Feebly interacting particles (aka dark sectors) in the early Universe.

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Lecture 1

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Driven to Discover[SM]
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Plan for 3 lectures

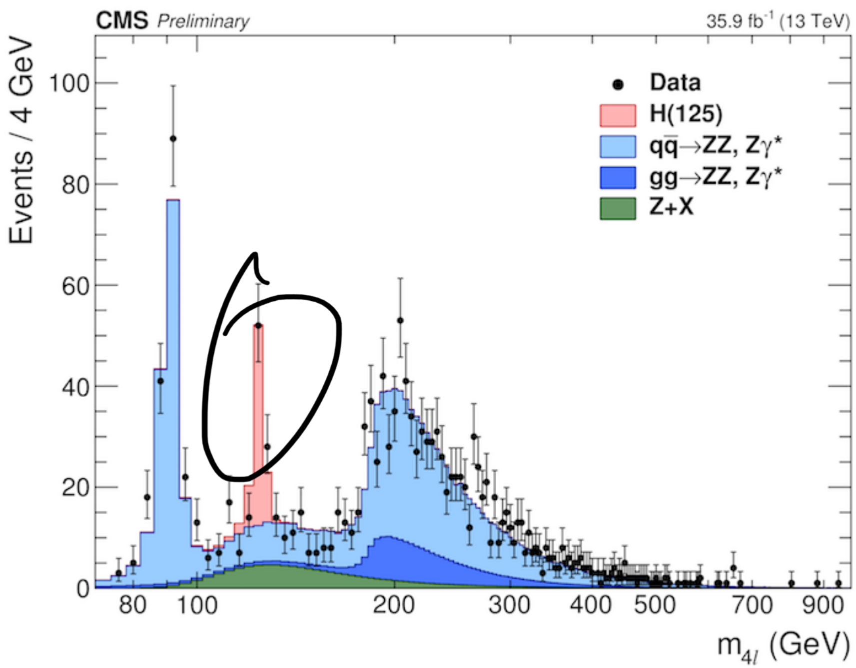
1. FIP framework. Standard Cosmological model (inflation, hot universe, BBN, CMB). Different way to probe new physics e.g. : "overclosure" and equation of state for dark energy, dark radiation and N_{eff}; energy dump during the BBN, CMB; spectral distortions and 21 cm, B-modes of CMB – all in possible connection to FIP physics.

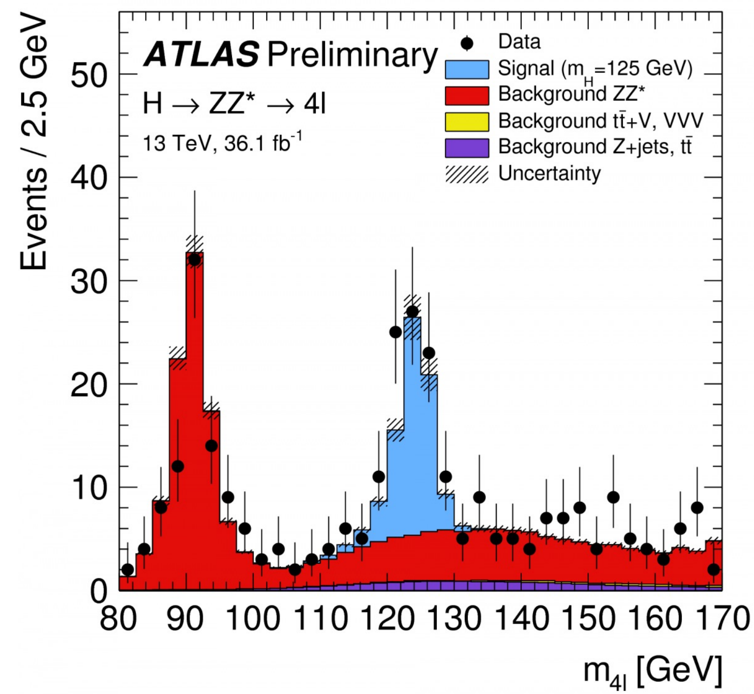
2. Examples of FIP models constrained/excluded by cosmology.

3. Models of dark matter. Cosmological anomalies (Lithium abundance ?, EDGES anomaly, H0 anomaly) and their possible connection to FIP physics.

Higgs boson discovery

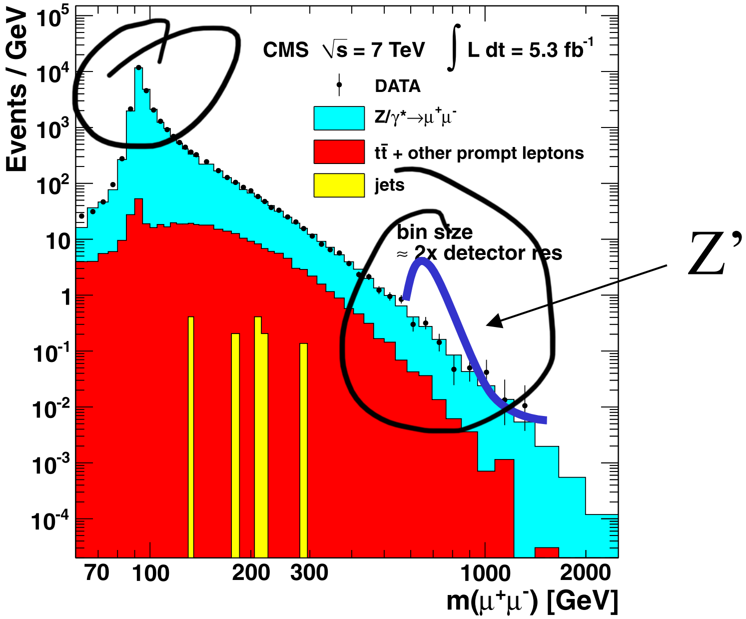
New particle and new type of fundamental force:

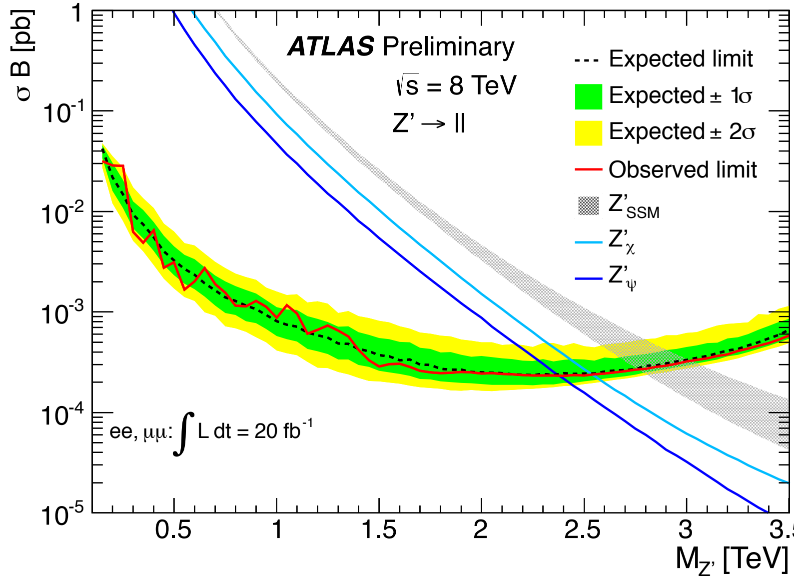


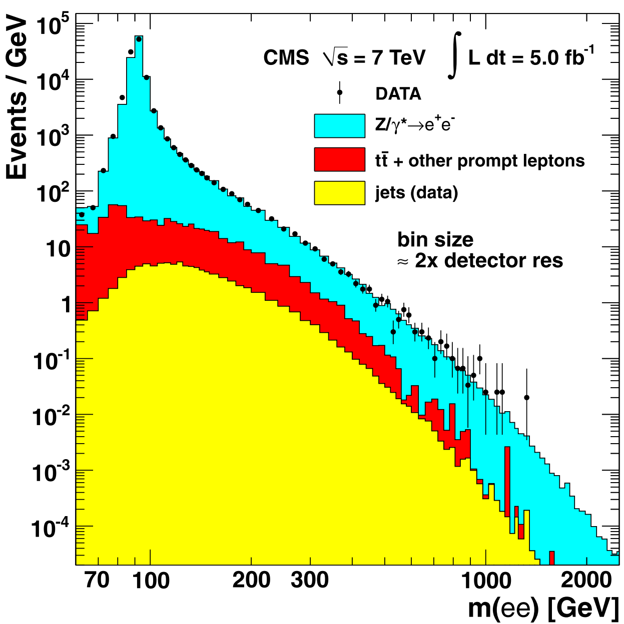


1. A new 0^+ resonance is observed at the LHC. ~50 years after prediction
2. Its properties are fully consistent with the properties of the Standard Model Higgs boson. Mass = 125 GeV (to 0.25%).
3. The discovery is remarkable because the prediction of the Higgs boson was based on theoretical consistency (and minimality!)

