Astrophysical and Cosmological Aspects of Dark Photons and ALPs

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Challenges in the Dark Sector: Alternatives to the WIMP paradigm

*supported by the New Frontiers Program by the Austrian Academy of Sciences

Portals to the Hidden Sector

connecting the visible world to the dark side

$(H^\dagger H)\,(A\phi + \lambda\phi^2)$

"Higgs Portal"
(a minimal model of DM)

$LH\,N$

"Neutrino Portal"
likely realized in nature (neutrinos have mass); sterile neutrinos

$F^Y_{\mu\nu}\,V^{\mu\nu}$

"Vector Portal"
kinetic mixing of abelian field strength tensors

The kinetic mixing portal "Dark Photons"

$$\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times U(1)'$$

Standard Model x "dark sector" with vector particle V^μ

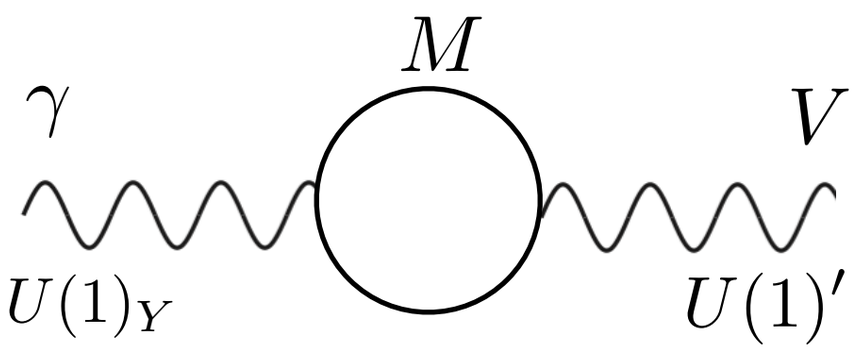
$$-\frac{\kappa'}{2} F^Y_{\mu\nu} V^{\mu\nu} \xrightarrow[\text{energies}]{\text{at low}} -\frac{\kappa}{2} F_{\mu\nu} V^{\mu\nu}$$

hypercharge field strength

photon field strength

NB: V_μ must be massive, otherwise κ can be rotated away.

Radiatively induced kinetic mixing



$$\longrightarrow \quad -\frac{\kappa'}{2} F^Y_{\mu\nu} V^{\mu\nu}$$

Assume there are particles charged both under $U(1)_Y$ and $U(1)'$ of *arbitrarily heavy* mass M

$$\kappa \sim \frac{g_Y g'}{16\pi^2} \times \log\left(\frac{\Lambda_{UV}}{M}\right)$$

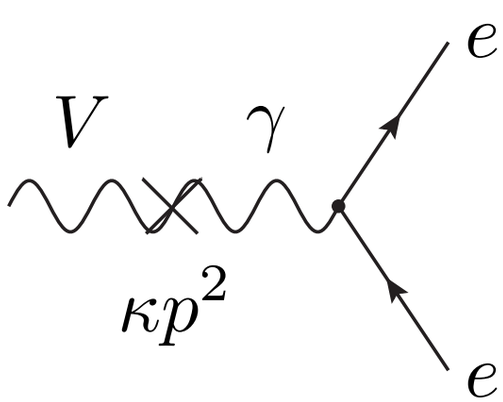
"non-decoupling" [Holdom '85]

=> kinetic mixing can be a low-energy messenger from high scale

Dark Photons

Two equivalent ways to think about $-\frac{\kappa}{2}F_{\mu\nu}V^{\mu\nu}$

A. Keep the mixing as a perturbation:

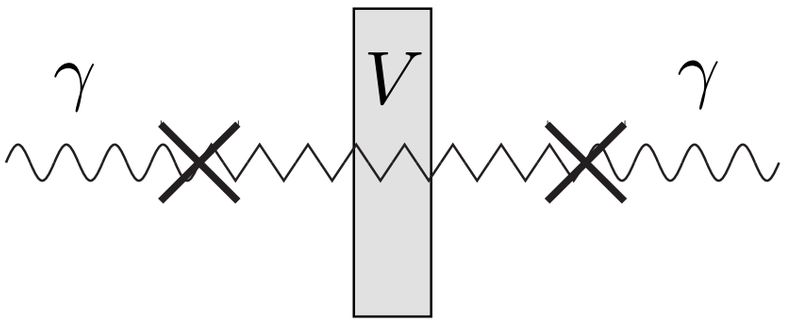


$eA_\mu J^\mu_{EM}$

Photon-Dark Photon mixing manifest

…suggests…

"Light-shining-through-wall" (LSW) experiments



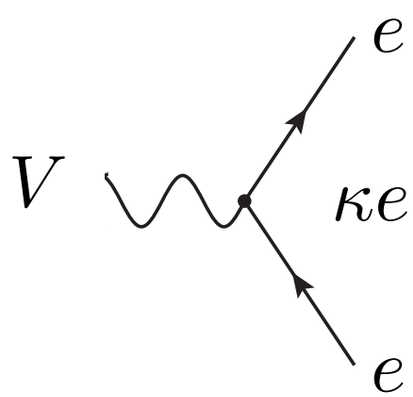
probability $\propto \kappa^4$

sensitivity when $m_V \sim \omega_\gamma$

Dark Photons

Two equivalent ways to think about $-\frac{\kappa}{2}F_{\mu\nu}V^{\mu\nu}$

B. Diagonalize kinetic term:

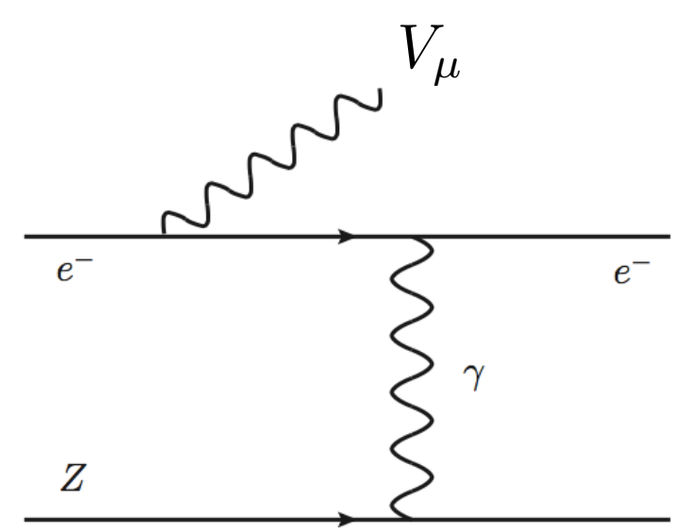


$$eA'_\mu J^\mu_{EM} - \kappa e V'_\mu J^\mu_{EM}$$

Ordinary matter has milli-charge under new force

…suggests…

Direct production in experiment:



"Intensity Frontier"

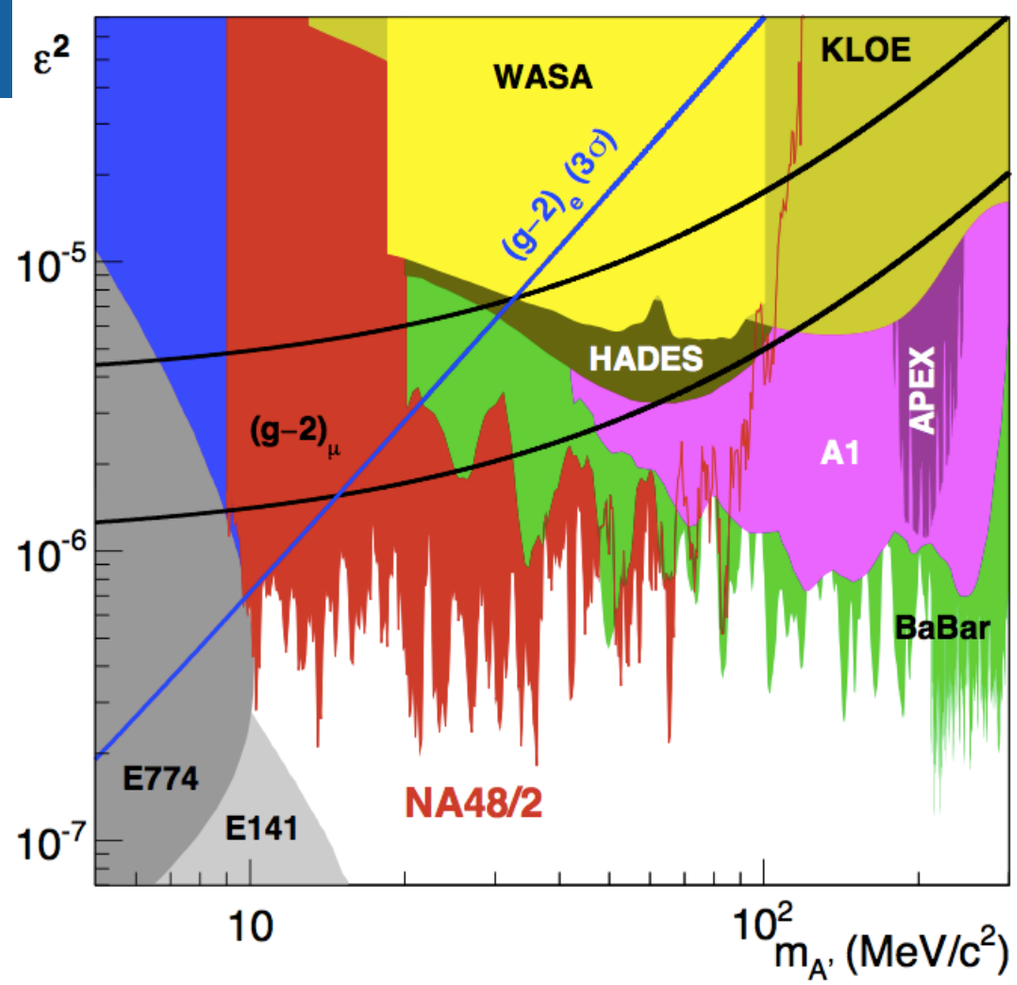
Dark Photons

"Intensity Frontier"

2015

precision tests

$(g-2)_e$



beams on fixed target

$Ze^- \to Ze^- V \to Ze^- e^+ e^-$

flavor factories

$e^+ e^- \to \gamma V \to \gamma l^+ l^-$

$\pi^0 \to \gamma V \to \gamma e^+ e^-$

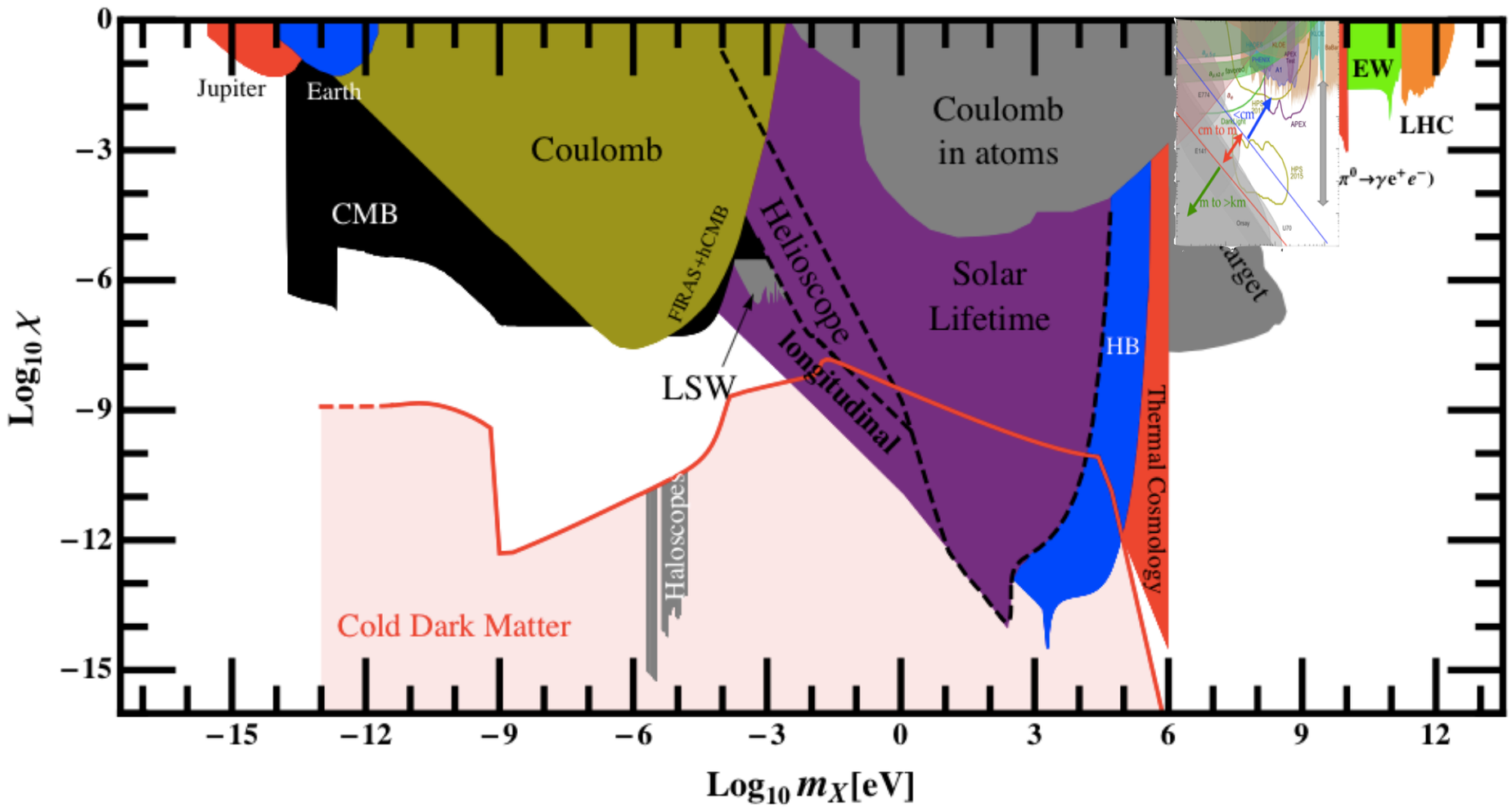
e-beam dumps

$Ze^- \to Ze^- V \to Ze^- e^+ e^-$

latest results from BaBar, A1, NA48

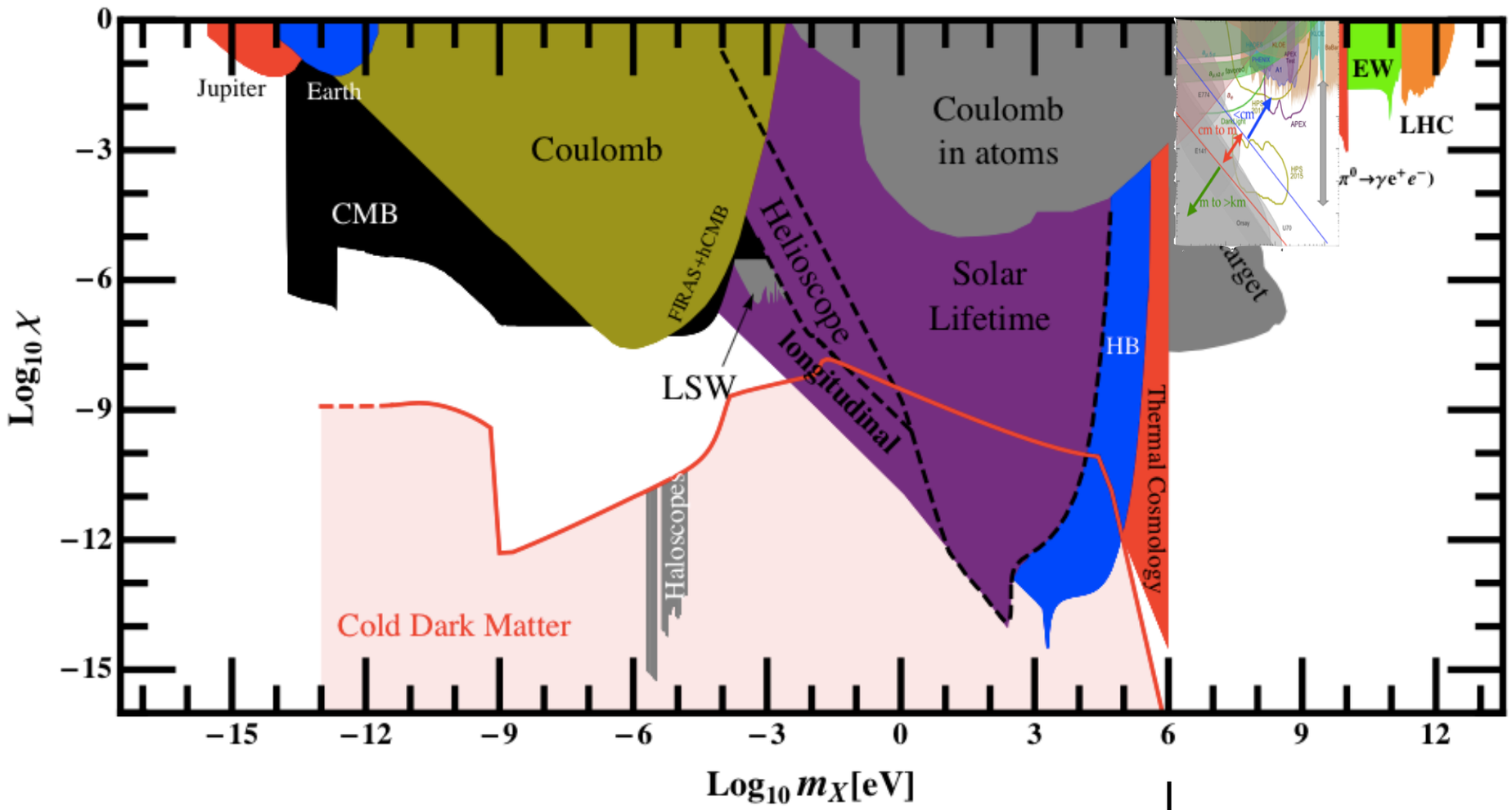
Future facilities, e.g. HPS, SHiP proposal,…

Dark Photon Landscape



(Fig. from Jaeckel 2013)

Dark Photon Landscape

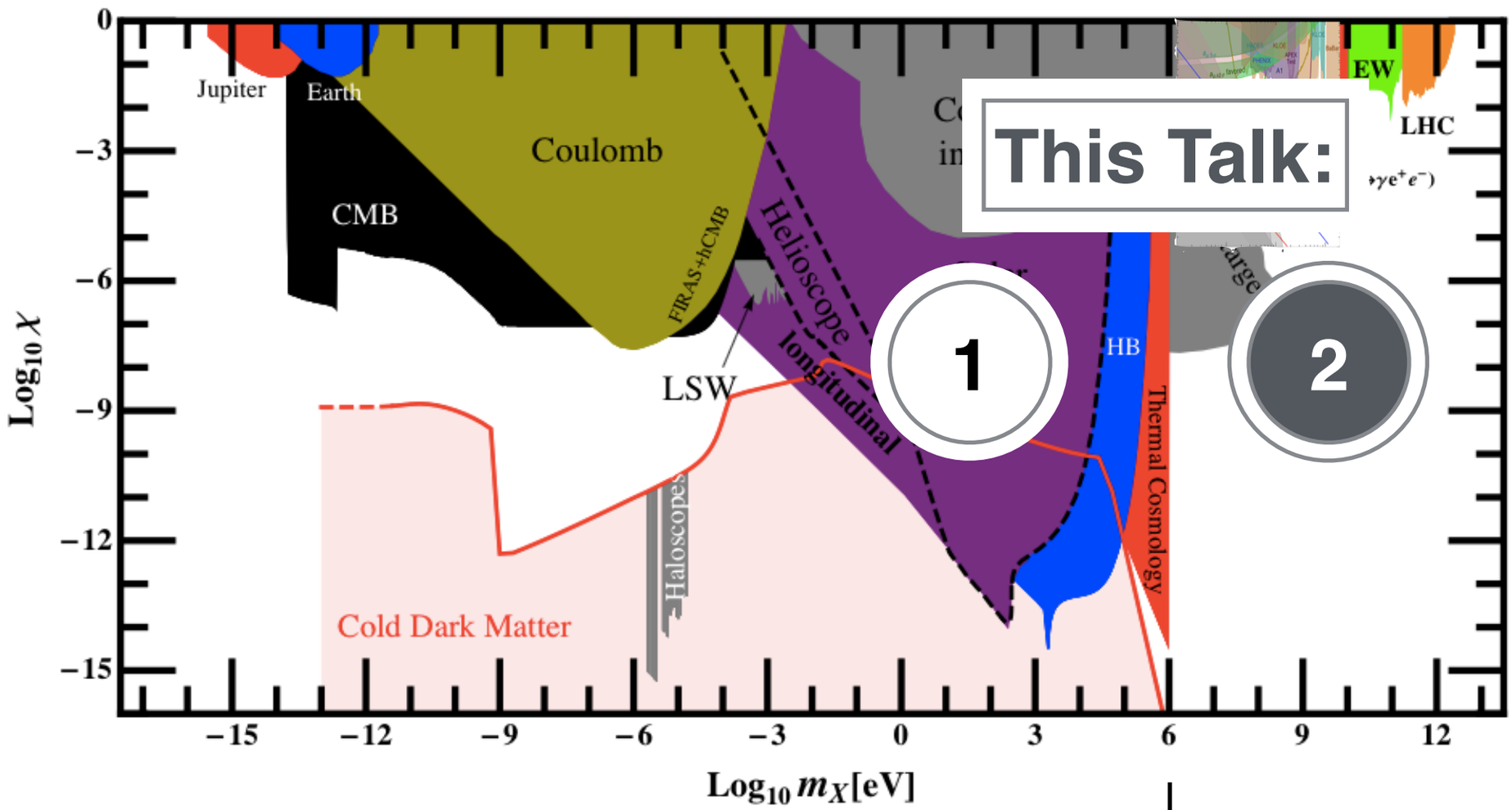


Dark Photon becomes
a dark matter candidate

Decays to
e+ e- possible

(Fig. from Jaeckel 2013)

Dark Photon Landscape



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(Fig. from Jaeckel 2013)

Outline

1 **Astrophysical constraints on keV-mass Dark Photons**

Mini-review on stellar energy loss (see also Javier's talk yesterday)

Laboratory limits from direct detection

An, Pospelov, JP, (Ritz) 2014 & 2015

2 **Cosmological constraints on MeV-mass Dark Photons**

Fradette, Pospelov, JP, Ritz 2014

Primordial nucleosynthesis as a tool test for new physics

3 **ALPs (or other MeV-scale particles) during BBN**

A new solution to the "cosmic lithium problem"

Goudelis, Pospelov, JP 2015

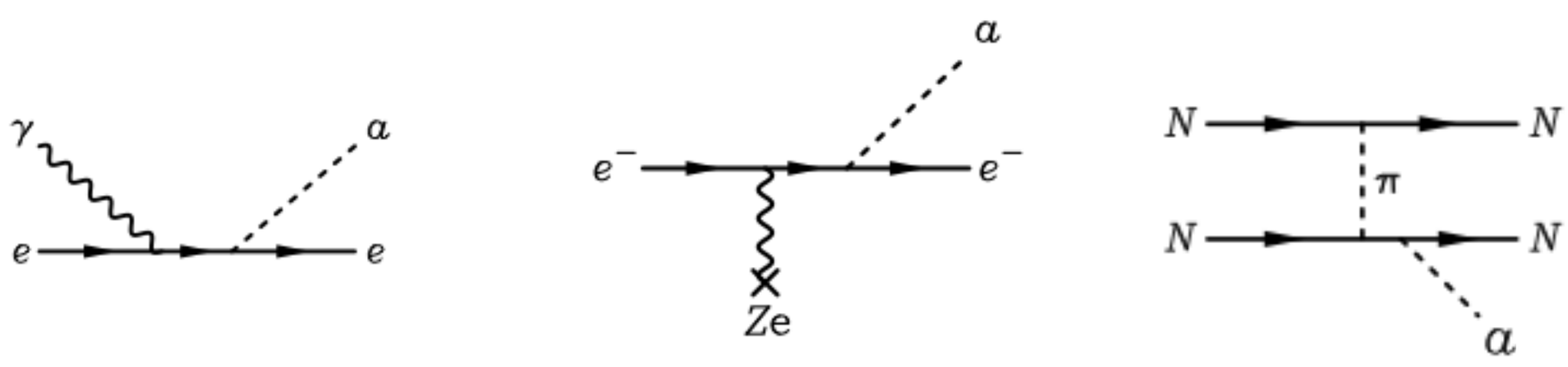
1 Astrophysical constraints

$$m_V < 1\,\mathrm{MeV}$$

Stars are supreme laboratories to test (and exclude!) light, feebly interacting new particles. E.g. Sun core temperature $T \sim 1\,\mathrm{keV}$

=> Particles with mass < $O(\mathrm{keV})$ are kinematically accessible and can be produced!

e.g.



=> Energy loss affects stellar structure and their lifespan.

Reaction to energy loss

$$\langle E_{\rm kin} + E_{\rm grav} \rangle \searrow$$

1. Stars supported by radiation pressure (active stars):

   Virial theorem: $\langle E_{\rm kin} \rangle = -\frac{1}{2} \langle E_{\rm grav} \rangle$

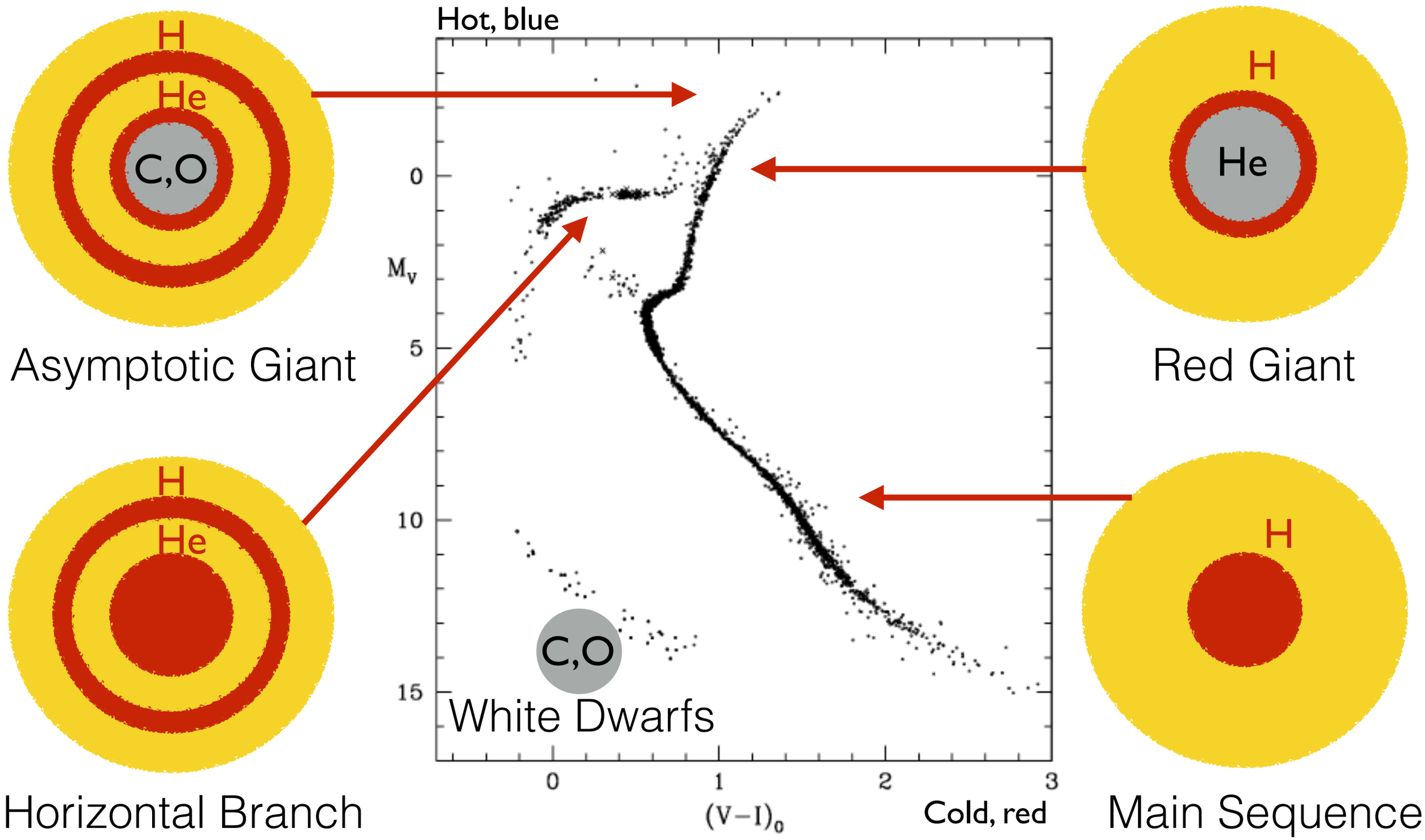
   => Gravitational potential energy becomes more negative (tighter bound)

   => average kinetic energy increases, star becomes hotter, negative heat capacity

2. Stars supported by degeneracy pressure (white dwarfs, neutron stars): possess positive heat capacity, the star indeed cools by the energy loss

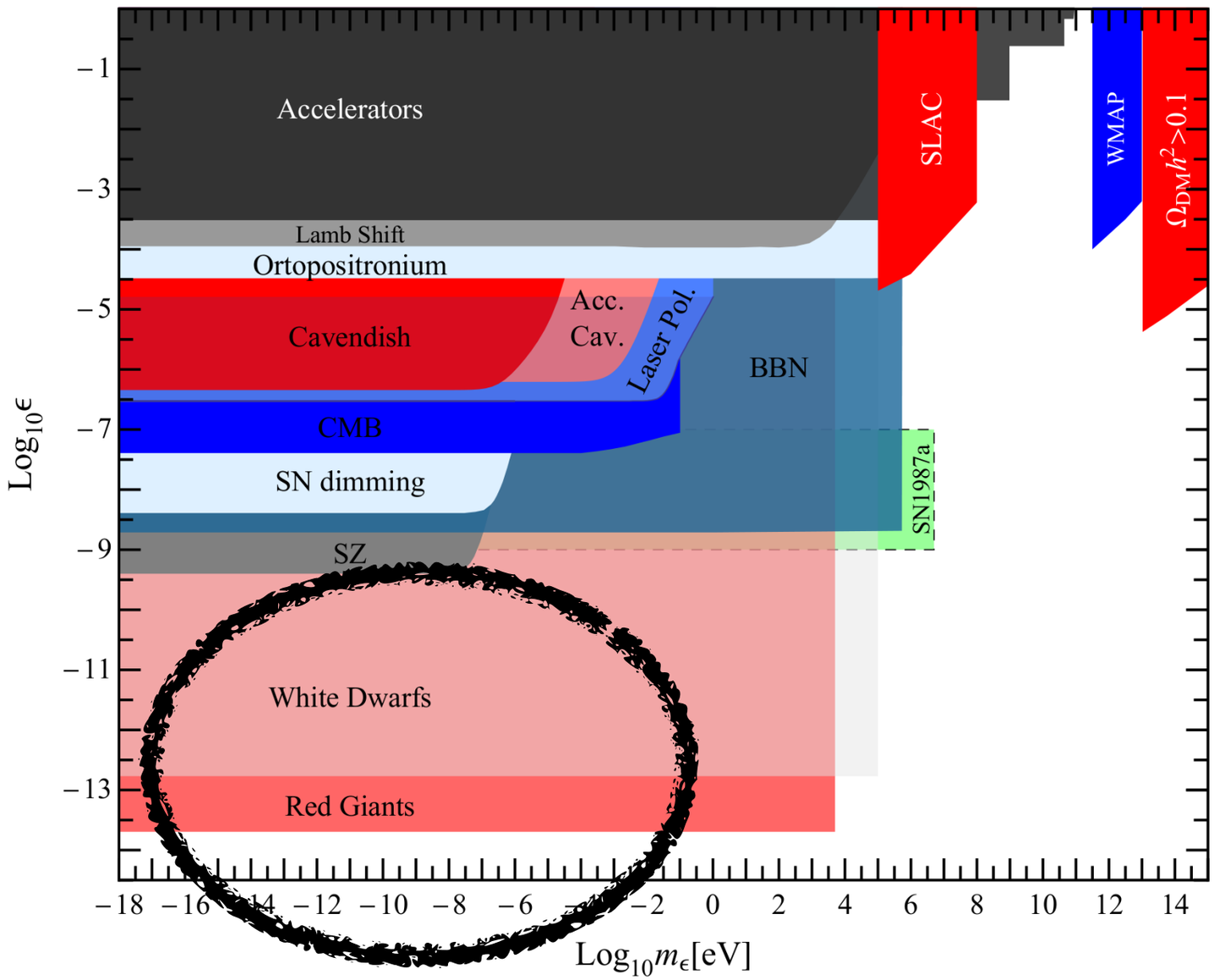
Stars as laboratories

See Raffelt's book!



