NAT-NET: WP4
Standard cosmological model and beyond

Francesco e Gianpiero

NAT-NET: WP4
Standard cosmological model and beyond

- Dark matter
- BBN
- Issues in the cosmological model
- Neutrinos in cosmology

Dark matter

Cold Dark Matter (CDM)
An electromagnetical close-to-neutral, non-baryonic matter species with negligible velocity from the standpoint of structure formation (PDG 2019)

$$\Omega_{\text{CDM}} \approx 0.26 \qquad \rho_{\text{CDM}} / \rho_{\text{Matter}} \approx 0.84$$

- ✓ DM is inferred "directly" in gravitationally collapsed structures - with sizes ranging from dwarf galaxies to galaxy clusters - by looking at stellar velocity dispersion, rotation curves, gravitational lensing, etc.

- ✓ DM is observed "indirectly" in structure formation: it speeds up the growth of pertubations in baryons after matter-radiation decoupling, allowing for the formation of non-linear collapsed structures in the present Universe.

Dark matter - Properties

Electric charge - If DM is (milli-)charged it might impact the baryon-to-photon plasma during recombination, altering the acoustic peaks:

$$Q < 3.5\times10^{-7}\left(m_{\rm DM}/1\ {\rm GeV}\right)^{0.58} \quad \text{for} \quad m_{\rm DM} > 1\ {\rm GeV}$$

$$Q < 4.0\times10^{-7}\left(m_{\rm DM}/1\ {\rm GeV}\right)^{0.35} \quad \text{for} \quad m_{\rm DM} < 1\ {\rm GeV}$$

Self-interactions - Limits from merging clusters and from ellepticity of galaxies:

$$\sigma_{\rm DM\text{-}DM}/m_{\rm DM} < 0.47\ {\rm cm^2/g} \simeq 0.84\ {\rm barn/GeV} \qquad (95\%\ {\rm CL})$$

but **velocity-dependent** self-interacting DM may help with small scales challenges [see next].

Mass lower limits: Arise from quantum effects.

Fermions - phase-space bounds from dwarf galaxies: $m_{\rm F} \geq 100\ {\rm eV}$ [see e.g. Di Paolo, Nesti, Villante, MNRAS 2018]

[more stringent bounds from Ly-α but they depend on the assumed DM thermal hystory]

Bosons - "uncertainty principle" bound: $m_{\rm B} \geq 10^{-22}\ {\rm eV}$

Mass upper limits: stability of structures immersed in DM halos: $m_{\rm DM} \leq 5\ {\rm M}_\odot$

Dark matter – Small scale challenges

ΛCDM is extremely successful at scales ≥ 1 Mpc. Observations at smaller scales, where structures are highly non-linear, pose few challenges to this paradigm.

Missing satellites problem: high resolution simulation of DM haloes with size comparable to MW predict the formation of hundreds or thousand subhaloes → Under-abundance of observed MW satellites

Cusp-core problem: ΛCDM simulations predict mass density profiles for DM haloes that steeply rise at small radii, $\rho(r) \propto r^{-\gamma}$ with $\gamma \approx 0.8 - 1.4$ → This cuspy behavior is in contrast with the density profile of low-mass galaxies (rotation curves are best fitted by assuming costant density cores).

Too-big-to-fail problem: under-abundance of massive subhaloes ($\approx 10^{10}\ M_{\odot}$) in the local Universe (which are too massive to have failed to form stars).

Dark matter - Local density and velocity distribution

The determination of the density and distributions of DM in the Milky Way is important for direct and indirect detection experiments (and to understand the dynamics of our Galaxy).

Local density (ρ_0) - average density over a volume of a few hundred parsecs in the solar neighbourhood.
It can be inferred from the vertical motions of stars in the vicinity of the Sun (local measure) or from the measured rotation curve (global measure)

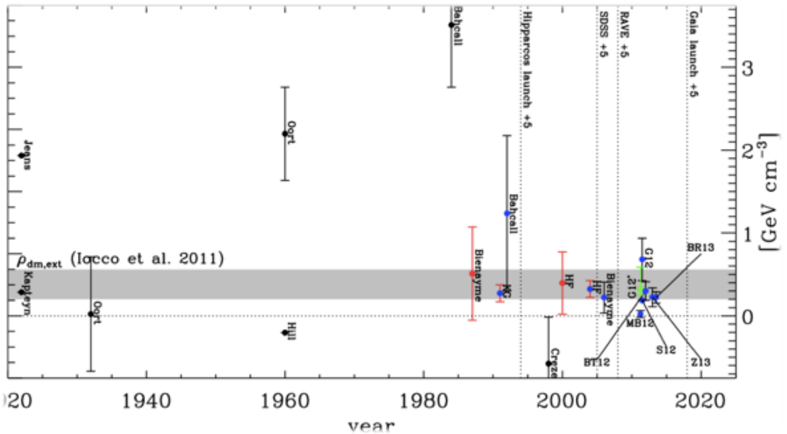
Local circular speed – $v_c = (218 - 246)\ km/s$

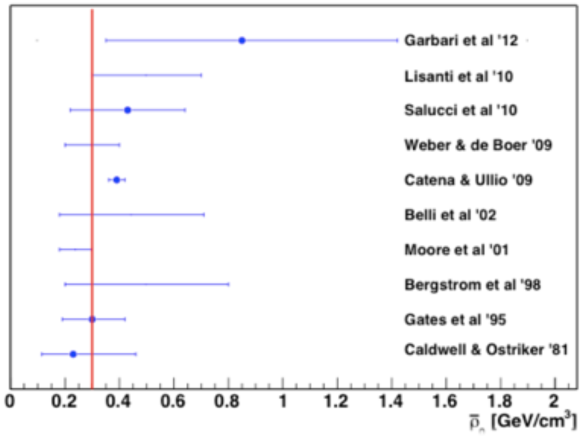
Escape velocity - $v_{esc} = 533^{+54}_{-41}\ km/s$

Standard halo model:
Isotropic isothermal sphere with velocity dispersion $\sigma_v = \frac{v_c}{\sqrt{2}}$ truncated at v_{esc}
… but reality can be much more complex than this

Dark matter in the Milky Way

Present determinations of the local DM density ρ_0 are consistent but noisy:





Fabio Iocco [NA node]:

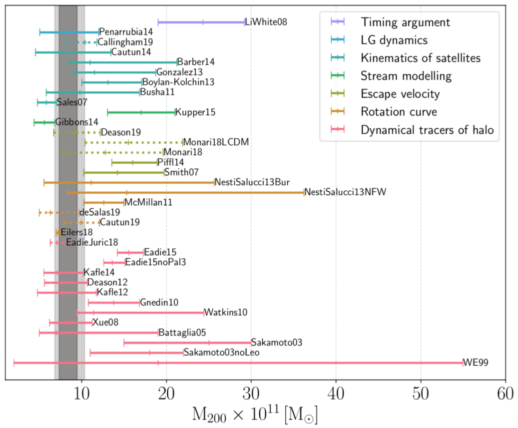
Determination of the DM distribution of the Milky Way.

Uncertainties and consequences for the search of new physics.

Dark matter in the Milky Way

Most recent works along this research line [F. Iocco in collaboration with G. Bertone, M. Pato, M. Benito, E. Karukes]:

https://arxiv.org/abs/1912.04296 - "A robust estimate of the Milky Way mass from rotation curve data"
https://arxiv.org/abs/1901.02463 - "Bayesian reconstruction of the Milky Way dark matter distribution"
https://arxiv.org/abs/1611.09861 - "An estimate of the DM profile in the Galactic bulge region"



$$\log_{10} M_{200}/\mathrm{M}_\odot = 11.92^{+0.06}_{-0.05}(\mathrm{stat}) \pm 0.28 \pm 0.27(\mathrm{syst}),$$

https://arxiv.org/abs/1901.02460 - "Handling the uncertainties in the Galactic DM distribution for particle DM searches"
https://arxiv.org/abs/1612.02010 - "Particle Dark Matter Constraints: the Effect of Galactic Uncertainties"

Dark matter in the Milky Way

Conclusions [from F. Iocco]:

- Determining the local DM density from actual data is possible;
- Rotation Curve method is accurate and precise, in spite of large range of observational systematic and statistical uncertainties.
- Slope (i.e. full profile of Milky Way) is not very accurate, and quite depending from several systematics. (Galactic Center region further complicated.)
- Astrophysical uncertainties are actually affecting determination of PP, in virtuous interplay with collider physics, direct and indirect probes.
- Providing a ready-to-use likelihood for PP use, including astrophysical uncertainties on DM distribution

DM candidates

WIMPs

Beyond-SM scenarios naturally provide DM candidates that can be thermally produced ("WIMP miracle"):

$$\Omega_W h^2 \simeq 0.1 \left(\frac{x_f}{20}\right)\left(\frac{10^{-8}\,\mathrm{GeV}^{-2}}{\sigma_{\mathrm{Ann}}}\right) \qquad x_f \equiv m_{\mathrm{DM}}/T_f \approx 10-50$$

Axions and axion-like particles

Scalars and pseudoscalar fields that can be eventually coupled to photons (QCD axion provides a solution to the strong CP problem) → See next slides from A. Mirizzi

Sterile neutrinos

Neutrinos (i.e. neutral fermions) not partecipating to weak interactions (gauge singlet) that are mixed with $SU(2)_L$-active neutrinos → discussed more in details in the following

Dark photons

Light vector bosons (that can be mixed with the visible photons)

Models with rich dark sectors:

DM may be charged under some hidden dark-sector (e.g. mirror matter)

COSMOLOGICAL BOUNDS ON HEAVY AXIONS

[Carenza, Mirizzi]

