BBN aspects of DM

Comments on light mediators and assumptions on the thermal history

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DarkMALT workshop Feb 2015

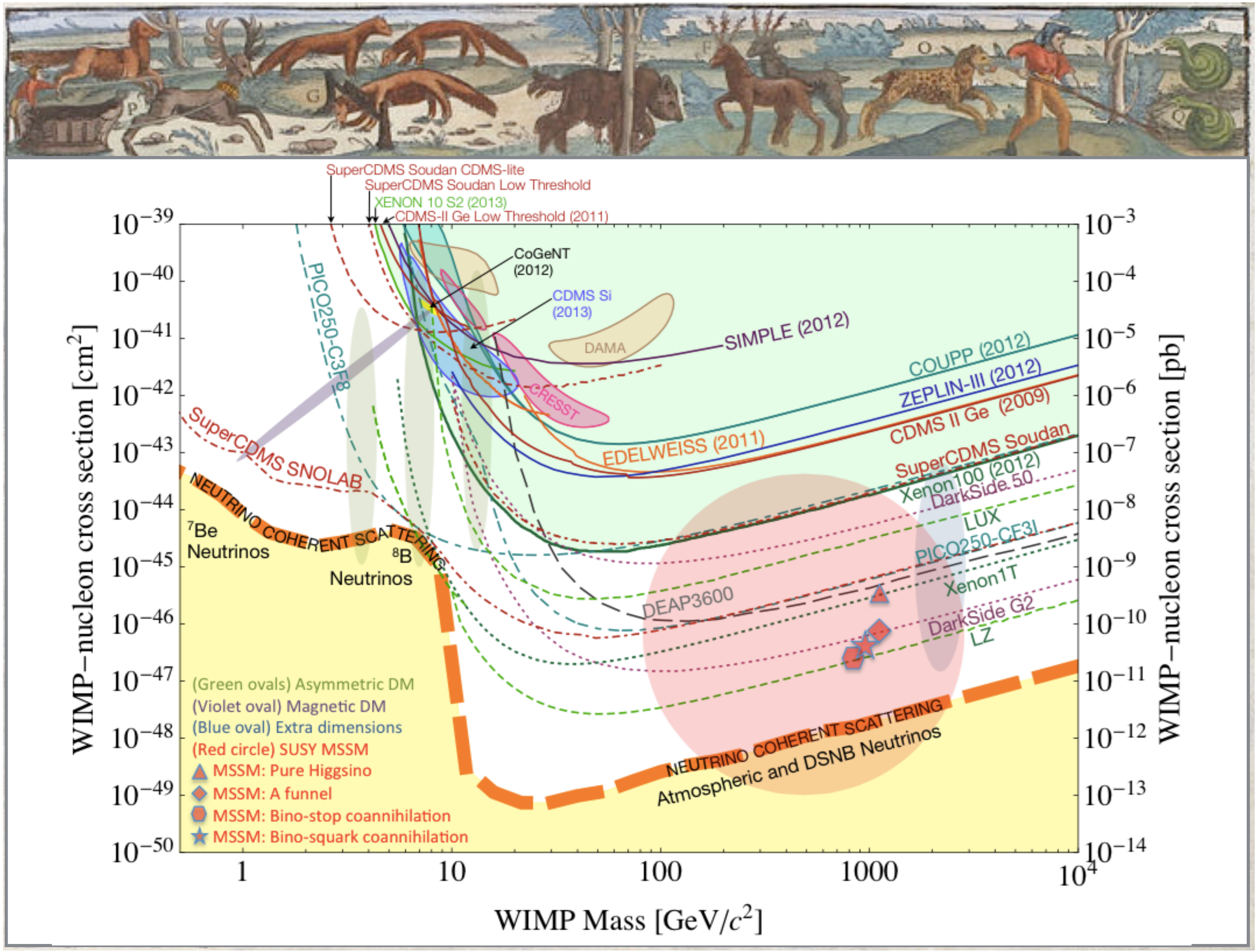
Plan

1. Addendum to the light mediator workshop last week
   (cosmological consequences of light mediators)

2. Non-standard thermal history without new particles
   (Silk damping at redshift one billion)

Jeong, JP, Chluba, Kamionkowski PRL 2014

Looking for new species



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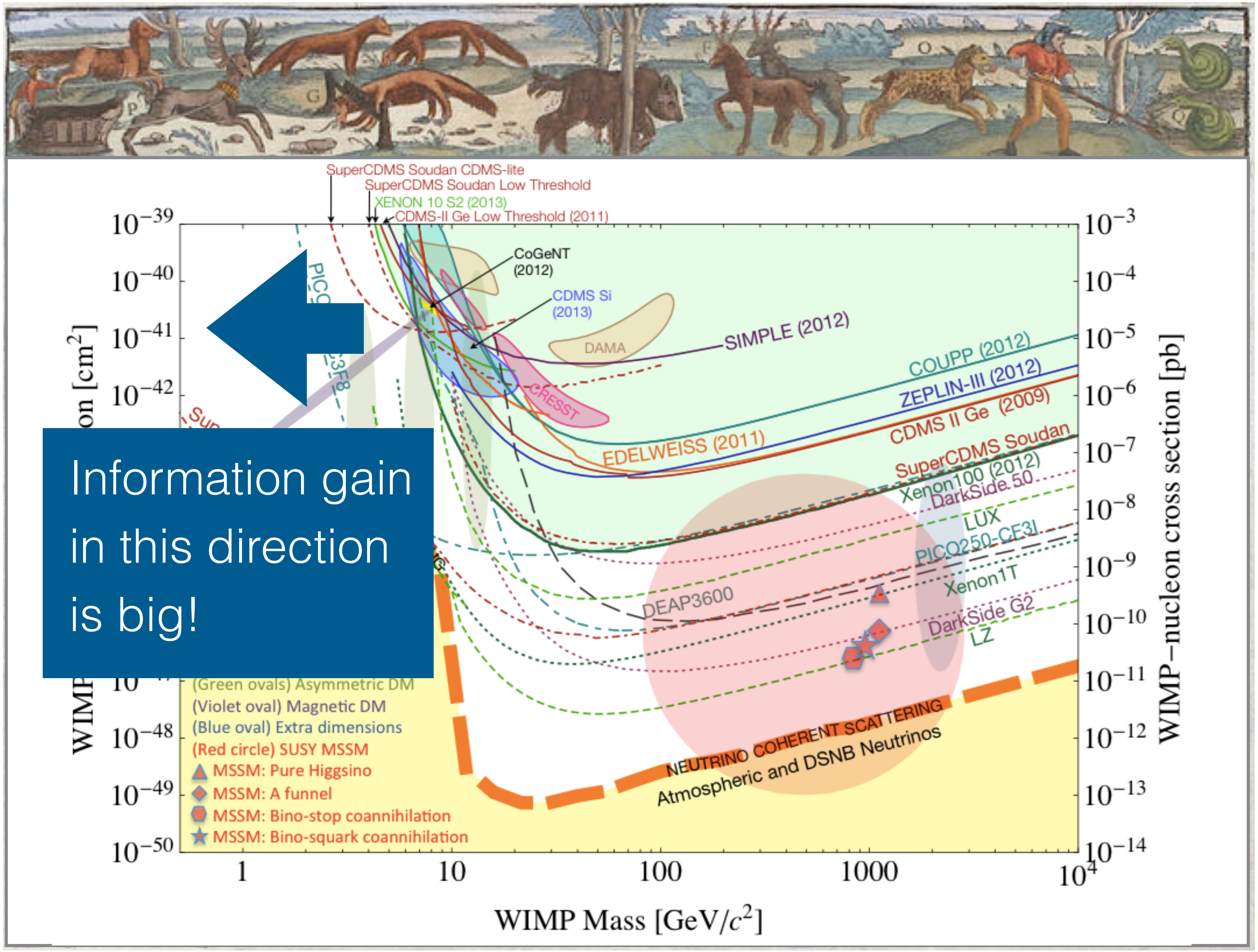


CF1 Snowmass report

Looking for new species

Light Dark Matter relic abundance

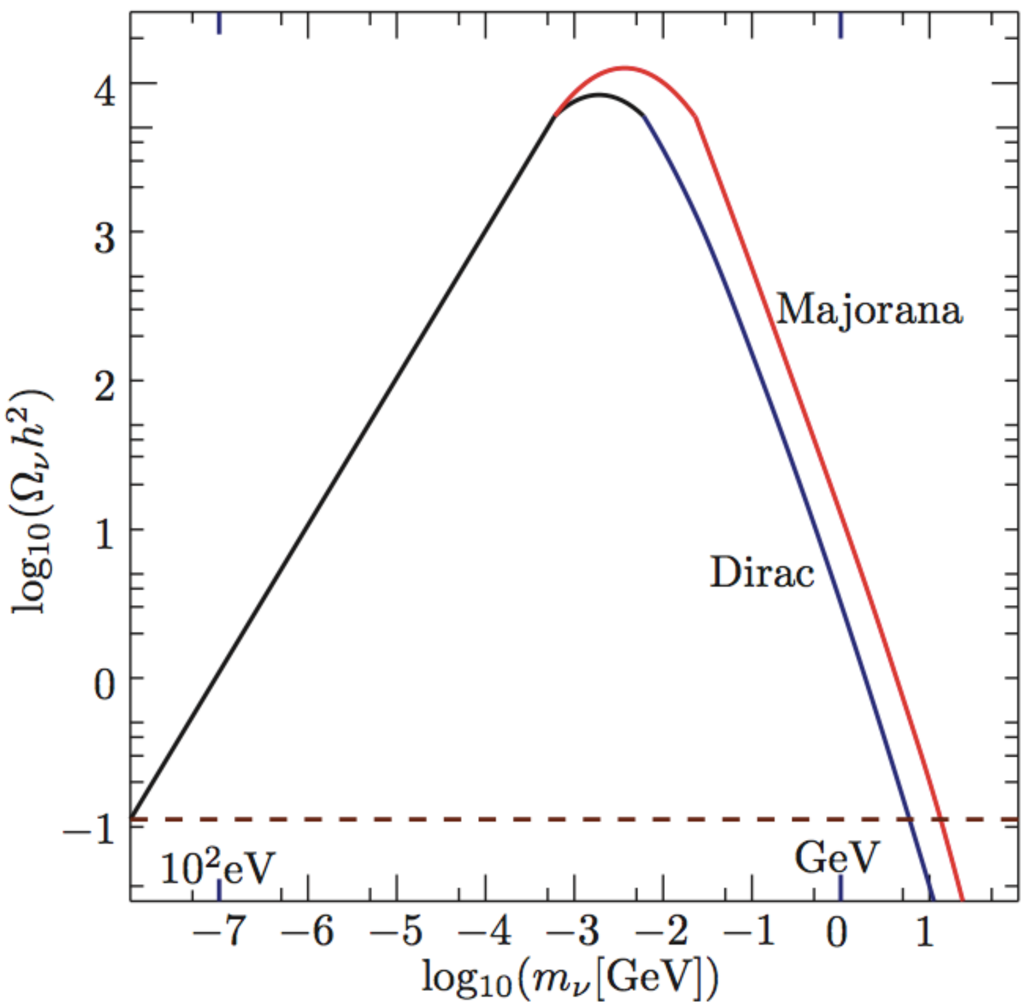
Recall the Lee-Weinberg bound:

Annihilation of a heavy neutrino through SM mediators excludes masses below ~ few GeV

