# Dark Radiation and Inflationary Freedom

Based on
[SG et al., JCAP 1504 (2015) 023]
[Di Valentino et al., PRD 91 (2015) 123505]

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# Primordial Power Spectrum from Inflation

**Slow roll inflation [Linde, 1982]:**

inflation occurred by a scalar field (Inflaton) rolling down a potential energy hill.

End of inflation depends on

- the shape of the inflaton potential $V(\phi)$;
- the spatially variating perturbation of the inflaton field $\delta\phi(t,\vec{x})$.

Fluctuations in the inflaton modulate the end of inflation:
in different regions, inflation ends at different times.
$\delta\phi(t,\vec{x})$ converted into energy density fluctuations $\delta\rho$ after inflation.

$\Rightarrow$ small scale dependence of the Primordial Power Spectrum (PPS) of scalar perturbations:

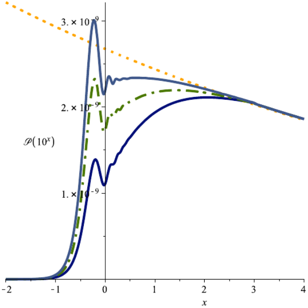
$$(n_s - 1) \equiv \frac{d \ln P_s(k)}{d \ln k} = 2\frac{V''}{V} - 3\left(\frac{V'}{V}\right)^2 ,$$

more general than $P_s(k) = A_s(k/k_\star)^{n_s-1}$.

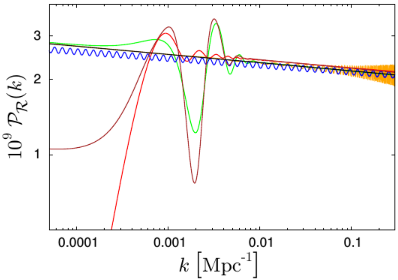
Is $n_s$ constant?
Can the PPS deviate from a Power-Law (PL)?

# Beyond Power-Law PPS: Theory

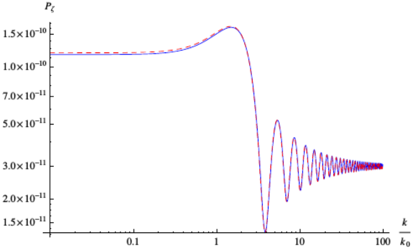
[Sagnotti et al, 2014]




[Planck Collaboration, 2015]




[Romano et al., 2014]



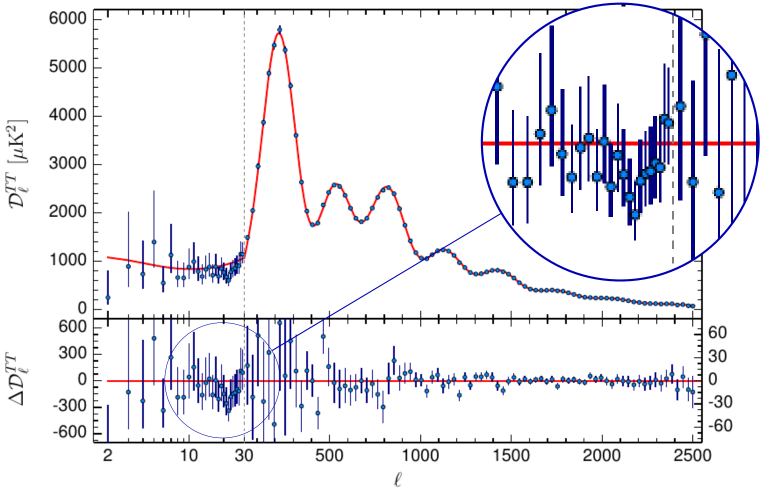

Given an inflationary model one gets one Primordial Power Spectrum (PPS), more or less complicated

Much more models were developed: see e.g. ["Encyclopædia Inflationaris", Martin et al., 2014]

