KITP - April 2018

Portal Couplings and Precision Cosmology

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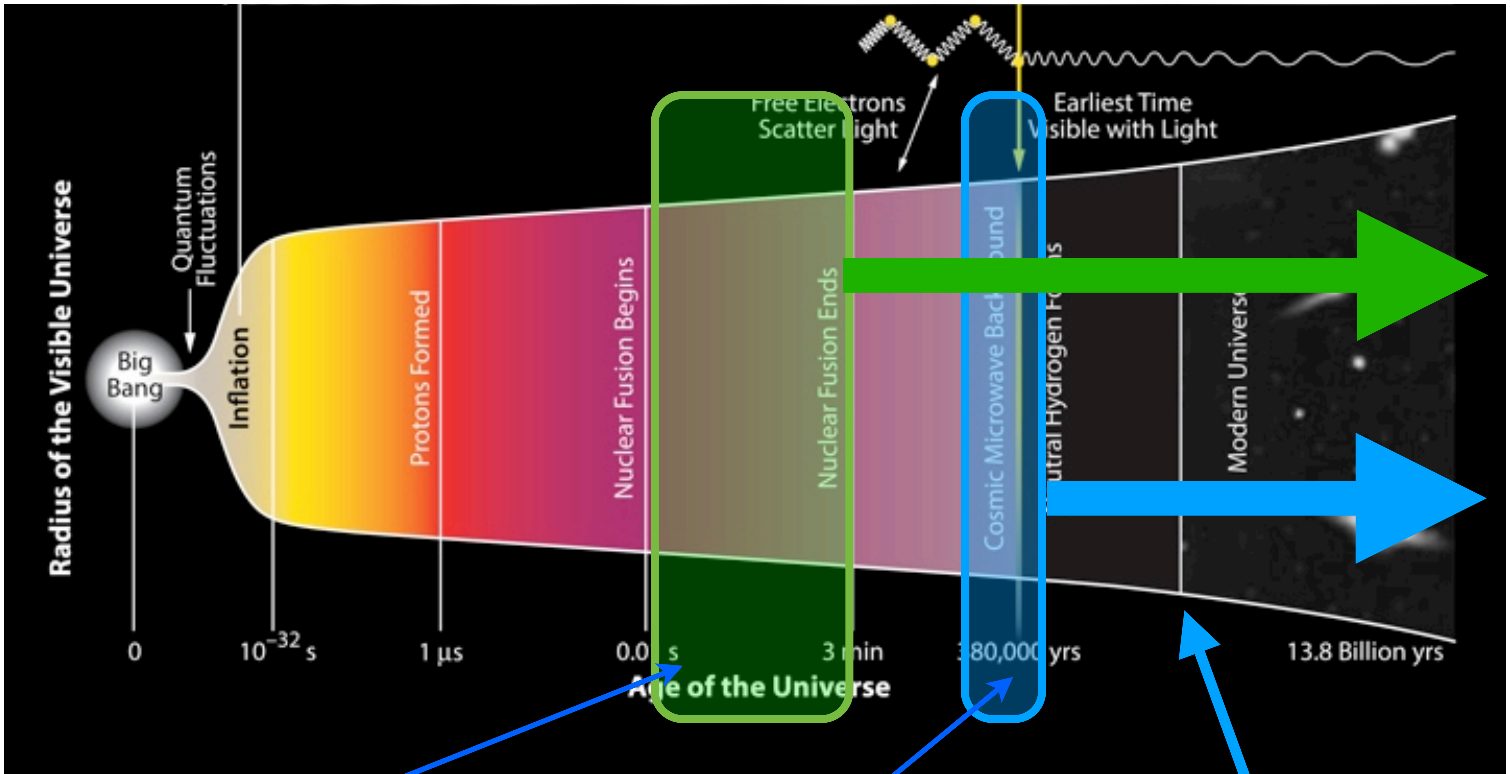
A. Fradette, M. Pospelov, J. Pradler, & AR (1407.0993; and to appear)
M. Pospelov, AR & C. Skordis (0808.0673, after BICEP2/Keck)

Cosmological probes of new physics

CMB (spectrum/anisotropies) and BBN (elemental abundances) provide precision *calorimeters* (and *polarimeters*) to test for new particle physics…



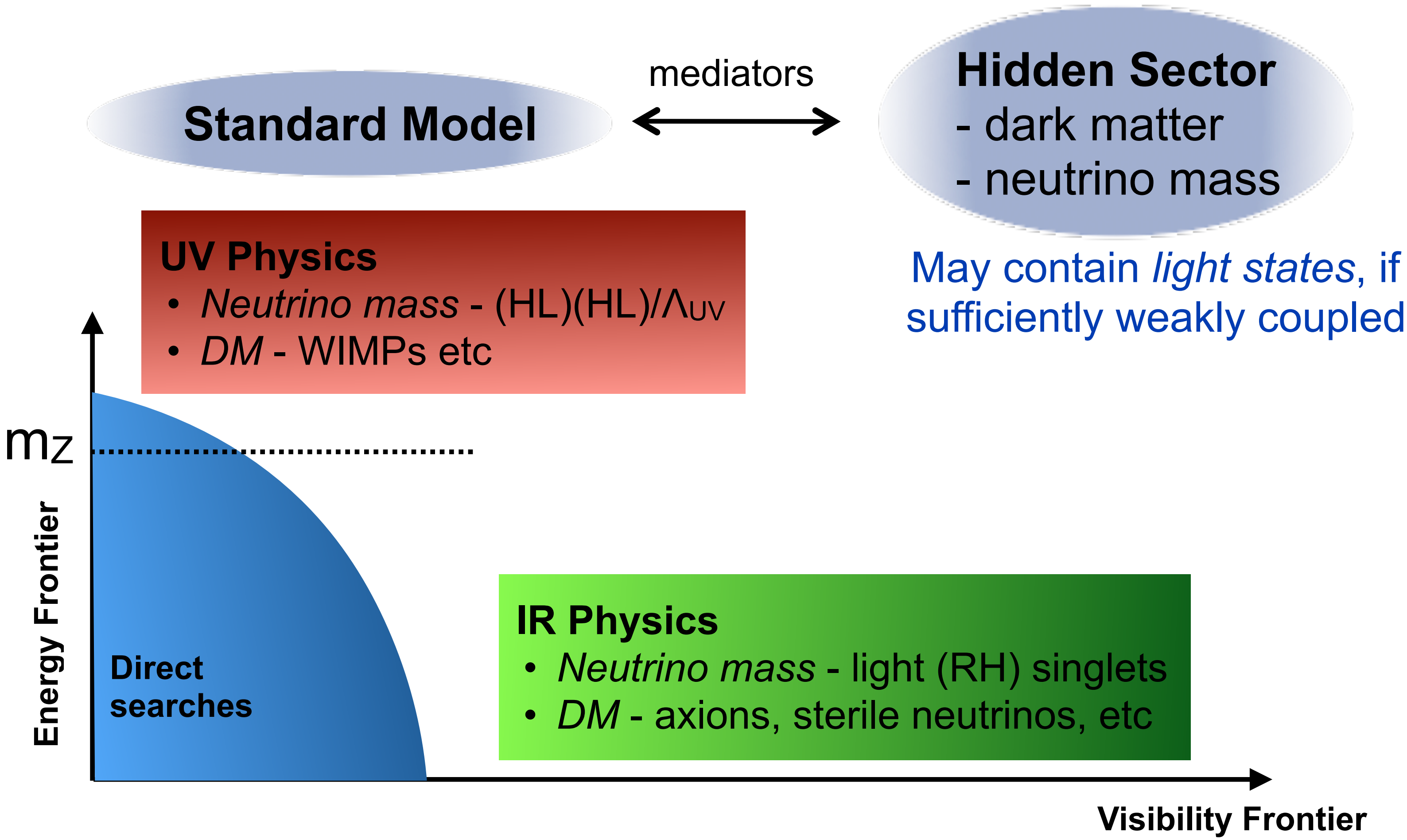
BBN (t~1s-3m)

CMB (t ~ 10^5 yrs)

First stars, reionization

New physics in a dark/hidden sector

E*mpirical* evidence for new physics (e.g. *neutrino mass, dark matter*) arguably points to a hidden/dark sector, but not directly to a specific mass scale



➠ a priori all options deserve exploration, so what theoretical guidance is there, and how far down can we probe the (in)visibility frontier?

New physics in a dark/hidden sector

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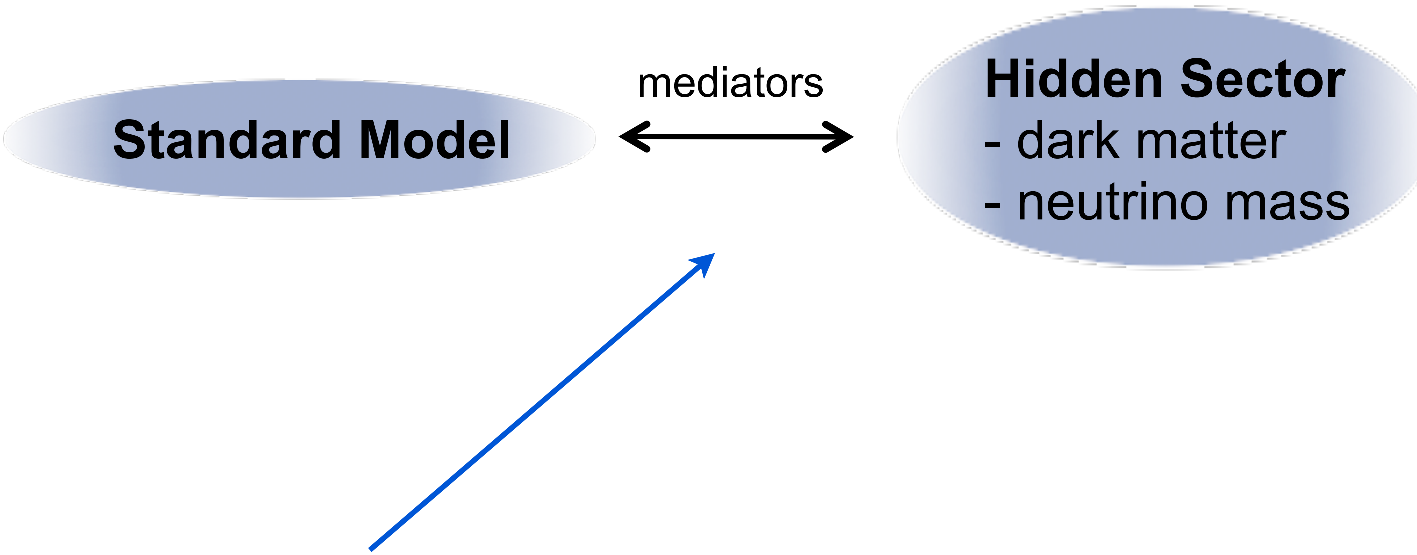


Easier to be systematic if we focus first on the mediation channels...

Substantial research effort over the past decade….

EFT for a (neutral) hidden sector

Standard Model $\longleftrightarrow$ **Hidden Sector**

mediators (+ gravity)

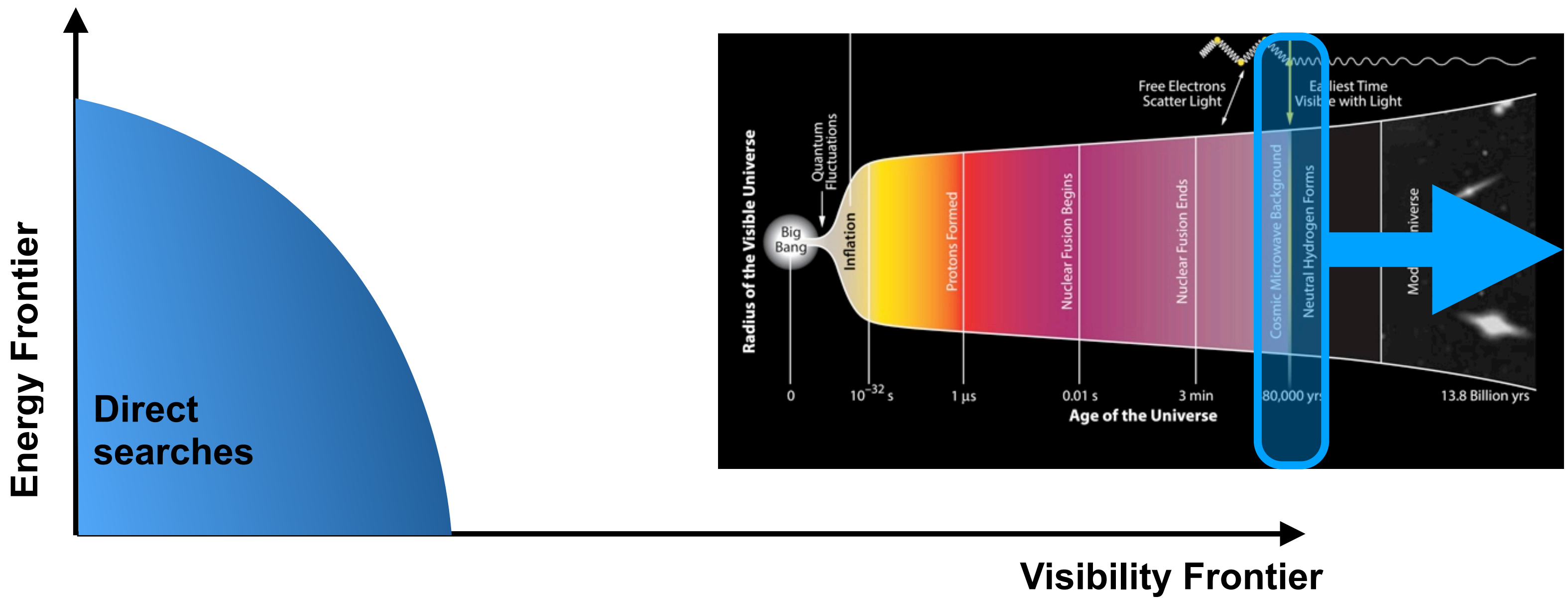
$$\mathcal{L} = \sum_{n=k+l-4} \frac{\mathcal{O}_k^{(SM)} \mathcal{O}_l^{(med)}}{\Lambda^n} \sim \mathcal{O}_{portals} + \mathcal{O}\left(\frac{1}{\Lambda}\right)$$

Generic interactions are irrelevant (dimension > 4), but there are three UV-complete relevant or marginal “portals” to a neutral hidden sector

- Vector portal: $\mathcal{L} = -\frac{\kappa}{2} B^{\mu\nu} V_{\mu\nu}$ [Okun; Holdom; Foot et al]
- Higgs portal: $\mathcal{L} = -H^\dagger H (AS + \lambda S^2)$ [Patt & Wilczek]
- Neutrino portal: $\mathcal{L} = -Y_N^{ij} \bar{L}_i H N_j$

higher dimensonal [• Axion portal: $\mathcal{L} = \frac{1}{2f_a}(F_{\mu\nu}\tilde{F}^{\mu\nu} + c_g G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu})a$]

