# DKPI Indian Summer School - lecture III

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# Summary from lecture 2

- Established the basic properties of DM (stability, neutrality, cold, collision- and dissipationless, “size”)

- The Boltzmann equation governs the time evolution of the distribution function. It is put to great use for the calculation of the relic abundance of dark matter (classification of dark matter particles follows by inquiring their by their abundance in the early universe)

- WIMPS regulate their abundance through the equation

$$\frac{dn_\chi}{dt} + 3\frac{\dot{a}}{a}n_\chi = -\sum_X \langle \sigma_{\chi\bar{\chi}\to X\bar{X}} v\rangle \left[n_\chi^2 - (n_\chi^{\rm eq})^2\right]$$

- WIMPs are the primary target for direct detection experiments, that are entering a decisive phase until they touch the irreducible “neutrino floor”.

# Plan of the lectures

*Lecture 1*

- Fundamentals of standard cosmology
- Gravitational evidence for Dark Matter

*Lecture 2*

- Basic properties of Dark Matter
- The Boltzmann equation and its applications for the early Universe
- WIMP Dark Matter
- Direct Detection of WIMPs

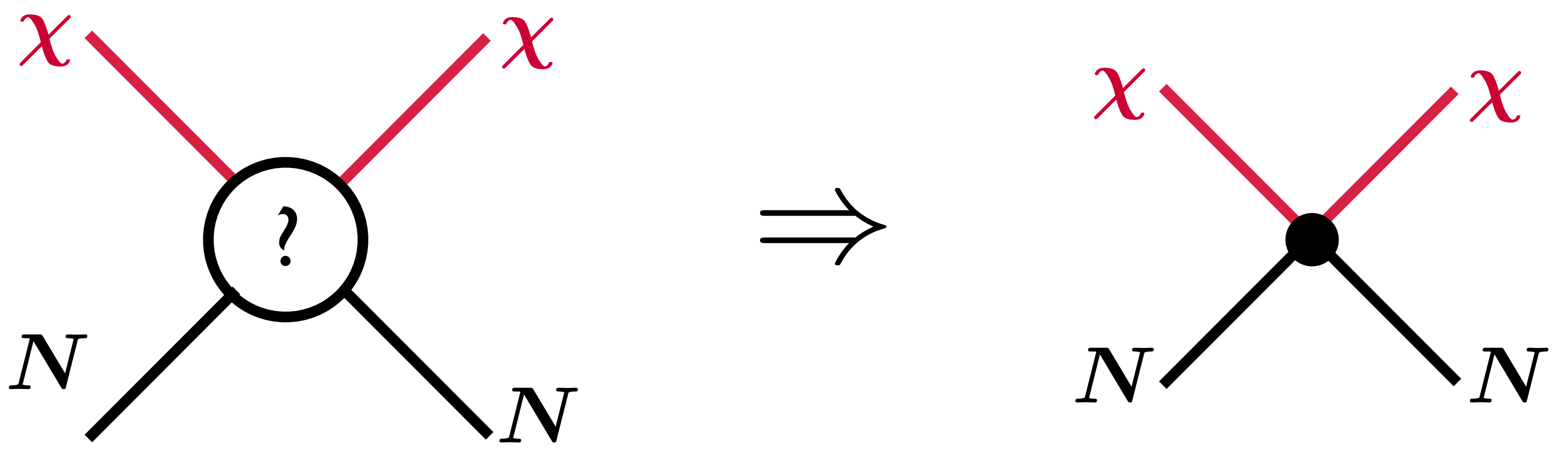
*Lecture 3*

- Effective operator approach
- Mediators - force carriers between the hidden and observable sector
- An alternative to the WIMP miracle
- The origin of chemistry - Big Bang Nucleosynthesis

# Effective Operators in direct detection

see, in particular,
Fan, Reece, Wang (2010)
Fitzpatrick et al. (2013)

- Effective operator approach between DM $\chi$ and nucleons $N$ often holds as $|q_{\rm max}| \sim O(100\,{\rm MeV})$




$$\mathcal{L}_{\rm eff} = \frac{1}{\Lambda^2}(\bar\chi\Gamma_\chi\chi)(\bar q\Gamma_q q)$$

- For example, fermionic DM

| | S | P | V | A | T | AT |
|---|---|---|---|---|---|---|
| $\Gamma_{\chi,q}$ | $1$ | $\gamma^5$ | $\gamma^\mu$ | $\gamma^\mu\gamma^5$ | $\sigma^{\mu\nu}$ | $\sigma^{\mu\nu}\gamma^5$ |

Non-relativistic limit (on tree level):

$S\times S$ or $V\times V$ coherent, spin-independent scattering

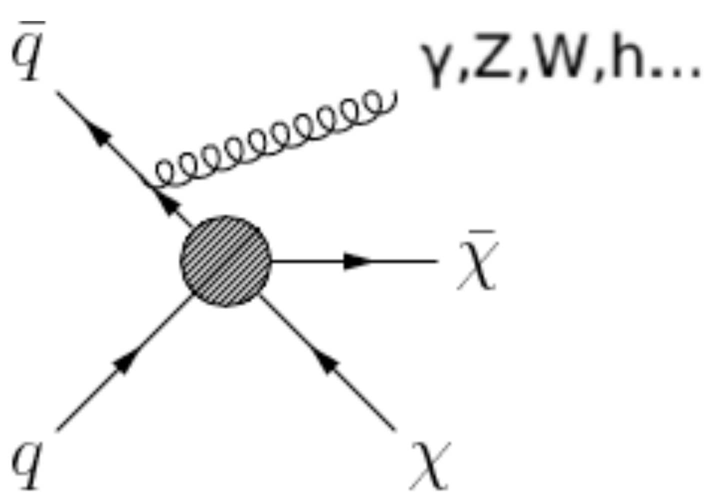
$A\times A$ or $T\times T$ spin-dependent, coupling to the unpaired nucleon

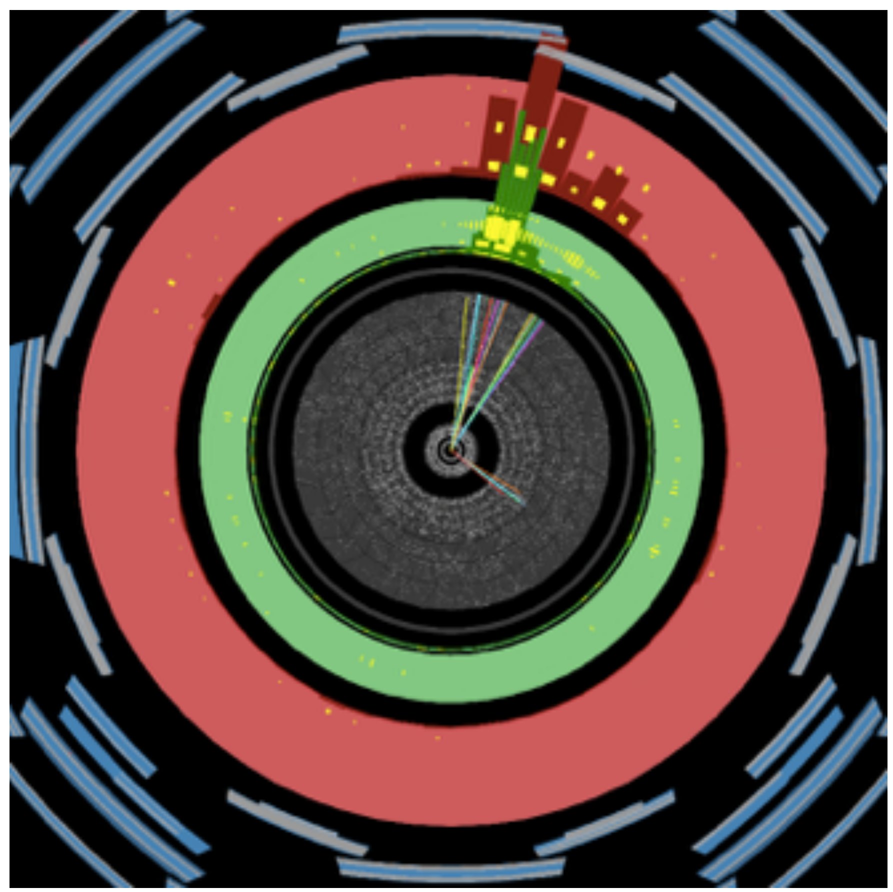
other combinations are suppressed by $v^2, \mathbf{q}^2/m_N^2 \sim 10^{-6}$

# Dark Matter at the LHC

- Effective theory in which only the DM and SM fields appear (=contact) provide the simplest parameterization of new physics

  => mono-jet/photon/W/Z + missing momentum

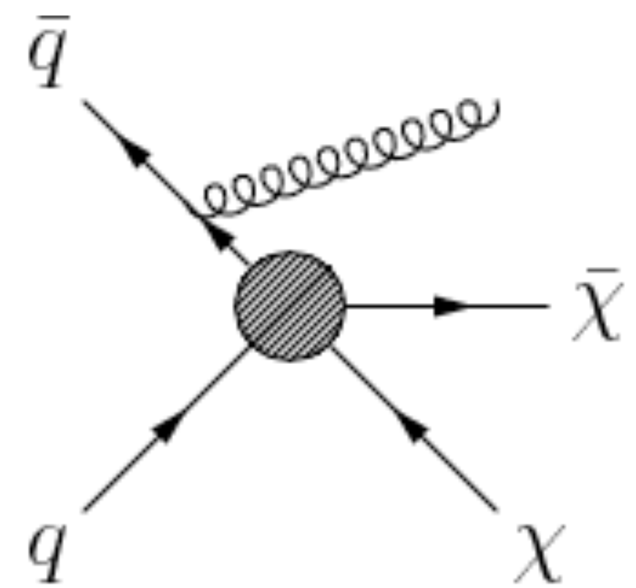


| Name | Operator | Coefficient |
|---|---|---|
| D1 | $\bar{\chi}\chi\bar{q}q$ | $m_q/M_*^3$ |
| D2 | $\bar{\chi}\gamma^5\chi\bar{q}q$ | $im_q/M_*^3$ |
| D3 | $\bar{\chi}\chi\bar{q}\gamma^5 q$ | $im_q/M_*^3$ |
| D4 | $\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$ | $m_q/M_*^3$ |
| D5 | $\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$ | $1/M_*^2$ |
| D6 | $\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$ | $1/M_*^2$ |
| D7 | $\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$ | $1/M_*^2$ |
| D8 | $\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$ | $1/M_*^2$ |
| D9 | $\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$ | $1/M_*^2$ |
| D10 | $\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$ | $i/M_*^2$ |
| D11 | $\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$ | $\alpha_s/4M_*^3$ |
| D12 | $\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$ | $i\alpha_s/4M_*^3$ |
| D13 | $\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$ | $i\alpha_s/4M_*^3$ |
| D14 | $\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$ | $\alpha_s/4M_*^3$ |

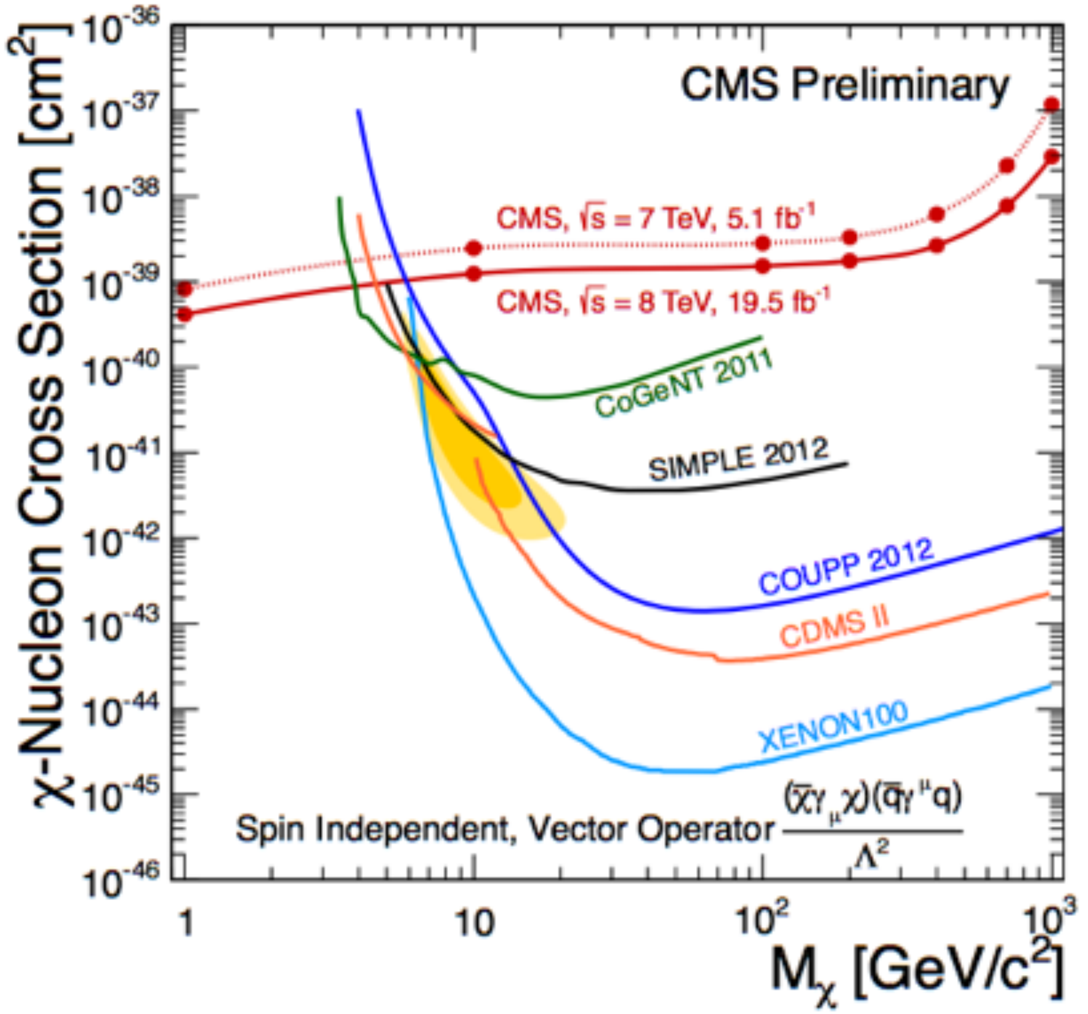
e.g. Goodman et al 2010

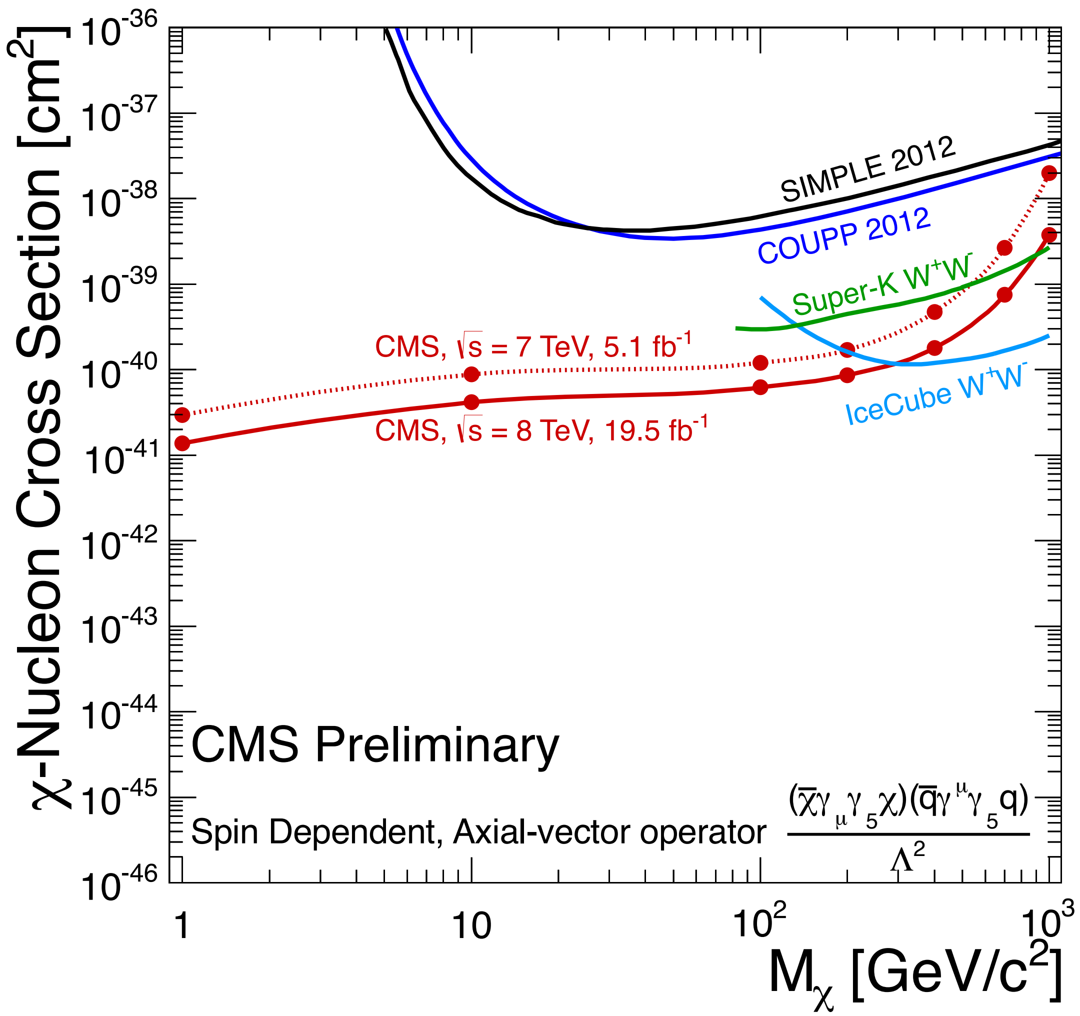
# DM at the LHC




LHC does exquisitely well for

- low WIMP masses $m_\chi \lesssim 10\,\mathrm{GeV}$
- operators that are velocity suppressed in direct detection

