Primordial Nucleosynthesis

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1. Standard Big-Bang Model and Nucleosynthesis

2. Nuclear Physics aspects

3. Beyond the Standard Model(s)

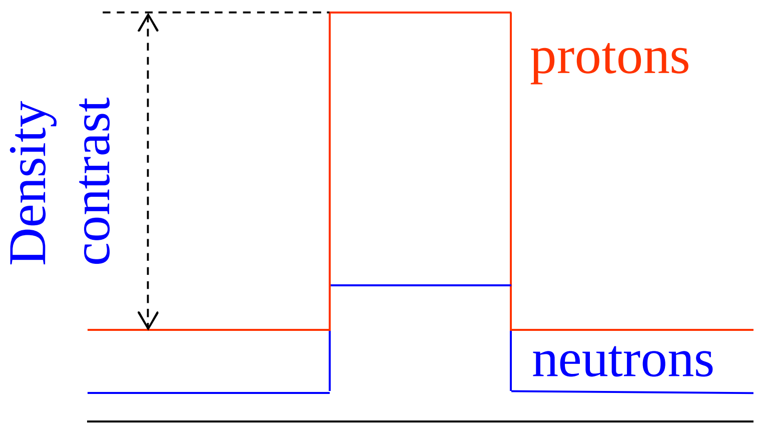
Beyond the Standard Model(s)

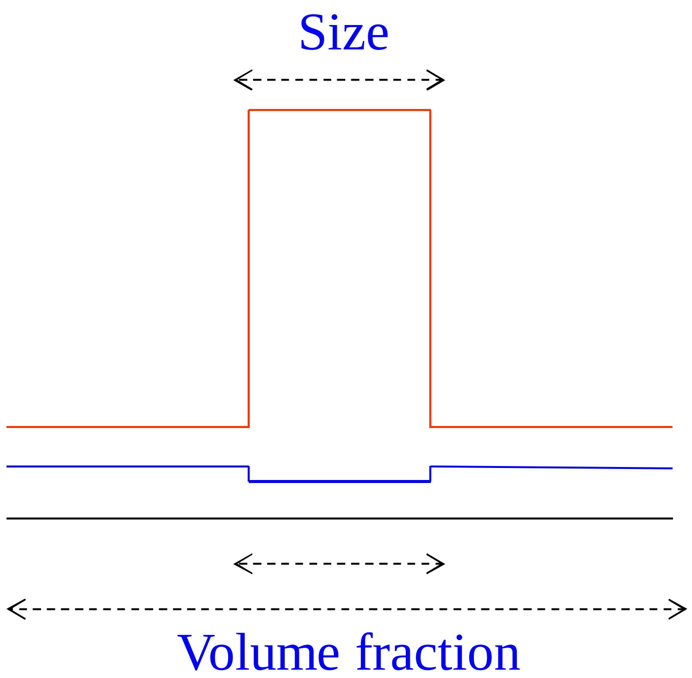
1. Non standard nucleosynthesis (Inhomogeneous BBN, relic particles, mirror neutrons)
2. Non standard expansion (extra Neff, Tensor-Scalar gravity)
3. Variation of constants (in stars, BBN,....)

Inhomogeneous BBN

Popular in the 80's in attempts to obtain $\Omega_B = 1$ (inflation models)

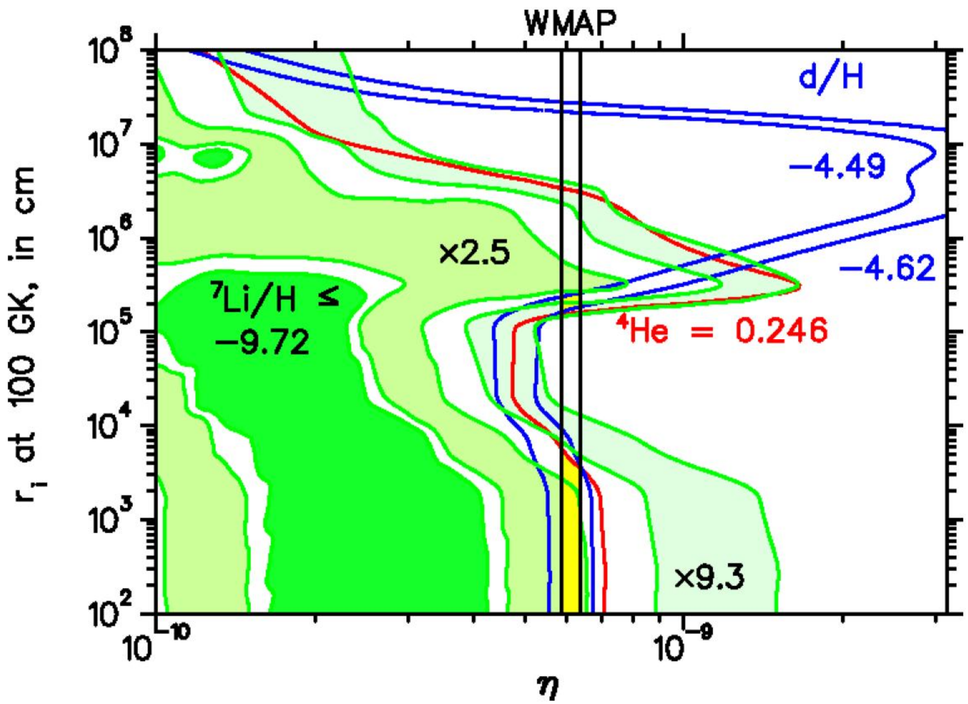
1) High and low baryonic density regions (QCD phase transition) with same initial n/p
2) Neutron diffusion out of high density regions
3) Nucleosynthesis with neutron back diffusion





Inhomogeneous BBN

Need and extended network as for CNO



- Density contrast: R
- Volume fraction: f_v
- Size at 100 GK: r_i

[Lara, Kajino & Mathews 2006]

← ≈ Standard BBN

Does not help for the lithium problem: more depletion needed

Relic particles acting on BBN

- Supersymmetry
  - Lightest Supersymmetric Particle, stable, Dark Matter candidate
  - Next to LSP, unstable (e.g. gravitino) could affect BBN, e.g.:
    - Hadronic decay (e.g. neutron injection)
    - Electromagnetic decay (e.g. D destruction after BBN)
    - Negatively charged relics (e.g. stau) $\Rightarrow$ bound states with nuclei

BBN catalysis by charged heavy relics

- Heavy long lived relic particles with negative charge (X^-) could form bound states with nuclei *[Pospelov 2006]*
- Lower Coulomb barrier ⇒ higher cross section
- Enable X^- transfer reactions
- Exotic physics but reaction rates from Nuclear Physics theory (quantum 3-body *[Kamikura+ 2009]*)

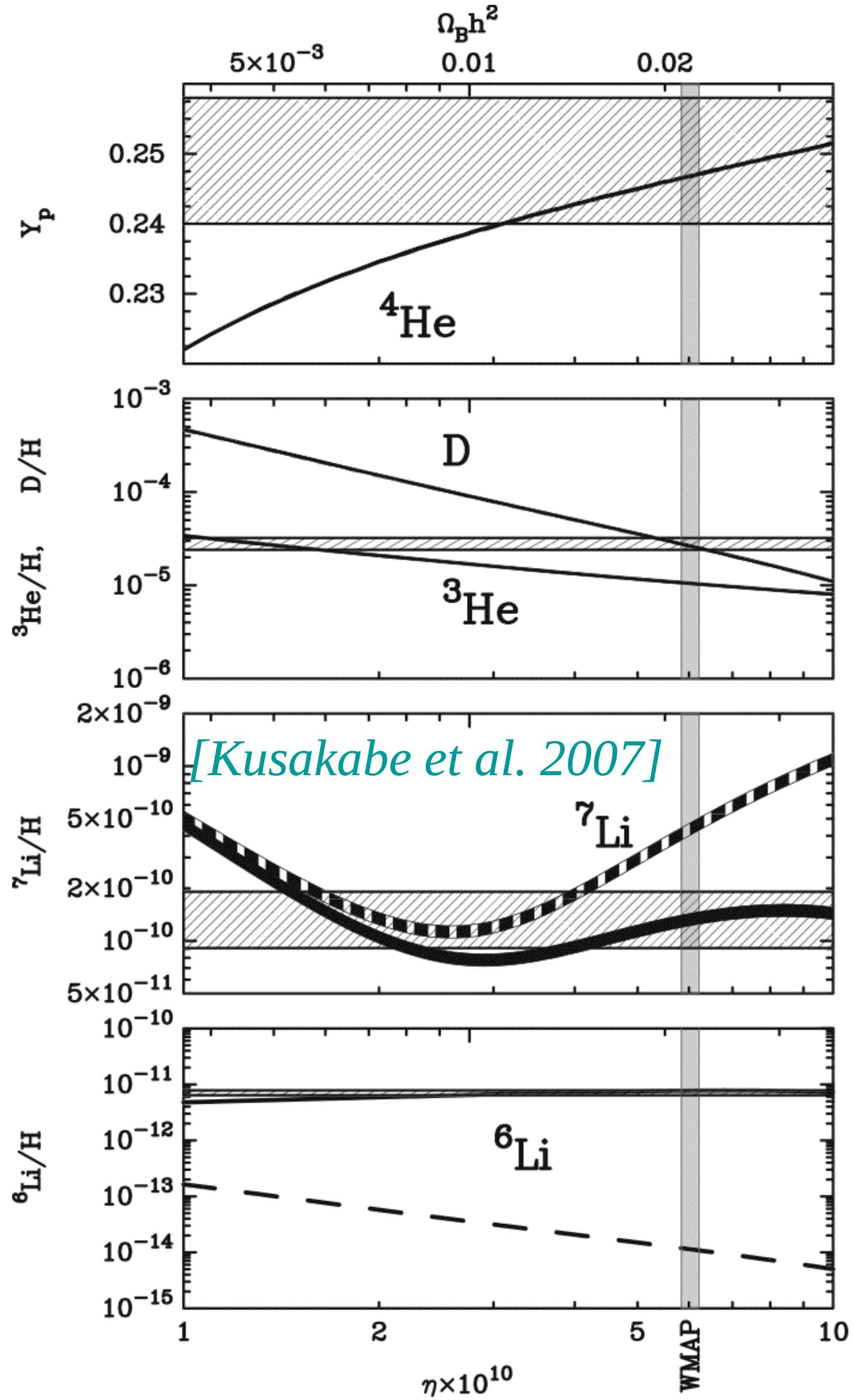
$(^4\mathrm{He}X^-)+\mathrm{D}\rightarrow {}^6\mathrm{Li}+X^-$ faster than
$^4\mathrm{He}+\mathrm{D}\rightarrow {}^6\mathrm{Li}+\gamma$

[Pospelov 2006, Hamaguchi et al. 2007]

- The stau (superpartner of the τ lepton) could be the X^- if it is the next to lightest supersymmetric particle *[Cyburt et al. 2006]*
- Affect also other BBN reactions

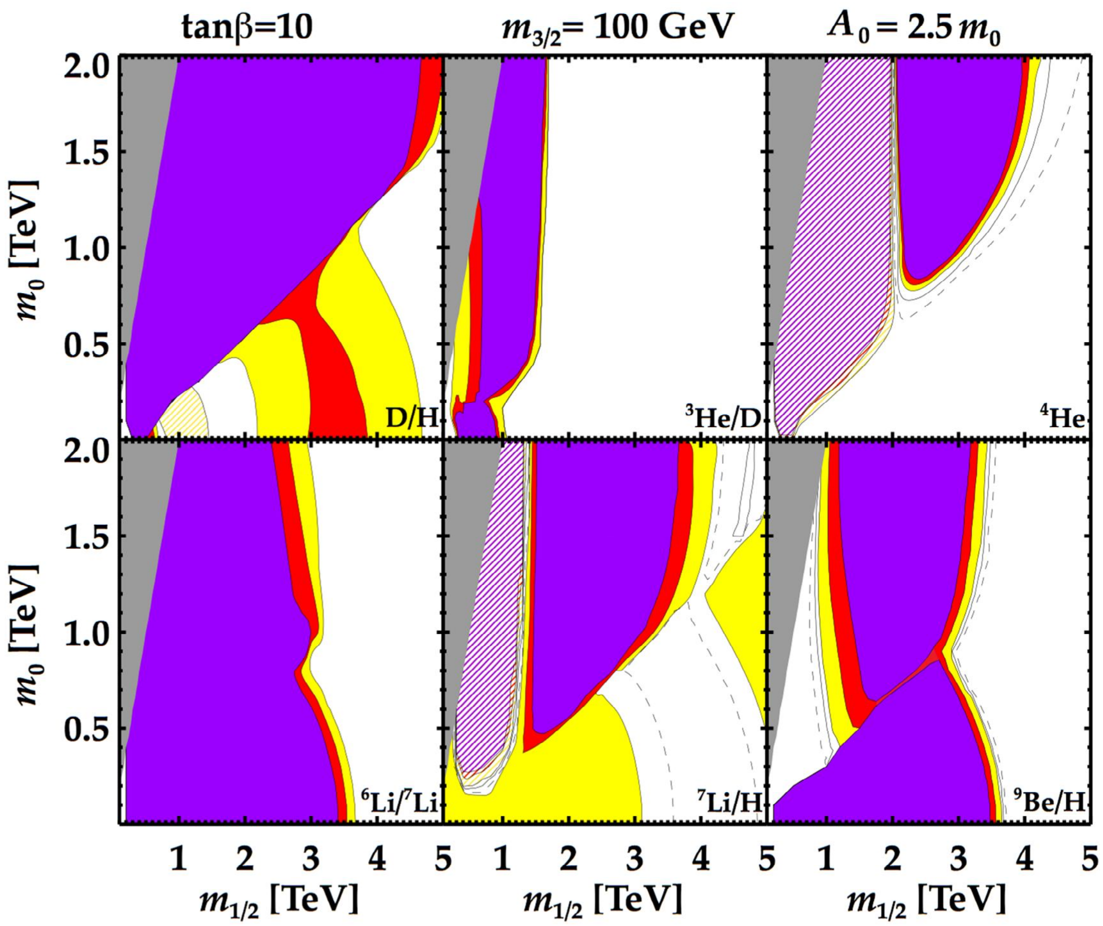
An X^- solution to the ^{6}Li and ^{7}Li problem

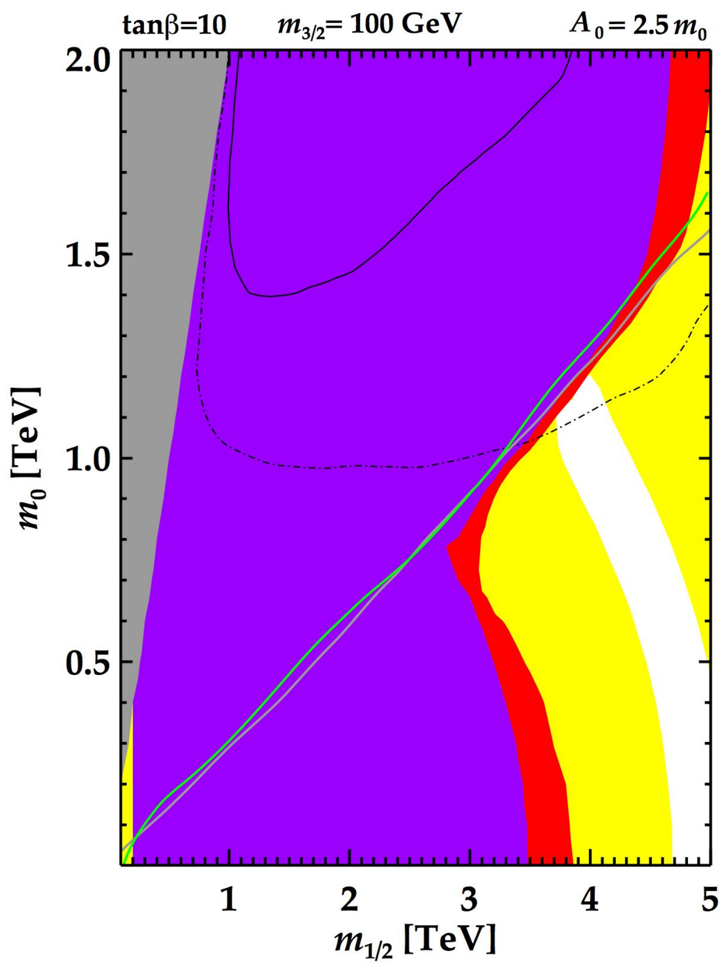
Within a range of X^- lifetime and relic abundances, it becomes possible to obtain the observed (?) ^{6}Li and ^{7}Li abundances *[Kusakabe+ 2007,2008, 2013; Jedamzik 2008,…; Cyburt+ 2012..]*



BBN with long lived stau

LSP = gravitino, NLSP = stau *[Cyburt+ 2012]*



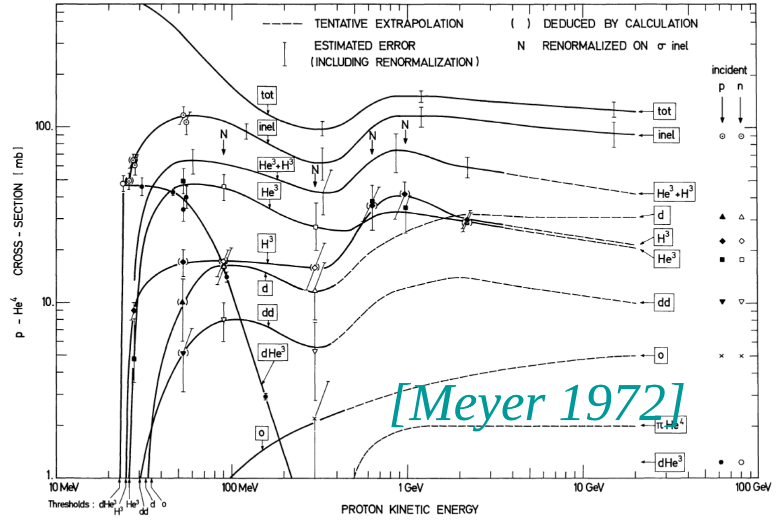


White = allowed

BBN and (SuperSymmetric) relics decay

[Jedamzik+; Kawasaki+; Cyburt+]

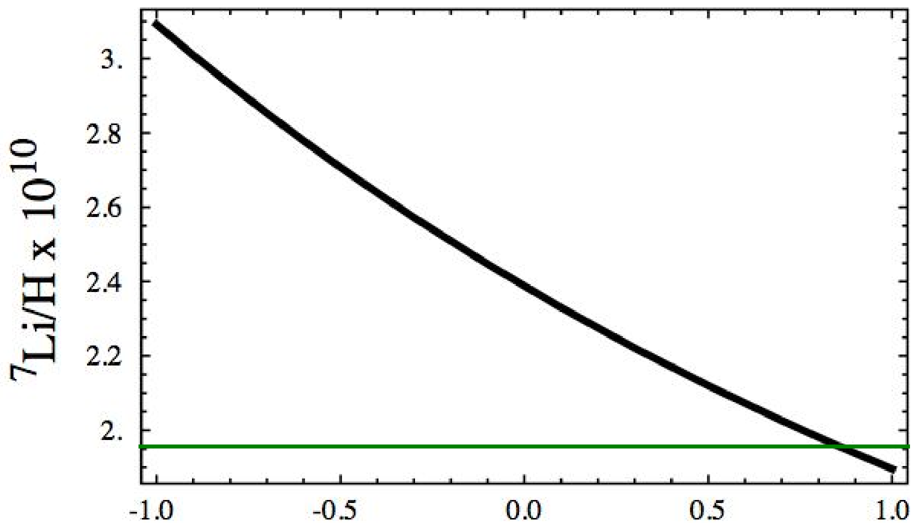
- NLSP → LSP + n/p + γ + ...
- After LHC, still a solution for ^{7}Li *[Cyburt+ 2013]*
- Non thermal n/p equilibrium spectra peak at a few GeV >> Gamow
- Larger uncertainties in cross-sections than in spectra



[Meyer 1972]

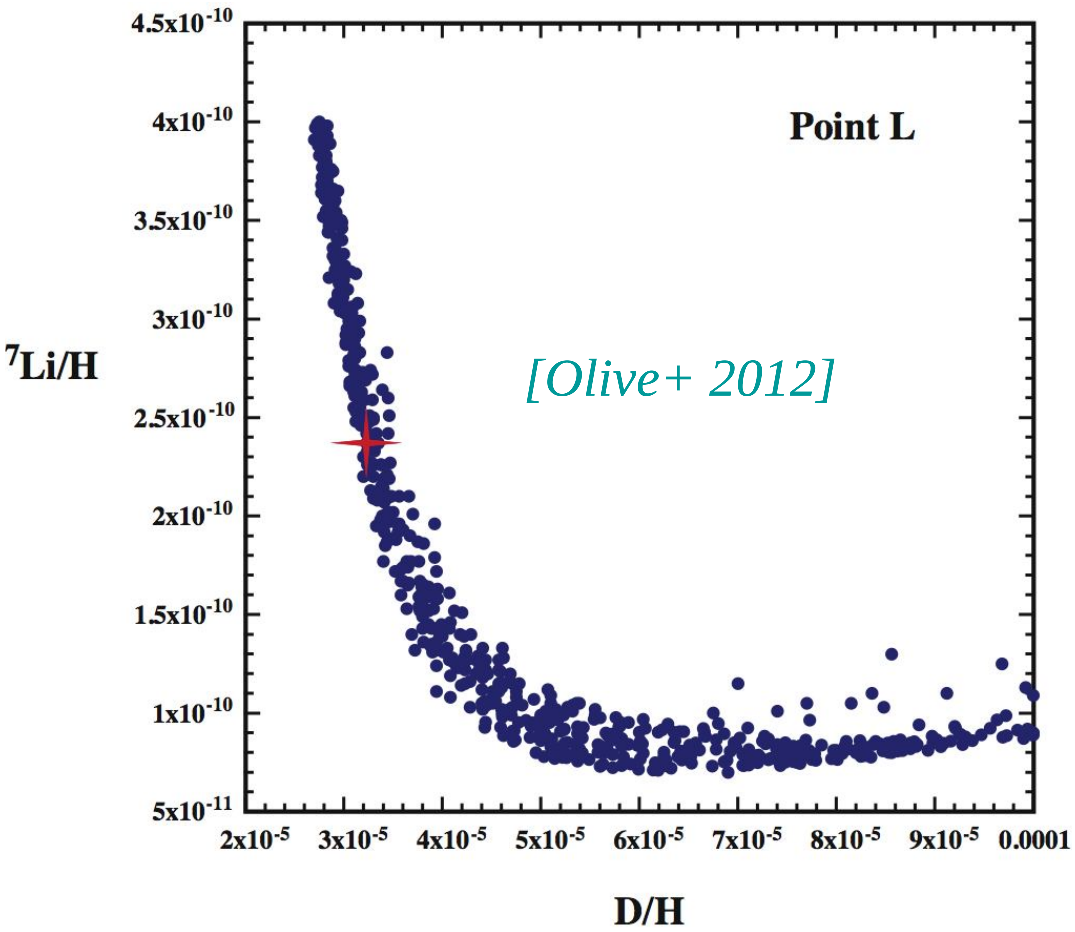
Reaction	Uncertainty (out of 36)
$p^4\mathrm{He} \to np^3\mathrm{He}$	20%
$p^4\mathrm{He} \to ddp$	40%
$p^4\mathrm{He} \to dnpp$	40%
$t^4\mathrm{He} \to {}^6\mathrm{Li}n$	20%
$^3\mathrm{He}^4\mathrm{He} \to {}^6\mathrm{Li}p$	20%
$n^4\mathrm{He} \to npt$	20%
$n^4\mathrm{He} \to ddn$	40%
$n^4\mathrm{He} \to dnnp$	40%
$p^4\mathrm{He} \to ppt$	20%
$n^4\mathrm{He} \to nn^3\mathrm{He}$	20%

[Cyburt+ 2010]



-100% $n^4\mathrm{He} \to npt$ +100%

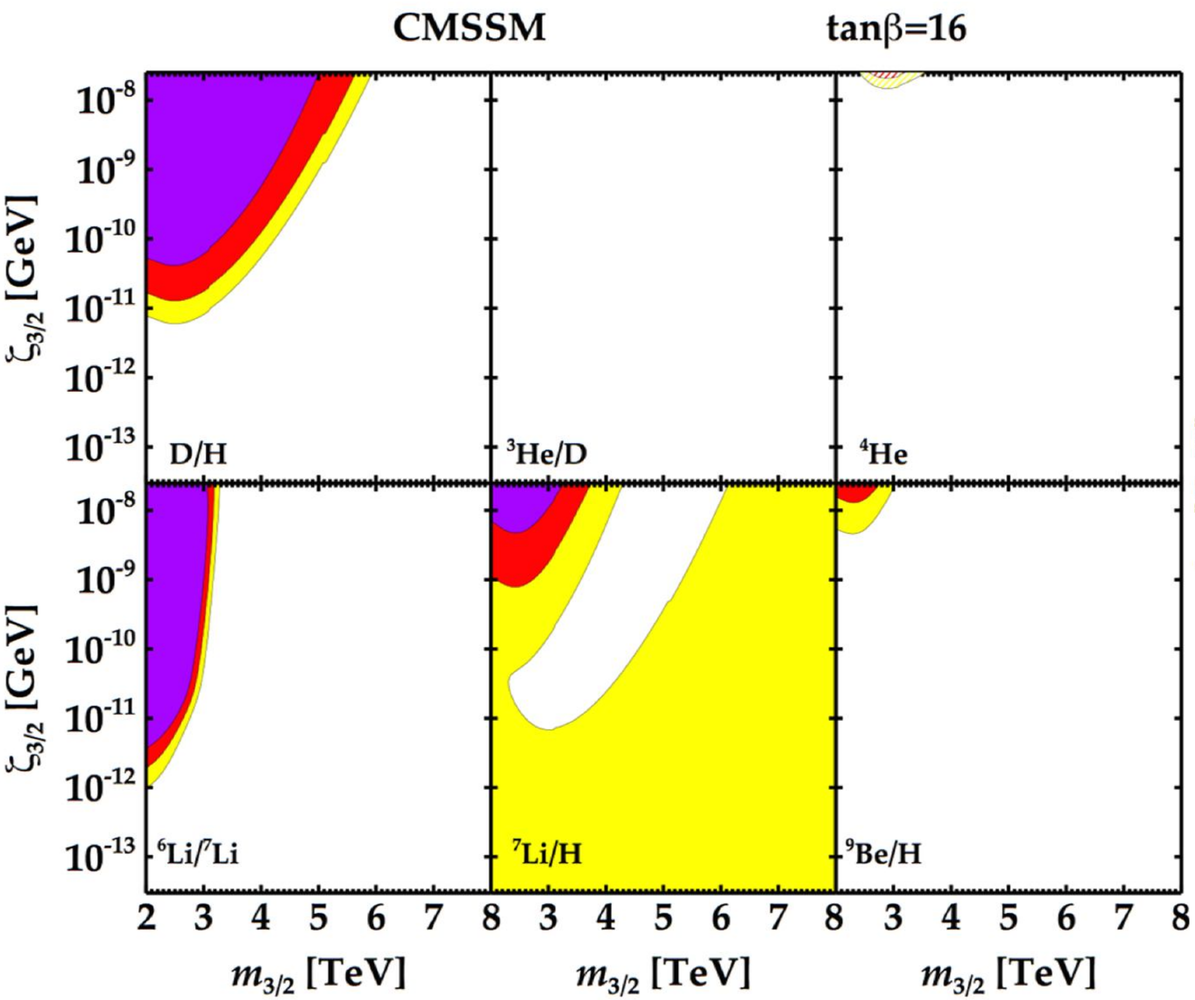
BBN and (SuperSymmetric) relics decay

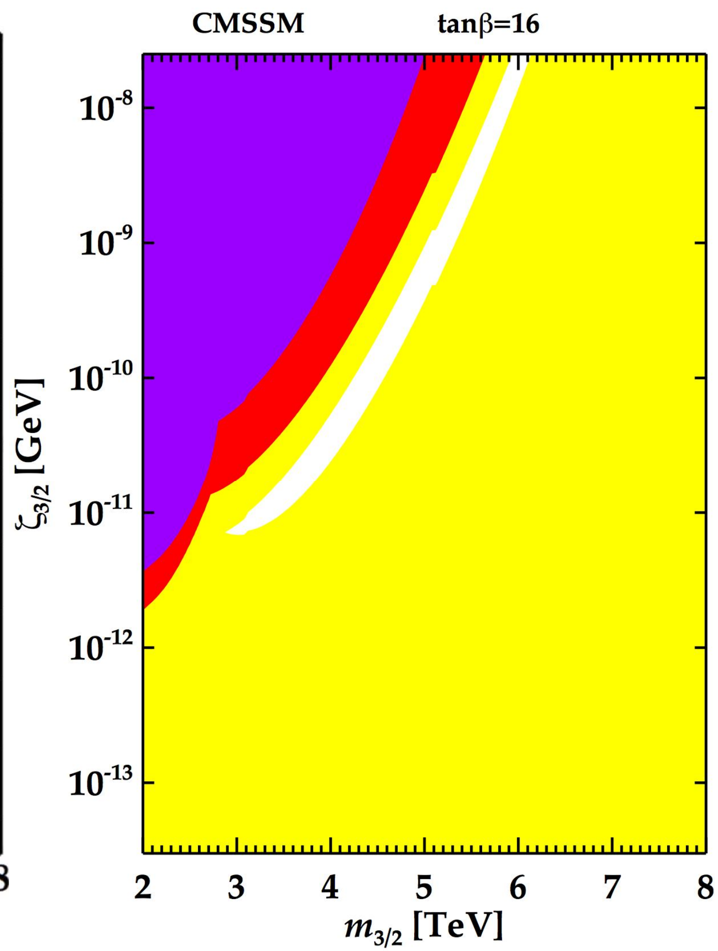


Low ^{7}Li/H ⇒ High D/H

BBN and gravitino decay

LSP = neutralino, NLSP = gravitino *[Cyburt+ 2013]*





White = allowed

Late neutron injection alleviate the Li problem

- Late time injection alleviate the Li problem at the expense of (harmless) D overproduction *[Jedamzik 2004; Coc+ 2007; Albornoz Vásquez+ 2012]*

- Due to higher neutron abundance at late time:
  $^{7}Be(n,p)^{7}Li(p,\alpha)^{4}He$

- Need extra (thermalized) neutron source
  - Nuclear ? Not likely (extended network)
  - Exotic ?
    - Dark matter decay
    - Dark matter annihilation
    - Mirror neutrons

Dark matter neutron injection

Extra source of neutrons from Dark Matter ?