$$\langle \sigma v \rangle \sim G_F^2 m_\nu^2 / 2\pi$$

A way out are new, light mediators ϕ

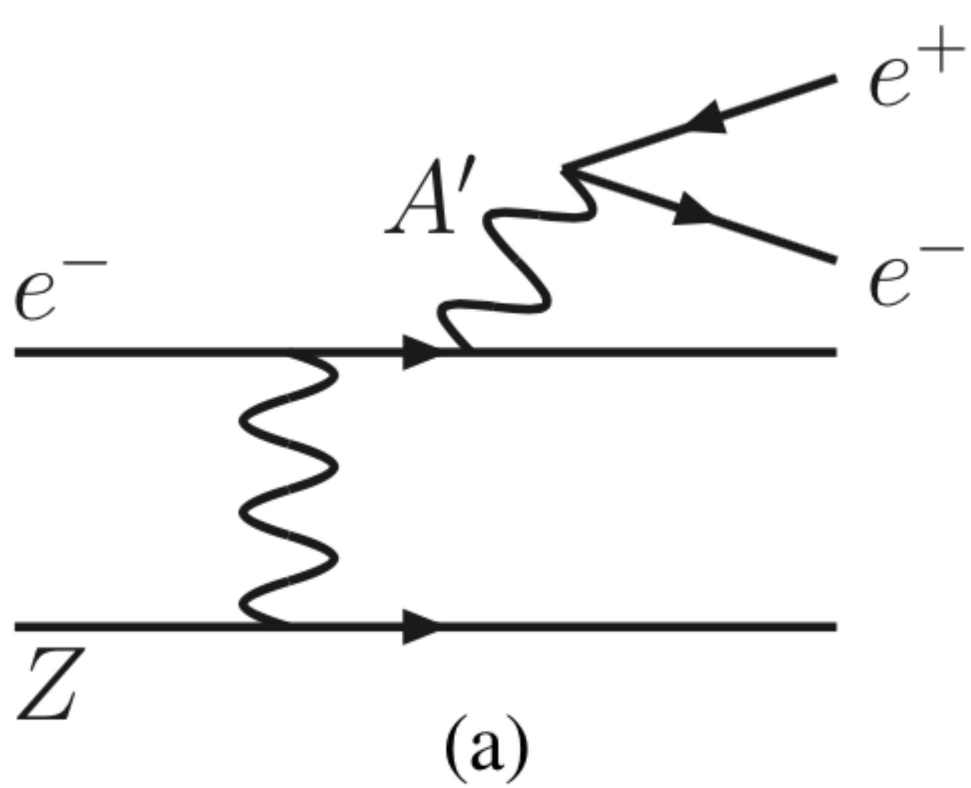
$$G_F \to g^2 / m_\phi^2$$

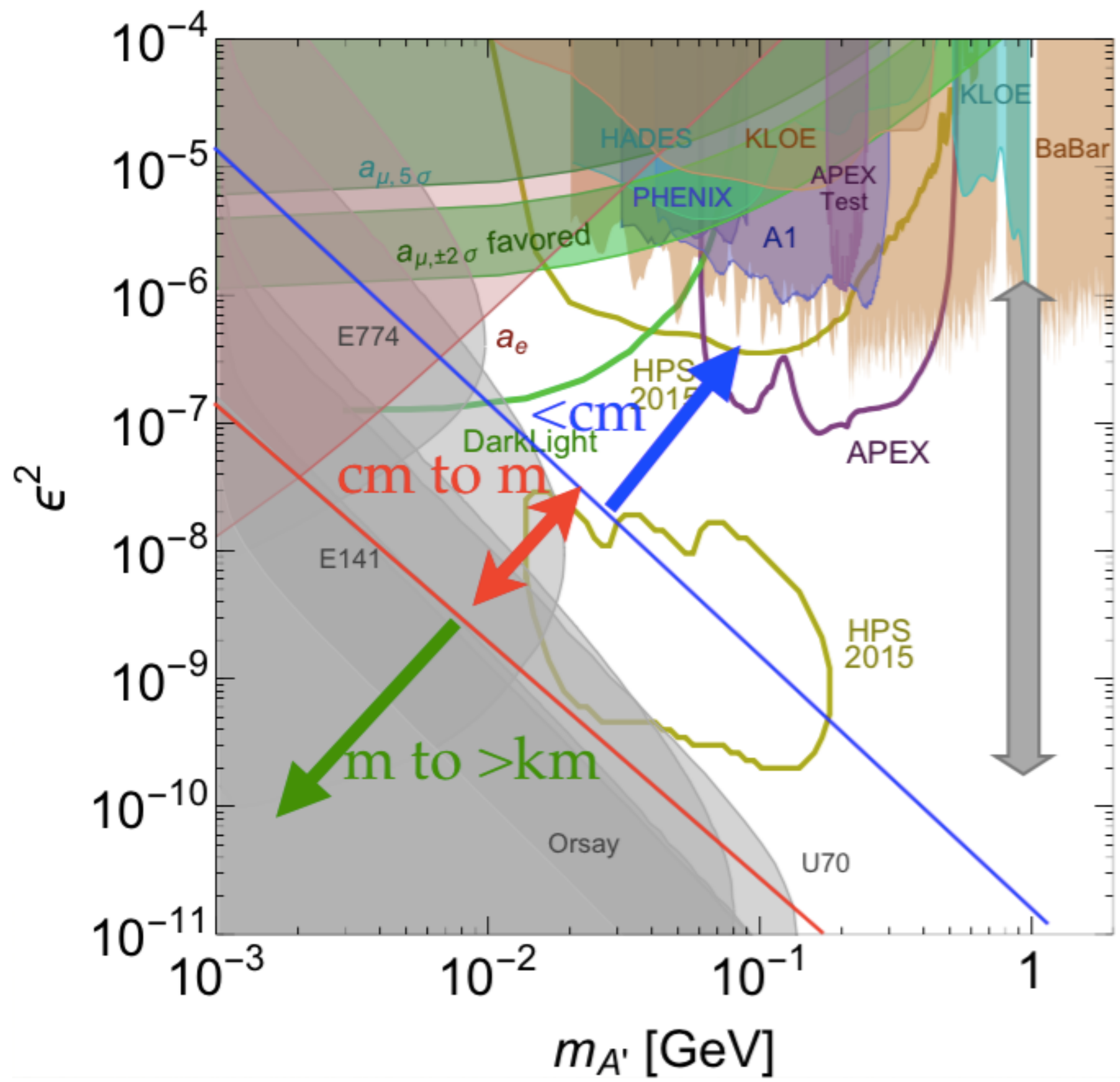


(...)

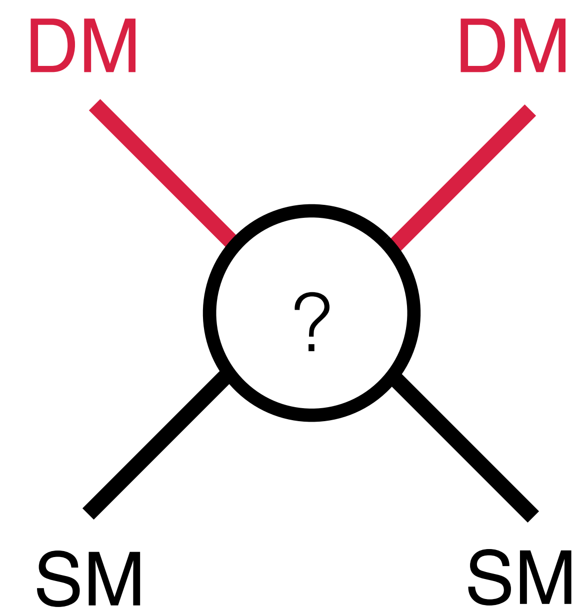
Search for light mediators is a field of its own now

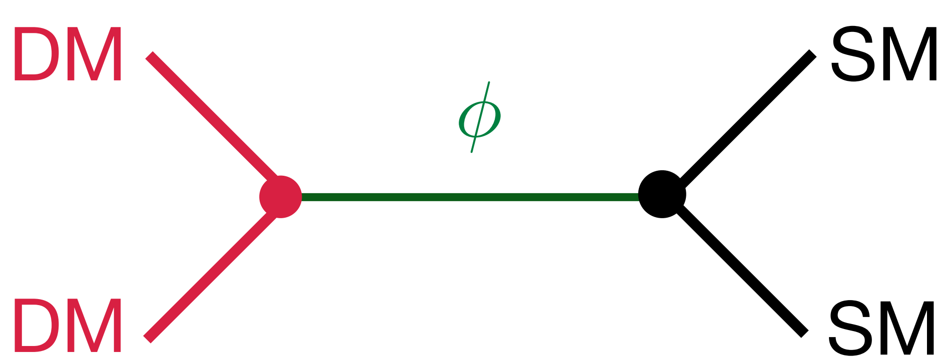
For example:





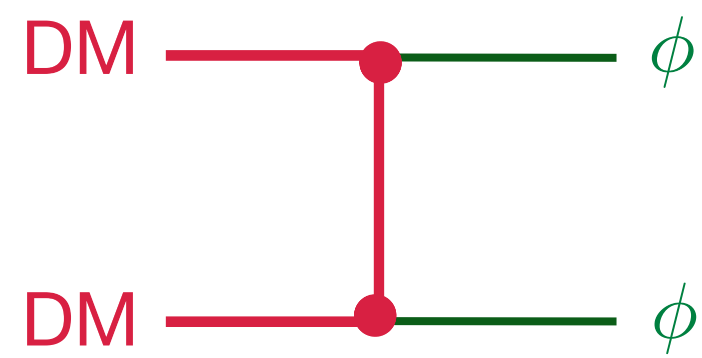
Do light mediators imply enhanced detection rates?





$m_\chi < m_\phi$

vs.

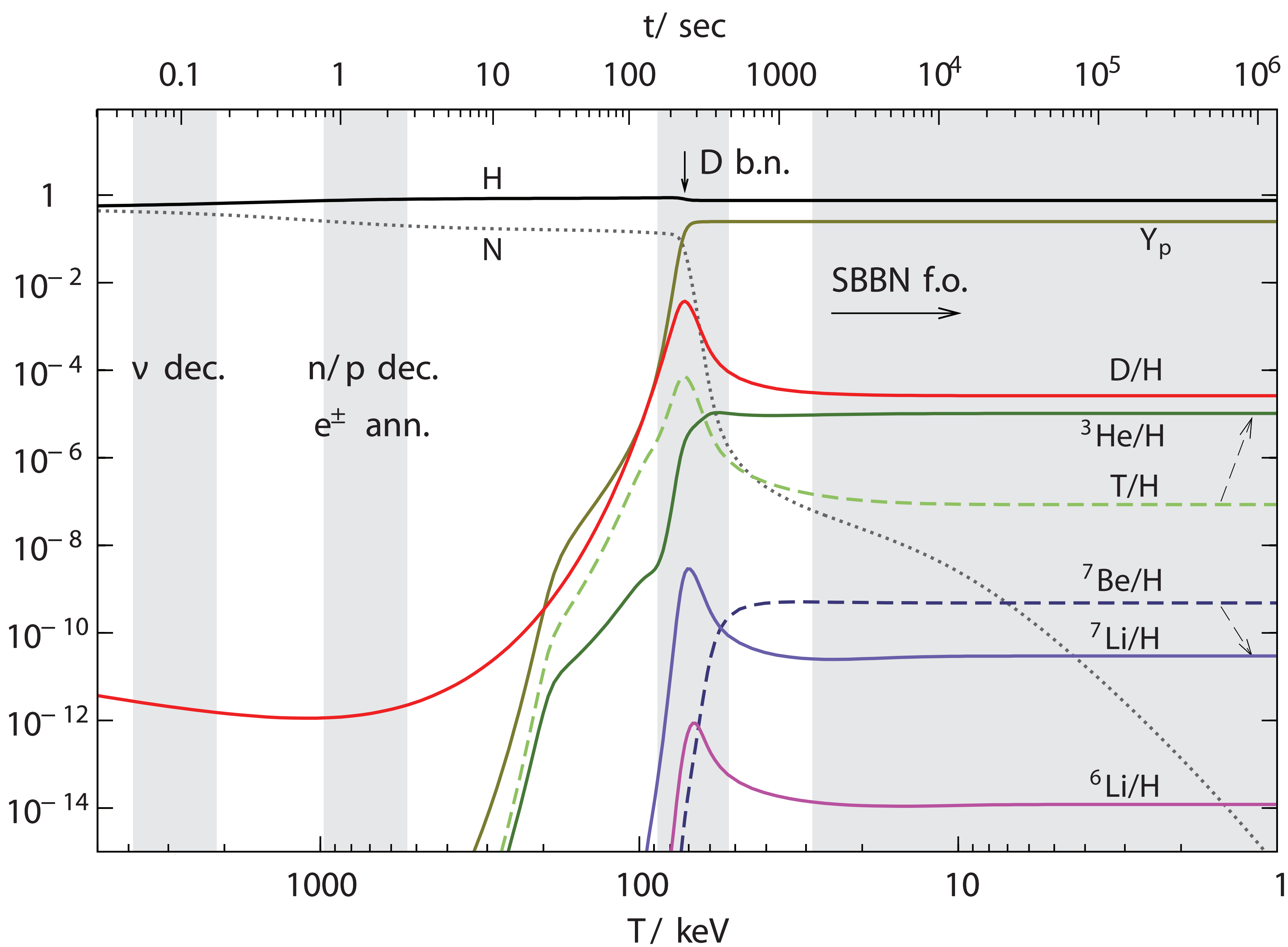


$m_\chi > m_\phi$

The situation at the right can completely elude direct detection, because couplings to SM can be tiny.

=> mediators can be long lived with implications for cosmology.