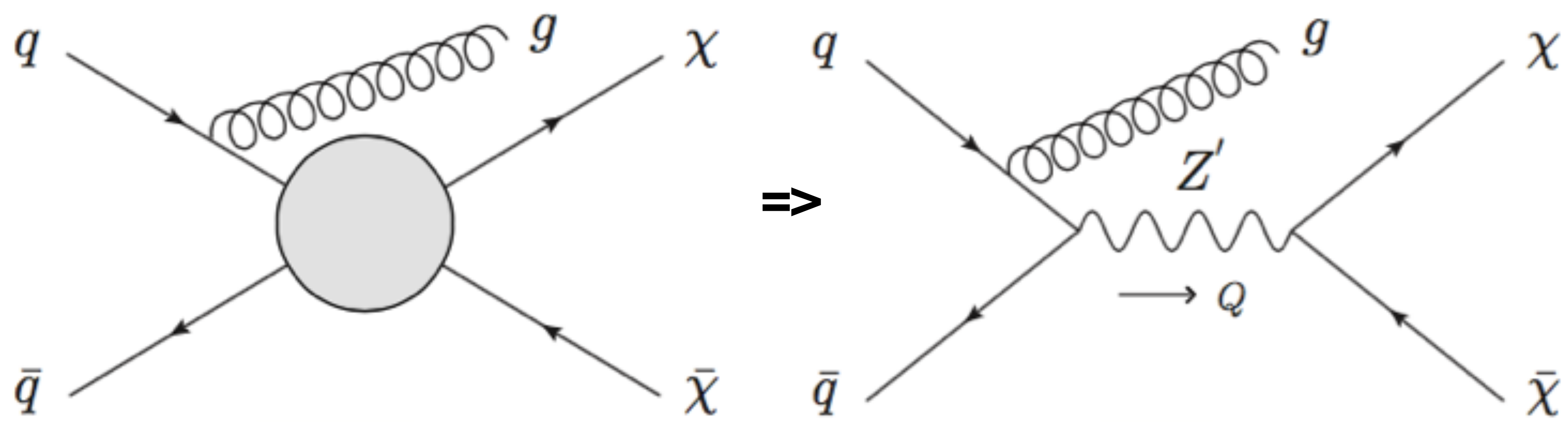



(same data-set as at EPS 2015)

# DM at the LHC

Effective field theory approach breaks down, once $q^2 \simeq m^2_{\rm mediator}$




$$\frac{g_q\, g_\chi}{Q^2 - m^2_{\rm med}} \approx -\frac{g_q\, g_\chi}{m^2_{\rm med}} \quad \Rightarrow \quad \frac{g_q\, g_\chi}{Q^2 - m^2_{\rm med}} \approx \frac{g_q\, g_\chi}{Q^2}$$

$$\Lambda \equiv \frac{m_{\rm med}}{\sqrt{g_q\, g_\chi}}$$ contact interaction

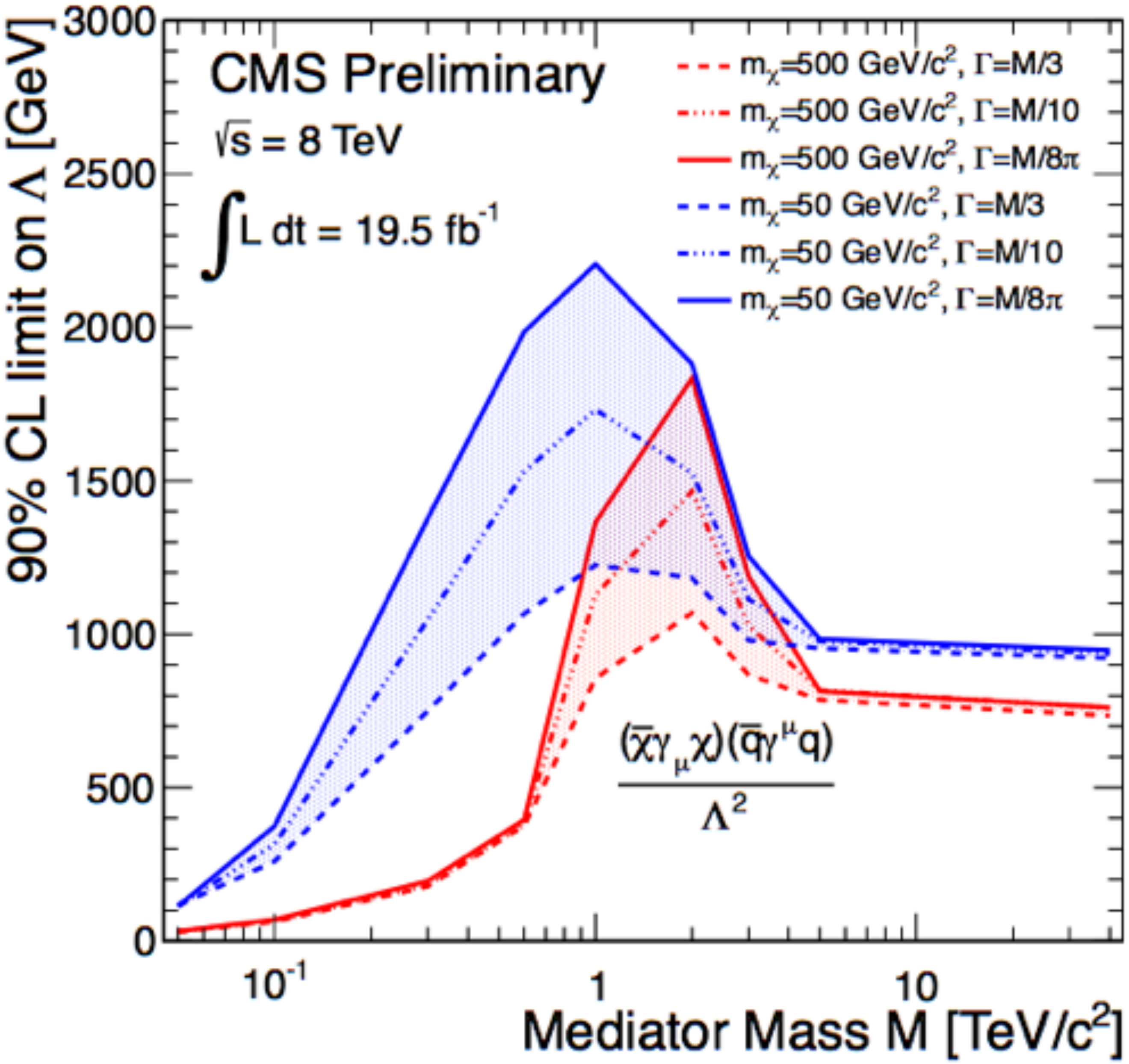
$\langle Q^2 \rangle^{1/2} \gtrsim 500\,\mathrm{GeV}$ @ 8TeV LHC

# Beyond effective operators

=> results can be cast as a limit on the contact interaction scale $\Lambda$

LHC limits are stringent for contact operators, but can go away completely for light mediators!

=> accessible UV content can be caught in "*simplified models*" with content **SM + DM + mediator**

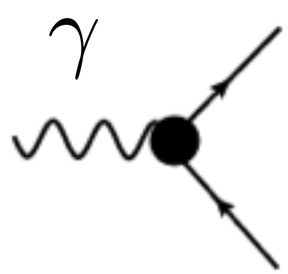



e.g. arXiv:1507.0096

# What are the force carriers/mediators?

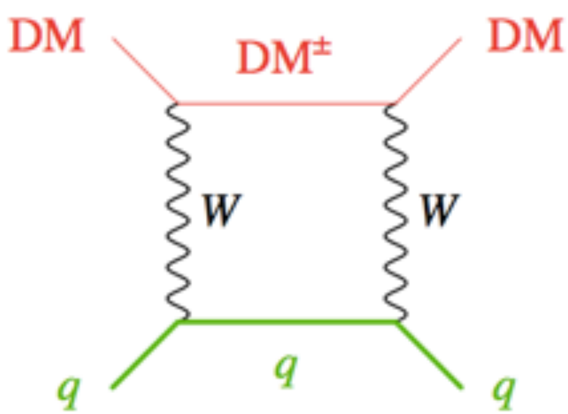
## Photon:
milli-charged DM; neutral DM interacting via EM form factors

… Kouvaris (2013);
Ho, Scherrer (2013);
Weiner, Yavin (2013)…




## EW-bosons:
DM in electroweak multiplets

Cirelli, Fornengo, Strumia (2007)




## Higgs boson:
Inert Higgs, Higgs portal models, SUSY

Deshpande, Ma (1978);
Silveira, Zee (1985);
McDonald (1993);
Burgess, Pospelov, ter Veldhuis (2000)
…

## New physics mediators
squarks, SUSY gauginos, dark photons…
(whatever you can think of)

# The role of the Higgs - I

- Neutralinos of SUSY stabilized by R-parity as DM

Bino, Wino

$$\mathcal{M}_\chi = \begin{pmatrix} M_1 & 0 & -m_Z c_\beta s_W & m_Z s_\beta s_W \\ 0 & M_2 & m_Z c_\beta c_W & -m_Z s_\beta c_W \\ -m_Z c_\beta s_W & m_Z c_\beta c_W & 0 & -\mu \\ m_Z s_\beta s_W & -m_Z s_\beta c_W & -\mu & 0 \end{pmatrix}$$

Higgsinos

Expectation we had: $M_{1,2}, \mu \sim \mathcal{O}(100\,\mathrm{GeV})$ => substantial mixing

Non-observation of SUSY at LHC pushes mass scales => diagonal dominance of

$\chi$ Majorana => ~~$(\bar{\chi}\gamma^\mu\chi)(\bar{n}\gamma_\mu n)$~~ => spin-spin or scalar exchange at LO

=> Higgs exchange contributes to SI

# Original expectations

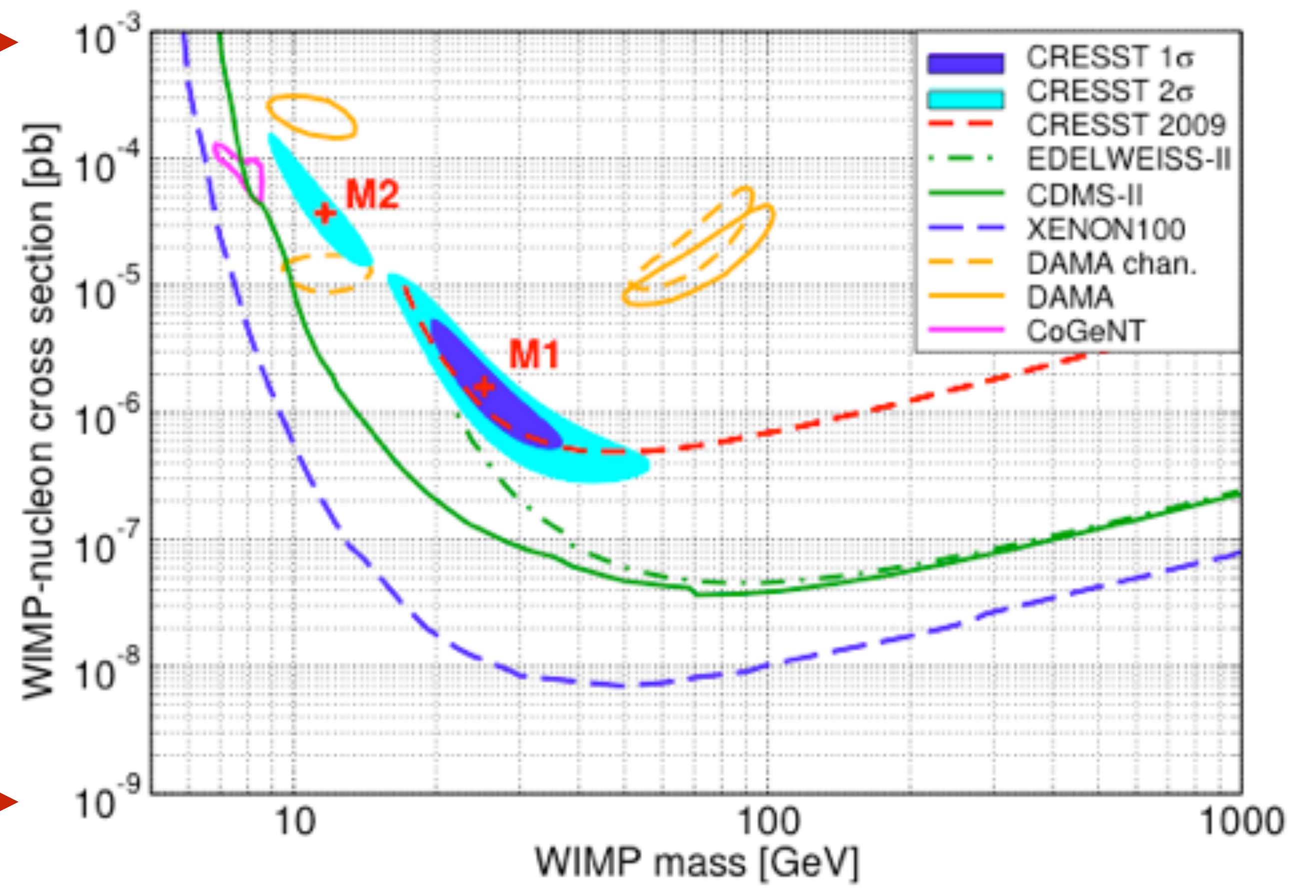

The “weakly” interacting 100 GeV WIMPs are long excluded

Z-mediated cross section

$\sigma_n \sim 10^{-3}\,\mathrm{pb}$

*Higgs-mediated* interactions are being probed right now!

$\sigma_n \sim 10^{-(9-10)}\,\mathrm{pb}$




NB: direct detection may never completely exclude neutralino:

*pure* neutralino (wino, bino, higgsino) has suppressed higgs couplings $h^\dagger \tilde{h} \tilde{w}$ $h^\dagger \tilde{h} \tilde{b}$
pure wino/bino does not couple to Z
*cancelations* in couplings to Z and Higgs

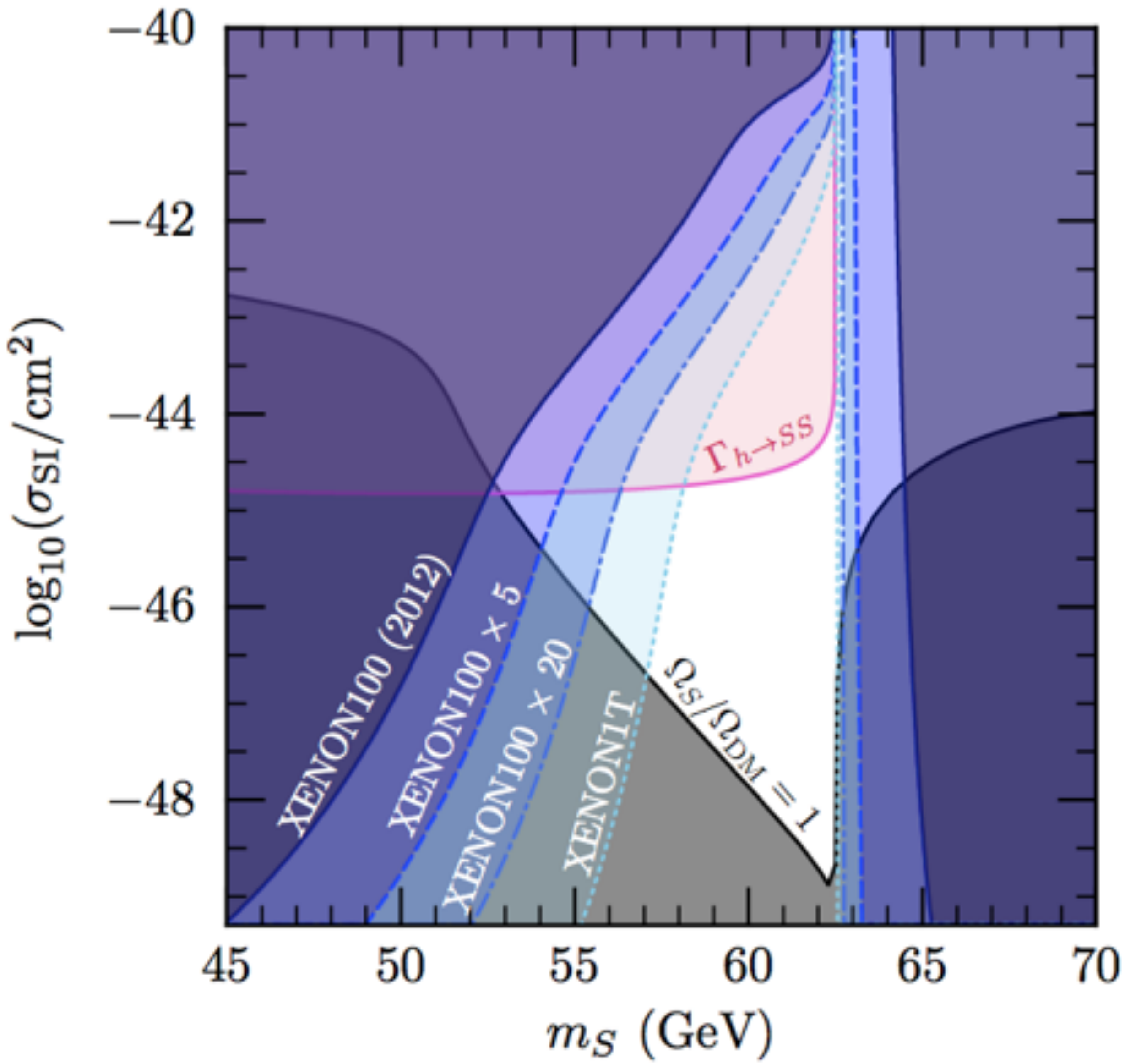
# The role of the Higgs - II

- "Higgs Portal"

$$\mathcal{L}_{\rm int} = -\lambda S^2 (H^\dagger H)$$

=> relic abundance via annihilation through H

=> direct detection via $\langle n | m_q \bar{q} q | n \rangle$ H-nucleon coupling




e.g. Cline et al. (2013)