Globular Cluster color-magnitude diagram

Astrophysical constraints

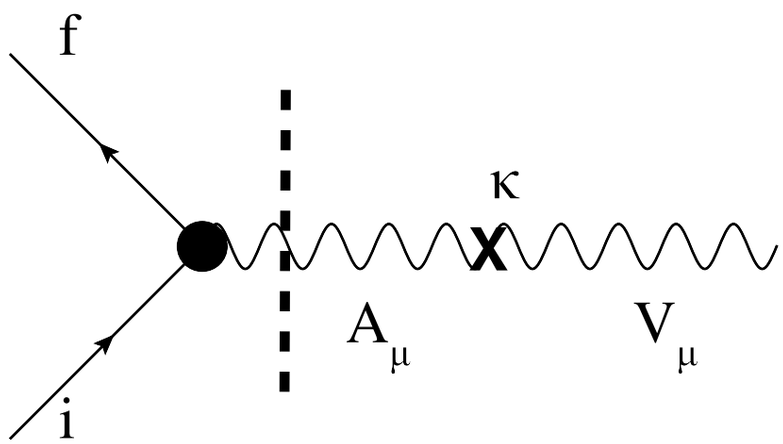


e.g. millicharged particles

Stellar Production

For $m_V \lesssim 1\,\mathrm{keV}$ hidden photons are produced in the solar interior

$$\frac{\kappa}{2} F_{\mu\nu} V^{\mu\nu} + e J^{\mu}_{\mathrm{em}} A_{\mu} \xrightarrow{\mathrm{on-shell\ V}} \mathcal{L}_{\mathrm{int}} = -\kappa m_V^2 A_{\mu} V^{\mu} + e J^{\mu}_{\mathrm{em}} A_{\mu}.$$



$$\mathcal{M}_{i \to f + V_{T,L}} = -\frac{\kappa m_V^2}{m_V^2 - \Pi_{T,L}} [e J^{\mu}_{\mathrm{em}}]_{fi} \epsilon_{\mu}^{T,L}$$

transverse resonance

$$m_V^2 = \mathrm{Re}\,\Pi_T = \omega_p^2$$

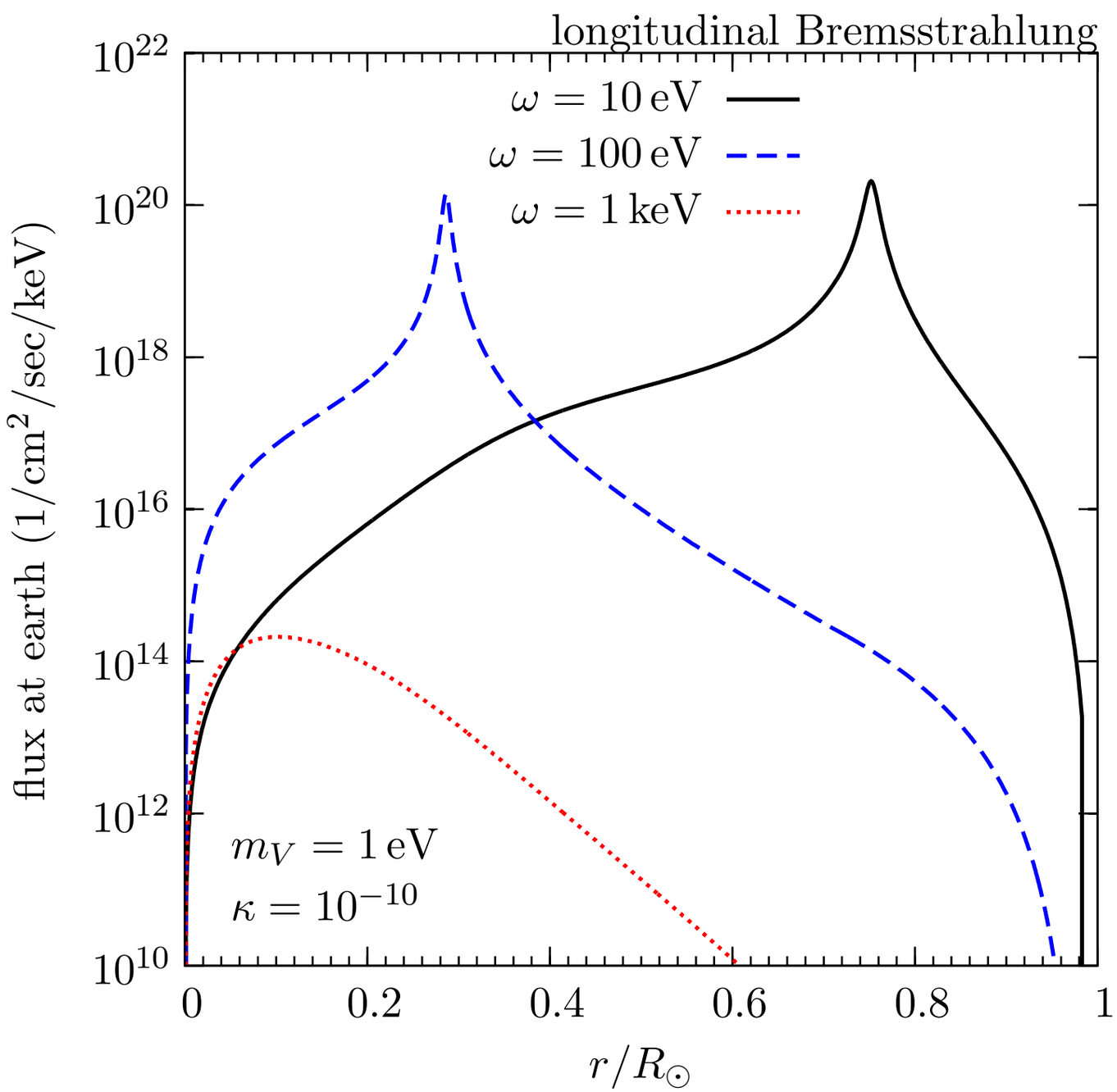
ω_p = plasma frequency

longitudinal resonance

$$m_V^2 = \mathrm{Re}\,\Pi_L = \omega_p^2 m_V^2 / \omega^2$$

$$\Leftrightarrow \omega^2 = \omega_p^2$$

Stellar energy loss (here: sun)



resonant emission of longitudinally polarized vectors

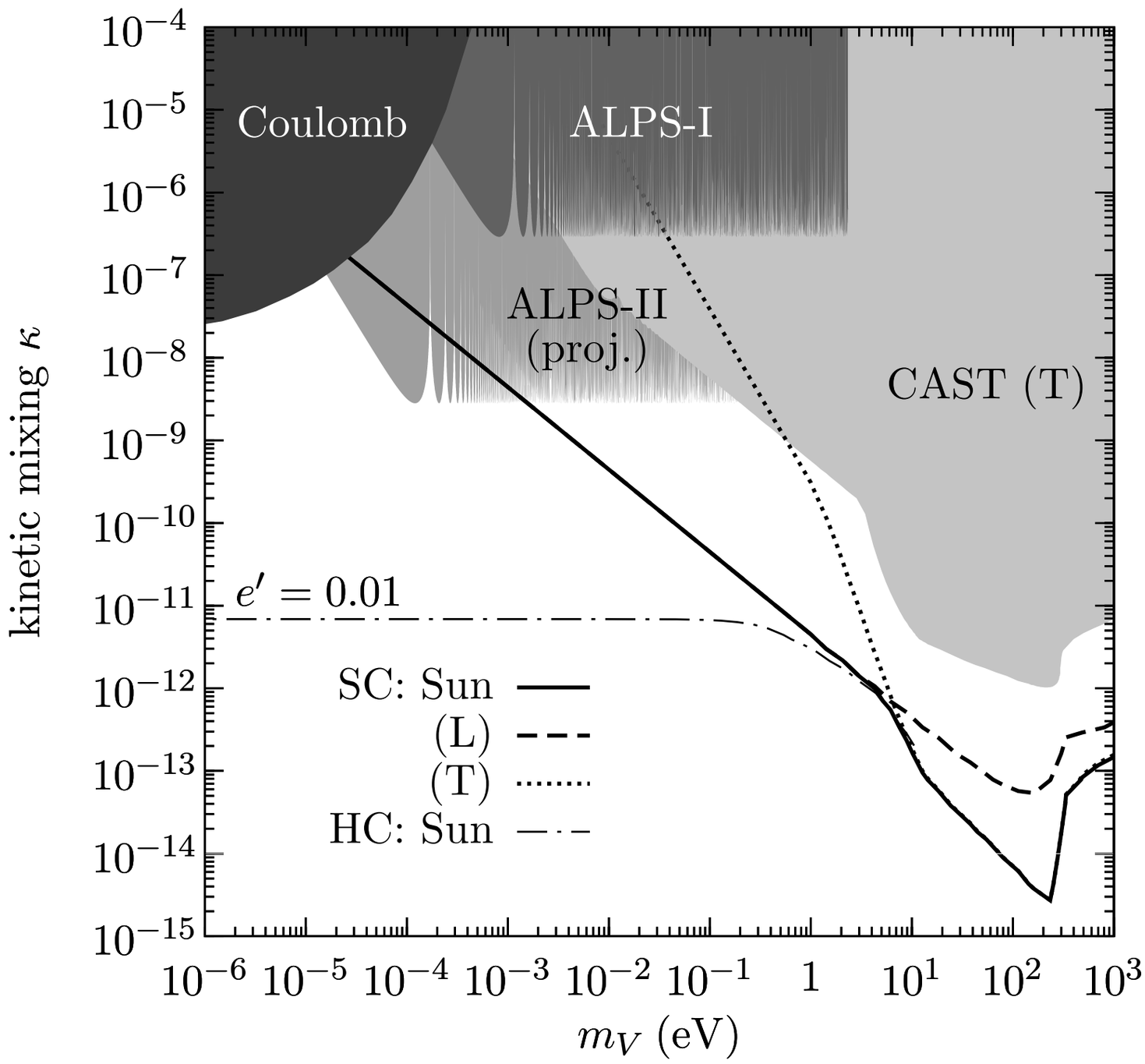
inside the sun:

$1\,\mathrm{eV} \lesssim \omega_p \lesssim 300\,\mathrm{eV}$

=> resonance can always be met for

$m_V \lesssim 1\,\mathrm{eV}$

Solar energy loss

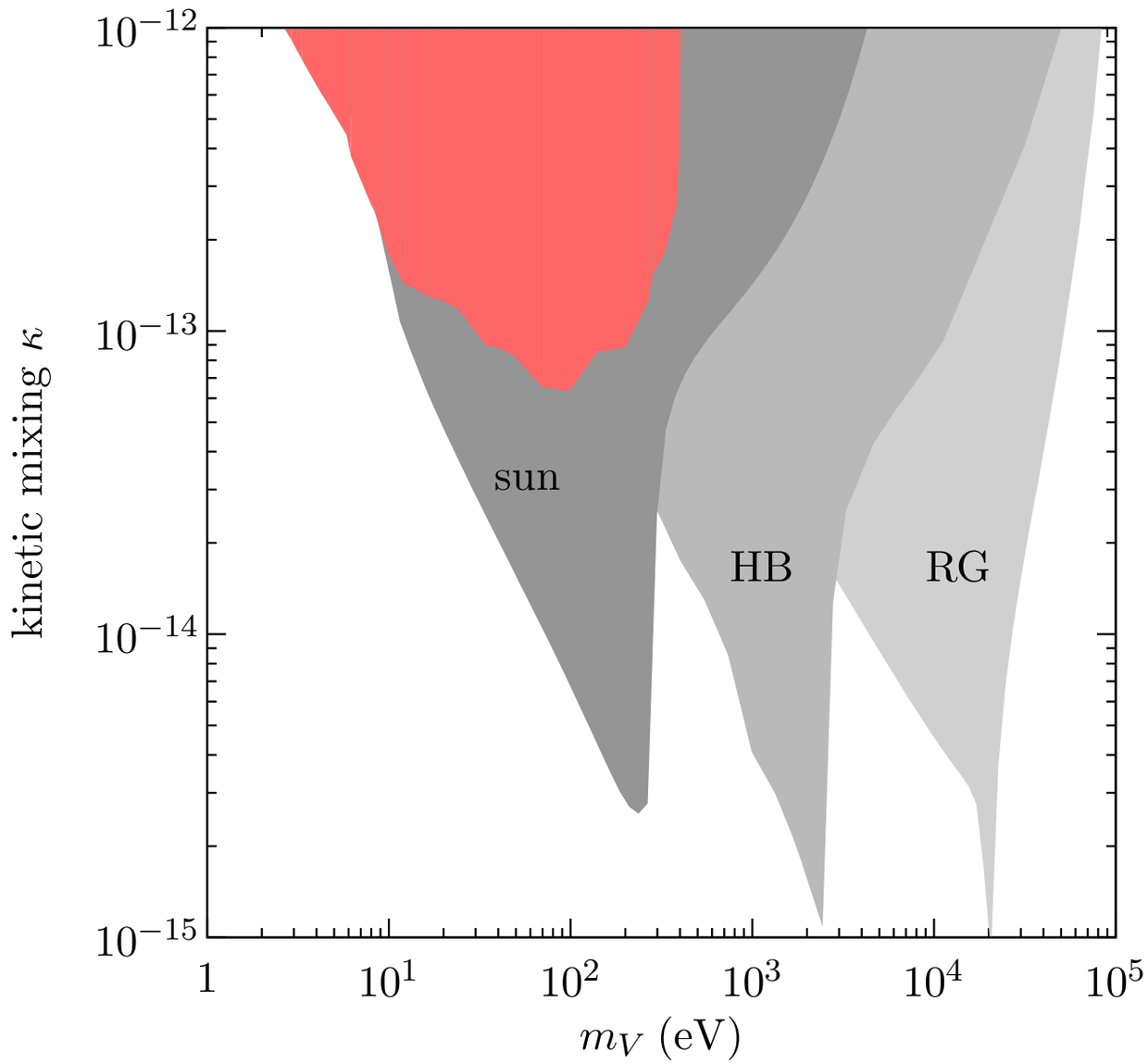


$L_{\rm dark} \leqslant 0.1 L_\odot$

$L_\odot = 4 \times 10^{26}$ Watt

energy loss heats up the sun => greater neutrino flux constrained by SNO

Solar energy loss



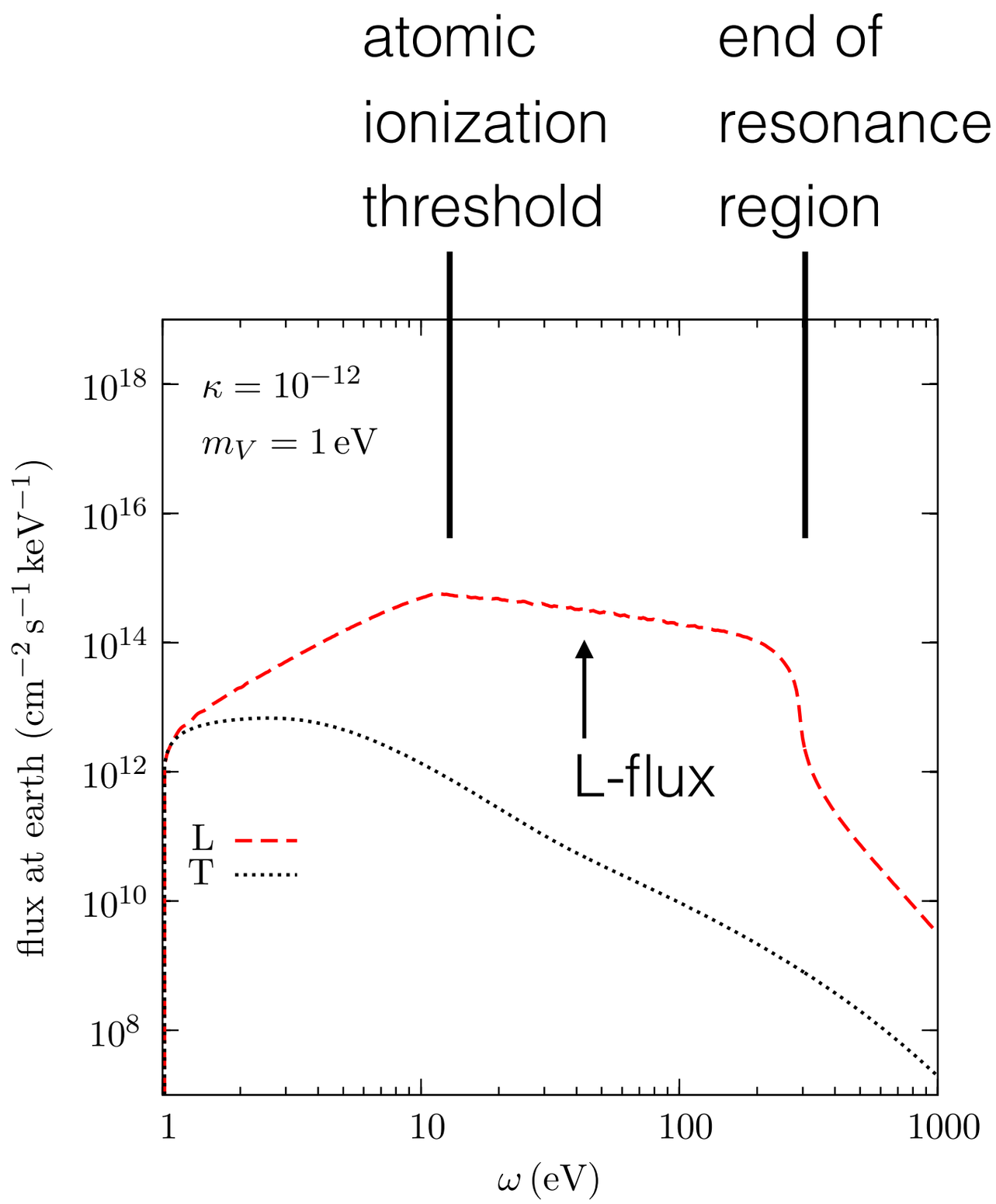
Position of stellar limits understood from:

Sun	$\omega_P(r=0) \simeq 300\,\mathrm{eV}$,
HB	$\omega_P(r=0) \sim 2.6\,\mathrm{keV}$,
RG	$\omega_P(r=0) \sim 200\,\mathrm{keV}$.

see also Redondo, Raffelt 2013

$$\frac{d\Gamma^{\mathrm{prod}}}{d\omega} \simeq \left(\frac{2r^2}{e^{\omega/T(r)}-1} \frac{\sqrt{\omega^2 - m_V^2}}{|\partial\omega_P^2(r)/\partial r|} \right)_{r=r_{\mathrm{res}}} \times \begin{cases} \kappa^2 m_V^2 \omega^2 & \text{longitudinal,} \\ \kappa^2 m_V^4 & \text{transverse,} \end{cases}$$

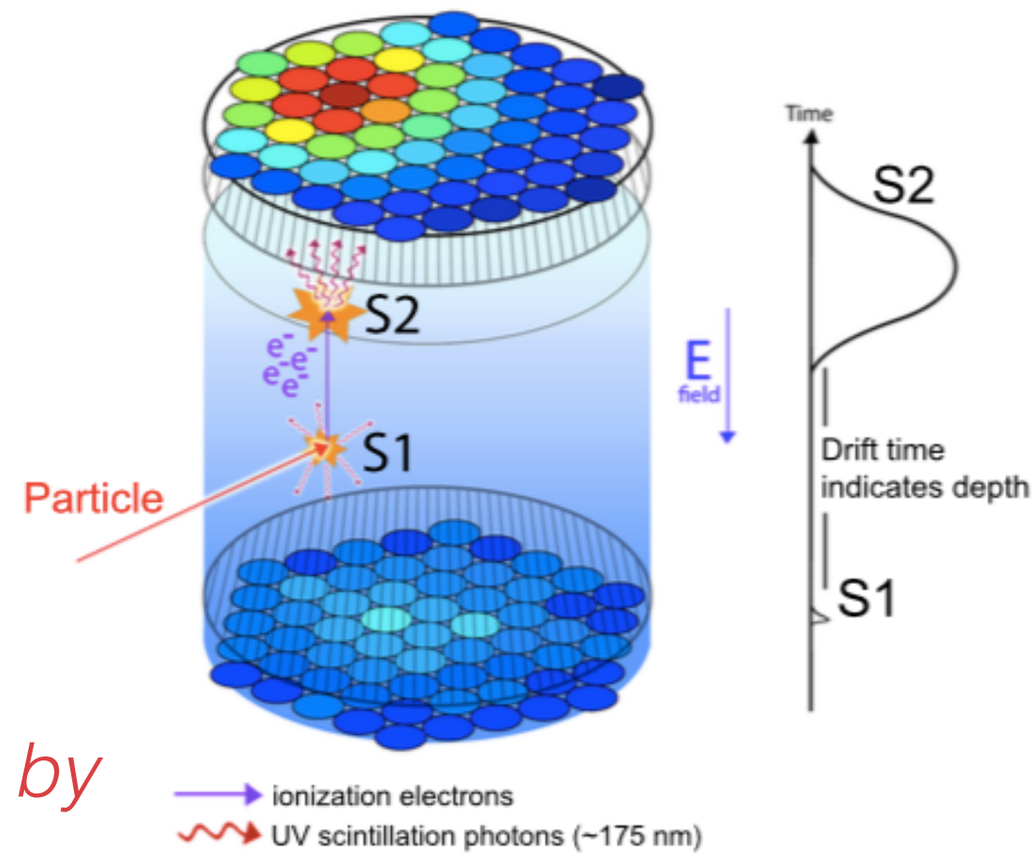
Solar Dark Photon flux



best sensitivity to stellar flux in the sub-keV energy regime

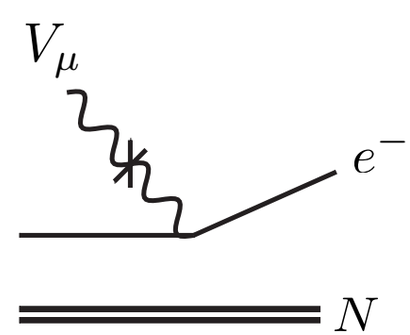
Dark Photon absorption in Dark Matter experiments

Direct detection experiments search for *Dark Matter - nucleus elastic scattering* via scintillation, ionization, heat, …



=> Liquid scintillators are amply suited for detecting *absorption of a new particle by electron*

$$E_{\rm ion}({\rm Xe}) = 12\,{\rm eV}$$



Dark Photon Absorption

(including medium effects)

Amplitude: $\mathcal{M}_{i\to f+V_{T,L}} = -\dfrac{e\kappa m_V^2}{m_V^2 - \Pi_{T,L}(q)}\langle p_f|J^\mu_{em}(0)|p_i\rangle\varepsilon^{T,L}_\mu(q)$

Rate: $\Gamma_{T,L} = \dfrac{e^2}{2\omega}\displaystyle\int d^4x\, e^{iq\cdot x}\kappa^2_{T,L}\varepsilon^*_\mu\varepsilon_\nu\langle p_i|[J^\mu_{em}(x), J^\nu_{em}(0)]|p_i\rangle$

Effective mixing angle inside the medium

$$\kappa^2_{T,L} = \kappa^2 \times \frac{m_V^4}{|m_V^2 - \Pi_{T,L}|^2}$$

Related to the polarization tensor $\Pi_{\mu\nu}$ of the photon in the medium

20

Dark Photon Absorption

(including medium effects)

Amplitude: $\mathcal{M}_{i\to f+V_{T,L}} = -\frac{e\kappa m_V^2}{m_V^2 - \Pi_{T,L}(q)}\langle p_f|J^\mu_{em}(0)|p_i\rangle\varepsilon^{T,L}_\mu(q)$

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$$\Gamma_{T,L} = -\frac{\kappa^2_{T,L}\,\mathrm{Im}\,\Pi_{T,L}}{\omega}$$

Absorption rate given by the imaginary part of the polarization function (optical theorem)