CMB calorimetry/polarimetry and *very* dark sectors



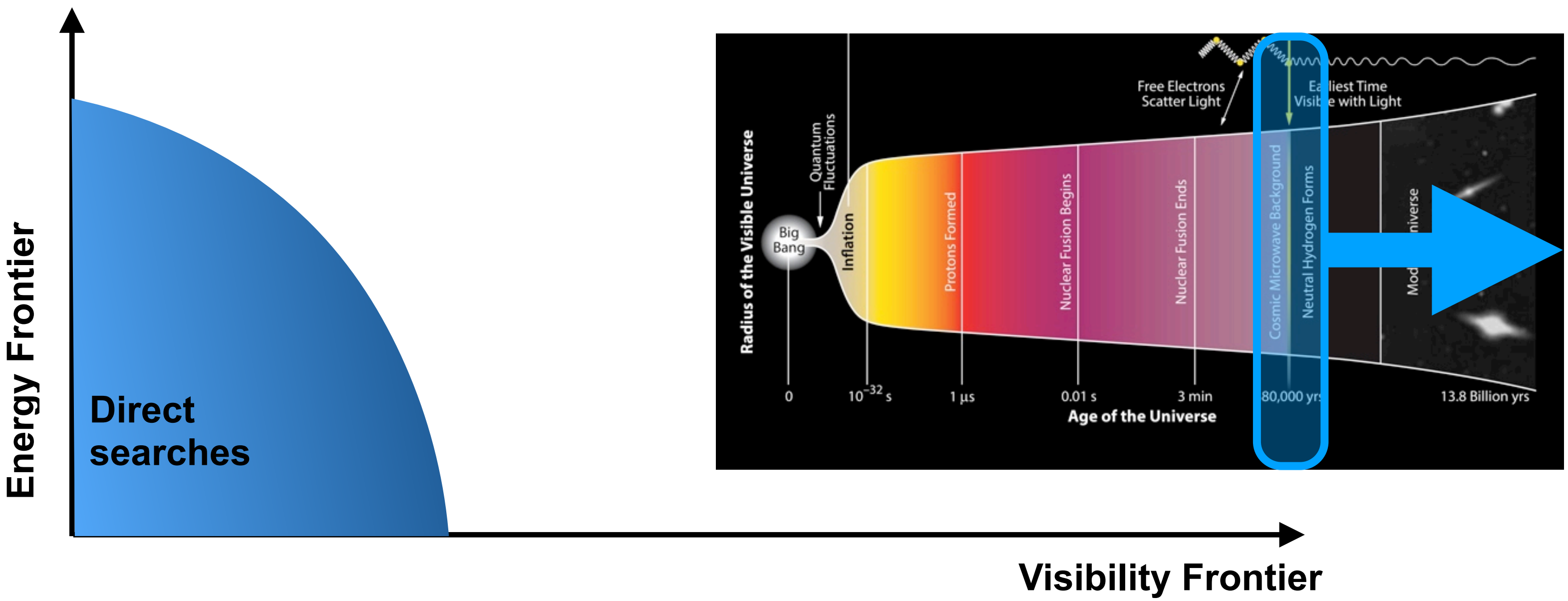
Case studies in this talk:

(i) (very) dark photons (vector portal)
(ii) (very) dark scalars (higgs portal)
(iii) (very) light axions

NB: Impact from late decays of `dark singlet leptons' through the neutrino portal was studied earlier [White et al '94, Adams et al '98, Lopez et al '98,…]

Case (i) - Dark photons (vector portal)

CMB calorimetry/polarimetry and *very* dark sectors



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Case (i) - Dark photons (vector portal)

mediators

Standard Model ⟷ **Hidden Sector**

$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}^2 - \frac{\kappa}{2}V_{\mu\nu}F^{\mu\nu} - \frac{1}{2}m_V^2 V_\mu^2 + \cdots$$

[Okun, Holdom]

$$\Downarrow$$

$$\mathcal{L}_{\rm int} = -\kappa e V_\mu J^\mu_{\rm em}$$

[Fayet, 1980,81]

A' - couples to the SM via the EM current

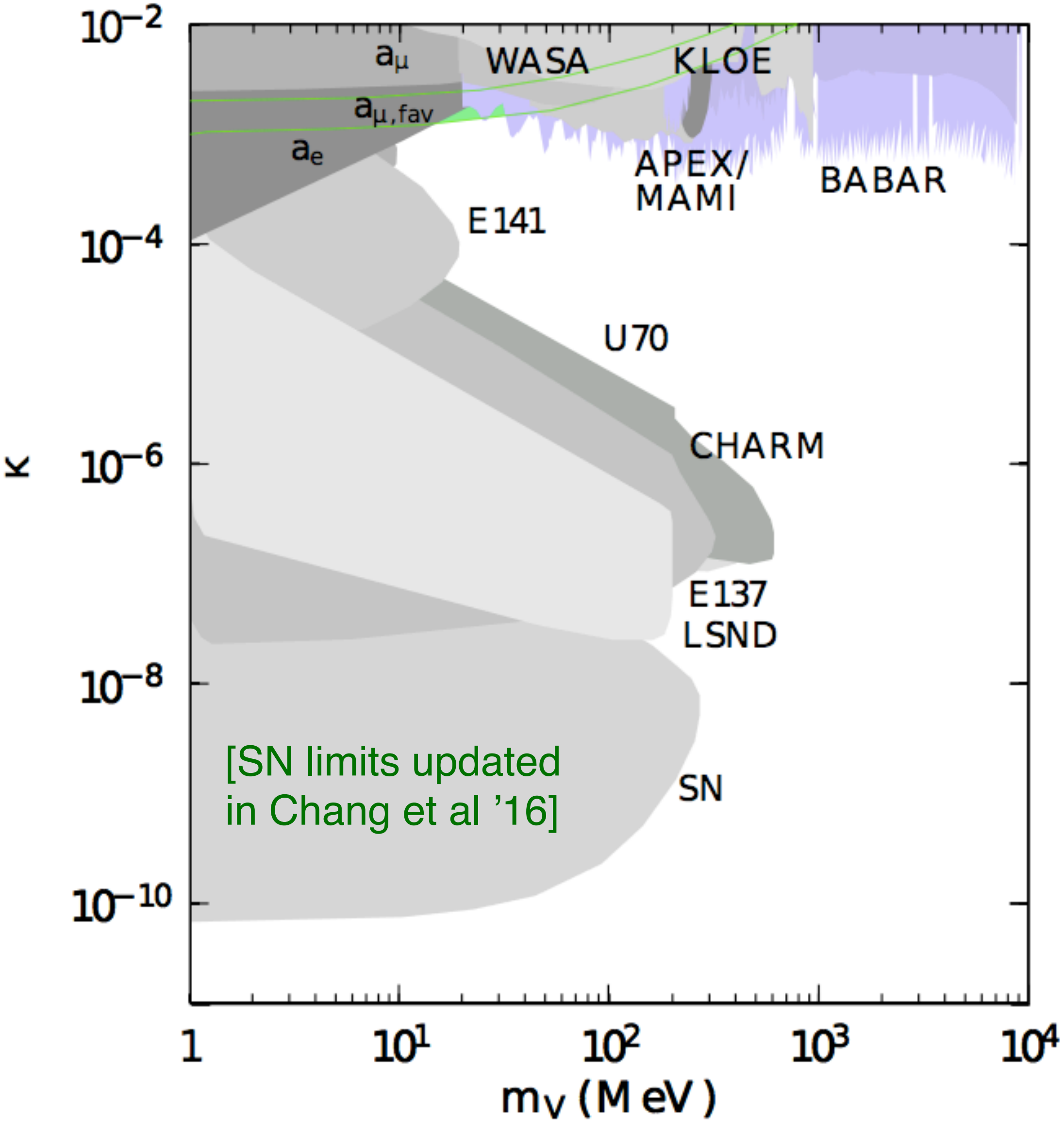
$$\alpha_{\rm eff} = \alpha\kappa^2$$

- Simple 2D parameter space $\{\kappa, m_V\}$
- Vector mass via Higgs or Stueckelberg mechanism
  - If $m_V > 2m_e$, $V \rightarrow$ leptons, hadrons, Br ~ $O(\kappa^2)$
  - If $m_V < 2m_e$, $V \rightarrow 3\gamma$ or 2ν and is a warm DM candidate
- Generic mediator for DM model-building over a large mass range

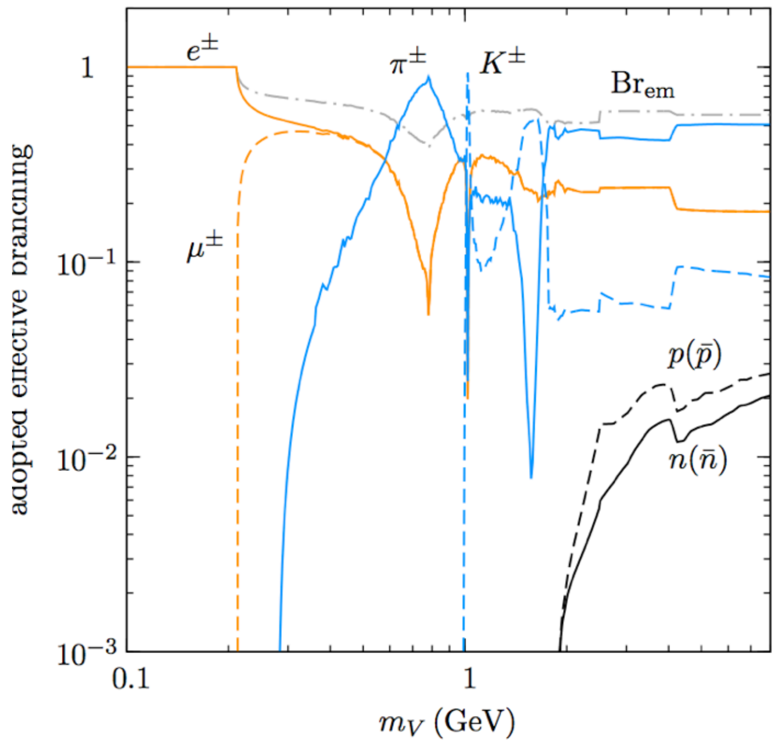
*Alternate Notation : $\kappa = \epsilon, \;\; V_\mu = A'_\mu$

Dark Photons - sensitivity if Br(SM) ~ 1

[See e.g. Snowmass NLWCP WG, Essig et al ’13; Dark Sectors Workshop ’16]



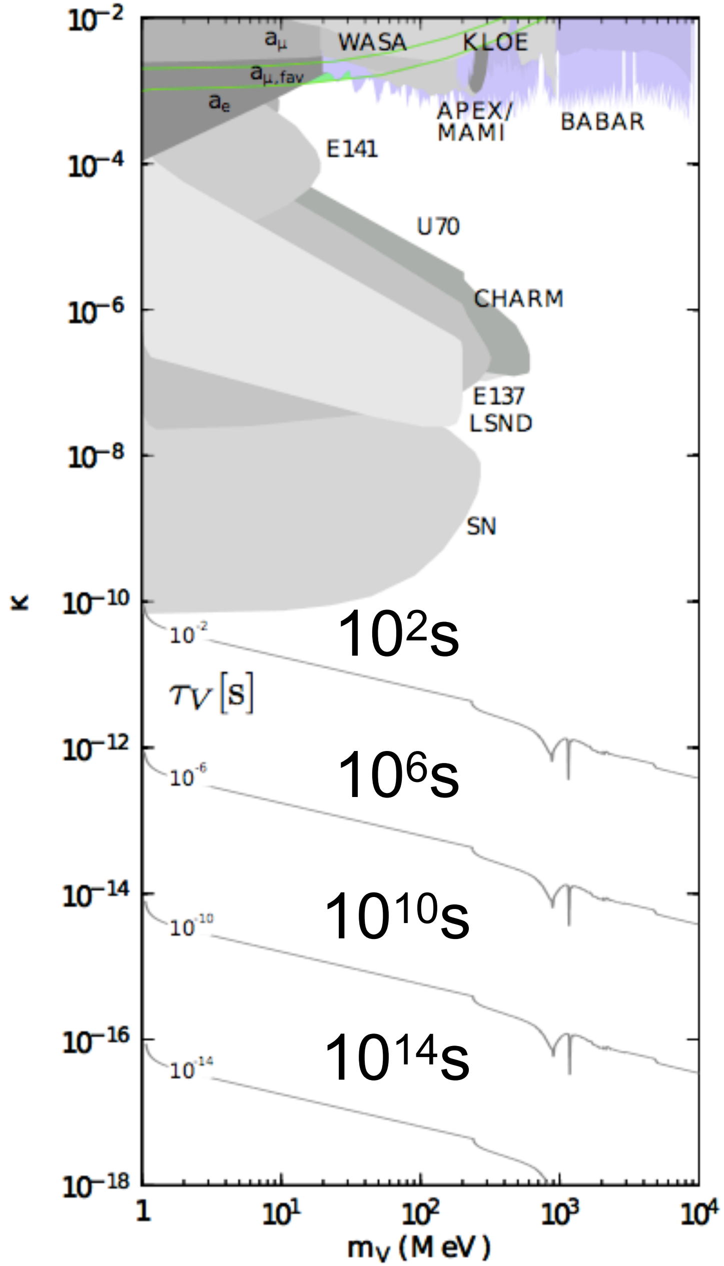
Assuming Br(V→SM)~1
(no extra light dark
sector states)



Very dark photons

Cosmological sensitivity to energy injection from late decays?

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



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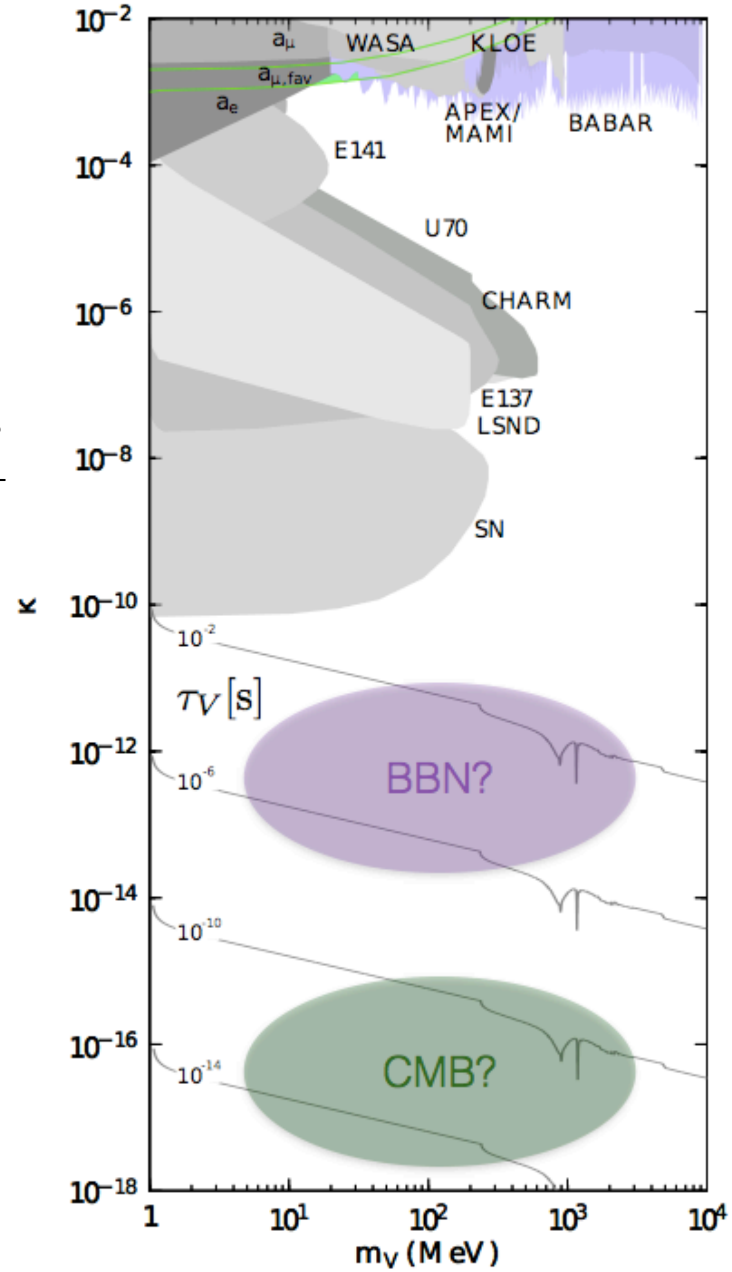
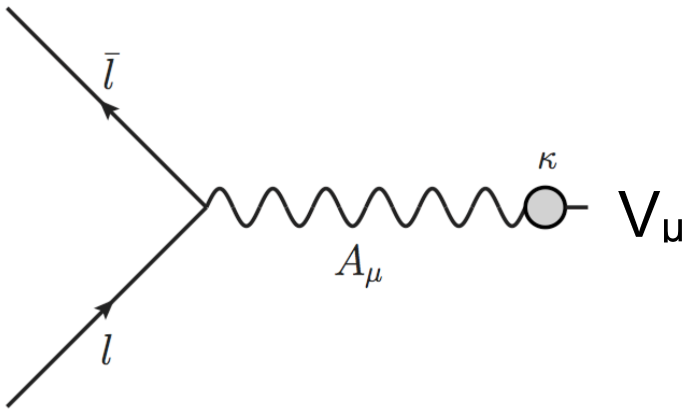
BBN (t ~ 1-10³ s) ⟶