- Dark Matter decay: $\chi \rightarrow n + \ldots.$

$$\lambda_{\rightarrow n} \propto \lambda_0 \exp(-t/\tau_\chi)$$

- Dark Matter annihilation: $\chi + \chi \rightarrow n + \ldots.$

  - non resonant: $\lambda_{\rightarrow n} \propto \lambda_0 a(t)^{-3}$
  - resonant $\lambda_{\rightarrow n} \propto \lambda_0 a(t)^{-3} \exp(-E_R/kT)$

  (dilution $a(t)^{-3} \propto (T/T_C)^3$)

[Albornoz Vásquez et al. 2012; Pospelov et al. in preparation]

Dark matter injection of thermal neutrons

- Thermalization of neutrons on shorter time-scale than
  - ✓ Expansion rate
  - ✓ Neutron lifetime
- Energy loss
  - ✓ From multiple scattering rather than single collision
- Negligible spallation
  - ✓ No ^{6}Li overproduction by spallation reactions:
    1. $n + {}^{4}He \rightarrow {}^{3}He + 2n$
    2. ${}^{4}He + {}^{3}He \rightarrow {}^{6}Li + p$

Achievable for $M\chi$ in the 1 to 30 GeV range

Representative results

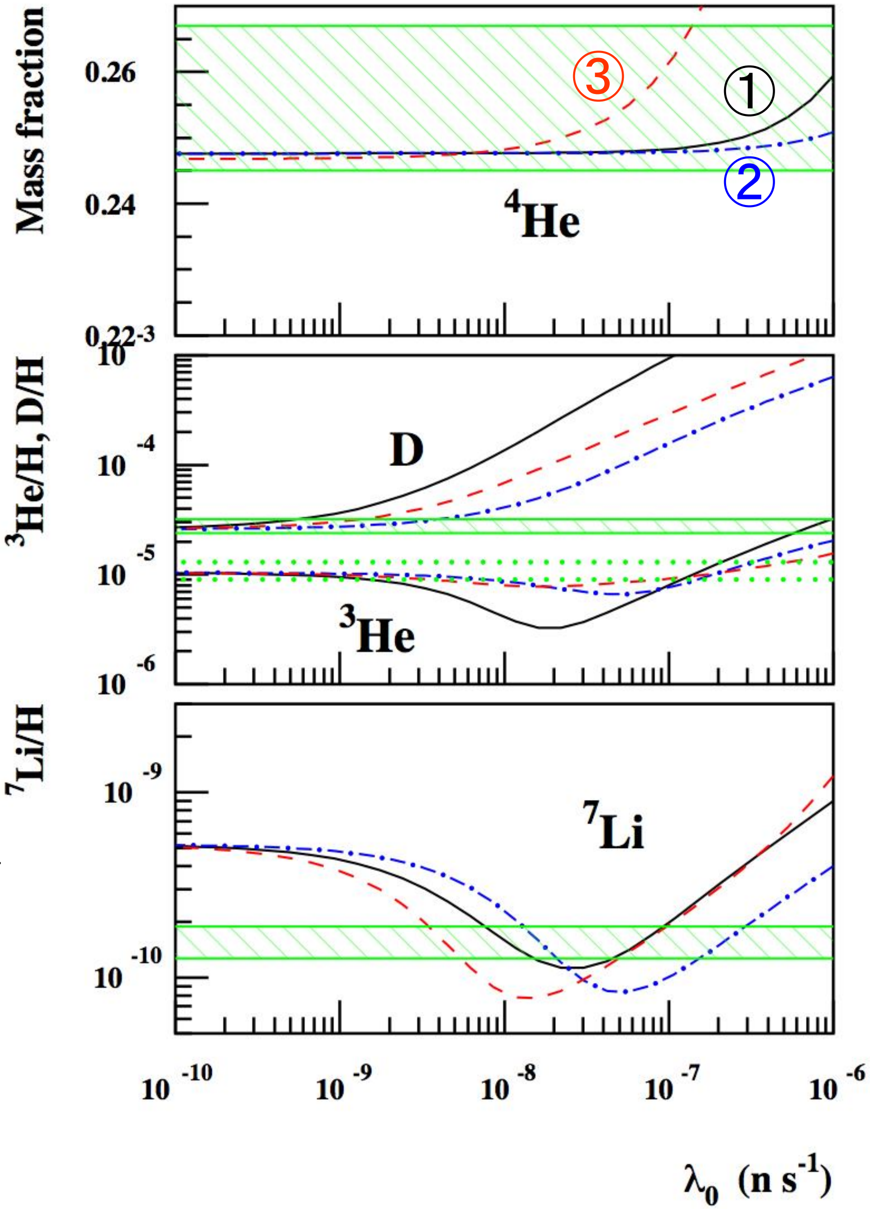
1. Neutron injection at constant rate

2. Neutron injection from decay with τ_χ = 40 mn

3. Neutron injection from annihilation with T_C = 0.3 GK

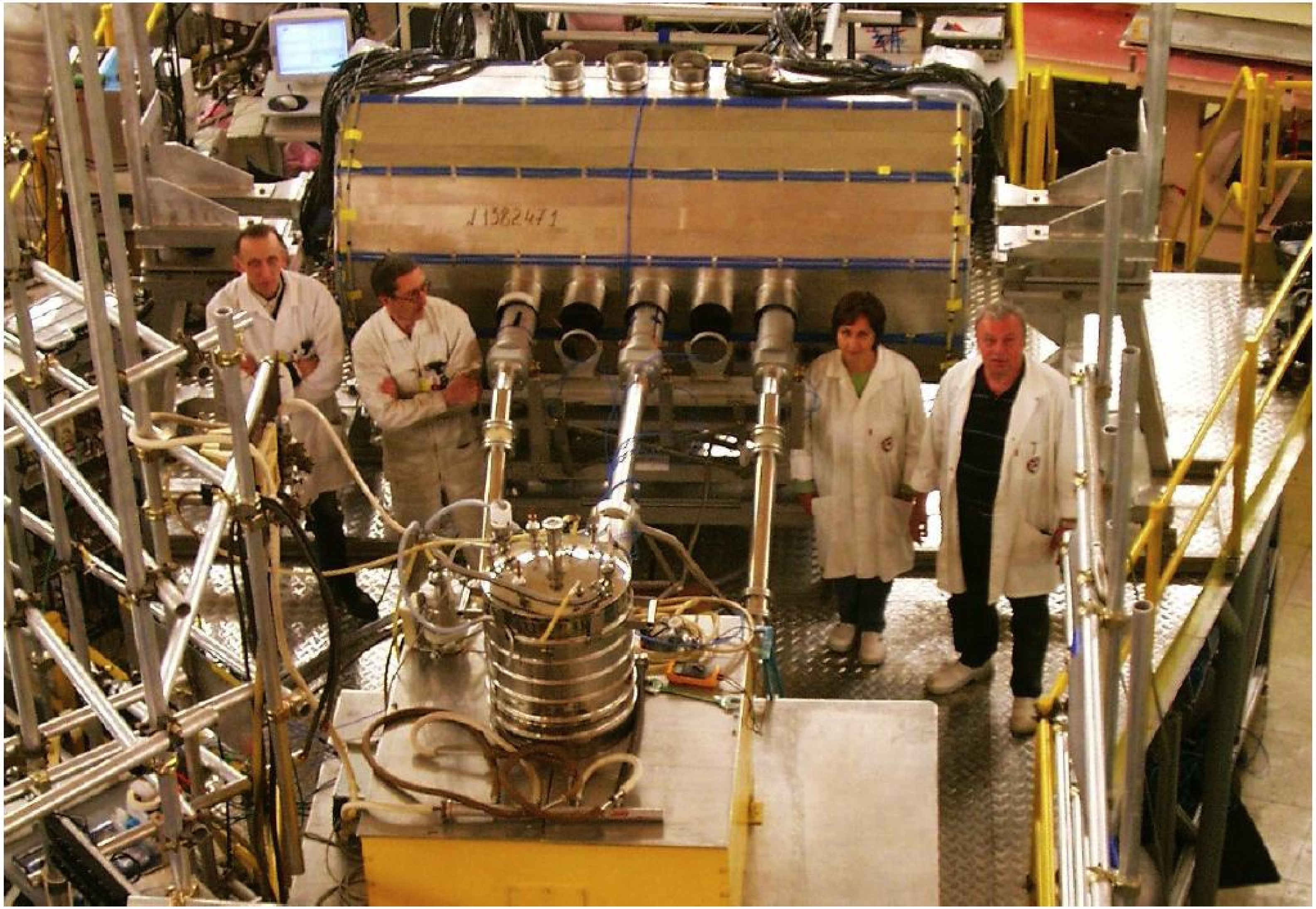
Alleviates the ^{7}Li problem at the expense of D

[Albornoz Vásquez+ 2012]



Experimental installation search for n-n′ oscillation and some members of PNPI-ILL-PTI collaboration

© Serebrov in International workshop on particle physics with slow neutrons (2008)



Mirror matter

- Mirror matter (noted with a prime "´" or "M")
  - Postulated to restore global Parity symmetry *[Lee & Yang 1956]*
  - Same particles but opposite parity, almost only gravitational interaction with ordinary matter, Dark Matter candidate *[Berezhiani+ 1996,...; Foot+ 1997,.....; Ciarcelluti+ 2008,....]*
  - Microphysics (including nuclear physics) identical in both sectors
  - But different cosmologies ($T' \neq T$ and $\eta' \neq \eta$) due to inflation

$$L = L_G(e,u,d,\varphi,...) + L_G(e',u',d',\varphi',...) + L_{mix}$$

  - Neutral particles (e.g. neutrons) could oscillate between the two worlds
  - Experimental search of neutron oscillations (at ILL, Grenoble, $\tau_{osc} > 414$ s *[Serebrov+ 2008]*)

Thermodynamics in the Standard Model

Cosmological distances ∝ $R \equiv (1+z)^{-1}$ (z = redshift)

Rate of expansion ∝ (radiation energy density)$^{1/2}$

① $$\frac{1}{R}\frac{dR}{dt} \propto \sqrt{\rho^{rad}_{e\gamma\nu}(T)} \propto \sqrt{g_*^{e\gamma\nu}(T)}\,T^2$$

$$g_*^{e\gamma\nu} = 2 + \frac{7}{8}\left(2 \times N_\nu \left[\frac{T_\nu}{T}\right]^4 + 2 \times 2\right)$$

$T_\nu = T$ for $T \gg 1$ MeV

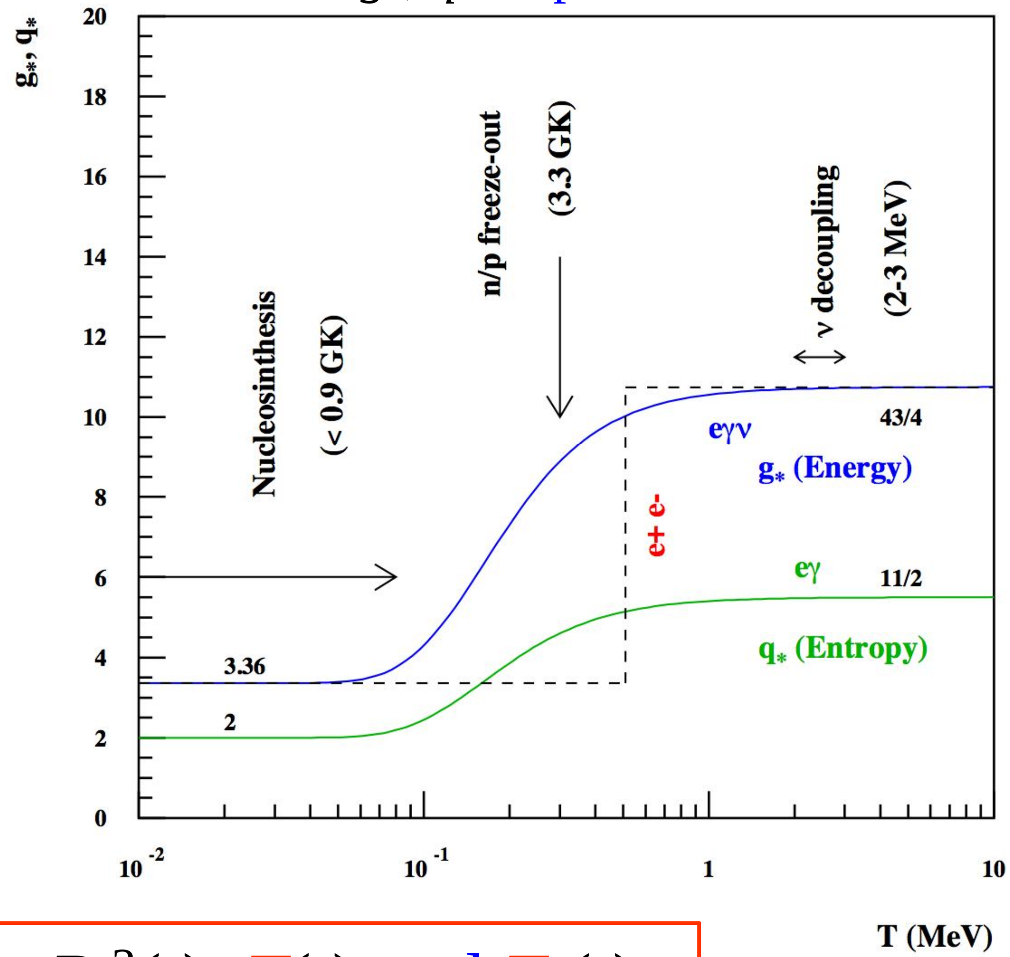
② $$R^3 T_\nu^3 = Cste$$

③ $$R^3 q_*^{e\gamma}(T)\,T^3 = Cste$$

Entropy constant

$T_\nu = T \times (4/11)^{1/3}$ for $T \ll 1$ MeV

g_*, q_* = spin factors



①+②+③ ⇒ $\rho_b(t) \propto \Omega_b\, R^{-3}(t)$, $T(t)$ and $T_\nu(t)$

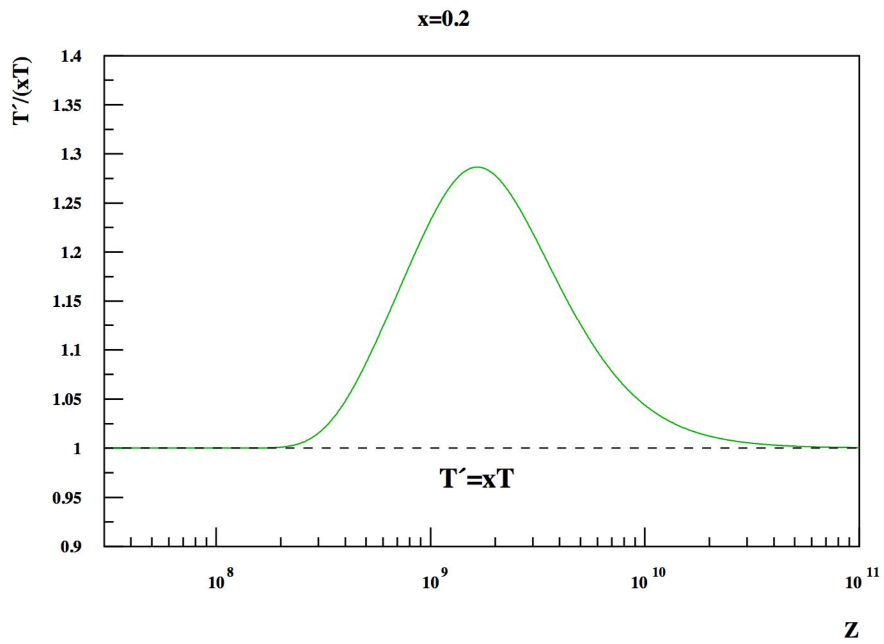
Thermodynamics with Mirror Matter

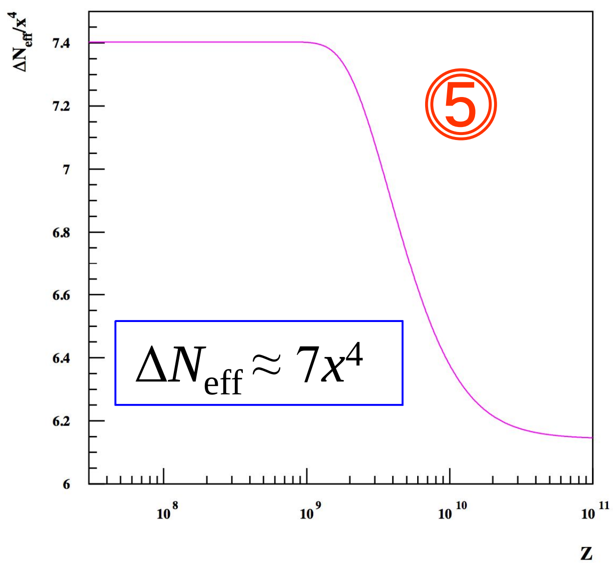
Increased radiation density $\rho_{e\gamma\nu} \longrightarrow \rho_{e\gamma\nu} + \rho'_{e\gamma\nu}$ in ① but BBN (^{4}He) limits

④ $$\Delta N_{\rm eff} \equiv \frac{\rho'(T')}{\frac{7}{8} a_R T_\nu^4} \leq 1.22$$

Need a lower temperature in M-world: $T'_\nu / T_\nu = x < 1$, a constant while $T'/T \approx x$ for the photon temperatures

- $x \lesssim 0.65$ from BBN (④ & ⑤)
- But no BBN constraint on η' : i.e. allows DM = Mirror Matter





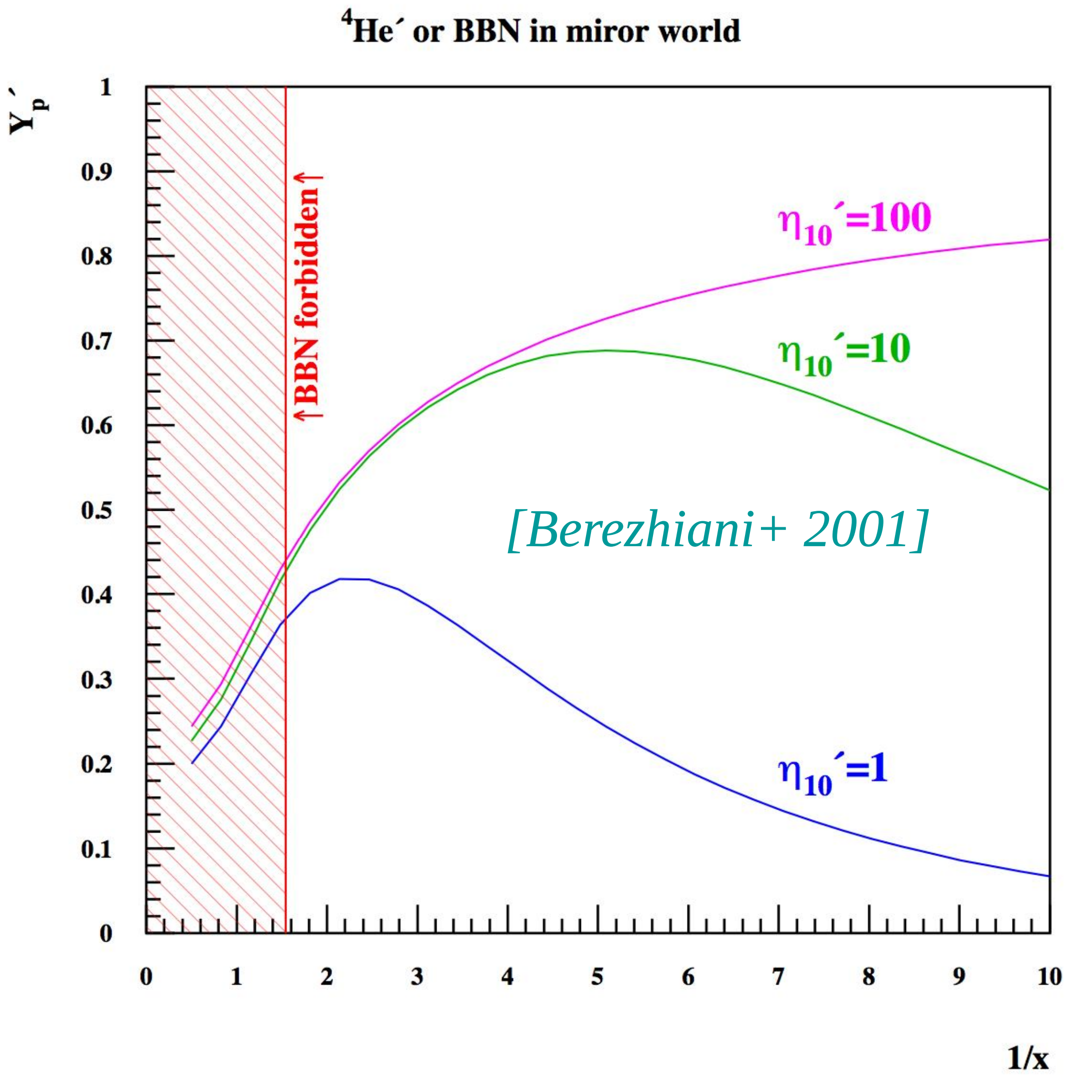
BBN in the Mirror World

Depending on $x \lesssim 0.65$ and η' values, a ≠ BBN in the M-World *[e.g. Ciarcelluti PhD]*:

- ≠ ^{4}He´ abundance
- ≠ Stellar evolution
- ....

and

- ≠ M-neutron (n´) abundance!☺But for low η' values ☹



Neutron oscillations in vacuum

Only neutral particles can interact, non-gravitationally, between the two worlds: neutrinos (sterile-neutrinos *[e.g. Foot+ 1996]*), photons (millicharged particles *[Foot 2012]*), neutrons (L_{mix}).

