Title: Dark forces and alternative BBN scenarios

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Dark forces and alternative BBN scenarios

Maxim Pospelov
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J. Pradler and M.Pospelov, to appear in a few days

University of Victoria | British Columbia Canada

Outline of the talk

1. Introduction and Motivation. New look at GeV scale phenomenology.
2. BBN redux. ^{7}Li is "over-predicted".
3. Decay of GeV scale particles: injection of pions, kaons, muons etc. Easy to fix Li with lifetimes 200-10000 seconds
4. WIMP model realisations: Secluded U(1) with metastable Higgses.
5. Super-WIMP realisations.
6. Conclusions.

"Revival" of new physics at (sub)-GeV scale

1. May help to solve some puzzles in low energy data

   (discrepancy in g-2 of muon, HyperCP events, possibly anomalous events in "neutrino factories")
2. May lead to novel phenomena if used as mediators between WIMP dark matter and Standard Model. (In particular can explain PAMELA and FGST excess of lepton cosmic rays, Arkani-Hamed et al. 2008, MP and Ritz 2008)
3. Could be searched for at the "luminosity frontier" : e.g. colliders, fixed targets etc.
4. Have some natural field theory realizations: kinetically mixed U(1) – (Holdom 1986); GeV-scale RH neutrinos, singlet scalars...

In this talk, I will investigate influence of metastable GeV scale particles on the outcome of primordial nucleosynthesis.

Indirect astrophysical signatures of secluded DM

Secluded DM – WIMPs connected to SM via metastable, possibly light mediator particles V. 2DM $\rightarrow$ 2V $\rightarrow$ 4 leptons

If m_V is under GeV, the following consequences are generic

(Arkani-Hamed et al, Oct 2008, Pospelov and Ritz, Oct 2008)

1. Annihilation products are dominated by electrons and positrons
2. Antiprotons are absent and monochromatic photon fraction is suppressed
3. The rate of annihilation in the galaxy, $\sigma_{\rm ann}$ v, is enhanced relative to the cosmological $\sigma_{\rm ann}$ v because of the long-range *attractive* V-mediated force in the DM sector.

All this is very topical in light of much discussed PAMELA results.

Possible sources of enhancement of σv over cosmological values (MP and Ritz, 2008)

- Accidental near-threshold resonances
- Sommerfeld factor $\pi\alpha/\mathrm{v}$ (if $m_V^{-1} > \lambda_{\text{de Broglie}}$) – typically not enough (e.g. Feng et al)
- Radiative capture into WIMP-onium, (if $m_V < (\alpha')^2 m_\psi/4$)

Cross section for DM+DM -> (DMDM) + V is given by

$$\sigma v|^{+-}_{\mathrm{rec}} = \frac{2^{10}\pi^2(\alpha')^2}{3\exp(4)m^2_{\psi(\phi)}}\left(\frac{v_V(3-v_V^2)}{2}\right)\left\langle\frac{\alpha'}{v}\right\rangle_h$$

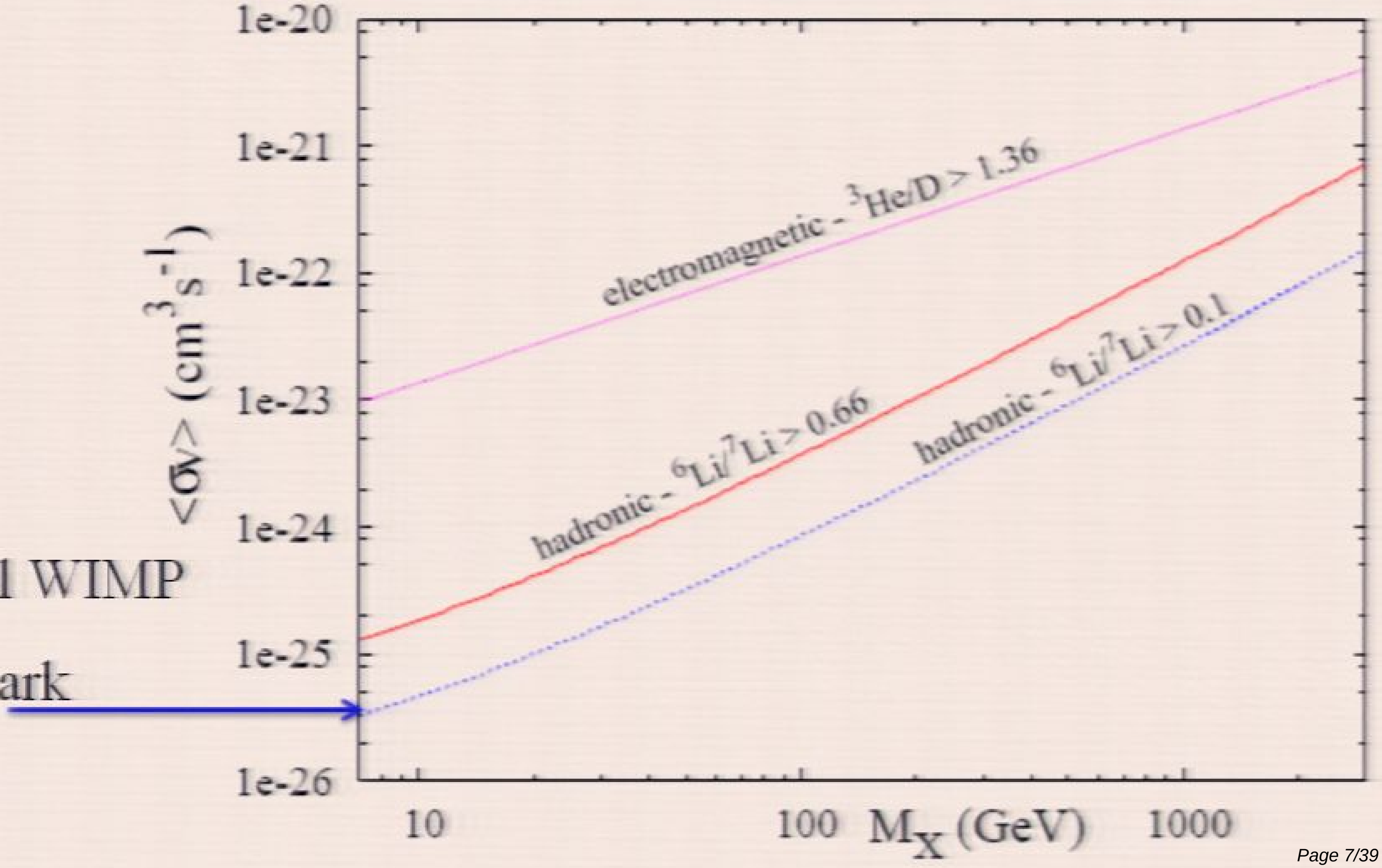
Enhancement factor constitutes

$$N^\psi \simeq 20\left\langle\frac{\alpha'}{v}\right\rangle$$

This is exactly a factor of 100-1000 “needed” for WIMP interpretation of Pamela signal

