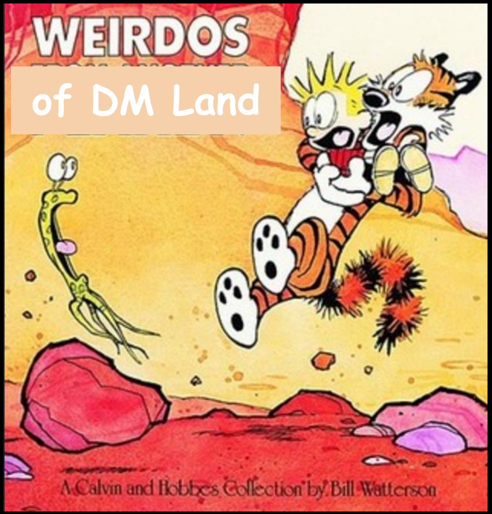
Exploring Weirdo Regions of WISPy Dark Matter (and other things)

(veeeery)
Weakly Interacting Sub-eV Particle



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J. Jaeckel[**]

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and The FUNK Collaboration

[**]Heidelberg U., [zz]MPP Munich, [z]CERN, [†]IPPP Durham, [*]DESY, [Y]MPIfR Bonn, [x]U. Zaragoza, [xx]Paris, [T]Imperial College London [tt]Warsaw INS, [s]U. of Adelaide

Standard

Axion Dark Matter

The axion has no clue where to start

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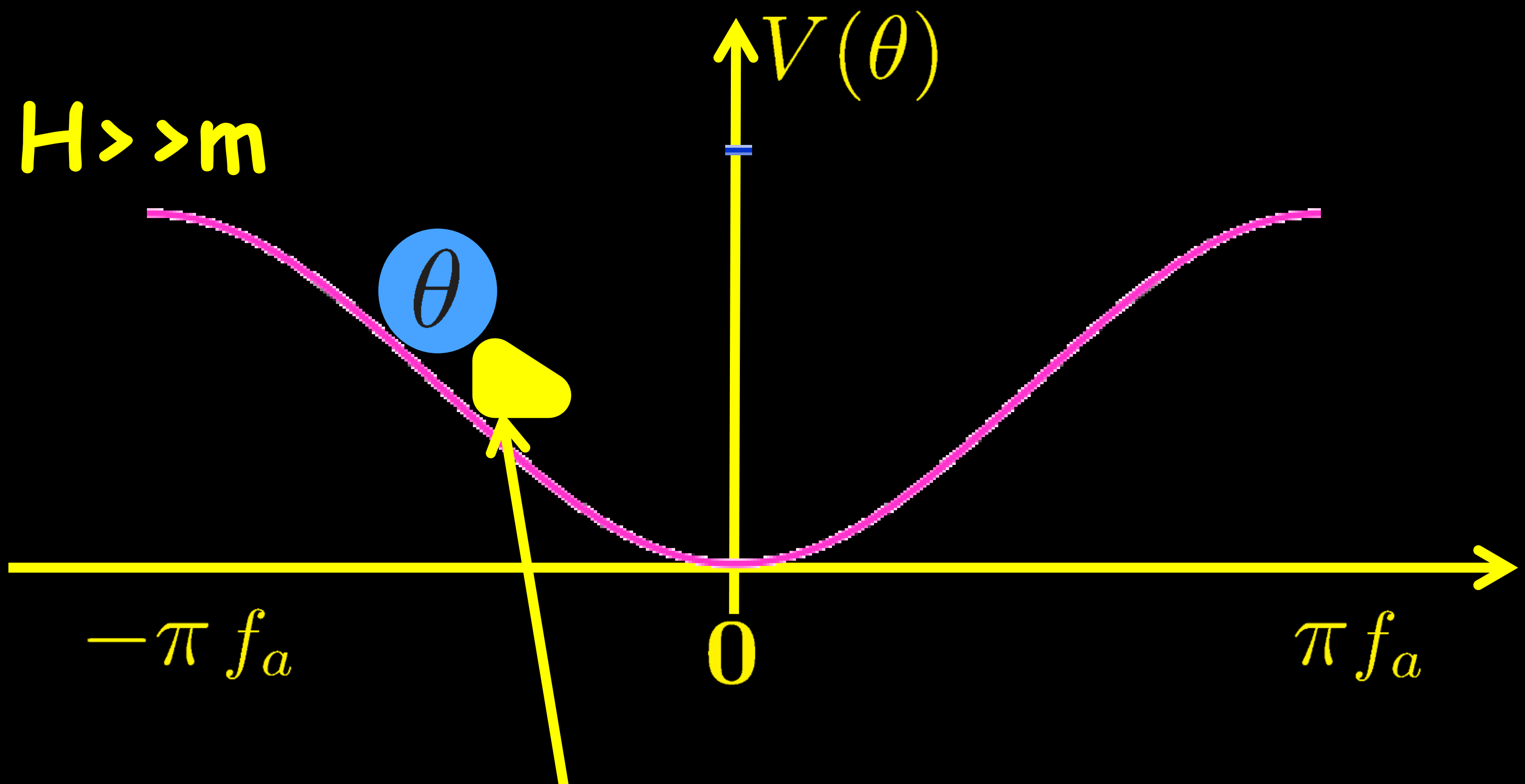
H>>m



Field is stuck because of Hubble "breaking"

The axion has no clue where to start

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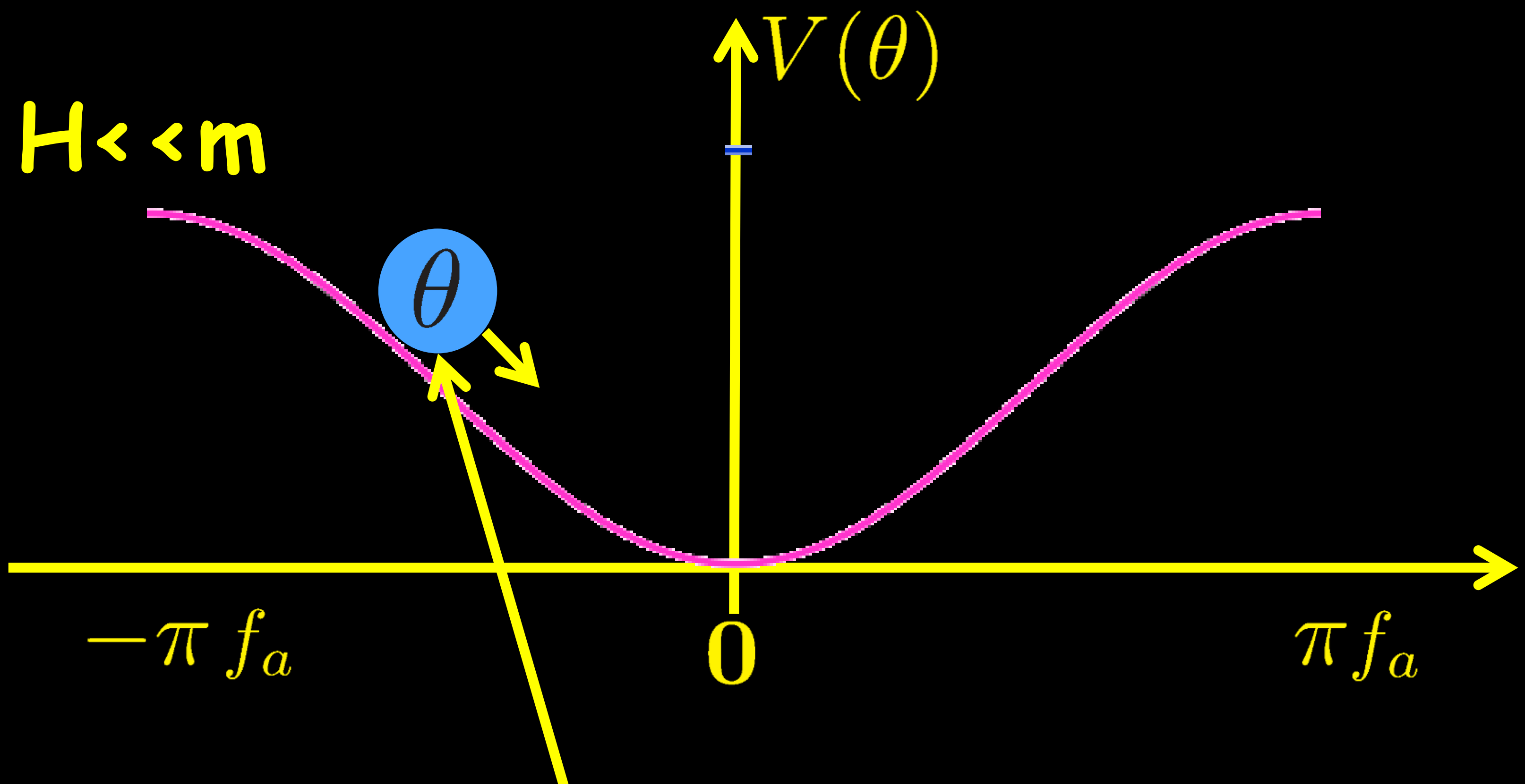
H<<m



Can start moving...

