Dark Vectors in Experiment and Cosmology

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Plan

1. Introduction
2. Astrophysics of light, feebly interacting particles
3. Light vector signals in direct detection experiments
4. Dark Photon Dark Matter
5. Cosmological constraints on decaying vectors

reports on works done in collaboration with
H. An, A. Fradette, M. Pospelov, A. Ritz

Dark Photons

Model parameters

$\kappa,\ m_V,\ (e',\ m_h')$

$\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \underbrace{\times\, U(1)'}$ with Vector V_μ

$$-\frac{\kappa'}{2} F^{Y}_{\mu\nu} V^{\mu\nu} \xrightarrow[\text{scale}]{\text{below EW}} -\frac{\kappa}{2} F_{\mu\nu} V^{\mu\nu}$$

$$\mathcal{L} = -\frac{1}{4} F^2_{\mu\nu} - \frac{1}{4} V^2_{\mu\nu} - \frac{\kappa}{2} F_{\mu\nu} V^{\mu\nu} + e J^{\mu}_{\mathrm{em}} A_\mu$$

Stueckelberg case

$$\mathcal{L} \supset -\frac{1}{2} m_V V_\mu^2$$

“hard photon mass”

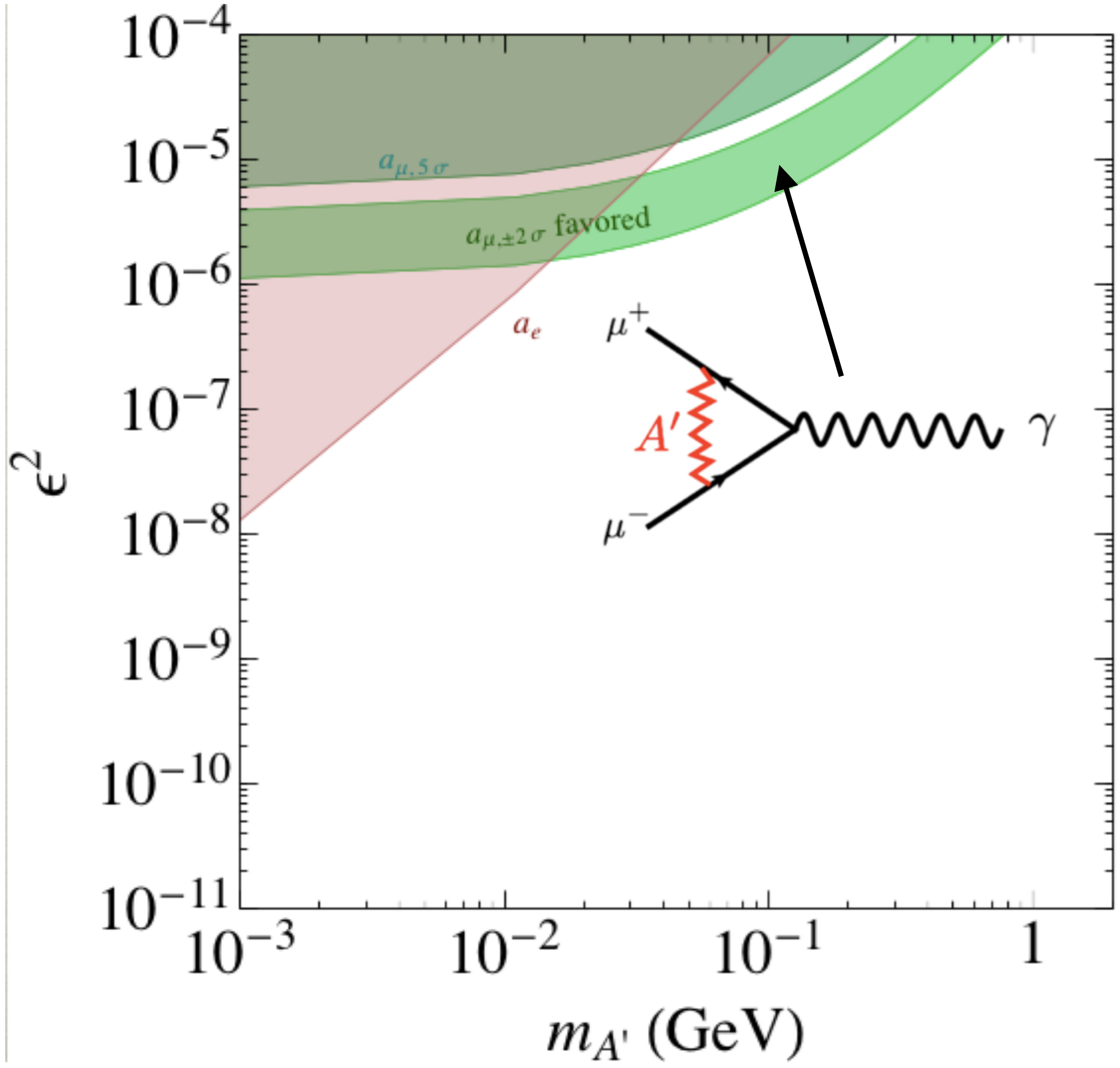
Higgsed case

$$\mathcal{L} \supset -\frac{1}{2} m_V V_\mu^2 + e' m_V h' V_\mu^2 + \frac{1}{2} e'^2\, h'^2 V_\mu^2$$

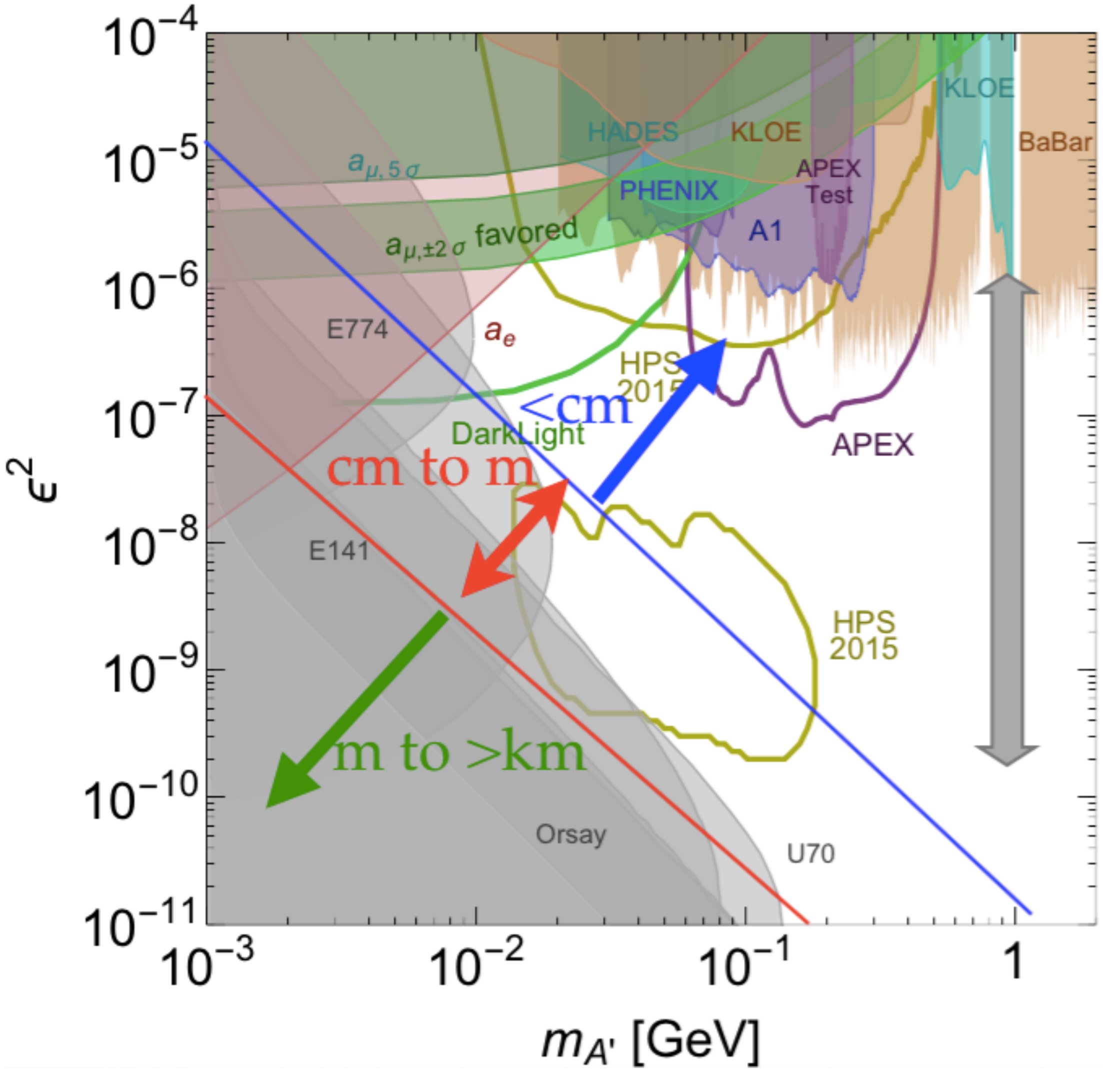
+ h’ self-interactions

Dark Photons

2008

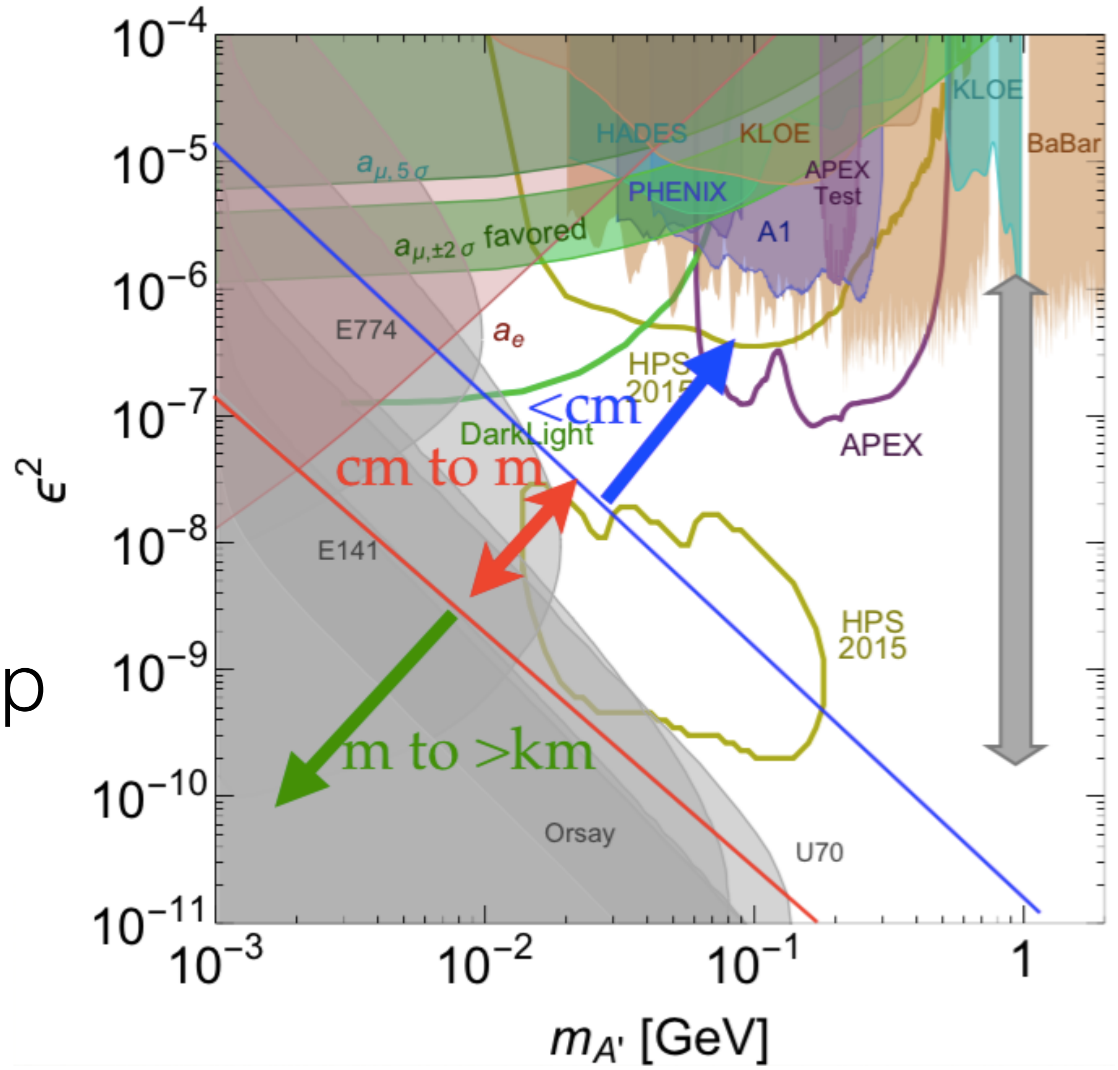


2014



plot illustrations from N.Toro

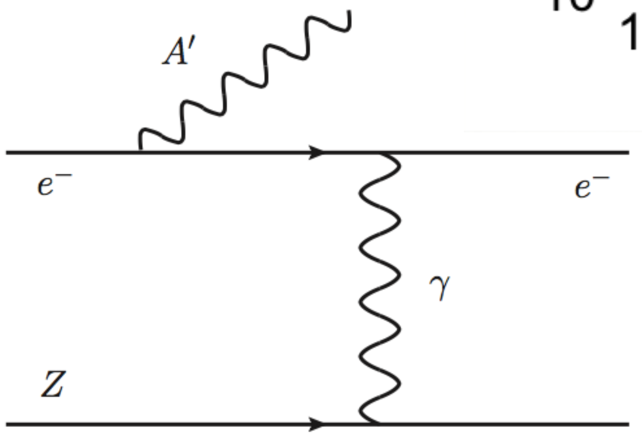
Dark Photons



e- fixed target expt.
(A1, APEX, HPS, …)

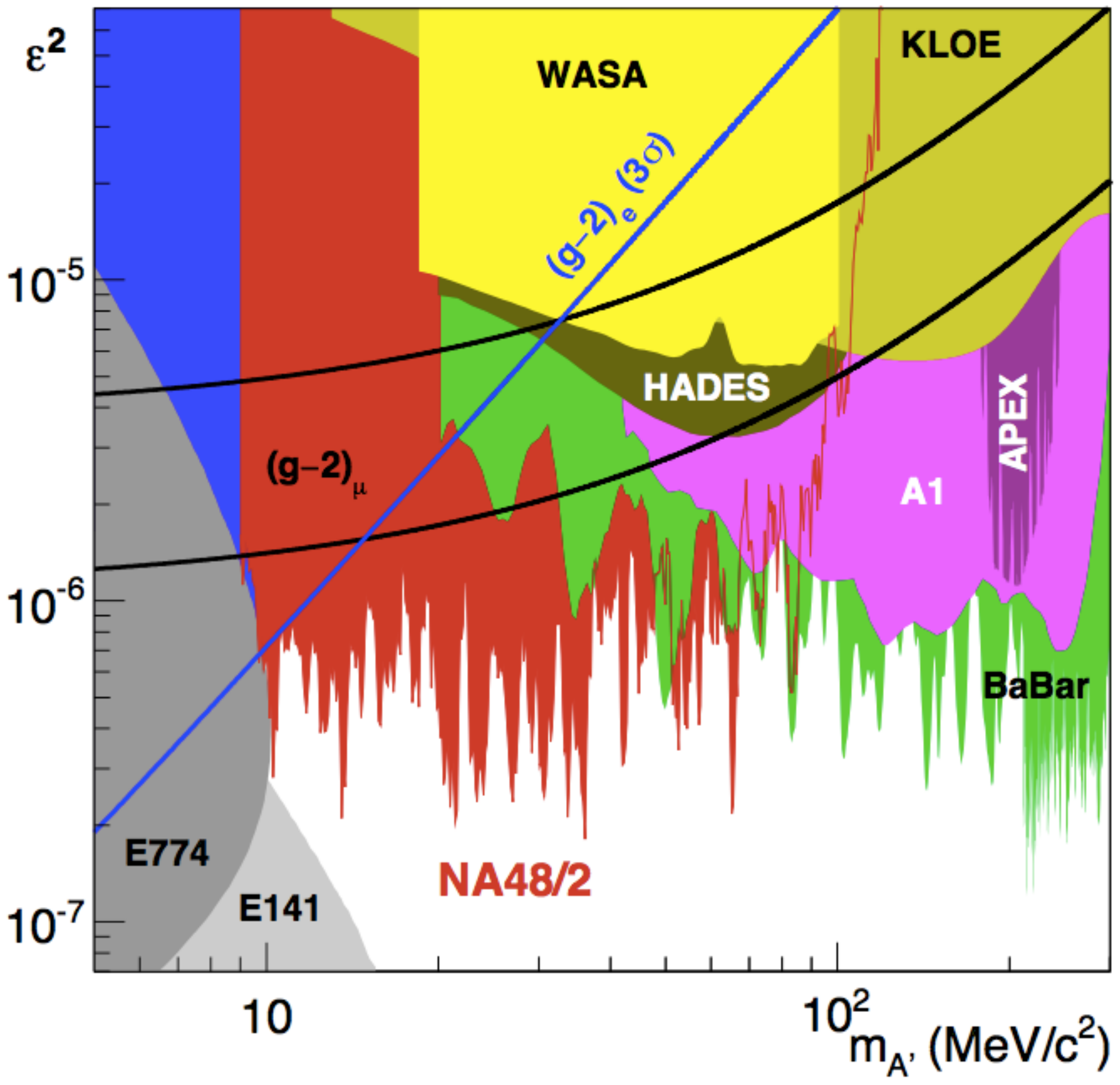
e+ e- colliders
(BaBar, KLOE, Belle)

e- beam dump
experiments



(among other searches)

Dark Photons

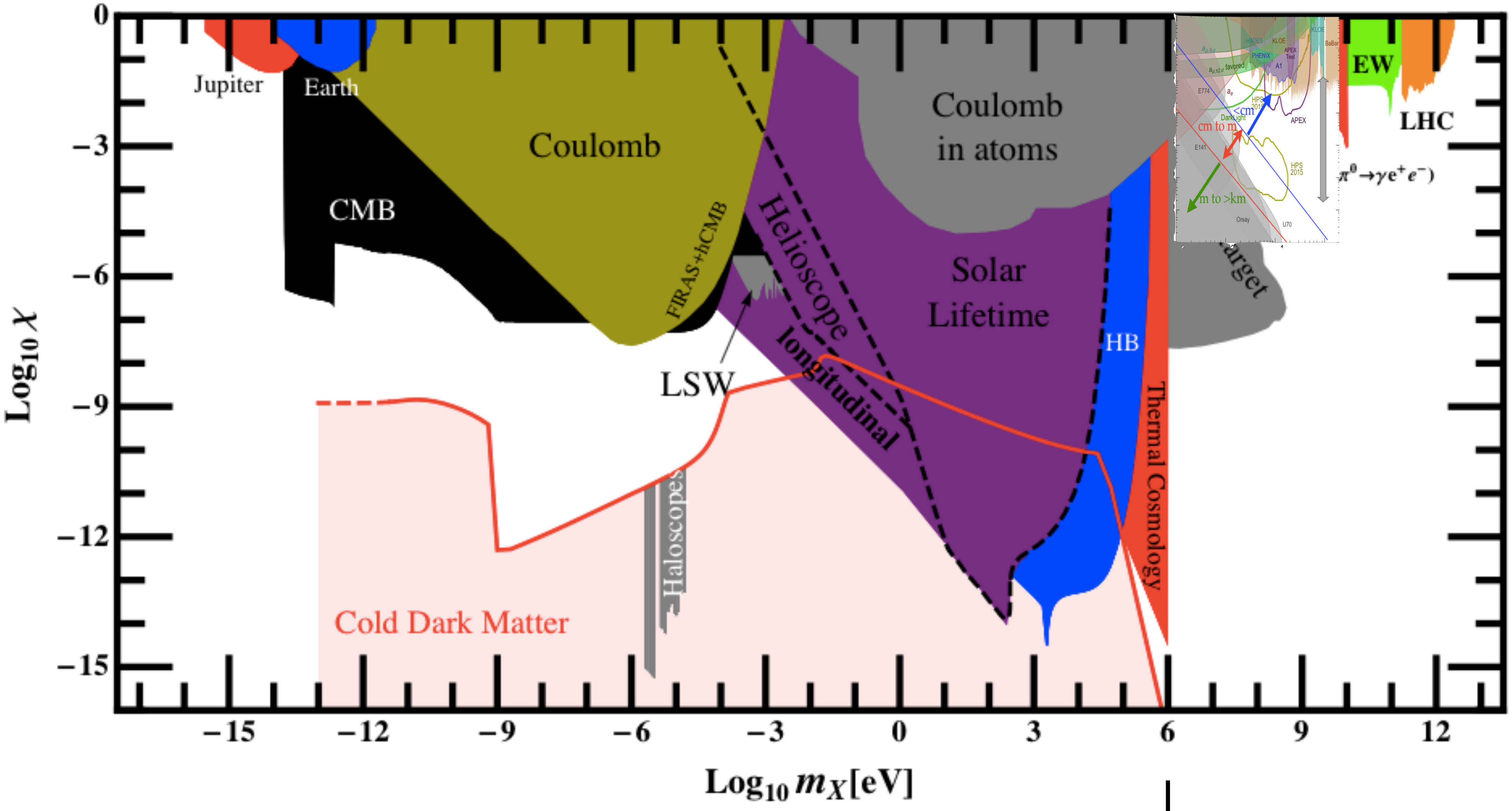


NA48/2 collaboration 2015
(data 2003-2004)

(g-2) explanation of the muon is now excluded from CERN SPS Kaon facility through

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

Dark Photons

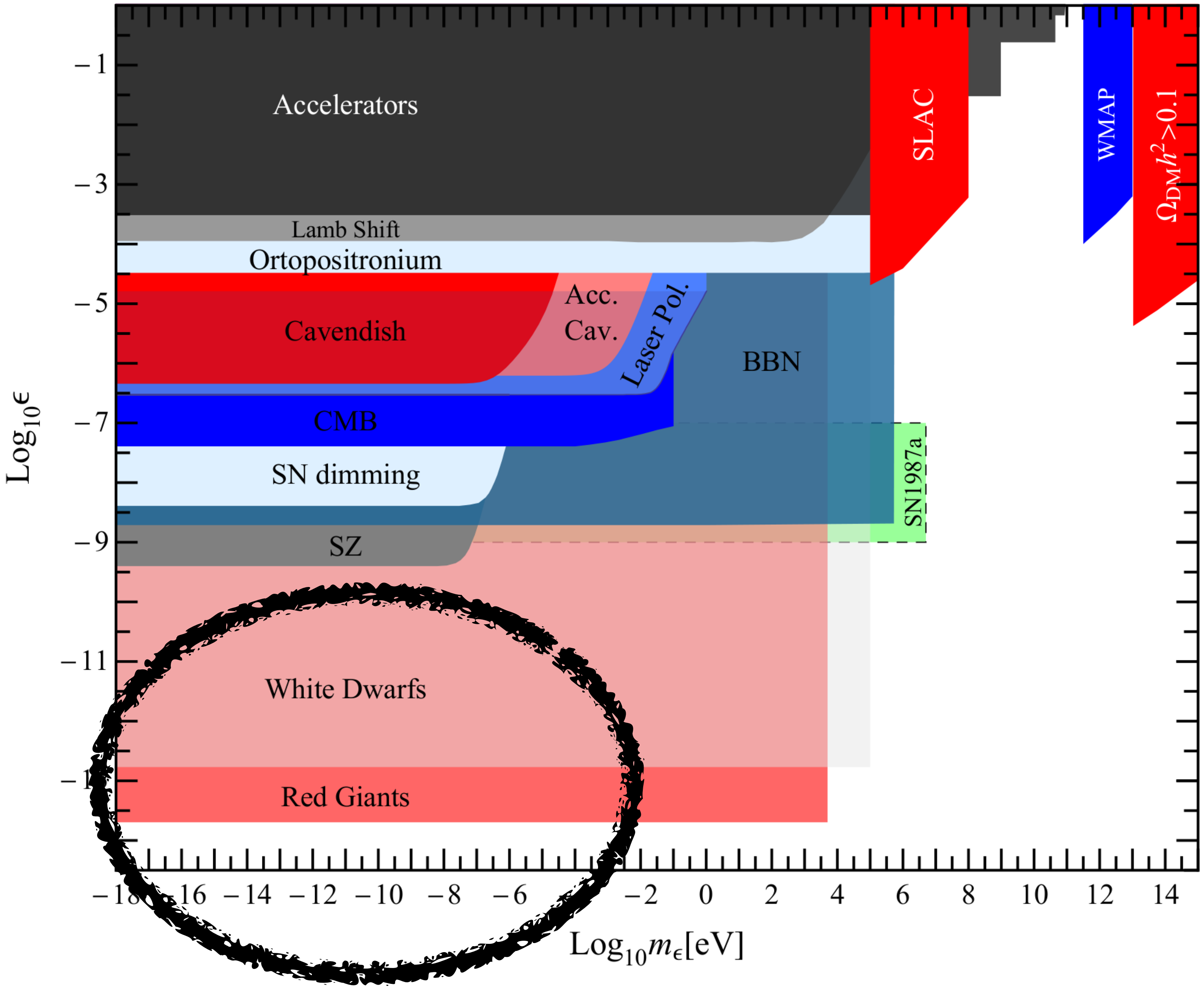


1. Astrophysical constraints vs. rare event searches

2. Cosmological constraints

Fig. from Jaeckel 2013

Devising *prospective* experimental searches for very light, feebly interacting particles is hard



e.g. millicharged particles

Name of the game:

beat astrophysical limits with direct laboratory probes

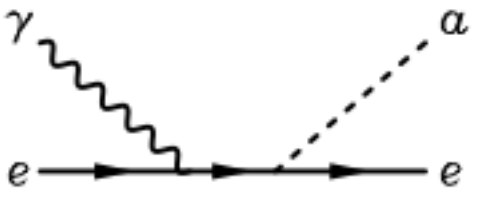
Stars as particle physics laboratories

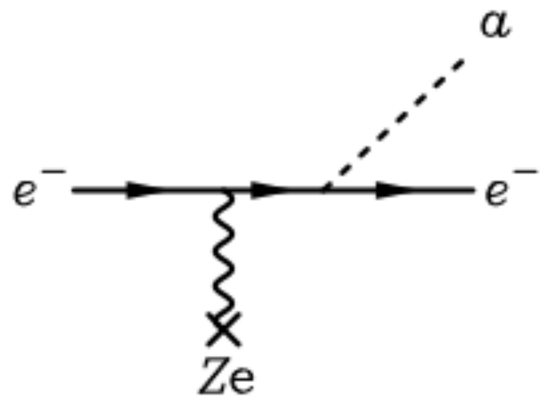
Virial theorem: $\langle E_{\rm kin}\rangle = -\frac{1}{2}\langle E_{\rm grav}\rangle$

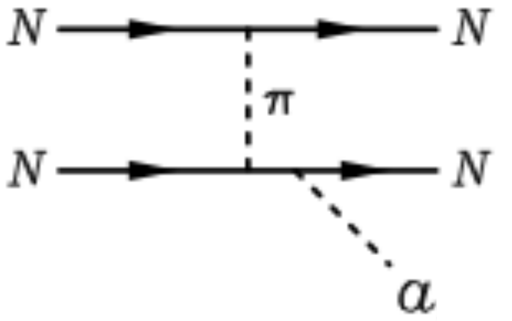
(imagine, the star forms from an initially dispersed cloud) $\frac{3}{2}T = \frac{1}{2}\frac{GM_\odot m_p}{R_\odot}$

=> $T = O(\rm keV)$ core temperature of solar mass star

=> Particles with mass < $O(\rm keV)$ are kinematically accessible and can be produced. E.g. axions







etc.

