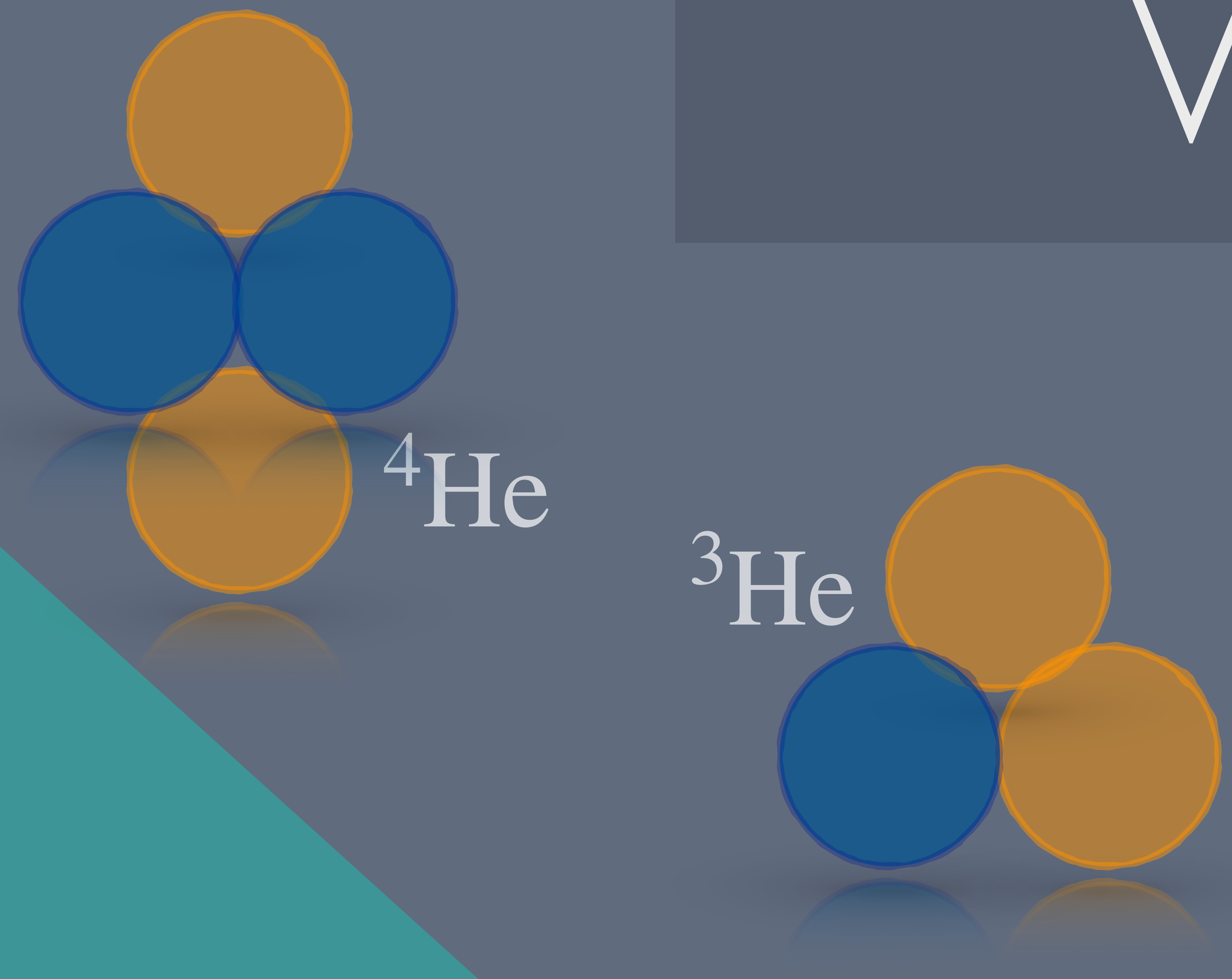
WHAT CAN YOU MEASURE WITH BBN IN 2021?



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Cosmology Talks
October 2021

Related to **JCAP01(2020)004** w/ N. Sabti, M. Escudero, D. Blas, M. Fairbairn
+ Addendum (2021)
with updated nuclear rates

WHY NOW? CURRENT STATUS OF BBN

(Blue Compact Galaxies) (Quasar/Gas Cloud Systems)

$$Y_P = 0.245 \pm 0.003, \; 10^5 \times \mathrm{D/H} = 2.547 \pm 0.025$$

- Measurements of abundances (He, D/H) at 1% level - it is a **precision** probe
- Standard Model theory predictions at the same level with only **one** free parameter
- Recently, rates for key parts of the reaction network **updated** (LUNA; see later)
- Theoretically **sensitive** to a wide range of particle physics and cosmological effects

So, **clean** probe to compare to other data e.g. CMB
or look for/constrain new physics

WHAT QUANTITIES DOES BBN "SEE"?

BBN can be used to measure* a combination of the **reaction** and **expansion rates**

*subject to the size of the effect being larger than the measurement errors

REST OF THE TALK

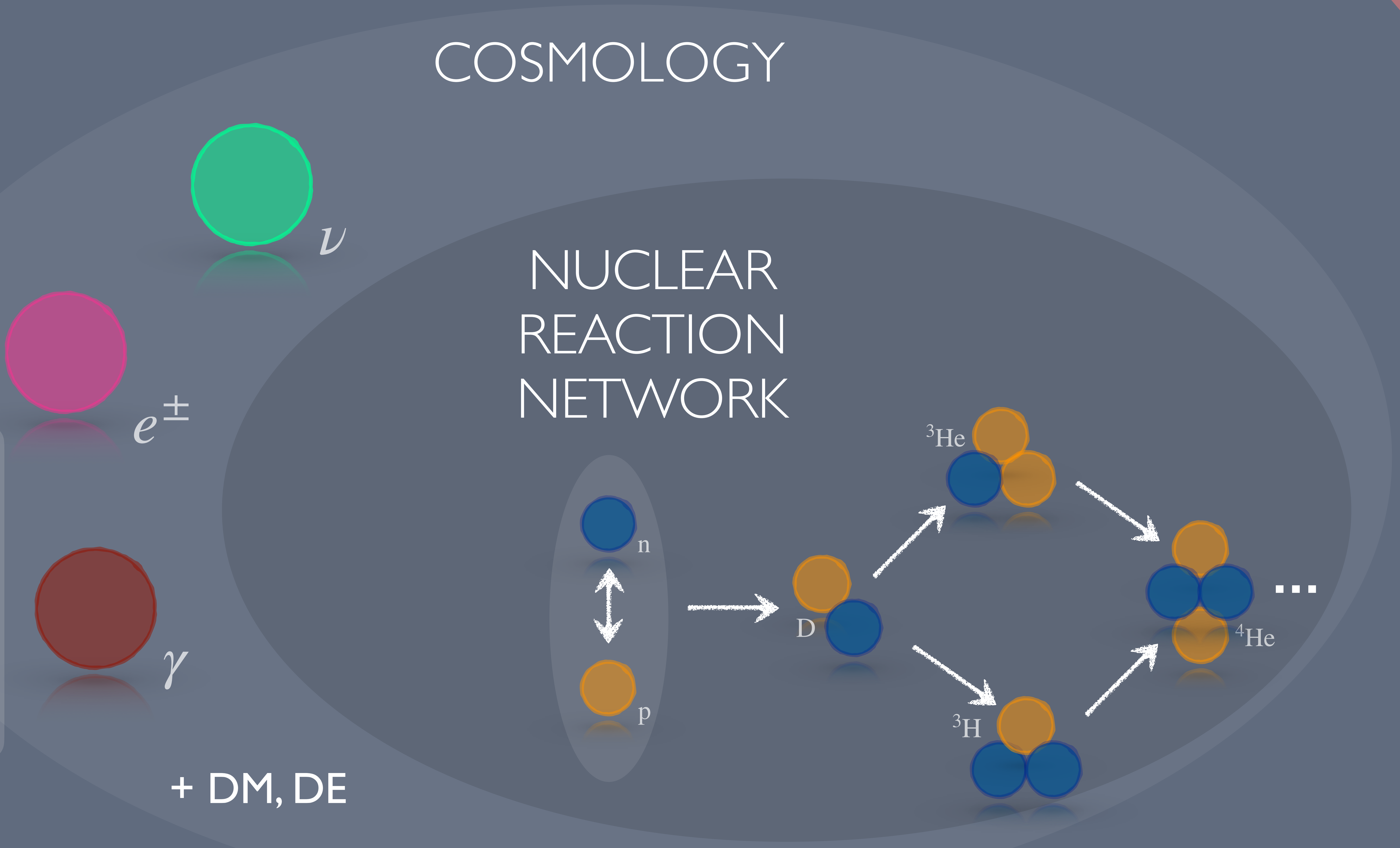
I — INTRO: Why now? What for?

II — PHYSICS OF BBN: Building a simple reaction network

- Discuss key events in BBN timeline
- Focus on (n, p, D, He) region

III — OUTLOOK: LUNA, Applications, Conclusions

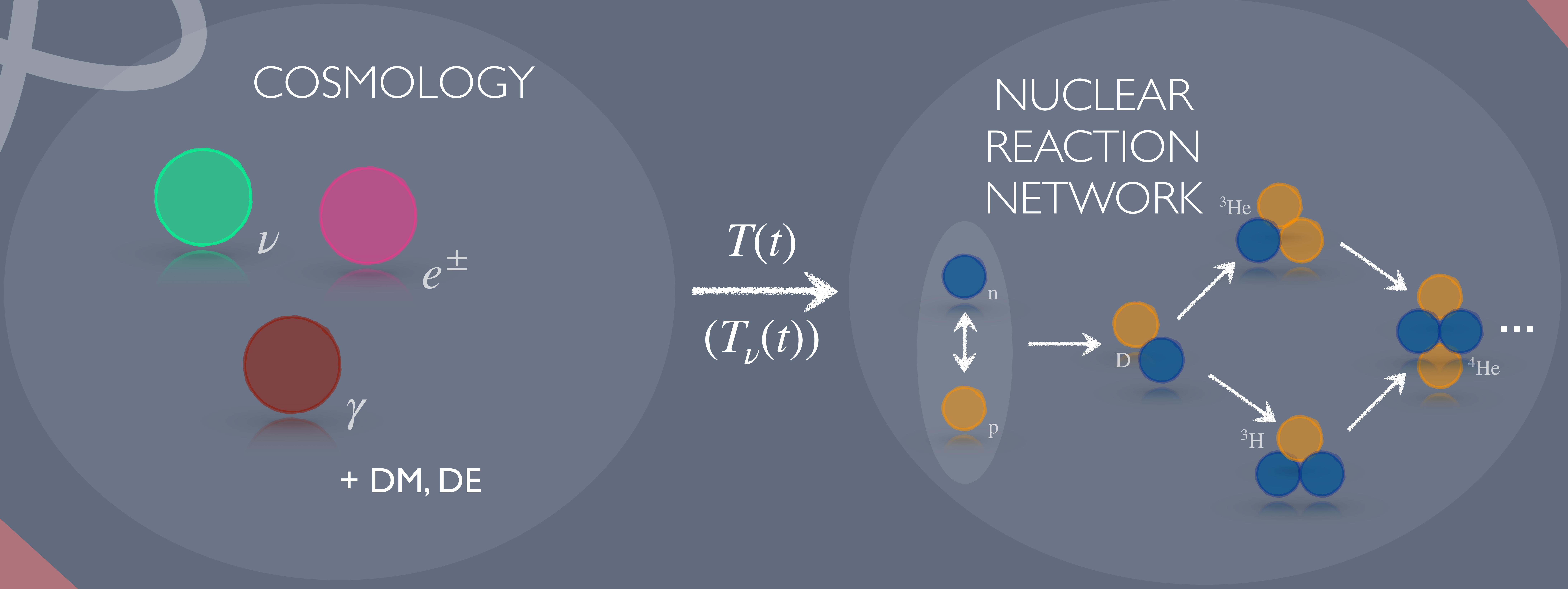
PHYSICS OF BBN



IDEA: You can solve **first** for the Cosmology and thermodynamics, and **then** for the reaction network