No New Physics at high energy thus far (?!)





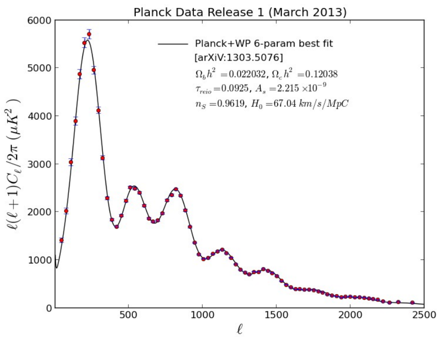


No hints for any kind of new physics. Strong constraints on SUSY, extra dimensions, technicolor resonances, etc.

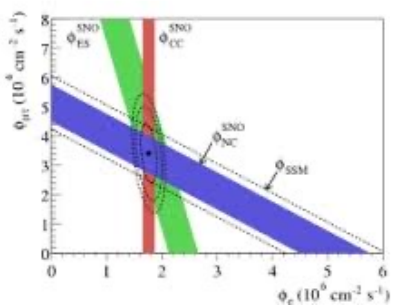
Constraints on new *Z'* bosons push new gauge groups into multi-TeV territory.

Clues for new physics

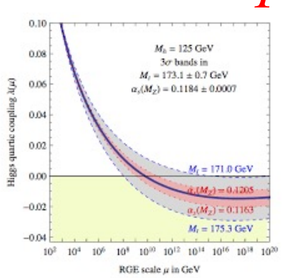
1. *Precision cosmology:* 6 parameter model (Λ-CDM) correctly describes statistics of 10^6 CMB patches. Existence of dark matter and dark energy. Strong evidence for inflation.



2. *Neutrino masses and mixing:* Give us a clue [perhaps] that there are new matter fields beyond SM. Some of them are not charged under SM.



3. *Theoretical puzzles:* Strong CP problem, vacuum stability, hints on unification, smallness of m_h relative to highest scales (GUT, M_{Planck})



?

4. *"Anomalous results":* muon g-2, ~~"proton radius puzzle"~~, "cosmological lithium problem", small scale CDM problems…

SM as an Effective Field Theory

Standard Model Lagrangian includes all terms of canonical dimension 4 and less, consistent with three generations of quarks and leptons and the SU(3)*SU(2)*U(1) gauge structure at classical and quantum levels.

$\mathcal{L}_{2020s}$ = - $m_H^2\ (H^+_{SM}H_{SM})$ + all dim 4 terms ($A_{SM},\ \psi_{SM},\ H_{SM}$) +

Neutrino mass operators (e.g. effective Dim=5) SM

+(W.coeff. /Λ^2) × Dim 6 etc ($A_{SM},\ \psi_{SM},\ H_{SM}$) + …

all lowest dimension portals ($A_{SM},\ \psi_{SM},\ H,\ A_{DS},\ \psi_{DS},\ H_{DS}$) × portal couplings

+ dark sector interactions ($A_{DS},\ \psi_{DS},\ H_{DS}$)

SM -- Standard Model

DS – Dark Sector or FIPs

Cosmological constraints on "portals" to the SM

Let us *classify* possible connections between Dark sector and SM

$H^+H\,(\lambda S^2 + A S)$ Higgs-singlet scalar interactions (scalar portal)

$B_{\mu\nu} V_{\mu\nu}$ "Kinetic mixing" with additional U(1)' group

(becomes a specific example of $J_\mu^i A_\mu$ extension)

LHN neutrino Yukawa coupling, N – RH neutrino

$J_\mu^i A_\mu$ requires gauge invariance and anomaly cancellation

It is very likely that the observed neutrino masses indicate that Nature may have used the *LHN* portal…

Dim>4

$J_\mu^A\ \partial_\mu a/f$ axionic portal

……….

$$\mathcal{L}_{\rm mediation} = \sum_{k,l,n}^{k+l=n+4} \frac{\mathcal{O}_{\rm med}^{(k)} \mathcal{O}_{\rm SM}^{(l)}}{\Lambda^n},$$

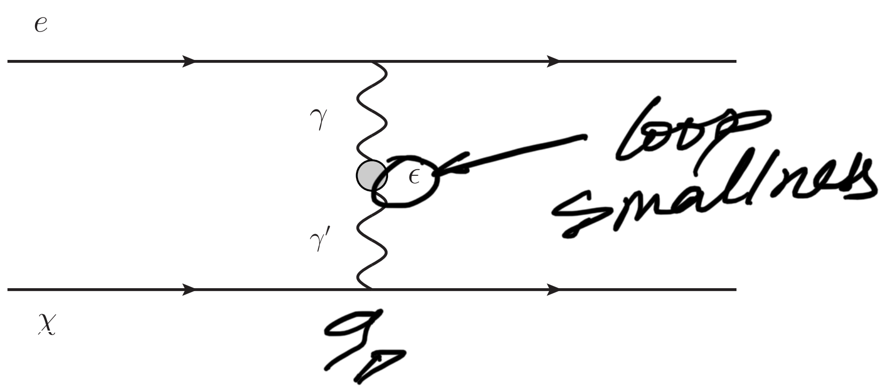
"Simplified model" for dark sector

(Okun', Holdom,…)

$$\mathcal{L} = \mathcal{L}_{\psi,A} + \mathcal{L}_{\chi,A'} - \frac{\epsilon}{2} F_{\mu\nu} F'_{\mu\nu} + \frac{1}{2} m^2_{A'} (A'_\mu)^2.$$

$$\mathcal{L}_{\psi,A} = -\frac{1}{4} F^2_{\mu\nu} + \bar{\psi}[\gamma_\mu (i\partial_\mu - eA_\mu) - m_\psi]\psi$$

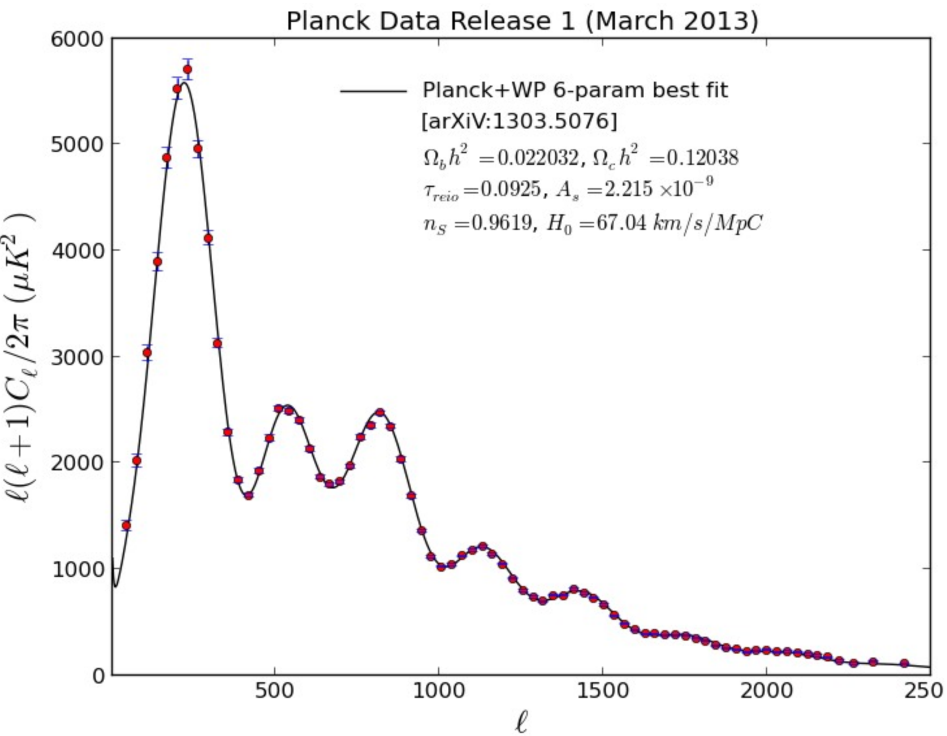
$$\mathcal{L}_{\chi,A'} = -\frac{1}{4} (F'_{\mu\nu})^2 + \bar{\chi}[\gamma_\mu (i\partial_\mu - g' A'_\mu) - m_\chi]\chi,$$

