Cosmological probes of light weakly coupled fields

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Plan

1. *Introduction: light and very weakly coupled things. "Intensity frontier" direction. Reasonable and not-so-reasonable models. Early cosmology building blocks: CMB, BBN, inflation*

2. Universe as an active detector: CMB and BBN limits on MeV-scale dark photons

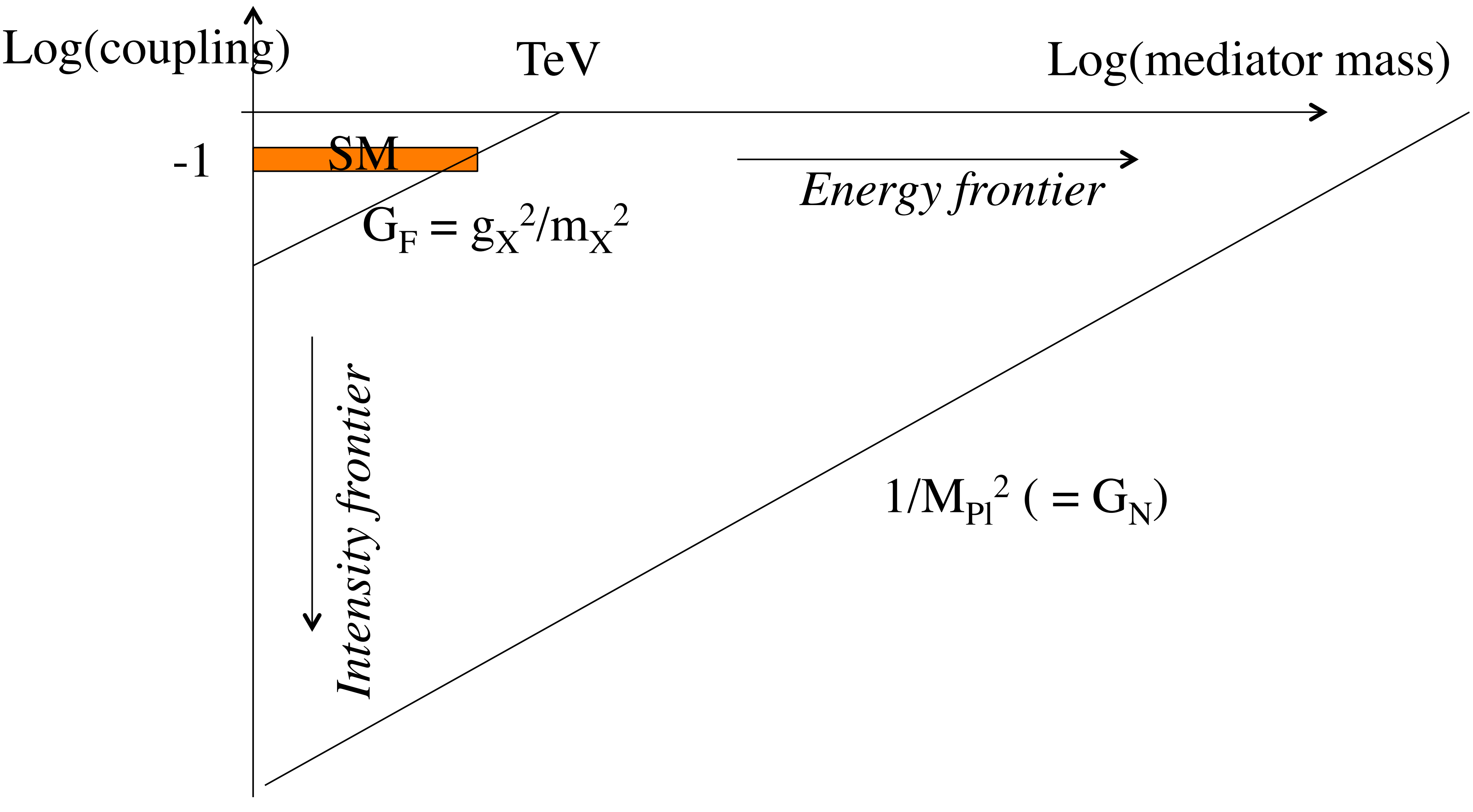
3. Bosonic super-WIMPs, and their absorption signature in direct detection.

4. Super-cool dark matter: oscillations of coherent fields. Examples and observational consequences.

5. Birefringence effects due to light pseudoscalar fluctuations generated by inflation.

Coupling vs mass plot

In 2012-2013 LHC experiments discovered a new particle (Higgs boson) and a new force (Yukawa force). What do we know about forces in nature ?



Intensity frontier direction

*** We often concentrate on trying to find O(0.1-1) strength coupled fields/particles with TeV scale energy mass. (hierarchy motivated)

How far in Energy can one explore this parameter space ? ***

*** Another direction, $m_X \sim$ (or $<$) m_{SM} , is also important, and far less thought through and explored

How far down in Coupling Constants can we explore? ***

(In low energy experiments *sometimes* it is not possible to distinguish whether an effect comes from O(1) coupled heavy physics, or from weakly coupled light physics: e.g. g-2 of the muon discrepancy)

Neutral "portals" to the SM

Let us *classify* possible connections between Dark sector and SM

$H^+H\,(\lambda S^2 + A\,S)$ Higgs-singlet scalar interactions

$B_{\mu\nu} V_{\mu\nu}$ "Kinetic mixing" with additional U(1)' group

(becomes a specific example of $J_\mu^i A_\mu$ extension)

$LH\,N$ neutrino Yukawa coupling, N – RH neutrino

$J_\mu^i A_\mu$ requires gauge invariance and anomaly cancellation

It is very likely that the observed neutrino masses indicate that Nature may have used the *LHN* portal…

Dim>4

$J_\mu^A\ \partial_\mu a/f$ axionic portal

……….

$$\mathcal{L}_{\text{mediation}} = \sum_{k,l,n}^{k+l=n+4} \frac{\mathcal{O}_{\text{med}}^{(k)} \mathcal{O}_{\text{SM}}^{(l)}}{\Lambda^n},$$

My simple criteria for appraising BSM models

Category 1: Well motivated. New particles and interactions that are introduced for a solid reason, and among other things satisfy stringent criteria of technical naturalness (QCD axions, SUSY partners, RH neutrinos participating in mass generation….).

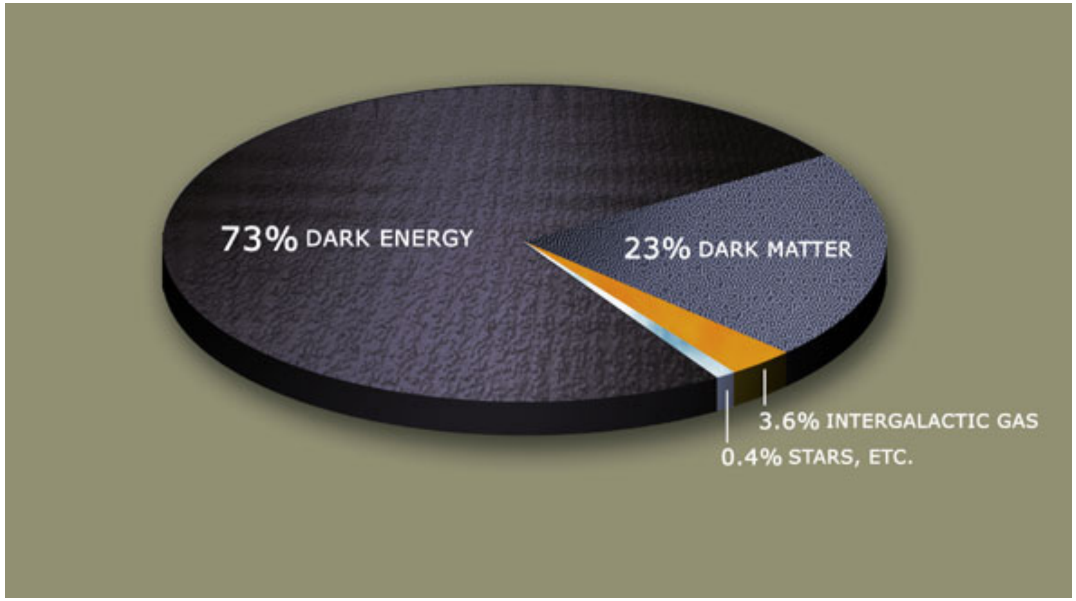
Category 2: Technically natural "why not" physics: New particles and interactions that are stable under quantum corrections without "black magic". Dark photons in certain mass ranges, ALPs, sterile neutrinos beyond those that give neutrino masses.

Category 3: Perhaps not natural, but addressing a specific observational anomaly. (DM anomalies, particle physics anomalies etc).

Category 4: Technically unnatural, but I and/or my friends work on them. (E.g. models of changing couplings; chameleons; ALPs with non-derivative couplings). Justification: coolness factor

Category 5: Technically unnatural models that other people work on….

Big Questions in Physics



"Missing mass" – what is it?

New particle, new force, …? *Both*? How to find out?

Challenges ?? Too many options for DM. *In "direct detection" there is an extrapolations from ~ kpc scale (~ 10^{21} cm) down to 10^{2} cm scale*.

Evolution of theoretical interest to DM

Mid 90's: In the 0th approximation: SUSY neutralino as WIMPs and axion models as "super-cold" DM.

$\downarrow$

Last ~15 years – O(few 100) or more models of WIMPs (sometimes much simpler than MSSM neutralino), super-WIMPs, and super-cold DM are developed. Some models have a much *broader* observational consequences than "neutralinos and/or axions". Some have no *observable properties* other than gravitational interactions.

$\downarrow$

Future? Any model of DM that has a chance of satisfying abundance (+may be some theory priors of "technical naturalness") is worth searching for. Category 2 → Category 1.

More on DM models

SM sector comes in with 3 generations, 3 gauge groups, ~ 20 free parameters and lots of particles with very strange names.

Is it reasonable to expect that the Dark Matter sector includes some isolated dark matter particles and nothing else?