Because
$\rho_{\rm b} \ll \rho_{\rm pl}, \rho_{\nu}$

PHYSICS OF BBN



SOLVING THE COSMOLOGY

ν $e^{\pm}$ γ

THERMODYANMICS

Method: Can use the fact that entropy is conserved in the adiabatic expansion to solve for the scale factor as a function of time

Result: $a(T)$

Non-instantaneous neutrino decoupling

$$\frac{\mathrm{d}\log(aT)}{\mathrm{d}\log T} = \frac{\mathcal{N} - (\mathrm{d}\mathcal{S}/\mathrm{d}\log T)}{\mathcal{N} + 3\mathcal{S}}$$

Can include e.g. plasma effects

TEMPERATURE-TO-TIME RELATION

$$H^2 = \frac{8\pi G}{3}(\rho_\nu + \rho_{\rm pl} + \rho_{\rm b} + \rho_{\rm cdm} + \rho_\Lambda)$$

Method: Can solve the Friedmann equation to obtain the time dependence of the scale factor, and therefore the temperature

Result: $T(t)$

TEMPERATURE-TO-TIME RELATION

(in SBBN)

	NEUTRINO DECOUPLING	WEAK RATE FREEZE-OUT	ELECTRON-POSITRON ANNIHILATION	PROTON TO NEUTRON FREEZE-OUT	DEUTERIUM BOTTLENECK OVERCOME	END OF NUCLEOSYNTHESIS
T	2 MeV	0.7 – 0.8 MeV	0.5 MeV	0.28 MeV	0.078 MeV	0.066 MeV
	2×10^{10} K	$8 - 9 \times 10^{9}$ K	6×10^{9} K	3×10^{9} K	9×10^{8} K	8×10^{8} K
t	0.1 secs	1 – 2 secs	3 secs	10 secs	200 secs	300 secs

The relation between temperature and time is **COSMOLOGY**-dependent

TEMPERATURE-TO-TIME RELATION

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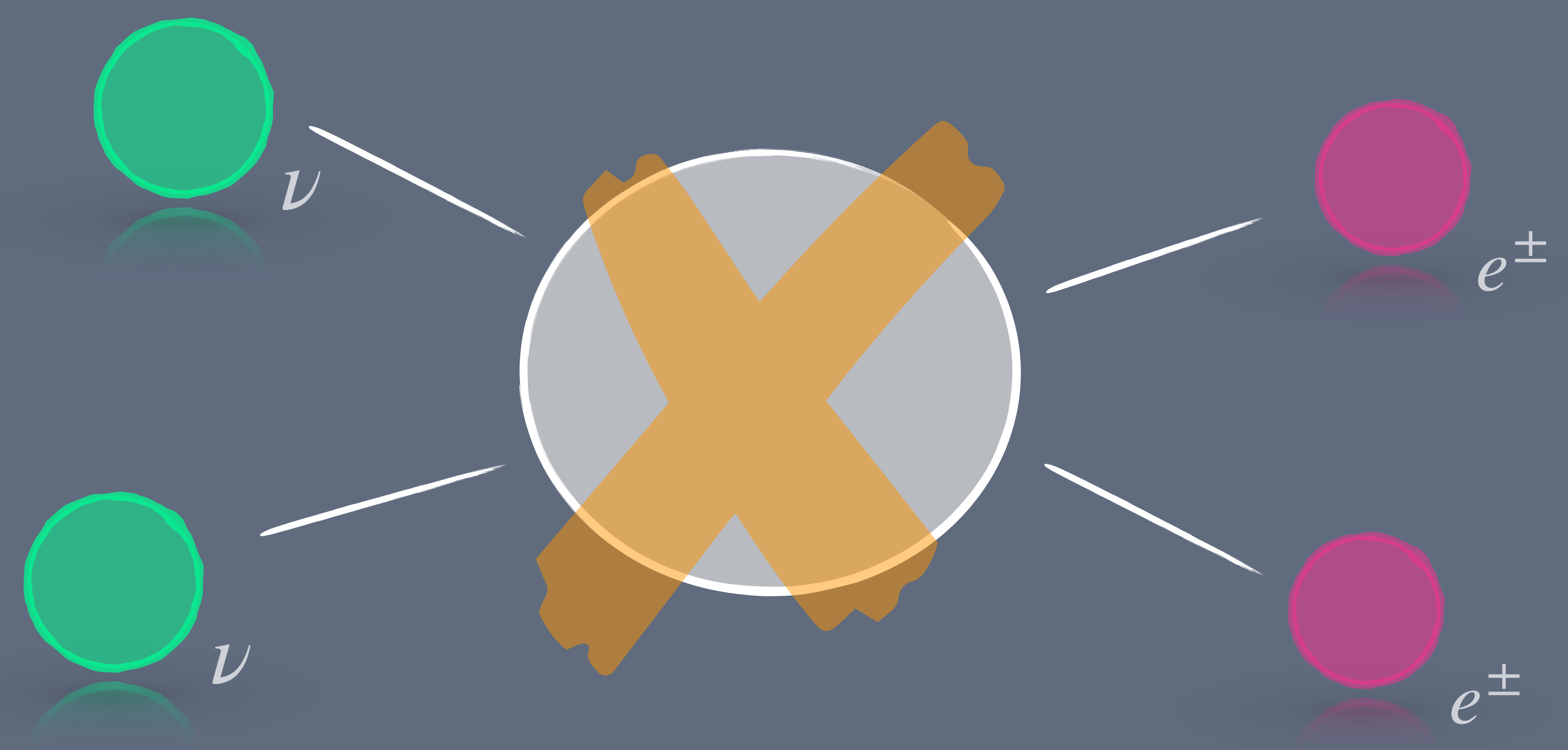

$$\Gamma_{\nu\nu\to ee} \sim G_F^2 T^5 \sim H$$

TEMPERATURE-TO-TIME RELATION

(in SBBN)