Off-diagonal terms in the mass matrix allows oscillations:

$$M = \begin{pmatrix} m - \frac{i}{2\tau_{\mathrm{n}}} & \frac{1}{\tau_{\mathrm{osc}}} \\ \frac{1}{\tau_{\mathrm{osc}}} & m - \frac{i}{2\tau_{\mathrm{n}}} \end{pmatrix}$$

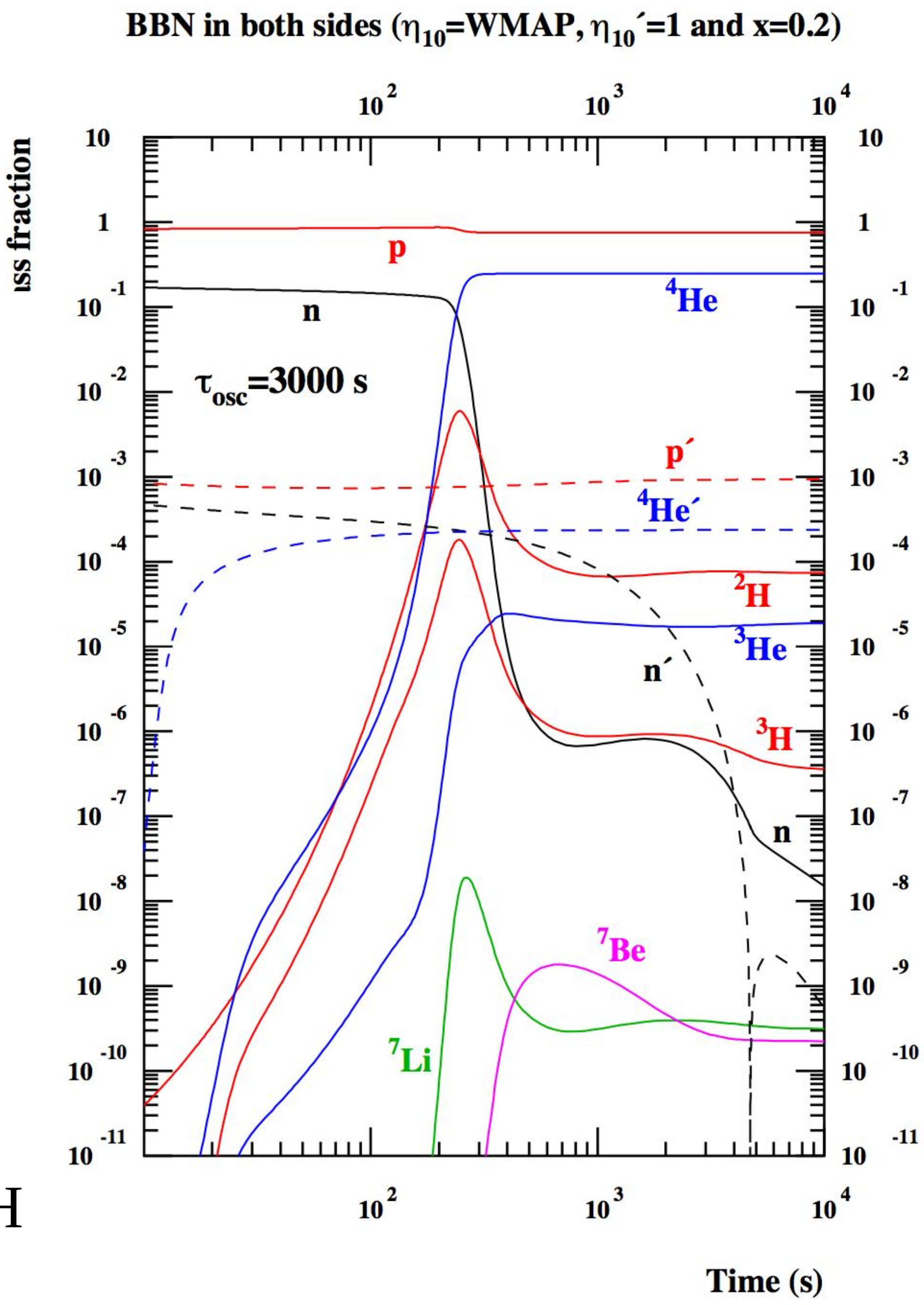
$$n' \propto e^{-t/\tau_{\mathrm{n}}} \cos^2\left(t / \tau_{\mathrm{osc}}\right)$$

To allow for late time neutron injection:

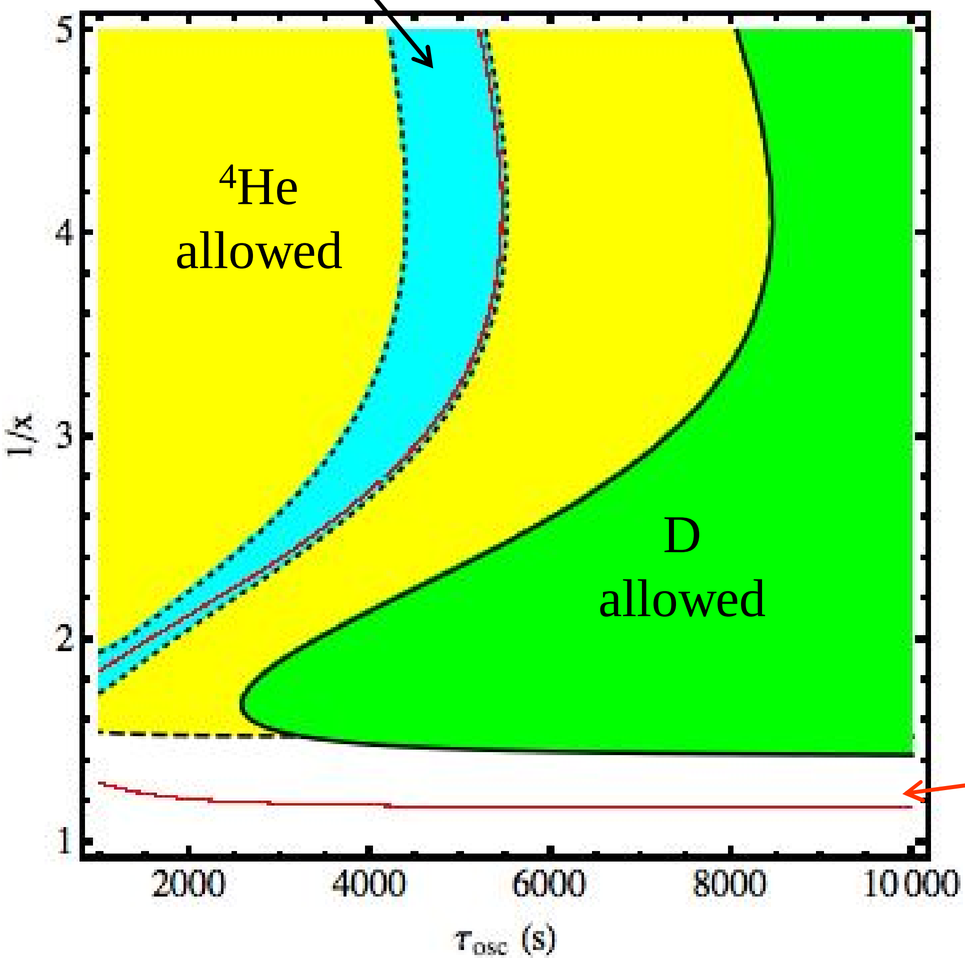
- n´ abundance remains high, i.e. low η'
- Oscillation time $\tau_{\mathrm{osc}} \sim 1000$ s, i.e. BBN time scale

BBN with Mirror Matter

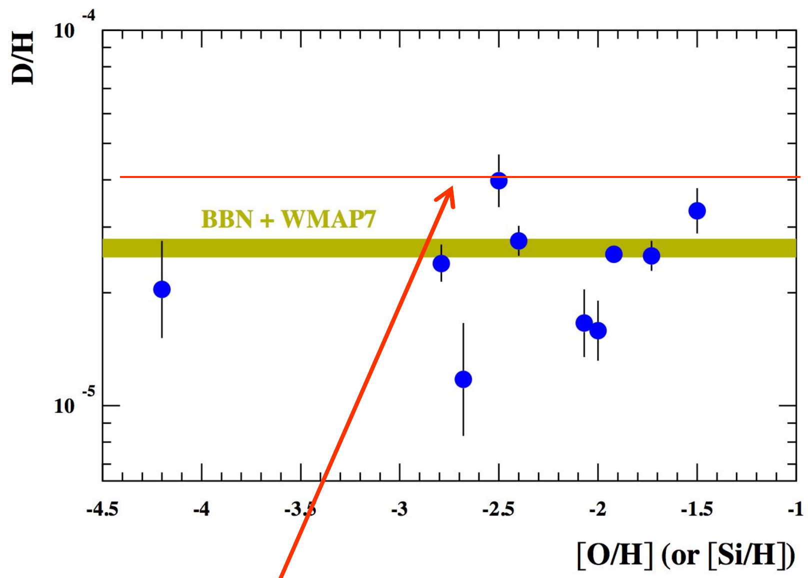
- Same isotopes (with ´), same cross sections, 3 parameters:
- Temperature ratio $x = T'/T$
- Baryonic density $\eta' \neq \eta$
- Oscillation time τ_{osc}
- ➪ Excess mirror neutrons can oscillate to normal neutrons i.e. $n' \rightarrow n$
- ➪ Destroy excess ^{7}Be
- ➪ with τ_{osc} compatible with experiments (> 414 s *[Serebrov+ 2008]*)
- ➪ At the expense of a higher D/H



Mirror Matter can reconcile BBN with observations



Primordial D/H: from observations of remote cosmological clouds on the line of sight of quasars

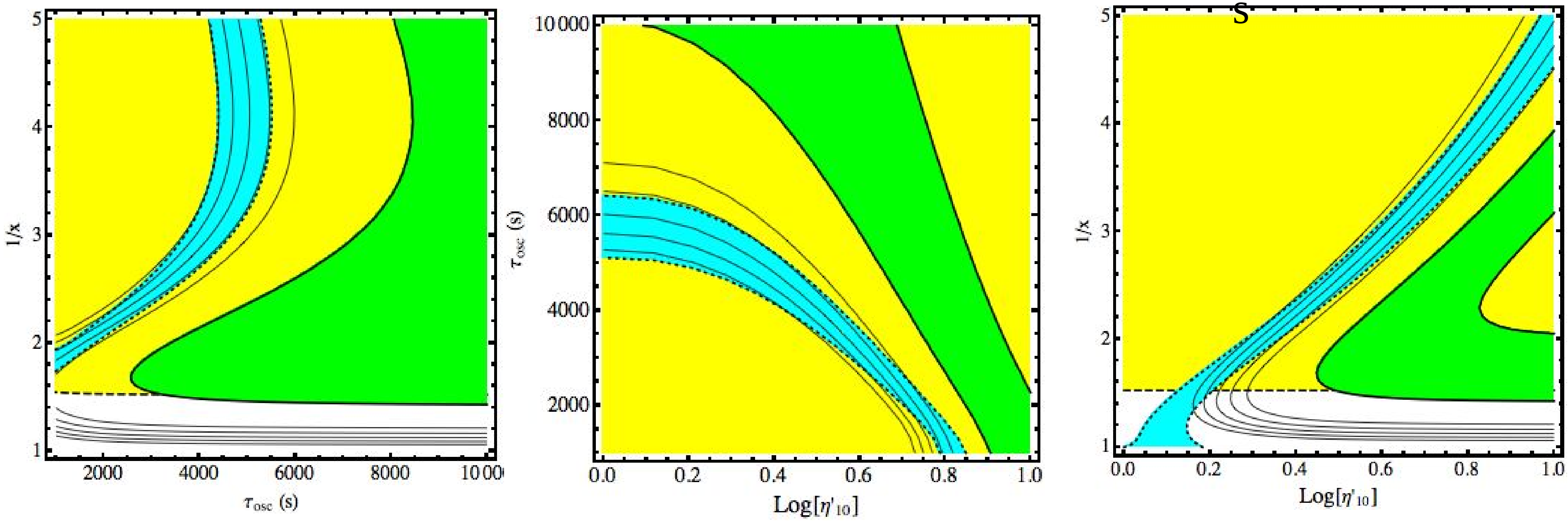


D/H = 4 10^{-5}

[Olive+ 2012]

Mirror Matter can reconcile BBN with observations

$\eta'_{10} = 3$ $1/x = 3$ $\tau_{osc} = 3 \times 10^3$ s

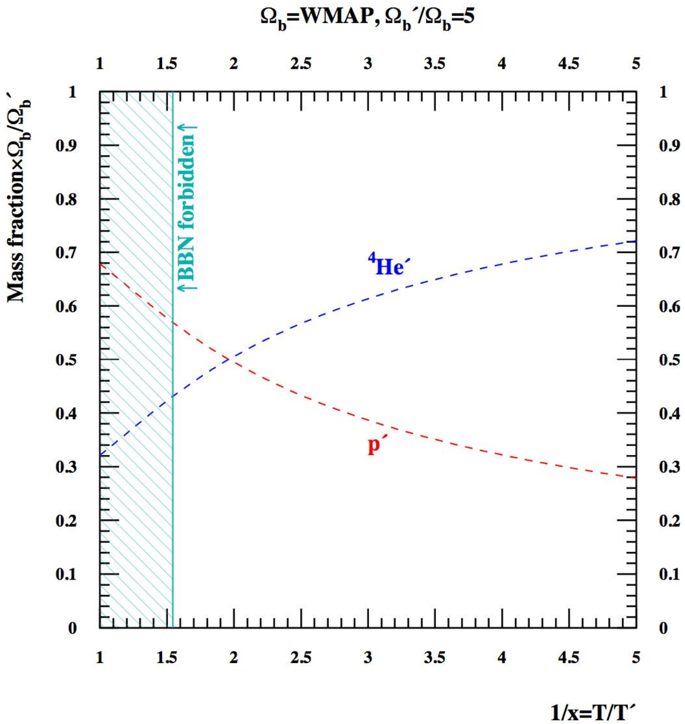


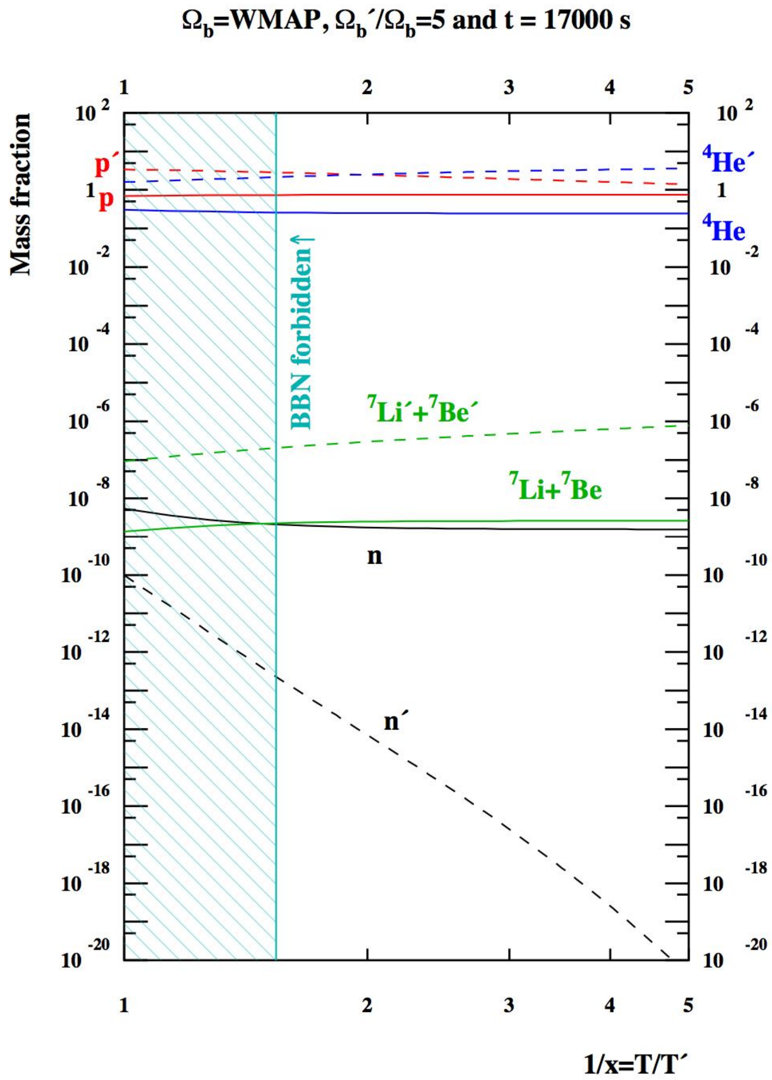
D/H = (3.8, 4.0, 4.2, 4.4, 4.6) $\times 10^{-5}$

Dark Matter = Mirror Matter : no help for ^{7}Li

When $\Omega_b{}' / \Omega_b \approx 5$ to identify Dark Matter with Mirror Matter, mirror neutrons are too scarce

W





Dark Matter = Mirror Matter ? *[Foot 2010; 2013]*

Photons M-photons interactions $\mathcal{L}_{\text{mix}} = \frac{\varepsilon}{2} F'_{\mu\nu} F^{\mu\nu}$ ($\varepsilon \sim 10^{-9}$)

⇒ M-charged particles seen as millicharged (εe) particles

⇒ M-nuclei (*A´,Z´*) can scatter off ordinary nuclei (*A,Z*) with a Rutherford cross-section reduced by ε^2 and *recoil detected!*

MM is self interacting and dissipative as ordinary matter ≠ WIMPs

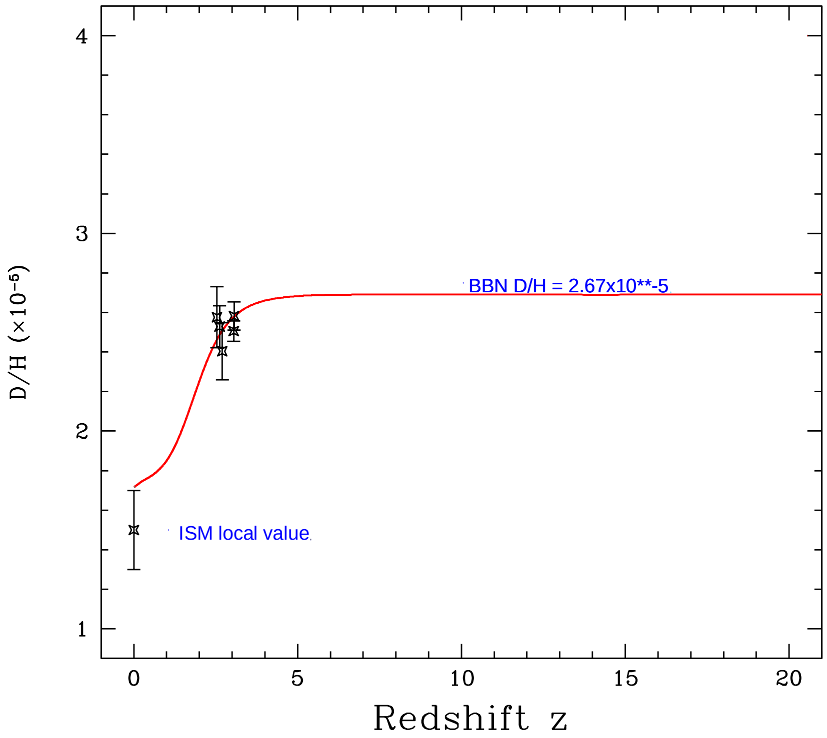
⇒ Different DM halo spatial and velocity distributions:

⇒ Compatible with the DAMA, CoGeNT, CRESST-II and CDMS/Si signals and no signals in other experiments according to *Foot 2013 [arXiv:1209.5602v3]*

Li or D overproduction

- Late time (low T) extra neutrons needed for ^{7}Be destruction
- D overproduction by ^{1}H(n,γ)D at low T
- At higher T, end up in ^{4}He
- Post BBN D destruction by astration from a first generation of intermediate mass stars

- More difficult after *Cooke+ 2014* D/H observations



Beyond the Standard Model(s)

1. Non standard nucleosynthesis (Inhomogeneous BBN, relic particles, mirror neutrons)
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3. Variation of constants (in stars, BBN,....)

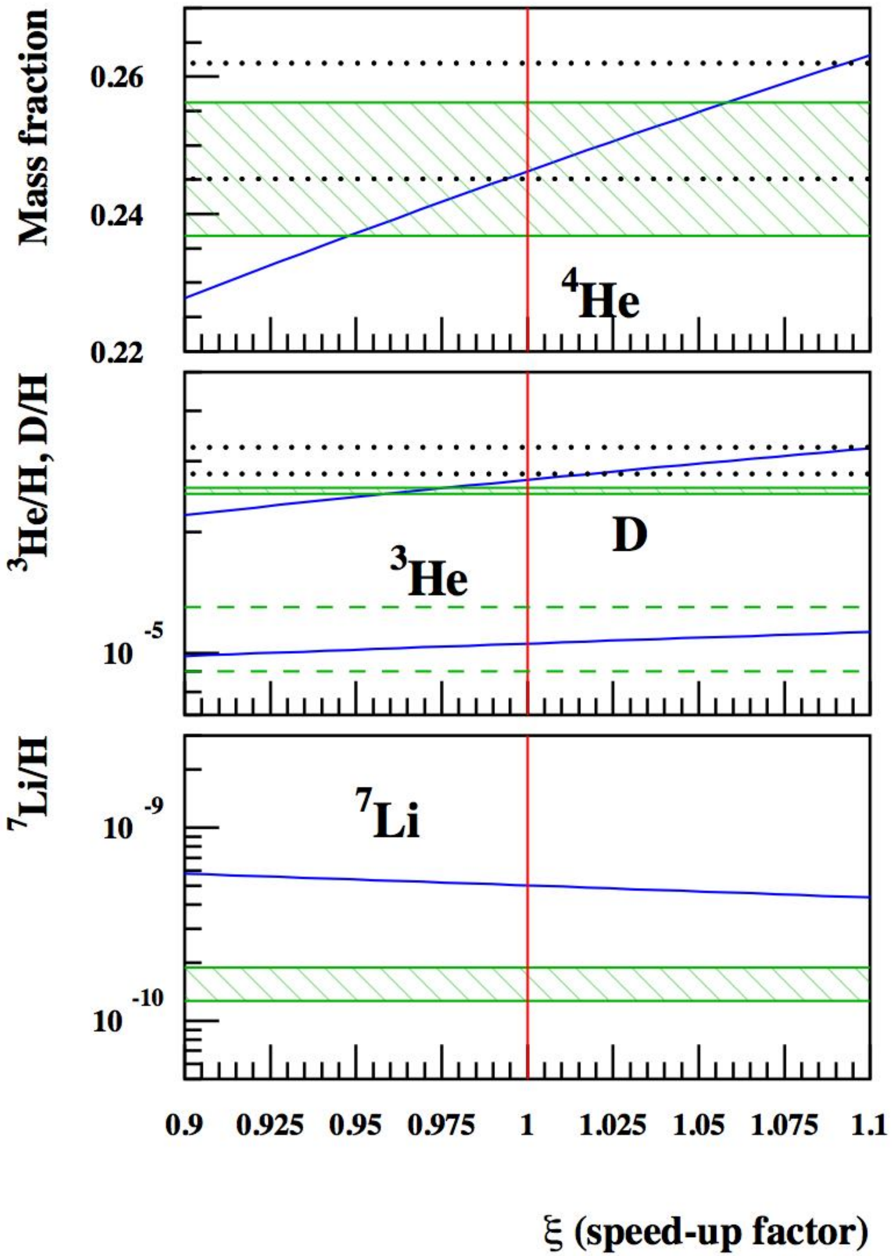
"Speedup factor"

$$\frac{\dot{a}}{a} \equiv H(t) \rightarrow \xi \times H(t)$$

A change the rate of expansion change the neutron/proton ratio at freezeout of weak rates:

$$\Gamma_{n\leftrightarrow p} \sim G_F^2 T^5 \sim \frac{\dot{a}}{a} = \sqrt{\frac{8\pi G \rho_R}{3}}$$

Equivalent to a constant factor change in G_F^{-2} ($\sim\tau_n^{\,2}$), $G^{1/2}$ or $\rho_R^{\,1/2}$ ($\sim N_{eff}$)



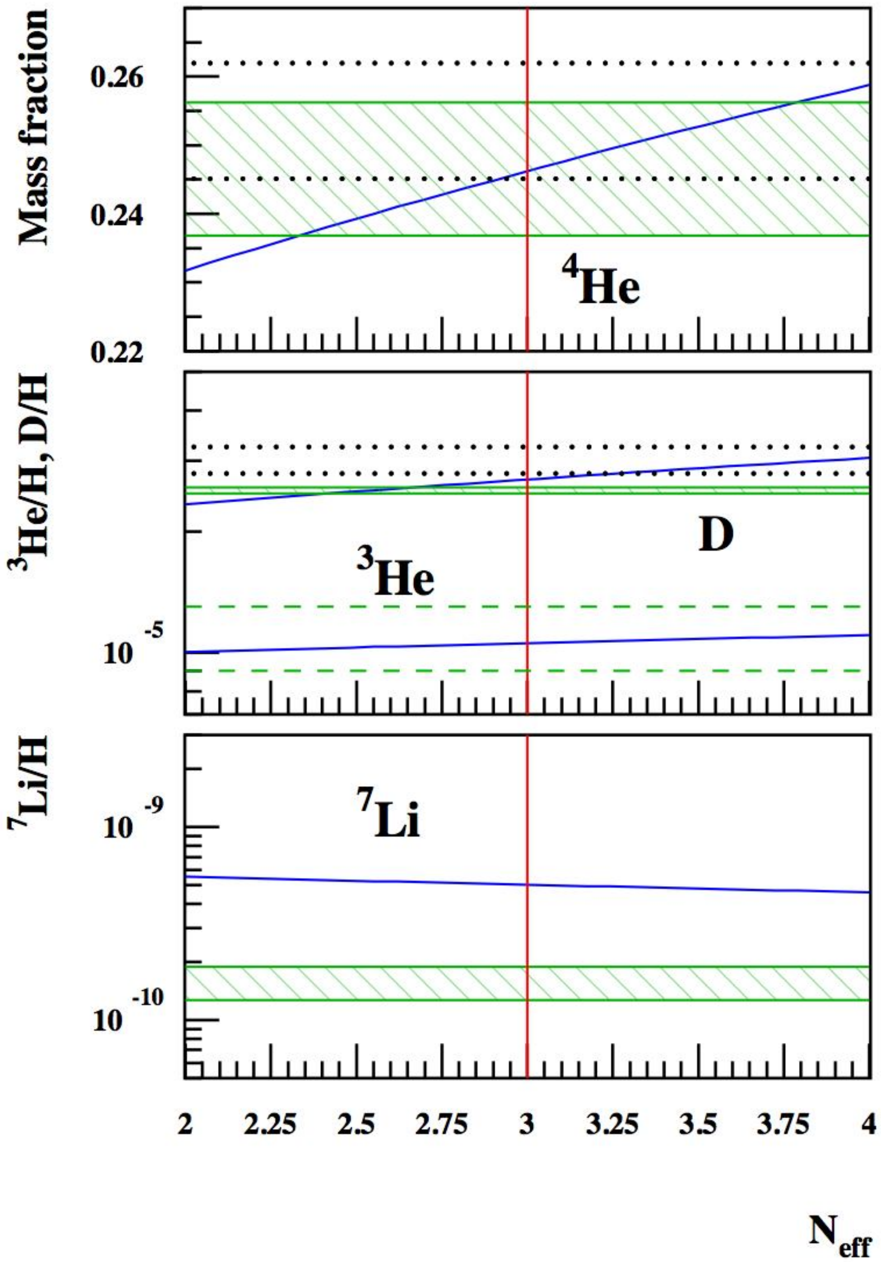
N_{eff} variations

N_{eff} = "*effective* number of neutrino families"

$$\rho_R = \rho_\gamma(T) + \frac{N_{\text{eff}}}{3}\rho_\nu(T_\nu) + \rho_{e+e-}(T)$$

$$\rho_R = \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\text{eff}}\right)\rho_\gamma(T)$$

Change the rate of expansion *H(t)* hence the neutron/proton ratio



Neutrino properties

- (Neutrino families)
- Lepton asymmetry or neutrino chemical potential *[e.g. Orito et al. 2002]*
- Neutrino oscillations (lead to flavor equillibration before BBN reduce limits on lepton asymmetry) *[Abazajian, Beacom & Bell 2002]*
- Sterile neutrinos *[Smith et al. 2006; Kishimoto, Fuller & Smith 2006]*
- …

Neutrino degeneracy

If neutrinos have a non zero chemical potential μ_ν ($\xi_\nu \equiv \mu_\nu / T$), $\nu = e, \mu, \tau$

- Shifts n/p ratio at freeze out (ξ_e):

  $N_n/N_p = \exp(-Q_{np}/kT - \xi_e)$

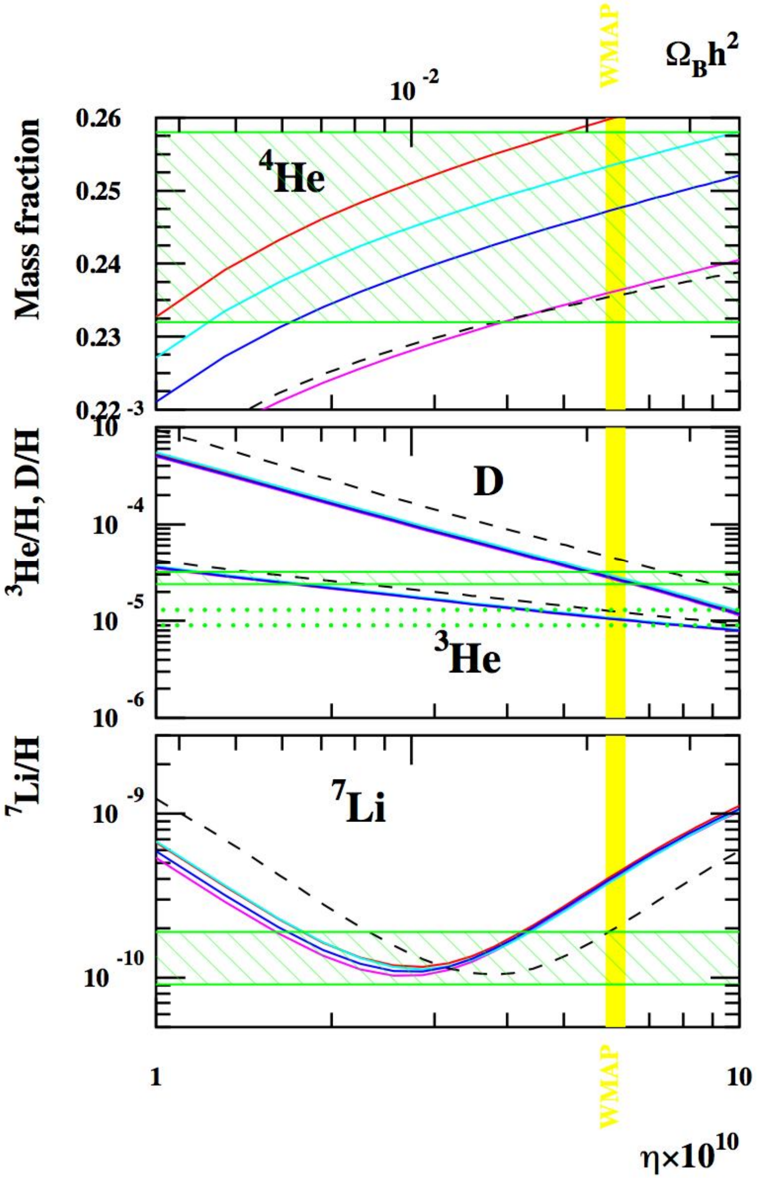
  $$\nu_e + n \leftrightarrow e^- + p$$
  $$\bar{\nu}_e + p \leftrightarrow e^+ + n$$