- LHC results slain DM models with $m_{\rm DM} \lesssim 60\,{\rm GeV}$

  Higgs decays invisibly into DM

  => *light-DM models run out of SM mediators*

# Light Dark Matter

Relic Abundance issues

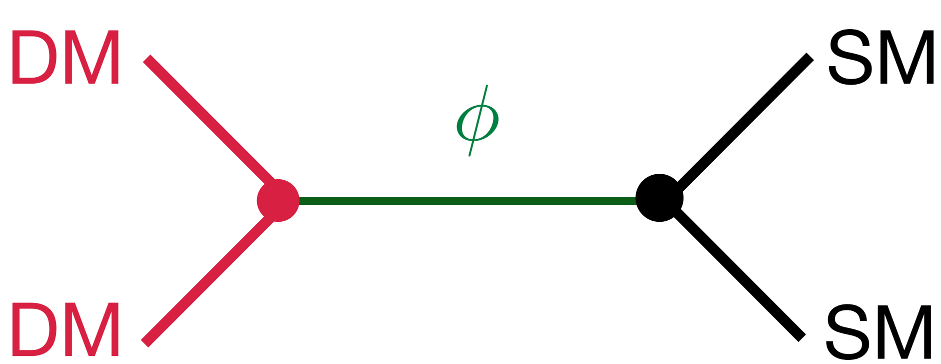
Lee-Weinberg bound:

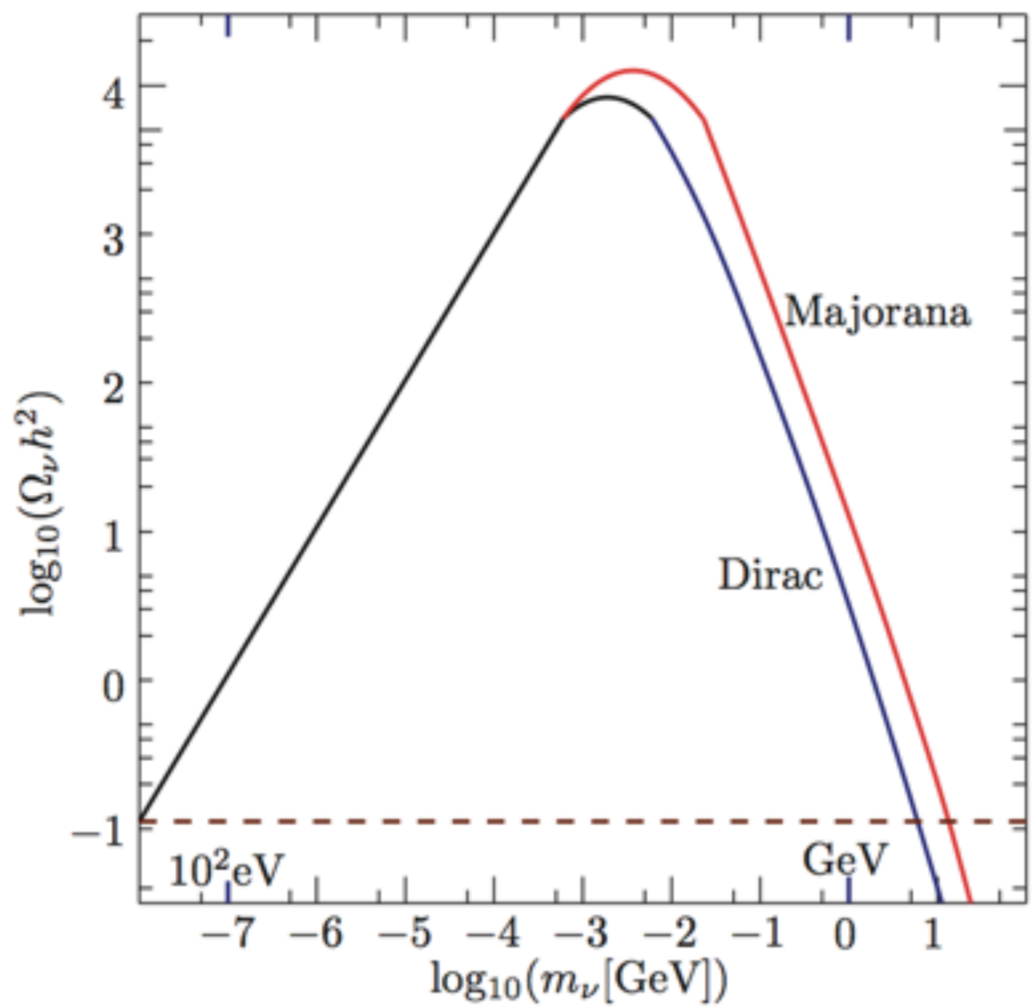
Annihilation of a heavy neutrino through SM mediators excludes masses below ~ few GeV

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

*A way out are new, light mediators*

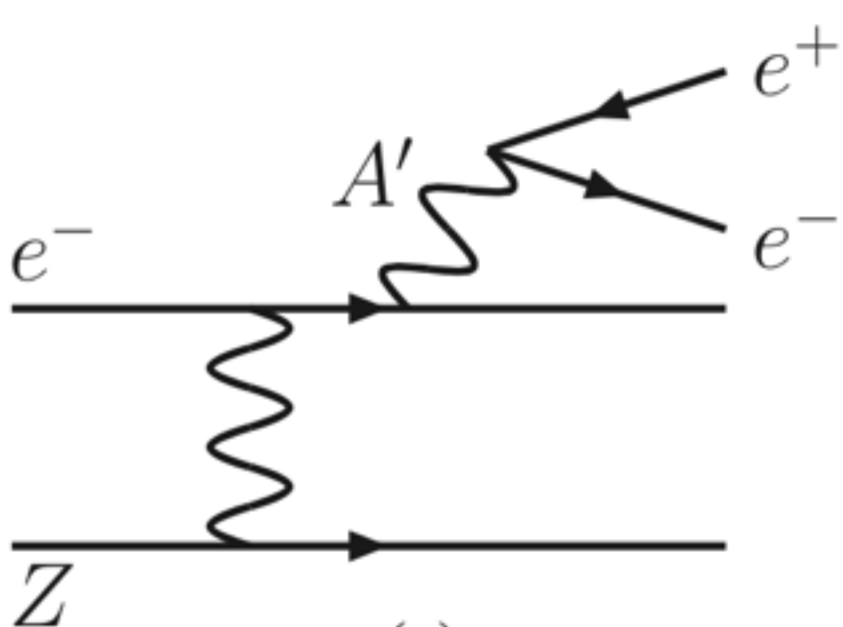
$$G_F \to g^2/m_\phi^2$$



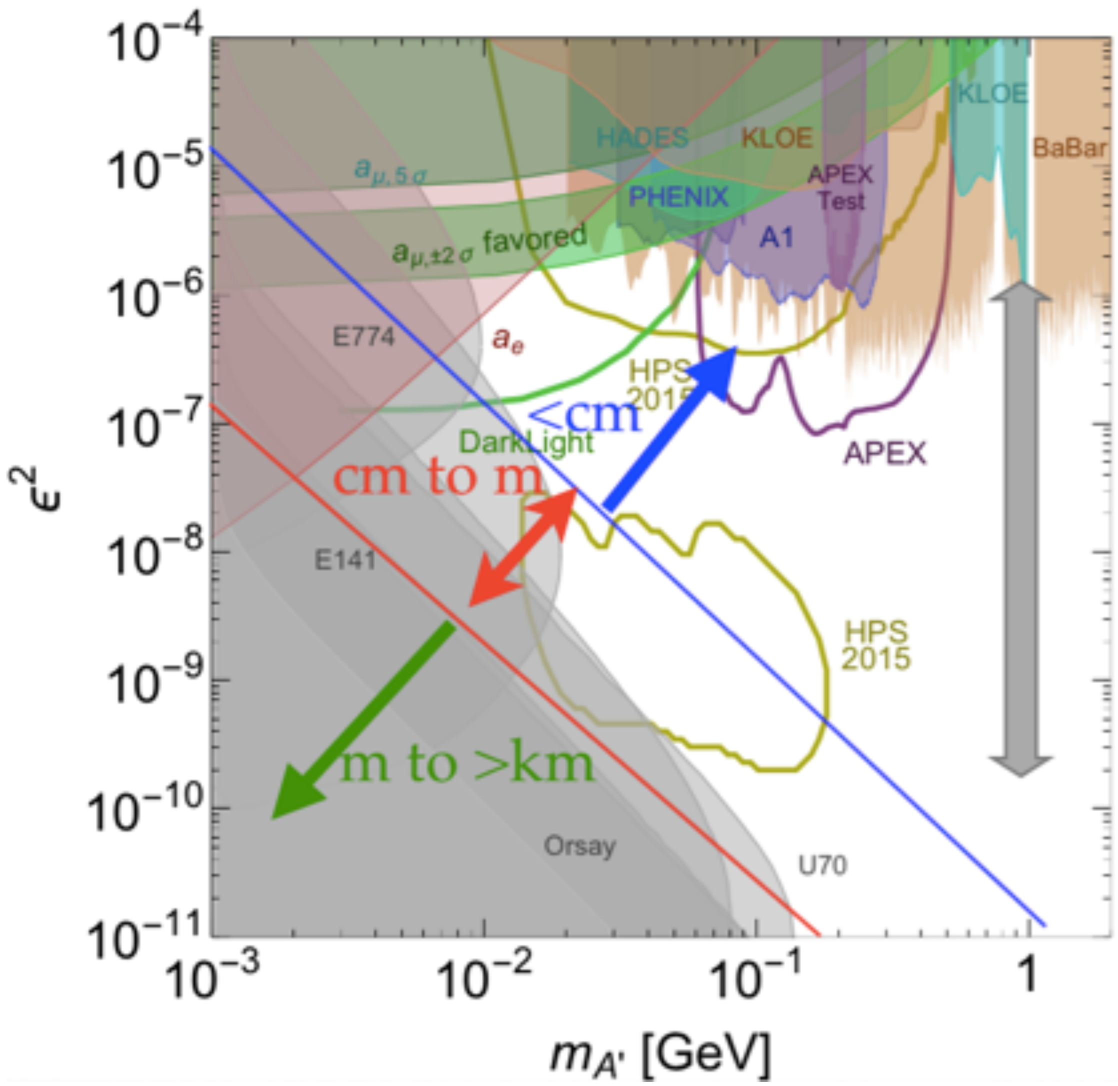



# Light Dark Matter - light mediators

The search for light mediators has become a field of its own “intensity frontier”

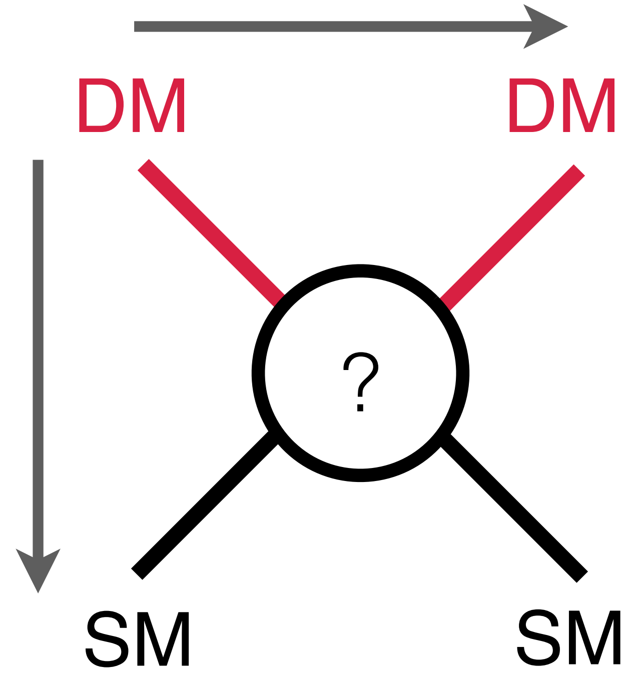



(a)

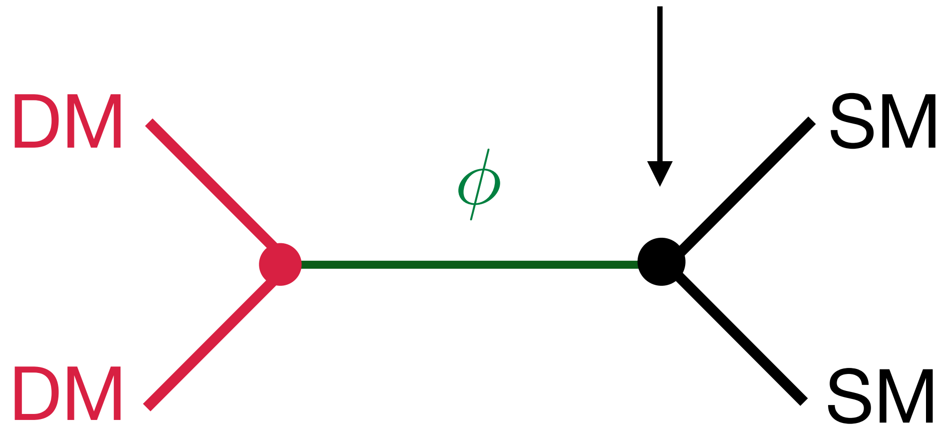



Light mediators, “force carriers of the hidden sector”, make a frequent occurrence. They are a minimal extension, make models “work”, and they open up new phenomenological signatures.

# Do light mediators imply an enhanced direct detection rate?

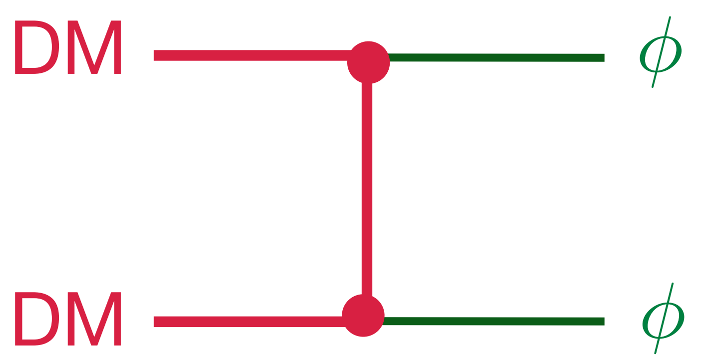



here a minimum coupling to SM required for efficient annihilation




$m_\chi < m_\phi$

vs.




$m_\chi > m_\phi$

The right situation can completely elude direct detection, because couplings to SM can be small, "cascade annihilation". So, it depends…