	NEUTRINO DECOUPLING	WEAK RATE FREEZE-OUT	**ELECTRON-POSITRON ANNIHILATION**	PROTON TO NEUTRON FREEZE-OUT	DEUTERIUM BOTTLENECK OVERCOME	END OF NUCLEOSYNTHESIS
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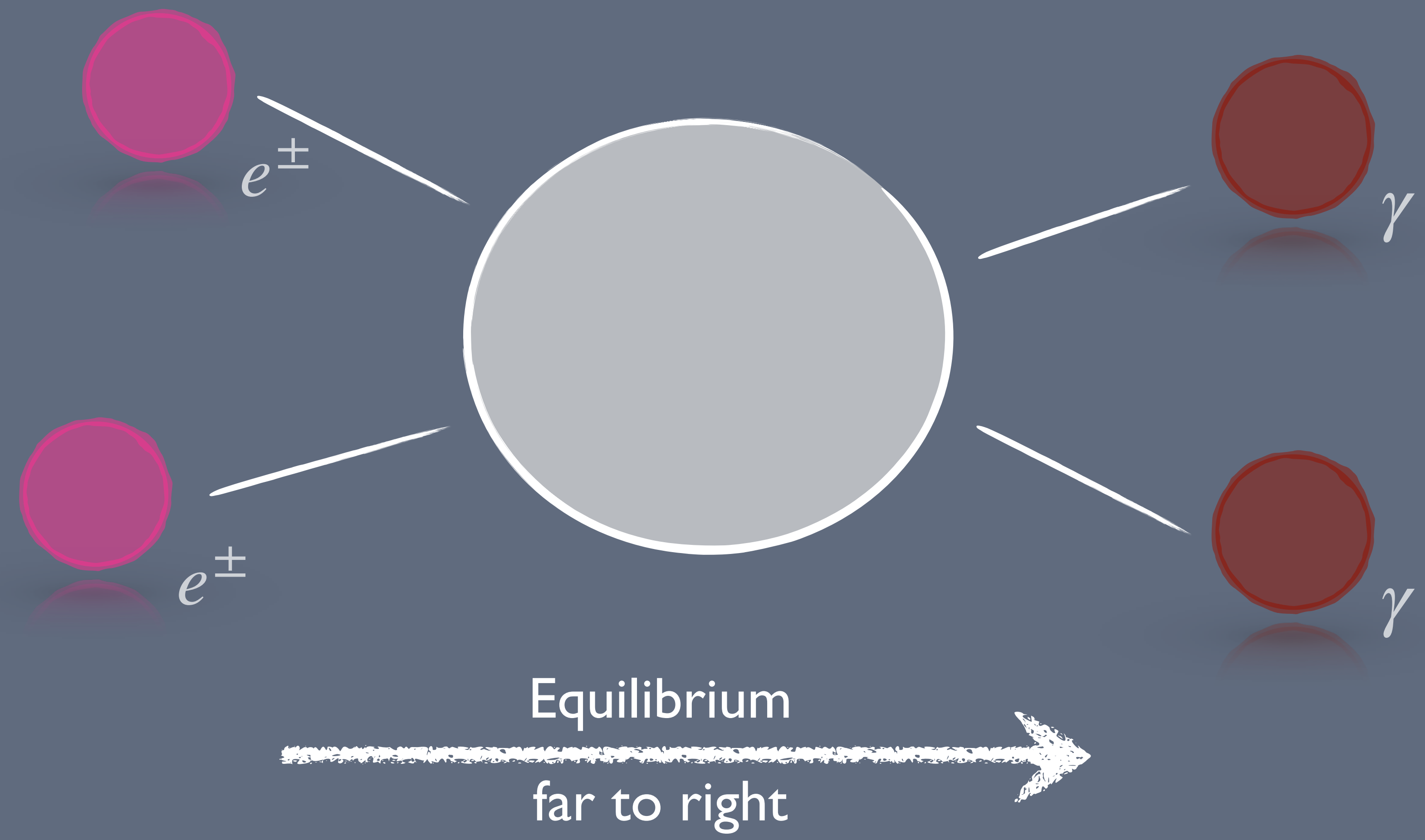
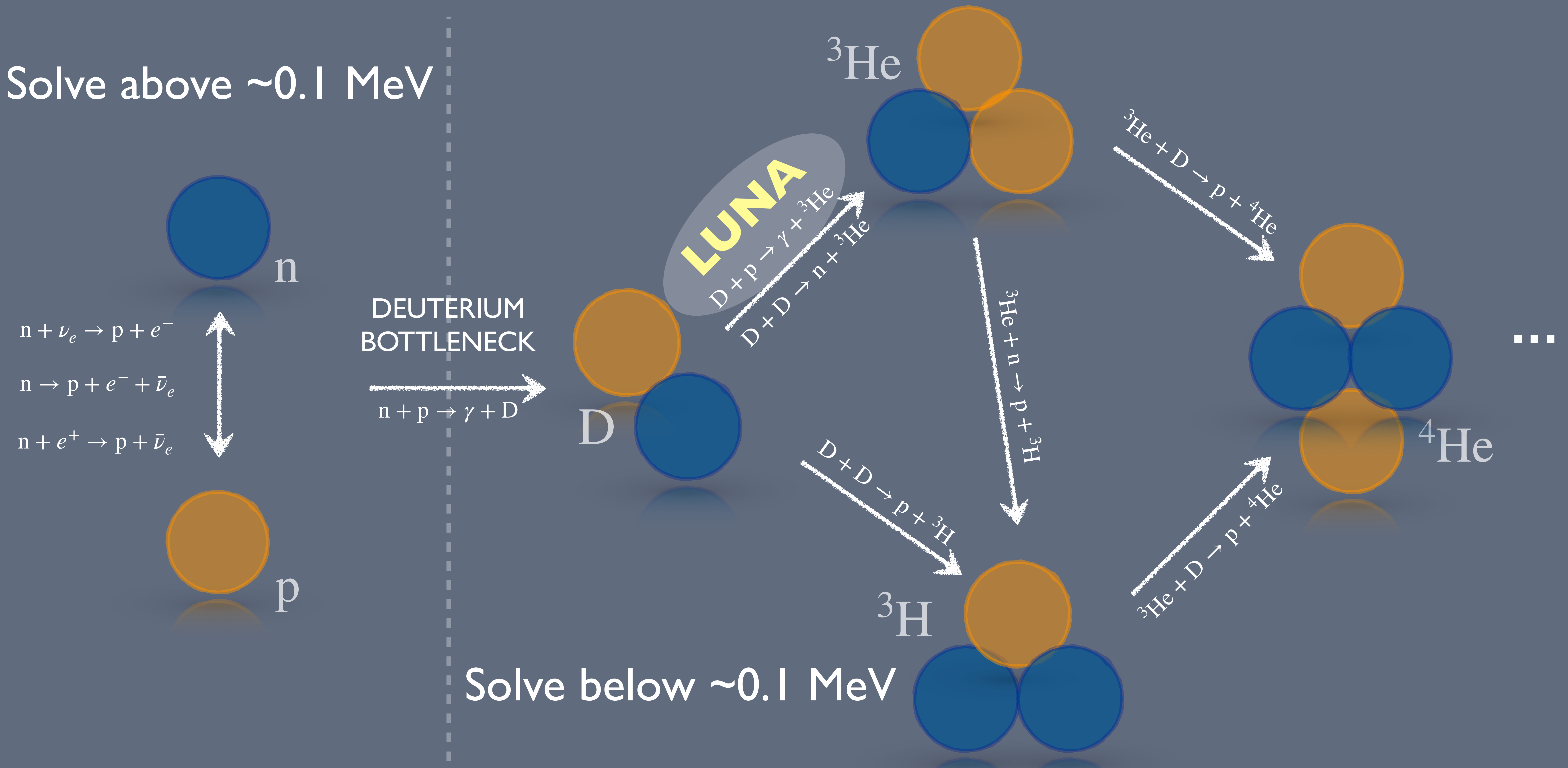
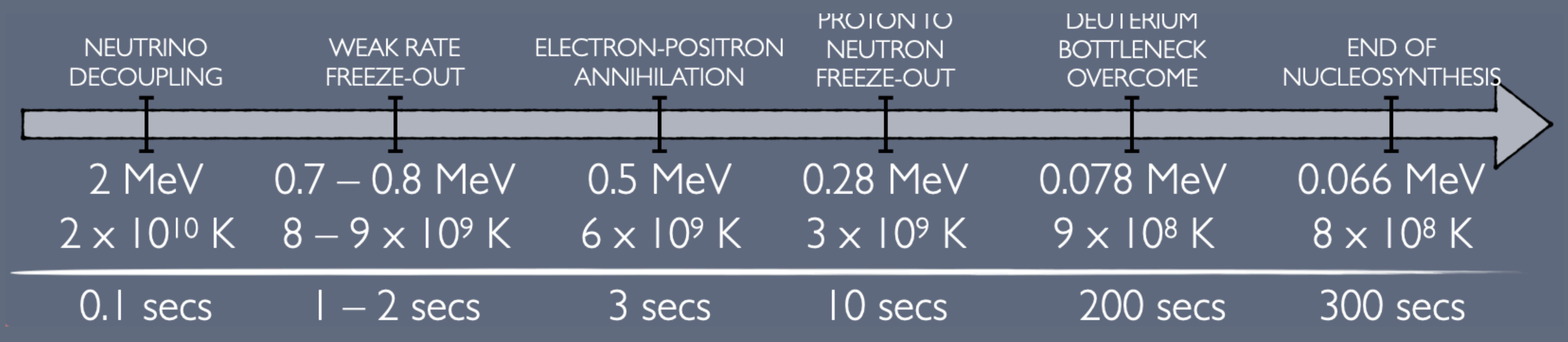