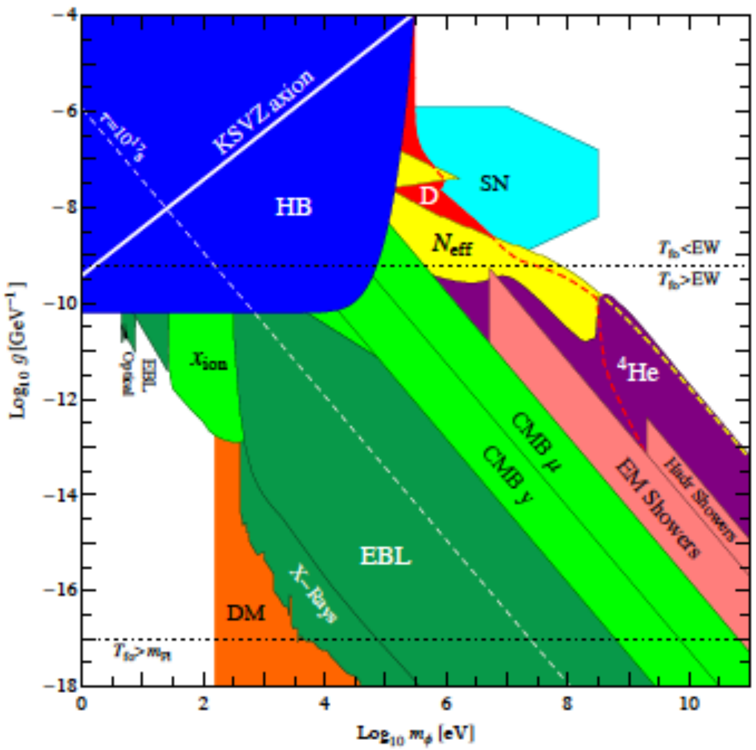
Axions and axion-like particles with a two-photons coupling

$$\mathcal{L} = -\frac{g_{a\gamma}}{4}\phi\tilde{F}^{\mu\nu}F_{\mu\nu} \;\; = g_{a\gamma}\phi\mathbf{E}\cdot\mathbf{B};$$

would have an efficient thermalization mechanism in the Early Universe, via the Primakoff process $\gamma + q \rightarrow \gamma + \phi$, and a prominent decay channel $\phi \rightarrow \gamma\ \gamma$. The lifetime under decays into gamma is given by

$$\Gamma_{a\to\gamma\gamma} = \frac{g_{a\gamma}^2 m_a^3}{64\pi} = 1.1 \times 10^{-24}\ \mathrm{s}^{-1}\left(\frac{m_a}{\mathrm{eV}}\right)^5$$

For m $\sim$ MeV the axion lifetime is smaller than the age of the Universe. Cosmological constraints can be obtained.



- **DM** — if ALPs are cosmologically stable and behave as dark matter (DM) they should not exceed the DM fraction measured by WMAP;
- **Optical, X-Rays, γ-Rays** — photons produced in ALP decays inside galaxies would show up as a peak in galactic spectra that must not exceed the known backgrounds;
- **EBL** — photons produced in ALP decays when the universe is transparent must not exceed the extragalactic background light (EBL);
- $\mathbf{x_{ion}}$ — the ionization of primordial hydrogen caused by the decay photons must not contribute significantly to the optical depth after recombination;
- **CMB y, μ** — if the decay happens when the universe is opaque, the decay photons must not cause spectral distortions in the CMB spectrum that cannot be fully rethermalized;
- **EM, Hadr showers** — the decay of high mass ALPs produces electromagnetic and hadronic showers that must not spoil the agreement of big bang nucleosynthesis with observations of primordial nuclei;
- **^{4}He, D** — the ALP decays produce photons (entropy) that dilute the baryon and neutrino densities, whose values affect the outcome of BBN, in particular the deuterium and ^{4}He yields. Again, this dilution should not compromise BBN;
- $\mathbf{N_{eff}}$ — the neutrino density must not disagree with the value measured by WMAP and other large-scale-structure probes. Currently, data points to a number of effective neutrinos $N_{\rm eff}$ greater than 3, which is disfavoured in the decaying ALP cosmology.

References

- D. Cadamuro, S. Hannestad, G. Raffelt and J. Redondo, ''Cosmological bounds on sub-MeV mass axions,'' JCAP 1102, 003 (2011) [arXiv:1011.3694 [hep-ph]].
- D. Cadamuro and J.Redondo, ''Cosmological bounds on pseudo Nambu-Goldstone bosons,'' JCAP 1202, 032 (2012) [arXiv:1110.2895 [hep-ph]].
- M. Millea, L. Knox and B. Fields, New Bounds for Axions and Axion-Like Particles with keV-GeV Masses,'' Phys. Rev. D 92, no. 2, 023010 (2015) [arXiv:1501.04097 [astro-ph.CO]].

Proposal: Is it worthwhile an update of the cosmo bounds using state-of-the art Planck and BBN data?

Big Bang Nucleosynthesis

- ✓ Deepest reliable probe of the early Universe
- ✓ The abundances of ^{4}He, D, ^{3}He, ^{7}Li produced by BBN depends on the following quantities:

Baryon density

$$\eta \equiv \frac{n_B}{n_\gamma} \qquad \Omega_B h^2 \approx 3.7\ 10^7\ \eta$$

Hubble expansion rate (T~1MeV; t~1 sec)

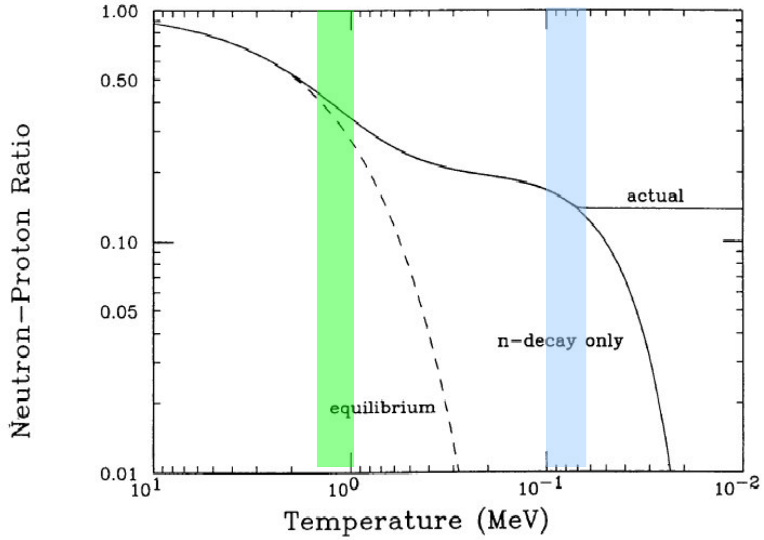
$$H \approx g_*^{1/2}\ G_N^{1/2}\ T^2$$

$$g_* = 10.75 + \frac{7}{4}(N_\nu - 3)$$

Weak rate (ν_e +n ←→ p+e)

$$\Gamma_W \approx G_F^2 T^5$$

Deuterium bottleneck $T_N \approx -\frac{B_d}{\ln(\eta)} \approx 0.1$ MeV



$H/\Gamma_W = 1$ → Weak interaction freeze-out $T_W \approx 1\,\mathrm{MeV}\cdot(g_*/10.75)^{1/6}$

- ✓ Essentially all neutrons surviving till the onset of BBN used to build ^{4}He
- ✓ D, ^{3}He, ^{7}Li are determined by a complex nuclear reaction network.

Big Bang Nucleosynthesis

Accuracy of ^{4}He calculation at the level of 0.1%

High precision codes (Lopez & Turner 1999, Esposito et al. 1999) take directly into account effects due to :
- *zero and finite temperature radiative processes;*
- *non equilibrium neutrino heating during $e^\pm$ annihilation;*
- *finite nucleon masses;*
- *………*

These effects are included "a posteriori" in the "standard" code (Wagoner 1973, Kawano 1992).

Reaction rate uncertainties translate into uncertainties in theoretical predictions of ^{4}He, d, ^{3}He and ^{7}Li:
- *Theoretical uncertainties are largely subdominant wrt observational errors with the exception of deuterium*

Relative contributions to deuterium error budget (Coc et al. JCAP 2014)

Reaction	$C_{D,k}$
D(p,γ)^{3}He	-0.7790
D(d,n)^{3}He	-0.4656
D(d,p)^{3}H	-0.4082

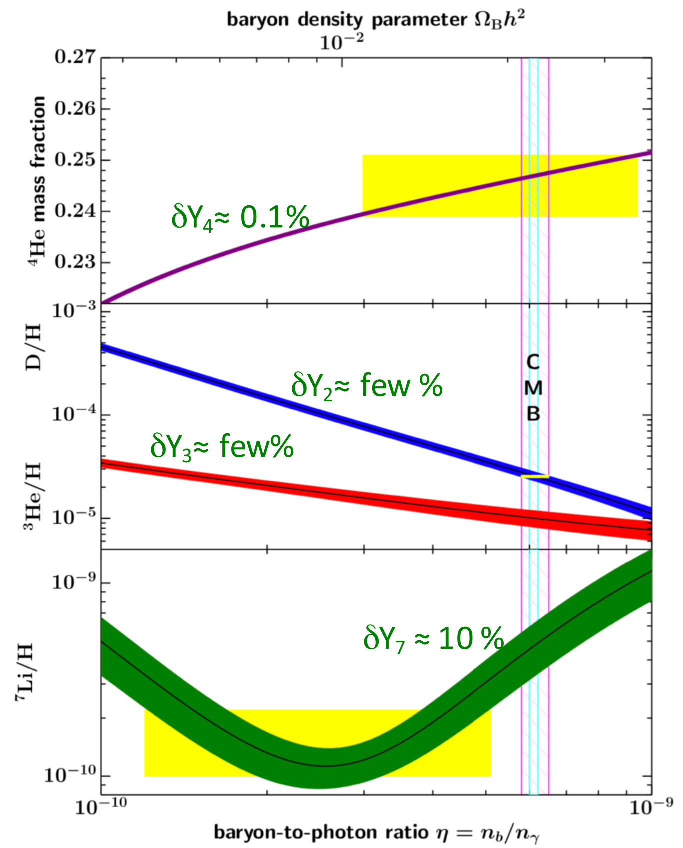


Figure 23.1: The primordial abundances of ^{4}He, D, ^{3}He, and ^{7}Li as predicted by the standard model of Big-Bang nucleosynthesis — the bands show the 95% CL range [47]. Boxes indicate the observed light element abundances. The narrow vertical band indicates the CMB measure of the cosmic baryon density, while the wider band indicates the BBN D+^{4}He concordance range (both at 95% CL).

