Very Dark Photons

(in Cosmology)

Anthony Fradette

University of Victoria

work presented in
AF, Maxim Pospelov, Josef Pradler, Adam Ritz : PRD Aug 2014 (arXiv:1407.0993)

Theoretical Perspective on New Physics at the Intensity Frontier - Victoria BC 2014

Plan

- Dark Photon review and motivation
- *Very* Dark Photon (VDP) thermal production
- VDP and Big Bang Nucleosynthesis
- VDP and Cosmic Microwave Background
- Non-thermal production from Inflation

Motivation

Standard Model

Dark Sector

Motivation

Leading SM coupling to Neutral Hidden Sector

Portals

Scalar	Right-Handed neutrino	U(1)
$\mathcal{O}_s H^\dagger H$	$L H N_R$	$B_{\mu\nu} V^{\mu\nu}$

Motivation

Standard Model ······ Hello? ······ Dark Sector

Leading SM coupling to Neutral Hidden Sector

Portals

Scalar	Right-Handed neutrino	U(1)
$\mathcal{O}_s H^\dagger H$	$L H N_R$	$B_{\mu\nu} V^{\mu\nu}$
		Dark Photon

For $m_V \ll m_Z$, only mixes kinetically with photons

$$\mathcal{L}_{V_{\rm int}} = -\frac{\kappa}{2} F_{\mu\nu} V^{\mu\nu} = e\kappa V_\mu J^\mu_{\rm em}$$

B. Holdom, Phys. Lett. B 166, 196 (1986)

$$e' = \kappa e$$

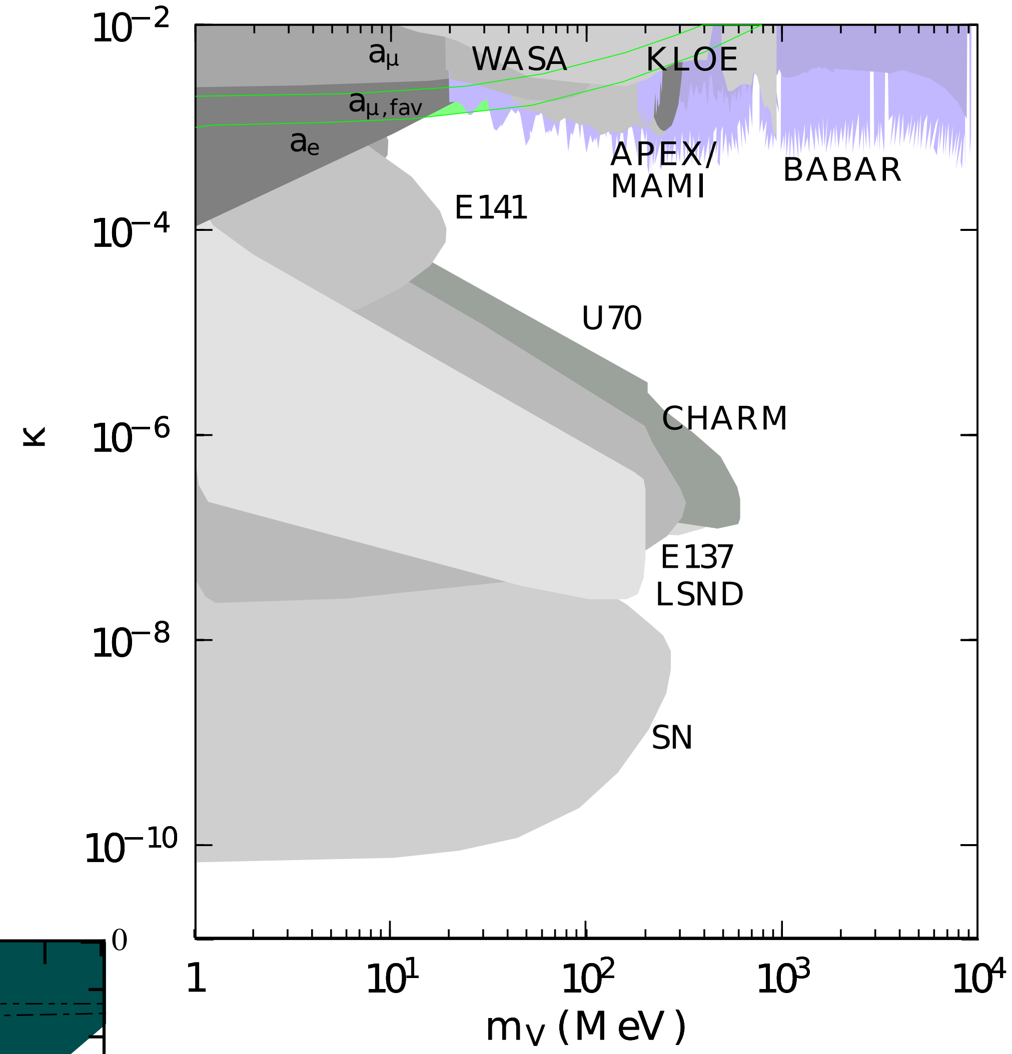
$$\alpha_{\rm eff} = \alpha \kappa^2$$

$\mathcal{L}_{V_{\rm mass}}$ → Stueckelberg

$\mathcal{L}_{V_{\rm mass}}$ → Higgs'