BBN with energy injection

annihilating dark matter



Thermal WIMP

benchmark

Burning of ^{7}Be using deuterium

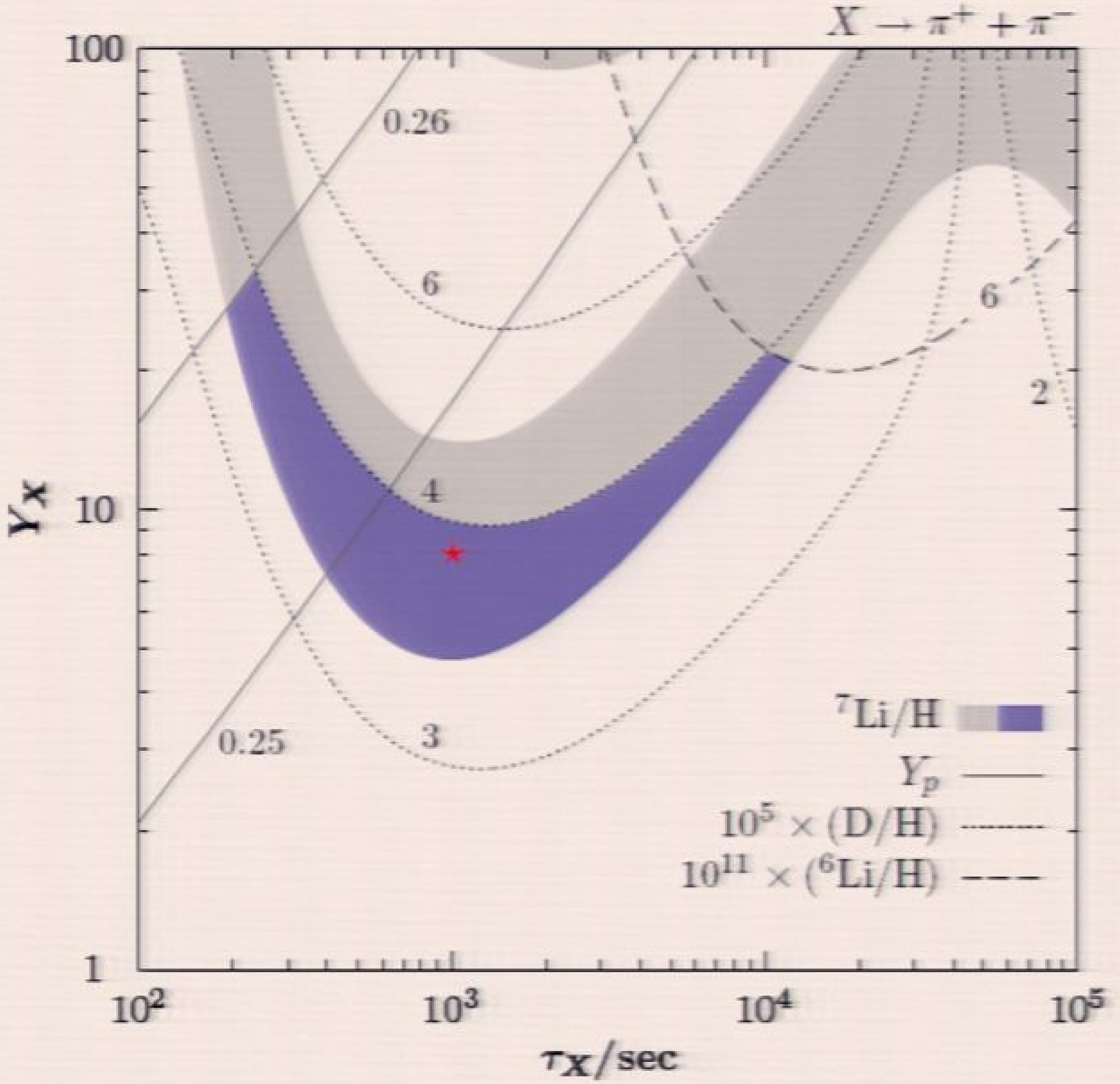
It has been suggested (Coc et al., 2004) that if the reaction rate of ^{7}Be(d,p)$\alpha\alpha$ is arbitrarily increased by a factor of ~ 100, the lithium problem can be "solved" right during the BBN.

Subsequent experimental search (Angulo et al., 2005) have shown no enhancement in this reaction.

It is important, however, that the search was made at E~400 keV, and the extrapolation to BBN regime was done *assuming* smoothness of astrophysical S-factor (cross section).

Such assumptions can be spectacularly violated by the presence of near threshold resonances (e.g. F. Hoyle, 1950s).

^{7}Li reduction from pion injection at threshold



Wide range of lifetimes is suitable (much wider than for EW relics)

Non-equilibrium BBN: synthesis of A=6,9,10 elements in secondary and tertiary collisions

- *Secondary processes*: Hadronic energy injection leads to spallation on ^{4}He, creating energetic A=3 nuclei. A=6 will form:

$$^3\mathrm{H} + {}^4\mathrm{He} \to {}^6\mathrm{Li} + n, \quad Q = -4.78\mathrm{MeV};$$

$$^3\mathrm{He} + {}^4\mathrm{He} \to {}^6\mathrm{Li} + p, \quad Q = -4.02\mathrm{MeV};$$

$$^3\mathrm{H} + {}^4\mathrm{He} \to {}^6\mathrm{He} + p, \quad Q = -7.5\mathrm{MeV},$$

Dimopoulos, Starkman et al., 80s

Below 5 keV, efficiency ~10^{-3}

- *Tertiary processes:* Emerging ^{6}He and ^{6}Li are energetic and will further collide with ^{4}He in the plasma forming ^{9}Be with similar efficiency, MP Pradler 2010.

$$^6\mathrm{Li} + {}^4\mathrm{He} \to {}^9\mathrm{Be} + p, \quad Q = -2.13\mathrm{MeV}$$

$$^6\mathrm{He} + {}^4\mathrm{He} \to {}^9\mathrm{Be} + n, \quad Q = 0.60\mathrm{MeV}$$

The early time energy injection (T~20 keV) would result in the enhancement of ^{9}Be/^{6}Li.

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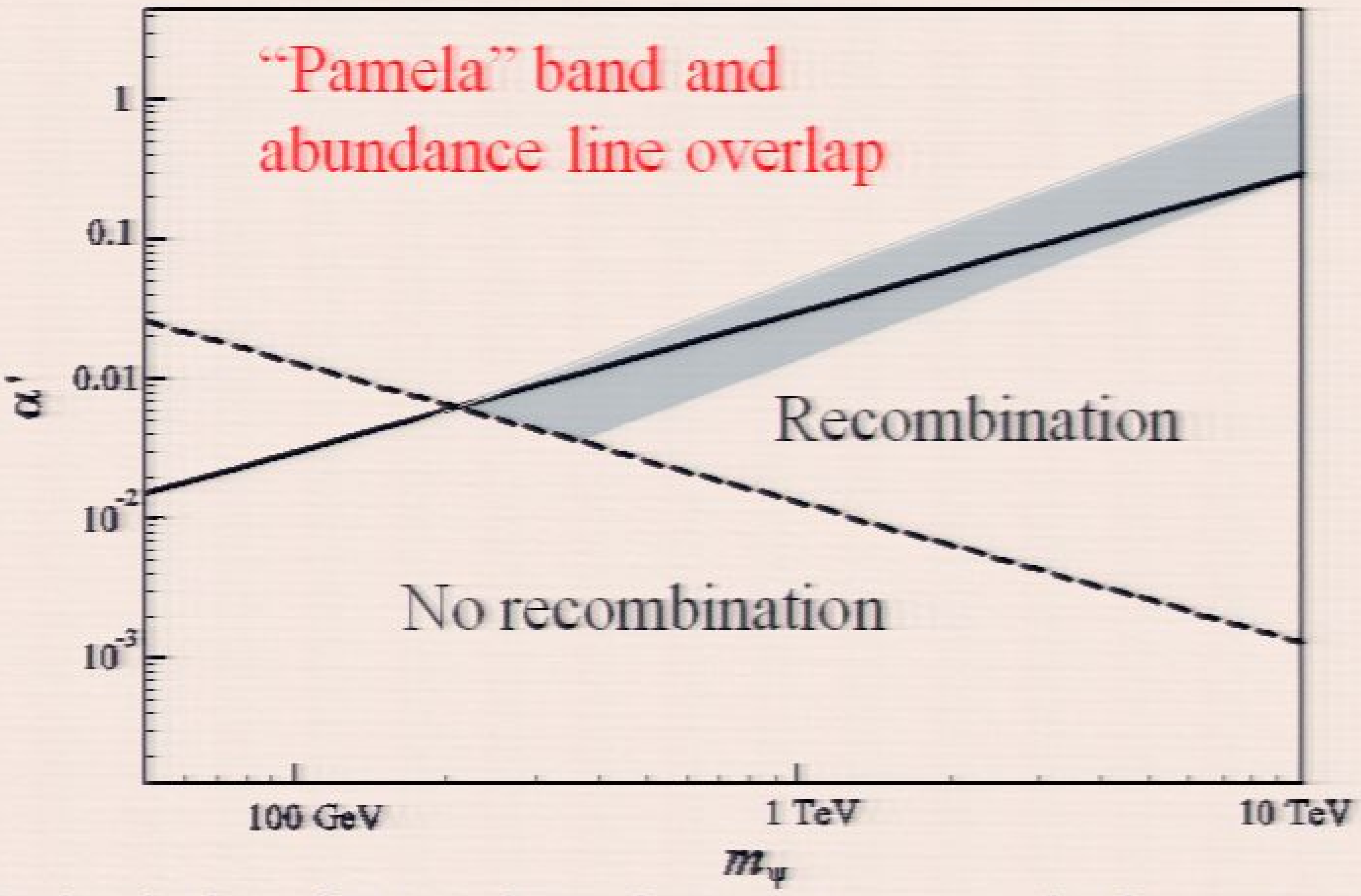
No problem to match PAMELA signal