An, Pospelov, JP, PRL 2013
An, Pospelov, JP, Ritz, PLB 2014

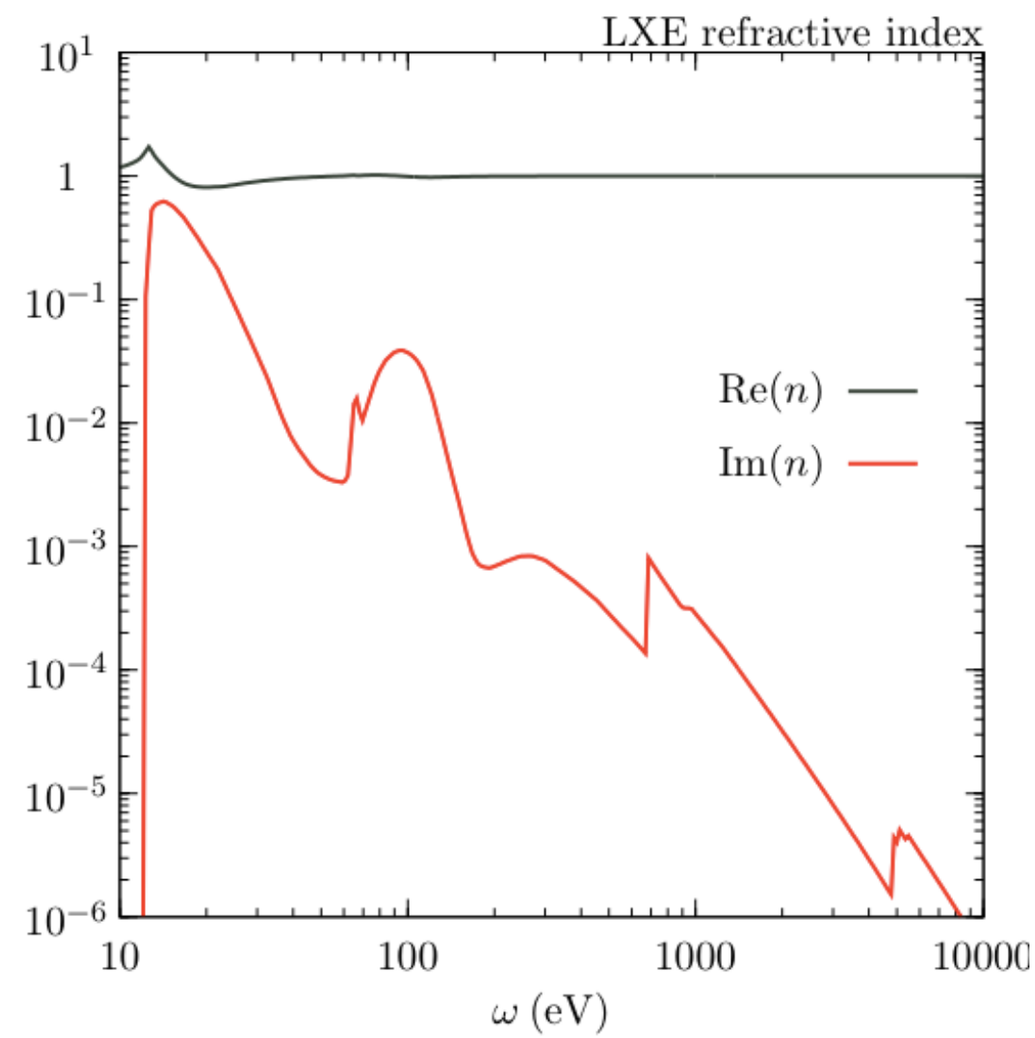
Absorption in Xenon

Compute absorption rate from Xenon *refractive index*

(via tabulated atomic X-ray data, using Kronig-Kramers relations)

$$\Pi_T = \omega^2(1 - n_{\text{refr}}^2)$$

$$\Pi_L = (\omega^2 - \vec{q}^2)(1 - n_{\text{refr}}^2)$$

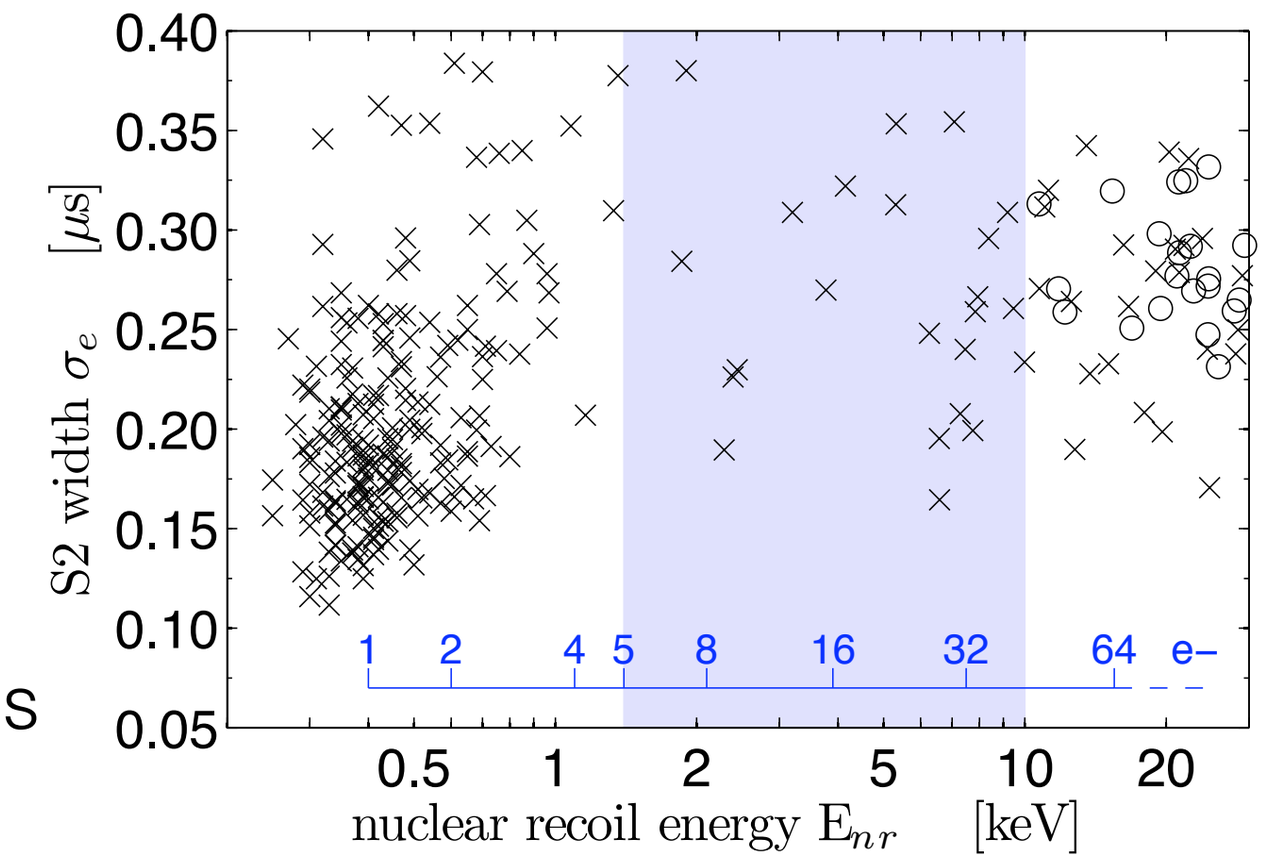


Absorption in Xenon

Ionization-only signal S2 can push sensitivity to lower masses

Despite uncertainties in electron yield, calibration, and background we can set a robust limit:

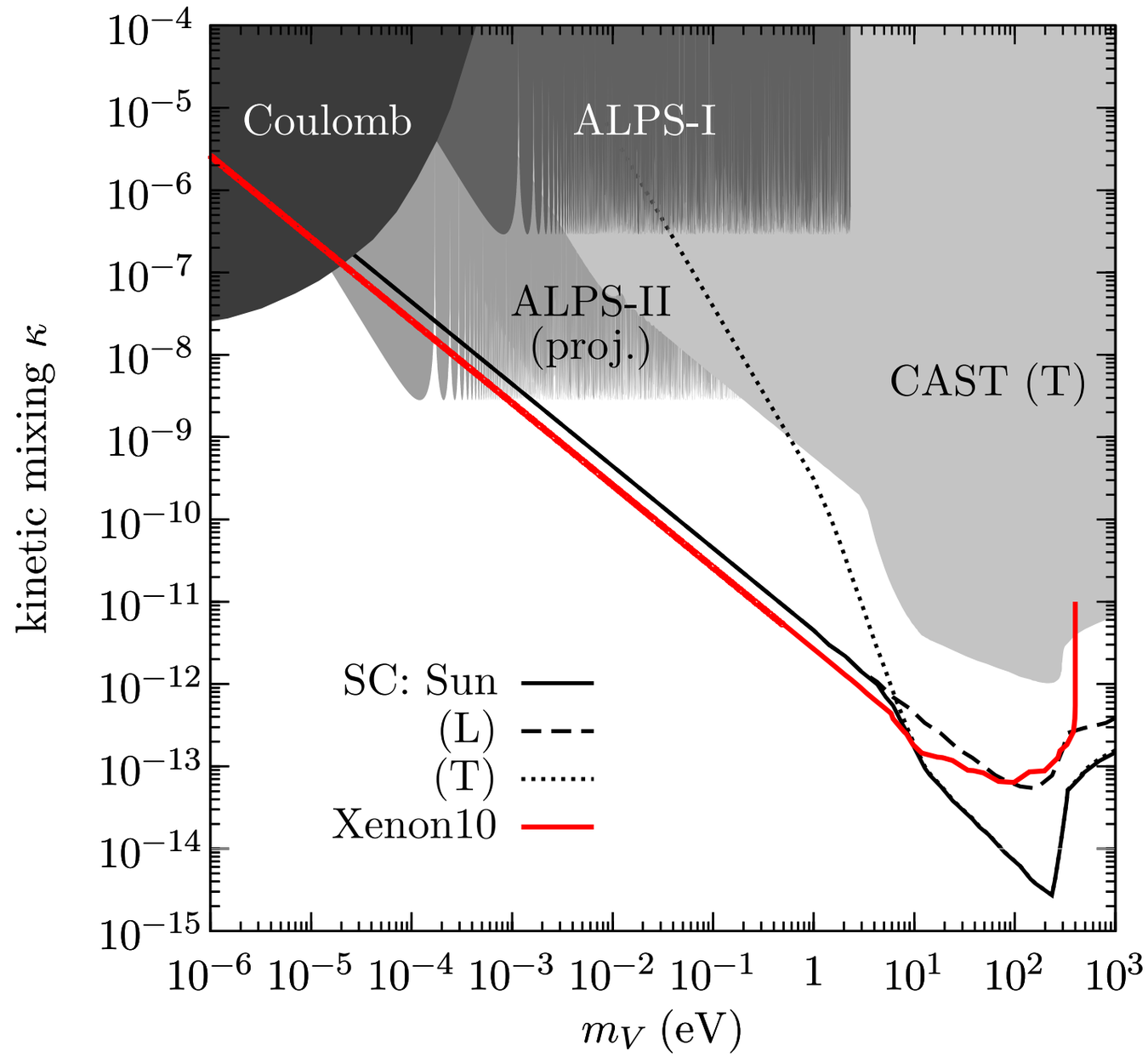
1. count *all* events
2. do not subtract backgrounds
3. infer limit *irrespective* of electron yield



XENON10 collaboration, 2011

Direct detection experiments as Dark Photon Helioscopes

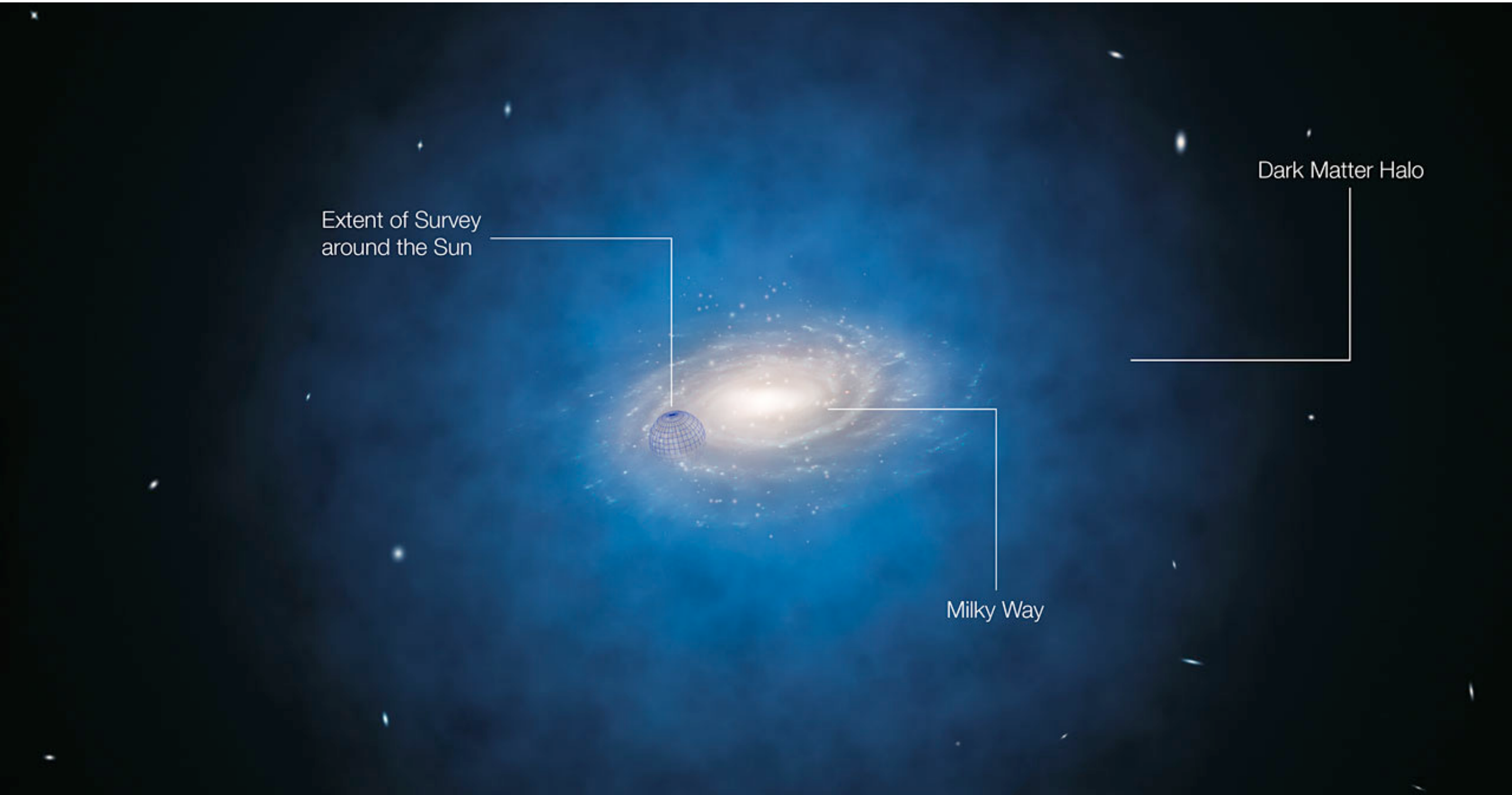
Re-utililizing existing Dark Matter data yields a laboratory test that is superior to astrophysical bounds



NB: the competition “astro vs. lab” is ongoing; see Redondo 2015

H. An, M. Pospelov, JP, PRL 2013

keV-Dark Photon **Dark Matter**



Abundance

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^2 - \frac{1}{4}V_{\mu\nu}^2 - \frac{\kappa}{2}F_{\mu\nu}V^{\mu\nu} + \frac{m_V^2}{2}V_\mu V^\mu + eJ_{\rm em}^\mu A_\mu$$

1. thermal production ✗
2. resonant production ✗
3. non-thermal production: field can be generated during inflation

Quantum fluctuations during inflation
yield abundance "for free"

$$\Omega_V \sim 0.3\sqrt{\frac{m_V}{1\,\mathrm{keV}}}\left(\frac{H_{\rm inf}}{10^{12}\,\mathrm{GeV}}\right)$$

Graham, Mardon, Rajendran 2014

Stability and lifetime

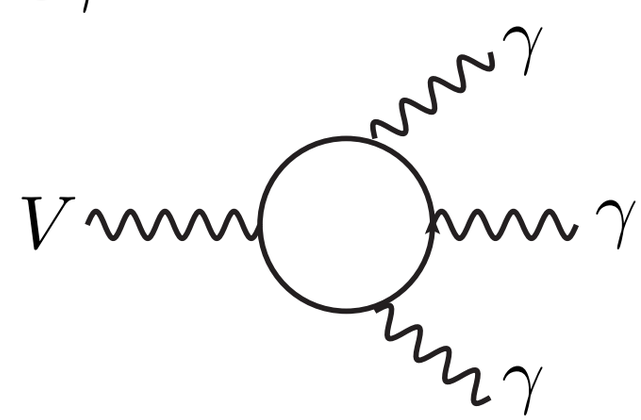
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^2 - \frac{1}{4}V_{\mu\nu}^2 - \frac{\kappa}{2}F_{\mu\nu}V^{\mu\nu} + \frac{m_V^2}{2}V_\mu V^\mu + eJ_{\rm em}^\mu A_\mu$$

1. Make it light, below $2m_e$. Prevents $V \to e^+e^-$ decay

2. Have small $\kappa \ll 1$, to slow down $V \to 3\gamma$

$$\Gamma_{V\to 3\gamma} = \frac{17\kappa^2\alpha^4}{2^7 3^6 5^3 \pi^3}\frac{m_V^9}{m_e^8}$$

Pospelov, Ritz, Voloshin 2008



=> Vectors can be have lifetime greater than the Universe

Dark Matter Absorption

Photon vs. Dark Photon Dark Matter absorption of energy $\omega = m_V$

Photon

$|\vec{q}| = \omega$

Dark Photon

$|\vec{q}| = m_V v_{\rm DM} \sim O(10^{-3})\omega$

=> little difference for us: $\lambda_{\gamma,V} \gtrsim r_e$ allows to expand Hamiltonian

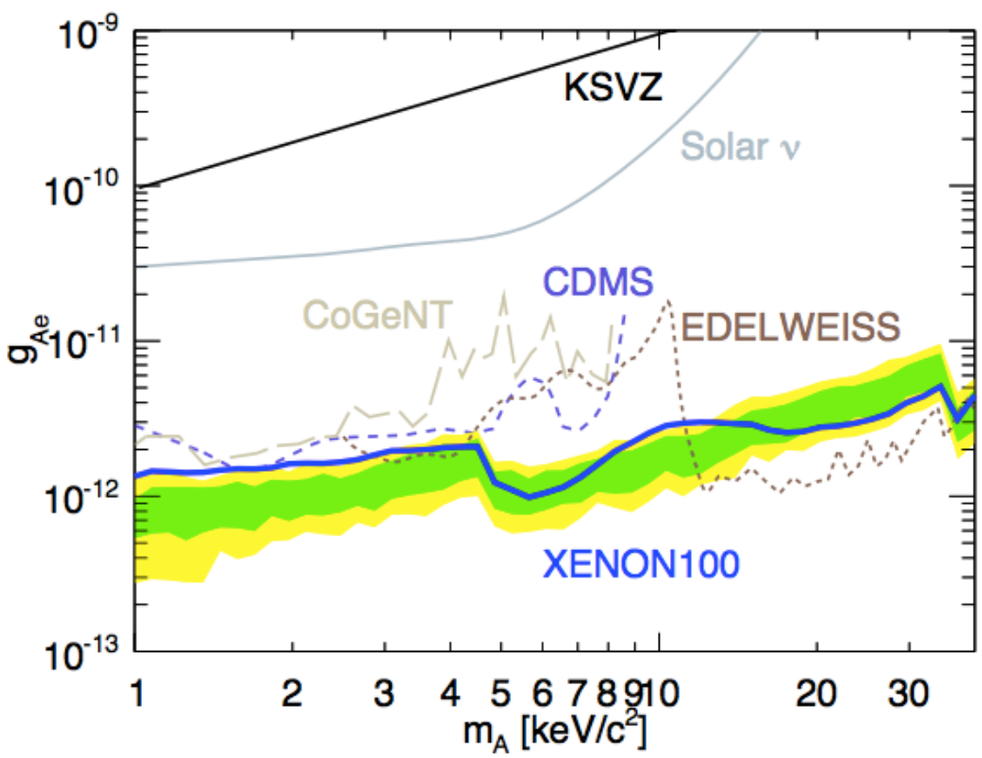
$$(\vec{p}_e \vec{\epsilon}) \exp(i\vec{q}\vec{r}_e) \simeq (\vec{p}_e \vec{\epsilon}) \times (1 + i\vec{q}\vec{r}_e + ...)$$

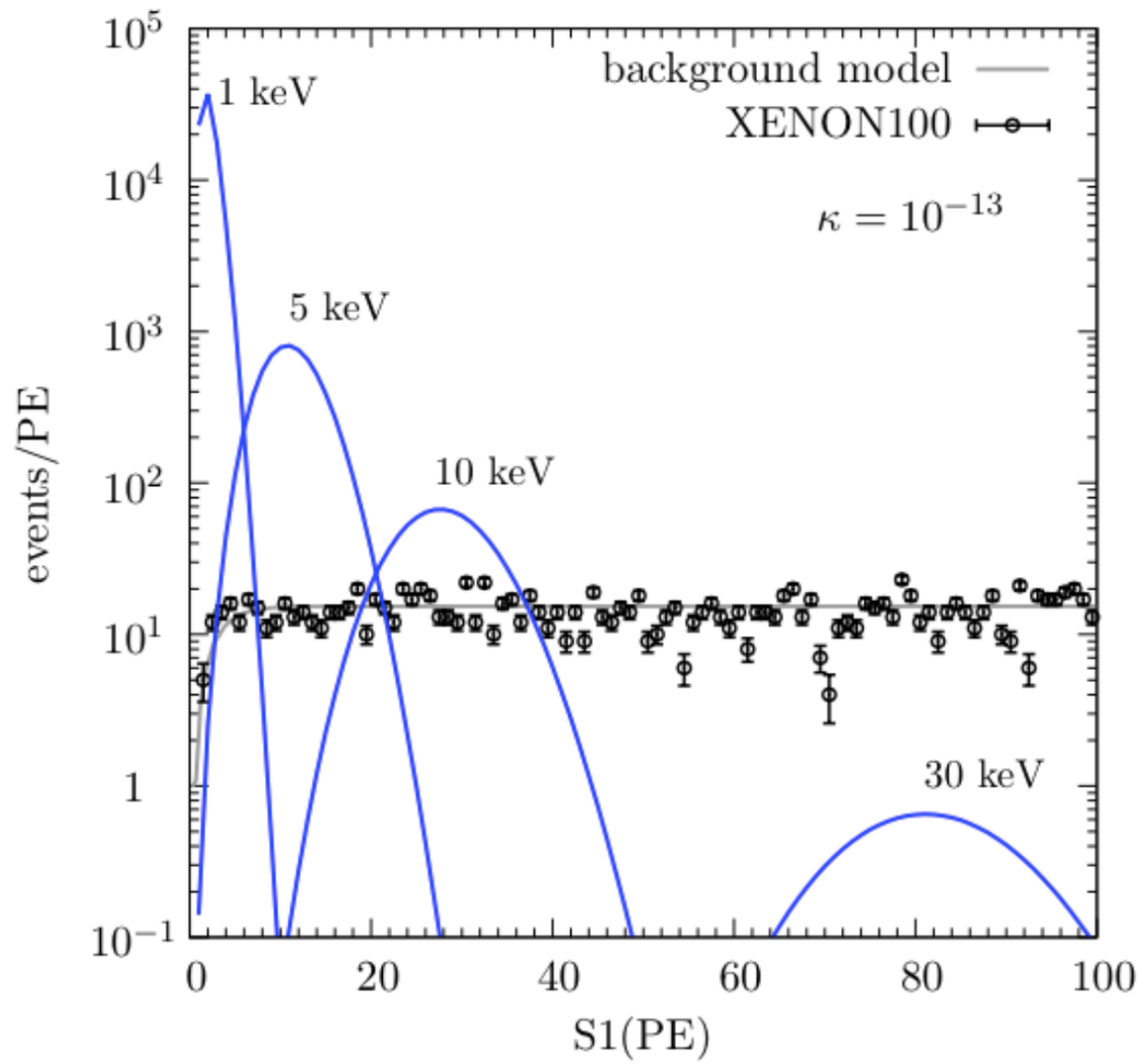
Using “normal” photon cross sections will be accurate to $O(\omega^2 r_{\rm shell}^2) \sim O(\alpha^2) - O((Z\alpha)^2)$

Absorption in Xenon

=> re-utilize XENON100 results on axion absorption

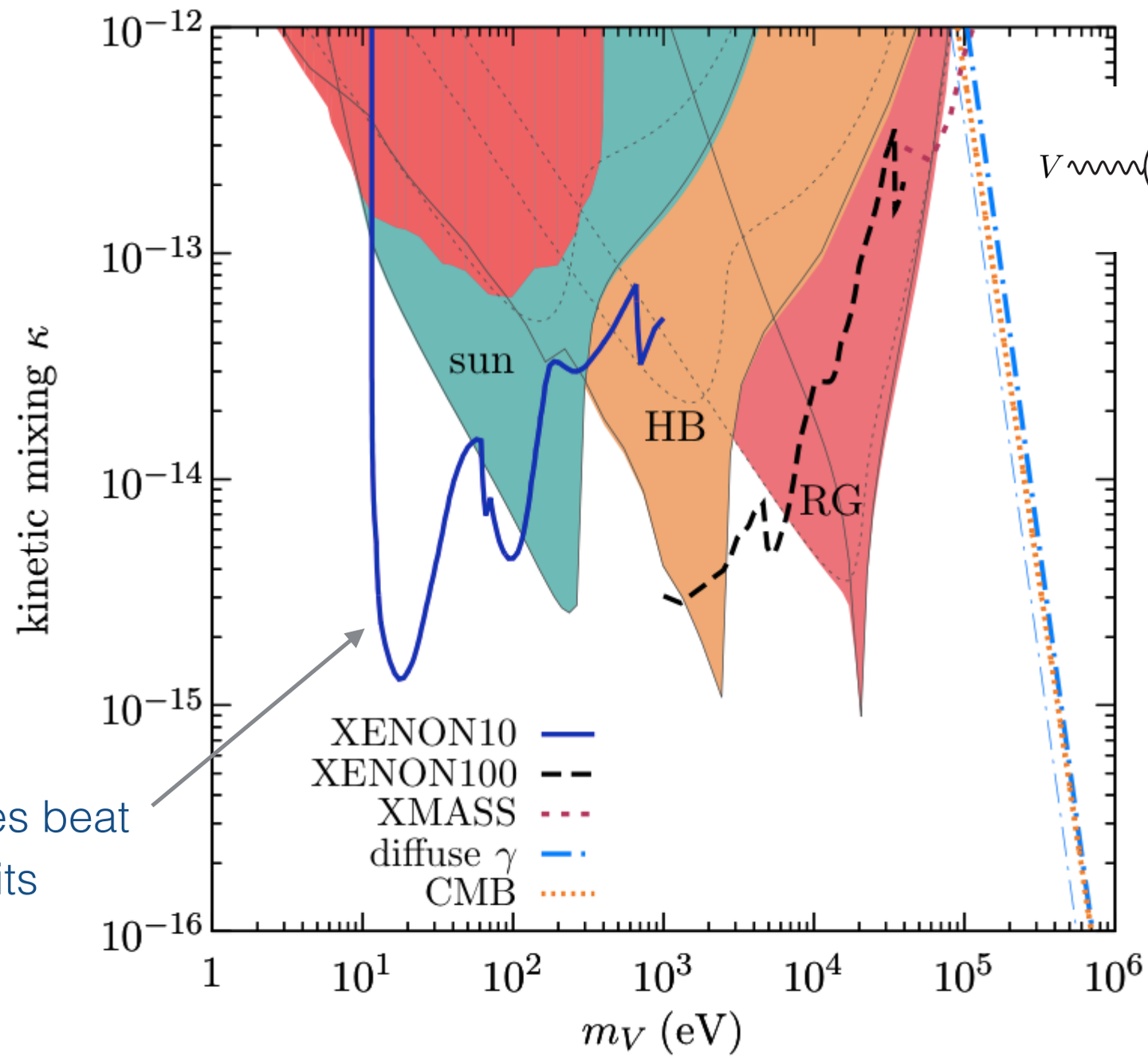
XENON100 collaboration, 2014

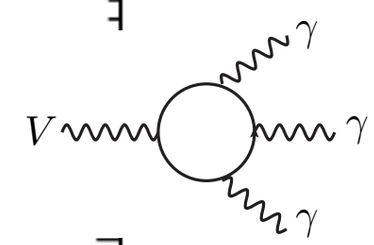




predicted Dark Photon scintillation signal (S1)

Dark Photon **Dark Matter**





limits from gamma rays and CMB

Laboratory probes beat astrophysical limits

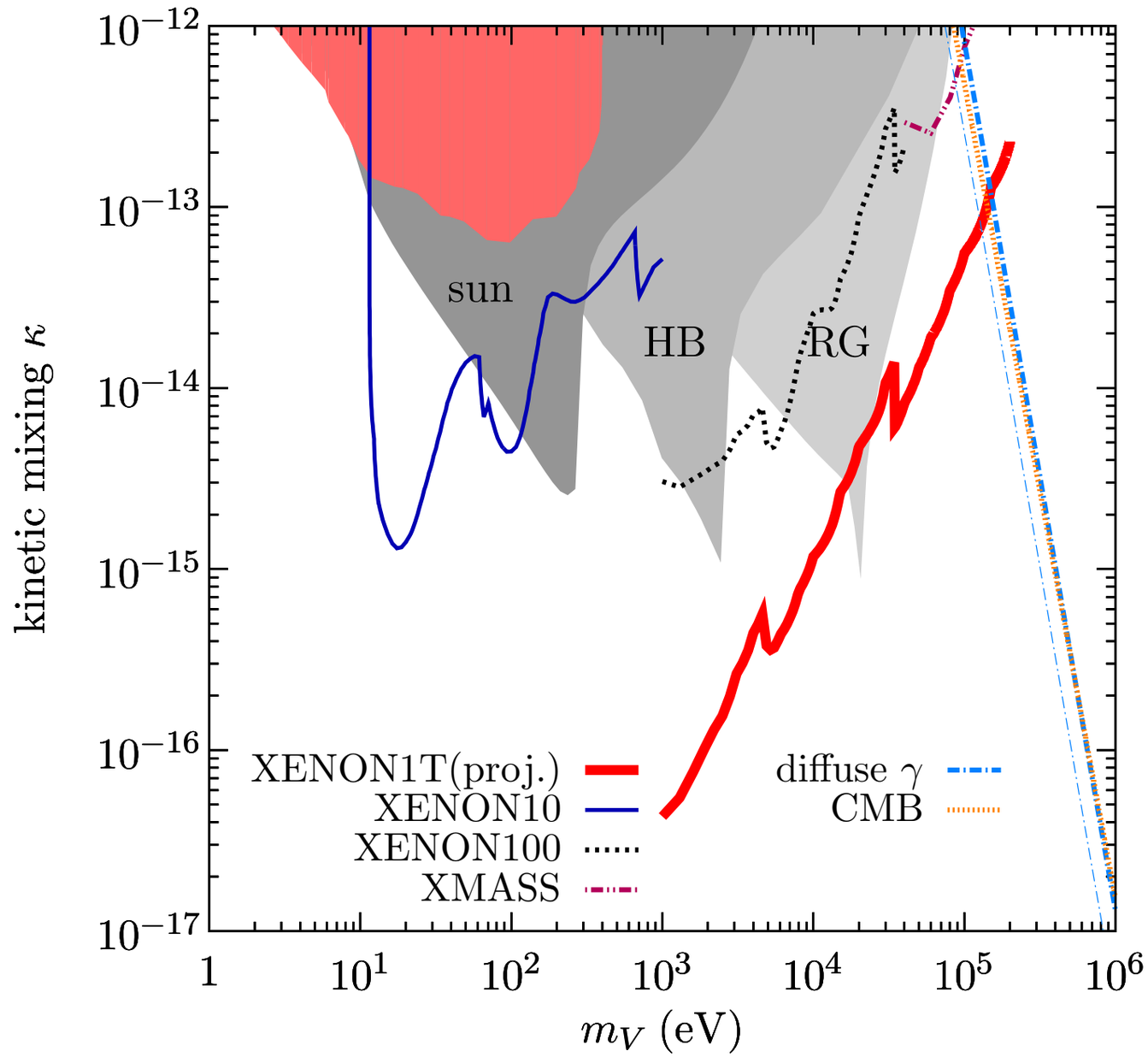
An, Pospelov, JP, Ritz, PLB 2015

Dark Photon **Dark Matter**

Future sensitivity

Projected improvement by XENON1T with scintillation

(EM background is almost 2 orders of magn. lower)



An, Pospelov, Pradler, Ritz + Ni (XENON) 2015

“Simplified Models” of Dark Matter absorption

(in contrast to WIMP-nucleon scattering)

(pseudo)scalar	$g_S S\bar{\psi}\psi, \quad g_P P\bar{\psi}\gamma_5\psi,$
(pseudo)vector	$g_V V_\mu\bar{\psi}\gamma_\mu\psi, \checkmark \; g_A \mathcal{A}_\mu\bar{\psi}\gamma_\mu\gamma_5\psi,$
tensor	$g_T T_{\mu\nu}\bar{\psi}\sigma_{\mu\nu}\psi, \quad \ldots$