Reaction to energy loss

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

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

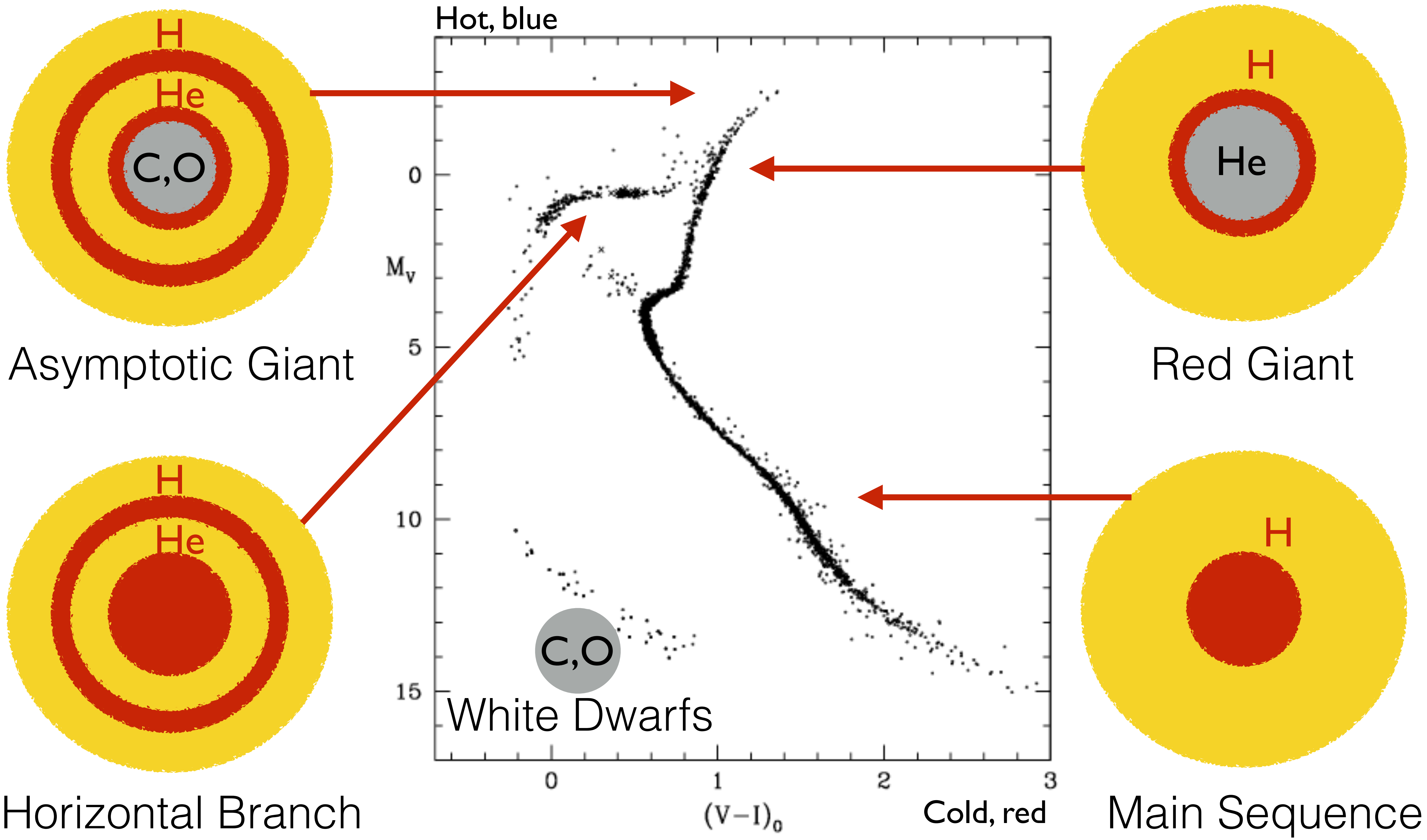
Virial theorem: $\langle E_{\mathrm{kin}} \rangle = -\frac{1}{2} \langle E_{\mathrm{grav}} \rangle$

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

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

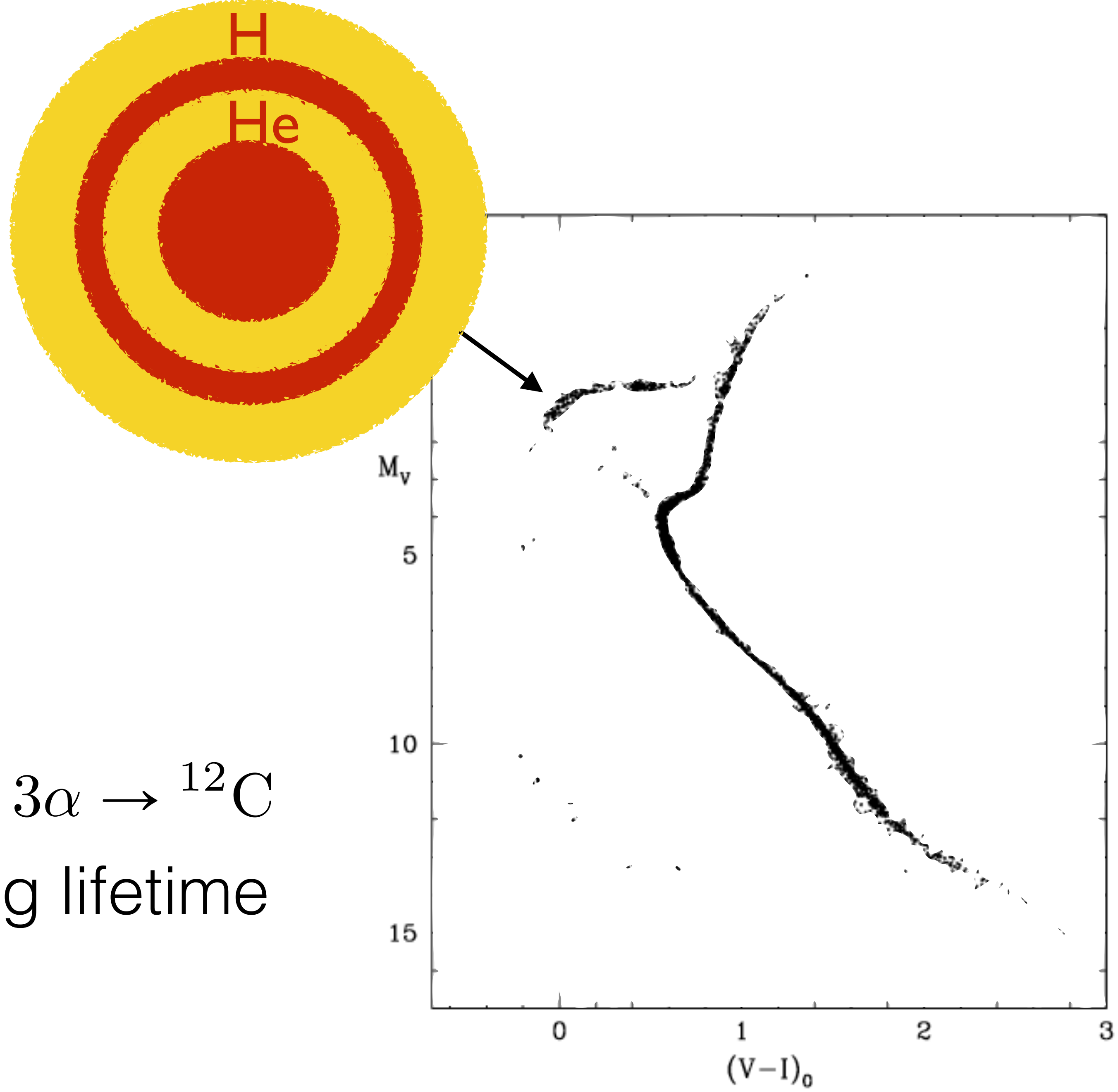
2. Stars supported by degeneracy pressure (white dwarfs, neutron stars): possess positive heat capacity, the star indeed cools by the energy loss

Stars as laboratories



Globular Cluster color-magnitude diagram

Horizontal Branch stars



HB helium burning core

$\rho \approx 10^4\,\mathrm{g\,cm^{-3}}$ $T \approx 10^8\,\mathrm{K}$

Energy loss leads to increased $3\alpha \to {}^{12}\mathrm{C}$ and shortens the helium burning lifetime

Observable:

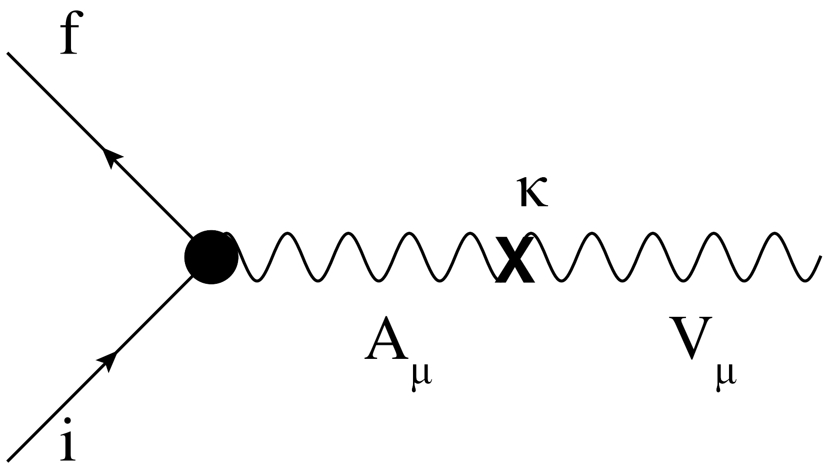
Predicted number of stars on HB vs on the RGB in Globular Clusters (which are all of the same age) agrees within 10% with observations

Limit: luminosity into new states should not exceed nuclear energy generation rate $L_x \lesssim 0.1 L_{3\alpha}$, which is $\epsilon \lesssim 10\,\mathrm{erg\,g^{-1}\,s^{-1}}$

DP Stellar production - revisited

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

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



in-medium propagator

$$\mathcal{M}_{i\to f+V_{T(L)}} = \kappa m_V^2 \, [e J_{\mathrm{em}\,\mu}]_{fi} \, \langle A^\mu , A^\nu \rangle \, \epsilon_\nu^{T(L)}$$

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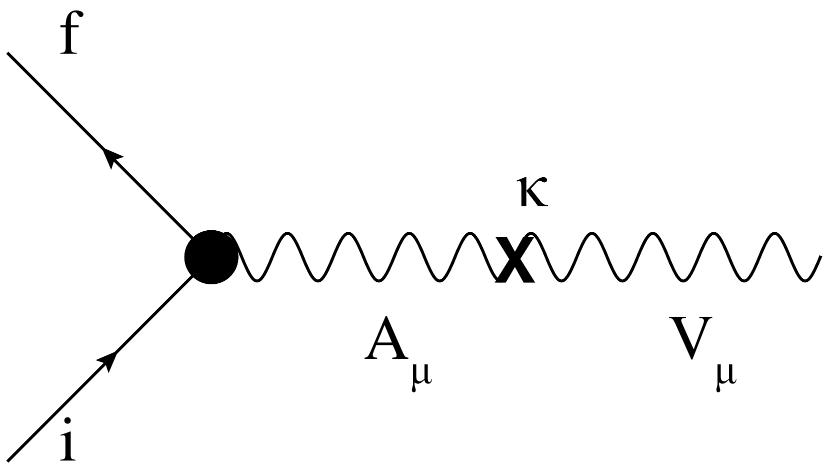


in-medium propagator

$$\mathcal{M}_{i \to f + V_{T(L)}} = \kappa m_V^2 \left[e J_{\mathrm{em}\,\mu} \right]_{fi} \langle A^\mu, A^\nu \rangle \, \epsilon_\nu^{T(L)}$$

$$\epsilon^L = m_V^{-1} (|\vec{k}|, 0, 0, \omega)$$

Longitudinal Part: $\langle A_0, A_0 \rangle = \frac{1}{|\vec{k}|^2}.$ $\quad (k \simeq \omega \gg \omega_p)$ Braaten, Segel 1993

Transverse vs. longitudinal modes

Transverse modes:

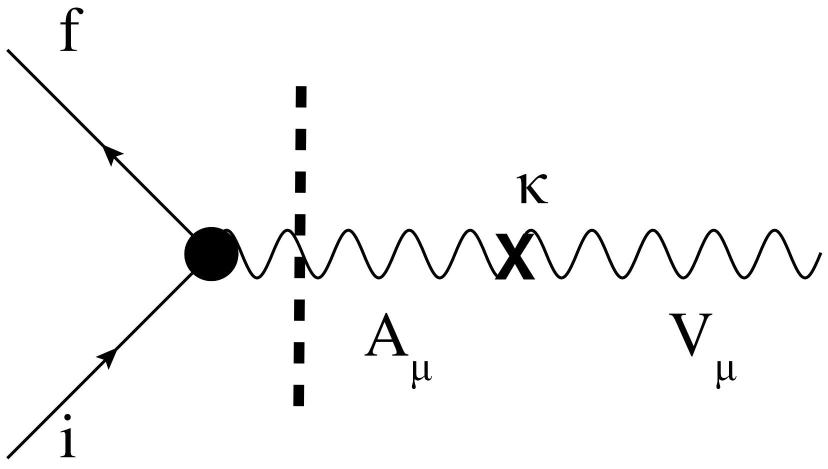
$$\text{Rate}_{SM\to V_T} \propto \begin{cases} \kappa^2 & \text{in vacuum, } m_V \gg \omega_p, \\ \kappa^2 m_V^4 \omega_p^{-4} & \text{in medium, } m_V \ll \omega_p. \end{cases}$$

Longitudinal modes (Stueckelberg case):

$$\text{Rate}_{SM\to V_L} \propto \kappa^2 m_V^2 \omega^{-2}, \quad \text{both in vacuum and in medium.} \ (k \simeq \omega \gg \omega_p)$$

=> can lead to enhancements of longitudinal mode by many orders of magnitude $\boldsymbol{\omega_P^2/m_V^2 \sim 10^{10}}$

Stellar V-production



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

Transverse Resonance

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

Longitudinal Resonance

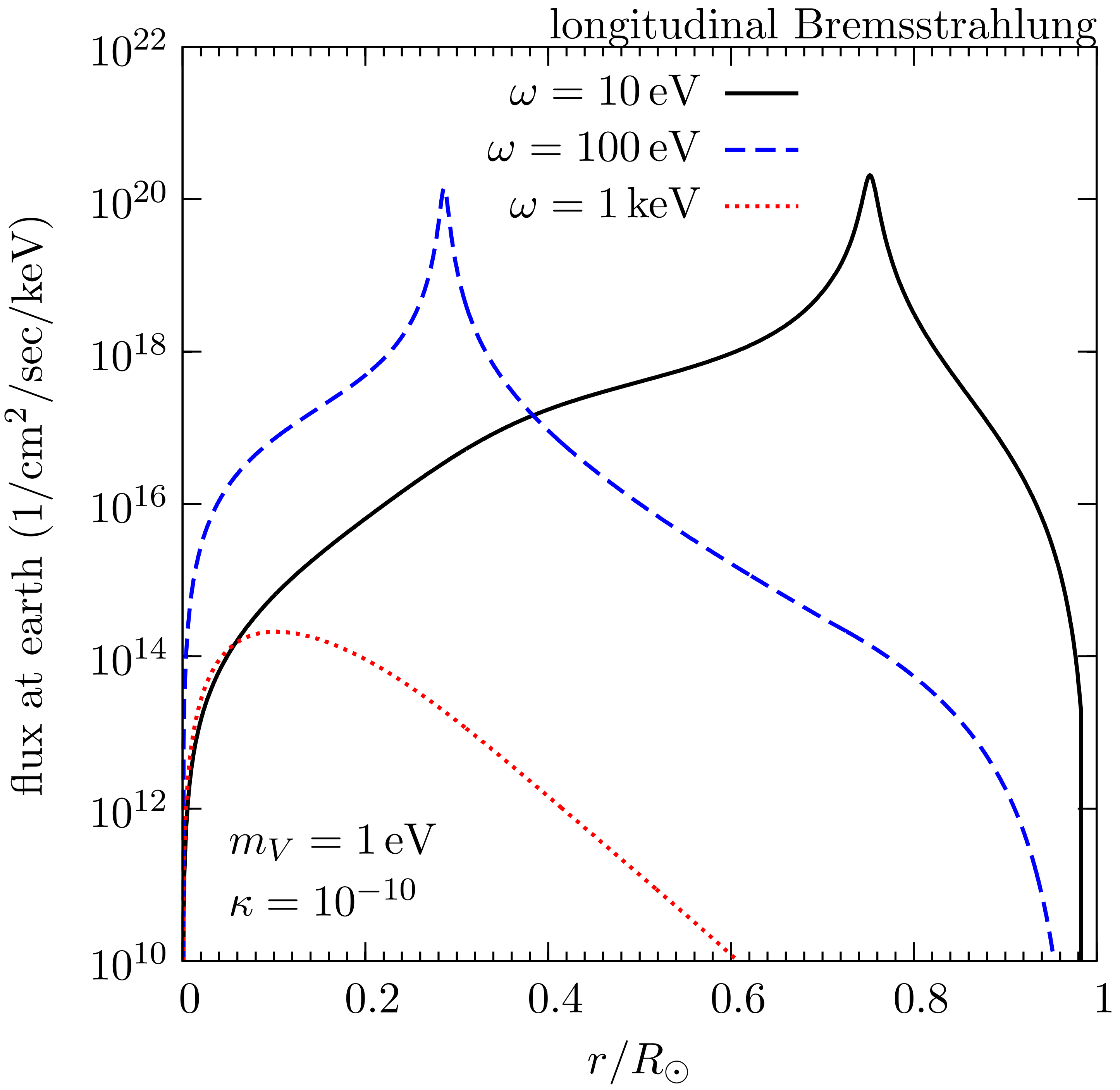
$$m_V^2 = \mathrm{Re}\,\Pi_L = \omega_p^2 m_V^2/\omega^2$$

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

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

(see also Redondo 2008 for transverse emission)

Stellar energy loss (here: sun)



new resonant emission found in the longitudinal mode

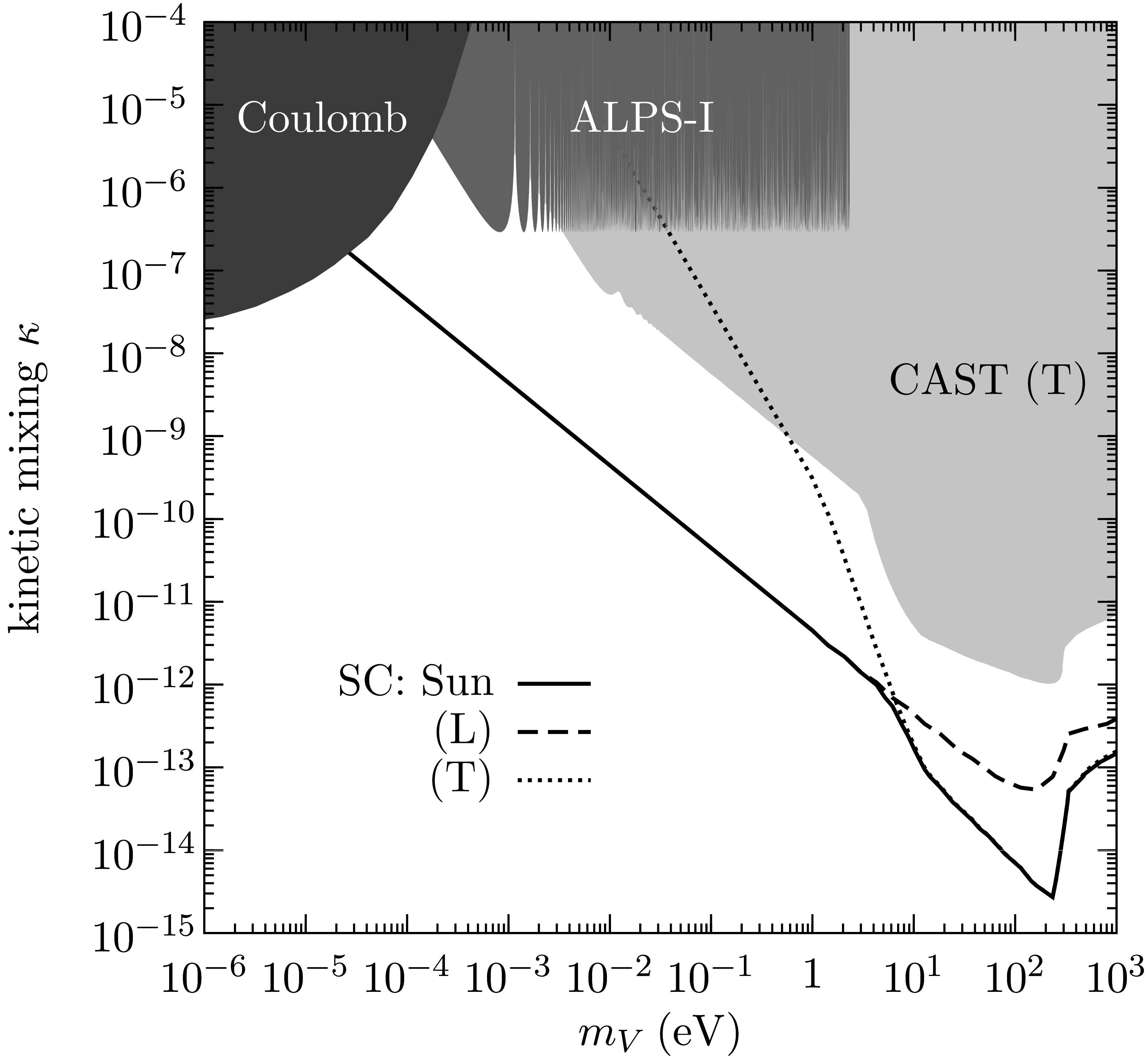
inside the sun:

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

=> resonance can always be met for

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

Stellar energy loss - revised



Energy loss constraint from sun:

Observable: SNO, 8B flux

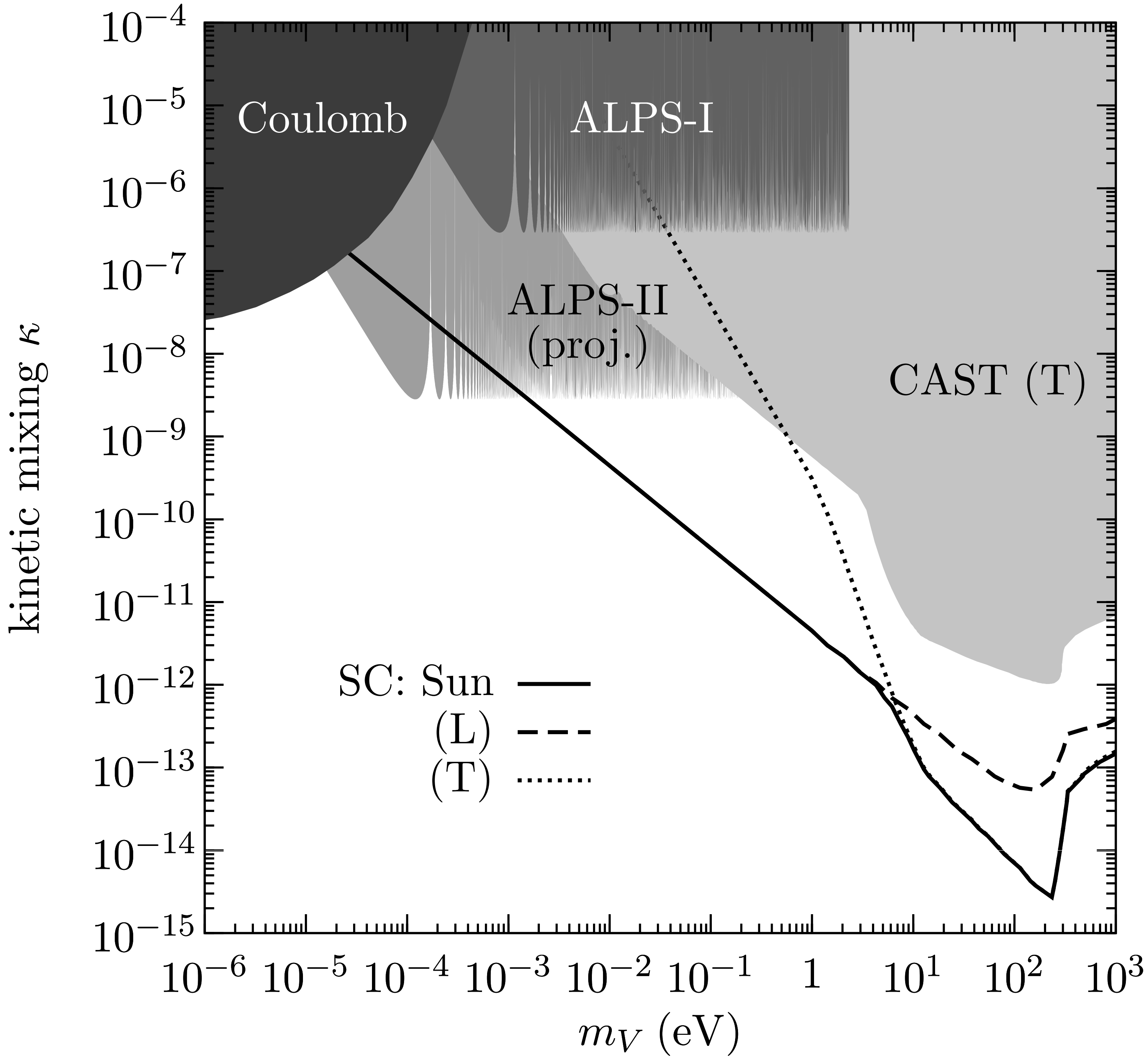
$$L_{\text{dark}} \leqslant 0.1 L_\odot$$

