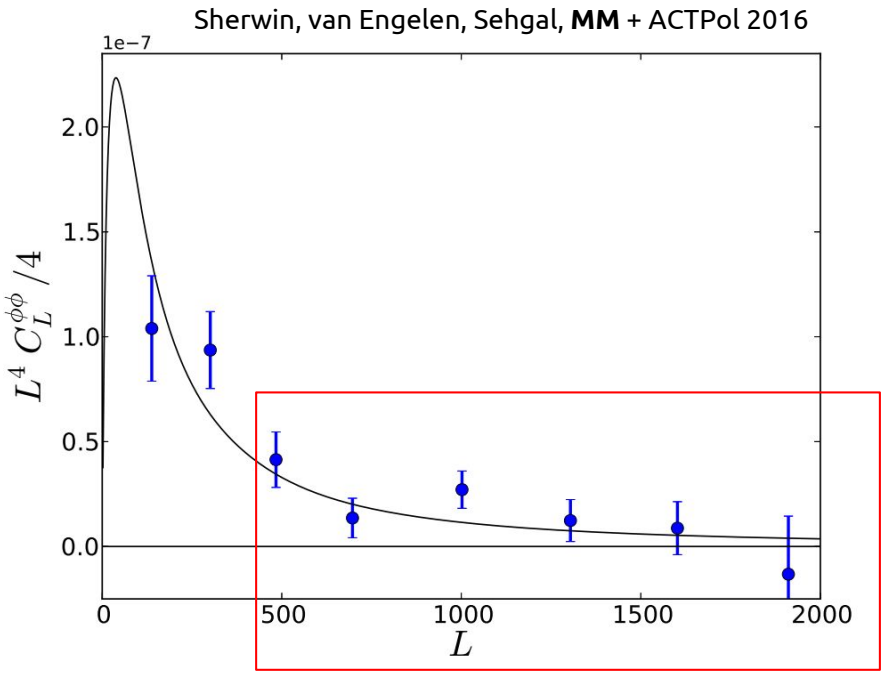


[Y. Chinone's talk]



[Y. Chinone's talk]

Not an easy measurement! Requires exquisite characterization of noise and calculation of noise-dependent biases and higher order corrections.



More scales available for cosmology analysis

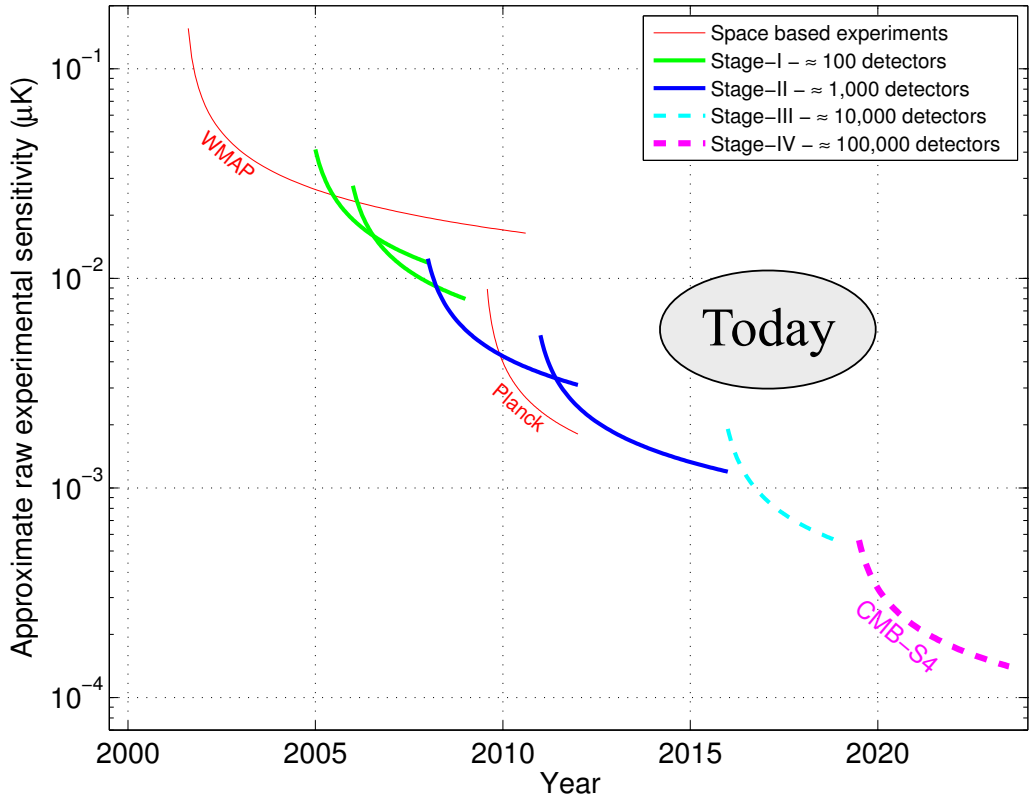
ACTPol two-season measurement of lensing power spectrum (based on 12% of data in the can)

Mathew Madhavacheril, Princeton University

[M. Madhavacheril's talk]

Snowmass: CF5 Neutrinos Document
arxiv:1309.5383

CMB Experimental Stages



Stage-III CMB experiments are starting now, e.g., BICEP3, CLASS, SPT-3G, AdvACT, Simons Array

Stage-IV CMB experiment = **CMB-S4**
~200x faster than the Stage 2 experiments that just finished

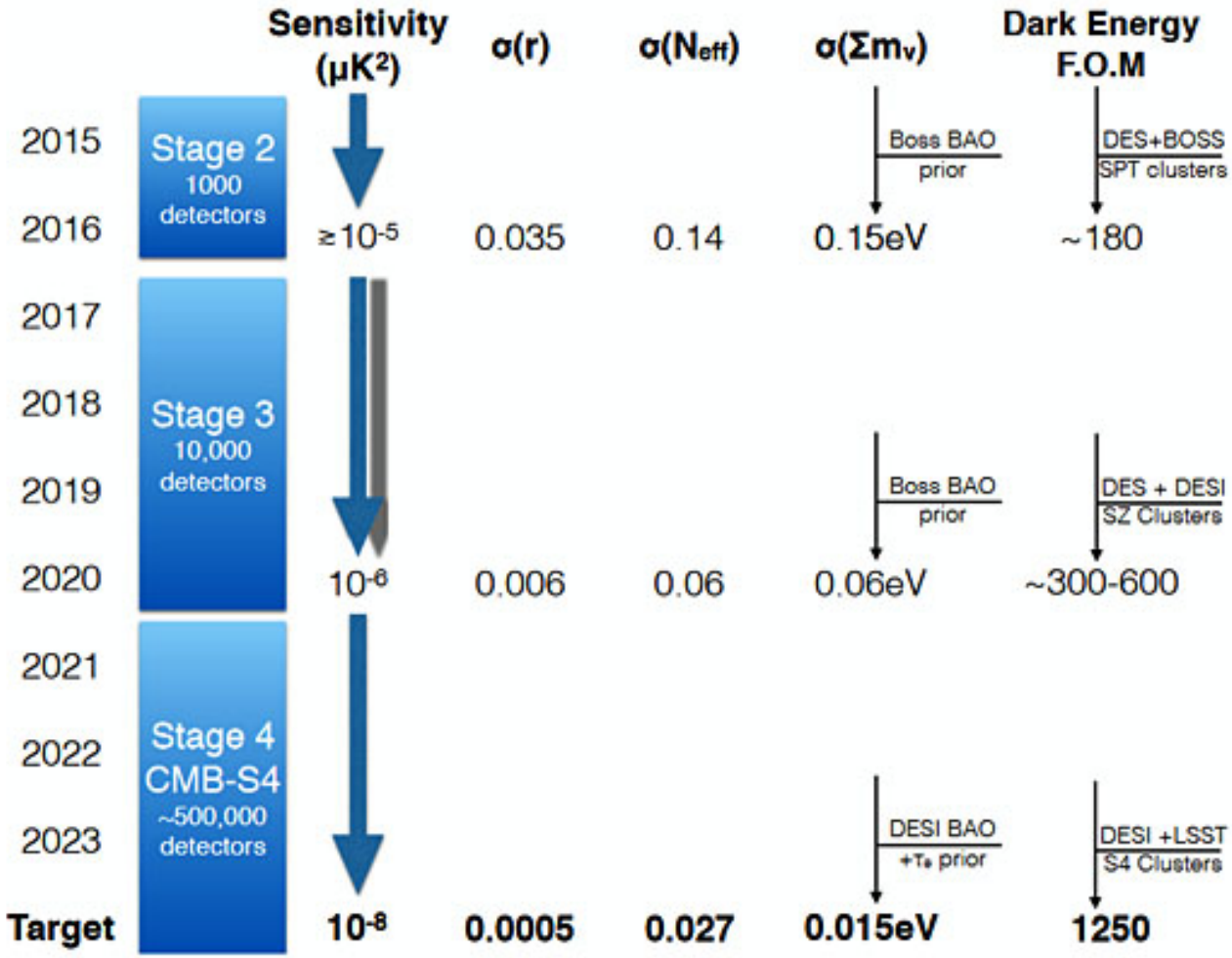
Enabling technologies:

- **First multichroic detectors on-sky in 2017.**
- **Better multiplexing**
- **Beginning to deploy tens of thousands of detectors**

[C. Reichardt's talk]

CMB-S4
Science
Book

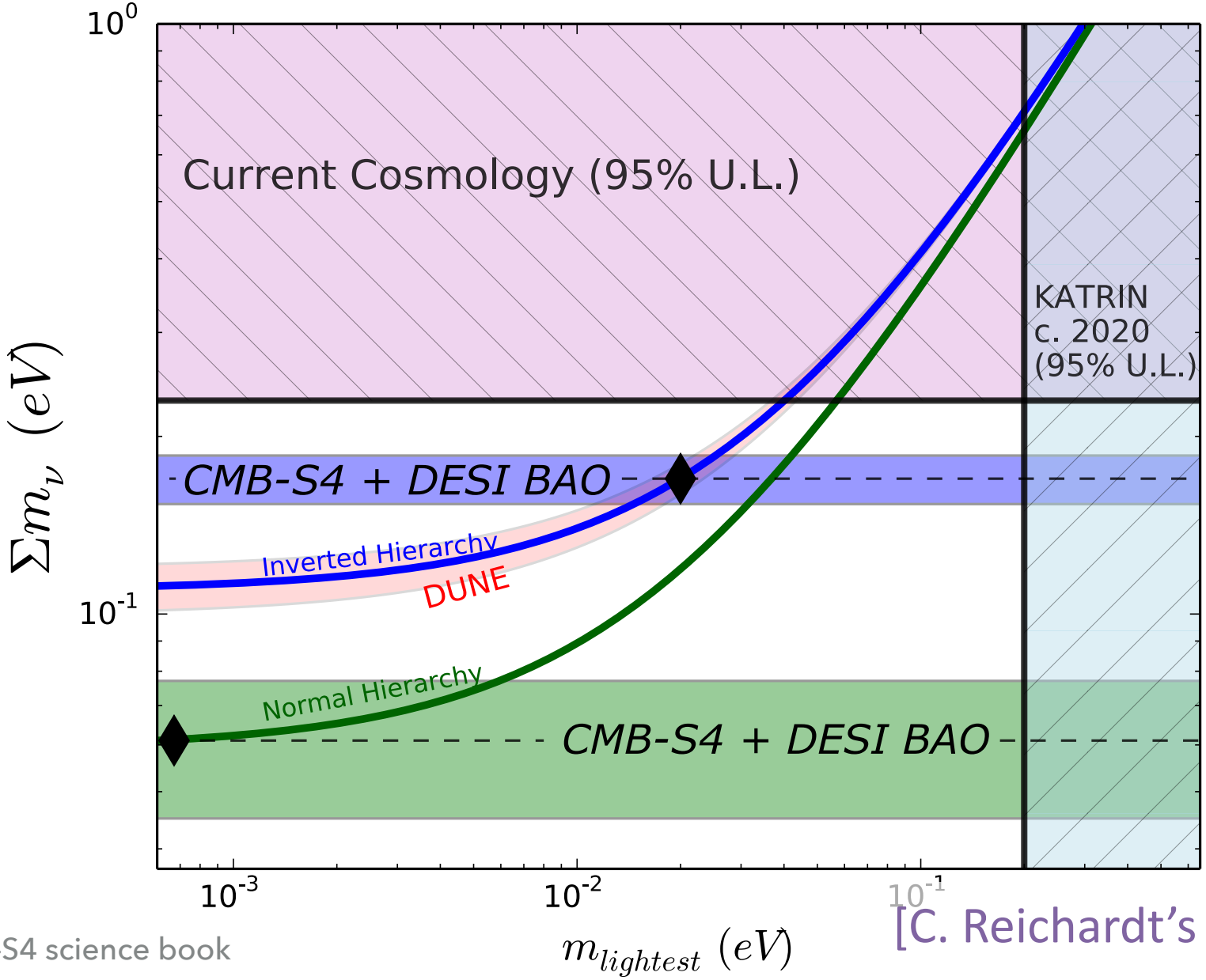
CMB Experimental Stages: Science forecasts