With the help of V-mediated attraction in dark sector, there is a broad agreement between secluded WIMPs and Pamela signal over a large range of WIMP masses

Models of mediators

Vector portal model: Higgs' can be accidentally long-lived

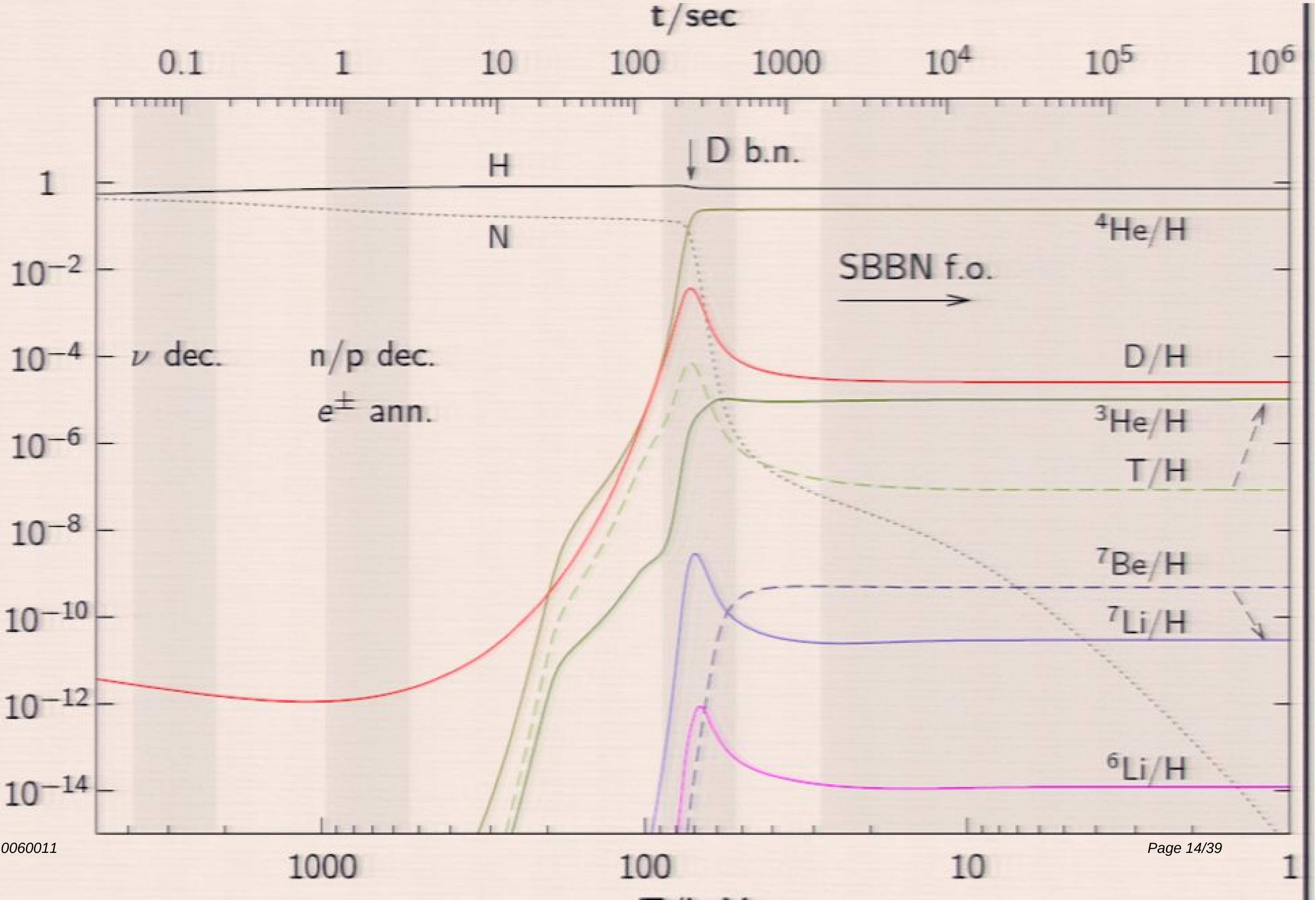
$$\mathcal{L}_{\mathrm{V-portal}} = -\frac{1}{4}V_{\mu\nu}^2 - \frac{\kappa}{2}F_{\mu\nu}^Y V^{\mu\nu} + |D_\mu\phi|^2 - V(\phi),$$

Higgs portal model:

$$\mathcal{L}_{\mathrm{H-portal}} = \frac{1}{2}(\partial_\mu S)^2 - V(S) - (\lambda SS + AS)(H^\dagger H).$$

Given that some of the mediator particles can be rather long-lived, are there any implications for the Big Bang Nucleosynthesis?