- Increase the expansion rate $N_{eff} > 3$ (ξ_e, ξ_μ and ξ_τ):

$$\rho_{\nu\bar{\nu}} = \frac{1}{2\pi^2\hbar^3} \int \left(\frac{1}{\exp(E/kT - \xi) + 1} + \frac{1}{\exp(E/kT + \xi) + 1} \right) E p^2 dp$$

$$= \frac{7}{8} a_R T^4 \left(1 + \underbrace{\frac{30}{7}\left(\frac{\xi}{\pi}\right)^2 + \frac{15}{7}\left(\frac{\xi}{\pi}\right)^4}_{\Delta N_{eff}} \right)$$

Neutrino degeneracy



Chemical potential ($\xi_\nu \equiv \mu_\nu / T$)

$$L_\nu = \frac{n_\nu - n_{\bar{\nu}}}{n_\gamma} = \frac{\pi^2}{12\varsigma(3)}\left(\frac{T_\nu}{T}\right)^3\left(\xi + \frac{\xi^3}{\pi^2}\right)$$

$(\xi_e, \xi_\mu/\xi_\tau)$ = (0,0)

(-0.05,0)

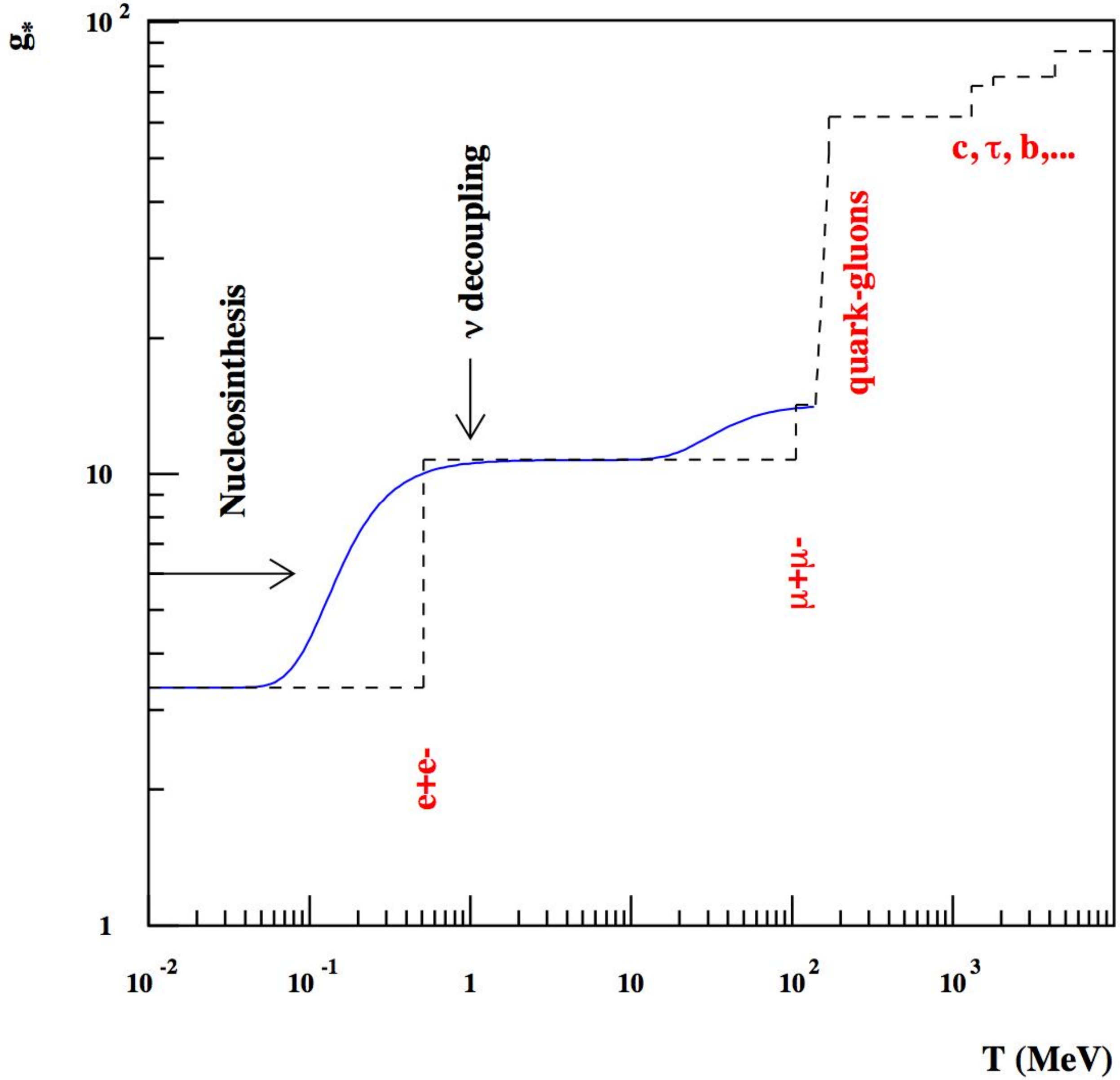
(+0.05,0)

(0,0.7)

(0.3,2.5)

But neutrino oscillations imply $\xi_e \approx \xi_\mu \approx \xi_\tau$ and D observations $|\xi| \leq 0.064$ *[Cooke+ 2014]*

Decoupling of relativistic relics and N_{eff}



Unification of forces and extra dimensions

Kaluza and Klein in the ‘20 : unify gravitation ($g_{\mu\nu}$) and electromagnetism (A_ν) by introducing a fifth spatial dimension

$$\bar{g}_{AB}^{(5)} = \left(\begin{array}{c:c} g_{\mu\nu}^{(4)} & A_\nu \\ \hdashline A_\mu & \Phi \end{array} \right)$$

A scalar field appears! → Φ

Unification of forces $\Rightarrow$ extra dimensions $\Rightarrow$ scalar field(s)

$\Rightarrow$ String theories D=11

Basics of Scalar Tensor theories of Gravitation (I)

Most general theories of gravity include a scalar field beside the metric

Mathematically **consistent**
Motivated by **superstring**
Preserve most **symmetries** of general relativity
Useful extension of GR (simple but general enough)

- The spin 2 graviton field is coupled to the EM tensor $T_{\mu\nu}$
- The scalar field ϕ is coupled to its trace $T^{\mu}{}_{\mu}$
- Constrains at z=0 (present), z=10^3 (CMB) and z~10^8 (BBN)

[see e.g. Damour & Pichon PRD 1999]

- Attracted towards GR *[Damour & Nordtvedt PRDL 1993]*

Action and field equation

$$R_{\alpha\beta} - \frac{1}{2} g_{\alpha\beta} R = 8\pi G T_{\alpha\beta}$$

$\Uparrow$ (see e.g. Landau & Lifchitz T. II)

$$\delta S = \delta \left(\int \frac{\mathrm{d}^4 x}{16\pi G} \sqrt{-g} R + S_{matter} \right) = 0$$

Basics of Scalar Tensor theories of Gravitation (II)

New action for the gravitational field coupled to matter:

spin 2

spin 0

$$S = \int \frac{d^4 x}{16\pi G}\sqrt{-g}\left[R - 2\partial^{\mu}\phi\partial_{\mu}\phi - V(\phi)\right] + S_m\left[\text{matter}; \bar{g}^{\mu\nu} = A^2(\phi) g^{\mu\nu}\right]$$

Basics of Scalar Tensor theories of Gravitation (III)

The modified Einstein (⇒Friedmann) equation :

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G T_{\mu\nu} \boxed{+ 2\partial_\mu \phi \partial_\nu \phi}$$

The modified Klein-Gordon equation :

$$\boxed{\partial^\mu \partial_\mu \phi = -4\pi G \alpha(\phi) T}$$

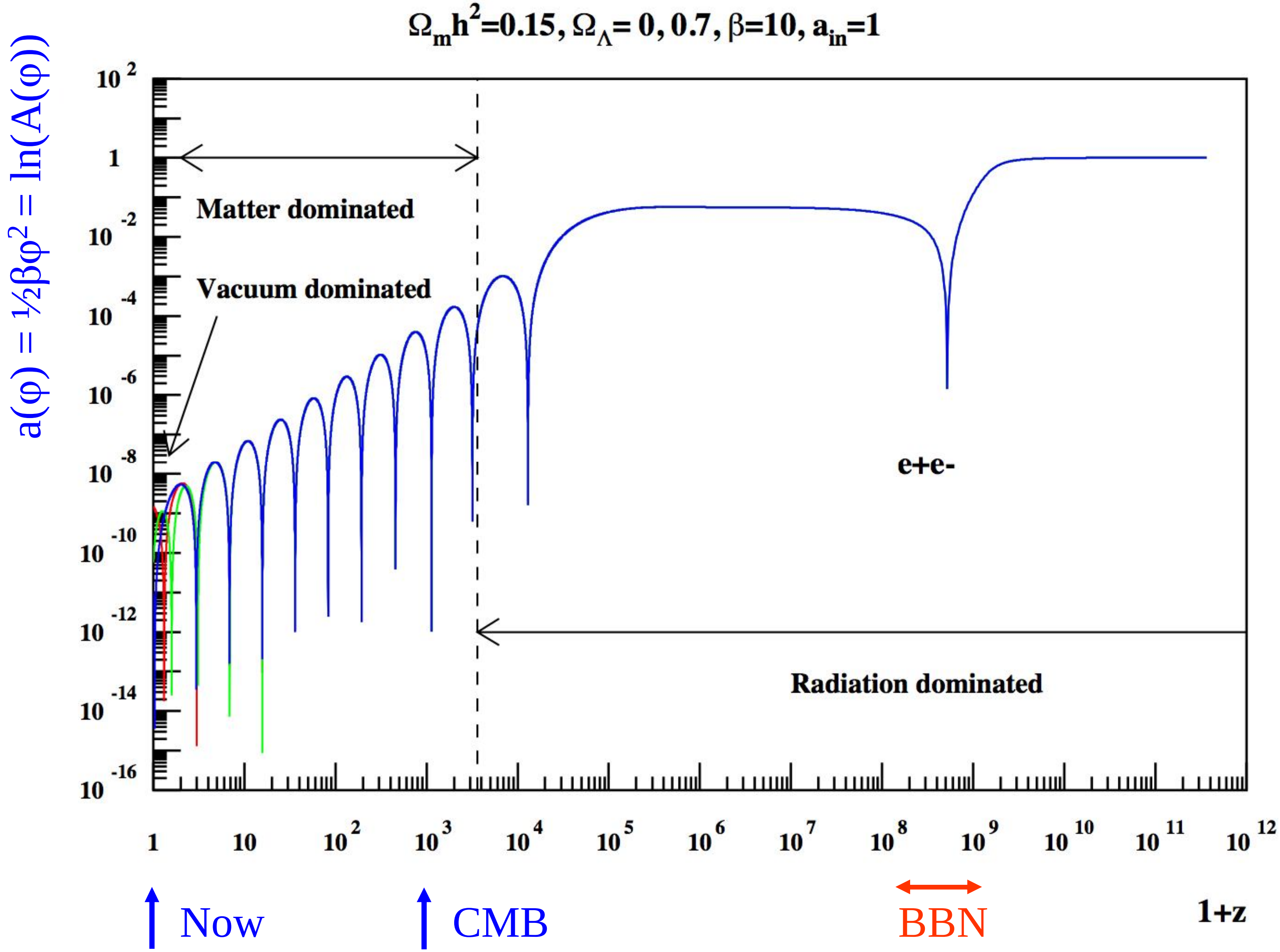
$T \equiv T^\mu{}_\mu \equiv \rho - 3p$ (=0 for radiation)

$$g^{\mu\nu} \rightarrow A^2(\phi) g^{\mu\nu} \qquad \ln(A(\phi)) \equiv \boxed{a(\phi)} \equiv \frac{1}{2} \boxed{\beta} \phi^2$$

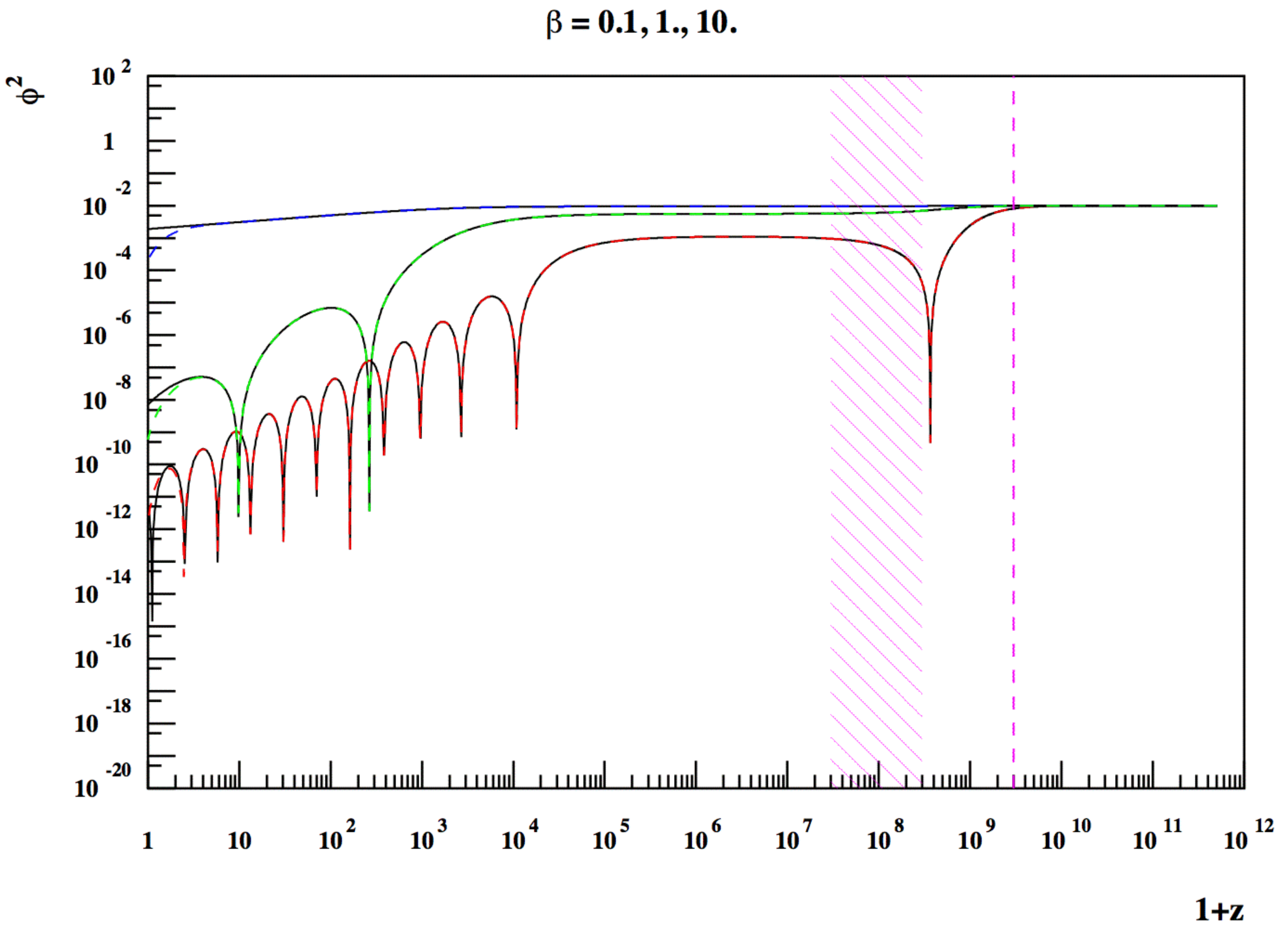
Parameters : β (attraction towards GR) and

$a_{in} \equiv \ln(A(\phi_{in}))$ (initial value at z~10^{12})

Evolution of the scalar component from $z=10^{12}$ until now



Effect of changing β



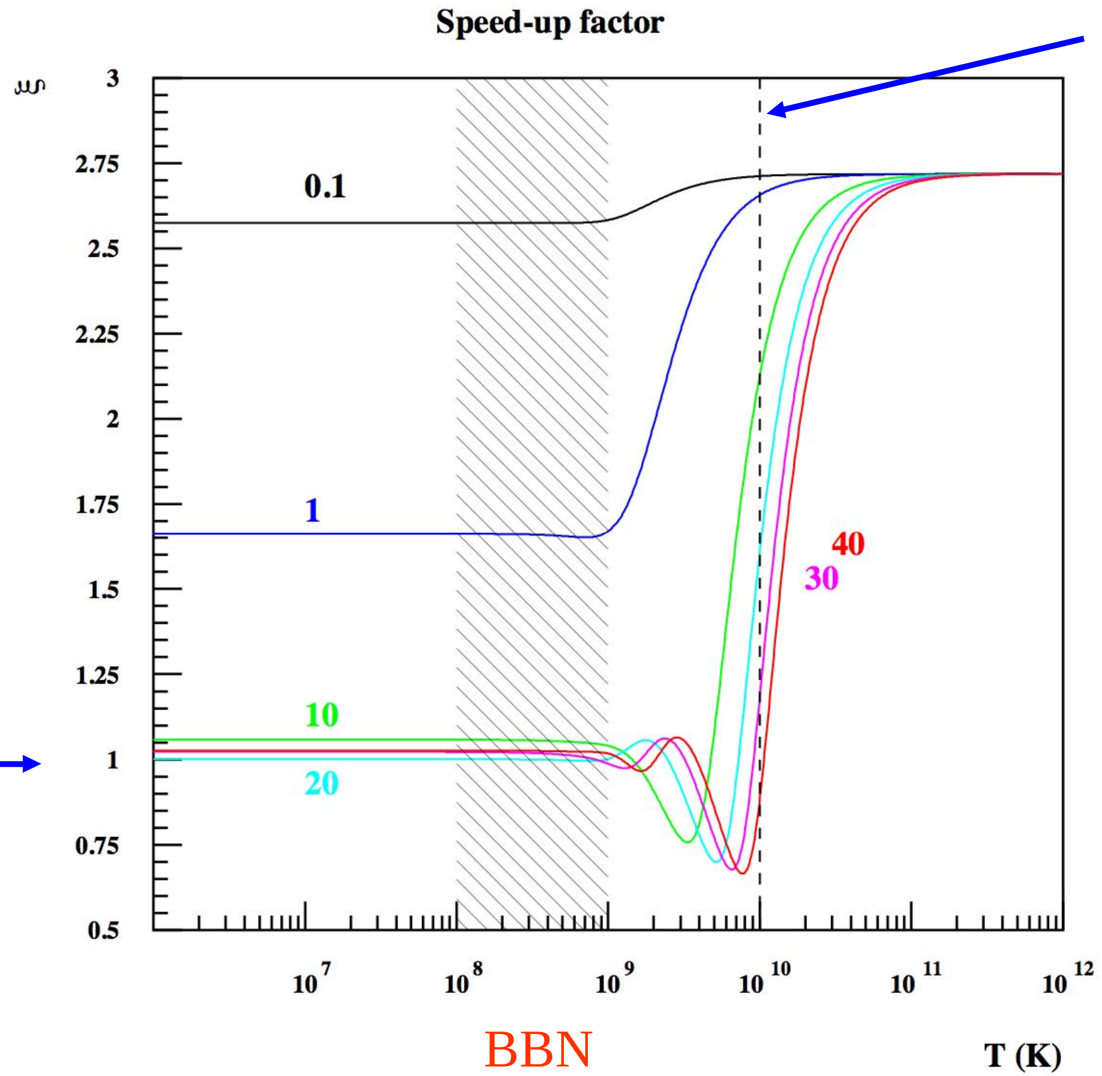
Modification of the expansion rate (H)

$$\xi \equiv H_{TSG} / H_{GR}$$

$$H \equiv \frac{\dot{a}}{a}$$

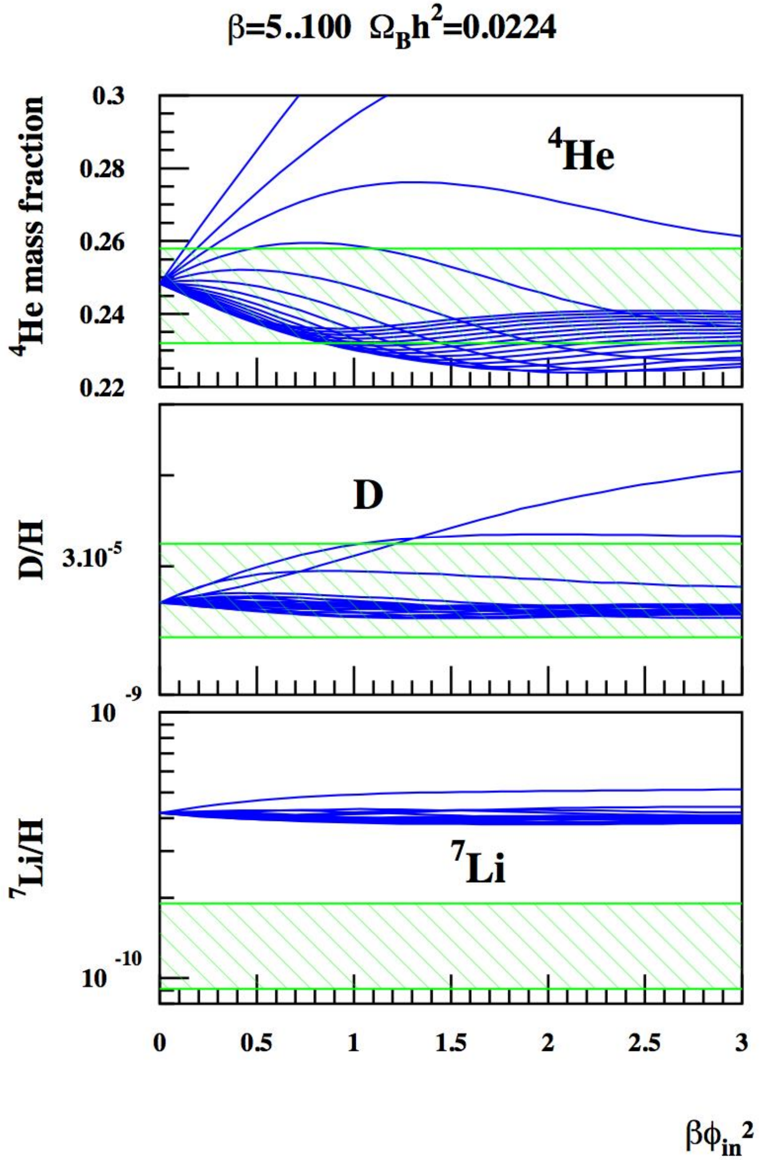
GR

n/p frezeout

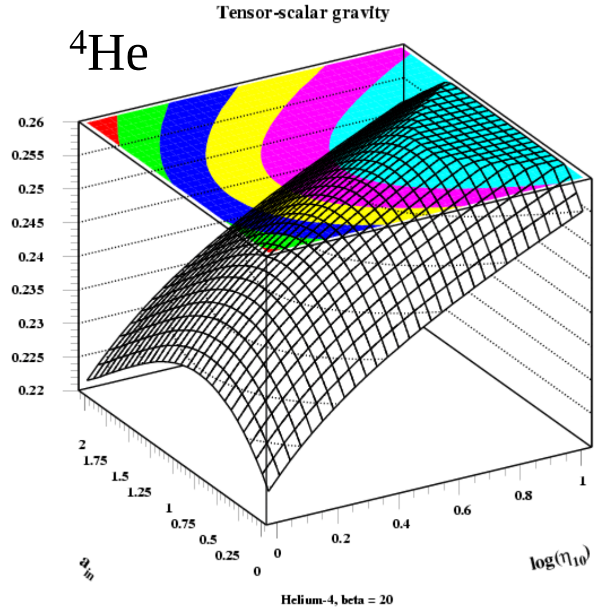


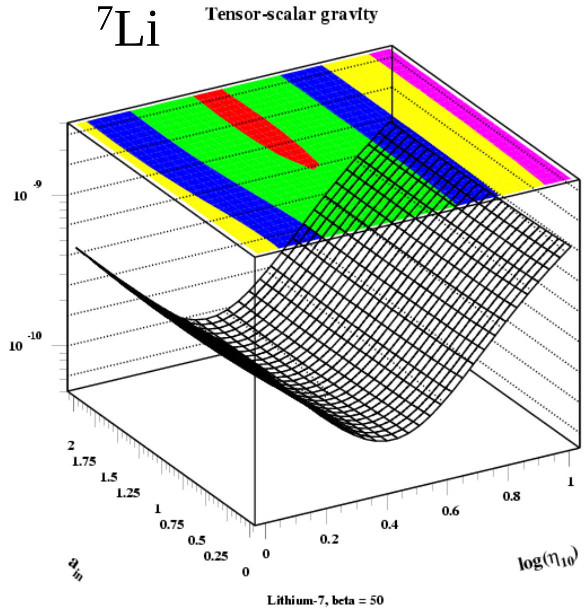
BBN

BBN constraints on Scalar Tensor theories of Gravitation



Coc, Olive, Uzan and Vangioni (2006)