In recent years, there has been a keen interest to “friends of dark matter” – new particles that connect SM with DM (known as “mediators” or “dark forces”), as well as to the possibilities that Dark Matter particles come in some multiplets with more particle states in close proximity to DM. ← *This greatly expands model-building possibilities and allows accommodating various anomalies within the DM framework*. (See N. Wiener’s talk)

Simple classification of particle DM models

At some early cosmological epoch of hot Universe, with temperature T >> DM mass, the abundance of these particles relative to a species of SM (e.g. photons) was

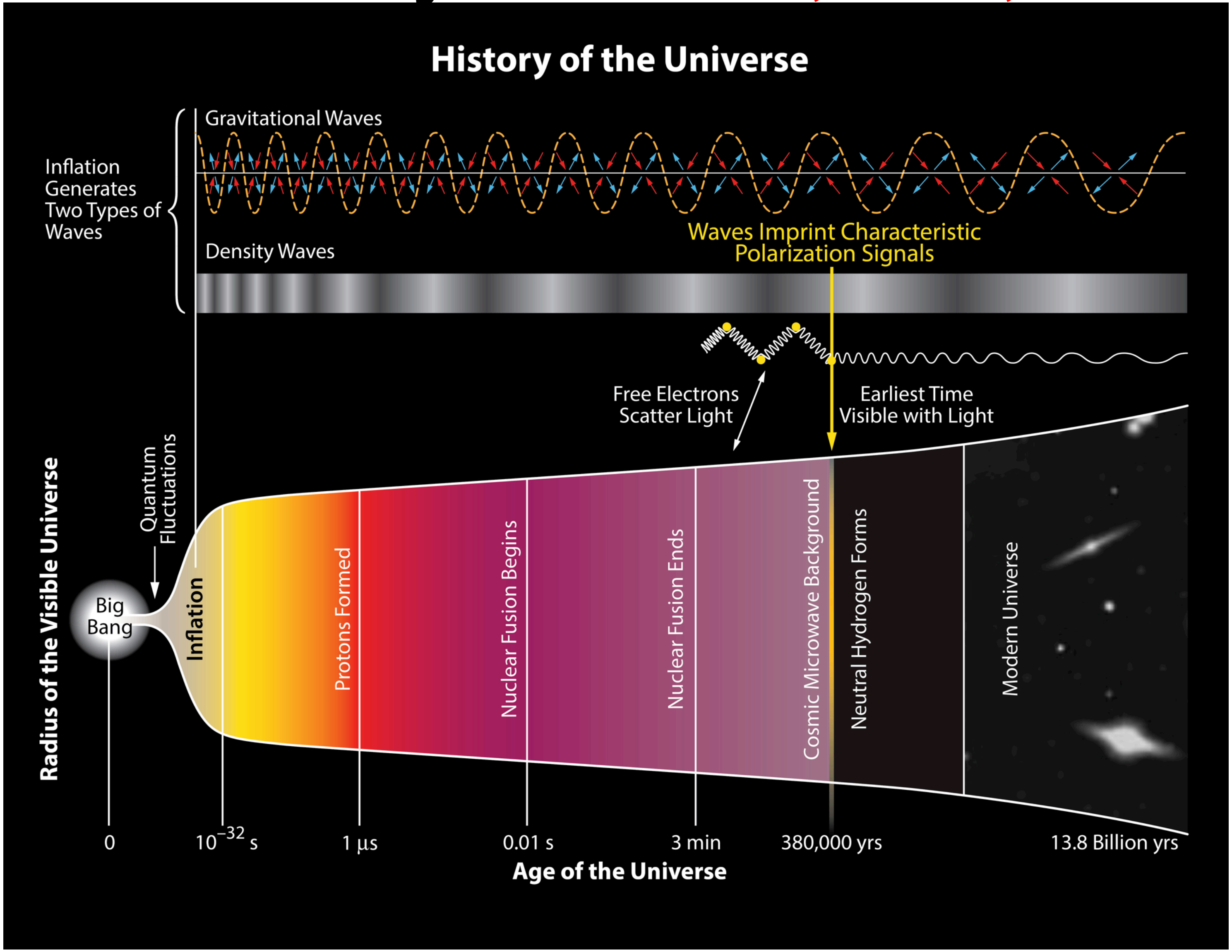
Normal: Sizable interaction rates ensure thermal equilibrium, $N_{DM}/N_{\gamma}=1$. Stability of particles on the scale $t_{Universe}$ is required. *Freeze-out* calculation gives the required annihilation cross section for DM -> SM of order ~ 1 pbn, which points towards weak scale. These are **WIMPs**.

Very small: Very tiny interaction rates (e.g. 10^{-10} couplings from WIMPs). Never in thermal equilibrium. Populated by thermal leakage of SM fields with sub-Hubble rate (*freeze-in*) or by decays of parent WIMPs. [Gravitinos, sterile neutrinos, and other “feeble” creatures – call them **super-WIMPs**]

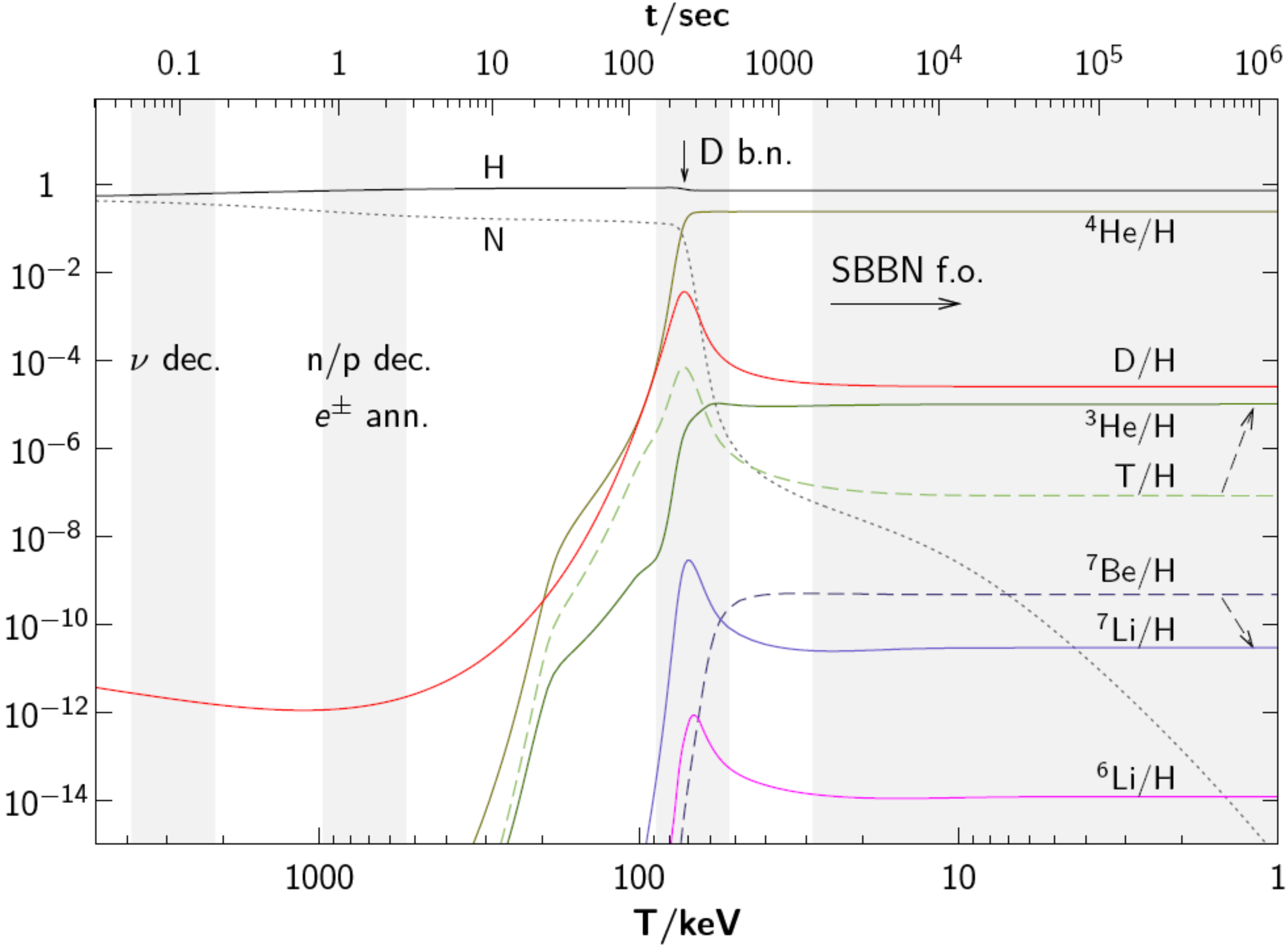
Huge: Almost non-interacting light, m< eV, particles with huge occupation numbers of lowest momentum states, e.g. $N_{DM}/N_{\gamma}\sim 10^{10}$. “Super-cool DM”. Must be bosonic. Axions, or other very light scalar fields – call them **super-cold DM**.

Signatures can be completely different.