BBN abundances at η_{WMAP}



BBN and Particle 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 $n_i =$

Particle physics can

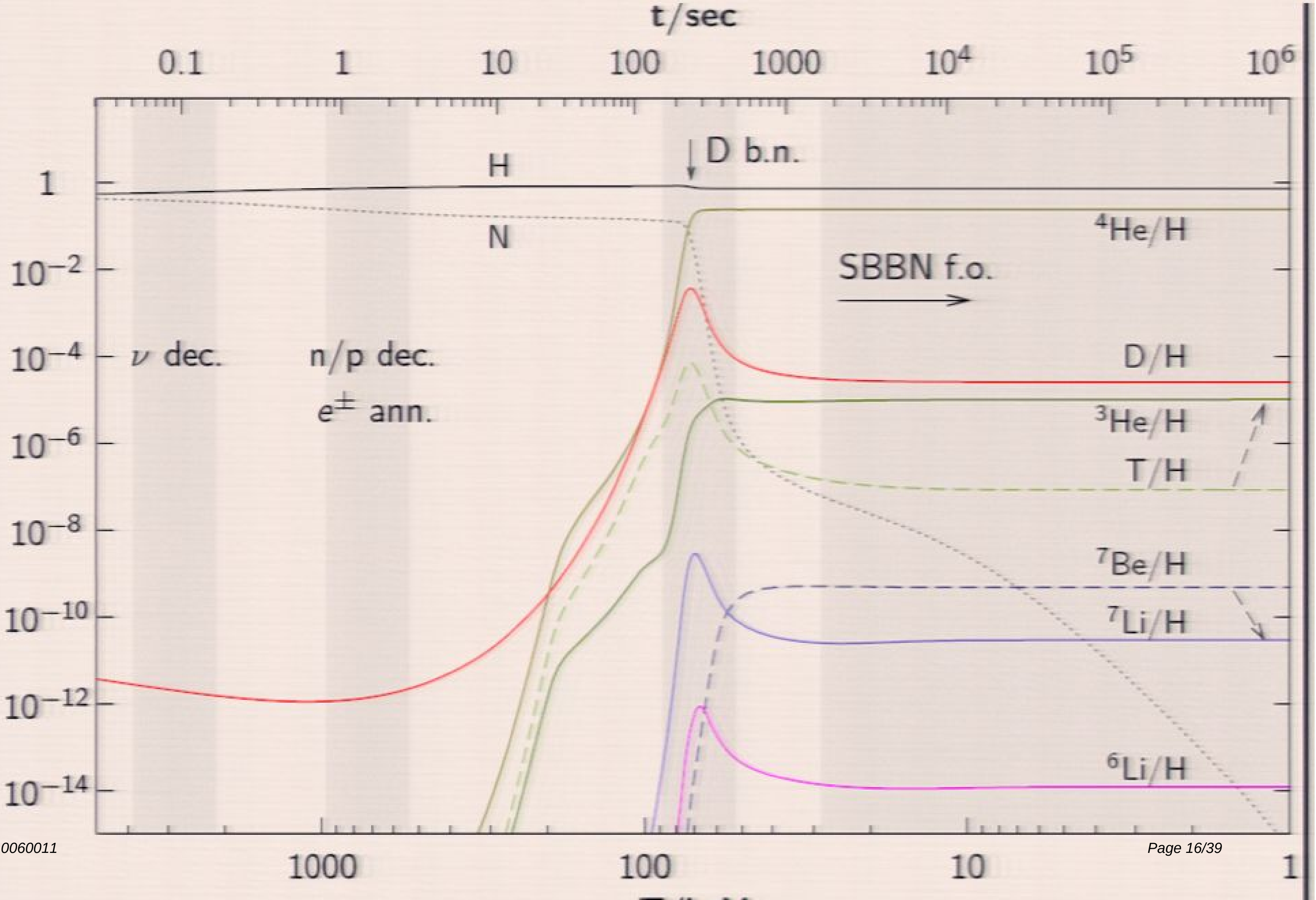
1. Affect the timing of reactions,

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

   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, $\underline{E \gg T}$.
3. Provide catalyzing ingredients that change $\underline{\langle \sigma_{ijk} v \rangle}$ (MP, 2006). Possible catalysts: electroweak scale remnants charged under $U(1)$ or color $SU(3)$ gauge groups. Relevant for charged NLSP-gravitino LSP scenario.

BBN abundances at η_{WMAP}



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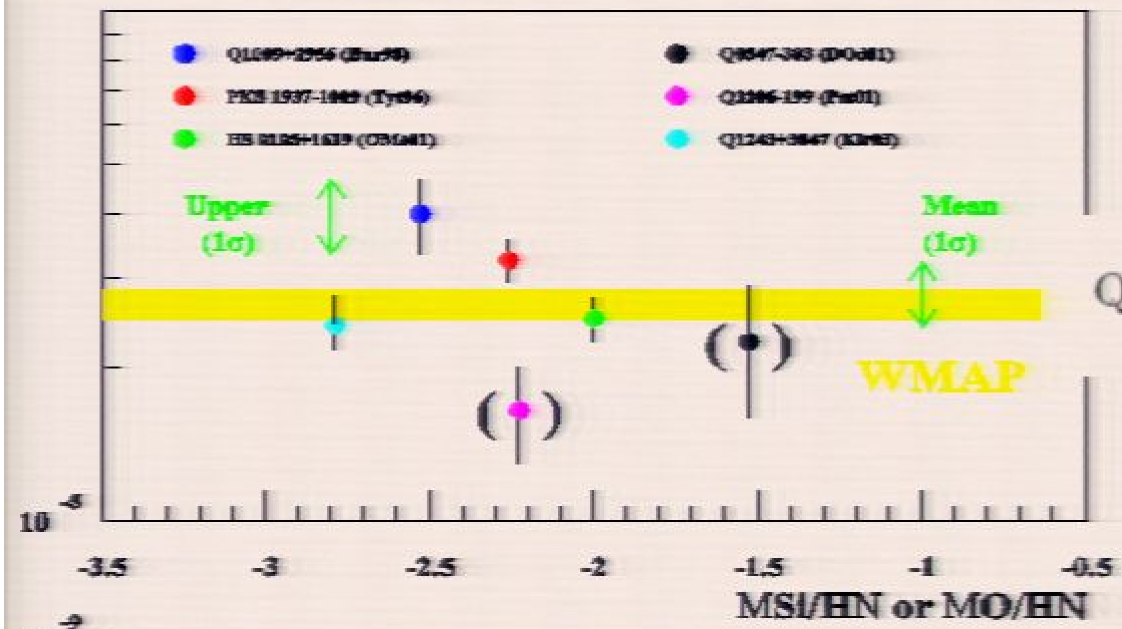
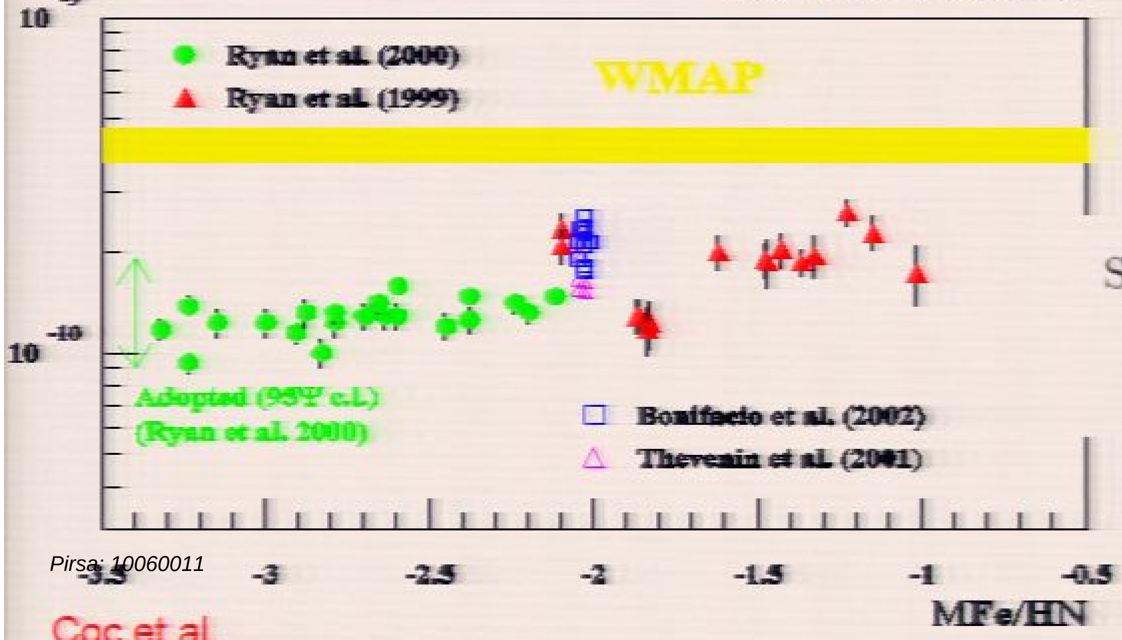
Status of standard BBN with CMB input



SBBN : $D/H = 2.49 \pm 0.17 \times 10^{-5}$

QALS observations : $\frac{D}{H} = (2.82 \pm 0.21) \times 10^{-}$



Spite plateau value : $\frac{^7\mathrm{Li}}{\mathrm{H}} = 1.23^{+0.34}_{-0.16} \times 10^{-}$