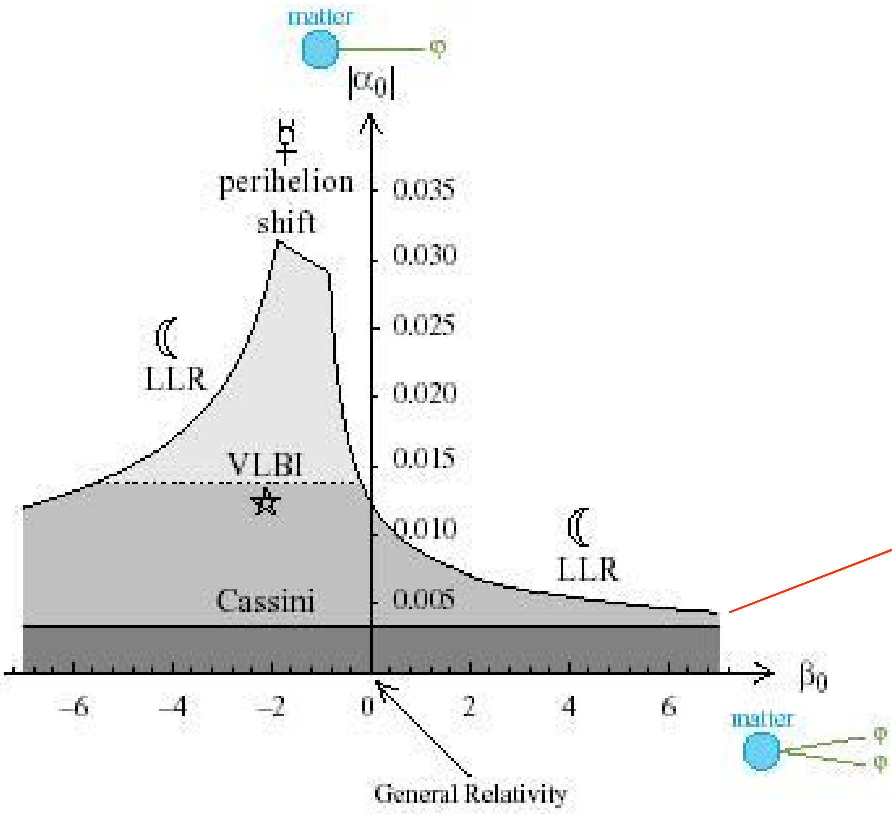




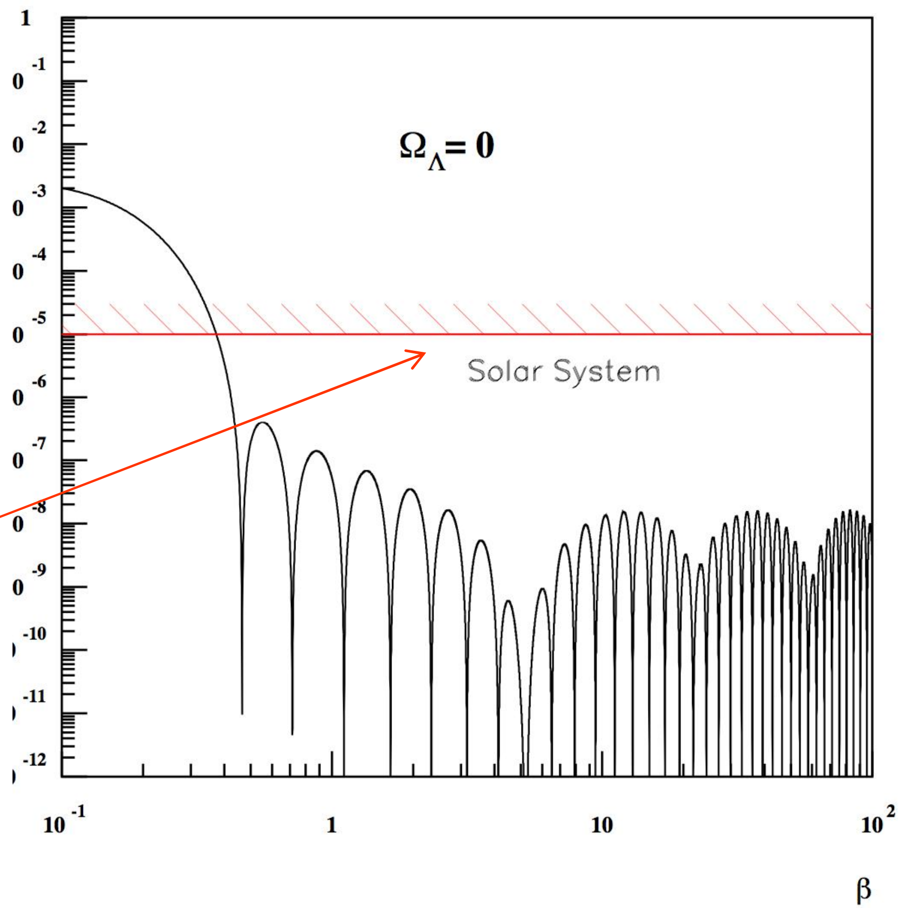
Constraints on Scalar Tensor theories of Gravitation

$$\alpha_0 \equiv \beta \times \phi_{z=0} \text{ and e.g. } G_{Cavendish} = G_{bare}(1+\alpha_0^2)$$

Solar System limits on α_0



BBN limits on α_0

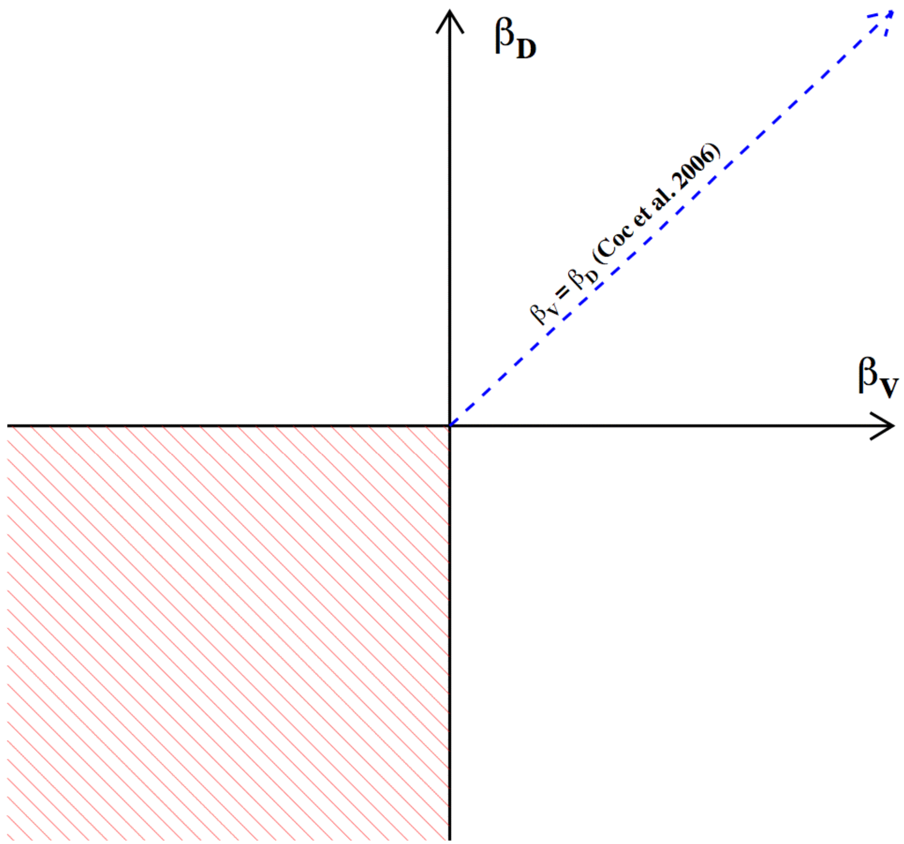


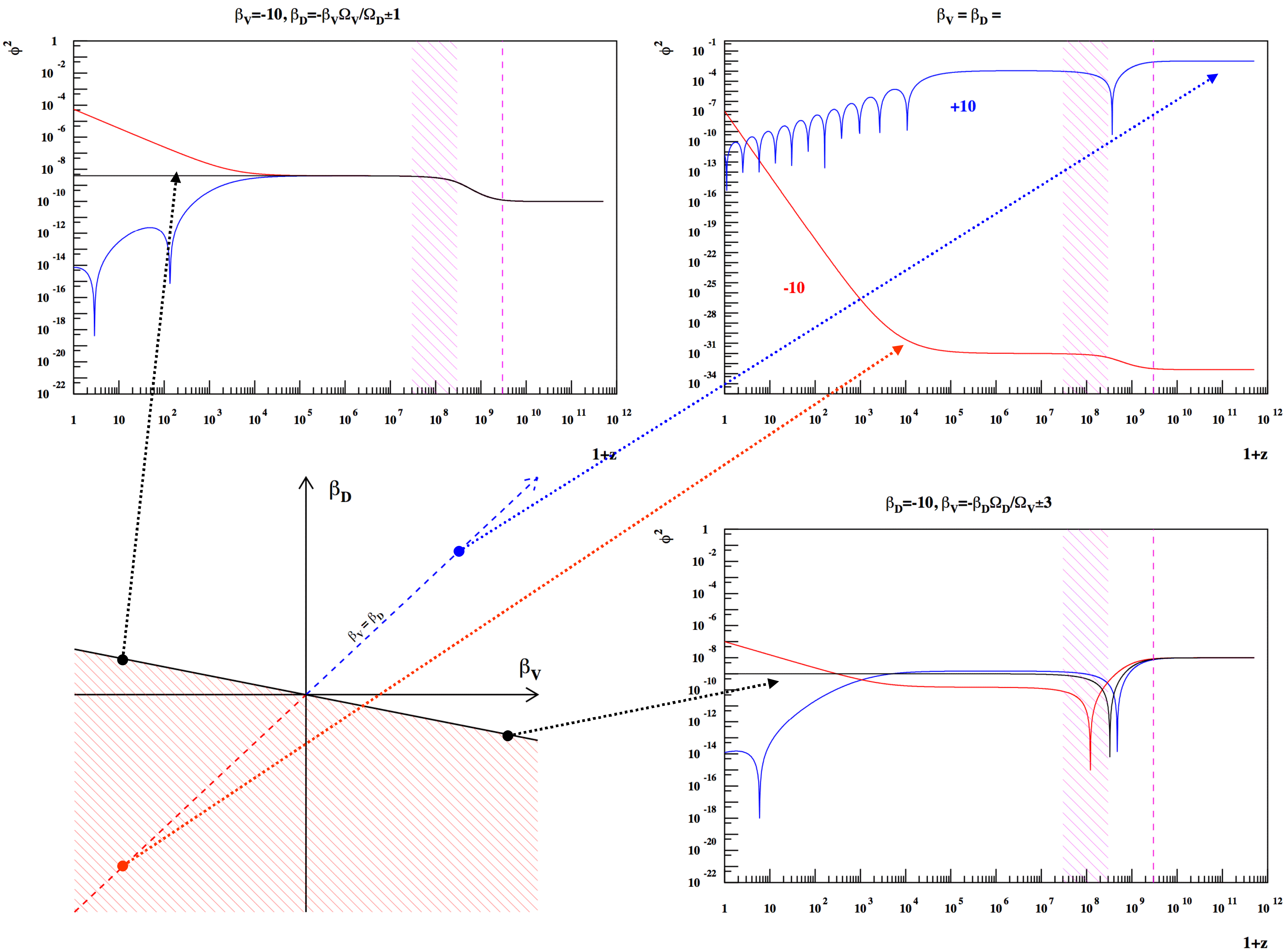
Constraints on Scalar Tensor theories of Gravitation

The coupling of the scalar field could be different for dark (D) and visible (V) matter *[Damour Gibbons & Gundlach, 1990]*.

Constraints from laboratory and solar system on the visible sector only!

- Determine the region in the $\beta_V \times \beta_D$ plane with attraction to GR *[Füzfa & Alimi, 2007]*
- Provide limits from BBN on scalar contribution



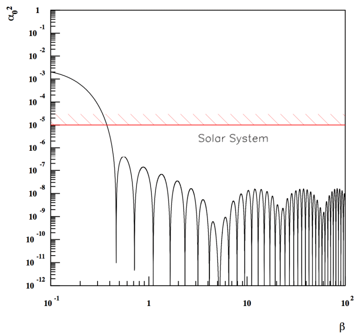


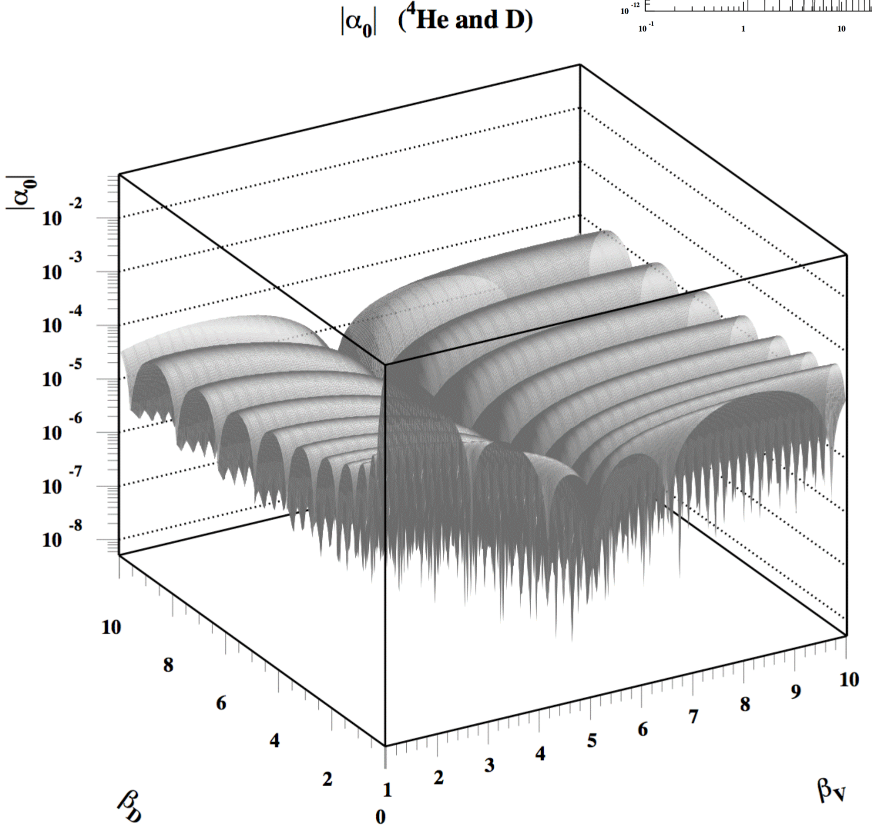
βV=-10, βD=-βVΩV/ΩD±1
βV = βD =
+10
-10
βD=-10, βV=-βDΩD/ΩV±3
φ2
1+z
βD
βV
βV = βD

BBN constraints on Scalar Tensor theories of Gravitation

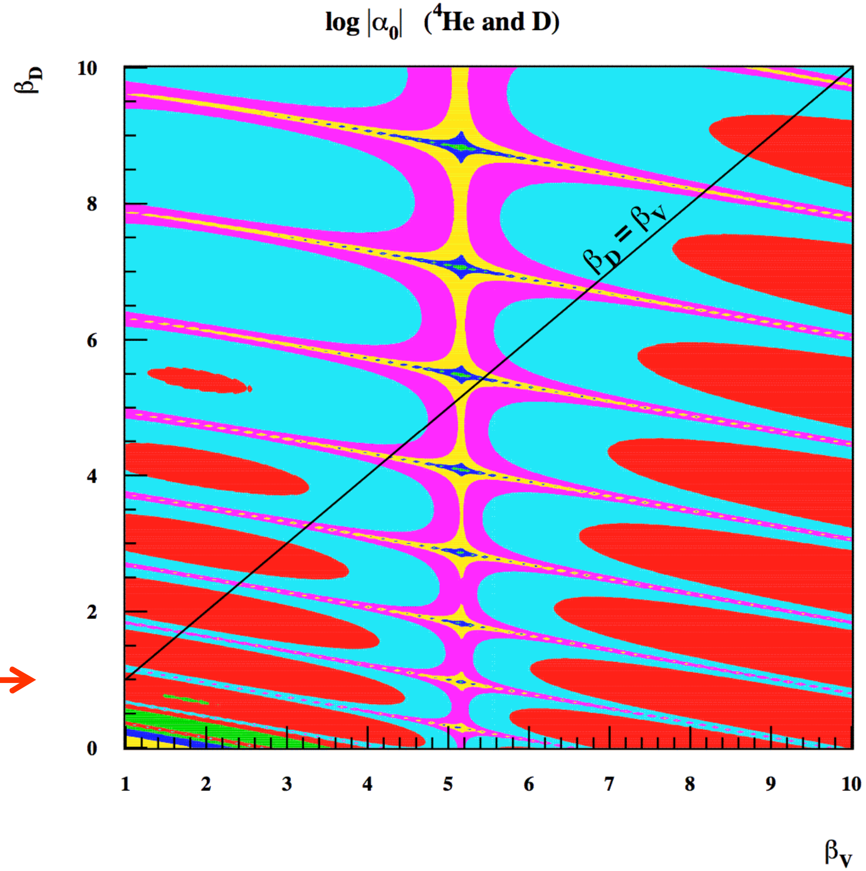
(~ 1 month on GRIF)

1D → 2D



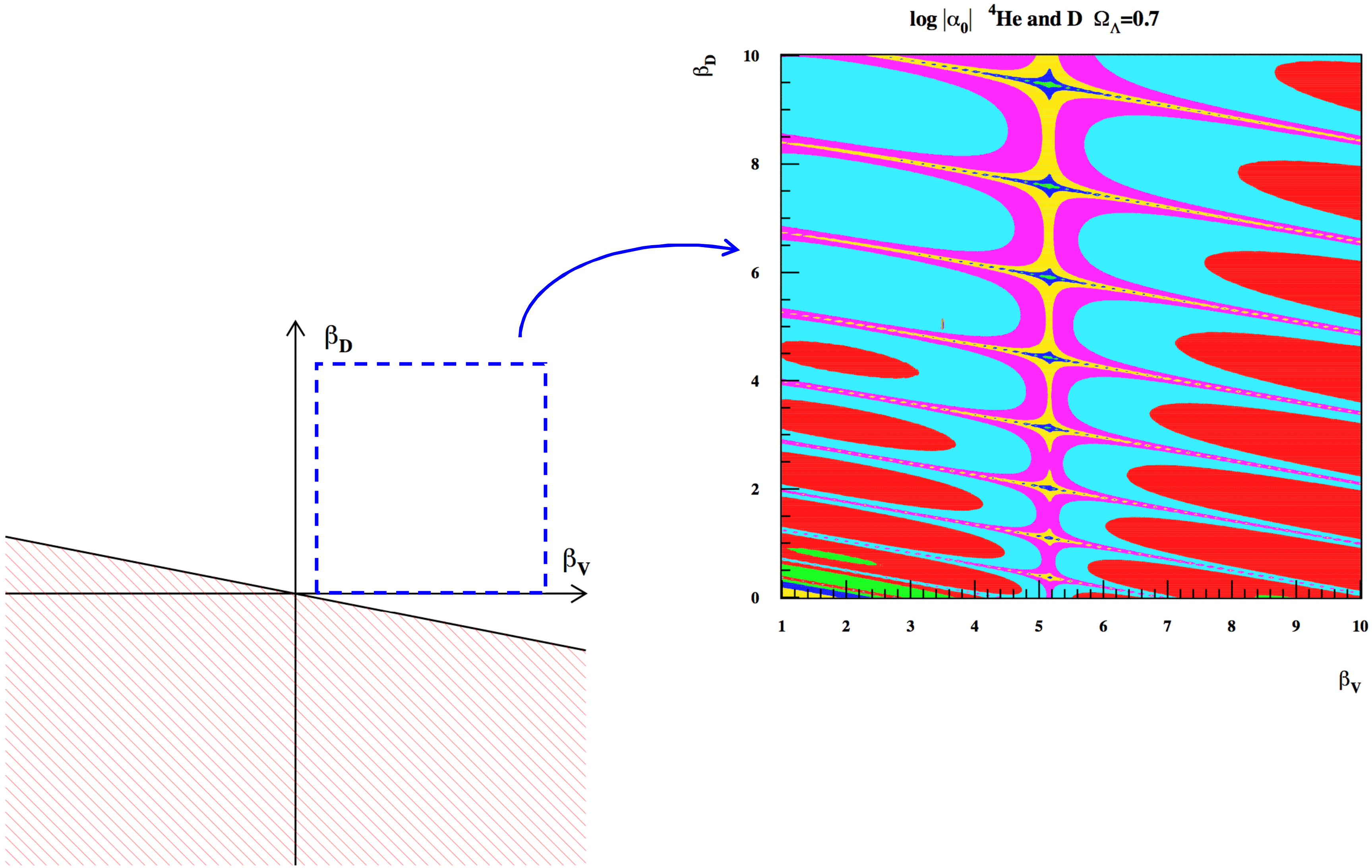


↔

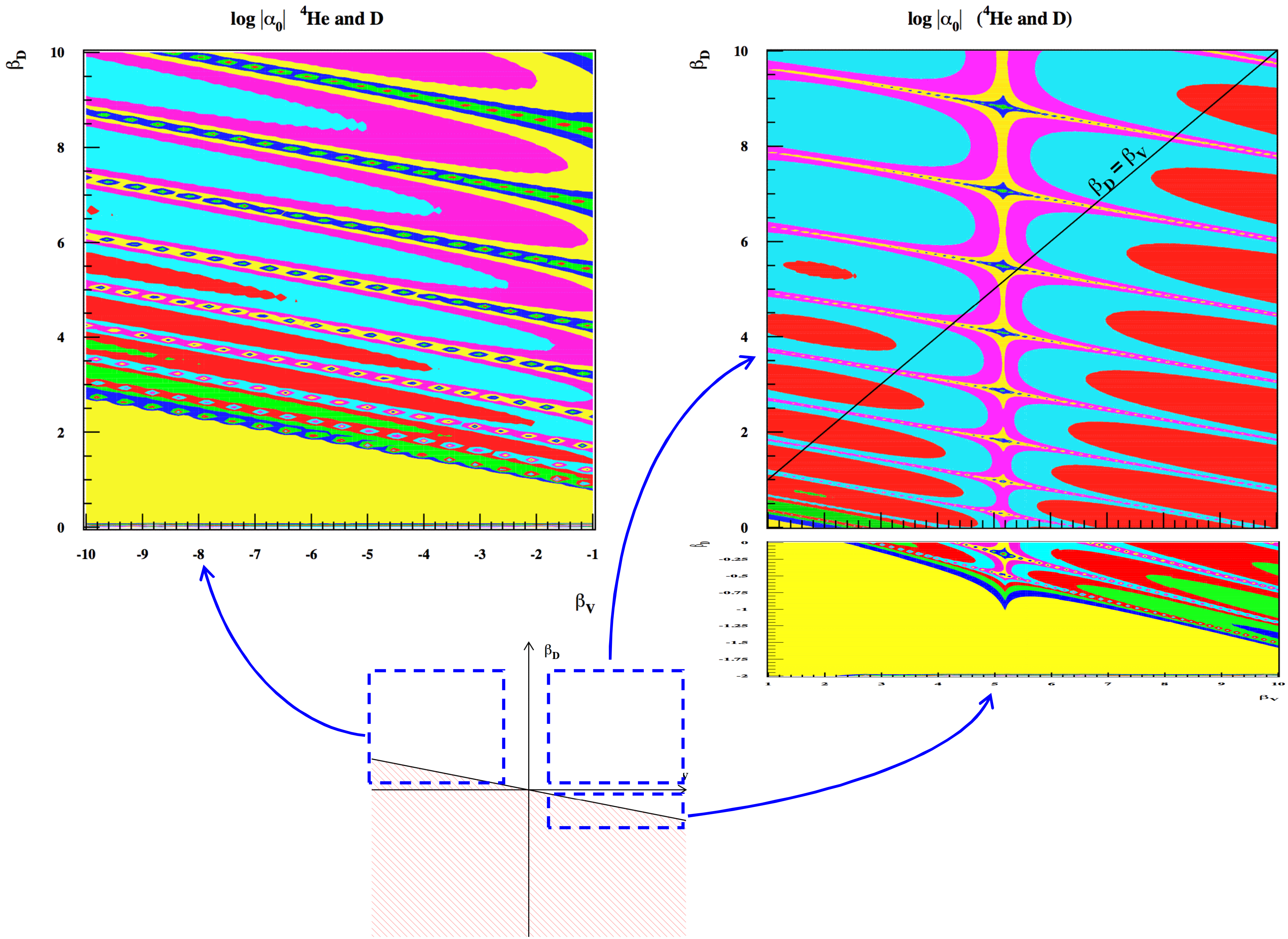


(No analytical solutions but structure understood.)

Coc, Olive, Uzan & Vangioni, 2009



β_D
β_V
log $|\alpha_0|$ ^{4}He and D Ω_Λ=0.7
β_D
0
2
4
6
8
10
1
2
3
4
5
6
7
8
9
10
β_V



log |α0| 4He and D
log |α0| (4He and D)
βD
βV
βD = βV
10
8
6
4
2
0
-10
-9
-8
-7
-6
-5
-4
-3
-2
-1

Beyond the Standard Model(s)

1. Non standard nucleosynthesis (Inhomogeneous BBN, relic particles, mirror neutrons)
2. Non standard expansion (extra Neff, Tensor-Scalar gravity)
3. Variation of constants (in stars, BBN,....)

Variation of the fundamental constants

Physical theories involve constants

These parameters cannot be determined by the theory that introduces them; we can only measure them.

These arbitrary parameters have to be assumed constant:

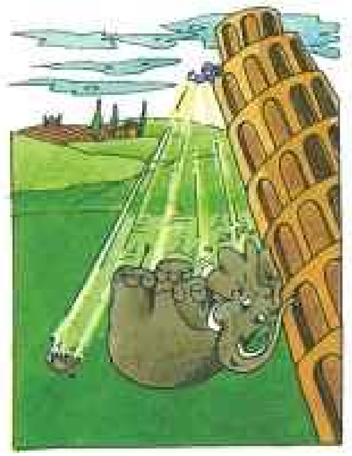
- *experimental validation*
- *no evolution equation*

1937 : Dirac develops his *Large Number hypothesis.*

Assumes that the gravitational constant was varying as the inverse of the age of the universe.

$$F_{grav}/F_{elec} = \frac{Gm_e m_p}{e^2/4\pi\varepsilon_0} \sim 10^{-40} \sim \frac{H_0 e^2/4\pi\varepsilon_0}{m_e c^3} = (t_U/\mathrm{atomic\ units})^{-1}$$

Equivalence principle and constants (© J.-Ph. Uzan)



In general relativity, any test particle follow a geodesic, which does not depend on the mass or on the chemical composition

Imagine some constants are space-time dependent

1- Local position invariance is violated.

2- Universality of free fall has also to be violated

Mass of test body = mass of its constituants + binding energy

In Newtonian terms, a free motion implies $\frac{d\vec{p}}{dt} = m\frac{d\vec{v}}{dt} = \vec{0}$

But, now

$$\frac{d\vec{p}}{dt} = \vec{0} = m\vec{a} + \underbrace{\frac{dm}{d\alpha}\dot{\alpha}\vec{v}}_{m\vec{a}_{\mathrm{anomalous}}}$$

Variation of the fundamental constants

- Theoretical motivations from string theories, extra dimensions,..