Order of magnitude improvements compared to today: x70 x6 x10 x7

[C. Reichardt's talk]

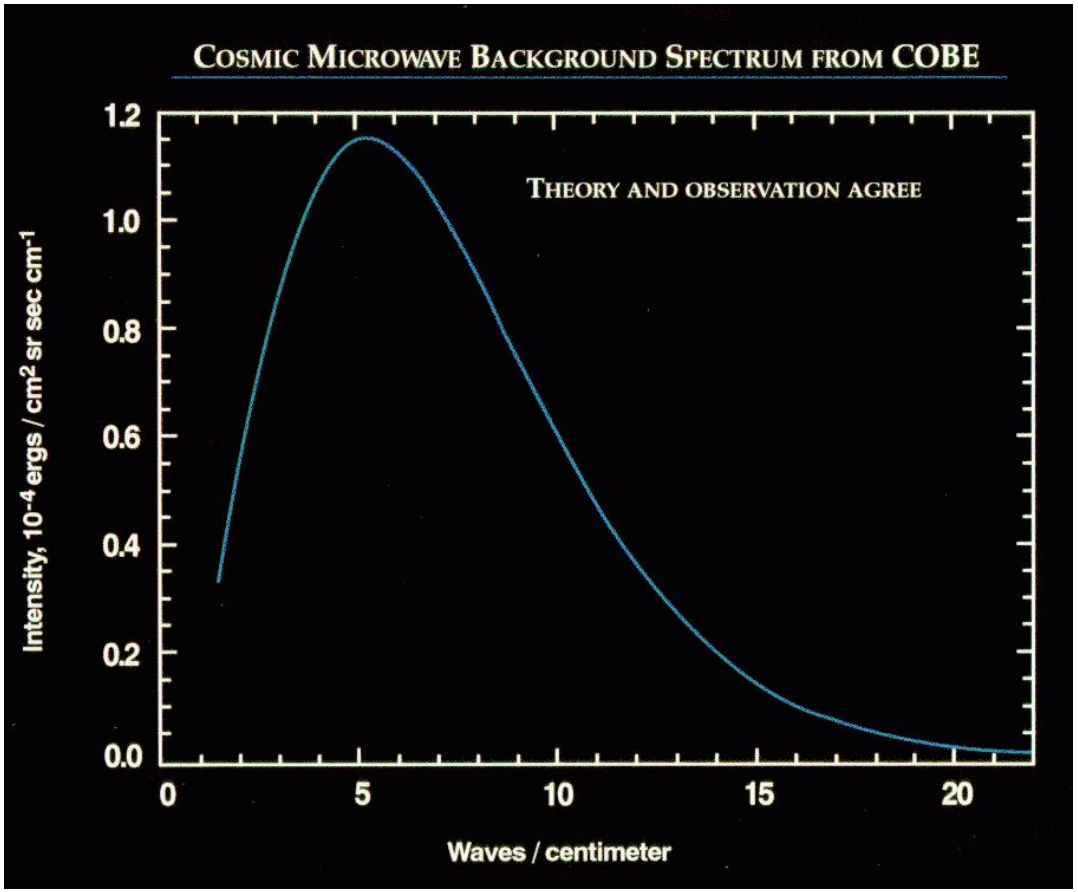
Neutrinos mass forecasts



from CMB-S4 science book

[C. Reichardt's talk]

CMB is not just about anisotropies…



- Look for distortions of blackbody spectrum, e.g., μ-distortion

$$I(\nu, T) = \frac{2h\nu^3}{c^2} \frac{1}{\exp(\frac{h\nu}{kT} + \mu) - 1}$$

$$\mu \simeq \mu_{ac} + \mu_{ex},$$

$(0 <)$

Khatri, Sunyaev & Chluba (2011)

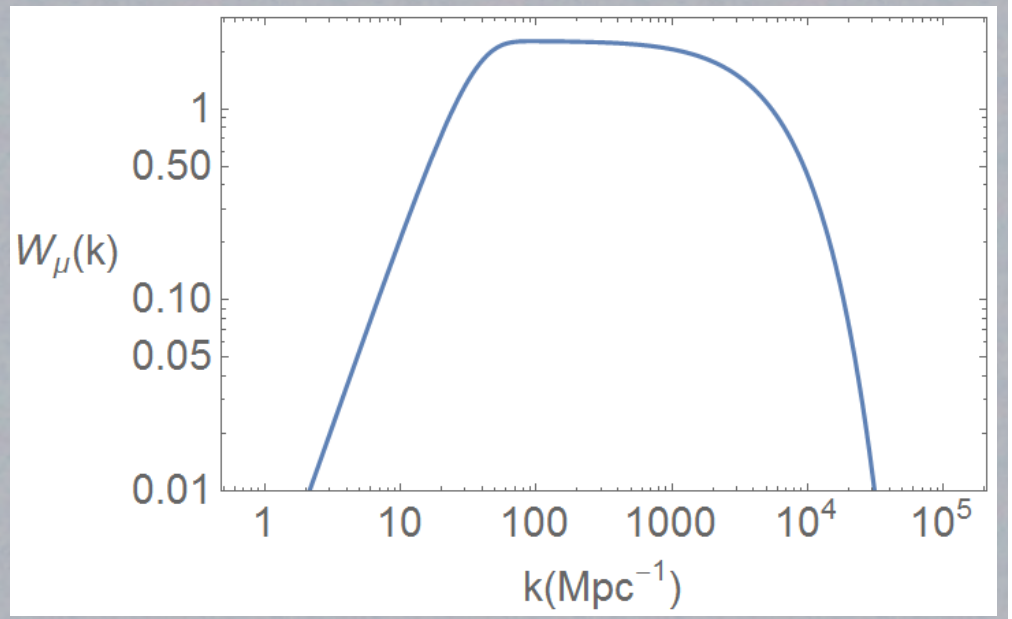
-3×10^{-9}

nondimensional power spectrum of curvature perturbation

$$\mu_{\rm ac} \simeq \int_{k_{\rm min}}^{\infty} \frac{dk}{k} \mathcal{P}(k) W_\mu(k),$$

$1\mathrm{Mpc}^{-1}$

Chluba & Grin (2013)



$\mu \simeq 2 \times 10^{-8}$ for standard nearly-scale inv. fluctuations.

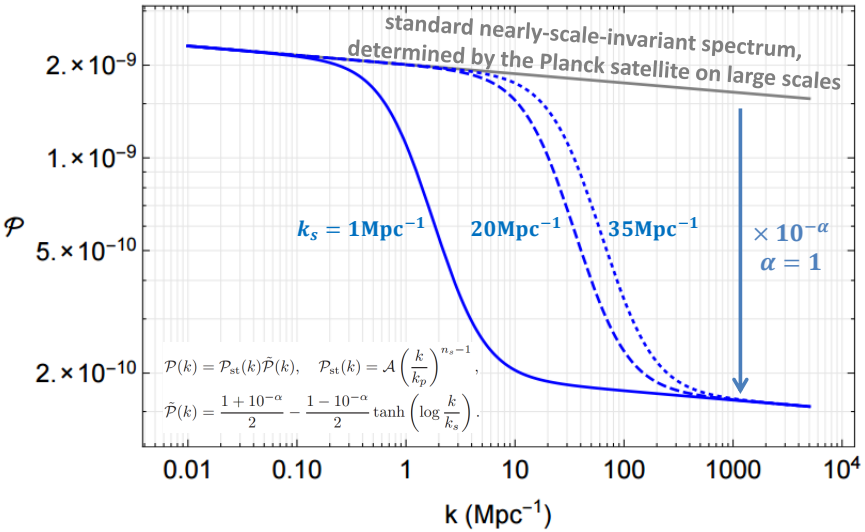
Chluba (2016)

If $\mathcal{P}(k)$ suppressed for $k \gtrsim \mathcal{O}(10)\mathrm{Mpc}^{-1}$, μ smaller.

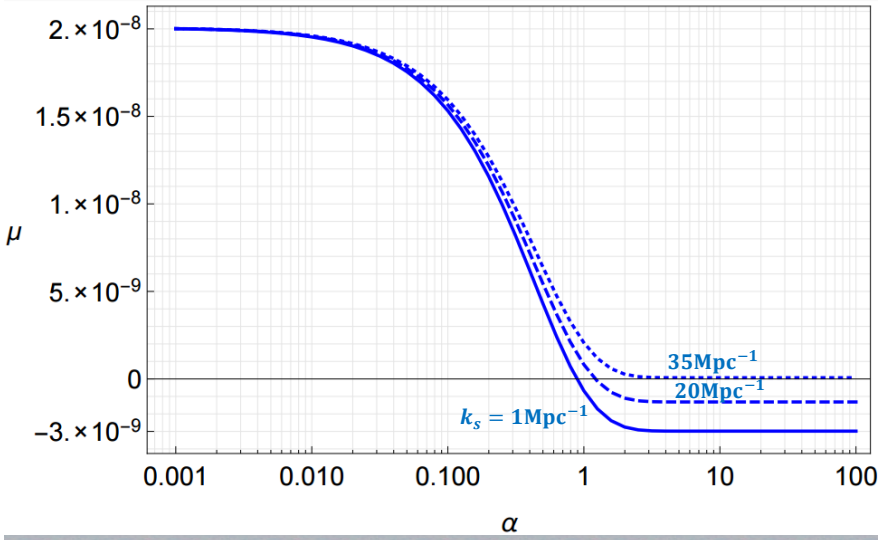
[T. Nakama's talk]

- Models with suppressed power on small scales [cf. cusp/core, too big to fail, missing satellites] have lower μ

Examples of primordial curvature perturbations suppressed on subgalactic scales



μ distortions can be much smaller than the standard value $\simeq 2\times10^{-8}$