The Universe at redshift one billion



Beyond SBBN

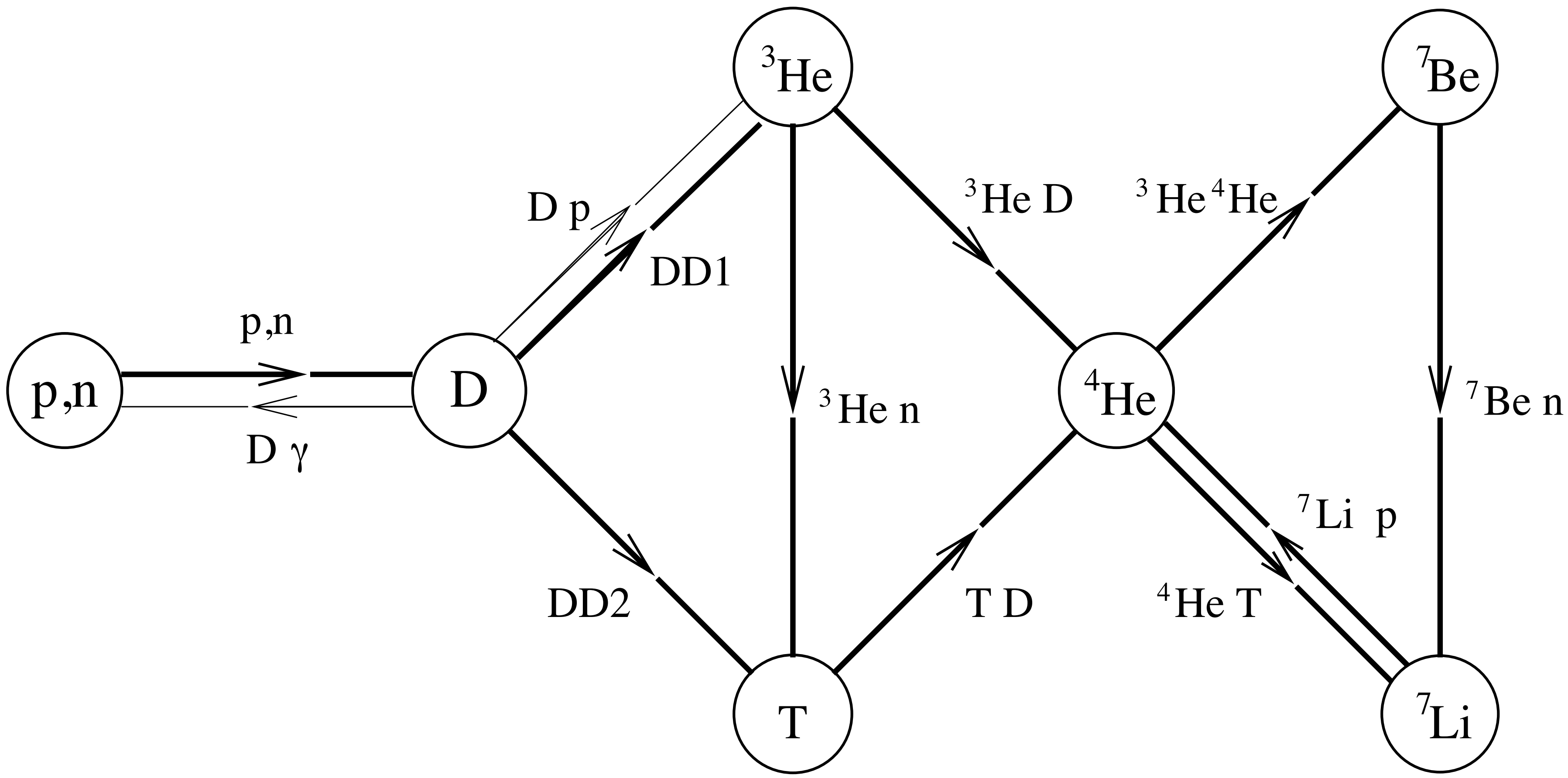


Fig. from Mukhanov

Beyond SBBN

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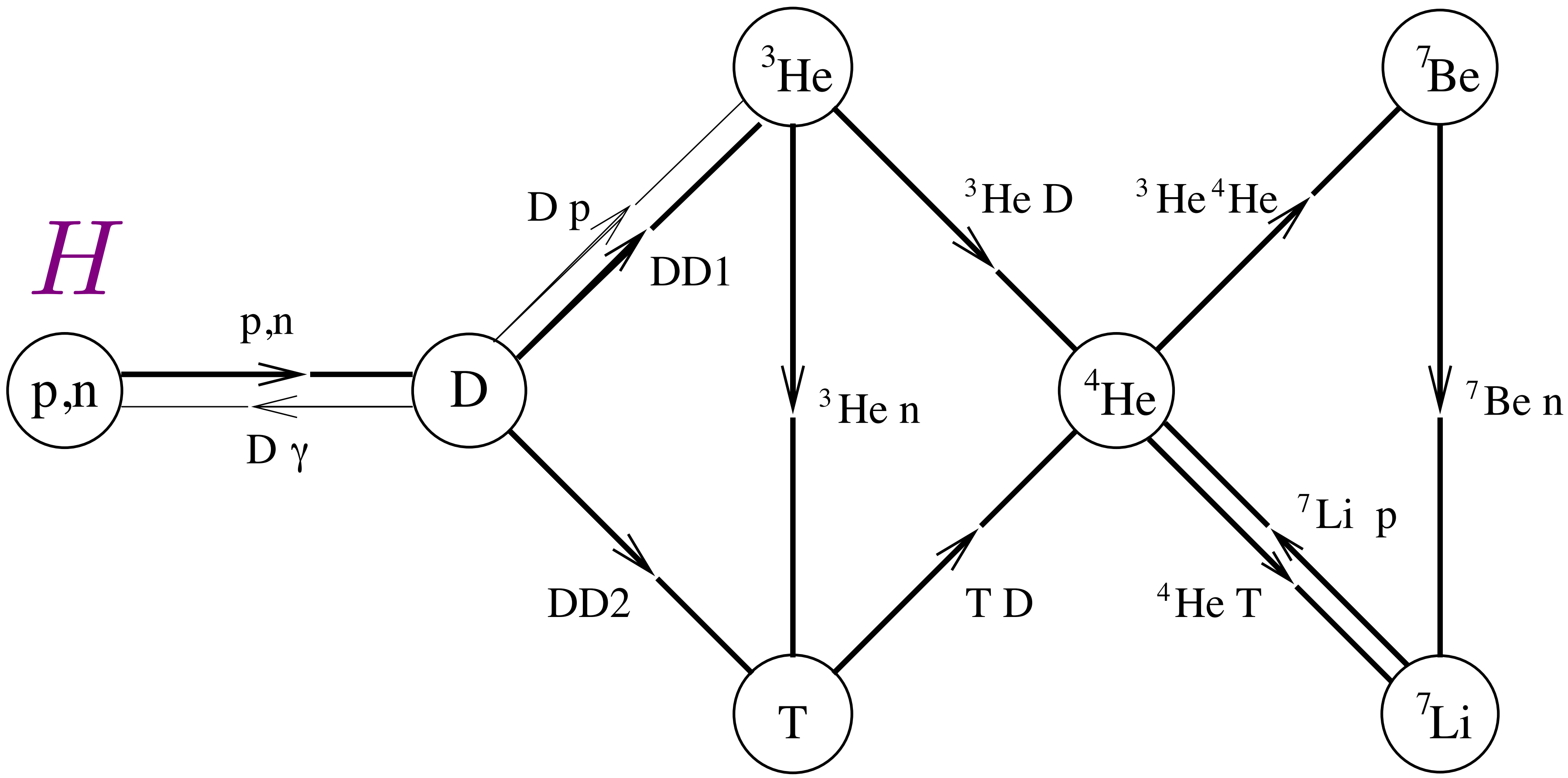
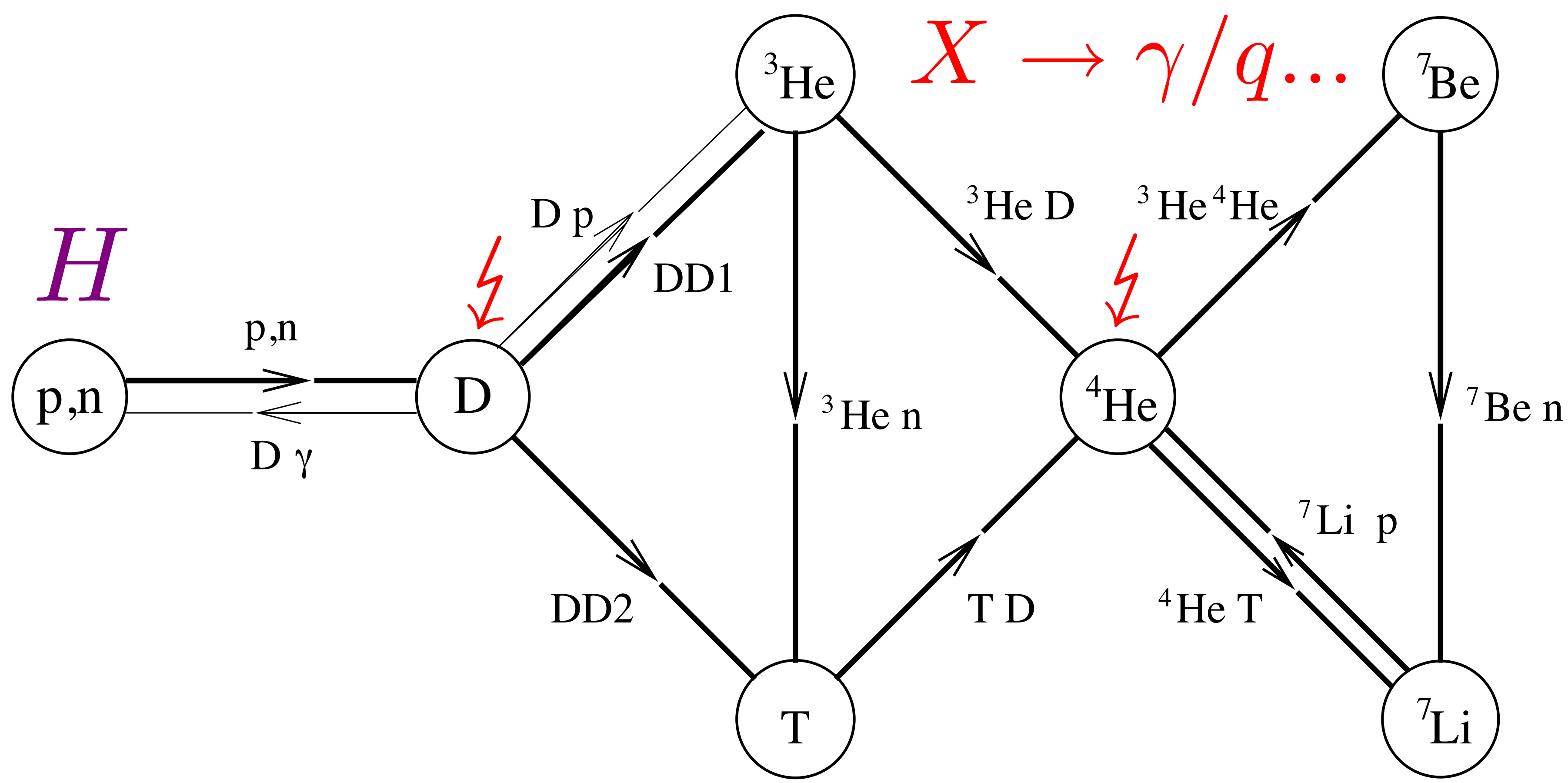