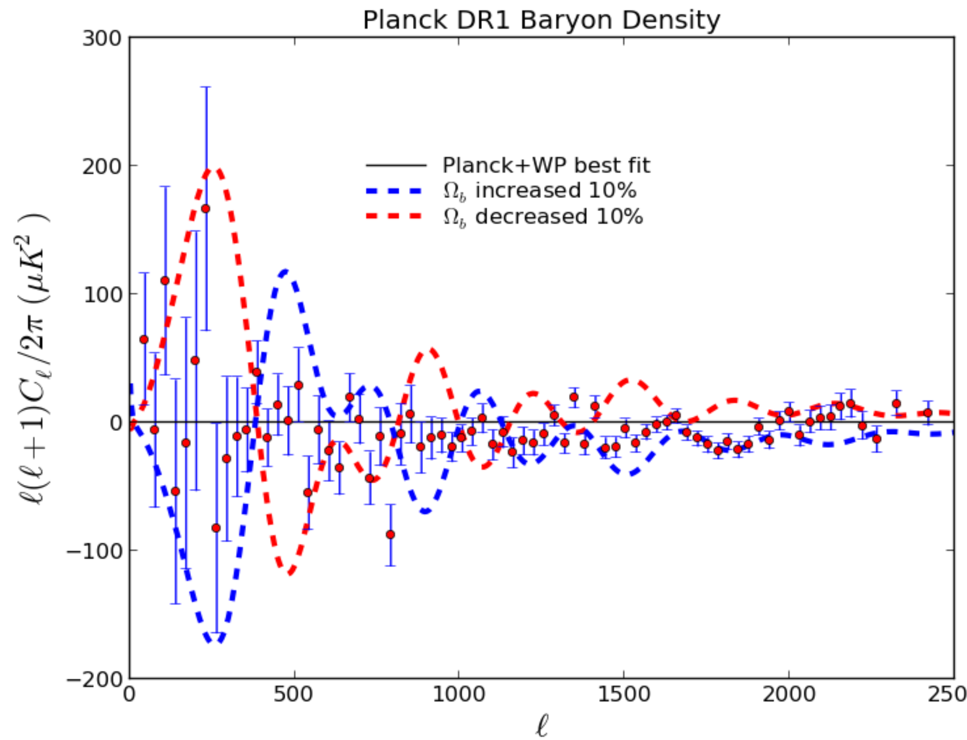


A – photon, *A'* – "**dark photon**", ψ - an electron, χ - a DM state, *g'* – a "dark" charge

- "Effective" charge of the "dark sector" particle χ is Q = e × ε (if momentum scale q > m_V). At q < m_V one can say that particle χ has a non-vanishing EM charge radius, $r_\chi^2 \simeq 6\epsilon m_V^{-2}$.
- Dark photon can "communicate" interaction between SM and dark matter. *It represents a simple example of BSM physics*.

Cosmology has its own SM - ΛCDM



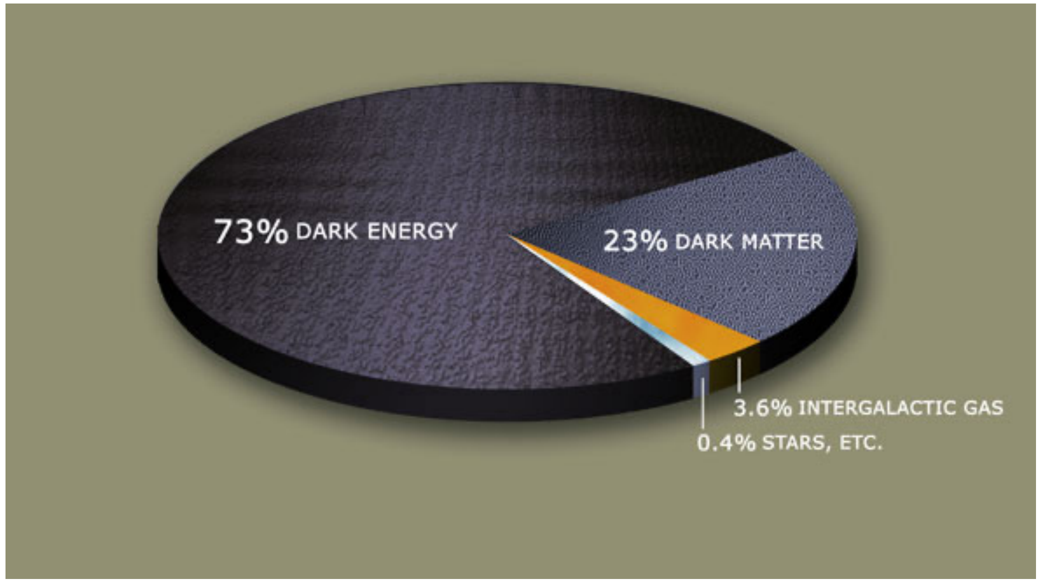


Parameter	Value (68%)
$\Omega_b h^2$	0.02207±0.00027
$\Omega_c h^2$	0.1198±0.0026 (is it high?)
$100\theta_*$ (acoustic scale at recombination)	1.04148±0.00062 (~ 500 parts per million accuracy)
τ	0.091±0.014 (WMAP seeded)
$\ln(10^{10}A_s)$	3.090±0.025
n_s	0.9585±0.0070 (<1 at > 5 σ)

Parameter	Value (95%)
Ω_K	-0.0005±0.006
Σm_ν (eV)	<0.23
N_{eff}	3.30±0.54
Y_P	0.267±0.040

Universe is dominated by "dark" substances

Energy balance chart, z=0



Existence of dark matter and dark energy calls into question whether there are other dark components:

Dark forces? Dark radiation?

Cosmic Expansion

Einstein's → Freidmann's equation:

$$\mathcal{R}_{\mu\nu} - \frac{1}{2} g_{\mu\nu}\mathcal{R} = 8\pi G_N T_{\mu\nu}$$

$$H^2 \equiv \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi}{3} G_N \rho$$

$$\frac{\ddot{R}}{R} = -\frac{8\pi}{3} G_N(\rho + 3p)$$

$$\dot{\rho} = -3H(\rho + p)$$

$$R(t)^3 = R_0^3 \frac{\Omega_m}{\Omega_\Lambda}\left[\sinh\left(\frac{3}{2}\Omega_\Lambda^{1/2} H_0 t\right)\right]^2$$

$V \sim R^3(t)$

$\rho_\Lambda \sim \Lambda R^0$

$\rho_{matter} \sim R^{-3}$

$\rho_{rad} \sim R^{-4}$

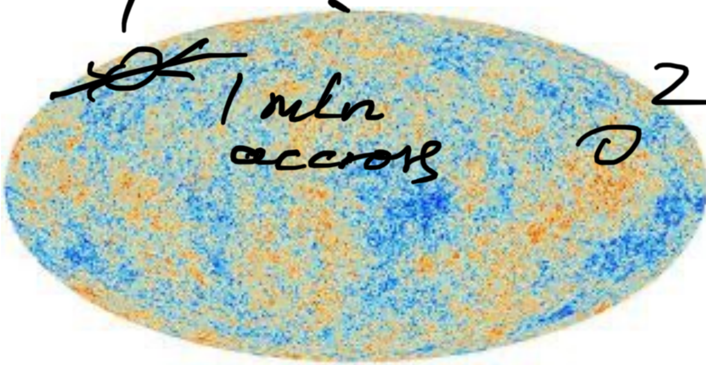
$R\,dR \sim dt$

$R \sim \sqrt{t}$; $H = \frac{1}{2t}$

FIPs can contribute to the r.h.s. of these equations

Inflation

Exponential expansion of the Universe with $H = H_{infl} \sim$ const , that stretches one small patch to many many horizons,



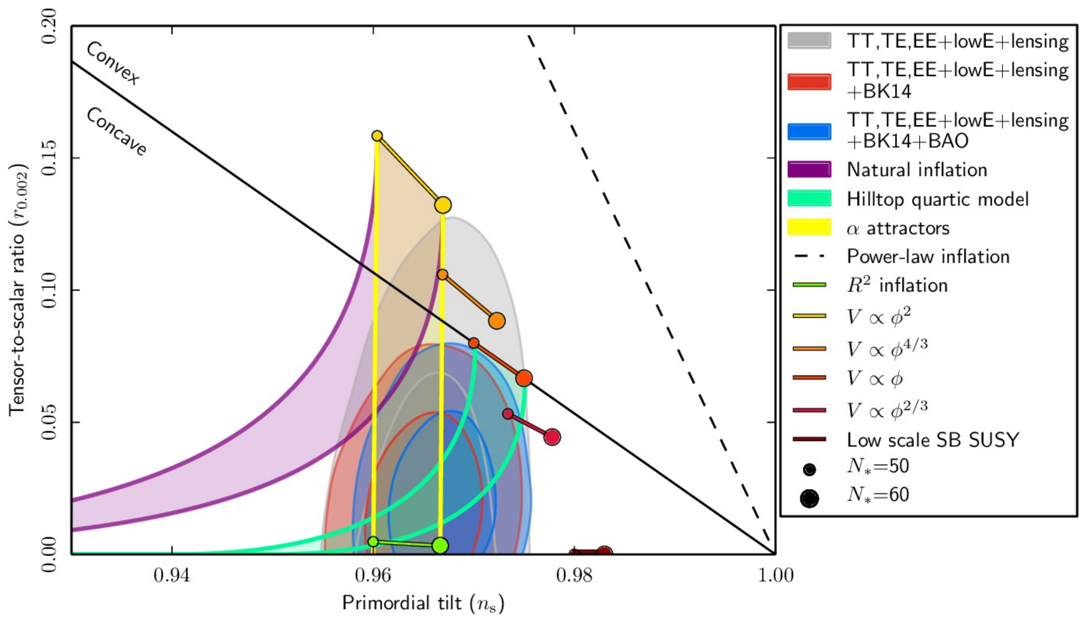
- Explains near-uniformity of the CMB temperature across many causal horizons at recombination.
- Makes Universe spatially flat
- Produces nearly scale-invariant spectrum of adiabatic density fluctuations via fluctuation of the inflaton field.