ψ …electron

Discussed the example of vector V with coupling $g_V = e\kappa$

NB: these models do not lead to any appreciable amount of modulation $\sigma_{\rm abs} v \approx \rm const$

“Simplified Models” of Dark Matter absorption

(in contrast to WIMP-nucleon scattering)

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(pseudo)vector	$g_V V_\mu\bar{\psi}\gamma_\mu\psi, \quad g_A \mathcal{A}_\mu\bar{\psi}\gamma_\mu\gamma_5\psi,$
tensor	$g_T T_{\mu\nu}\bar{\psi}\sigma_{\mu\nu}\psi, \quad \cdots$

If the DM mass is not protected by some symmetry (like for dark photons or axions), loop corrections induce a mass shift

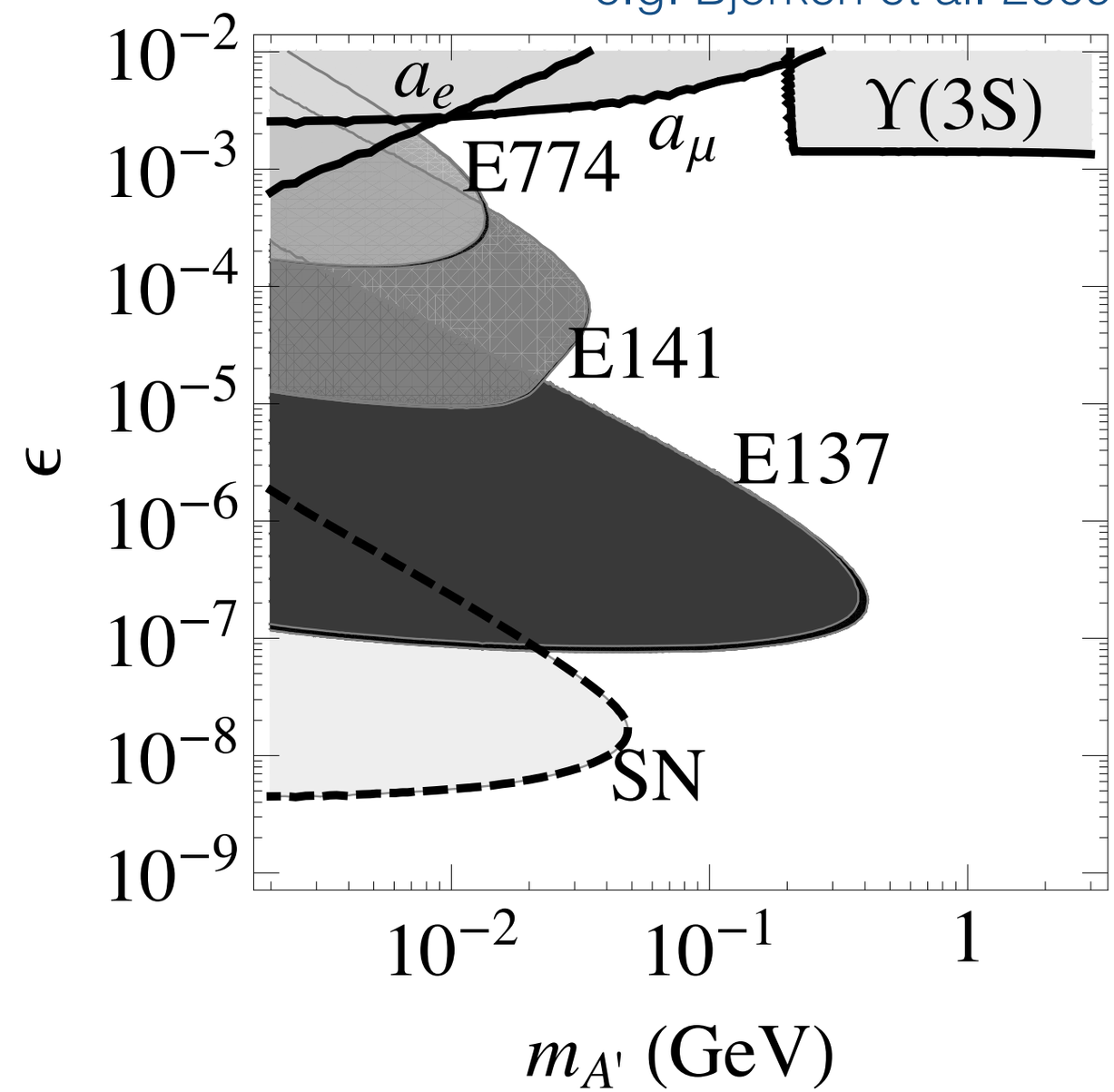
$$\Delta m \sim g_i \Lambda_{\rm UV} \qquad \Rightarrow \qquad g_i \lesssim 10^{-10} \quad \text{for} \quad m \sim 100\,\text{eV}$$

As we have just seen, such couplings in the “naturalness regime” are being probed by direct detection!

2 Cosmology

E.g. Dark Photons:

e.g. Bjorken et al. 2009



2 Cosmology

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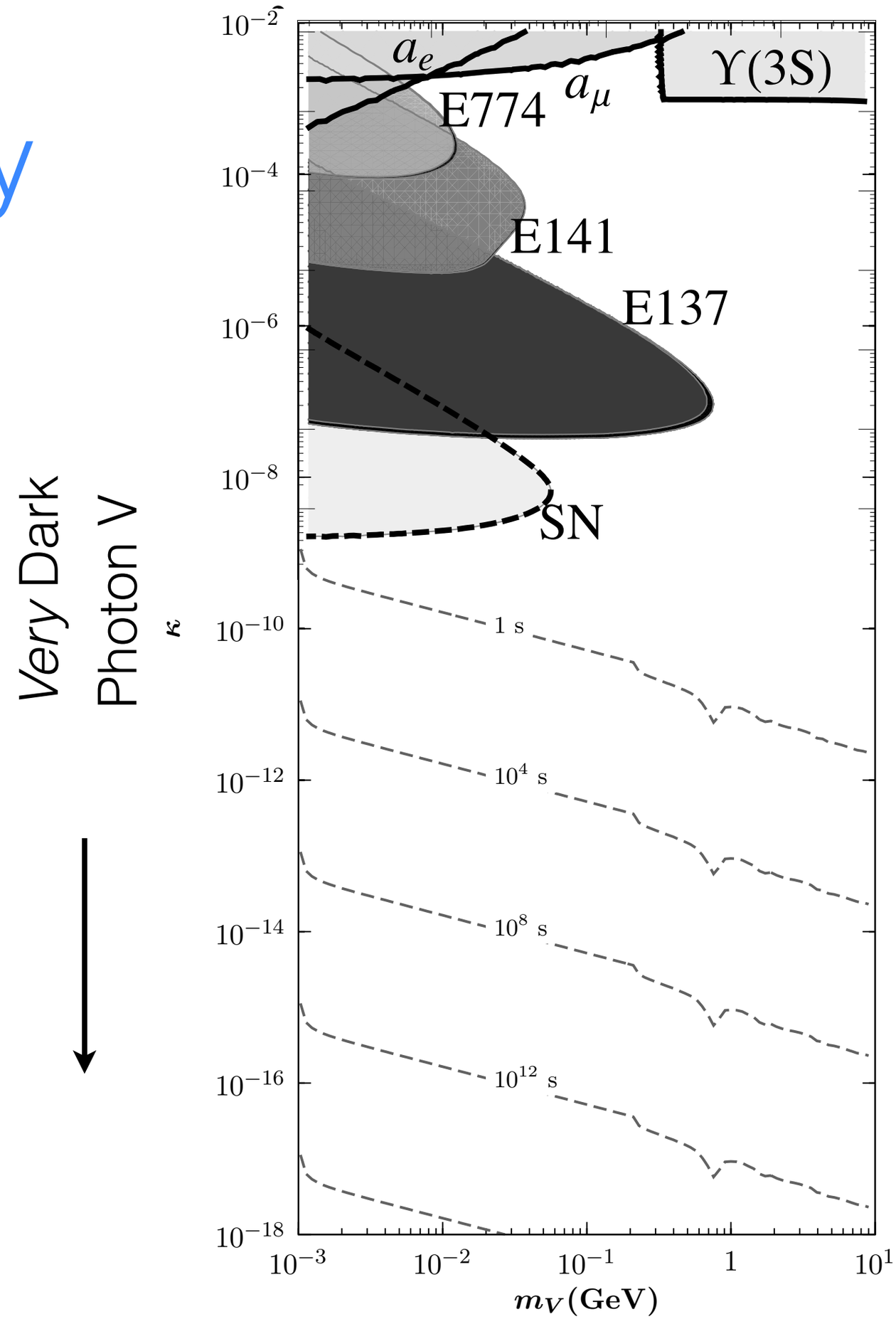


Very Dark Photon V

2 Cosmology

E.g. Dark Photons:

$$E_{p.b.} = \frac{m_V n_V}{n_b}$$

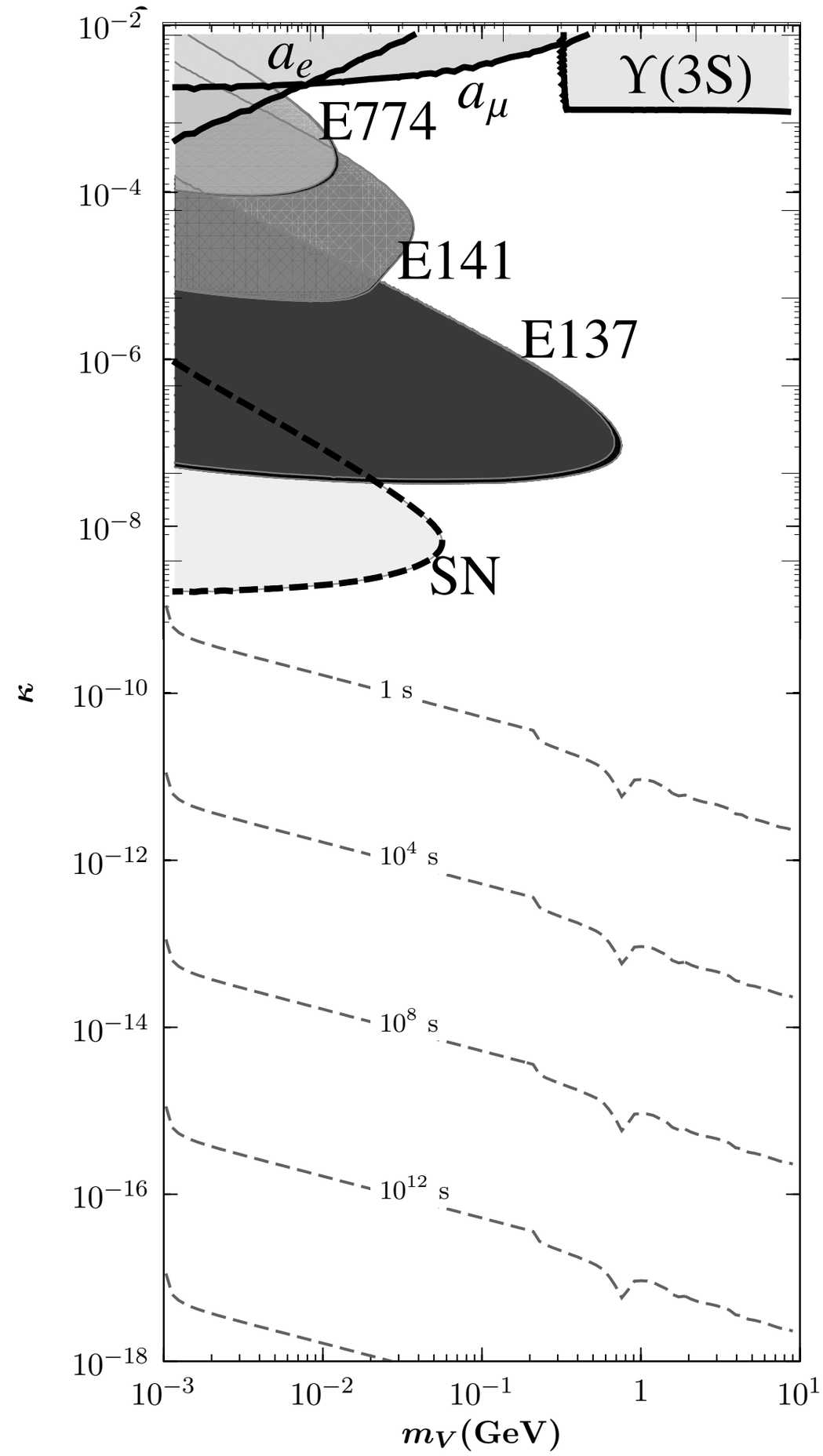
$$\sim \frac{m_V \Gamma_{\rm prod} H^{-1}_{T=m_V}}{n_{b,T=m_V}}$$

$$\sim \alpha_{\rm eff} \times 10^{36}\,{\rm eV}$$

$$\alpha_{\rm eff} = \kappa^2 \alpha$$

$$\Gamma_{\rm prod} \sim \tau_V^{-1} n_{\gamma,T=m_V}$$

Very Dark Photon V



BBN sensitivity: MeV/baryon

CMB sensitivity: eV/baryon

2 Cosmology

E.g. Dark Photons:

$$E_{p.b.} = \frac{m_V n_V}{n_b}$$

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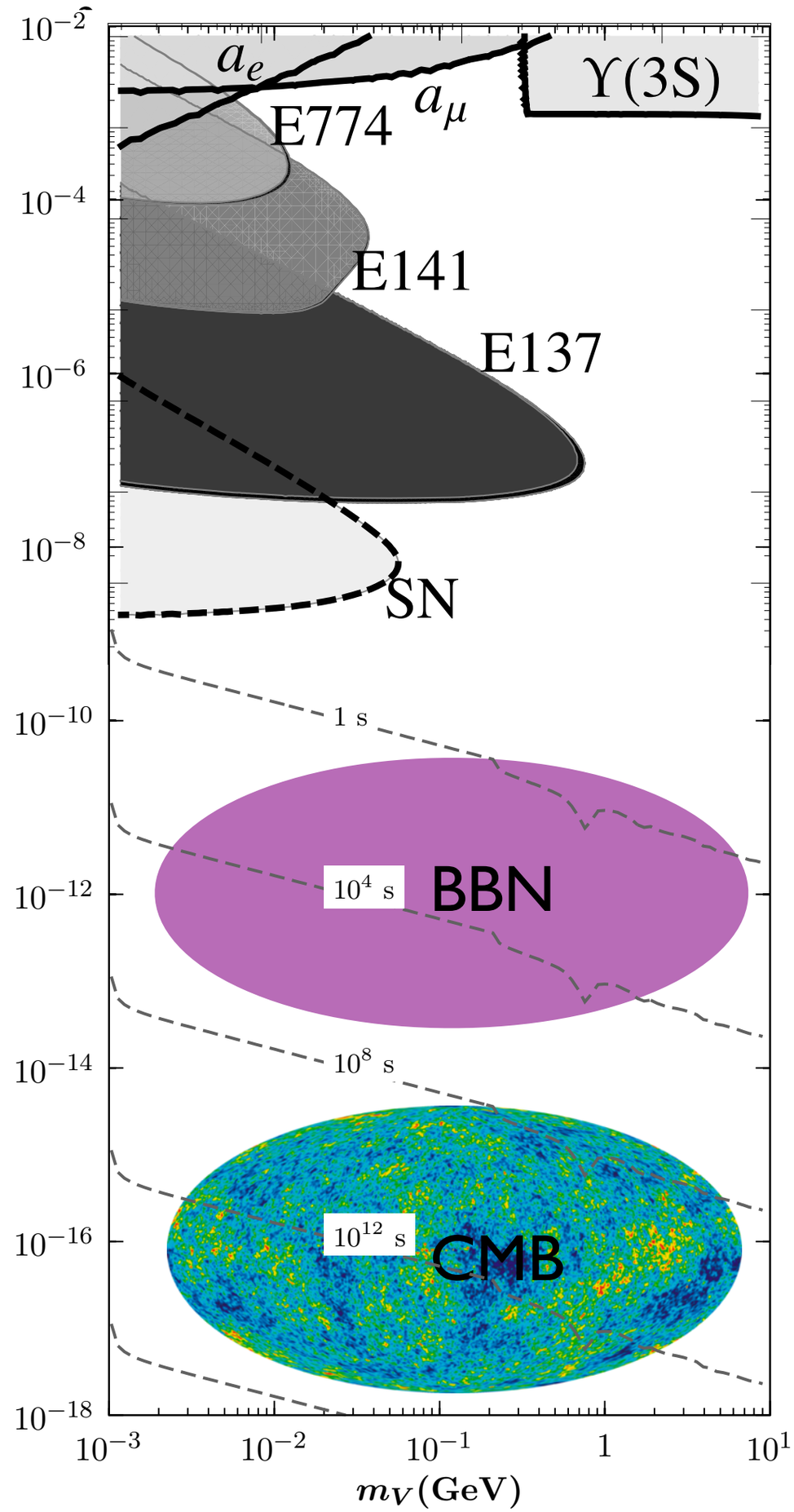
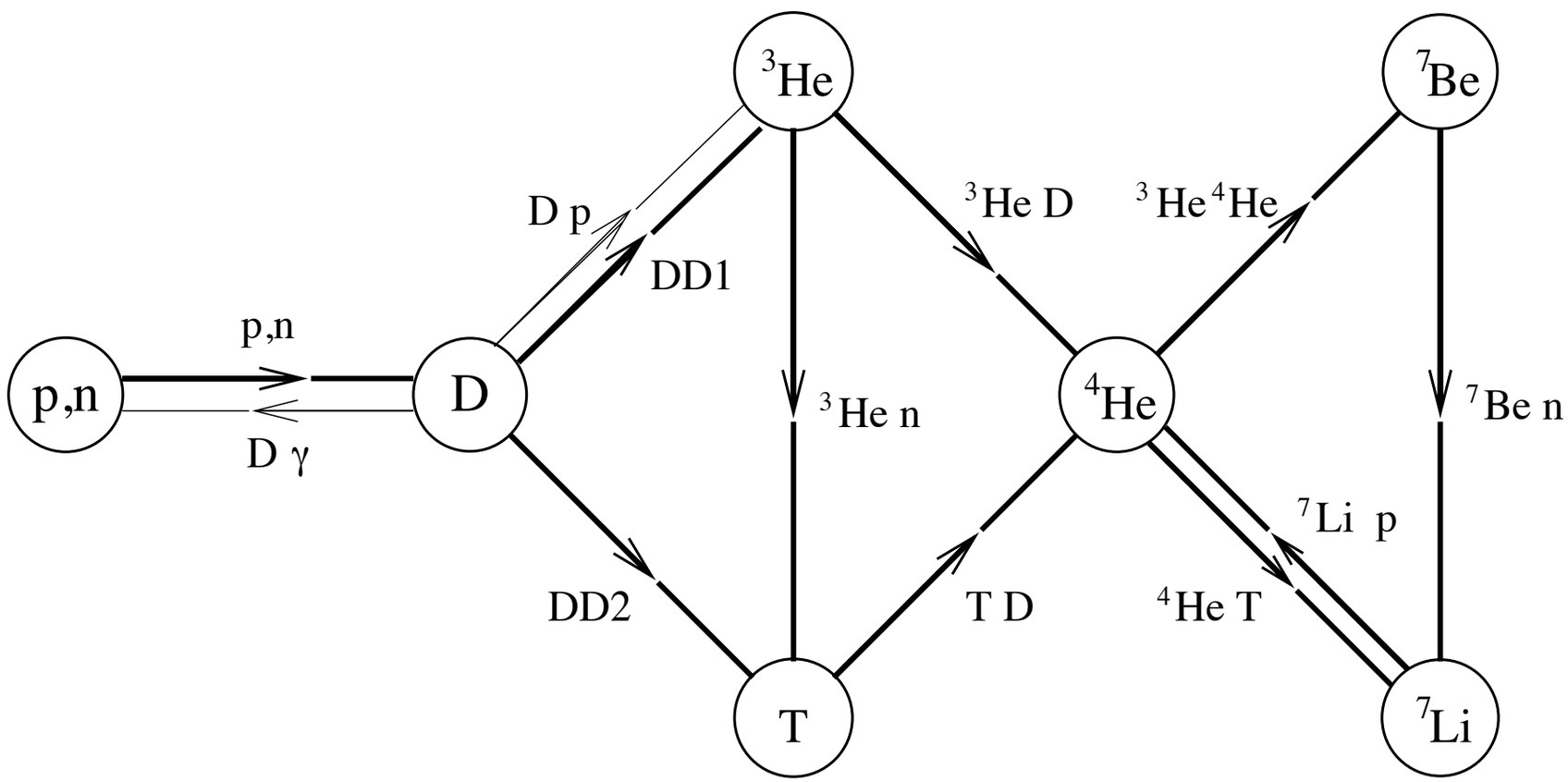


BBN sensitivity: MeV/baryon

CMB sensitivity: eV/baryon

BBN: the Universe at a redshift of a billion

Nuclear reaction network

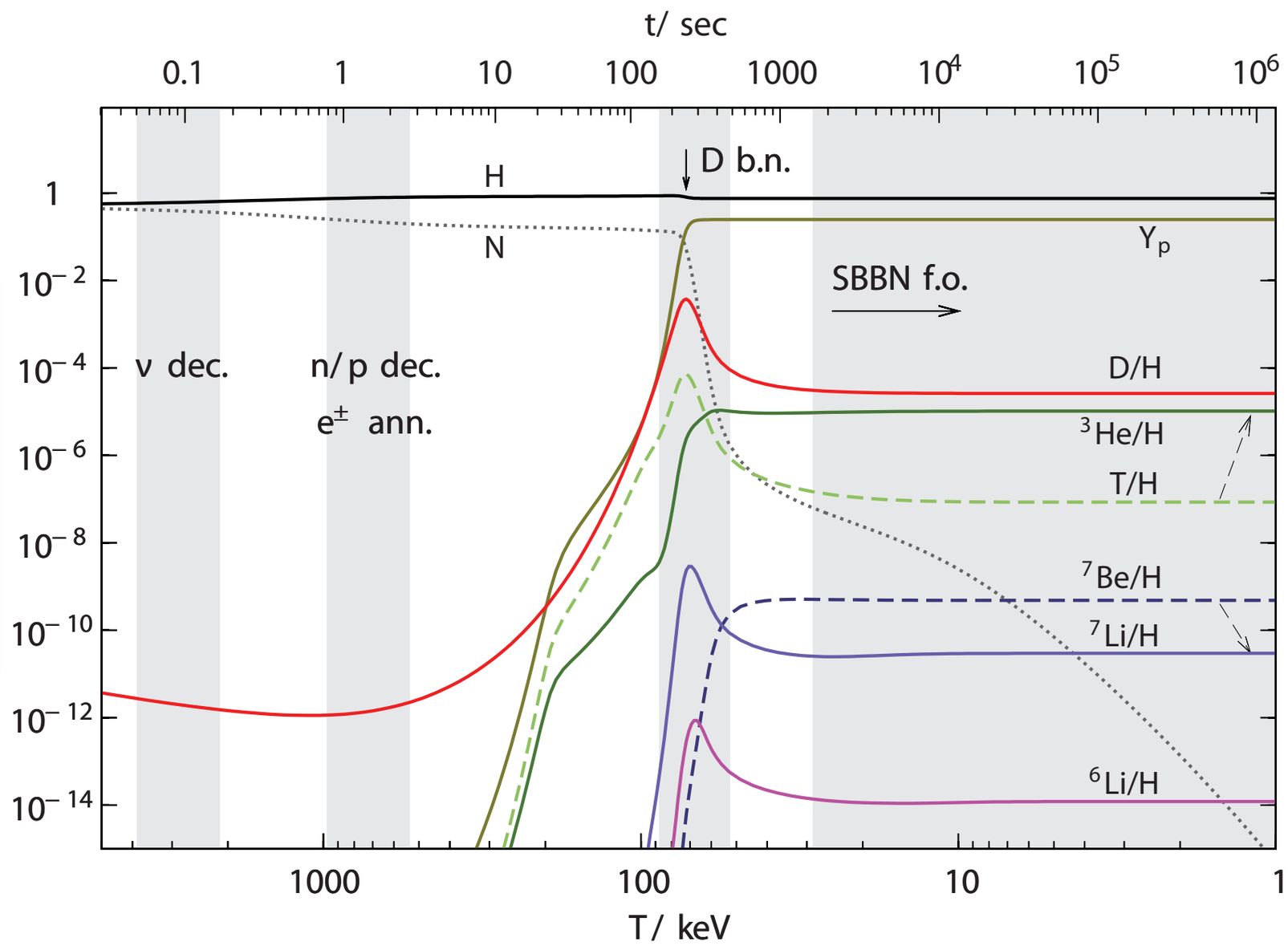


Today: parameter free theory (baryon density from CMB)!

The origin of chemistry: t = 100 sec

Big Bang Nucleosynthesis

p, n, photons, electrons, neutrinos



light elements have formed

HOT

time →

COLD

Light element observations

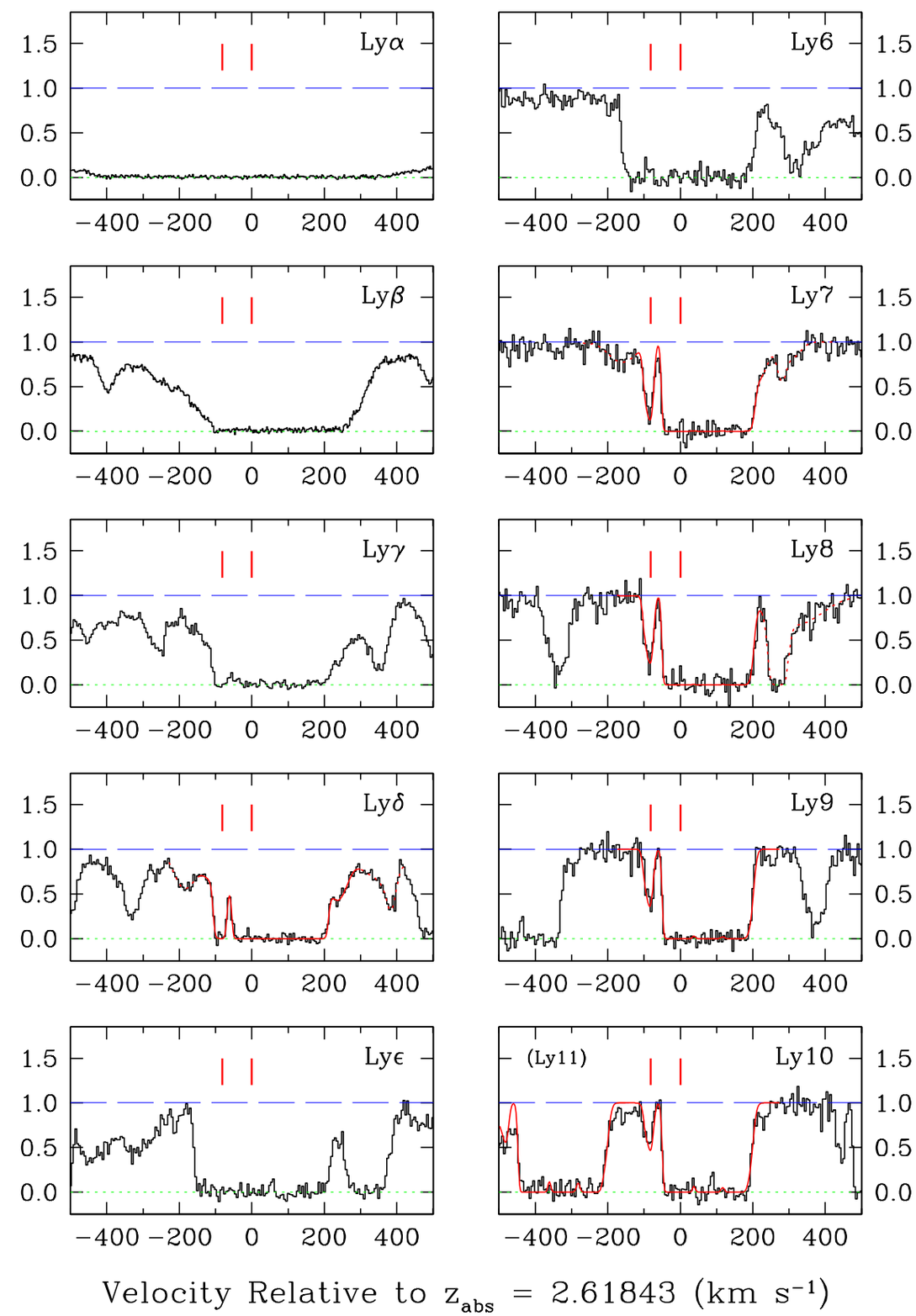
Deuterium $\mathrm{D/H} \simeq 10^{-5}$

- no known astrophysical sources (monotonic)

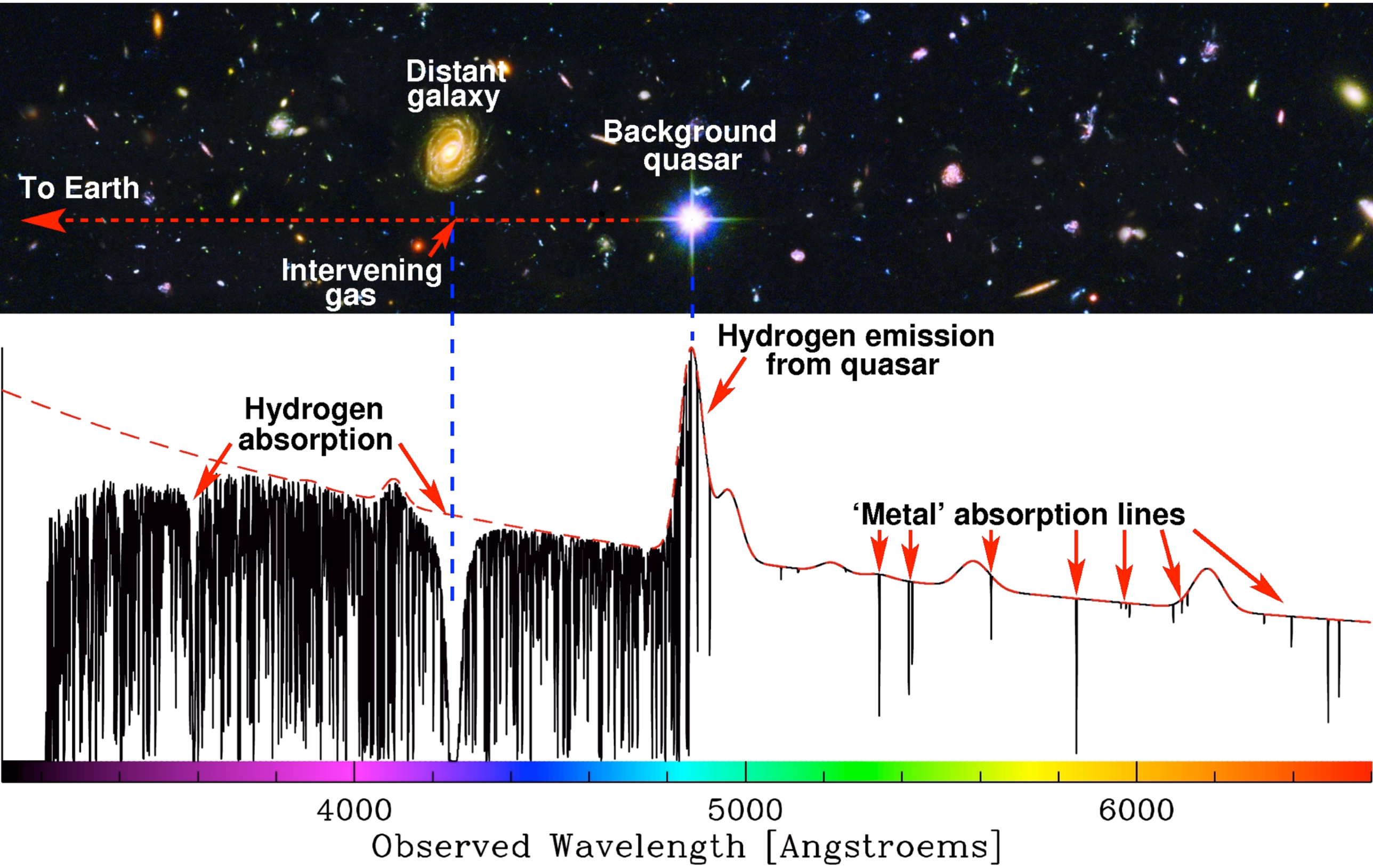
- ISM measurements (FUSE) show dispersion in the local gas D-absorption on dust grains?