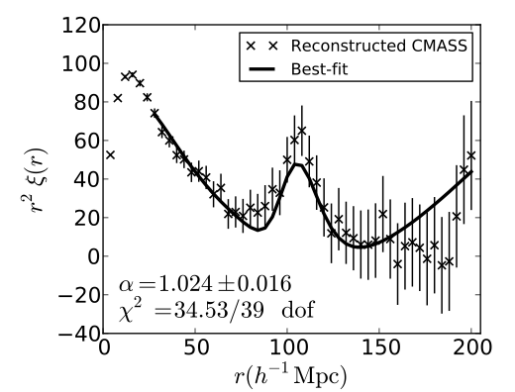


- Next-to-next generation of experiments will be able to distinguish this from other solutions, e.g., WDM

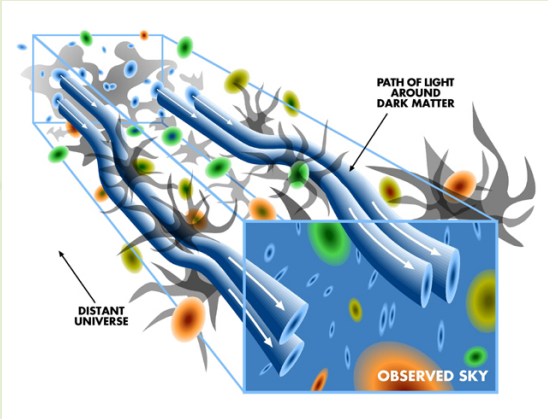
[T. Nakama's talk]

Large scale structure observables

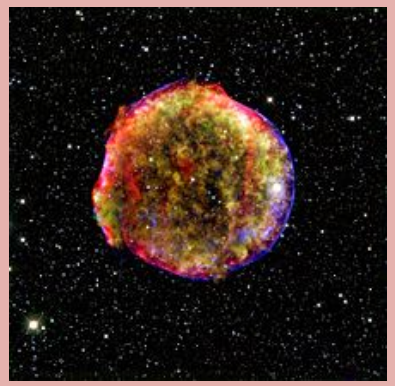
BAO scale



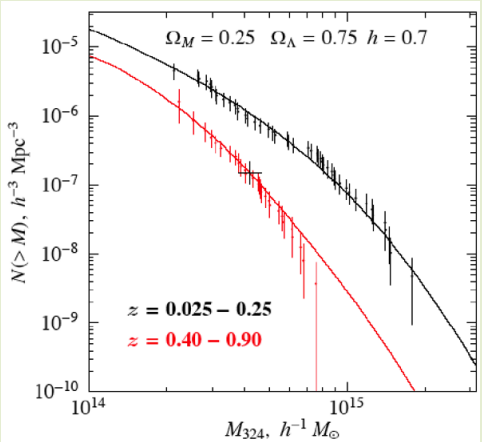
Cosmic shear



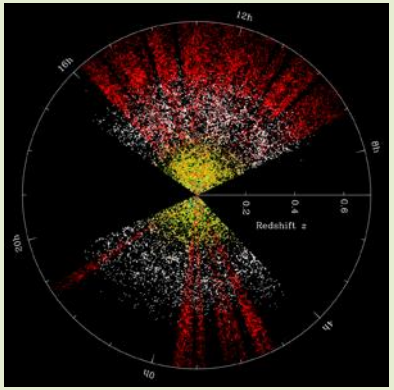
Type Ia supernovae



Cluster counts



Galaxy clustering



Geometric observables

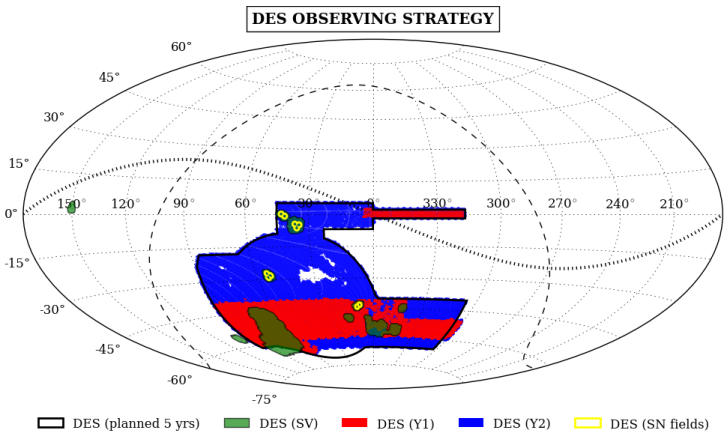
Perturbation-based observables

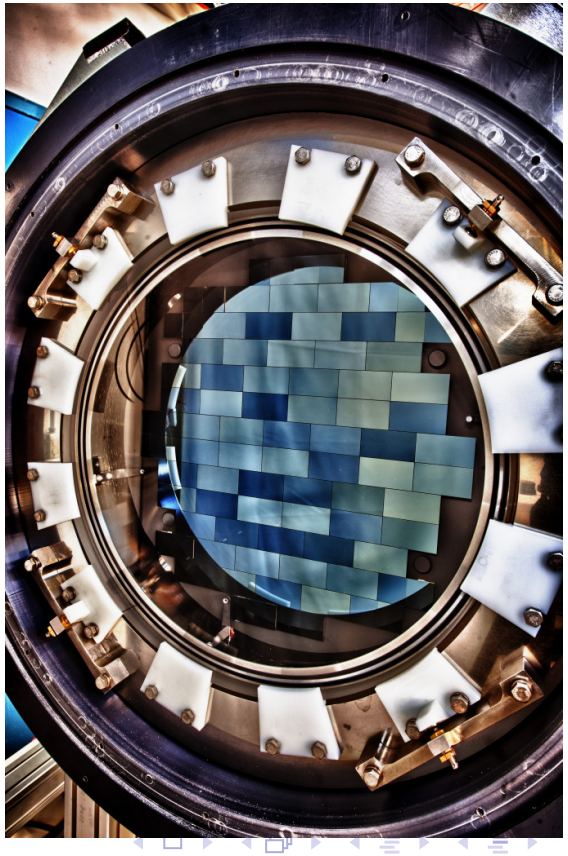
Large scale structure observables

- Unlike CMB, large scale structure probes are directly sensitive to the matter distribution at low redshifts and allow us to see the evolution of structure
- Particularly helpful for constraining late-time physics, such as neutrino masses or Dark Energy, and disentangling their effects

The Dark Energy Survey

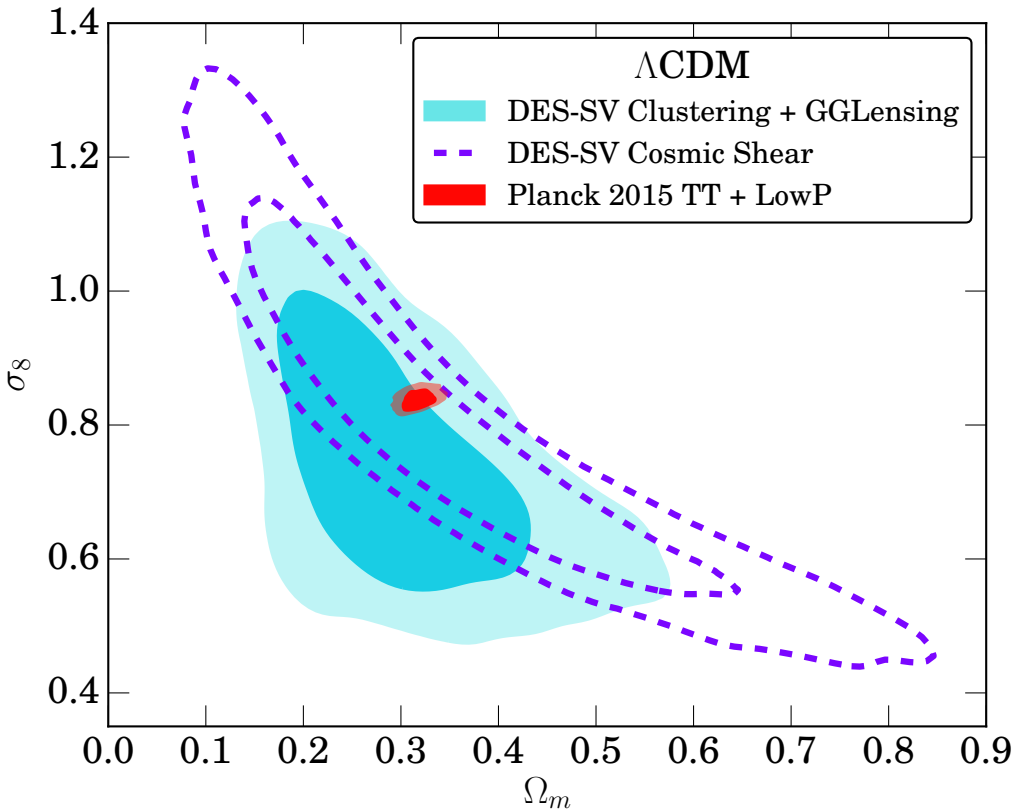
DES is an on-going imaging survey of the Southern Sky using DECam on the 4m Blanco Telescope in Chile.





[J. Kwan's talk]

Cosmology: Constraints on σ_8 and Ω_m (ΛCDM)



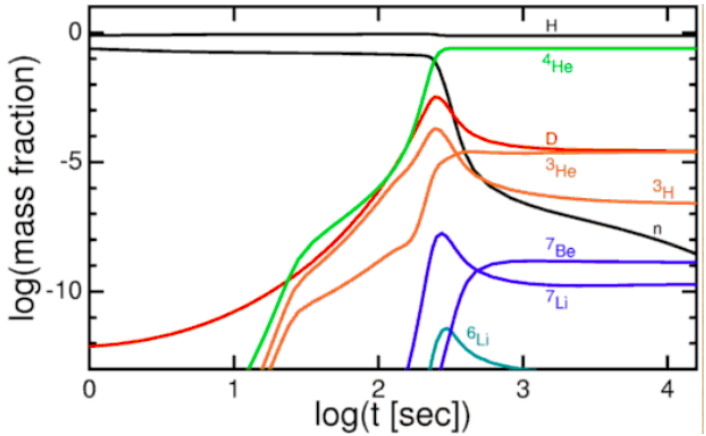
- First results based on science verification area
- More data being analysed and taken

- Several further surveys in progress or on the way, e.g., KiDS, Hyper Suprime Cam, DESI, LSST, Euclid...

[J. Kwan's talk]

Big Bang Nucleosynthesis

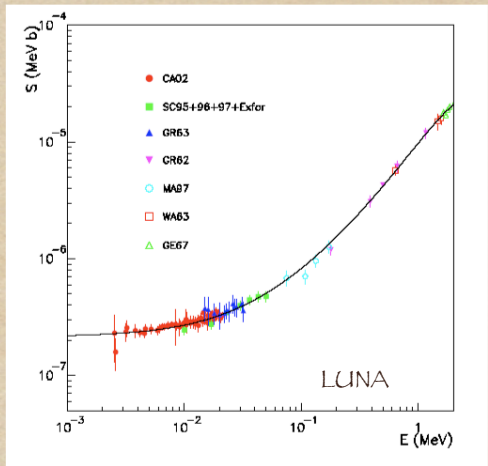
- Formation of light elements around t = O(1) min
- Infer primordial element abundances from astrophysical measurements, compare to theoretical predictions



- Sensitive to baryon density, effective number of neutrino species, neutrino chemical potential

- Moderate discrepancy between theoretically calculated and experimentally measured nuclear rates

Nuclear rates: for d(p,γ) ^{3}He also available ab initio calculations (Viviani et al 2000 PRC, Marcucci et al 2005 PRC, …,Marcucci et al 2016 PRL)



Larger cross section than present data fit (Adelberger et al, 2011, Rev. Mod. Phys.)

$R \approx \langle S \rangle_{TH} / \langle S \rangle_{exp} > 1$!

Important to check experimentally this result! LUNA 2017-2018?