Result: $T_{\nu} < T_{\gamma}$

THE BBN REACTION NETWORK



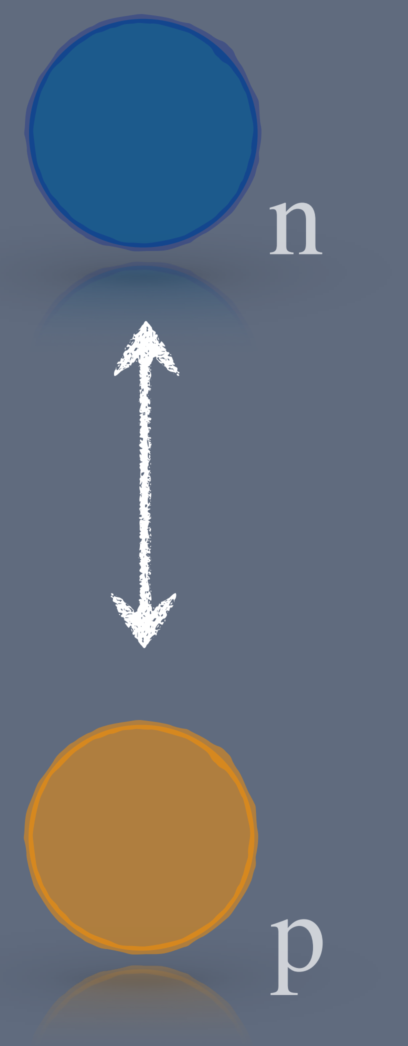


$T \simeq 0.8\,\mathrm{MeV}$
$t \sim 1\,\mathrm{sec}$

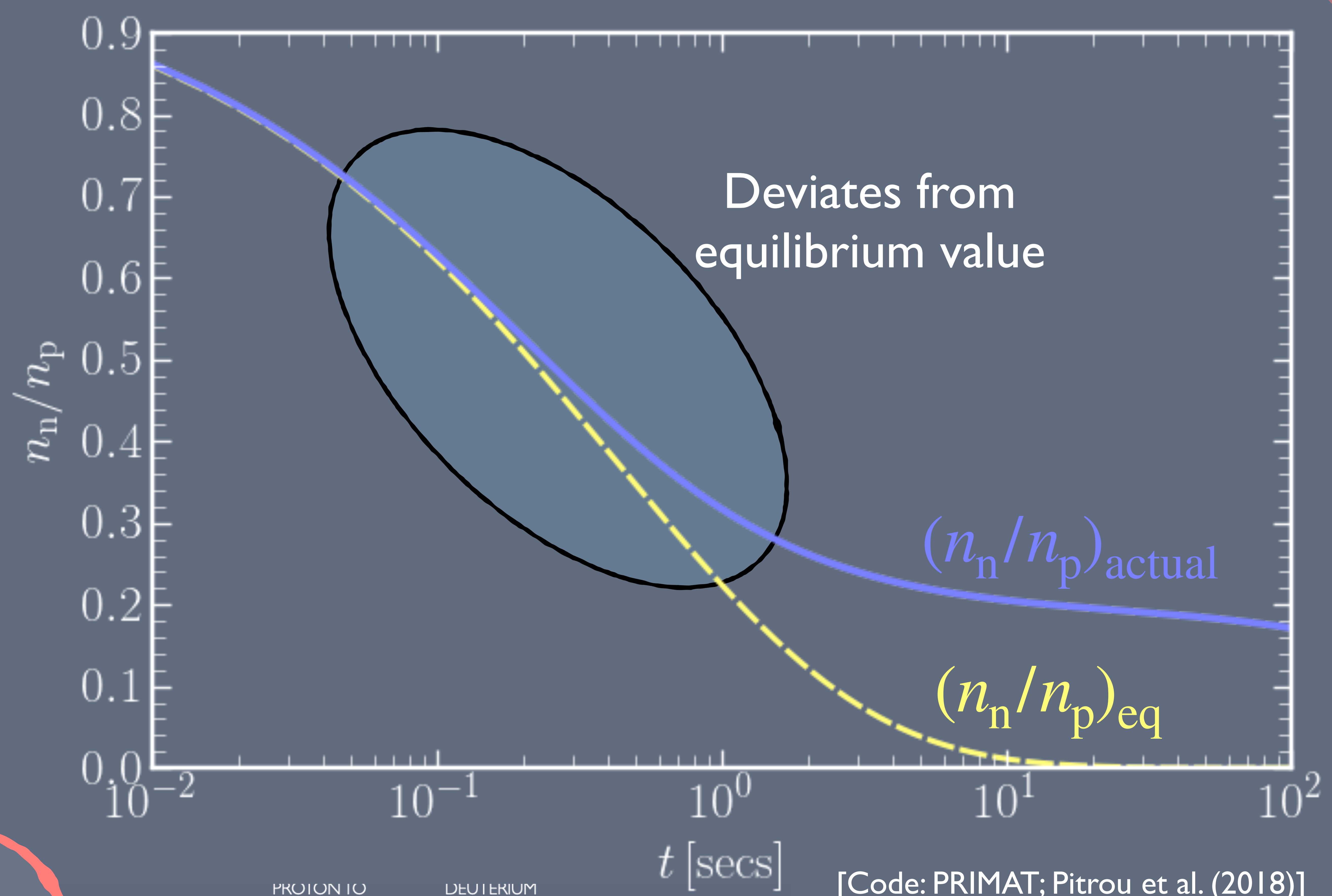
PROTONS AND NEUTRONS:
WEAK FREEZE-OUT

Kept in **equilibrium** by the reactions

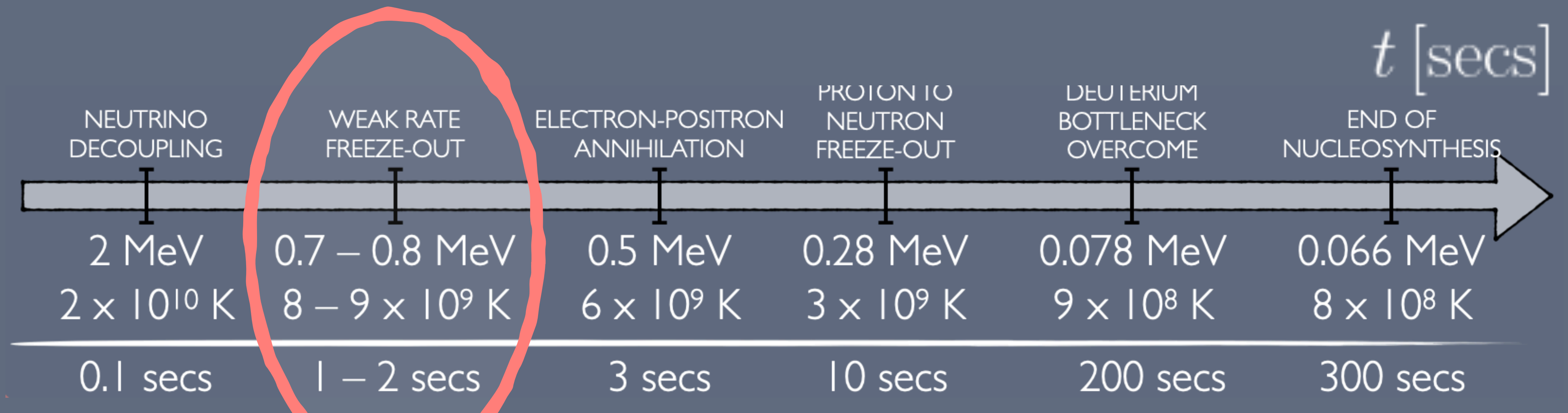
$$\mathrm{n} + \nu_e \to \mathrm{p} + e^-$$
$$\mathrm{n} \to \mathrm{p} + e^- + \bar{\nu}_e$$
$$\mathrm{n} + e^+ \to \mathrm{p} + \bar{\nu}_e$$



…until around 0.8 MeV



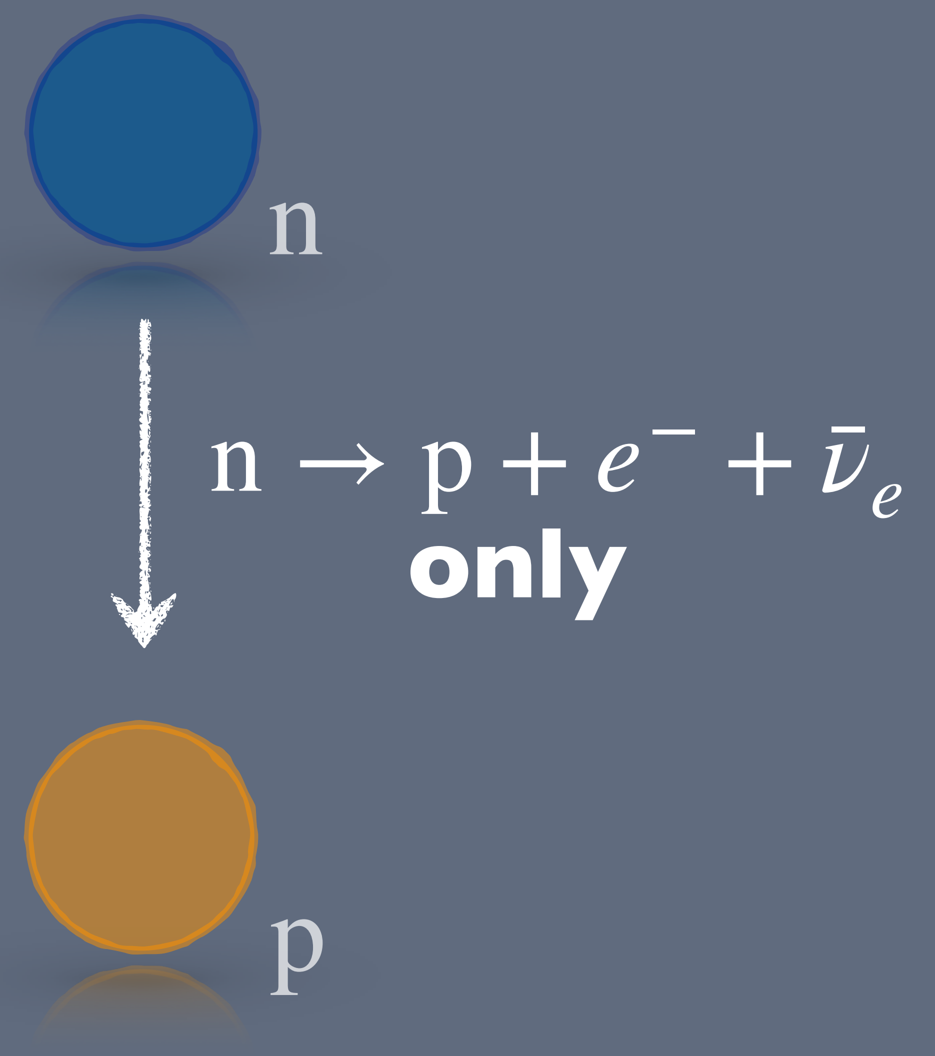
[Code: PRIMAT; Pitrou et al. (2018)]



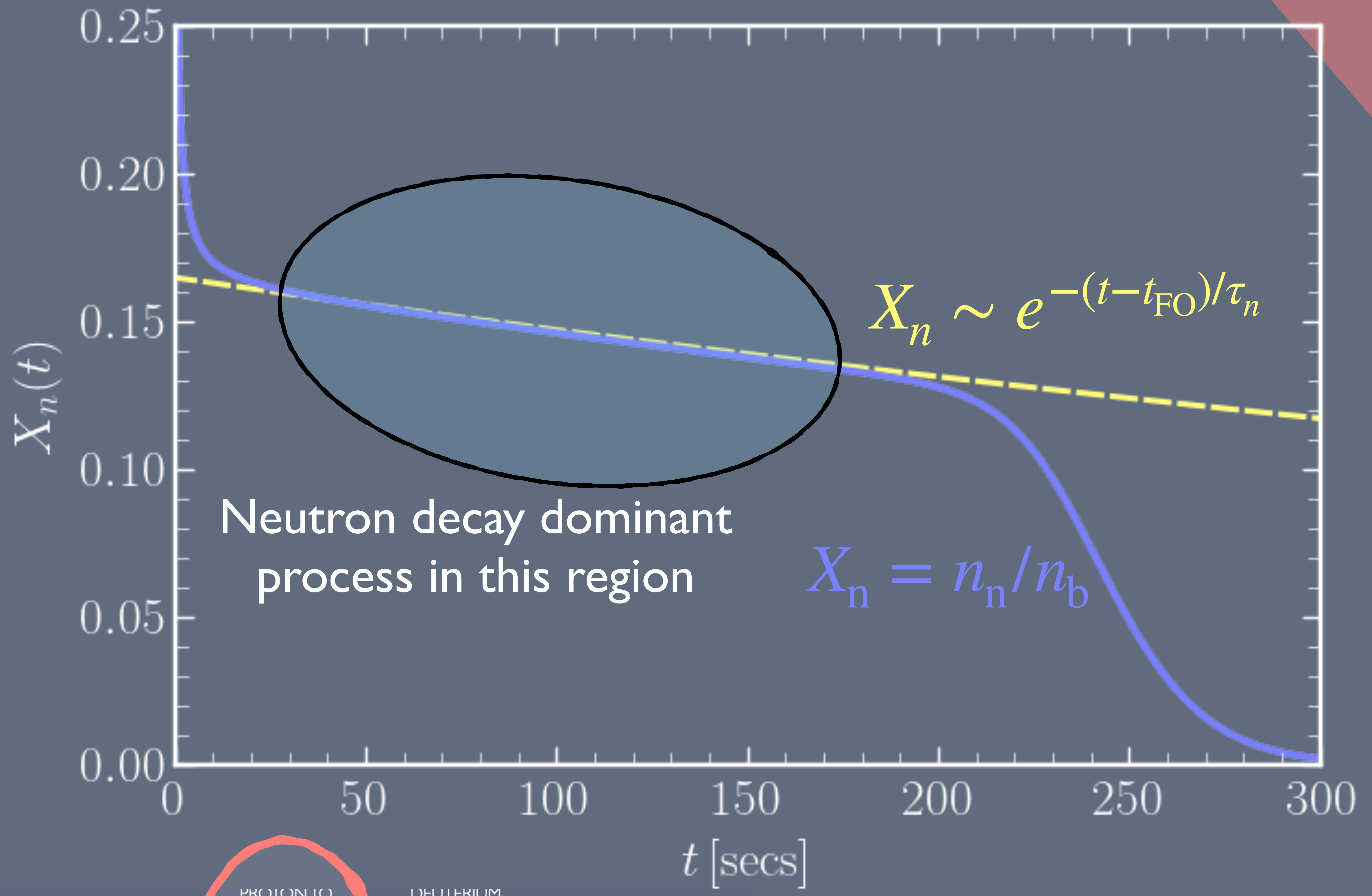
$T \simeq 0.3\,\mathrm{MeV}$
$t \sim 10\,\mathrm{secs}$

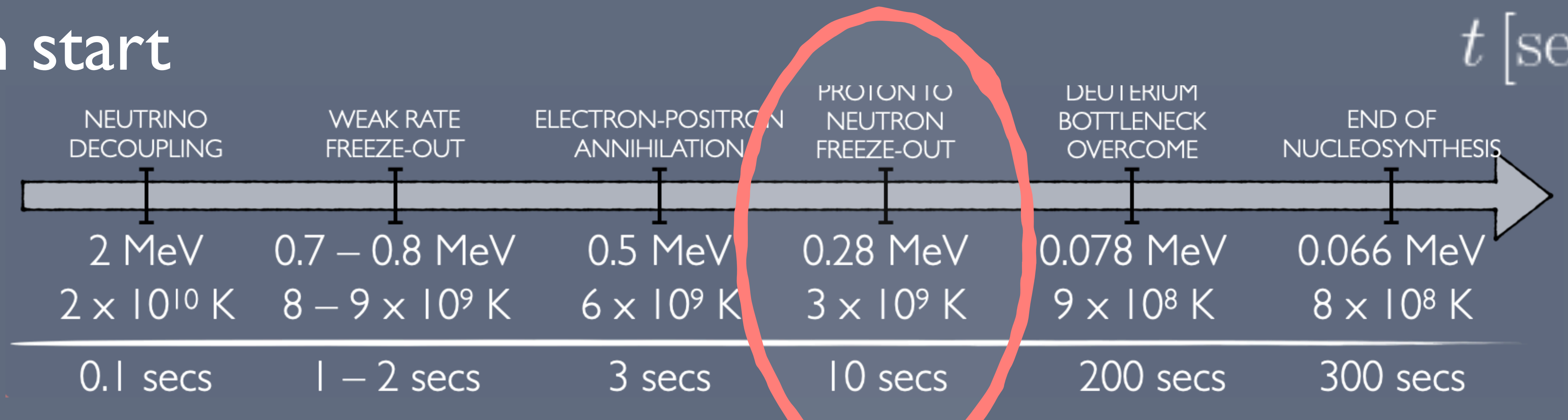
PROTONS AND NEUTRONS:
NEUTRON DECAY

Then, at about 0.28 MeV, protons can no longer be efficiently converted into neutrons