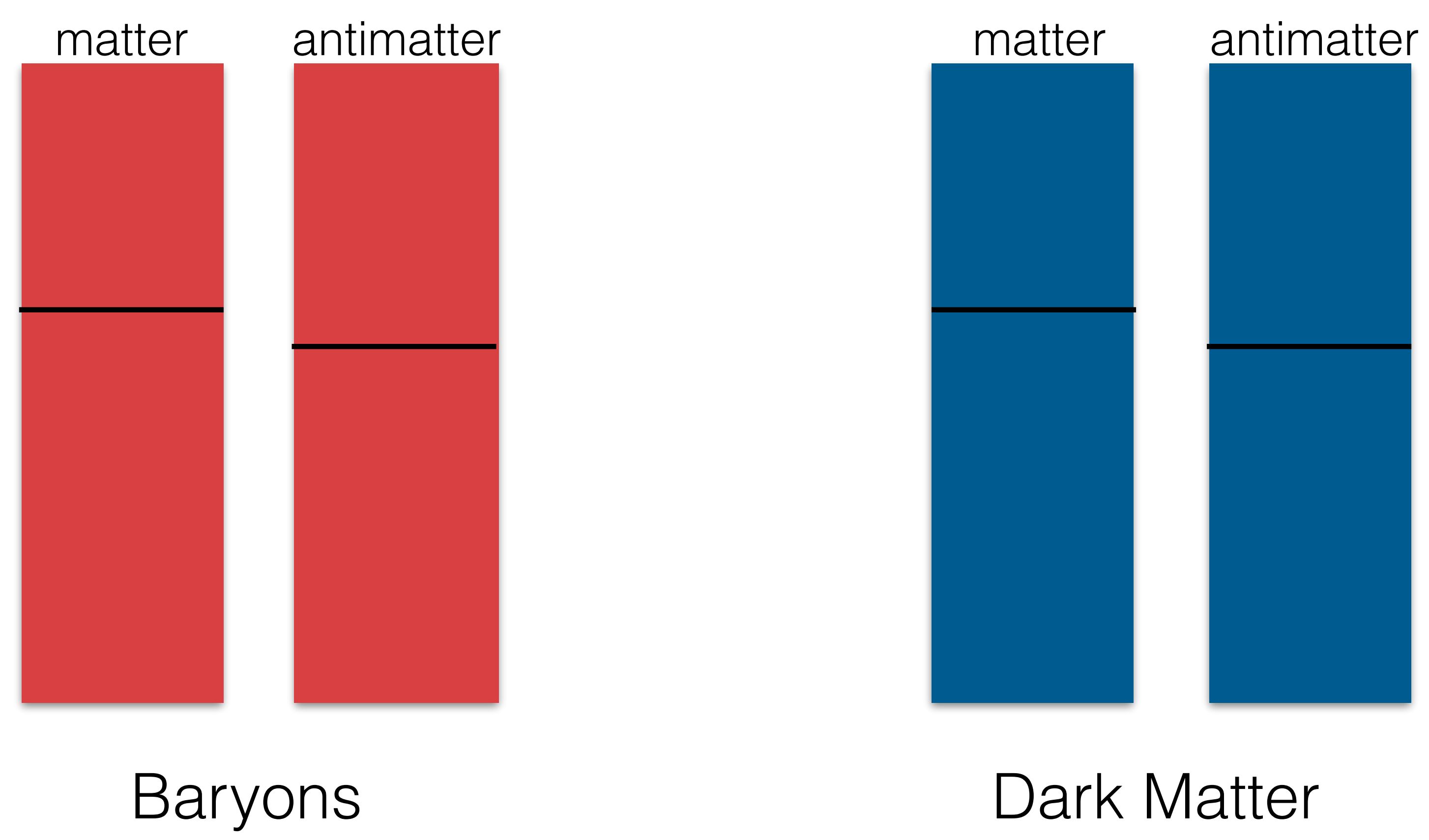
# An alternative to the WIMP miracle

$$\Omega_{dm} \simeq 5\Omega_b$$

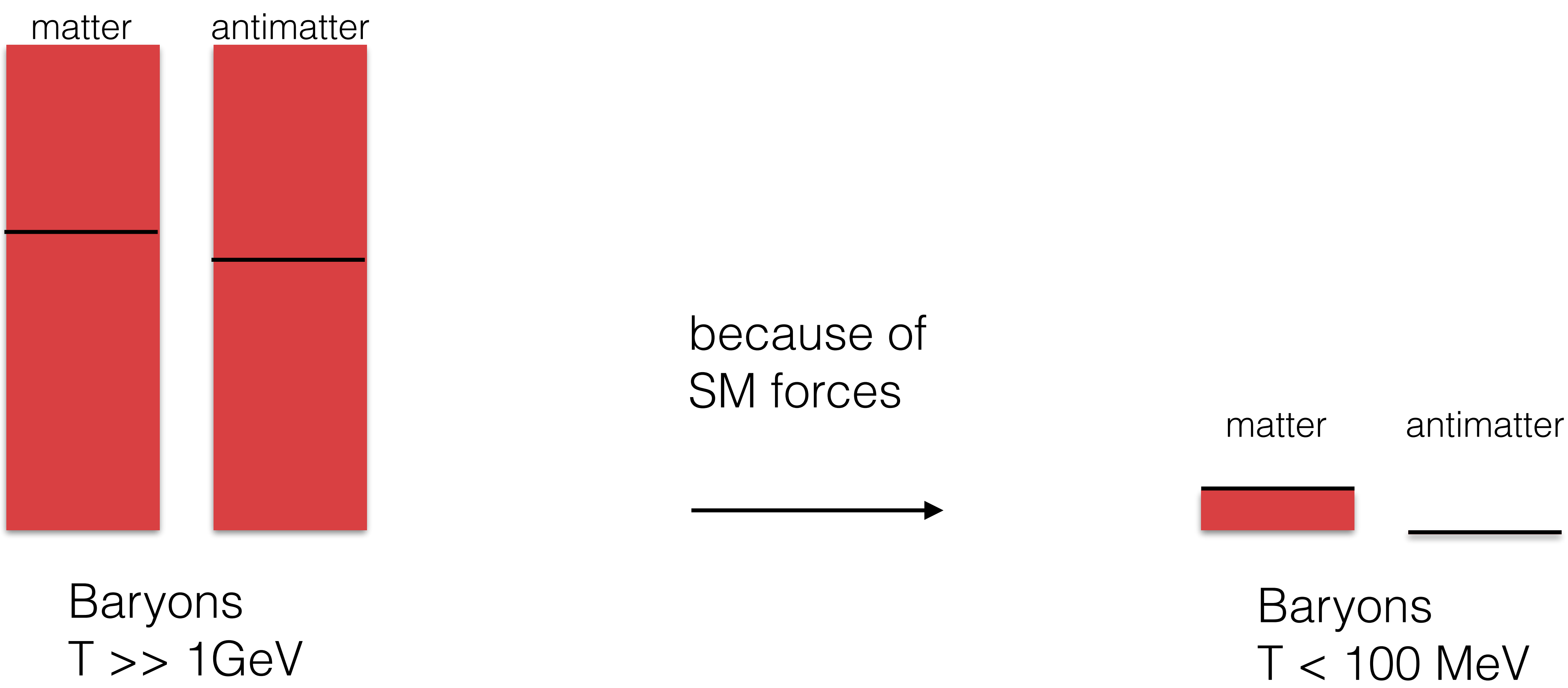
—

Why?

Maybe because dark matter carries a chemical potential
(i.e. a matter-antimatter asymmetry)

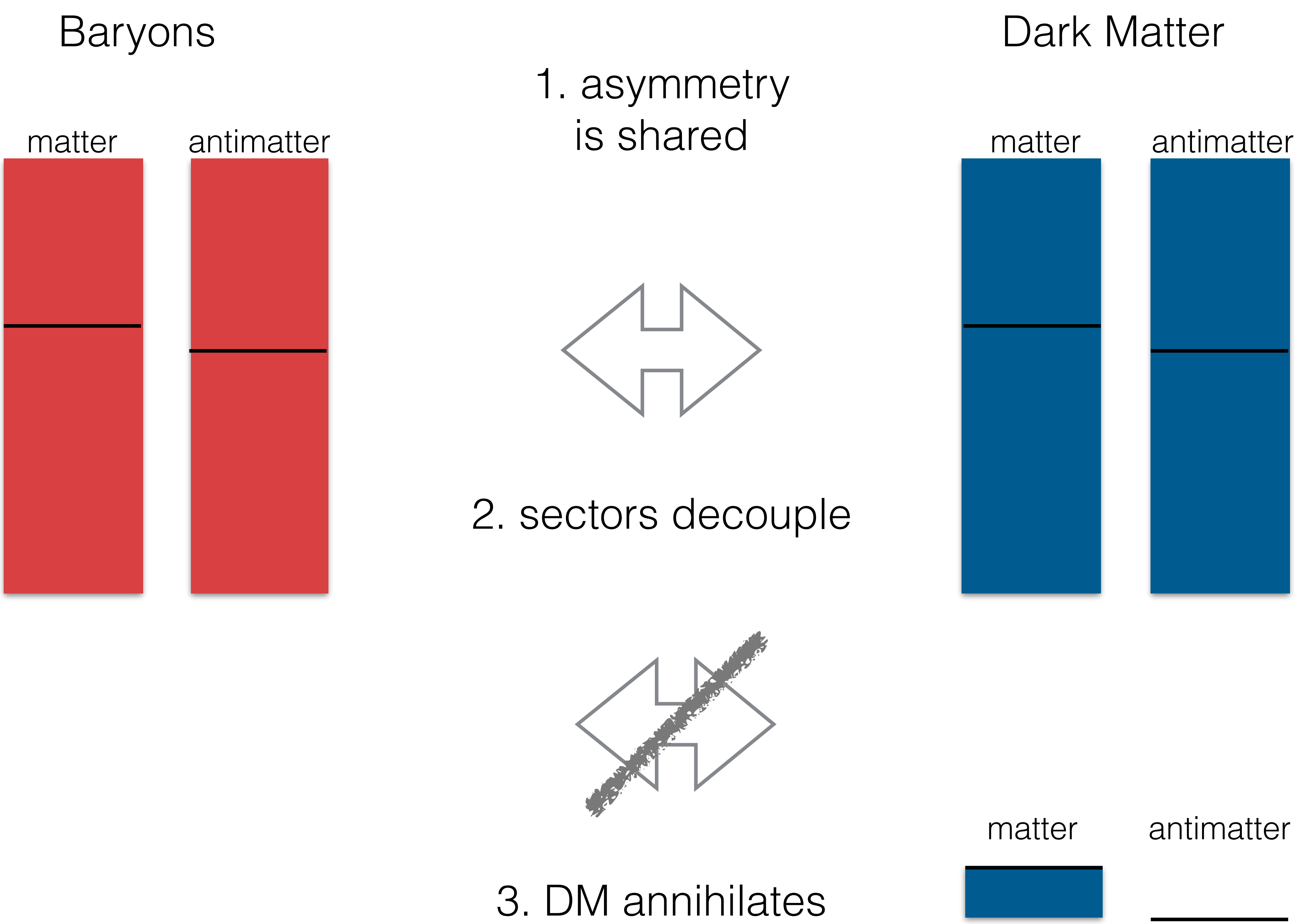


# An alternative to the WIMP miracle




Without a chemical potential of baryons, we would be living in a Universe with $n_b/n_\gamma = 10^{-18}$ and not $n_b/n_\gamma = 10^{-10}$

# An alternative to the WIMP miracle

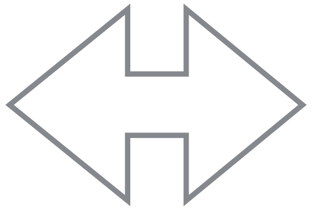



=> abundance is set by the chemical potential

# An alternative to the WIMP miracle - asymmetric DM

$$n_\chi - n_{\bar{\chi}} \sim n_B - n_{\bar{B}}$$

1. asymmetry
is shared



Dark Matter


Use sphalerons, or
higher dimensional operators

$$\mathcal{O}_{B-L} = u^c d^c d^c,\ q\ell d^c,\ \ell\ell e^c,\ \ell H_u$$

$$\mathcal{O}_D = X^n$$

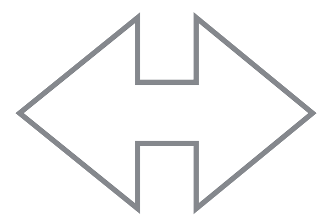
$$W = \frac{\mathcal{O}_D \mathcal{O}_{B-L}}{M^{m+n-3}}$$

# An alternative to the WIMP miracle - asymmetric DM

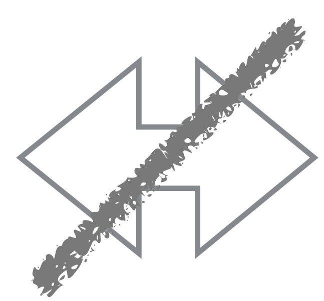
$$n_\chi - n_{\bar\chi} \sim n_B - n_{\bar B}$$

1. asymmetry is shared

Dark Matter

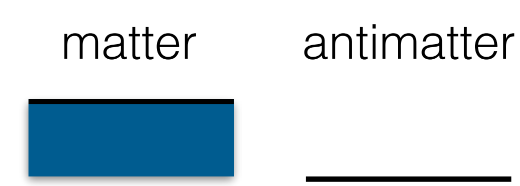
2. sectors decouple



$$\rho_{\rm DM}/\rho_B \simeq 5$$

$$m_\chi \sim 5 m_B \simeq 5\,{\rm GeV}$$

3. DM annihilates



# An alternative to the WIMP miracle - asymmetric DM

Relic density determined by chemical potential.

Annihilation must be efficient enough to remove the symmetric abundance:

EW scale mediators don't work, required couplings are excluded by LHC.

$$\sigma_{ann} v = \frac{g_d^2 g_f^2 m_X^2}{\pi m_M^4} \simeq 10^{-26}\ \mathrm{cm}^3/\mathrm{s} \left(\frac{g_d g_f}{0.25}\right)^2 \left(\frac{10\mathrm{GeV}}{m_X}\right)^2 \left(\frac{200\ \mathrm{GeV}}{m_M}\right)^4$$

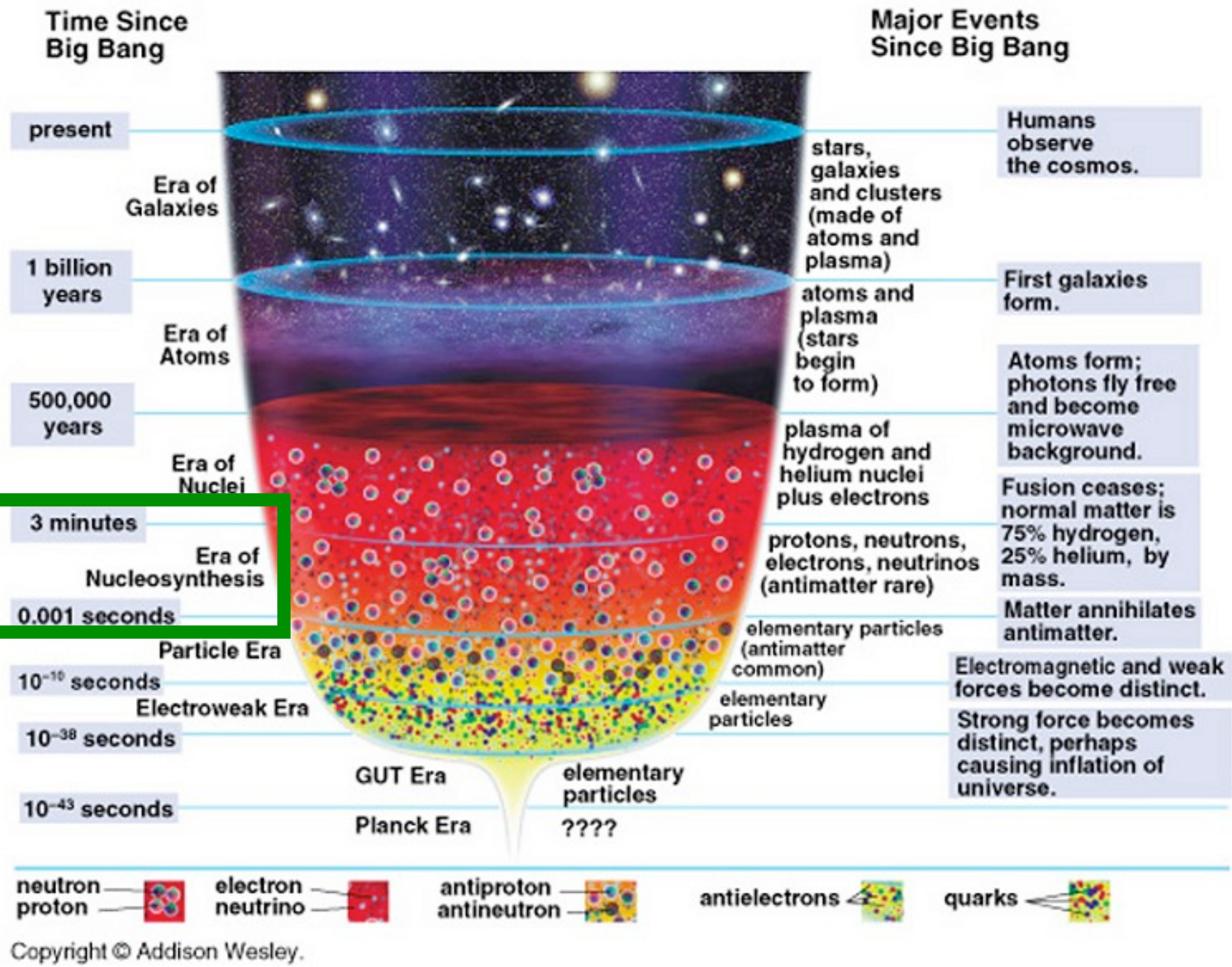
Again, relic abundance typically relies on new, light mediators that enhance annihilation cross section.

Note: Indirect detection prospects / astro-constraints depend on the residual abundance of anti-DM after freeze out! The symmetric component does not annihilate.

Detection prospects are built on the interaction that annihilates the symmetric component (model dependent.)

# The origin of chemistry

Primordial Nucleosynthesis



# The origin of chemistry

| | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| hydrogen 1 H 1.0079 | | | | | | | | | | | | | | | | | | helium 2 He 4.0026 |
| lithium 3 Li 6.941 | beryllium 4 Be 9.0122 | | | | | | | | | | | | boron 5 B 10.811 | carbon 6 C 12.011 | nitrogen 7 N 14.007 | oxygen 8 O 15.999 | fluorine 9 F 18.998 | neon 10 Ne 20.180 |
| sodium 11 Na 22.990 | magnesium 12 Mg 24.305 | | | | | | | | | | | | aluminium 13 Al 26.982 | silicon 14 Si 28.086 | phosphorus 15 P 30.974 | sulfur 16 S 32.065 | chlorine 17 Cl 35.453 | argon 18 Ar 39.948 |
| potassium 19 K 39.098 | calcium 20 Ca 40.078 | | scandium 21 Sc 44.956 | titanium 22 Ti 47.867 | vanadium 23 V 50.942 | chromium 24 Cr 51.996 | manganese 25 Mn 54.938 | iron 26 Fe 55.845 | cobalt 27 Co 58.933 | nickel 28 Ni 58.693 | copper 29 Cu 63.546 | zinc 30 Zn 65.39 | gallium 31 Ga 69.723 | germanium 32 Ge 72.61 | arsenic 33 As 74.922 | selenium 34 Se 78.96 | bromine 35 Br 79.904 | krypton 36 Kr 83.80 |
| rubidium 37 Rb 85.468 | strontium 38 Sr 87.62 | | yttrium 39 Y 88.906 | zirconium 40 Zr 91.224 | niobium 41 Nb 92.906 | molybdenum 42 Mo 95.94 | technetium 43 Tc [98] | ruthenium 44 Ru 101.07 | rhodium 45 Rh 102.91 | palladium 46 Pd 106.42 | silver 47 Ag 107.87 | cadmium 48 Cd 112.41 | indium 49 In 114.82 | tin 50 Sn 118.71 | antimony 51 Sb 121.76 | tellurium 52 Te 127.60 | iodine 53 I 126.90 | xenon 54 Xe 131.29 |
| caesium 55 Cs 132.91 | barium 56 Ba 137.33 | 57-70 * | lutetium 71 Lu 174.97 | hafnium 72 Hf 178.49 | tantalum 73 Ta 180.95 | tungsten 74 W 183.84 | rhenium 75 Re 186.21 | osmium 76 Os 190.23 | iridium 77 Ir 192.22 | platinum 78 Pt 195.08 | gold 79 Au 196.97 | mercury 80 Hg 200.59 | thallium 81 Tl 204.38 | lead 82 Pb 207.2 | bismuth 83 Bi 208.98 | polonium 84 Po [209] | astatine 85 At [210] | radon 86 Rn [222] |
| francium 87 Fr [223] | radium 88 Ra [226] | 89-102 * * | lawrencium 103 Lr [262] | rutherfordium 104 Rf [261] | dubnium 105 Db [262] | seaborgium 106 Sg [266] | bohrium 107 Bh [264] | hassium 108 Hs [269] | meitnerium 109 Mt [268] | ununnilium 110 Uun [271] | unununium 111 Uuu [272] | ununbium 112 Uub [277] | | ununquadium 114 Uuq [289] | | | | |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| * Lanthanide series | lanthanum 57 La 138.91 | cerium 58 Ce 140.12 | praseodymium 59 Pr 140.91 | neodymium 60 Nd 144.24 | promethium 61 Pm [145] | samarium 62 Sm 150.36 | europium 63 Eu 151.96 | gadolinium 64 Gd 157.25 | terbium 65 Tb 158.93 | dysprosium 66 Dy 162.50 | holmium 67 Ho 164.93 | erbium 68 Er 167.26 | thulium 69 Tm 168.93 | ytterbium 70 Yb 173.04 |
| * * Actinide series | actinium 89 Ac [227] | thorium 90 Th 232.04 | protactinium 91 Pa 231.04 | uranium 92 U 238.03 | neptunium 93 Np [237] | plutonium 94 Pu [244] | americium 95 Am [243] | curium 96 Cm [247] | berkelium 97 Bk [247] | californium 98 Cf [251] | einsteinium 99 Es [252] | fermium 100 Fm [257] | mendelevium 101 Md [258] | nobelium 102 No [259] |