The axion solution to the strong CP problem

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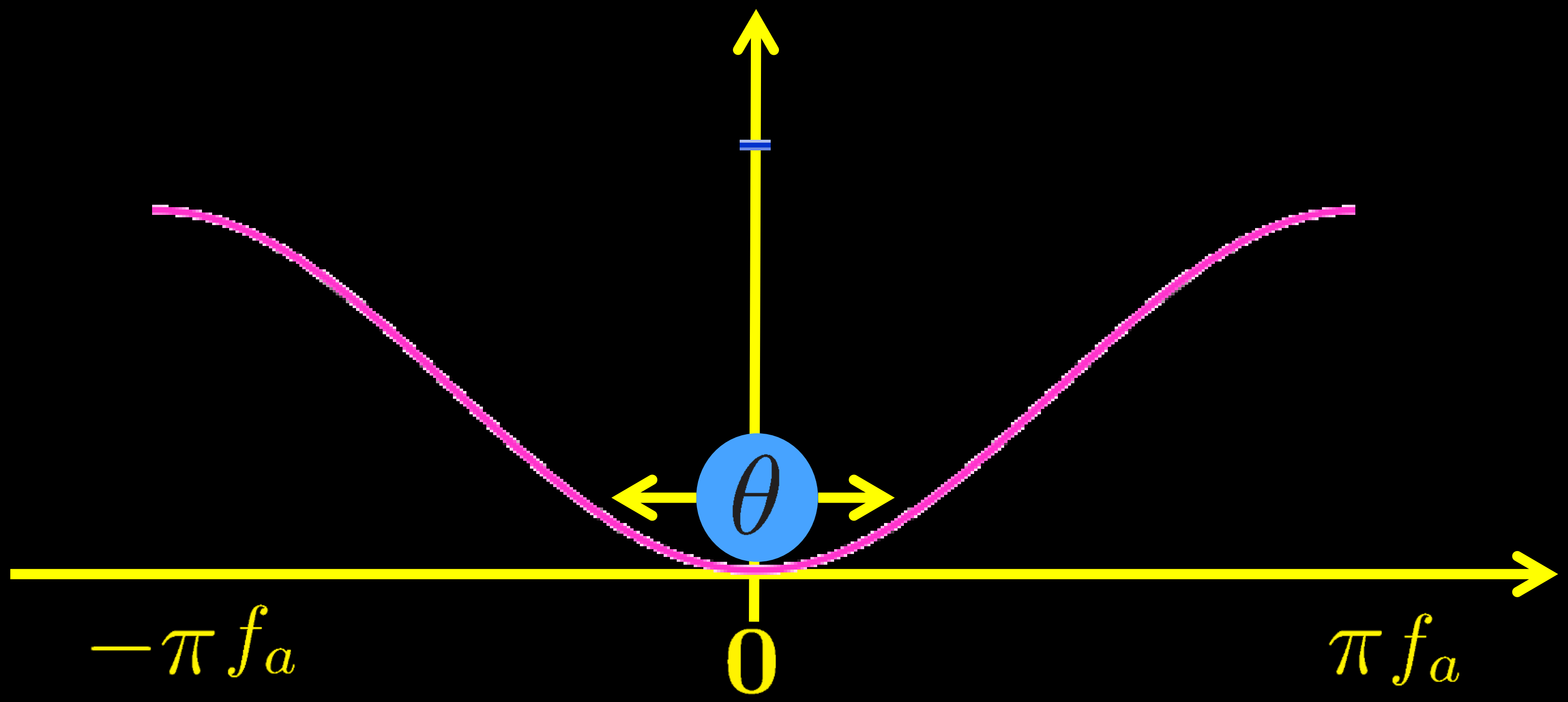

➔ Oscillations contain energy

➔ behave like non-relativistic particles (T=0)

Why Cold? Inflation!

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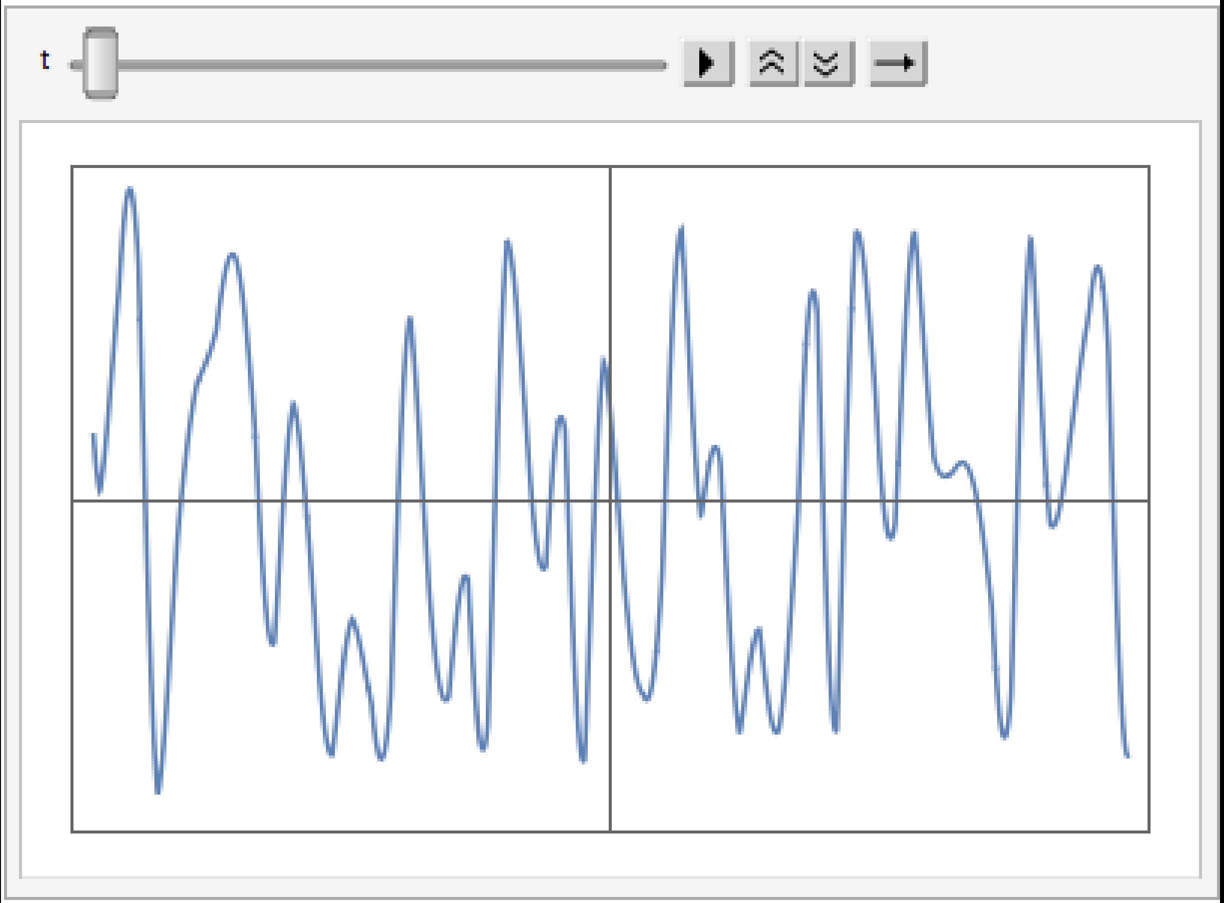
Field value



space

$$velocity \sim \frac{p}{m} \sim \frac{\hbar}{m}\frac{d}{dx} \to 0$$

Dark Matter Density

- Depends on the initial field value

$$\rho_{\phi,0} \simeq 0.17 \, \frac{\text{keV}}{\text{cm}^3} \times \sqrt{\frac{m_0}{\text{eV}}} \sqrt{\frac{m_0}{m_1}} \left(\frac{\phi_1}{10^{11}\,\text{GeV}} \right)^2 \mathcal{F}(T_1)$$

- Pseudo-Goldstone

➔ Field value $\phi_1 \leq \pi f_a$

Naturally $\phi_1 \sim \pi f_a$

Axion(-like particle) Dark Matter

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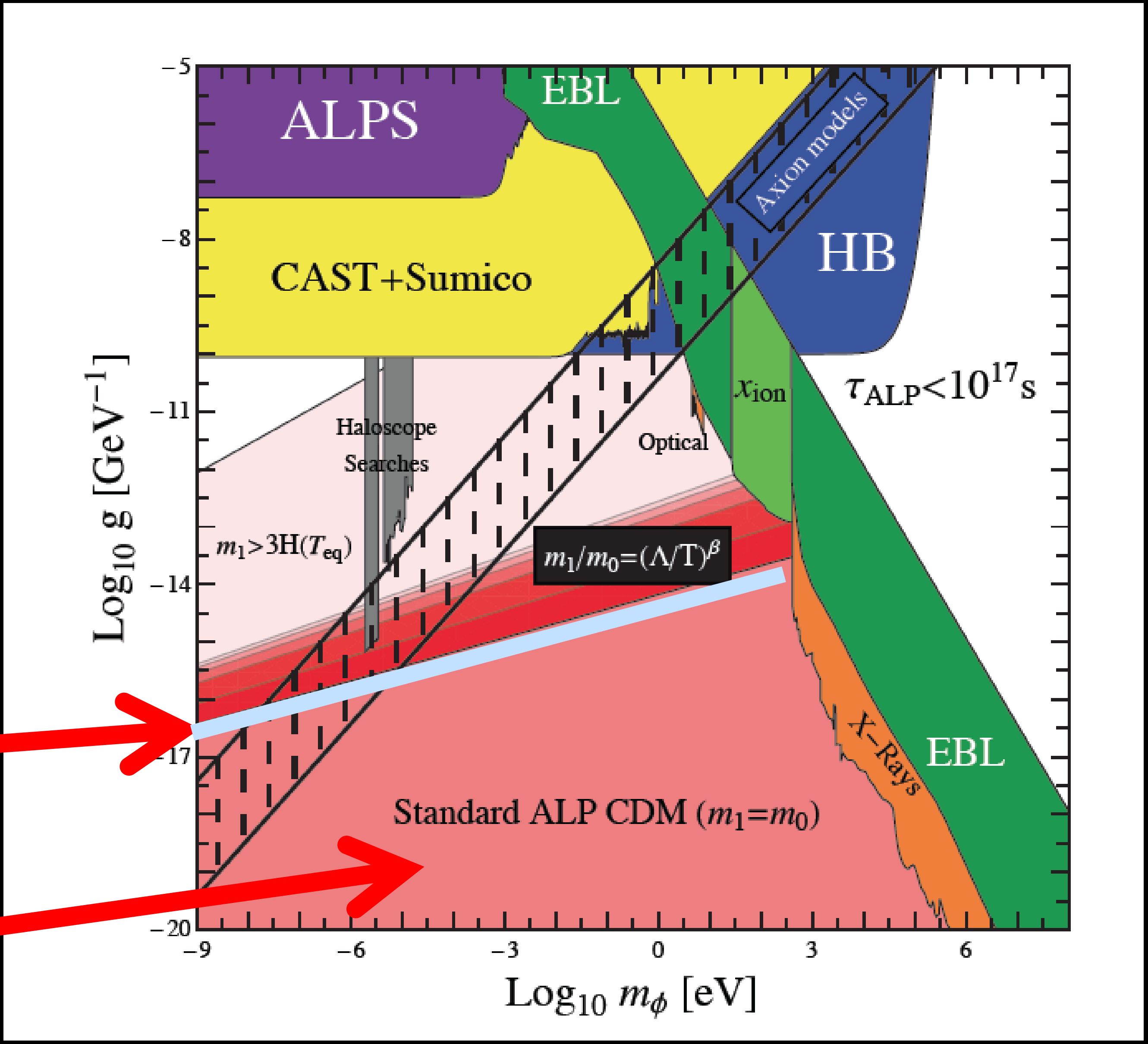
$$\mathcal{L} \supset \frac{1}{4} g_{a\gamma\gamma} F^{\mu} \tilde{F}_{\mu\nu}$$