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

Helioscope and LSW experiments inside excluded regions

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

Stellar energy loss - revised



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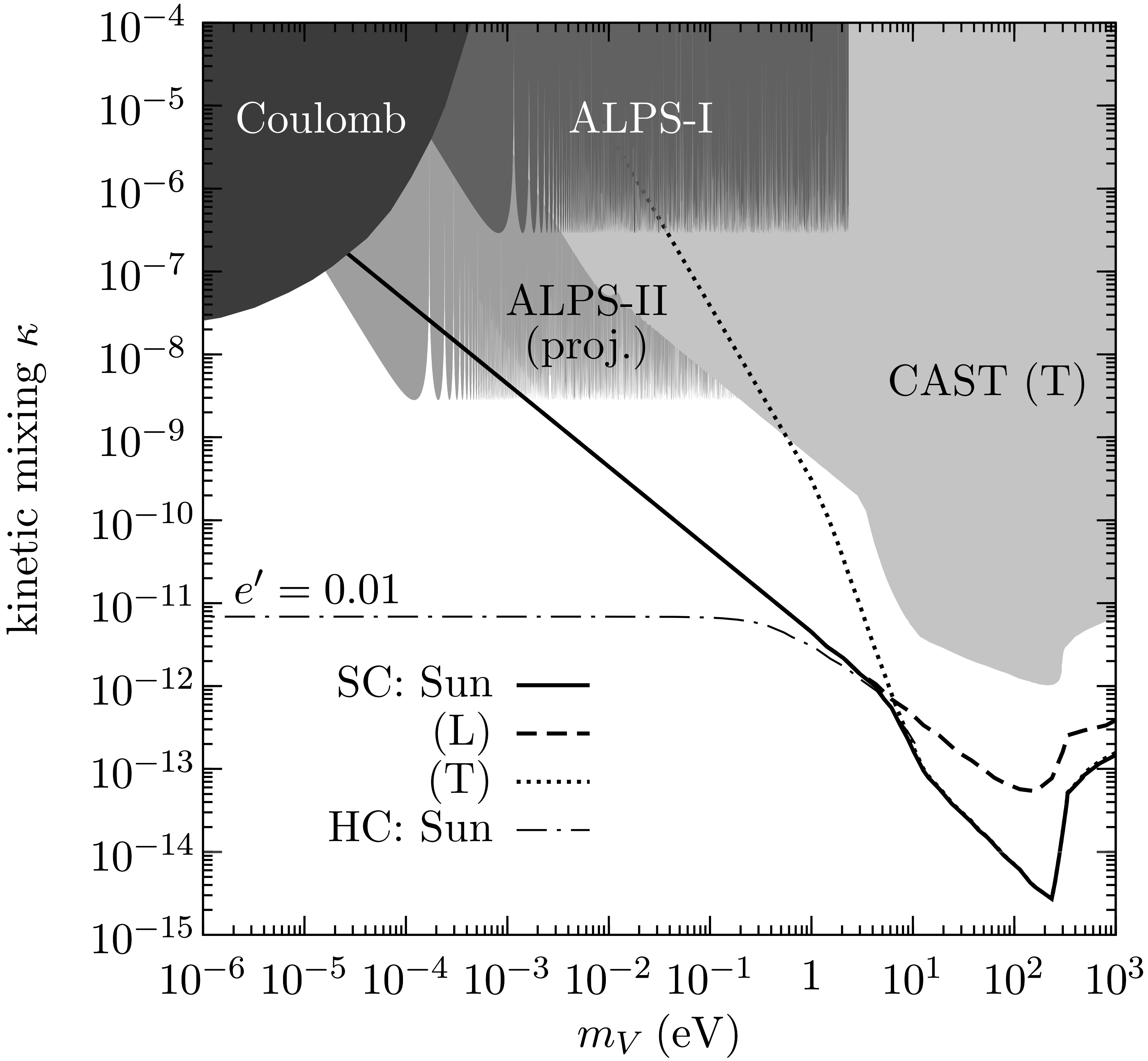

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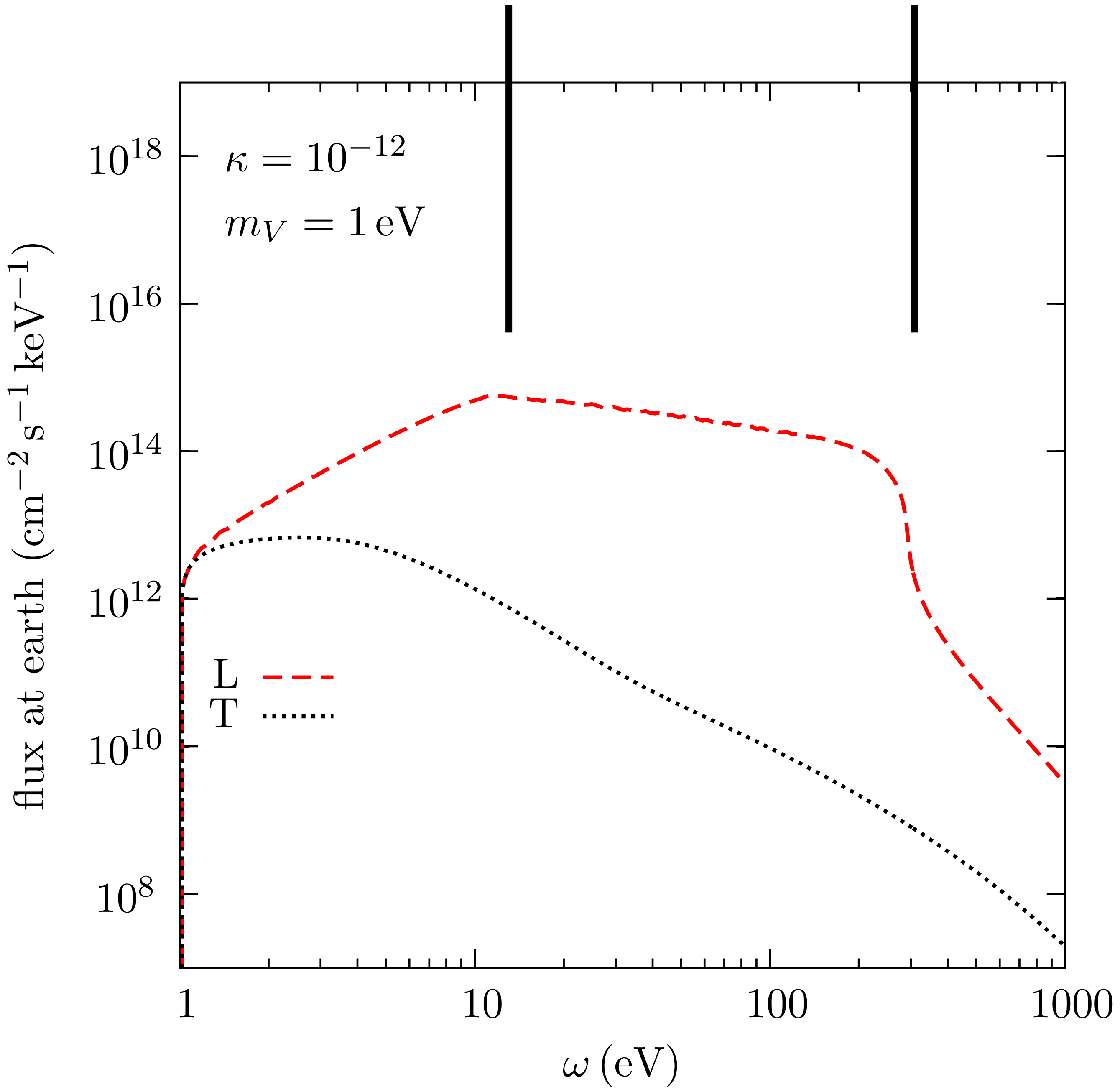
Direct Detection of Dark Photons

atomic ionization threshold

end of resonance region



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

Tapping into the Dark Matter “liquid scintillator revolution”

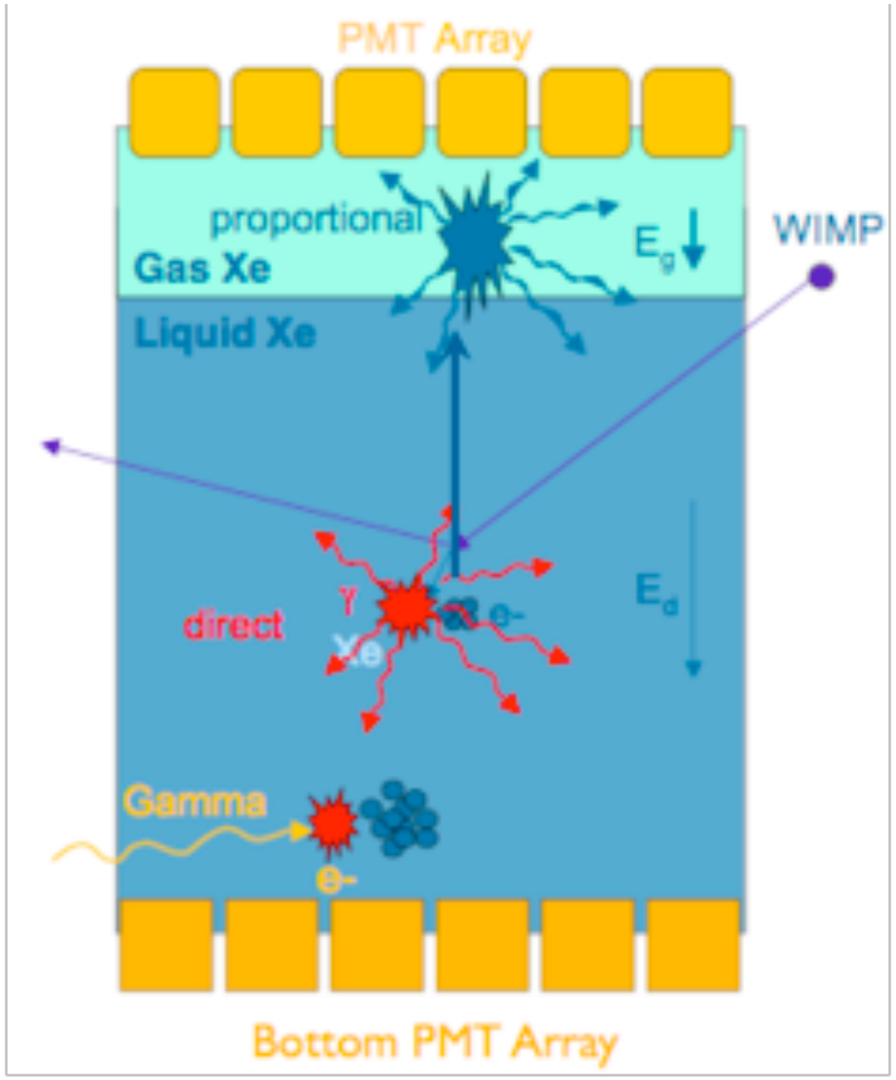
Inexpensive, scalable, dense, and can be purified.

High scintillation yields without absorbing own scintillation light.

Drifting charges in an electric field is a powerful amplification mechanism

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

=> ionization only analyses push this boundary.



Dark Photon Absorption

(including medium effects)

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

Rate: $\Gamma_{T,L} = \frac{1}{2\omega}(2\pi)^4\delta^{(4)}(q+p_i-p_f)e^2\kappa^2_{T,L}\varepsilon^*_\mu\varepsilon_\nu\sum_f\langle p_i|J^\mu_{em}(0)|p_f\rangle\langle p_f|J^\nu_{em}(0)|p_i\rangle$

Dark Photon Absorption

(including medium effects)

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

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

Dark Photon Absorption

(including medium effects)

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

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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

An, Pospelov, JP, 2013
An, Pospelov, JP, Ritz 2014

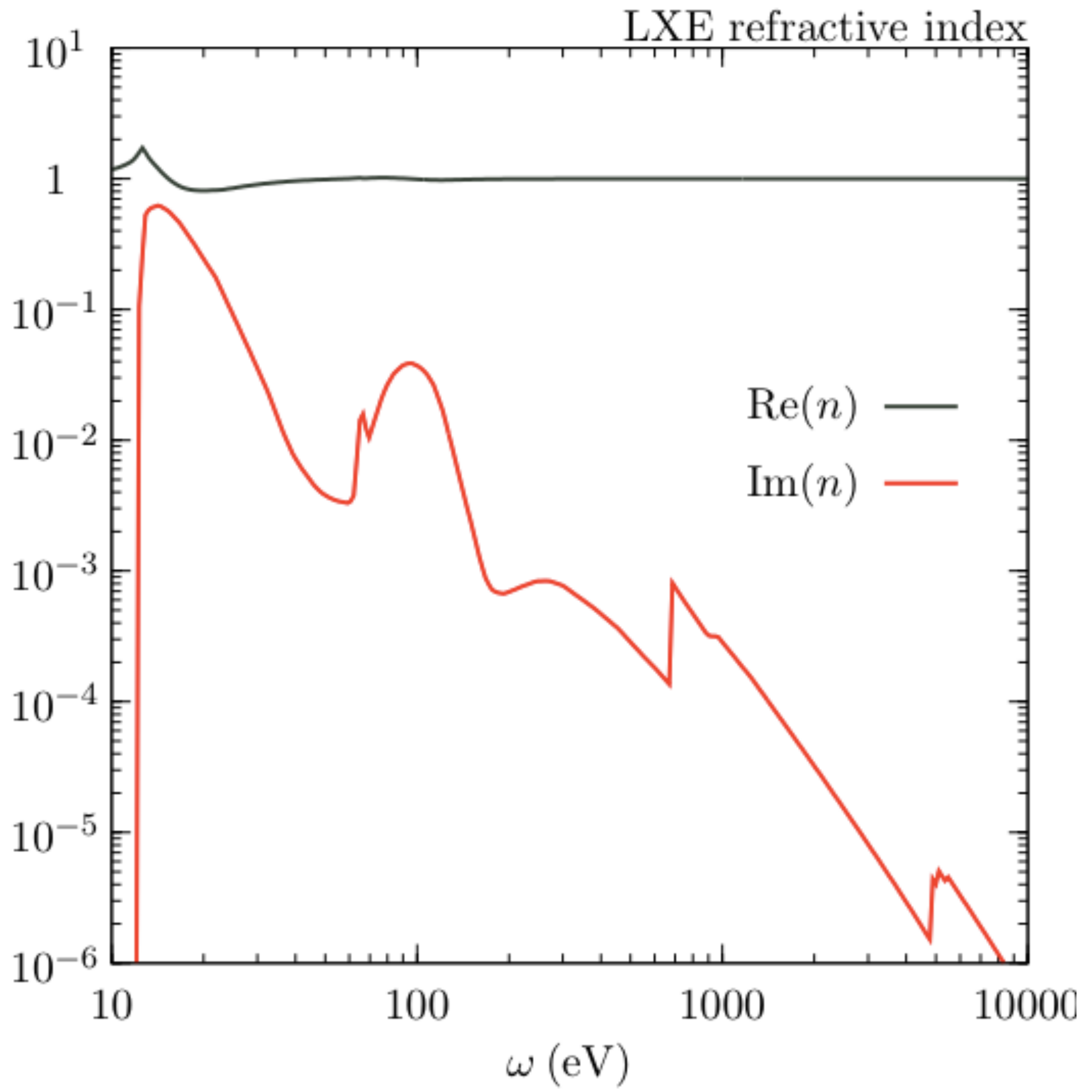
Absorption in Xenon

Compute absorption rate from Xenon refractive index

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

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

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

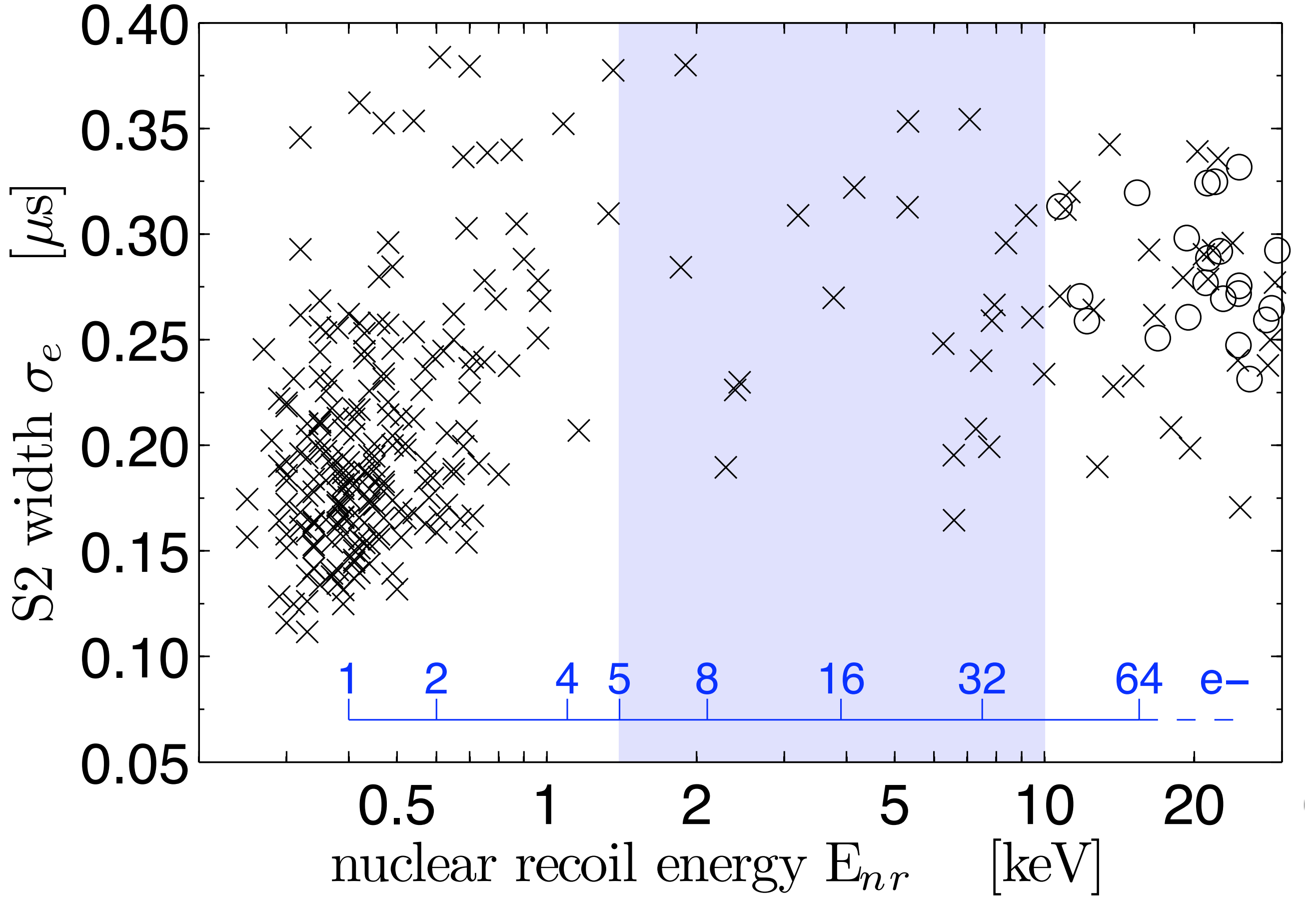


Absorption in Xenon

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

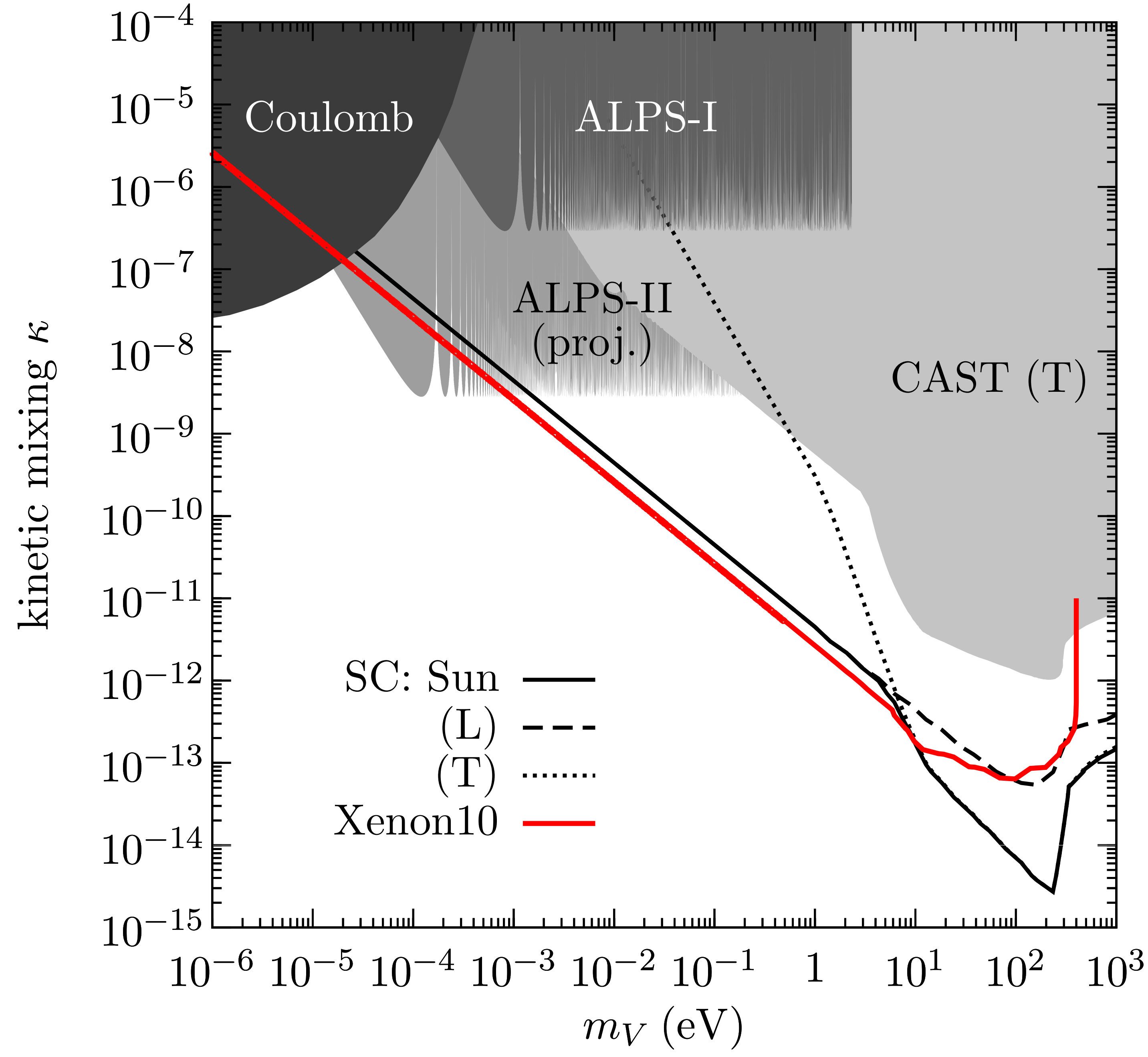


XENON10 collaboration, 2011

Direct detection experiments as Dark Photon Helioscopes

New direct detection limit superior to astrophysical bounds

something to look for in liquid Xenon experiments

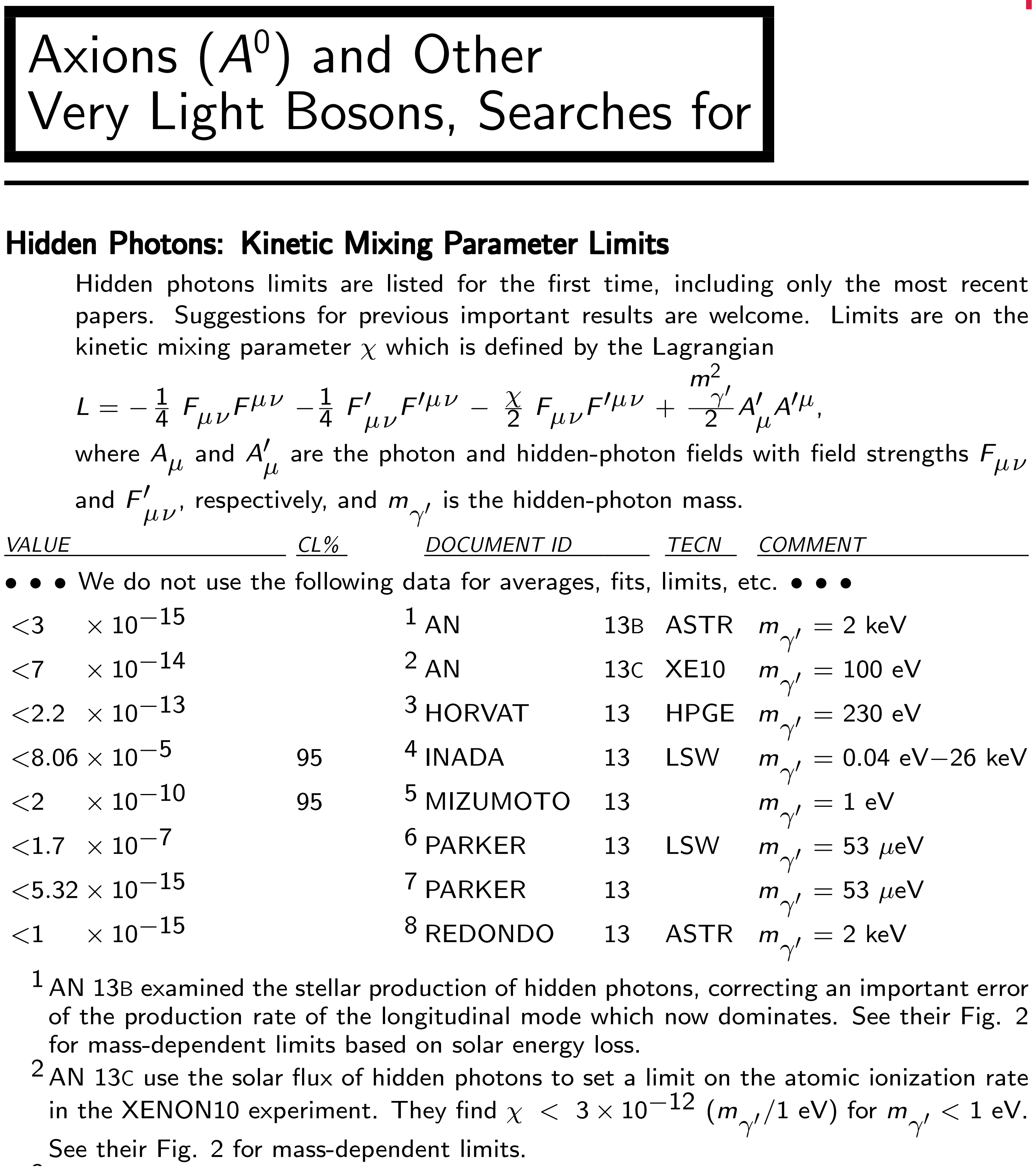


H. An, M. Pospelov, JP, PRL 2013

PDG

Stellar

XENON10



Axions (A^0) and Other Very Light Bosons, Searches for

Hidden Photons: Kinetic Mixing Parameter Limits

Hidden photons limits are listed for the first time, including only the most recent papers. Suggestions for previous important results are welcome. Limits are on the kinetic mixing parameter χ which is defined by the Lagrangian

$$L = -\frac{1}{4} F_{\mu\nu}F^{\mu\nu} - \frac{1}{4} F'_{\mu\nu}F'^{\mu\nu} - \frac{\chi}{2} F_{\mu\nu}F'^{\mu\nu} + \frac{m^2_{\gamma'}}{2} A'_{\mu}A'^{\mu},$$

where A_μ and A'_μ are the photon and hidden-photon fields with field strengths $F_{\mu\nu}$ and $F'_{\mu\nu}$, respectively, and $m_{\gamma'}$ is the hidden-photon mass.