Change in timing

Fig. from
Mukhanov

Beyond SBBN

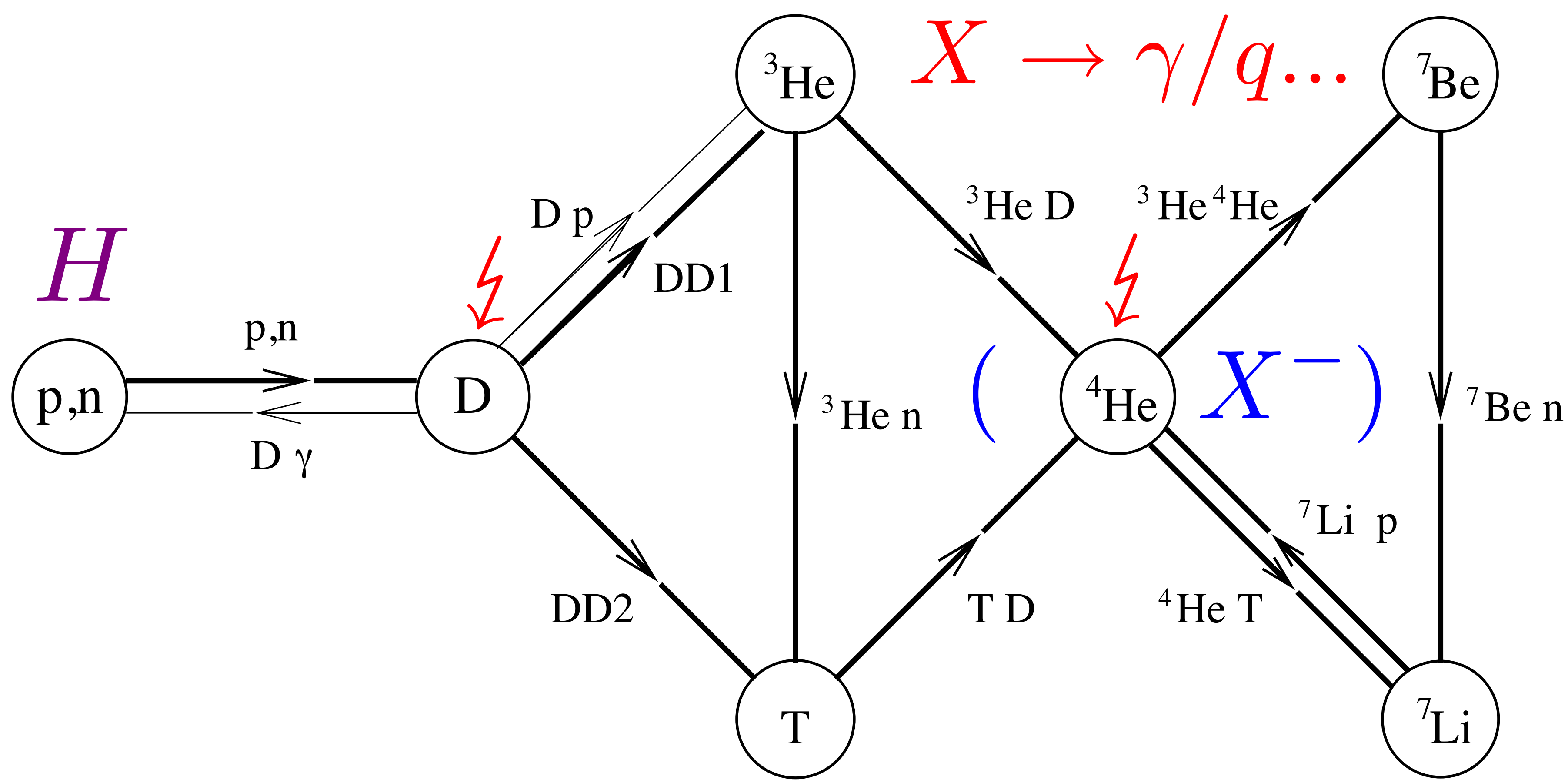


Change in timing

non-equilibrium BBN

Fig. from Mukhanov

Beyond SBBN



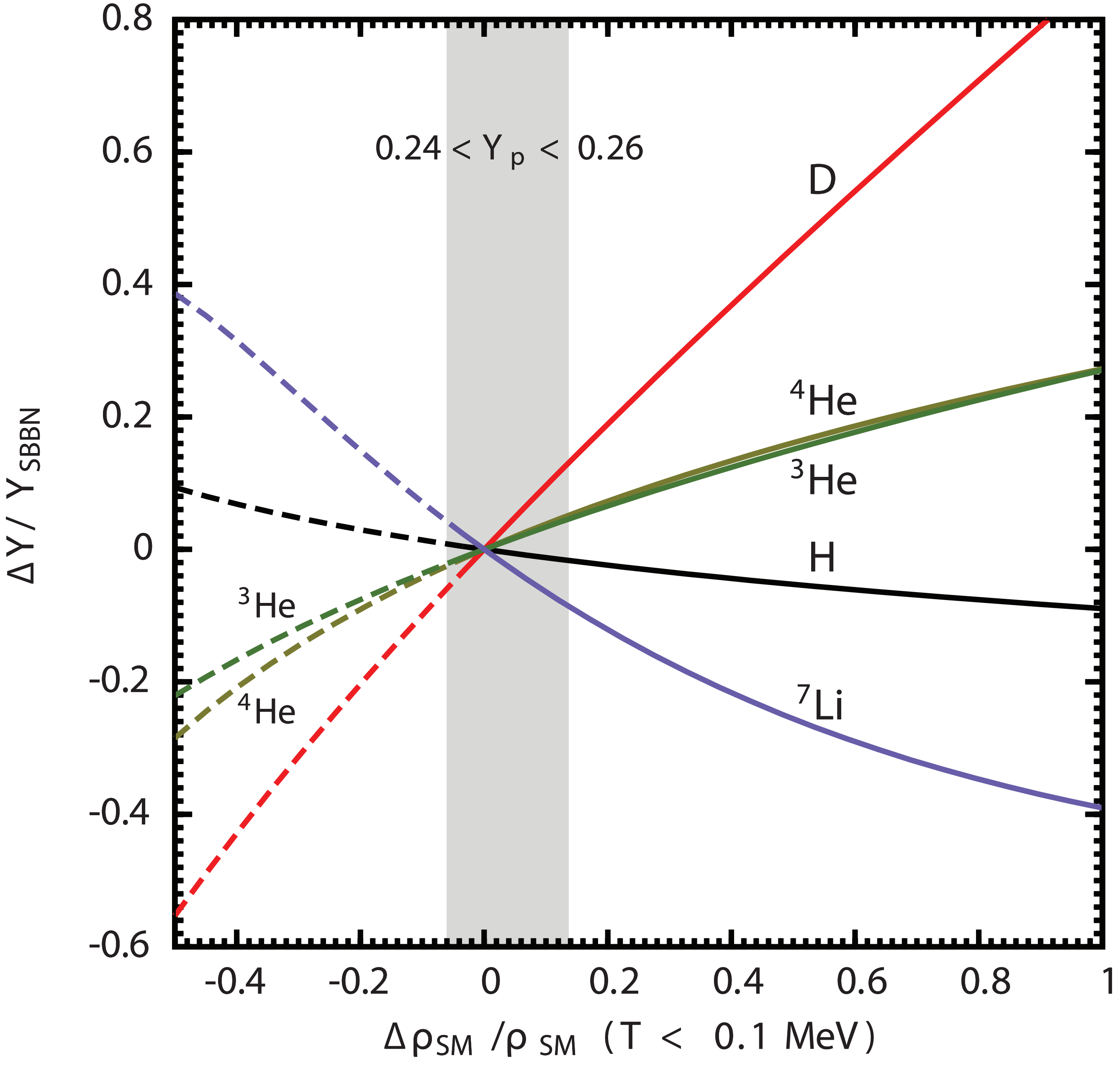
Change in timing

non-equilibrium BBN

catalyzed BBN

Fig. from Mukhanov

Dark radiation



$$\rho_{\rm rad} = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\rho_\gamma$$

Mediator decays one example

Visible decays > 1 sec are not necessarily excluded, even for very large mediator abundances!

Invisible decays > 1 sec can still yield constraints!

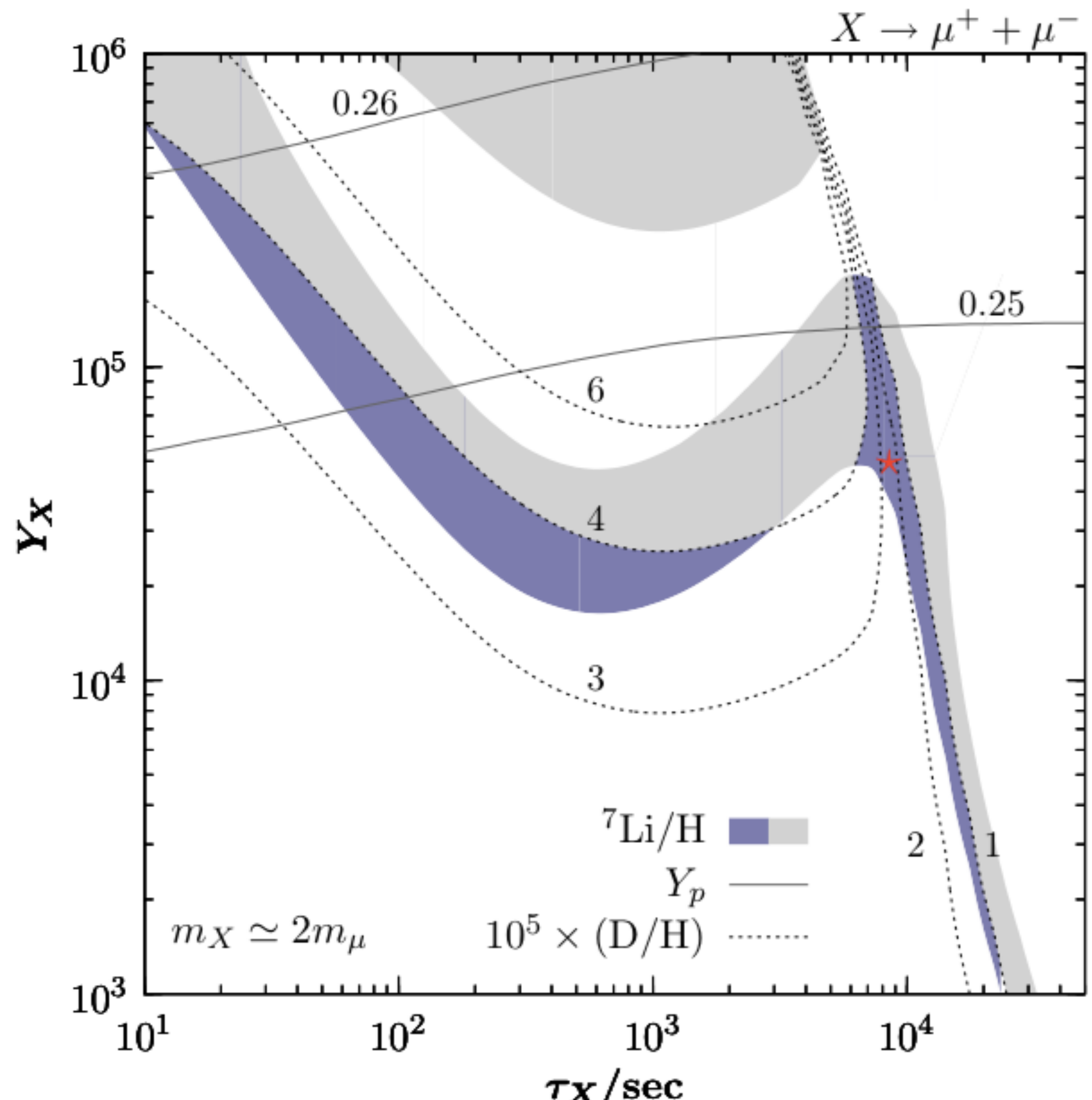
$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$$

$$\downarrow$$

$$\bar{\nu}_e + p \to n + e^+$$

$$^7\mathrm{Be} + n \to ^7\mathrm{Li} \to ^4\mathrm{He} + ^4\mathrm{He}$$

can solve Lithium problem.



Pospelov, JP 2010

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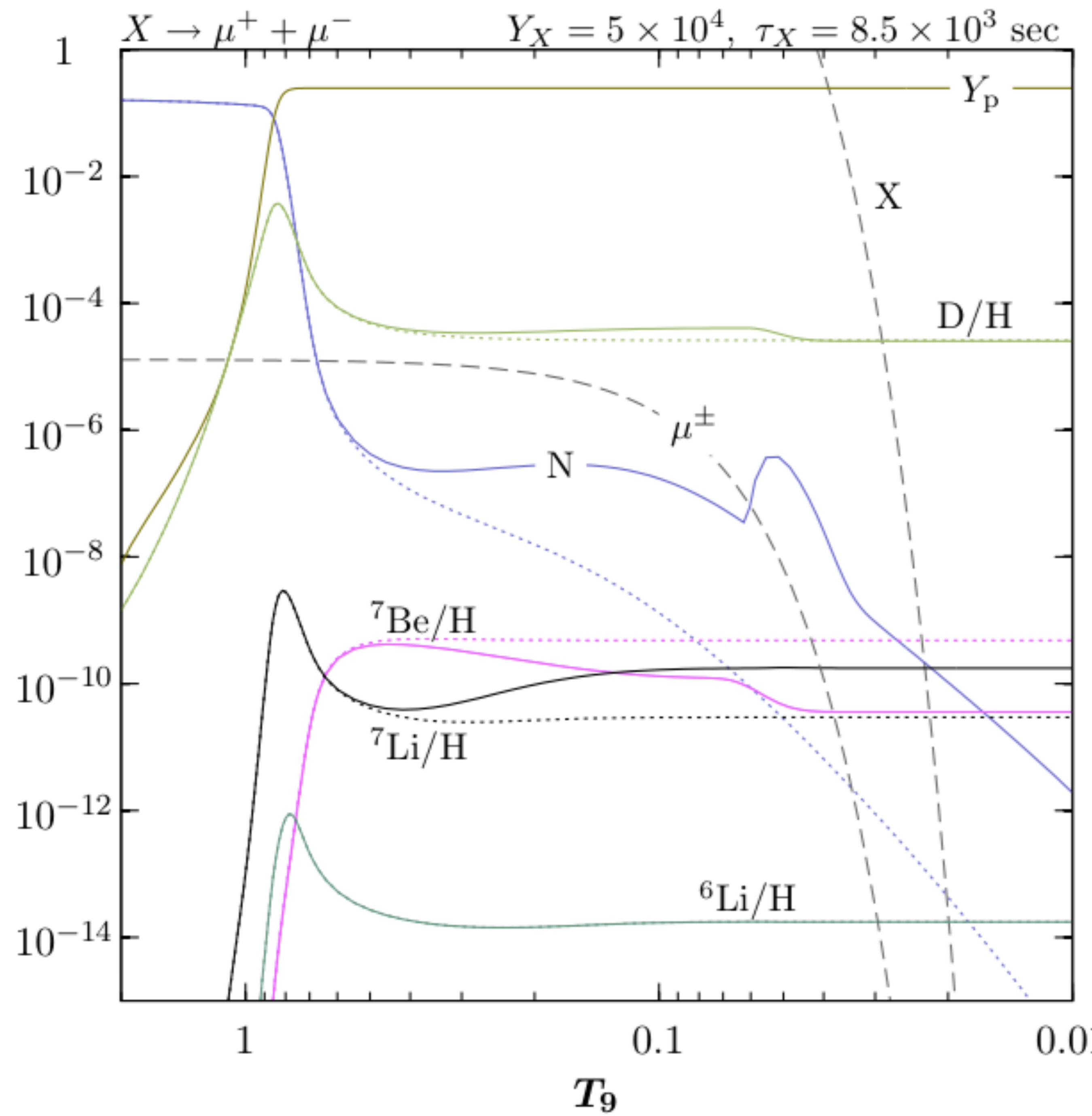
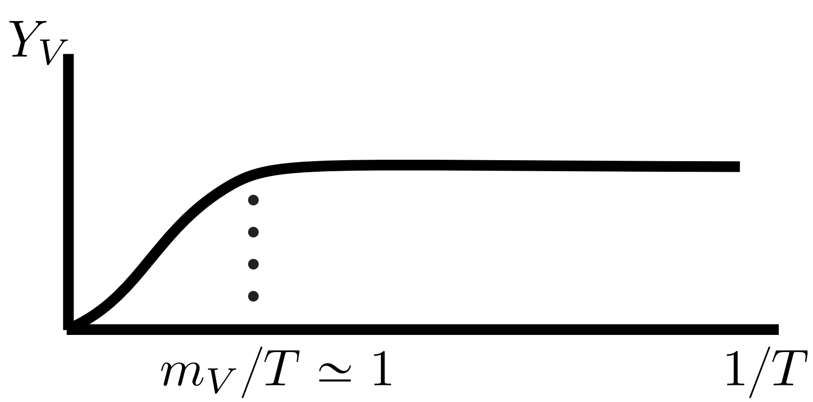