Application to FIPs: any light [non-conformally coupled] spectator (i.e. subdominant) scalar field receives gaussian fluctuations

$$\delta\phi = H_{infl}/(2\pi)$$

Open problems of inflation (vs FIPs)

- There are some conceptual problems: nearly arbitrary choice for an inflaton potential, eternal inflations, initial conditions etc
- Only the upper bound on H_{infl} exists. This is usually phrased as a limit on the so-called tensor-to-scalar ratio "r".



Current limit on r implies

$H_{infl} < 10^{14}$ GeV .

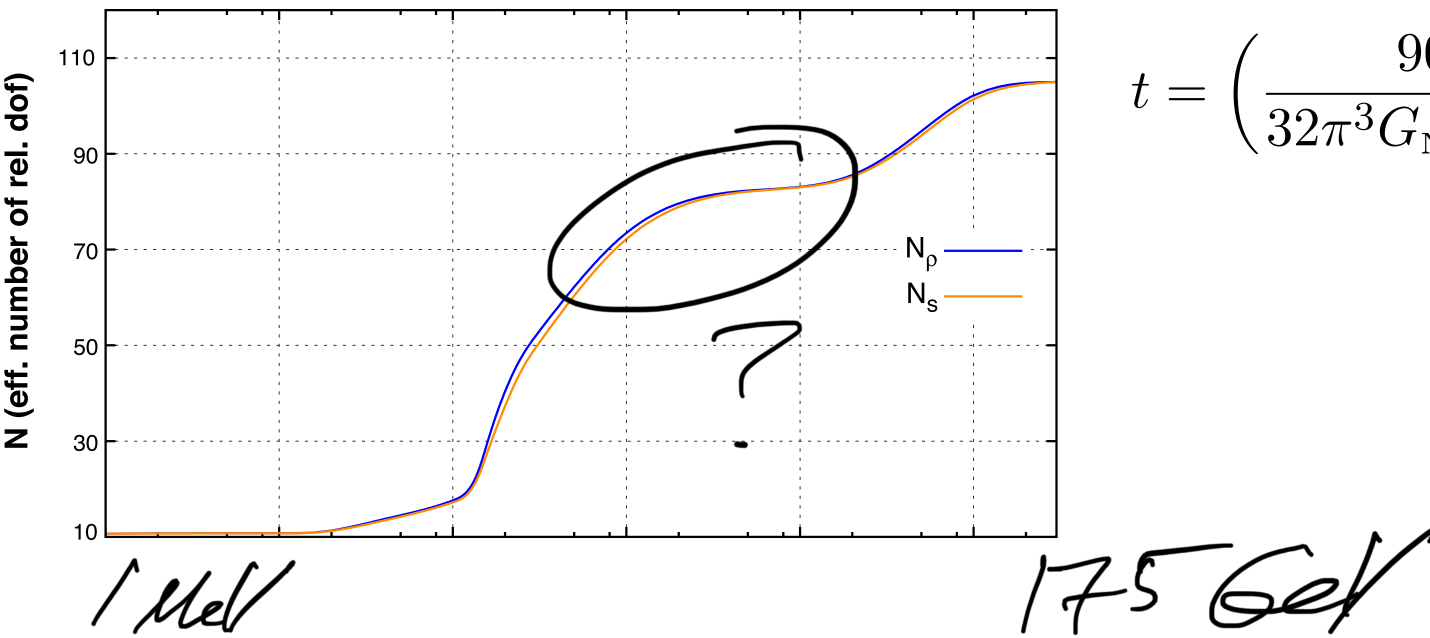
What is the amplitude of $\delta\phi$?

- We do not know at what temperature T inflation ended and created hot Universe. *We do not know what maximum mass relics can be produced.*

Hot Universe

$$\rho = \left(\sum_{\mathrm{B}} g_{\mathrm{B}} + \frac{7}{8}\sum_{\mathrm{F}} g_{\mathrm{F}}\right)\frac{\pi^2}{30}T^4 \equiv \frac{\pi^2}{30}N(T)\,T^4$$

$$H(t) = \frac{1}{2t}$$



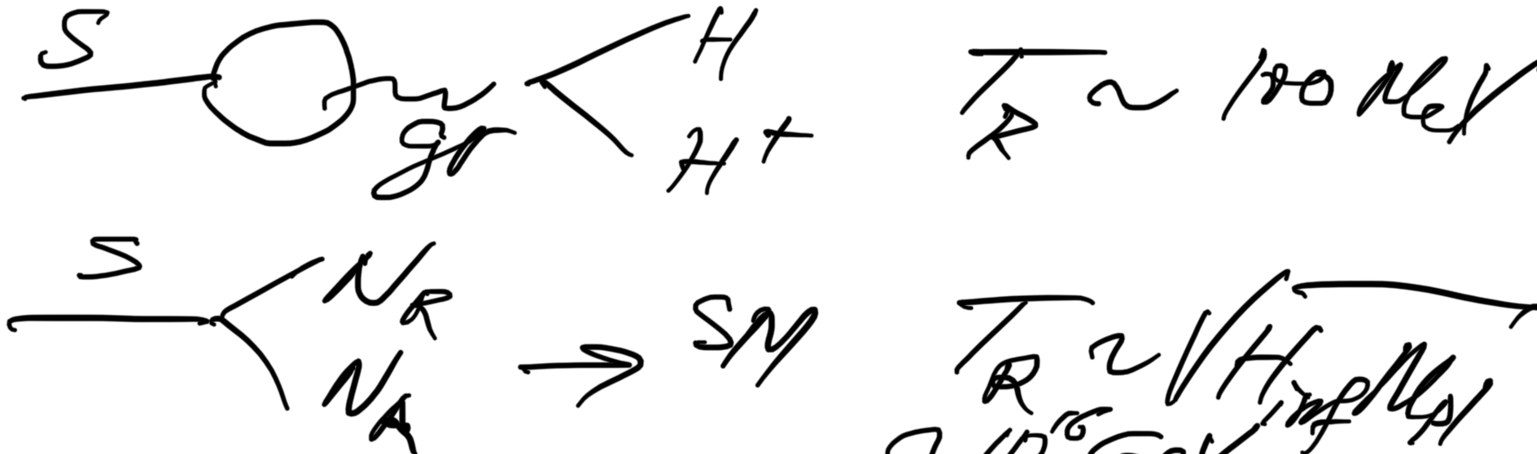
$$t = \left(\frac{90}{32\pi^3 G_{\mathrm{N}} N(T)}\right)^{1/2} T^{-2}\ .$$

After electron-positron annihilation, time and temperature are related via

$$\frac{t}{178\mathrm{sec}} = \left(\frac{10^9\mathrm{K}}{T}\right)^2$$

Unknowns of hot Universe

- What was the initial temperature of hot Universe?



- Did "we" live through the electroweak phase transition? Based on popular/minimal models of baryogenesis, most likely "yes". In that sense, existence of an epoch with $T > m_{W,Z,h}$ is very likely.