Cosmological history: we can extrapolate back in time very well: CMB, BBN, inflation

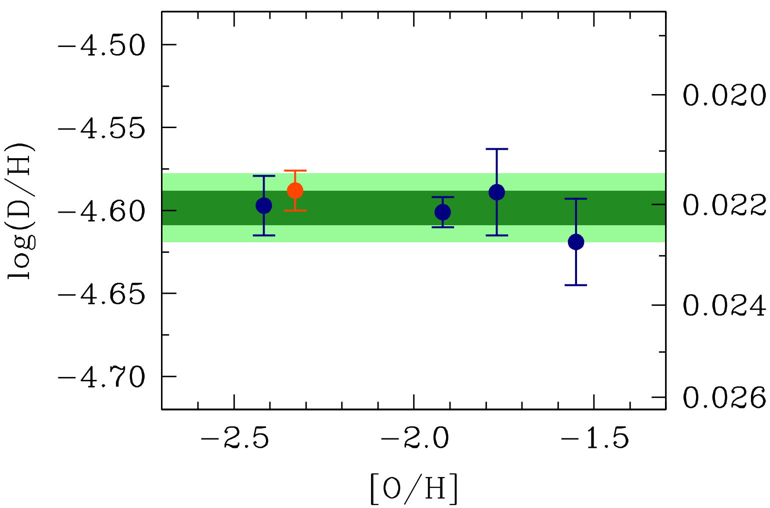


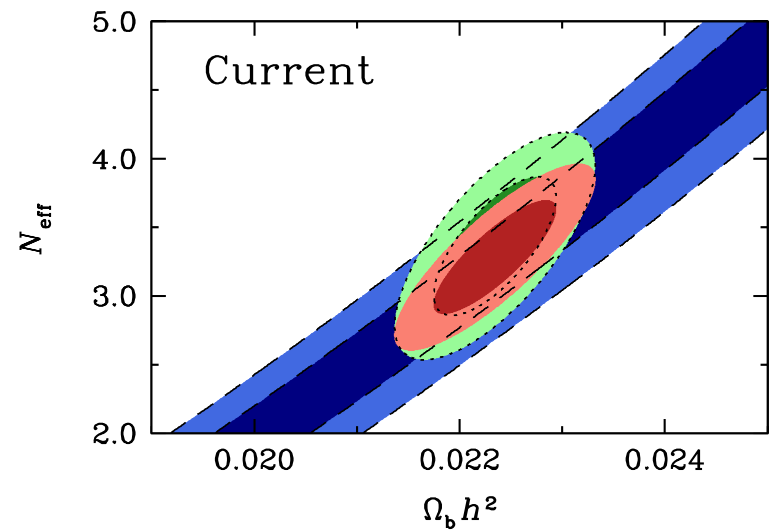
BBN abundances at η_{CMB}



Latest BBN developments

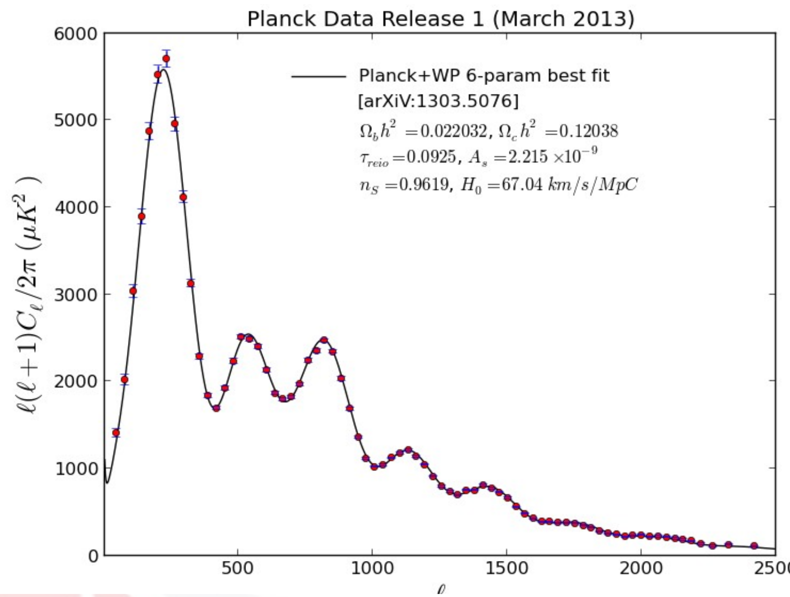
- Planck re-measures most of the cosmological parameters, but there is no drastic change in η compared to WMAP/SPT/ACT.
- Planck determines helium abundance Y_p. Accuracy approaches 10%.
- Cooke et al (2013) claim better accuracy and less scatter for the re-evaluated observational abundance of D/H. Perfect agreement, it seems!





- With latest results, no evidence of ^{6}Li in the stellar atmospheres.
- Only ^{7}Li remains a problem [it is not clear if observed=primordial]

Precision physics with CMB anisotropies



Parameter	Value (68%)
$\Omega_b h^2$	0.02207±0.00027
$\Omega_c h^2$	0.1198±0.0026 (is it high?)
$100\theta_*$ (acoustic scale at recombination)	1.04148±0.00062 (~ 500 parts per million accuracy)
τ	0.091±0.014 (WMAP seeded)
$\ln(10^{10}A_s)$	3.090±0.025
n_s	0.9585±0.0070 (<1 at > 5 σ)

Parameter	Value (95%)
Ω_K	-0.0005±0.0066
$\Sigma\, m_\nu$ (eV)	<0.23
N_{eff}	3.30±0.54
Y_P	0.267±0.040

CMB [in my opinion] gives strong support to inflation: but no definitive H_{infl} yet (until BICEP2 claim is verified): L. Senatore's talk

Dark Photons

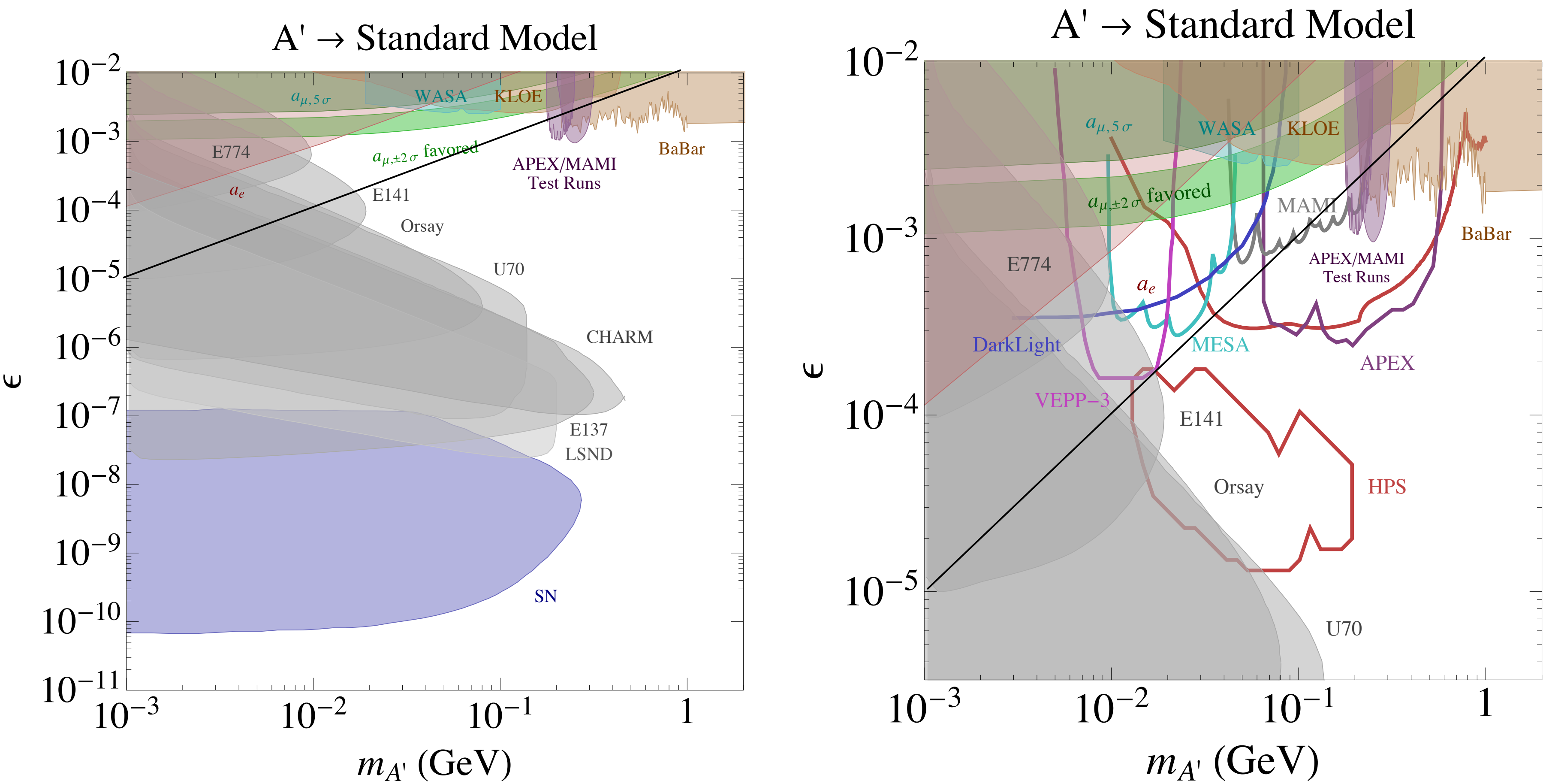
Consider a new vector particle with the mass, and the coupling to the electromagnetic current, i.e. massive photon (Okun; Holdom…)

$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}^2 - \frac{\kappa}{2}V_{\mu\nu}F^{\mu\nu} + |D_\mu\phi|^2 - V(\phi),$$

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

- This is an extremely popular model, subject to a variety of experimental searches in MeV-GeV range with $\kappa \sim 10^{-3}$. Can be used to "regulate" DM abundance or form the super-WIMP DM.

κ-m_V parameter space, Essig et al 2013



Dark photon models with mass under 1 GeV, and mixing angles ~ 10^{-3} represent a "window of opportunity" for the high-intensity experiments, and soon the g - 2 ROI will be completely covered. *Gradually, all parameter space in the "SM corner" gets probed/excluded.*

A theorist's suggestion:

Let us study ~ a few MeV mass Vector with coupling $\kappa \sim 10^{-18}$ so that

$$\alpha_{\mathrm{eff}} \sim \alpha\,\kappa^2 \sim 10^{-38}$$!!!!

NB: $m_p^2/M_{Pl}^2 \sim 10^{-38}$

Production cross section for the $e^+e^- \to V\gamma$ process is

....

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

HEP experimentalist's reaction:  

But ….. *Not only such a model can be tested – as it turns out it is excluded by the data* !!!