CMB (t ~ 10¹²-10¹⁴ s) ⟶

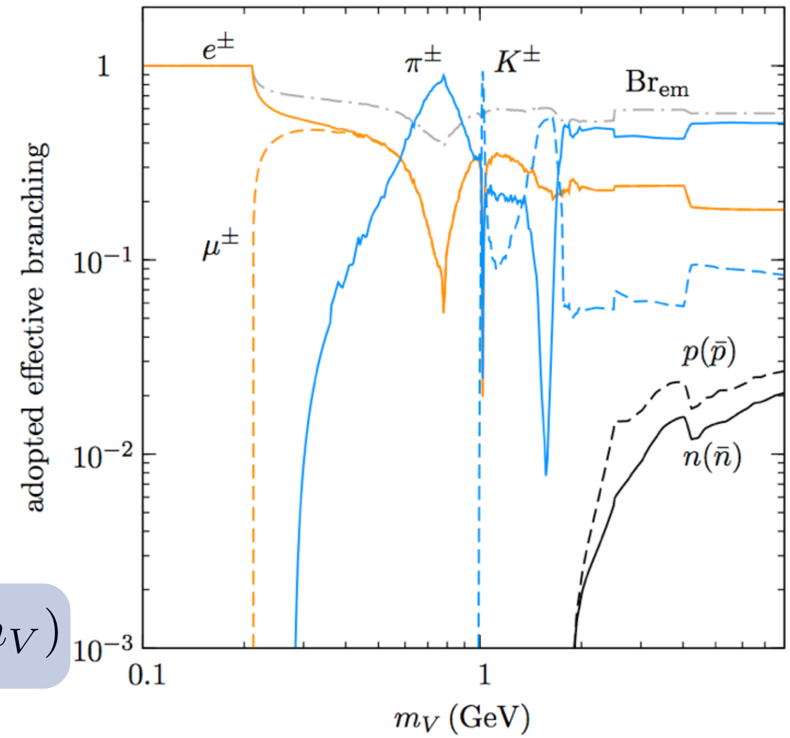


Thermal production

- Production in the early universe via freeze-in



$$s\dot{Y}_V = \dot{n}_V + 3Hn = \frac{3}{2\pi^2}\Gamma_V m_V^2 T K_1(m_V/T)$$



Freeze-in abundance $(T_{\text{max prod}} \sim m_V)$

$$Y_{V,\text{fo}} \sim \frac{\Gamma_V m_V^3}{H(m_V)s(m_V)}$$

$$\sim 2 \times 10^{-17} \times \left(\frac{10^{14}\,\text{s}}{\tau_V}\right) \times \left(\frac{10\,\text{MeV}}{m_V}\right)^2$$

NB: conservatively ignoring production modes during inflation

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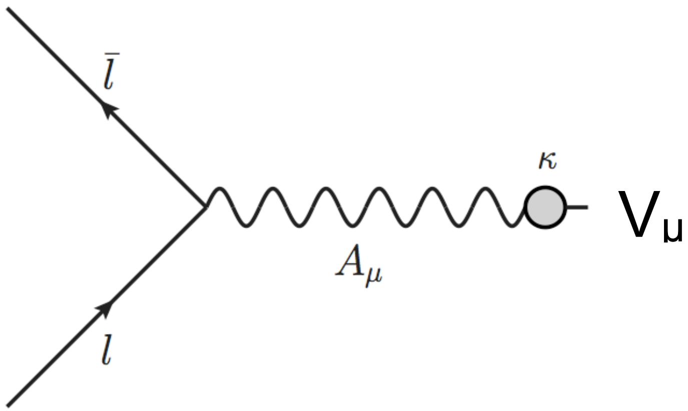

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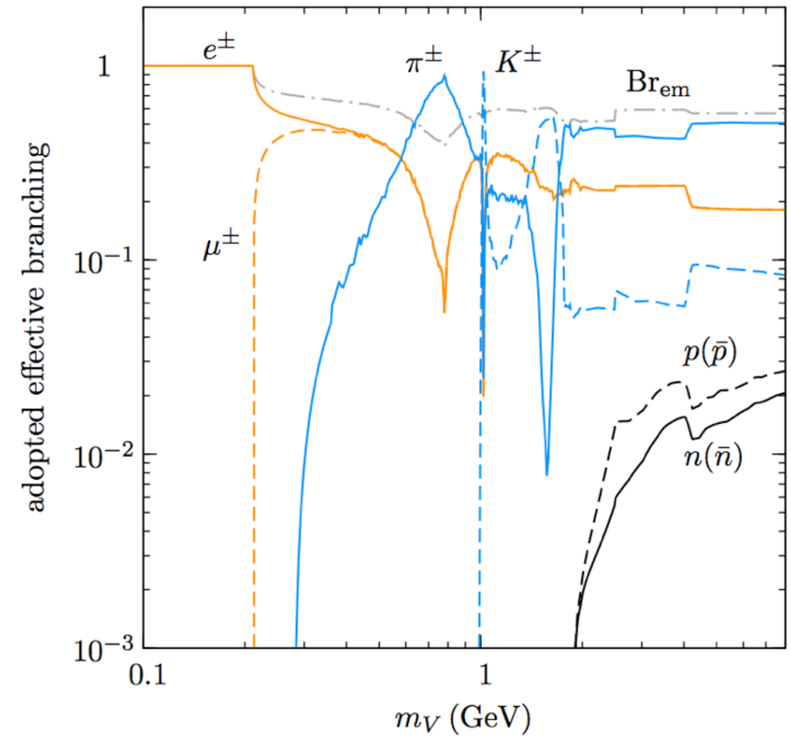
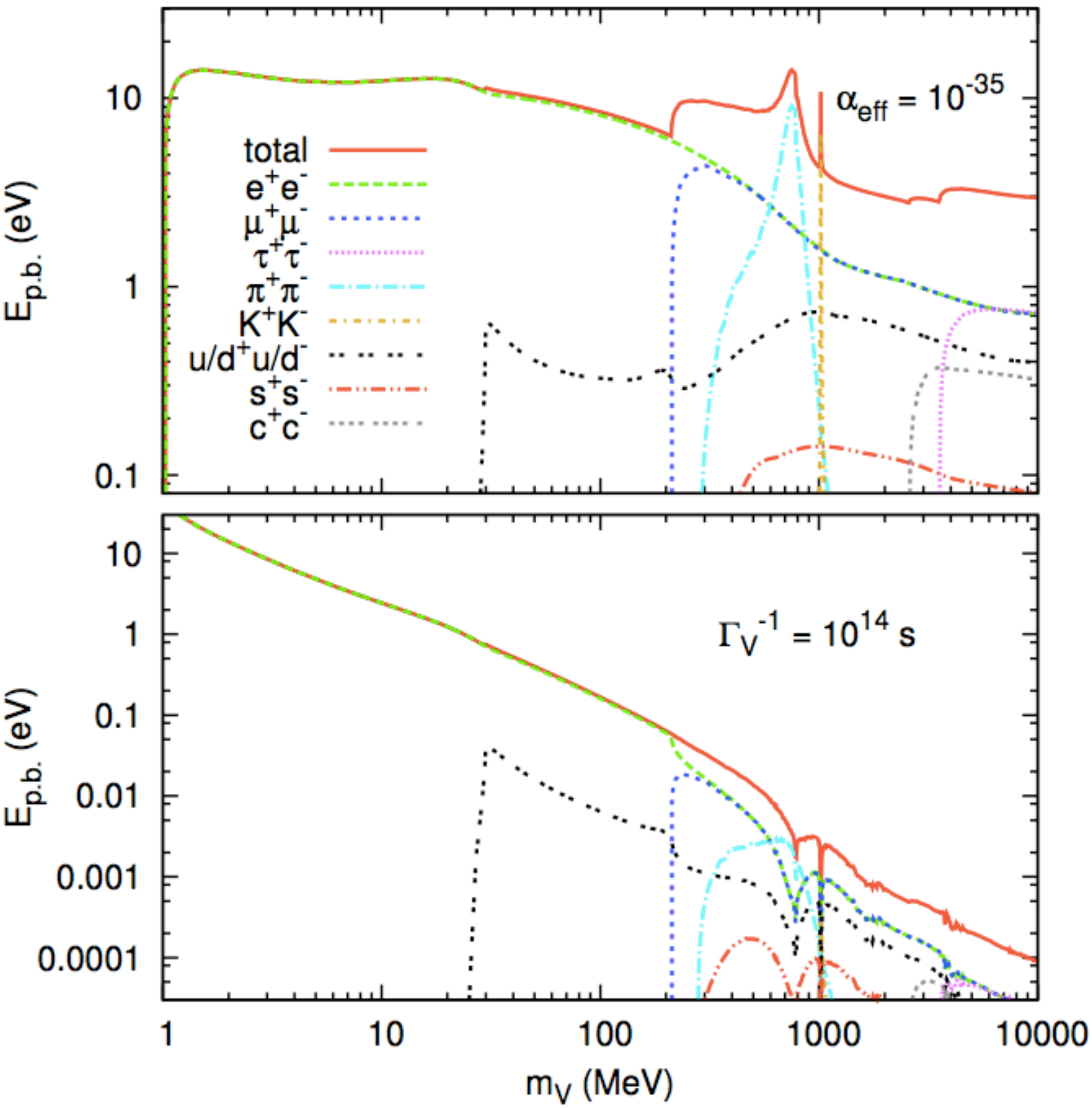


➠ Energy stored per baryon

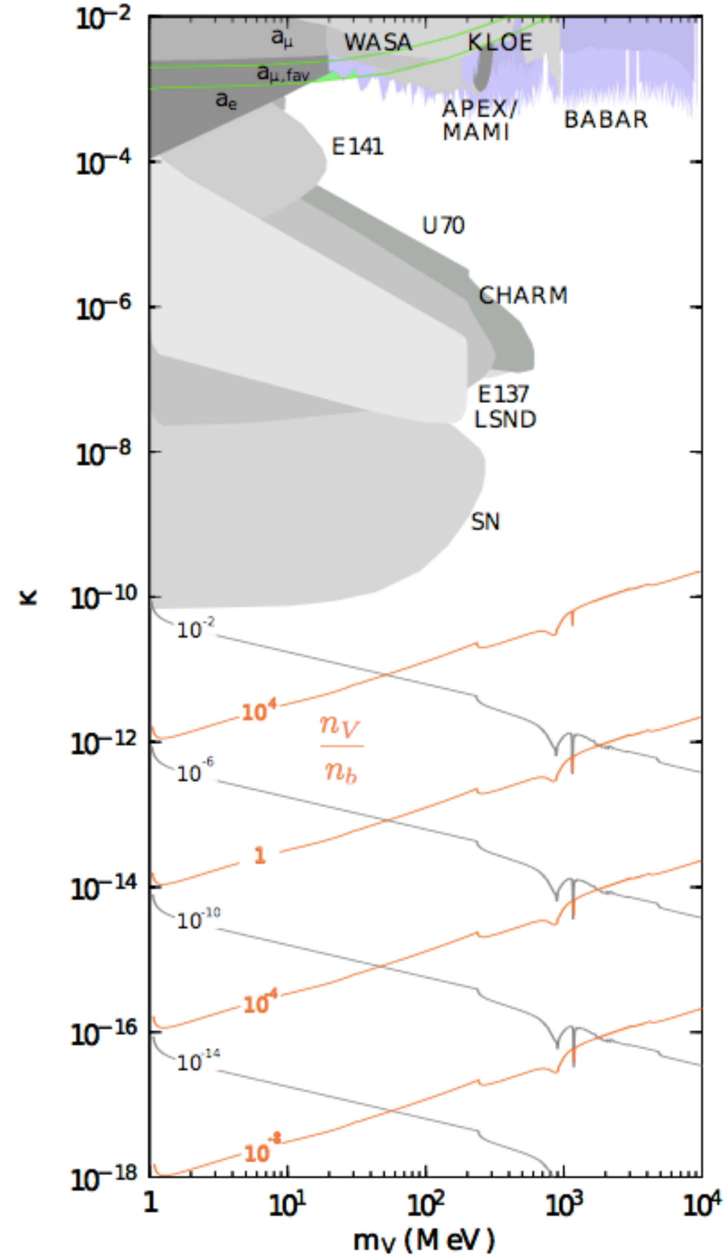
$$E_{\mathrm{p.b.}} = m_V Y_{V,f} \left.\frac{s}{n_b}\right|_0 \sim 2.6\mathrm{eV} \times \left(\frac{10^{14}\mathrm{s}}{\tau_V}\right) \times \left(\frac{10\,\mathrm{MeV}}{m_V}\right)$$

CMB has sensitivity to ~ 0.1eV p.b. !

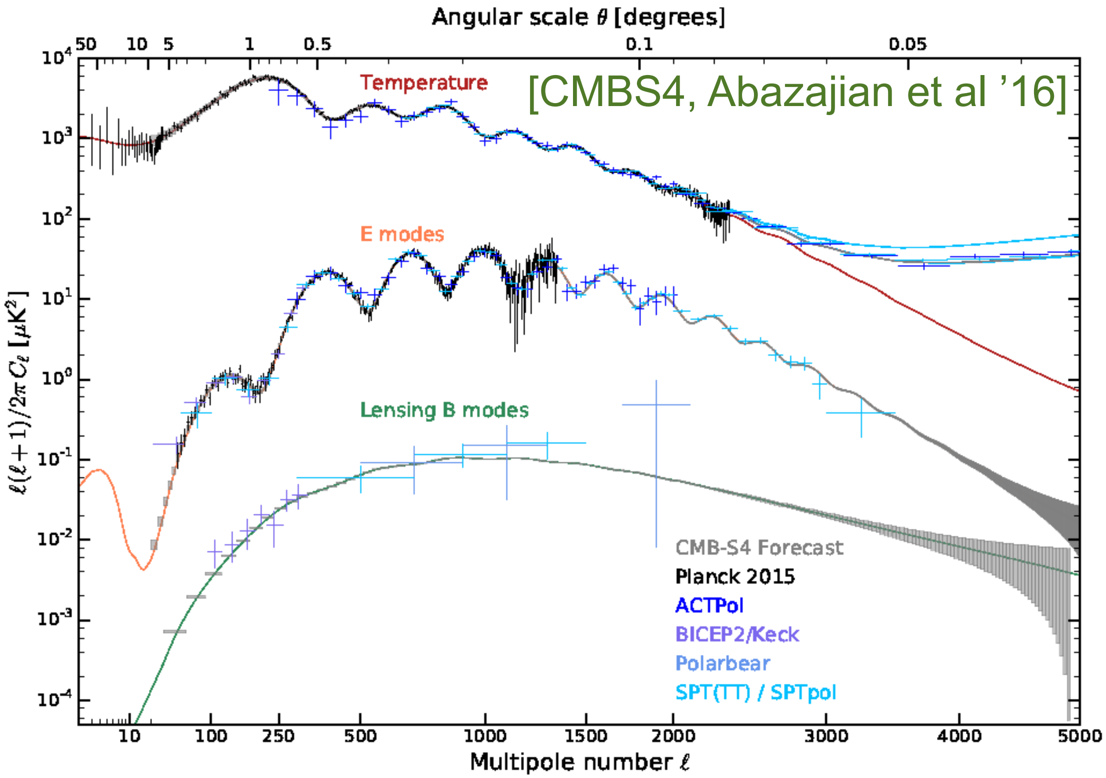
Energy injection

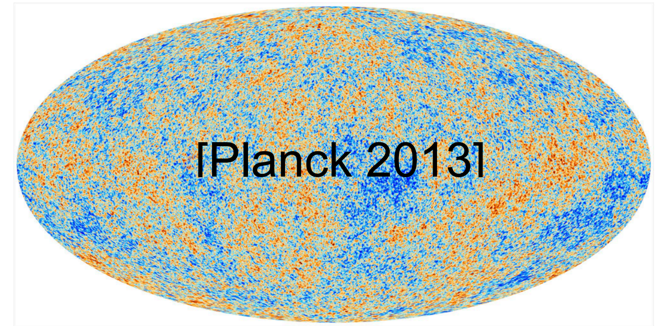


Simplified QCD transition
(quarks → mesons at T~157 MeV)