Theory .vs. observations

Helium 4: determined by extrapolating to Z=0 the (Y,Z) relation or by averaging Y in extremely metal poor HII regions (N and O used as metallicity tracers)

$$Y_p = 0.245 \pm 0.003$$

Deuterium: observed in the high resolution spectra of QSO absorption systems at high redshift:

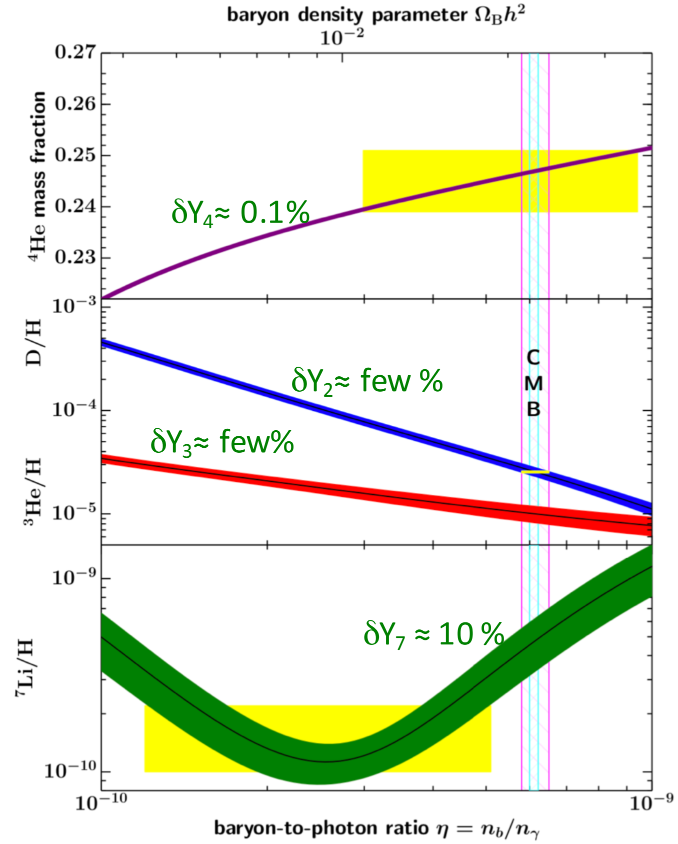
$$D/H|_p = (25.47 \pm 0.25) \times 10^{-6}$$

Concordance:
The baryon density deduced from $D/H|_p$ agrees with that extracted from CMB

Lithium-7: observed in metal poor (Pop II) stars of our galaxy. Abundance does not vary significantly in stars with metallicities lower than 1/30 of solar (Spite Plateau)

$$Li/H|_p = (1.6 \pm 0.3) \times 10^{-10}$$

The Lithium-7 problem:
Observational values are factor 3 lower than required to obtain concordance



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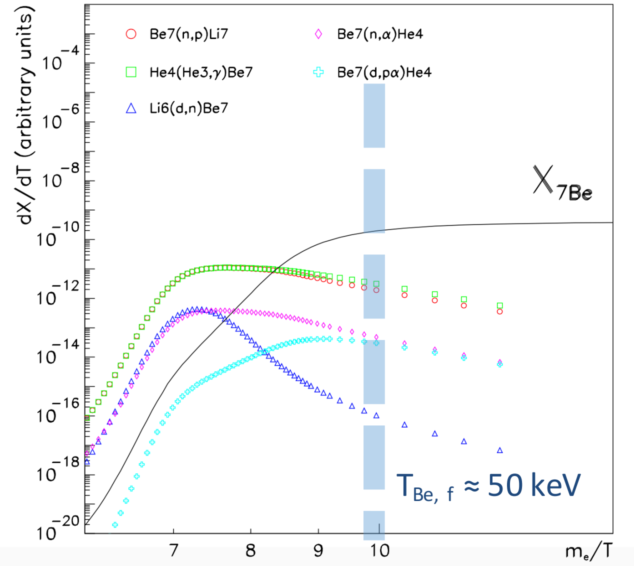
PDG, 2019

The Lithium problem

Observational values for Li/H$|_p$ are a factor 3 lower than required by D/H$|_p$ and CMB. The mismatch may come from:

- Systematic errors in obs. abundances and/or uncertainties in stellar astrophysics;
- Errors in nuclear physics inputs (cross sections) for BBN
- New physics

Serpico et al., 2004



Note that:
At $\eta = 6 \times 10^{-10}$, ^{7}Li is mainly produced from ^{7}Be ($e^- + {}^7$Be→ ^{7}Li + ν_e at "late" times):

The dominant ^{7}Be production mechanism is through the reaction ^{3}He(α,γ)^{7}Be
→ Studied in detail both experimentally (LUNA) and theoretically. The cross section is known to 7% uncertainty.

The dominant ^{7}Be destruction channel is through the process ^{7}Be(n,p)^{7}Li
→ Experimental data obtained from direct data and reverse reaction. R matrix fit to expt. data provide the reaction rate with 1% accuracy.

Nuclear physics solution of the Lithium problem?

Requires to increase (by large amounts) the rate of ^{7}Be destruction processes:

- ^{7}Be(n,p)^{7}Li: dominant process, **well studied**;
- ^{7}Be(n,α)^{4}He: expected to be subdominant, **no expt. data** in BBN energy range;
- New resonances (^{7}Be + a → C* → b + Y)?

The case for a nuclear physics solution has been disussed e.g. in [Broggini, Canton, Fiorentini, Villante, JCAP 1206 (2012) 030]

The various possibilities have been explored (^{7}Be+d: Kirseborm et al 2011, O' Malley et al. 2011; ^{7}Be+^{3}He,^{7}Be+^{4}He: Hammache et al. 2013) or are being considered (^{7}Be(n,α)^{4}He: BELICOS, Lamia et al. 2019) in dedicated expts.

→ Nuclear fix is increasingly unlikely

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New physics during BBN?

- Injection of hadronic or electromagnetic particles (due e.g. to DM decays) that may produce non thermal neutrons and dissociate light elements;
- Time variations of the fundamental constants;
- Most scenarios can be significantly constrained by the very precise determination of $D/H|_p$

Big Bang Nucleosynthesis: more on Deuterium

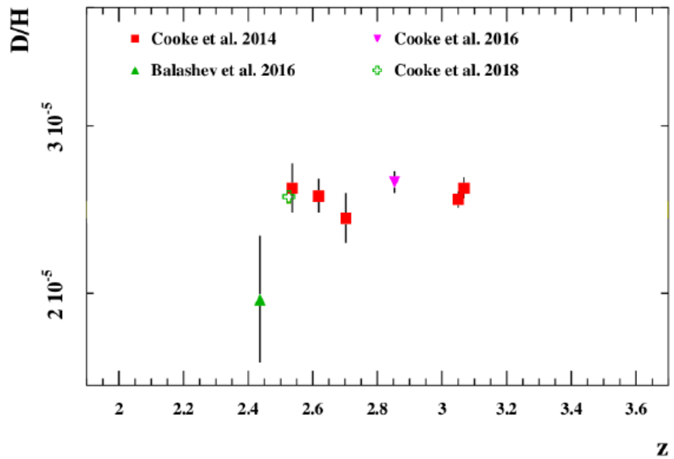
Astrophysical observations

1. observations in systems negligibly contaminated by stellar evolution;
2. careful account for galactic chemical evolution.

For D, the most convenient astrophysical environments are the H_I clouds on the line of view of QSO's at high redshifts with low metallicity (negligible astration of D) and narrow absorption lines (distinguishable isotope shift between D and H).

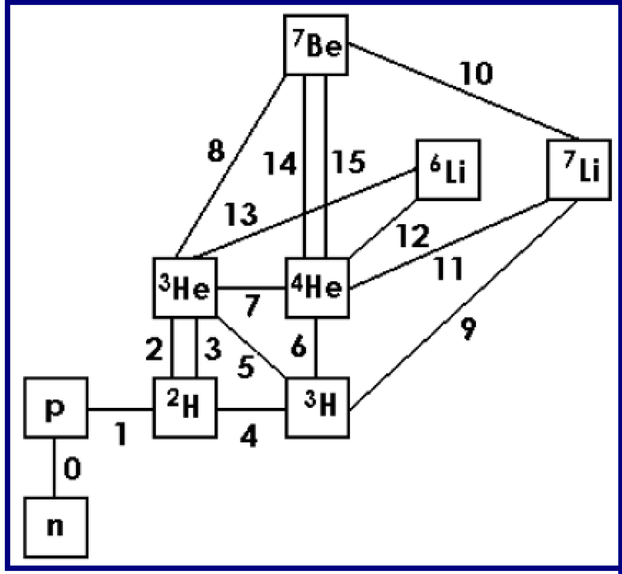
Recent observations and reanalysis of existing data show a plateau as a function of redshift (for z ≥ 2) with a very small scattering for systems with comparable metallicity.