…after this, neutrons simply **decay** until Deuterium synthesis can start

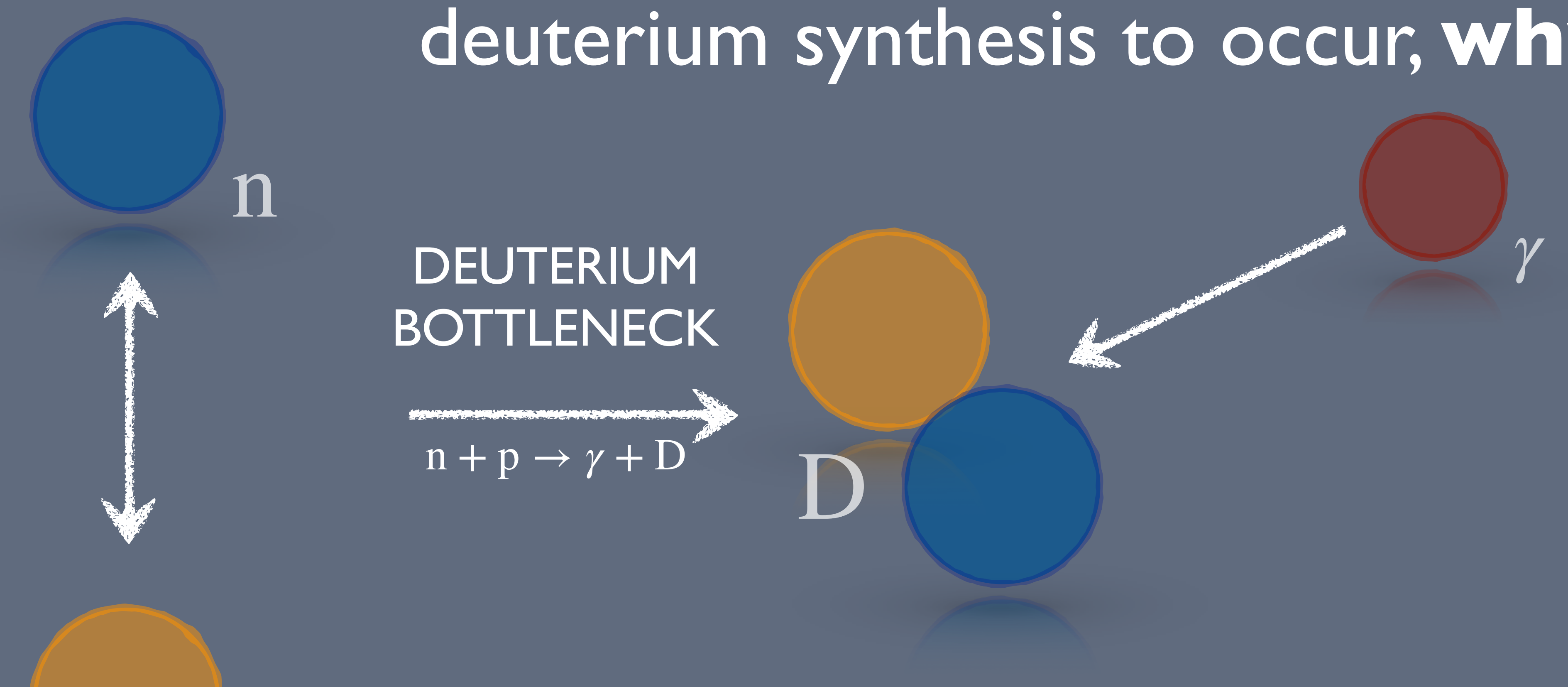




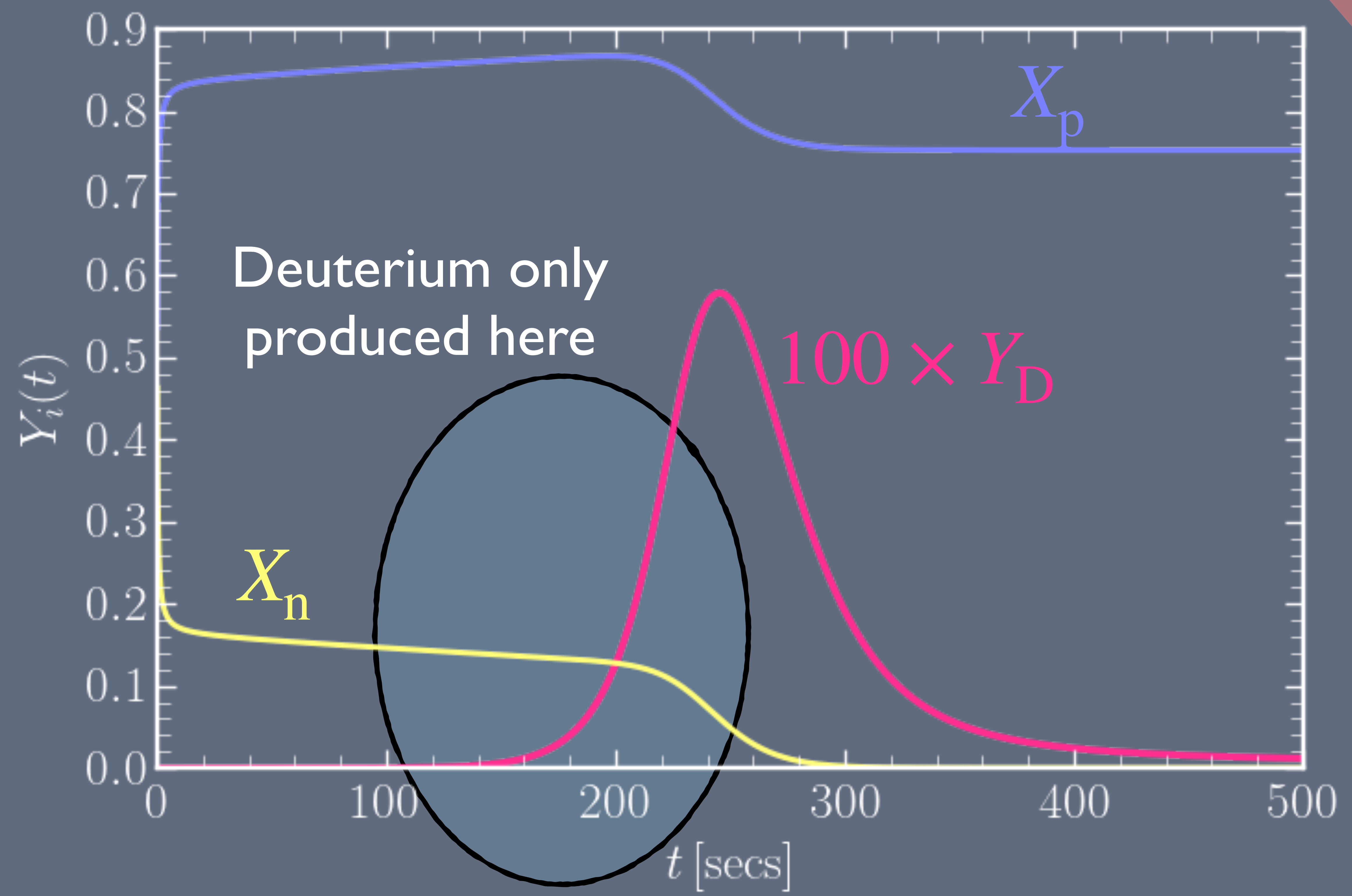
$T \simeq 0.078$ MeV
$t \sim 200$ secs

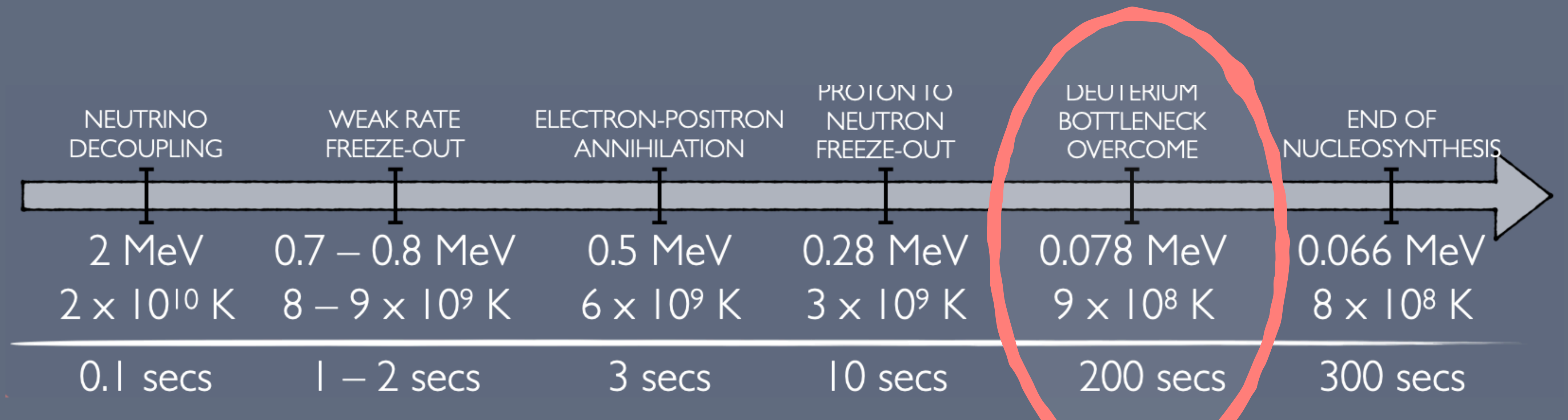
THE BOTTLENECK

Even though the binding energy of D is 2.2 MeV, it takes until 0.078 MeV for deuterium synthesis to occur, **why?**