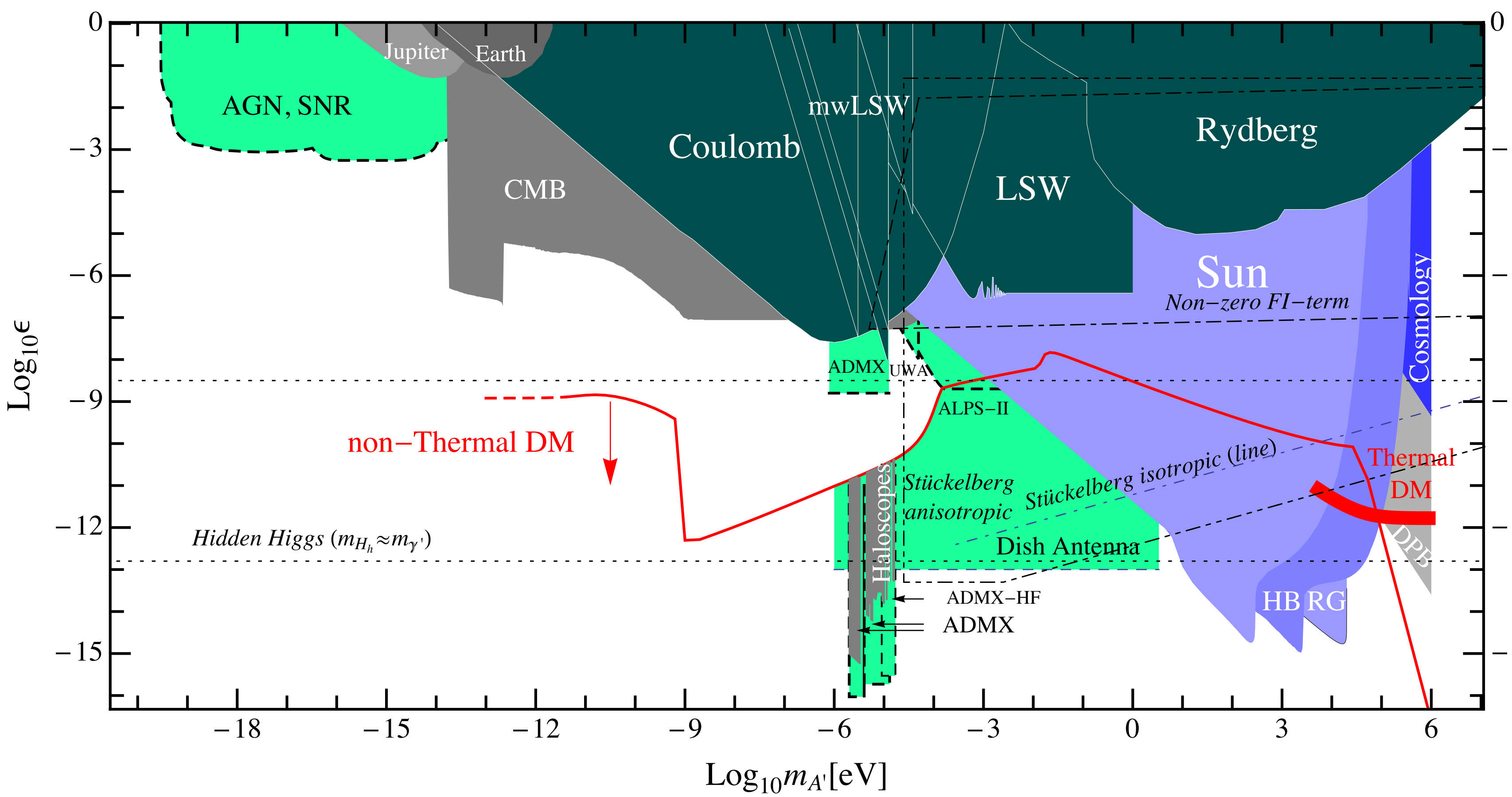
Dark Photon Landscape

See Review from: Essig *et al.*, Snowmass 2013



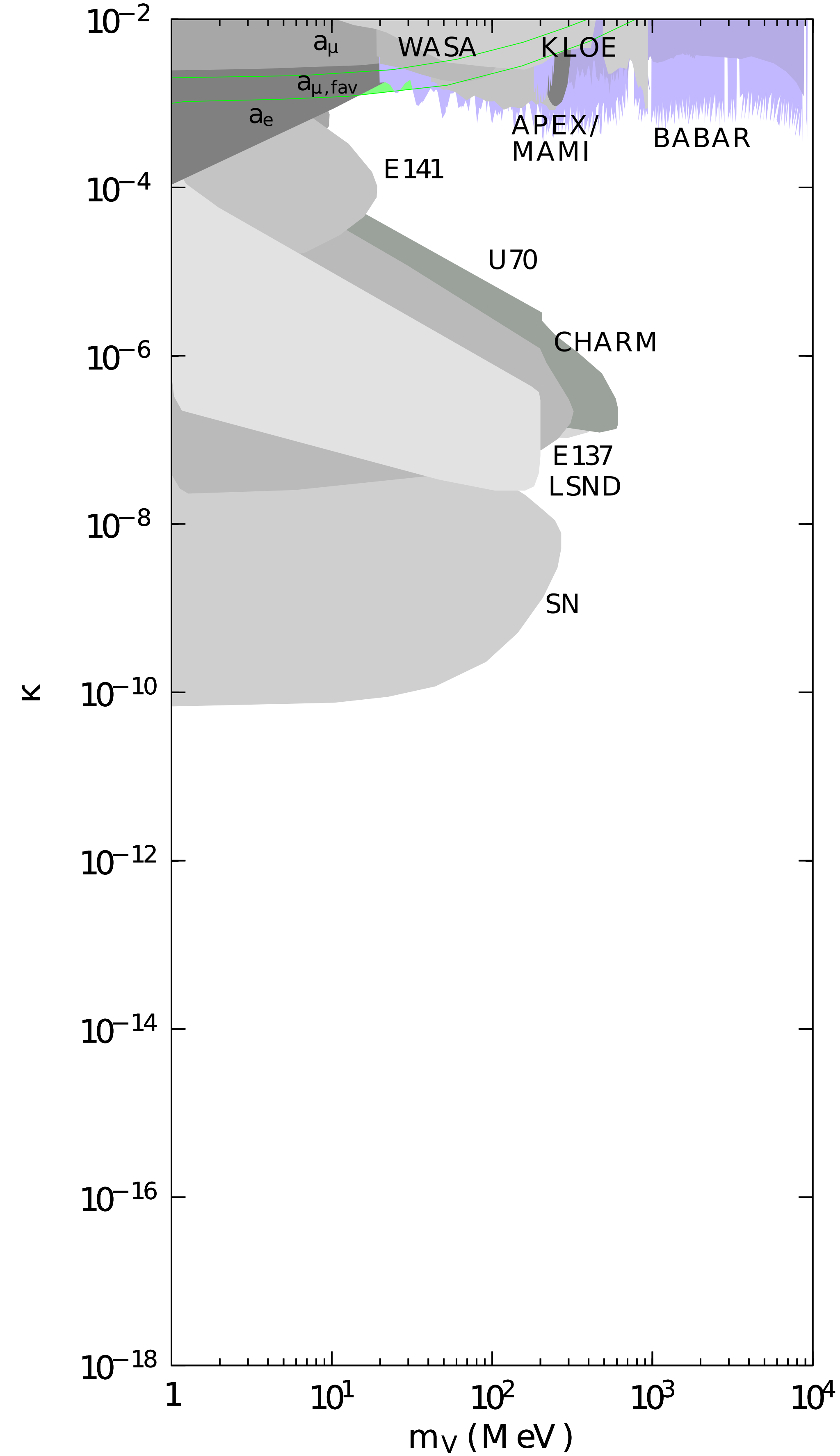
$$m_V > 2m_e$$

$$m_V < 2m_e$$



Very Dark Photon ?

Can we use the Universe as a detector?



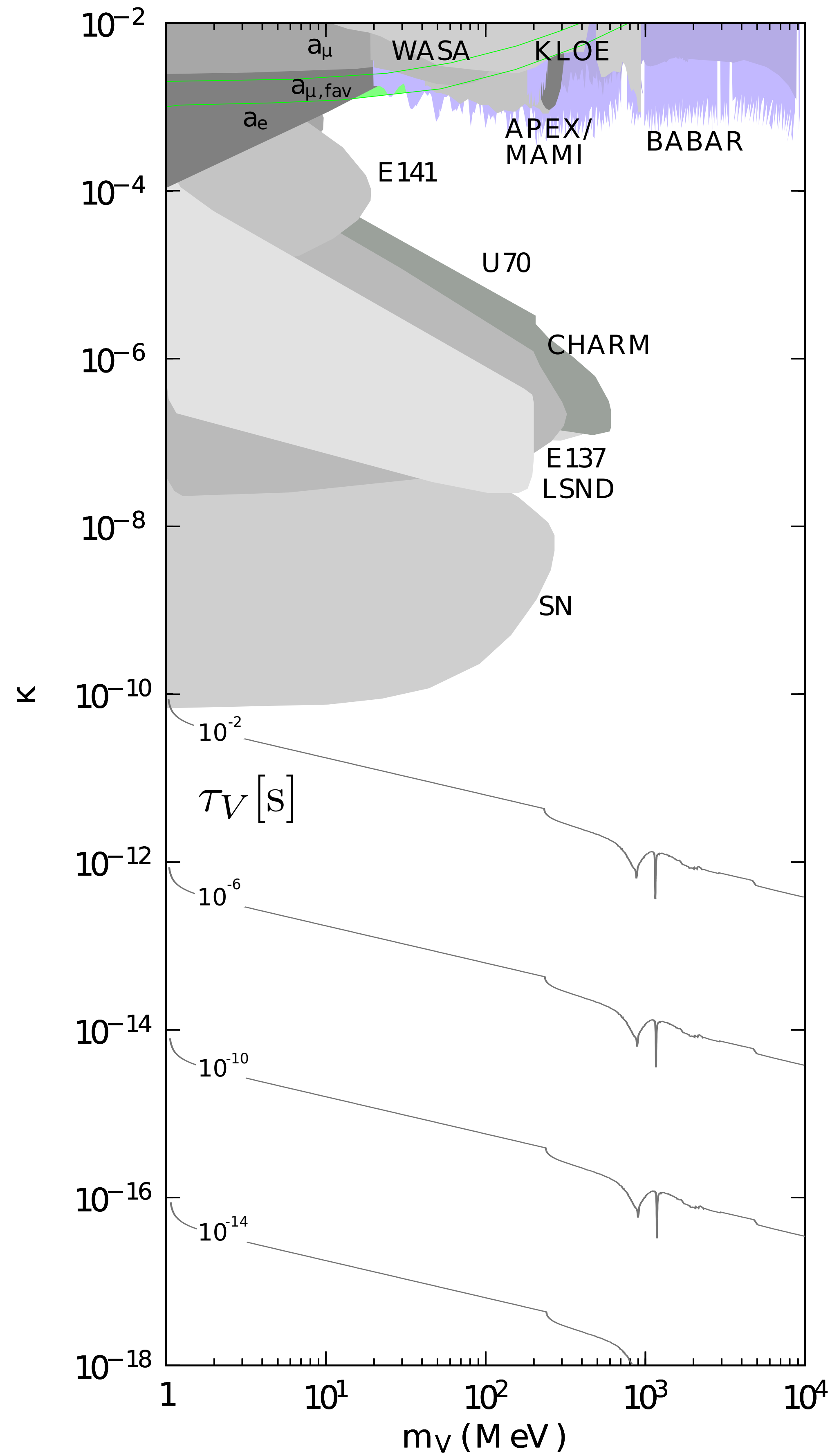
Very Dark Photon ?

Can we use the Universe as a detector?

$$\tau_V \simeq \frac{3}{\alpha_{\rm eff} m_V} = 6 \times 10^5\ \mathrm{yr} \times \frac{10\ \mathrm{MeV}}{m_V} \times \frac{10^{-35}}{\alpha_{\rm eff}}$$

Recombination

Very Dark!



Very Dark Photon ?

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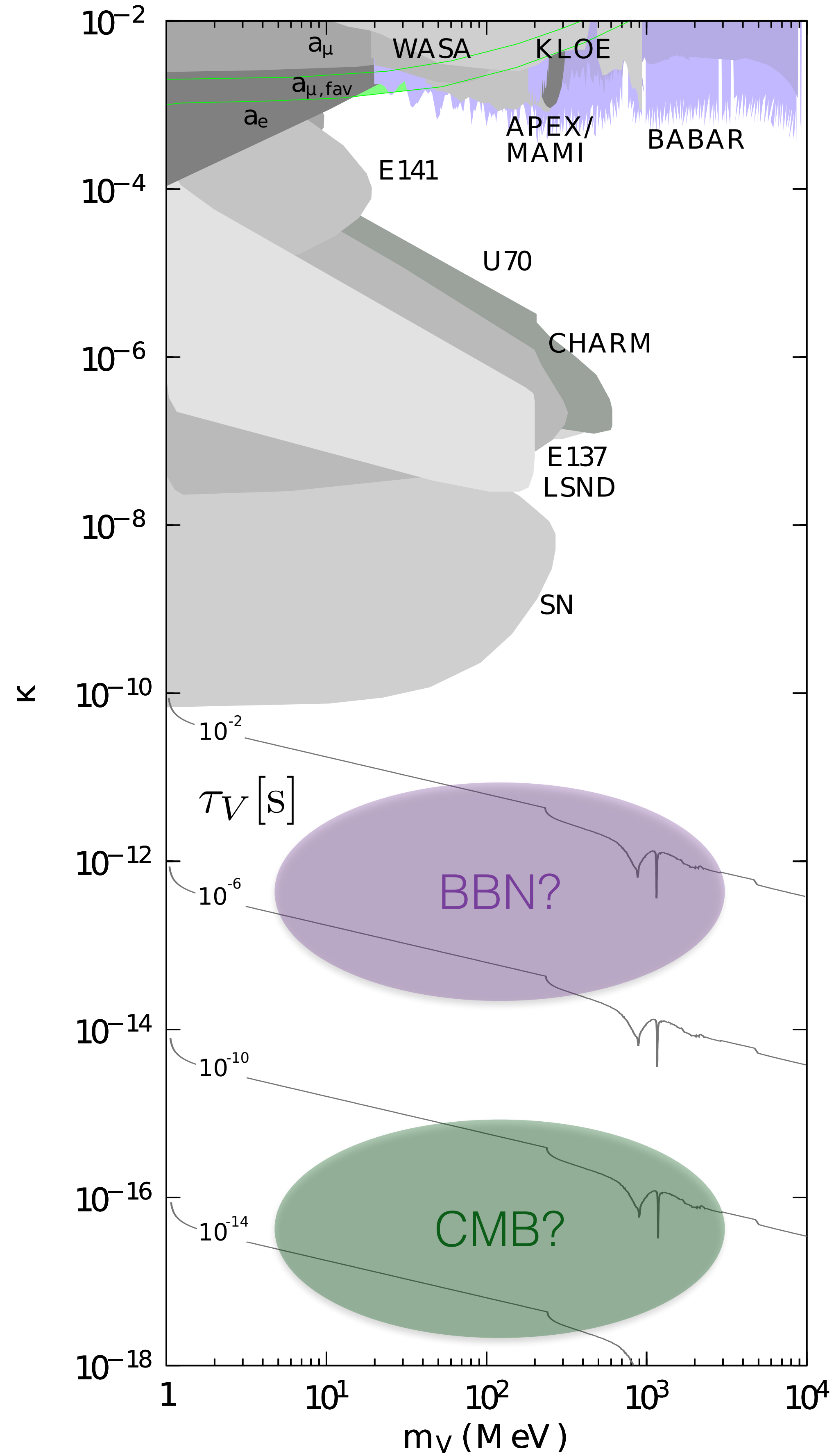
Recombination   Very Dark!