New constraints on very dark photons

- The production cross section is ridiculously small, but in the early Universe at $T > m_V$, in fact, *every colliding pair of particles can produce such Vectors*, and there is a lot of time available for this.
- Once produced such particles *live for a very long time*, and decay in the “quiet” Universe, depositing non-thermal amounts of energy and changing physics of primordial matter after recombination.
- Precision determination of optical depth during the CMB, position of Doppler peaks and the slope of the Silk diffusion tale provide tight restrictions on the amount of energy injected.
- Due to BBN we also have a pretty good evidence that the Universe in fact once was at least T ~ a few MeV hot…..
- Fradette, Pradler, MP, Ritz, to appear in ~ 1week.

Filling out details….

- Lifetime against the decay to electron-positron pairs

$$\tau_V \simeq \frac{3}{\alpha_{\rm eff} m_V} = 0.6 \text{ mln yr} \times \frac{10\,{\rm MeV}}{m_V} \times \frac{10^{-35}}{\alpha_{\rm eff}}$$

- $e^+e^- \rightarrow V$ in the early Universe leads to the energy stored per baryon

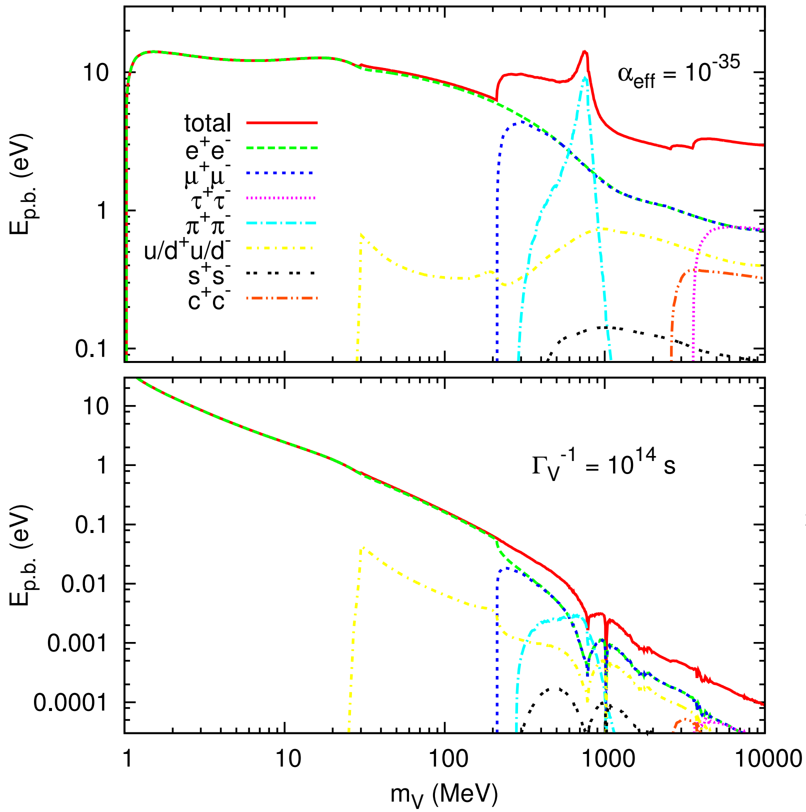
$$E_{\rm p.b.} \sim \frac{m_V \Gamma_{\rm prod} H^{-1}_{T=m_V}}{n_{b,T=m_V}} \sim \frac{0.1\alpha_{\rm eff} M_{\rm Pl}}{\eta_b} \sim \alpha_{\rm eff} \times 10^{36}\,{\rm eV}$$

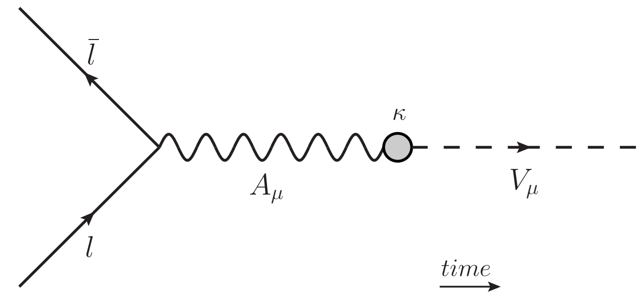
$$\text{for} \quad \Gamma_V^{-1} = 10^{14}{\rm s}.$$

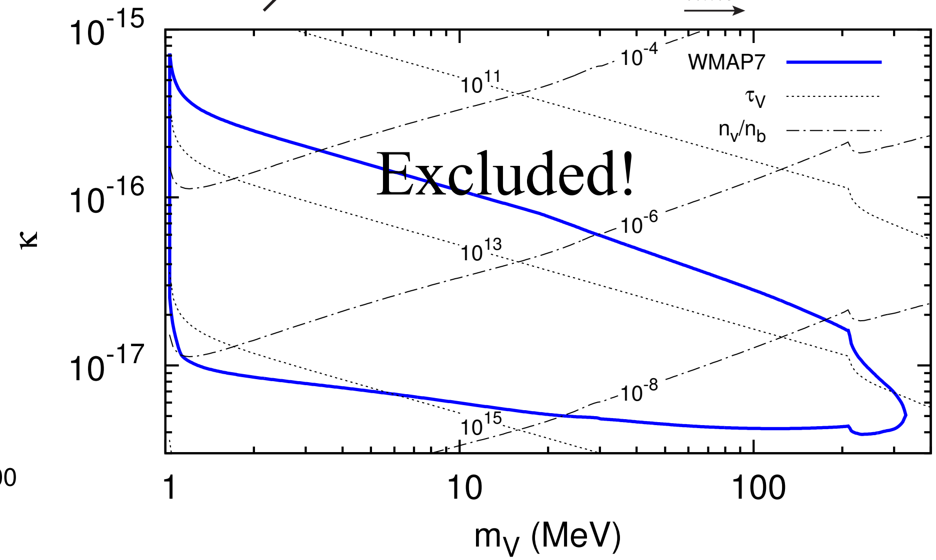
(Previously calculated in Postma, Redondo, 2008 – we improve over it by including hadronic channels and resonant production.)

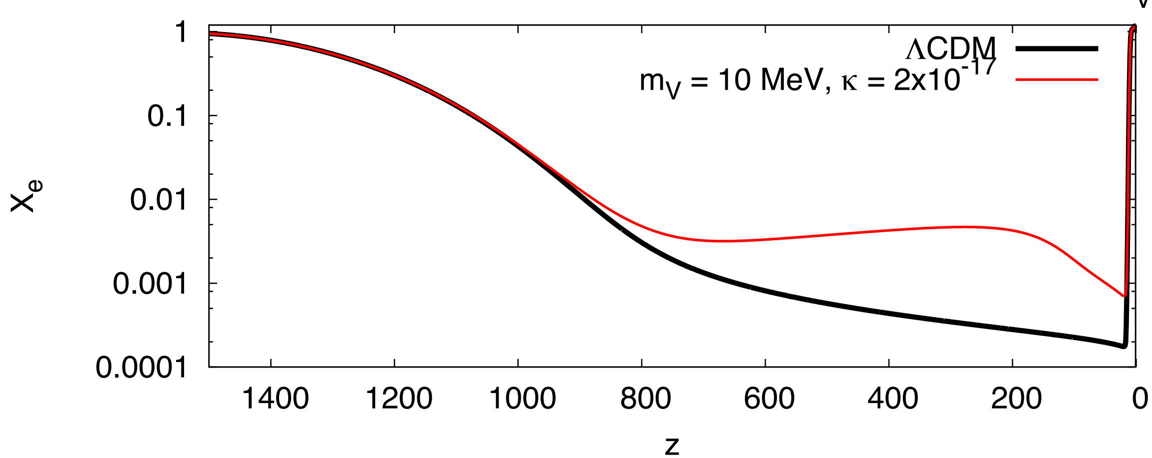
- Once injected back to the medium via $V \rightarrow e^+e^-$ ~ 1/3 of the stored energy leads to ionization. E.g. 1 eV p.b. recreates $X_e \sim$ few 10^{-2}.