Cooke et al., **Astrophys.J. 855 (2018) no.2, 102**



Big Bang Nucleosynthesis

Deuterium synthesis



Symbol	Reaction	Symbol	Reaction
R_0	τ_n	R_8	$^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$
R_1	$p(n,\gamma)d$	R_9	$^3\mathrm{H}(\alpha,\gamma)^7\mathrm{Li}$
R_2	$^2\mathrm{H}(p,\gamma)^3\mathrm{He}$	R_{10}	$^7\mathrm{Be}(n,p)^7\mathrm{Li}$
R_3	$^2\mathrm{H}(d,n)^3\mathrm{He}$	R_{11}	$^7\mathrm{Li}(p,\alpha)^4\mathrm{He}$
R_4	$^2\mathrm{H}(d,p)^3\mathrm{H}$	R_{12}	$^4\mathrm{He}(d,\gamma)^6\mathrm{Li}$
R_5	$^3\mathrm{He}(n,p)^3\mathrm{H}$	R_{13}	$^6\mathrm{Li}(p,\alpha)^3\mathrm{He}$
R_6	$^3\mathrm{H}(d,n)^4\mathrm{He}$	R_{14}	$^7\mathrm{Be}(n,\alpha)^4\mathrm{He}$
R_7	$^3\mathrm{He}(d,p)^4\mathrm{He}$	R_{15}	$^7\mathrm{Be}(d,p)2\,^4\mathrm{He}$

Reaction	Rate symbol	$\sigma_{^2\mathrm{H/H}} \times 10^5$	
$p(n,\gamma)^2\mathrm{H}$	R_1	± 0.002	0.1%
$d(p,\gamma)^3\mathrm{He}$	R_2	± 0.062	87%
$d(d,n)^3\mathrm{He}$	R_3	± 0.020	9%
$d(d,p)^3\mathrm{H}$	R_4	± 0.013	3.8%

Di Valentino et al, **Phys.Rev. D90 (2014) no.2, 023543**

Big Bang Nucleosynthesis

BBN codes

- BBN Wagoner code (Wagoner, 1969&1973)
- Kawano code (Kawano, 1988)
- …
- PArthENoPE (Pisanti et al., 2008) (FORTRAN+Python)
- AlterBBN (Arbey, 2012) (C)
- PRIMAT (Pitrou et al., 2018) (Mathematica)

Today, three public codes. All of them essentially equivalent from the numerical point of view.

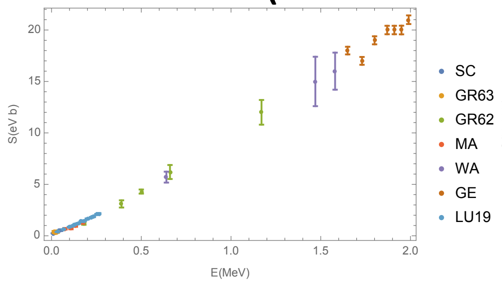
Pisanti et al., **Comput.Phys.Commun. 178 (2008) 956-971**
Arbey , **Comput.Phys.Commun. 183 (2012) 1822-1831**
Pitrou et al., **Phys.Rept. 754 (2018) 1-66**

Nuclear rates

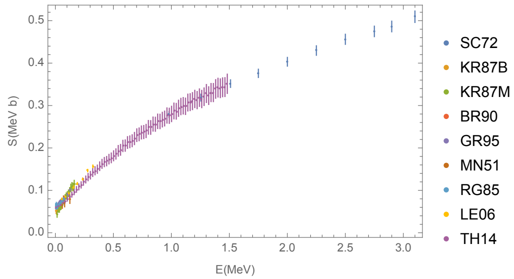
Evolution of nuclides determined by cross sections of associated processes. For charged particle induced reactions the astrophysical S-factor is the intrinsic nuclear part of the reaction probability

$$\langle \sigma v \rangle = \sqrt{\frac{8}{\pi \mu_{ab}}} T^{-3/2} \int_0^\infty \mathrm{d}E\, E\, \sigma(E)\, \mathrm{e}^{-E/T} \qquad S(E) = \sigma(E) E\, e^{\sqrt{E_G/E}}$$

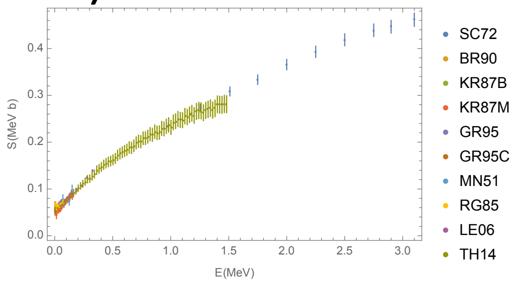
It is fitted by experiments. Problem: data sets cover limited energy ranges and have different normalization errors (in some cases not even estimated).



dpγ



ddn



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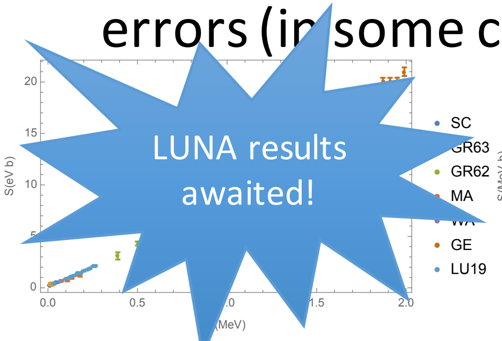
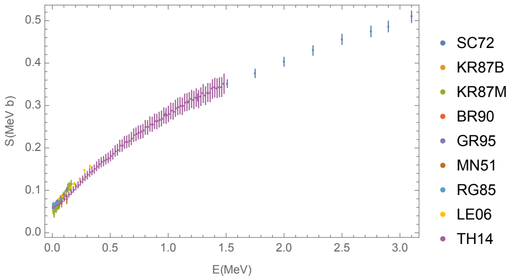


dpγ



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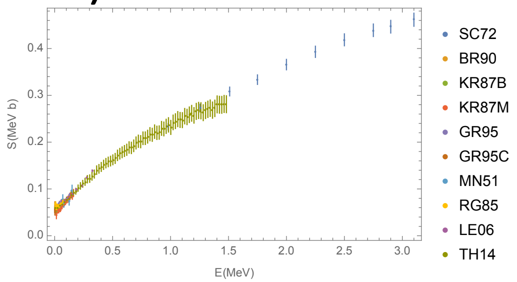


ddp

- Coc2015/Cyburt2016: energy dependence from nuclear physics + normalization from chi-squared

$$\chi^2(\alpha_k) = \sum_{i_k} \frac{[S_{i_k} - \alpha_k S_{th}(E_{i_k})]^2}{\sigma_{i_k}^2} \qquad \chi^2(\alpha) = \sum_k \sum_{i_k} \frac{[S_{i_k} - \alpha S_{th}(E_{i_k})]^2}{\sigma_{i_k}^2}$$

Same definition of the overall scaling factor multiplying the astrophysical S-factor:

$$\overline{\alpha} = \sum_k \frac{\widehat{\alpha}_k}{\sigma_{\widehat{\alpha}_k}^2} \left(\sum_k \frac{1}{\sigma_{\widehat{\alpha}_k}^2} \right)^{-1} = \frac{\sum_k \sum_{i_k} S_{i_k} S_{th}(E_{i_k})/\sigma_{i_k}^2}{\sum_k \sum_{i_k} S_{th}^2(E_{i_k})/\sigma_{i_k}^2}$$

- Serpico2004/present work: standard chi-squared plus a penalty factor that does not allow ω_k-1 to be greater than the quoted normalization, ε_k:

$$\chi^2(a_l, \omega_k) = \sum_{i_k} \frac{(S_{th}(E_{i_k}, a_l) - \omega_k\, S_{i_k})^2}{\omega_k^2\, \sigma_{i_k}^2} + \sum_k \frac{(\omega_k - 1)^2}{\epsilon_k^2}$$

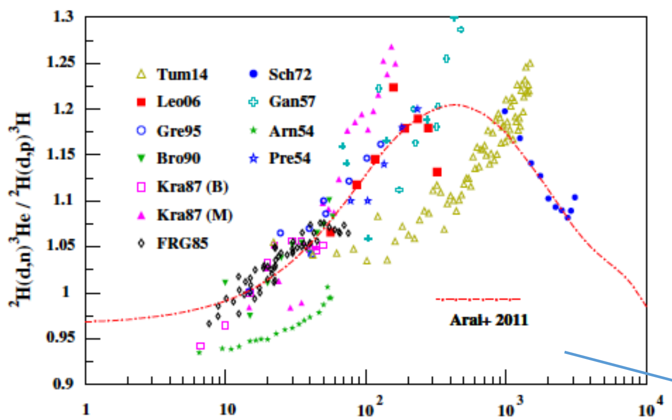
Serpico 2004: **JCAP 0412 (2004) 010**
Coc2015: **Phys.Rev. D92 (2015) no.12, 123526**
Cyburt2016: **Rev.Mod.Phys. 88 (2016) 015004**

α,ω: scaling factors

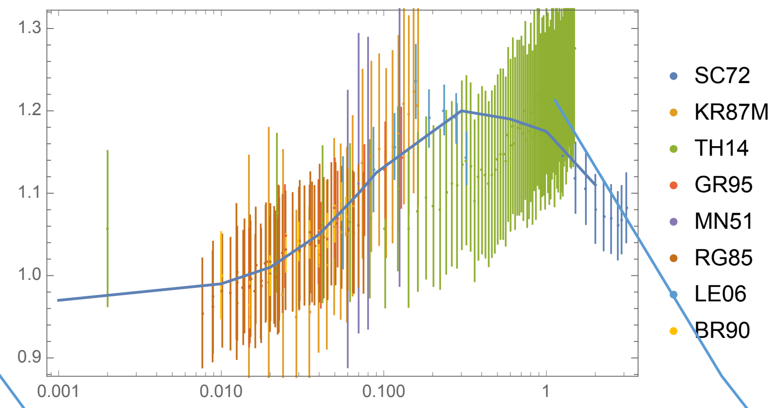
Data selection

Strict selection on data applied by some authors, excluding all experiments with not quoted/too large systematic uncertainty.