- Problem: *very few observational clues from epochs earlier than BBN: baryon-antibaryon asymmetry, and perhaps dark matter.*

BBN with $n_b/n_\gamma = 6\ 10^{-10}$ (cmb)

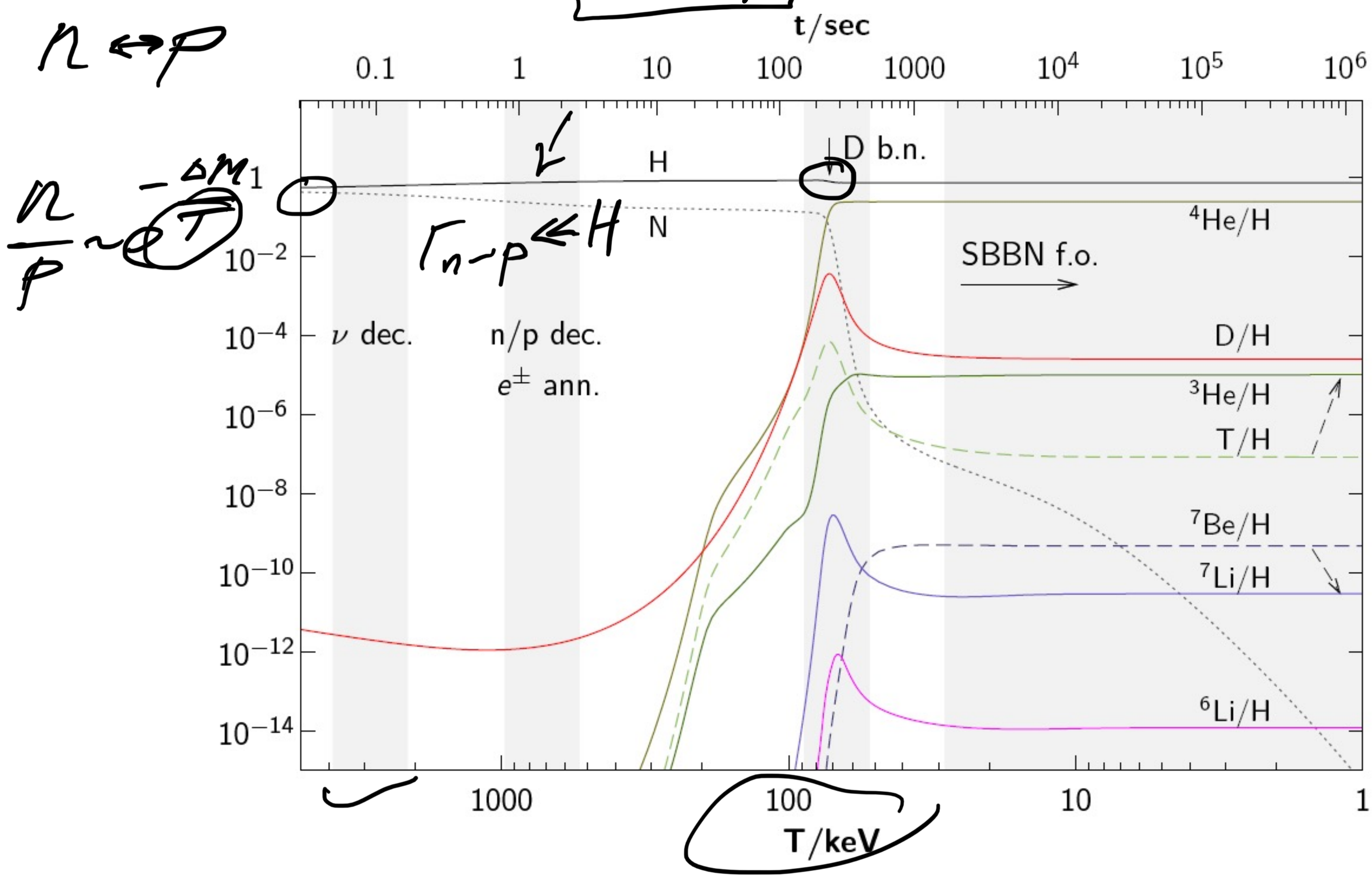
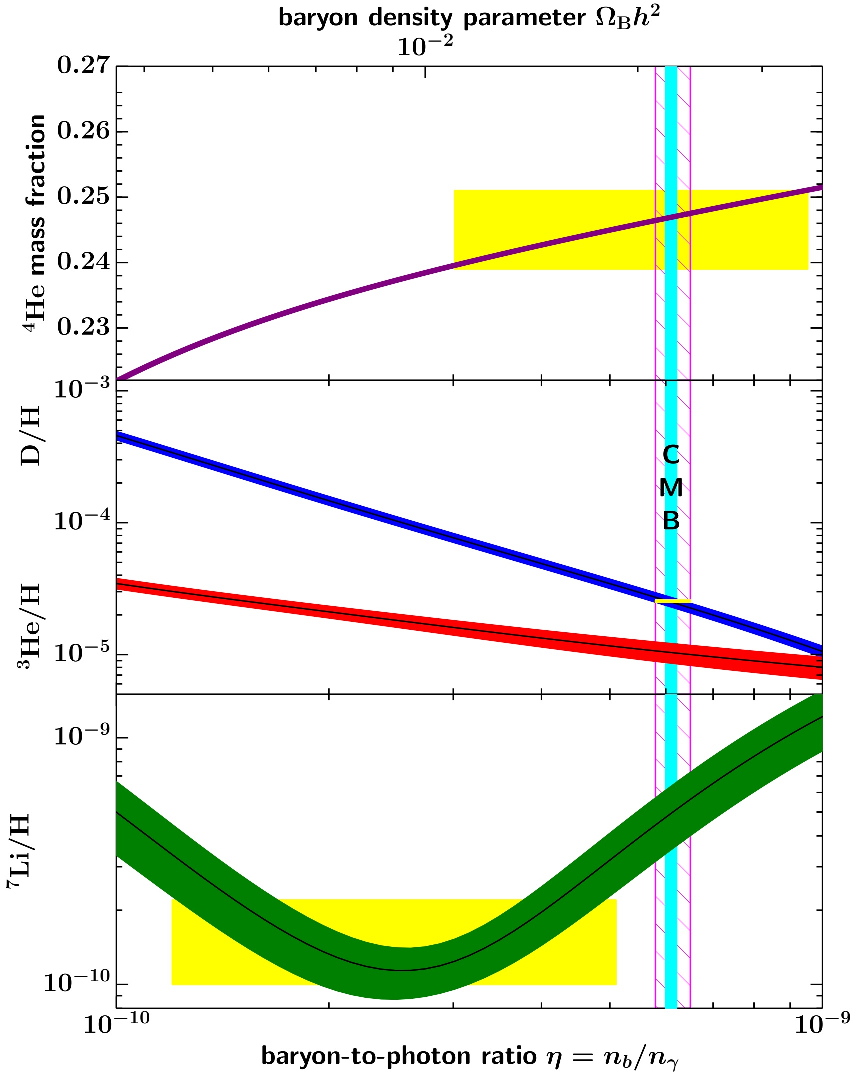


Figure from MP, Pradler (2010).

Helium, Deuterium and Lithium



Helium and D agree with observations

$$Y_p = 0.2449 \pm 0.0040.$$

$$(\mathrm{D/H})_p = (2.53 \pm 0.04) \times 10^{-5}.$$

Lithium is off ← we will discuss it separately.

(Figure is from the PDG review)

BBN sensitivity to New Physics

$$\frac{dn_i}{dt} = -H(T)T\frac{dn_i}{dT} = \langle \sigma_{ijk} v \rangle n_j n_k + \ldots - \ldots$$

Energy of reactants ~ MeV or less; Initial conditions $n_p \approx n_n$; other $n_i = 0$.

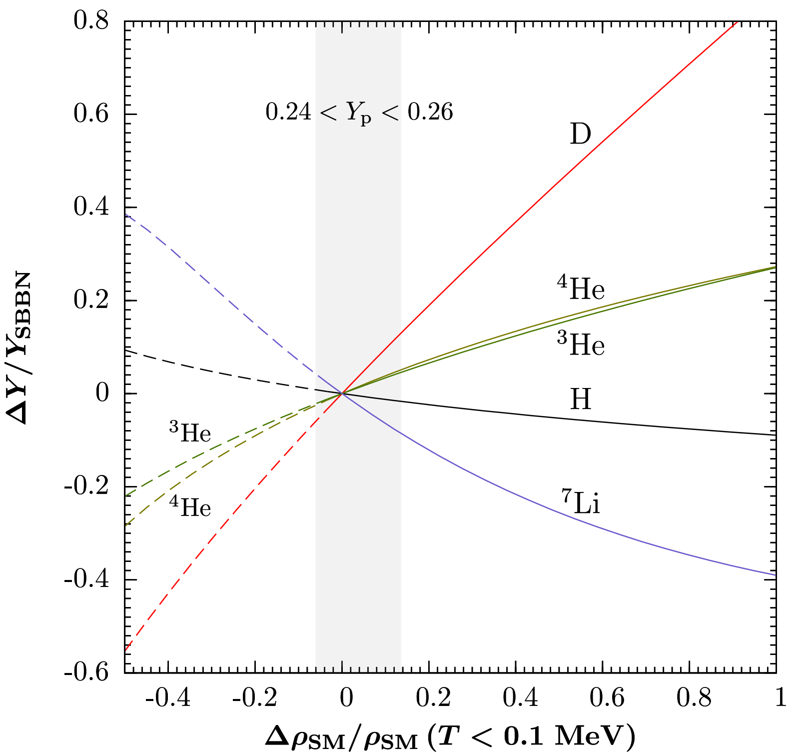
Particle theorists love it because it is sensitive to New Physics