$$g_{a\gamma\gamma} \sim \frac{\alpha}{4\pi f_a}$$



Natural

Possible

Axion Dark Matter

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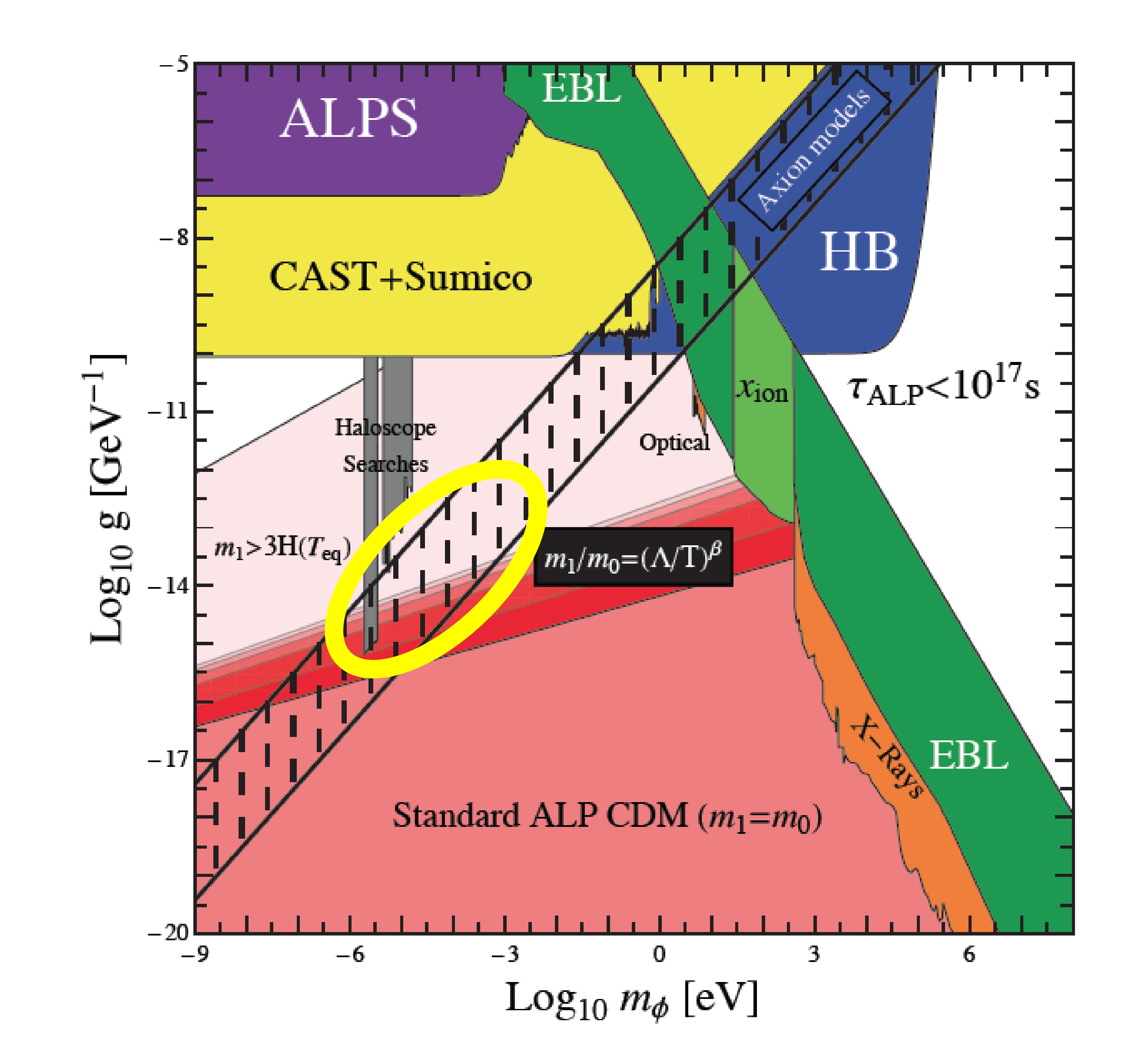
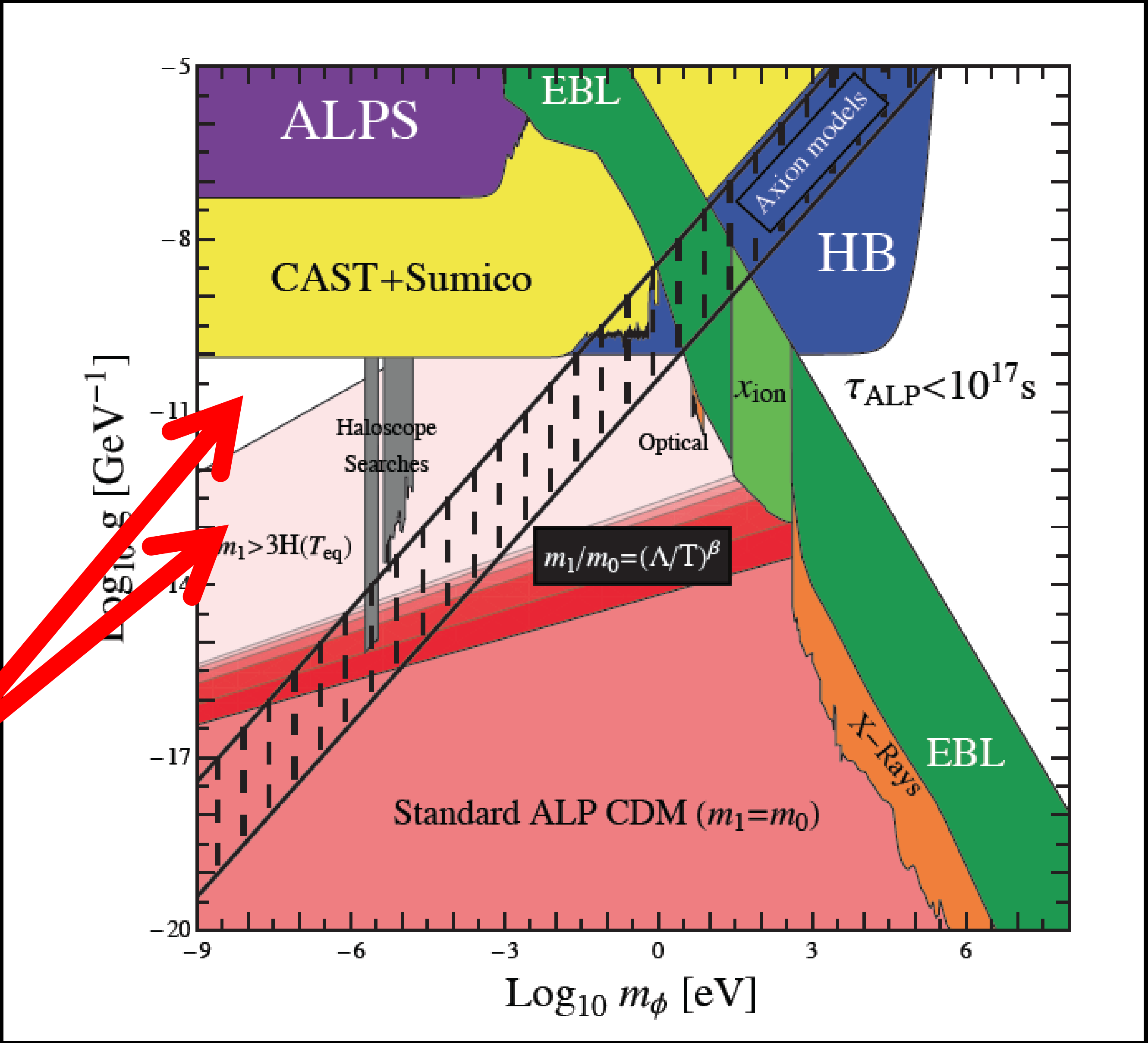


Axion(-like particle) Dark Matter



Want to get here!

Detecting WISPy DM

Use a plentiful source of axions

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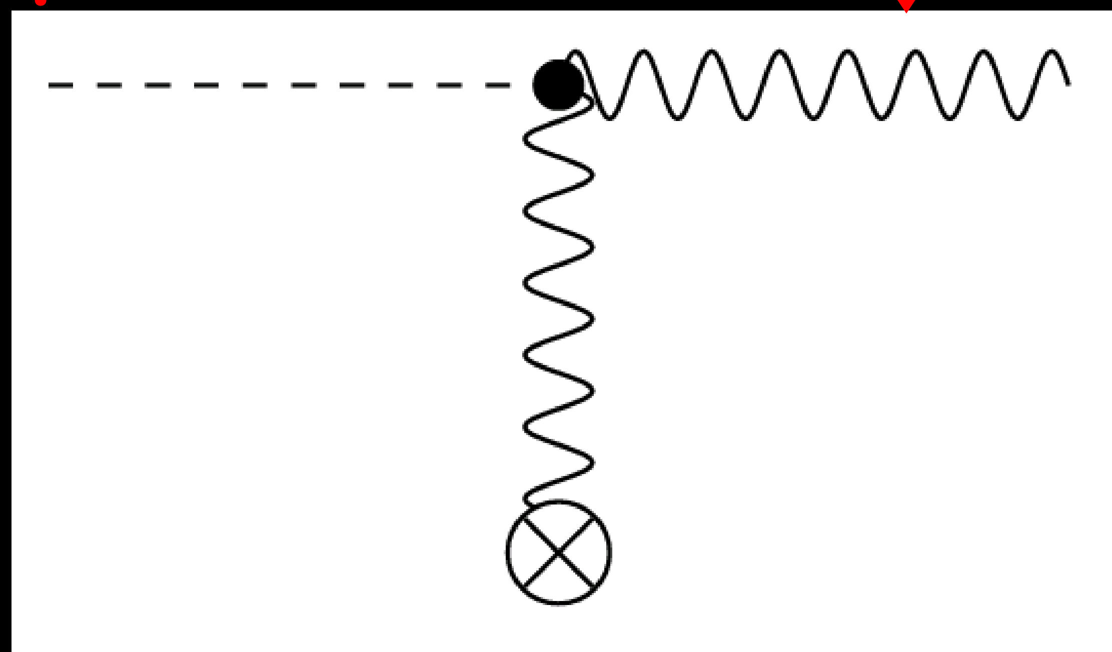
- Photon Regeneration