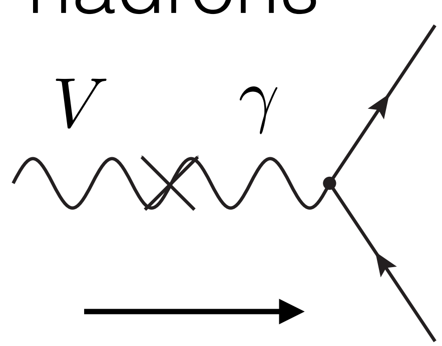
Pospelov, JP 2010

Example: Dark Photons

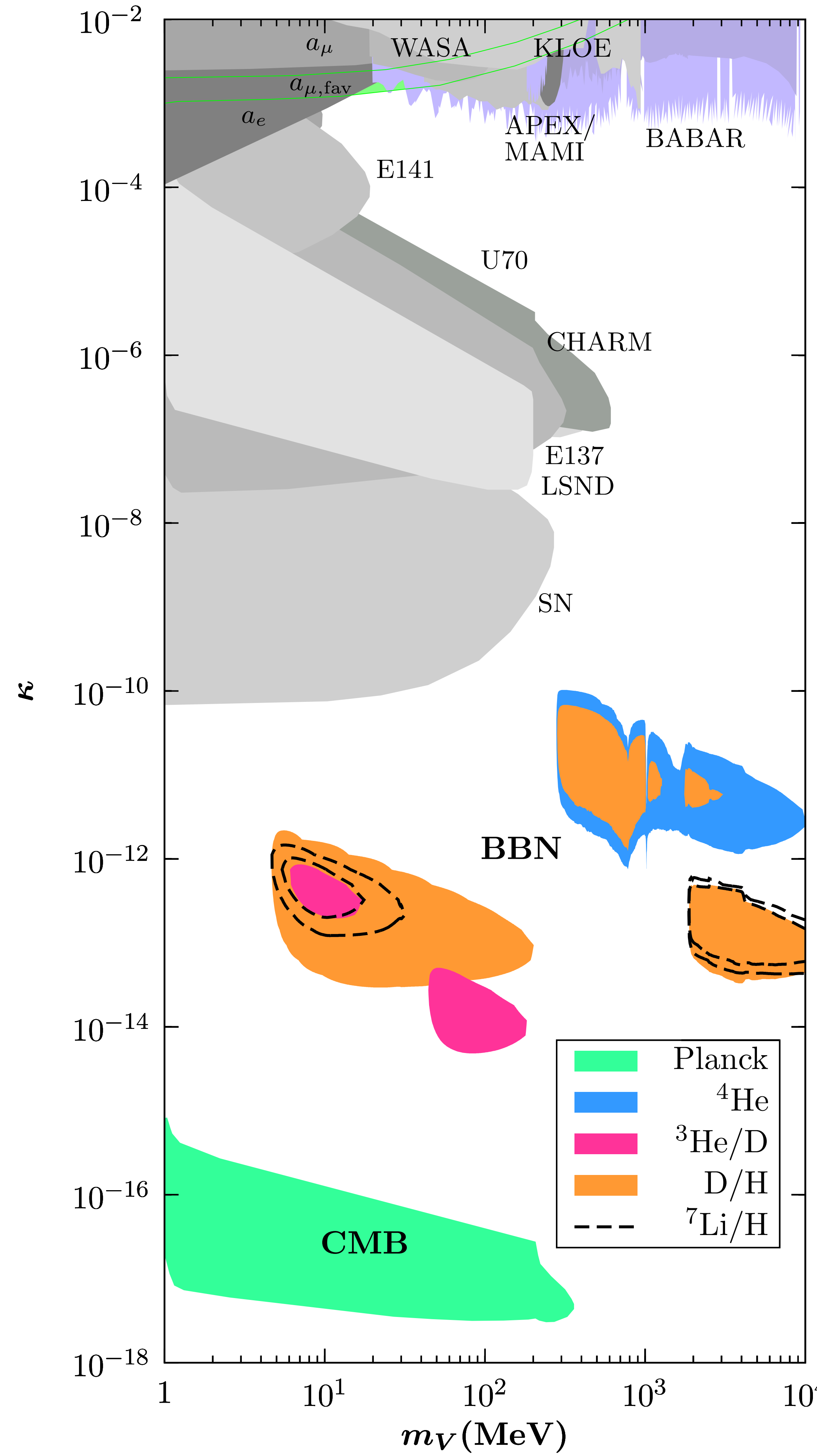
1. Production with sub-Hubble rates, “freeze in”



2. Late decay back to leptons and hadrons



Fradette, Pospelov, JP, Ritz 2014



Plan

1. Addendum to the light mediator workshop last week (cosmological consequences of light mediators)

2. Dissipation of acoustic modes (Silk damping at redshift one billion)

Jeong, JP, Chluba, Kamionkowski PRL 2014

The Standard Lore of Standard Cosmology

Common belief: SM + DM field content leads to an "uneventful" standard thermal history between the CMB epoch and BBN (or even DM freeze out)

$$\Rightarrow \quad \left.\frac{N_{b,c,\nu} - N_{\bar{b},\bar{c},\bar{\nu}}}{S}\right|_{\rm CMB} = \left.\frac{N_{b,c,\nu} - N_{\bar{b},\bar{c},\bar{\nu}}}{S}\right|_{\rm BBN/FO}$$

Cosmological concordance test from BBN, viability of DM models, parameters for successful baryogenesis, possible extensions of neutrino sector all depend on this assumption.

That rationale carries the implicit assumption $\int \Delta^2_{\mathcal{R}}(k)\, d\ln k \ll 1$

Primordial scalar curvature perturbations

$$\Delta^2_{\mathcal{R}}(k) \equiv k^3 P_\zeta(k)/(2\pi^2)$$

↑ power spectrum of scalar curvature perturbations ζ

$$\Delta^2_{\mathcal{R}}(k) = \Delta^2_{\mathcal{R}0} \left(\frac{k}{k_0}\right)^{n_s - 1}$$

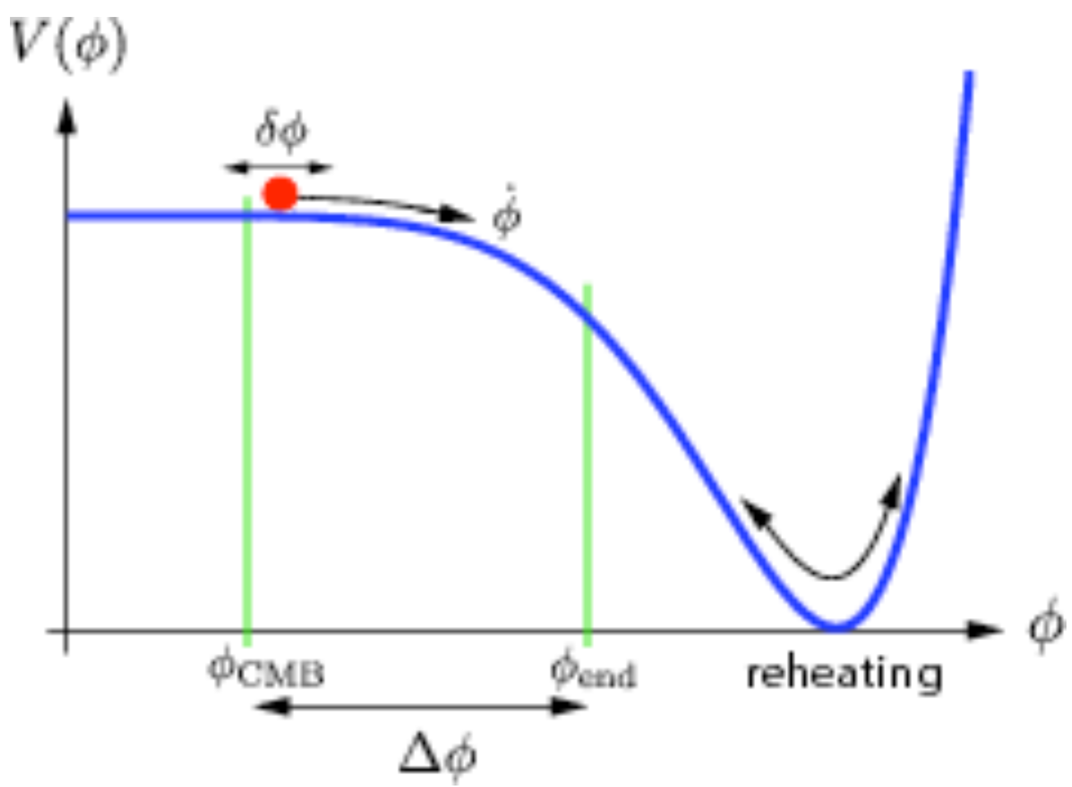
$$\Delta^2_{\mathcal{R}}(k) \equiv \langle|\zeta|^2\rangle = \mathrm{const} \quad (n_s = 1)$$

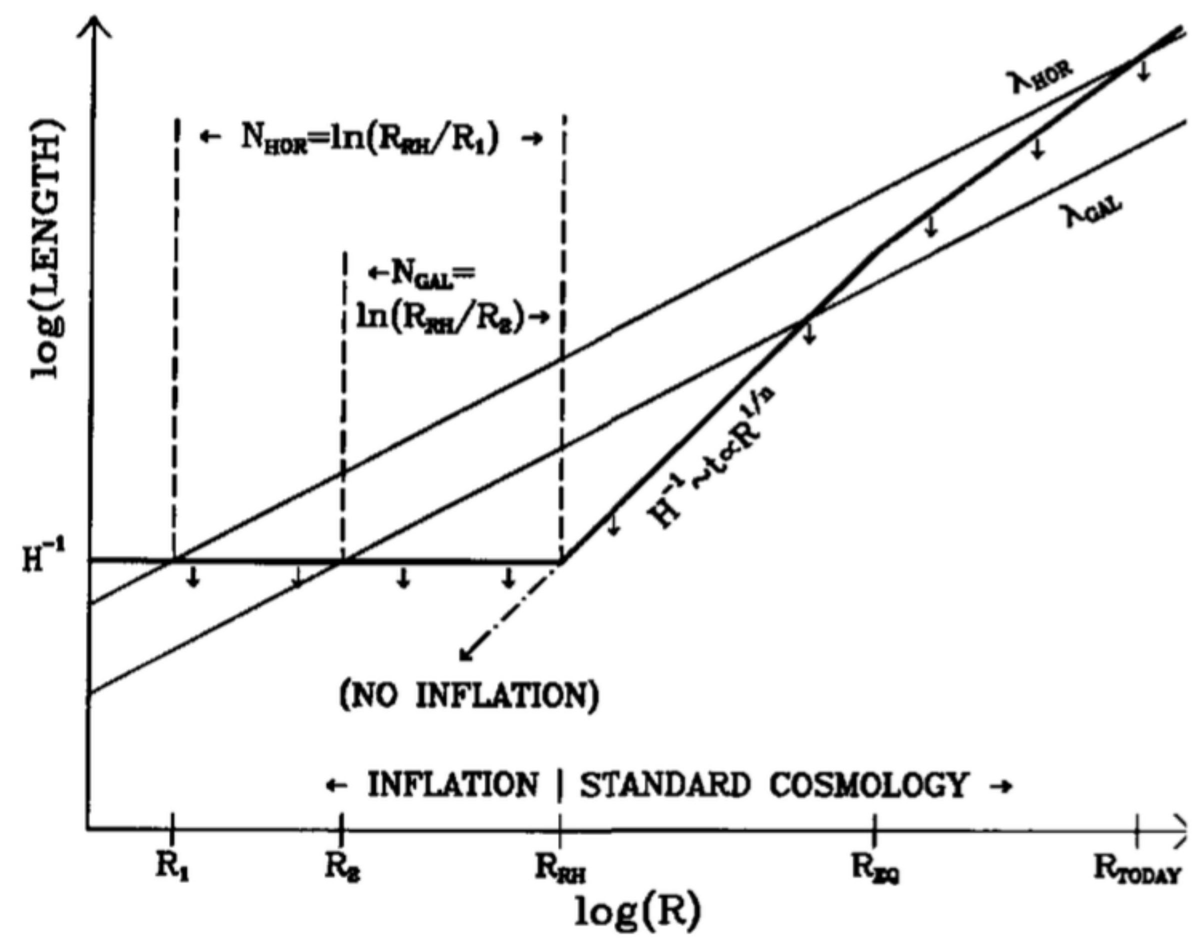
Inflation:

$$\zeta_{N_\lambda} \sim \left(\frac{\delta\phi V'}{\dot{\phi}^2}\right)_{N_\lambda} \simeq \left(\frac{H^2}{\dot{\phi}}\right)_{N_\lambda}$$

$$V' = -3H\dot{\phi}, \ \delta\phi \simeq H/2\pi$$

Primordial scalar curvature perturbations





Existing insights on $\Delta^2_{\mathcal{R}}$

CMB, galaxy clustering, Ly-alpha forest:

e.g. Nicholson et al 2009
Bird et al 2011

$$\Delta^2_{\mathcal{R}}(k) \simeq \mathcal{O}(10^{-9}) \qquad 10^{-3}\,\mathrm{Mpc}^{-1} \lesssim k \lesssim 3\,\mathrm{Mpc}^{-1}$$

Constraints on PBH (gravitational and evaporation)

see, e.g., Josan et al 2009

$$\Delta^2_{\mathcal{R}}(k) \lesssim 0.01 - 0.1$$

Spectral distortions on the CMB

e.g. Chluba et al 2012

$$\Delta^2_{\mathcal{R}}(k) \lesssim 10^{-5} \qquad k \lesssim 10^4\,\mathrm{Mpc}^{-1}$$

Ultracompact Minihalos (indirect, model dep. DM annihilation)