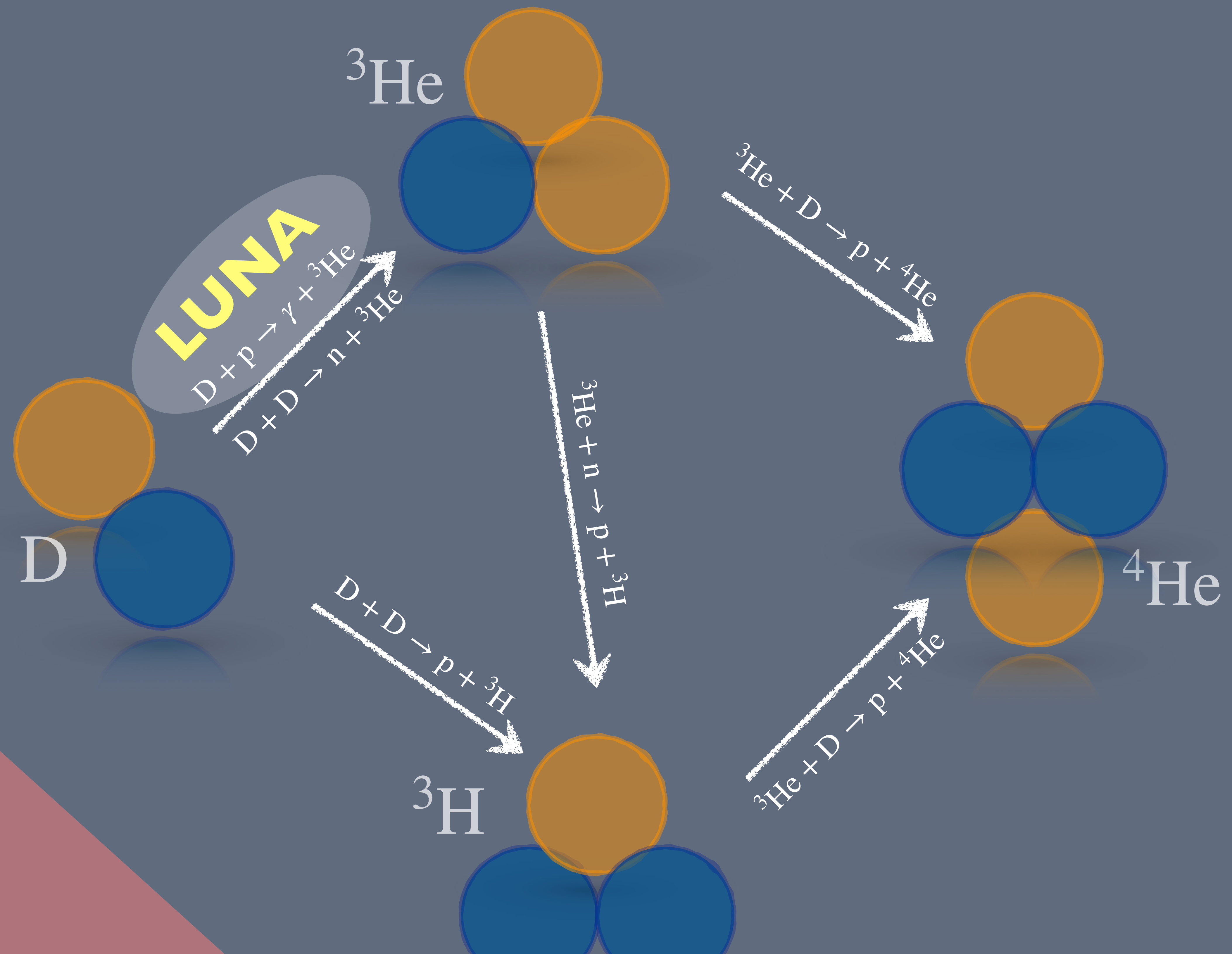
Answer: there are **lots** of photons that can easily dissociate any deuterium that is formed — parameterised by baryon-to-photon ratio