- 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

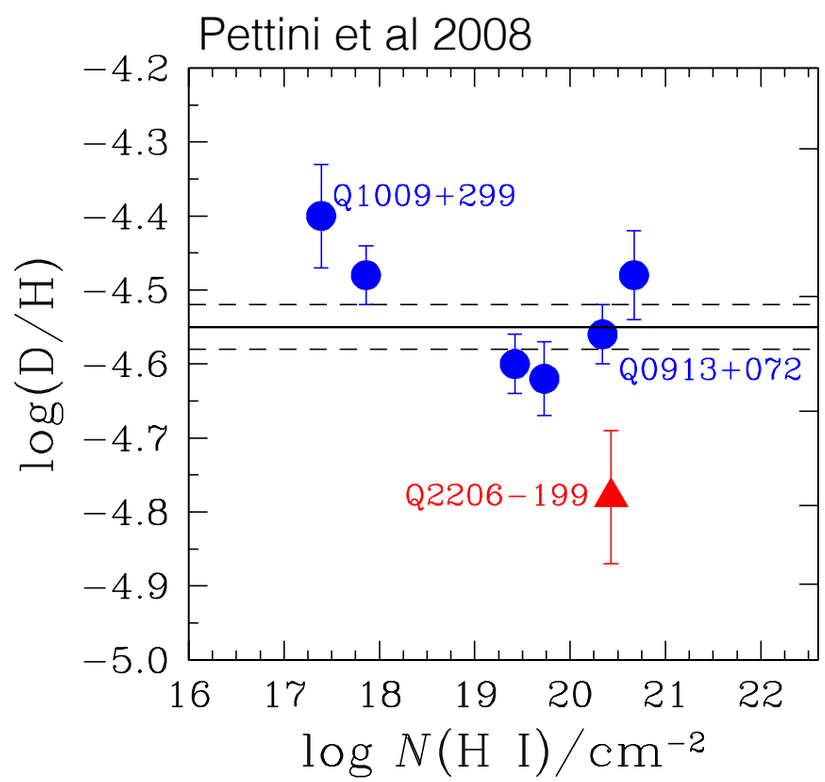


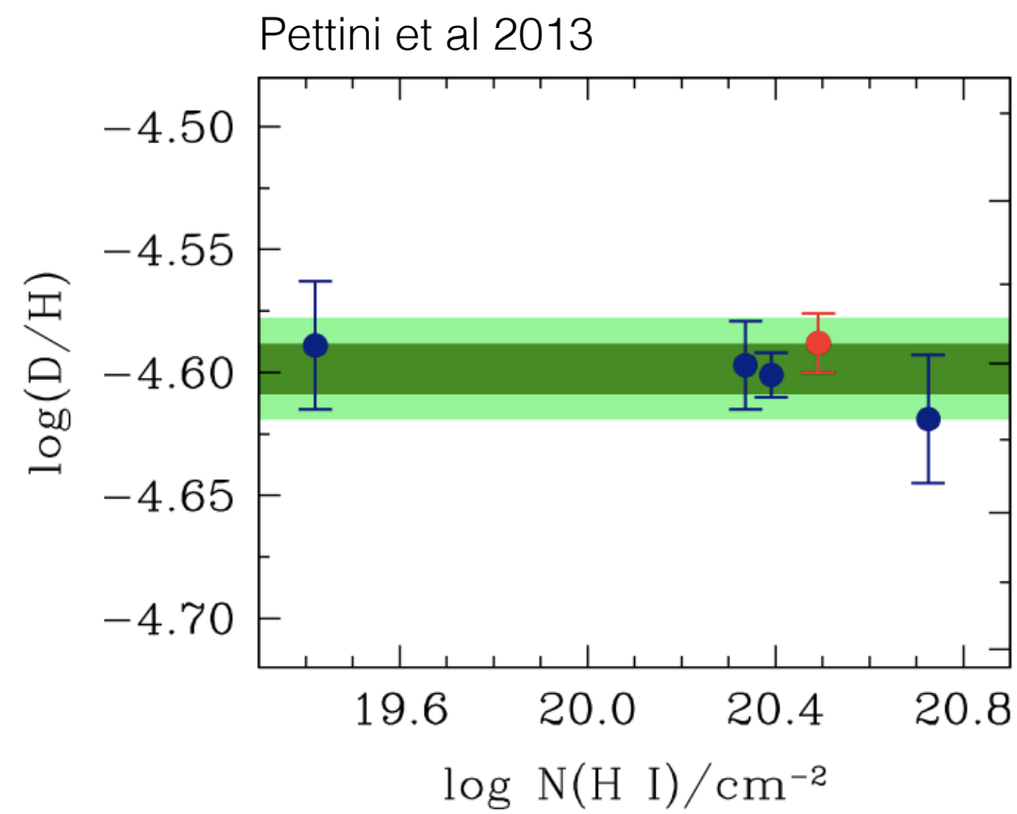
Light element observations Deuterium $\mathrm{D/H} \simeq 10^{-5}$



Light element observations

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





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

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

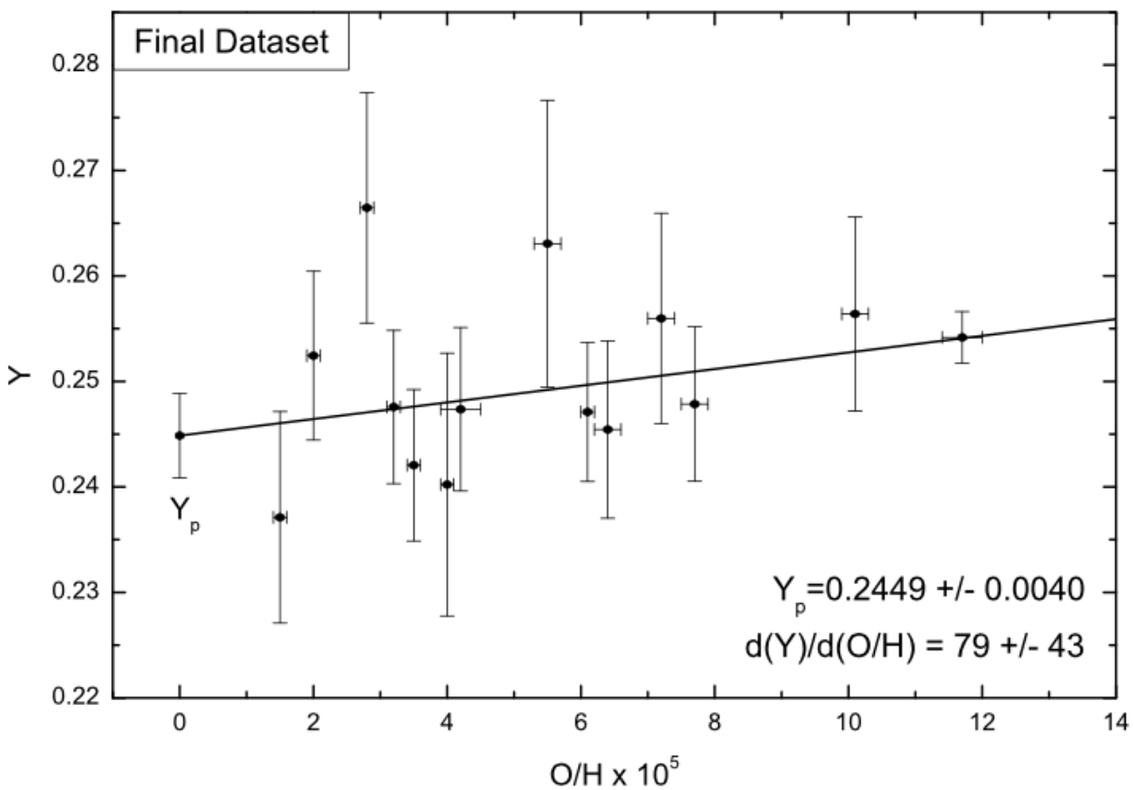
=> substantial improvement of the error bar
Now D/H at %-precision and in agreement with predictions!

Light element observations

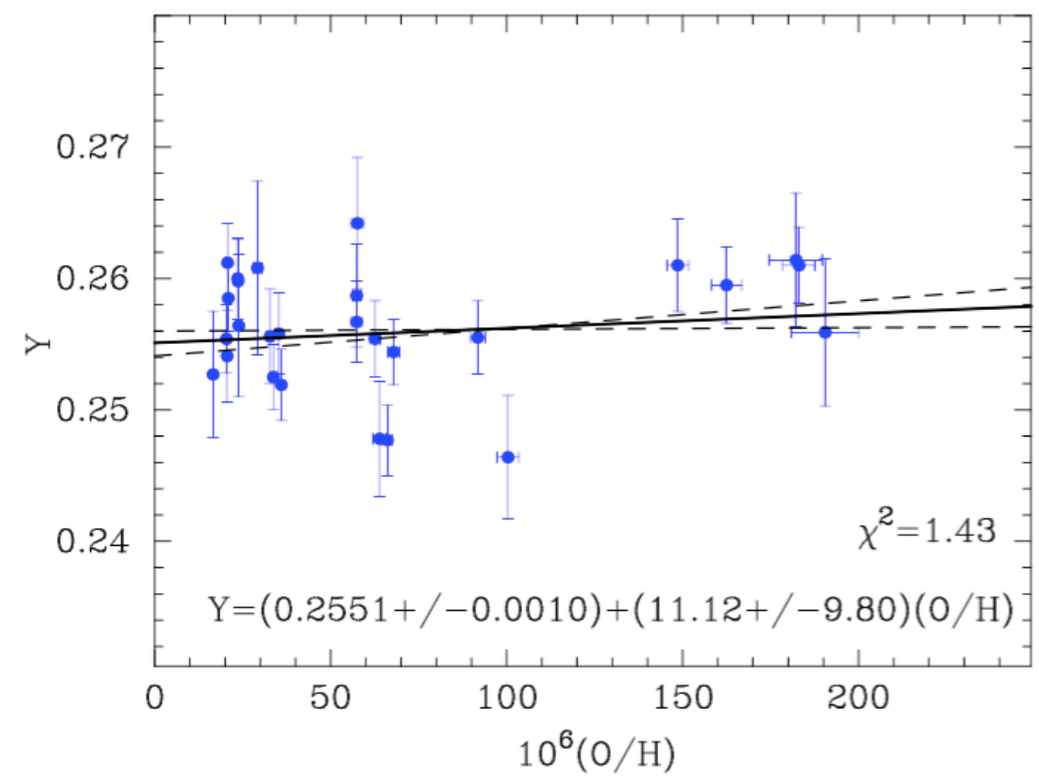
Helium mass fraction

$$Y_p \simeq 25\%$$

Aver et al 2015



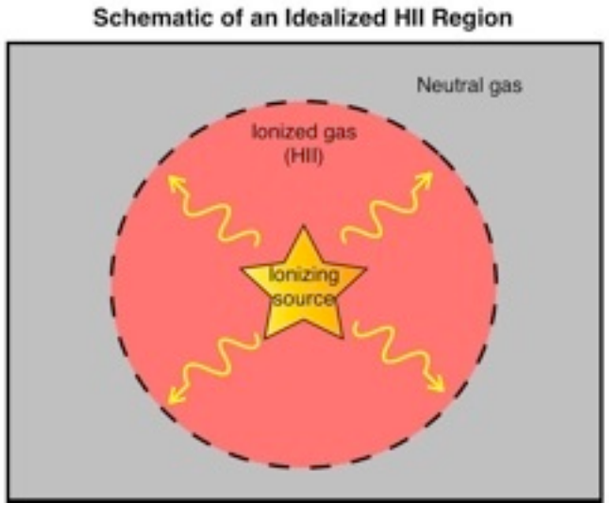
Izotov et al 2014



Helium gets illuminated in HII (ionized hydrogen) regions

=> emission lines

now claim few %-level accuracy (systematics limited)



Light element observations
Helium @ z=1000

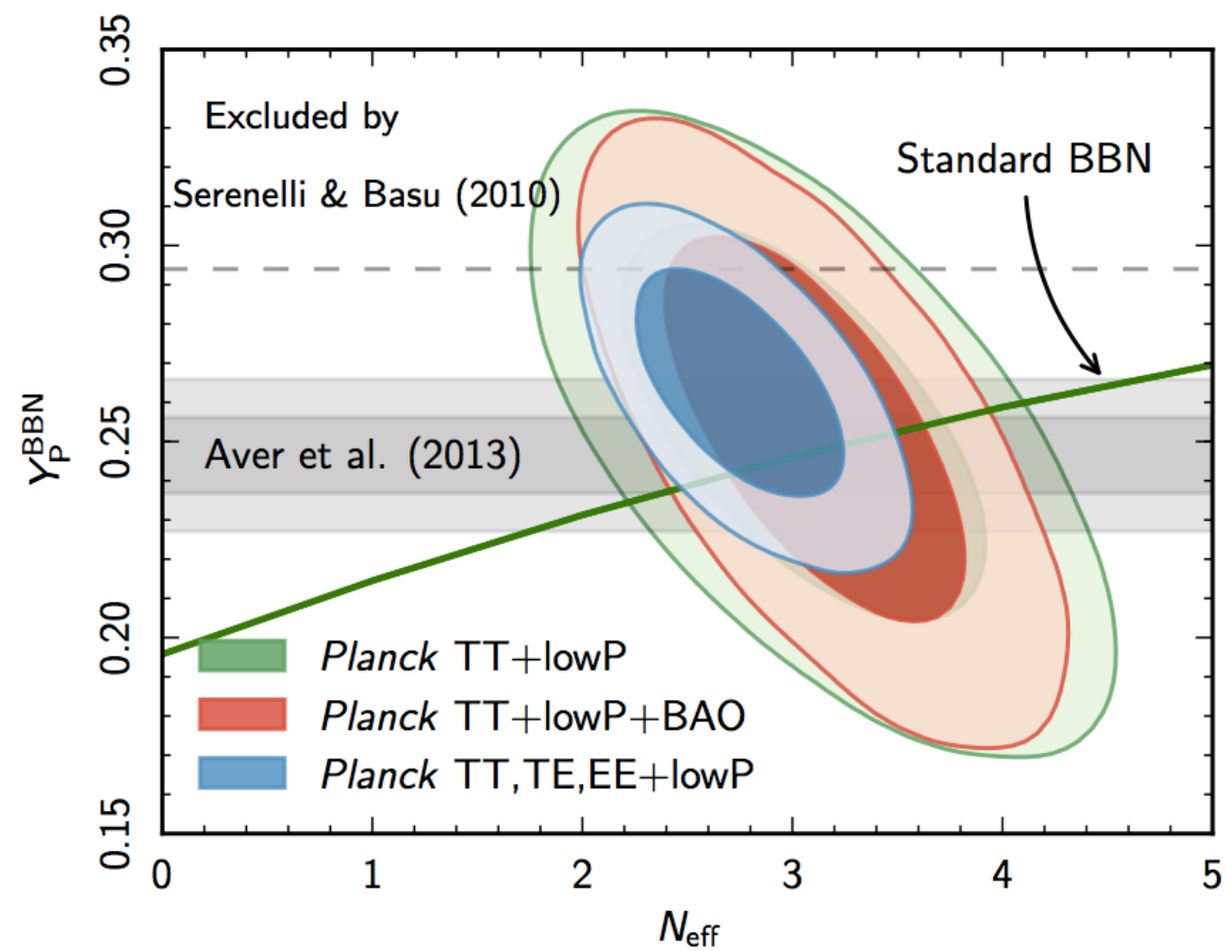
Planck 2015

- *true primordial detection* of Helium in the CMB

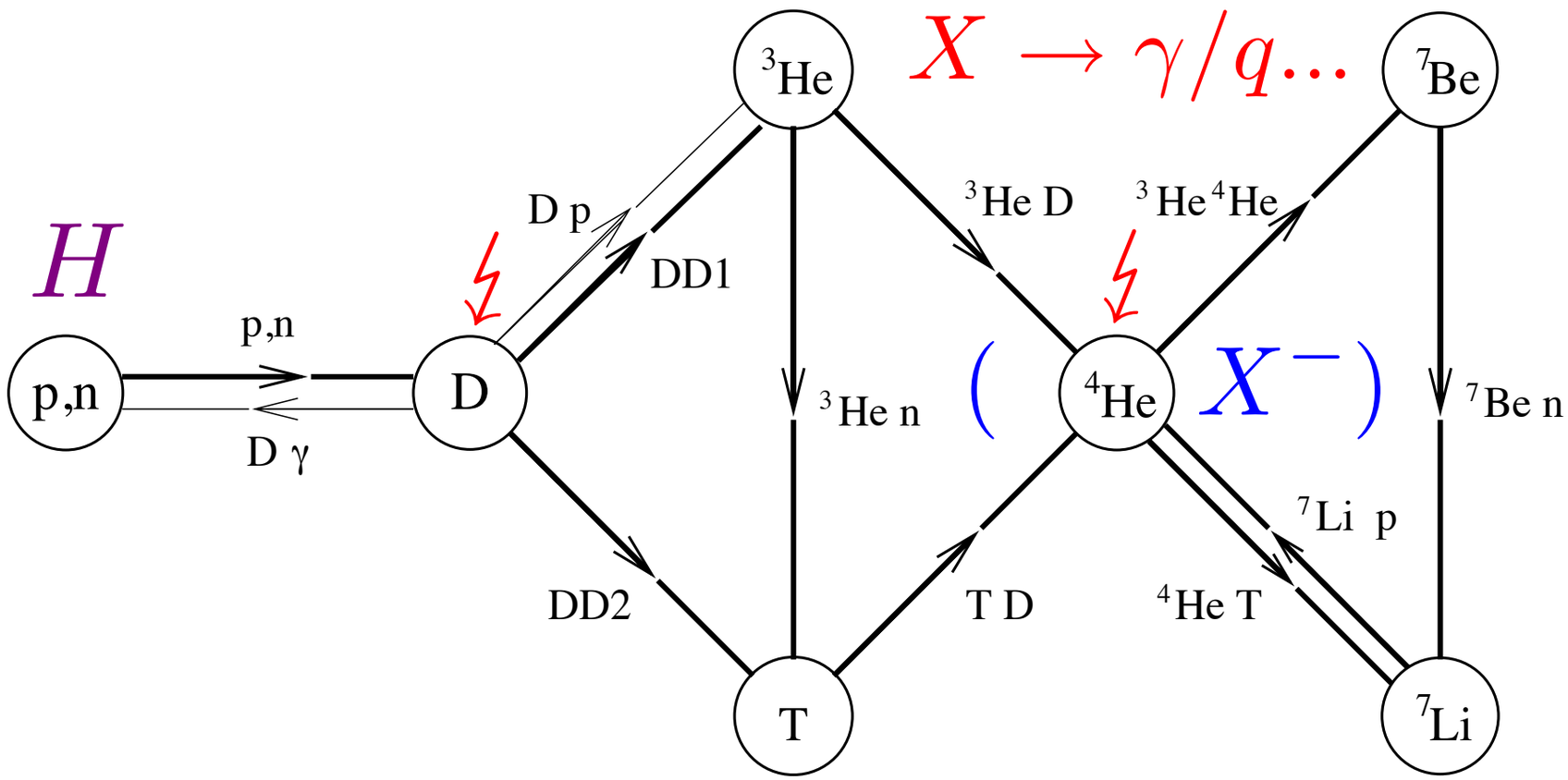
- Helium recombines before H, affecting the free electron fraction

=> 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)



Beyond SBBN



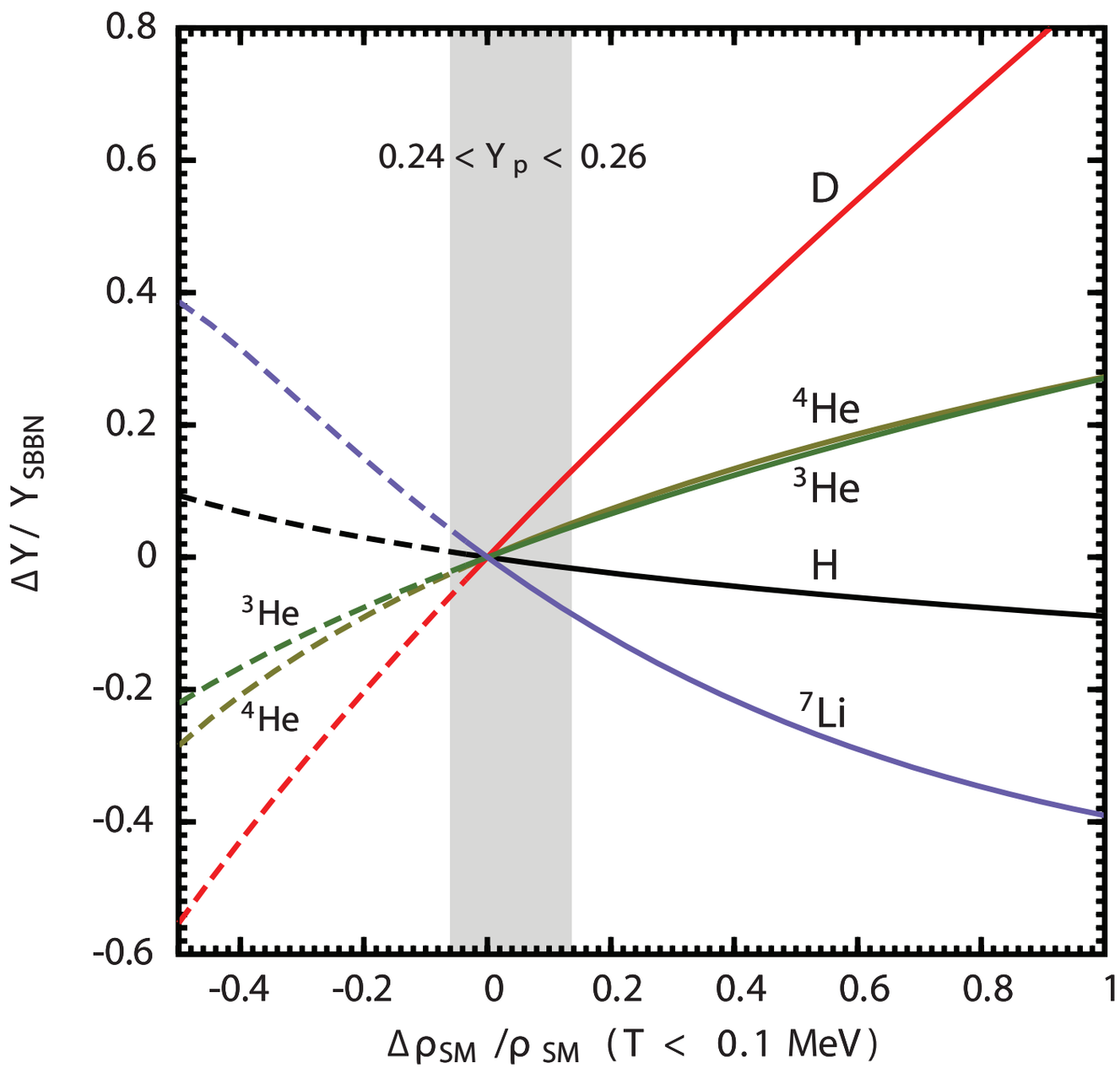
Change in timing

non-equilibrium BBN

catalyzed BBN

Change in timing

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



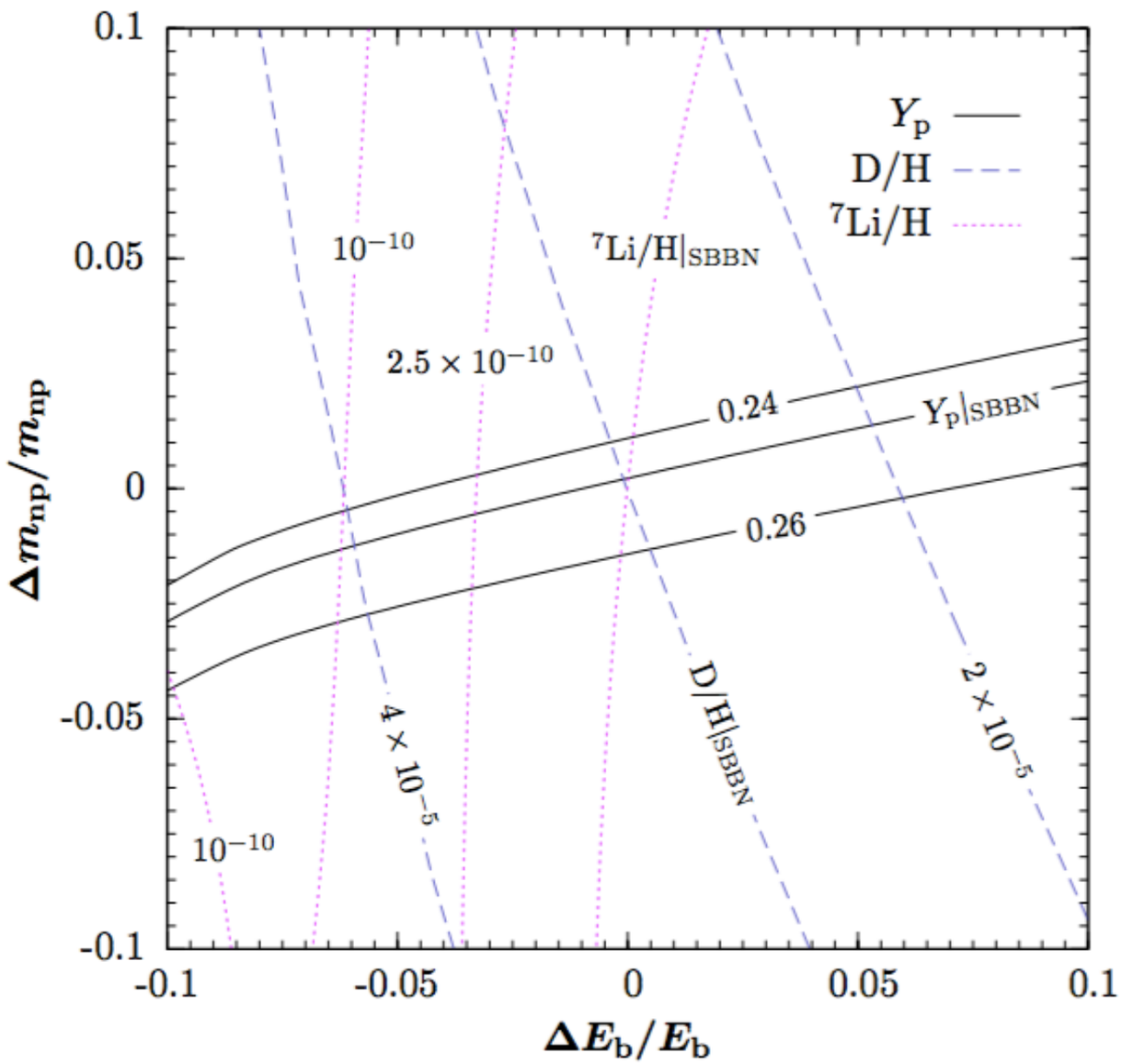
$N_{\rm eff} = 3.15 \pm 0.23$

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, Λ_{QCD}, Higgs vacuum expectation value….
=> induce changes in the reaction rates, nuclear binding, and the position of resonances