# Planck 2015 results

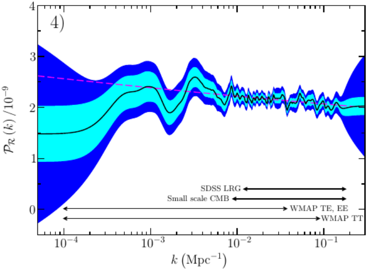
Planck 2015 temperature auto-correlation power spectrum:

[Planck Collaboration, 2015]

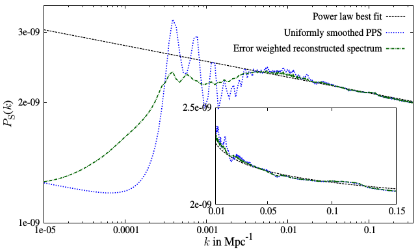


# Beyond Power-Law PPS: Reconstructions

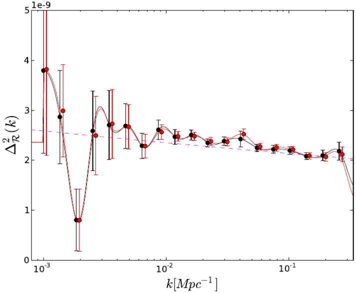
[Hunt et al., 2014] (WMAP data)



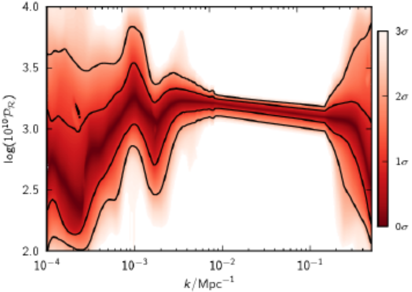

[Hazra et al, 2014] (Planck 2013 data)




[de Putter et al, 2014] (Planck 2013)




[Planck Collaboration, 2015]



# PCHIP Parametrization

Fix the Primordial Power Spectrum (PPS) form leads to possible bias:

$\Rightarrow$ analysis with free, non-parametric form for the PPS.

*Proposal*: fix a series of nodes $k_1, \ldots, k_{12}$ and use an interpolating function among them,

$$P_s(k) = P_0 \times f(k; P_{s,1}, \ldots, P_{s,12}) \qquad \text{with } P_0 = 2.2\times10^{-9},\ P_{s,j} = P_s(k_j)$$

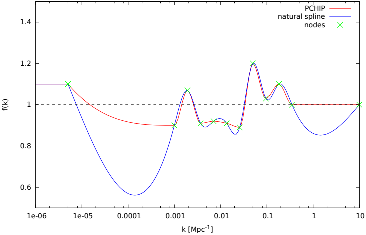
In our case we use:

**PCHIP** [Fritsch et al., 1980]

"piecewise cubic Hermite interpolating polynomial"

$$f(k; P_{s,1}, \ldots, P_{s,12}) = \mathrm{PCHIP}(k; P_{s,1}, \ldots, P_{s,12})$$

Advantage over *natural cubic splines*: no spurious oscillations.




Interpolate piecewise a series of nodes $P_{s,j} = P_s(k_j)$ with $j \in [1, 12]$:

- continue and derivable;
- preserve monotonicity of the nodes:
  - $1^{st}$ derivative in the node fixed using the secants between consequent nodes;
  - if the monotonicity changes, the node is a local extremum;
- $2^{nd}$ derivative not continue in the nodes.

# Motivations for a Light Sterile Neutrino

neutrino oscillations
see e.g. [PDG - Olive et al. (2014)]

+

Short BaseLine (SBL) anomalies

$$\nu_\alpha = \sum_{k=1}^{3} U_{\alpha k} \nu_k \quad (\alpha = e, \mu, \tau)$$

Parameters: $\Delta m^2_{SOL}$, $\Delta m^2_{ATM}$
$\sin^2(2\theta_{12})$, $\sin^2(2\theta_{23})$, $\sin^2(2\theta_{13})$
CP violating phase $\delta$