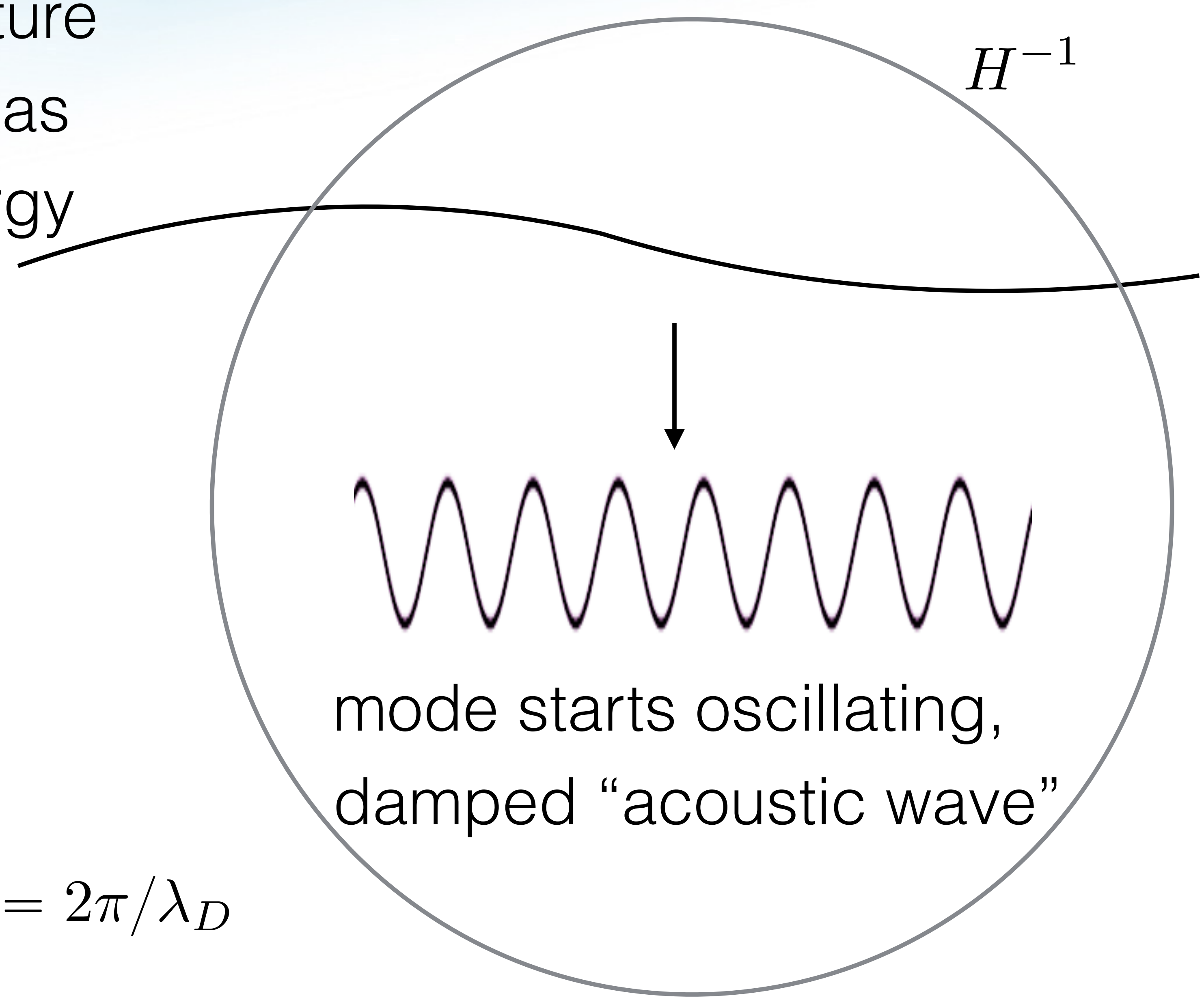
$$\Delta^2_{\mathcal{R}}(k) \lesssim 10^{-7} \qquad k \lesssim 10^{4-7}\,\mathrm{Mpc}^{-1}$$

e.g. Bringmann et al 2012

For $k \gtrsim 10^4\,\mathrm{Mpc}^{-1}$, power spectrum remains rather unconstrained from *direct* observables.

Primordial perturbations

After inflation, adiabatic curvature perturbations re-enter horizon as universal perturbations in energy



$$\delta^i_\gamma(\mathbf{k}) = \frac{\delta\rho_\gamma}{\rho_\gamma} = -(4/3)\,C\,\zeta(\mathbf{k})$$

$$\downarrow$$

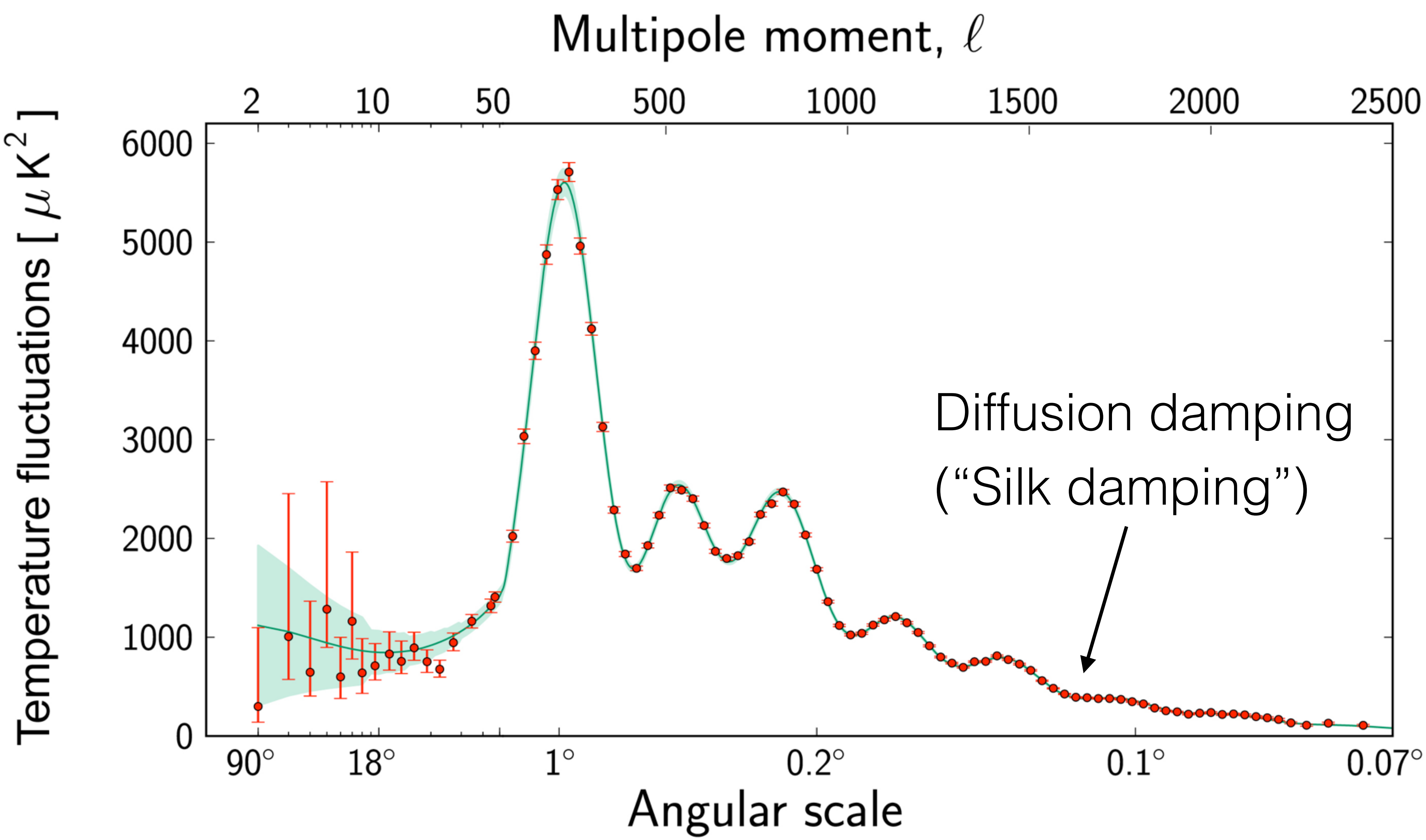
$$\delta_\gamma(t, \mathbf{k}) = \delta^i_\gamma(\mathbf{k}) T(t)$$

$$T(t) \approx 3\cos\left[k r_s(t)\right] e^{-k^2/k_D^2(t)}$$

=> damping set by scale $k_D = 2\pi/\lambda_D$

For $z > 10^6$ Universe perfectly thermalizes perturbation in the photon field

Diffusion damping - photons

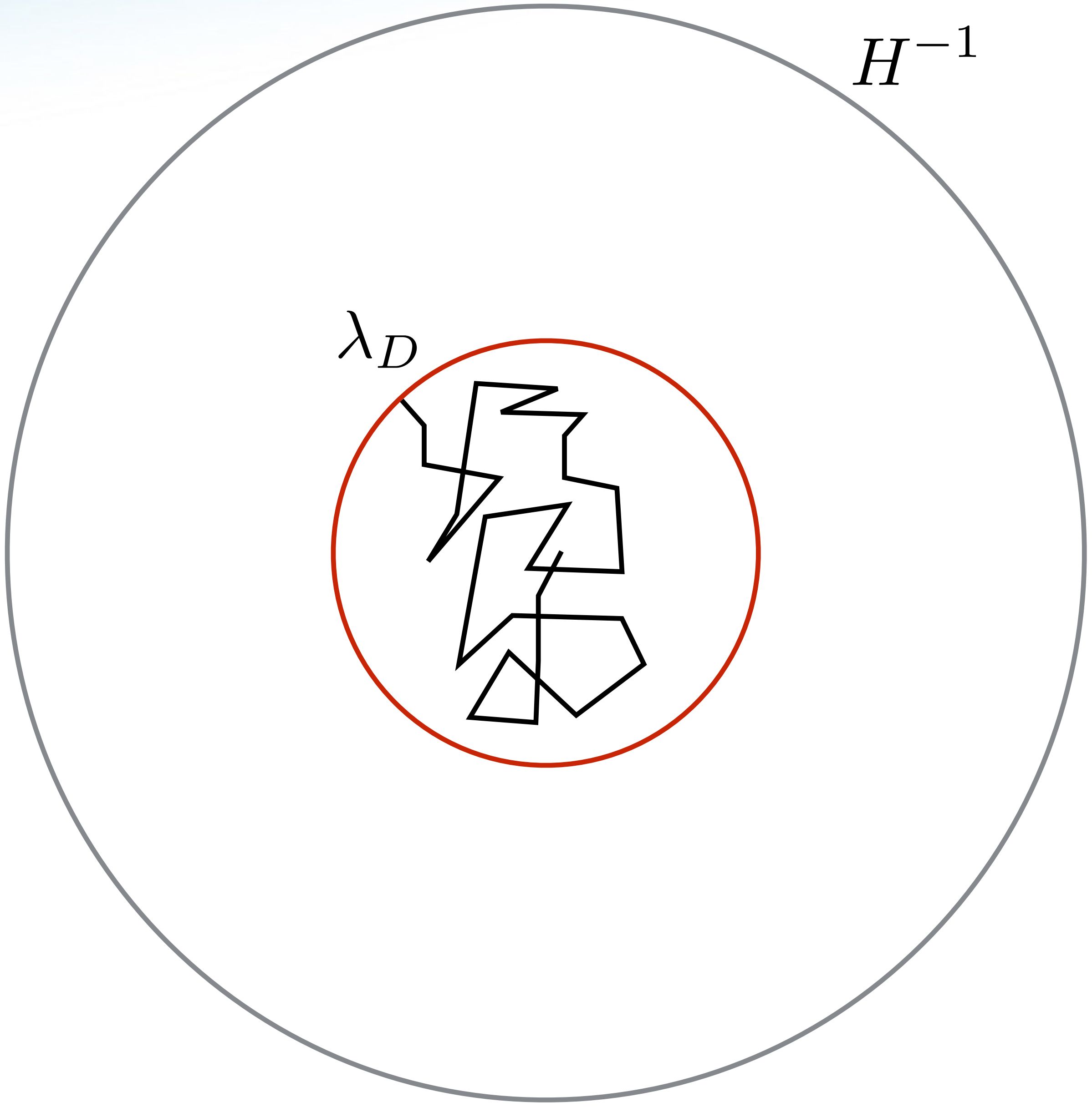


Diffusion damping - photons

mean free path   number of scatters

$$\lambda_{mfp} \approx \frac{1}{\sigma_T n_e} \qquad N \approx \sigma_T n_e H^{-1}$$

=> $\lambda_D \approx \lambda_{mfp}\sqrt{N} \approx \frac{1}{\sqrt{\sigma_T n_e H}}$