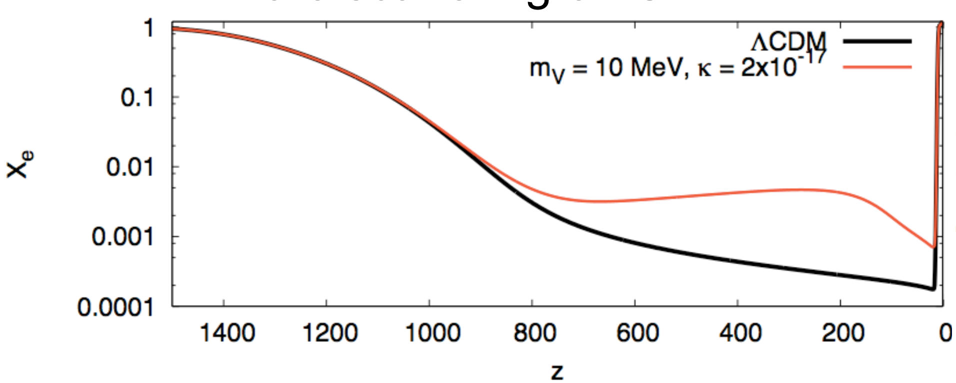
CMB sensitivity



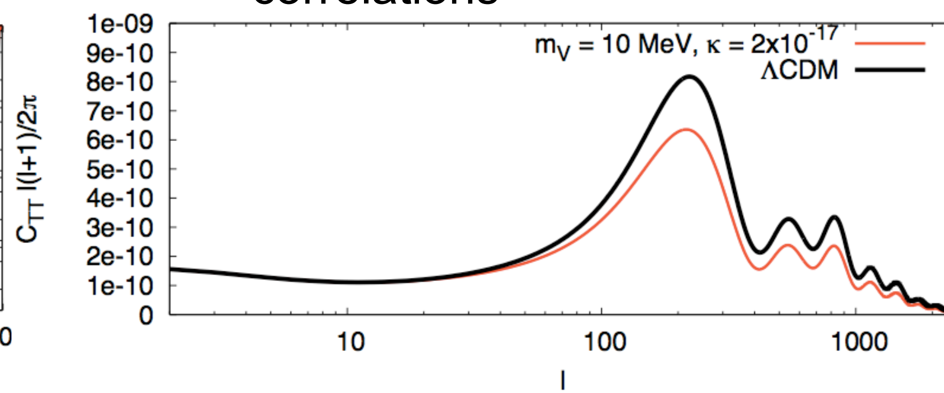


Precision TT and EE anisotropy spectrum constrains modifications to the visibility function, e.g. from energy injection

Partial reionization enhances late scattering off CMB



Washes out small-scale TT correlations



CMB - VDP energy injection

[Following Chen & Kamionkowski ’03; Zhang et al ’07; Slatyer ’12]

$$\frac{dE}{dtdV} = 3\zeta m_p \Gamma e^{-\Gamma t}$$

$$\zeta = \frac{f}{3}\frac{\Omega_V}{\Omega_b} = \frac{f}{3}\frac{E_{\mathrm{p.b.}}}{m_p}$$

f = efficiency for deposited energy to produce ionization (~1/3) and heating (~2/3)

➠ $\zeta\Gamma_V < (2-10)\times 10^{-25}\,\mathrm{Hz}$

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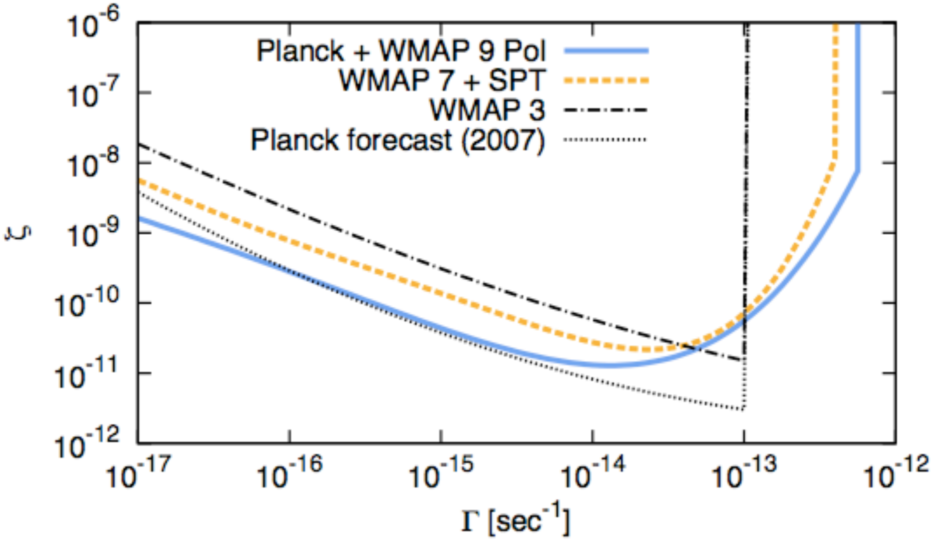
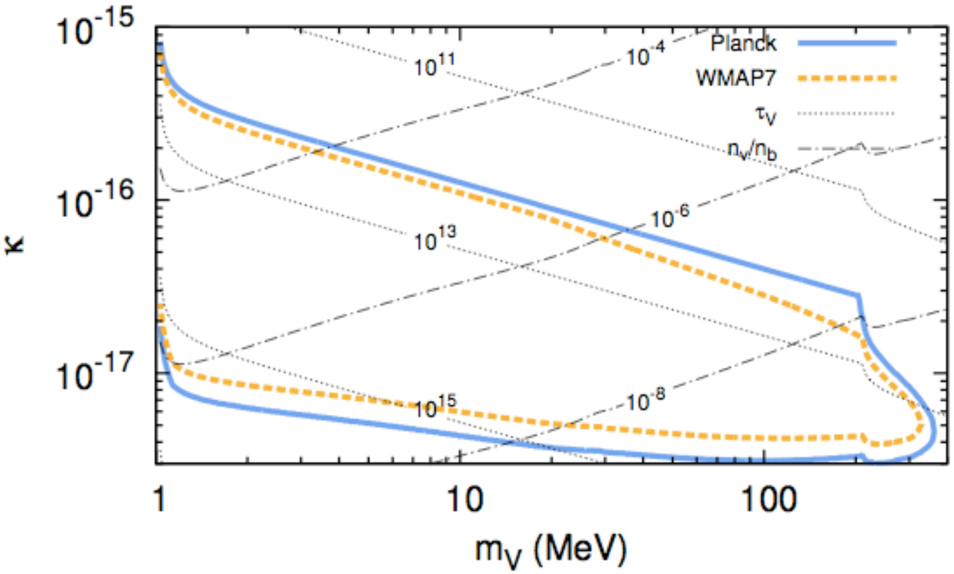
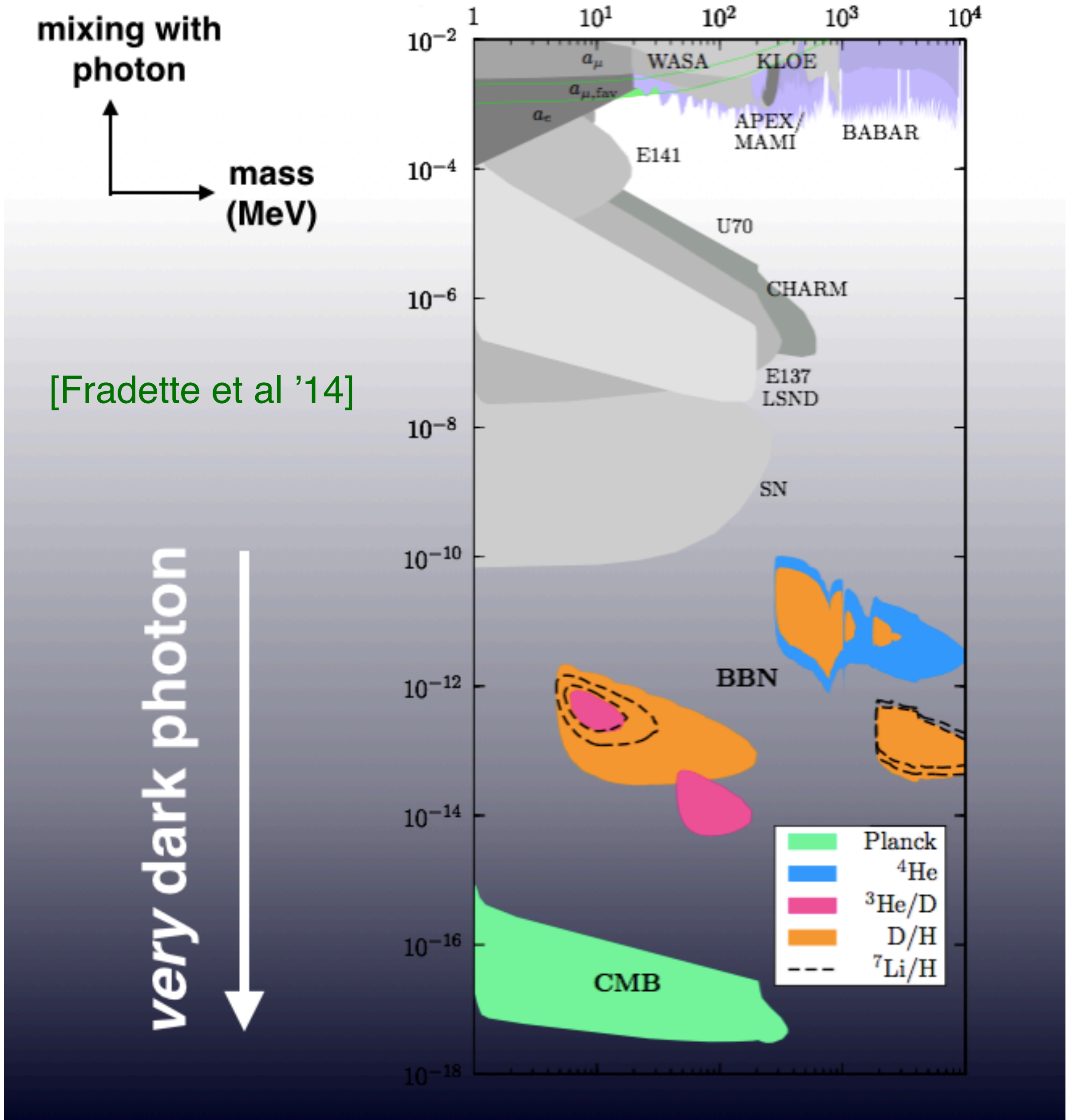
[Fradette et al ’14]



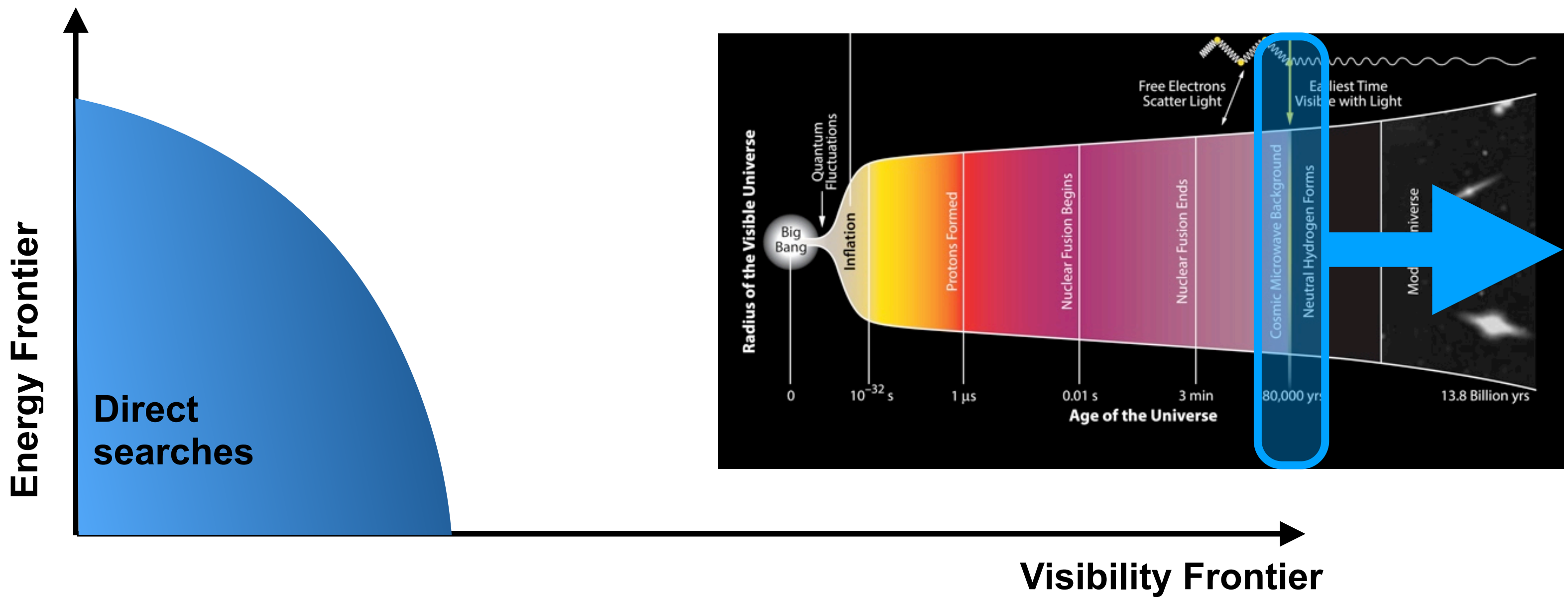


Cosmological constraints on VDP



[See also Berger et al '16]

CMB calorimetry/polarimetry and *very* dark sectors



(i) (very) dark photons (vector portal)
(ii) (very) dark scalars (higgs portal)
(iii)(very) light axions

Case (ii) - Dark scalars (Higgs portal)

mediators

Standard Model ⟷ **Hidden Sector**

$$\mathcal{L}_{H/S} \supset \mu^2 H^\dagger H - \lambda_H (H^\dagger H)^2 - \frac{1}{2} m_S^2 S^2 - A S H^\dagger H$$

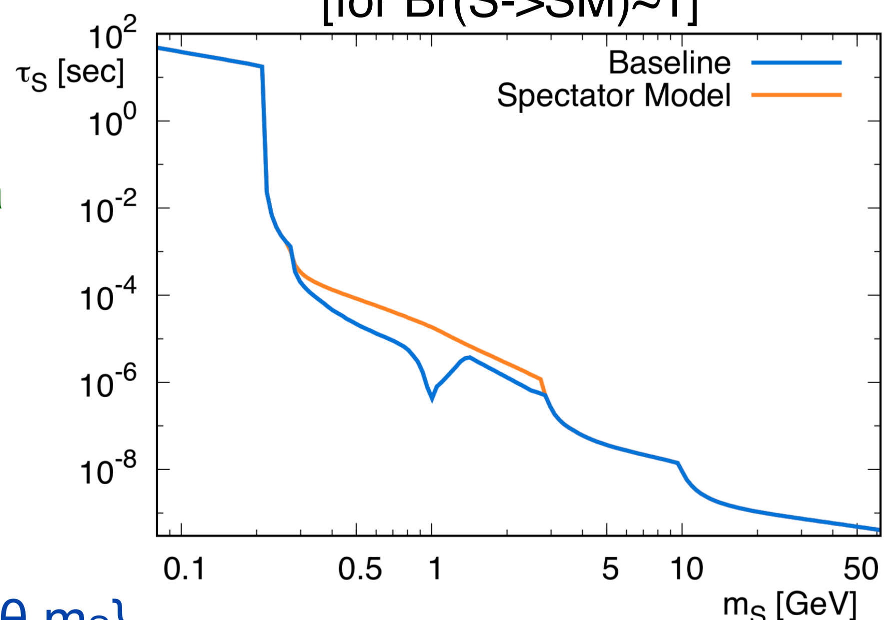
$$\Downarrow$$

$$\mathcal{L}_{\rm int} = -\theta S J_S$$

S - couples to the SM via the scalar current

$$\theta = \frac{Av}{m_H^2 - m_S^2}$$

[for Br(S->SM)~1]