Example: ratio between ddn and ddp rates should be independent of the nuclear matrix elements. So, deviations may indicate normalization errors. Then, it has been used for discriminating among data sets.



Coc2015: **Phys.Rev. D92 (2015) no.12, 123526**

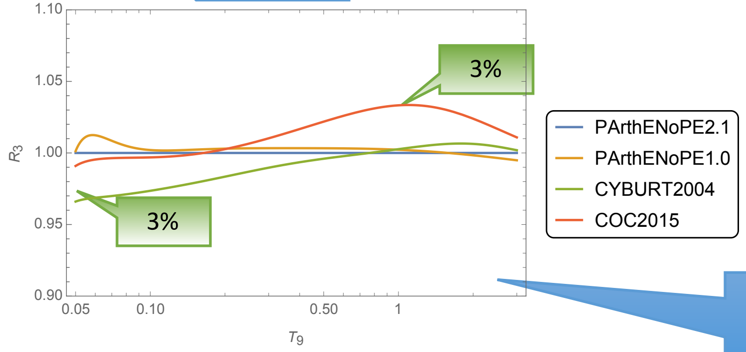


Trojan Horse data: **Astrophys.J. 785 (2014)**

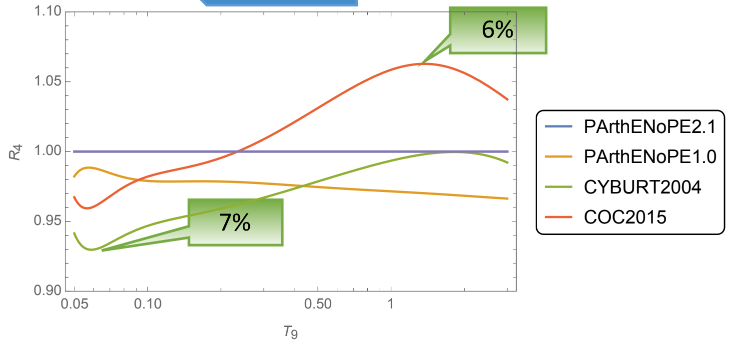
However, data within uncertainties seem to be consistent with theoretical *ab initio* calculation (Arai et al., 2011) once the fitted scaling factors are applied.

Rate comparison

ddn

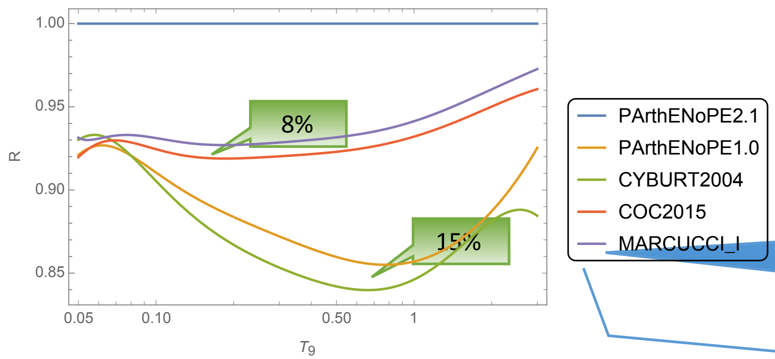


ddp



Update of PArthENoPE (TH data), difference with CYBURT2004/COC2015 is due to different data selection/analysis

dpγ

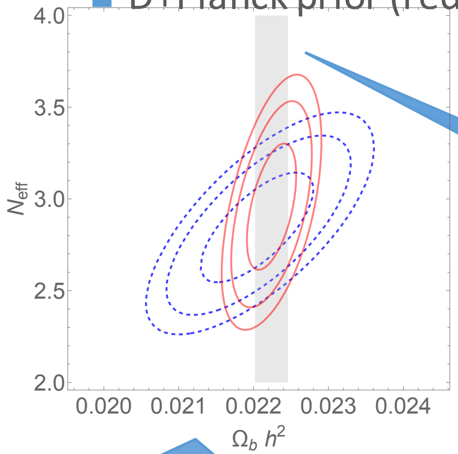


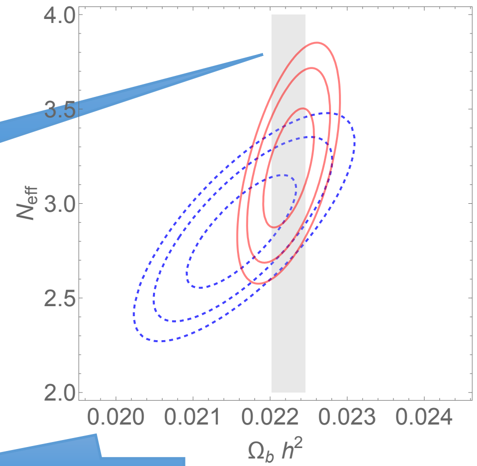
Update of PArthENoPE (MARCII versus AD2011), difference with CYBURT2004/COC2015 is MARCII versus AD2011/MARCI

MARCI: Marcucci et al., **Phys.Rev. C72 (2005) 014001**
MARCII: Marcucci et al., **Phys.Rev.Lett. 116 (2016) no.10, 102501**

BBN/CMB analysis

- Exp. values:
  - $\Omega_B h^2 = 0.02242 \pm 0.00014$ (Planck 2018)
  - D/H = (2.527±0.030) (Cooke et al., 2018)
  - $Y_p = 0.2446 \pm 0.0029$ (Peimbert et al., 2016)
- ddn+ddp = PArthENoPE2.1, dpγ = MARCI or MARCII
- D+Planck prior (red) and D+He (only BBN,blue) analyses



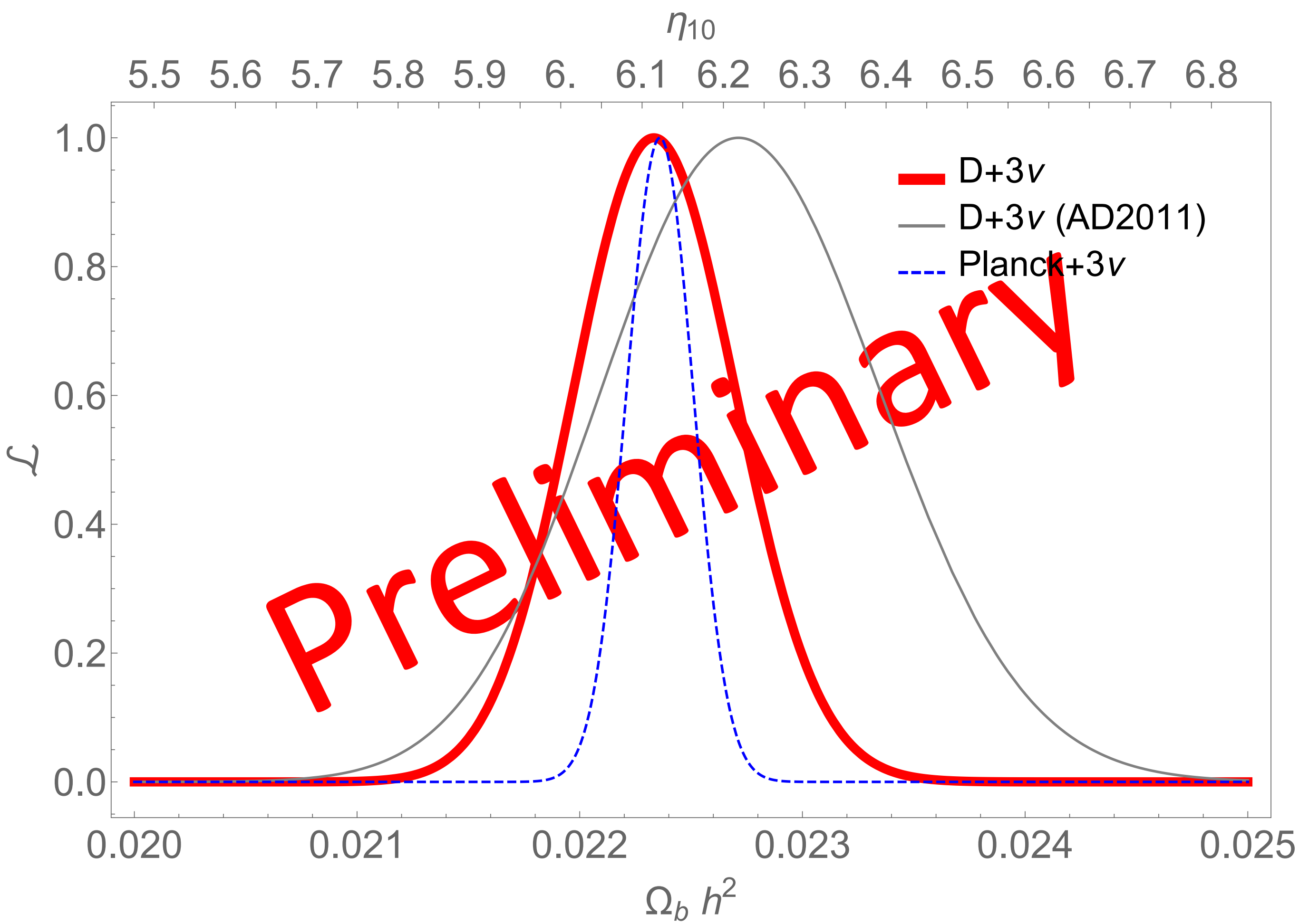


Planck 1-σ band

MARCI: $N_{eff} = 3.04 \pm 0.12$

MARCII: $N_{eff} = 3.28 \pm 0.12$

Big Bang Nucleosynthesis



Excellent agreement between baryon density as measured from deuterium abundance and CMB

Uncertainty is now reduced by a Factor 1.6 and is closer to that of Planck

Issues in Cosmology

M- Gasperini in collaborazione con G. Fanizza (Universidade de Lisboa), G. Marozzi (Universita' di Pisa), G. Veneziano (CERN)

1. Studio della relazione tra le direzioni angolari nel sistema di Coordinate Normali di Fermi e le direzioni angolari calcolate in altri gauges.