Postma and Redondo, 2008
→ No explicit bounds derived

Can it been seen on Earth?

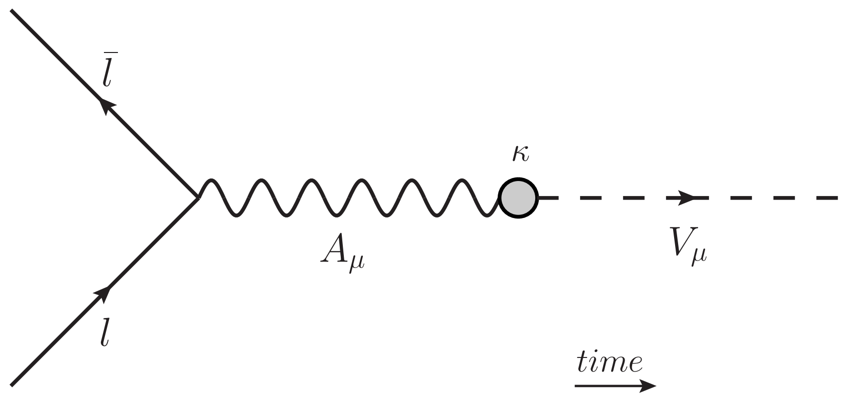
$$e^+e^- \to V\gamma$$

$$\sigma_{\rm prod} \sim \frac{\pi \alpha \alpha_{\rm eff}}{E^2_{\rm c.m.}} \sim 10^{-66} - 10^{-52} \text{ cm}^2$$



VDP Thermal Production

Dominant contribution from coalescence



The Boltzmann equation

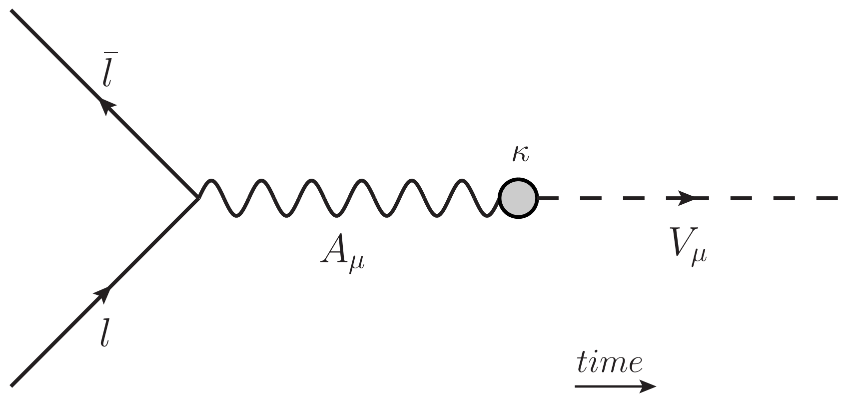
$$s\dot{Y} = \prod_{i=l,\bar{l},V} \int \left(\frac{d^3\mathbf{p}_i}{(2\pi)^3 2E_i} \right) (N_l N_{\bar{l}} - N_V)(2\pi)^4 \delta^{(4)}(p_l + p_{\bar{l}} - p_V) \sum |M_{l\bar{l}}|^2$$

$\left(Y = \frac{n_V}{s}\right)$

is modified because of *darkness*

VDP Thermal Production

Dominant contribution from coalescence



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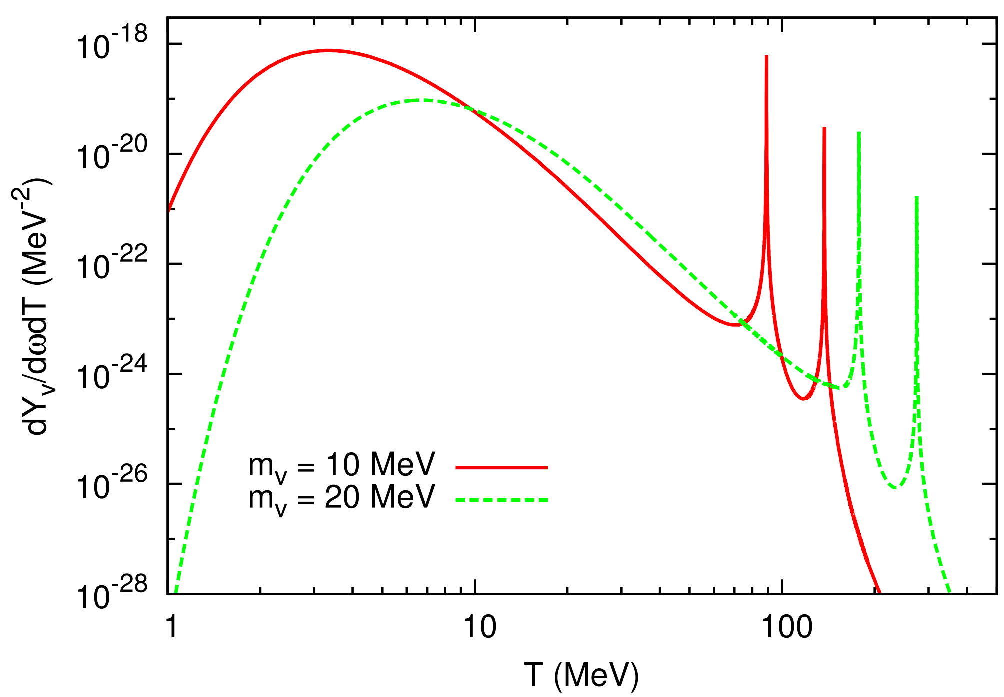
$\left(Y = \frac{n_V}{s}\right)$

is modified because of ***darkness*** → *V* not in equilibrium

→ Freeze-in production



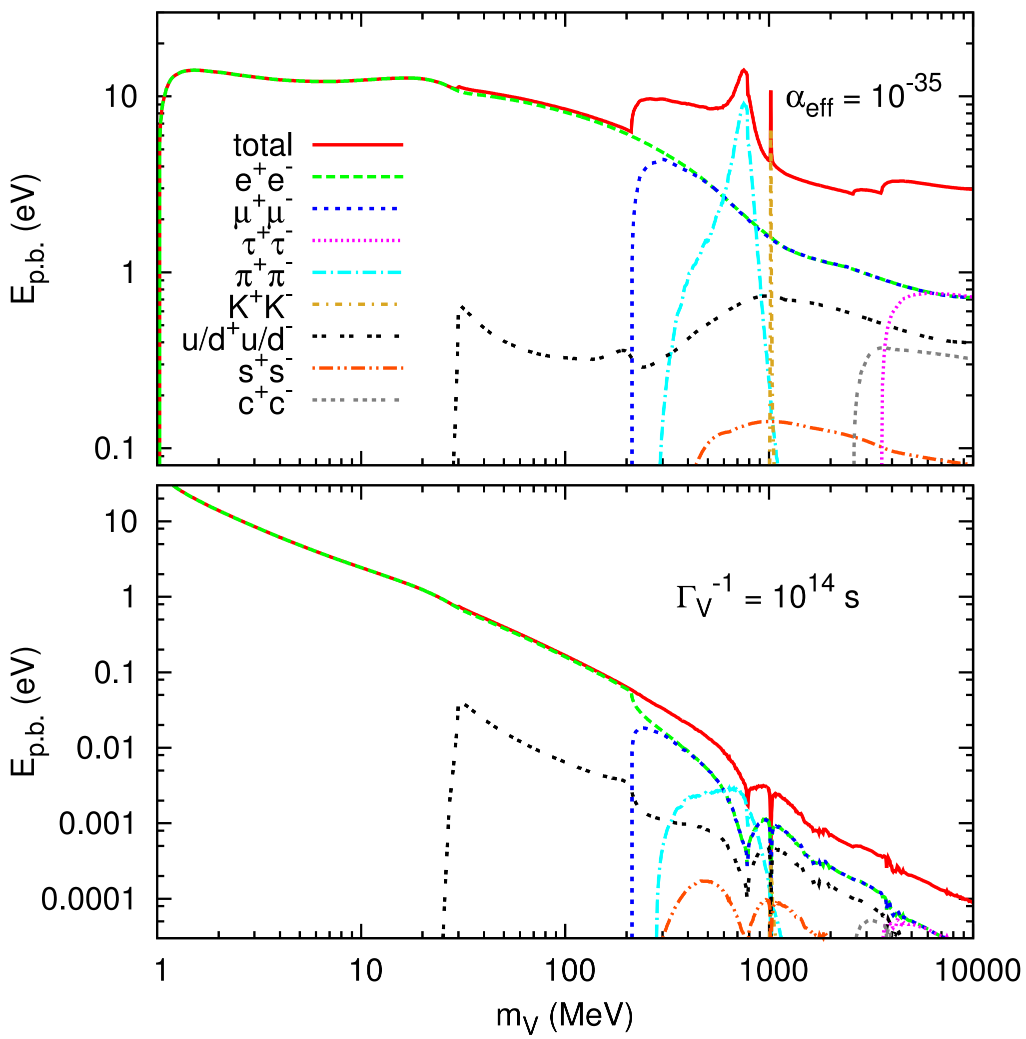
$$\frac{d^2\Gamma_{\text{prod}}}{d\omega dT} \propto \frac{1}{3}\frac{m_V^4}{|m_V^2 - \Pi_L|^2} + \frac{2}{3}\frac{m_V^4}{|m_V^2 - \Pi_T|^2}$$