In string theory, the value of any constant depends on the geometry and volume of the extra-dimensions

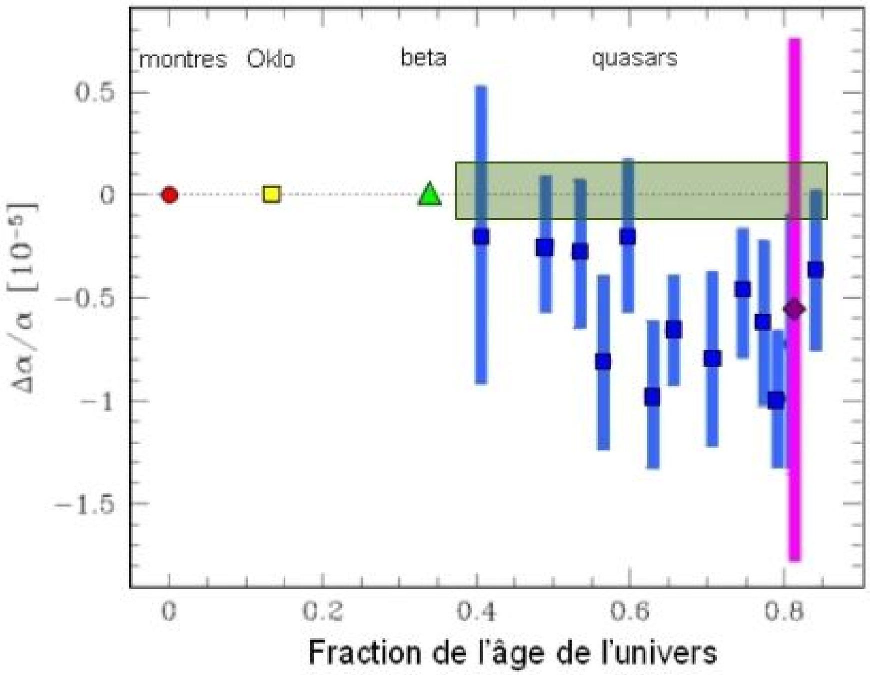
• Opens a window the extra-dimensions
• Why do the constants vary so little ?
• Why have the constants the value they have ?
• Related to the equivalence principle and allow tests of GR on astrophysical scales *[dark matter/dark energy vs modified gravity debate]*

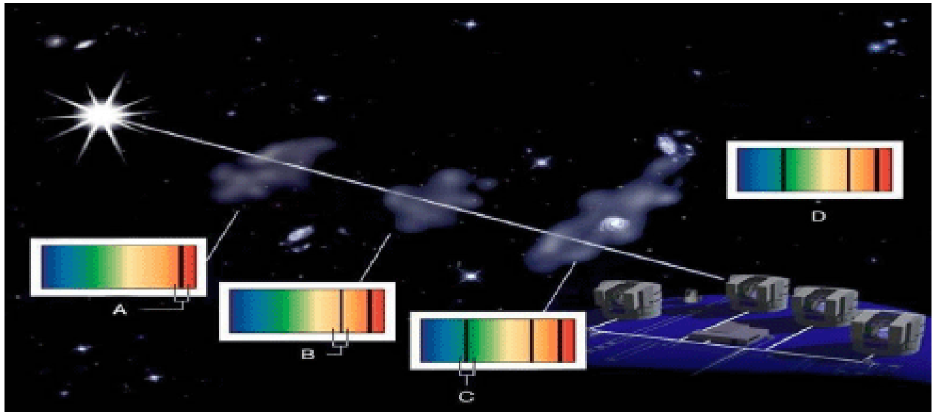
- Claim of an observed variation of the fine structure constant

Very small variations, best studied on cosmological scales, from astronomical observations

See reviews : *J.-P. Uzan in* Rev. Mod Phys. *2003*, Living Rev. Relativity *2011; E. García-Berro, J. Isern & Y.A. Kubishin in* Astron. Astrophys. Rev. *2007*

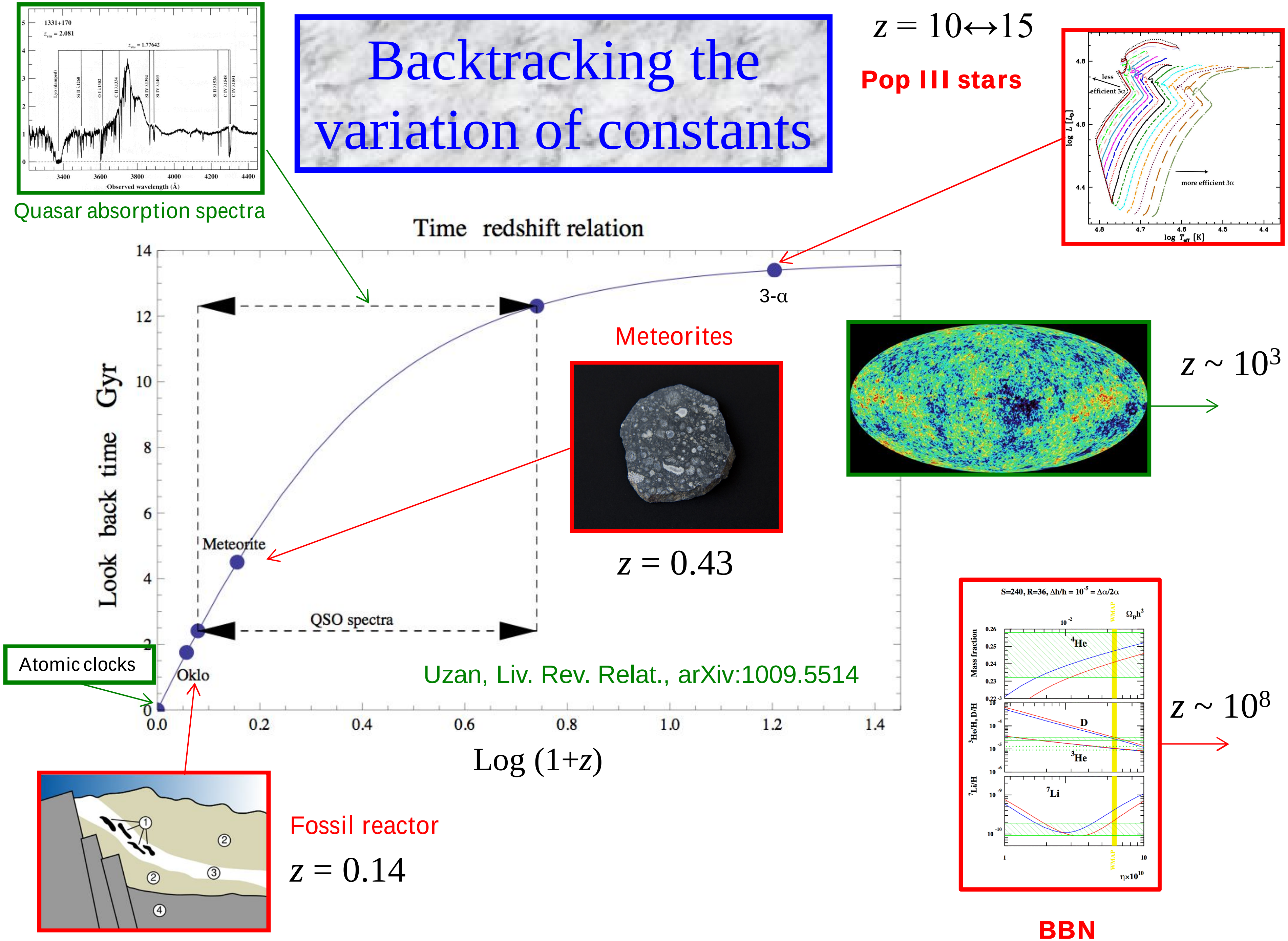
Possible variation of fine structure constant





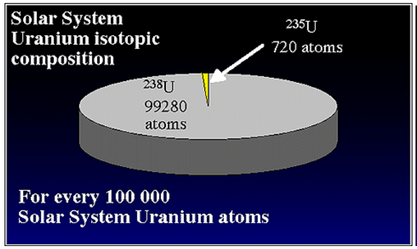
- Claim of an observed variation of the fine structure constant
  - $\Delta\alpha/\alpha = (-0.57 \pm 0.10) \times 10^{-5}$ at Keck/Hires *[Webb+ 1999; Murphy+ 2003]*
  - $\Delta\alpha/\alpha = (-0.06 \pm 0.06) \times 10^{-5}$ at VLT *[Chand+ 2004]*
  - Dipole in the spatial distribution ? *[King+ 2012]*

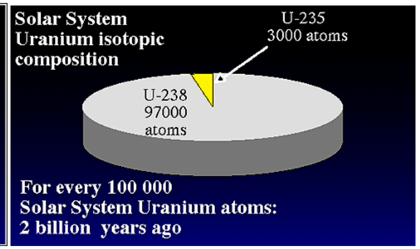
Backtracking the variation of constants



Oklo- a natural nuclear reactor

It operated 2 billion years (2 Gy) ago, during 200 000 years !!





Samarium isotope ratio abnormally low

$^{149}\mathrm{Sm} + \mathrm{n} \rightarrow {}^{150}\mathrm{Sm} + \gamma$ resonant absorption at $E_R = 0.0973$ eV

Variation of $\alpha \Rightarrow$ variation of the Coulomb energy in ^{149}Sm and ^{150}Sm* $\Rightarrow$ shift of the resonance energy E_R

$$\Delta\alpha/\alpha = (0.5 \pm 1.05) \times 10^{-7} \text{ over 2 Gy}$$

Damour, Dyson, NPB **480** (1996) 37

Variation of Constants in Meteorites : ^{187}Re

Peebles & Dicke 1962; Dyson 1972

^{187}Re : a very long lived isotope 63% of terrestrial Re

$^{187}Re \rightarrow {}^{187}Os + \beta^+$ $0.693/\lambda_{Lab} = 42.3 \times 10^9$ years half-life

$^{187}Os|_{Now} = {}^{187}Os|_{Initial} + {}^{187}Re_{Now}[\exp(<\lambda>/(t_{Initial}-t_{Now})-1]$ isochron

With $<\lambda>$ the *averaged* lifetime over $t_{Initial}-t_{Now} = 4.6$ Gy

$$\lambda \propto G_F^2 Q_\beta^3 m_e^2 \qquad \frac{\Delta\lambda}{\lambda} = 3\frac{\Delta Q_\beta}{Q_\beta} = \frac{3}{Q_\beta}\frac{(Z+1)^2 - Z^2}{A^{1/3}} a_C \frac{\Delta\alpha}{\alpha}$$

$(\lambda_{Lab} - <\lambda>)/\lambda_{Lab} = -0.016 \pm 0.016$

$Q_\beta = 2.66$ keV; $a_C = 0.717$ MeV; $Z = 75$

$-24 \times 10^{-7} < \Delta\alpha/\alpha < 8 \times 10^{-7}$ over 4.6 Gy

Olive et al. 2004

Variation of Constants in Massive Pop. III stars

- Astrophysical context
  - Born within a few 10^8 years, typical redshift $z \sim 10 - 15$
  - First stars were probably very massive : $30\ M_\odot < M < 300\ M_\odot$ (but theoretically uncertain)
  - Zero metallicity (BBN abundances) ⇒Very peculiar stellar evolution
  - Observations of metal-poor stars (Pop. II) allow us to investigate the first objects (Pop. III) formed after the Big Bang
  - Constraint from C and O observations in Pop. II
  - Learn about the formation of the elements and nucleosynthesis processes, and how the Universe became enriched with heavy elements

The triple alpha reaction, stellar evolution and variation of fundamental constants

- ^{12}C production and variation of the strong interaction *[Rozental 1988]*
- C/O in Red Giant stars *[Oberhummer et al. 2000; 2001]*
  - 1.3, 5 and 20 $M_\odot$ stars, $Z=Z_\odot$ up to TP-AGB
  - Limits on effective N-N interaction ($|\delta_{NN}| < 5\ 10^{-3}$ and $|\Delta\alpha/\alpha| < 4\ 10^{-2}$)
- C/O in low, intermediate and high mass stars *[Schlattl et al. 2004]*
  - 1.3, 5, 15 and 25 $M_\odot$ stars, $Z=Z_\odot$ up to TP-AGB / SN
  - Limits on resonance energy shift ($-5 < \Delta E_R < +50$ keV)
- This study : stellar evolution of massive Pop. III stars
  - We choose ***typical*** masses of 15 and 60 $M_\odot$ stars
  - Triple alpha influence in both He and H burning
  - Limits on effective N-N interaction and on fundamental couplings

Importance of the triple-alpha reaction

- Helium burning (T = 0.2-0.3 GK)
  - Triple alpha reaction $3\alpha \rightarrow {}^{12}C$
  - Competing with ${}^{12}C(\alpha,\gamma){}^{16}O$
- Hydrogen burning ($T \approx$ 0.1 GK)
  - Slow pp chain (at Z = 0)
  - CNO with C from $3\alpha \rightarrow {}^{12}C$
- Three steps :
  - $\alpha\alpha \leftrightarrow {}^{8}Be$ (lifetime ~ 10^{-16} s) leads to an equilibrium
  - ${}^{8}Be + \alpha \rightarrow {}^{12}C^*$ (288 keV, l=0 resonance, the "Hoyle state")
  - ${}^{12}C^* \rightarrow {}^{12}C + 2\gamma$
- Resonant reaction unlike e.g. ${}^{12}C(\alpha,\gamma){}^{16}O$
  - Sensitive to the position of the "Hoyle state"
  - Sensitive to the variation of "constants"

The “Hoyle state”

Phys. Rev. 92 (1953) 1095

SESSIONS N AND O 1095

N6. A State in C^{12} Predicted from Astrophysical Evidence.* F. Hoyle, *Cambridge University* and D. N. F. Dunbar, W. A. Wenzel, and W. Whaling, *Kellogg Radiation Laboratory, California Institute of Technology.*—It is assumed that oxygen and carbon are produced in stars that have largely exhausted their central hydrogen by the reactions: $2He^4 \rightarrow Be^8$; $Be^8 + He^4 \rightarrow C^{12}$; $C^{12} + He^4 \rightarrow O^{16}$. The observed cosmic abundance ratio of He:C:O can be made to fit the yields calculated for these reactions if the reaction $Be^8(\alpha, \gamma)C^{12}$ has a resonance near 0.31 Mev, corresponding to a level at 7.68 Mev in C^{12}.[1] A level had previously been reported at 7.5 Mev.[2] The 16-in. double-focusing magnetic spectrometer has been used in an analysis of the α-spectrum from $N^{14}(d, \alpha)C^{12}$ covering the excitation energy range from 4.4 to 9.2 Mev in C^{12}. The level was found at 7.68 ± 0.03 Mev. No other levels were found, although a group 1 percent as strong as the transition to the 4.4-Mev state could have been detected. At $E_d = 620$ kev, $\theta_{lab} = 90°$, the transition to the 7.68-Mev state is 6 percent as strong as that to the state at 4.43 Mev.

* Assisted in part by the joint program of the U. S. Office of Nava Research and the U. S. Atomic Energy Commission.
[1] F. Hoyle, to appear in the Astrophys. J.
[2] See F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **24**, 321 (1952).

- Observation of the level at predicted energy *[Dunbar, Pixley, Wenzel & Whaling, PR 92 (1953) 649]* from $^{14}N(d,\alpha)^{12}C^*$
- Observation of its decay by $^{12}B(\beta^-)^{12}C^* \rightarrow \alpha + ^8Be$ and confirmation of $J^\pi = 0^+$ *[Cook, Fowler, Lauritsen & Lauritsen PR 107 (1957) 508]*

“The Synthesis of the Elements” by G. Shaviv

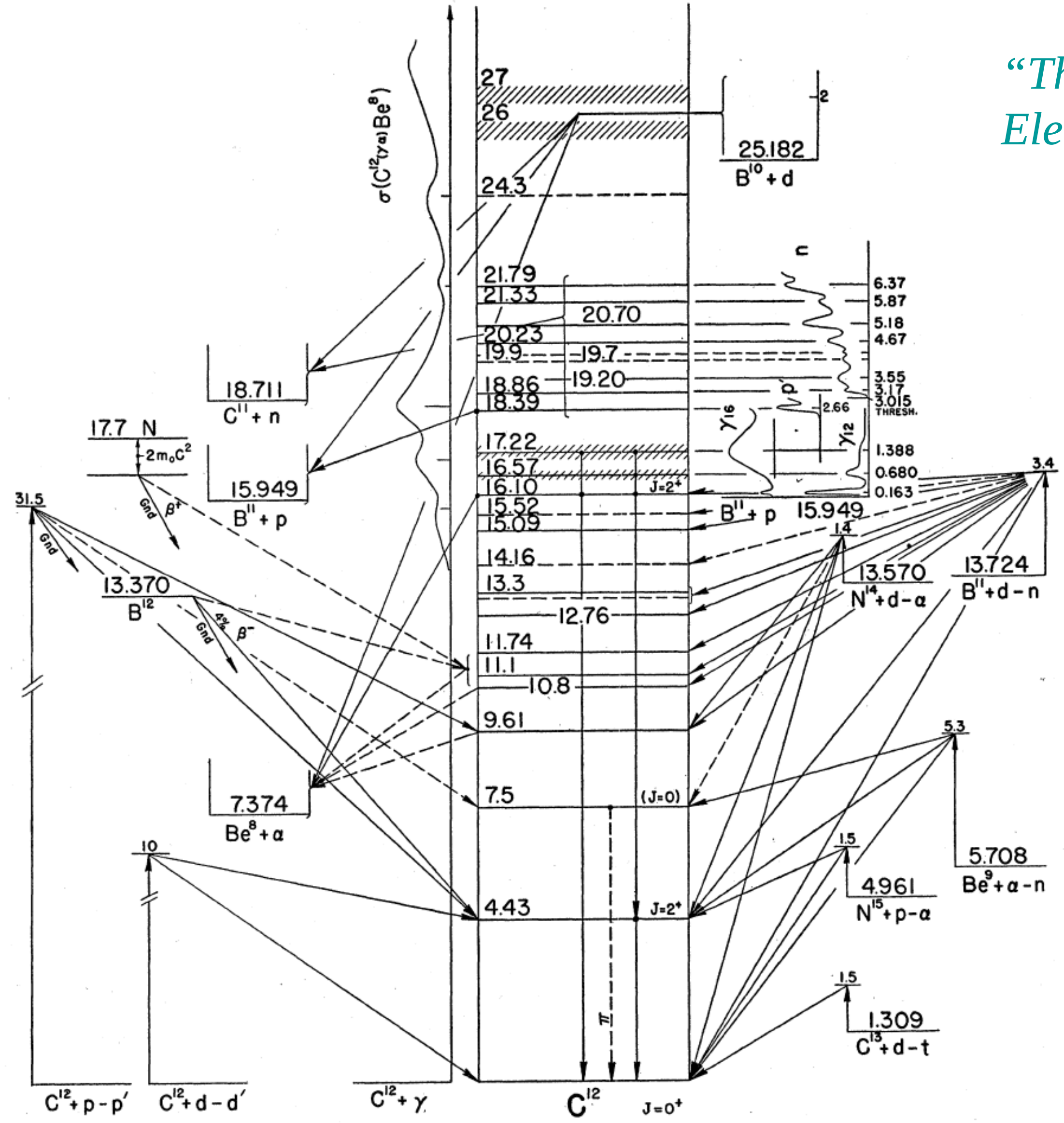


Fig. 15. Energy levels of C^{12}: for notation, see Fig. 1.

Ajzenberg & Lauritsen (1952)

The triple-alpha reaction

1. Equilibrium between ^{4}He and the short lived (~10^{-16} s) ^{8}Be : $\alpha\alpha \leftrightarrow {}^{8}$Be
2. Resonant capture to the (l=0, $J^{\pi}=0^{+}$) Hoyle state: $^{8}\mathrm{Be}+\alpha \rightarrow {}^{12}\mathrm{C}^{*} (\rightarrow {}^{12}\mathrm{C}+\gamma)$

Simple formula used in previous studies

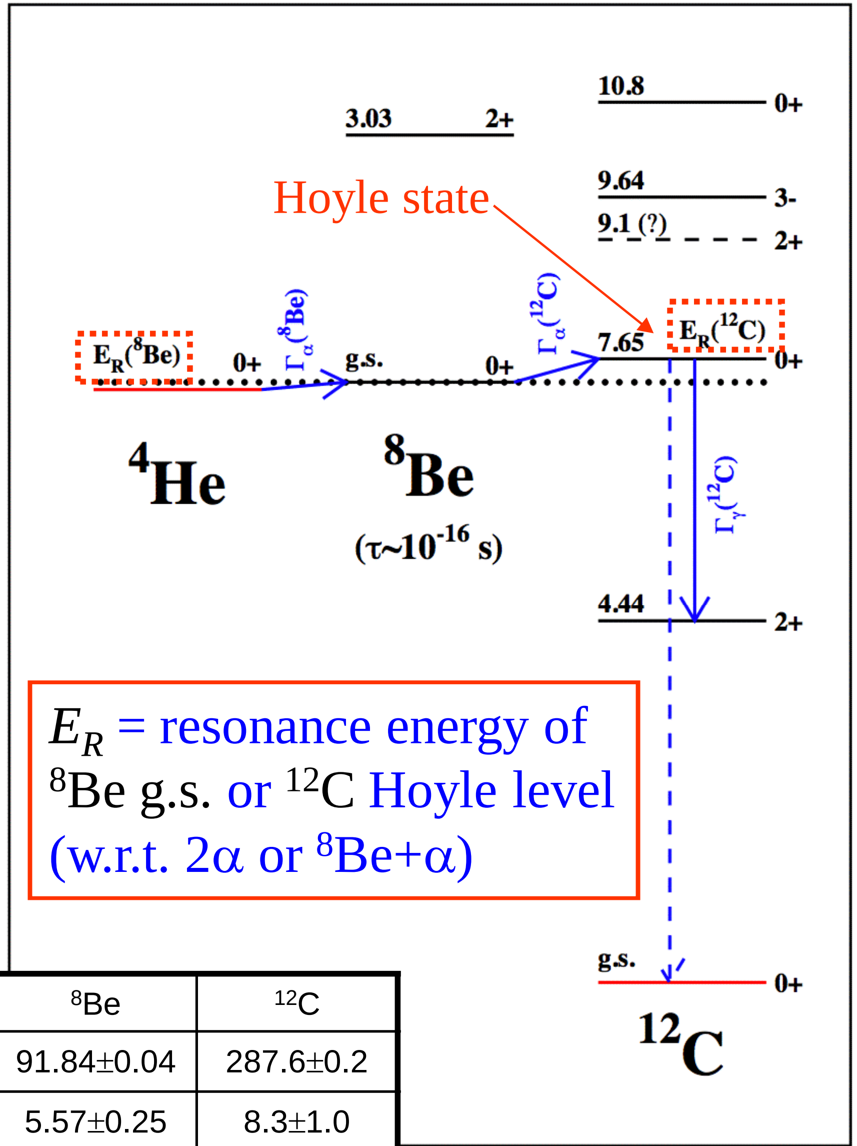
1. Saha equation (thermal equilibrium)
2. Sharp resonance analytic expression:

$$N_A^2 \langle \sigma v \rangle^{\alpha\alpha\alpha} = 3^{3/2} 6 N_A^2 \left(\frac{2\pi}{M_\alpha k_B T} \right)^3 \hbar^5 \gamma \exp\left(\frac{-Q_{\alpha\alpha\alpha}}{k_B T} \right)$$

with $Q_{\alpha\alpha\alpha} = E_R(^{8}\mathrm{Be}) + E_R(^{12}\mathrm{C})$ and $\gamma \approx \Gamma_\gamma$

Approximations

1. Thermal equilibrium
2. Sharp resonance
3. ^{8}Be decay faster than α capture



E_R = resonance energy of ^{8}Be g.s. or ^{12}C Hoyle level (w.r.t. 2α or ^{8}Be+α)

Nucleus	^{8}Be	^{12}C
E_R (keV)	91.84±0.04	287.6±0.2
Γ_α (eV)	5.57±0.25	8.3±1.0
Γ_γ (meV)	-	3.7±0.5

Nuclear microscopic calculations

- Hamiltonian:

$$H = \sum_{i=1}^{A} T(r_i) + \sum_{i<j=1}^{A} \left(V_{Coul.}(r_{ij}) + V_{Nucl.}(r_{ij}) \right)$$

Where $V_{Nucl.}(r_{ij})$ is an effective Nucleon-Nucleon interaction

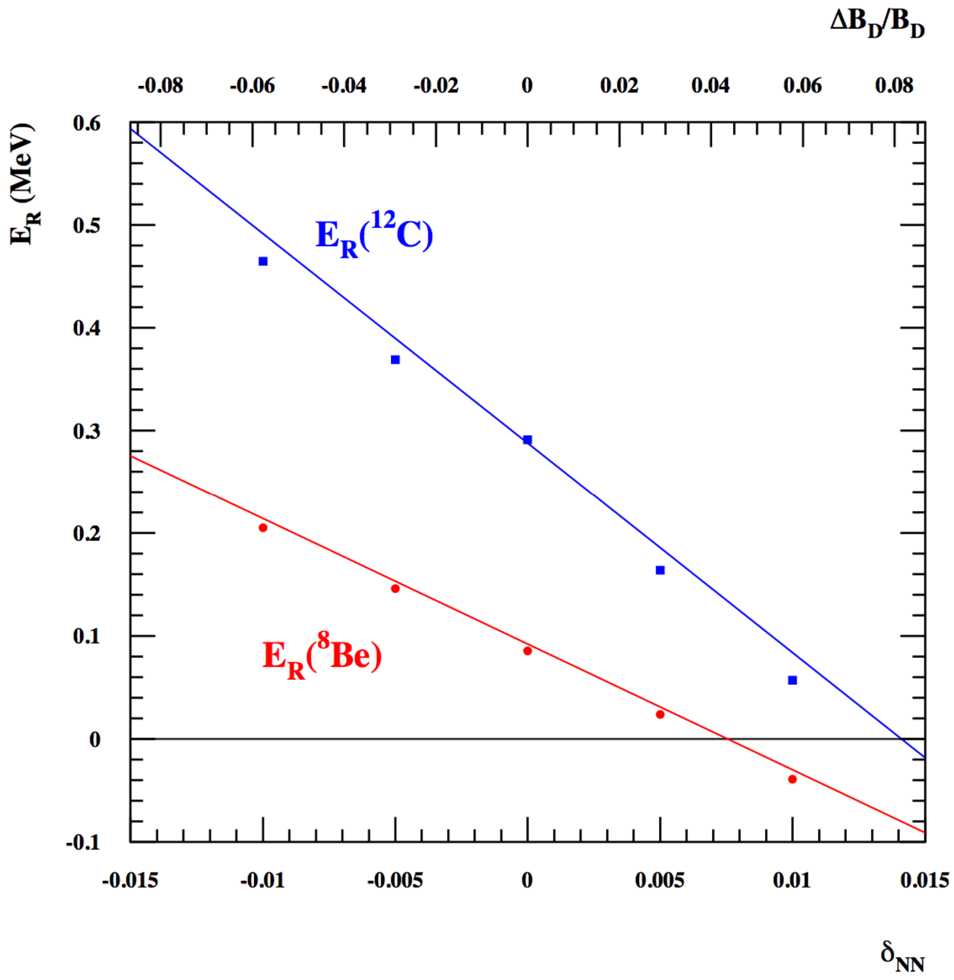
- Minnesota N-N force *[Thompson et al. 1977]* optimized to reproduce low energy N-N scattering data and B_D (deuterium binding energy)

- α-cluster approximation for $^{8}Be^{g.s.}$ (2α) and the Hoyle state (3α) *[Kamimura 1981]*

- Scaling of the N-N interaction

$$V_{Nucl.}(r_{ij}) \rightarrow (1+\delta_{NN}) \times V_{Nucl.}(r_{ij})$$

to obtain B_D, $E_R(^{8}Be)$, $E_R(^{12}C)$ as a function of δ_{NN} :



- Link to fundamental couplings through B_D or δ_{NN}

Numerical rate calculation

❑ At “low temperatures”, capture via resonance tails *[Nomoto et al. 1985]* requires numerical integration

➢ Even more important when resonances are shifted upwards with larger widths

• Radiative widths : $\Gamma_\gamma(E) \propto E^{2L+1}$ (with L=2 here)

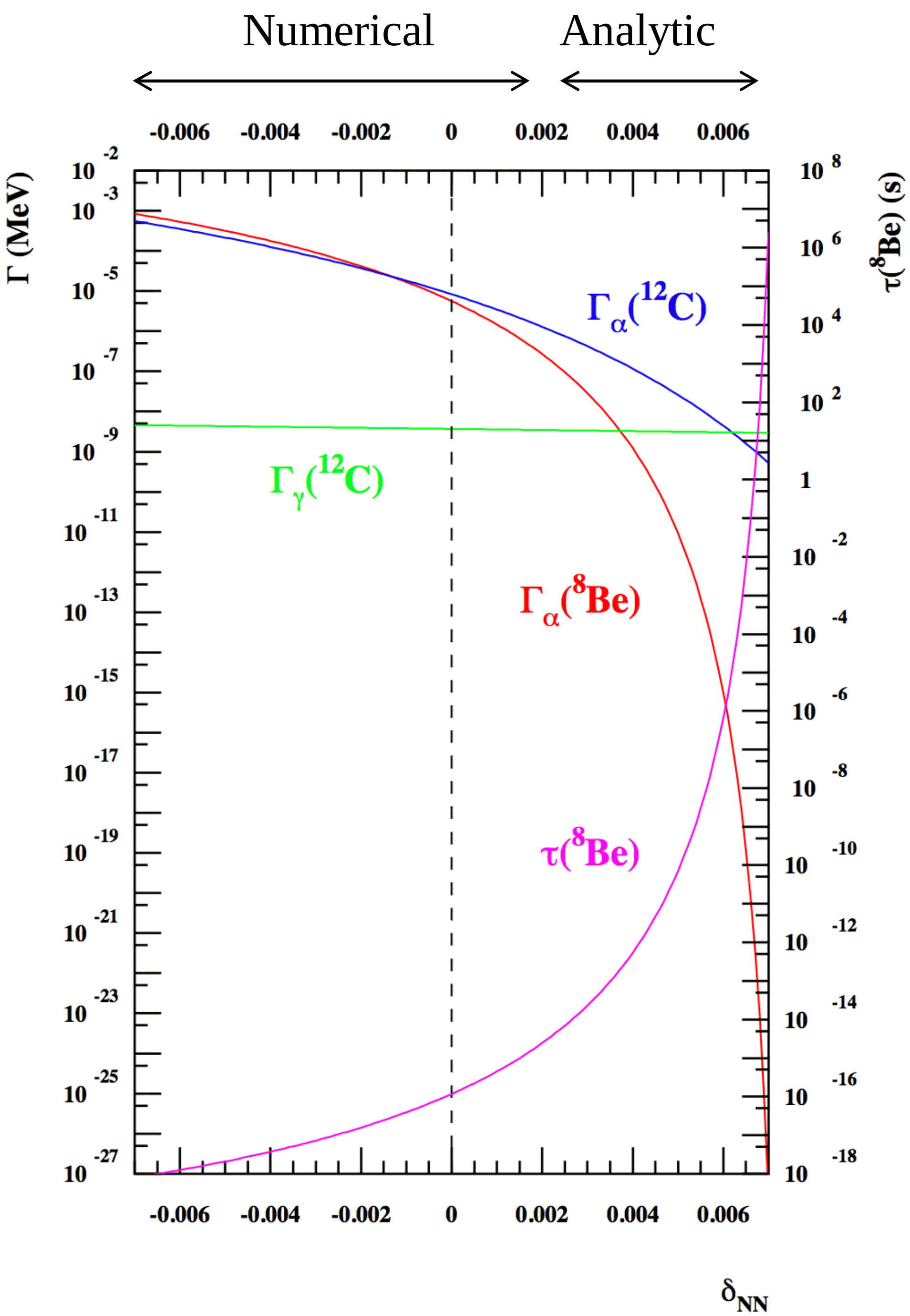
• Charged particle widths :