Photon
(amplified in resonator)

axion
(dark matter)



Signal: Total energy of axion

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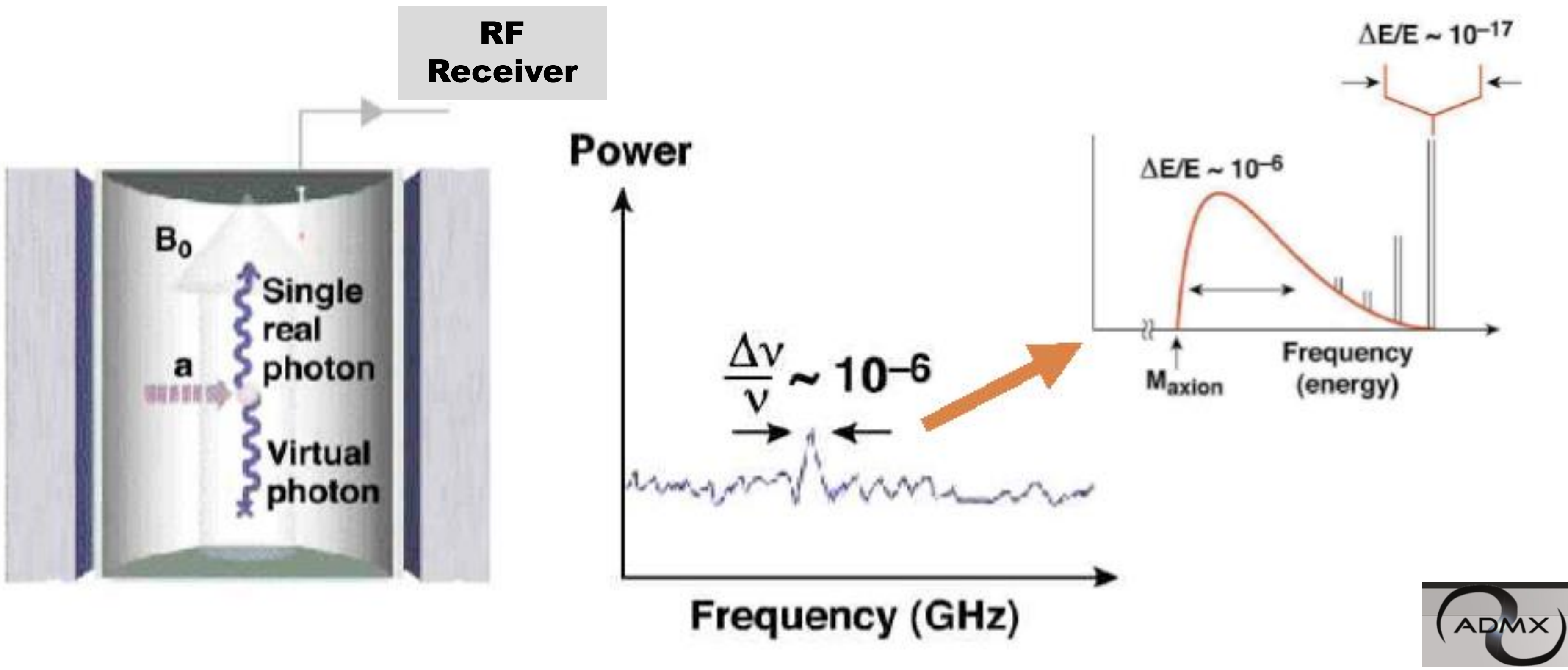
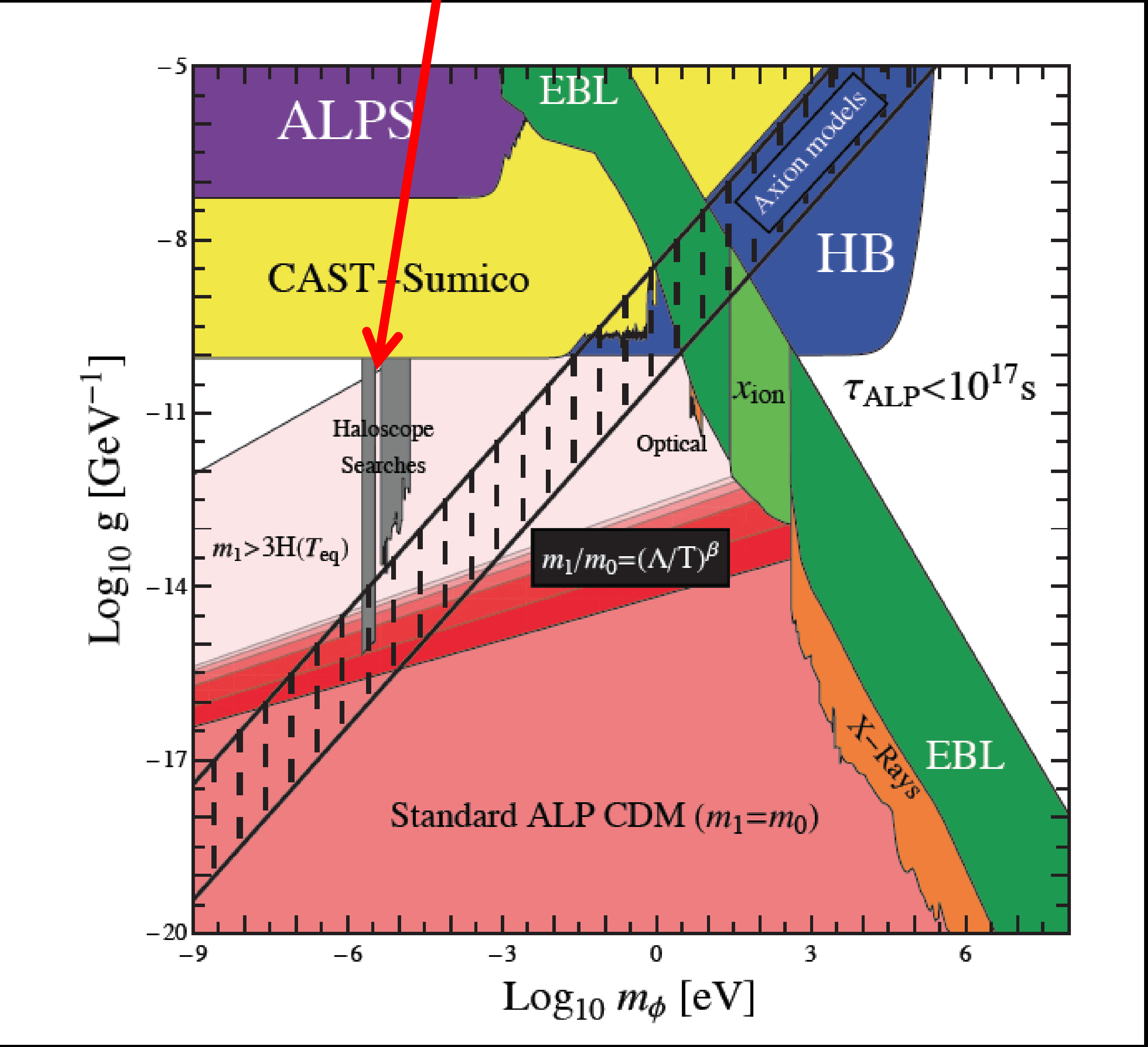


$$h\nu = m_a c^2[1 + \mathcal{O}(\beta^2 \sim 10^{-6})]$$

Virial velocity in galaxy halo!

An extremely sensitive probe!!!



A discovery possible any minute!

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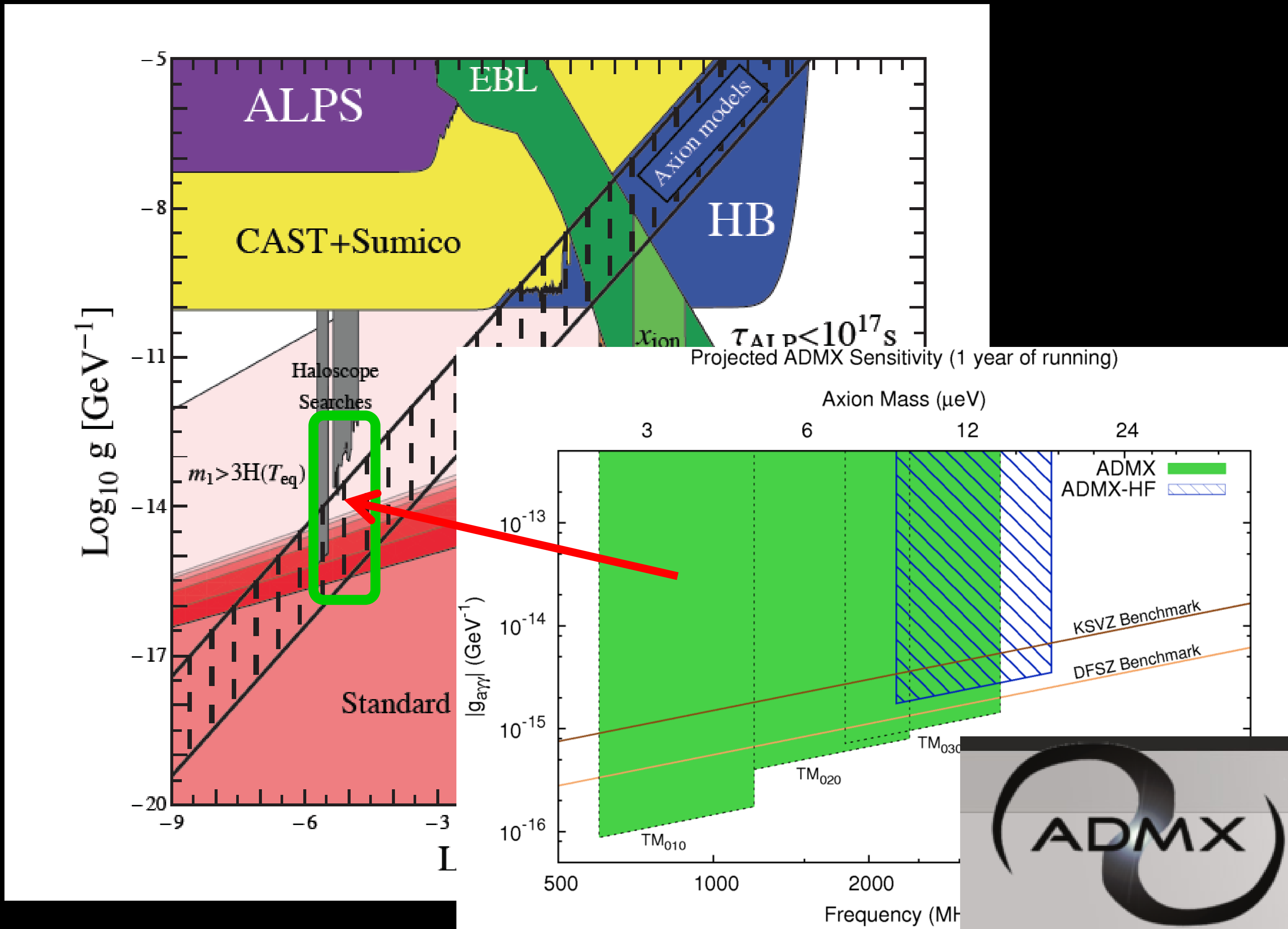