1. Affect the timing of reactions,

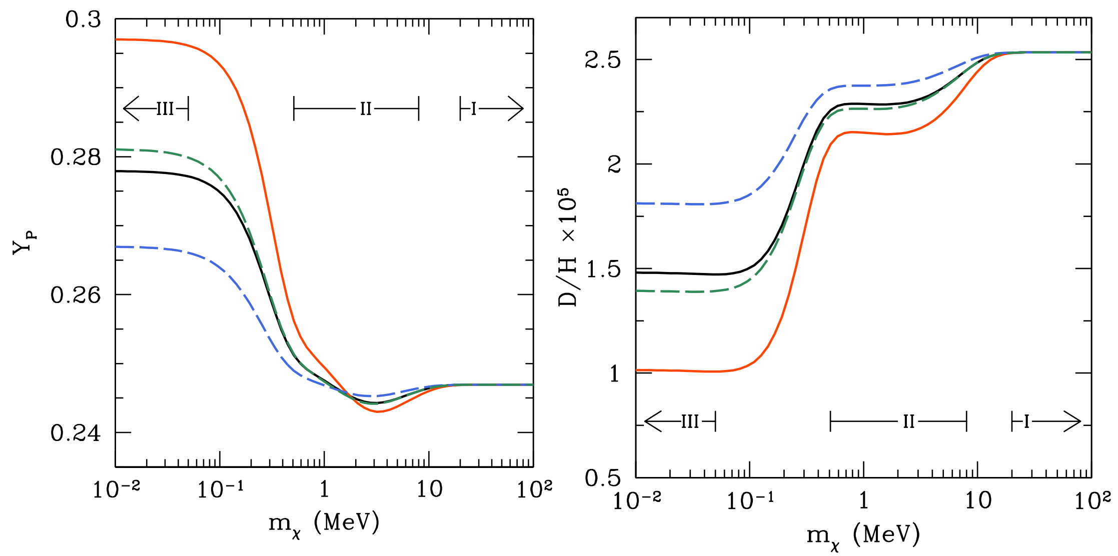
   $$H(T) = \text{const} \times N_{\text{eff}}^{1/2} \frac{T^2}{M_{\text{Pl}}}; \quad N_{\text{eff}} = 2 + \frac{7}{8} \times 2 \times 3 + N_{\text{boson}}^{\text{extra}} + \frac{7}{8} N_{\text{fermion}}^{\text{extra}}$$

   via e.g. new thermal degrees of freedom or via changing couplings.
2. Introduce non-thermal channels *e.g.* via late decays or annihilations of heavy particles, $E > T$.
3. Provide catalyzing ingredients that change $<\sigma_{ijk}v>$. Possible catalysts: electroweak scale remnants charged under EM $U(1)$ or color $SU(3)$ gauge groups. (CBBN, MP 2006)
4. Inhomogeneous BBN etc

Sensitivity to Hubble rate during BBN



The neutron/proton freezeout ratio and Deuterium bottleneck are sensitive to extra contributions to the Hubble expansion rate, by e.g. FIPs.



$H = H^{SM} + \Delta H$

Nollett, Steigmann, 2013

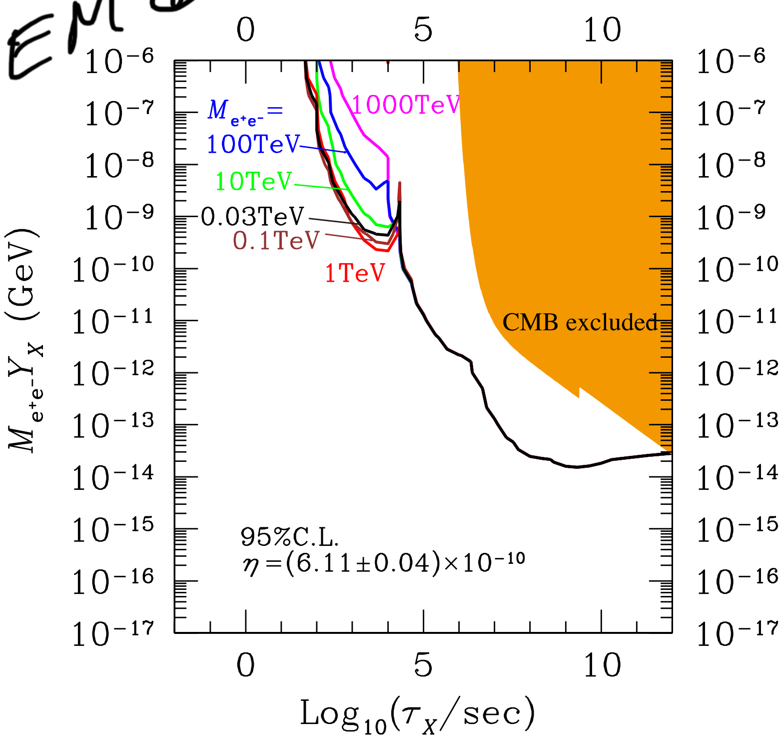
BBN tightly constrains N_{eff}.

(CMB does it even better, N_{eff} = 2.99(17), from Planck, N_{eff}^{SM} = 3.04)

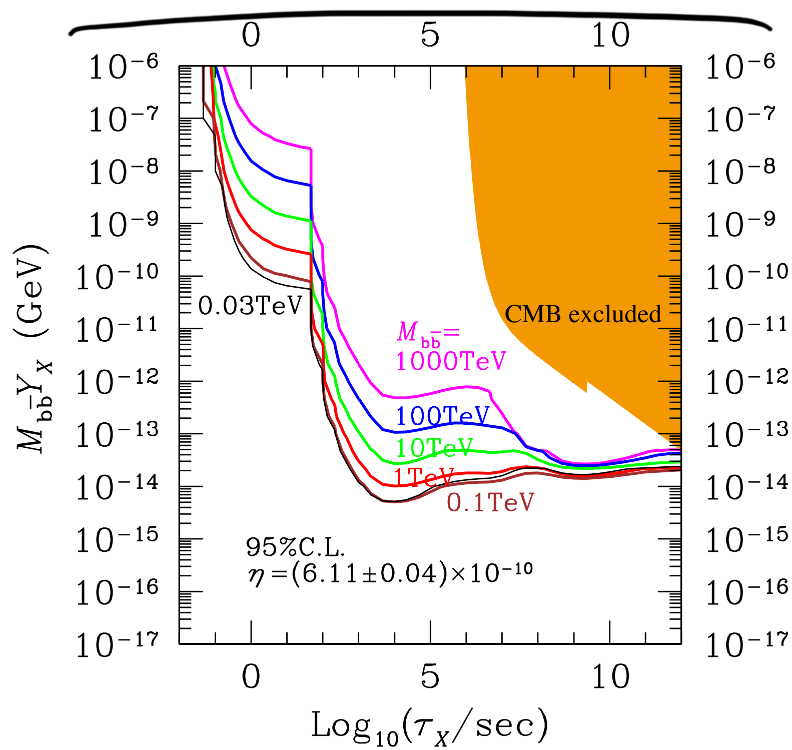
Sensitivity to energy dump after BBN

A subdominant species decay can lead to energy injection – and if it is not dispersed quickly – will lead to the non-thermal reactions altering the outcome of the BBN

EM decay



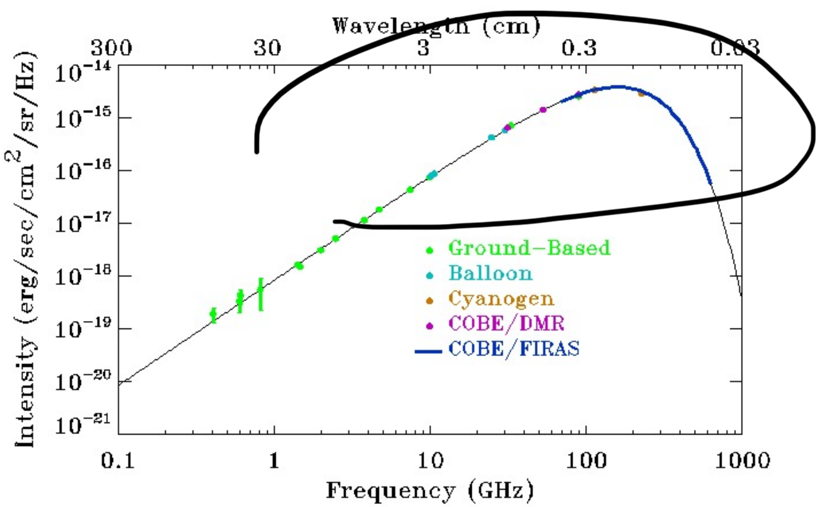
hadronic decays



From Kawasaki, Kohri, Moroi, Takaesu, 2017

CMB spectrum and its distortion

CMB spectrum is shown to be precisely Planckian (FIRES experiment on COBE) with 1 part per 10^4. Standard cosmology does not predict much more than 1ppb deviations.