*LSND* [Aguilar et al., 2001]
*MiniBooNE* [MiniBooNE, 2013]
*Reactors* [Azabajan et al, 2012]
*Gallium anomaly*
[Giunti, Laveder, 2011]

$$\nu_\alpha = \sum_{k=1}^{3+1} U_{\alpha k} \nu_k \quad (\alpha = e, \mu, \tau, s)$$

with

$$\sum m_{\nu,\text{active}} \simeq 0 \, (\ll m_s)$$
$$m_s \simeq \sqrt{\Delta m^2_{\text{SBL}}} \simeq 1 \text{ eV}$$

More details:
recent review
[SG et al., 2015],
dedicated talks
in next days

$\nu_\alpha$ flavour eigenstates, $U_{\alpha k}$ PMNS mixing matrix, $\nu_k$ mass eigenstates, $\Delta m^2_{ji} = m^2_j - m^2_i$, $\theta_{ij}$ mixing angles

# Parameterization in Cosmology

**Light** ($m_s \simeq 1$ eV)
**sterile** (no weak interactions)
**neutrino**

| Relativistic in the early Universe | Non-relativistic in the late Universe |
|---|---|
| $\rho_r = [1 + 0.2271 N_{\rm eff}]\, \rho_\gamma$ | $\rho_m = \rho_c + \rho_b + \rho_\nu + \rho_s$ |
| and | and |
| $\nu_s$ contributes with $\Delta N_{\rm eff} = N_{\rm eff} - 3.046$ | $\nu_s$ contributes with $\rho_s \propto m_s \cdot (\Delta N_{\rm eff})^{3/4}$ |

$N_{\rm eff} = 3.046$ from active neutrinos [Mangano et al., 2005]

We consider a thermalized sterile neutrino: $T_s = \Delta N_{\rm eff}^{1/4} T_\nu$

$\rho_i$ energy density, for the fluid $i$:
$m$ (matter), $\gamma$ (photons), $r$ (radiation), $c$ (cold dark matter), $b$ (baryons), $s$ (sterile neutrino), . . .

# Light Sterile Neutrino Results - I

PPS

Standard: Power-Law (PL)

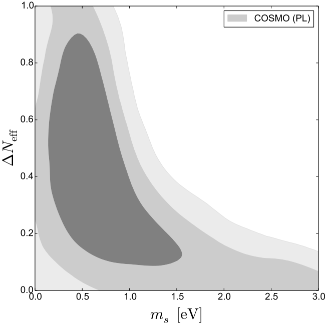
free form: nodes $P_{s,1}, \ldots, P_{s,12}$, interpolate with PCHIP function

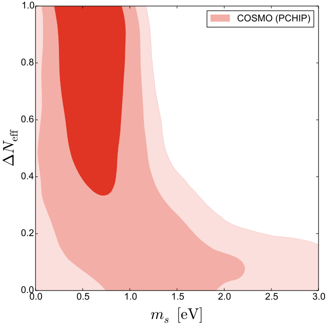
$\Lambda$CDM(PL PPS) + $\nu_s$ model   versus   $\Lambda$CDM(PCHIP PPS) + $\nu_s$ model

$P_s(k) = A_s(k/k_{\rm pivot})^{n_s-1}$

$P_s(k) = P_0 \times f(k; P_{s,1}, \ldots, P_{s,12})$

Results for the Thermal sterile neutrino, mass $m_s$, no SBL prior on $m_s$:




- higher $\Delta N_{\rm eff}$ admitted;
- change on $m_s$ constraints due to $\Delta N_{\rm eff}$ change;
- fully thermalized sterile neutrino preferred.