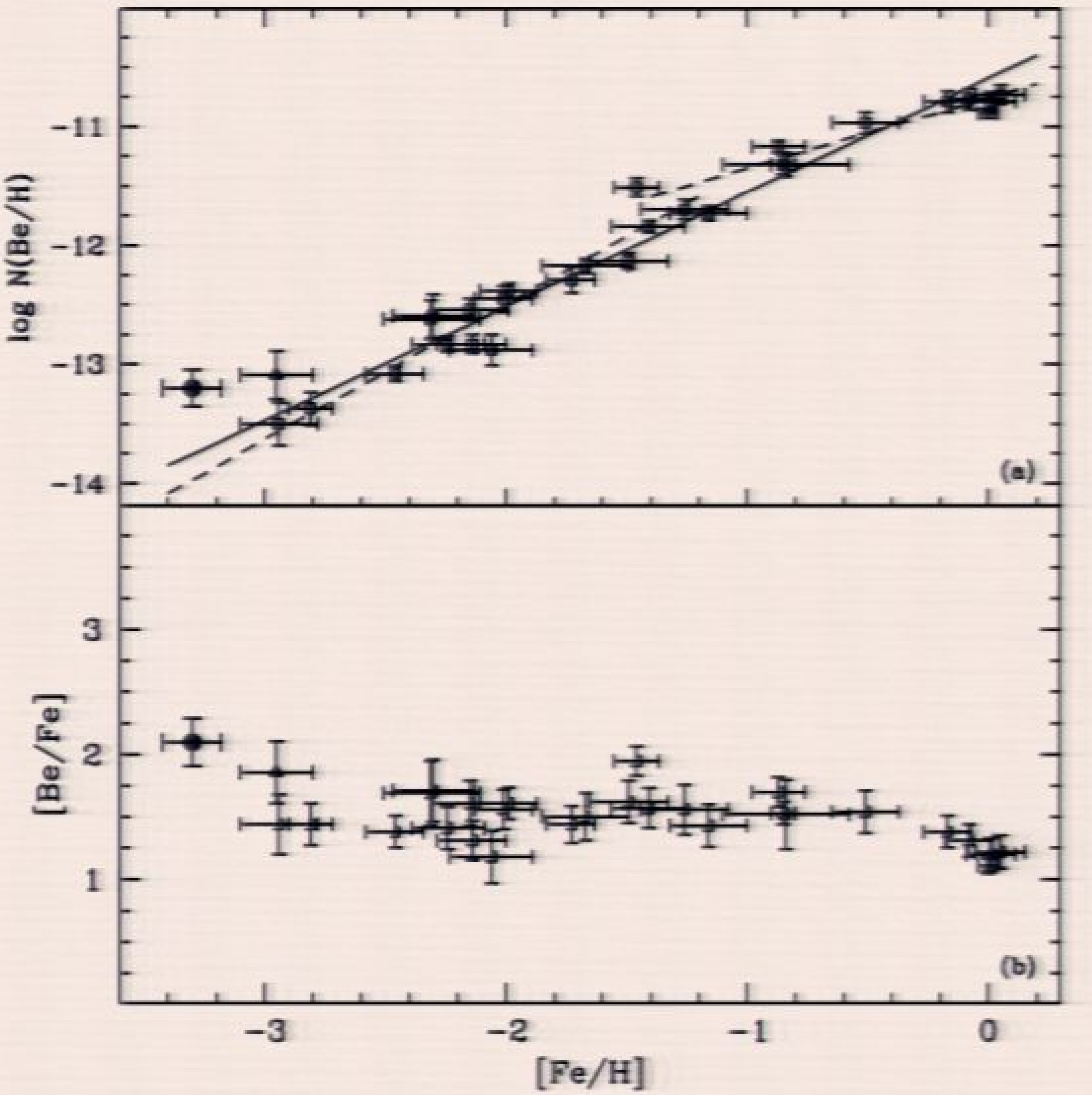
BBN theory : $\frac{^7\mathrm{Li}}{\mathrm{H}} = 5.24^{+0.71}_{-0.67} \times 10^{-}$

“Lithium problem”!!

Coc et al

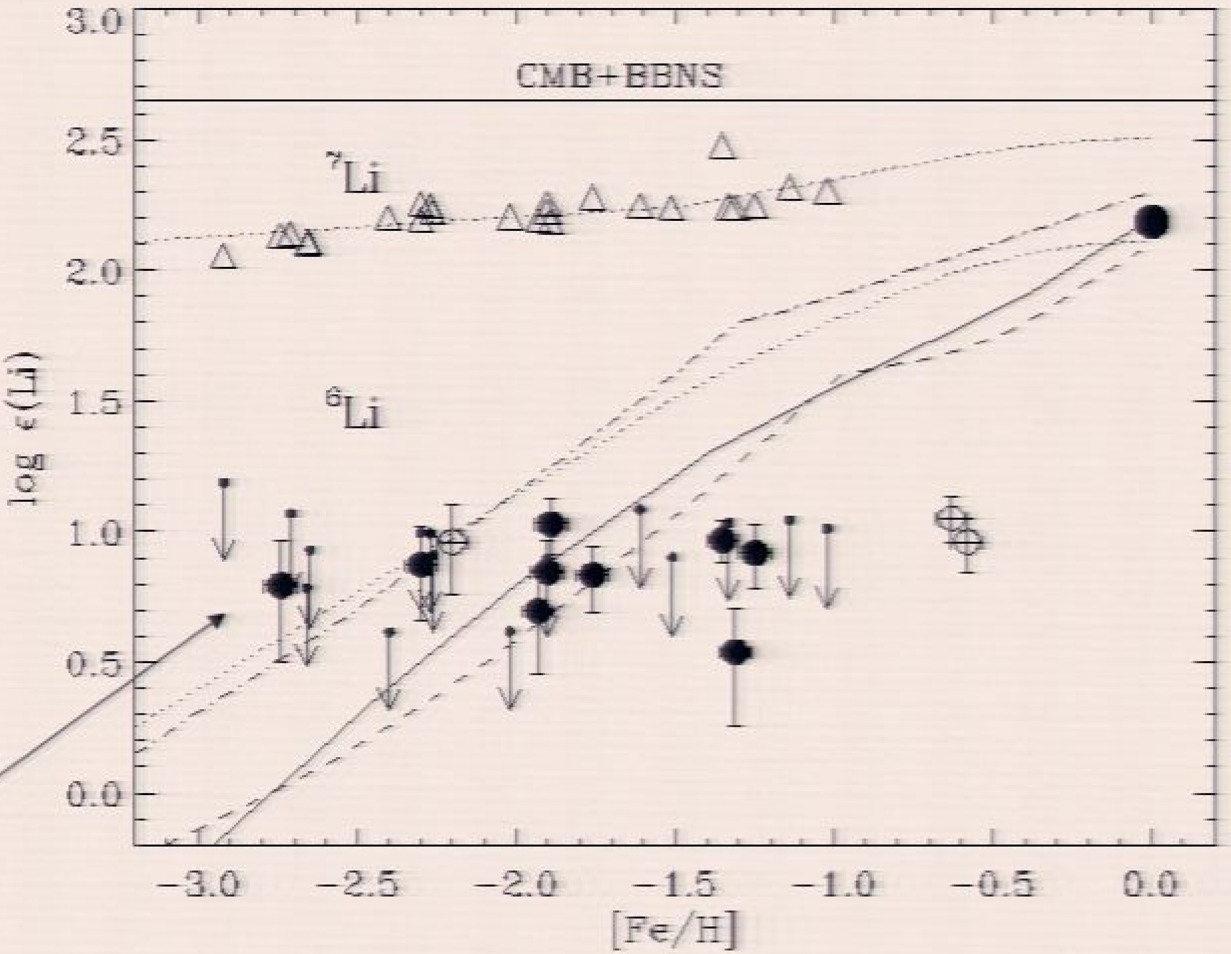
^{9}Be vs metallicity

There is no evidence for primordial plateau



^{6}Li is detected in a handful of stars

A lot of speculations about primordial ^{6}Li!



^{6}Li/H ~ 10^{-11}

Unexpected plateau (?) of ^{6}Li with metallicity (Asplund et al., 2005);

More on ^{7}Li generation during the BBN

In fact, it is ^{7}Li+^{7}Be that we are interested in (much later, ^{7}Be captures an electron and becomes ^{7}Li). Things are simple: *there is one reaction in, and one reaction out*

^{3}He+$\alpha \to {}^7$Be + γ - IN.

^{7}Be +$n \to p$ +^{7}Li – OUT, (followed by ^{7}Li+p $\to 2\alpha$)

At T>25 keV, ^{7}Li is unstable being efficiently burned by protons.

^{4}He, ^{3}He, D, p, and n can be all considered as an input for lithium calculation.

1. ^{3}He and n abundances ? All reactions are too well-known. ^{3}He is indirectly measured by the solar neutrino flux.
2. ^{3}He(α,γ)^{7}Be reaction is now known with better than 10% accuracy.

New ways of destroying ^{7}Be ?

Ways the ^{7}Li problem can be resolved

- *Astrophysical:* Extra depletion of lithium along Spite plateau
- Nuclear: SBBN prediction is somehow not correct (MP, Cyburt: suggestion of a resonant enhancement of ^{7}Be(D,p)^{8}Be reaction. Unlikely last hope…)
- *Cosmological:*

  ^{7}Li is measured locally, while D and baryon-to-photon ratio globally. If baryon density fluctuates on sub-horison to CMB scales, one could "place" Milky Way in the baryon-underdense region.