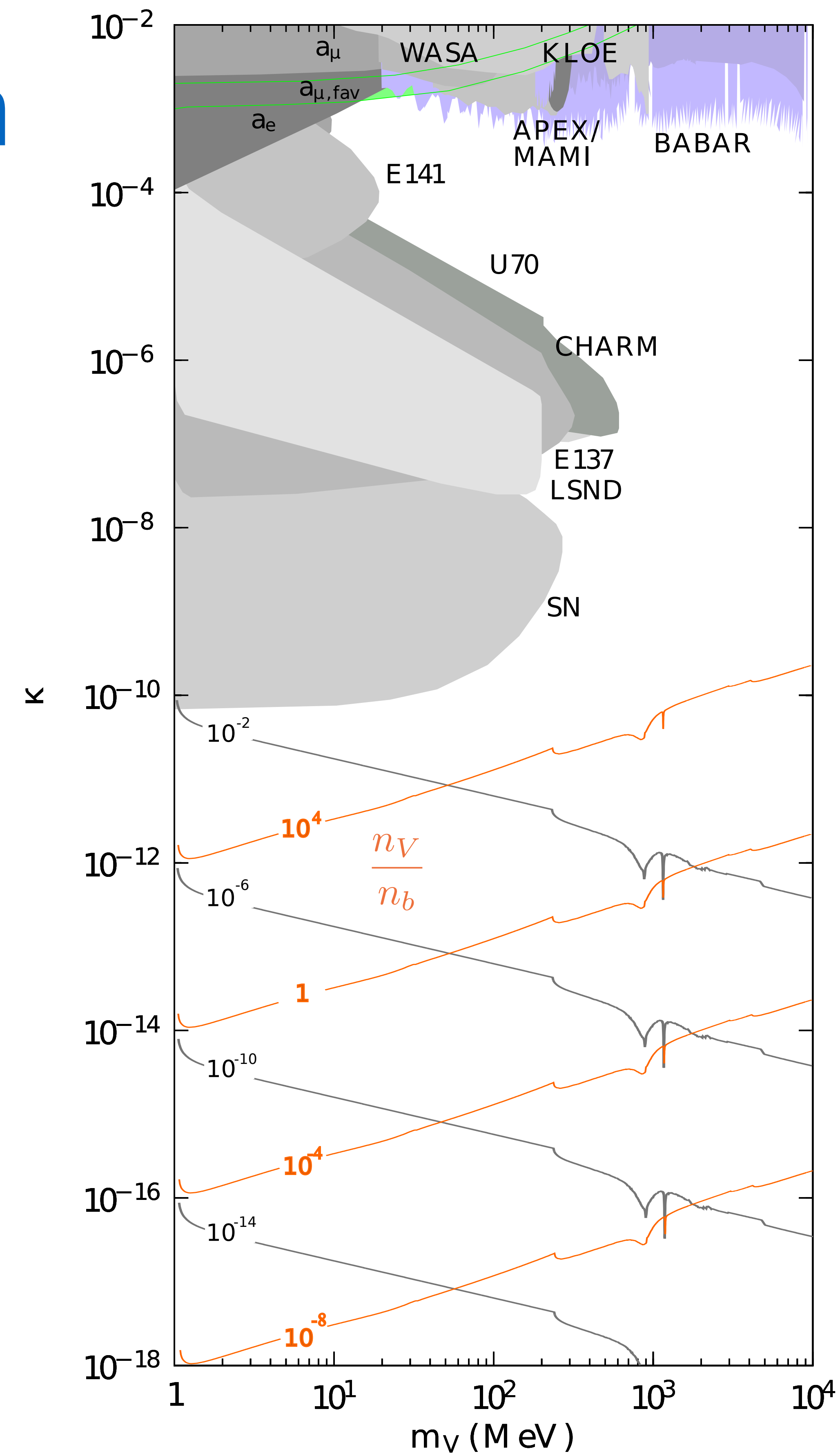
VDP Thermal Production

Basic QCD transition model

Free meson gas | Free quarks

$$T_c = 157 \text{ MeV}$$





VDP and Big Bang Nucleosynthesis

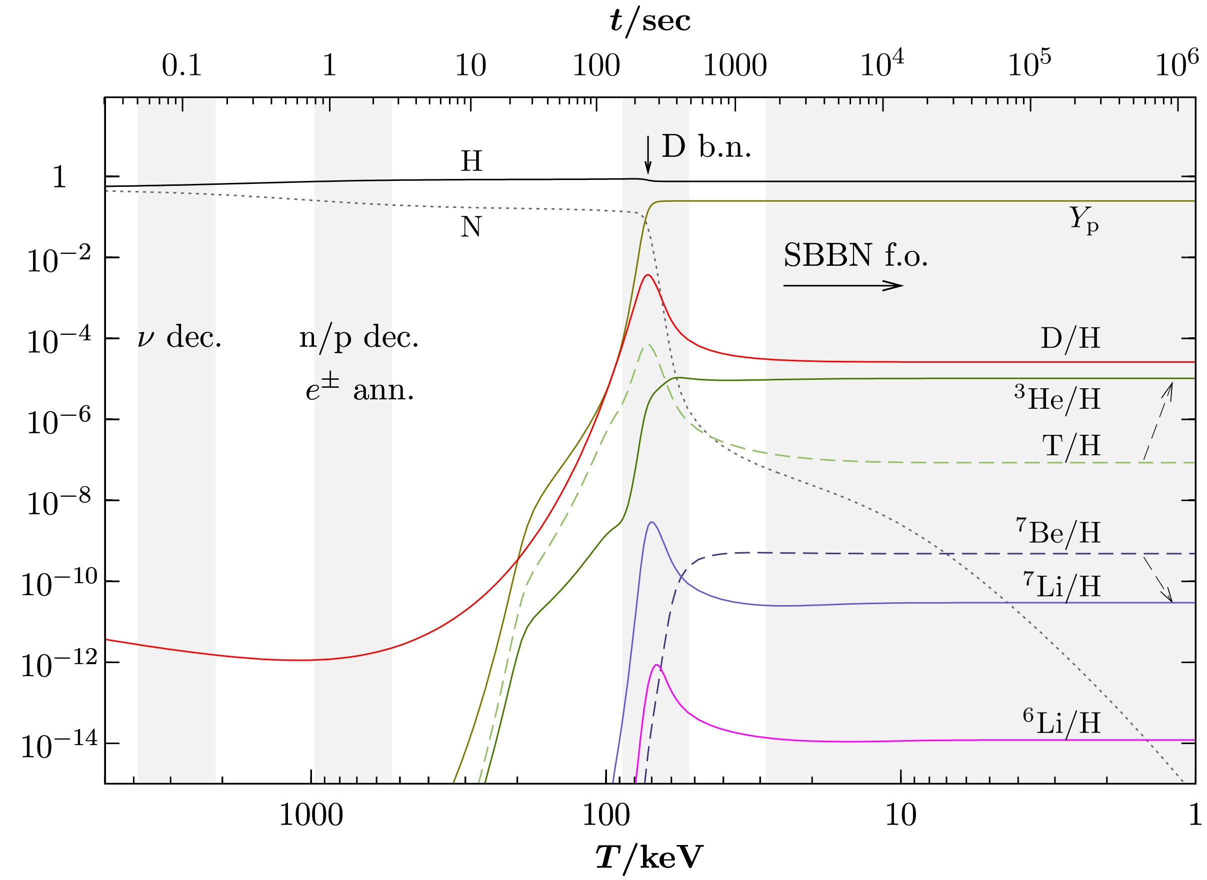
BBN is a good probe for New Physics

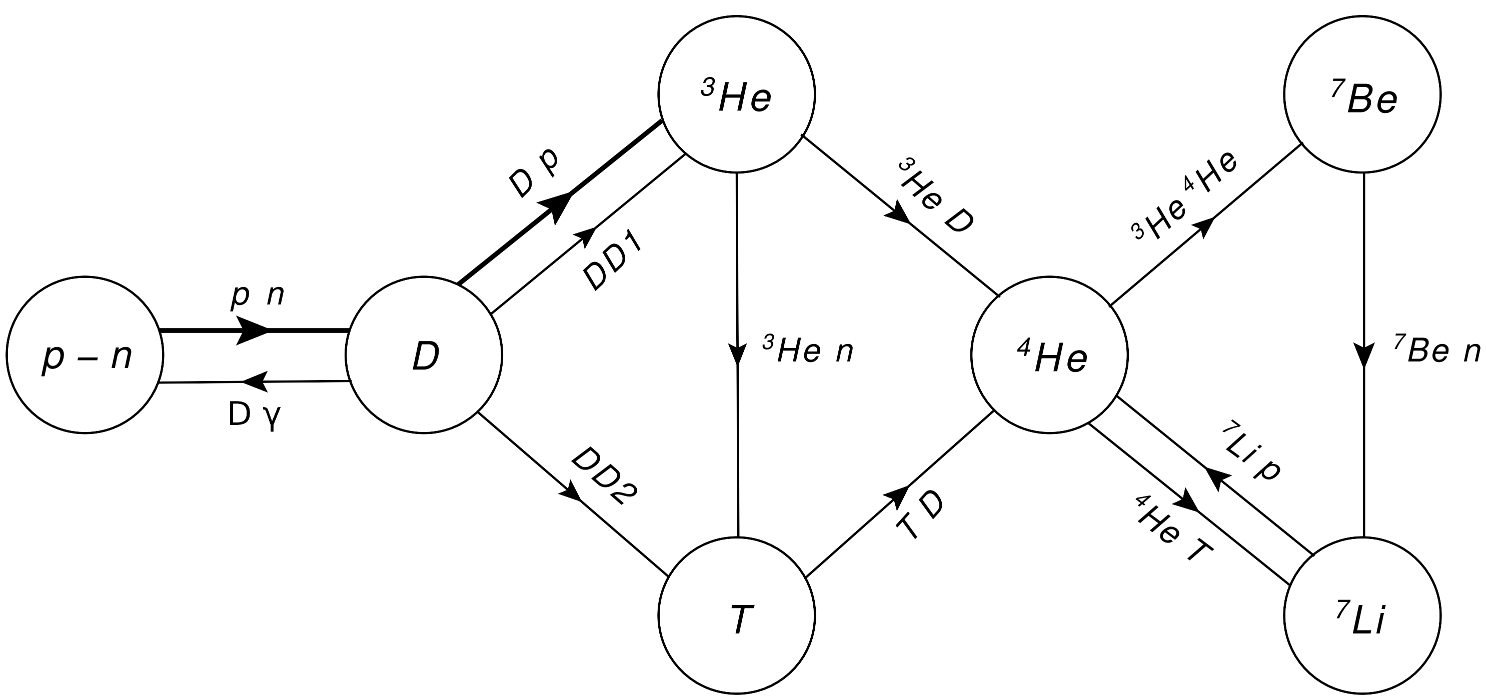
Pospelov and Pradler, 2010

- Minimal assumptions
- 1 parameter : η_b (Planck, WMAP)