- Simple 2D parameter space $\{\theta, m_S\}$
- If $m_S > 2m_e$, *S* decays to leptons, hadrons, Br ~ $O(\theta^2)$

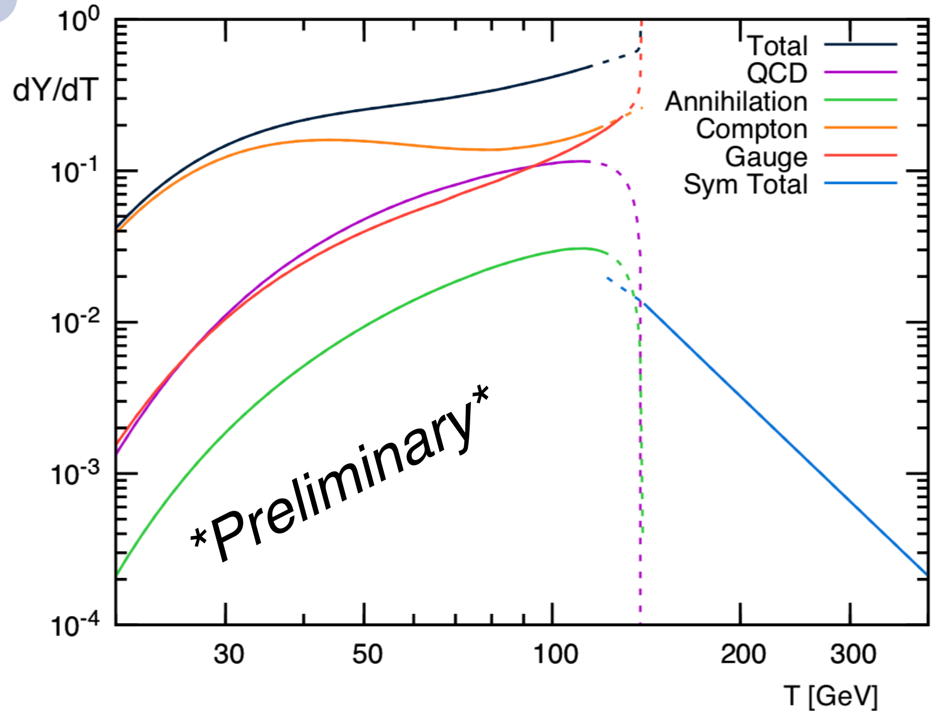
Thermal production

Production in the early universe via freeze-in

[Fradette et al - to appear]

Production Channel i	$Y_i^{v\gg 0}$	$Y_i^{v\gtrsim 0}$	$Y_i^{\rm sym}$	$Y_i^{\rm tot}[10^{10}\theta^2]$
$t\bar{t} \to gS$	2.11	0.93	0	6.29-8.11
$tg \to tS$ $(\times 2)$	4.17	0.90		
$t\bar{t} \to hS$	0.41	0.08	0.03-0.05	1.72-2.01
$t\bar{t} \to ZS$	0.44	0.11		
$t\bar{b} \to W^+S$ $(\times 2)$	0.82	0.11		
$th \to tS$ $(\times 2)$	0.38	0.13	0.14-0.21	14.40-17.77
$tZ \to tS$ $(\times 2)$	1.46	0.77		
$tW \to bS$ $(\times 2)$	3.66	1.43		
$bW \to tS$ $(\times 2)$	8.70	1.11		
$Zh \to ZS$	0.26	0.10	0.01-0.02	8.68-10.93
$ZZ \to hS$	0.33	0.17		
$WW \to hS$	0.57	0.25		
$WW \to ZS$	3.47	0.89		
$Wh \to WS$ $(\times 2)$	0.46	0.16		
$WZ \to WS$ $(\times 2)$	3.57	0.69		
$hh \to hS$	0.01	< 0.01	0	
Total	30.81	7.84	0.19-0.28	31.1-38.8

$(T_{\rm max\ prod} \sim m_W)$



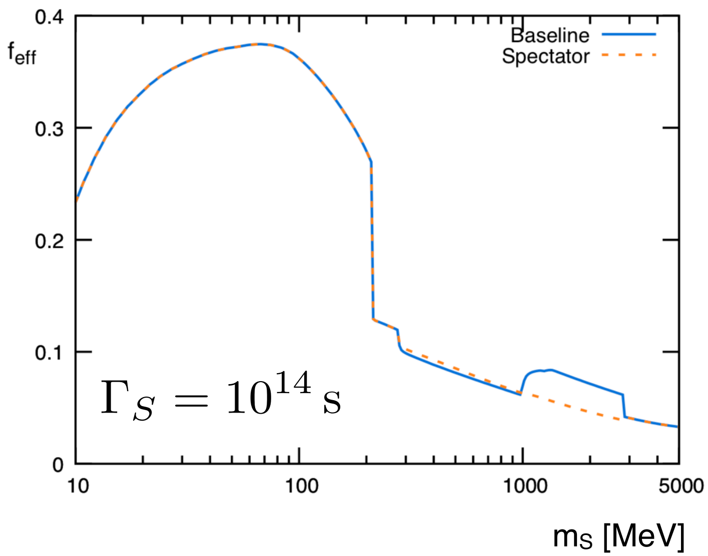
Freeze-in abundance

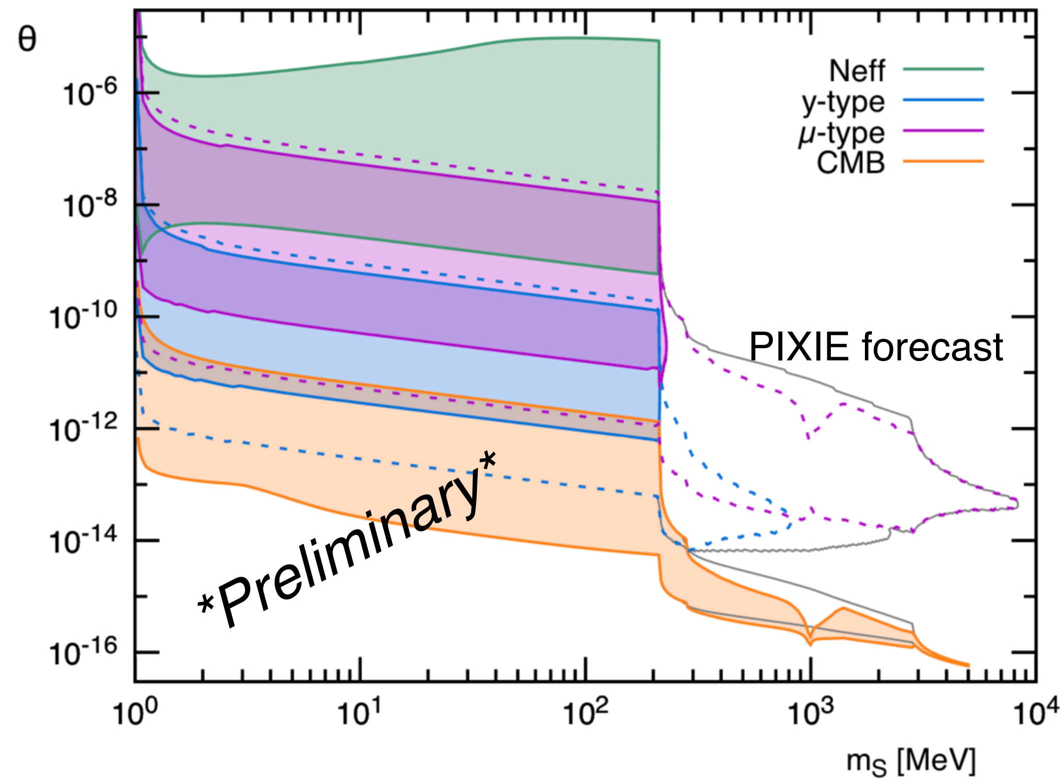
NB: Thermal effects are important (need to include thermal masses and v(T)), and production is significant around the EWPT

CMB constraints (Planck, COBE-FIRAS)

Energy injection from decays: $$\frac{dE}{dtdV} = 3\zeta m_p \Gamma e^{-\Gamma t}$$

$$\zeta = f_{\rm eff} \frac{m_S Y_S s_0}{m_p n_{b,0}}$$

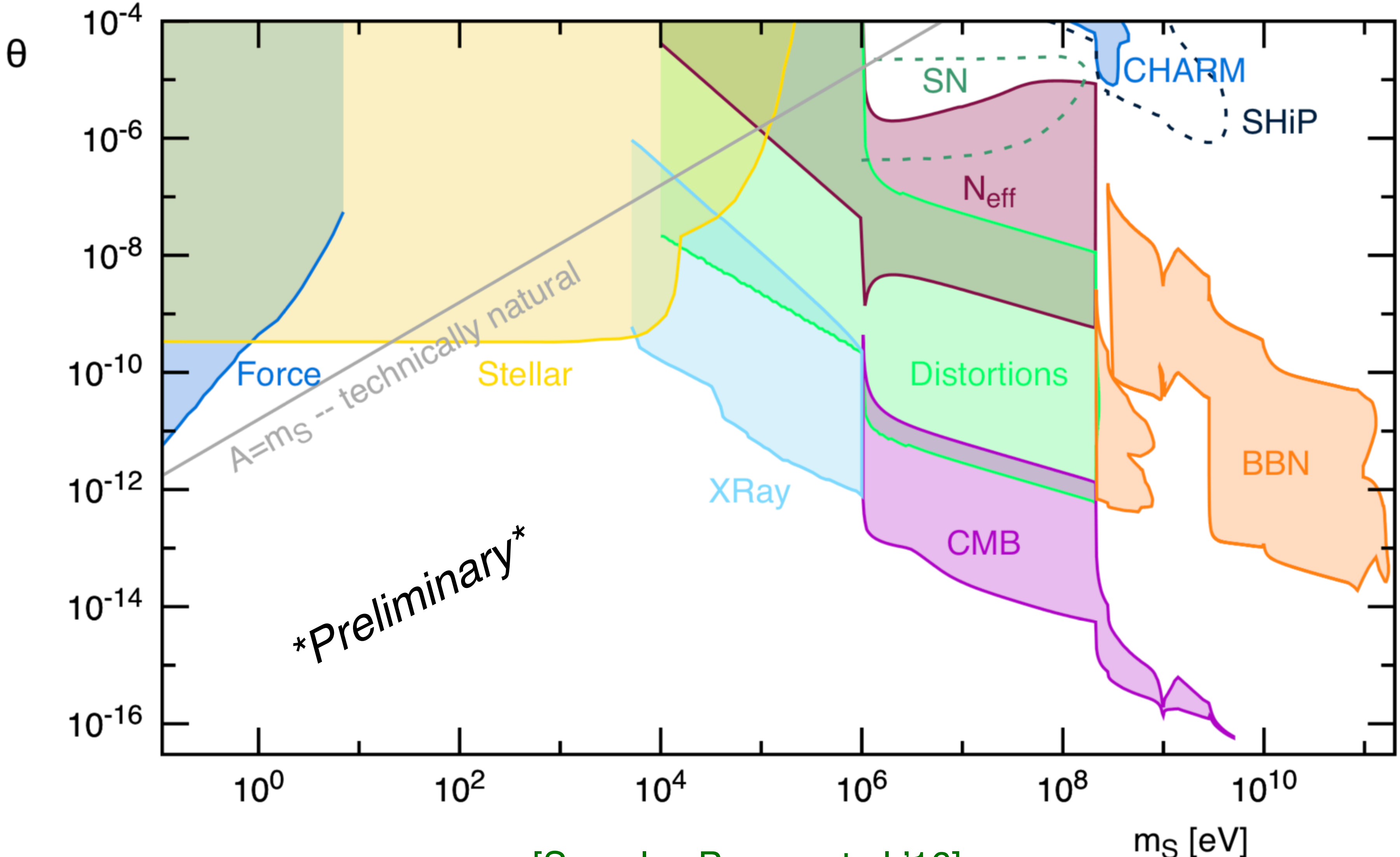




[Fradette et al - to appear]

Cosmological constraints

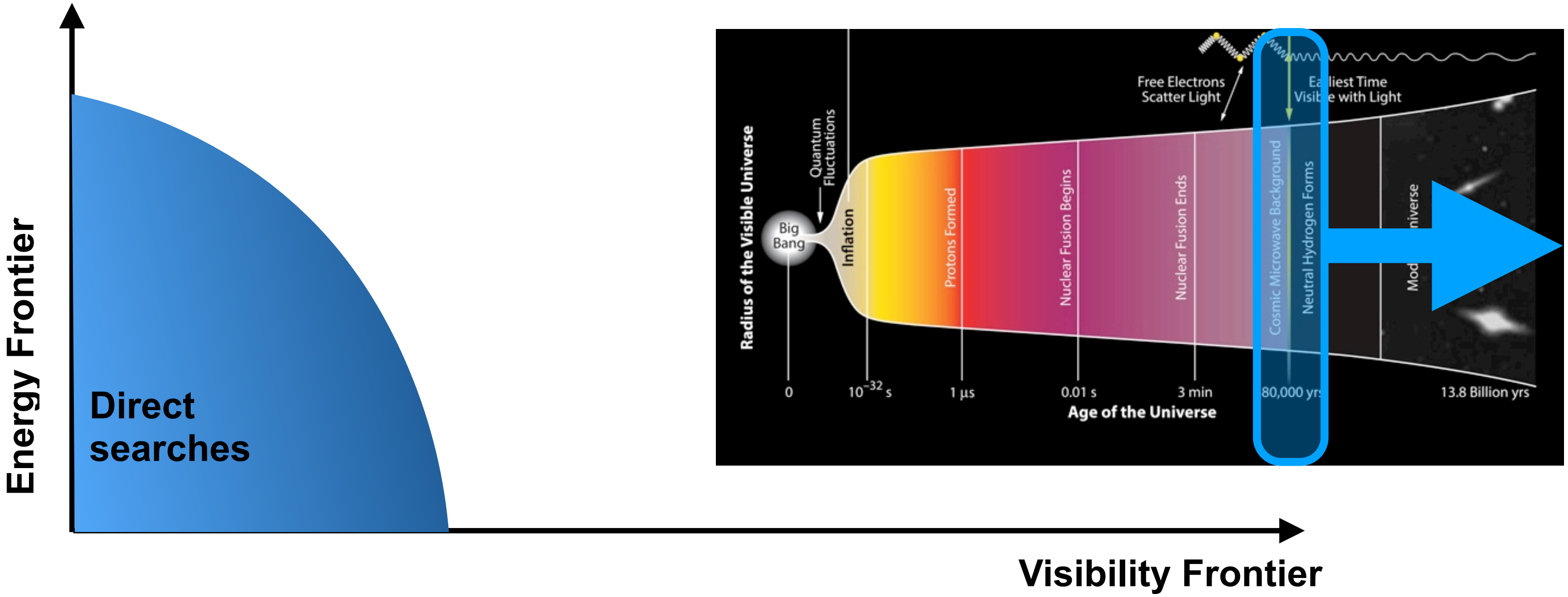
[Fradette et al - to appear]



[See also Berger et al '16]