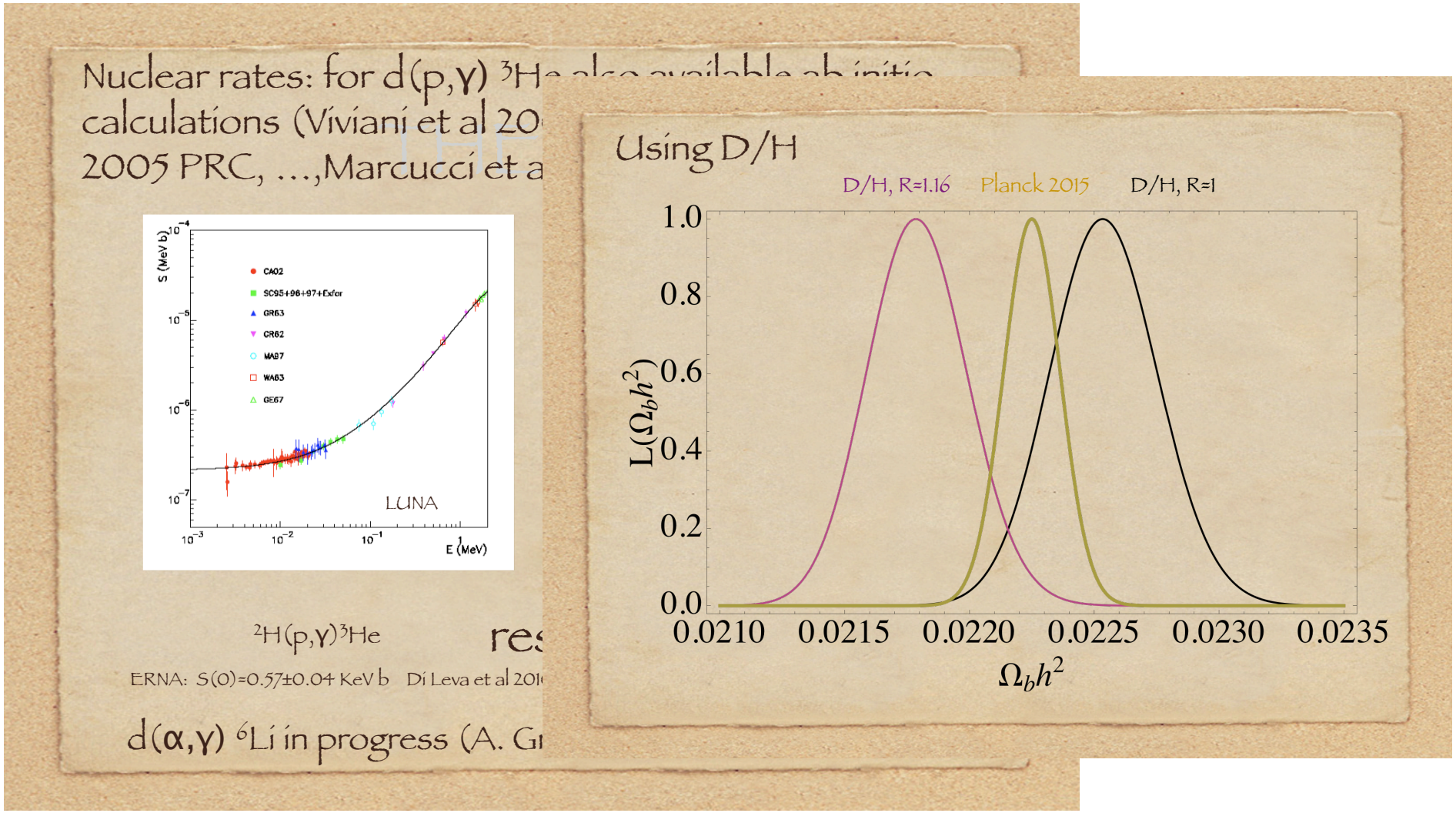
^{2}H(p,γ)^{3}He

ERNA: S(0)=0.57±0.04 KeV b Di Leva et al 2010

d(α,γ) ^{6}Li in progress (A. Grassi et al)

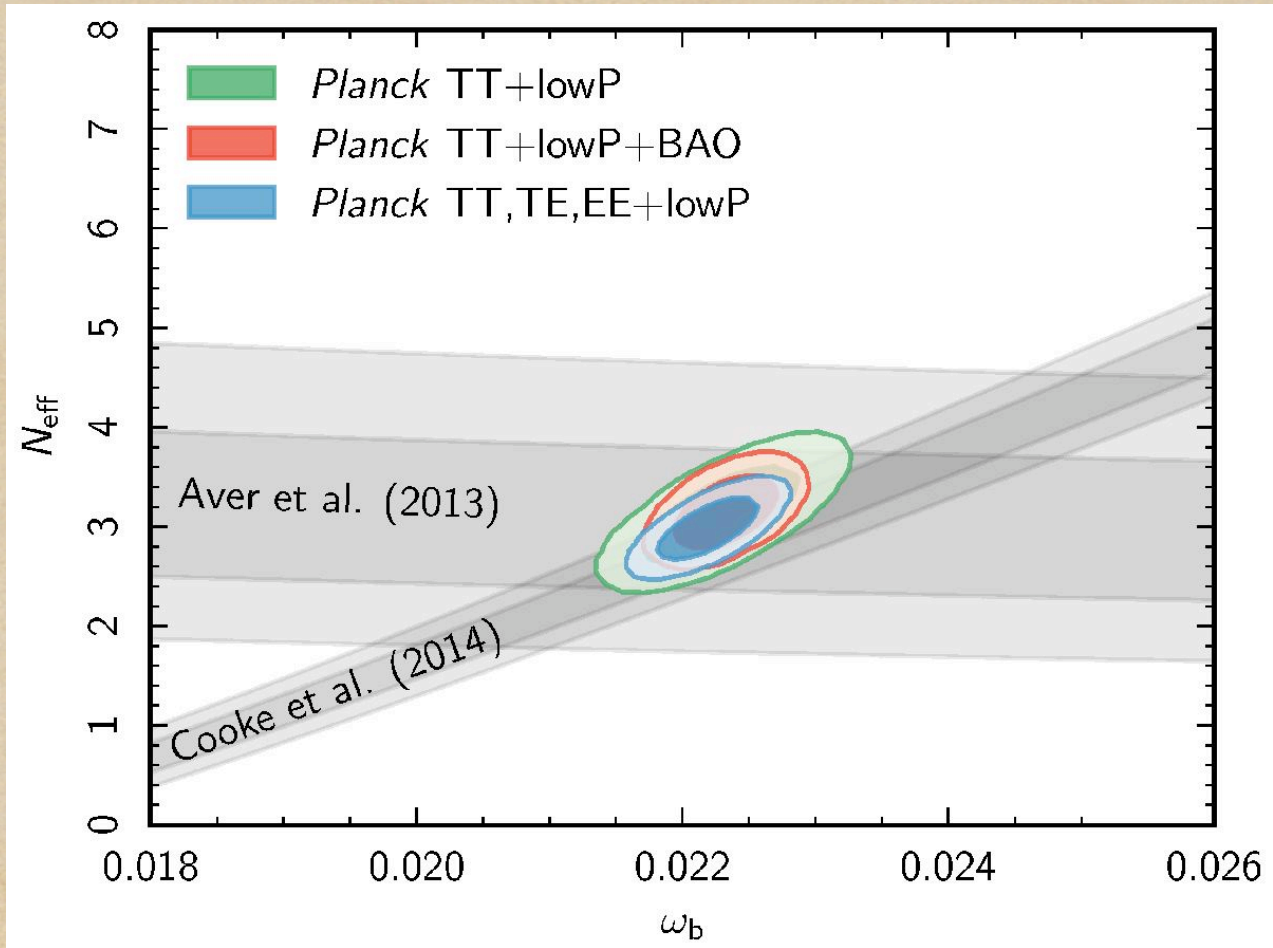
[G. Mangano's talk]

- Moderate discrepancy between theoretically calculated and experimentally measured nuclear rates



- Still good consistency with CMB results [G. Mangano's talk]

Planck 2015



[G. Mangano's talk]

Cosmic neutrino background

- Strong indirect evidence from CMB and BBN
- Is there any way to detect it directly?

Direct detection of CνB neutrinos

[Long et al., JCAP 08 (2014) 038]

At least two CνB neutrinos over three are non-relativistic now!

How to detect non-relativistic neutrinos?

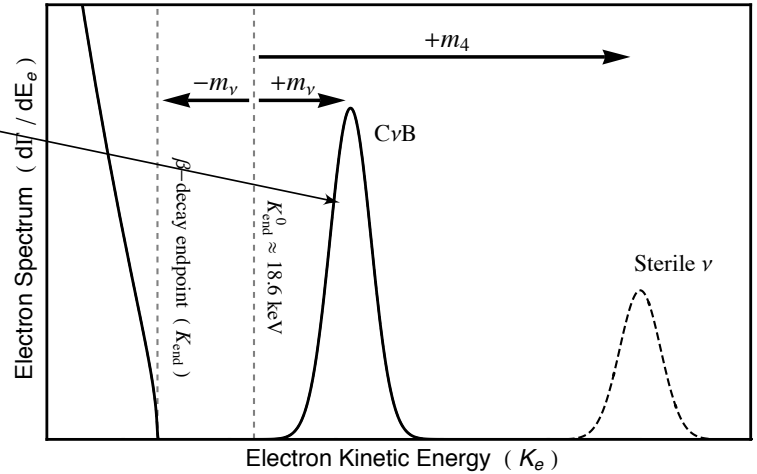
a process without energy threshold is necessary

[Weinberg, 1962]: neutrino capture in β–decaying nuclei $\nu + n \rightarrow p + e^-$

signal is a peak at $2m_\nu$ above β–decay endpoint

only with a lot of material

need a very good energy resolution



Good candidate: tritium

(low Q–value) + (good availability of ^{3}H) + (high cross section of $\nu + {}^3\mathrm{H} \rightarrow {}^3\mathrm{He} + e^-$)

PTOLEMY

(Princeton Tritium Observatory for Light Early-Universe Massive-Neutrino Yield)

[S. Gariazzo's talk]

ν clustering with N-one-body simulations

[arxiv:170(6|7).[0-9]{5}]

Milky Way (MW) matter attracts neutrinos!

clustering →

$$\Gamma_{C\nu B} = \sum_{i=1}^{3} |U_{ei}|^2 \, f_c(m_i) \, [n_{i,0}(\nu_{h_R}) + n_{i,0}(\nu_{h_L})] \, N_T \, \bar{\sigma}$$

$f_c(m_i)$ clustering factor ⟶ How to compute it?

Idea from [Ringwald & Wong, 2004] ⟶ N-one-body= N × single ν simulations

→ each ν evolved from initial conditions at $z = 3$

→ spherical symmetry, coordinates (r, θ, p_r, l)

→ need $\rho_{\rm matter}(z) = \rho_{\rm DM}(z) + \rho_{\rm baryon}(z)$

Assumptions:

- νs are independent
- only gravitational interactions
- νs do not influence matter evolution ($\rho_\nu \ll \rho_{\rm DM}$)

how many νs is "N"?