Provides constraints on any modification to nuclear reaction network

e.g. energy injection from non-SM particle decays





$m_V < 2m_\pi$
Electromagnetic energy injection

$m_V > 2m_\pi$
Hadronic energy injection

Opposing trends in $Y_V - \tau_V$

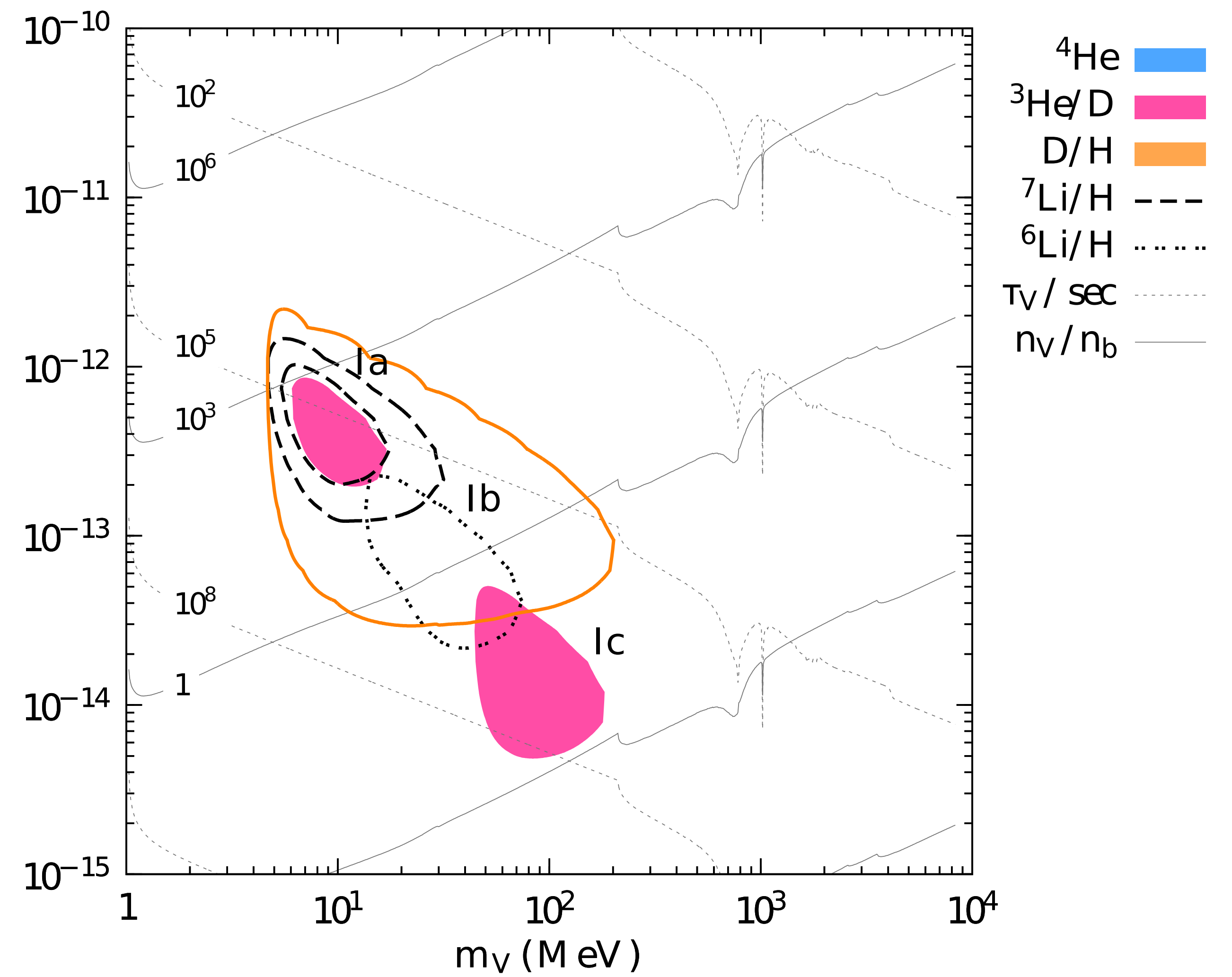
Localized constraints in $m_V - \kappa$

VDP and Big Bang Nucleosynthesis

$m_V < 2m_\pi$: EM energy injection

- Injection of e^+e^- $(\mu^+\mu^-)$ quickly transfers energy to photons via inverse Compton scattering
- $\gamma + \gamma_{\rm bgd} \to e^+e^-$ allowed for $E_\gamma \gtrsim m_e^2/22T$
- For smaller E_γ, the energy is dissipated through photodestruction of nuclei

$$t_{\rm ph} \simeq \begin{cases} 2\times 10^4 \mathrm{s}, & {}^7\mathrm{Be} + \gamma \to {}^3\mathrm{He} + {}^4\mathrm{He} \quad (1.59\,\mathrm{MeV}), \\ 5\times 10^4 \mathrm{s}, & \mathrm{D} + \gamma \to n + p \quad (2.22\,\mathrm{MeV}), \\ 4\times 10^6 \mathrm{s}, & {}^4\mathrm{He} + \gamma \to {}^3\mathrm{He/T} + n/p \quad (20\,\mathrm{MeV}), \end{cases}$$



Region Ia

- Reduction of ^{7}Li (3-4 x 10^{-10})
- Underproduction of D

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

Cooke *et al.*, 2013

$$^3\mathrm{He/D} < 1$$

Region Ib

- Increase of ^{6}Li by $\mathcal{O}(100)$

Not a constraint

Region Ic

- Creation of ^{3}He ruled out by

$$^3\mathrm{He/D} < 1$$

VDP and Big Bang Nucleosynthesis

$m_V > 2m_\pi$: Hadronic energy injection

- Simplified by considering long-lived mesons $\pi^\pm$, $K^\pm$, K_L^0 and (anti-)nucleons
- Important reactions

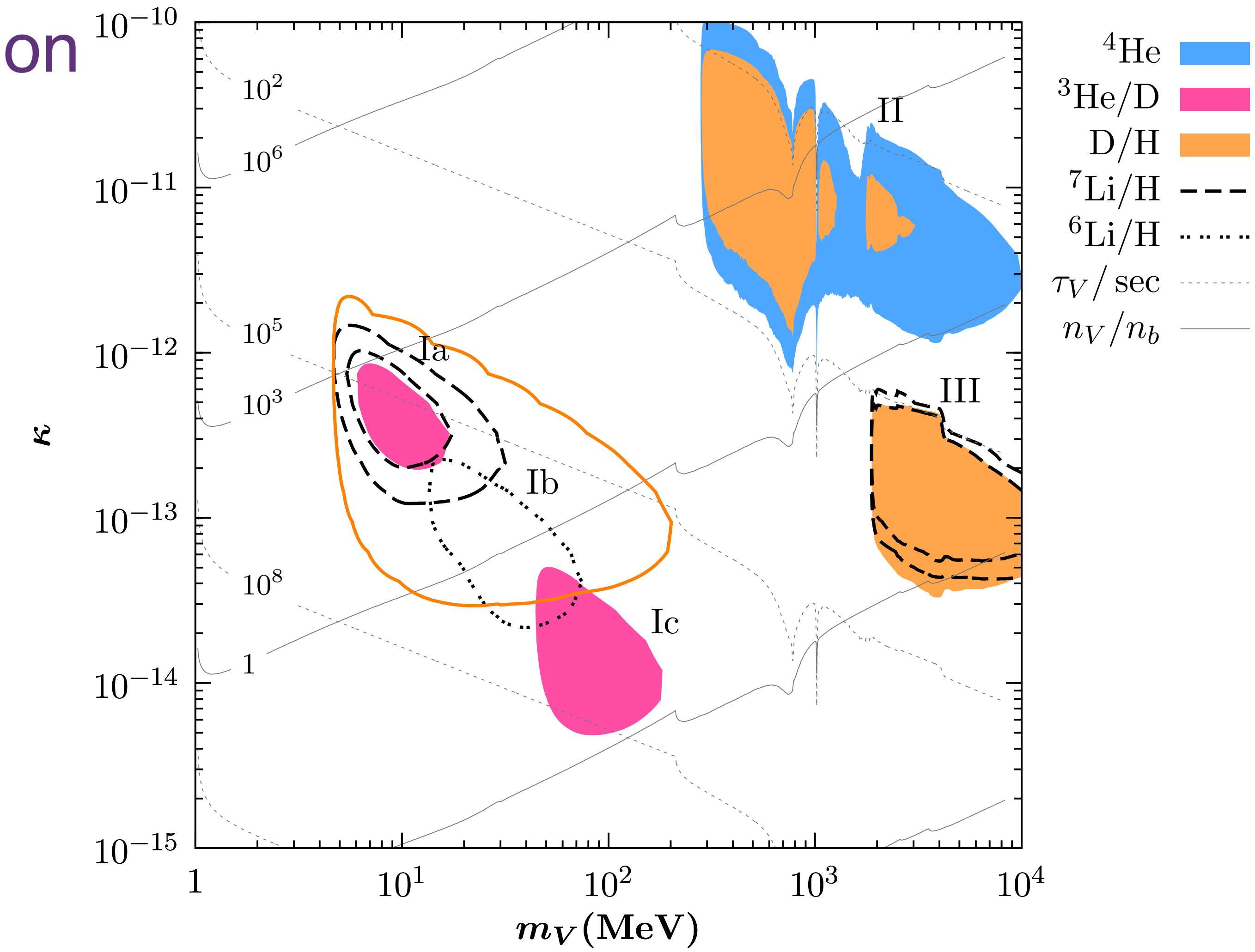
Charge exchange

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

Lithium depletion

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

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



Region II

- Short lifetime (before D-bottleneck)
- Additional $p \leftrightarrow n$, n/p rises