Case (iii) - Very light (but dark!) axions

CMB calorimetry/polarimetry and *very* dark sectors



(i) (very) dark photons (vector portal)
(ii) (very) dark scalars (higgs portal)
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Case (iii) - Very light (but dark!) axions

- With multiple $U(1)_{PQ}$ symmetries broken at high scales, only one linear combination of Goldstone modes becomes the massive PQ axion (with a potential role in the strong CP problem, and as dark matter)

  [Peccei & Quinn, Weinberg, Wilczek, KSVZ, ZDFS]

  - A simple realization involves two "axions" with a shift symmetry a→a+const [Anselm & Uraltsev '82]

$$\frac{1}{2}\left(\frac{a_1}{g_1}+\frac{a_2}{g_2}\right)G_{\mu\nu}\tilde{G}^{\mu\nu}+\frac{1}{2}\left(\frac{a_1}{f_1}+\frac{a_2}{f_2}\right)F_{\mu\nu}\tilde{F}^{\mu\nu} \quad \rightarrow \quad \mathcal{L}_{QCDa}+\frac{a}{2f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

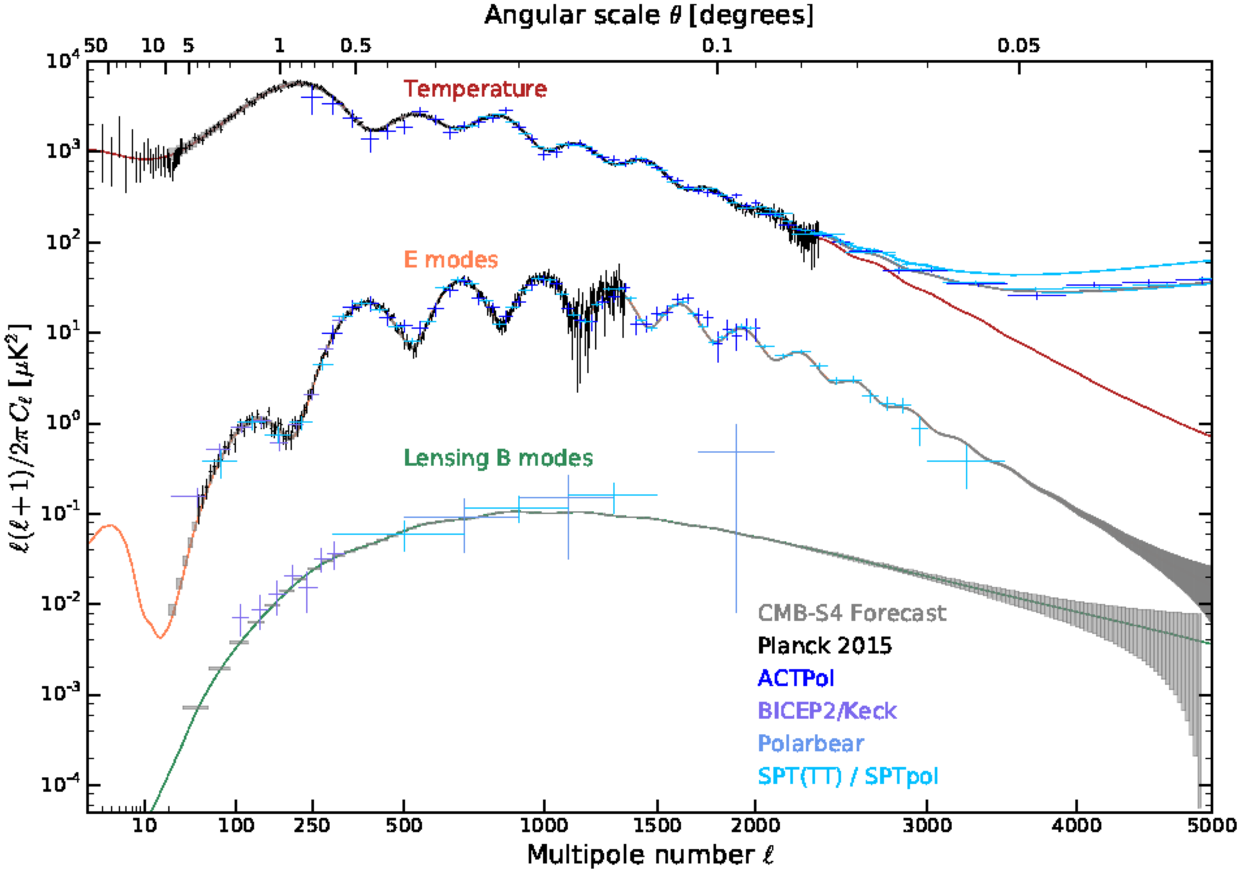
QCD axion (massive)

$m_a \sim m_\pi f_\pi / f_a$

massless pseudoscalar

Probing new dofs with CMB polarization

[CMBS4, Abazajian et al '16]



Temperature quadrupole anisotropy only produces E-mode (gradient-type) polarization, Q≠0

➠ Precision measurements of CMB polarization (with BB « EE) now allow its use as a precision probe of physics affecting photon polarization

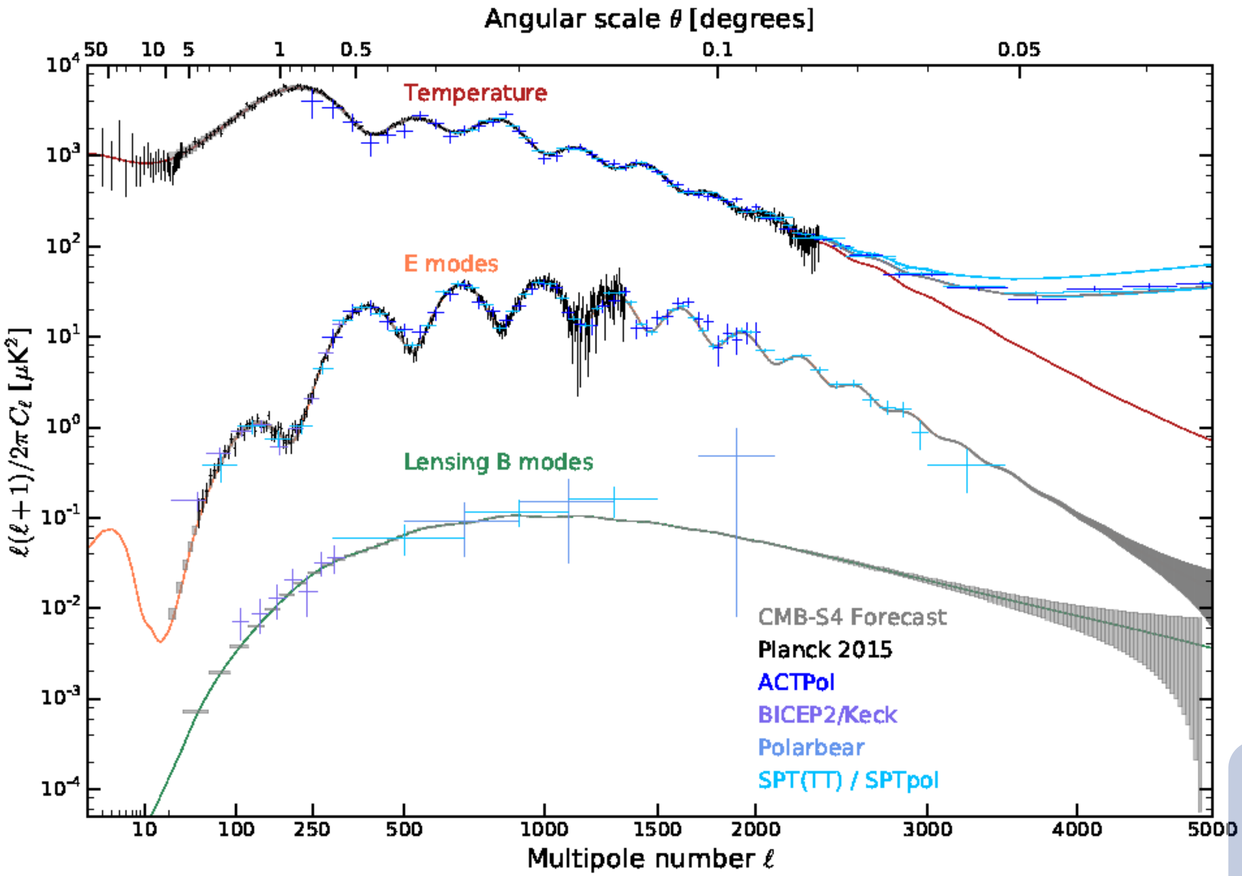
E.g. gravitational waves (tensor perturbations) from inflation,

$$r = 16\varepsilon \propto \left(\frac{H_{inf}}{M_{Pl}}\right)^2$$

$$P_{ij} = E_i^* E_j - \frac{1}{2}\delta_{ij} E^2 \propto Q\sigma_3 + U\sigma_1$$

Probing new dofs with CMB polarization

[CMBS4, Abazajian et al ’16]



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➠ Precision measurements of CMB polarization (with BB « EE) now allow its use as a precision probe of physics affecting photon polarization

Inflationary perturbations are generic ⇒ B-mode can be used as a diagnostic of any new dofs present during inflation that affect photon polarization

Axions and EM polarization

Axion electrodynamics:

$$\mathcal{L} = \frac{a}{2f_a} F_{\mu\nu}\tilde{F}^{\mu\nu} \sim -\frac{\partial_\mu a}{f_a} A_\nu \tilde{F}^{\mu\nu}$$

As photons propagate over a region with $\lambda_\gamma \ll \lambda_a$ the equations take the form [Harari & Sikivie '92]

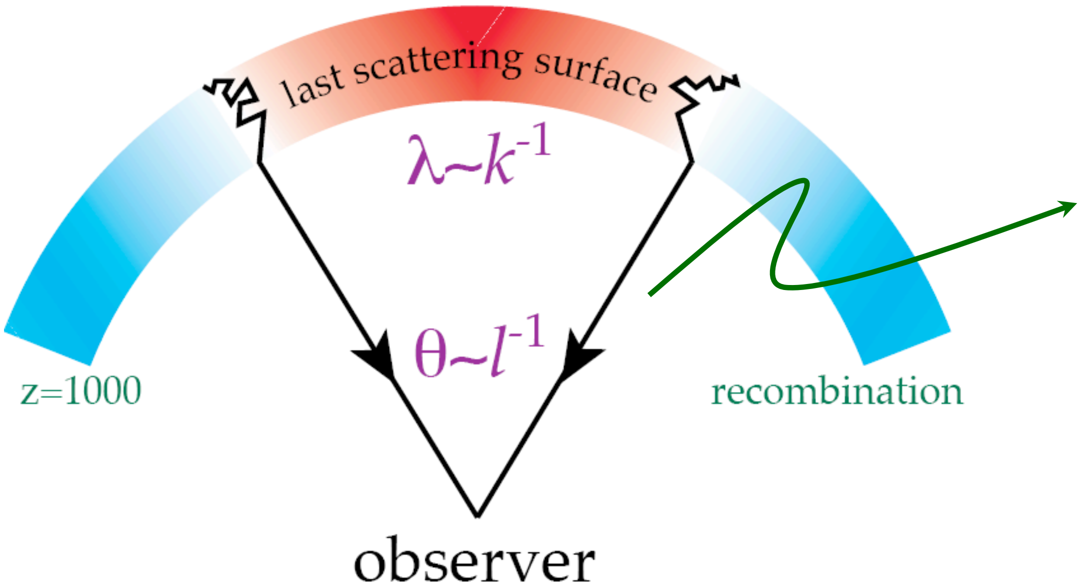
$$\Box\left(\vec{E} + \frac{a}{f_a}\vec{B}\right) = \frac{a}{f_a}\Box\vec{B}, \qquad \Box\left(\vec{B} - \frac{a}{f_a}\vec{E}\right) = -\frac{a}{f_a}\Box\vec{E}$$

➠ resulting rotation of polarization, by angle

$$\Delta\psi = \frac{\Delta a}{f_a}$$

(Perturbative) rotation of CMB polarization

Thomson scattering and the TT quadrupole anisotropy produce linear (E-mode) polarization at the SLS



[W.Hu, background.uchicago.edu/~whu/physics/tour.html]

$$\mathcal{L}_{\gamma a} = \frac{a}{2 f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

$$\Downarrow$$

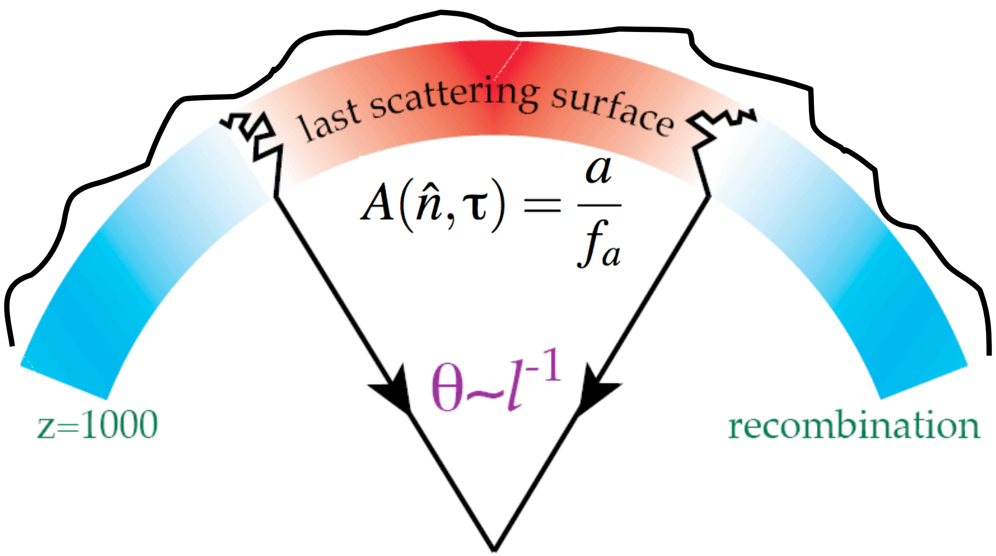
$$\Delta\psi = \frac{\Delta a}{f_a}$$

[Harari & Sikivie '92; Lue et al '98]