  Slight variation in D binding can deplete ^{7}Li (scalar-tensor theories)
- *Particle physics:*

  Decays/annihilations of heavy relics can reduce ^{7}Li.

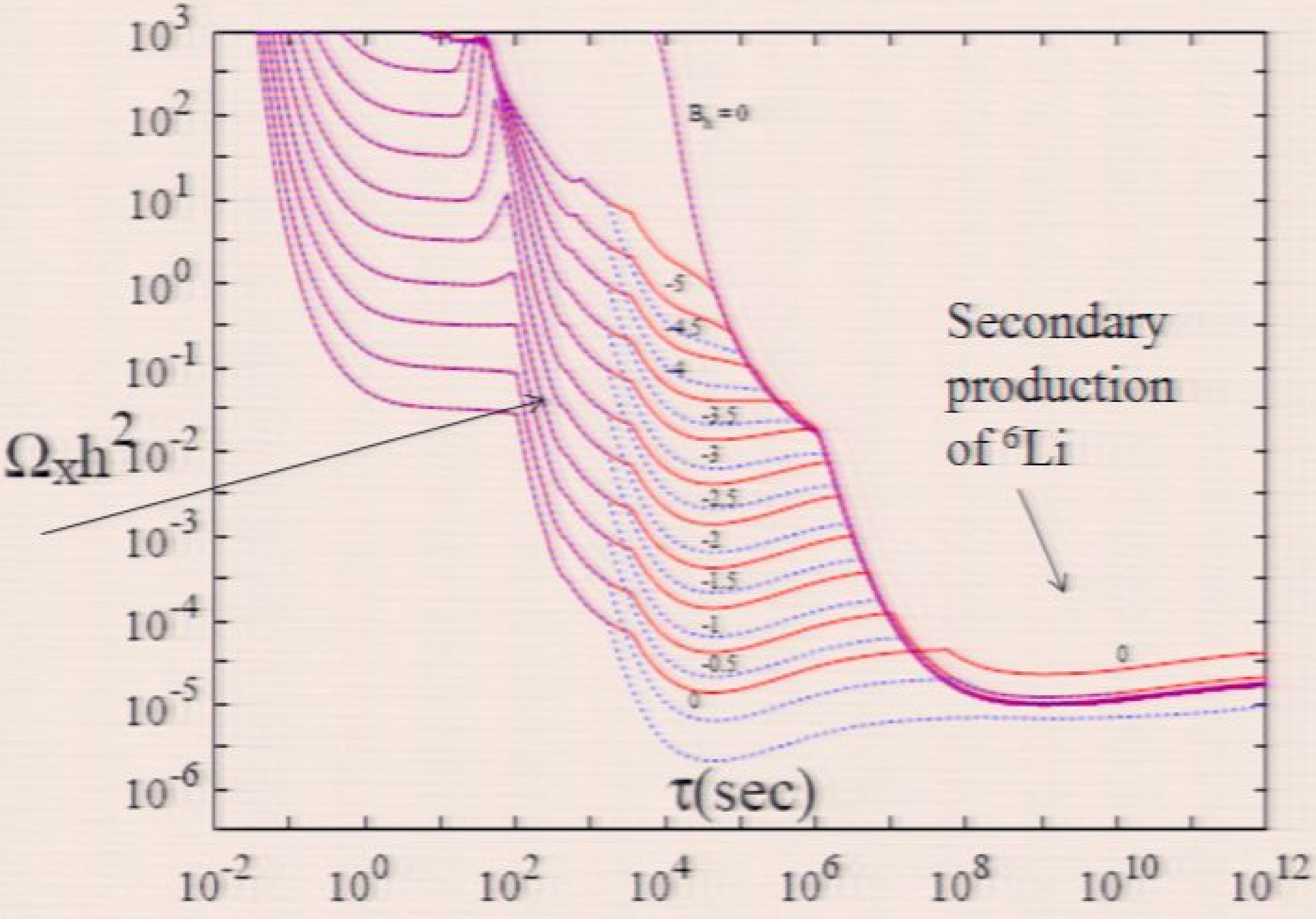
  ^{7}Li can also be destroyed in catalyzed reactions.

BBN with energy injection

Effect of the “baryonic” energy injection

(Dimopoulos et al.; Reno and Seckel, 1980s.)

Neutron-reach
energy injection at
t~500 sec is capable
of reducing ^{7}Li by ~2
(Reno and Seckel
K. Jedamzik).
D/H is higher
About 10^{-5}
extra neutrons need
to be injected to get
an appreciable
reduction of lithium.



Secondary production of ^{6}Li

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What was known:

1. WIMP DM annihilation cannot solve ^{7}Li problem. Not enough neutrons; too much of ^{6}Li is generated as colateral damage.
2. One could "get rid" of ^{7}Li excess using decays of EW scale relics with ~ some baryons/antibaryons in the final states.
3. None of the secluded models with light mediators (e.g. tuned to fit PAMELA) is suitable for that because (anti)-nucleons in the final states are either absent or suppressed.

What we found:

1. If some particles from GeV sector are *metastable* (100-1000s), and decay producing pions/kaons or muons - ^{7}Li can be suppressed while other BBN predictions are not worsened.
2. There are different classes of models that *easily* fit this requirement. Including the most popular "light U(1)" of Holdom-type.

General picture

We assume some (sub)-GeV scale neutral relics X with appropriate lifetime (that cannot decay to nucleons) and consider

$X \rightarrow \pi+\pi-$

$X \rightarrow K^+, K^-$ and K_L, K_S

X → Muons → electron antineutrinos

Main calculation : meson-induced p → n conversion with ensuing change to the BBN network. (Requires proper treatment of EM stopping of particles, meson-nucleon and meson-helium reactions at-rest and in-flight (delta resonance!), spectrum of energetic A=3 nuclei etc. Overall, not an easy problem.)

How many pions, kaons etc and with what injection rates (determined by lifetime of X) are required in order to ensure ^{7}Li in the interval $(1\text{--}2.5) \times 10^{-10}$?

Estimates of p→ n efficiency

How many pions do we need ? = what is the probability of producing a neutron within pion lifetime?

Proton capture rate by π^-

$$\Gamma_p^\pi = n_p \langle \sigma v \rangle_{pn}^\pi \simeq (3 \times 10^2 \ \mathrm{s}^{-1}) \ \frac{T_9^3 \langle \sigma v \rangle_{pn}}{1 \ \mathrm{mb}}.$$