→ must sample all possible r, p_r, l

→ must include all possible νs that reach the MW (fastest ones may come from several (up to $\mathcal{O}(100)$) Mpc!)

given N ν:

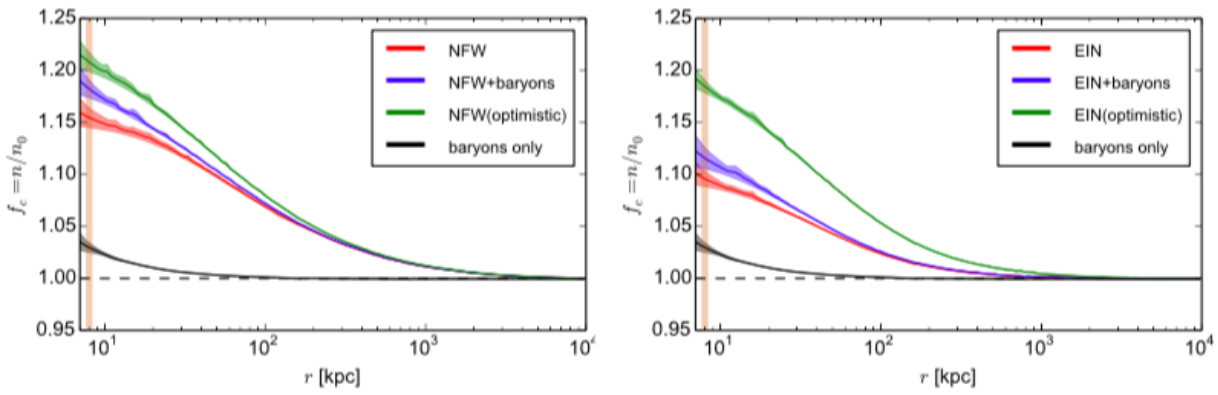
→ weigh each neutrinos

→ reconstruct final density profile with kernel method from [Merritt&Tremblay, 1994]

[S. Gariazzo's talk]

Overdensity when $m_{\text{heaviest}} \simeq 60$ meV

[arxiv:170(6|7).[0-9]{5}]

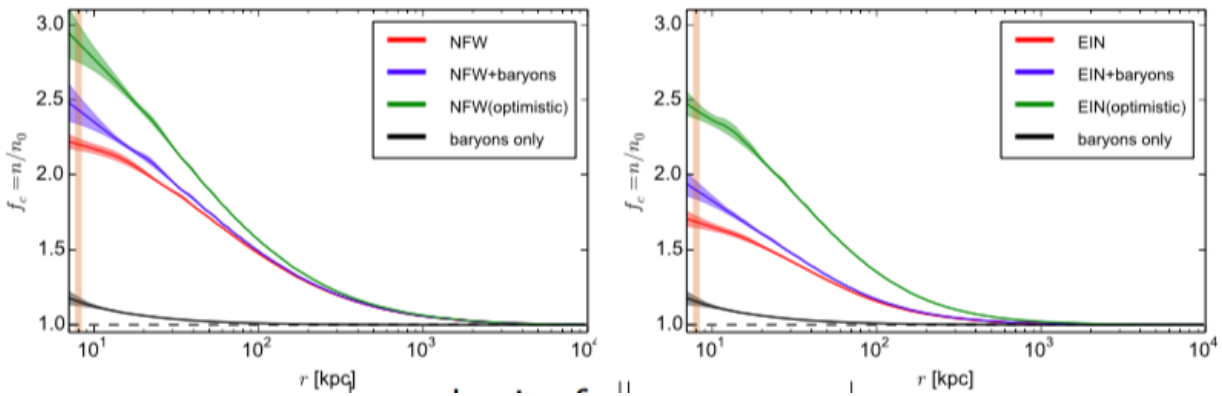


Not detectable by PTOLEMY (energy resolution too low)

Overdensity when $m_\nu \simeq 150$ meV

[arxiv:170(6|7).[0-9]{5}]

$\Longrightarrow$ minimal mass detectable by PTOLEMY if $\Delta \simeq 100$–150 meV

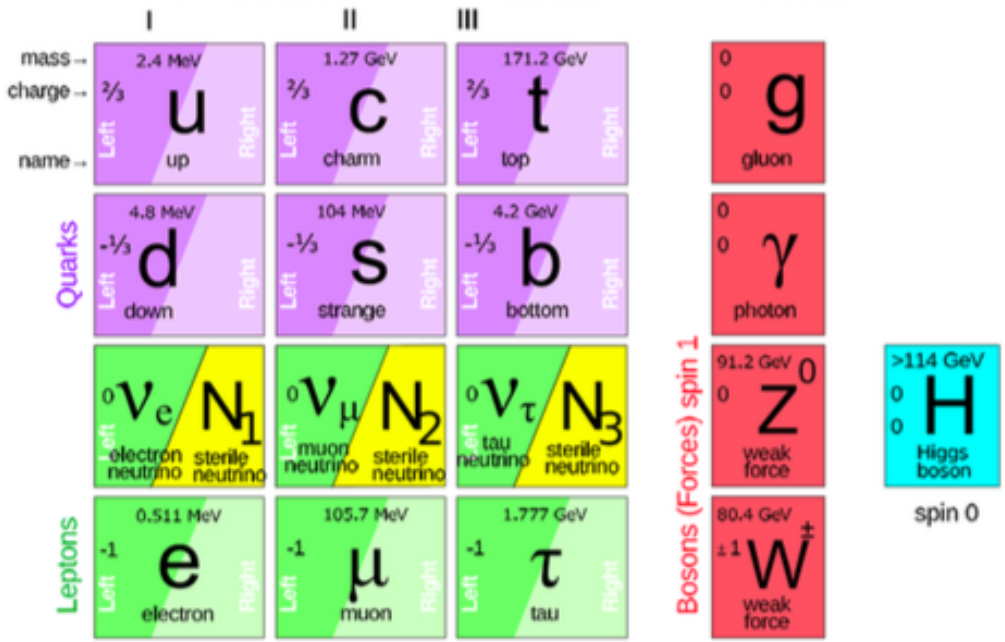


Minimum mass detectable by PTOLEMY, density enhanced by factor ~2

[S. Gariazzo's talk]

Beyond standard neutrinos…

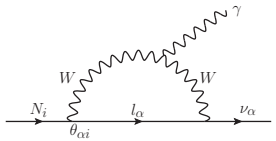
- eV sterile neutrino [C. Giunti's talk]
- keV sterile neutrino as DM candidate



How to fill the templates with physical models for SN?

The popular production mechanisms are:

- ~~Dodelson-Widrow production~~ (DW), aka non-resonant active-sterile conversion (freeze-in), $\Omega_{\mathrm{DM}} \propto \sin^2(2\theta)$



- Shi-Fuller production (SF), aka resonant active-sterile conversion (freeze-in)
- ~~Diluted thermal freeze-out: $SU(3)_C \times SU(2)_L \times U(1)_Y \times \mathcal{G}_X$~~
- DW/SF + late thermalisation in dark sector → Talk by R. S. L. Hansen.
- Decay production via some parent particle, e.g. real scalar singlet S coupled to Higgs sector.

[M. Totzauer's talk]

A simple model for scalar decay – Lagrangian

- Field content beyond SM: real scalar singlet S and one sterile neutrino N.
- Lagrangian:

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \left[i\overline{N}\partial\!\!\!/ N + \frac{1}{2}\left(\partial_\mu S\right)\left(\partial^\mu S\right) - \frac{y}{2} S \overline{N^c} N + \mathrm{h.c.} \right] - V_{\mathrm{scalar}}$$

where

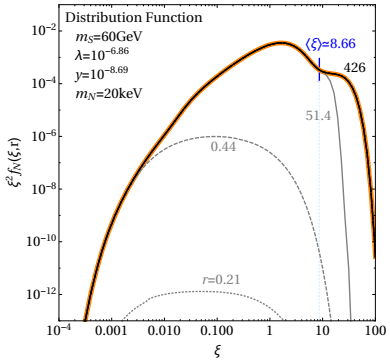
$$V_{\mathrm{scalar}} = -\mu_\Phi^2 \Phi^\dagger \Phi - \frac{1}{2}\mu_S^2 S^2 + \lambda_\Phi \left(\Phi^\dagger \Phi\right)^2 + \frac{\lambda_S}{4} S^4 + 2\lambda \left(\Phi^\dagger \Phi\right) S^2$$

- Processes for DM production: $SS \leftrightarrow \Phi\Phi$ (from plasma)
  $S \to NN$.

[M. Totzauer's talk]

A simple model for scalar decay – non-thermal spectra

The interplay between decay of S in-eq. and out-of-eq. can yield highly non-thermal spectra:



Can't simply use standard (thermal) WDM constraints

SD model and the half-mode analysis

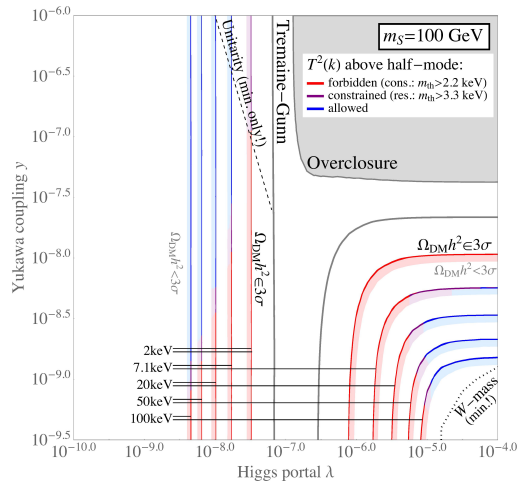
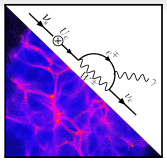


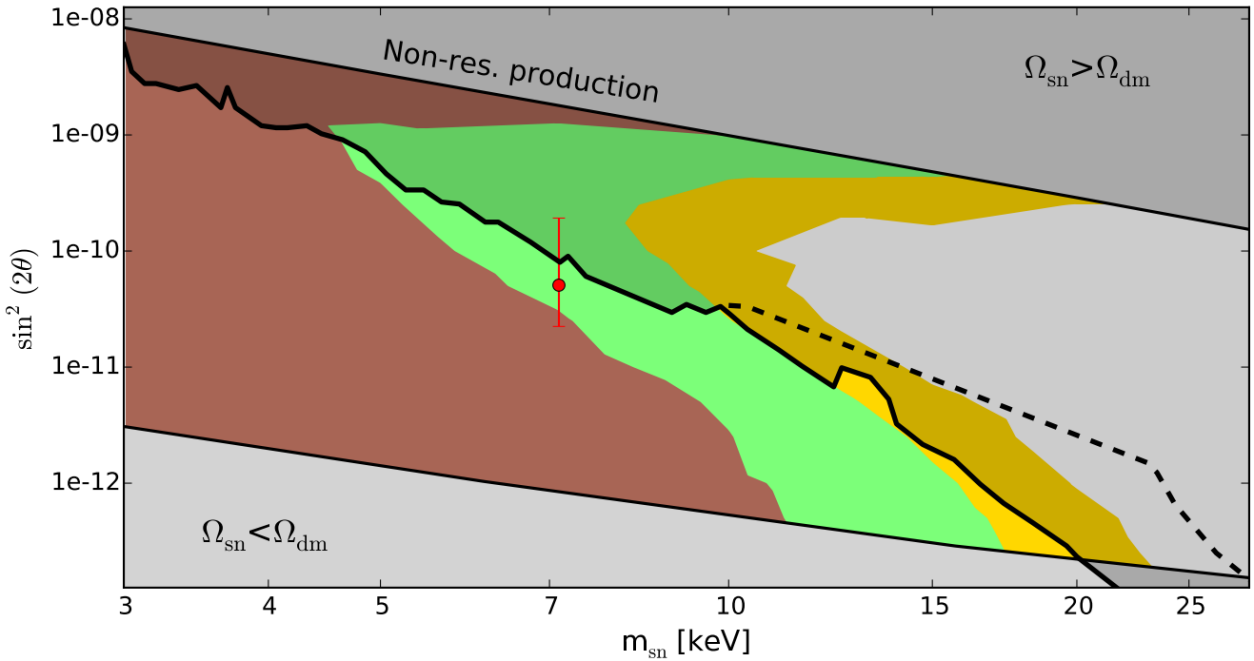
Figure: Constraints from structure formation in the plane λ-vs.-y for $m_S = 100\,GeV$. Taken from JCAP 1611(038) (König, Merle, MT).