Induced rotation from E-mode to B-mode: $U \simeq 2\Delta\psi Q$

Inflationary pseudoscalar perturbations

$$\delta a = \frac{H}{2\pi}$$



$$A(\hat{n},\tau_0) = 0$$

$$\langle \xi_A^*(\vec{q}_1), \xi_A(\vec{q}_2) \rangle = P_A(q_1)\delta^{(3)}(\vec{q}_1 - \vec{q}_2)$$

$$P_A(q) = \frac{1}{4\pi q^3}\left(\frac{H}{2\pi f_a}\right)^2 q^{n_a - 1}$$

$$\Downarrow$$

stochastic rotation of
linear polarization

$$\Delta\psi(\hat{n}) = \frac{\Delta a(\hat{n})}{f_a} = A(\hat{n},\tau_{LSS})$$

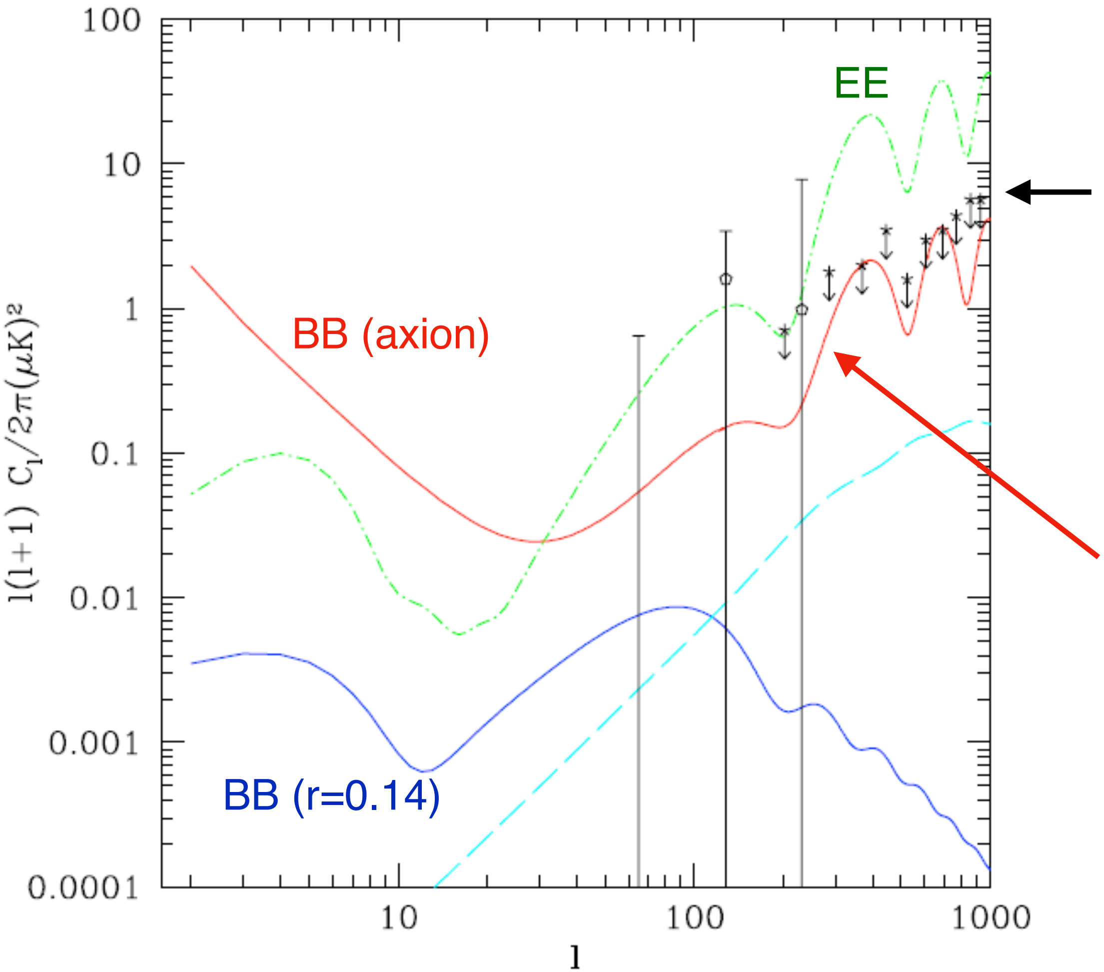
Induced stochastic rotation from E-mode to B-mode

$$U(\hat{n}) \simeq 2A(\hat{n})Q(\hat{n}) + \cdots$$

Compute C_{Bl}'s by generalizing the formalism of Zaldarriaga and Seljak ('96), for scalar and pseudoscalar modes [Pospelov, AR, Skordis, '08]

Constraint (from 2008)

In 2008, QUaD had the best sensitivity to l~O(10^2-10^3) B-modes



[Pospelov, AR, Skordis, '08]

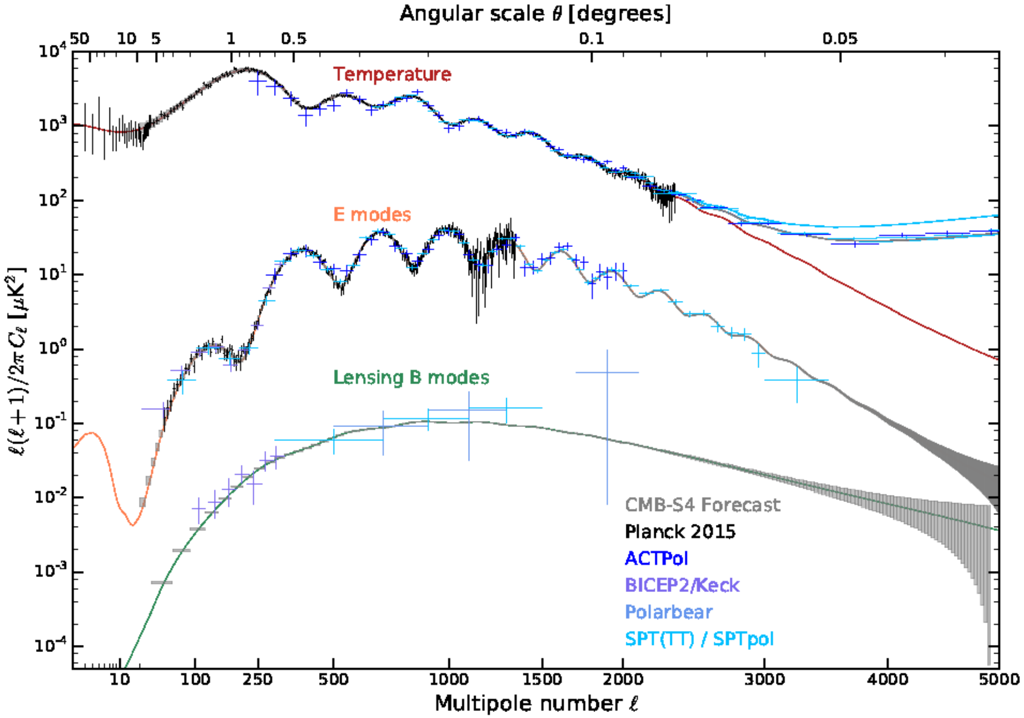
QUaD data constrain H/f_a, and observationally $r \sim 0.14(H_{14})^2$, where $H_{14} = H/10^{14}$ GeV

Induced B-modes (from axion-induced rotation) track E-mode for large l's

$$f_a > 2 \times 10^{14}\text{GeV} \times H_{14} \sim 5 \times 10^{14}\text{GeV} \times \sqrt{r}$$

Updated constraint from BICEP-2/Keck

BICEP-2/Keck Array & Planck provide the best sensitivity to l~O(10^2) B-modes



[CMBS4, Abazajian et al '16]

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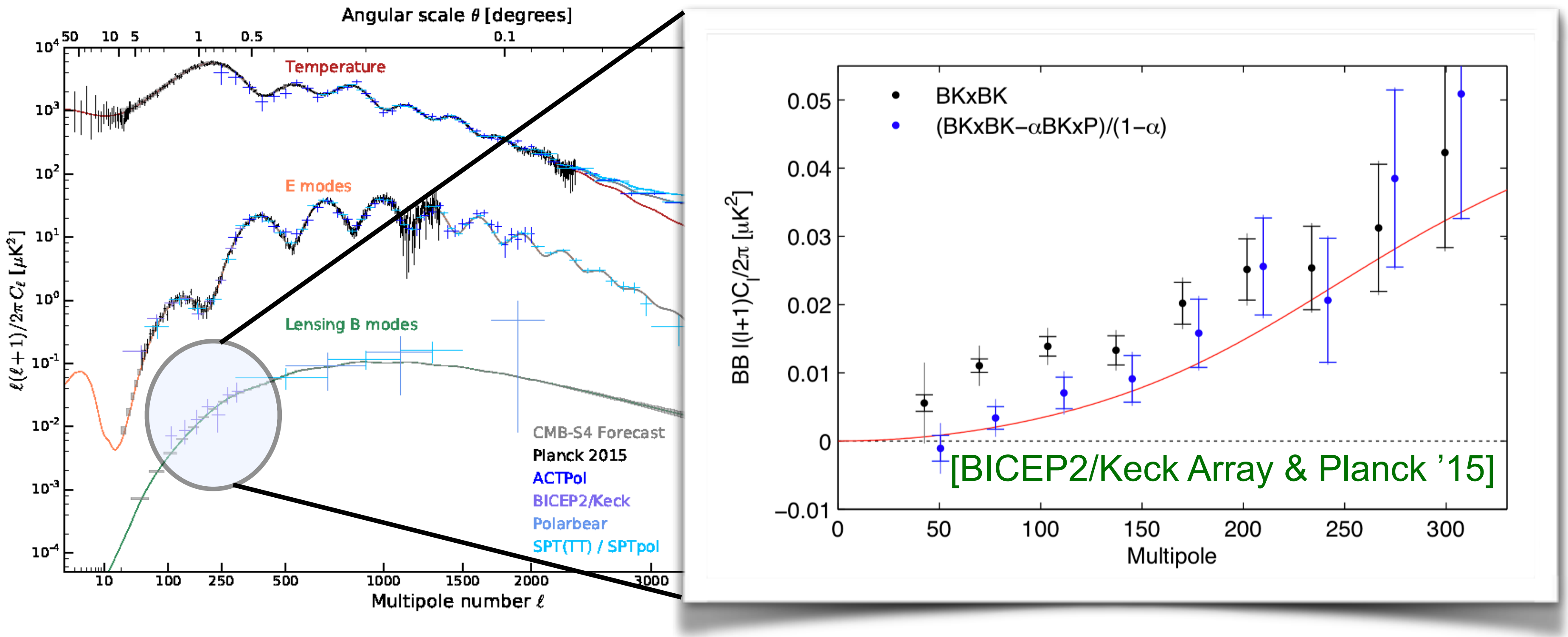

➠ Updated constraint: $f_a \geq 10^{15} GeV \times H_{14}$ [see also Lee et al '14]

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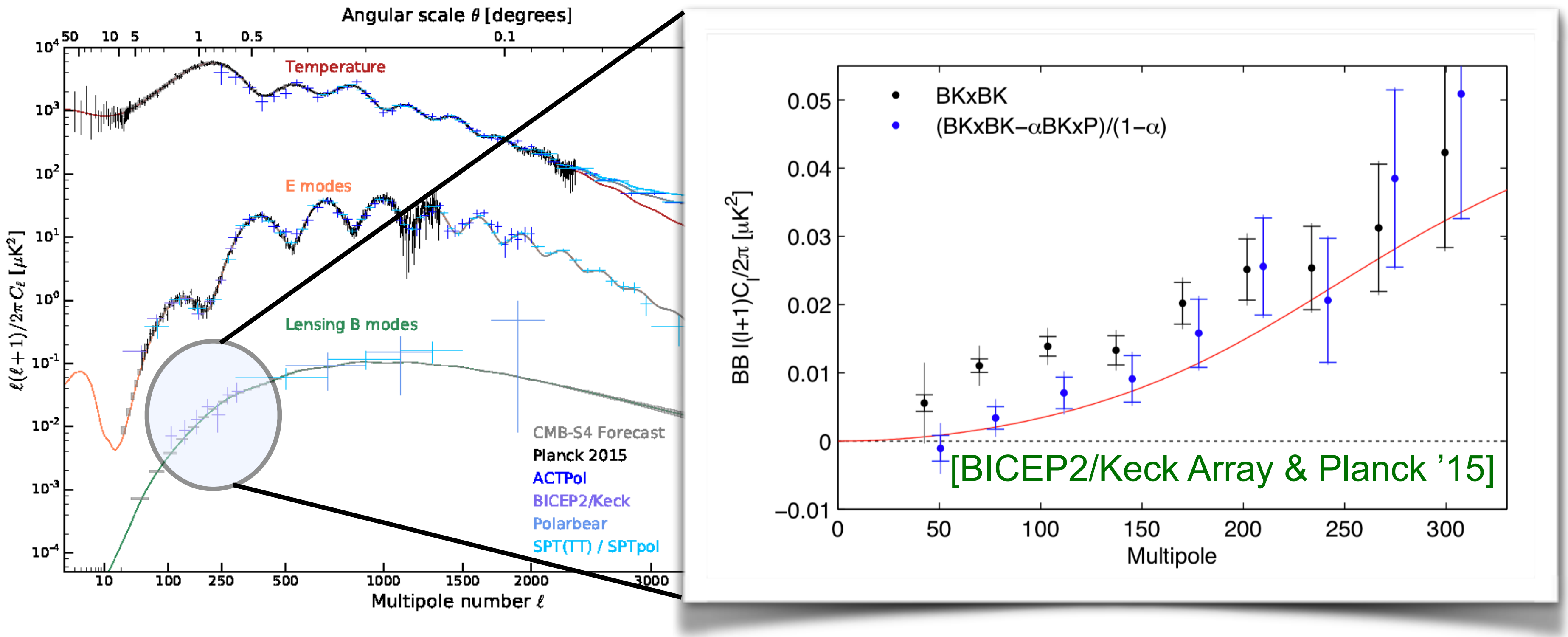


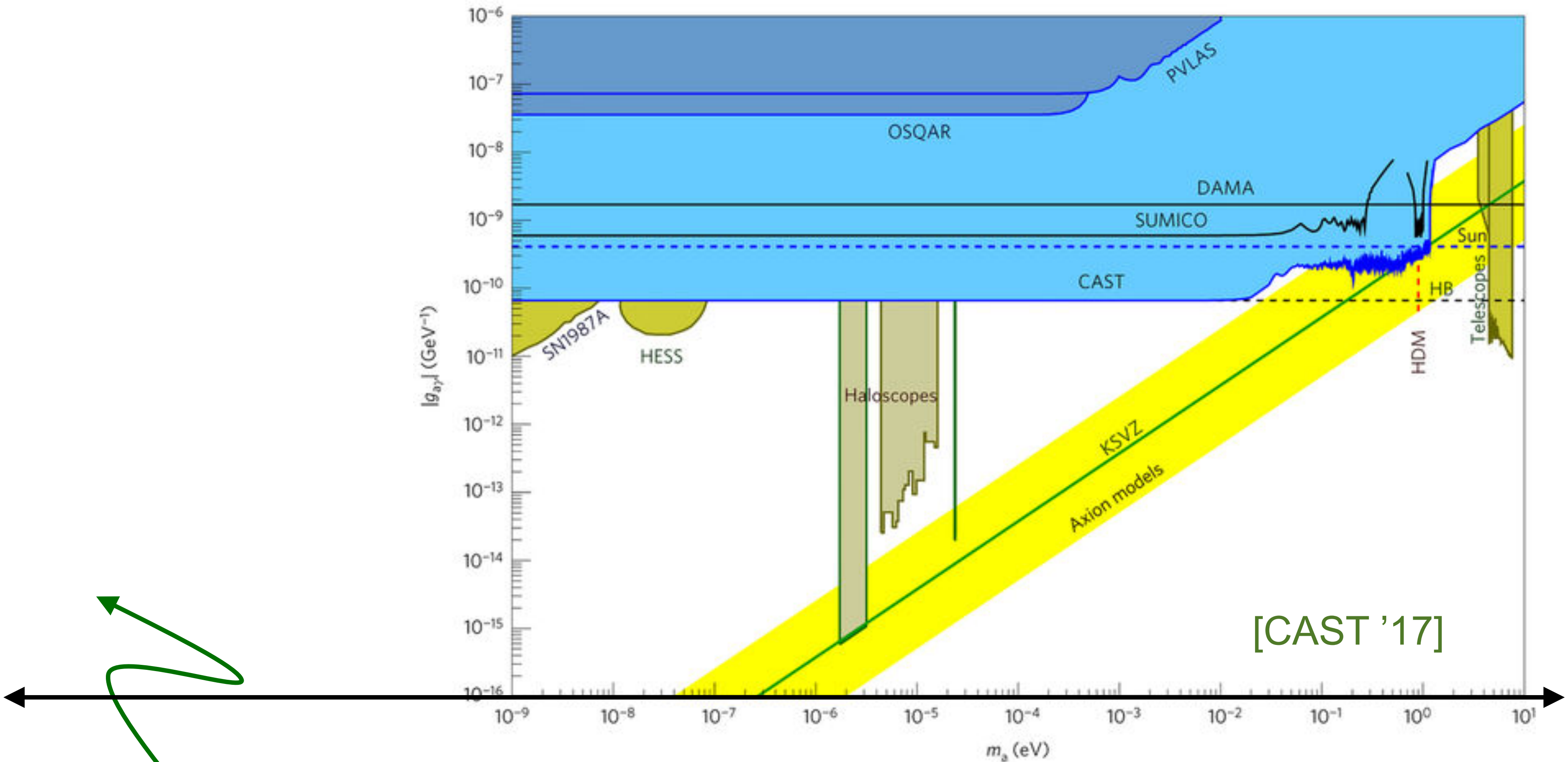
➠ Updated constraint: $f_a \geq 10^{15} GeV \times H_{14}$ [see also Lee et al '14]