Electricity from Dark Matter ;-).

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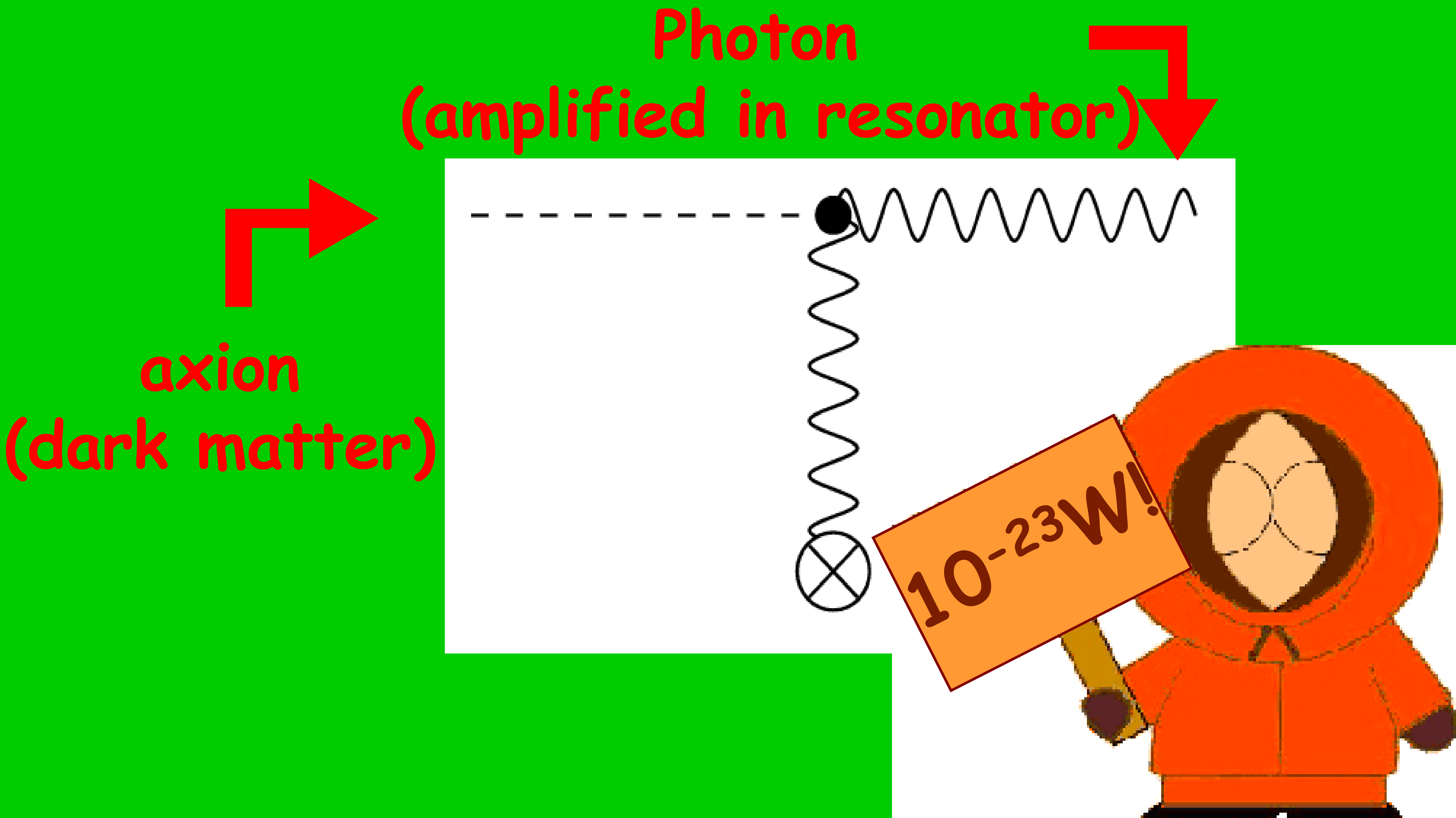
- Photon Regeneration



Really sustainable Energy

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- Galaxy contains (6-30)x10^{11} solar masses of DM

  → (3-15)x10^{43} TWh

@100000 TWh per year (total world today)

  → 10^{38} years ☺

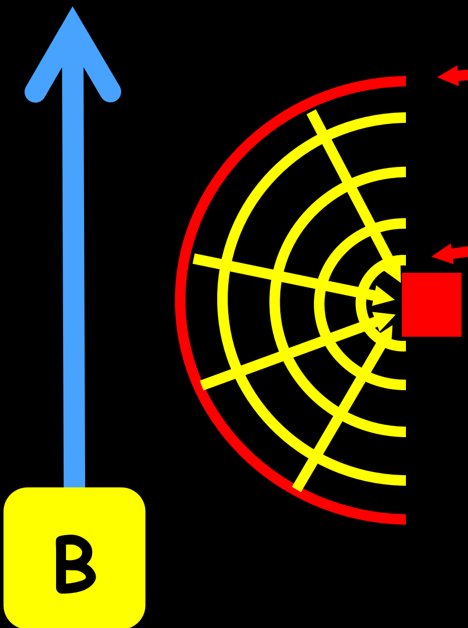
DM power

½*v~300 MeV/cm^3*300km/s~10 W/m^2

compared to 2W/m^2 for wind

Broadband Search Strategy

Dark Matter Antenna

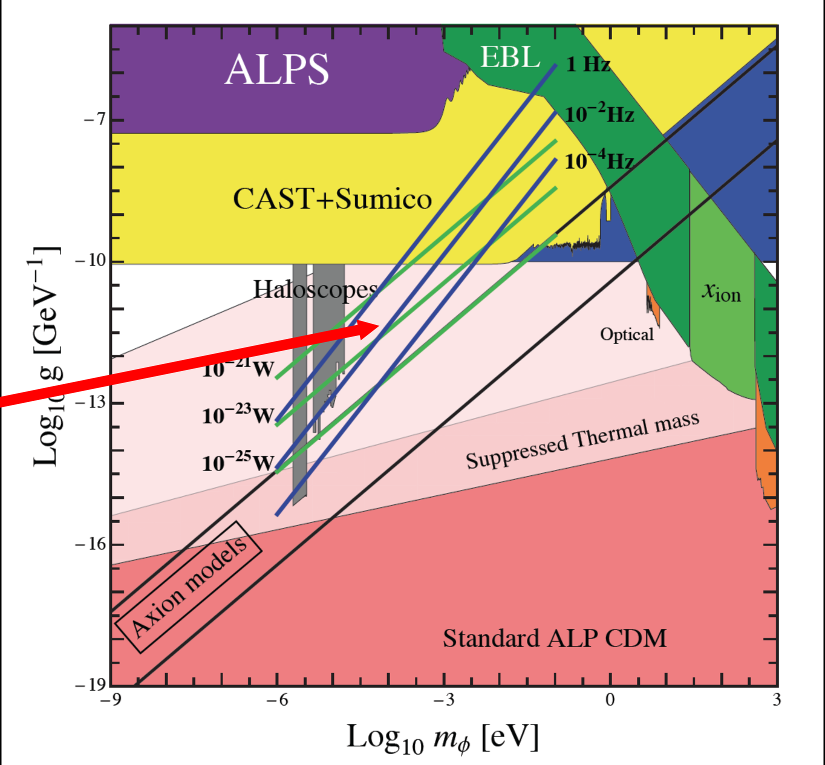


Antenna converts axion->photon

Radiation concentrated in center

Detector

Probes here;
very sensitive!!