$$Y_p \leq 0.26$$
$$\mathrm{D/H} \leq 3 \times 10^{-5}$$

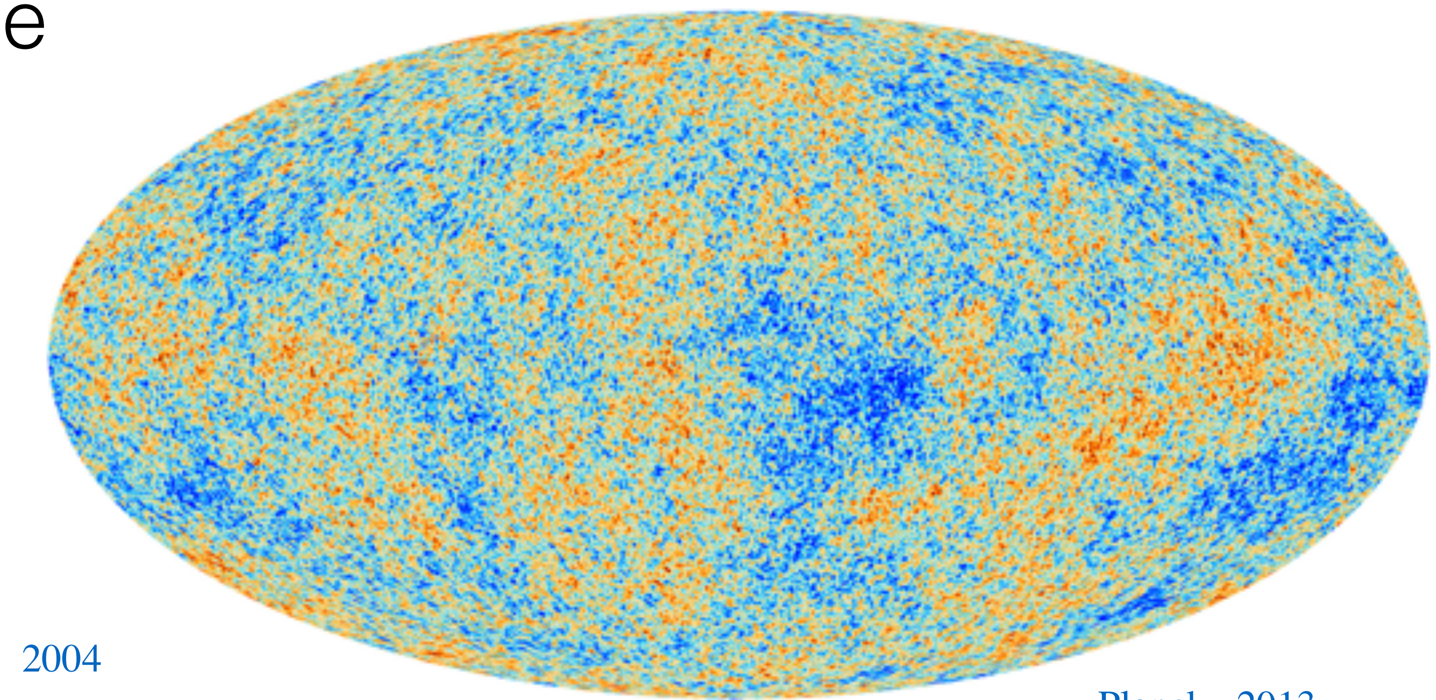
Region III

- Extra neutrons from $V \to n\bar{n}$ or indirect production
- Lithium depletion
- Extra neutrons yield more D

$$\mathrm{D/H} \leq 3 \times 10^{-5}$$

VDP and Cosmic Microwave Background

The CMB is an integrated image over the recombination epoch



Planck, 2013

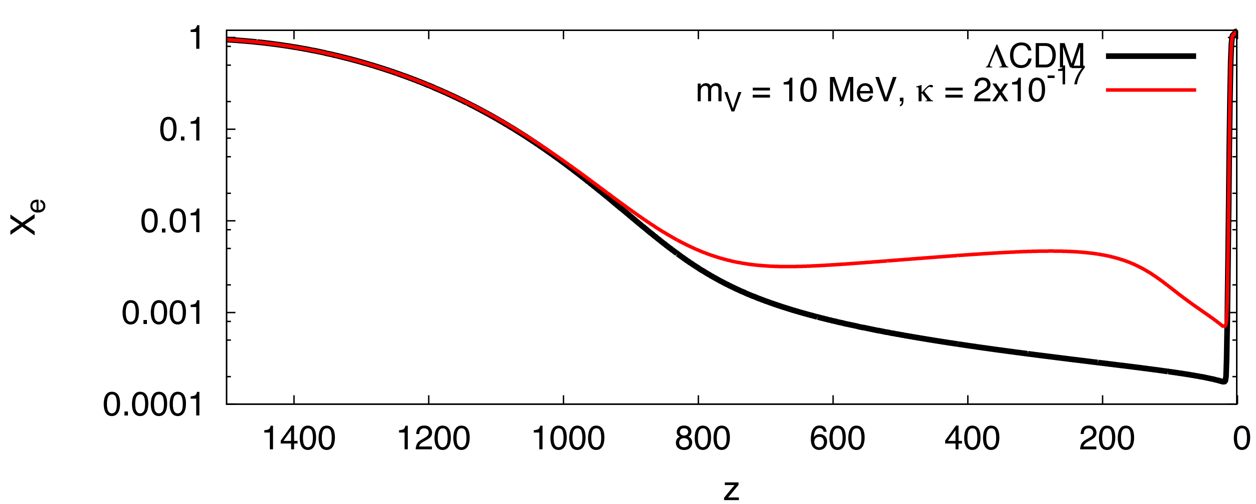
Provides constraints on any modification to visibility function

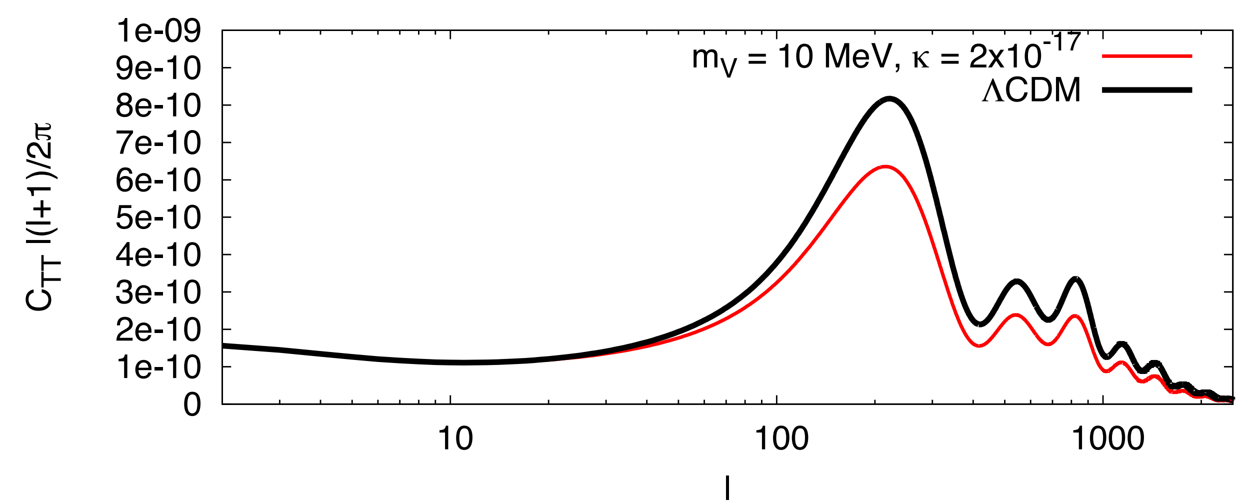
e.g. energy injection from non-SM particle decays