VDP change ionization history



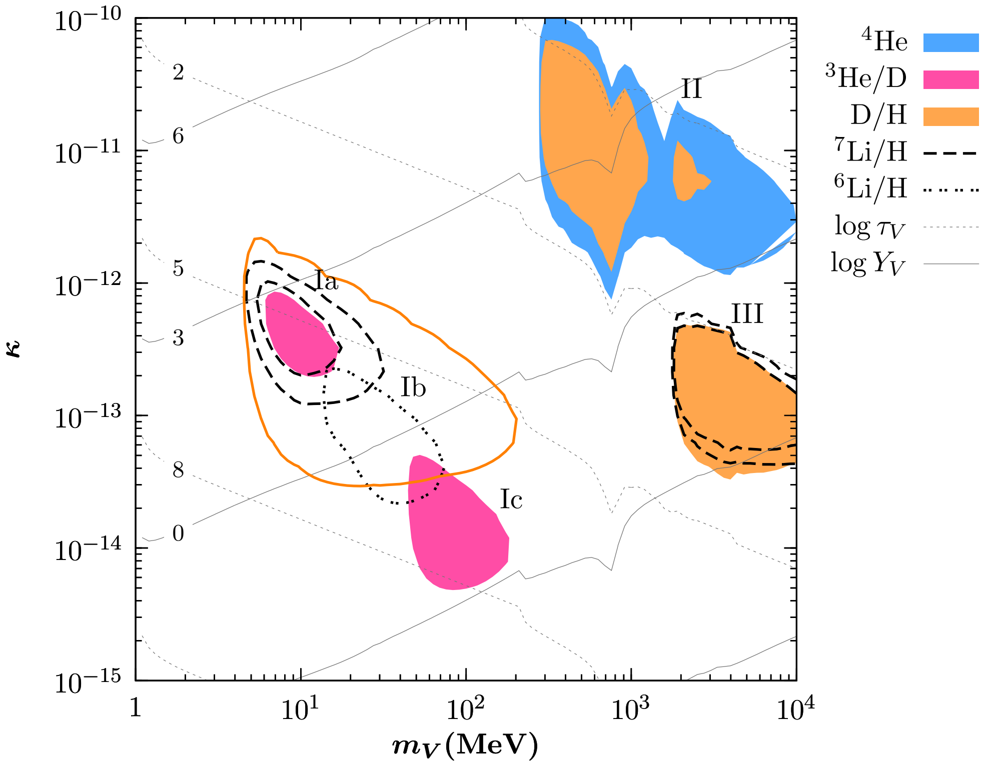






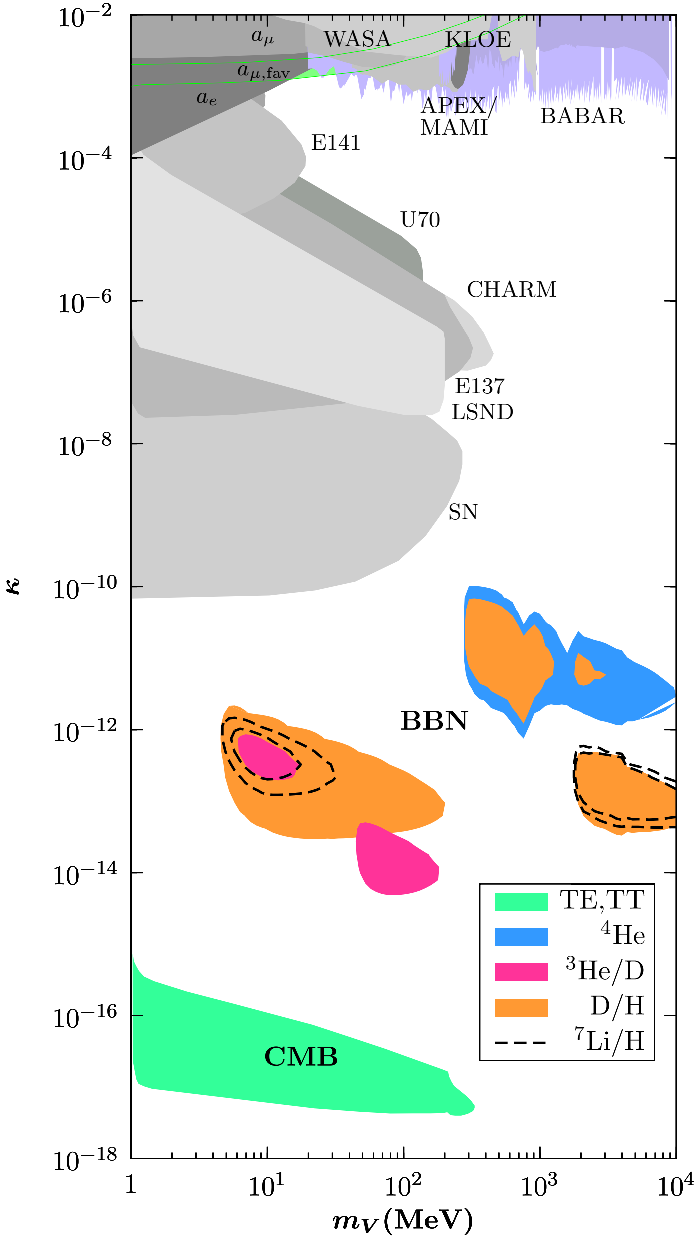
VDP can change BBN

Previously studied in Postma, Redondo, 2008, MP, Pradler 2010



Late decays during/immediately after BBN can alter D/H; increase He3/D; could affect Lithium somewhat (the latter perhaps not an unwanted change)

Master plot



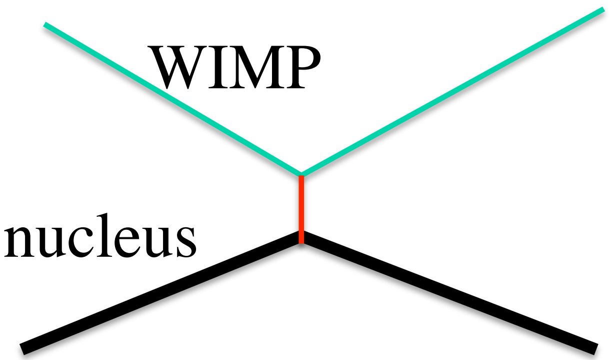
- We rule out significant fraction of dark photon parameter space.
- These new limits are inevitable: only rely on thermal production and require that the Universe was T~ 0.3 m_V hot.
- Non-thermal component of $< V_\mu >$ (so-called "vacuum misalignment") will only make limits stronger. Existence of "dark Higgs" can only make limits stronger.
- Limits/sensitivity can be further improved with Planck polarization data. Independent assessment of D/H is needed.

VDP dark matter

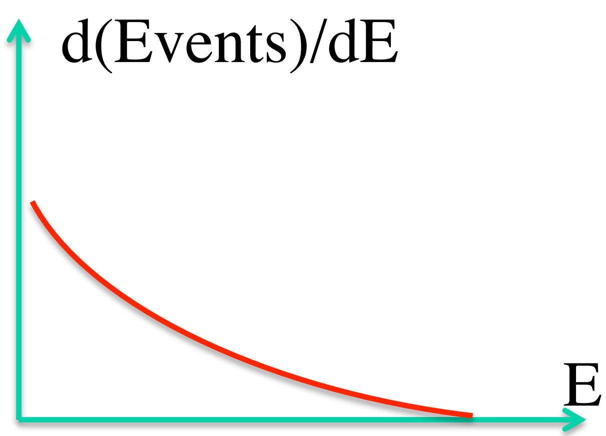
- Very weakly coupled dark photons can be dark matter in sub-eV regime due to misalignment mechanism (see J Mardon's talk) or in the keV regime due to thermal emission (MP, Ritz, Voloshin; Postma, Redondo, 2008)
- If $m_V < 2\, m_e$ then only V → 3 γ is possible. It is a delayed decay – larger couplings will be consistent with bounds. No monochromatic photons = weaker limits from x- and gamma-rays.
- Direct coupling to electrons = mono-energetic electron recoil in direct dark matter detection.
- First searches of spikes in electronic recoil have been performed by several dark matter detection collaborations.

New signal: absorption of super-WIMPs

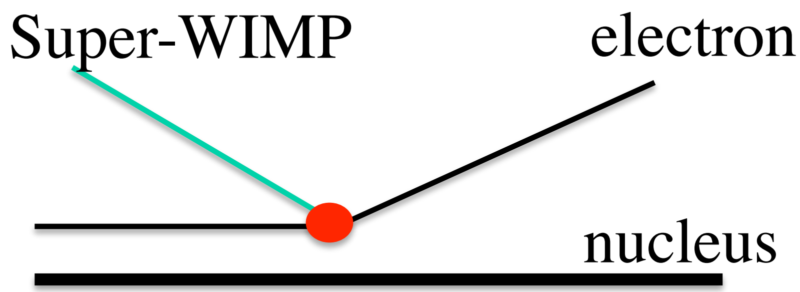
WIMP-nucleus scattering



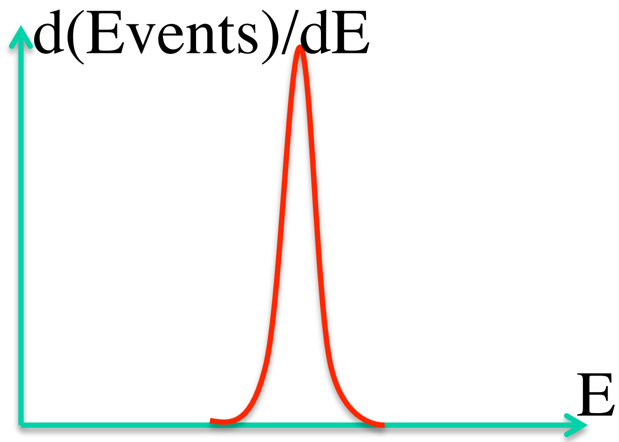
Signal: ionization + phonons/light



Atomic absorption of super-WIMPs



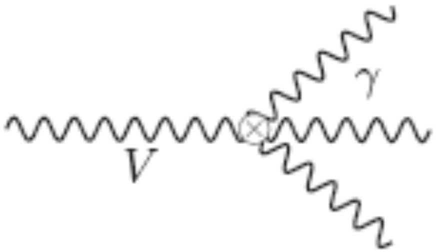
Ionization at $E=m_{superWIMP}$



Superweakly interacting Vector Dark Matter

$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}^2 - \frac{\kappa}{2}V_{\mu\nu}F_{\mu\nu} + \mathcal{L}_{h'} + \mathcal{L}_{\dim>4},$$

- Vectors are long-lived if $m_V < 2\, m_e$. V has to decay to 3 photon via the light-by-light loop diagram:



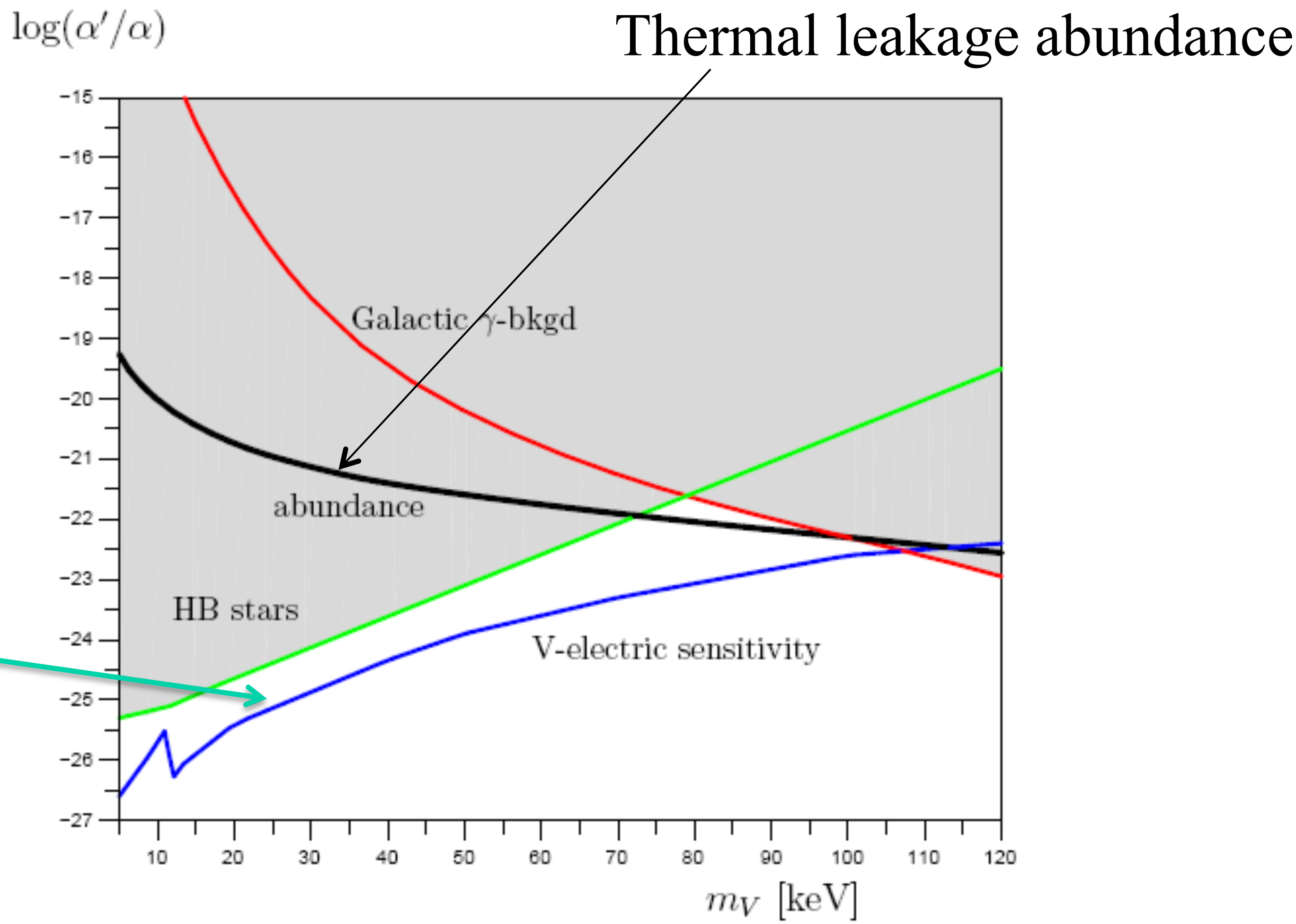
$$\Gamma = \frac{17\,\alpha^3\alpha'}{2^7 3^6 5^3 \pi^3}\,\frac{m_V^9}{m_e^8} \approx \left(4.70\times 10^{-8}\right)\,\alpha^3\alpha'\,\frac{m_V^9}{m_e^8}.$$

$$\tau_{\mathrm{U}}\Gamma_{V\to 3\gamma} \lesssim 1 \quad\Longrightarrow\quad m_V\,(\alpha')^{1/9} \lesssim 1\,\mathrm{keV}\ .$$

The γ-background constraints are weak. (No monochromatic lines)

Absorbing Dark Photon DM

Very "approximate", proper Experimental analysis is needed

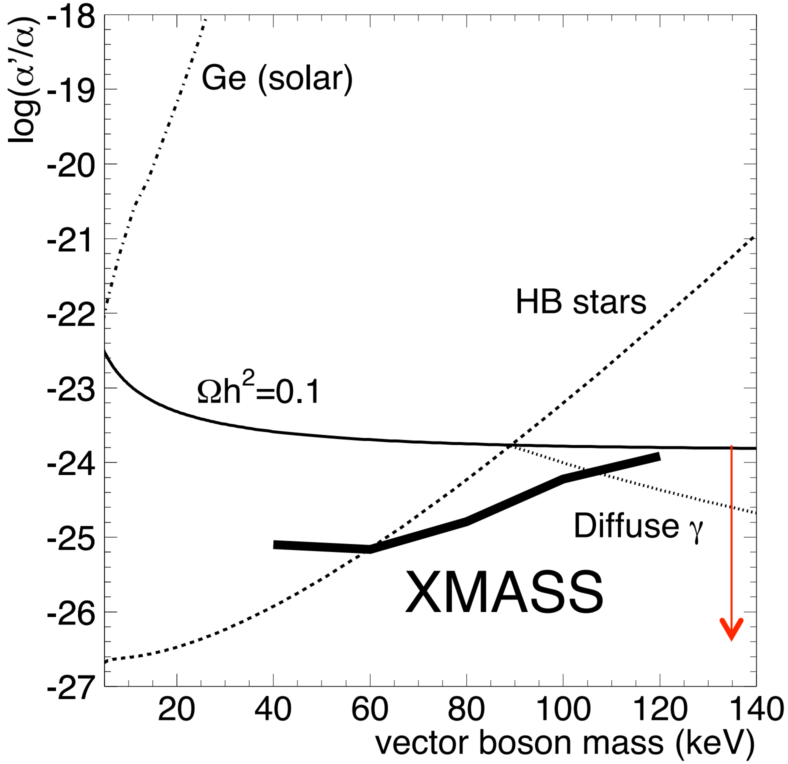


Direct detection search of Vector super-WIMP should be competitive with other constraints. MP, Ritz, Voloshin, 2008.

- Searches for “odd lines” in electron recoil was performed by e.g. CDMS, EDELWEISS, CoGeNT (but only in the limited range of energies up to ~ 10 keV)

- Xenon100 analysis extends it to 30 keV.

- X-mass group publishes new constraint, arXiv:1406.0502



- Red arrow indicates where the abundance curve will move if there is some non-thermal component to the DM abundance
- Current constraints already require extra contributions to abundance (non-thermal component or additional couplings giving more of thermal production)

Super-cool Dark Matter from misalignment

Sub-eV mass ranges – has to be non-thermal.

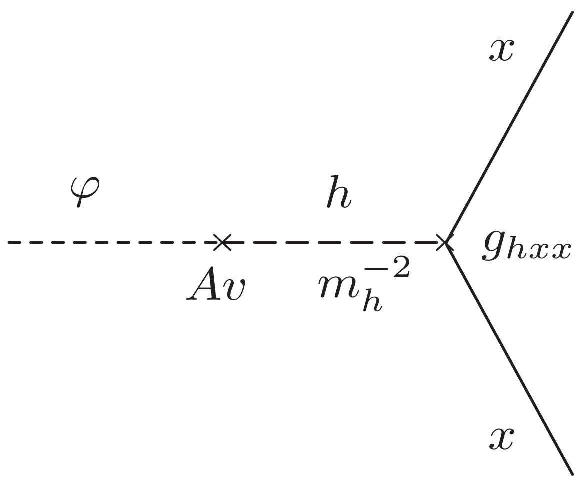
- QCD axion (1981- onwards): J Redondo's talk
- …
- Scalar DM through the super-renormalizable Higgs portal (Piazza, MP, 2010) Pointed out Dark Photon DM possibility.
- Nelson, Scholtz (2011); Arias et al (2012); Jaeckel, Redondo, (2013); … J Mardon, this meeting.
- … many other options remain to be explored.
- Most models are subject to uncertainty related to the "initial displacement" of the field from minimum (and possible isocurvature perturbation constraints.)

Scalar DM through super-renormalizable portal

- Piazza, MP, 2010: *There is a unique portal in the SM*

$$V = -\frac{m_h^2}{2} H^\dagger H + \lambda (H^\dagger H)^2 + A H^\dagger H \phi + \frac{m_\varphi^2}{2} \phi^2 \,.$$

- There is no runaway direction if $A^2/m_\varphi^2 < 2\lambda$
- After integrating out the Higgs, the theory becomes very similar to Brans-Dicke – but *better* because of UV completeness our theory.



$$g_{\varphi xx} = \frac{Av}{m_h^2} g_{hxx}$$

$$g_{hNN} \simeq \frac{200 - 500\,\mathrm{MeV}}{v} \sim O(10^{-3})$$

- Parameter "A" is of positive mass dimension. Loop corrections to mass^2 of scalar field scale as ~ $A^2\,\mathrm{Log}(\Lambda)$. *Under control* !

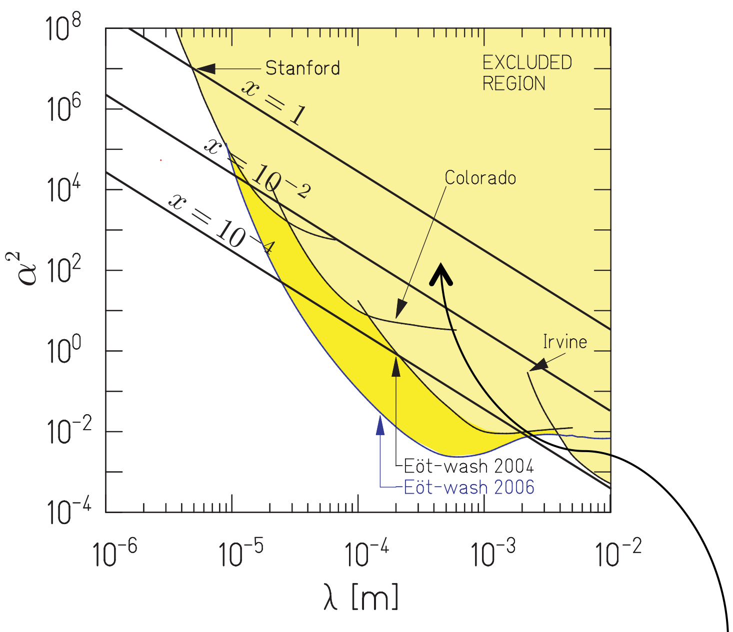
5th force from Dark Matter exchange

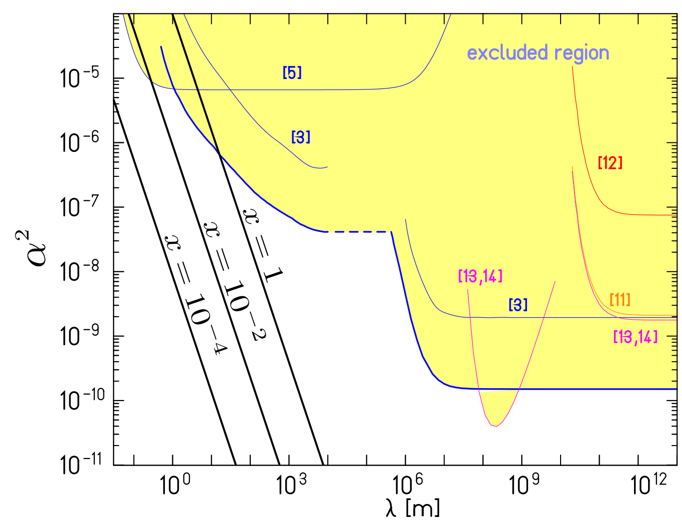
- The main observational consequence of this model: possibility to have an observable 5th force (x= A/mass)
- For the traditional parametrization, $$V(r) = -G\frac{m_A m_B}{r}\left(1 + \alpha_A \alpha_B \, e^{-m_\varphi r}\right).$$

we can derive the strength of coupling

$$\begin{aligned} \alpha &= g_{hNN}\frac{\sqrt{2}M_P}{m_{\rm nuc}}\frac{Av}{m_h^2} \\ &\simeq 10^{-3}\left(\frac{m_h}{115\,{\rm GeV}}\right)^{-2}\frac{A}{10^{-8}{\rm eV}}. \end{aligned}$$

(! *the second bracket* = 0.83)





One can expect a “natural” 5th force from DM in 10 micron – 100 m range

Changing couplings from DM?