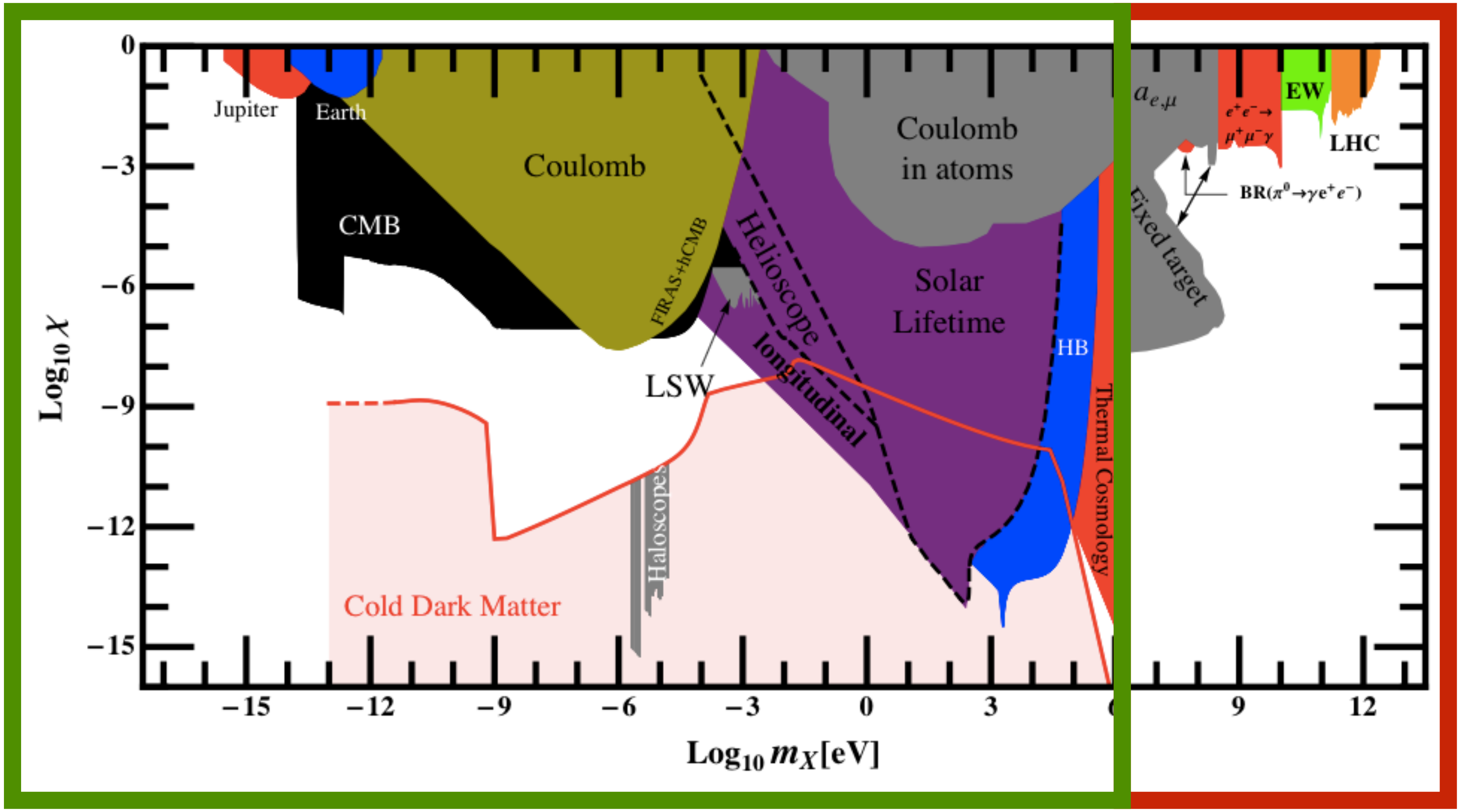
VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<3 \times 10^{-15}$		[1] AN	13B	ASTR	$m_{\gamma'} = 2$ keV
$<7 \times 10^{-14}$		[2] AN	13C	XE10	$m_{\gamma'} = 100$ eV
$<2.2 \times 10^{-13}$		[3] HORVAT	13	HPGE	$m_{\gamma'} = 230$ eV
$<8.06 \times 10^{-5}$	95	[4] INADA	13	LSW	$m_{\gamma'} = 0.04$ eV$-$26 keV
$<2 \times 10^{-10}$	95	[5] MIZUMOTO	13		$m_{\gamma'} = 1$ eV
$<1.7 \times 10^{-7}$		[6] PARKER	13	LSW	$m_{\gamma'} = 53$ μeV
$<5.32 \times 10^{-15}$		[7] PARKER	13		$m_{\gamma'} = 53$ μeV
$<1 \times 10^{-15}$		[8] REDONDO	13	ASTR	$m_{\gamma'} = 2$ keV

[1] AN 13B examined the stellar production of hidden photons, correcting an important error of the production rate of the longitudinal mode which now dominates. See their Fig. 2 for mass-dependent limits based on solar energy loss.

[2] AN 13C use the solar flux of hidden photons to set a limit on the atomic ionization rate in the XENON10 experiment. They find $\chi < 3 \times 10^{-12}$ $(m_{\gamma'}/1\text{ eV})$ for $m_{\gamma'} < 1$ eV. See their Fig. 2 for mass-dependent limits.

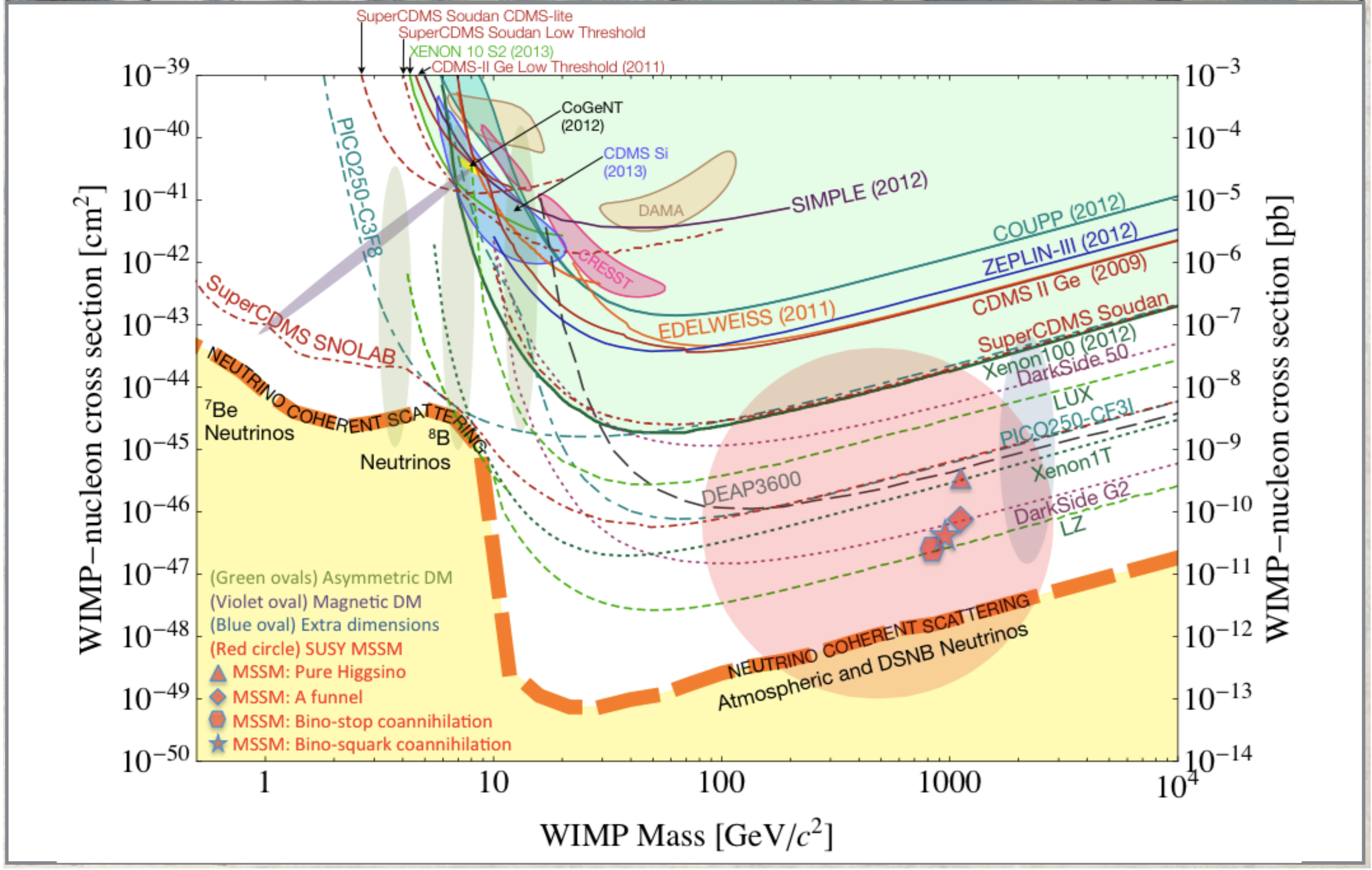
Can we make
Dark Photon Dark Matter?

Dark Photon Dark Matter?



V decays to
e+ e-, hadrons,…

Looking for new species



CF1 Snowmass report

Those were the good ole days

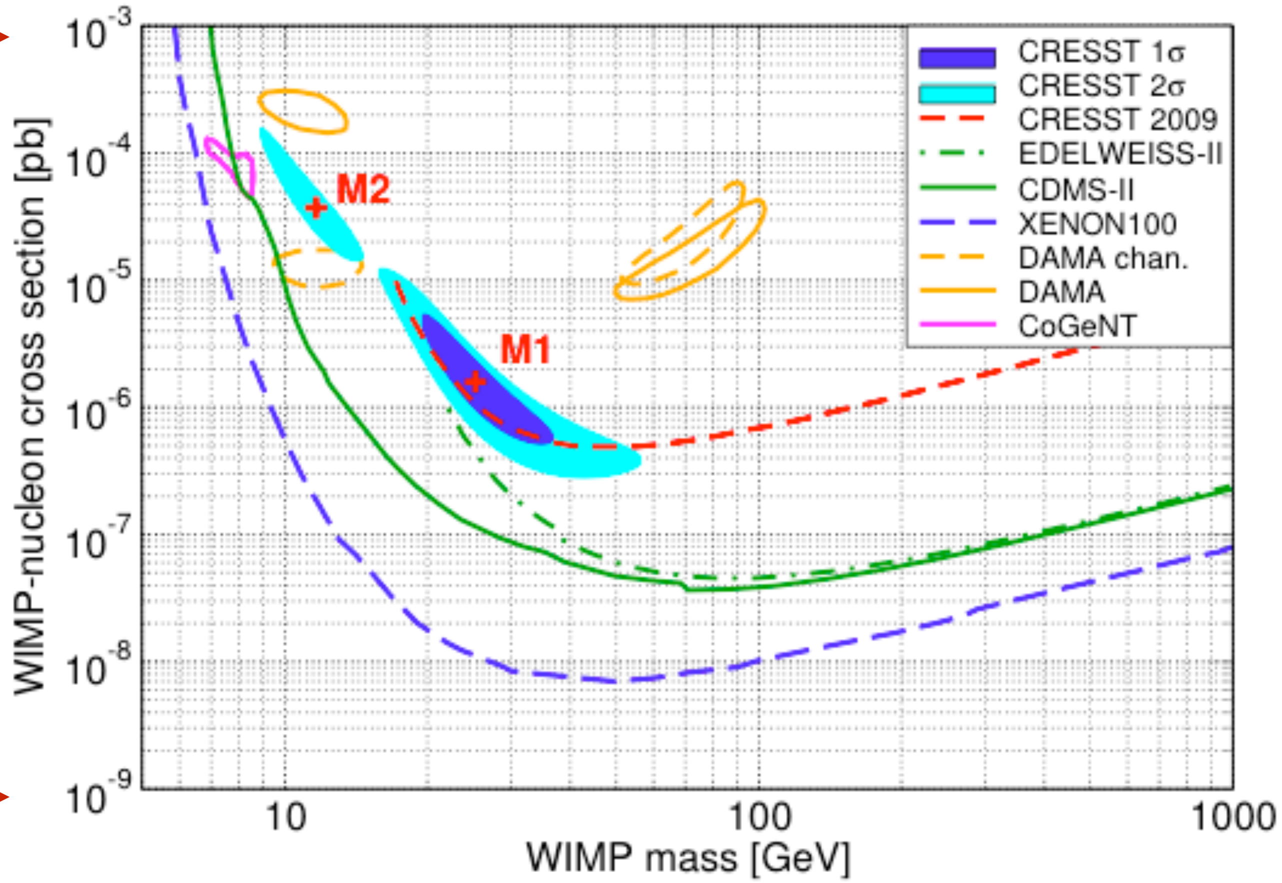
What about the Neutralino?

“Weakly” (= Z-mediated)
massive (=100 GeV)
particles (WIMPs)
are long gone:

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

Higgs-mediated interactions
are being probed right now!

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



What about the Neutralino?

NB: Direct detection may never completely exclude neutralino:

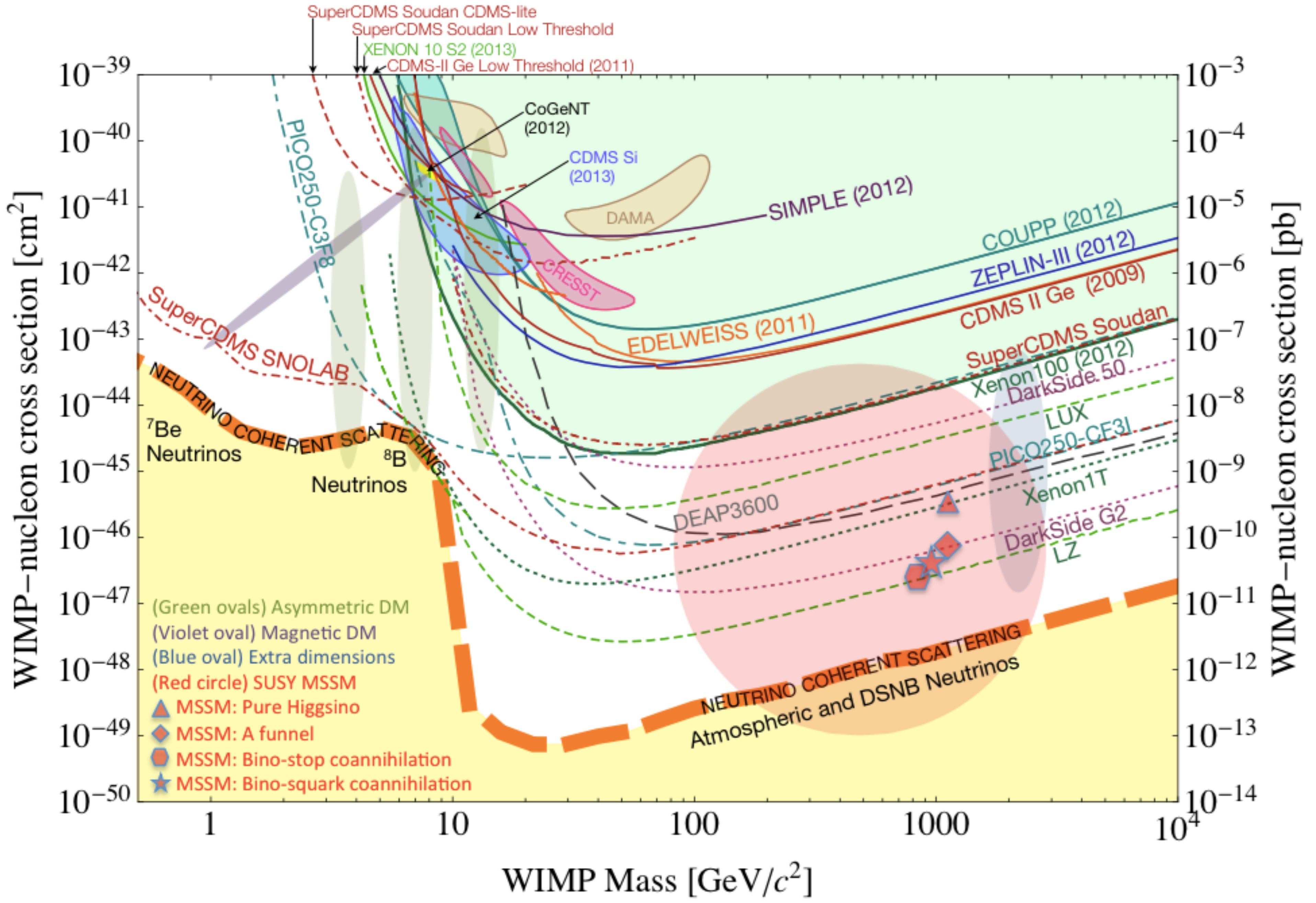
- *pure* neutralino (wino, bino, higgsino):

  Higgs couplings suppressed, because $h^\dagger \widetilde{h}\widetilde{w}\, , h^\dagger \widetilde{h}\widetilde{b}$
  pure wino/bino does not couple to Z

- *cancelations* in couplings to Z and Higgs

  “Well tempered neutralino” => “very fine tuned neutralino”

Looking for new species



CF1 Snowmass report

There may be other creatures than WIMPs!

“Simplified Models” of Dark Matter electron scattering

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

ψ …electron

Let’s take the example of our vector V with coupling $g_V = e\kappa$

Dark Photon Dark Matter

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

Only two free parameters, κ, m_V. Can we make Dark Matter?

Dark Photon Dark Matter

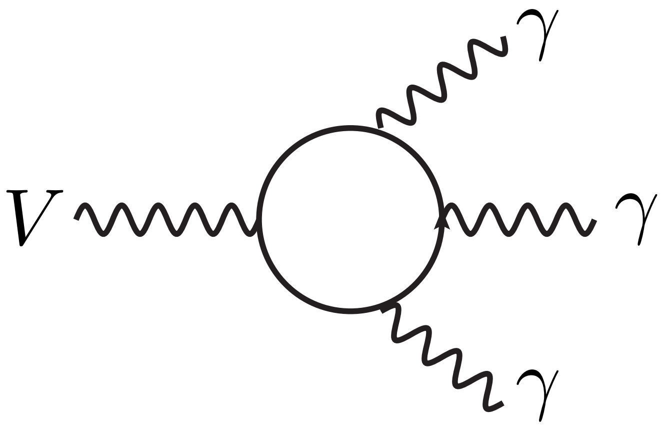
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^2 - \frac{1}{4}V_{\mu\nu}^2 - \frac{\kappa}{2}F_{\mu\nu}V^{\mu\nu} + \frac{m_V^2}{2}V_\mu V^\mu + eJ^\mu_{\rm em}A_\mu$$

Only two free parameters, κ, m_V. Can we make Dark Matter?

1. Make it light, below 2me. Prevents $V \rightarrow e^+e^-$ decay
2. Have small $\kappa \ll 1$, to slow down $V \rightarrow 3\gamma$

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

Pospelov, Ritz, Voloshin 2008



=> Vectors can be have lifetime greater than the Universe

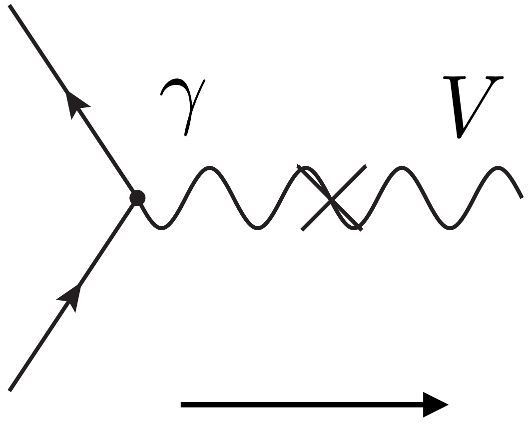
Dark Photon Dark Matter

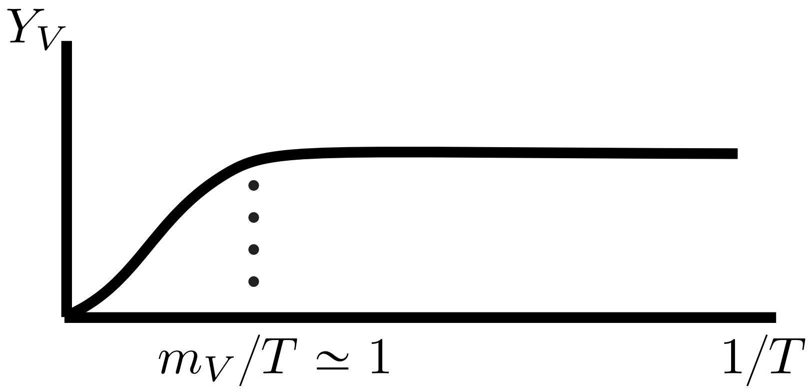
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^2 - \frac{1}{4}V_{\mu\nu}^2 - \frac{\kappa}{2}F_{\mu\nu}V^{\mu\nu} + \frac{m_V^2}{2}V_\mu V^\mu + eJ^\mu_{\rm em}A_\mu$$

Early Universe production. Can we make Dark Matter?

1. thermal production

$$\Gamma_{\rm int}/H \sim \kappa^2\alpha^2 n_e/sH \sim 1/T$$

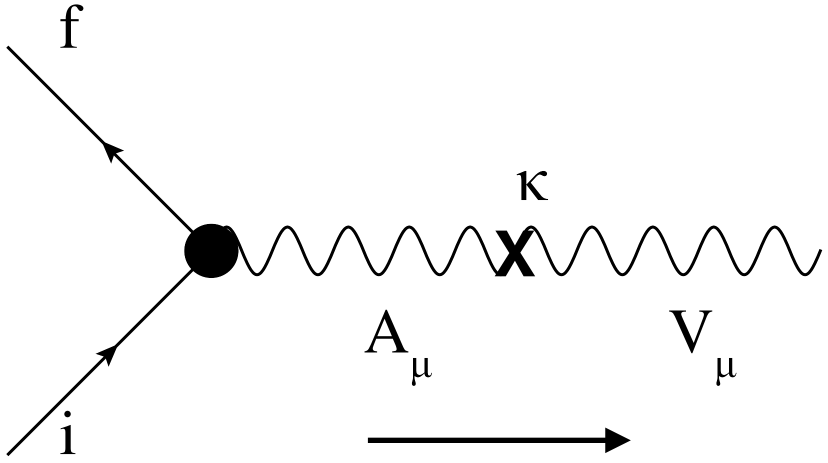




“freeze in”

Resonant production?

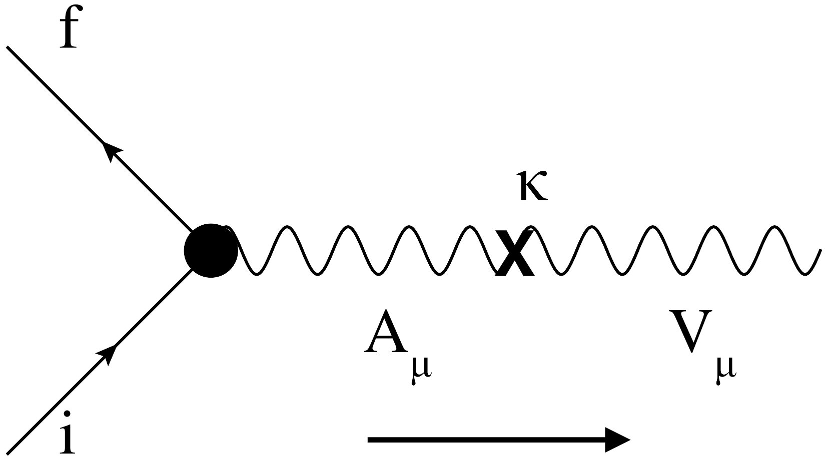
$$\frac{\kappa}{2}F_{\mu\nu}V^{\mu\nu} + eJ^{\mu}_{\mathrm{em}}A_{\mu} \xrightarrow{\mathrm{on-shell\ V}} \mathcal{L}_{\mathrm{int}} = -\kappa m_V^2 A_\mu V^\mu + eJ^{\mu}_{\mathrm{em}}A_{\mu}.$$



$$\mathcal{M}_{i\to f+V_{T(L)}} = \kappa m_V^2\,[eJ_{\mathrm{em}\,\mu}]_{fi}\,\langle A^\mu, A^\nu\rangle\,\epsilon_\nu^{T(L)}$$

Resonant production?