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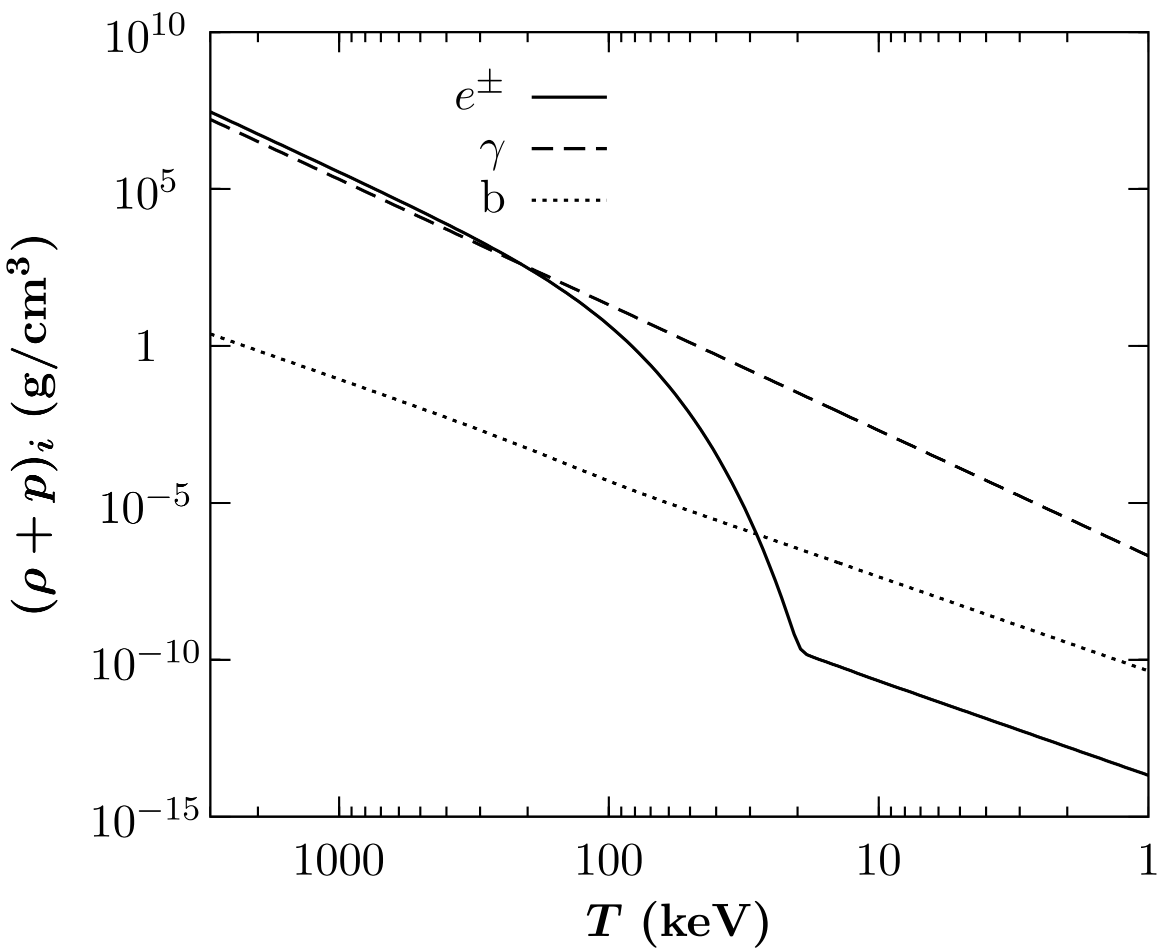
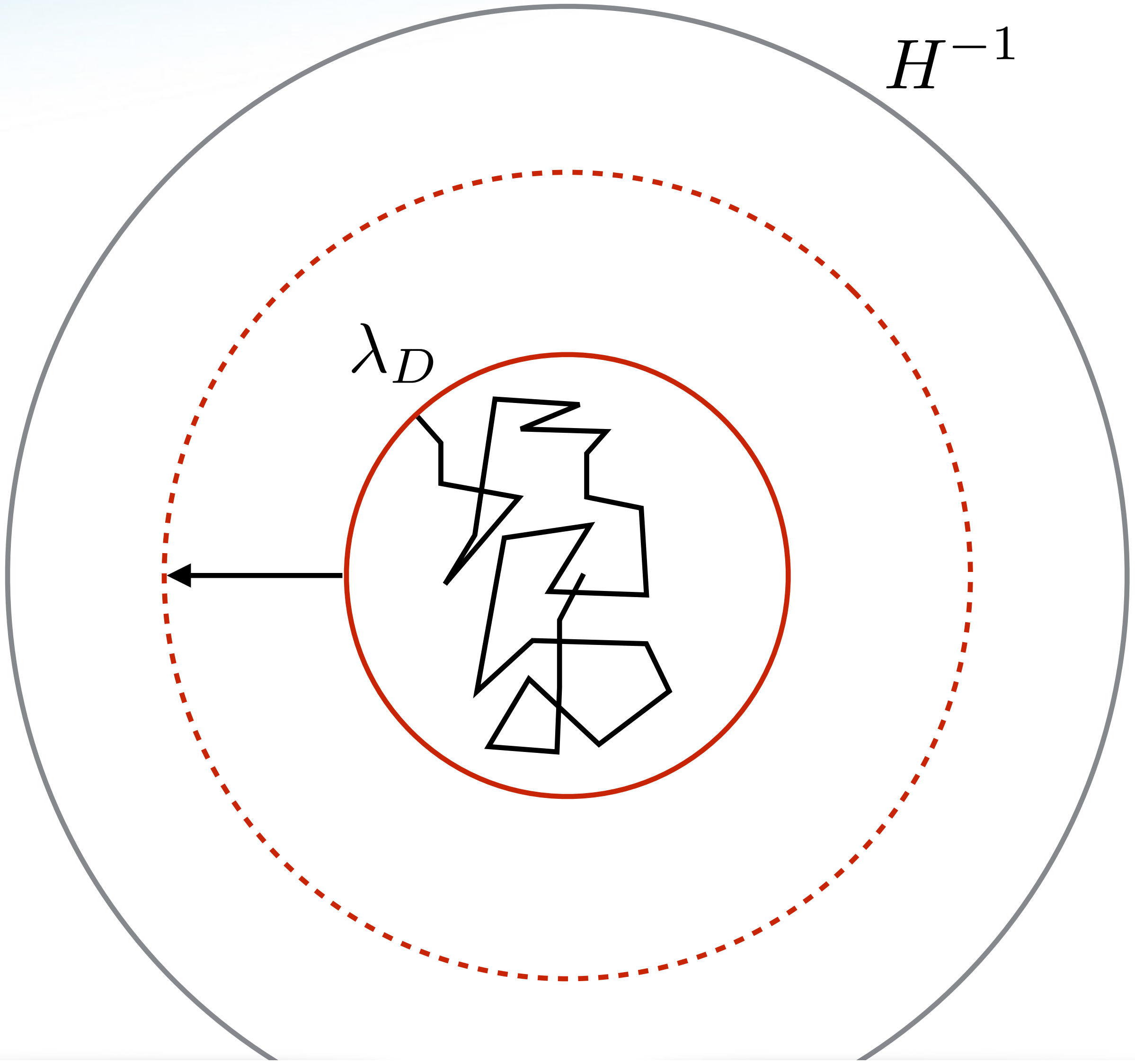




exponential drop in $e^\pm$ during BBN
=> corresponding increase in the photon damping scale

Consequence of damping of acoustic modes?

Particle production!

Consider perturbed photon fluid with $\Theta(t, \mathbf{x}, \hat{n}) = \Delta T/\bar{T}$, $\bar{T} = \langle T \rangle$

Energy and number densities:

$$\rho_\gamma = \left\langle a_B T^4 \right\rangle \simeq a_B \bar{T}^4 \left(1 + 6\left\langle \Theta^2 \right\rangle\right)$$

$$N_\gamma = \left\langle b_B T^3 \right\rangle \simeq b_B \bar{T}^3 \left(1 + 3\left\langle \Theta^2 \right\rangle\right)$$

=> not a blackbody (out of eq.)

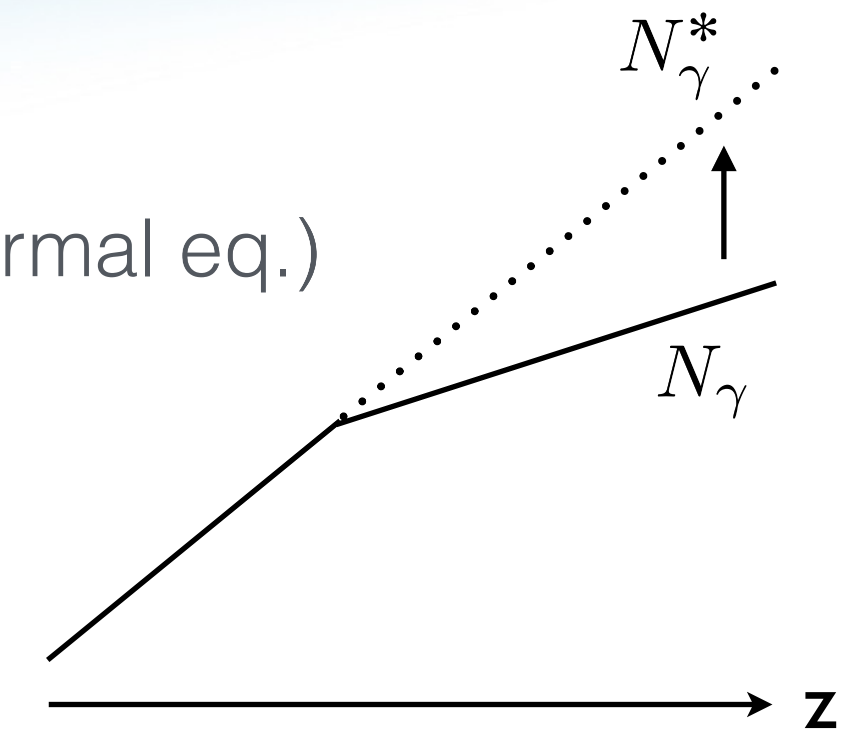
For given energy density there is a momentary lack of photons

$\Delta N_\gamma / N_\gamma \approx (3/2)\left\langle \Theta^2 \right\rangle$ => replenished when perturbations are thermalized (e.g. through double Compton)

Consequence of damping of acoustic modes?

Non-standard evolution of photon number

(and similarly for any relativistic species in thermal eq.)



$$N_\gamma(z) \approx N^*_\gamma(z)\exp\left[-\frac{3C^2}{4}\int_0^z \Delta^2_{\mathcal{R}}(k_D)\frac{\Gamma(k_D)}{H}dz\right]$$

$$\frac{\Gamma(k_D)}{H} \leftarrow \frac{d\ln k_D}{d\ln z}$$

Damping rate (at high-T)