# Big Bang Nucleosynthesis (BBN) - A pillar of modern cosmology

- recent progress primarily clarifies state of the Universe at z = few (Galaxy surveys, SN,…) and exposes relevant physics at recombination $z = 1000$
- light element formation happens at $z = 10^9$ ; direct window into the early Universe at t=1sec
- qualitative agreement between $z = 0 \div 10^3$ and $z = 10^9$ tells us that early Universe was governed by the same physical laws and contained similar particle content

  => invaluable piece that helps to establish the standard cosmological model
- BBN can react sensitively on departures from General Relativity and the Standard Model of particle physics => a toolbox to test new physics

# The Universe at a redshift of a billion

Basic assumptions for “Standard BBN”

- Universe is flat, spatially homogeneous and isotropic and dominated by radiation => General Relativity:

$$H \equiv \frac{\dot{a}}{a} = \sqrt{8\pi G_N \rho/3} \simeq \frac{1}{2t}$$

- Universe was “hot” enough $T|_{\rm init} \gg \Delta m_{np} = 1.293 \text{ MeV}$

$$(n_n \simeq n_p)|_{T \gg \Delta m_{np}} = \frac{1}{2} n_b$$

- Particle content & their interactions given by the SM

$$\frac{n_b}{s}(t_{\rm BBN}) = \frac{n_b}{s}(t_{\rm CMB}).$$ => “parameter free theory”

# The Universe at a redshift of a billion

Excellent approximations

- tight kinetic coupling of nucleons/nuclei to the radiation field

  => nucleons/nuclei are approximately thermally distributed

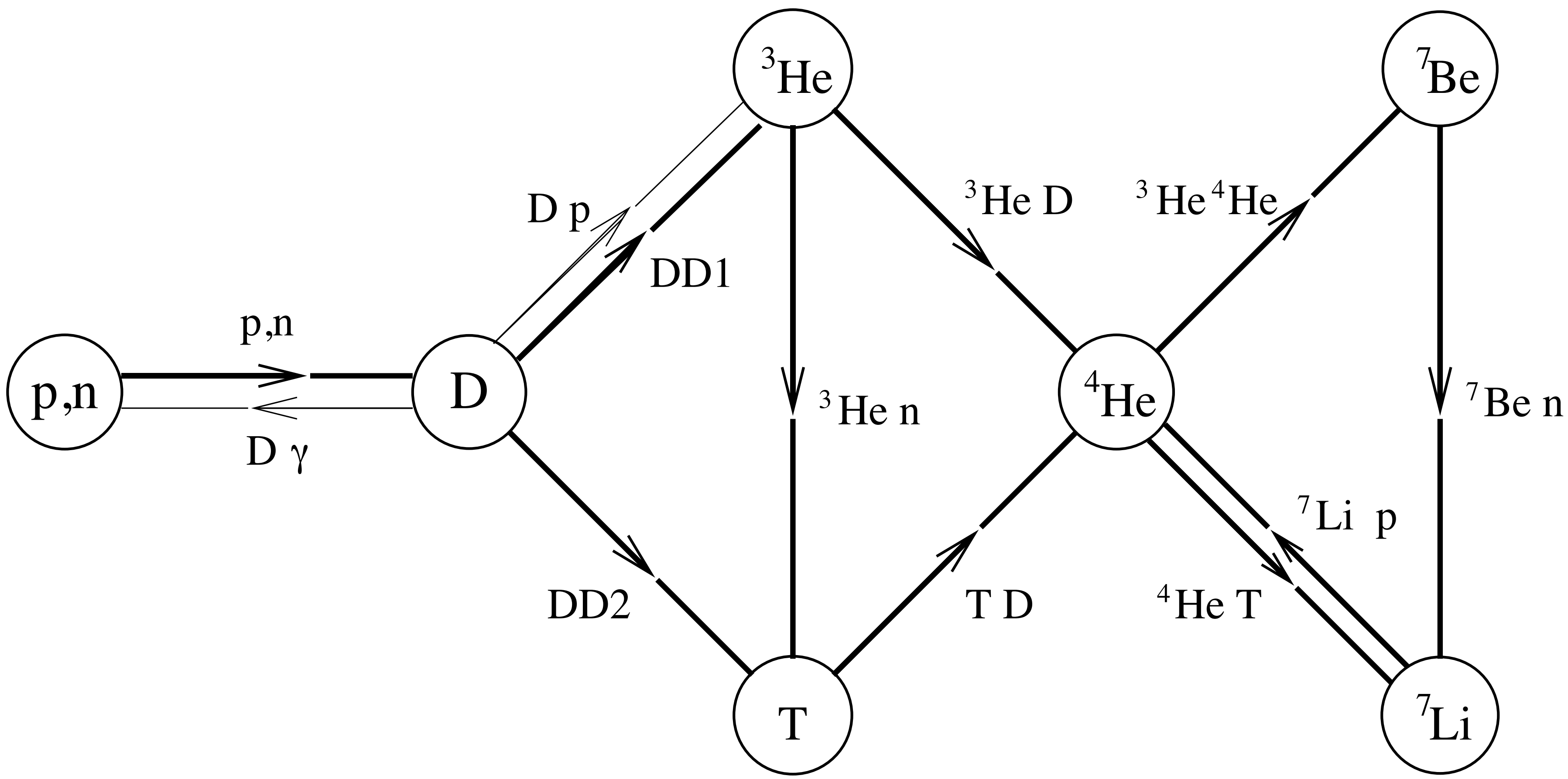
$$\Gamma(E,T) = n\,v \times \sigma \qquad \longrightarrow \qquad \Gamma(T) = n\,\langle \sigma v \rangle$$

=> their abundances are found by solving the coupled set of integrated Boltzmann equations

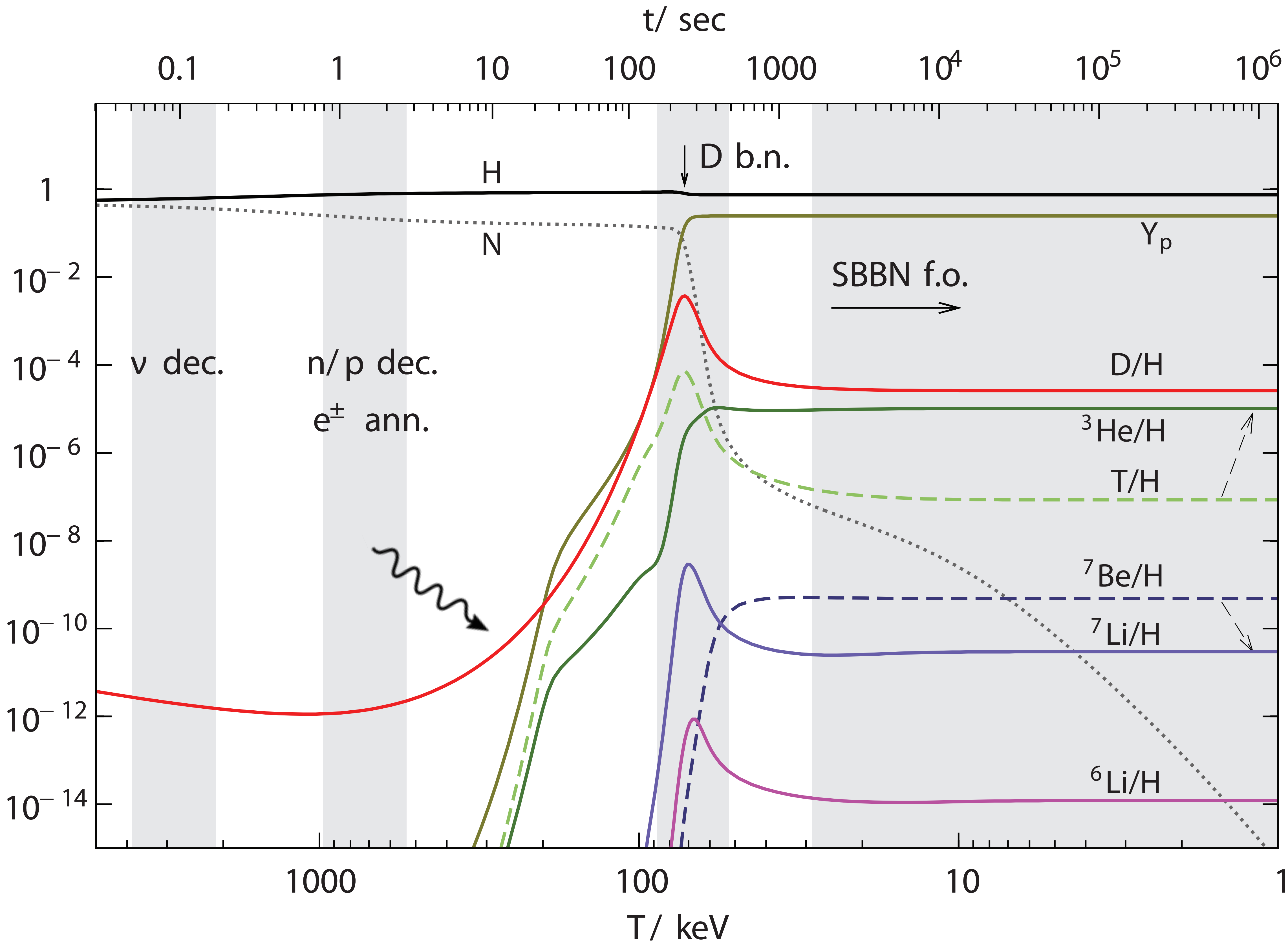
$$\frac{dn_3}{dt} + 3Hn_3 = n_1 n_2 \langle \sigma_{1+2\to 3+X} v \rangle - n_3 \Gamma_{\mathrm{des},3}$$

# The Universe at a redshift of a billion

Nuclear reaction network



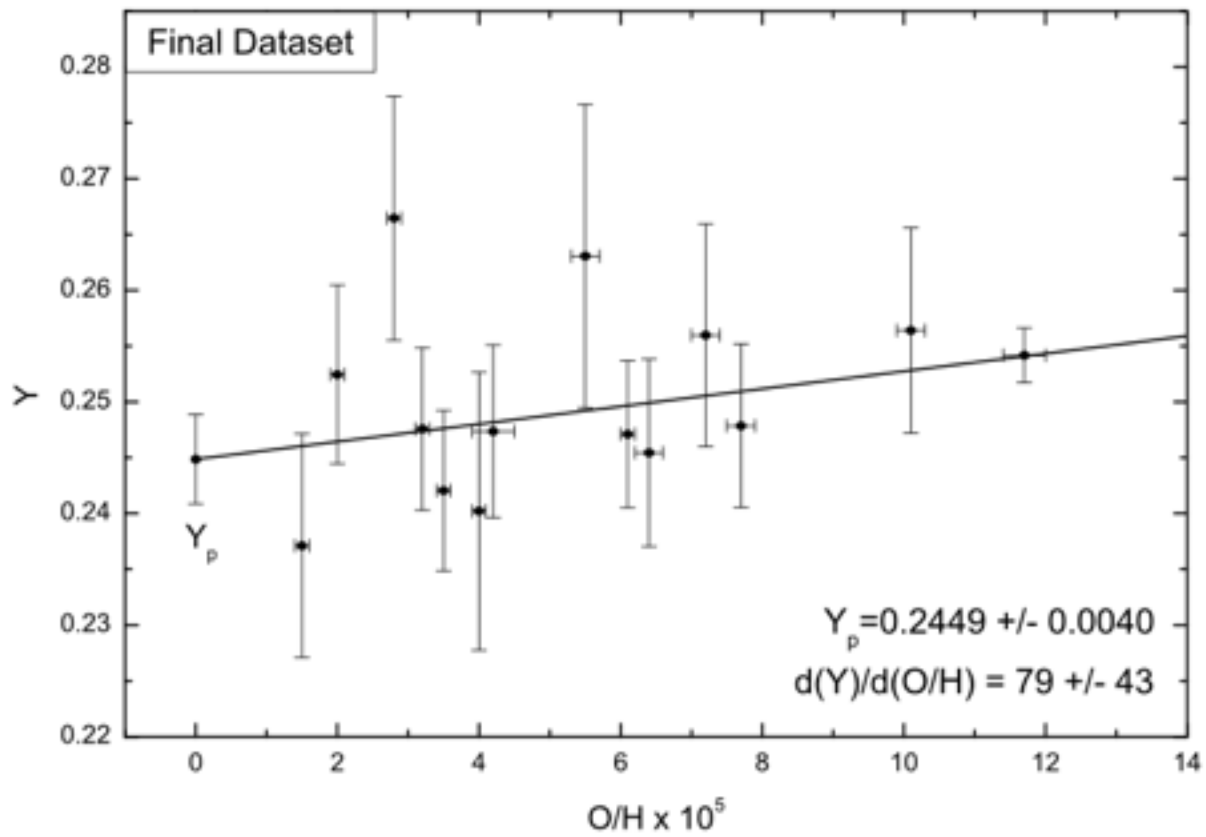
# The Universe at a redshift of a billion



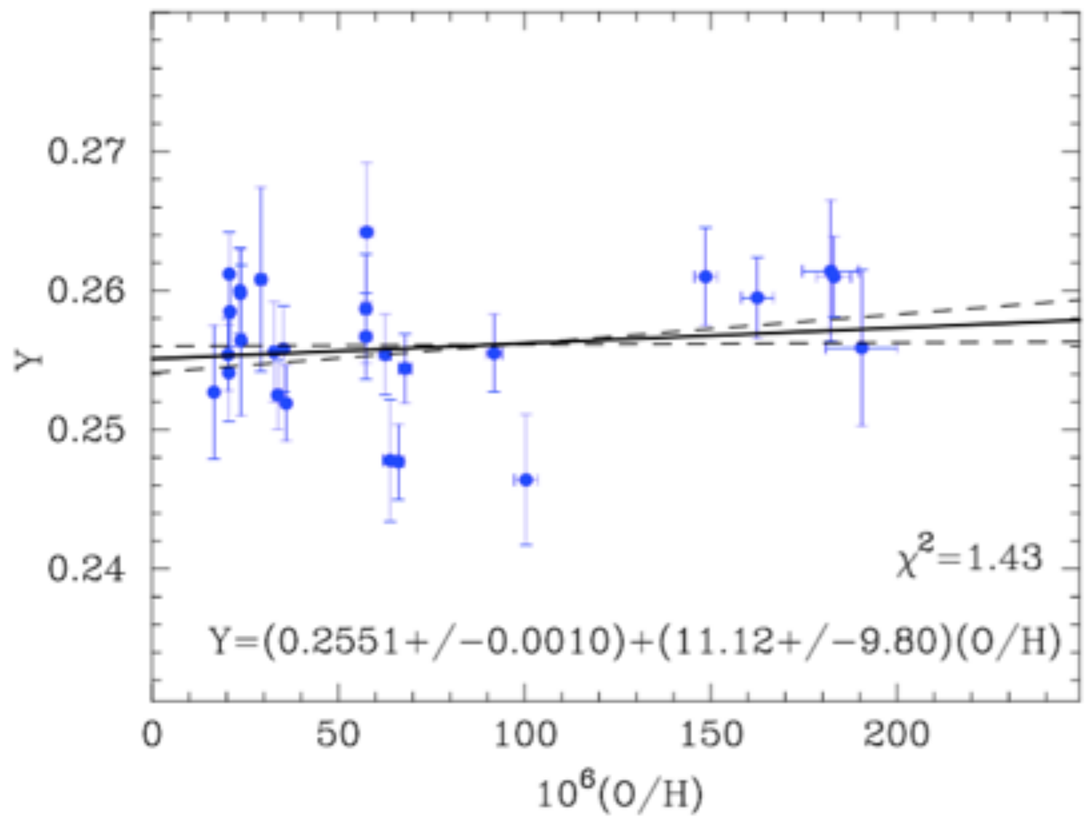
# Light element observations

## Helium mass fraction $Y_p \simeq 25\%$

Aver et al 2015




Izotov et al 2014

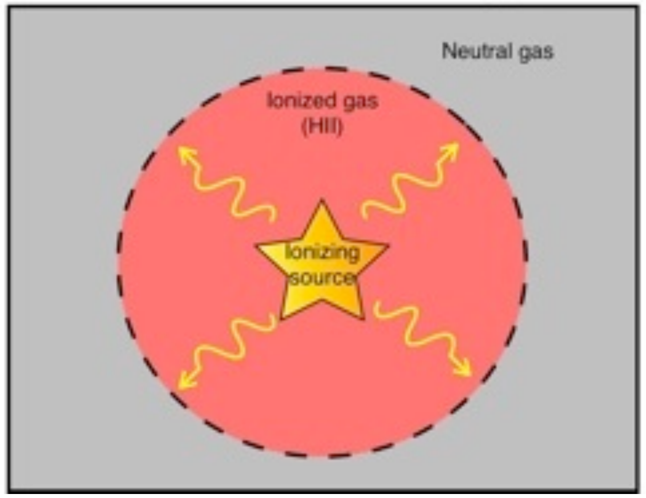



Helium gets illuminated in HII (ionized hydrogen) regions

=> emission lines

now claim few %-level accuracy (systematics limited)