[M. Totzauer's talk]

Sterile neutrino production through oscillation



Constraints on ν_s produced through oscillations



Schneider (1601.07553)

[R. Hansen's talk]

Thermalization

Goal:

- Lower average momentum.
- Enhanced number density.

Prerequisites:

- Coupling to a new boson φ with $m_{\nu_s} \ll m_\varphi \ll T_{\nu_s,\mathrm{production}}$.
- Efficient number changing processes for φ.

Toy model

Scalar boson φ coupled to ν_s:

$$\mathcal{L} = \frac{1}{2}\partial^\mu\varphi\partial_\mu\varphi - \frac{1}{2}m_\varphi^2\varphi^2 - \frac{\lambda}{4}\varphi^4 + y\bar{\nu}_s\nu_s\varphi$$

We assume no coupling to Higgs.

e.g. Heikinheimo et al. (1604.02401 and 1704.05359) discuss a Higgs coupling

Decay width:

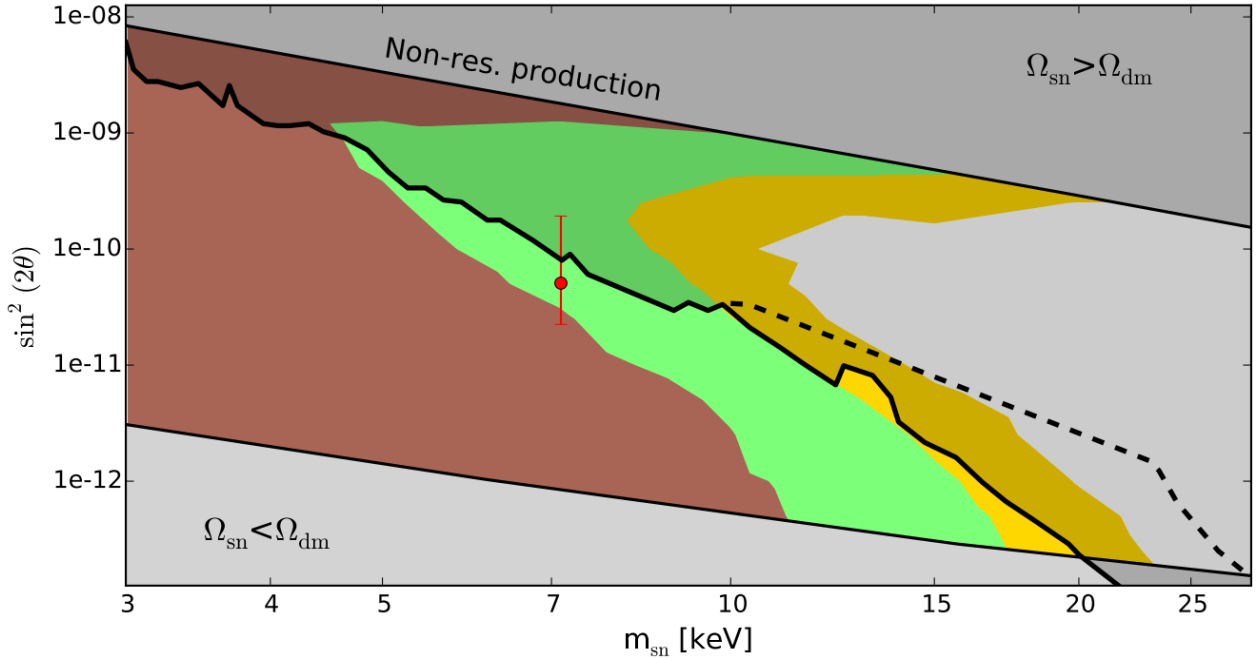
$$\Gamma_\varphi \approx \frac{1}{4\pi}y^2 m_\varphi \ ,$$

Number changing interactions:

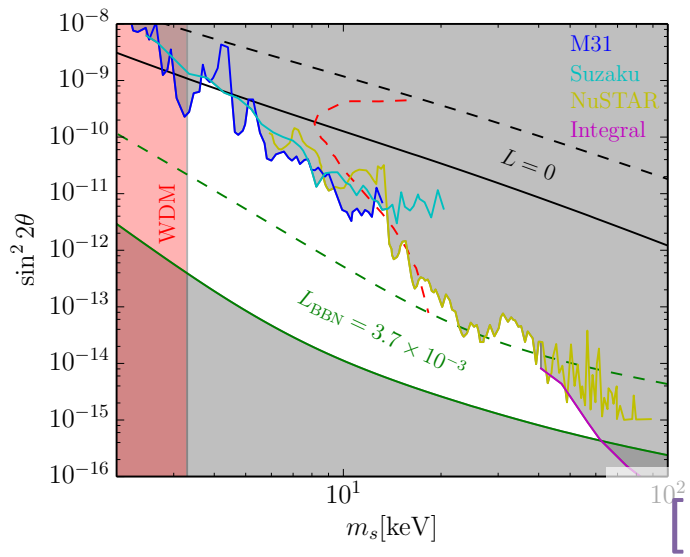
$$\sigma v_{2\to 4} \approx \frac{27\sqrt{3}}{64\pi^4}\frac{\lambda^4 T^3}{m_\varphi^5}\exp\left(-\frac{2m_\varphi}{T}\right) \ .$$

[R. Hansen's talk]

through oscillations



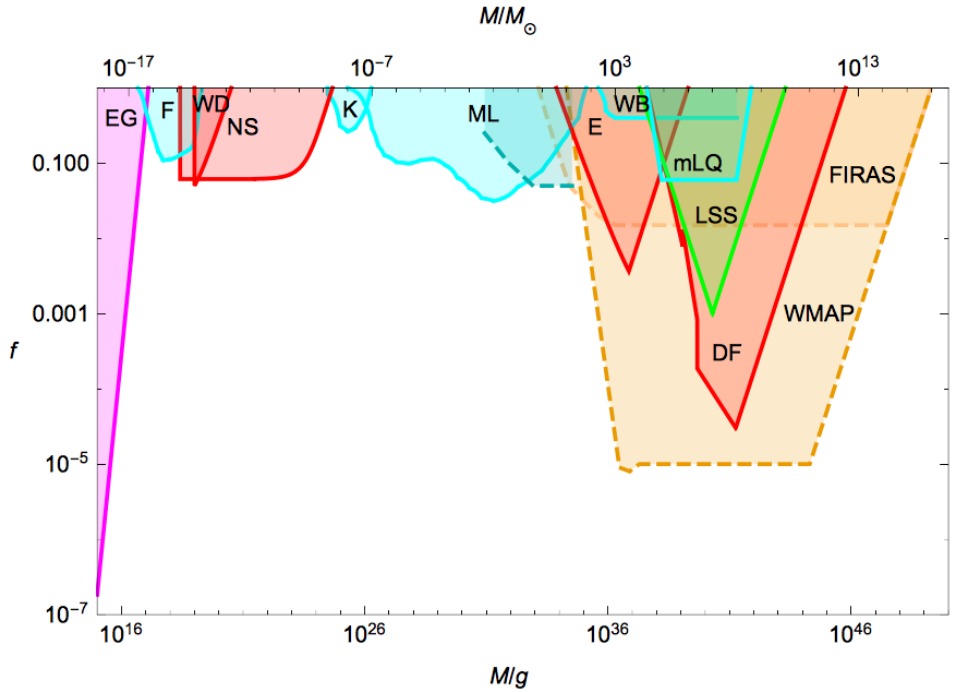
Impact on allowed mixing parameters



[R. Hansen's talk]

Primordial black holes

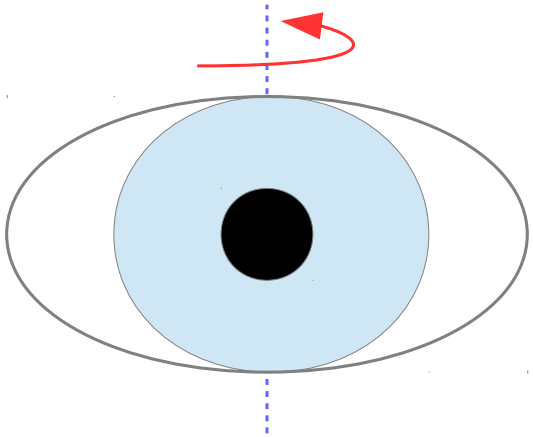
- Black holes formed in the early Universe are a viable DM candidate
- Can cover mass range from 10^{15} to 10^{55} g
- Strong constraints, but interesting phenomenology



Growing BH in NS: angular momentum transfer

- MSP spinning near mass shedding limit → elongated spheroid (Roche lobe model)

[Shapiro,Teukolsky,83]



Gravitational capture of PBH in spinning neutron star

Add BH → can analytically show (see paper) surface matter exceeds escape speed → **ejected mass !!**

Ejected neutronic matter leads to r-process nucleosynthesis!

[V. Takhistov's talk]

Summary

- PBH favorable DM candidate, expect in many scenarios
- PBH-NS interactions generic
- Analytically studied the setup:

  - site favorable to r-process, can explain amount in Galaxy + UFDs

  - mechanisms for other signatures (e.g. FRBs, 511-keV line, kilonova)

→ possibility to resolve major astronomy puzzles simultaneously !

- Search identification:

  - no neutrino emission → easy to distinguish vs. SN

  - no gravity waves → easy to distinguish vs. COM

→ tested in upcoming experiments !

[V. Takhistov's talk]

Leptogenesis

- Generate baryon asymmetry of the Universe in the lepton sector

Why neutrinos have masses and these masses are so tiny?

In the SM without extending particle content, the only way to generate a neutrino mass is using higher dimensional operators.

Weinberg operator

$$\mathcal{L}_W = \frac{\lambda_{\alpha\beta}}{\Lambda} \ell_{\alpha L} H C \ell_{\beta L} H + \text{h.c.}$$

$$m_\nu = \lambda \frac{v_H^2}{\Lambda} \qquad \frac{\Lambda}{\lambda} \sim 10^{15}\ \text{GeV}$$

Typically realised through see-saw mechanism

[Y.-L. Zhou's talk]

Leptogenesis via Weinberg operator

Silvia Pascoli, Jessica Turner, **YLZ**, arXiv:1609.07969

Three Sakharov conditions are satisfied as follows:

- The Weinberg operator violates lepton number and leads to LNV processes.

$$H^*H^* \leftrightarrow \ell\ell\,, \quad \bar{\ell}H^* \leftrightarrow \ell H\,, \quad \bar{\ell}H^*H^* \leftrightarrow \ell\,,$$
$$\bar{\ell} \leftrightarrow \ell HH\,, \quad H^* \leftrightarrow \ell\ell H\,, \quad 0 \leftrightarrow \ell\ell HH$$

- The Weinberg operator is very weak and can directly provide out of equilibrium dynamics in the early Universe.