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



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

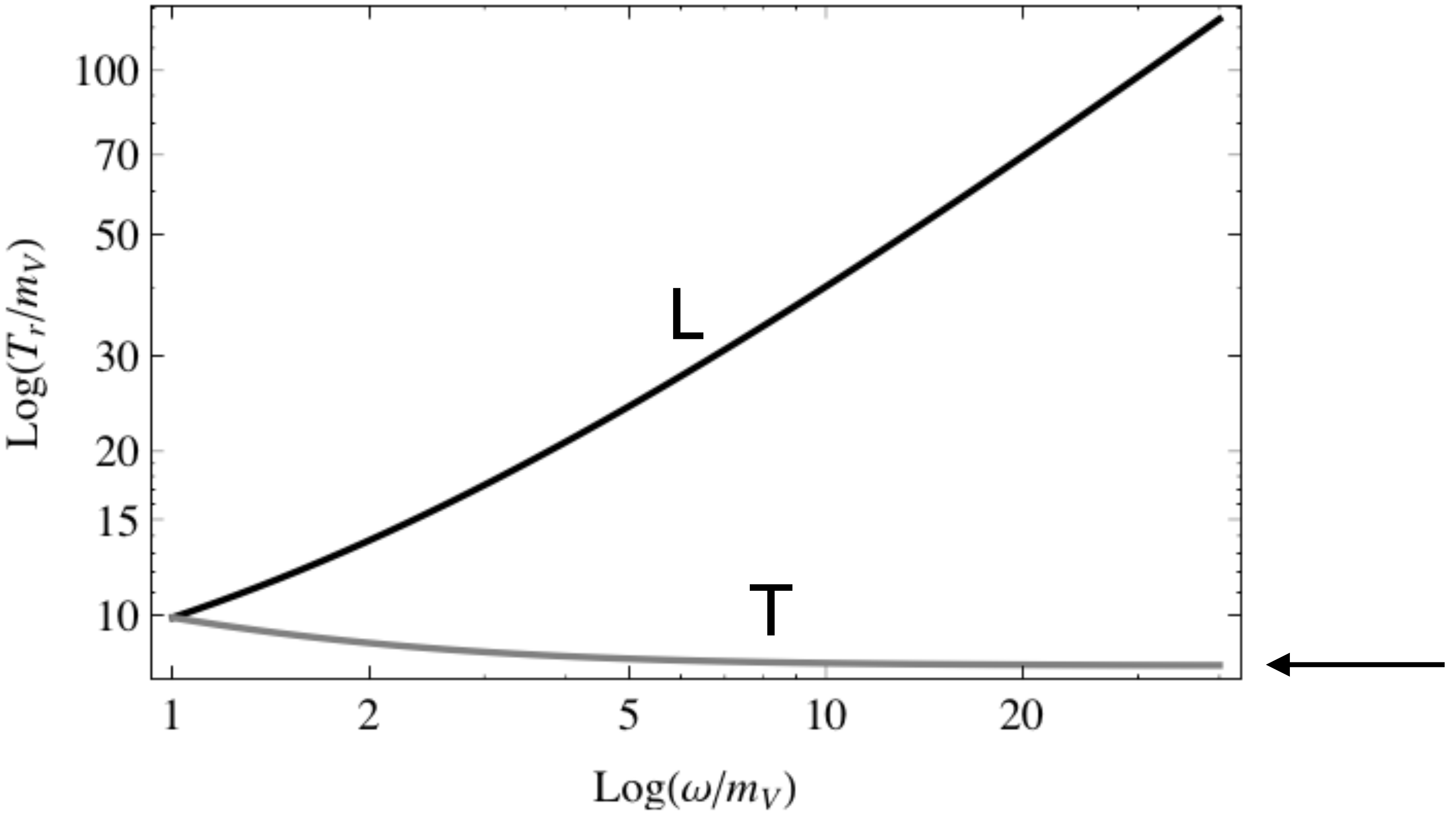
Resonance condition

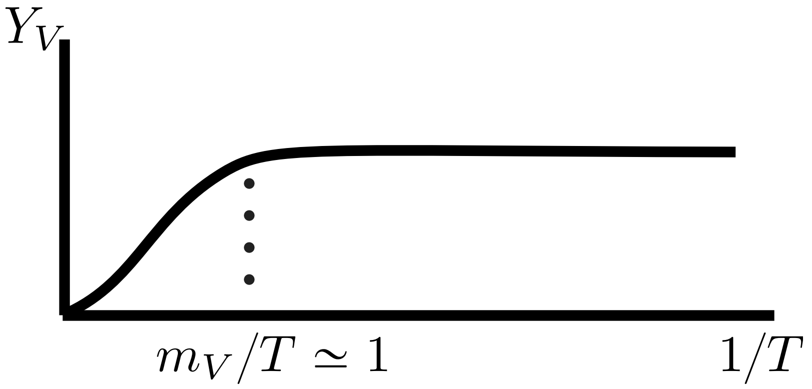
$$\mathrm{Re}\, \Pi_{T,L}(\omega, T_{r,T,L}) = m_V^2$$

Resonant production?

Resonance condition

$$\mathrm{Re}\,\Pi_{T,L}(\omega, T_{r,T,L}) = m_V^2$$





Resonance temperature is parametrically larger by factor $\alpha^{-1/2}$ then m_V

$$T_{r,\min} = \sqrt{\frac{3}{2\pi\alpha}}\,m_V$$

=> small effect in early Universe

Dark Photon Dark Matter

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

Early Universe production. Can we make Dark Matter?

1. thermal production ✗
2. resonant production ✗
3. Field can be generated during inflation

Initial Displacement

Simplest case: assume a non-minimal coupling to gravity $RV_\mu V^\mu/12$

=> gives simple boundary conditions after inflation

$$V_0 = 0, \quad \ddot{\tilde{V}}_i + 3H\dot{\tilde{V}}_i + m_V^2 \tilde{V}_i = (\text{interactions}) \qquad \tilde{V}_i = V_i/a$$

see e.g. Golovnev, Mukhanov, Vanchurin 2008

$3H \gg m_V^2$ field is over-damped at initial value $\tilde{V}_{I,i}$

$3H(T_\text{osc}) = m_V$ oscillations commence (redshift like matter)

$$\rho_V(T_\text{osc}) \approx \frac{1}{2} m_V^2 \tilde{V}_{I,i}^2 \quad \text{=>} \quad \Omega_V h^2 \approx 0.4 \frac{g_*(T_\text{osc})^{3/4}}{g_{*S}(T_\text{osc})} \sqrt{\frac{m_V}{1\,\text{keV}}} \left(\frac{\tilde{V}_{I,i}}{10^{11}\,\text{GeV}} \right)^2$$

Dark Photon Dark Matter

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

Early Universe production. Can we make Dark Matter?

1. thermal production ✗
2. resonant production ✗
3. Field can be generated during inflation

=> vacuum condensate can yield almost arbitrary values of the energy density, BUT creating the seeds of structure as observed in the CMB is an issue in the simplest model ✗

Dark Photon Dark Matter

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

Early Universe production. Can we make Dark Matter?

1. thermal production ✗
2. resonant production ✗
3. Field can be generated during inflation

Quantum fluctuations during inflation
yield abundance “for free”

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

Graham, Mardon, Rajendran 2014

Dark Photon Dark Matter

Can we detect it?

1. Small mass ~ keV means large number density
2. photo-ionization cross sections of ordinary photons can be huge, 10^7 bn

Those compensating factors make up for tiny coupling $\kappa \ll 10^{-10}$ that renders V stable on cosmological timescale!

=> absorption of V can be looked for in electron band

$$\mathrm{Xe\ I} + V \to \mathrm{Xe\ II} + e^-; \quad \mathrm{Xe\ I} + V \to \mathrm{Xe\ III} + 2e^-; \ldots$$

Dark Photon Absorption

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

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

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

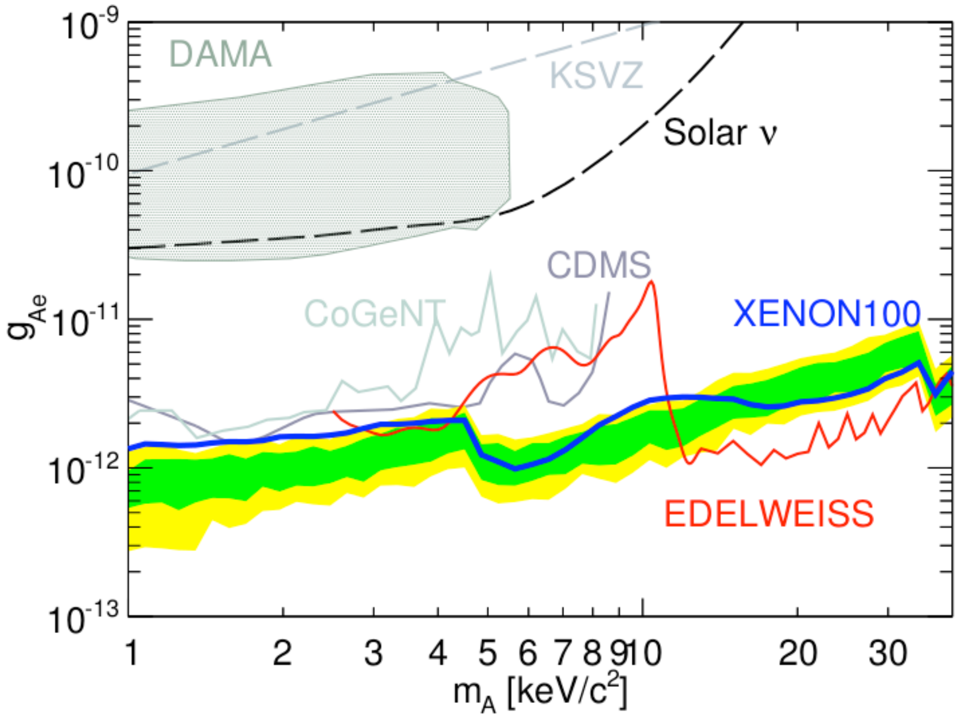
$$(\vec{p}_e\vec{\epsilon})\exp(i\vec{q}\vec{r}_e) \simeq (\vec{p}_e\vec{\epsilon}) \times (1 + i\vec{q}\vec{r}_e + ...)$$

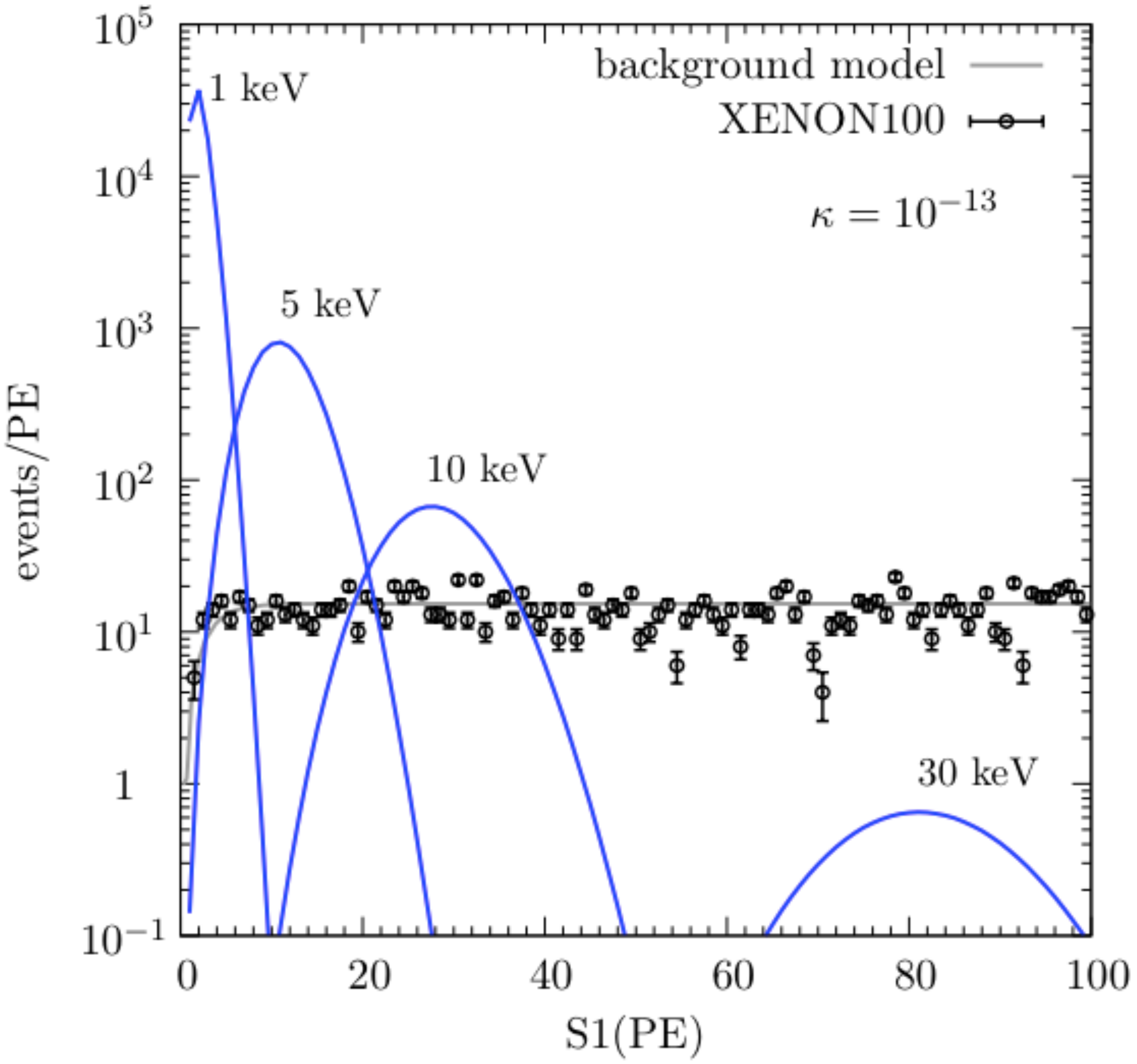
Using “normal” photon cross sections will be accurate to $O(\omega^2 r^2_{\rm shell}) \sim O(\alpha^2) - O((Z\alpha)^2)$

Absorption in Xenon

=> utilize XENON100 study on axion absorption

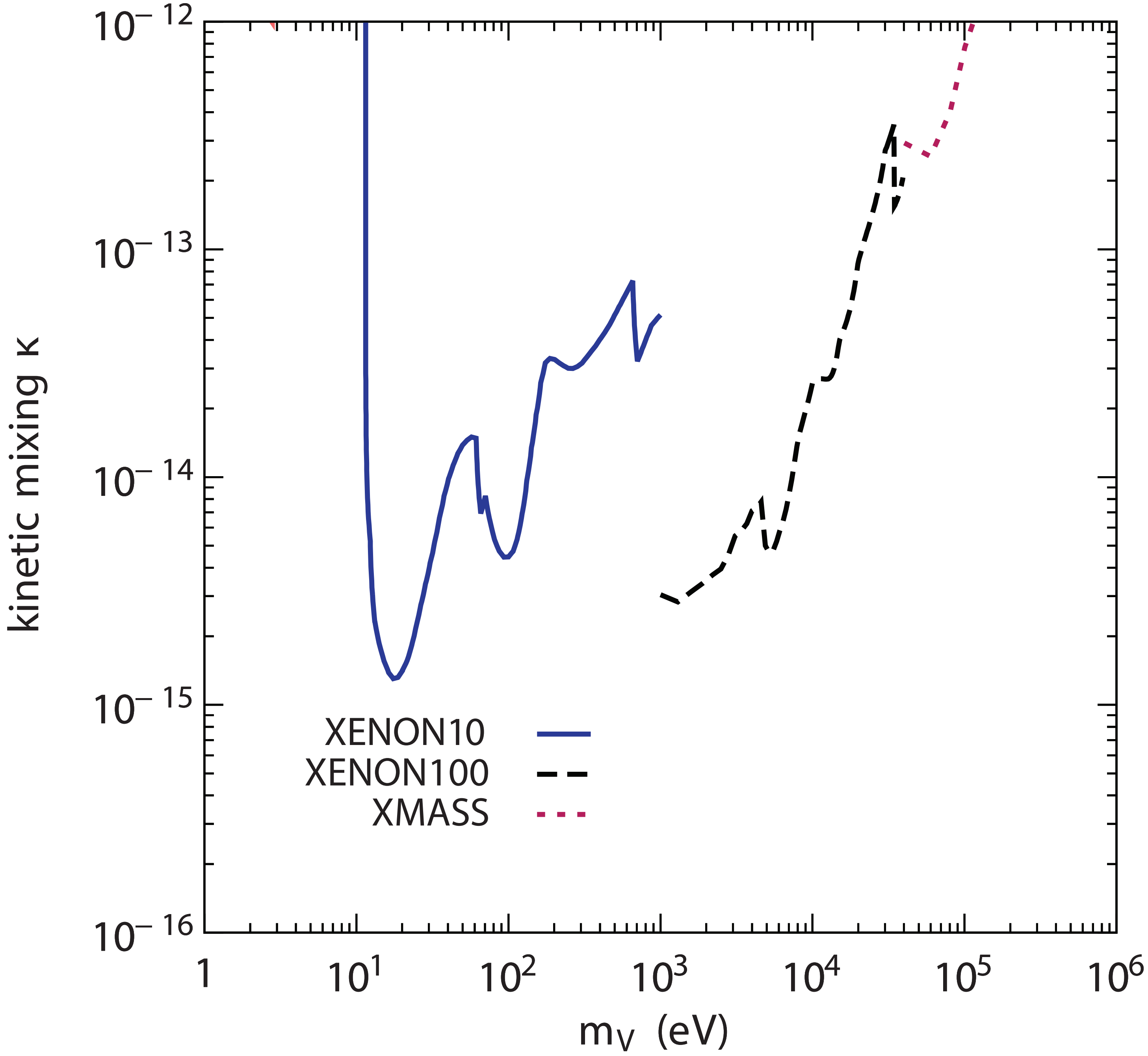
XENON100 collaboration, 2014





predicted Dark Photon scintillation signal (S1)

Direct Detection Limits



=> direct detection has sensitivity to keV-scale "super-WIMPs" (other than axions)

“Simplified Models” of Dark Matter electron scattering

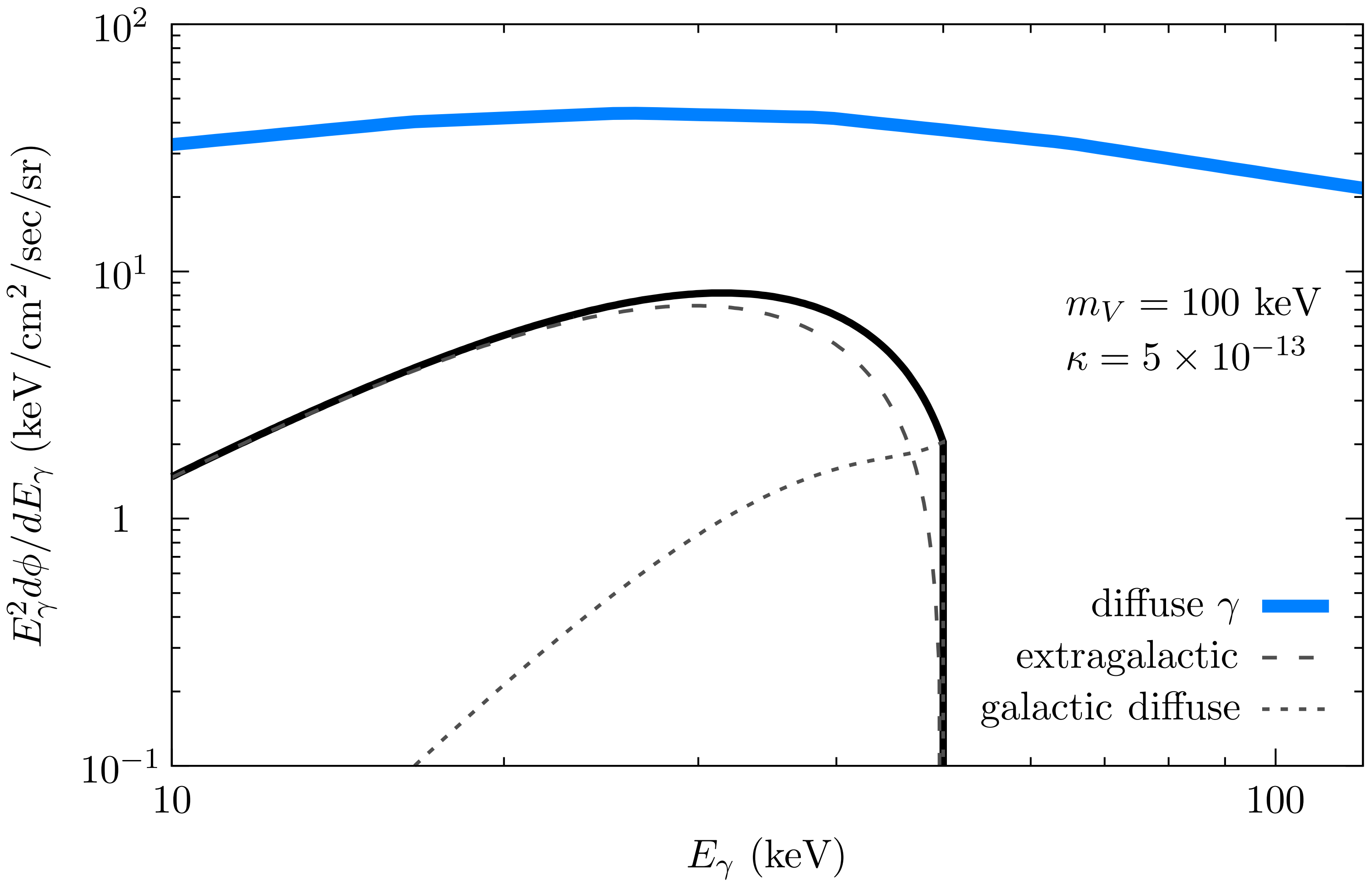
(pseudo)scalar	$g_S S\bar{\psi}\psi, \quad g_P P\bar{\psi}\gamma_5\psi,$
(pseudo)vector	$g_V V_\mu\bar{\psi}\gamma_\mu\psi,$ ✓ $g_A \mathcal{A}_\mu\bar{\psi}\gamma_\mu\gamma_5\psi,$
tensor	$g_T T_{\mu\nu}\bar{\psi}\sigma_{\mu\nu}\psi, \quad \cdots$

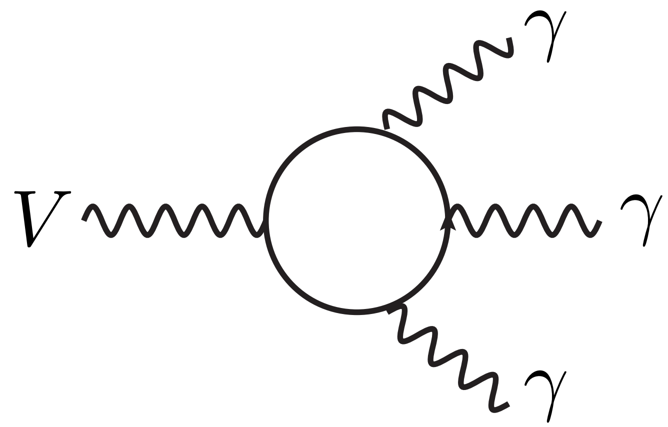
If the DM mass is not protected by some symmetry (like for dark photons or axions), loop corrections induce a mass shift

$\Delta m \sim g_i \Lambda_{\mathrm{UV}}$ => $g_i \lesssim 10^{-10}$ for $m \sim 100\,\mathrm{eV}$

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

Astrophysical Limits





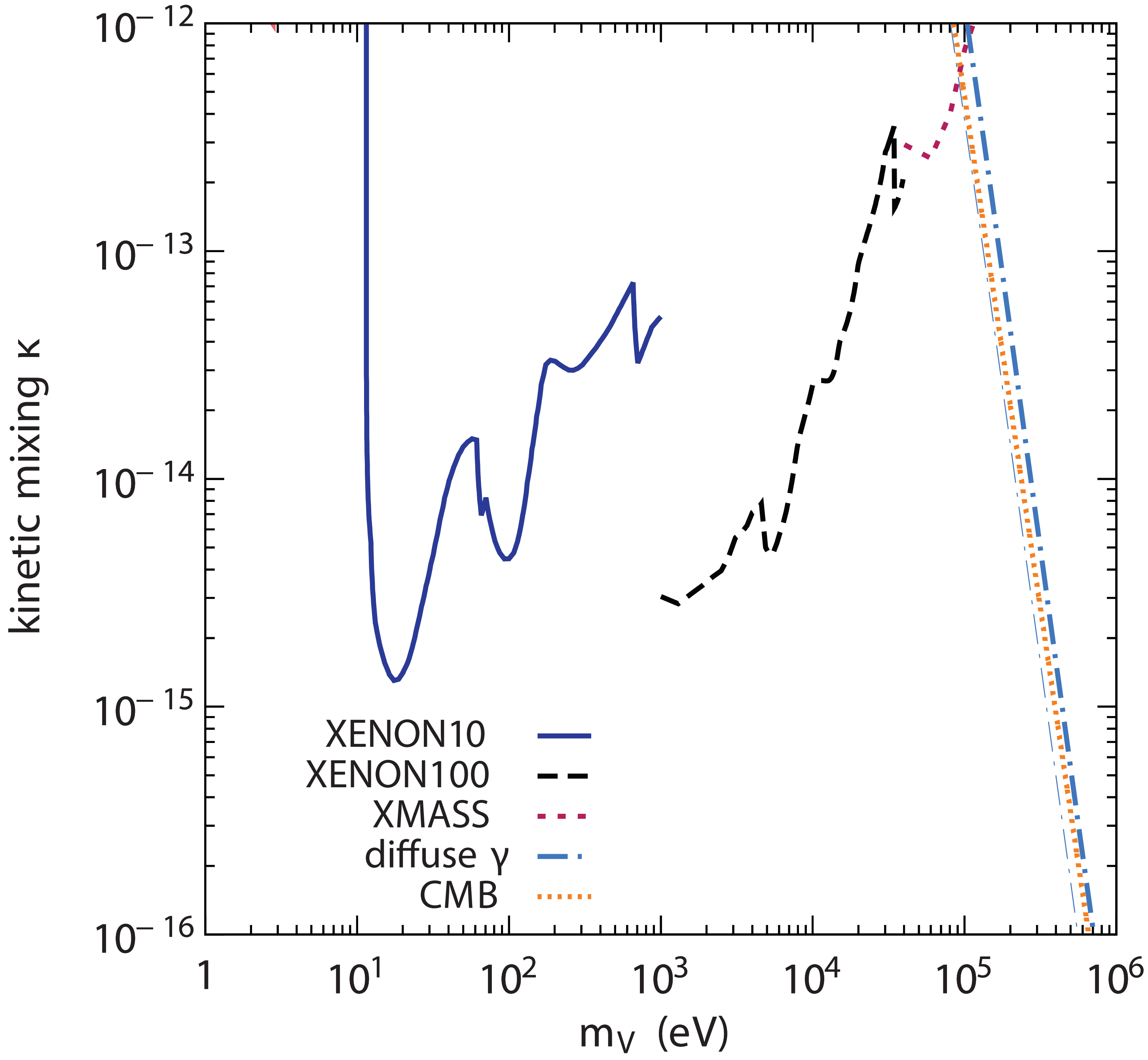
$$E_\gamma \frac{d\phi_{\rm gal}}{dE_\gamma} = \frac{\Gamma_{V\to 3\gamma}}{4\pi m_V} E_\gamma \frac{dN}{dE_\gamma} \rho_{\rm sol} R_{\rm sol} \mathcal{J}$$

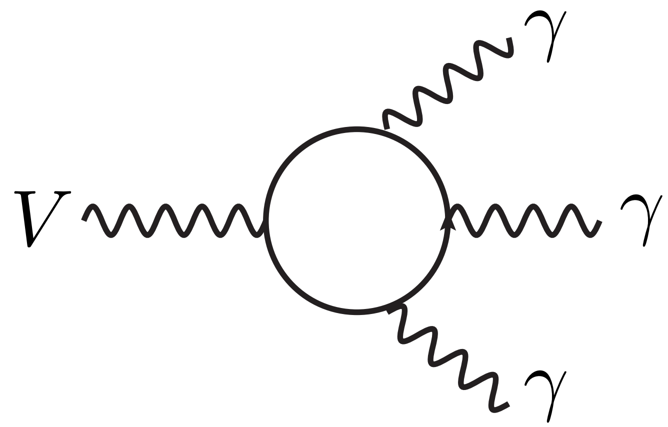
diffuse galactic

$$E_\gamma \frac{d\phi_{\rm eg}}{dE_\gamma} = \frac{\Omega_V \rho_c \Gamma_{V\to 3\gamma}}{4\pi m_V} \int_0^{z_f} dz \, \frac{E_\gamma}{H(z)} \frac{dN[(1+z)E_\gamma]}{dE_\gamma}$$

extragalactic

Astrophysical Limits





gamma rays
+ CMB limits exclude
Dark Photon Dark Matter
heavier than
few x 100 keV