Schematic of an Idealized HII Region



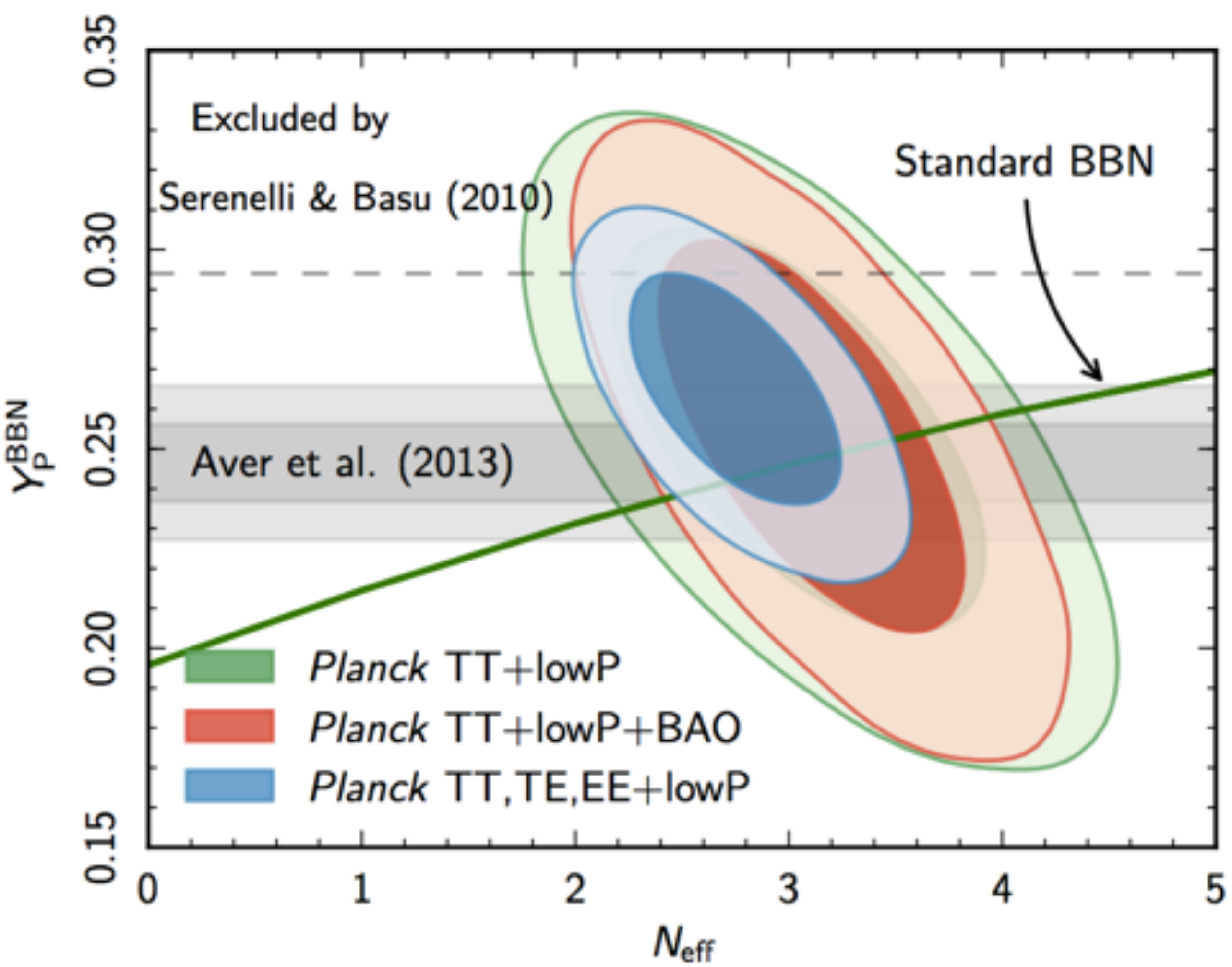
# Light element observations
## Helium @ z=1000

- *true primordial detection* of Helium in the CMB
- Helium recombines before H, affecting the free electron fraction

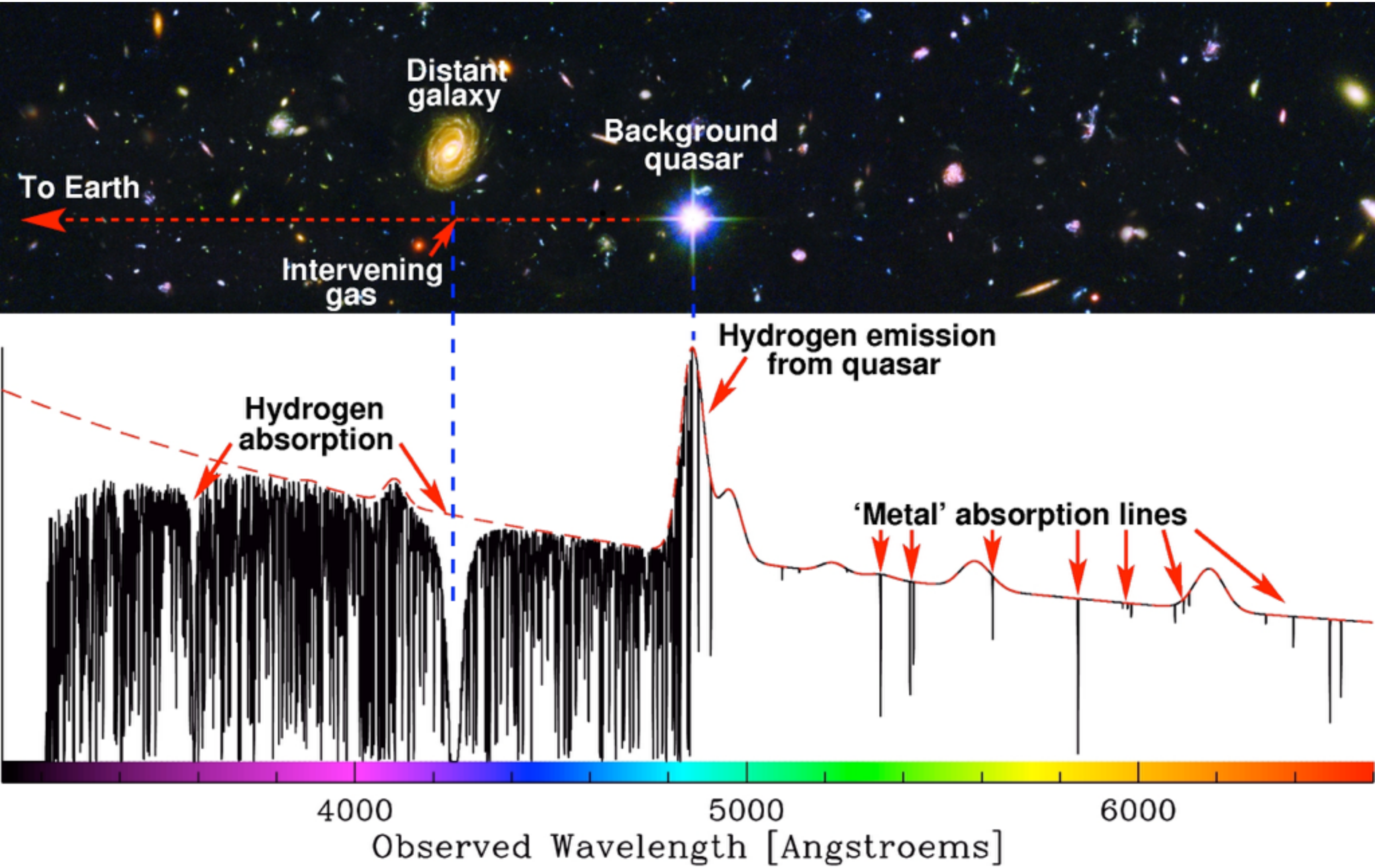
=> affects redshift of last scattering and Silk damping tail

CMB only detection of Helium yields 10% level uncertainty (high-l polarization data will yield improvement)

Planck 2015



# Light element observations Deuterium $D/H \simeq 10^{-5}$



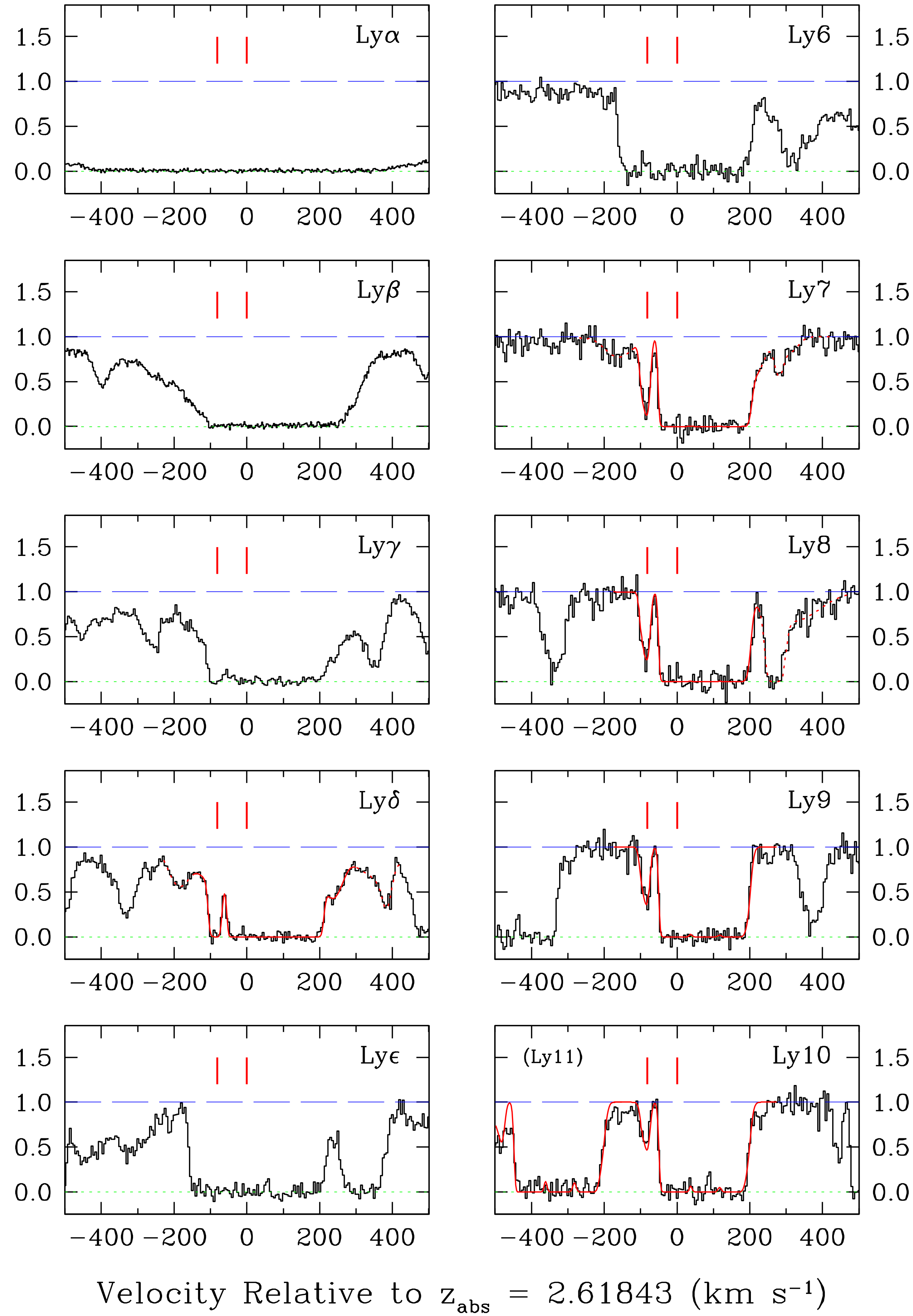
# Light element observations

## Deuterium $\mathrm{D/H} \simeq 10^{-5}$

- no known astrophysical sources (monotonic)
- ISM measurements (FUSE) show dispersion in the local gas D-absorption on dust grains?
- high-z QSO systems are the way to go

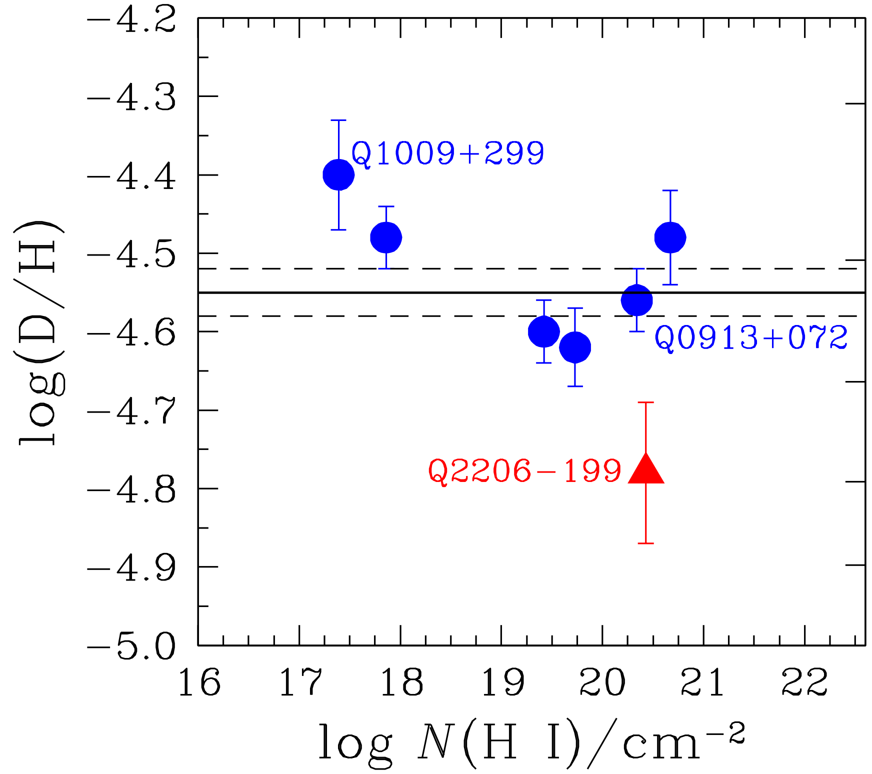
  => metal poor Ly-alpha systems have > 98% of primordial D

  => measured through the isotopic shift from H



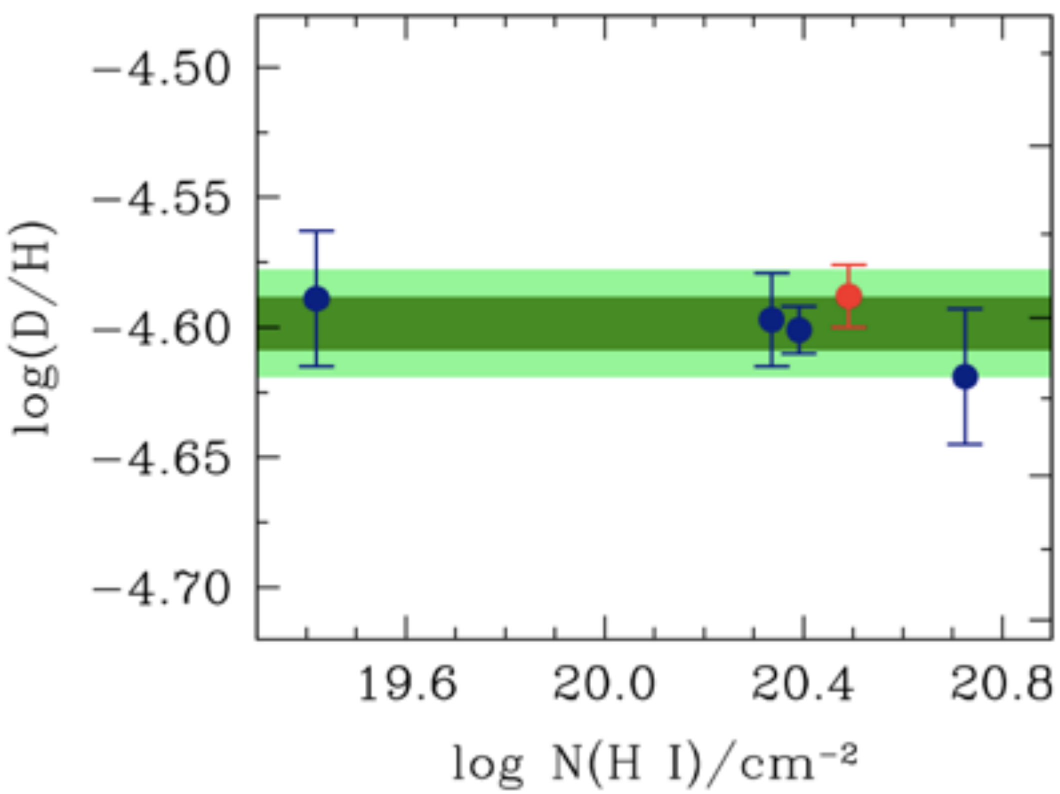
# Light element observations
## Deuterium $D/H \simeq 10^{-5}$