The FUNK Experiment

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Recycle Auger mirror

Detector

Dark Matter Antenna

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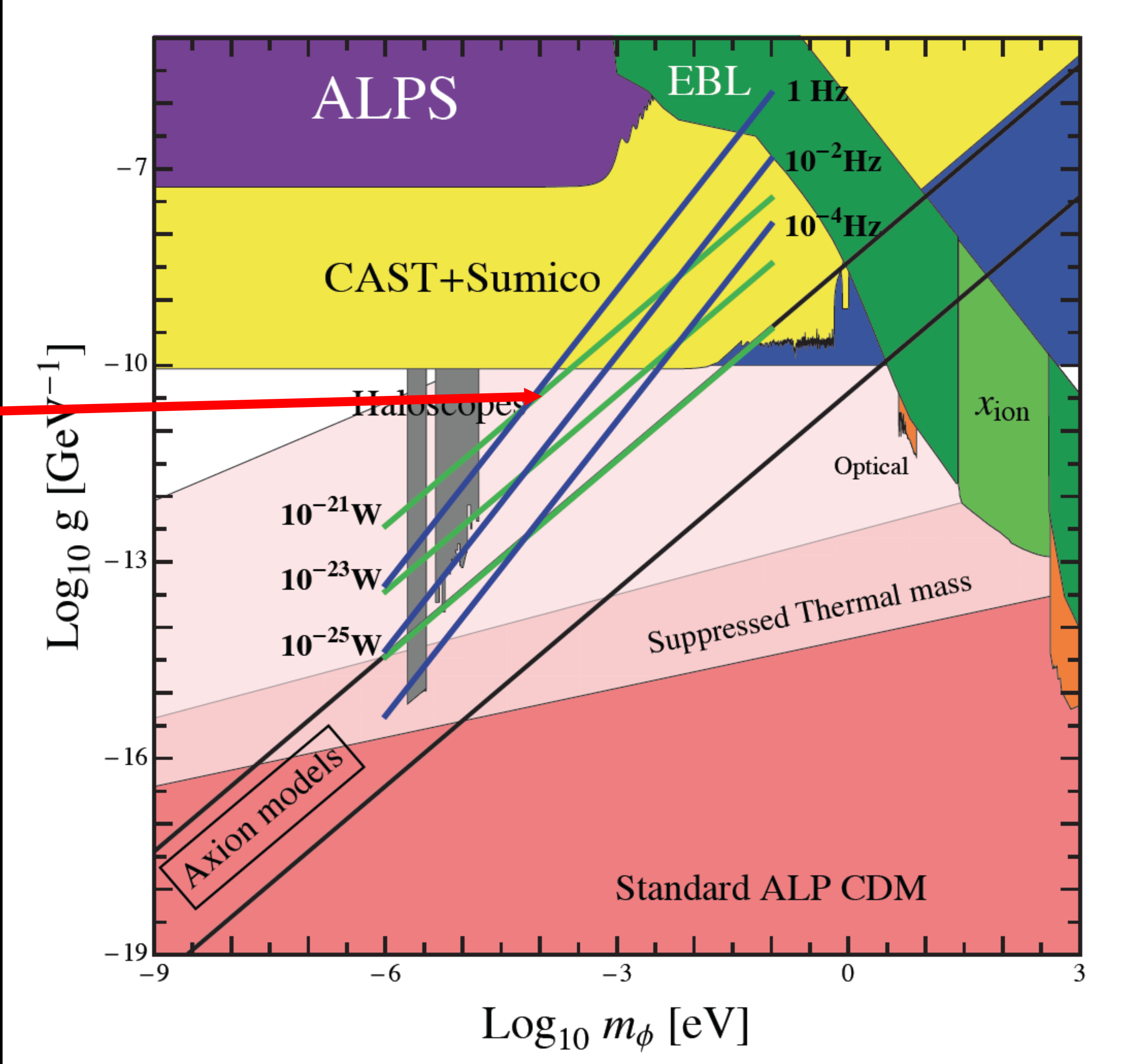
Difficult to have enough dark matter here



Perhaps even better: MadMax

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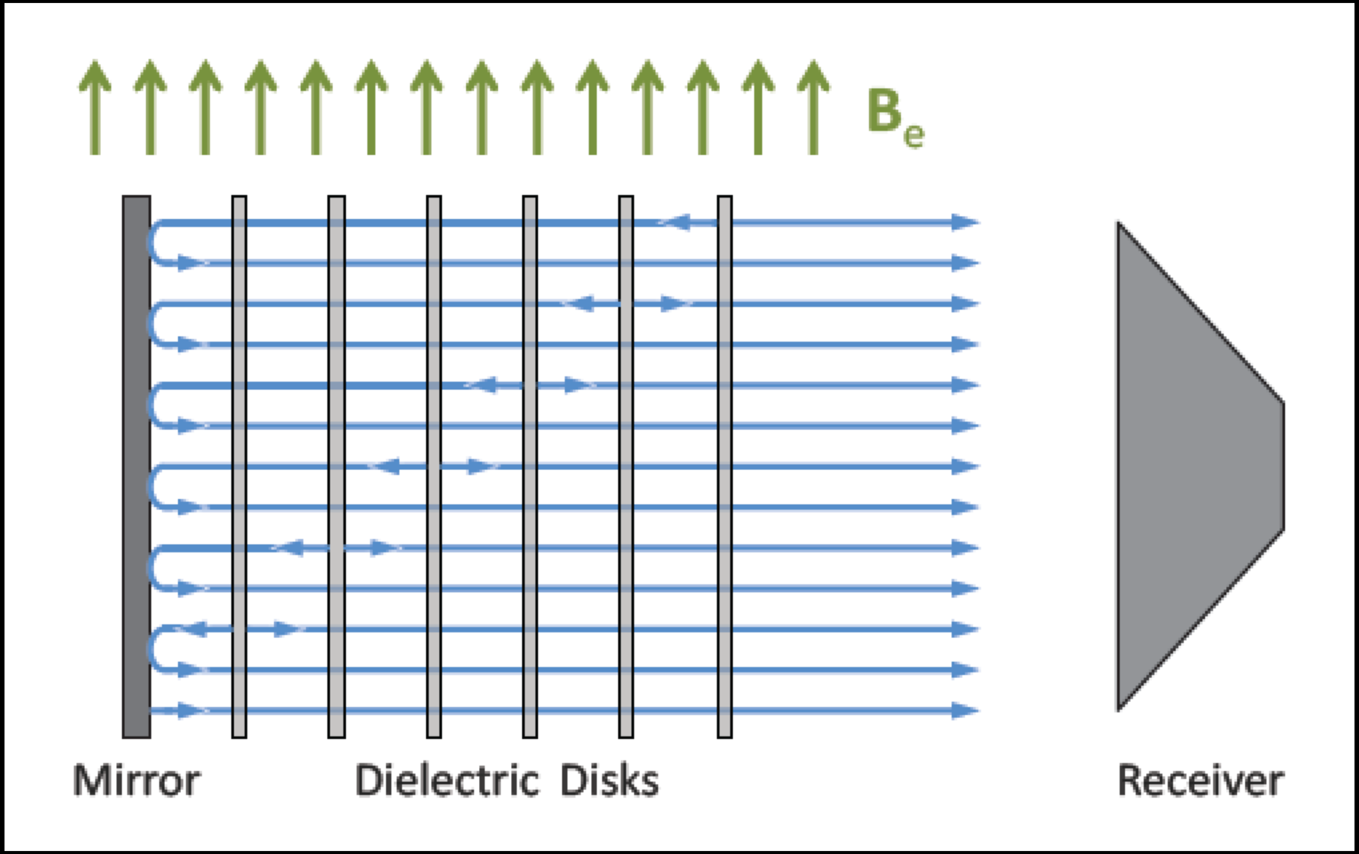
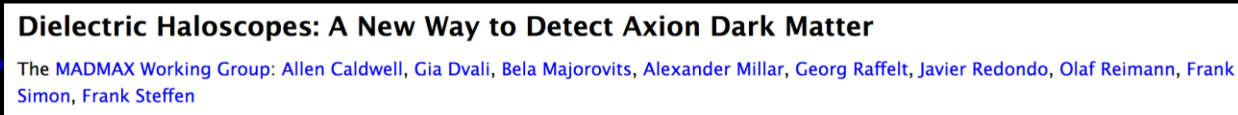
Ambitious new project at MPP



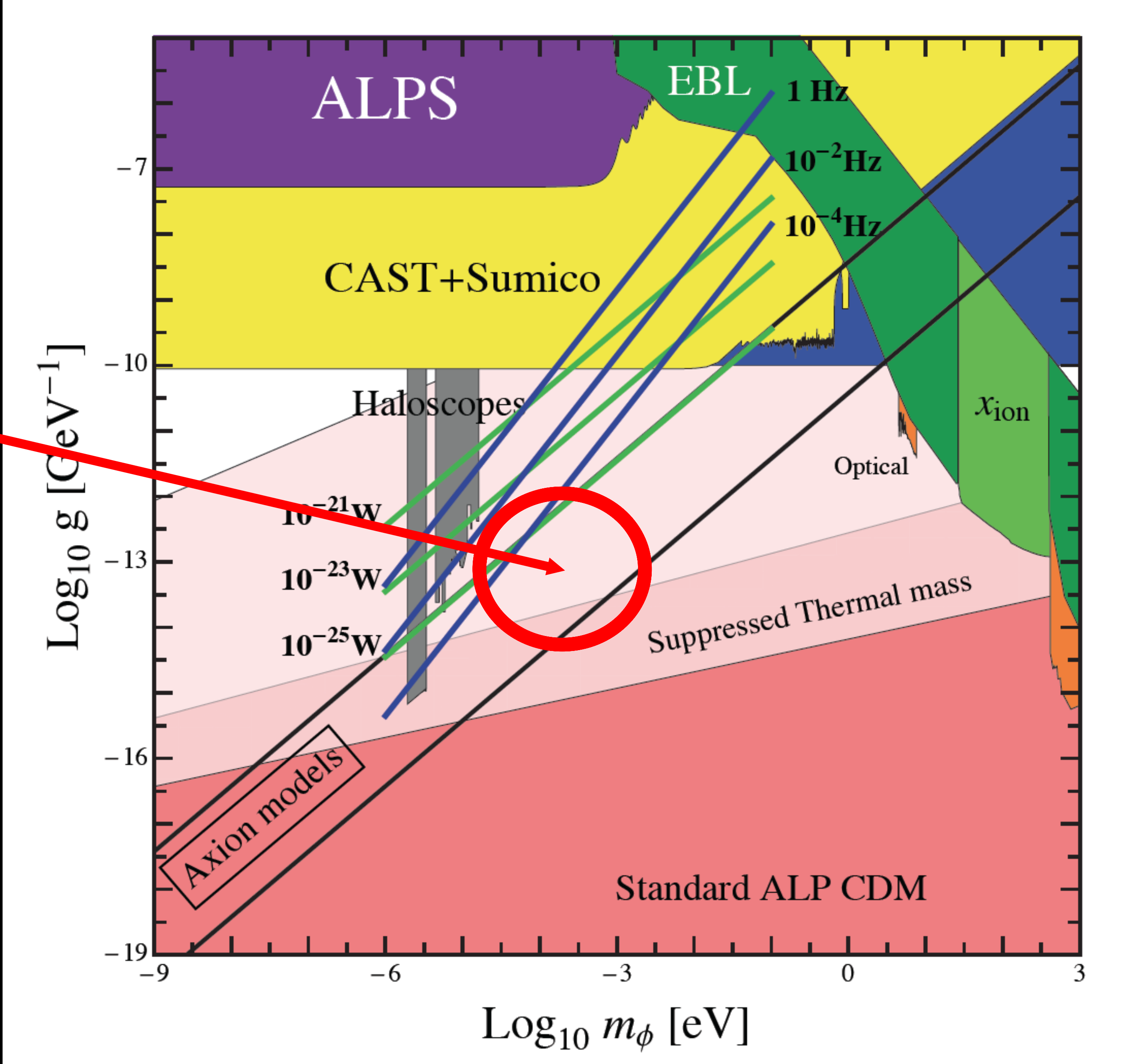

Dielectric Haloscopes: A New Way to Detect Axion Dark Matter

The MADMAX Working Group: Allen Caldwell, Gia Dvali, Bela Majorovits, Alexander Millar, Georg Raffelt, Javier Redondo, Olaf Reimann, Frank Simon, Frank Steffen

Dark Matter Antenna

MadMax
aims
to go here…

this is tough!!