2. Studio di diverse prescrizioni di media (e loro differenze numeriche) per osservabili cosmologici in un background geometrico perturbato

1. Coordinate Normali di Fermi e direzioni angolari in altri gauges

- Le coordinate angolari di Fermi si identificano con quelle di un osservatore geodetico nel sistema localmente inerziale centrato attorno alla sua "world-line", e sono direttamente collegate agli angoli localmente misurati nei nostri laboratori

- Gli angoli di Fermi si possono sempre far coincidere con quelli specificati dalle coordinate del Geodesic-Light-Cone gauge (GLC) , mentre in altri gauges (es: sincrono, post-Newtonian) cio' non e' in generale possibile.

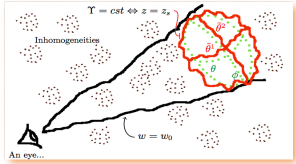
⇨ importante motivazione fisica per l'uso del gauge GLC (da noi proposto nel 2011) per il calcolo di grandezze osservabili quali redshift, luminosity-distance e/o angular-distance.

si veda in particolare il lavoro:

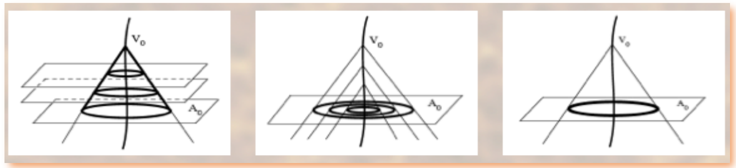
"Observation angles, Fermi coordinates, and the Geodesic-Light-Cone gauge"
pubblicato su **JCAP 01 (2019) 004**

2. Diverse prescrizioni di media in un background cosmologico perturbato

il fondo stocastico di perturbazioni primordiali disturba le osservazioni delle distanti sorgenti astrofisiche, e introduce errori nella determinazione dei parametri cosmologici



per minimizzare gli errori, il flusso d'energia ricevuto va mediato su un opportuno dominio spazio-temporale collegato al cono-luce dell'osservatore



3 necessari ingredienti geometrici per una corretta (covariante e gauge-invariante) prescrizione di media:

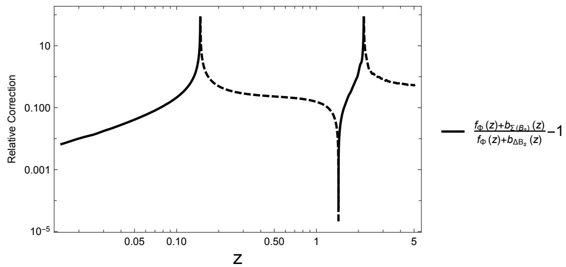
- classe di (space-like) ipersuperfici su cui localizzare le sorgenti
- (iper)cono spazzato dalle (null o time-like) traiettorie dei messaggeri ricevuti
- world-line tipica della classe di osservatori che effettua la misura

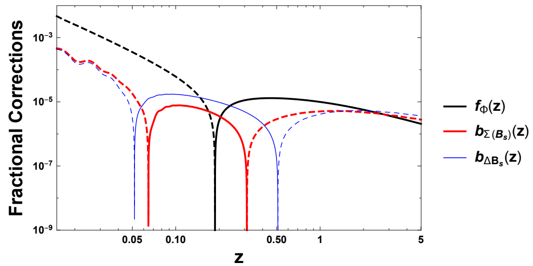
In particolare, ci sono due possibili classi di diverse prescrizioni, relative a:

i) sorgenti esattamente localizzate su una ipersuperficie data (es: a redshift costante)

ii) sorgenti confinate entro un sottile strato spazio-temporale, controllato dallo "spread" sperimentale della variabile osservativa (es: redshift data bin $\Delta z \neq 0$)

➡ i corrispondenti risultati numerici per la media del flusso differiscono per almeno il 10% in una ampia banda di distanze cosmiche





si vedano i dettagli nel lavoro

"Generalized covariant prescriptions for averaging cosmological observables"
arXiv:1911.09469 (2019)

Previsioni di possibile attivita' futura

Produzione cosmologica di primordial Black Holes (PBH) come possibili componenti di materia oscura

- significativa produzione di PBH possibilmente indotta da disomogeneita' di origine inflazionaria

- produzione di PBH di massa $M \sim 10^{20}$ g (tipica per Dark Matter) richiede spettro scalare primordiale di ampiezza $P(k) \geq 10^{-2}$ alla scala $k \sim 10^{12}$ Mpc^{-1} (ovvero frequenza ~ 0.01 Hz)

- indispensabili modelli inflazionari che prevedono spettro elevato ad alte frequenze (piccole scale), come naturalmente avviene in cosmologia di stringa

- difficolta': compatibilita' con gli attuali vincoli sullo spettro imposti da CMB, LSS, GW detectors, etc.

in corso di studio ...

Neutrinos in cosmology (CNB)

Neutrinos decoupled at T~MeV, keeping a spectrum as that of a relativistic species

$$f_\nu(p,T) = \frac{1}{e^{p/T_\nu}+1}$$

$$n_\nu = \int \frac{d^3p}{(2\pi)^3} f_\nu(p,T_\nu) = \frac{3}{11} n_\gamma = \frac{6\zeta(3)}{11\pi^2} T_{CMB}^3$$

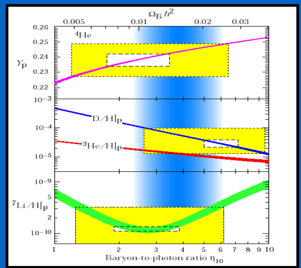
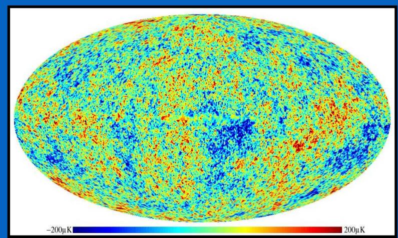
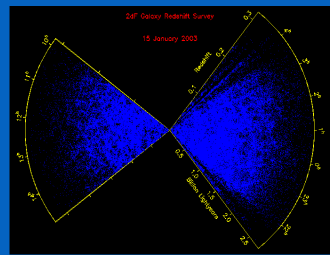
$$\rho_{\nu_i} = \int \sqrt{p^2+m_{\nu_i}^2}\, \frac{d^3p}{(2\pi)^3} f_\nu(p,T_\nu) \rightarrow \begin{cases} \frac{7\pi^2}{120}\left(\frac{4}{11}\right)^{4/3} T_{CMB}^4 & \text{Massless} \\ m_{\nu_i} n_\nu & \text{Massive } m_\nu \gg T \end{cases}$$

$$\Omega_\nu h^2 = 1.7 \times 10^{-5}$$

$$\Omega_\nu h^2 = \frac{\sum_i m_i}{94.1\ \text{eV}}$$

De Broglie wavelength today $\lambda \approx mm$ coherent scattering on targets?

CNB indirect evidences

		
Primordial Nucleosynthesis BBN	Cosmic Microwave Background CMB	Formation of Large Scale Structures LSS
T ~ MeV	T < eV	
flavor dependent	Flavor blind	

Neutrinos in cosmology

Issues:

- masses, abundance, asymmetries, Majorana vs Dirac
- direct detection
- sterile states (N_{eff}...e non solo)
- Non standard distribution (N_{eff})

Neutrinos in cosmology

Sterile states

• eV scale: strong bounds from cosmology

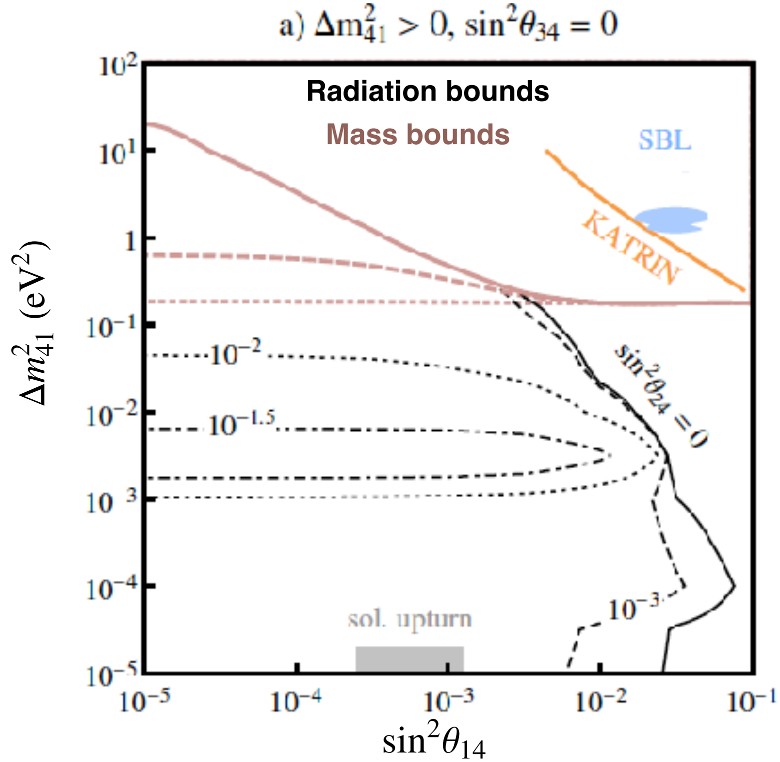
Way outs: secret interactions, active state chemical potentials,…

• keV mass range (Ptolemy)