Pettini et al 2008




$$(D/H)_p = (2.81 \pm 0.21) \times 10^{-5}$$

Pettini et al 2013

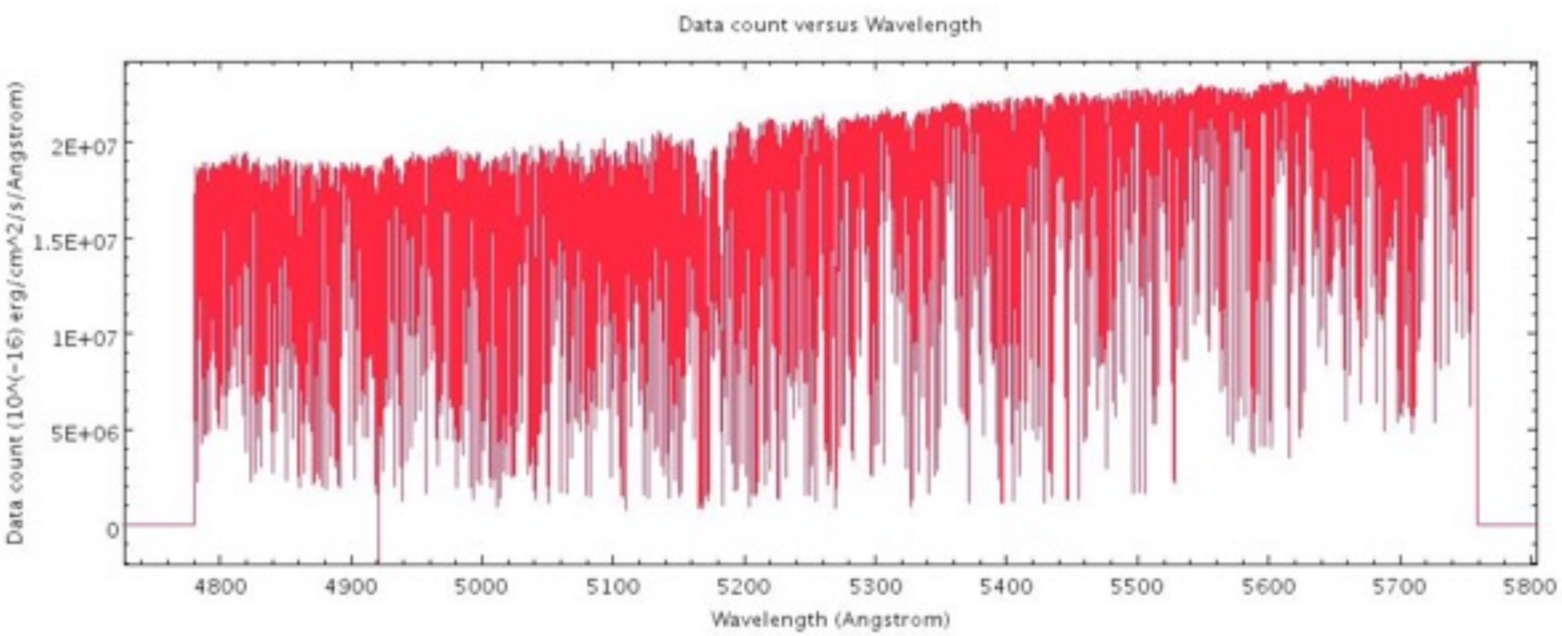



$$(D/H)_p = (2.53 \pm 0.04) \times 10^{-5}$$

=> drastic improvement of the error bar by factor 5 in a few years
Now D/H at %-precision!

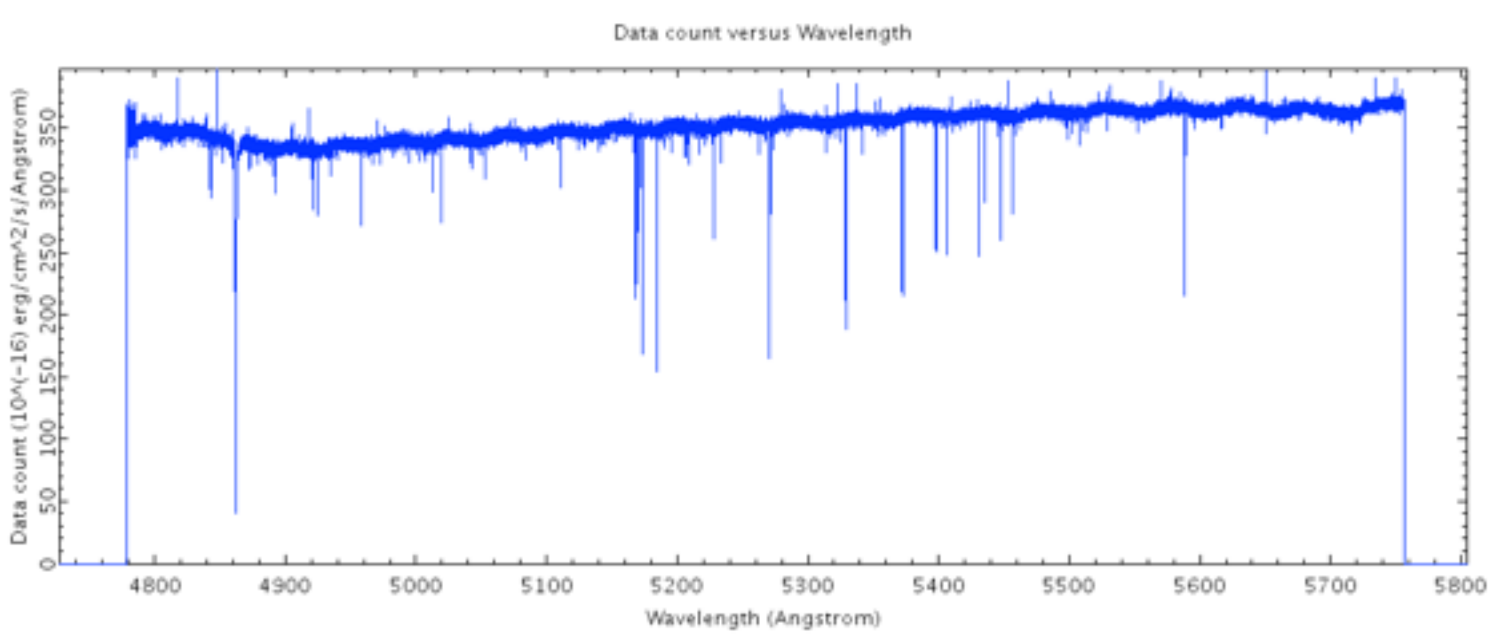
# Lithium observations

- can be observed in atmospheres of stars
- metallicity traces age => stars (formed) at lowest metallicities are thought to represent the chemical composition of the pre-galactic gas he formulas again!




HD 124897
[Fe/H] = -0.5 light

Spectra obtained with applet "SPLAT" [http://star-www.dur.ac.uk/]




CD-38-245
[Fe/H] = -4

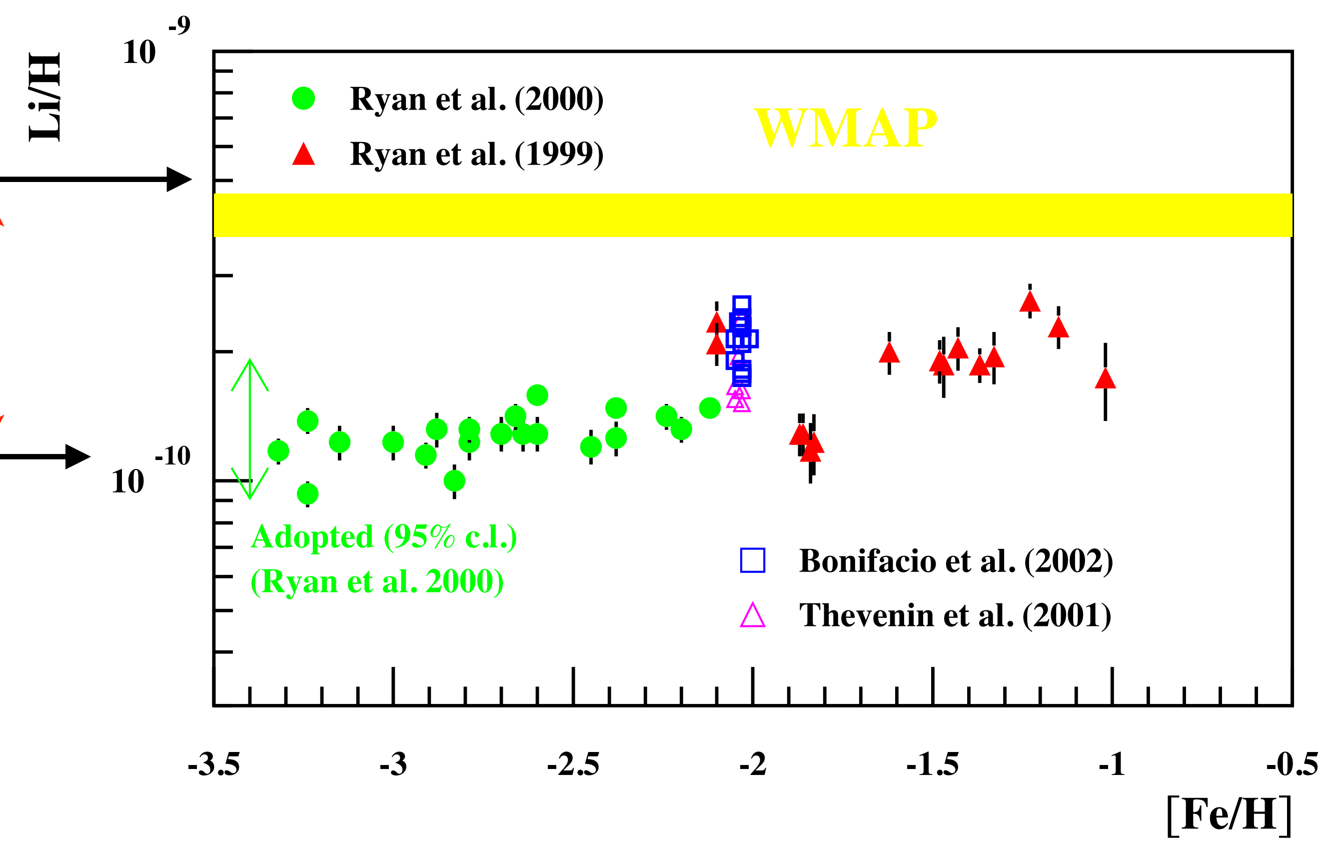

# Lithium observations

- can be observed in atmospheres of stars
- metallicity traces age => stars (formed) at lowest metallicities are thought to represent the chemical composition of the pre-galactic gas
- Li shows plateau structure with small scatter at lowest metallicities: “Spite plateau” (1982) => points towards primordial origin

SBBN

*“cosmological lithium problem”*

$$^{7}\mathrm{Li/H}|_{\mathrm{obs}} = (1 \div 2.5) \times 10^{-10}$$

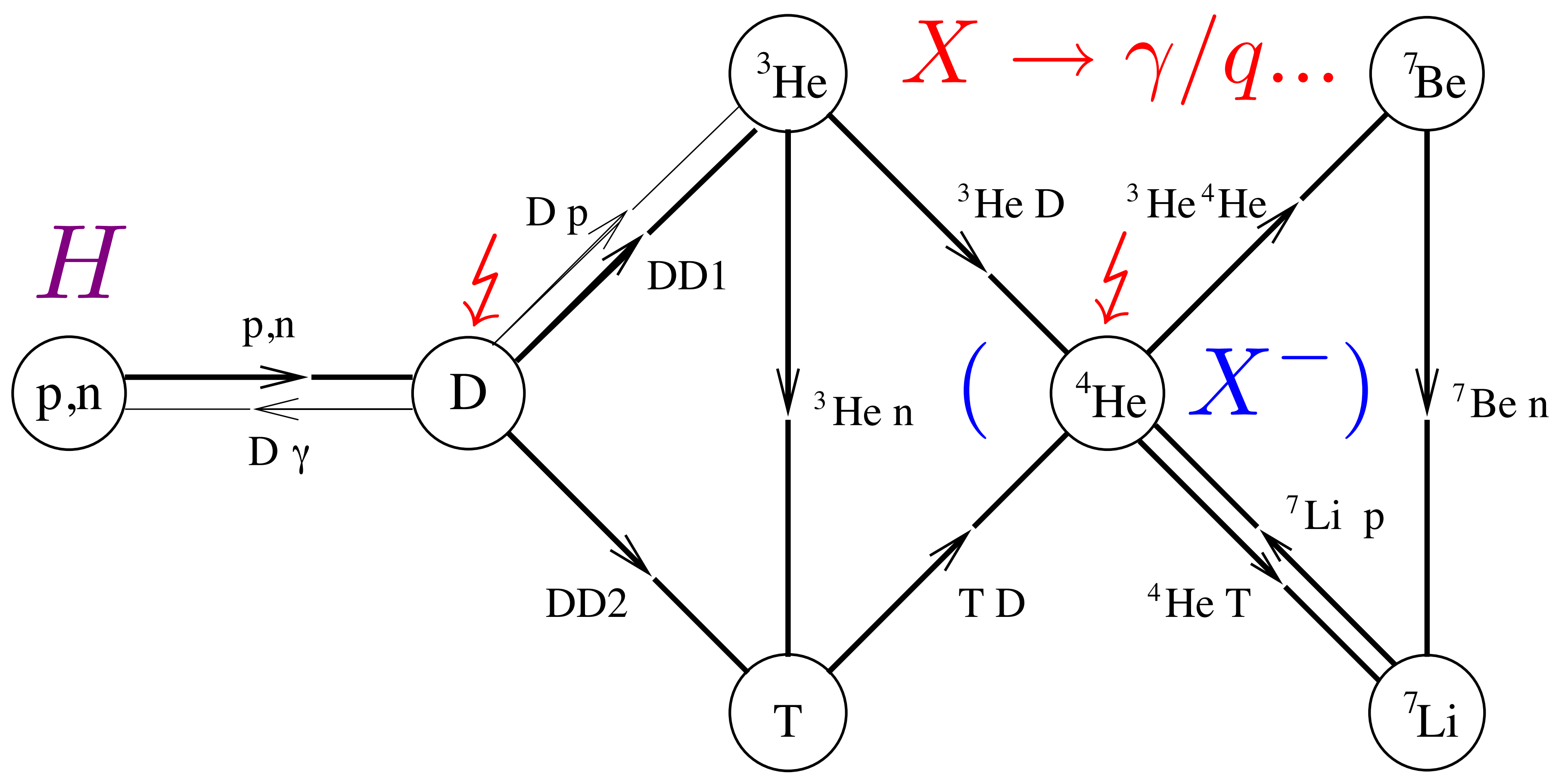



Coc et al 2004

# SBBN take-home message

- Light element predictions from helium to lithium span roughly 9 orders of magnitude in number
- Impressive agreement with observations of D and He
- *One quantitative problem:* Lithium abundance is high by a factor of 3-5, with high statistical significance
- Nuclear physics lithium solution is ruled out; solution may be of astrophysical origin but could also signal new physics operative during BBN