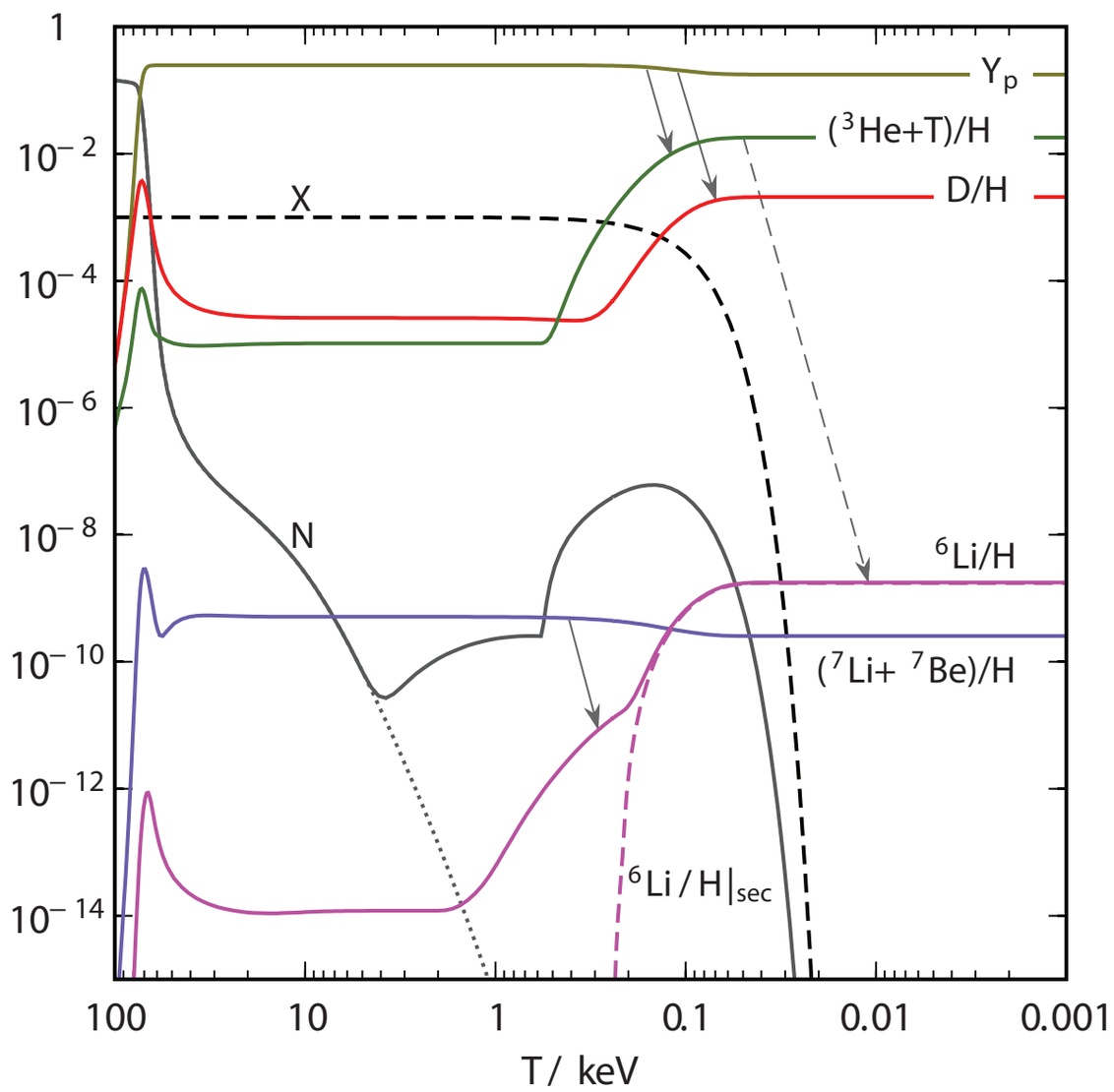


BBN: exponential sensitivity on

Δm_{np} determines n/p freeze out

E_d determines end of the D-bottleneck

↯ non-equilibrium BBN: (t > 10^6 sec) electromagnetic injection



photons in EM-cascade below $e^{\pm}$ threshold are not efficiently dissipated => spallation of nuclei

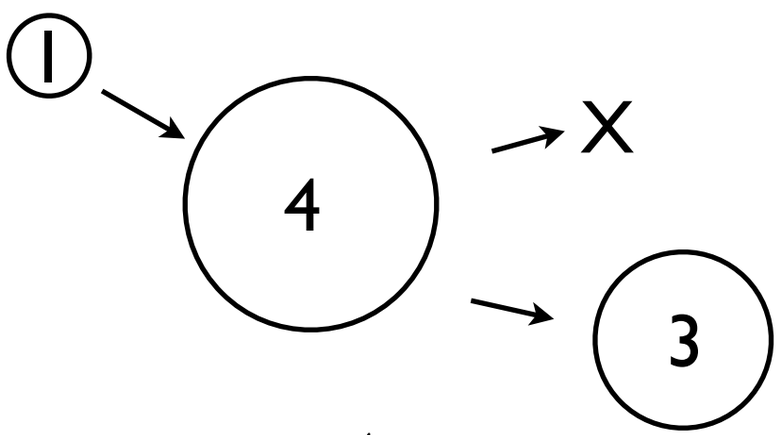
$$^7\mathrm{Be} + \gamma \rightarrow {}^3\mathrm{He} + {}^4\mathrm{He}$$
$$\mathrm{D} + \gamma \rightarrow n + p$$
$$^4\mathrm{He} + \gamma \rightarrow {}^3\mathrm{He/T} + n/p$$

Secondary effects:

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

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

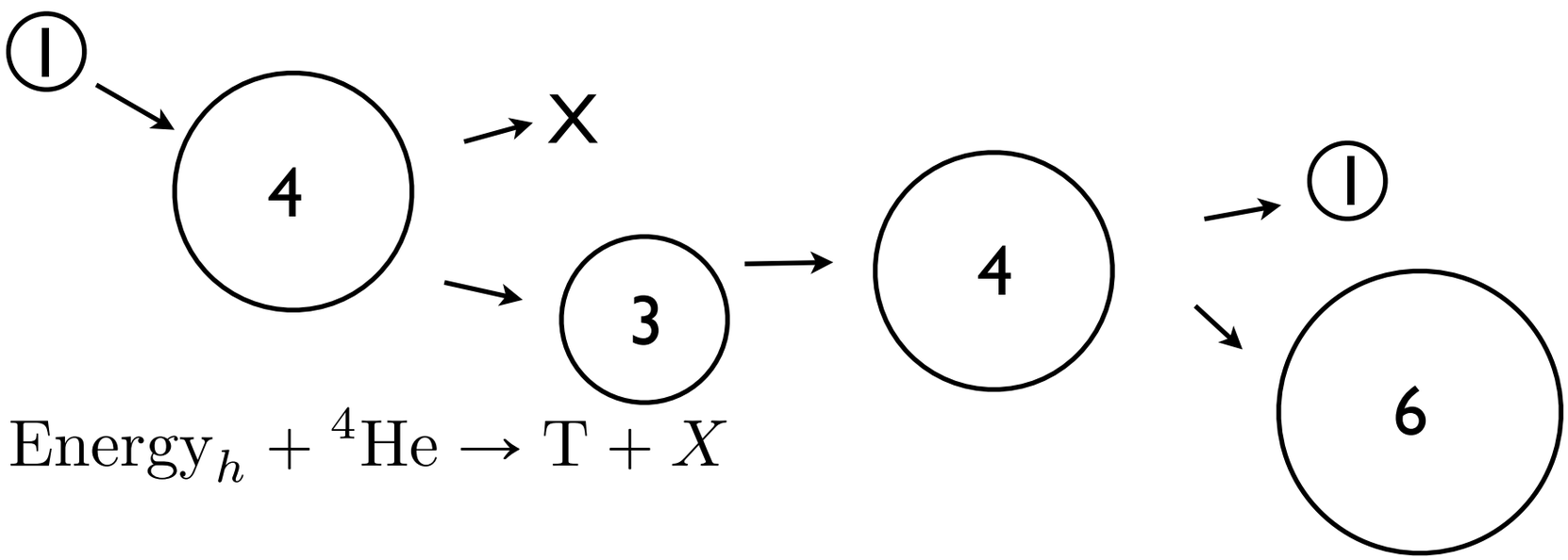
non-equilibrium BBN (hadronic injection)



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

Important for electroweak-scale
decaying relics (large initial energy depositions)

non-equilibrium BBN (hadronic injection)



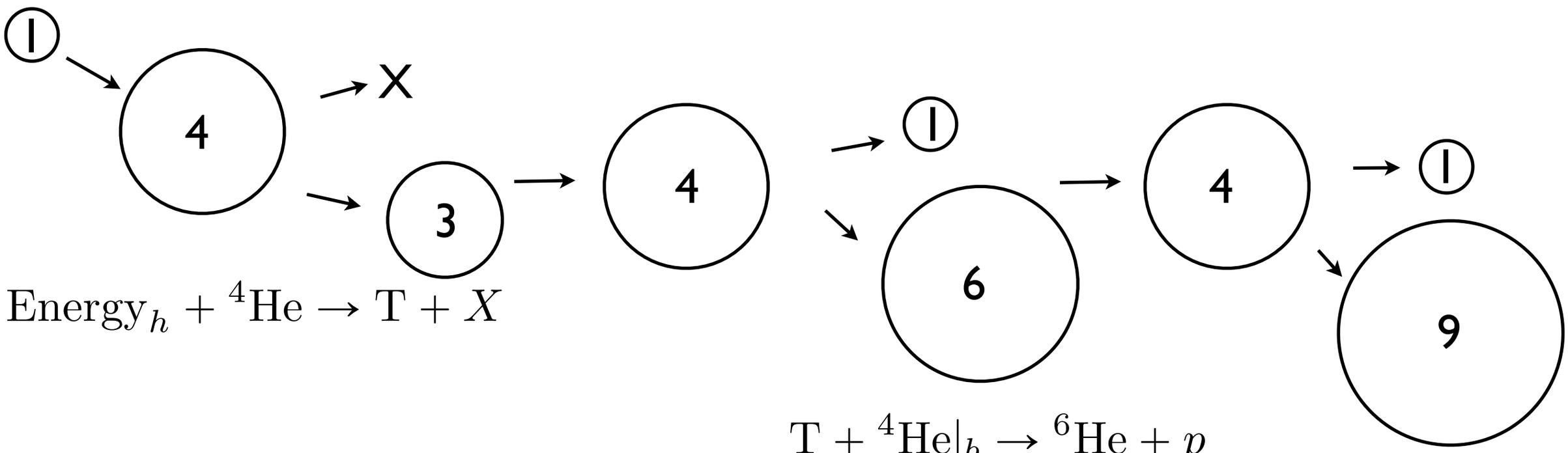
$$\mathrm{Energy}_h + {}^4\mathrm{He} \to \mathrm{T} + X$$

$$\mathrm{T} + {}^4\mathrm{He}|_b \to {}^6\mathrm{He} + p$$

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

Important for electroweak-scale
decaying relics (large initial energy depositions)

non-equilibrium BBN (hadronic injection)



$$\mathrm{Energy}_h + {}^4\mathrm{He} \to \mathrm{T} + X$$

$$\mathrm{T} + {}^4\mathrm{He}|_b \to {}^6\mathrm{He} + p$$

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

$${}^6\mathrm{He} + {}^4\mathrm{He}|_b \to {}^9\mathrm{Be} + n$$

Important for electroweak-scale decaying relics (large initial energy depositions)

Pospelov, JP, PRL 2010

BBN Limits
soft hadronic injection

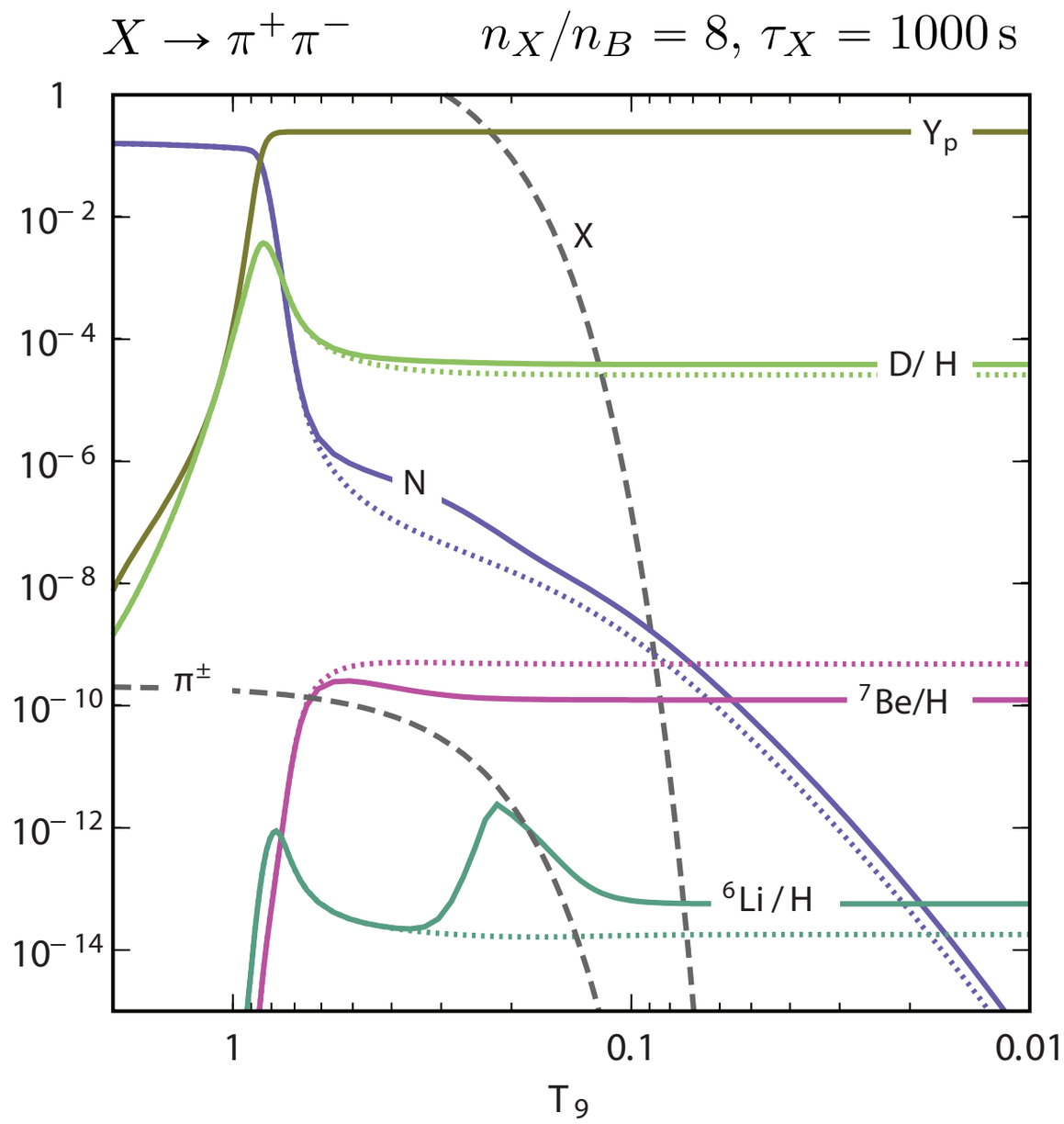
"Extra neutrons", also through captures like

$$K^- + {}^4\mathrm{He} \to \Lambda(\Sigma^0)(pnn)$$

=> A path to ameliorate the lithium problem

$${}^7\mathrm{Be} + n \to {}^7\mathrm{Li} + p$$

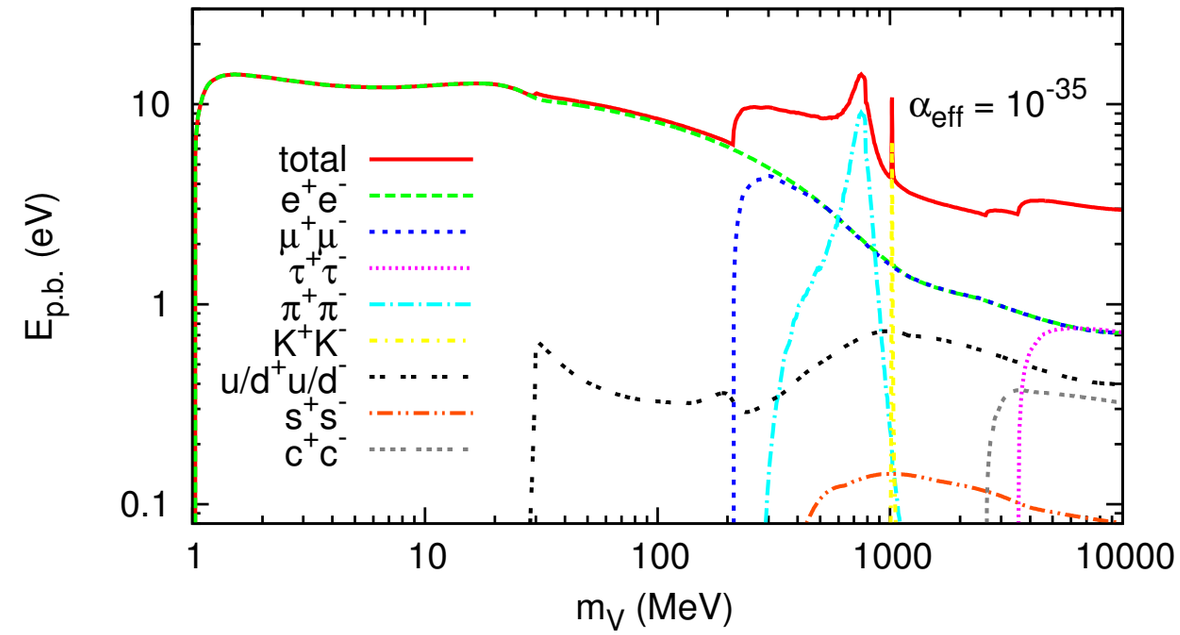
$${}^7\mathrm{Li} + p \to {}^4\mathrm{He} + {}^4\mathrm{He}$$



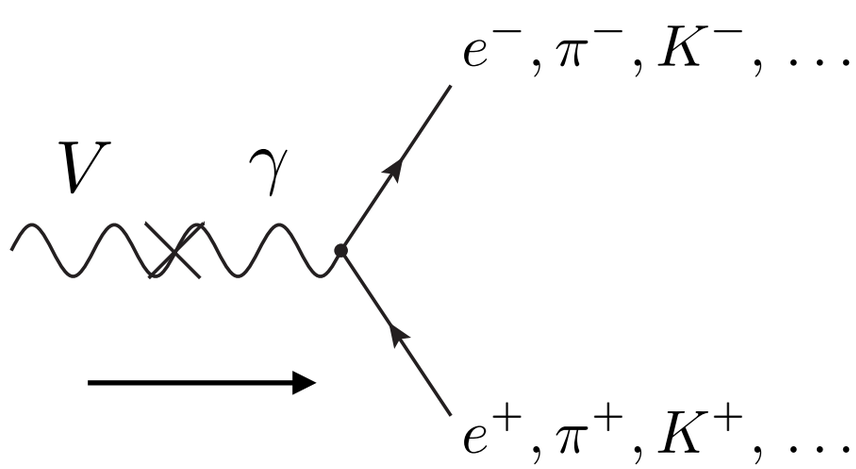
non-equilibrium BBN with Dark Photons

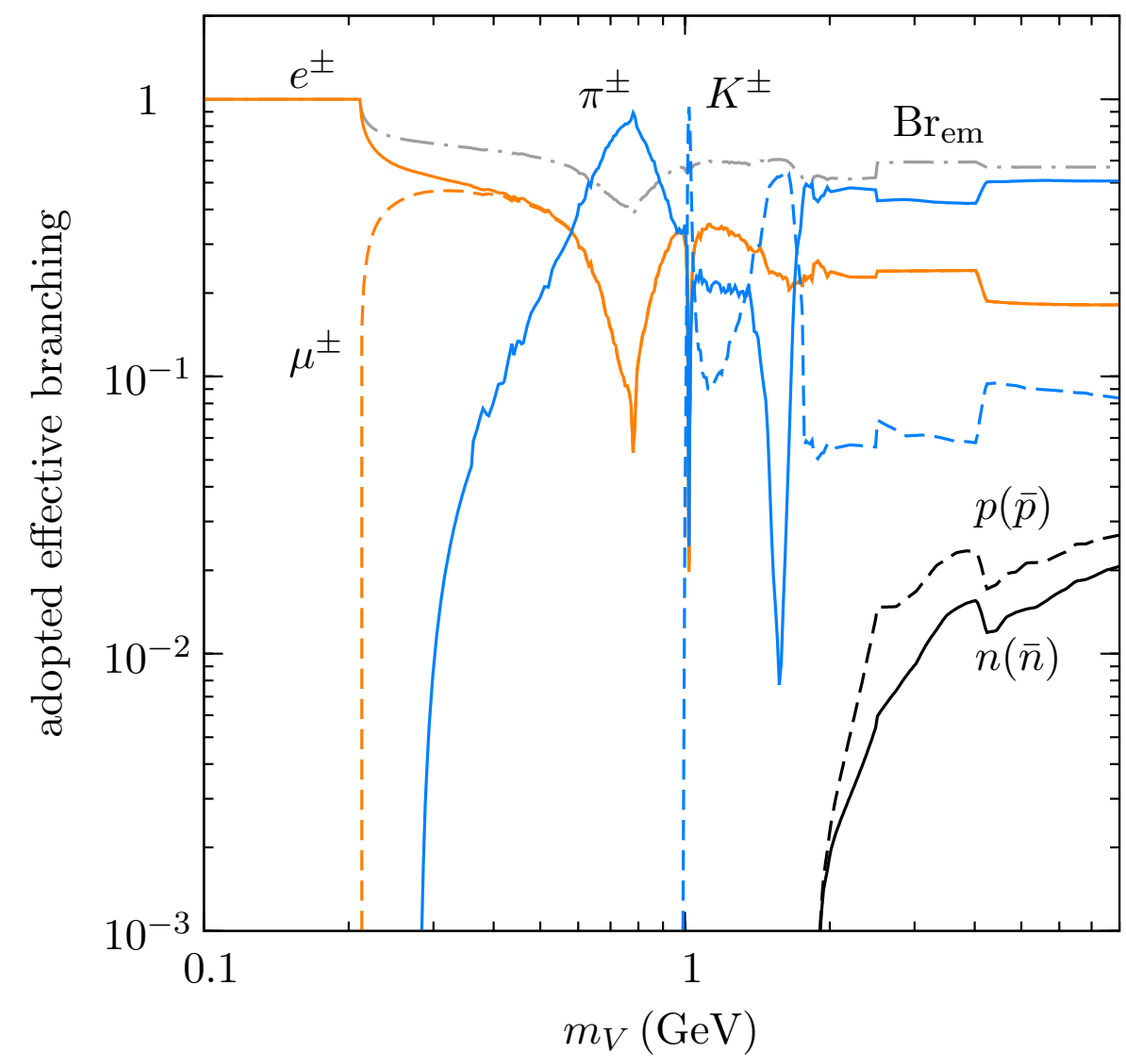
1. V Production

"leakage" from SM with sub-Hubble rates



2. V Decay





Lifetime macroscopic, because of tiny value of κ

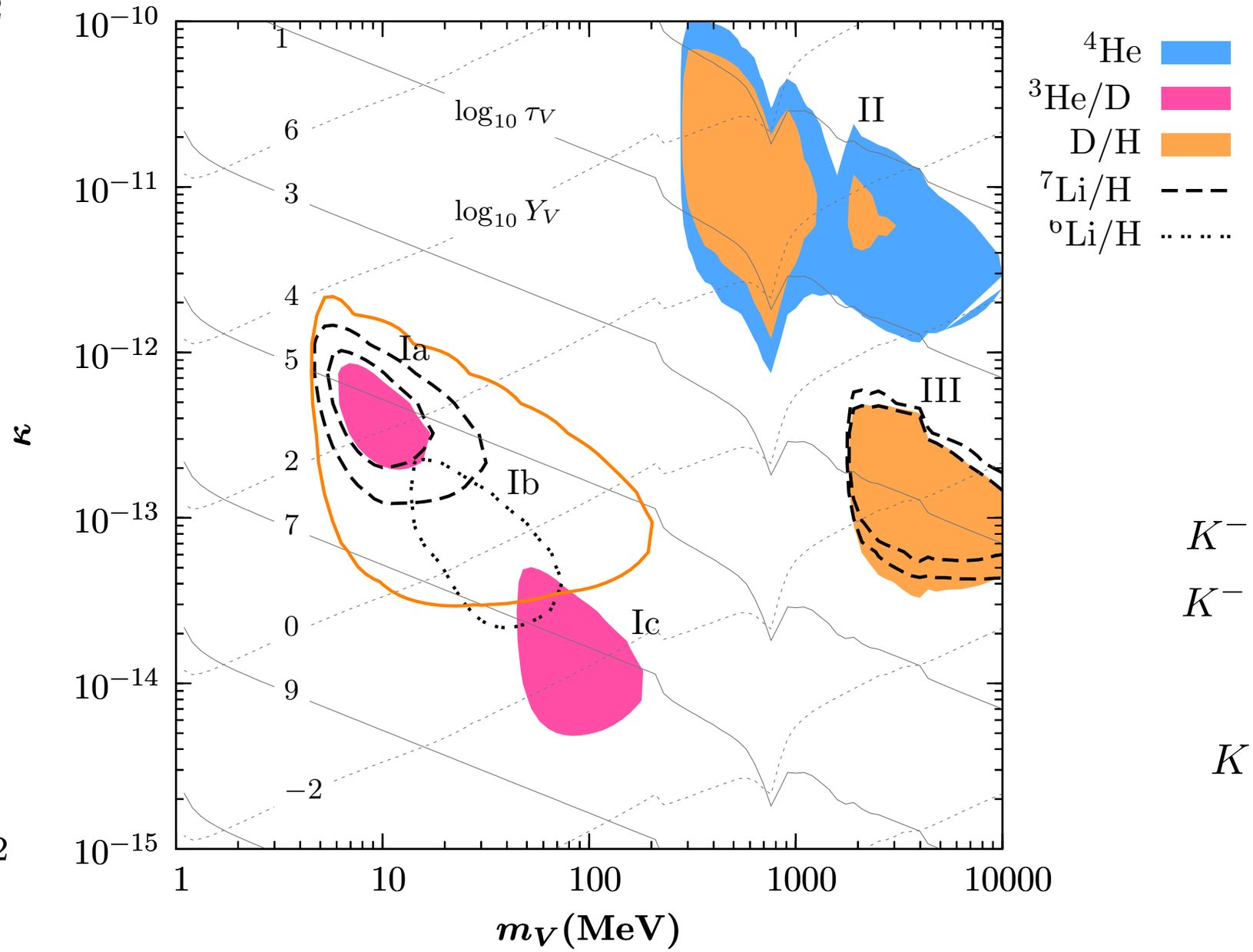
Predictions vs. observations

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

10^{-22}

10^{-32}

10^{-36}



CMB-constraints

charge exchange

$$\pi^- + p \to \pi^0 + n$$

s-quark exchange

$$K^- + p \to \Sigma^\pm \pi^\mp,\ \Sigma^0 \pi^0,\ \Lambda \pi^0$$
$$K^- + n \to \Sigma^- \pi^0,\ \Sigma^0 \pi^-,\ \Lambda \pi^-$$

Kaon captures

$$K^- + {}^4\mathrm{He} \to \Lambda(\Sigma^0)(pnn)$$

photodissociations

$${}^7\mathrm{Be} + \gamma \to {}^3\mathrm{He} + {}^4\mathrm{He}$$
$$\mathrm{D} + \gamma \to n + p$$
$${}^4\mathrm{He} + \gamma \to {}^3\mathrm{He/T} + n/p$$

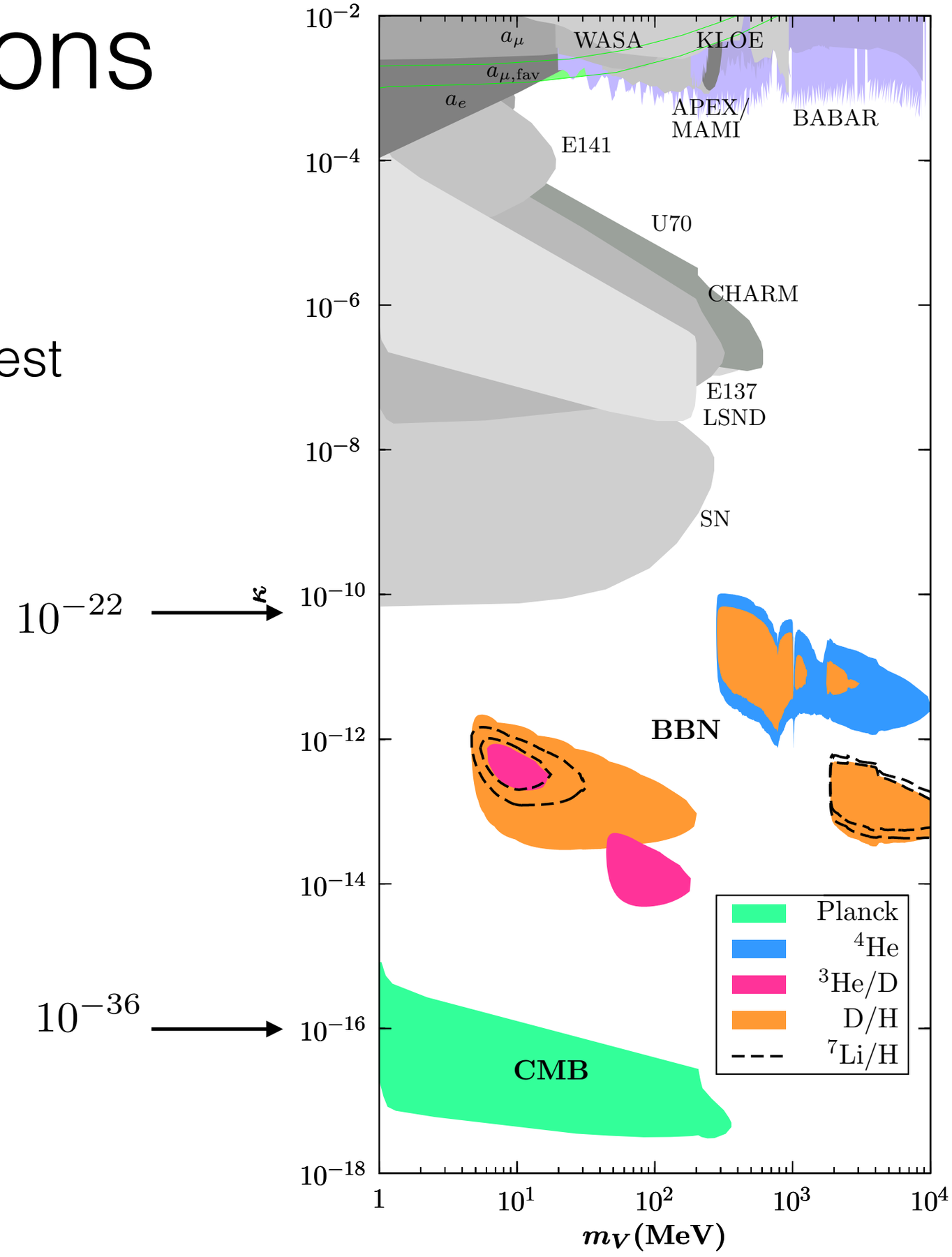
etc….