*COSMO* = CMB(Planck13+WMAP Polarization+ACT/SPT)+LSS(WiggleZ)+HST(Riess2011)+CFHTLenS+PlanckSZ

# Light Sterile Neutrino Results - II

PPS

Standard: Power-Law (PL)

free form: nodes $P_{s,1}, \ldots, P_{s,12}$, interpolate with PCHIP function

$\Lambda$CDM(PL PPS) + $\nu_s$ model versus $\Lambda$CDM(PCHIP PPS) + $\nu_s$ model

$P_s(k) = A_s(k/k_{\rm pivot})^{n_s-1}$

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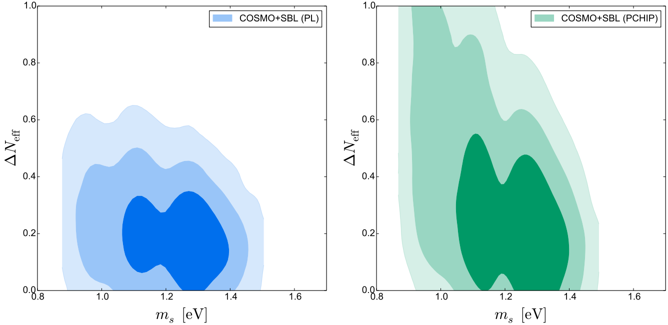
Results for the Thermal sterile neutrino, mass $m_s$, with SBL prior on $m_s$:




- higher $\Delta N_{\rm eff}$ admitted;
- no change on $m_s$ constraints;
- fully thermalized sterile neutrino admitted (inside $2\sigma$ region).

*COSMO* = CMB(Planck13+WMAP Polarization+ACT/SPT)+LSS(WiggleZ)+HST(Riess2011)+CFHTLenS+PlanckSZ

# Motivations

Strong CP problem

↓

**Axions**

↔ pseudo-Nambu-Golstone bosons for a global $U(1)_{PQ}$ (Peccei-Quinn) symmetry

↓

spontaneously broken at the axion scale $f_a$

**Nonthermal production**

by misalignment mechanism

↓

not hot, but cold DM
(total fraction of DM?)

not explored here!

**Thermal production**

$\pi + \pi \rightarrow \pi + a$

can be only hot DM

↓

effects similar to the massive neutrinos

explored here ⇒

# Parameterization

thermal process $\pi + \pi \to \pi + a$

$+\ U(1)_{PQ}$ breaking at $f_a$

decoupling $T_D(f_a)$ from $\Gamma(T_D) = H(T_D)$ (numerically)

axion mass

$$m_a = \frac{f_\pi m_\pi}{f_a}\frac{\sqrt{R}}{1+R} = 0.6\text{ eV}\frac{10^7\text{GeV}}{f_a}$$

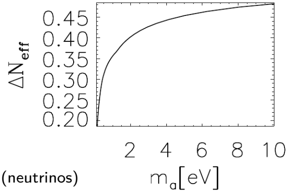
d.o.f. at decoupling $g_{\star S}(T_D)$

density parameter

$$\omega_a \propto m_a n_a \propto m_a/g_{\star S}(T_D)$$

axion number density

$$n_a(f_a) = \frac{g_{\star S}(T_0)}{g_{\star S}(T_D)} \times \frac{n_\gamma}{2}$$




$$\Delta N_{\rm eff} = \frac{4}{7}\left(\frac{3n_a}{2n_\nu}\right)^{4/3}$$

More details:
Rosenberg talk tomorrow

$T_0$ CMB temperature today
$n_{\gamma\,(\nu)}$ number density of photons (neutrinos)
$f_\pi$ =93 MeV pion decay constant
$R = 0.553 \pm 0.043$ up-to-down quark masses ratio

# Thermal Axion Results

[Di Valentino et al., PRD 91 (2015) 123505]

PPS

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$\Lambda$CDM(PL PPS) + $m_a$ model versus $\Lambda$CDM(PCHIP PPS) + $m_a$ model

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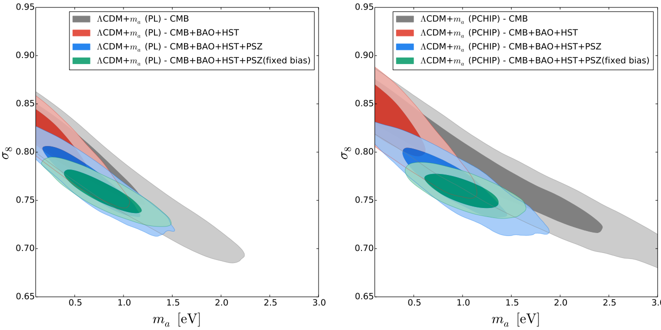



- inflationary freedom ⇒ relaxed bounds on $m_a$;
- cluster counts give $m_a > 0$ (free-streaming lowers $\sigma_8$), more evident with non-standard PPS.