• 100 MeV scale

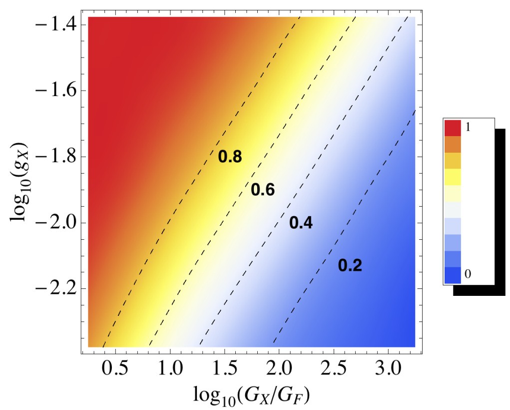
See WP2

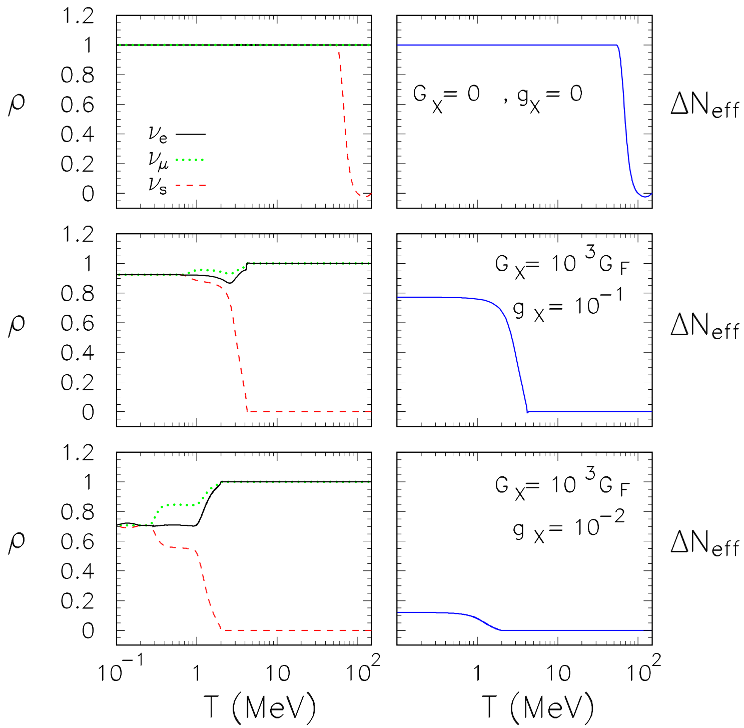
Planck constraints on the parameter space of ν oscillation:



Neutrinos in cosmology: secret interactions

$$G_X = \frac{\sqrt{2}}{8} \frac{g_X^2}{M_X^2} \, .$$

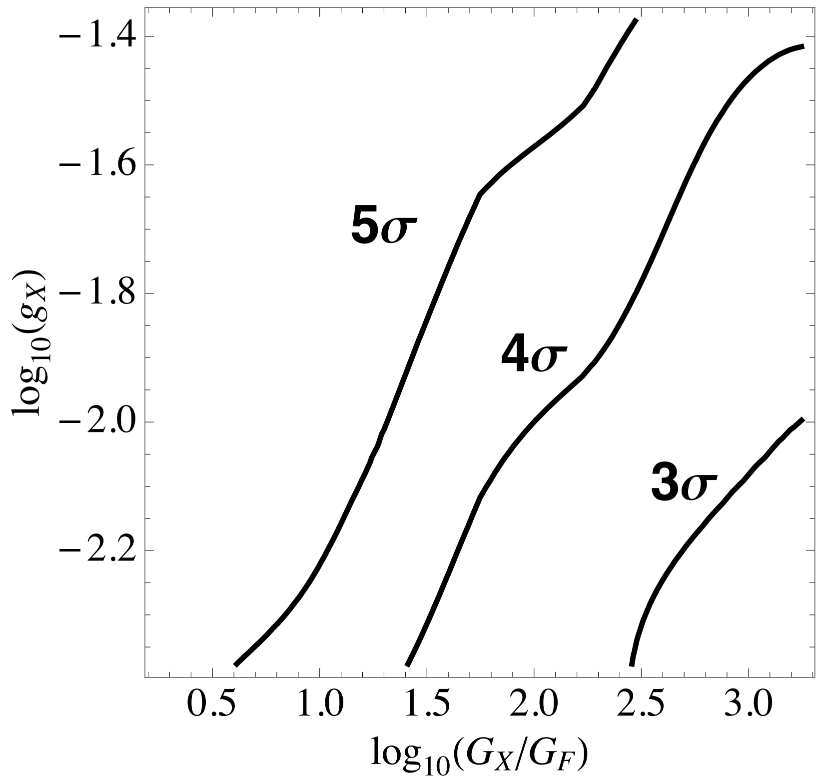




Distortion on ν_e spectra!

Neutrinos in cosmology: secret interactions

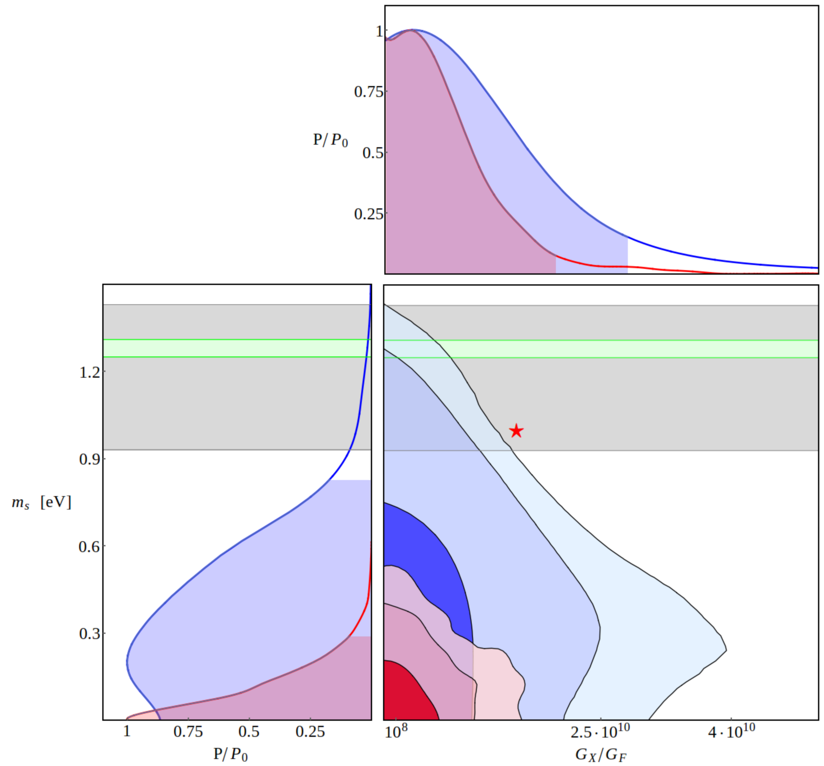
From Deuterium abundance



Saviano et al 2014

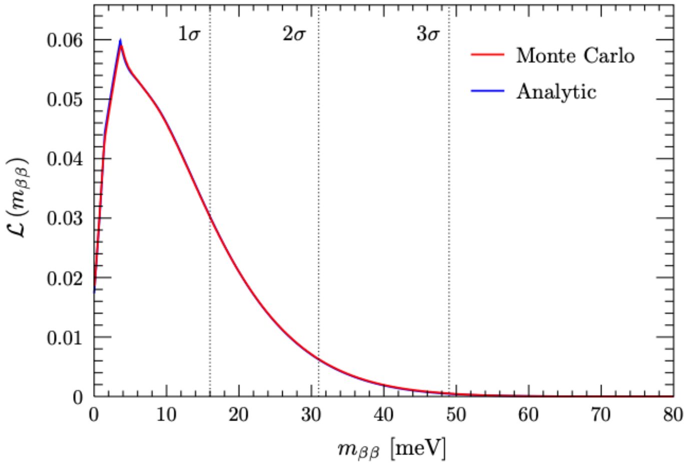
Neutrinos in cosmology: secret interactions

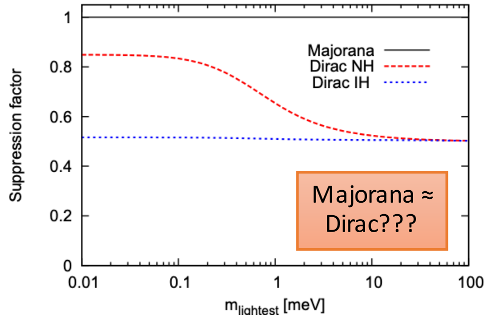
Other bounds come from CMB and LSS: late production for large collisional term even for a tiny oscillation angle



Vincoli da misure indirette della CNB

Extra relativistic states (N_{eff}), masse,
implicazioni sul doppio beta, ...





m_1=1 meV
Δ=7 meV

CNB direct detection

CNB: very low energy, difficult to measure directly by ν-scattering

1. Large De Broglie wavelength λ~0.1 cm

   Coherent scattering over nuclei (or macroscopic domain)

   Wind force on a test body,

Cross section

$\sigma_{\nu N} \sim 10^{-56} (m_\nu/eV)^2 cm^2$ non relativistic

$\sigma_{\nu N} \sim 10^{-63} (T_\nu/eV)^2 cm^2$ relativistic

acceleration

$n_\nu \beta$ NA/A $\sigma_{\nu N}$ dp ~ $(100/A)10^{-51} (m_\nu /eV)$ cm s^{-2}

Today: Cavendish torsion balances can test acceleration as small as 10^{-13} cm s^{-2} !!

2. Accelerators:

Too small even at LHC or beyond !