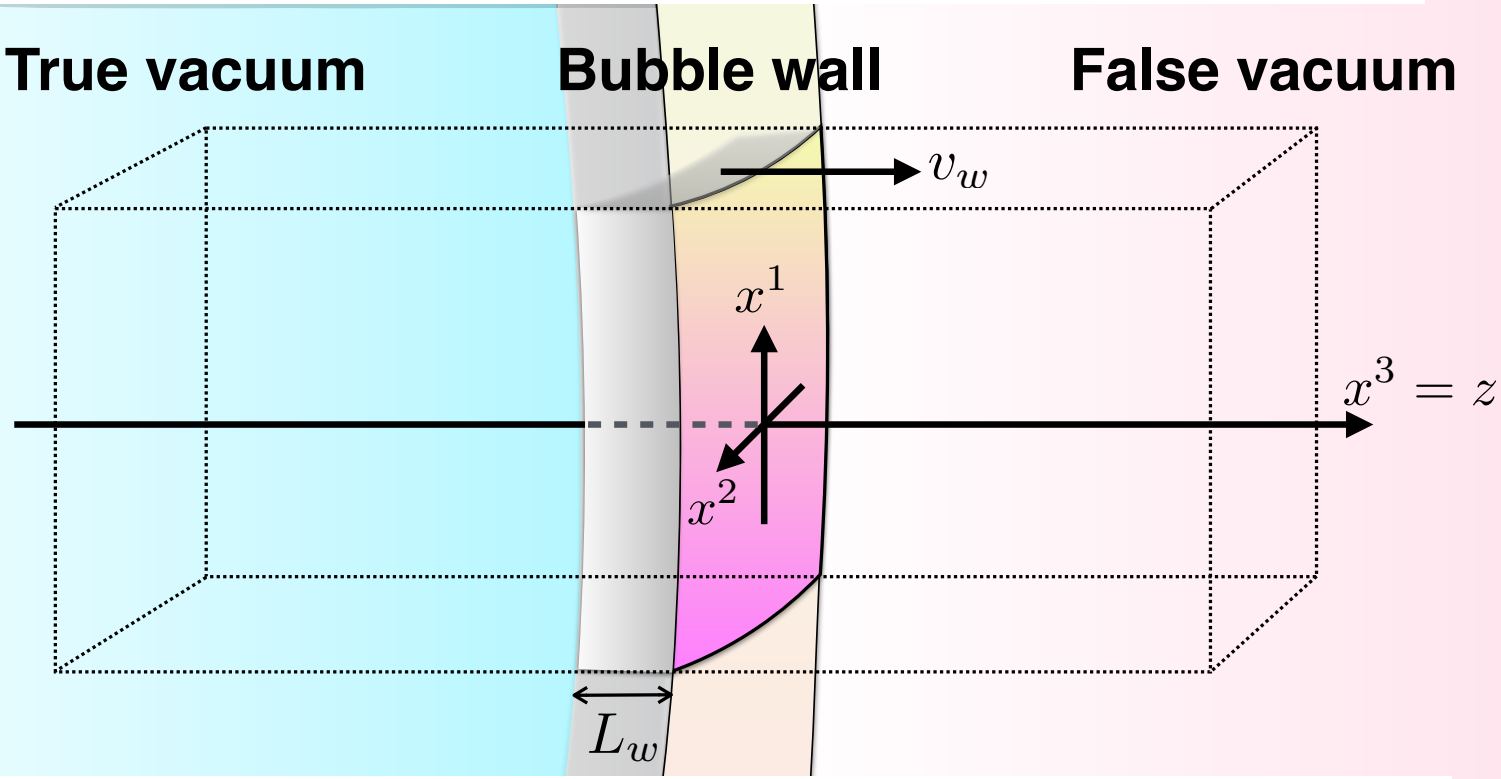
$$\Gamma_{\rm W} \sim \langle \sigma n \rangle \sim \frac{1}{4\pi}\frac{\lambda^2}{\Lambda^2}T^3 \sim \frac{1}{4\pi}\frac{m_\nu^2}{v_H^4}T^3 \quad \overset{T < 10^{12}\,\mathrm{GeV}}{<} \quad H_u \sim 10\frac{T^2}{m_{\rm pl}}$$

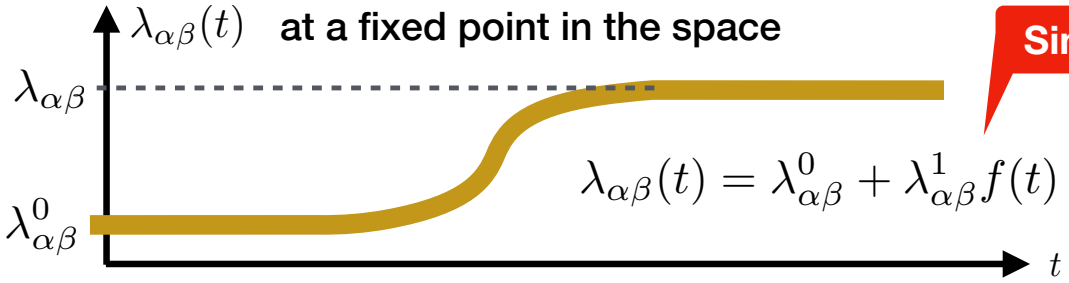
No washout if there are no other LNV sources.

- We assume that a phase transition triggers a time-varying Weinberg operator, giving rise to CP violation.

[Y.-L. Zhou's talk]

Assuming first-order phase transition





Single-scalar case

$$\lambda_{\alpha\beta}(t) = \lambda^0_{\alpha\beta} + \lambda^1_{\alpha\beta} f(t)$$

$$f(t \to -\infty) = 0$$

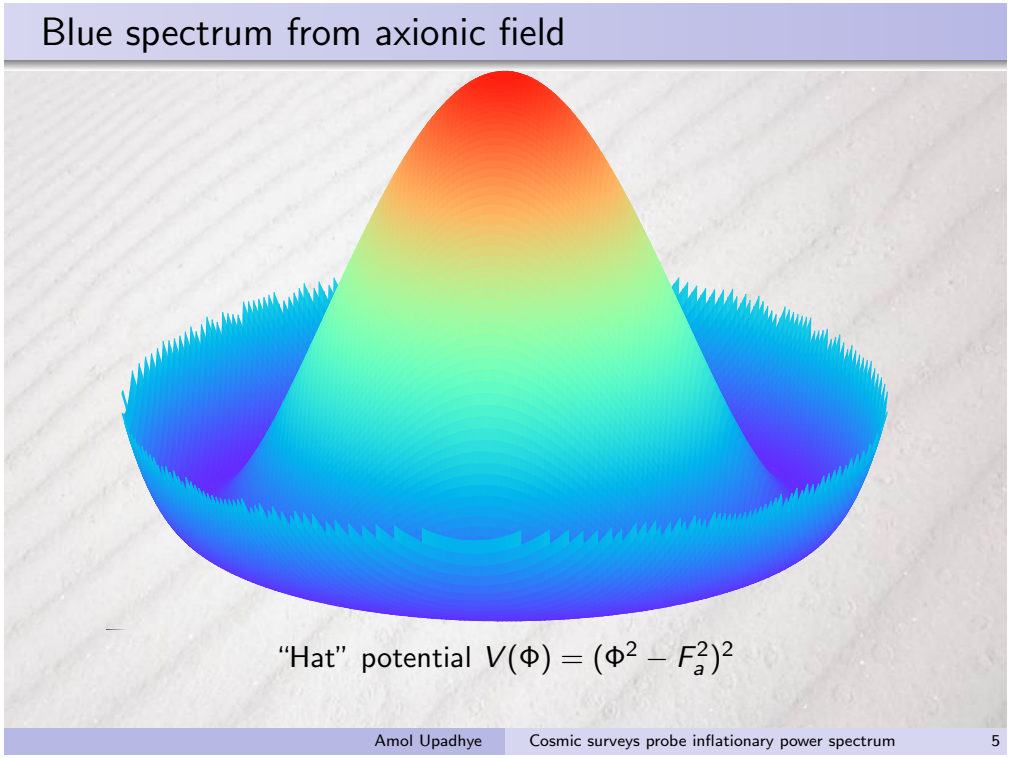
$$f(t \to +\infty) = 1$$

$$\lambda^0_{\alpha\beta} + \lambda^1_{\alpha\beta} \equiv \lambda_{\alpha\beta}$$

[Y.-L. Zhou's talk]

Inflation

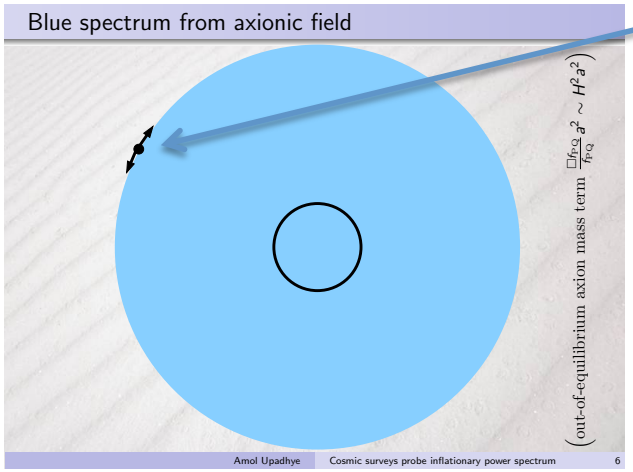
- Hundreds of models in the literature, mostly predicting a power-law scalar spectrum (and not much else)
- What makes a model interesting?
  -- A potentially observable non-standard prediction

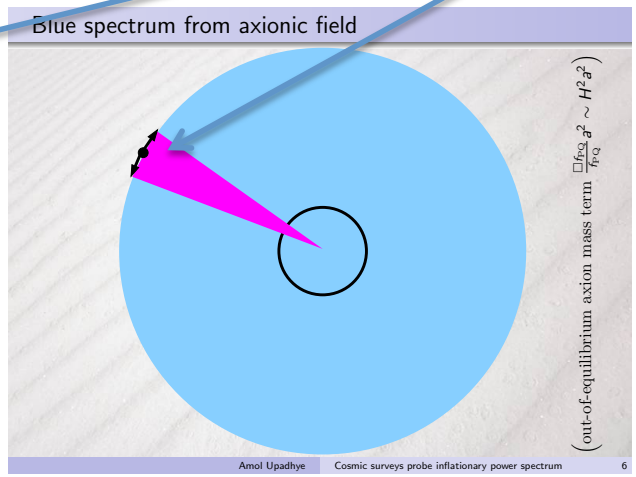


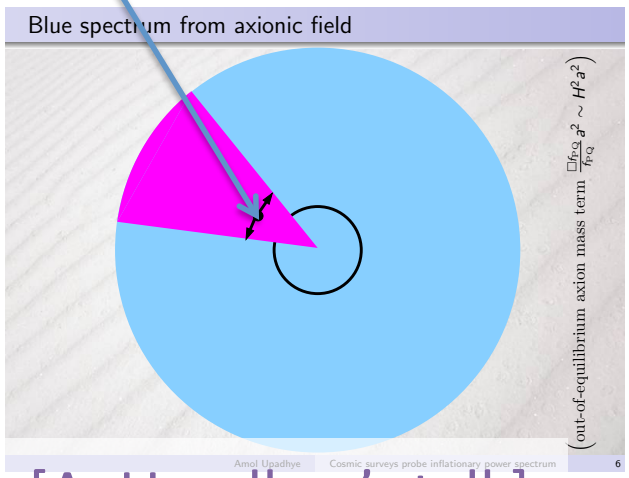
Amplitude of fluctuations grows as field rolls down in radial direction

➔ blue spectrum of fluctuations in tangential direction

quantum fluctuations in tangential direction

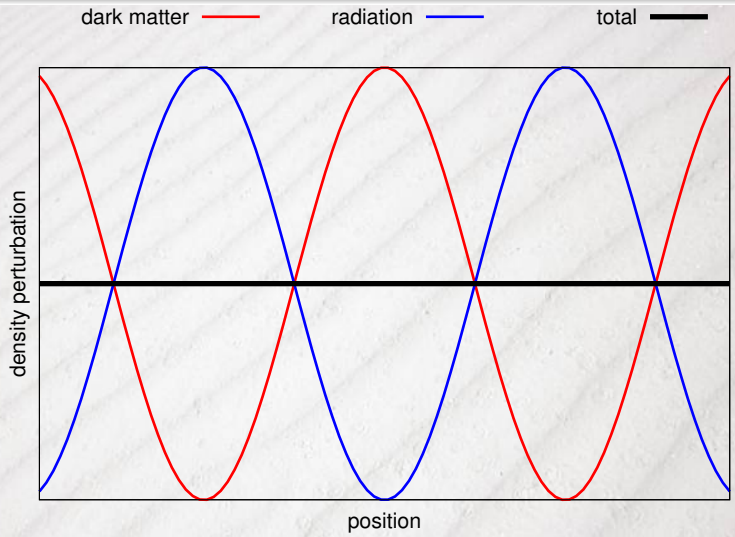






[A. Upadhye's talk]

Isocurvature



We expect isocurvature perturbations when additional fields are non-negligible during inflation.