NB: $\langle B_{lm} E_{l'm'} \rangle$ ➠ optimal estimator for rot^n angle $\alpha(\hat{n}) = \sum \alpha_{lm} Y_{lm}(\hat{n})$

[Kamionkowski '08, Gluscevic et al '09, Yadav et al '09]

$$0.1^\circ \leftrightarrow f_a/H_{14} \sim 10^{15}\,\mathrm{GeV}$$

Light axion/pseudoscalar constraints



Depending on the scale of inflation, could provide new sensitivity at very low f_a (for very low mass)

NB: CASPEr NMR proposal targets a similar coupling regime [Budker et al ’13]

Concluding Remarks

Summary

- BBN and the CMB are powerful "calorimeters" to use in testing for late energy injection from dark sector decays via *all portal interactions*

- CMB polarization is also a precision probe of inflationary pseudoscalar perturbations, through rotation of E to B modes

Comments

- Important *Assumption:* Br(SM) ~ 1. The phenomenology changes significantly if Br(hidden) is dominant (due to the change in lifetime)

- Freeze-in is a generic production mode, but inflation is a further non-thermal production source, can be relevant for a wide range of hidden sector states [e.g. Nelson & Scholtz '11; Graham et al '15]

- Possible to target sensitivity to the gravitational scale, e.g.

$$g_{Se} \sim 10^{-16}\left(\frac{\theta}{10^{-16}}\right)\left(\frac{m_e}{v}\right) \sim \left(\frac{\theta}{10^{-16}}\right) \times \left(\frac{m_e}{M_{\rm pl}}\right)$$

Extra slides…

CMB - Induced B-modes

- Using the formalism of Zaldarriaga and Seljak ('96), for scalar and pseudoscalar modes (with momenta k and q):

$$U(k,q,\hat{n}) = \frac{3}{2}(1-(\hat{n}\cdot\hat{k})^2)\int_0^{\tau_0} d\tau e^{i(\tau_0-\tau)\hat{n}\cdot(\vec{k}+\vec{q})} g(\tau)\Pi(k,\tau)\Delta_A(\tau,q) + \cdots$$

source→Q(k,τ)

- The basis-independent expansion coeffs are:

$$a_{Blm} = -\frac{1}{2}\int d\Omega(Y^*_{2,lm} + Y^*_{-2,lm})U(\hat{n})$$

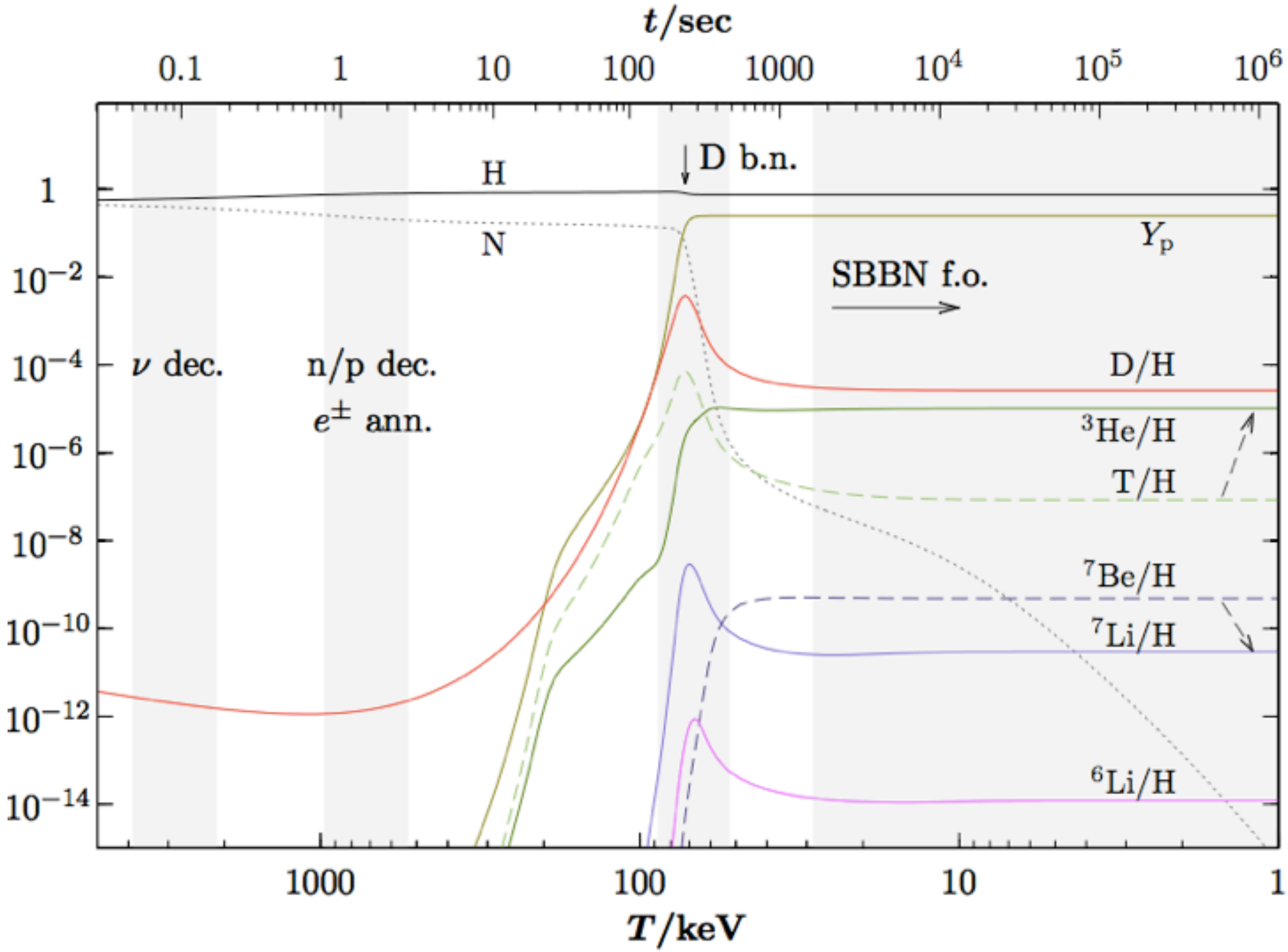
- Integrating over generic (k,q) perturbations:

$$a_{Blm} = \frac{3}{2}\left[\frac{(l-2)!}{(l+2)!}\right]^{1/2}\int d\Omega_n d^3k d^3q Y^*_{0,lm}(\hat{n})$$
$$\times\int_0^{\tau_0} d\tau(m^2-(1+\partial_x^2)^2x^2)e^{ix\mu+iy\nu}g(\tau)\Pi(k,\tau)\Delta_A(q,\tau)\xi(\vec{k})\xi_A(\vec{q})$$

$$\Longrightarrow \quad C_{Bl} = \frac{1}{2l+1}\sum_m \langle a^*_{Blm}a_{Blm}\rangle = \cdots$$

perturbations of inflaton and A

BBN

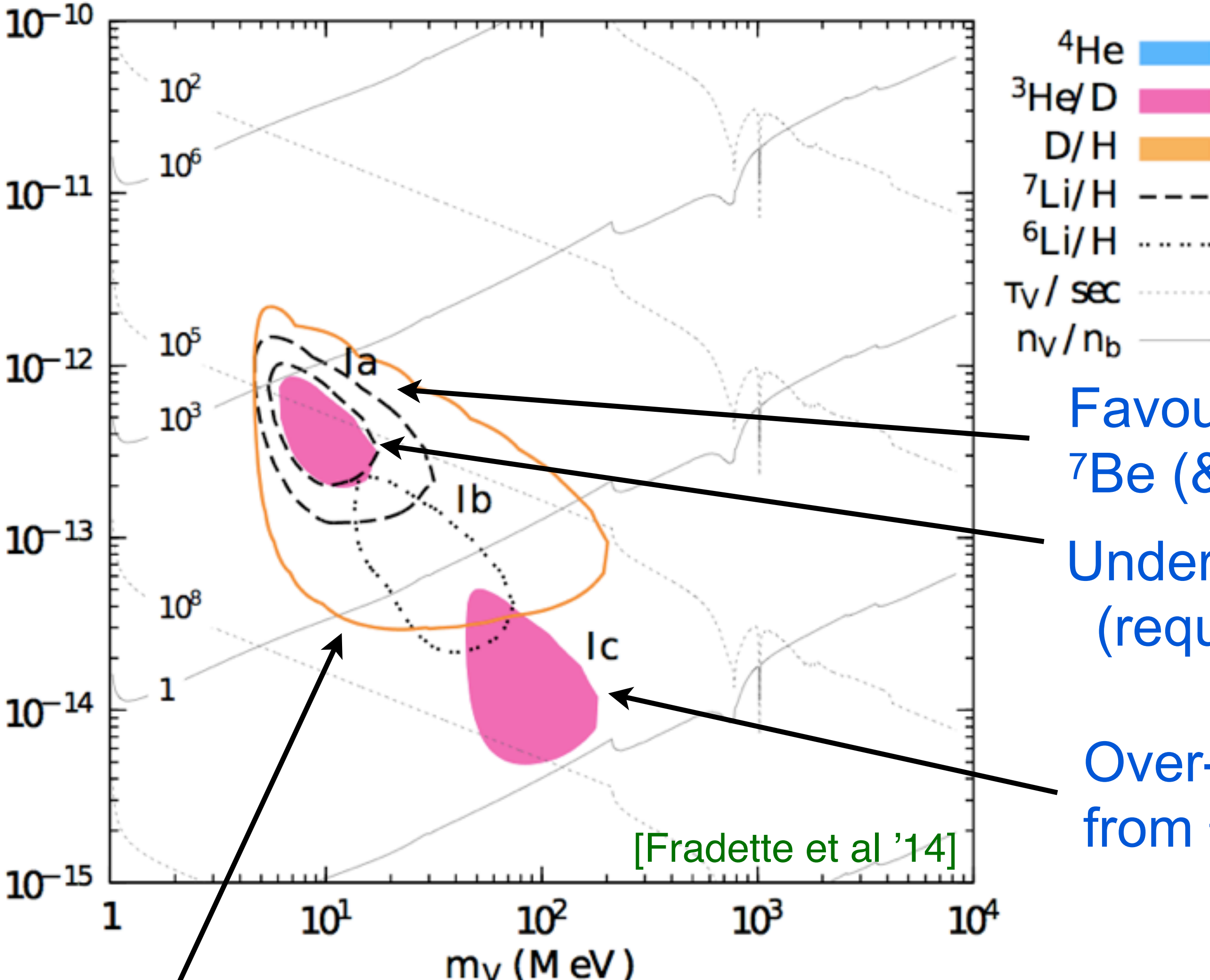


t/sec
0.1
1
10
100
1000
10^4
10^5
10^6
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
H
D b.n.
N
Y_p
SBBN f.o.
ν dec.
n/p dec.
$e^{\pm}$ ann.
D/H
^{3}He/H
T/H
^{7}Be/H
^{7}Li/H
^{6}Li/H
1000
100
10
1
T/keV

BBN - VDP (EM) energy injection ($m_V < 2m_\pi$)

$V \to e^+e^-$ (EM cascade)

$$t_{ph} \simeq \begin{cases} 2\times10^4\text{s}, & {}^7\text{Be}+\gamma \to {}^3\text{He}+{}^4\text{He} \quad (1.59\,\text{MeV}) \\ 5\times10^4\text{s}, & \text{D}+\gamma \to n+p \quad (2.22\,\text{MeV}) \\ 4\times10^6\text{s}, & {}^4\text{He}+\gamma \to {}^3\text{He/T}+n/p \quad (20\,\text{MeV}) \end{cases}$$



[See also Berger et al '16]

Favourable reduction of ^{7}Be (& ^{7}Li)

Under-production of D (require ^{3}He/D <1)

Over-production of ^{3}He from ^{4}He dissociation

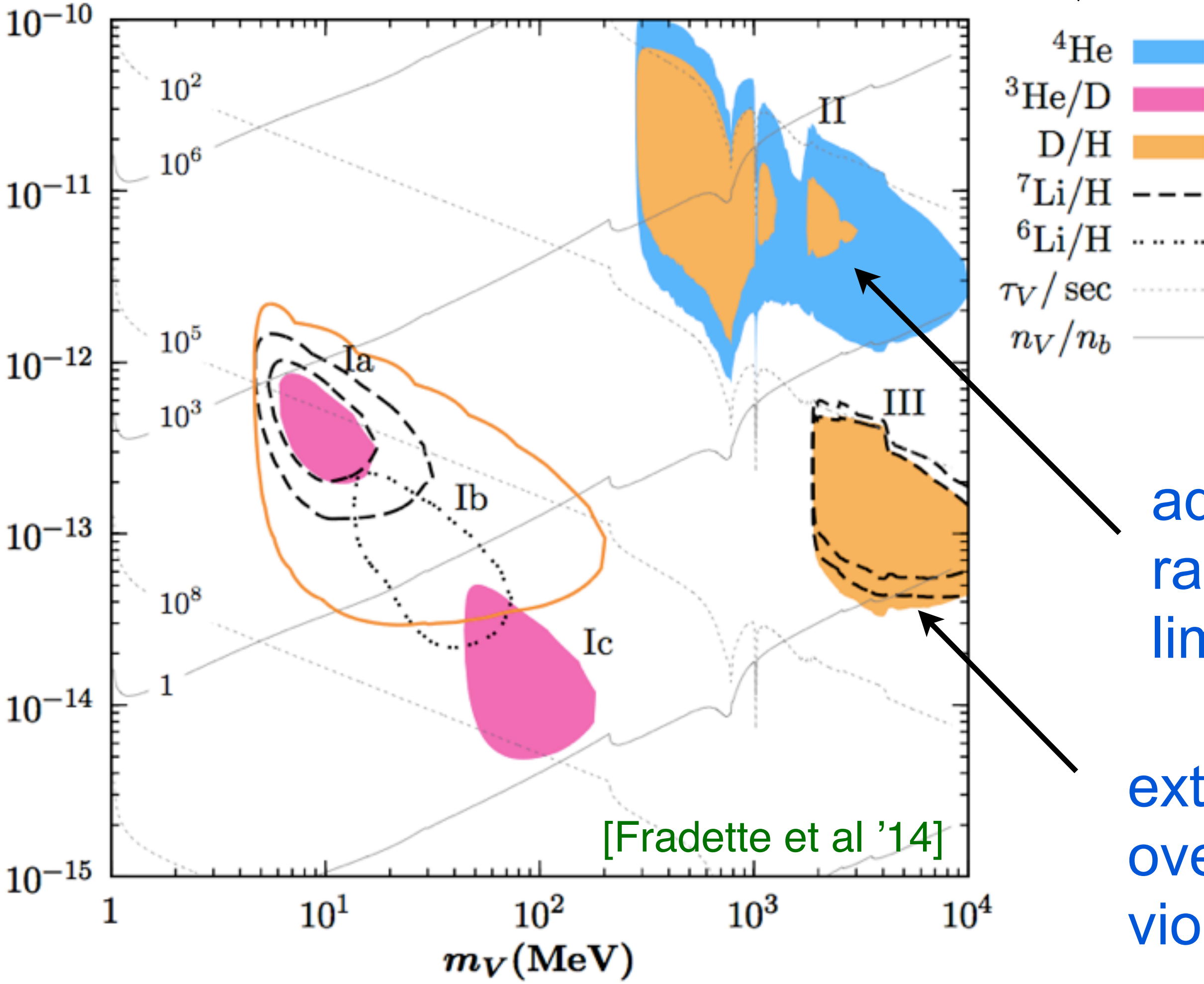
Exclusion based on measured D/H [Pettini & Cooke]

BBN - VDP (had) energy injection ($m_V > 2m_\pi$)

Charge exchange/absorption

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

$$\pi^- + {}^4He \to T + n$$



additional p ⟷ n raises n/p and violates limits on D/H and ^{4}He

extra n from V → nn over-produces D, violating D/H < 3×10^{-5}