This gives sensitivity to e.g. late injection of energy:

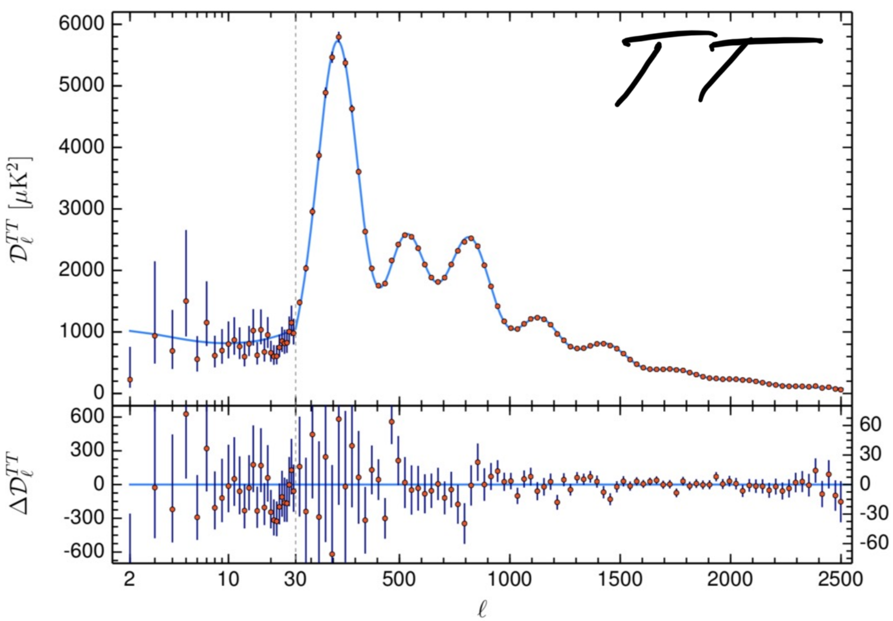
After z ~ 2 10^5 (i.e. between BBN and CMB decoupling) photon number density does not equilibrate anymore:

$$\Gamma_{e+\gamma\to e+2\gamma} < H; \quad \Gamma_{e+\gamma\to e+\gamma} > H$$

Injection of energetic photons leads to the photon chemical potential. *There are not that many other probes of the post-BBN, pre-CMB decoupling Universe.*

Recombination and decoupling

- Extremely important epoch in cosmology
- After matter-radiation equality, structures start growing, DM develops potential wells where baryon-photon fluid is “falling”, developing pressure waves.
- Electrons and protons form neutral H, and photon mean free path becomes large, i.e. they no longer scatter. We see ”2d” information of where photons last scattered

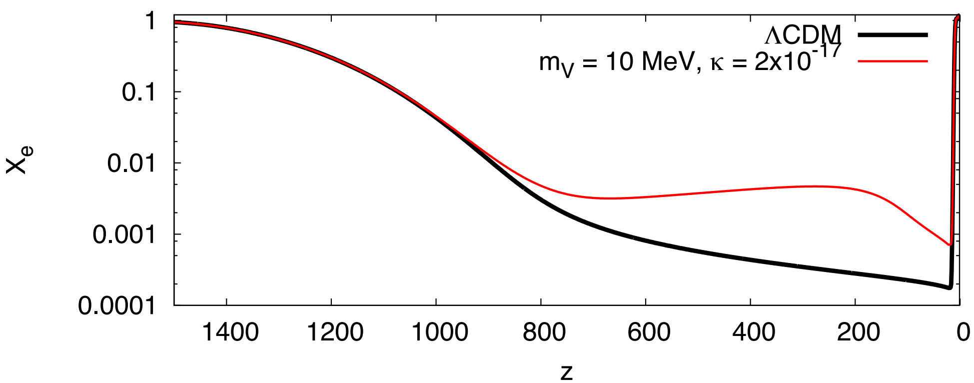


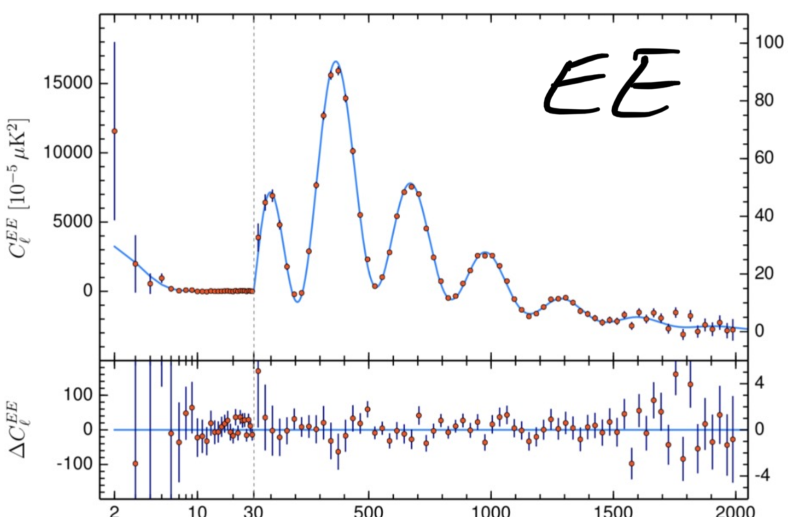
FIPs can contribute to “dark radiation”, i.e. N_{eff}, leading to additional suppression of high l modes.

And evidently FIPs can contribute to dark matter.

CMB sensitivity to energy dump

Unstable or annihilating particles can inject energy during the CMB epoch, affecting the ionized fraction, optical depth, and consequently the statistics of anisotropy peaks.





FIP decay → visible radiation → ionization of neutral hydrogen → increase in X_e → change of angular anisotropies, especially polarization.

Rule of thumb: ~1/3 of released EM energy goes to ionization, to keep $X_e < 10^{-3}$ one needs no more than 10^{-2} eV per baryon E release.

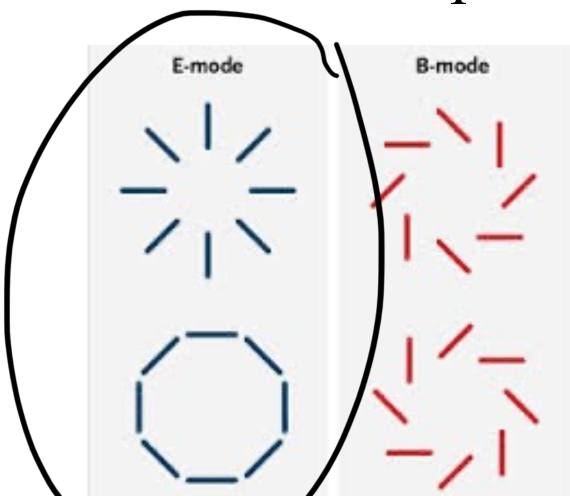
CMB polarization. E and B modes

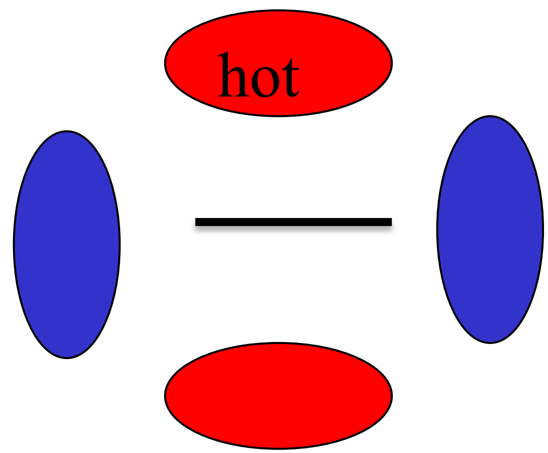
(Kamionkowski, Stebbins, Kosowsky; Seljak, Zaldarriaga, 1997…)

$$\vec{P} = \nabla S + \text{curl}\ \vec{V}$$

E-mode B-mode

Polarization is generated by quadrupole temperature anisotropy, and scalar perturbations are capable of generating only the E-modes.

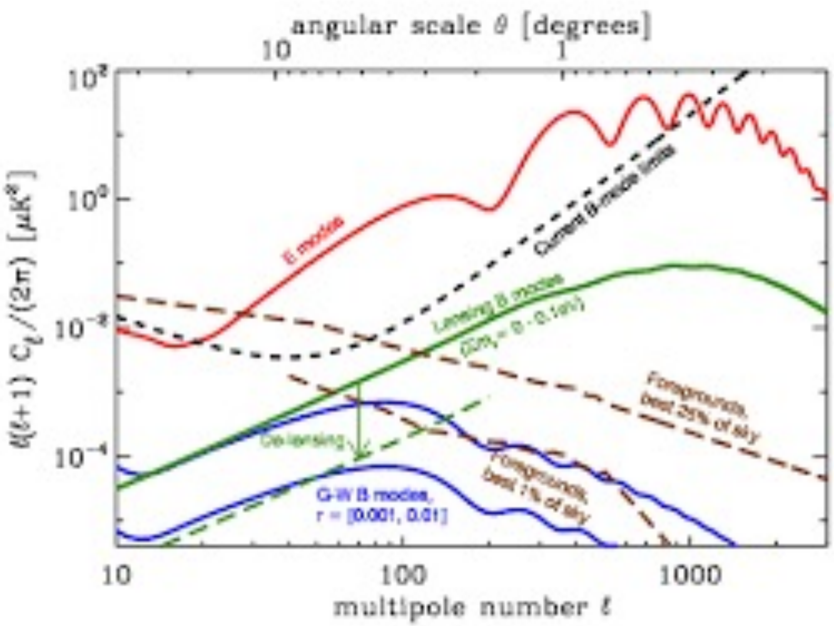




Scalar perturbations [of Newtonian potential] can only generate E-mode but perturbations of the full metric tensor [grav waves] can also give B.