Identify angular direction with a dark matter component

Supersymmetric example

Supersymmetric axion model

Superpotential $W = h(\Phi_+\Phi_- - F_a^2)\Phi_0$ for chiral superfields with charges $+1$, -1, and 0 under $U(1)$ Peccei-Quinn symmetry

$$\Rightarrow V = h^2 \left|\Phi_+\Phi_- - F_a^2\right|^2 + h^2 \left|\Phi_0\right|^2 \left(\left|\Phi_+\right|^2 + \left|\Phi_-\right|^2\right)$$

Flat direction: $\Phi_0 = 0$, $\Phi_+\Phi_- = F^2$.

Potential along the flat direction, including Hubble-scale mass corrections (from Kähler potential):

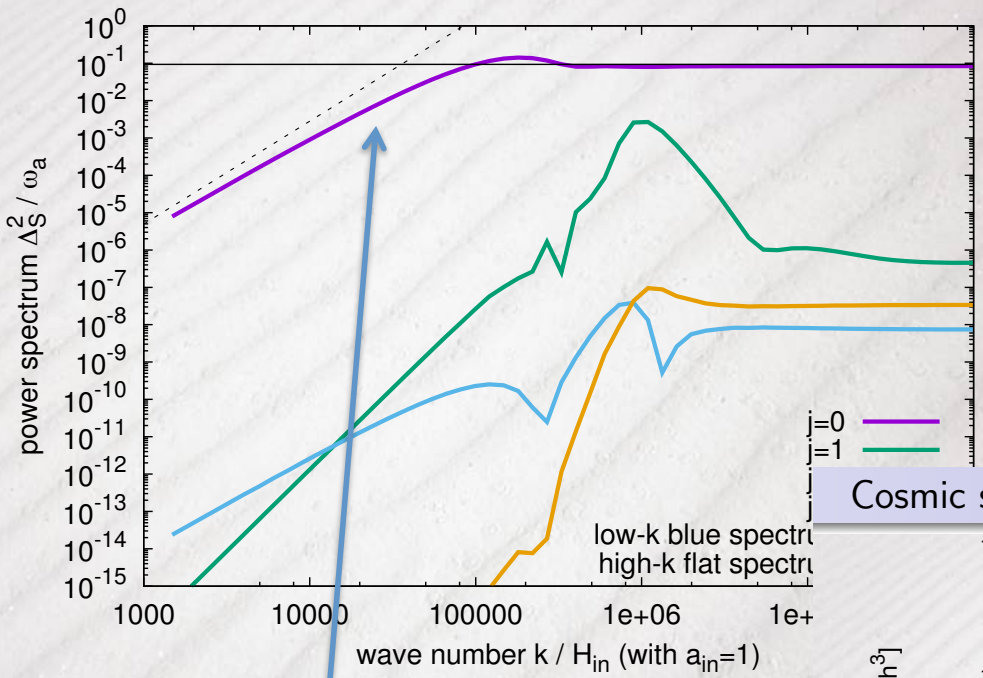
$$V = h^2 \left|\Phi_+\Phi_- - F_a^2\right|^2 + c_+ H^2 \left|\Phi_+\right|^2 + c_- H^2 \left|\Phi_-\right|^2$$

- "roll speed" $\gamma = \frac{3}{2}\left(1 - \sqrt{1 - \frac{4}{9}c_+}\right)$ with $\Phi_+ \propto \exp(-\gamma H t)$;
- spectral index $n_I = 1 + 2\gamma = 4 - 3\sqrt{1 - \frac{4}{9}c_+}$
- blue e-folds: $\eta_* = \gamma^{-1} \log\left(\frac{\Phi_{+,\mathrm{in}}}{F_a}\frac{c_+^{1/4}}{c_-^{1/4}}\right)$

Kasuya and Kawasaki, PRD **80**:*023516(2009)[0904.3800]*,
Chung and Yoo, PRD **91**:*083530(2015)[1501.05618]*

[A. Upadhye's talk]

Power spectrum, $c_+ = 2.235$

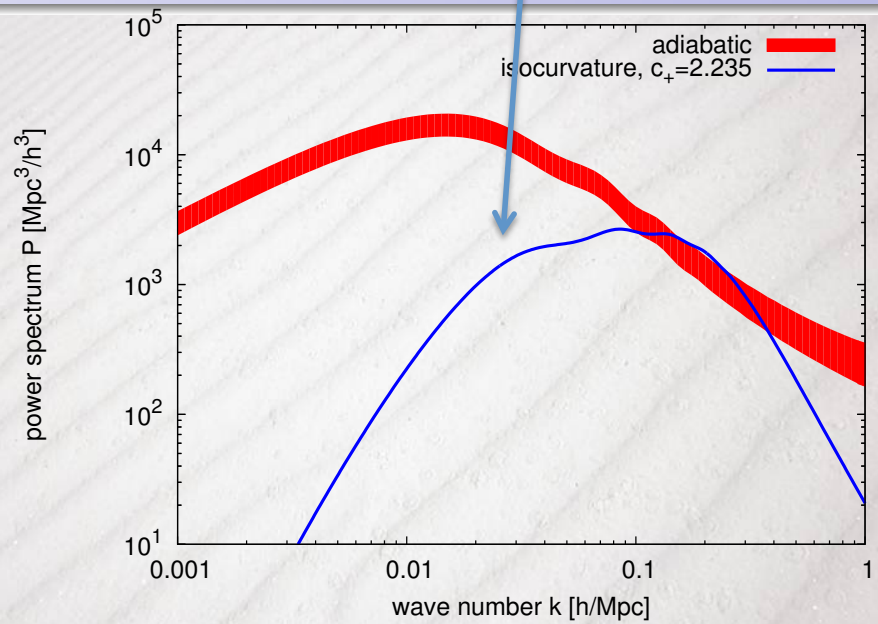


Chung and Upadhye, PRD 95:023503(2017)[1610.04284]

Blue isocurvature spectrum

Model can be tested with LSS (and CMB) data

Cosmic structure constrains models invisible to the CMB

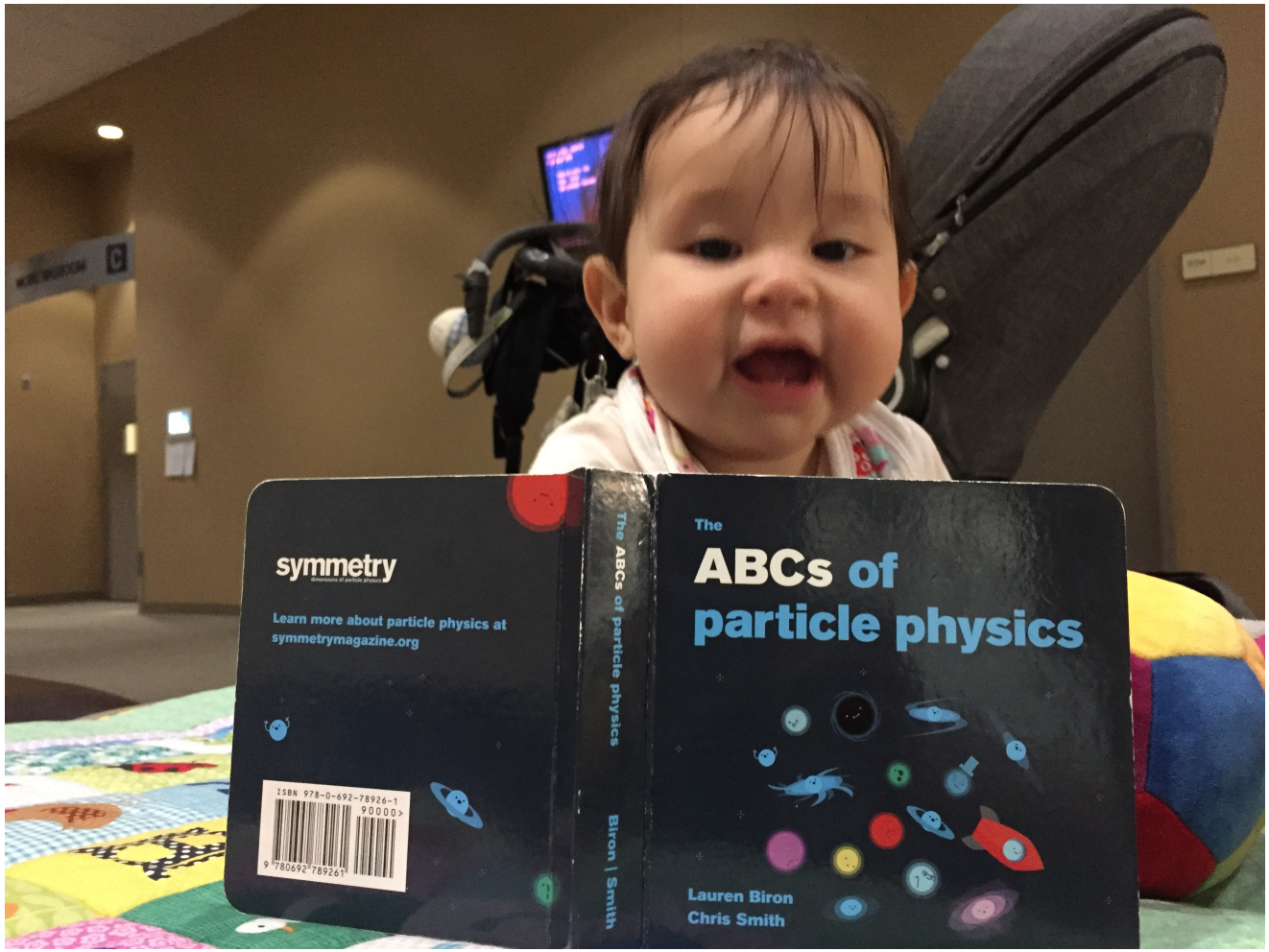


Upadhye and Chung (2017, in prep.)

[A. Upadhye's talk]

Conclusions

- Vanilla ΛCDM still rules
- Fully thermalised eV-sterile neutrino excluded
- Lots of interesting new data expected in the next 10 years (CMB polarisation, lensing, galaxy surveys)
  - O(10) meV sensitivity to sum of neutrino masses
  - O(0.05) sensitivity to effective # of neutrino species
  - O(0.001) sensitivity to tensor-to-scalar ratio



The youngest (and loudest) participant of the meeting would like to thank everyone for their support, patience, and the splendid entertainment provided to her.