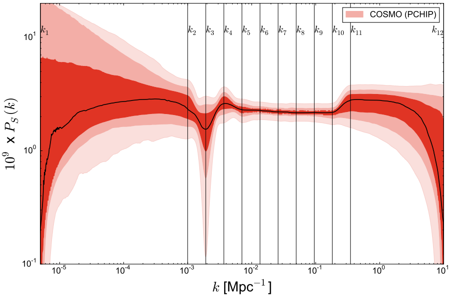
CMB=Planck13+WMAP Polarization+ACT/SPT – BAO=BOSS DR11+WiggleZ+6dF+SDSS-II – HST=Efstathiou2013

PSZ=PlanckSZ: prior $\sigma_8\,(\Omega_m/0.27)^{0.3} = 0.764 \pm 0.025\,(0.78 \pm 0.01$ with fixed bias)

# PPS Results

$\Lambda$CDM(PCHIP PPS) + $\nu_s$

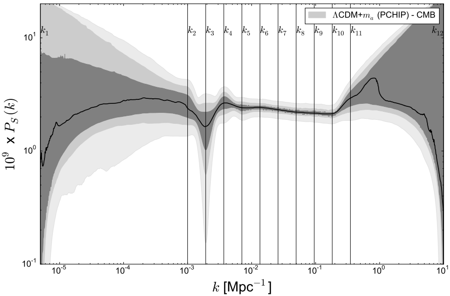
CMB(Planck13+WMAP Polarization+ACT/SPT)+
LSS(WiggleZ)+HST(Riess2011)+CFHTLenS+PlanckSZ




[SG et al., JCAP 1504 (2015) 023]

$\Lambda$CDM(PCHIP PPS) + $m_a$

CMB(Planck13+WMAP Polarization+ACT/SPT)




[Di Valentino et al., PRD 91 (2015) 123505]

Different cosmological models, similar results:

- CMB constraints for $1 \times 10^{-4}\,\mathrm{Mpc}^{-1}(\ell = 2) \leq k \leq 0.3\,\mathrm{Mpc}^{-1}(\ell \simeq 2500)$;
- power-law is a good approximation in the range $7 \times 10^{-3}\,\mathrm{Mpc}^{-1} \leq k \leq 0.2\,\mathrm{Mpc}^{-1}$;
- feature at $k = 2 \times 10^{-3}\,\mathrm{Mpc}^{-1}$ correspond to dip $\ell \simeq 22$ in CMB spectrum;
- feature at $k = 3.5 \times 10^{-3}\,\mathrm{Mpc}^{-1}$ correspond to small bump $\ell \simeq 40$.

# Conclusions

- Theoretical and experimental reasons to study features in the Primordial Power Spectrum for scalar perturbations:
  - features if inflation cannot be described by the simplest model;
  - observed features in low-$\ell$ CMB spectrum from Planck, WMAP;
- only statistical fluctuations or a signals for new physics?
- Non-standard spectrum from inflation have an impact on extensions of the $\Lambda$CDM model! Main degeneracy with $N_{\rm eff}$:
  - wider range allowed for the thermal axion mass;
  - light sterile neutrino fully compatible with cosmology.
  - update with Planck 2015 data: work in progress!
- Inflationary freedom can bias also other constraints:
  - e.g. degeneracies with primordial non-gaussianities in future probes, see [SG et al., arxiv:1506.05251, accepted by PRD].

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**Thank you for the attention!**