$$\Gamma(k,t) = \frac{2}{3}\frac{k^2}{a^2(\rho+p)}\eta(t)$$

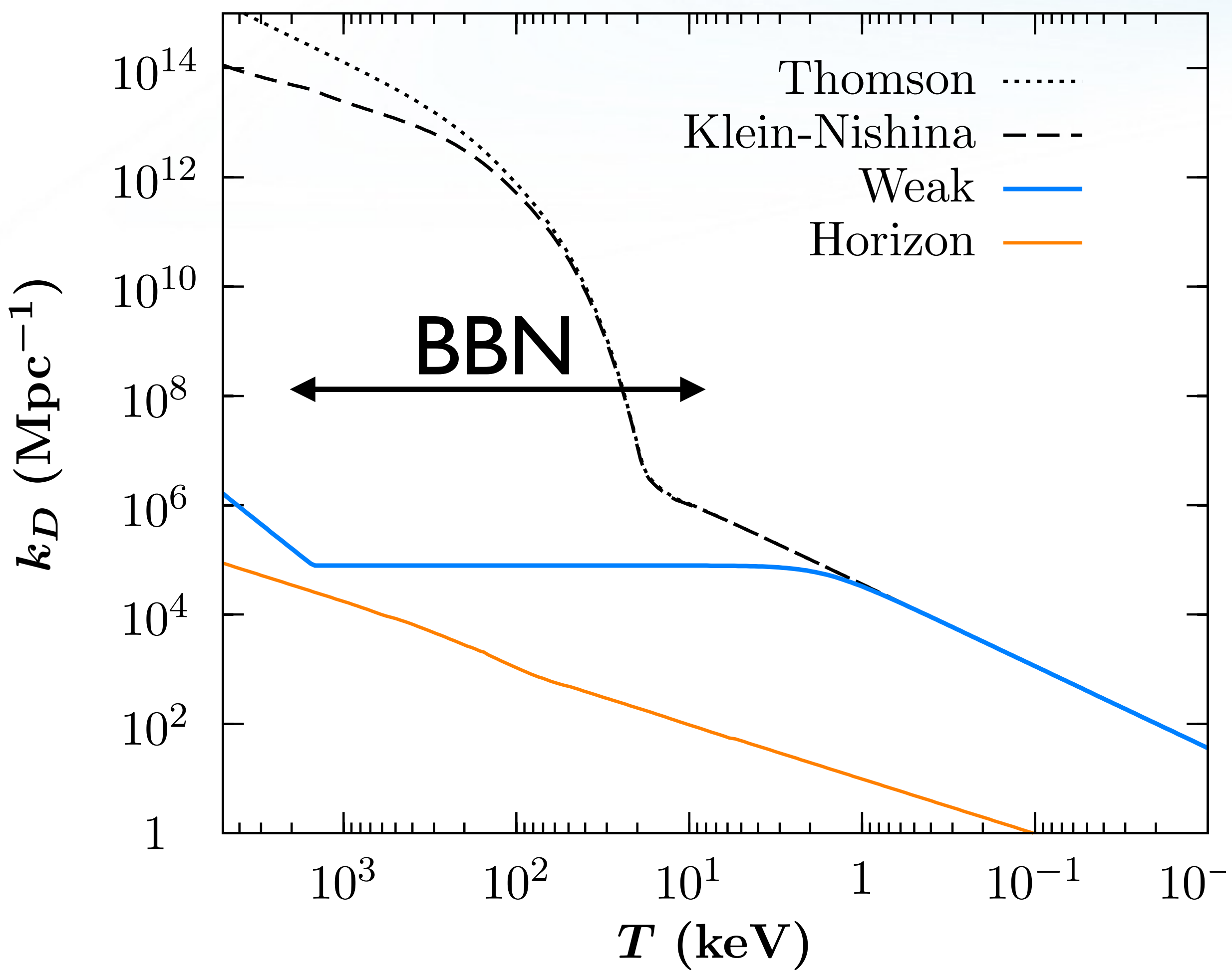
Shear viscosity dissipates waves

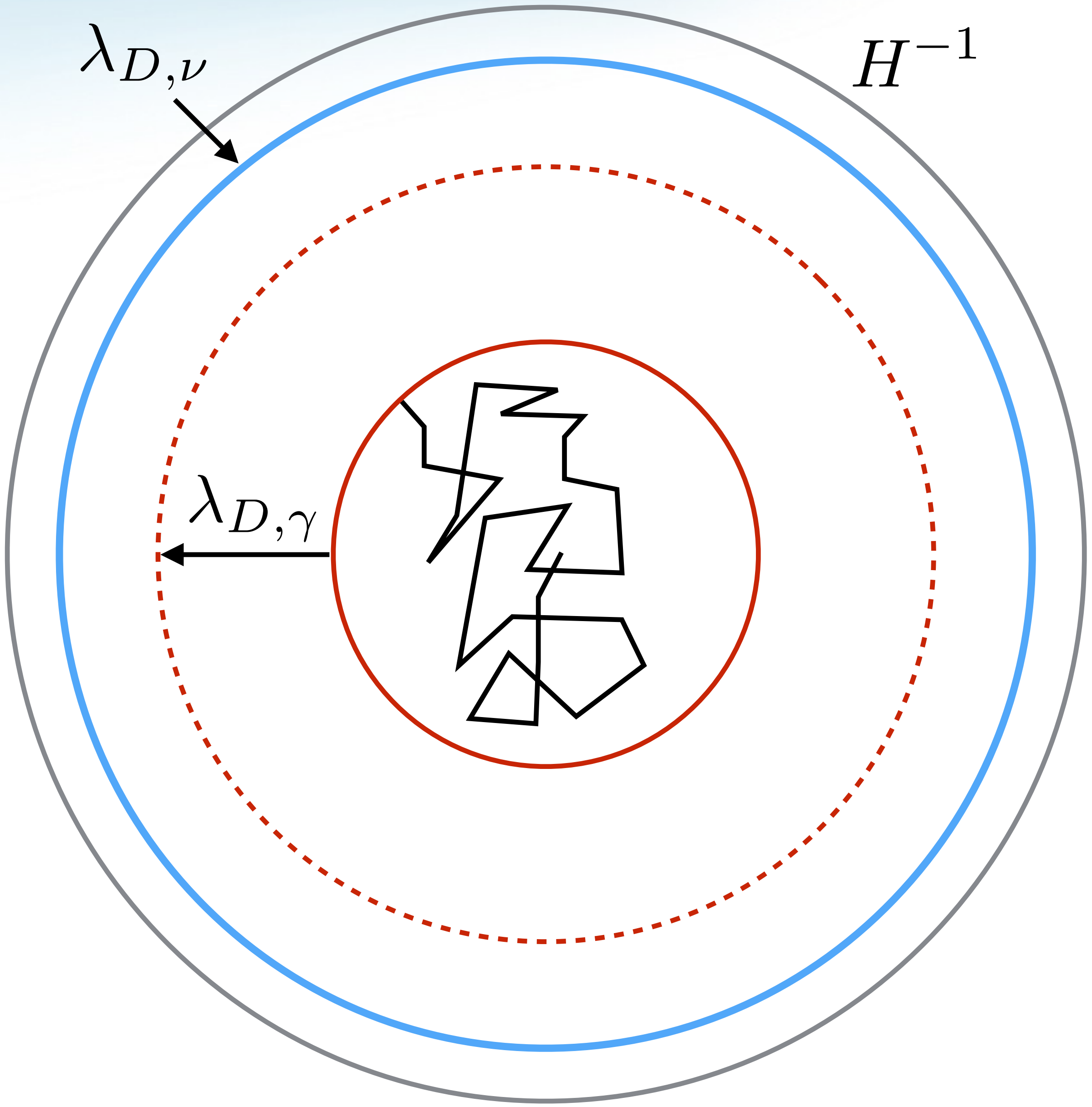
$$\eta = \frac{16}{45}\rho_\gamma t_\gamma + \frac{4}{15}\rho_\nu t_\nu \Theta(T - T_{\nu,\text{dec}})$$

no spectral distortions to CMB are created at T > 0.5 keV (z > 10^6)

=> photon production dilutes Baryon number, affects DM freeze out, changes neutrino/photon number ratio

Diffusion damping - full picture





What really happens:

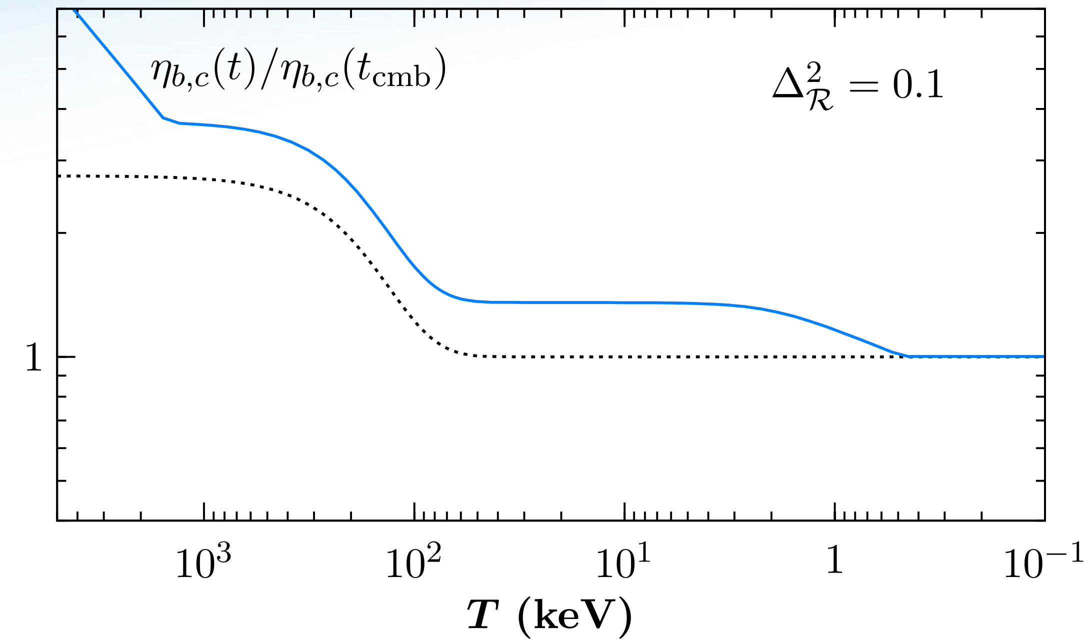
Neutrino diffusion wipes out all acoustic modes that would have dissipated by photon diffusion during BBN

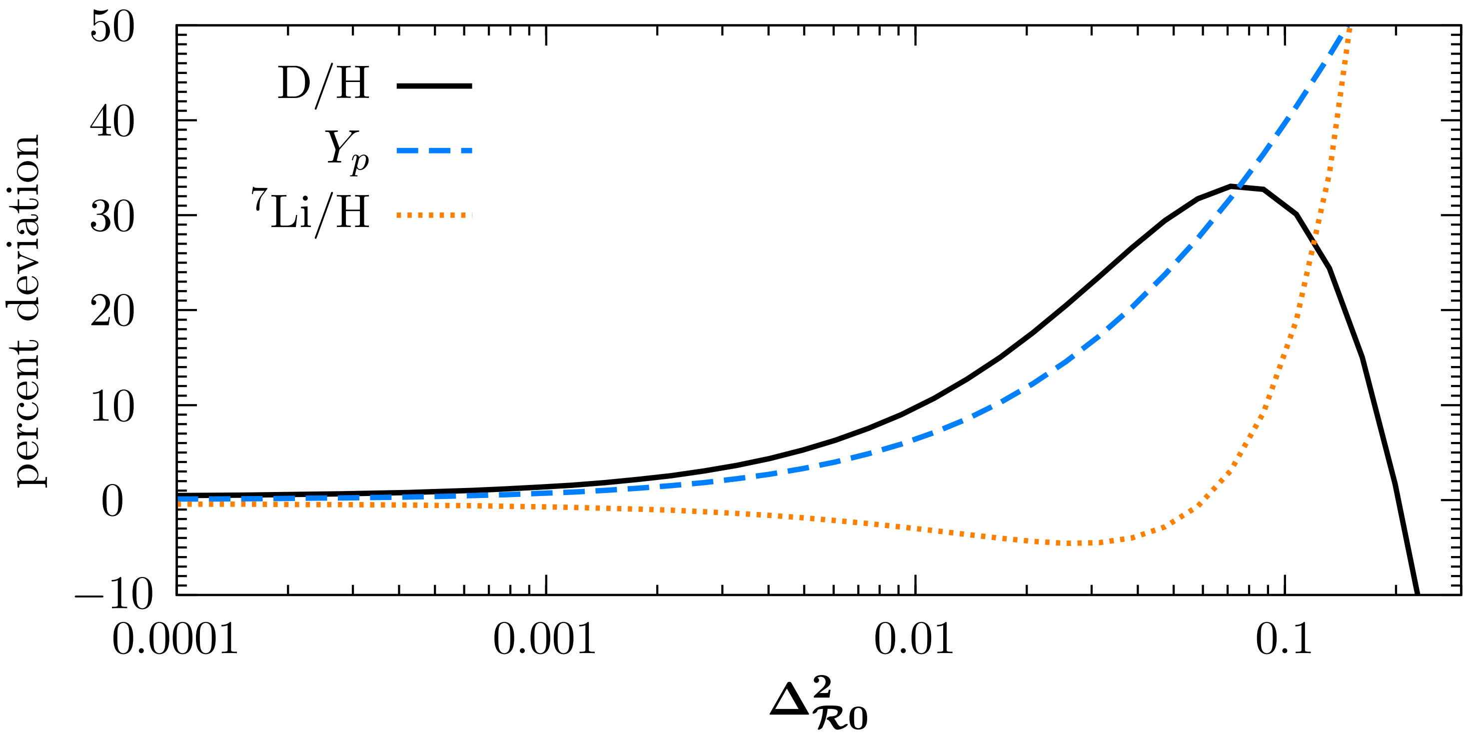
Constraint from BBN

Corrections to BBN come from modes that dissipate *after* BBN (present *during* BBN)

=> elevated baryon asymmetry

=> modified avg. energy/particle





$$Y_p : \Delta^2_{\mathcal{R}0} < 0.007$$

$$({\rm D/H})_p : \Delta^2_{\mathcal{R}0} < 0.2$$

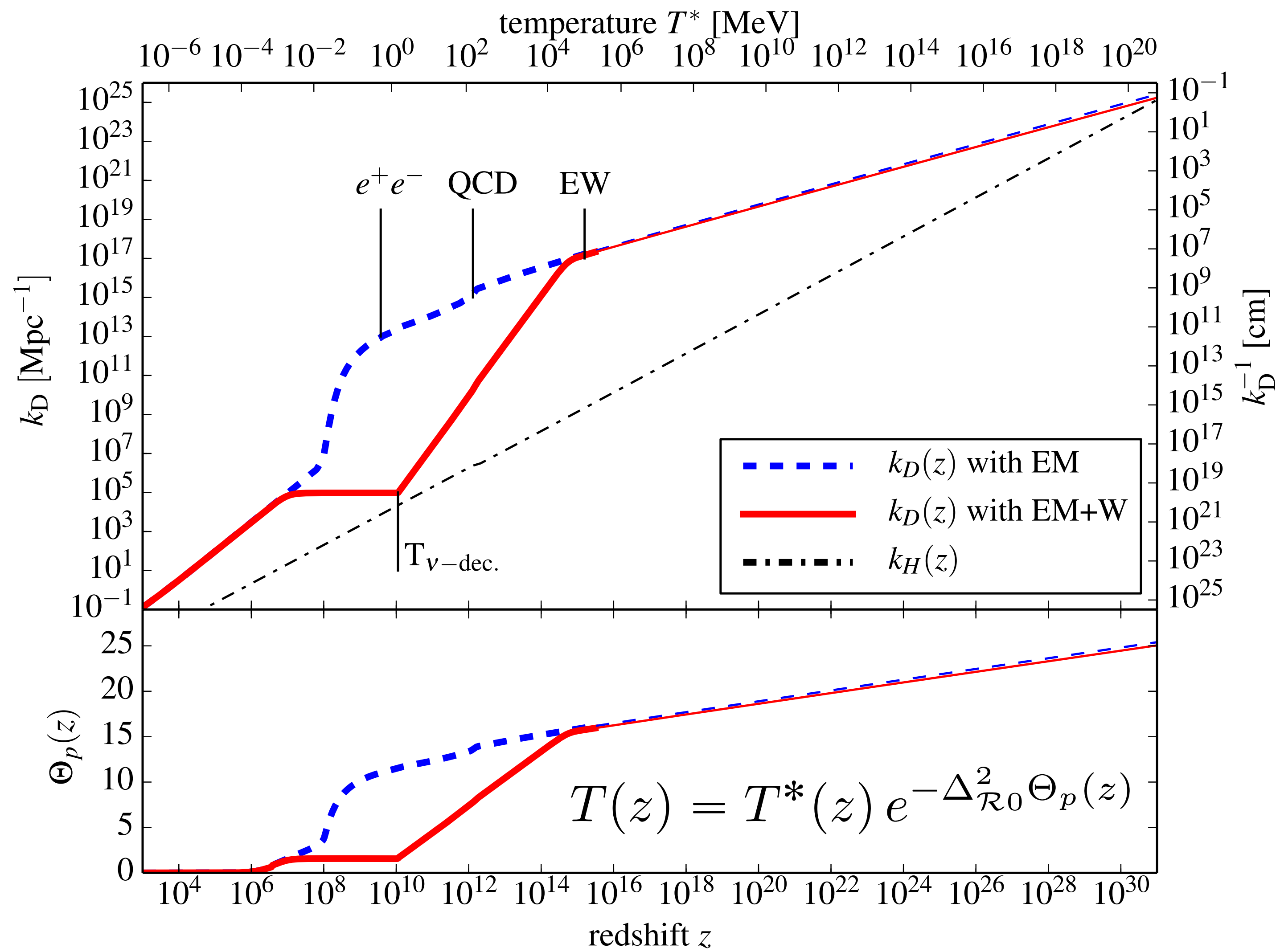
$$10^4\,{\rm Mpc}^{-1} \lesssim k \lesssim 10^5\,{\rm Mpc}^{-1}$$

constraint from *direct* early Universe observable

Diluting particle numbers

Dilution $\frac{\eta_b}{\eta_b^*} = e^{3\Delta^2_{\mathcal{R}0}\Theta_p}$

Extrapolation for SM



If quarks are thermalized, principal bound:

$$(N_B - N_{\bar{B}})/N_\gamma \lesssim \mathcal{O}(1)$$

=> $\Delta^2_{\mathcal{R}0} \lesssim 0.3$

If baryogenesis happens above 1TeV.

Weak bound, but

1. applies on very small scales
2. dilution factor is substantial

Diluting particle numbers

Dark Matter:

For WIMPs the effect can be a factor 2 on the annihilation cross section

But for DM particles with UV-dominated production (e.g. gravitinos) effect can be very large!