CMB polarization. E and B modes

(Kamionkowski, Stebbins, Kosowsky; Seljak, Zaldarriaga, 1997…)

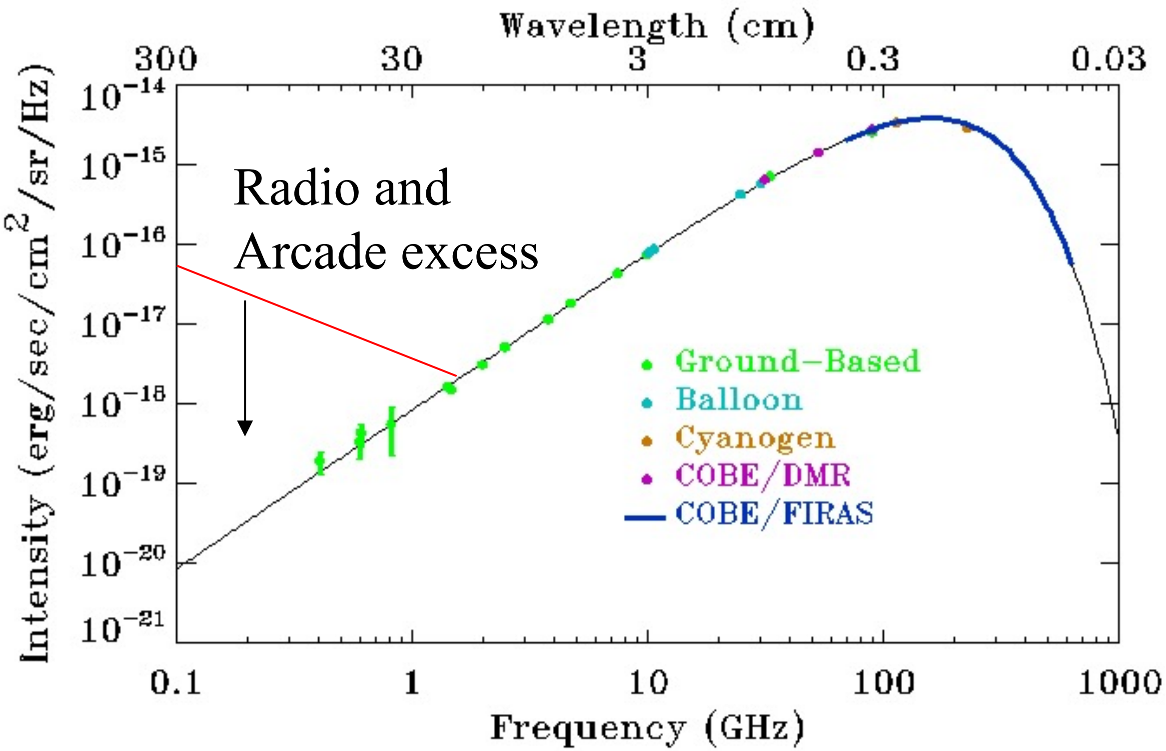


The amplitude of <BB> correlation function coming from tensor modes is not known and depends on H_{infl}.

Measuring it away from zero (after separating from the lensed contribution) would be perhaps the most important measurement in cosmology, as it would prove that cosmology had excess to large energy scales.

FIPs can change the picture as e. g. axion like fileds can rotate linear polarization, and transfer <EE> → <BB>

21 cm and CMB Planckian spectrum

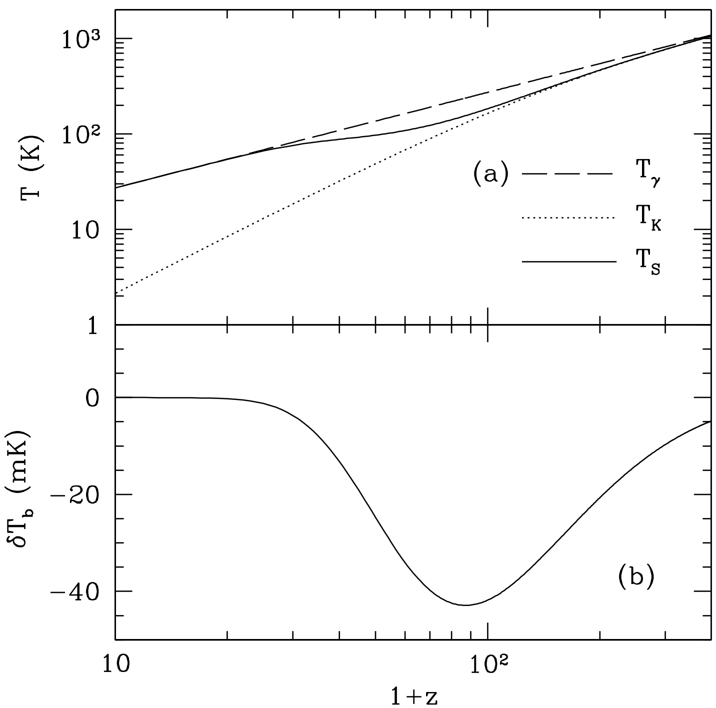


$$x \equiv \omega/T_{\rm CMB}$$

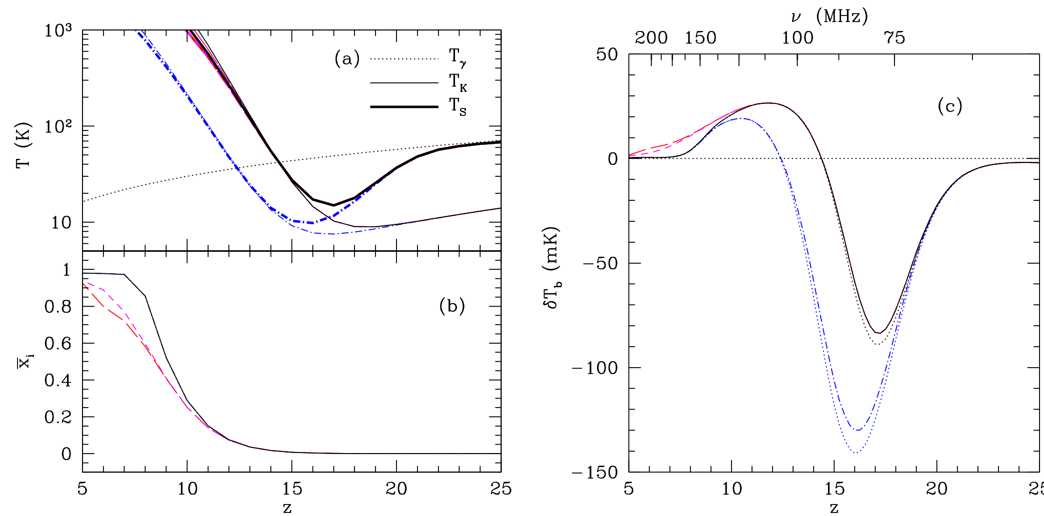
- Primordial Rayleigh-Jeans part of the spectrum at x ~ 10^{-3}, relevant for cosmic 21 cm signal is not measured – dominated by the foreground + diffuse emission. Part of it could be primordial.
- Cosmological 21 cm physics has to rely on theoretical extrapolation into relevant frequency range

Cosmic 21 cm line signal

- (Figures from Furlanetto et al, 2006, Phys. Rep.)



Naïve picture



First stars produce Lyman α photons that recouple spin and baryonic temperatures. Later – gas is heated and absorption switches to emission.

Through scattering or decay FIPs can change baryonic temperature, or add photons

Conclusion

- We live in the era of precision cosmology and know that atoms are a subdominant component to other forms of energy: Dark Matter and Dark energy.
- Early Universe has some periods that are relatively well understood by us (e.g. BBN, CMB epoch). We understand what inflation does "to the sky map" and to formation of structure, but do not know what energy content it had.
- FIPs, depending on their mass, coupling and the way they are produced and decay can: modify/saturate DM, change equation of state for dark energy, lead to radiation-like degree of freedom that modify N_{eff}, cause late time energy injection modifying BBN and CMB observational patterns …..

Examples – in the next lecture.