Dark Photon Dark Matter

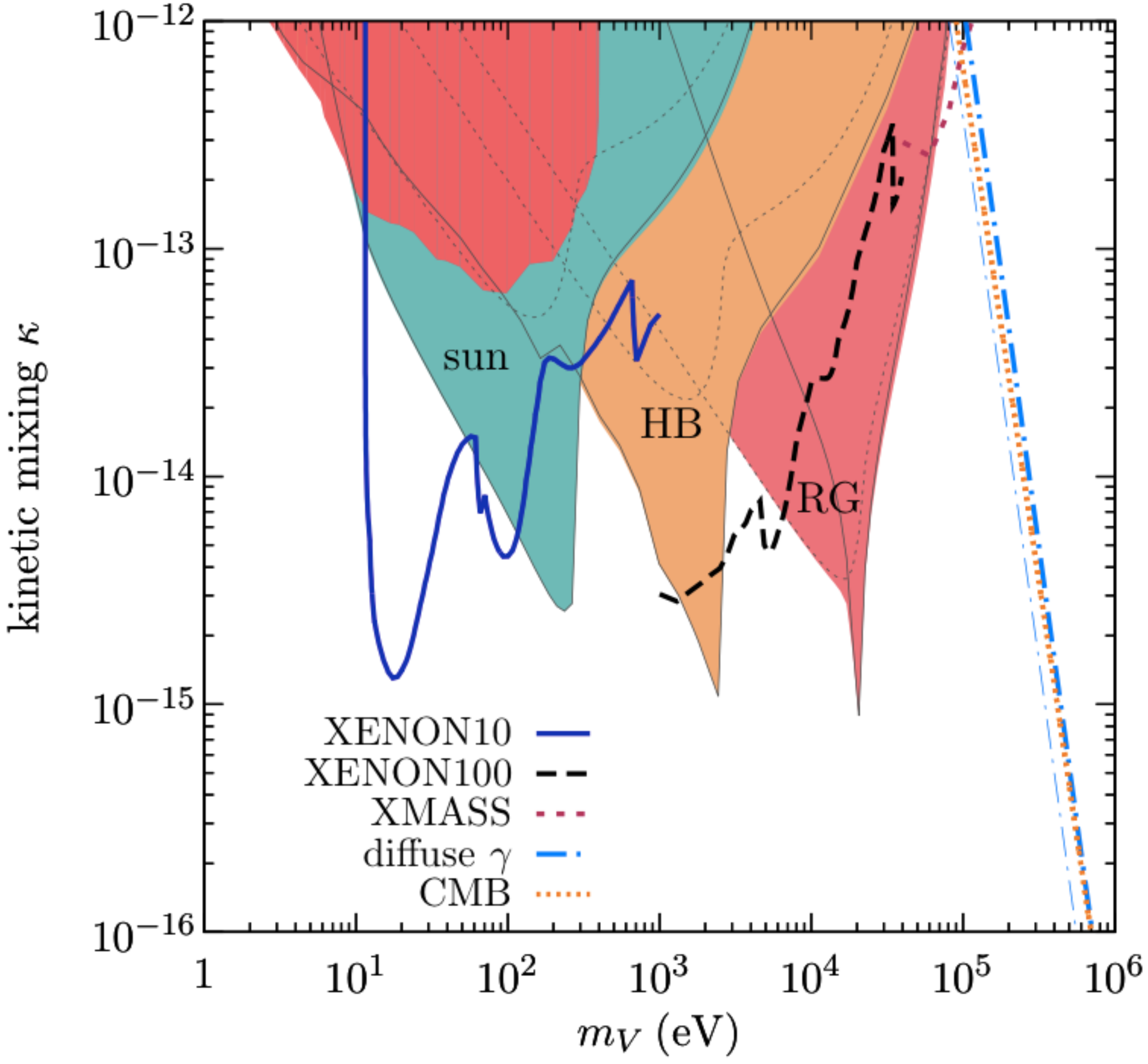
Position of stellar limits understood from:

Sun $\omega_P(r=0) \simeq 300\,\mathrm{eV},$

HB $\omega_P(r=0) \sim 2.6\,\mathrm{keV},$

RG $\omega_P(r=0) \sim 200\,\mathrm{keV}.$

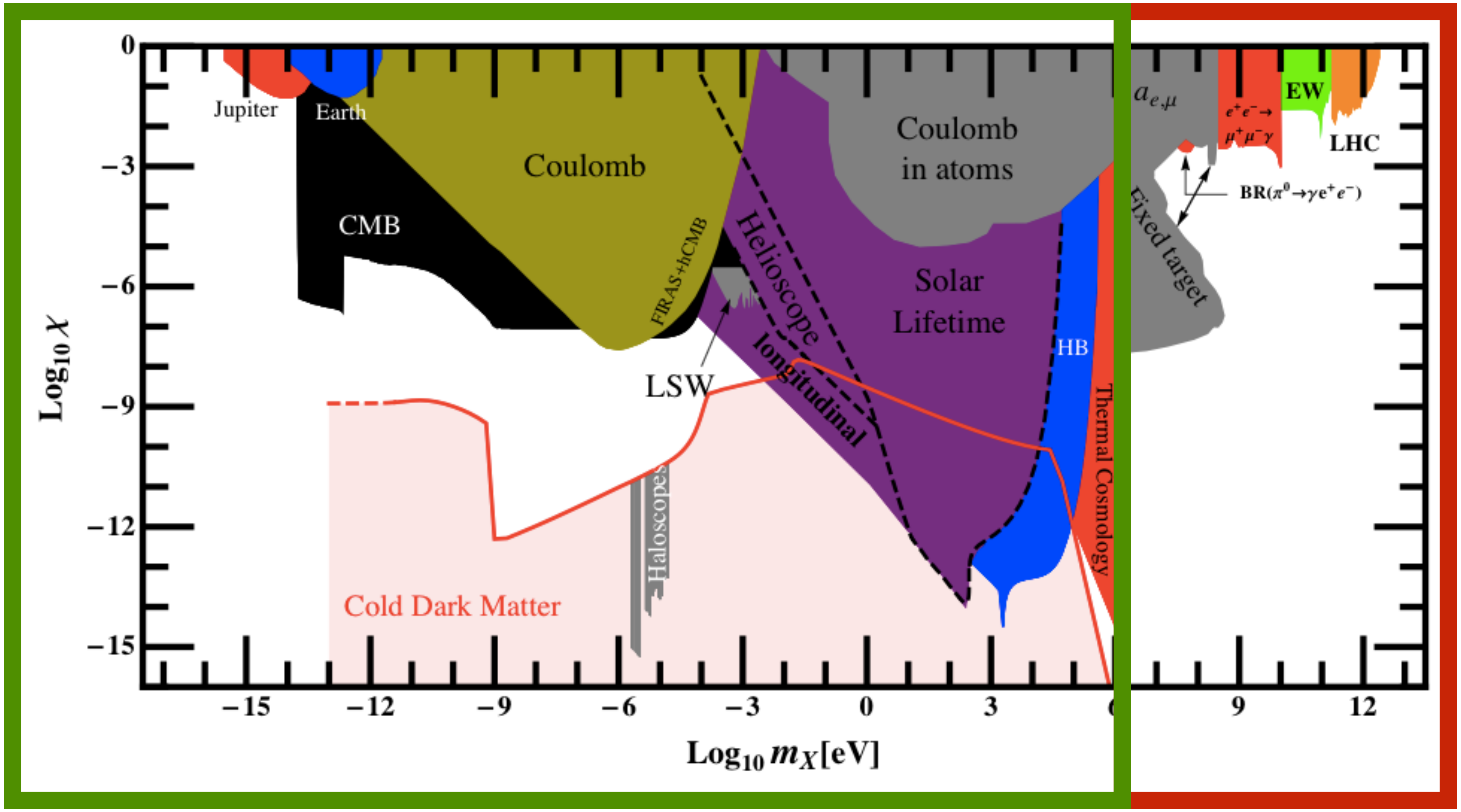
Astrophysical limits are strong, but direct detection can probe unchartered territory



An, Pospelov, JP, Ritz 2014

solar constraints: An, Pospelov JP PLB 2013

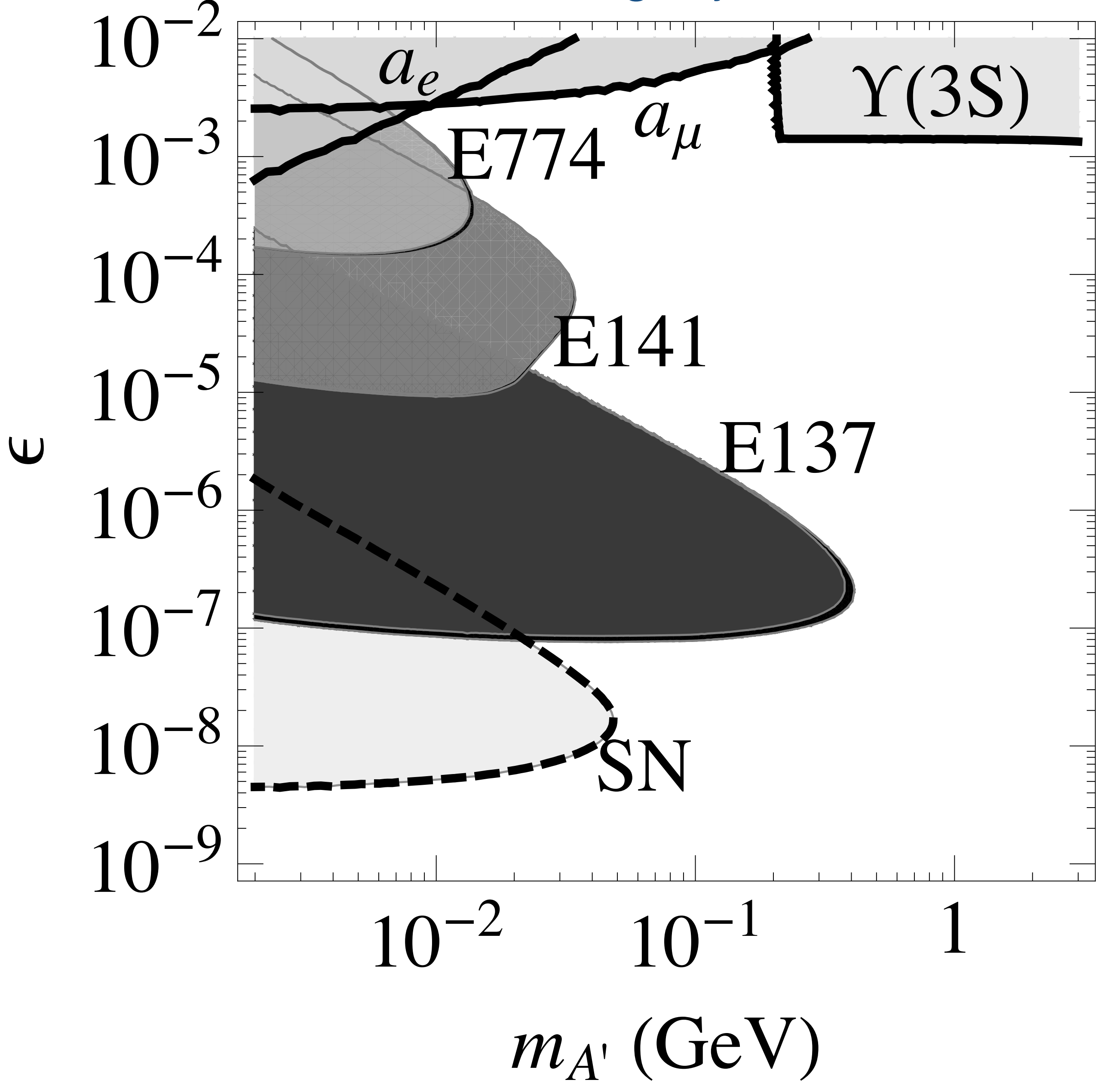
PART II: Heavier Vectors



V can be DM ⟷ V decays to e+ e-, hadrons,…

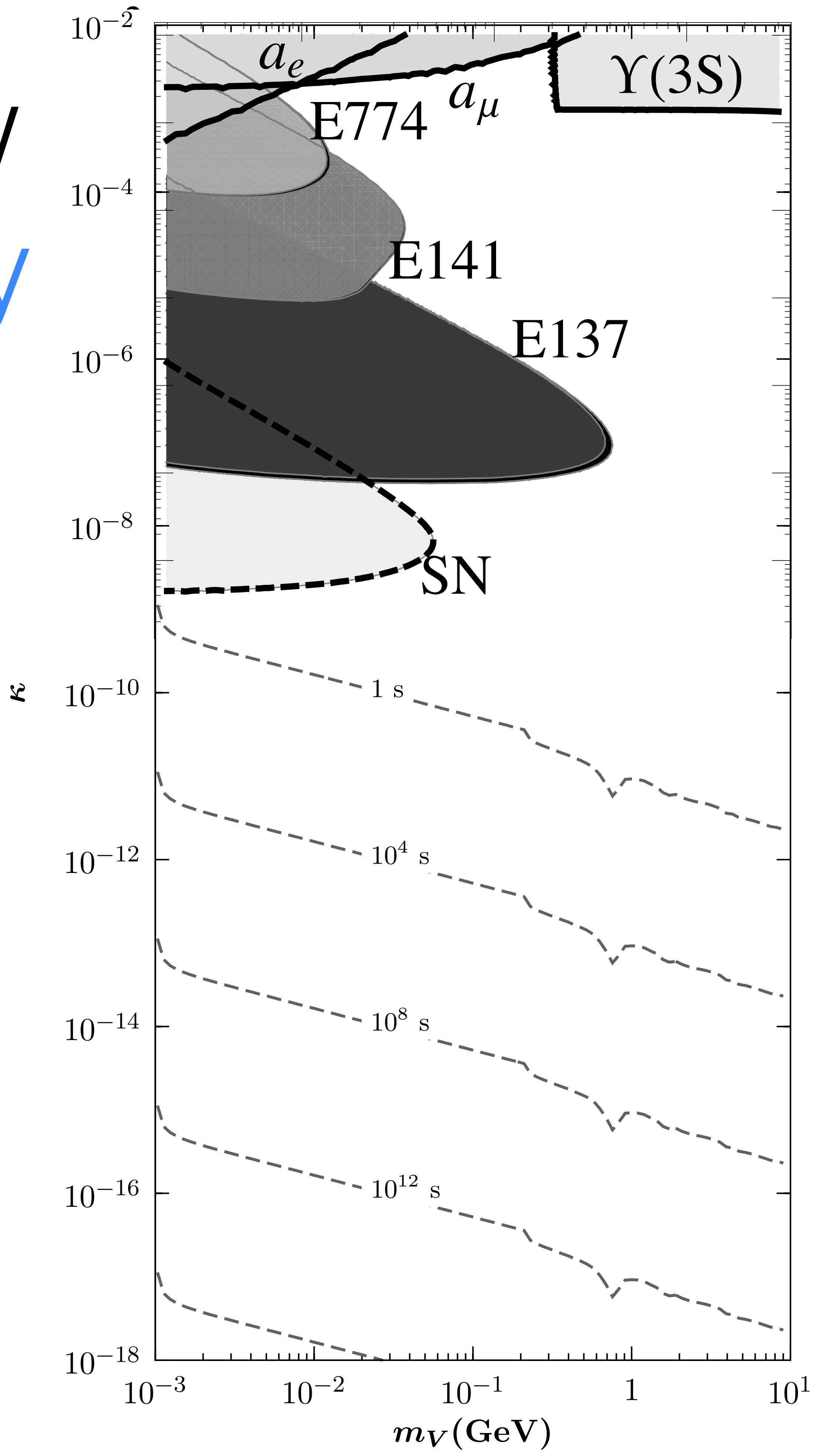
Extending our view through cosmology

e.g. Bjorken et al. 2009



Extending our view through cosmology

Very Dark Photon V



Extending our view through cosmology

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

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

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

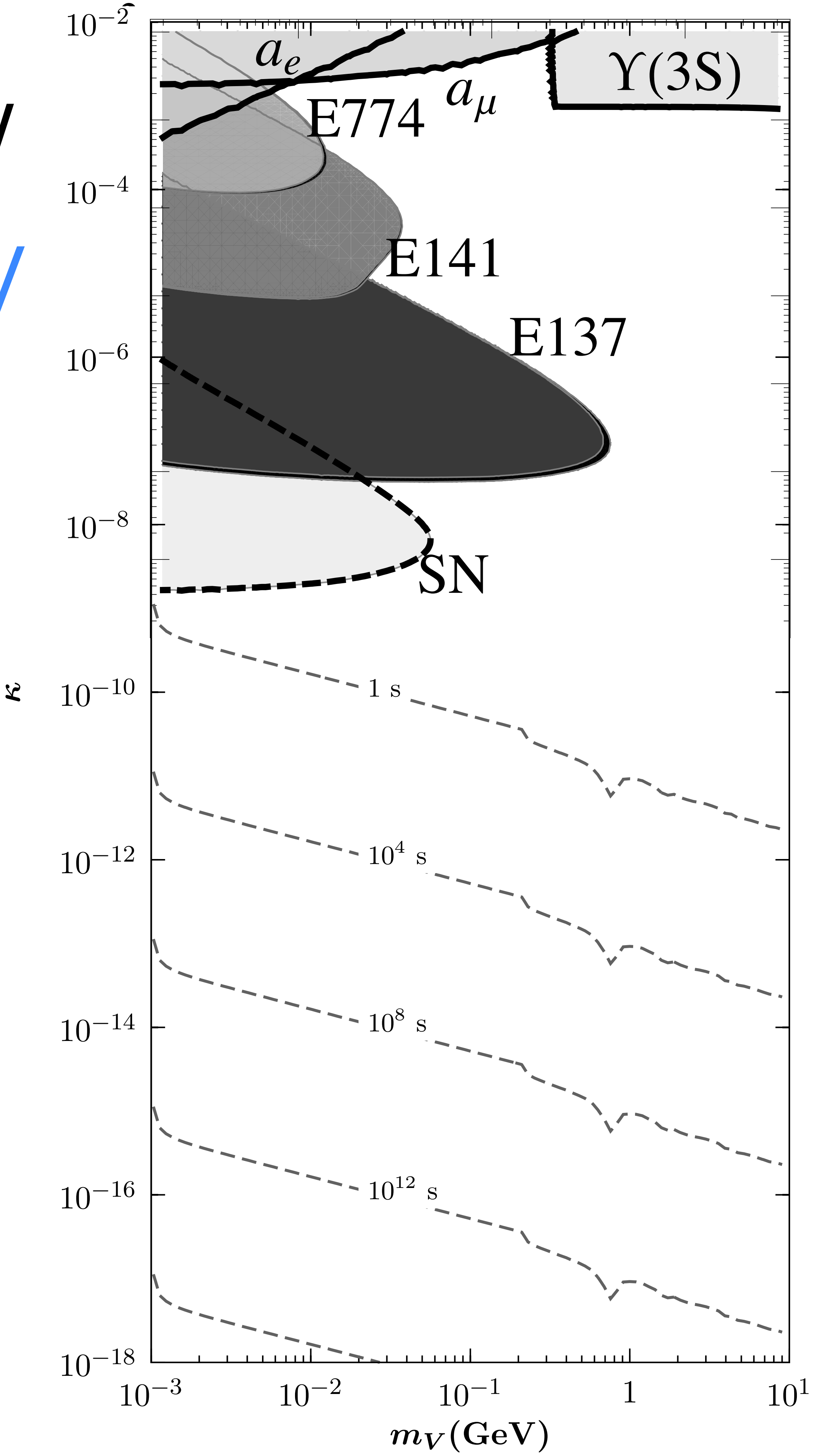
$$\alpha_{\rm eff} = \kappa^2 \alpha$$

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

BBN sensitivity: MeV/baryon

CMB sensitivity: eV/baryon

Very Dark Photon V



Extending our view through cosmology

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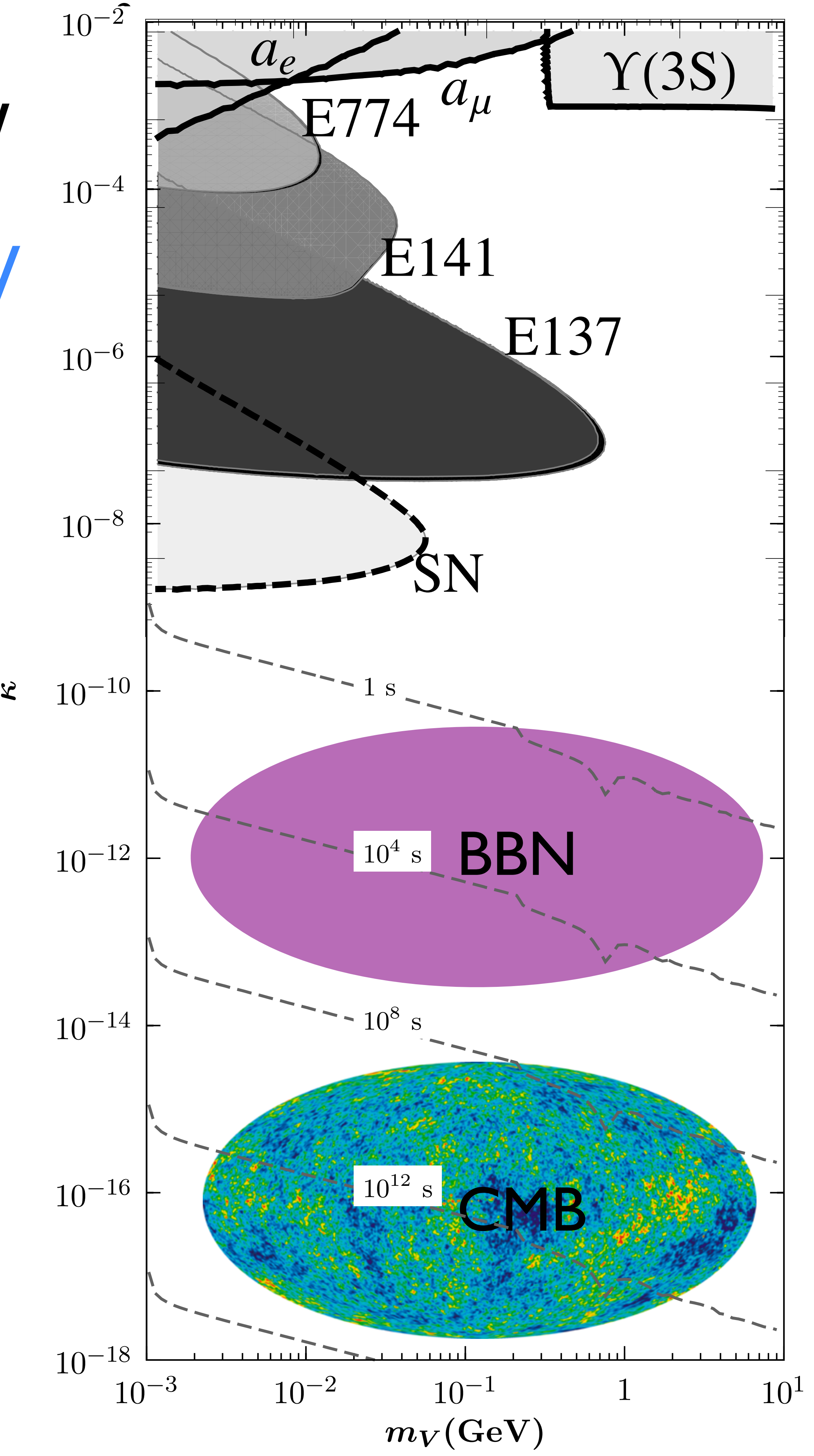
Very Dark Photon V

BBN sensitivity: MeV/baryon

CMB sensitivity: eV/baryon



Primoridal nucleosynthesis - a pillar of modern cosmology

Recent progress primarily clarifies state of the Universe at z = few and exposes relevant physics at $z = 1000$

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

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 => GR:

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

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

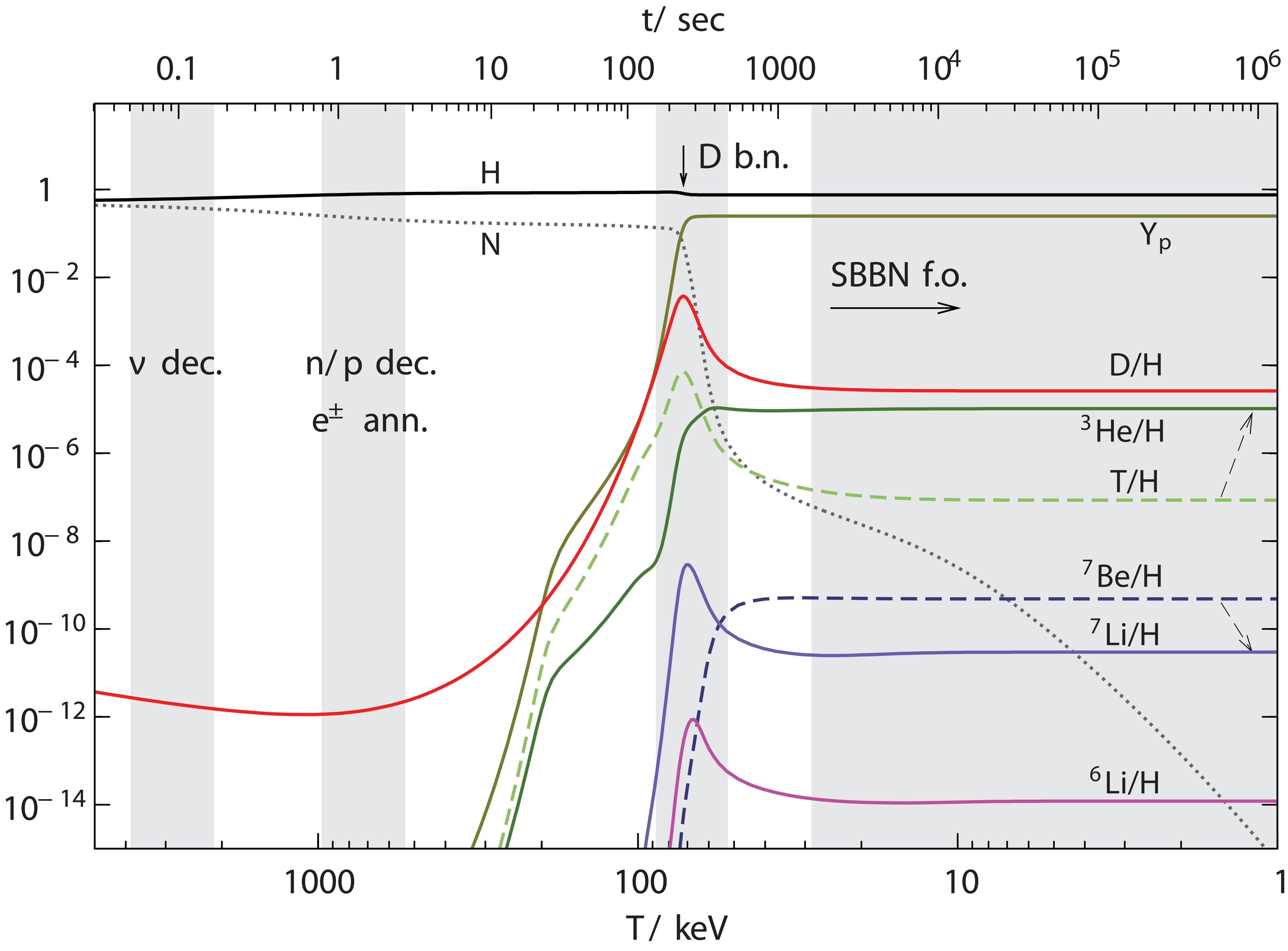
$$(n_n \simeq n_p)|_{T \gg \Delta m_{np}} = \frac{1}{2} n_b$$