eg.: Chen and Kamionkowski, 2004
Slatyer *et al.*, 2009

Partial reionization enhances late scatterings of CMB photons

Washes out small scale TT correlation



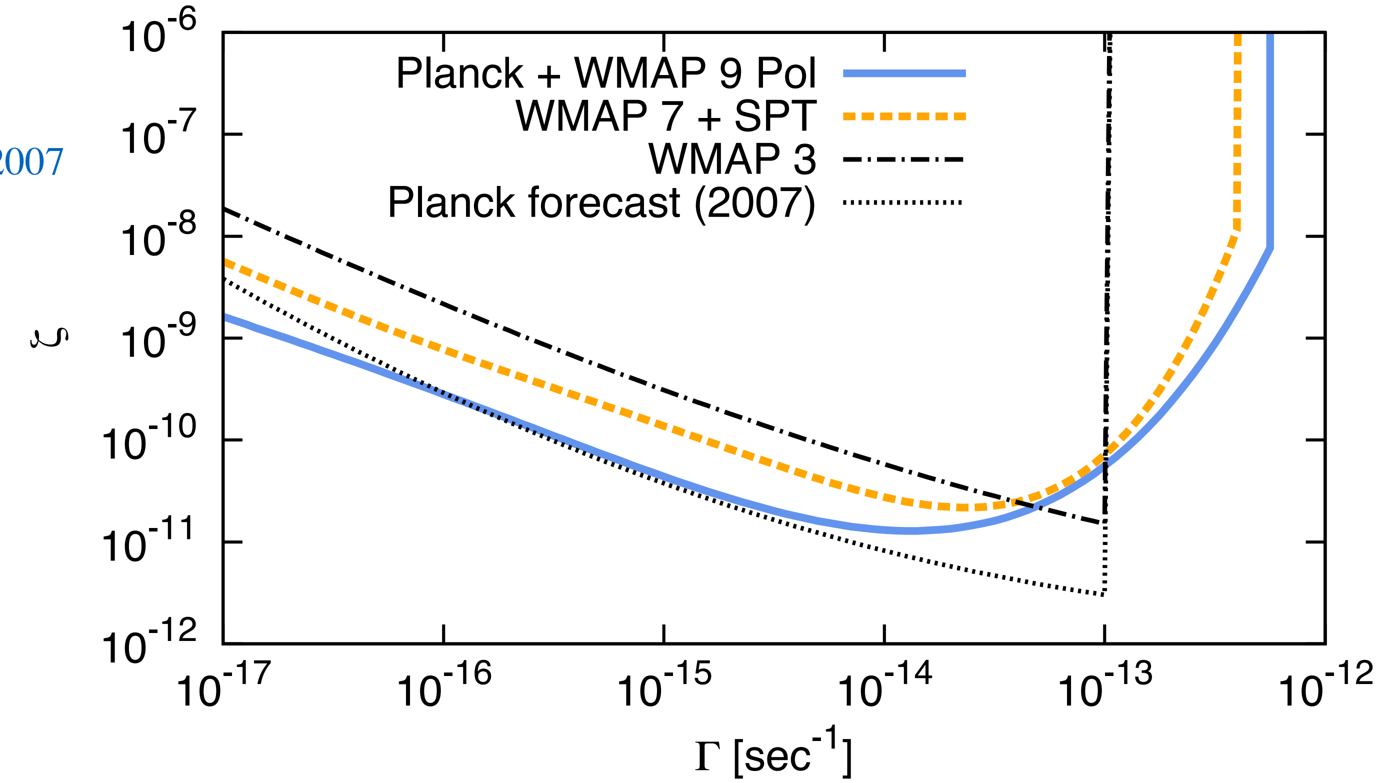


VDP and Cosmic Microwave Background

Generic constraints on decaying particle

For eg. Zhang *et al.*, 2007

$$\frac{dE}{dtdV} = 3\zeta m_{\rm p}\Gamma e^{-\Gamma t}$$

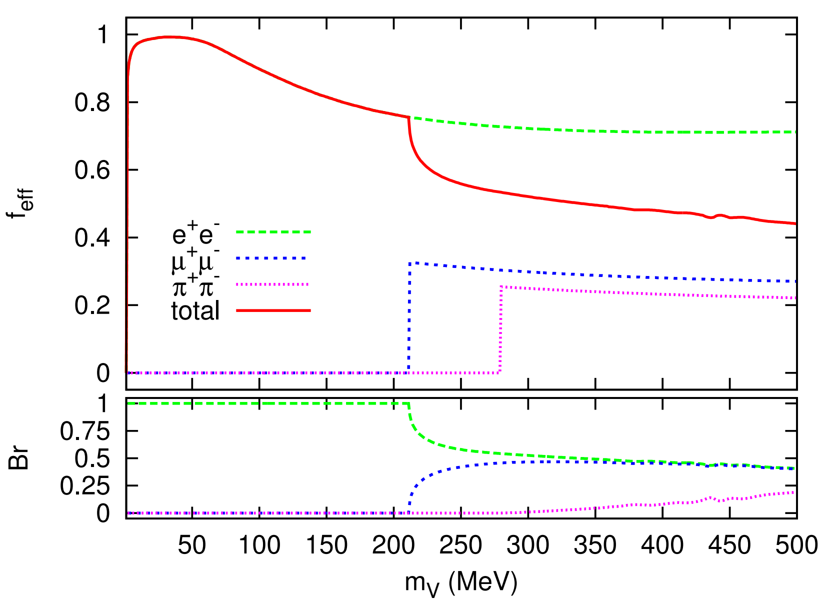


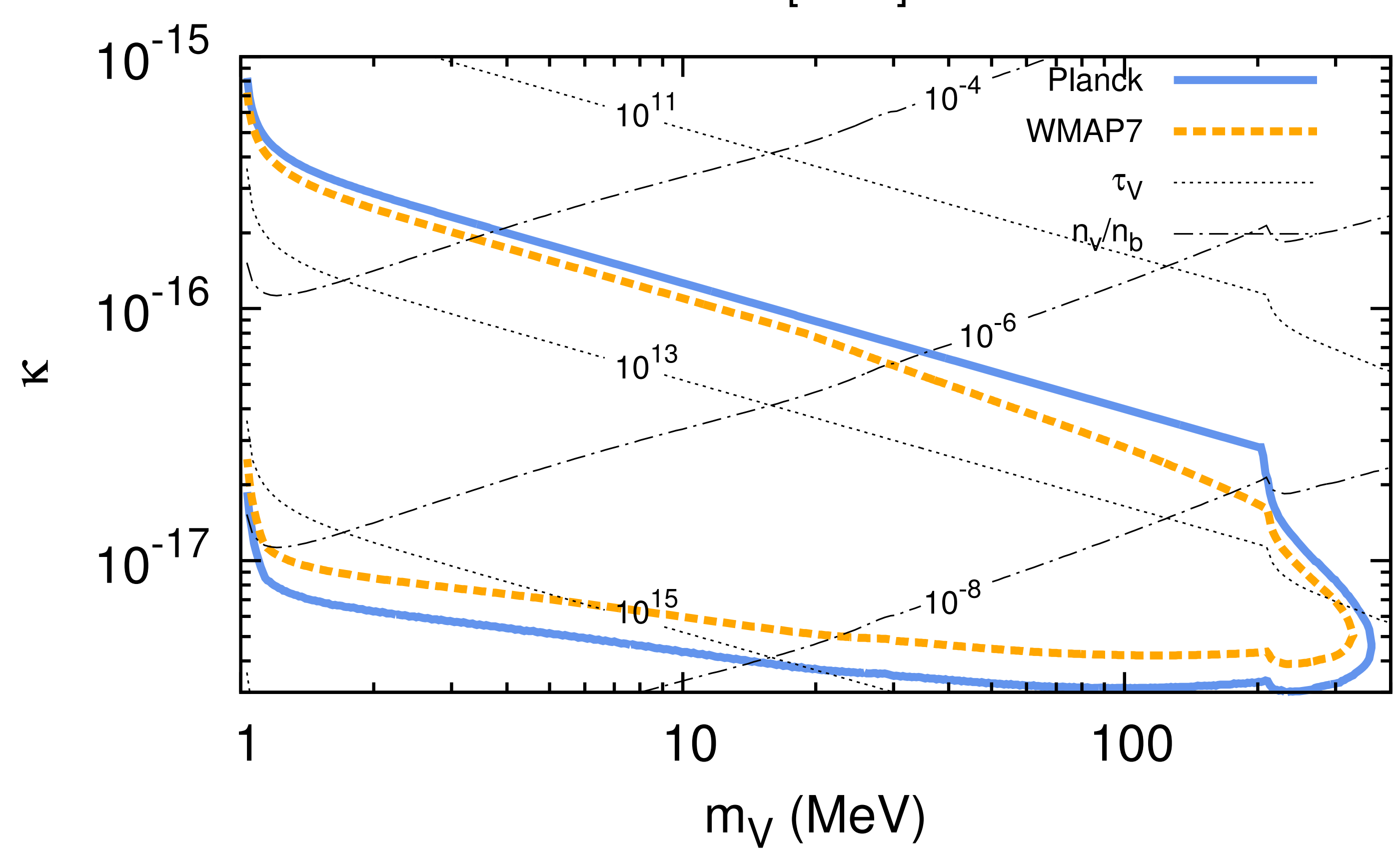
ζ Energy output $\frac{1}{3}$ ionization