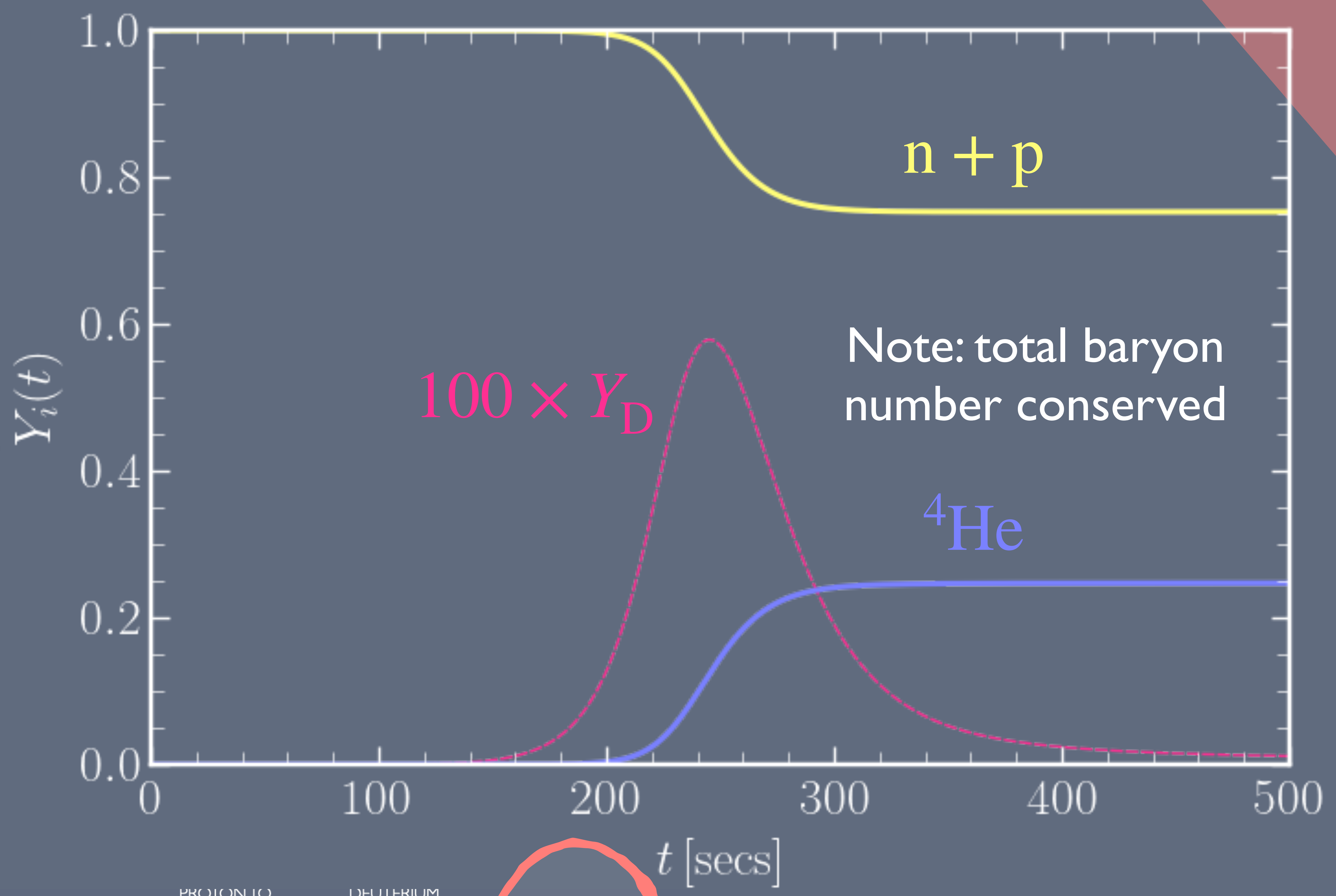




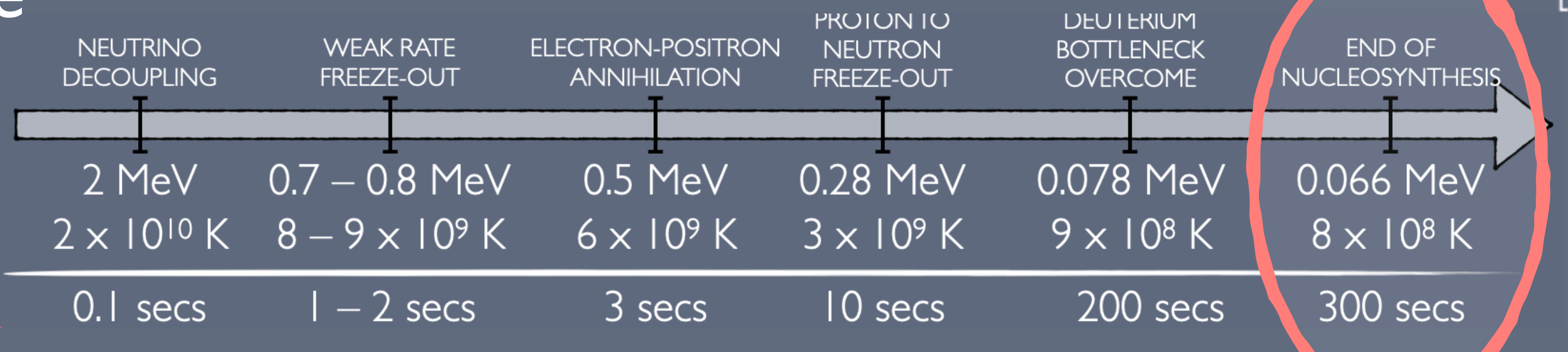
$T \simeq 0.066$ MeV
$t \sim 300$ secs

PRODUCING HELIUM-4

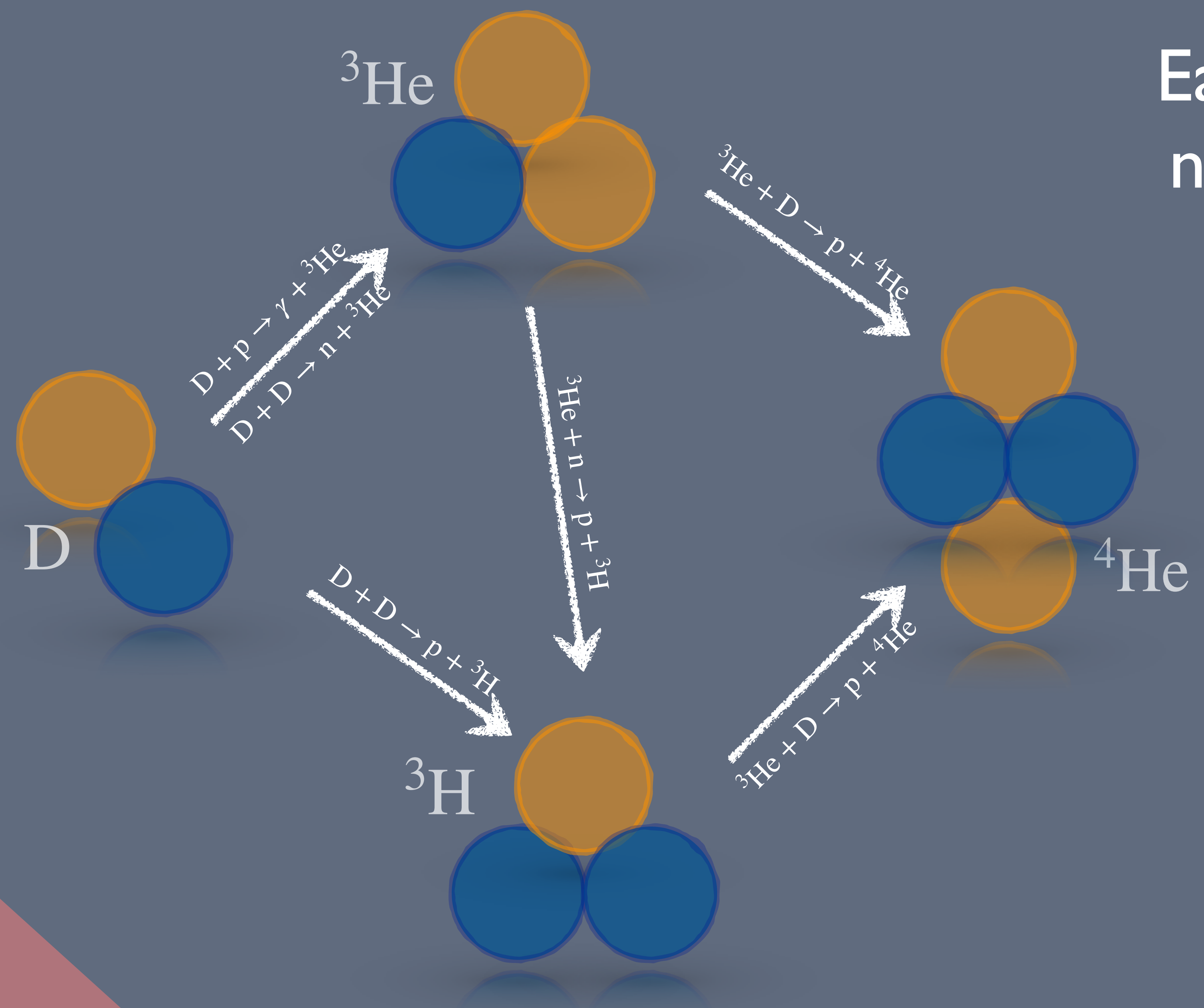




Once deuterium can be produced, the remainder of the free neutrons can be **very efficiently** transferred into Helium-4, since it has a very high binding energy (~28 MeV)



DESCRIBING THE NETWORK



Each **isotope** in the nuclear reaction network is described by a Boltzmann equation compiling all the relevant **reaction rates**

Reaction Rates

LUNA

$$\frac{dn_i}{dt} + 3Hn_i = \cdots + n_i n_j \langle \sigma v \rangle_{ij \rightarrow kl} + \cdots$$

Expansion

Boltzmann Equation

Ultimately, the reason BBN is a good probe of reaction rates and the expansion rate is because it is an **out-of-equilibrium** process

LUNA AND DEUTERIUM

Reaction Rates

$$\frac{dn_i}{dt} + 3Hn_i = \cdots + n_i n_j \langle \sigma v \rangle_{ij \to kl} + \cdots$$

Recently, the LUNA experiment has re-measured the reaction rate for

$$\mathrm{D} + \mathrm{p} \to \gamma + {}^3\mathrm{He}$$

This reaction previously **dominated** theoretical error budget for precision determinations of D and Helium-3 predictions

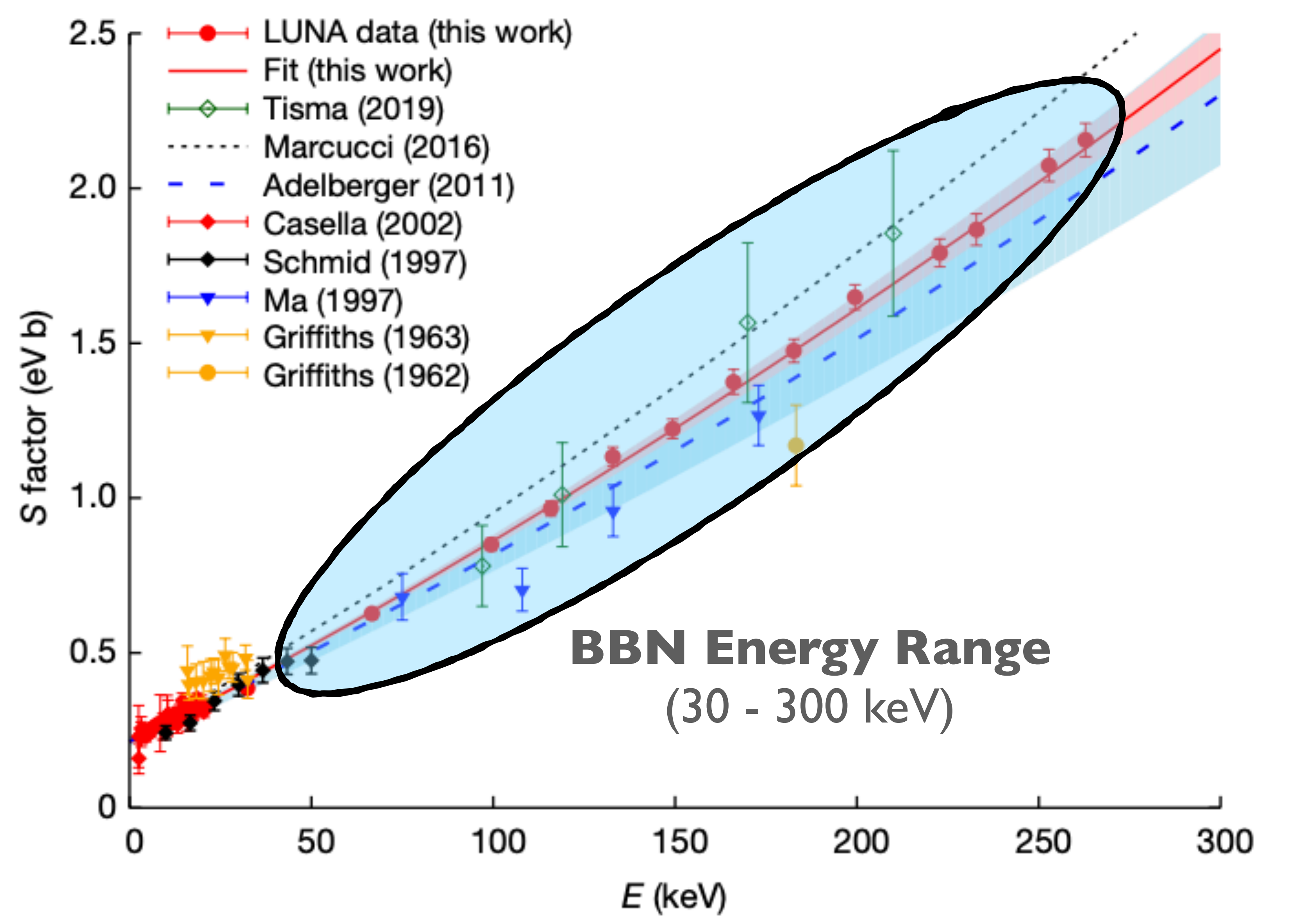


Fig. 1 | The *S* factor of the D(*p*,*γ*)^{3}He reaction. At BBN energies ($E_{cm} \approx$ 30–300 keV), the new LUNA results (filled red circles, with total (statistical + systematic) error bars) indicate a faster deuterium destruction compared with a best fit[19] (blue dashed line) of previous experimental data, but a slower destruction compared with theoretical calculations[18] (black dotted line). At BBN energies, the best fit (red solid line, equation (2)) obtained in this work is entirely dominated by the LUNA data. The fit includes all experimental data[13–16,29–31] (note that those by Warren et al.[30] and Geller et al.[31] lie outside the energy range shown here). Bands represent the 68% confidence level.

V. Mossa et al., [Nature 587 (2020) 210]

S-Factor

$$\eta \equiv \frac{Z_1 Z_2 e^2}{\hbar v}$$

$$\sigma(E) \equiv \frac{S(E)}{E}\exp(-2\pi\eta)$$

$$\langle \sigma v \rangle = \int_0^\infty \sigma(v)\phi_{\mathrm{MB}}(v) v dv$$

$$\phi_{\mathrm{MB}}(v) v \, dv = \sqrt{\frac{8}{\pi m}} \frac{1}{(k_B T)^{3/2}} e^{-\frac{E}{k_B T}} E \, dE$$

LUNA AND DEUTERIUM

Question: What are the implications of LUNA for SBBN?

Answer: It depends slightly on who you ask and whether there is a corresponding tension in the baryon density. However, having a more precise determination of the other two key reactions will be key to pin down theoretical uncertainties

$$D + D \rightarrow n + {}^3He$$

$$D + D \rightarrow p + {}^3H$$

Link to Slides

Article

The baryon density of the Universe from an improved rate of deuterium burning

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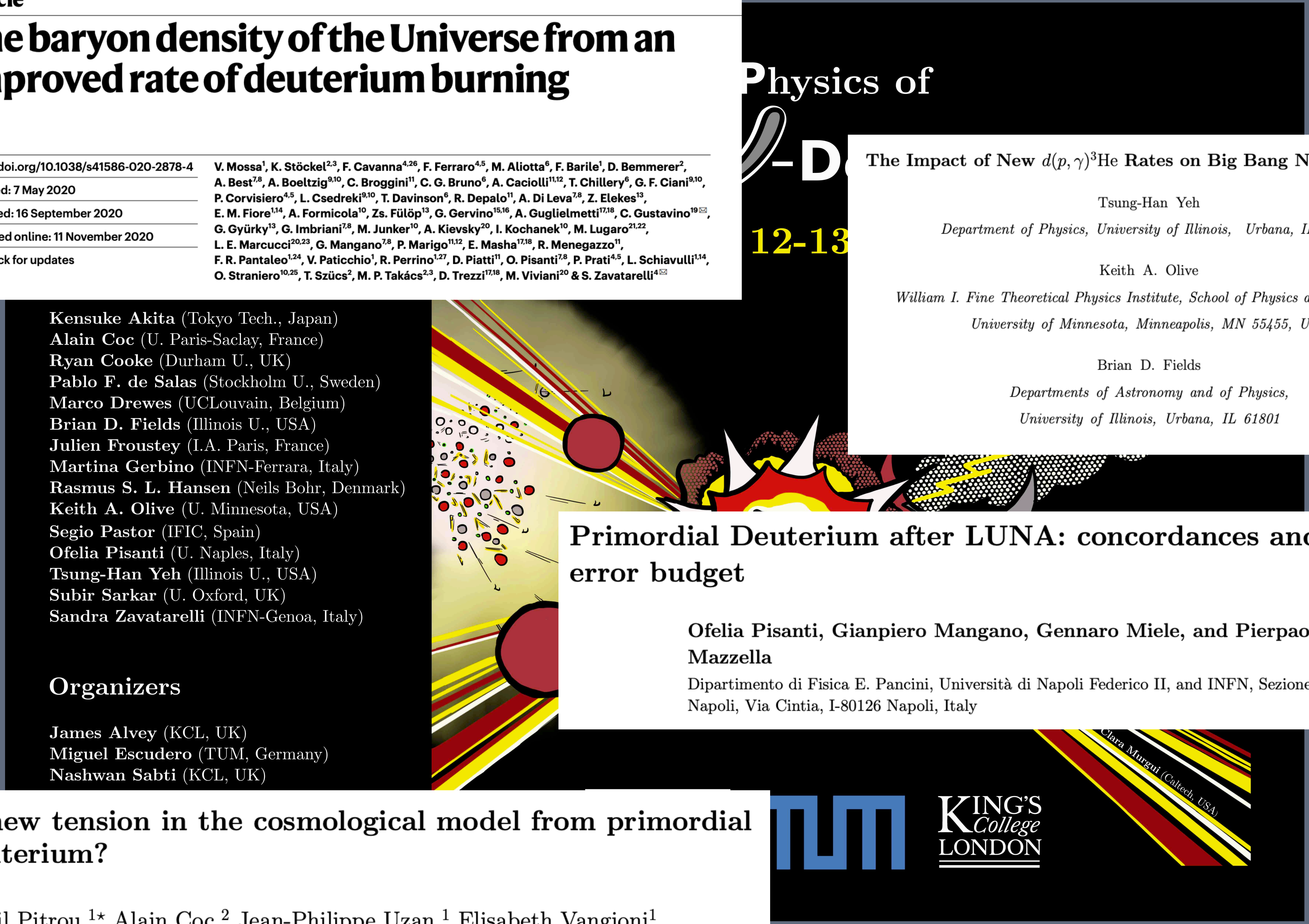

The Impact of New $d(p,\gamma)^3$He Rates on Big Bang Nucleosynthesis

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Primordial Deuterium after LUNA: concordances and error budget

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A new tension in the cosmological model from primordial deuterium?