Particle content & their interactions given by the SM

$$\frac{n_b}{s}(t_{\rm BBN}) = \frac{n_b}{s}(t_{\rm CMB}).$$

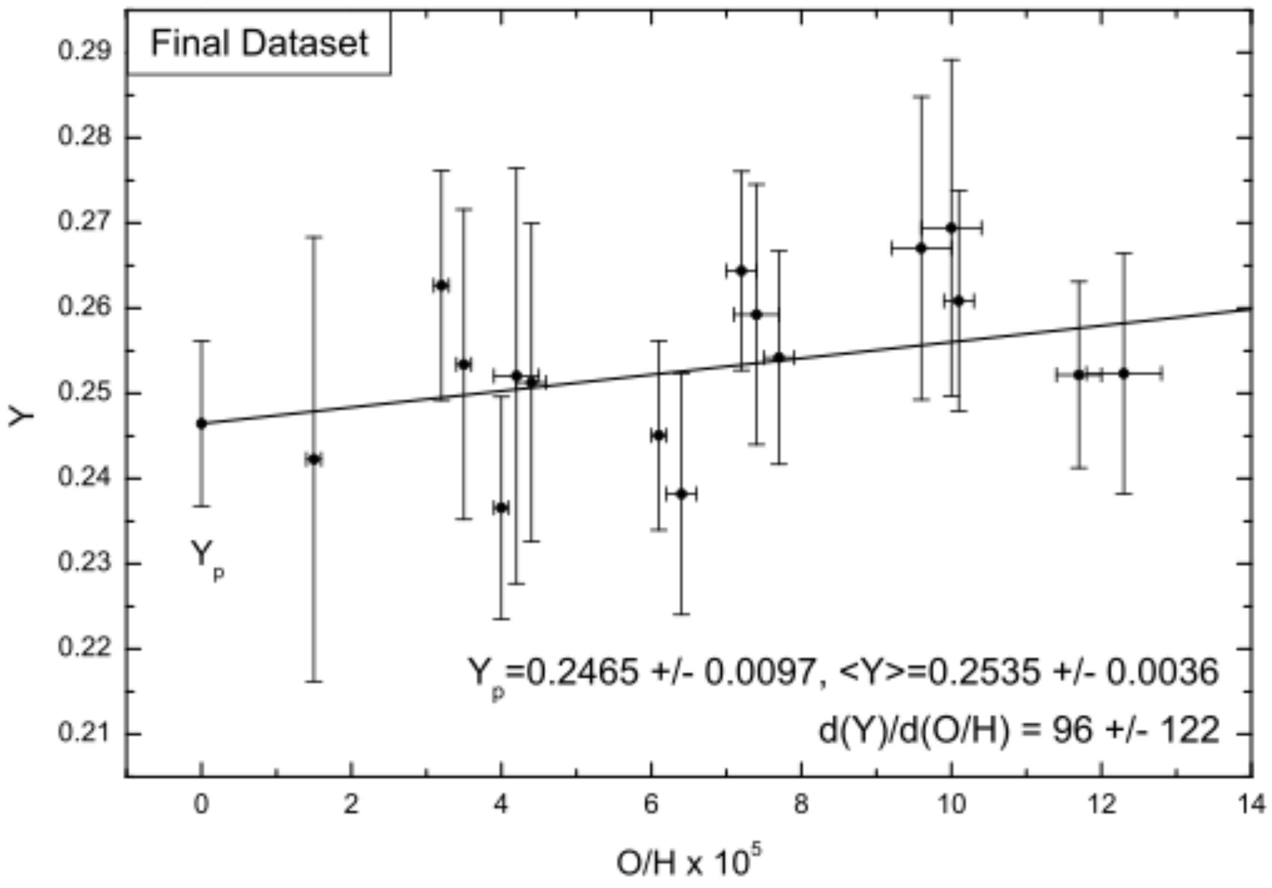
=> “parameter free theory”

The Universe at a redshift of a billion

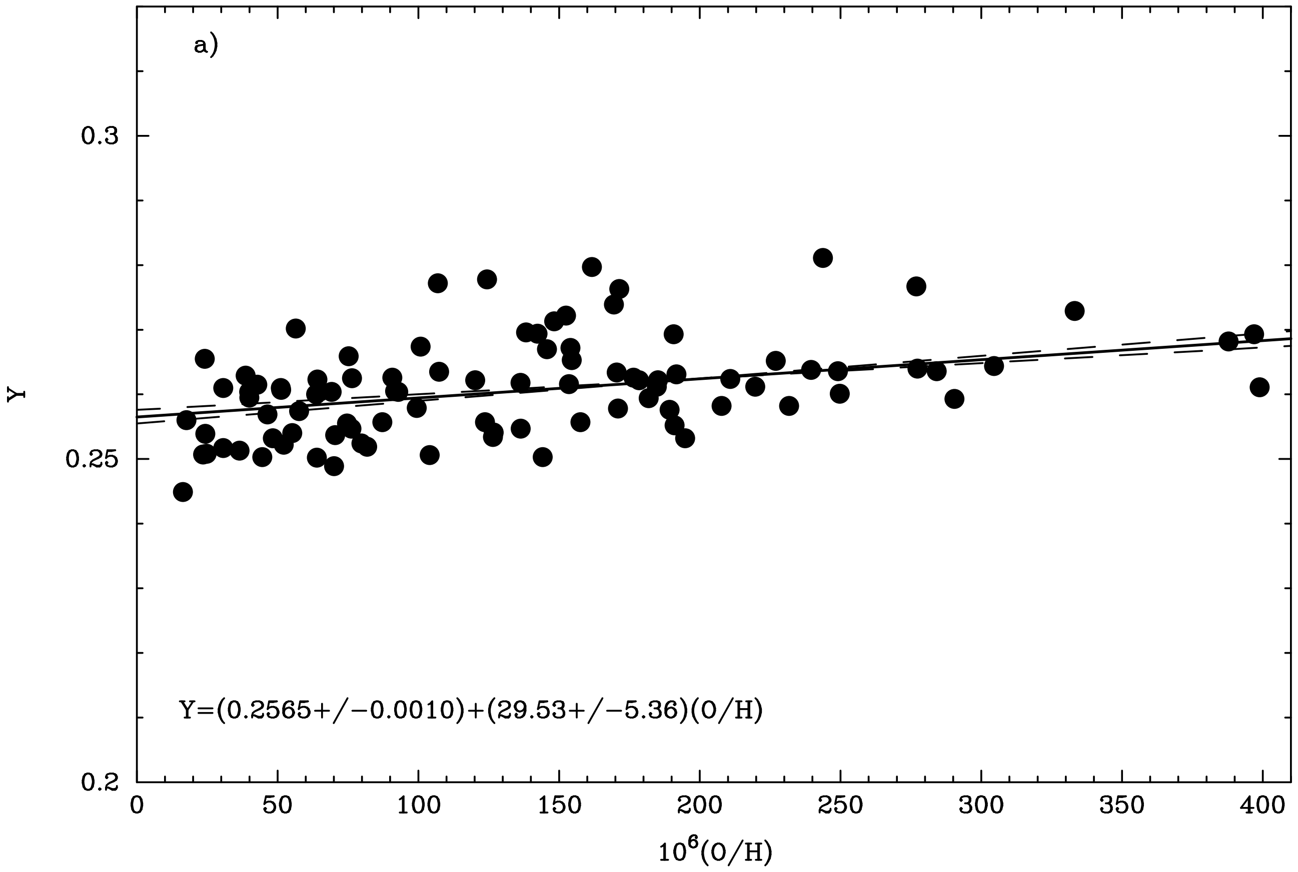


Light element observations

Helium mass fraction $Y_p \simeq 25\%$



Aver, Olive, Porter, Skillman JCAP 2013



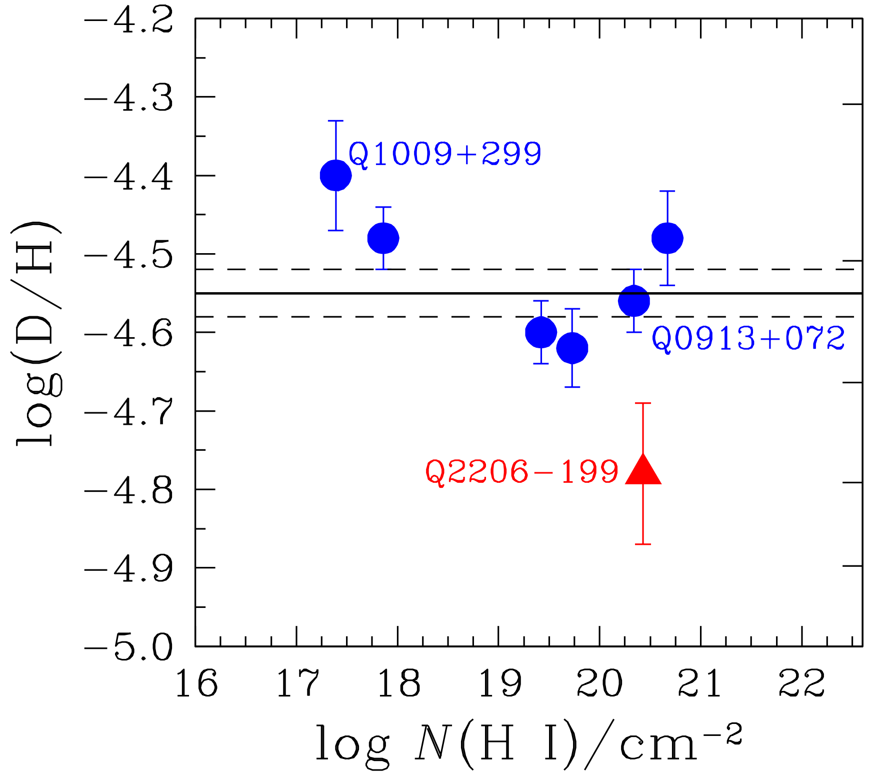
Izotov, Thuan Astrophysical J. 2010

determinations from He emission lines in ionized HII regions
now claim few %-level accuracy (systematics limited)

Light element observations

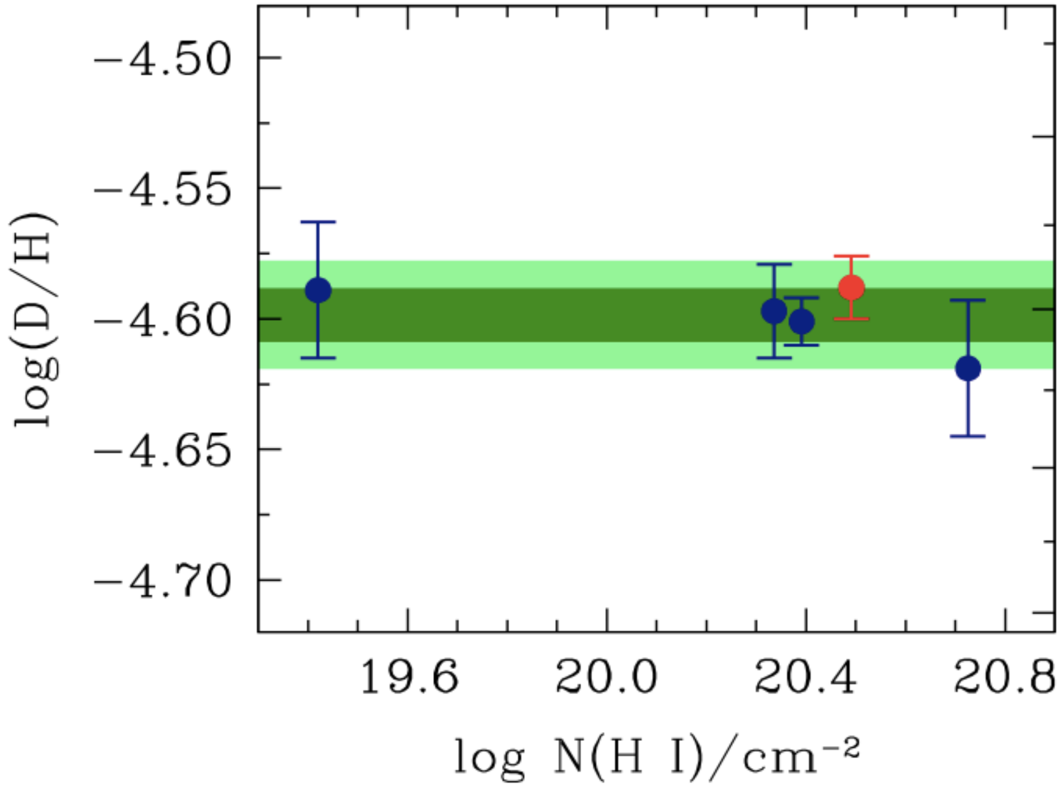
Deuterium $\mathrm{D/H} \simeq 10^{-5}$

Pettini et al MNRAS 2008



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

Pettini et al MNRAS 2013



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

=> drastic improvement of the error bar by factor 5 in a few years

Now D/H at %-precision!

SBBN take-home message

Light element predictions from helium to lithium span roughly 9 orders of magnitude in number

In qualitative agreement with observations; impressive success of the hot Big Bang model; significant advances in D and He observations can be expected

At least one quantitative problem: Lithium abundance is high by a factor of a few, but 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

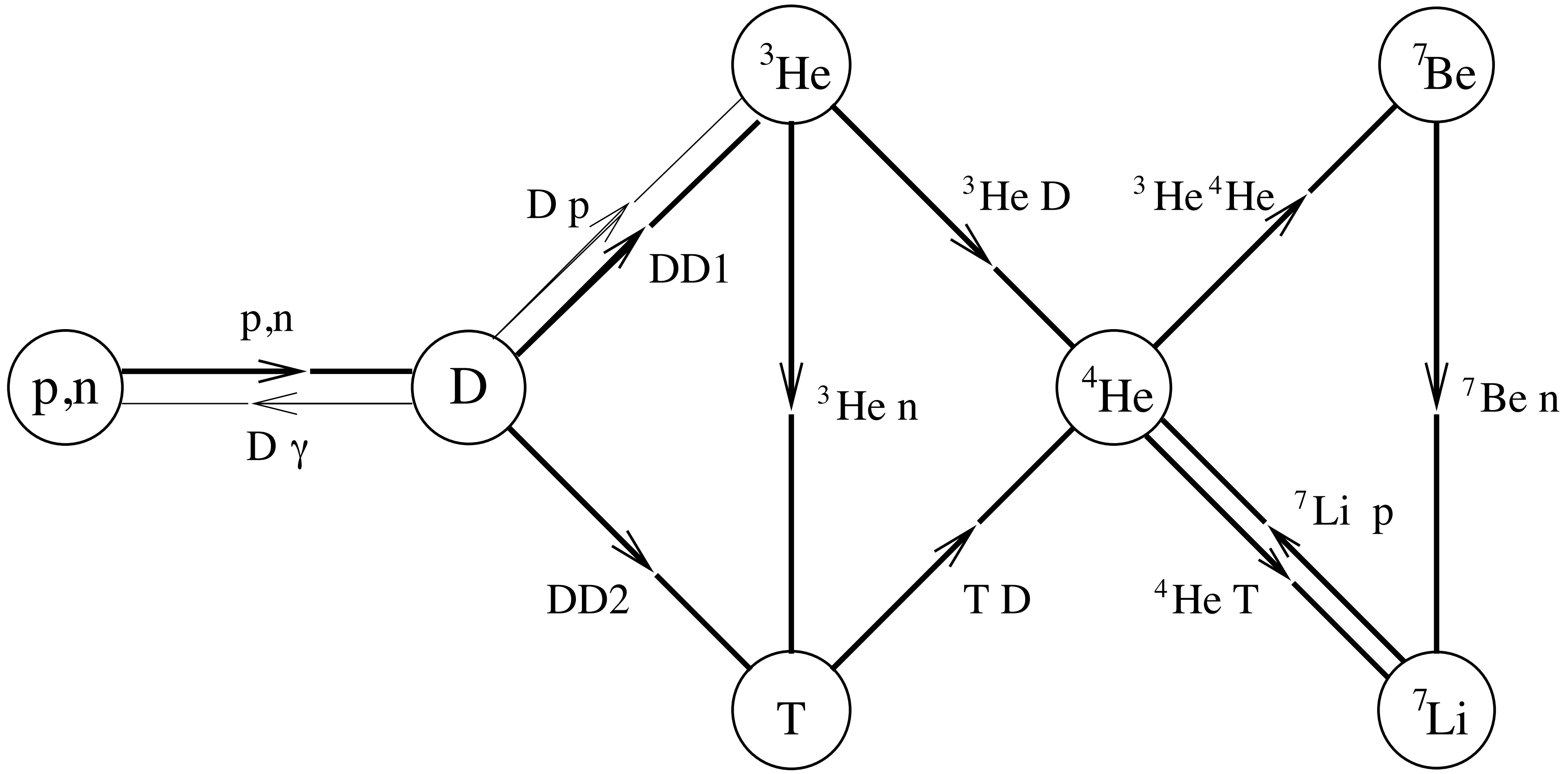
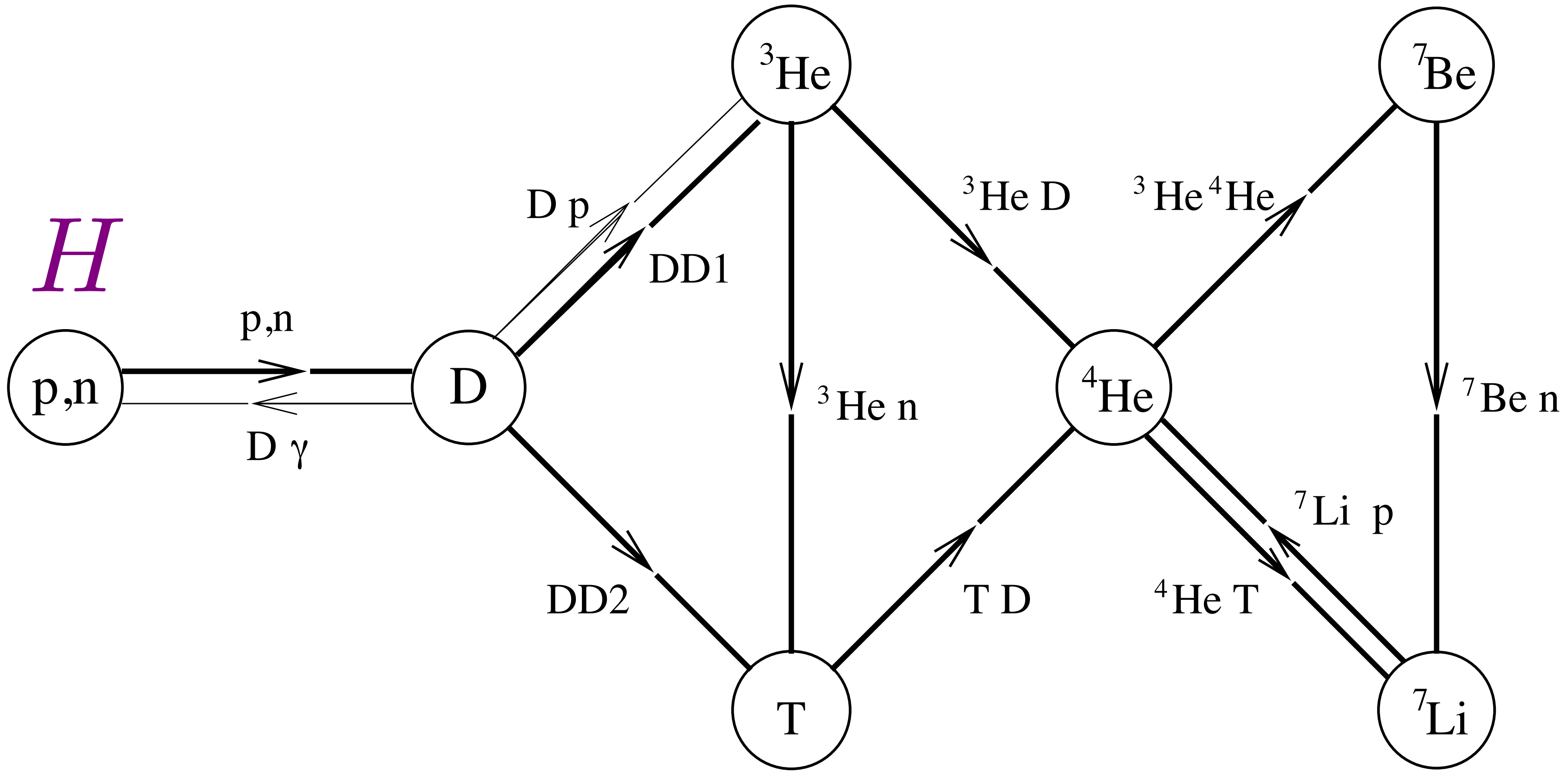