MeV Dark Photons

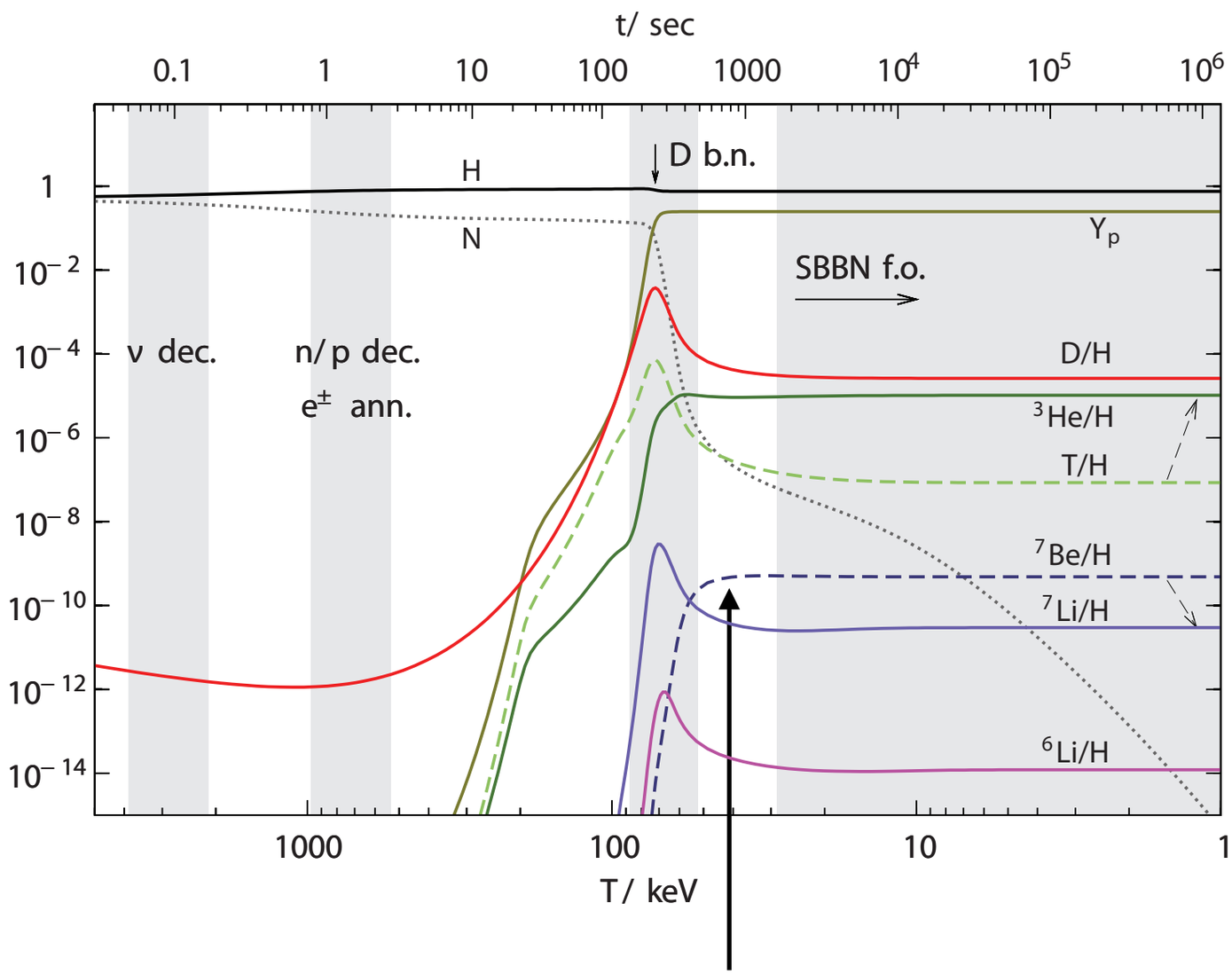
Cosmology becomes the *only* test for very feeble couplings to SM

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

effective fine structure constant



3 ALPs and the lithium problem



because rate is sub-Hubble (and because there is no stable/long-lived A=5 element)

$$[^7\mathrm{Li/H}]_{\mathrm{BBN}} = (4.68 \pm 0.67) \times 10^{-10}$$

most lithium comes from 7Be (at η_{CMB}): $^3\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma$

followed by (much later) $^7\mathrm{Be} + \mathrm{e}^- \rightarrow {}^7\mathrm{Li} + \nu_\mathrm{e}$

3 Lithium - observations

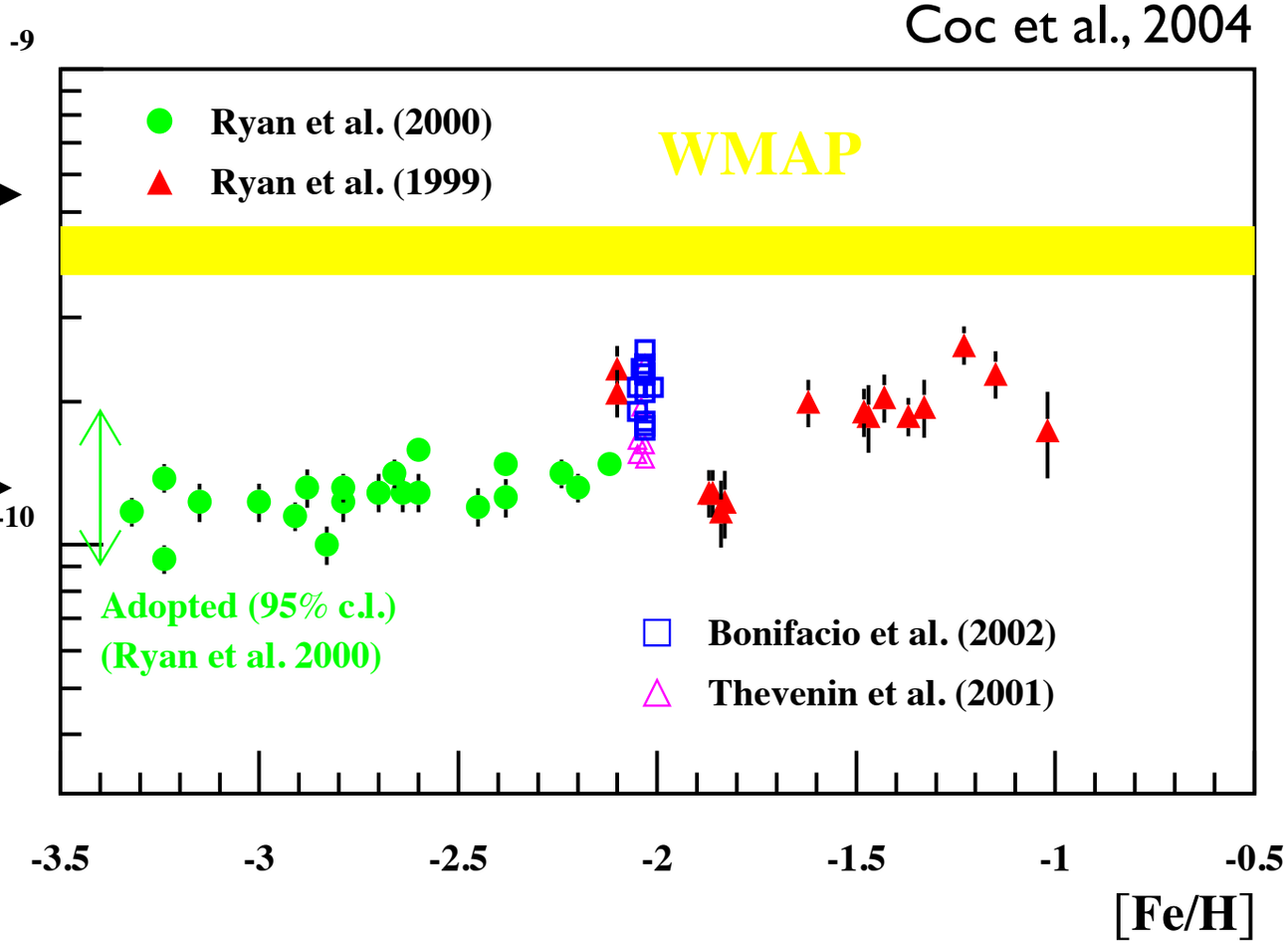
tiny lithium abundance forbids extragalactic absorption measurements; can be observed in atmospheres of stars

SBBN

"cosmological lithium problem"

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

Coc et al., 2004



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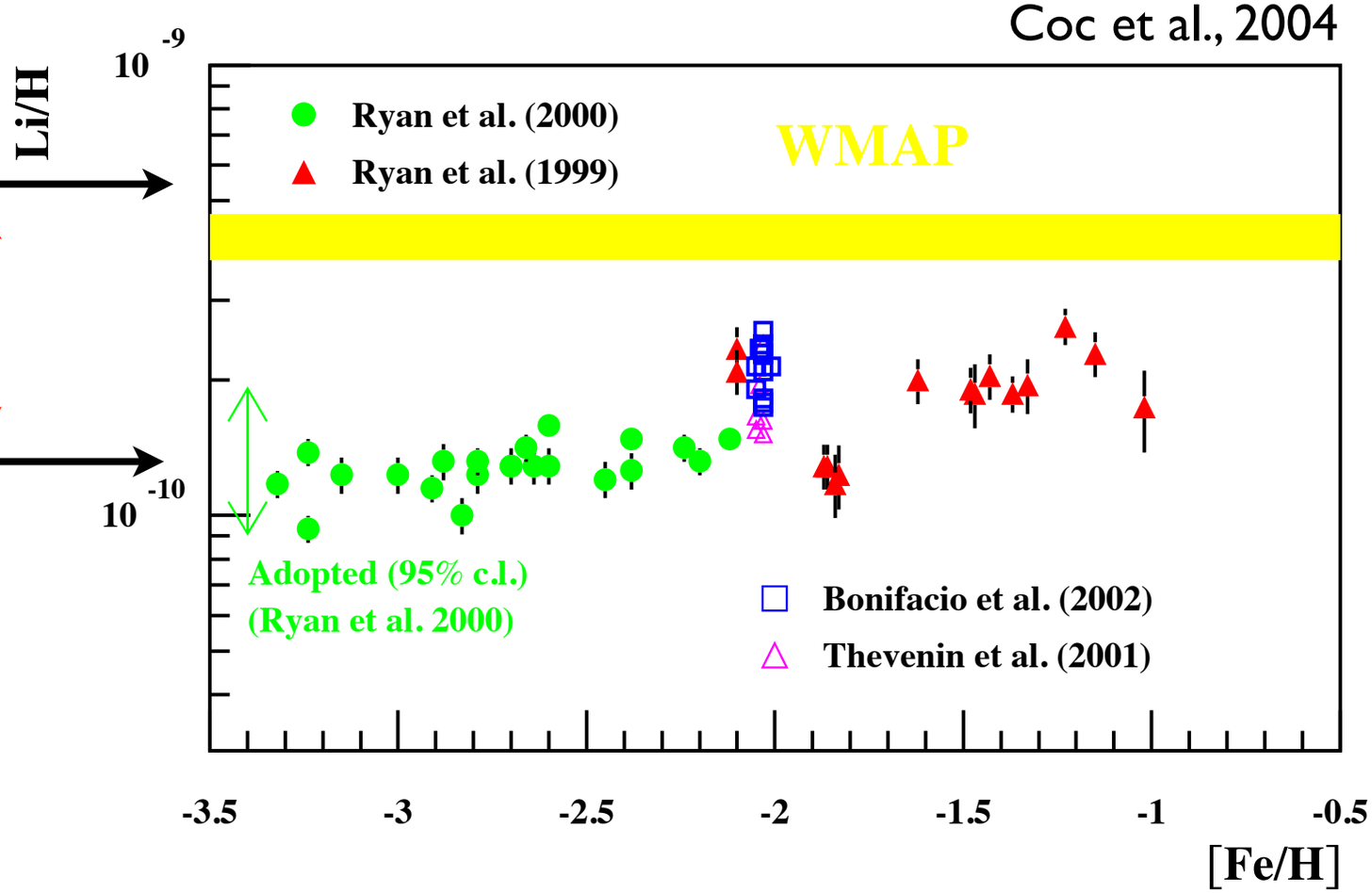
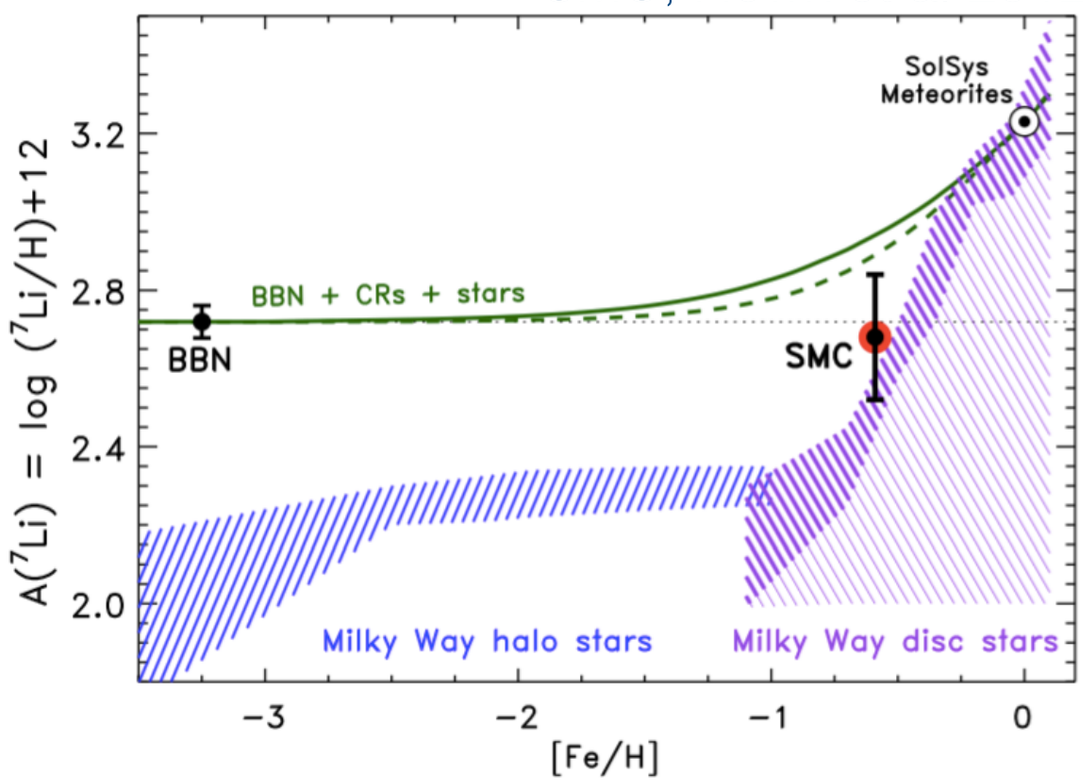
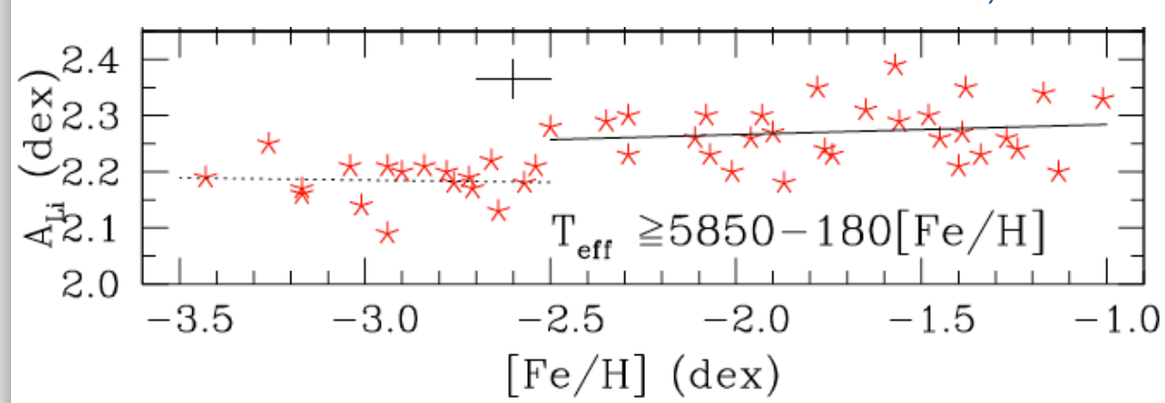


A better look at the Li-plateau

SMC, Howk et al 2012



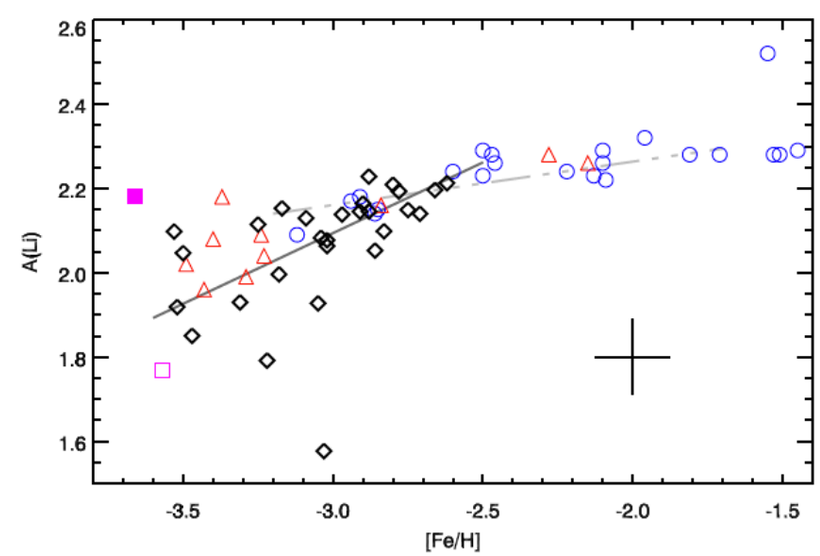
Melendez et al., 2010



extragalactic measurements exists

stars drop off the plateau at low metallicities

Aoki et al. (2009),
Sbordone et al. (2010& 2012)

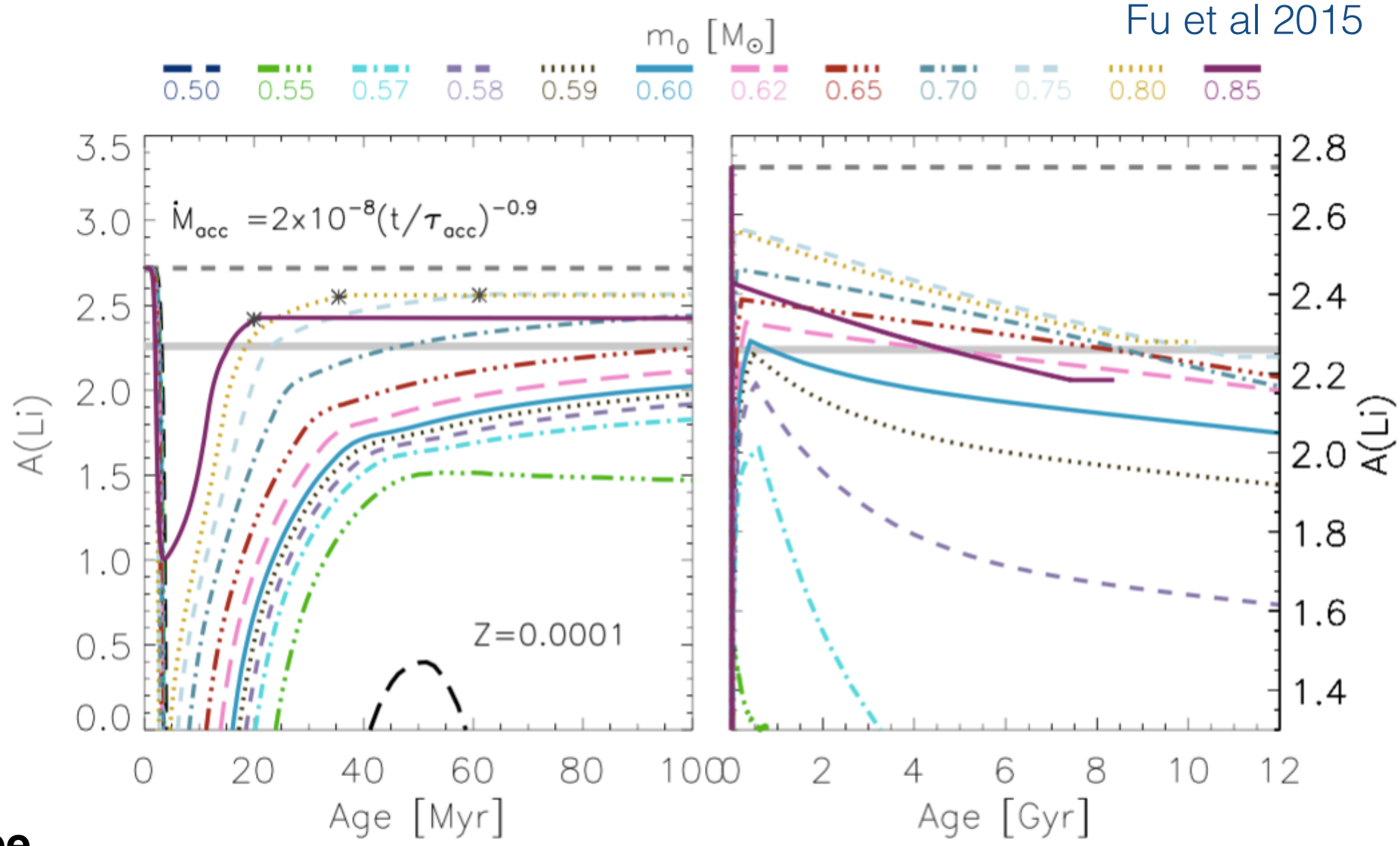


A better look at the Li-plateau

Atmospheres of stars may process some of the Li, by transporting it via convection to the hotter interior where it gets burned. Creating the Spite plateau without much scatter requires severe fine tuning of stellar models.

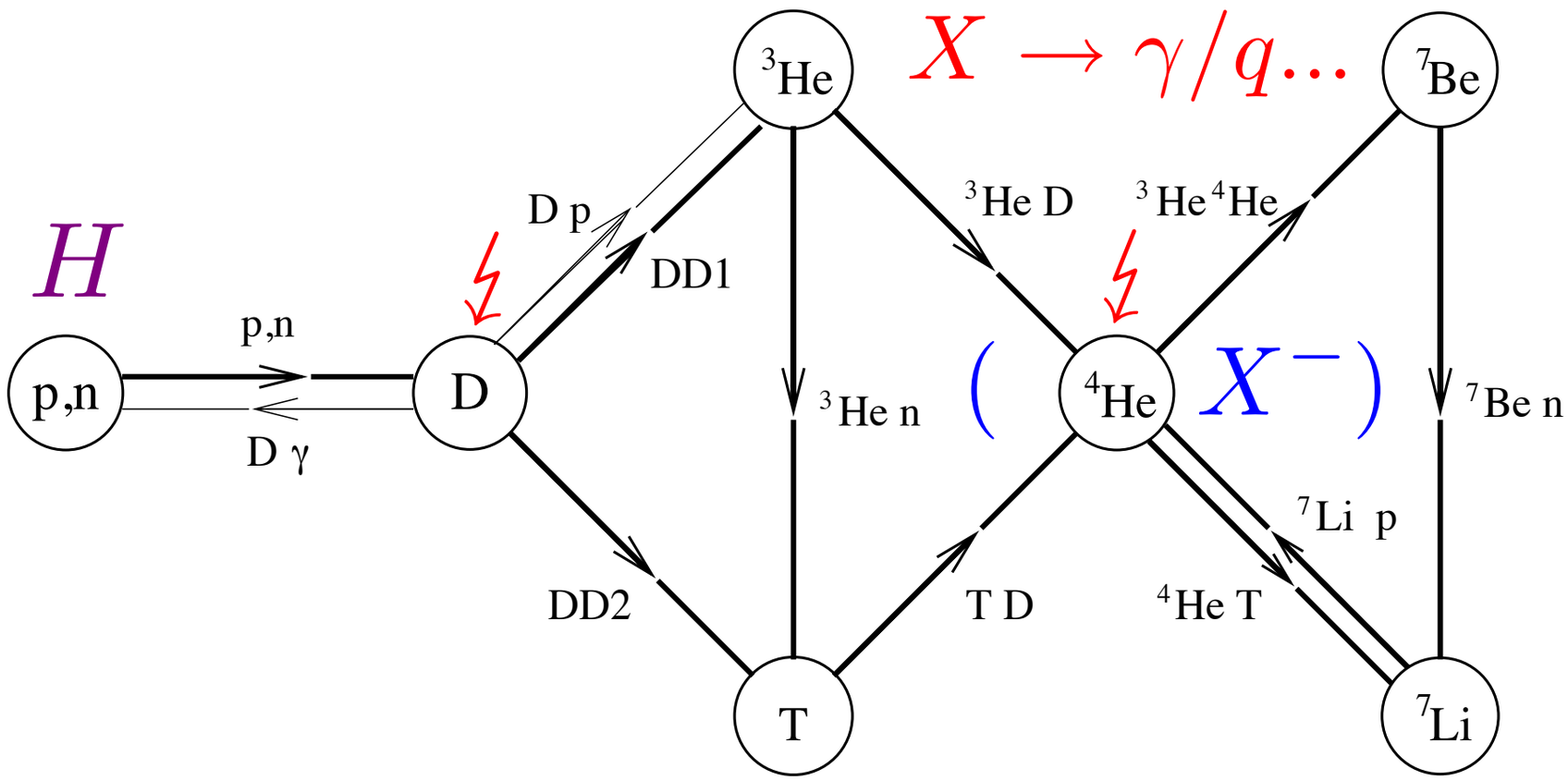
Fu et al 2015

One possibility: all Li got destroyed in PMS phase, and accretion replenishes Li, regulated by EUV photo-evaporation



Li-solution may be astrophysical, but could also be due to to new physics.

Beyond SBBN - Lithium solution?



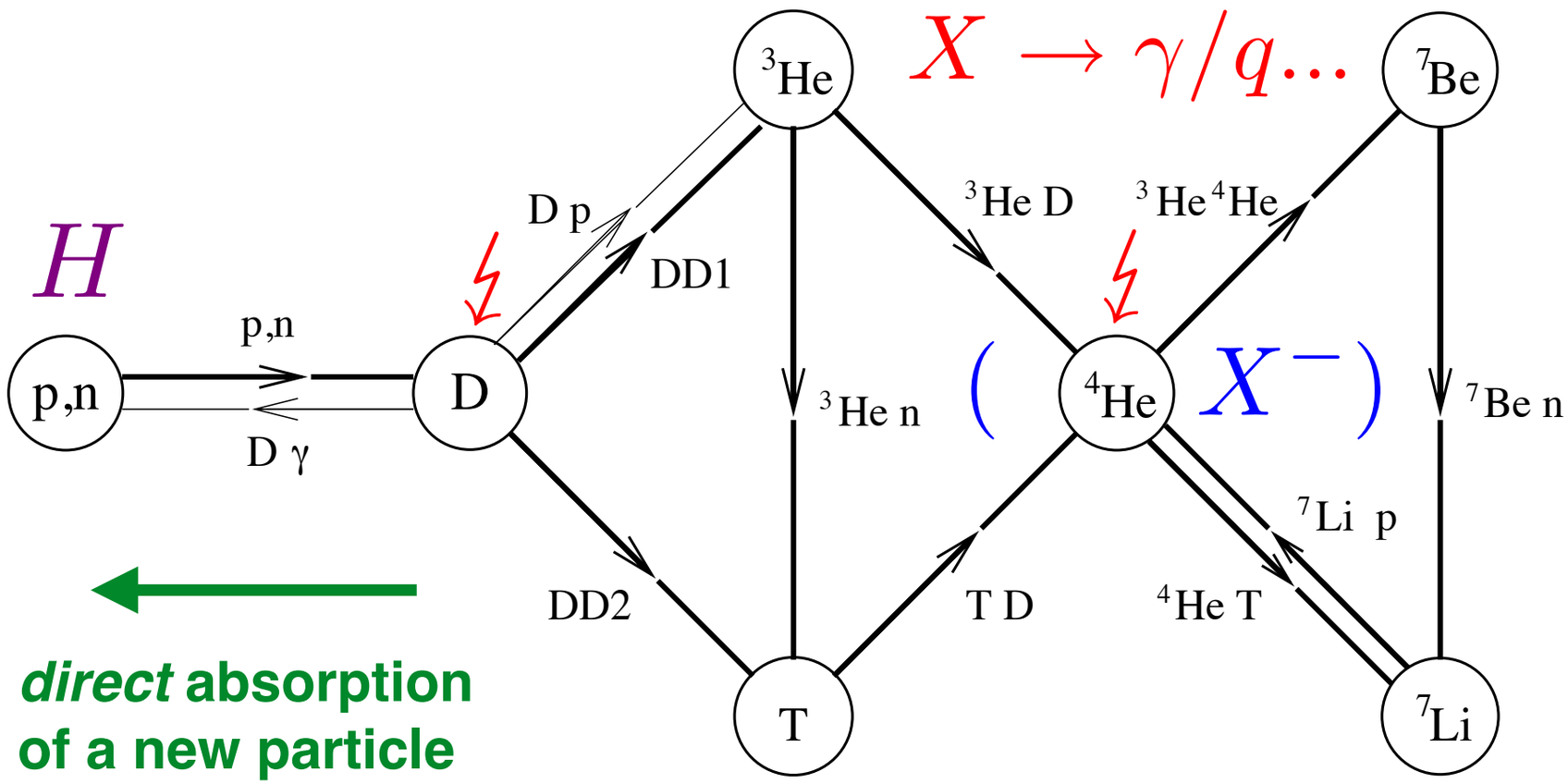
Change in timing

non-equilibrium BBN

catalyzed BBN

Precise D/H measurements disfavors practically all lithium solutions that utilize energy injection to spall ^{7}Be (requires substantial fine-tuning)

Beyond SBBN - Lithium solution?