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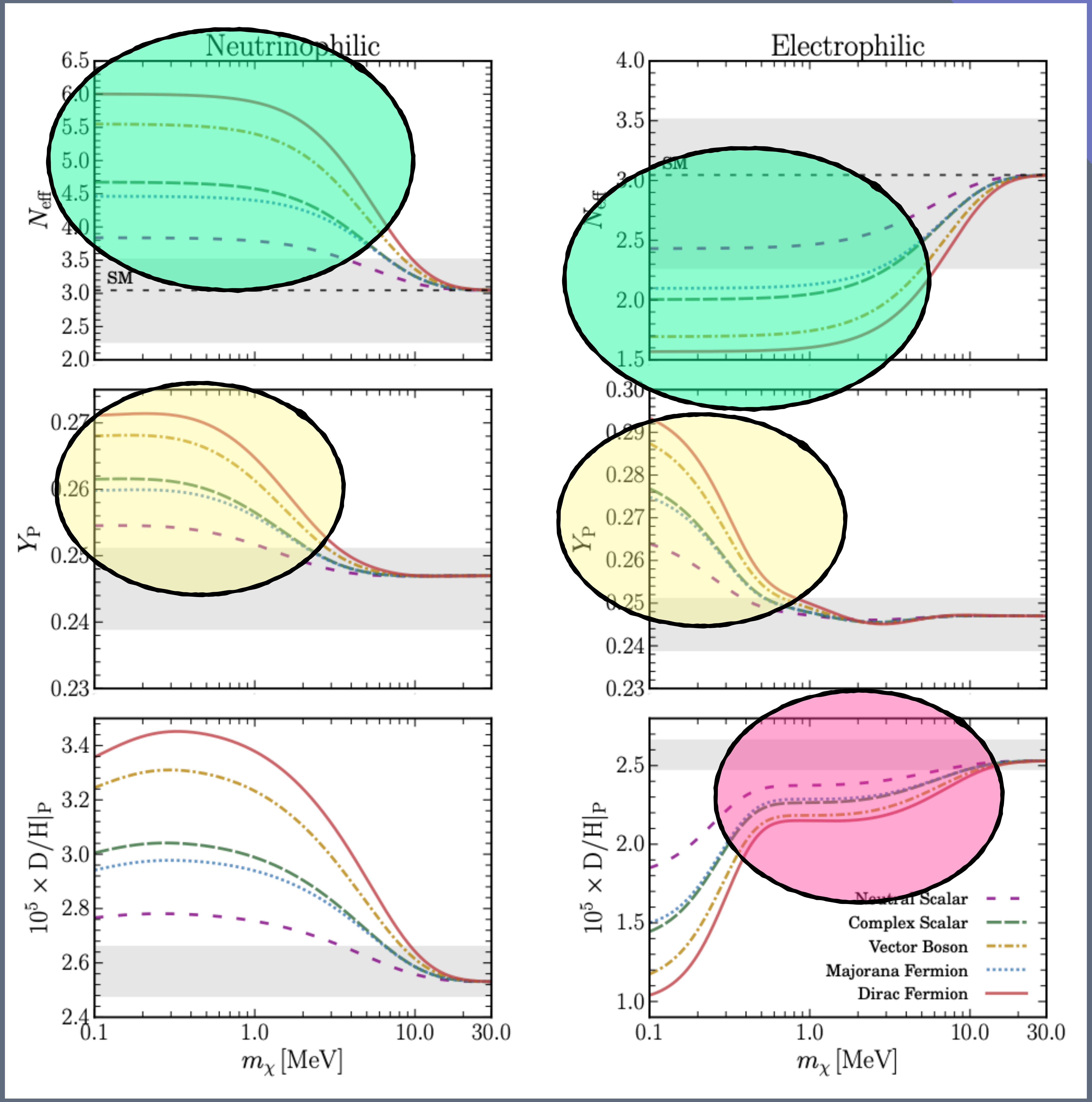
IMPACT ON CONSTRAINTS

Question: What are the implications of LUNA for constraints on light dark sectors?

Answer: Light dark sectors coupled to neutrinos, electrons/photons, or both can modify the history of BBN in a number of ways:

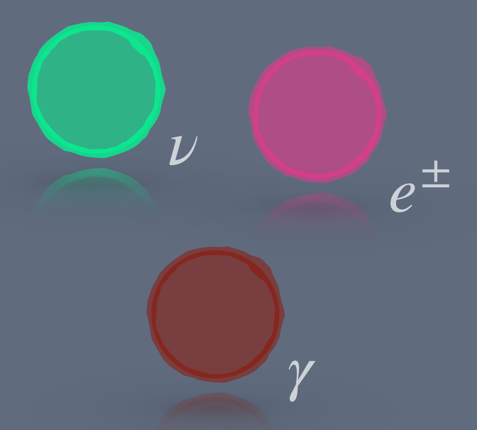
- Modify the **expansion rate** — this changes the temperature-to-time relation
- Modify the **temperature** of neutrinos relative to photons — this can change the weak rates and their freeze-out history
- Modify the **baryon-to-photon ratio** (for electrophilic species)

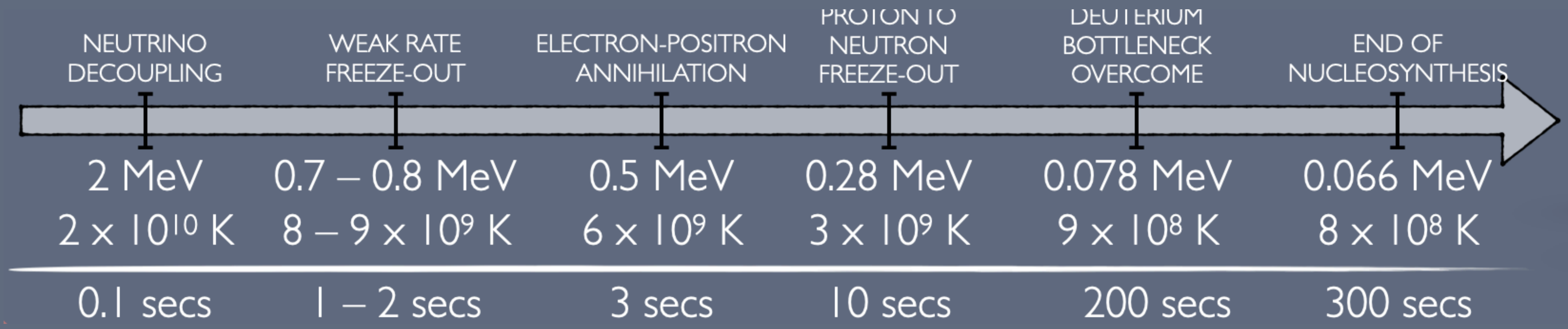
But, the constraints are largely driven by Helium-4 predictions, which are not sensitive to changes in the deuterium rates

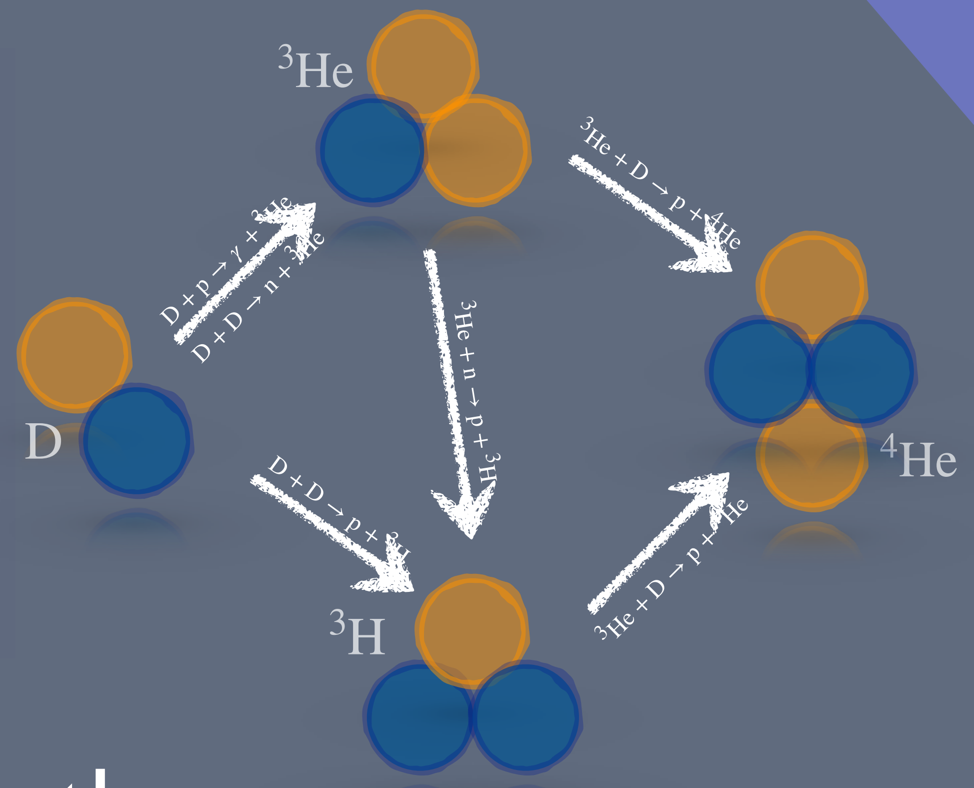


SUMMARY AND CONCLUSIONS

I. There are a number of **key events** in the physics of BBN which are controlled by the relevant reaction rates, sector temperatures and expansion







II. Precise measurements of both the nuclear reaction rates as well as the primordial abundances let us test SM and BSM physics extremely well

III. The new results from **LUNA** require some care and attention.

Recommendation: If probing new physics is the aim, the "safest" thing to do is consider both the theoretical and data-driven fits and see how your results vary

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