Probability is small

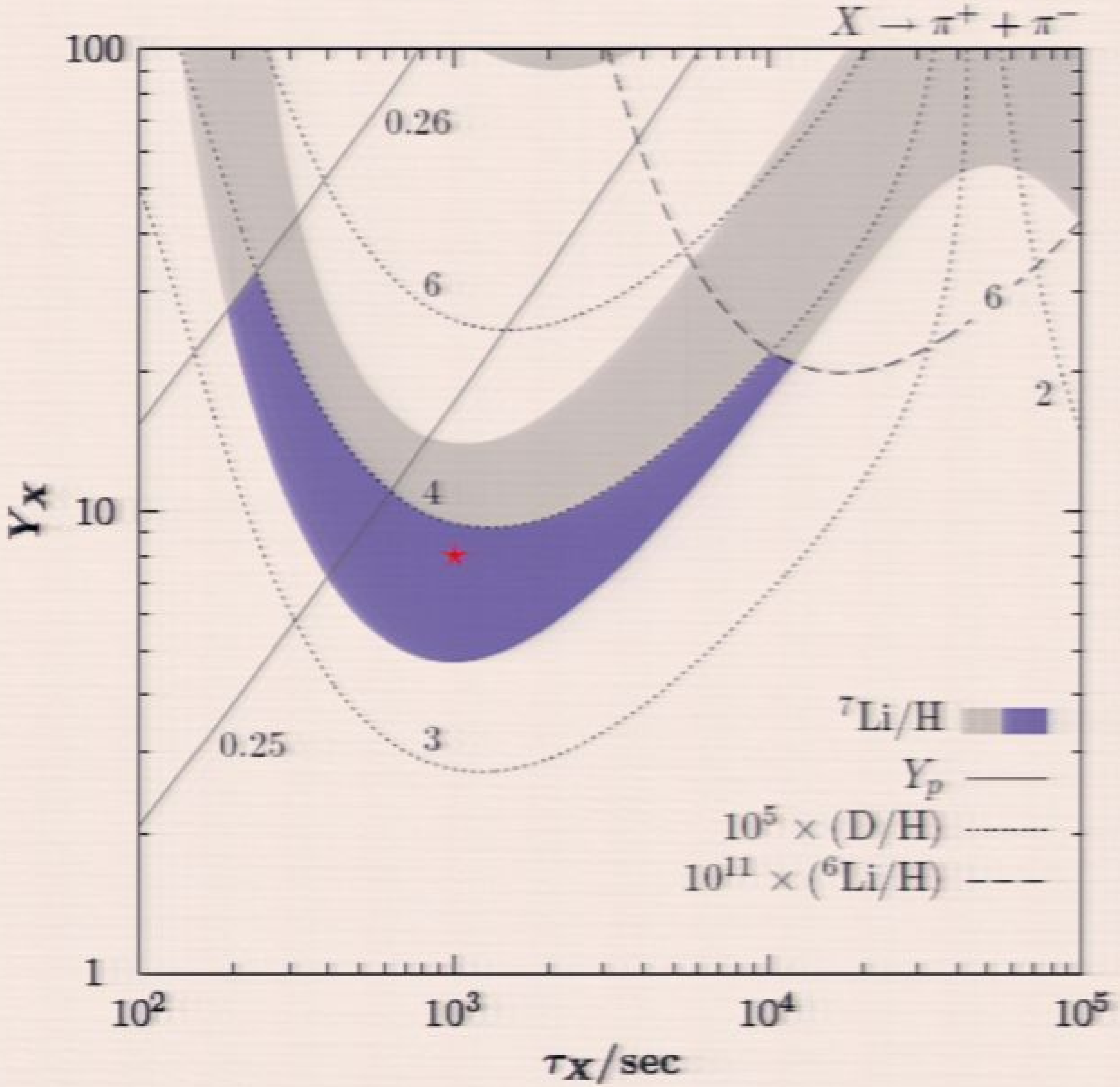
$$P_{p\to n}^\pi = \int_{t_{\mathrm{inj}}}^{\infty} \exp(-\Gamma_{\mathrm{dec}}(t - t_{\mathrm{inj}}))\Gamma_p dt \simeq \Gamma_p^\pi \tau_{\pi^\pm} \sim O(10^{-6})$$

But not too small, given that we need 10^{-5} extra neutrons per proton.

Therefore about ~10 pions per proton injected around T=40 keV will do the job.

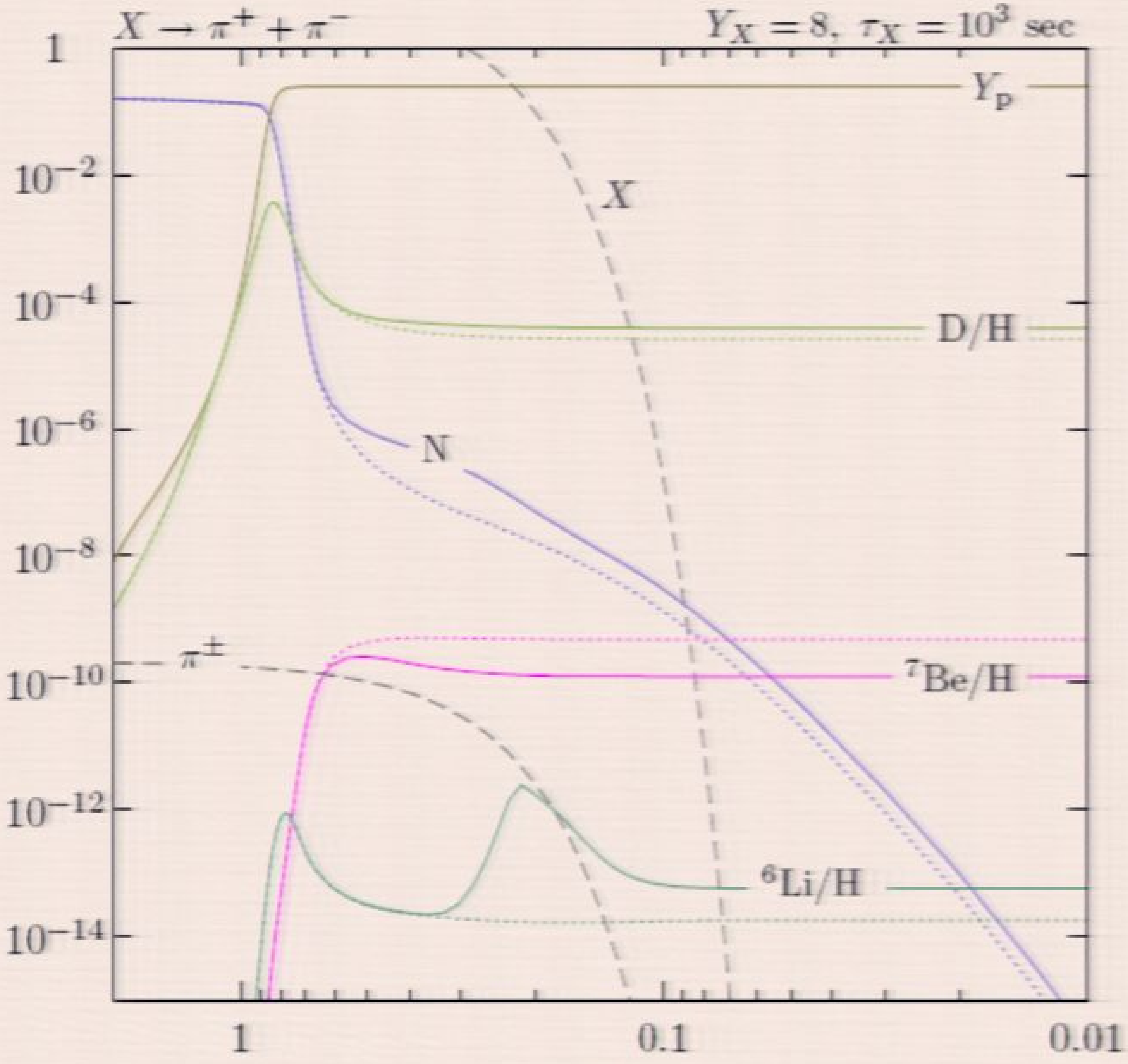
Kaon case is similar. O(1) K- per proton is enough

^{7}Li reduction from pion injection at threshold



Wide range of lifetimes is suitable (much wider than for EW relics)

Time evolution of abundances in πBBN



μBBN or νBBN

How many muons (source of antineutrinos) do we need?

Rate for proton-induced conversion of neutrino to neutron is smaller

$$\Gamma_p^\nu = n_p \sigma_{pn}^{\bar{\nu}} \simeq 10^{-41}\ \mathrm{cm}^2 \times \frac{n_p E_\nu^2}{(10\ \mathrm{MeV})^2} \simeq (3.6 \times 10^{-12}\ \mathrm{sec}^{-1}) \times \frac{T_9^3 E_\nu^2}{(10\ \mathrm{MeV})^2}$$