- The same model would predict the "oscillating" pattern of couplings, as emphasized by Arvanitaki, Huang, Tilburg, 2014.
- The chance to detect it is for $m_\phi < 10^{-15}$ eV, and the ROI is [of course] in an unnatural range of parameters (category 2 → category 4).
- Oscillating couplings is such a *cool signature* anyways, so it should be searched for directly in experiment. (Leefer, Budker;…) [not crazier than a constant drift of couplings]

Oscillating force on spin in ALP DM

- "CASPEr-yesterday or CASPEr-USSR":

P.V. Vorob'ev, A.I. Kakhidze, I.V. Kolokolov, *Axion wind: A search for cosmological axion condensate (in Russian)*, Yadernaya fizika, 58, 1032-1036 (1995) [P.V. Vorob'ev, A.I. Kakhidze, I.V. Kolokolov, *Axion wind: A search for cosmological axion condensate*, Phys. Atom. Nucl., 58(6), 959-963 (1995)]

P.V. Vorobyov, I.V. Kolokolov, *Detectors for the Cosmic Axionic Wind*, Gravit. Cosmol., 4, Suppl., 62-69 (1998)

arXiv:astro-ph/9501042v1 13 Jan 1995

DETECTORS FOR THE COSMIC AXIONIC WIND

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[**]INFN, Sez.di Milano, 20133 Milano, Italia

We propose experimental schemes for detection an axionic condensat supposed to be a cosmic dark matter. Various procedures are considered in dependence on the value of the axion mass.

$$\mathbf{B}_{eff} = 2\kappa\sqrt{\rho_a}\mathbf{v}\sin(m_a t + m_a \mathbf{v}\mathbf{x} + \theta).$$

Recently revived by Graham, Rajendran, 2013

Oscillating force on He3 spin

Easy to see if e.g. M. Romalis' "Lorentz violation" search is sensitive to ALPs dark matter:

$$\mathcal{L} = \frac{\partial_\mu a}{f_a} \overline{n} \gamma_\mu \gamma_5 n$$

As everyone else in this game, I will saturate ρ_{DM} by oscillating a(t).

I will take the *maximum allowed* f_a from stellar constraints.

I will take the range of masses 10^{-17} to 10^{-15} eV where the K-He3 magnetometer is the most sensitive

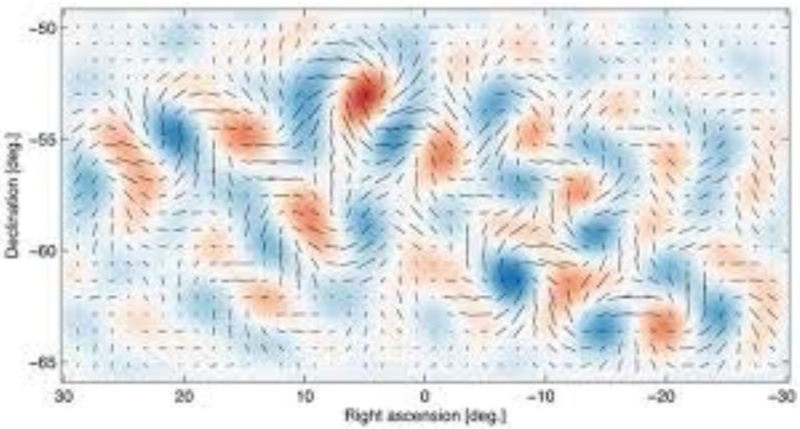
The energy shift due to DM:

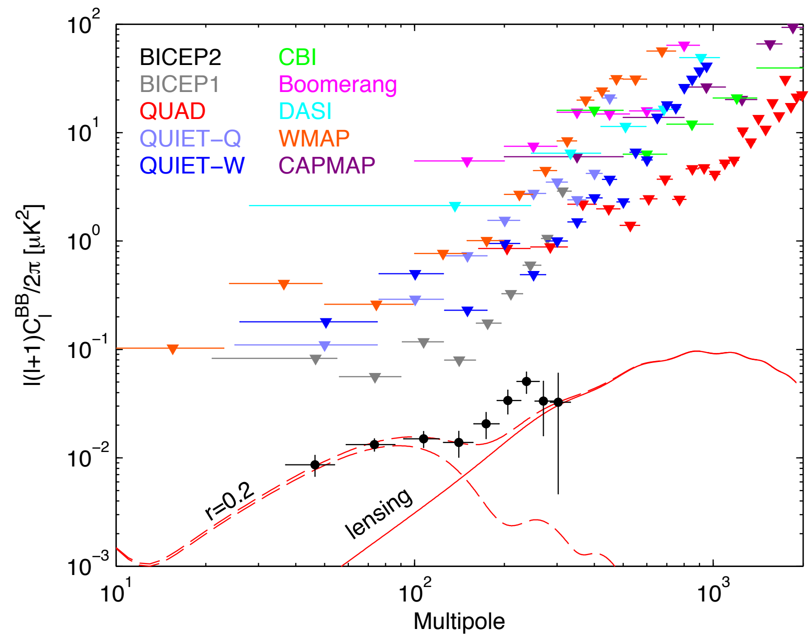
$$\Delta E = \frac{m_a a}{f_a} \frac{v}{c} = \frac{\sqrt{\rho_{DM}}}{f_a} \frac{v}{c}$$

$$= 1.5 \times 10^{-33} \text{GeV} \times \frac{10^9 \text{ GeV}}{f_a} \times \left(\frac{\rho_{DM}}{0.3 \text{GeV} \text{cm}^{-3}}\right)^{1/2} \times \frac{v/c}{10^{-3}}$$

Right at the edge of current sensitivity!!

March, April 2012– Bicep 2 results!!





If interpreted as the signature of primordial tensor perturbations generated by inflation it gives very high Hubble rate during inflation, with H_{infl}=1.4 10^{14} GeV. Well, it poses a lot of questions to anyone who tries to play with some physics that has fundamental scale below10^{14} GeV. **Profound consequences for theoretical physics, if true!**

Problems with Bicep-2 claim

Bicep B-mode = Lensed E-mode + c_2*dust + c_3*(Tensor mode contribution) + c_4*Birefringence effect + …

Initial claim: $c_2 \sim 0$, $c_3 \neq 0$

Subsequent re-analysis: $c_3 = 0$ and $c_2 \neq 0$ is also possible.

*****

Nobody analyzed data for the presence of c_4 (this is non-minimal model)

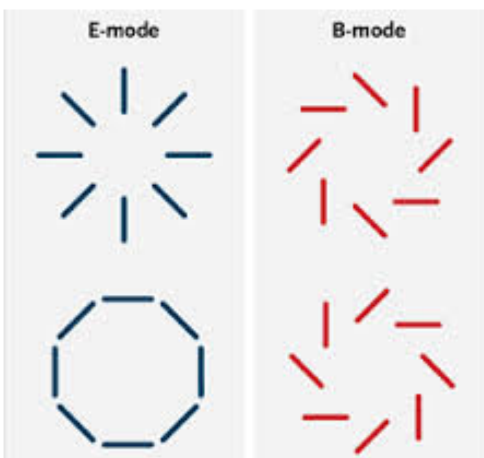
- There is one modification – massless ALP with initial field profile generated by inflation – that is quite predictive in terms of $C_l(BB)$ *
- *Inflation provides access to large values of light fields – allows probing small couplings*

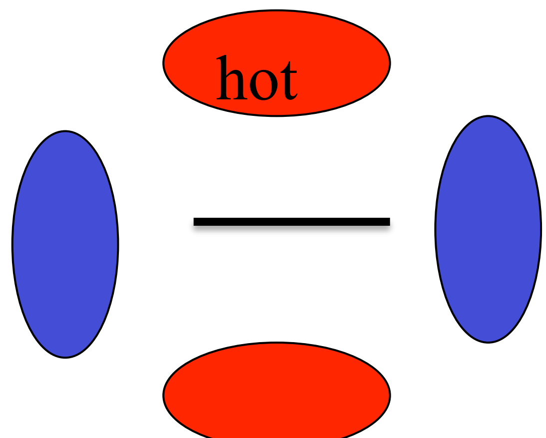
Some background on CMB polarization

(Kamionkowski, Stebbins, Kosowsky; Seljak, Zaldarriaga, 1997…)

$$\vec{P} = \underset{\substack{\uparrow \\ \text{E-mode}}}{\nabla S} + \underset{\substack{\uparrow \\ \text{B-mode}}}{\text{curl}\ \vec{V}}$$

Polarization is generated by quadrupole temperature anisotropy, and scalar perturbations are capable of generating only the E-modes.