New couplings: A spin experiment

J. Crespo Urrutia , S. Hansmann-Menzemer, S. Kempf , JJ , U. Schmidt

Looking for oscillating dipoles

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- Remember:
  Axion field controls electric dipole moment:

$$d_e \sim \theta \sim \frac{a}{f_a}$$

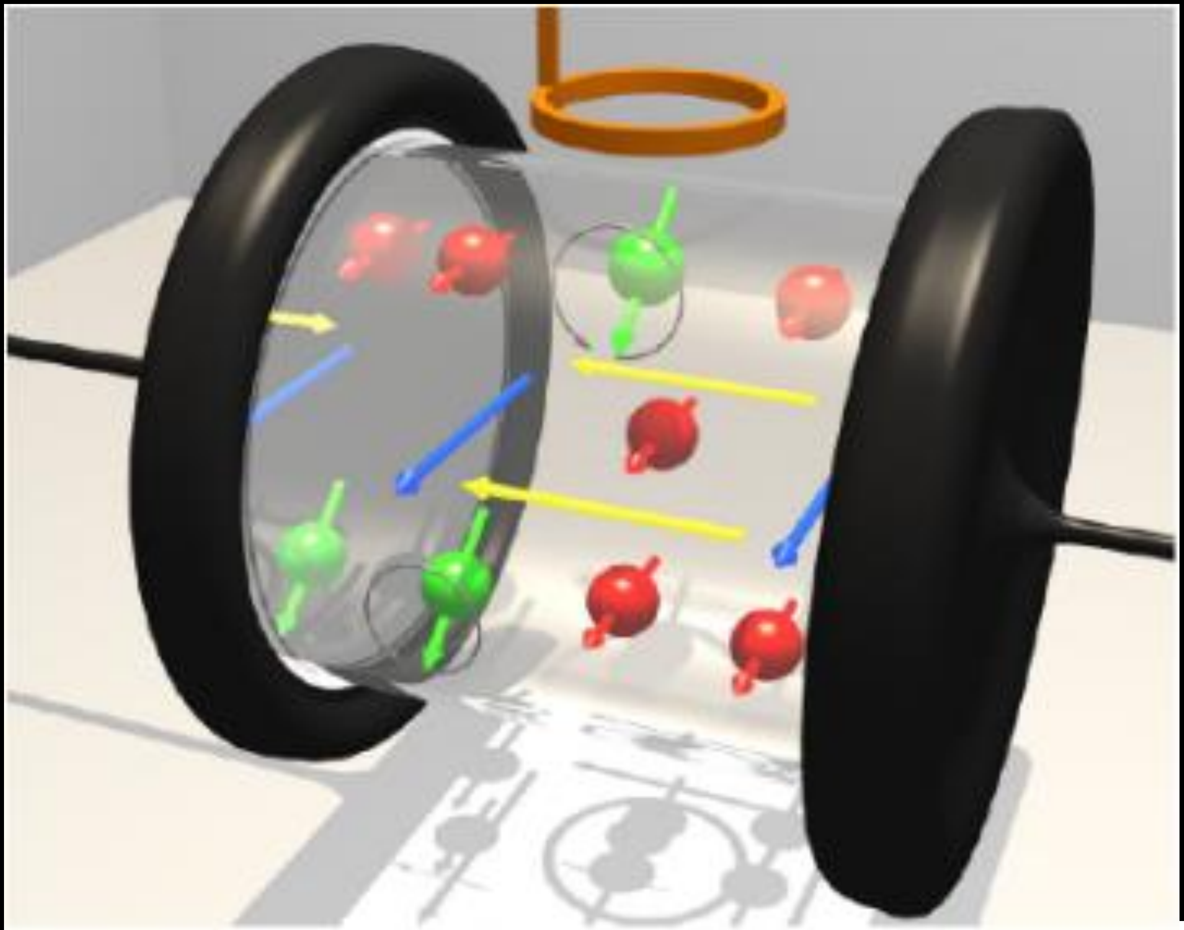
- Dipole moments follow the oscillating axion field
  → Tiny oscillating electric dipole

$$d_e \sim 10^{-35} e\,\mathrm{cm}\cos(m_a t)$$

New Observables for Direct Detection of Axion Dark Matter
Peter W. Graham, Surjeet Rajendran (Stanford U., ITP). Jun 25, 2013. 13 pp.
Published in **Phys.Rev. D88 (2013) 035023**
DOI: 10.1103/PhysRevD.88.035023
e-Print: arXiv:1306.6088 [hep-ph] | PDF

Modification of Xenon EDM

Modification of Xenon EDM experiment to be sensitive to time varying nuclear EDM



Proposal for a Cosmic Axion Spin Precession Experiment (CASPEr)

Dmitry Budker (UC, Berkeley & LBNL, NSD), Peter W. Graham (Stanford U., ITP), Micah Ledbetter (Unlisted, US, CA), Surjeet Rajendran (Stanford U., ITP), Alex Sushkov (Harvard U., Phys. Dept.).

Published in **Phys.Rev. X4 (2014) no.2, 021030**
DOI: 10.1103/PhysRevX.4.021030
e-Print: **arXiv:1306.6089 [hep-ph]** | PDF

Sensitivity

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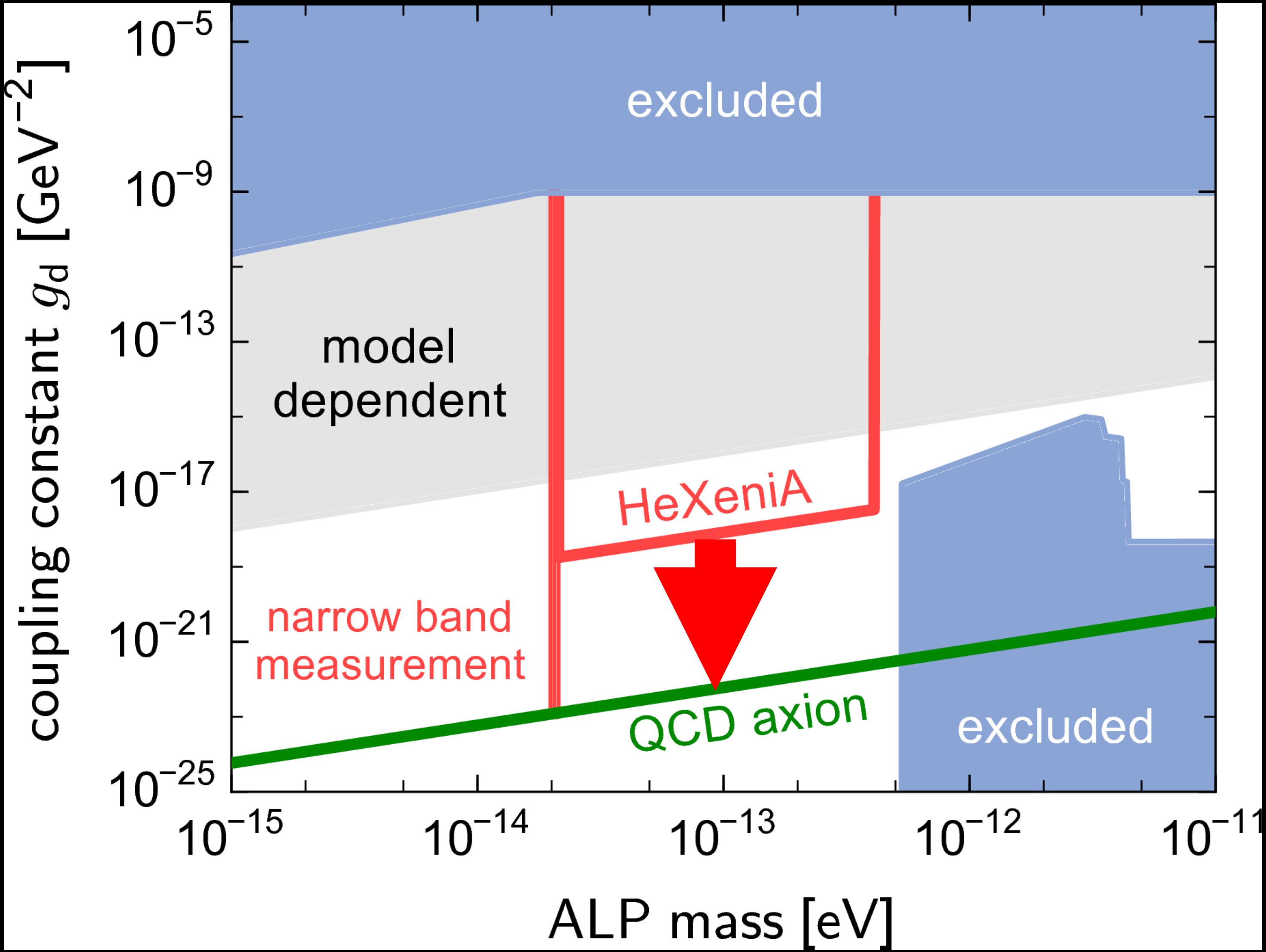

f_a in Plancky region $4*Pi*M_{Pl} \sim M_{Pl}$

Stranger things...

Going Monodromic

1605.01367

JJ, V. Mehta, L.Witkowski

Monodromy potential

$$V(\phi) = \qquad\qquad \Lambda^4 \cos\left(\frac{\phi}{f} + \gamma\right)$$

Monodromy add-on

"Axion" potential (pseudo-Goldstone pot.)