# Beyond SBBN



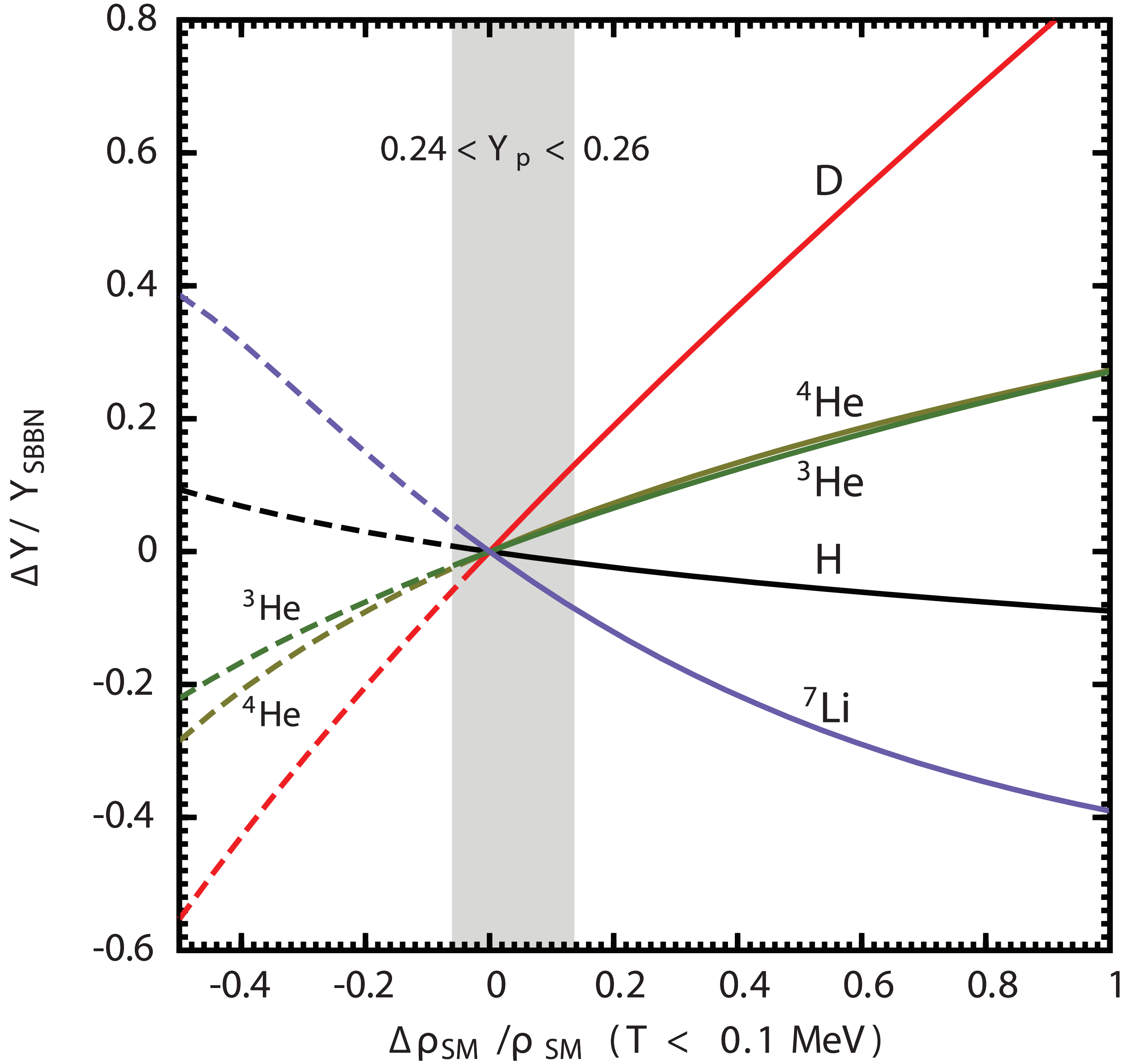

Change in timing

non-equilibrium BBN

catalyzed BBN

# Change in timing

$$H_{\rm SBBN} \to H = H_{\rm SBBN}\sqrt{1+\rho_{dr}/\rho_{\rm SM}}$$





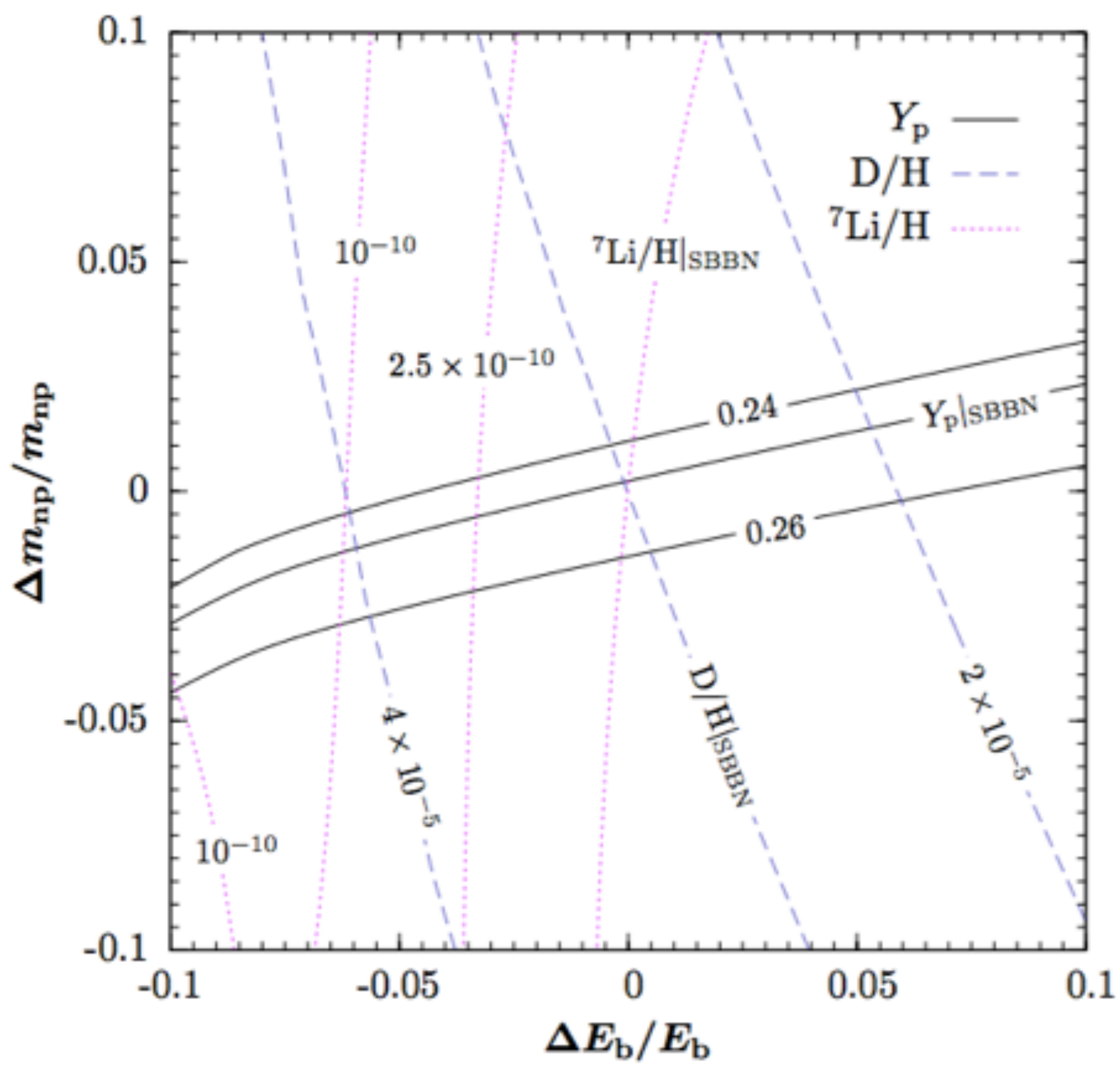
$N_{\rm eff} = 3.15 \pm 0.23$

Planck 2015

# Time evolution of fundamental constants

A time evolution of, e.g. $\frac{\langle\phi\rangle}{M} F_{\mu\nu}^2$ or $\frac{\langle\phi\rangle}{M} m_q \bar{q} q$

=> yields changes in $m_q$, electric charge, $\Lambda_{QCD}$, Higgs vacuum expectation value….
=> induce changes in the reaction rates, nuclear binding, and the position of resonances




BBN: exponential sensitivity on

$\Delta m_{np}$ determines n/p freeze out

$E_d$ determines end of the D-bottleneck

# Non-equilibrium BBN Energy injection

- energy release during SBBN (mass conversion into nuclear binding energy)

  $\sim 2 \text{ MeV/nucleon}$ => marginal effect at z = 1 billion

- most prominent class: decays of long-lived particles X

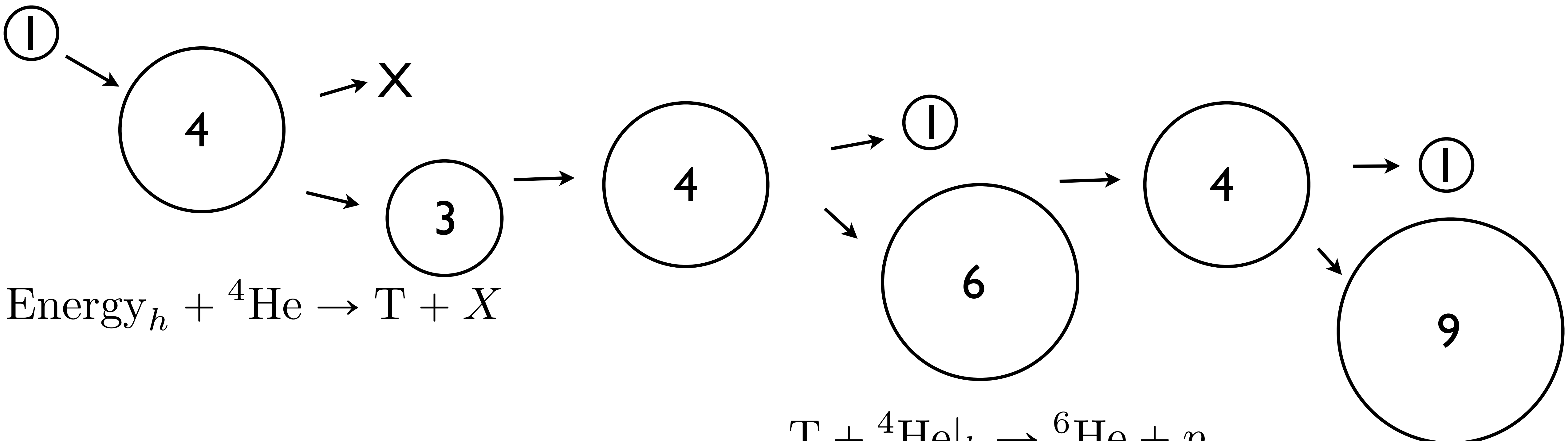
  => previous works focused on $m_X = \mathcal{O}(100 \text{ GeV})$ , e.g. $\widetilde{G} \rightarrow SM + \widetilde{\chi}^0$

  Dimopoulos 1988; ….; Kawasaki et al 2004; Jedamzik 2006; Cyburt et al 2009

  => yield electromagnetic and hadronic showers which dissociated light elements

  => drastic departures from the equilibrium picture

# non-equilibrium BBN




$$\text{Energy}_h + {}^4\text{He} \rightarrow \text{T} + X$$

$$\text{T} + {}^4\text{He}|_b \rightarrow {}^6\text{He} + p$$

$$T_{1/2}({}^6\text{He}) = 0.8\,\text{s}$$

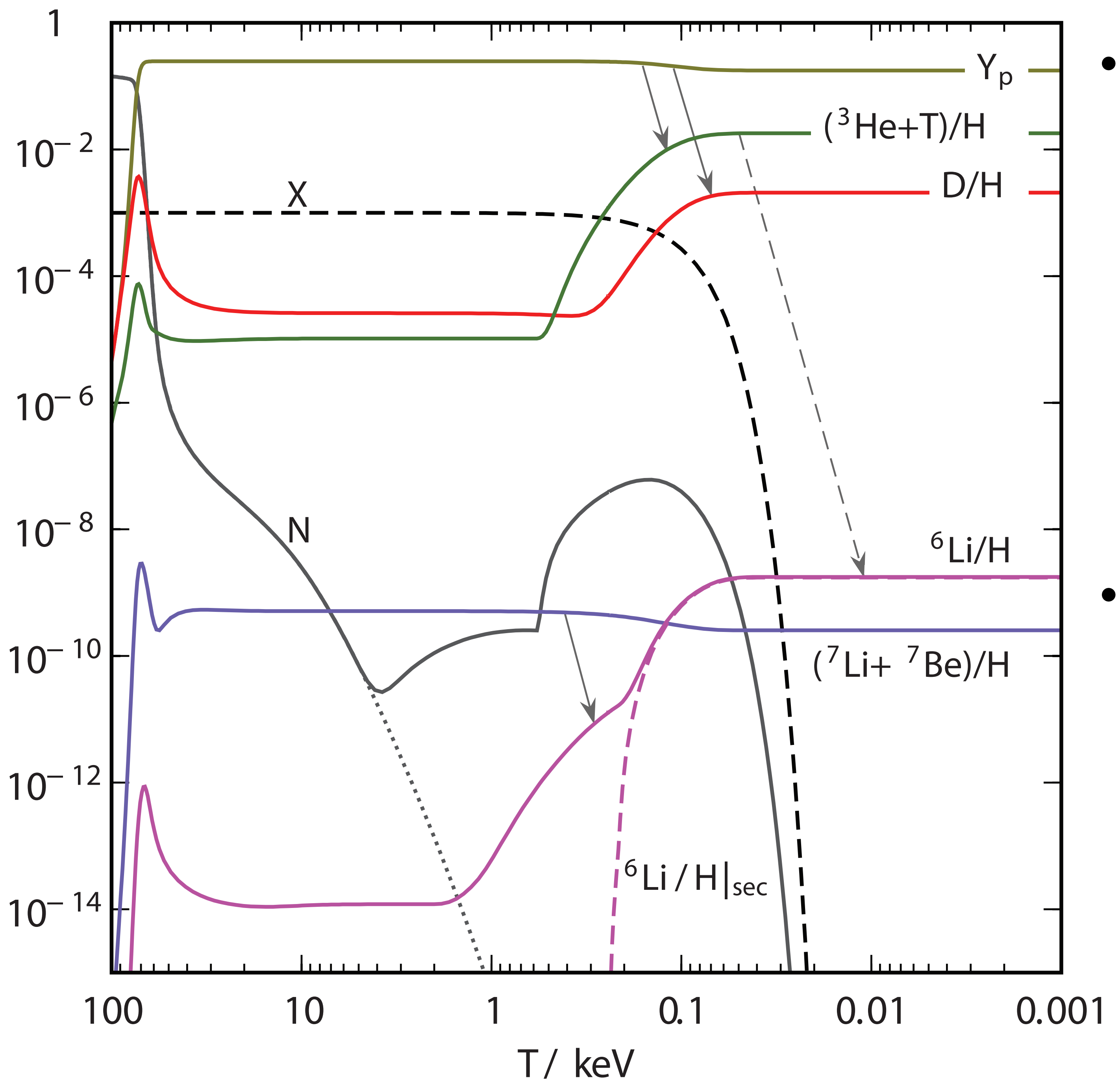
$${}^6\text{He} + {}^4\text{He}|_b \rightarrow {}^9\text{Be} + n$$

Pospelov, JP, 2010

Beryllium becomes the BBN “calorimeter”;
its abundance is constrained from observations in stars

# Non-equilibrium BBN

Electromagnetic energy injection (t > 10^6 sec)




- photons in EM-cascade below $e^{\pm}$ threshold are not efficiently dissipated

=> spallation of nuclei

- Important secondary effect:

$$^3\mathrm{H} + {}^4\mathrm{He}|_{bg} \to {}^6\mathrm{Li} + n$$

$$^3\mathrm{He} + {}^4\mathrm{He}_{bg} \to {}^6\mathrm{Li} + p$$

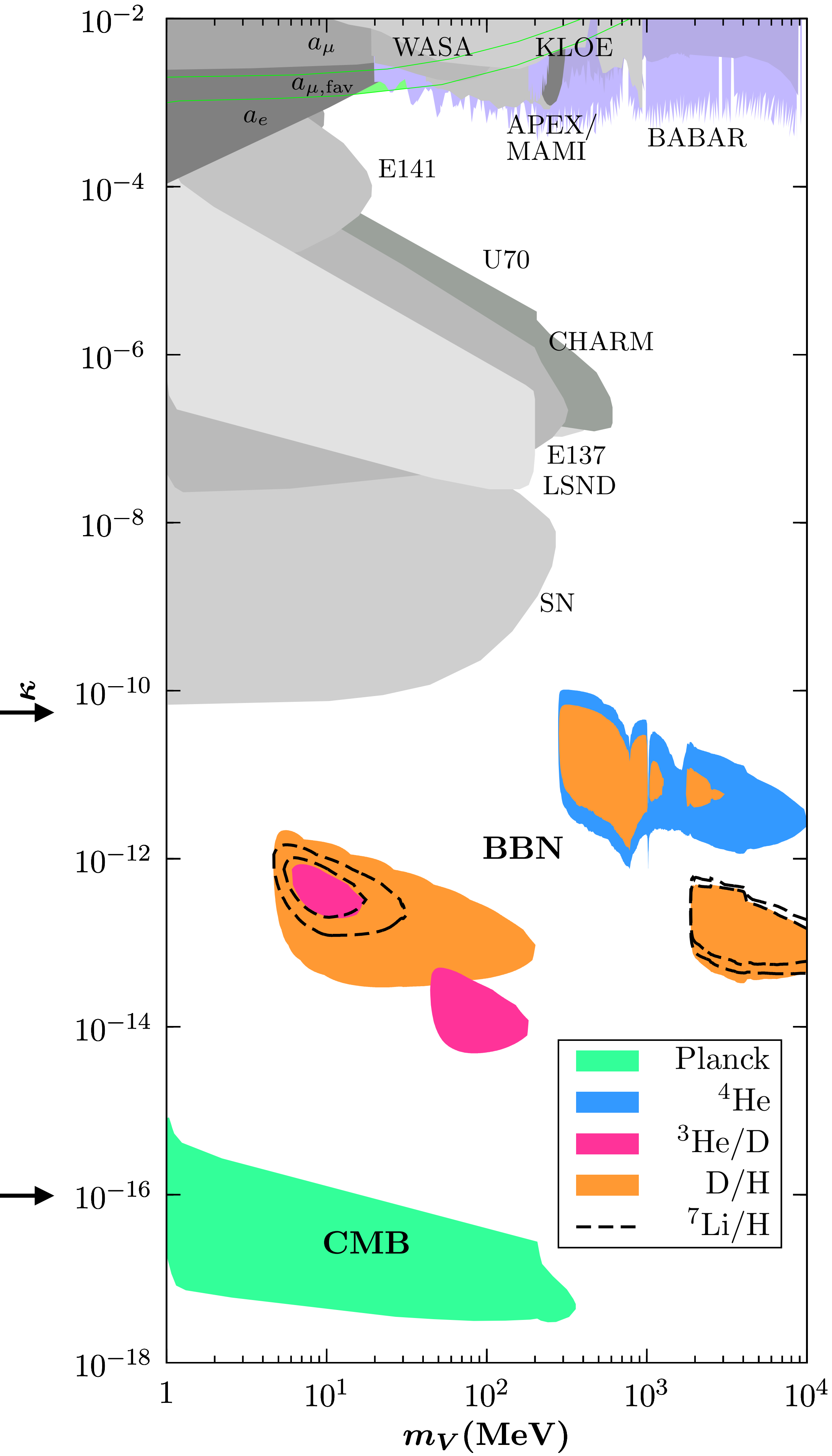
# An application to Dark Photons

Cosmology becomes the only test for very feeble couplings to SM

$10^{-22}$ →

$10^{-36}$ →

$$\alpha' = (\kappa e)^2/(4\pi)$$



# Summary

- Organizational principle of new physics in terms of effective operators in direct detection and at the collider; approach has its limitation, when mediator goes on-shell
- With the Higgs discovery, many models fell on July 4, 2012. A minimal extension of the dark sector by a new mediator opens up many new possibilities of phenomenology (e.g. intensity frontier)
- DM may carry a chemical potential (asymmetric DM) => alternative to the WIMP miracle
- Nucleosynthesis is one of the pillars the standard cosmological rests on; its sensitivity to new physics makes BBN a valuable tool to test BSM physics => every model of new physics has to pass this cosmological consistency test.

Thank you — and keep up the good work!