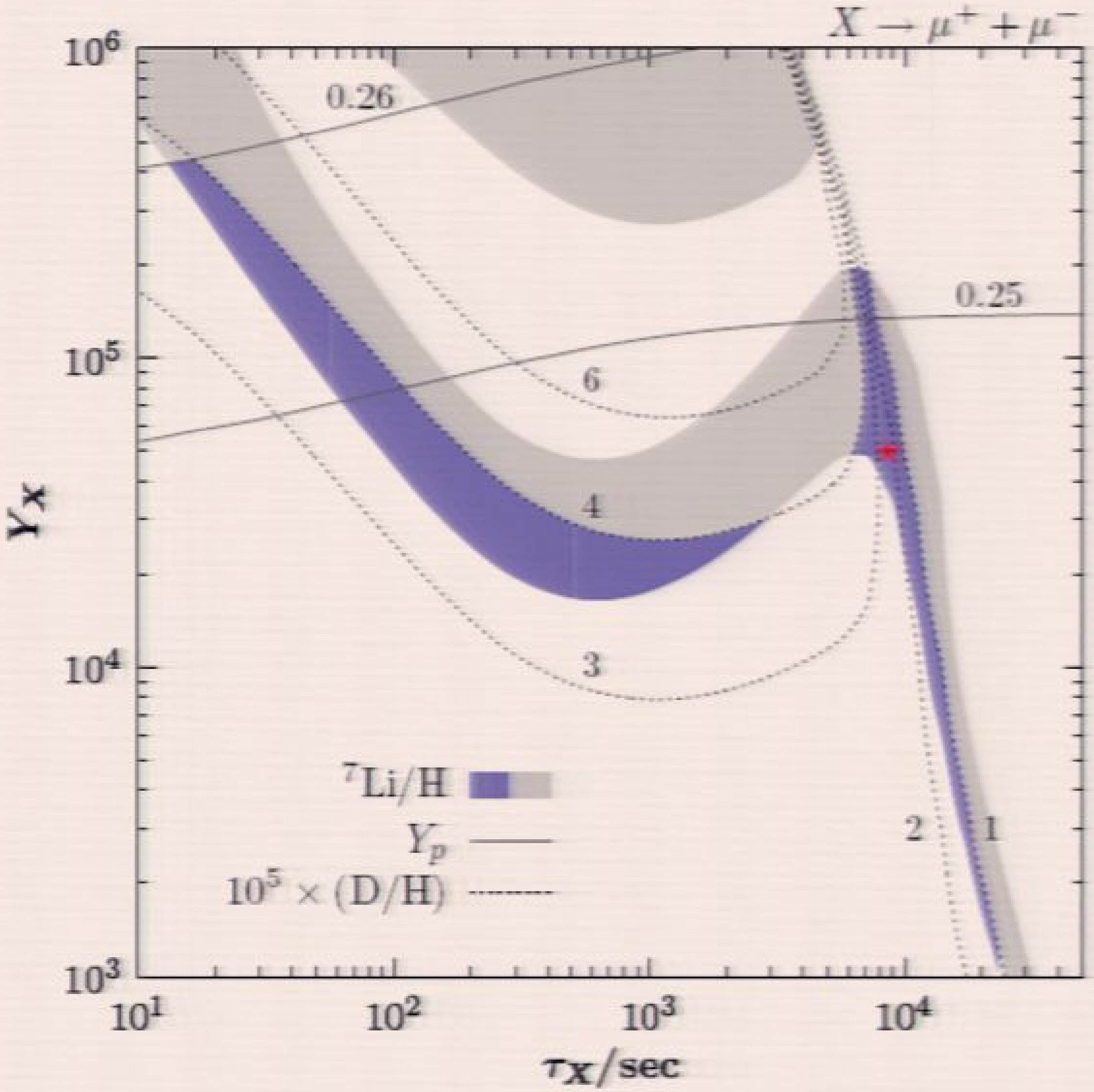
than Hubble rate by about nine orders of magnitude

$$P_{p\to n}^\nu = \int_{t_{\mathrm{inj}}}^\infty \Gamma_p^\nu dt = \frac{1}{3}\frac{\Gamma_p^\nu(T_{\mathrm{inj}})}{H(T_{\mathrm{inj}})} \sim 2 \times 10^{-9}$$

O(10^4) muons per proton is required.

“Easy to arrange”

μBBN or νBBN



Extra region at lifetime ~3hr. Energy injection corrects D/H back to SBB

Model Connections

Two types:

"WIMPs" – initially very abundant (e.g. as photons) – then deplete themselves at T~m, and in our case decay after 100-10^4 sec.

"super-WIMPs" – initially not present at all – get generated by thermal leakage of SM, then decay.

Vector portal model: ← will be considered in this talk

$$\mathcal{L}_{\mathrm{V-portal}} = -\frac{1}{4}V_{\mu\nu}^2 - \frac{\kappa}{2}F_{\mu\nu}^Y V^{\mu\nu} + |D_\mu \phi|^2 - V(\phi),$$

Higgs portal model:

$$\mathcal{L}_{\mathrm{H-portal}} = \frac{1}{2}(\partial_\mu S)^2 - V(S) - (\lambda SS + AS)(H^\dagger H).$$

WIMP or Super-WIMP depends on strength of couplings

Vector portal model in WIMP regime

Long-lived particle – Higgs' boson, if $m_{h'} < m_V$ (SUSY mass pattern)
Decay rate ~ (mixing angle)^4.

$$\tau_{h'} \sim (10^3 \div 10^4)\,\mathrm{s} \times \left(\frac{\alpha}{\alpha'}\right)\left(\frac{3.4\times 10^{-5}}{\kappa}\right)^4\left(\frac{250\ \mathrm{MeV}}{m_{h'}}\right)\left(\frac{m_V}{500\ \mathrm{MeV}}\right)^2.$$

In contrast, Vector particle decays in a picosecond.

Perfect candidate – provided that one can somehow reduce its abundance to an acceptable level.

(For a long time I thought that lifetimes > second should be excluded by over-closure of the Universe at the time of the BBN. Not so. I acknowledge a conversation with N. Weiner.)

Cosmological abundance of secluded Higgses

- Initial abundance of h' is thermal. They live ~ 1000 seconds, and cannot annihilate very efficiently. Naively, they should overclose the Universe at ~ 1 second, and such models are ruled out.
- However, "co-decay" processes save the day:

$$\begin{aligned} h' + h' &\to V + V, & \Gamma_1 &\propto (\alpha')^2\kappa^0 \exp(-m_{h'}/T - 2\Delta m/T) \\ h' + V &\to l^+ l^-, & \Gamma_2 &\propto \alpha'\alpha\kappa^2 \exp(-m_{h'}/T - \Delta m/T) \\ h' + l^\pm &\to V + l^\pm, & \Gamma_3 &\propto \alpha'\alpha\kappa^2 \exp(-\Delta m/T), \end{aligned}$$

where $\Delta m = m_V - m_{h'}$. The last process is the most efficient.

- kappa ~ 3 × 10^{-5} is required for the right lifetime range.

$2\,m_\mu < m_h < 2\,m_\pi$ and $m_V = 1.7\,m_h$ solves lithium problem via injection of muons.

$m_h > 2\,m_\pi$ and $m_V = 1.3\,m_h$ solves lithium problem via injection of pions (kaons).

Super-WIMP regime

Take coupling effective coupling constant

$(\kappa)^2\alpha = 10^{-26}$

Then vector lives 1000 sec. Model has almost no free parameters. – And it works!

Vectors do not exist initially, then get thermally produced at the level O(1) per baryon, and then decay after 1000 sec or so.

Straight calculation of abundance (well... assuming massless quarks):

$$Y_V = \frac{s}{n_b}\frac{n_V}{s}\bigg|_f \simeq (1.2 \div 4.9) \times \frac{s}{n_b}\frac{1}{h_{\rm eff}(m_V)}\frac{\Gamma_{V\to e^+e^-}}{H(m_V)} \sim 0.3 \times \left(\frac{10^3\,{\rm s}}{\tau_V}\right)\left(\frac{\rm GeV}{m_V}\right)^2\left(\frac{40}{g_{\rm eff}}\right)^{3/2}$$

M_V ~ 700 MeV reduces lithium rather efficiently because of the large branching to pions and E_π ~ delta resonance.

I see no other probes of this model except BBN... ☺

Conclusions

- Lithium is discrepant by a factor 3-5. Nobody *really* knows why.
- Particle physics looks as an attractive yet speculative possibility of curing Li problem. Injection of not-so-energetic mesons can easily solve the problem, provided that there are at least O(1) exotic GeV scale particles sourcing these mesons.
- Minimalistic models of different kinds can provide such particles.

  In particular, GeV-scale U(1) is a natural candidate because of the accidental longevity of the Higgs'.

And it "works" – correct cosmological abundances can be easily obtained with moderate splitting between h and V.

Lots of other experimental signatures that I have no time to talk

No Signal

VGA-1

No Signal

VGA-1

No Signal

VGA-1