Change in timing

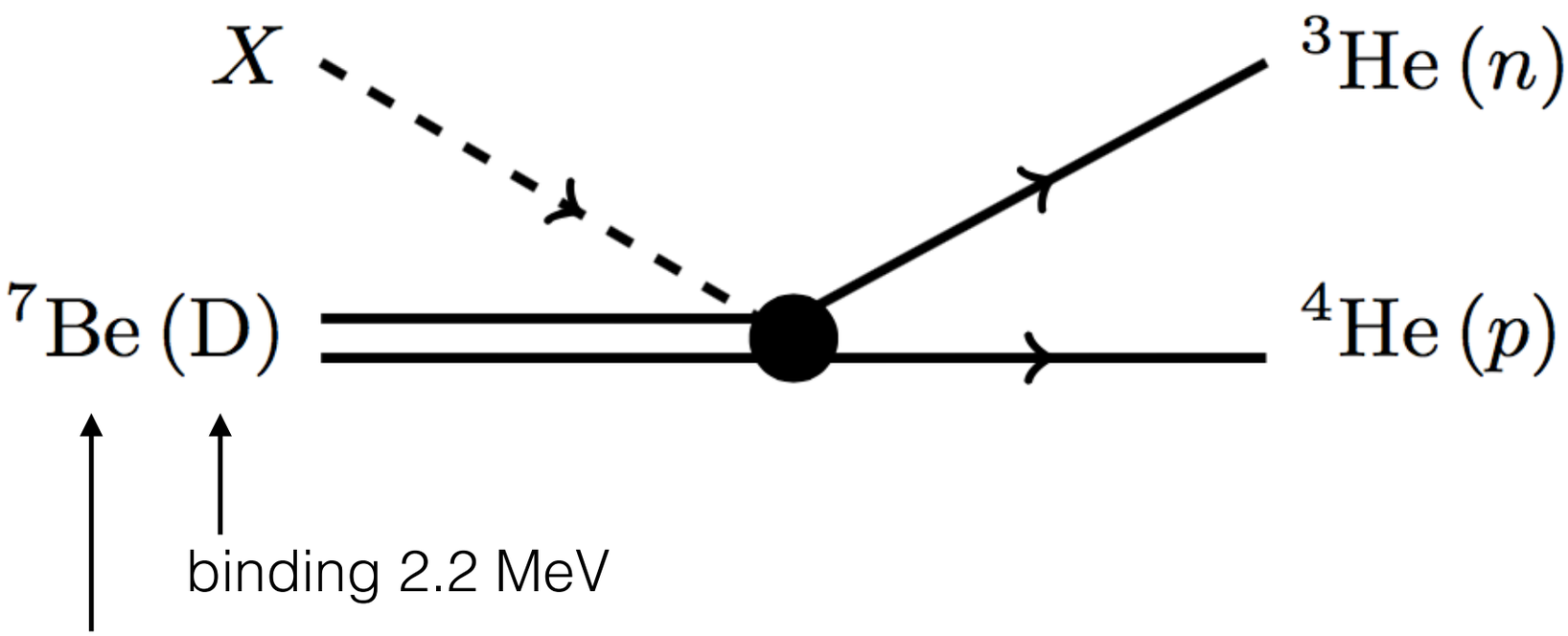
non-equilibrium BBN

catalyzed BBN

A new solution to the lithium problem

Ingredients: a bosonic state X that

1. lives 100 sec or longer
2. couples to quarks
3. has a mass/energy between 1.6 - 20 MeV
4. is abundant (relative to baryons)



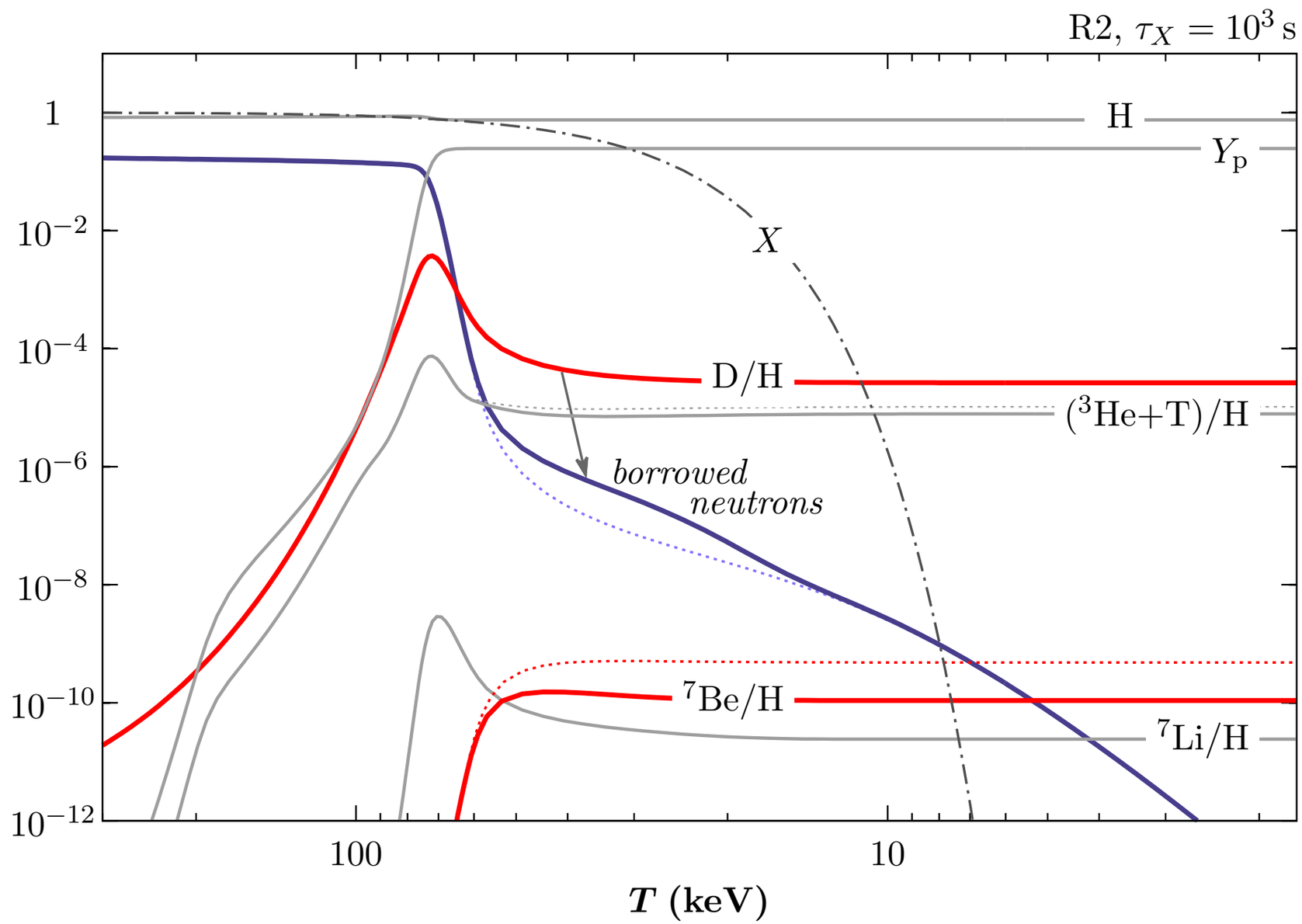
=> use mass/energy of X
to undo the binding

“Borrowed neutrons” as a solution to the lithium problem

neutrons are dug from their nuclear graves; they set in motion a ^{7}Be depleting sequence:

$$^7\mathrm{Be} + n \rightarrow {}^7\mathrm{Li} + p$$

$$^7\mathrm{Li} + p \rightarrow {}^4\mathrm{He} + {}^4\mathrm{He}$$



Keeps all other element yields unchanged!

A new solution to the lithium problem

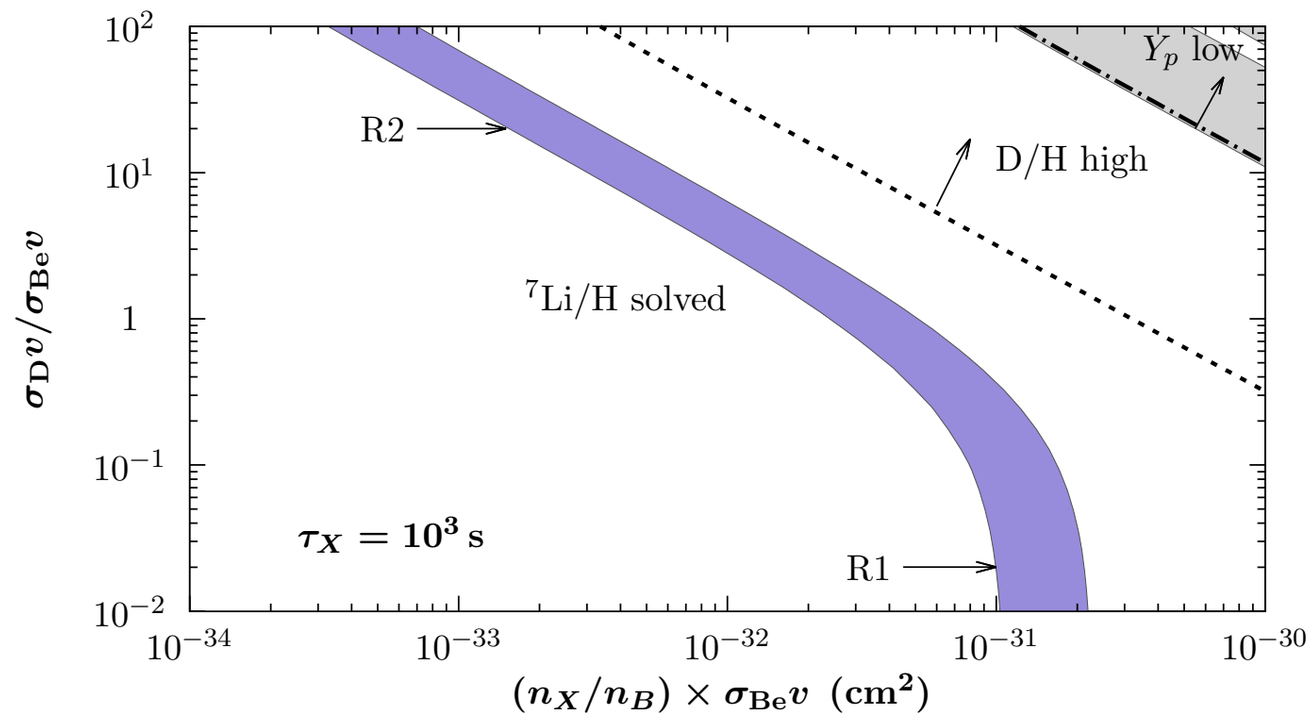
$$\mathrm{R1}: \ {}^7\mathrm{Be}(X,\alpha)^3\mathrm{He}$$

$$\mathrm{R2}: \ \mathrm{D}(X,p)n$$

In blue band, essentially,

$$n_X \sigma_{\mathrm{abs}} v \ \sim \ H$$

at ^{7}Be formation (~50 keV)



E.g. 5 MeV particle, 1% of photon energy density

=> $\sigma_{\mathrm{abs}} v \sim 10^{-38} \ \mathrm{cm}^2$

=> much smaller than photo-nuclear reactions, and much larger than weak interactions, but lifetimes comparable to β decays

=> very small couplings to electrons, photons, and neutrinos to make it work (“leptophobic models”)

Axion-like particle (ALP) version

Consider ALP that couples to down quarks

$$\mathcal{L}_{aq} = \frac{\partial_\mu a}{f_d} \bar{d}\gamma_\mu\gamma_5 d \qquad => \qquad \mathcal{L}_{a\pi N} = \frac{\partial_\mu a}{f_d}\left[f_\pi \partial_\mu \pi^0 + \frac{4}{3}\bar{n}\gamma_\mu\gamma_5 n - \frac{1}{3}\bar{p}\gamma_\mu\gamma_5 p\right]$$

we use naive quark model estimates
for spin content of nucleons

Decays through axion-pion mixing $\theta = (f_\pi/f_d)\times(m_a^2/m_\pi^2)$

$$\Gamma^a_{\gamma\gamma} \simeq \theta^2 \left(\frac{m_a}{m_\pi}\right)^3 \Gamma^{\pi^0}_{\gamma\gamma} = \left(\frac{1\ \mathrm{TeV}}{f_d}\right)^2 \left(\frac{m_a}{5\ \mathrm{MeV}}\right)^7 \frac{1}{100\ \mathrm{s}}$$

Scenario A: relic X = a

Absorption cross section for non-relativistic ALPs can be related to photo-absorption cross section

$$\frac{\sigma_{\mathrm{abs},i} v}{\sigma_{\mathrm{photo},i} c} \simeq \frac{C_i}{4\pi\alpha} \times \frac{m_a^2}{f_d^2}$$

"Scenario A"

(C's are spin-factors)

Despite the small width, ALP get thermally populated during QCD epoch

$$\Gamma^a_{\gamma\gamma} \simeq \theta^2 \left(\frac{m_a}{m_\pi}\right)^3 \Gamma^{\pi^0}_{\gamma\gamma} = \left(\frac{1\ \mathrm{TeV}}{f_d}\right)^2 \left(\frac{m_a}{5\ \mathrm{MeV}}\right)^7 \frac{1}{100\ \mathrm{s}}$$

"expert comment": short lifetime helps with EM constraints, but large required abundance creates entropy

Depletion of the relic abundance requires additional light particles!

Scenario B: X = a from decay of X_p

Freeze-in of a progenitor state that decays to $X_p \to aa$

For example:

$$\mathcal{L}_{XX_p} = AX_p(H^\dagger H) + BX_p a^2 + \mathcal{L}_{aq}$$

Abundance controlled by $A \sim (10^{-9} - 10^{-5})$ GeV.

Lifetime controlled by trilinear coupling. $\tau_{X_p} \sim 10^3$ s => $B \sim 10^{-11}$ MeV.

Scenario B: X = a from decay of X_p

Once X=a is injected, the particles free stream

=> distribution function of "piled-up" a-particles from X_p decay

$$g(T,E) = 2\int_T dT_1 \frac{\Gamma_{in} Y_{X_p}(T_1)}{H(T_1)T_1}\delta\left(\frac{T}{T_1}E_{in} - E\right)$$

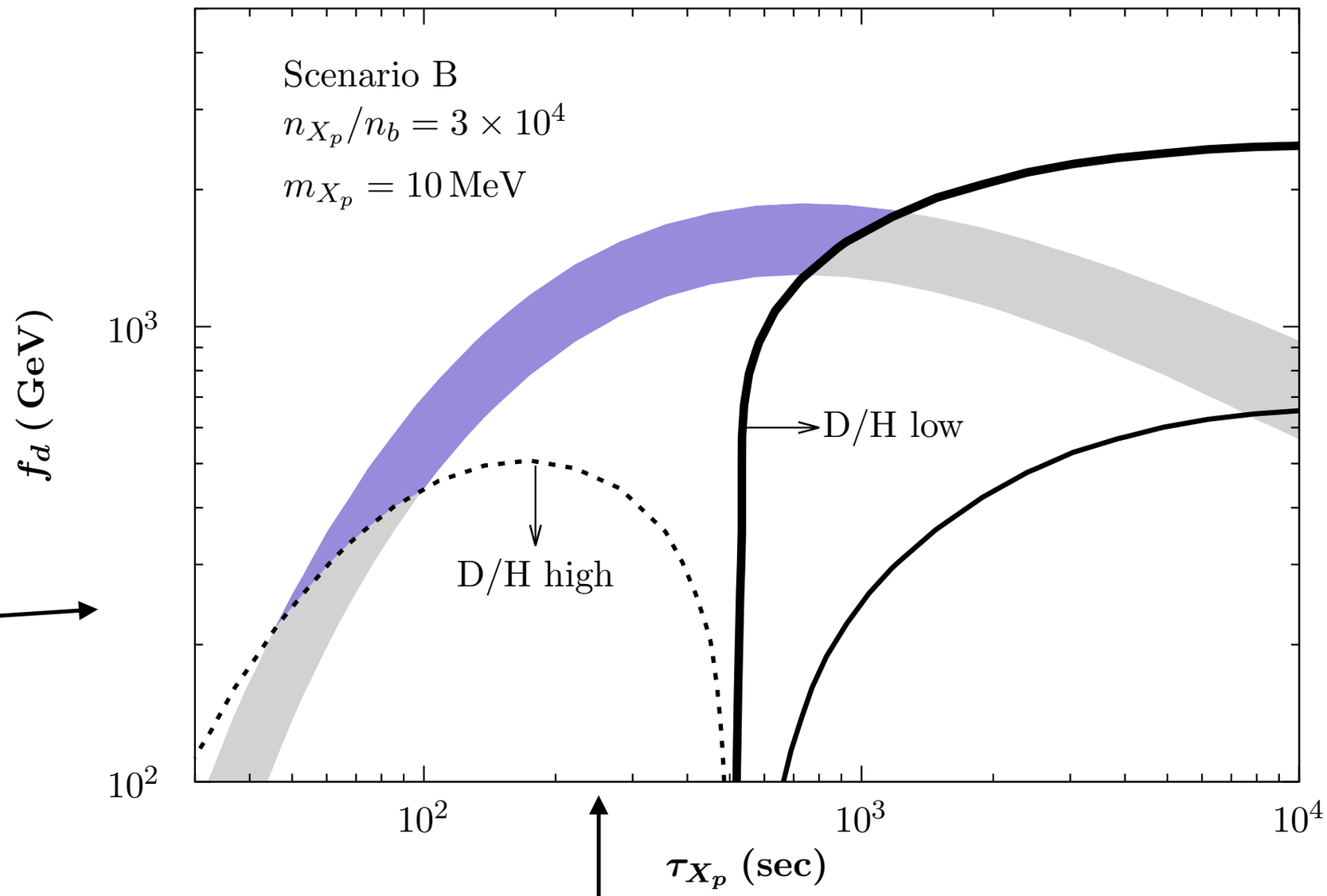
=> absorption rate

$$\Gamma_{\rm abs} = \int_{|E_B|}^{E_{in}} dE\, g(T,E)s(T)\sigma_{\rm abs}(E)v(E)$$

$$\frac{\sigma_{{\rm abs},i}}{\sigma_{{\rm photo},i}} \simeq \frac{D_i}{4\pi\alpha} \times \frac{E_a^2}{f_d^2}$$

Scenario B: ALP solution to Li

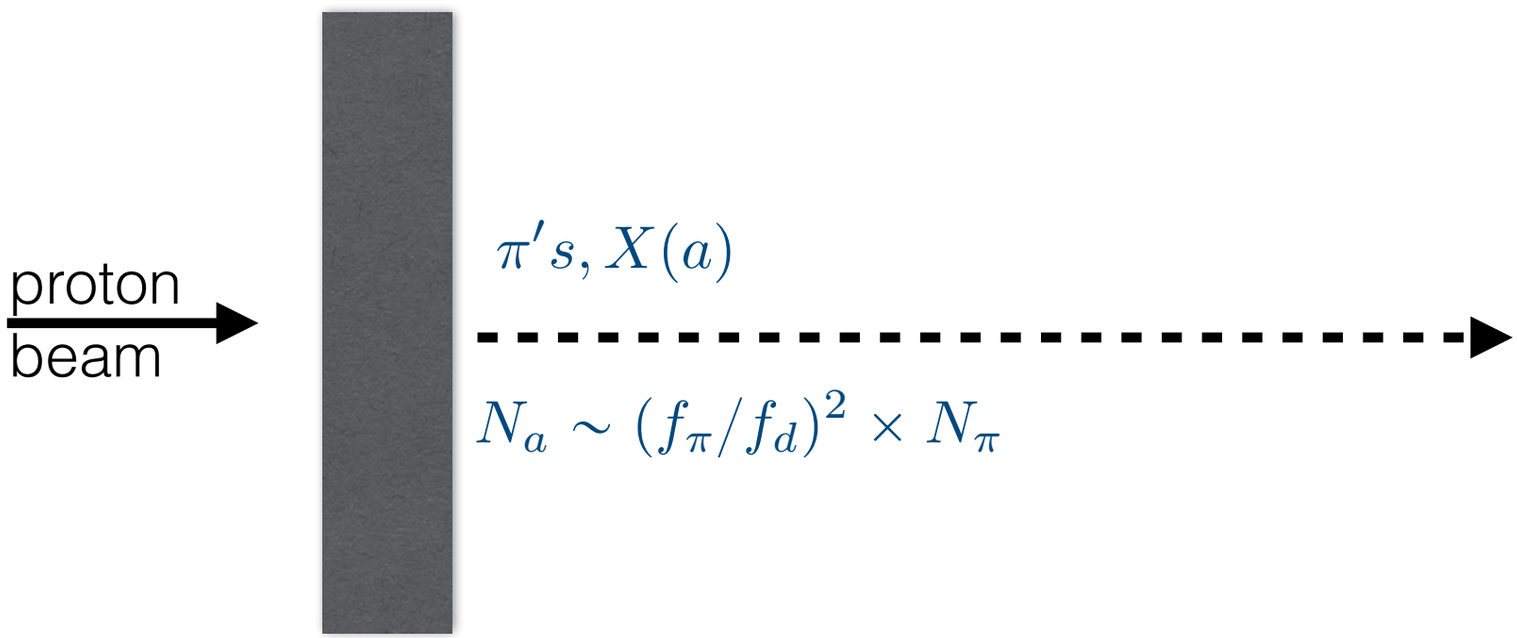
Abundance of X_p determines the vertical position of curves

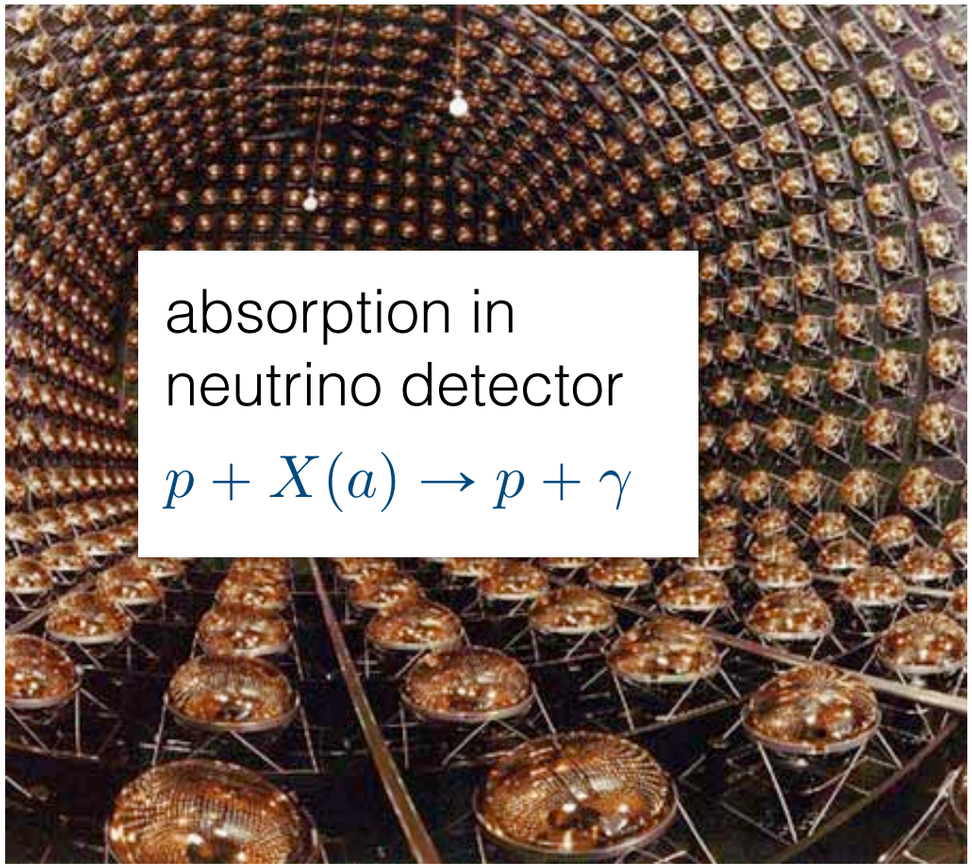


D only forms, here but a from early decays survive

Intensity frontier prospects

Target for neutrino experiments with hadronic drivers

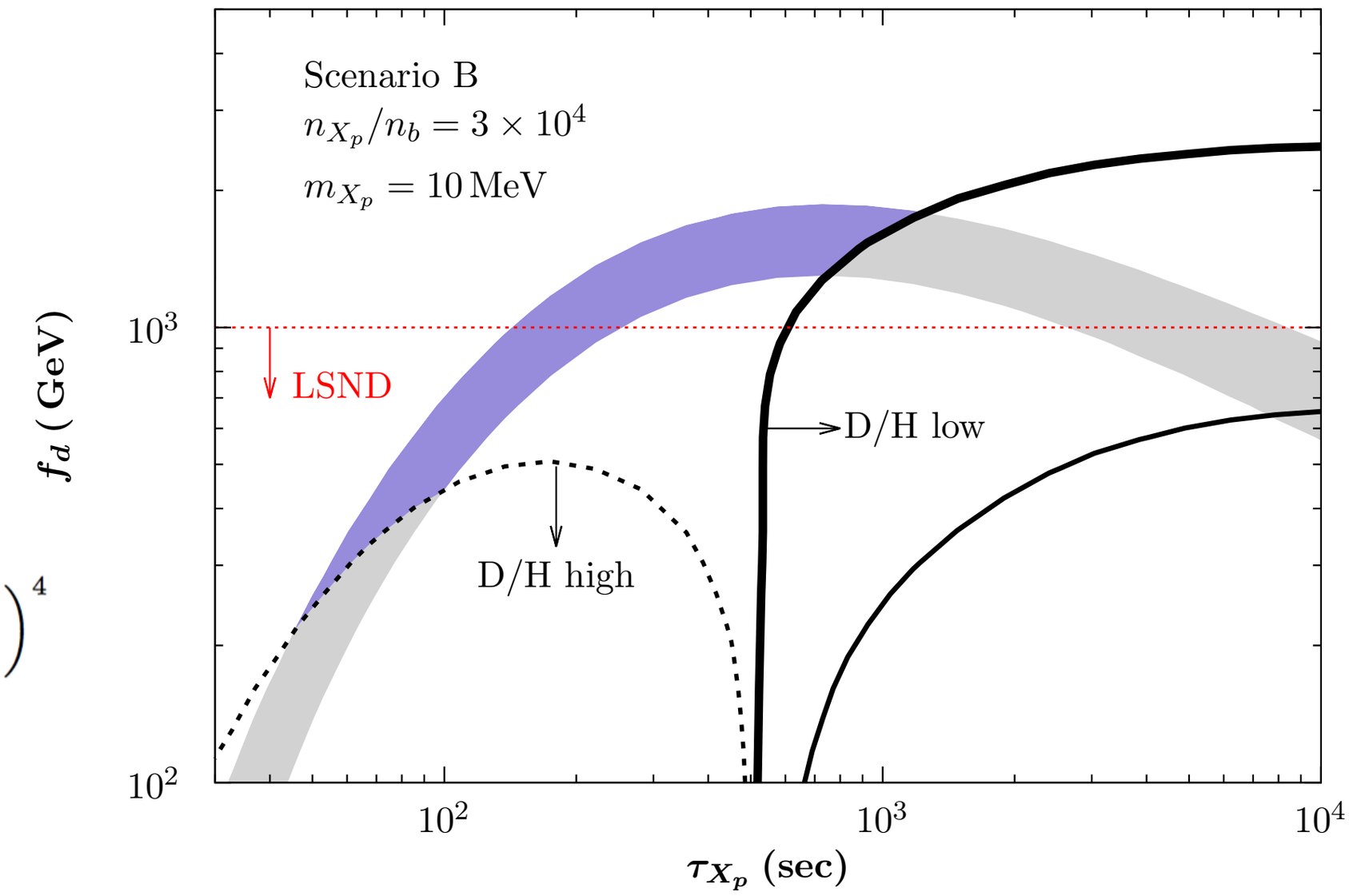




Intensity frontier prospects

LSND puts most stringent limits (adopted from their measurement of neutrino-electron elastic scattering)

$$N_{\text{events}} \sim \frac{N_a N_p \sigma_{ap}}{4\pi L^2} \sim 6 \times \left(\frac{\text{TeV}}{f_d}\right)^4$$



(a more detailed studies, including a consideration of astro-constraints will go into a longer paper)

Conclusions

1. Excursion to non-WIMP Dark Matter scenario: sub-MeV “dark photons”; probed through stellar energy loss; DP-DM is a rare case where direct laboratory limits are superior to astrophysical constraints

2. BBN provides a cosmological consistency test that must be passed by any new physics model with particle content present > 1 sec after Big Bang

3. *One quantitative problem in BBN:* predicted lithium abundance in disagreement with observations at high statistical significance

   => new solution with MeV particles that are searchable at the intensity frontier

Discussion workshop following the winter conferences

- LHC and collider physics
- Flavor
- Dark Matter

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