$\Gamma_\alpha(E) = \Gamma_\alpha(E_R)\, P_L(E,R_C) \,/\, P_L(E_R,R_C)$ with

$P_L(E,R_C) =\propto (F_L^2(\eta,kR_C)+G_L^2(\eta, kR_C))^{-1}$

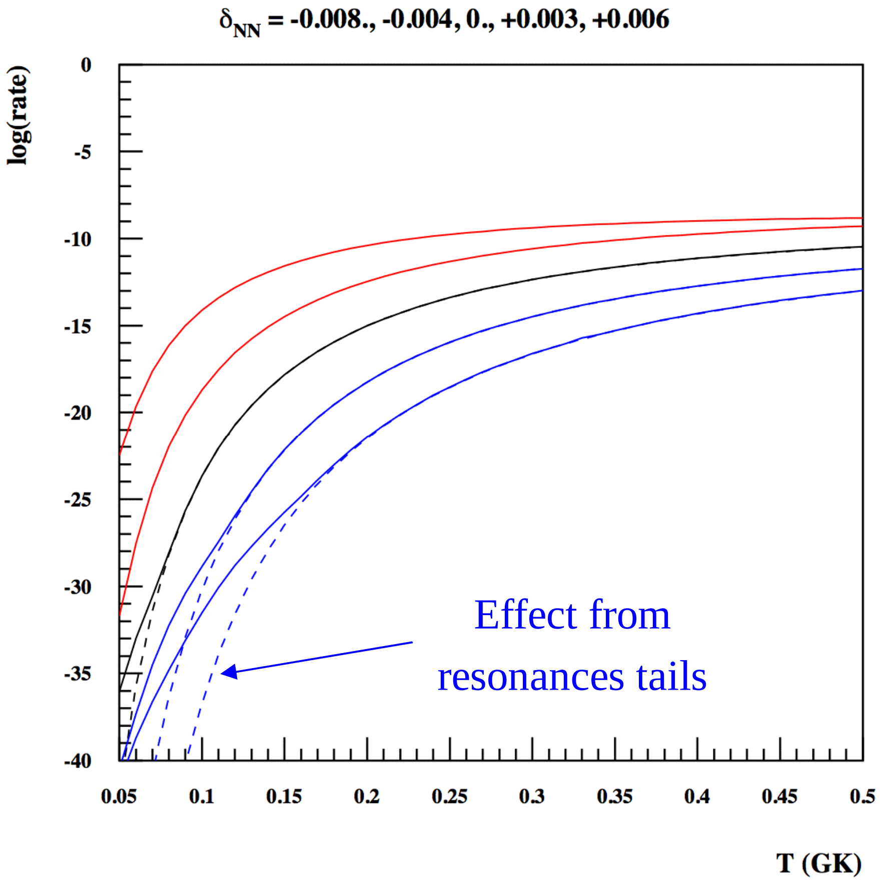
the penetrability

$\gamma \equiv \Gamma_\alpha(E)\, \Gamma_\gamma(E) \,/\, (\Gamma_\alpha(E) + \Gamma_\gamma(E)) \approx \Gamma_\gamma(E)$
if $\Gamma_\gamma(E) << \Gamma_\alpha(E)$ in analytic expression

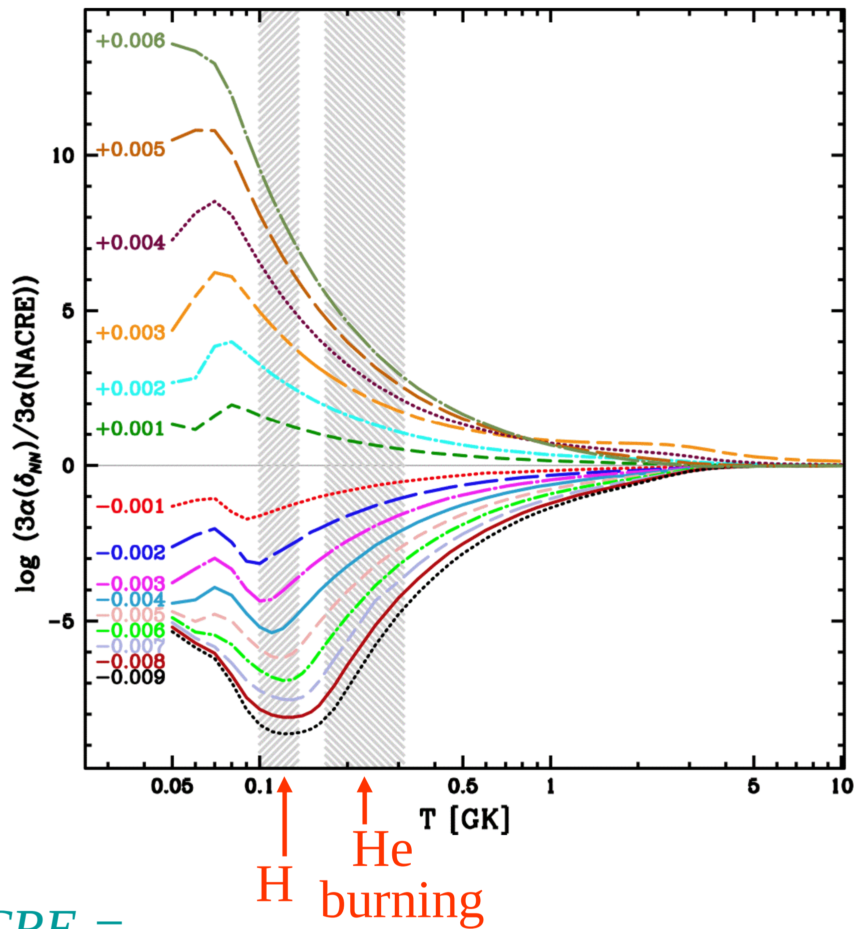


Calculated rates compared to NACRE

Rates



Rates / NACRE



NACRE =

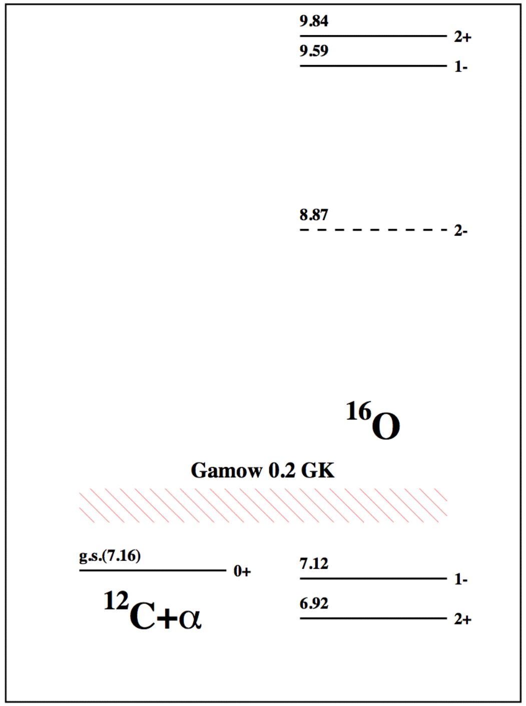
“A compilation of charged-particle induced thermonuclear reaction rate”,

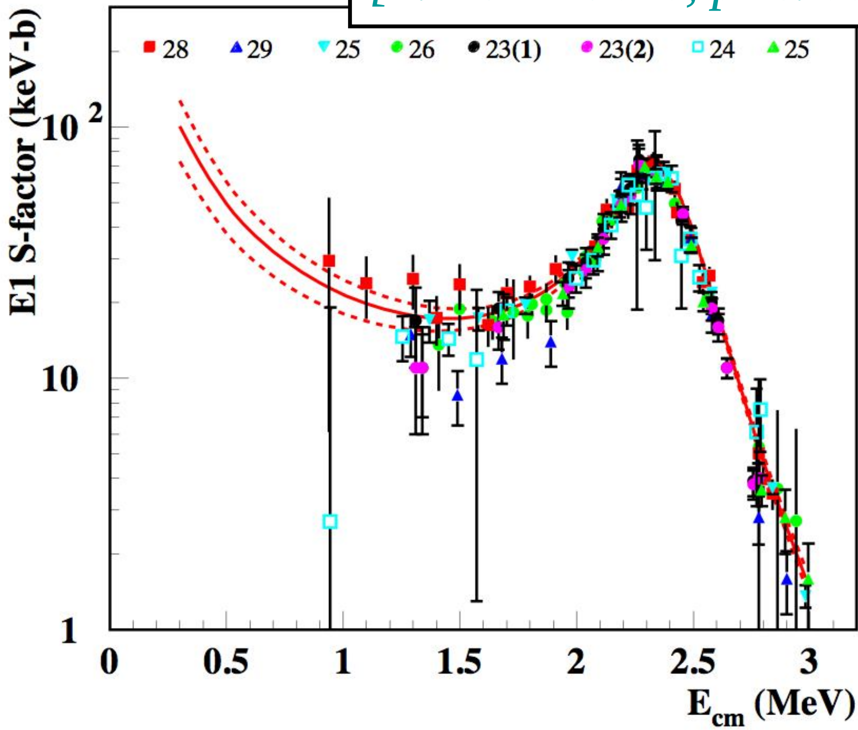
Angulo et al. 1999

The $^{12}C(\alpha,\gamma)^{16}O$ reaction

- In competition with $3\alpha \rightarrow {}^{12}C$ during He burning
- Tails of ***broad*** resonances

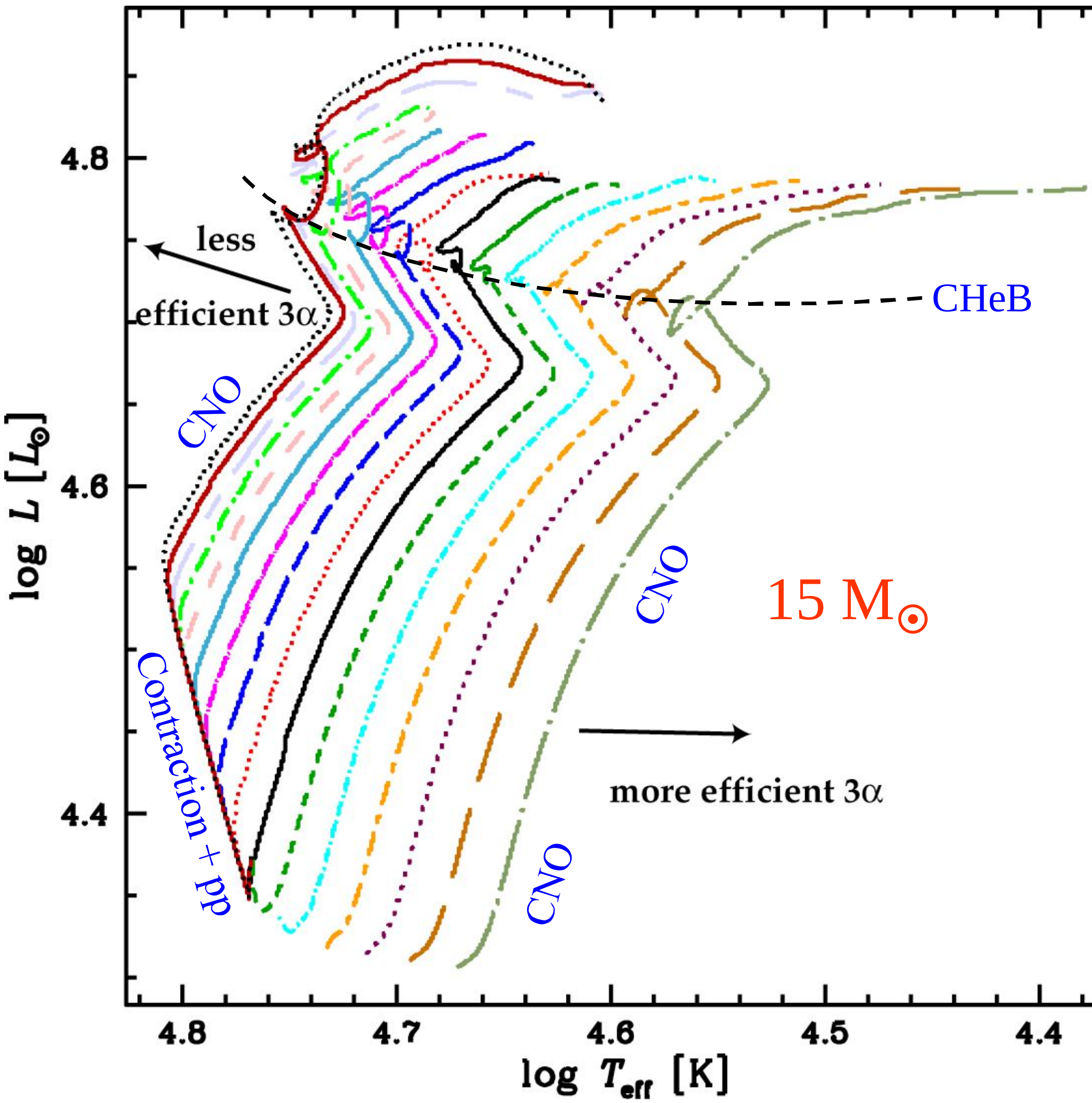
Typical $^{12}C(\alpha,\gamma)^{16}O$ S-factor extrapolation at low energy *[F. Hammache, priv. comm.]*





- Negligible effect expected

Influence on HR diagram (15 $M_\odot$)



Composition at the end of core He burning

- **The standard region:**

Both ^{12}C and ^{16}O are produced.

- **The ^{16}O region:**

The 3α is slower than $^{12}C(\alpha,\gamma)^{16}O$ resulting in a higher T_C and a conversion of most ^{12}C into ^{16}O

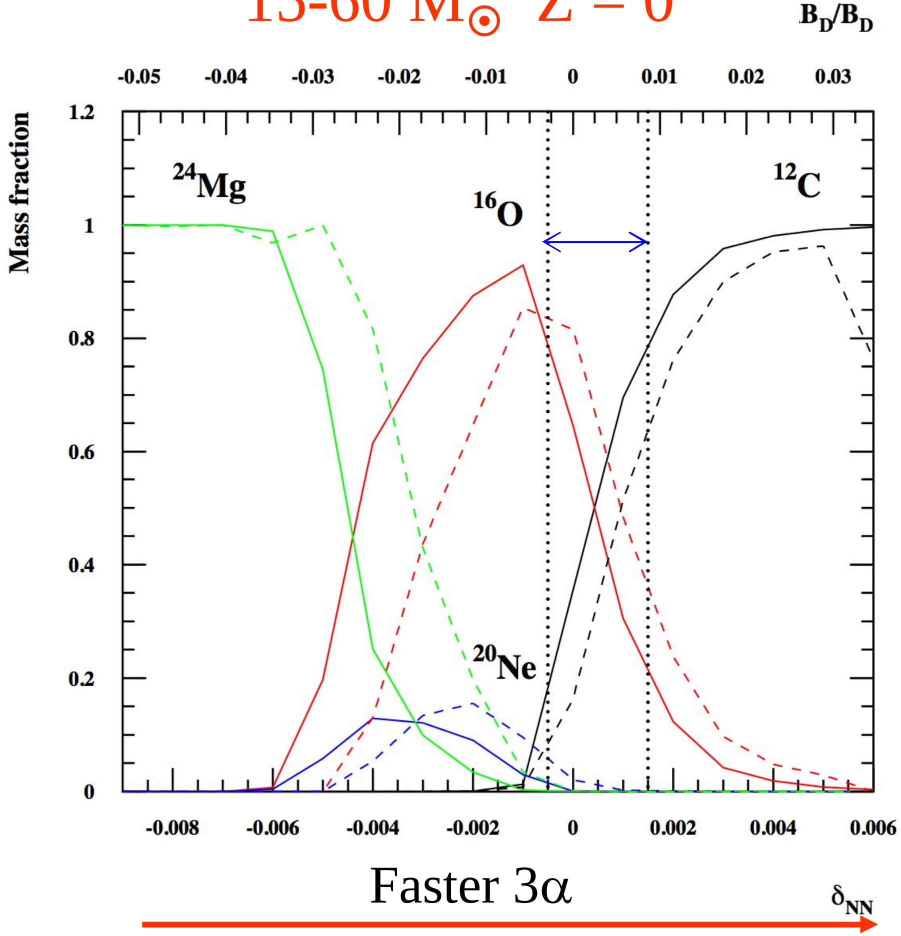
- **The ^{24}Mg region:**

With an even weaker 3α, a higher T_C is achieved and $^{12}C(\alpha,\gamma)^{16}O(\alpha,\gamma)^{20}Ne(\alpha,\gamma)^{24}Mg$ transforms ^{12}C into ^{24}Mg

- **The ^{12}C region:**

The 3α is faster than $^{12}C(\alpha,\gamma)^{16}O$ and ^{12}C is not transformed into ^{16}O

15-60 $M_\odot$ Z = 0



Faster 3α

Lower T_C

Final stage : core of 3.55-3.84 $M_\odot$ composed of ^{24}Mg, ^{16}O or ^{12}C according to δ_{NN} or B_D

Requiring $^{12}C/^{16}O$ close to unity

$\Rightarrow -0.0005 < \delta_{NN} < 0.0015$

Variation of constants in BBN

Deuterium binding energy (B_D), neutron lifetime (τ_n), neutron-proton mass difference (Q_{np}), electron mass (m_e) all ***precisely known*** from ***present day*** laboratory experiments.

These values could have been different at the epoch of BBN.

Because of variation of fundamental parameters as the Higgs vacuum expectation value (v), the "Yukawa couplings" (h's), QCD energy scale (Λ), fine structure constant (α_{em})

We limit ourselves to the effect on n↔p and n(p,γ)D cross sections as

- the ^{4}He abundance is essentially determined by the n↔p weak rates,
- n(p,γ)D is the starting point of BB nucleosynthesis and
- difficult to determine the effects on other reactions

Variation of fundamental couplings in BBN

- ρ_R and hence H (slightly) depend on m_e (e+e- annihilation)

  $m_e = h_e v$ ($v \equiv$ Higgs field v.e.v.; $h \equiv$ Yukawa couplings)

- weak rates depend on G_F, Q_{np} and m_e $\qquad G_F=1/\sqrt{2}v^2$

  $Q_{np}=Cste\ \alpha_{em}\Lambda_{QCD}+(h_d-h_u)v$ *[Gasser & Leutwyler, 1982]*

- n(p,γ)D cross section depend mostly on B_D *[Dmitriev, Flambaum & Webb 2004; Carrillo-Serrano+ 2013; Berengut+ 2013]*

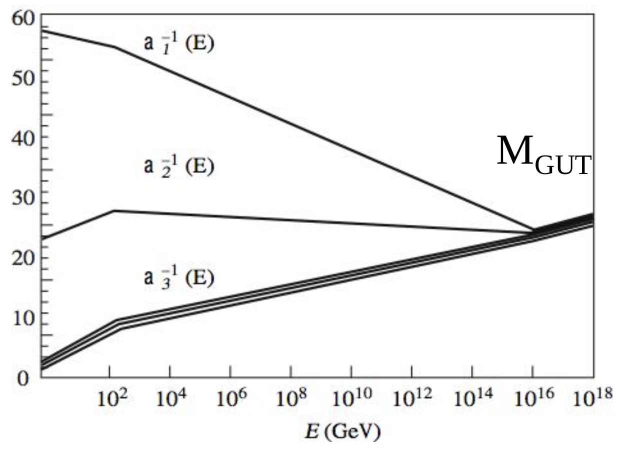
Links between the N-N interaction and α_{em}

[Coc, Nunes, Olive, Uzan, Vangioni 2007]

1. Effective (Minnesota) N-N interaction: $\Delta B_D/B_D \approx 5.77 \times \delta_{NN}$
2. ω and σ meson exchange potential model ↔ B_D *[Flambaum & Shuryak 2003]*
3. ω and σ meson properties ↔ Λ_{QCD} and (u, d,) s quark masses
4. From $\alpha_{em}(M_{GUT}) \sim \alpha_s(M_{GUT})$: $\Lambda_{QCD} \leftrightarrow \alpha_{em}$ and c, b, t quark masses
5. With $m_q = hv$ relations between h (Yukawa coupling), v (Higgs vev) and α_{em} *[Campbell & Olive (1995); Ellis et al. 2002]*

$$\frac{\Delta B_D}{B_D} = -\left[6.5(1+S) - 18R\right]\frac{\Delta\alpha_{em}}{\alpha_{em}} \sim -1000\frac{\Delta\alpha_{em}}{\alpha_{em}}$$

Assuming $R \sim 30$ and $S \sim 200$, typical but model dependent values



Links between the N-N interaction and α_{em}

From an ω and σ exchange potential model *[Flambaum & Shuryak 2003]*:

$$\frac{\Delta B_D}{B_D} = -48\frac{\Delta m_\sigma}{m_\sigma} + 50\frac{\Delta m_\omega}{m_\omega} + 6\frac{\Delta m_N}{m_N}\left(-7\frac{\Delta\Lambda}{\Lambda}\right) \quad \Rightarrow \quad \frac{\Delta B_D}{B_D} = 18\frac{\Delta\Lambda}{\Lambda} - 17\left[\frac{\Delta h_s}{h_s} + \frac{\Delta v}{v}\right]$$

($m_x \equiv h_x v$ with v the Higgs field vev, h_x the Yukawa coupling, and assuming $\Delta h_x/h_x$ independent of $x = u, d, s, c, b, t, \ldots$)

$\Delta m_s/m_s$ dominant

From $\alpha_{em}(M_{GUT}) \sim \alpha_s(M_{GUT})$:

$R \sim 30$ (GUT model dependent)

$$\Lambda = \mu\left(\frac{m_c m_b m_t}{\mu^3}\right)^{2/27}\exp\left(-\frac{2\pi}{9\alpha_s(\mu)}\right) \quad \Rightarrow \quad \frac{\Delta\Lambda}{\Lambda} = R\frac{\Delta\alpha_{em}}{\alpha_{em}} + \frac{2}{27}\left[3\frac{\Delta v}{v} + \frac{\Delta h_c}{h_c} + \frac{\Delta h_b}{h_b} + \frac{\Delta h_t}{h_t}\right]$$

Following *Campbell & Olive (1995); Ellis et al. 2002* :

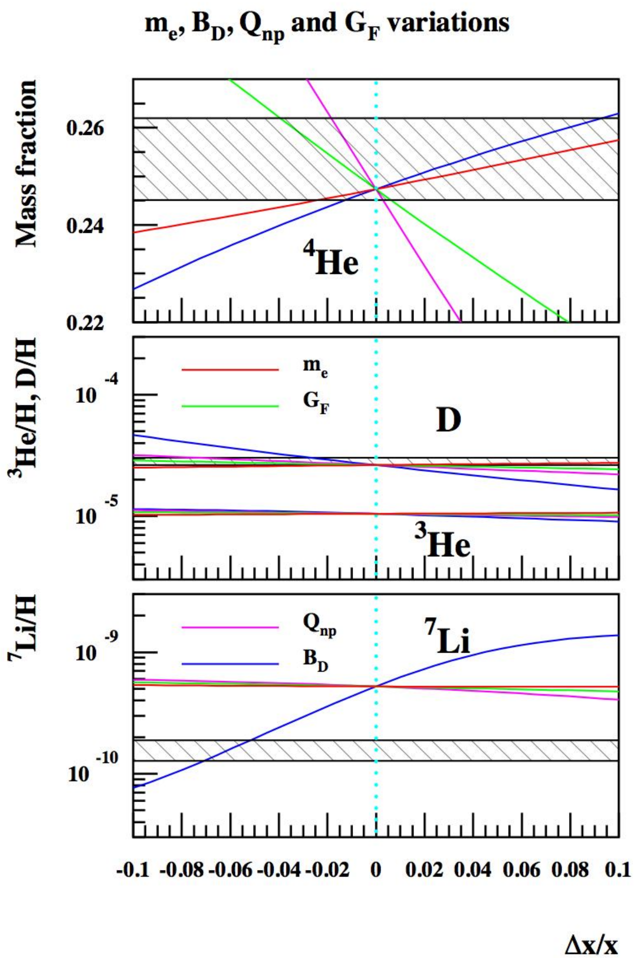
$\frac{\Delta v}{v} = S\frac{\Delta h_t}{h_t}$ with $S \sim 200$ (model dependent) and $\frac{\Delta h}{h} = \frac{1}{2}\frac{\Delta\alpha_{em}}{\alpha_{em}}$ (dilaton)

$$\frac{\Delta B_D}{B_D} = -\left[6.5(1+S) - 18R\right]\frac{\Delta\alpha_{em}}{\alpha_{em}} \sim -1000\frac{\Delta\alpha_{em}}{\alpha_{em}}$$

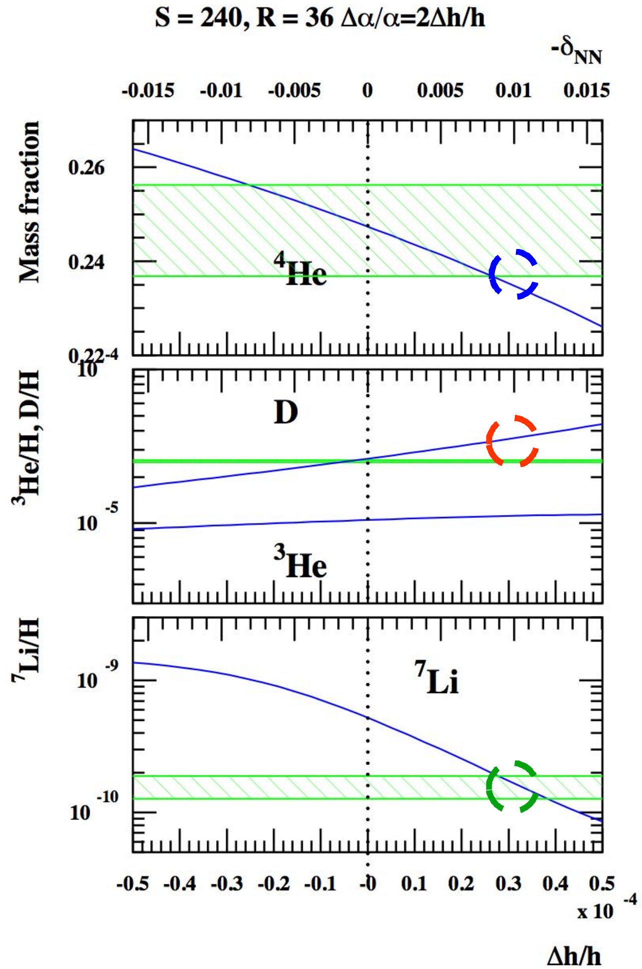
(but could be much different)