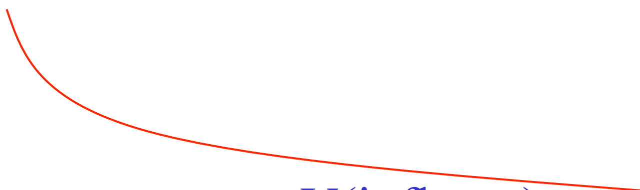
Scalar perturbations [of Newtonian potential] can only generate E-mode but perturbations of the full metric tensor [grav waves] can also give B.

Inflation, perturbations

Main observational outcome of inflation is density perturbations. Density perturbations are seeded by the fluctuation of the inflaton field:

$\delta \phi \sim H_{infl}/(2\pi)$. Unfortunately, the measurement of $\Delta \rho/\rho$ *does not fix the scale of inflation*:

$(1.93 * 10^{-10})_{\mathrm{COBE,WMAP}} \sim G_N H_{\mathrm{infl}}^2/(4\pi\varepsilon)$



V(inflaton)

Slow-roll parameter $\varepsilon = M^2_{pl}(V'/V)^2$ can be small…

V(inflaton)

or very very small

Amplitude of tensor perturbations is not fixed by inflationary framework!

Fluctuating pseudoscalar driven by inflation

The model:

$$\mathcal{L}_{everything} = \mathcal{L}_{SM+gravity} + \mathcal{L}_{inflation} + \frac{1}{2}(\partial_\mu a)^2 + \frac{a}{2f_a} F_{\mu\nu}\tilde{F}_{\mu\nu}$$

[Can be viewed as a generic consequence of two QCD axions.]

Massless field a receives [random, Gaussian, nearly flat-spectrum] fluctuations during inflation, $\delta a \sim H_{infl}/(2\pi)$.

Rotation of polarization plane after travelling from point 1 to point 2 is

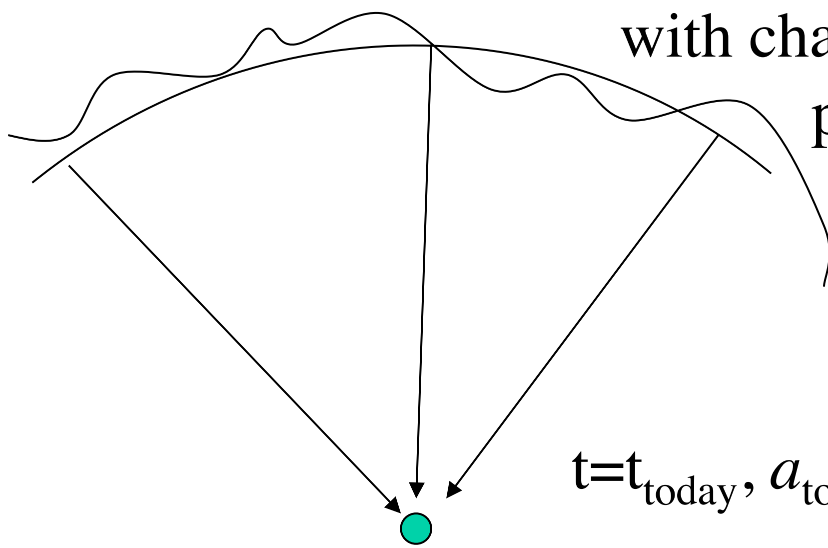
$$\psi = \frac{a_1 - a_2}{f_a}$$

$$\langle EE \rangle \to \langle BB \rangle; \qquad \langle TB \rangle = \langle EB \rangle = 0$$

The measure of the r.m.s. angular rotation is $\delta a \sim H_{infl}/(2\pi f_a)$ Log z

Propagation of CMB from the LSS

Surface of Last Scattering with chaotic pseudoscalar profile $t=t_{LSS}$, a_{LSS} *is given by inflation*.



$t=t_{today}$, $a_{today}=0$.

$$c_a = \left(\frac{H}{2\pi f_a}\right)^2, \quad |\Delta\psi| \sim \sqrt{c_a}.$$

Polarization of arriving to us CMB photons is randomly rotated by $\Delta\psi(n) = A_{LSS}(n) = a_{LSS}(n)/f_a$. Since $f_a > 10^{11}$ GeV is a mild constraint, $H \sim 10^{10}$ GeV or below can generate BB

Master formula for <BB> calculation

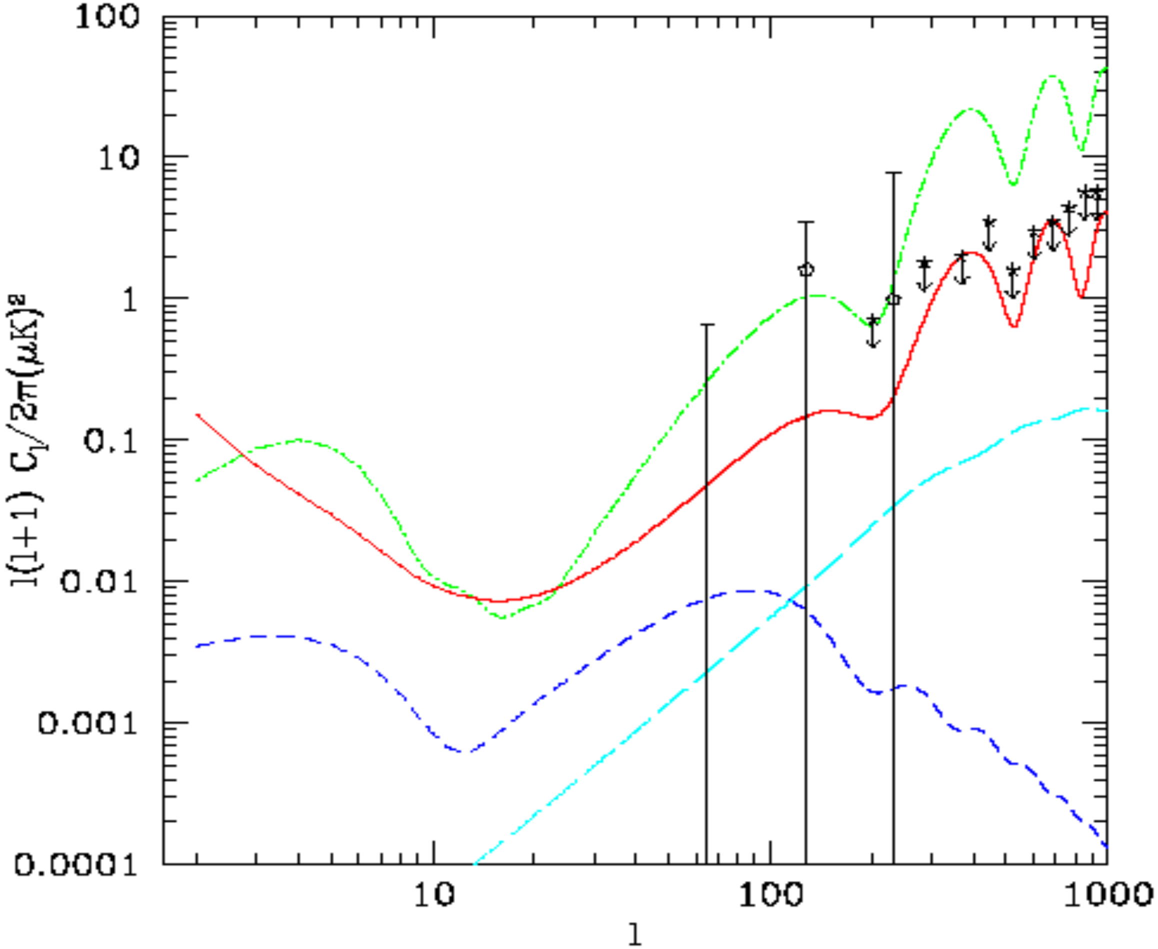
MP, Ritz, Skordis, 2008

$$
\begin{aligned}
C_{Bl} &= \frac{1}{2l+1}\sum_m \langle a^*_{Blm} a_{Blm}\rangle = \frac{4(4\pi)^3}{2l+1}\frac{(l-2)!}{(l+2)!} \\
&\times \sum_{m,l_1,l_2} (2l_1+1)(2l_2+1)\begin{pmatrix} l & l_1 & l_2 \\ 0 & 0 & 0 \end{pmatrix}^2 \\
&\times \int k^2 \underline{P_\Phi}\, q^2 \underline{\underline{P_A}}\, dk dq |\Delta_{l_1 l_2 m}(k,q)|^2,
\end{aligned}
$$

with the generalized transfer function,

$$
\begin{aligned}
\Delta_{l_1 l_2 m}(k,q) &= \frac{3}{4}\int_0^{\tau_0} d\tau g(\tau) j_{l_1}(x) j_{l_2}(y) \\
&\times \left(\frac{(l_1+2)!}{(l_1-2)!}\frac{1}{x^2} - m^2\right)\Delta_A(\tau,q)\Pi(\tau,k).
\end{aligned}
$$

Numerical Results and comparison with experiment



Points: upper limits from WMAP5 and QUaD

Green: EE; Red: BB with c_a =0.004; Dark blue: BB from gravity waves with r=0.14; light blue: BB lensing background .

If Bicep B-modes are confirmed as T-modes

Then an unbelievably strong constraints can be derived on the coupling of a massless axion to photons:

$\boldsymbol{f_a > 10^{15}}$ **GeV**

Compare it with direct lab bounds of $\sim 10^{10}$ GeV

Or ….

If $l < 100$ excess is coming from the foregrounds, then massless pseudoscalars could provide an alternative explanation to Bicep results.

Conclusions

Universe is an "active detector"!

It works according to A.P. Chekhov's principle:

> "*If you say in the first chapter that there is a rifle hanging on the wall, in the second or third chapter it absolutely must go off. If it's not going to be fired, it shouldn't be hanging there.*"

On three examples considered today I "hang the gun on the wall" (MeV temperatures, or inflation), and in the subsequent act "they fired": leading to CMB distortion, altering BBN reaction chains, and creating the B-mode pattern of polarization.

Several terrestrial experimental categories (precision magnetometry, precision gravimeters, and direct detection experiments discussed today) are capable of accessing very weakly coupled fields.