3. Effects linear in G_F:

No go theorem (Cabibbo & Maiani, Langacker et al) effect vanishes if

static source - background interaction

Homogeneous ν flux on the target scale

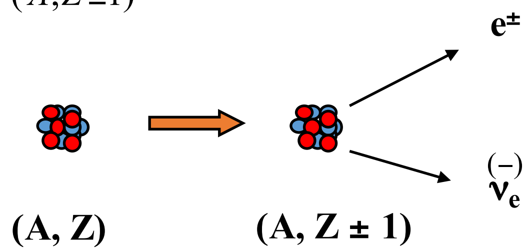
Stodolski effect: polarized electron target experiences a tourque due to helicity energy splitting in presence of a polarized (asymmetry) neutrino wind

dE ~$g_A \vec{\sigma} \cdot \vec{\beta}(n_\nu - n_{\bar{\nu}})$

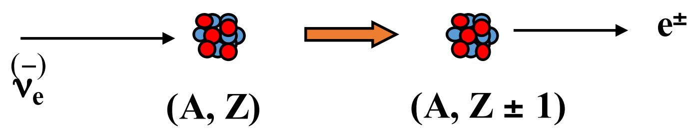
$$N_{(A,Z)} \rightarrow N'_{(A,Z\pm1)} \; e^{\pm} \; \overset{(-)}{\nu}_e$$

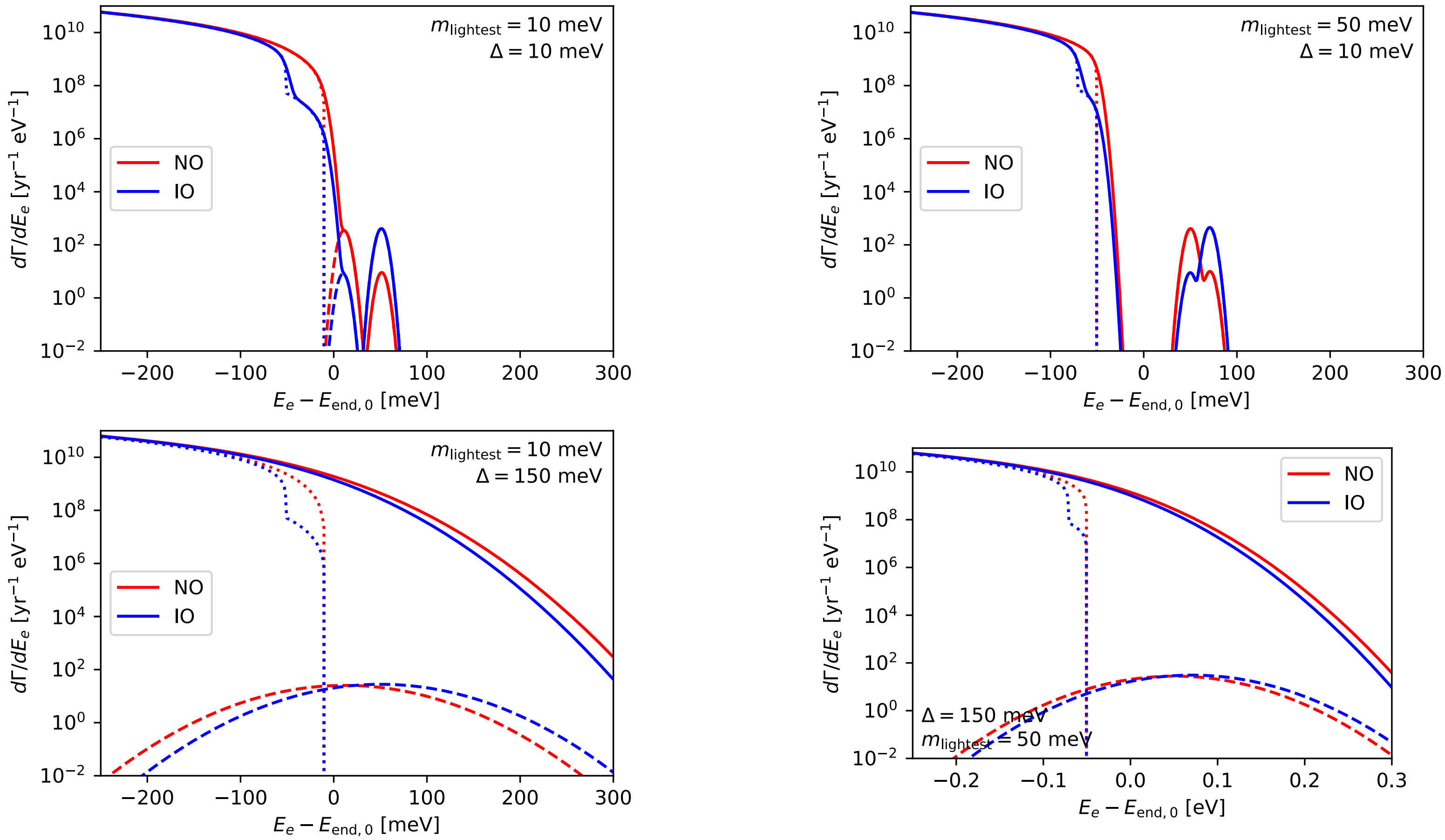
$$\overset{(-)}{\nu}_e \; N_{(A,Z)} \rightarrow N'_{(A,Z\pm1)} \; e^{\pm}$$

Beta decay



Neutrino Capture on a
Beta Decaying Nucleus
(NCβ)





$m_{\rm lightest} = 10$ meV
$\Delta = 10$ meV
NO
IO
$d\Gamma/dE_e$ [yr^{-1} eV^{-1}]
$E_e - E_{\rm end,0}$ [meV]
$m_{\rm lightest} = 50$ meV
$\Delta = 10$ meV
$m_{\rm lightest} = 10$ meV
$\Delta = 150$ meV
$\Delta = 150$ meV
$m_{\rm lightest} = 50$ meV
$E_e - E_{\rm end,0}$ [eV]

The case of ^{3}H

$$\lambda_\beta = 2.85 \cdot 10^{-2} \frac{\sigma_{\rm NCB} v_\nu / c}{10^{-45} {\rm cm}^2} {\rm yr}^{-1} \ {\rm mol}^{-1} . \quad \sigma_{\rm NCB}(^3{\rm H}) \frac{v_\nu}{c} = (\ 7.84 \pm 0.03\ ) \times 10^{-45}\ {\rm cm}^2 ,$$

m_ν (eV)	FD (events yrs^{-1})	NFW (events yrs^{-1})	MW (events yrs^{-1})
0.6	7.5	90	150
0.3	7.5	23	33
0.15	7.5	10	12

The number of NCB events per year for 100 g of ^{3}H

8 events yr^{-1} per 100g of ^{3}H (no clustering)

up to 10^2 events yr^{-1} per 100 g of ^{3}H due to clustering effect

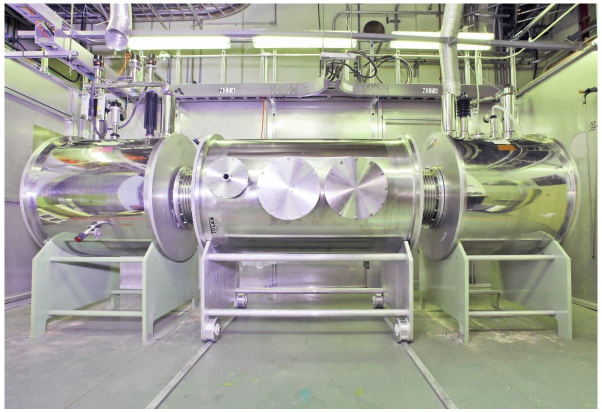
signal/background = 3 for Δ=0.2 eV if m_ν=0.7 eV

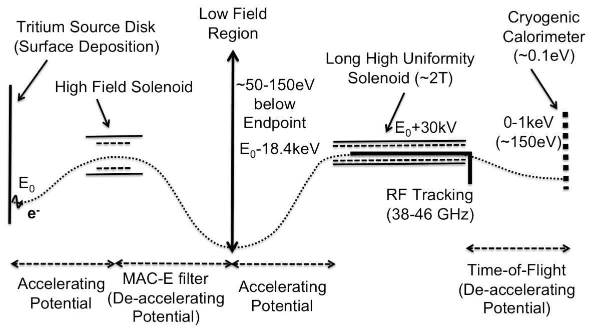
Δ=0.1 eV if m_ν=0.3 eV

The Ptolemy Project

Development of a Relic Neutrino Detection Experiment at PTOLEMY:
Princeton Tritium Observatory for Light, Early-Universe, Massive-Neutrino Yield

Pontecorvo

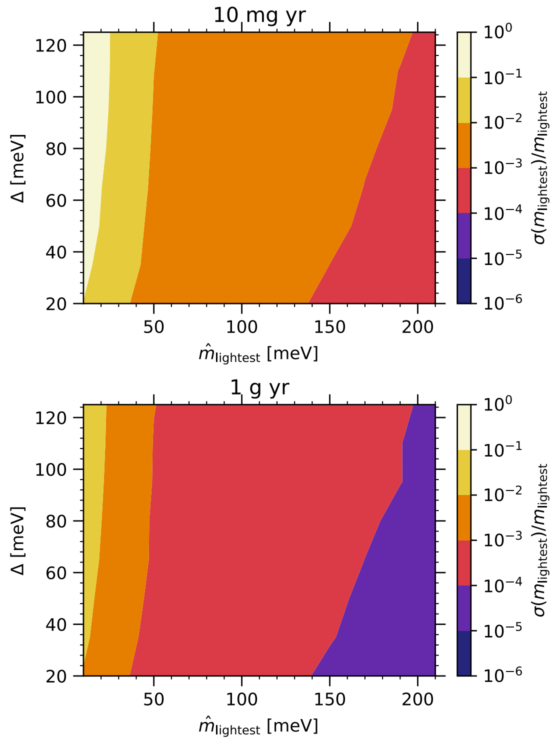




INFN Laboratori Nazionali del Gran Sasso, Italy,

See Pasquale and Marco talk

Neutrino mass sensitivity



Outlooks

Settore molto attivo nel panorama generale e nella nostra comunità

Collaborazioni fra vari nodi con diversi expertise