$\frac{2}{3}$ heating

Energy is **not** deposited right away

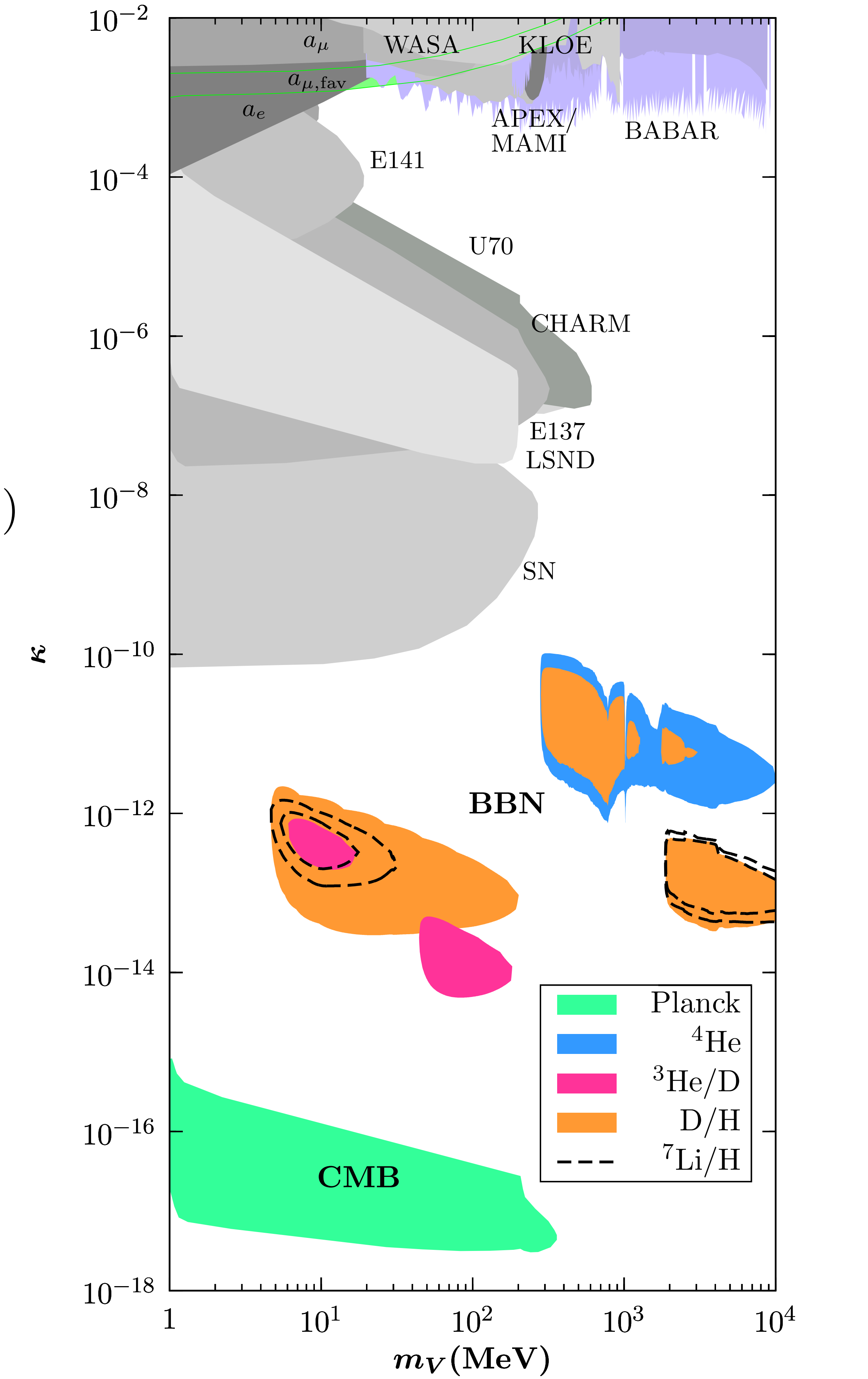
Slatyer, 2012





Dark photon constraints

- The Universe is a great particle detector
- Minimal assumptions $V \not\to \chi\chi$
  $T \sim \mathcal{O}(1 - 1000\ \mathrm{MeV})$
- Additional contributions can only strengthen constraints
- Present-day decays ? Abundance falls short by **many** orders of magnitude (antimatter, gamma-ray, neutrino signals…)
- Non-thermal production?



Dark photons from Inflation?

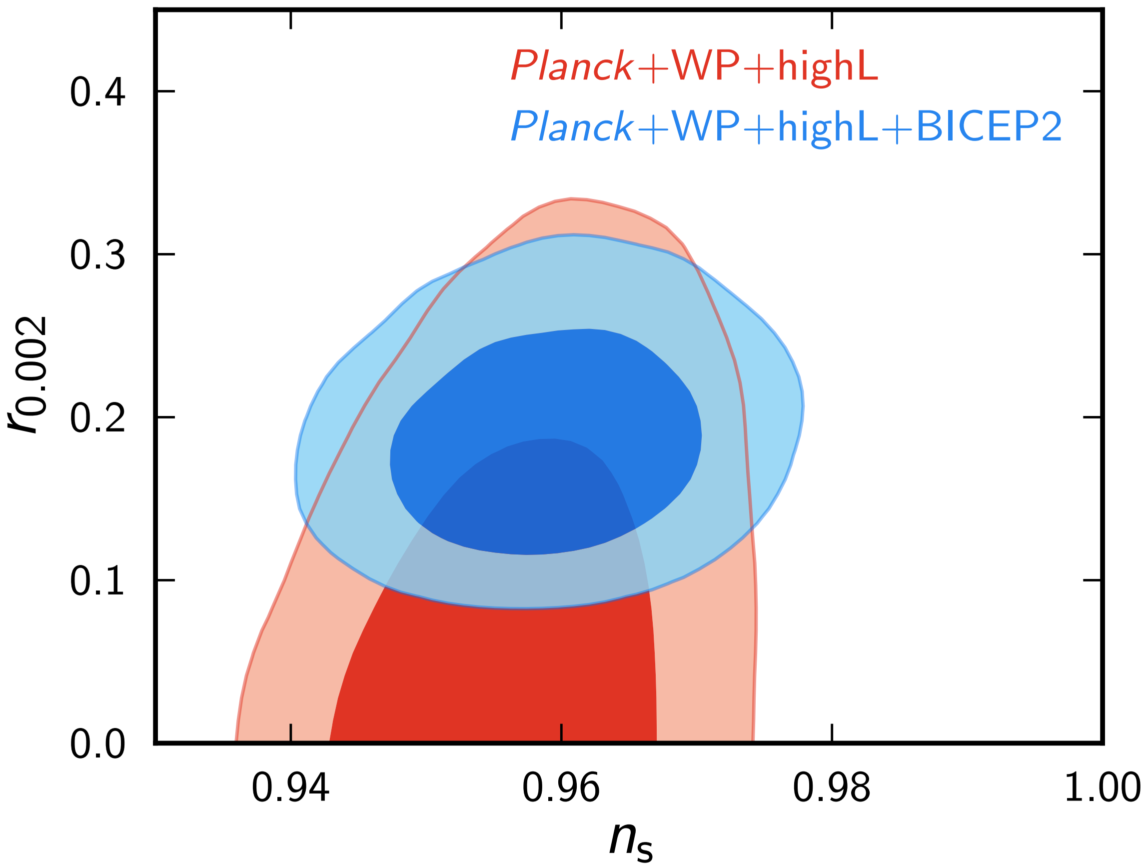
March 2014

BICEP2

Detection of B-Mode Polarization

$$r = 0.20^{+0.07}_{-0.05}$$

$$H_{\rm Inf} \sim 10^{14}\ {\rm GeV}$$



BICEP2 Collaboration, 2014

To be continued...

Particles can be produced through coherent oscillations

Axions: Preskill, Wise & Wilczek 1983 - Abbott & Sikivie 1983 - Dine & Fischler 1983

Vectors: Nelson & Scholtz 2011 - Arias *et al*. 2012

Dark photons from Inflation?

Analogous to scalar production

Preliminary

EOM $$\ddot{\phi} + 3H\dot{\phi} + m_\phi^2 \phi = 0$$

Oscillations start when

$$3H(T_{\rm osc}) = m_\phi(T_{\rm osc})$$

Evolution of energy density

$$\rho_\phi(t_0) \simeq m_{\phi,0} m_{\phi,{\rm osc}} \langle \delta\phi^2 \rangle \left(\frac{a_{\rm osc}}{a_0} \right)^3$$

$$\langle \delta\phi^2 \rangle = \left(\frac{H_{\rm Inf}}{2\pi} \right)^2$$

Dark photons from Inflation?

Analogous to scalar production

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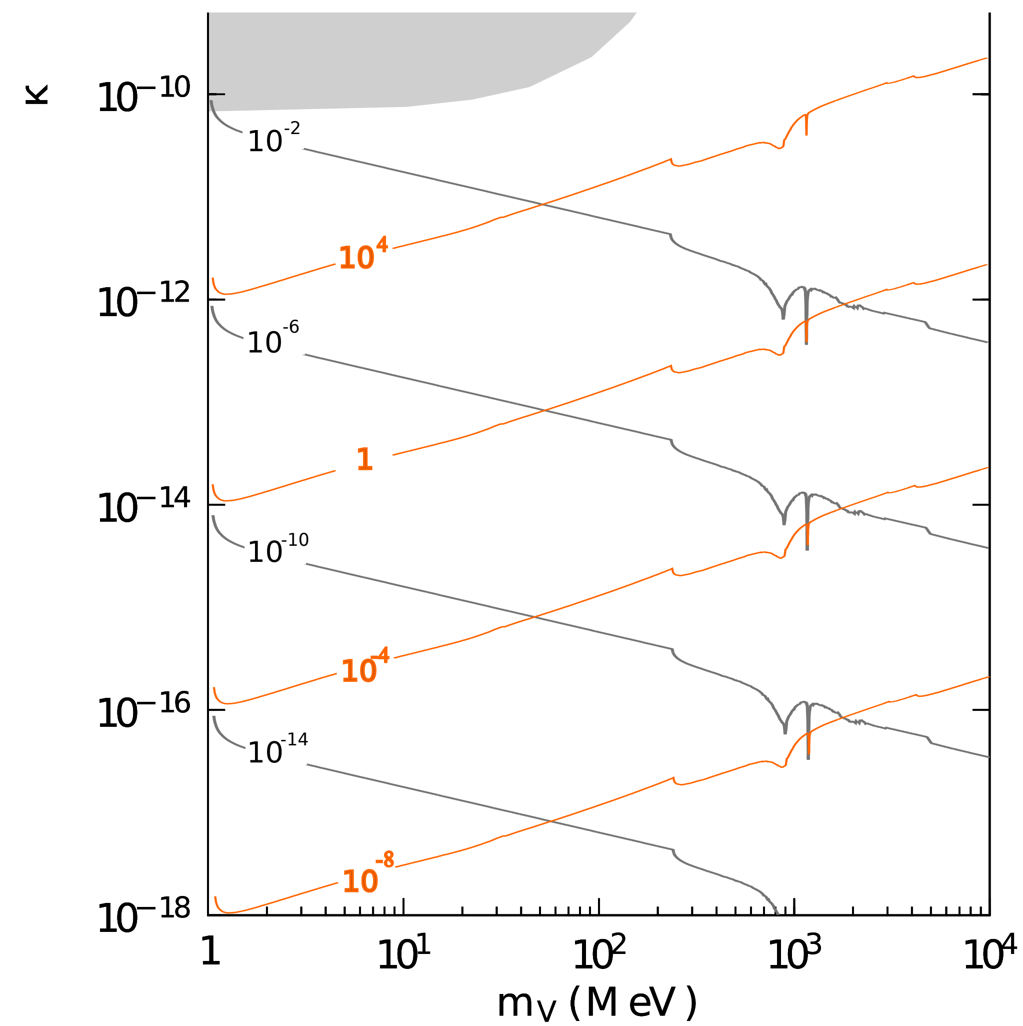
$$\langle\delta\phi^2\rangle = \left(\frac{H_{\rm Inf}}{2\pi}\right)^2$$

V abundance from inflation : Huge!

$$\frac{n_V}{n_b} \sim 10^{10}\sqrt{\frac{10\ {\rm MeV}}{m_V}}\left(\frac{H_{\rm Inf}}{10^{14}\ {\rm GeV}}\right)^2$$



Summary

- The Universe is a great particle detector

- Minimal assumptions $V \not\to \chi\chi$
  $T \sim \mathcal{O}(1 - 1000 \text{ MeV})$

- Additional contributions can only strengthen constraints

  Non-thermal production from inflation might have a huge impact

- Present-day decays ? Abundance falls short by **many** orders of magnitude (antimatter, gamma-ray, neutrino signals…)

  Non-thermal production from inflation might bring some sensitivity