Variation of fundamental couplings and BBN

Individual variations

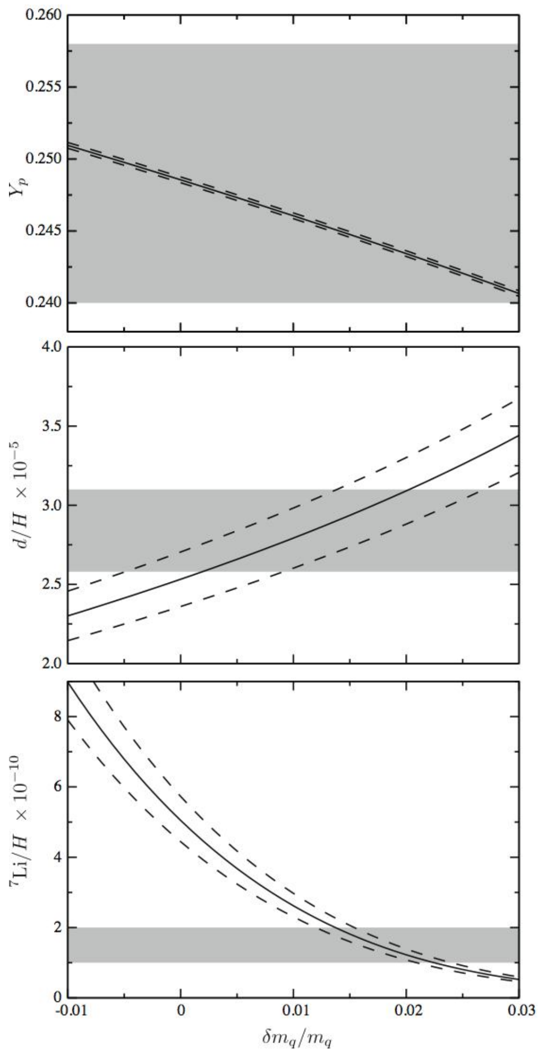


Coupled variations

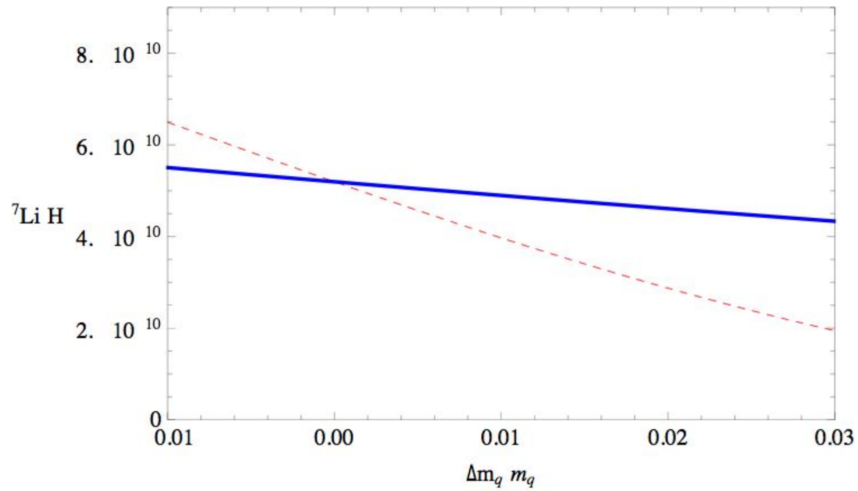


- Set limits on variations of fundamental couplings
- ∃ solution compatible with ^{4}He, ^{3}He, D and ^{7}Li

Cross sections / fundamental parameters



[Berengut , Flambaum & Dmitriev 2010]



Carrillo-Serrano+ 2013 with a different n(p,γ)D cross section dependence with B_D

Cheoun, Kajino, Kusakabe & Mathews 2011 with different ground / excited states dependence

Constrains on the variations of the fundamental constants

$$\Delta B_D/B_D \approx 5.77 \times \delta_{NN}$$

(Our nuclear model)

$$\Delta B_D/B_D \approx -1000 \times \Delta\alpha/\alpha$$

(Model dependent but typical value)

same conditions

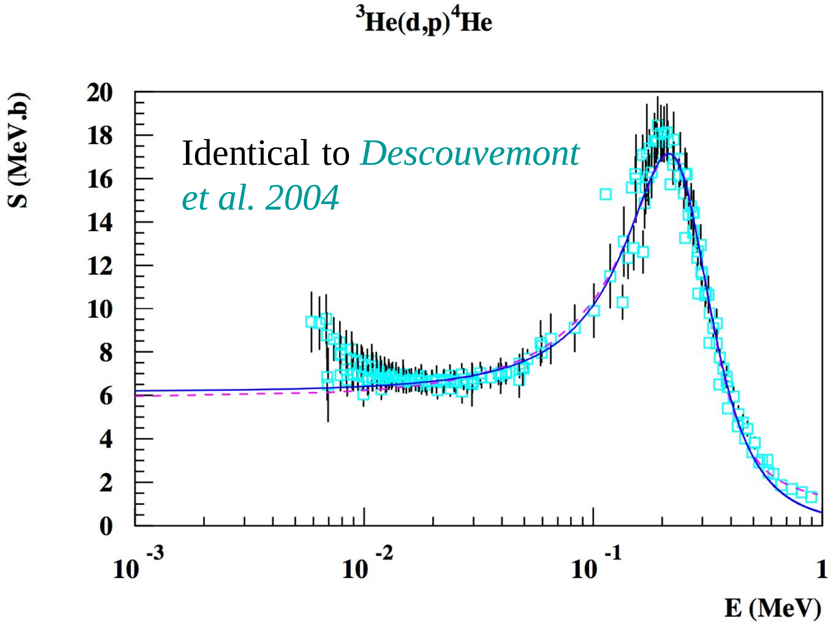
BBN (z~10^8) : $-0.0025 < \square_{NN} < 0.0006$ or $-4.\ 10^{-6} < \Delta\alpha/\alpha < 1.6\ 10^{-5}$ *[Coc et al. 2007; 2012]*

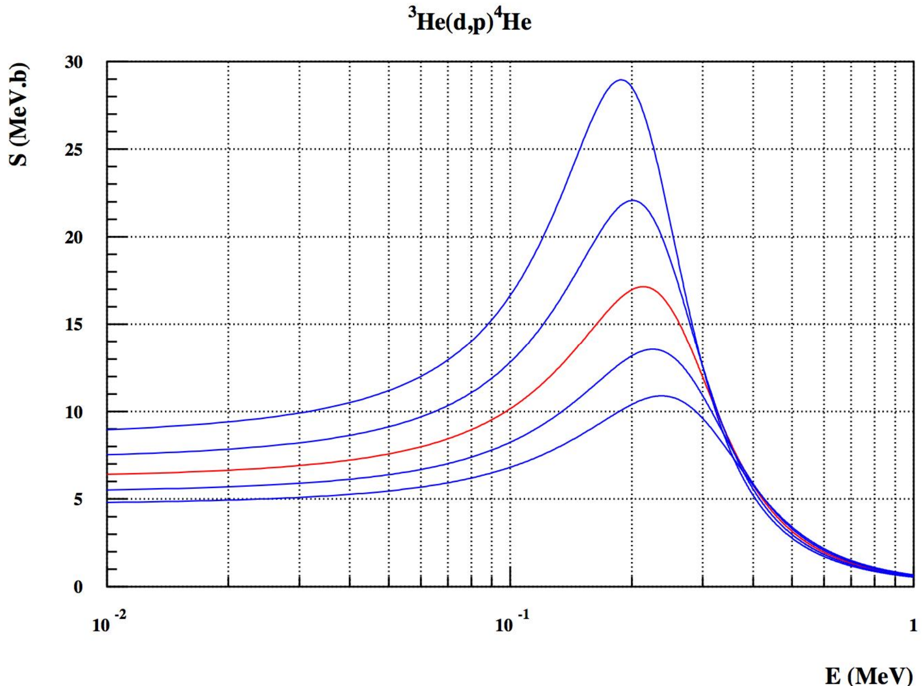
Pop. III (z = 10 -15) : $-0.0005 < \square_{NN} < 0.0015$ or $-1.\ 10^{-5} < \Delta\alpha/\alpha < 3.\ 10^{-6}$ *[Ekström et al. 2010]*

- Quasars ($0.5 < z < 3$) : $|\Delta\alpha/\alpha| < 10^{-5}$ *[Chand et al. (2004)]*
- Pop. I ($z \approx 0$) $|\delta_{NN}| < 5\ 10^{-3}$ and $|\Delta\alpha/\alpha| < 4\ 10^{-2}$ *[Oberhummer et al. 2000]*

^{3}He(d,p)^{4}He and ^{3}H(d,n)^{4}He and the A=5 gap

- ^{5}He and ^{5}Li respectively unbound by 0.798, 1.69 MeV compared to the 0.092 MeV of ^{8}Be
- No stable A=5 nor even a two steps process like 3-α
- Calculated ΔE_R function of δ_{NN} for broad analog 3/2+ resonances
- Single pole R-matrix with $\Delta E_R(\delta_{NN})$
- Weak sensitivity of S(E) to $\Delta E_R(\delta_{NN})$ variations

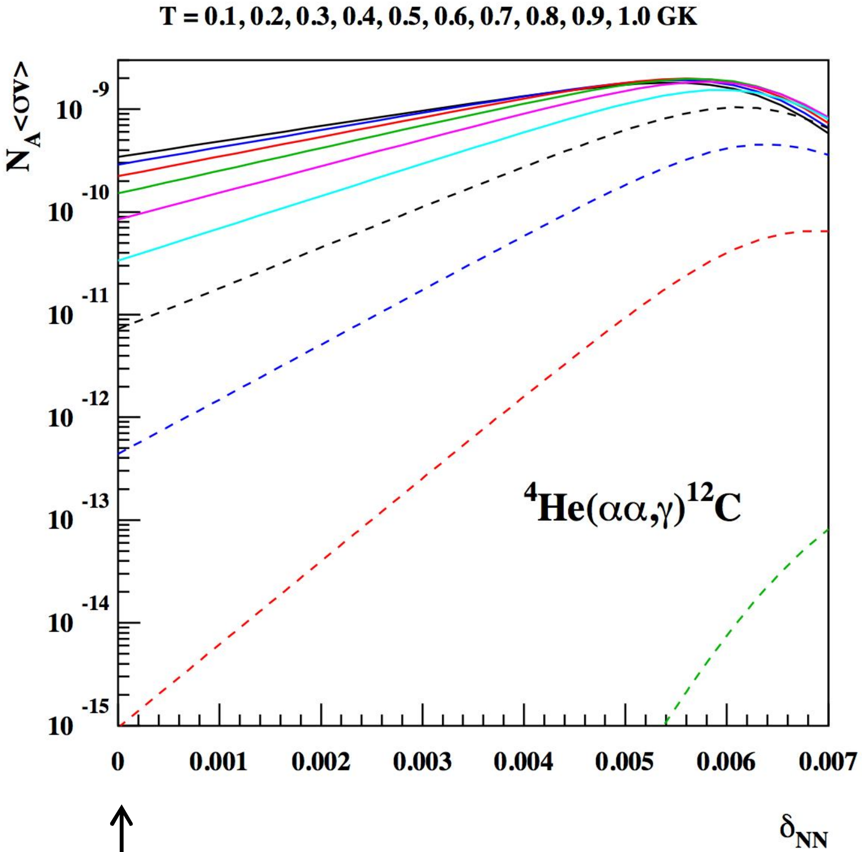




δ_{NN}= -0.3, -0.15, 0, 0.15, 0.30 (!)

The 3-α reaction in BBN and the A=8 gap

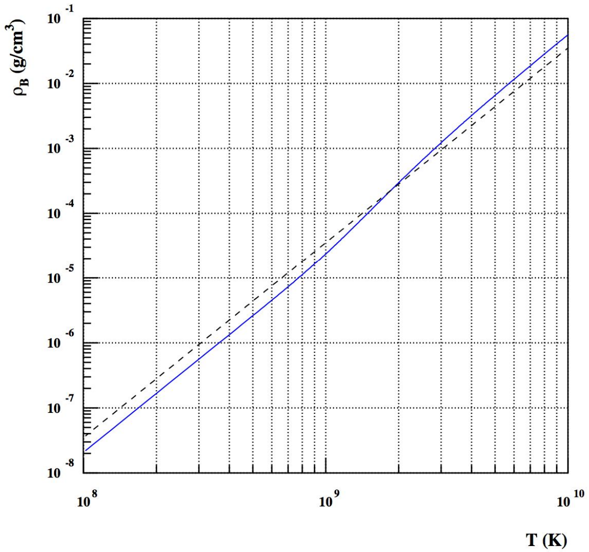
$^{4}He(\alpha\alpha,\gamma)^{12}C$ reaction rate function of N-N interaction:



Normal (δ_{NN}=0)

^{8}Be bound (δ_{NN}≈0.0075)

But density lower (3 body reaction) and timescale shorter than in stars!

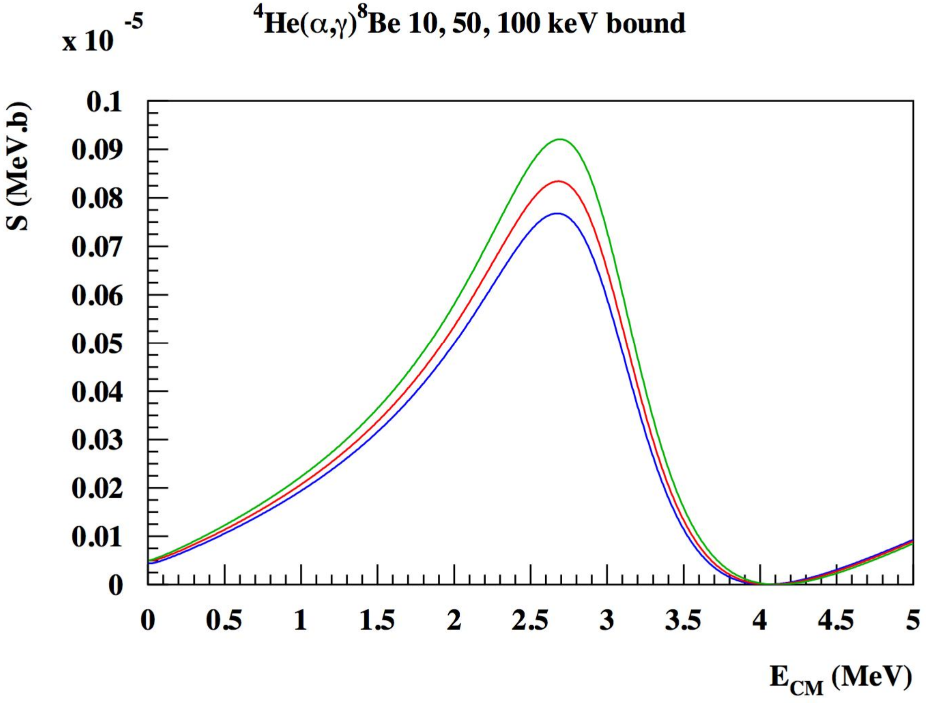


However, *well known* that a stable ^{8}Be would bridge the A=8 gap!

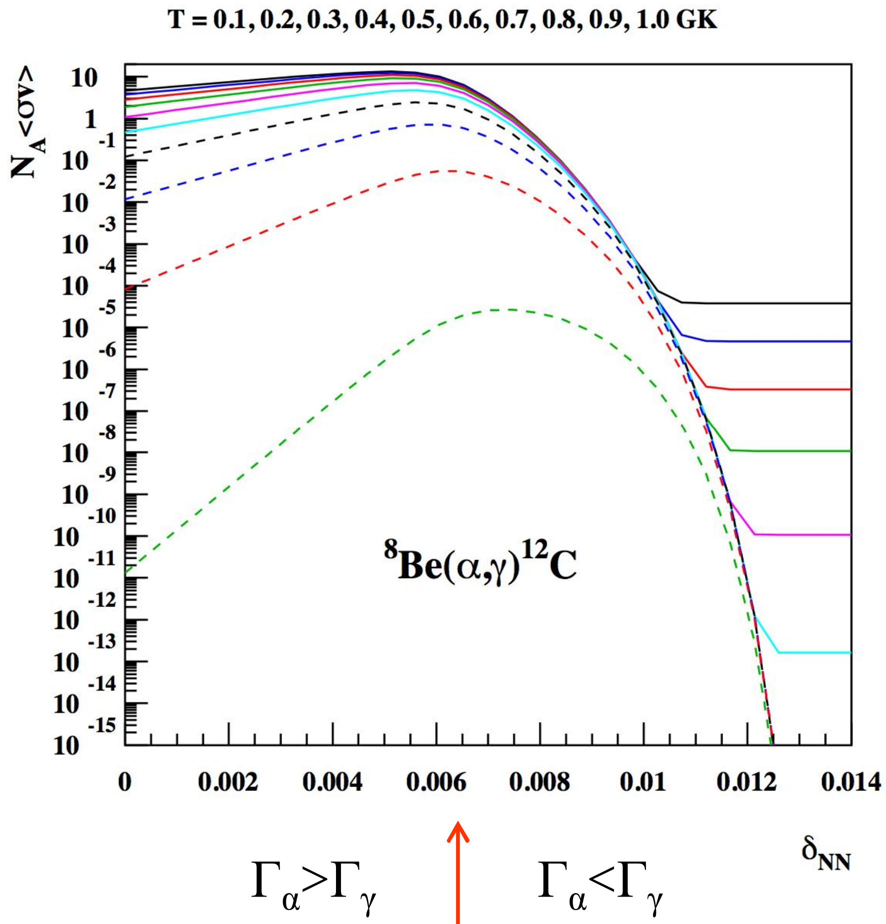
The triple-alpha with a stable ^{8}Be

^{8}Be bound by 10, 50 or 100 keV (δ_{NN}=0.0083, 0.0116, 0.0156)

^{4}He(α,γ)^{8}Be^{bound} cross-section in continuity with unbound one *[Baye & Descouvemont 1985]*



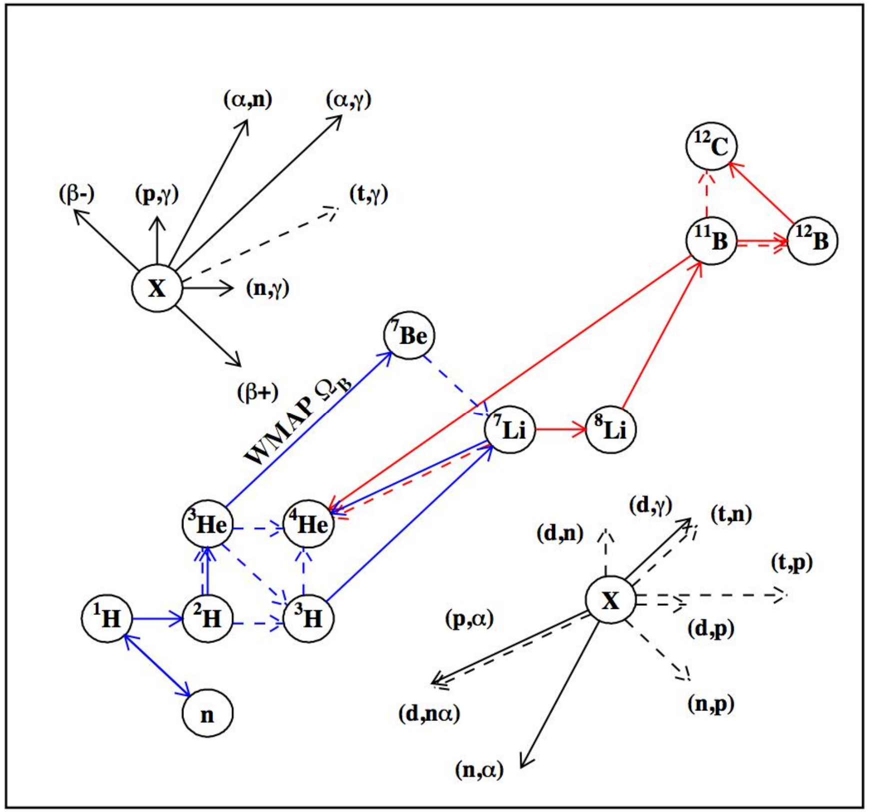
^{8}Be^{bound}(α,γ)^{12}C from sharp resonance formula



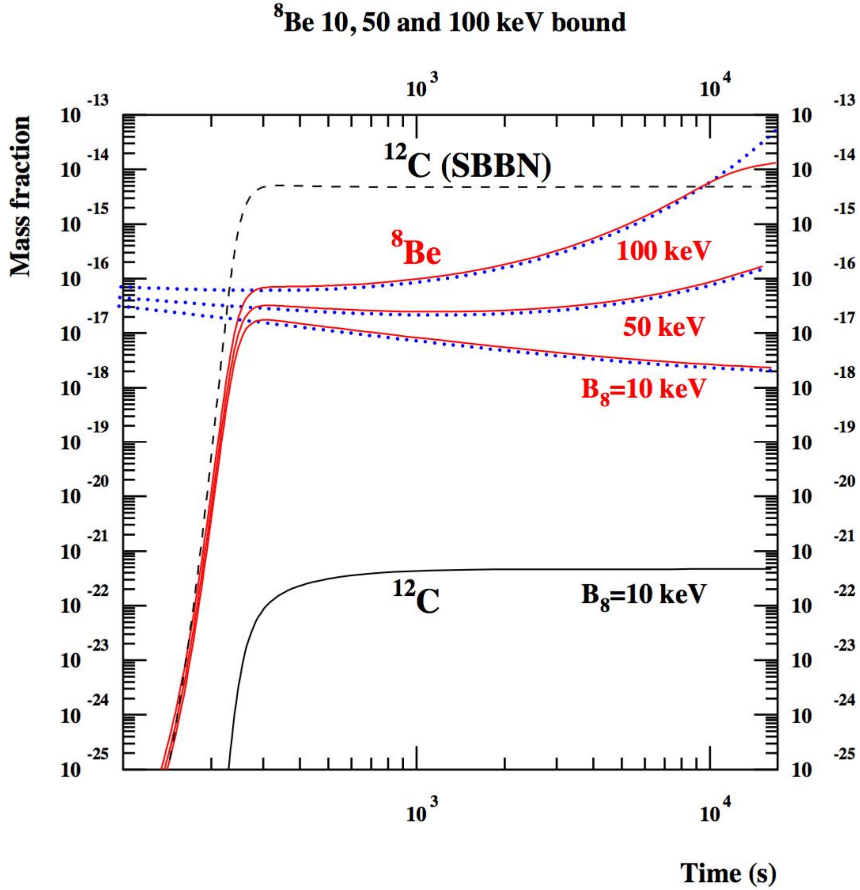
[Newton et al. 2007]

CNO production with a stable ^{8}Be

[Coc, Goriely+ 2012]



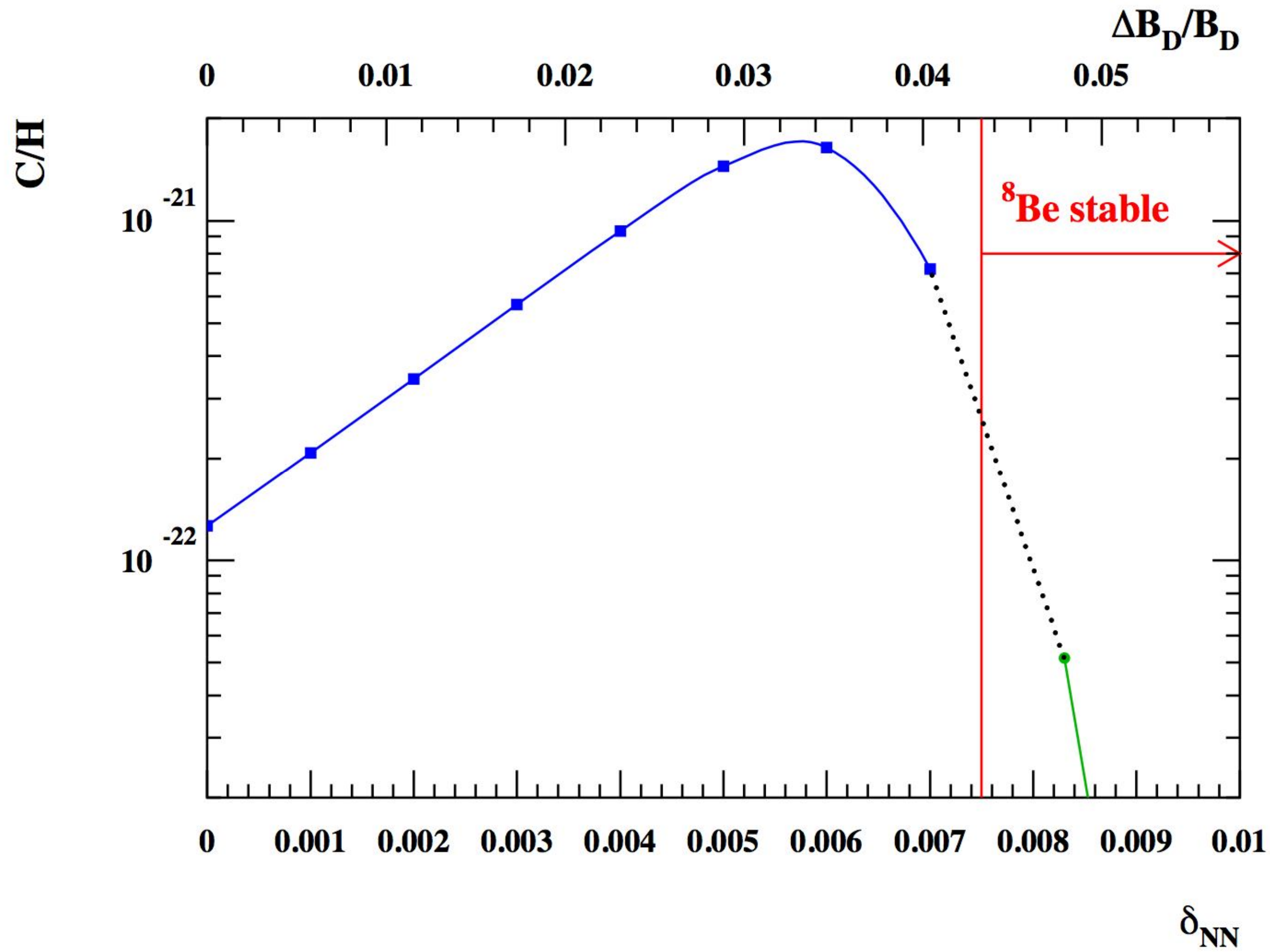
[Coc, Descouvemont+ 2012]



^{8}Be stable for N-N interaction higher by 0.75%

But ^{4}He(α,γ)^{8}Be(α,γ)^{12}C still too slow

CNO production in BBN



- $^4He(\alpha\alpha,\gamma)^{12}C$ or $^4He(\alpha,\gamma)^8Be(\alpha,\gamma)^{12}C$ only: CNO/H < 2×10^{-21}
- With the full network : CNO/H =$(0.5\text{-}3) \times 10^{-15}$

Conclusions

- SBBN is now a parameter free model, that can be used to probe of the physics of the early Universe
  - Exotic particles (supersymmetric, neutrinos, mirror,....)
  - Theory for Gravity (quantum gravity, extra-dimensions,…)
  - Variation of fundamental couplings : nuclear physics involved in several tests (BBN, 3-alpha and stellar evolution, meteorites)
  - ….
- Non Standard models can solve the lithium problem….. at the expense of the “deuterium problem”