Fig. from
Mukhanov

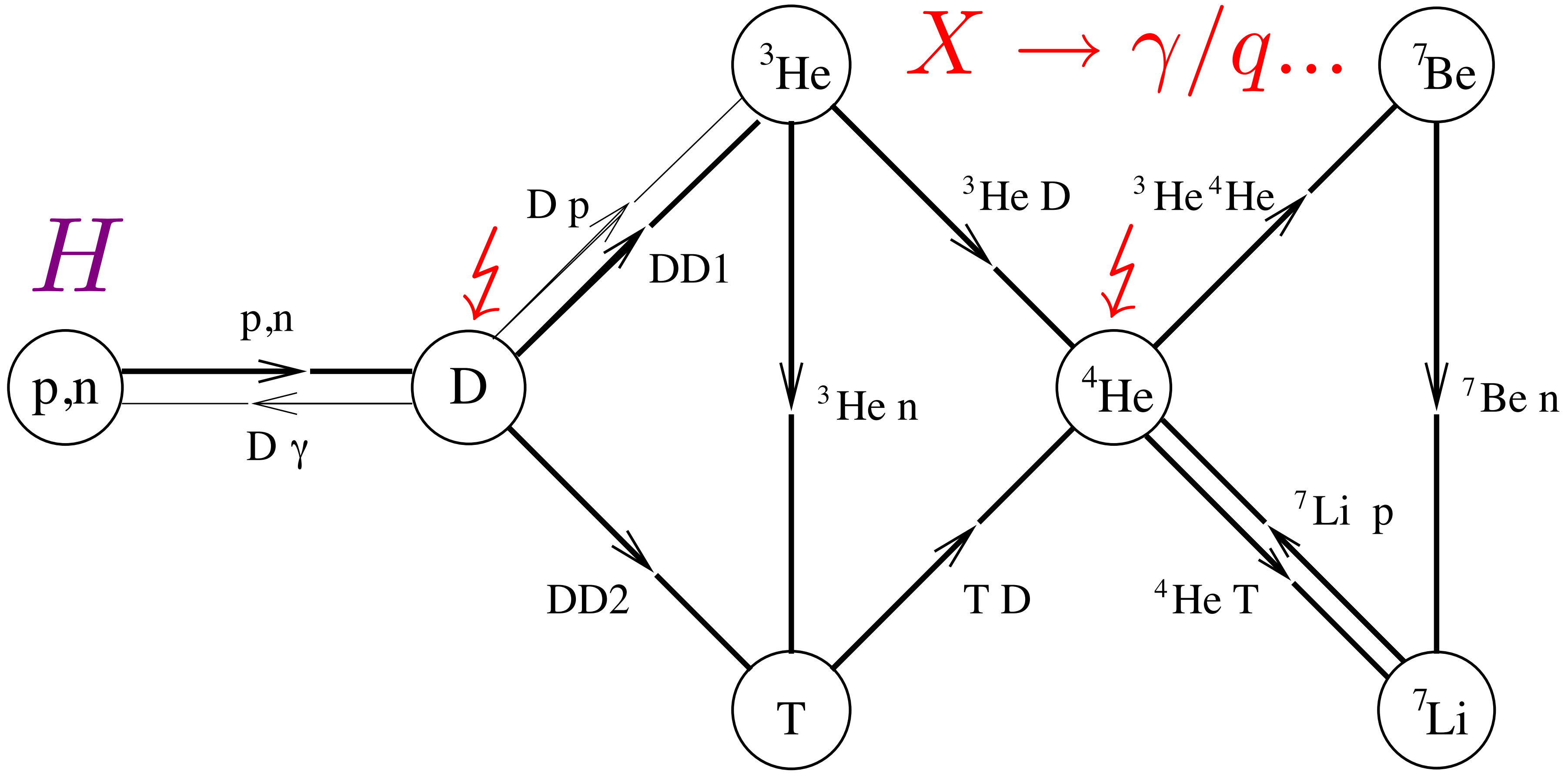
Beyond SBBN



Change in timing

Fig. from Mukhanov

Beyond SBBN

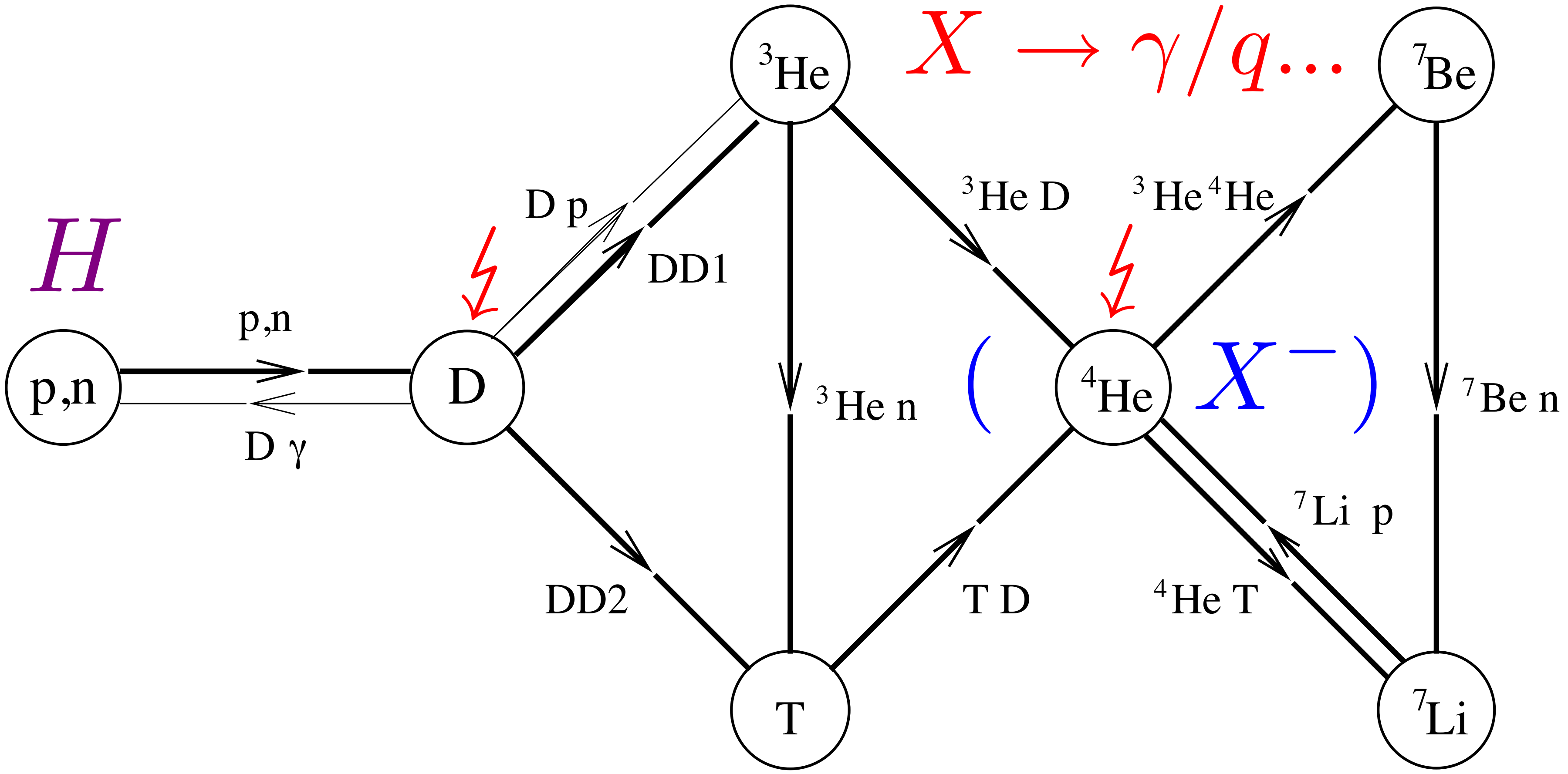


Change in timing

non-equilibrium BBN

Fig. from Mukhanov

Beyond SBBN



Change in timing

non-equilibrium BBN

catalyzed BBN

Fig. from
Mukhanov

Non-equilibrium BBN
Energy injection

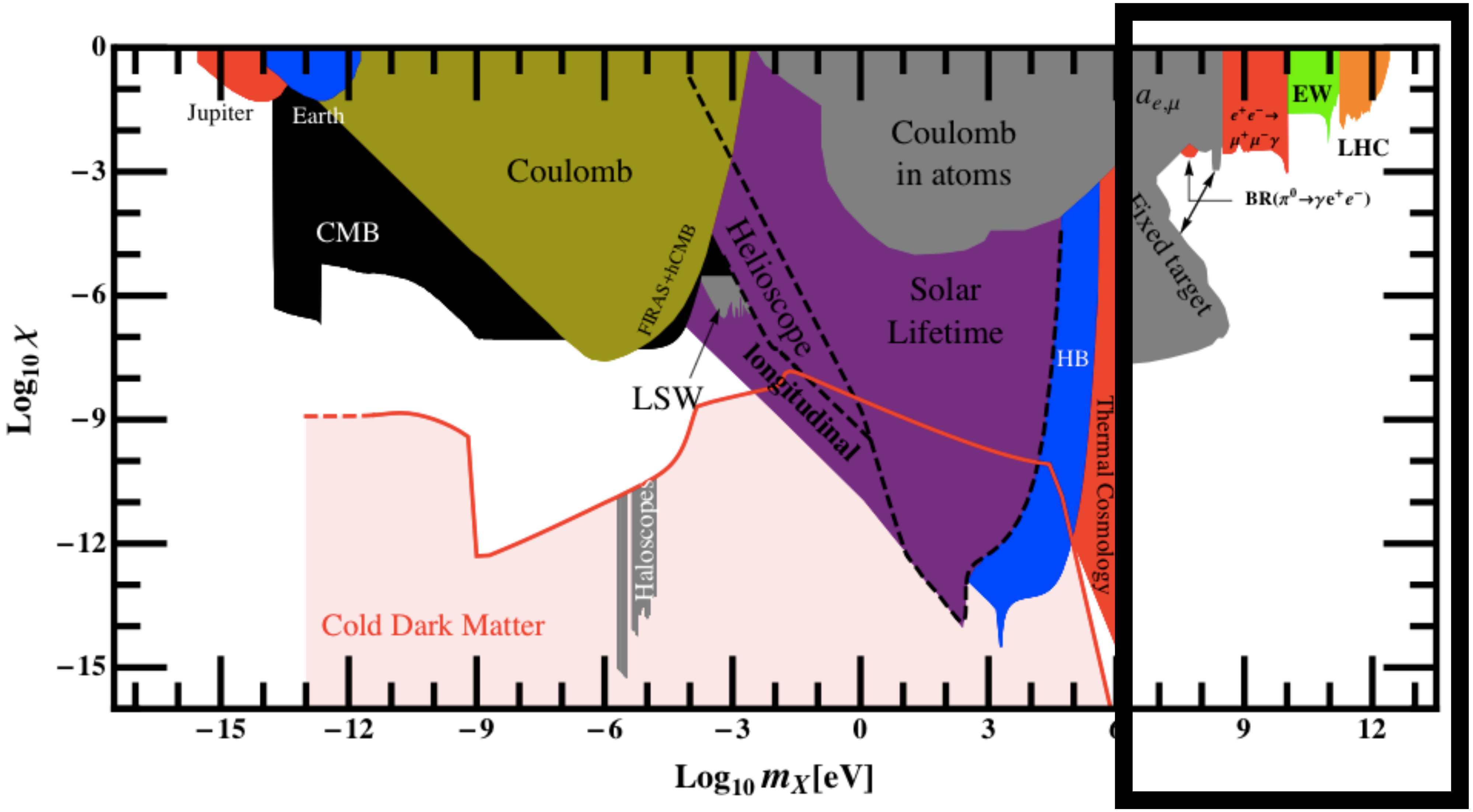
Most often discussed in literature: decays of long-lived particles X

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

=> yield electromagnetic and hadronic showers which dissociate light elements (drastic departures) [Dimopoulos 1988, … many works]

What if X is light?

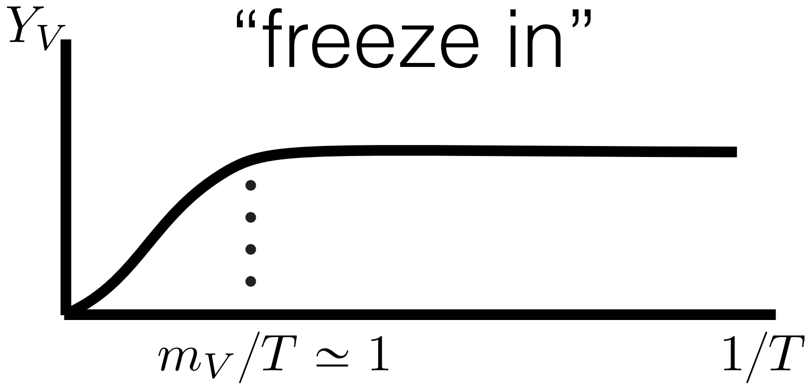
Dark Photons are light



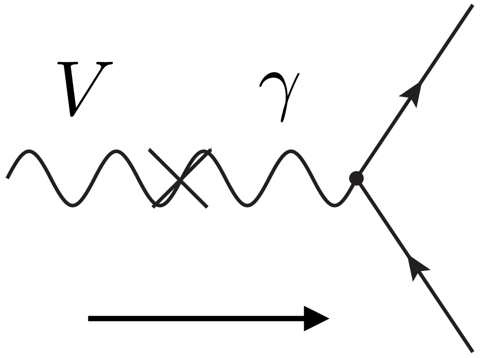
decays to
e+ e- kinematically
allowed

V Abundance / V decay

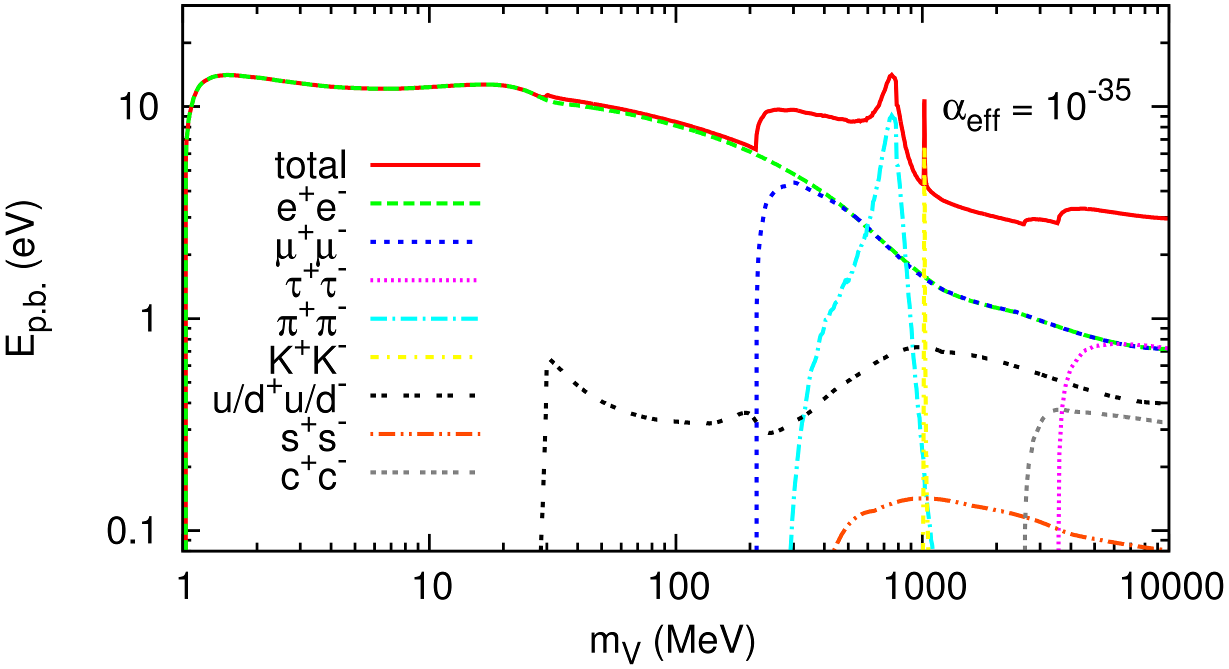
1. Thermal production with sub-Hubble rate

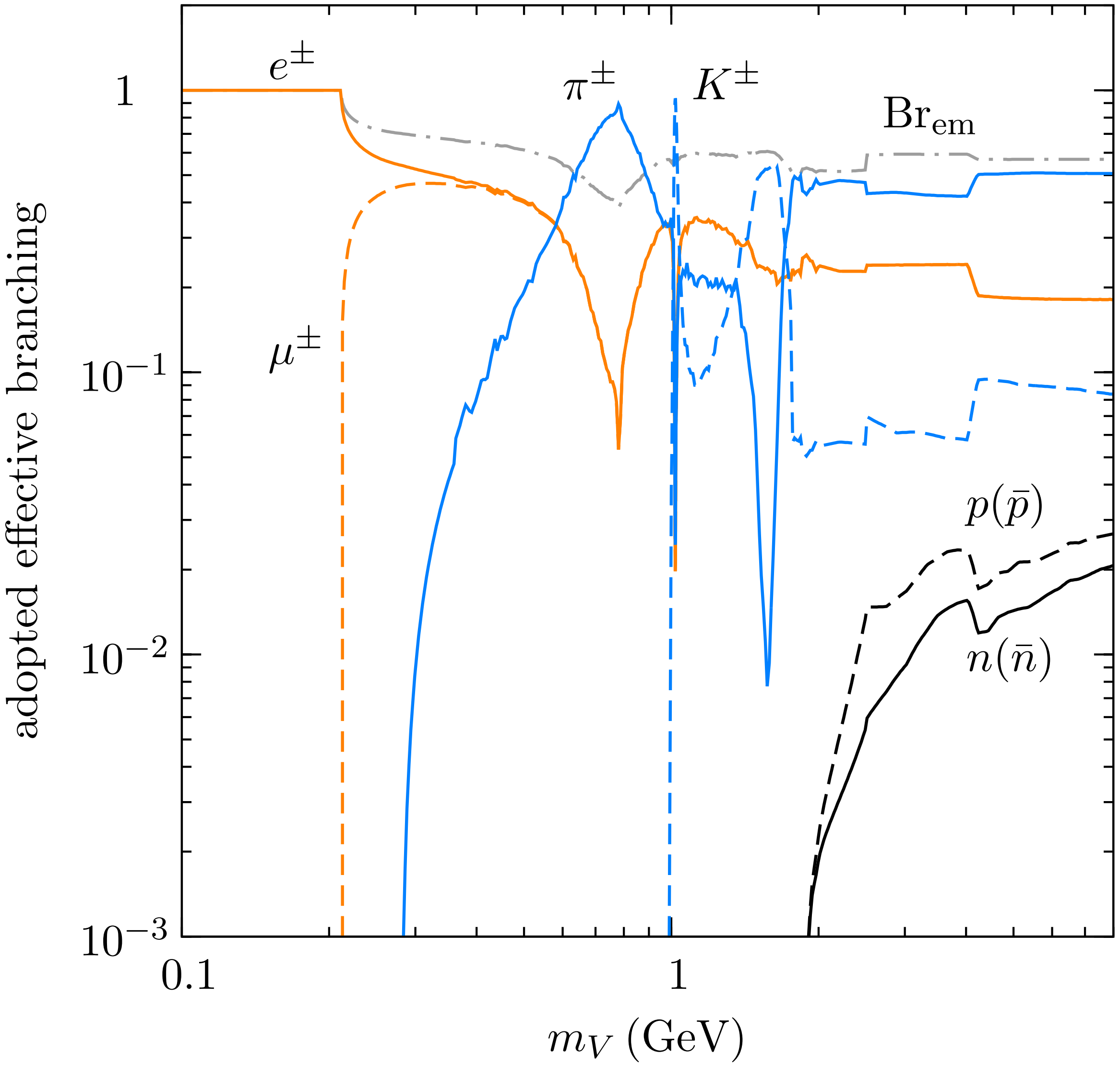


2. Late decay back to leptons and hadrons

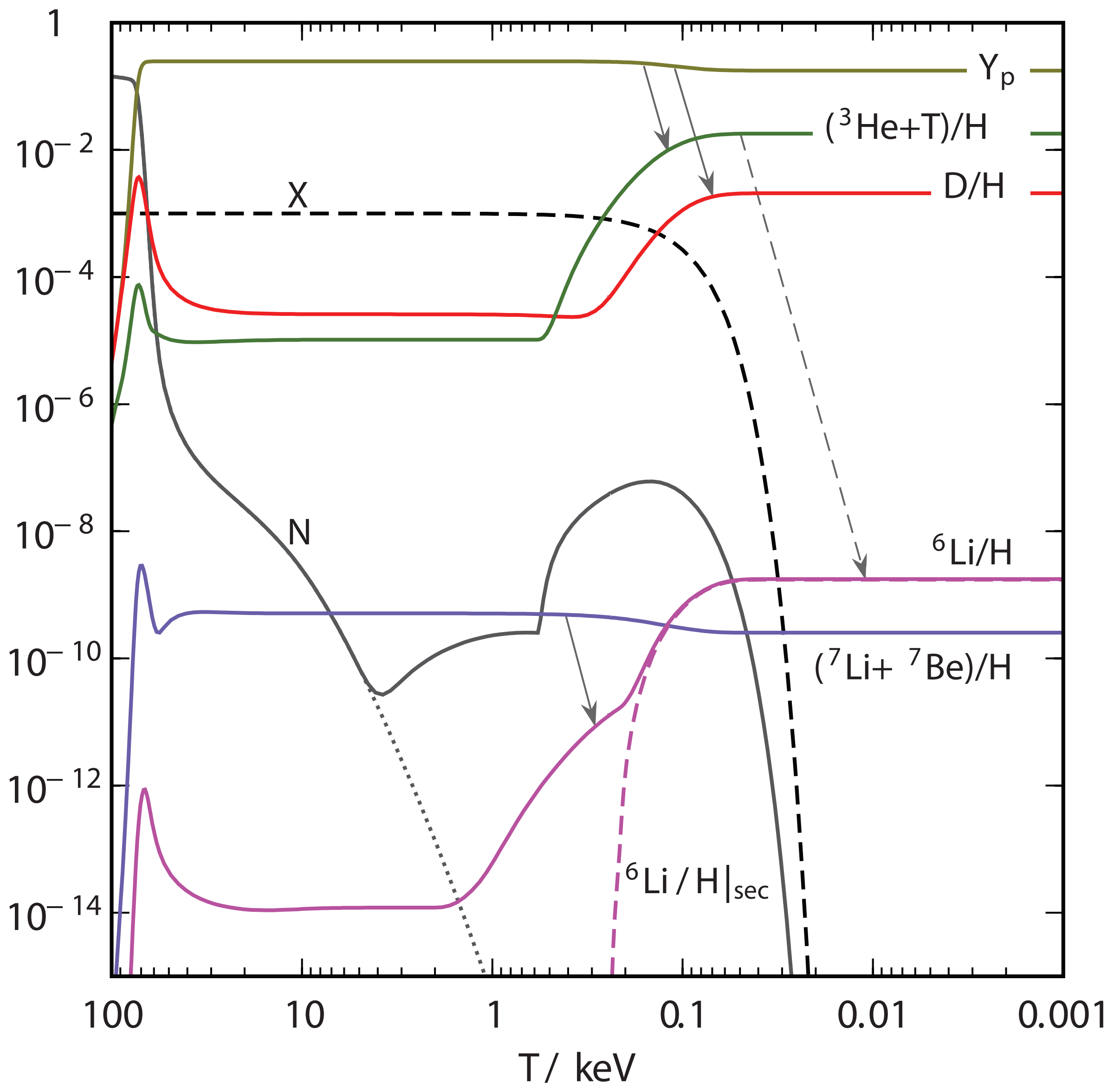


Fradette, Pospelov, JP, Ritz PRD 2014





BBN Limits
EM injection (t > 10^6 sec)



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

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

Secondary effects:

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

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

BBN Limits
soft hadronic injection

"Extra neutrons", also through captures like

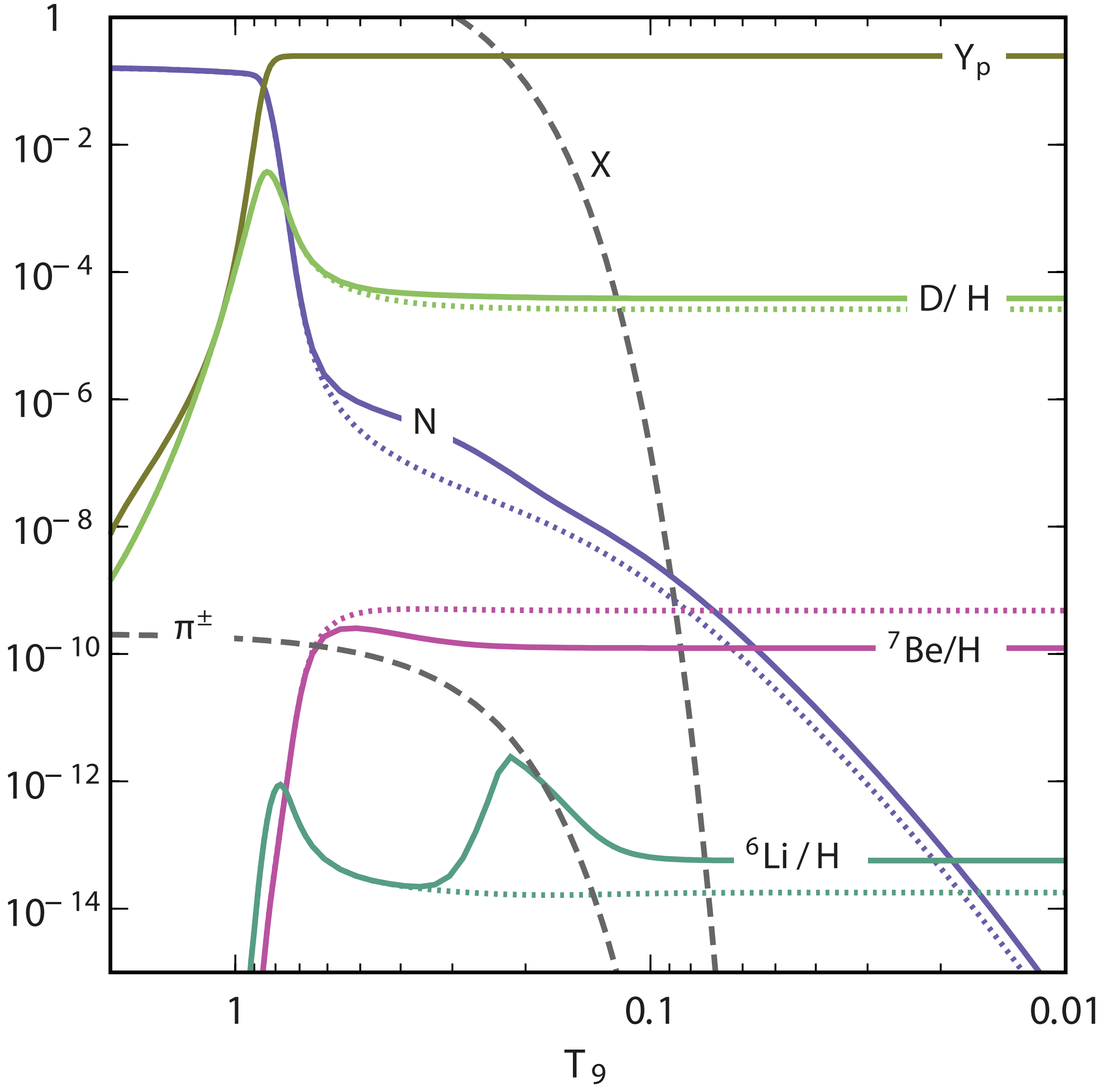
$$K^- + {}^4\mathrm{He} \to \Lambda(\Sigma^0)(pnn)$$

=> A path to ameliorate the lithium problem

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

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

$X \to \pi^+\pi^-$ $n_X/n_B = 8,\ \tau_X = 1000\,\mathrm{s}$



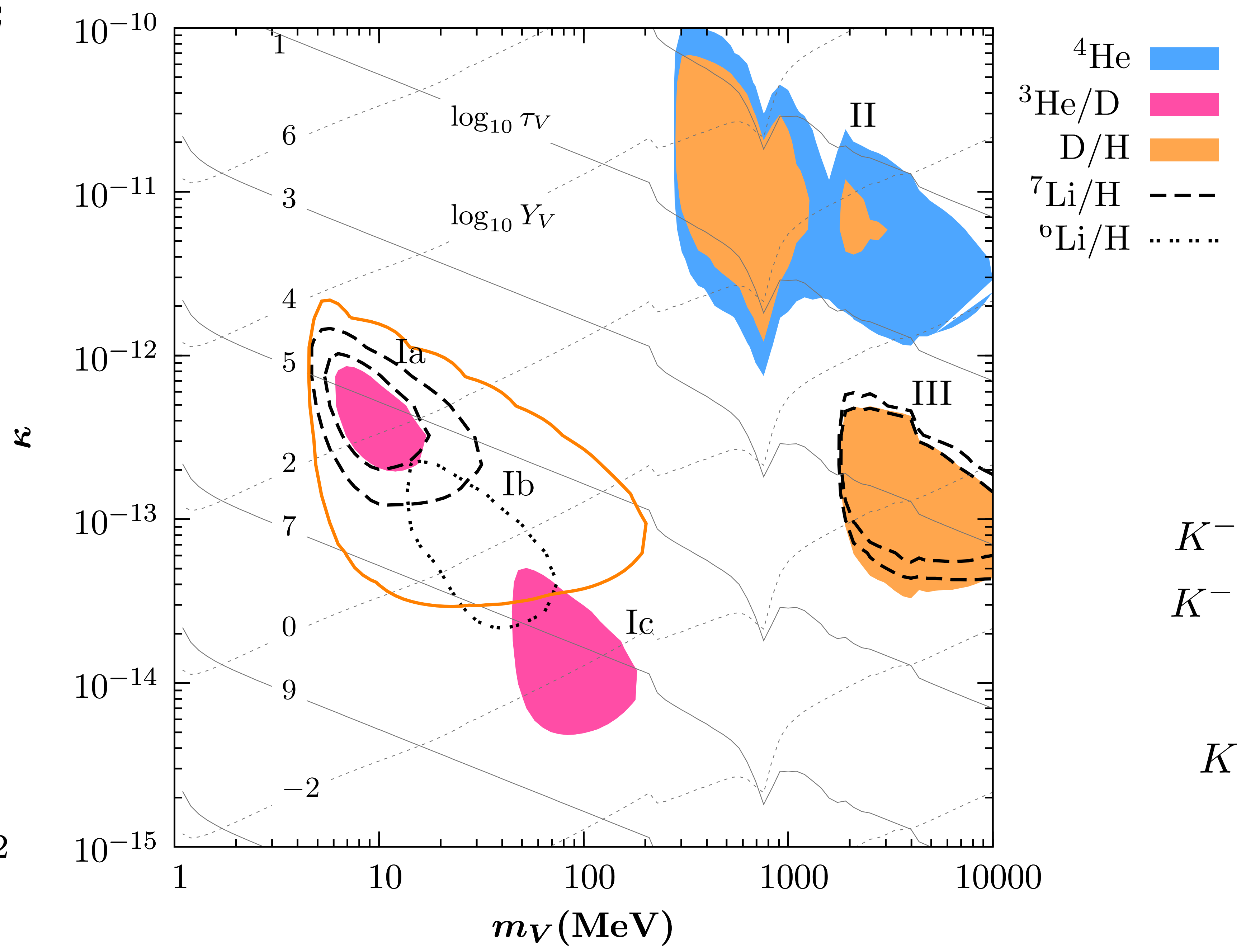
BBN Limits

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

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….

Summary

“Heavy” Dark Photon:
BBN and CMB probe
the *faint* vector portal
inaccessible in even
futuristic experiments

“Light” keV-Dark Photon
Dark Matter candidate;
accessible in Direct Detection,
constrained through astrophysics