Monodromy potential

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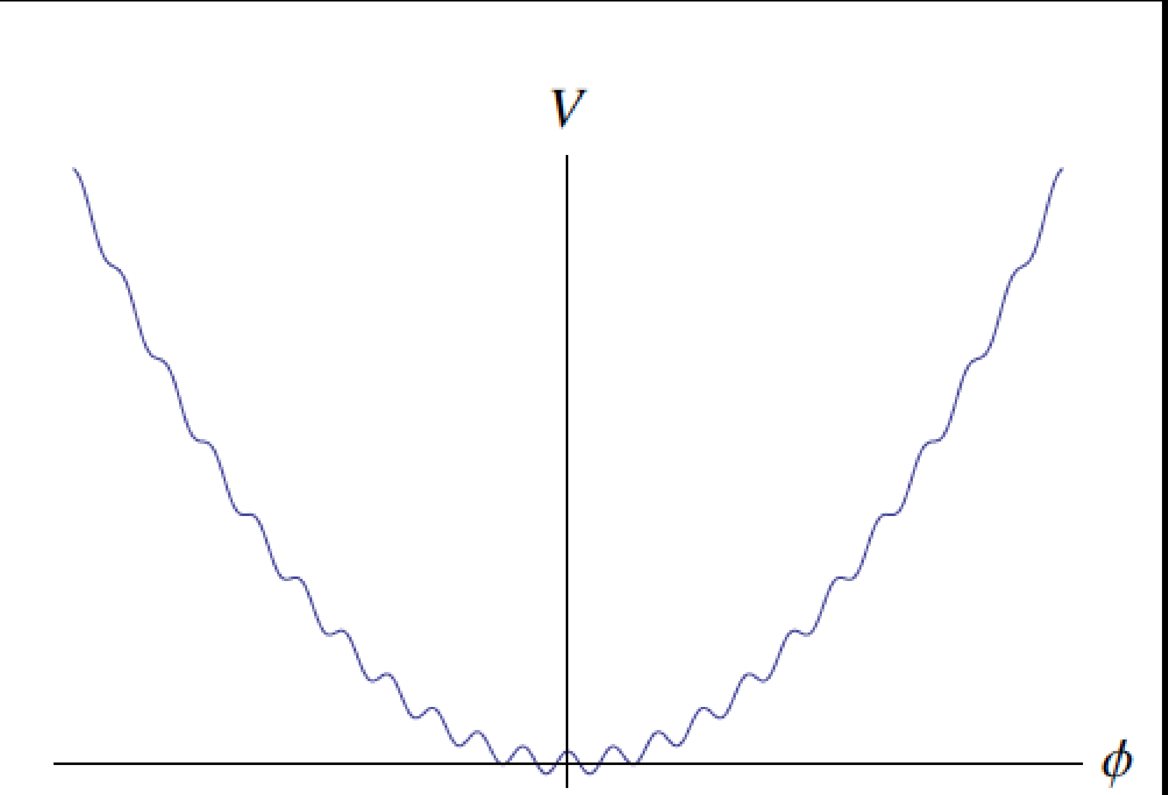
$$V(\phi) = \frac{1}{2}m^2\phi^2 + \Lambda^4 \cos\left(\frac{\phi}{f} + \gamma\right)$$

Funny potential

+ enlarged field range



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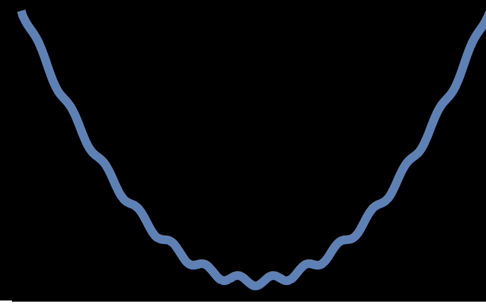
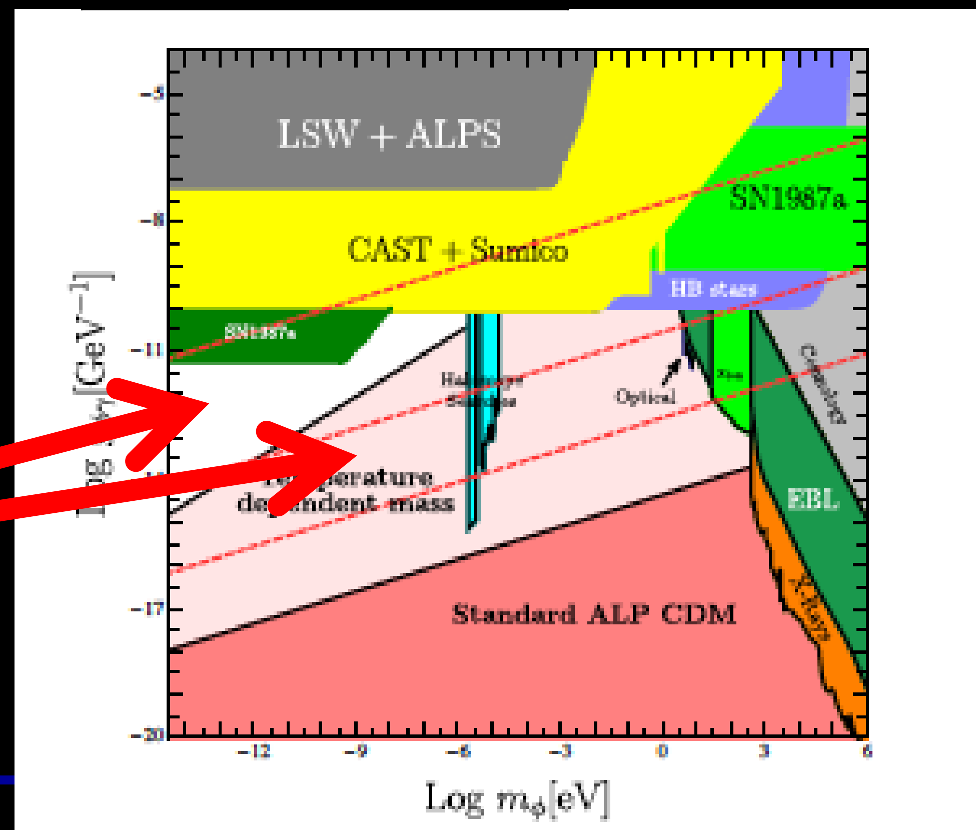
Advantages

- Allows to start with higher energy density
  → More DM

vs



Models
in this region!



Interesting Phenomena??

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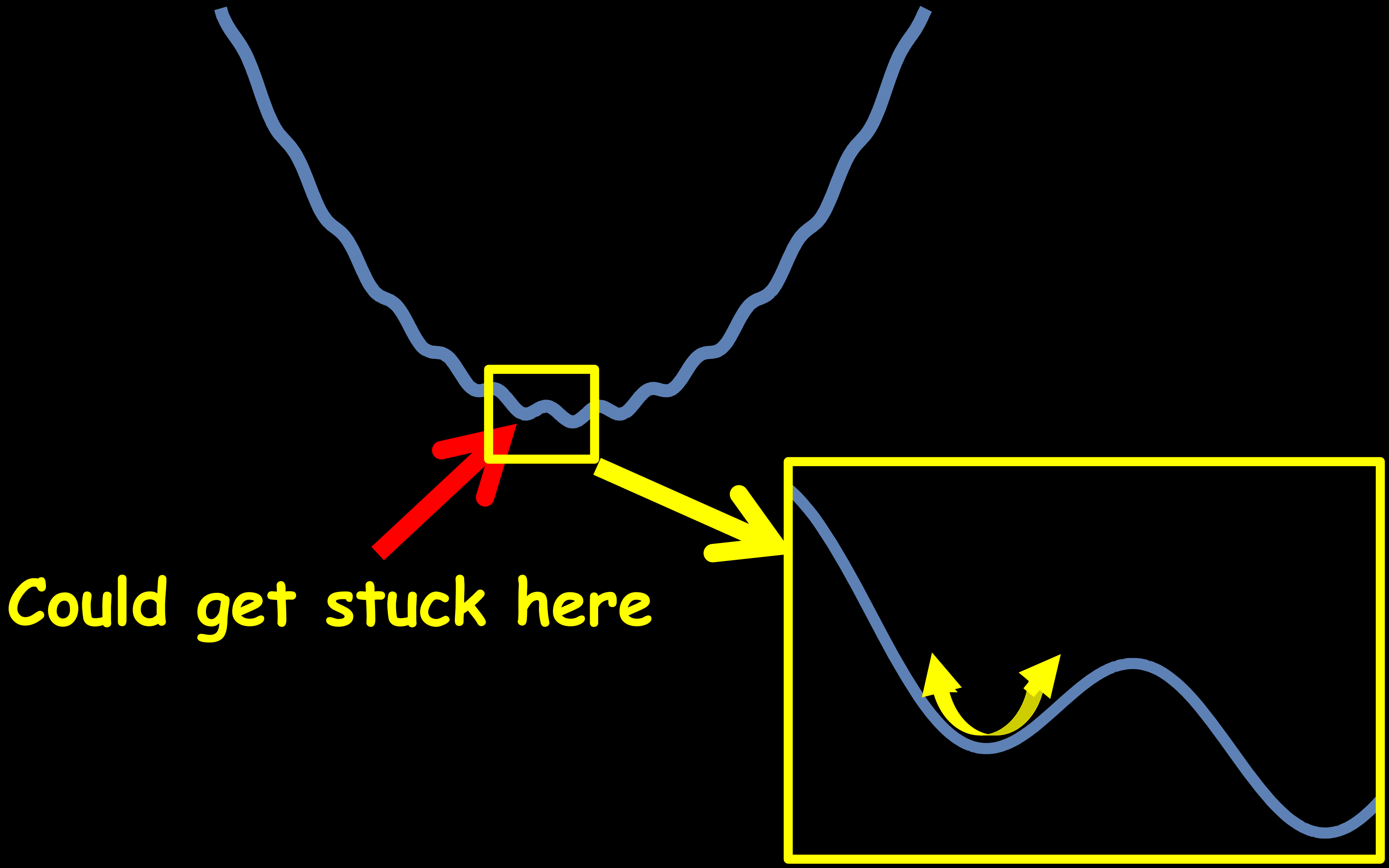

Oscillations like DM!

Interesting Phenomena??

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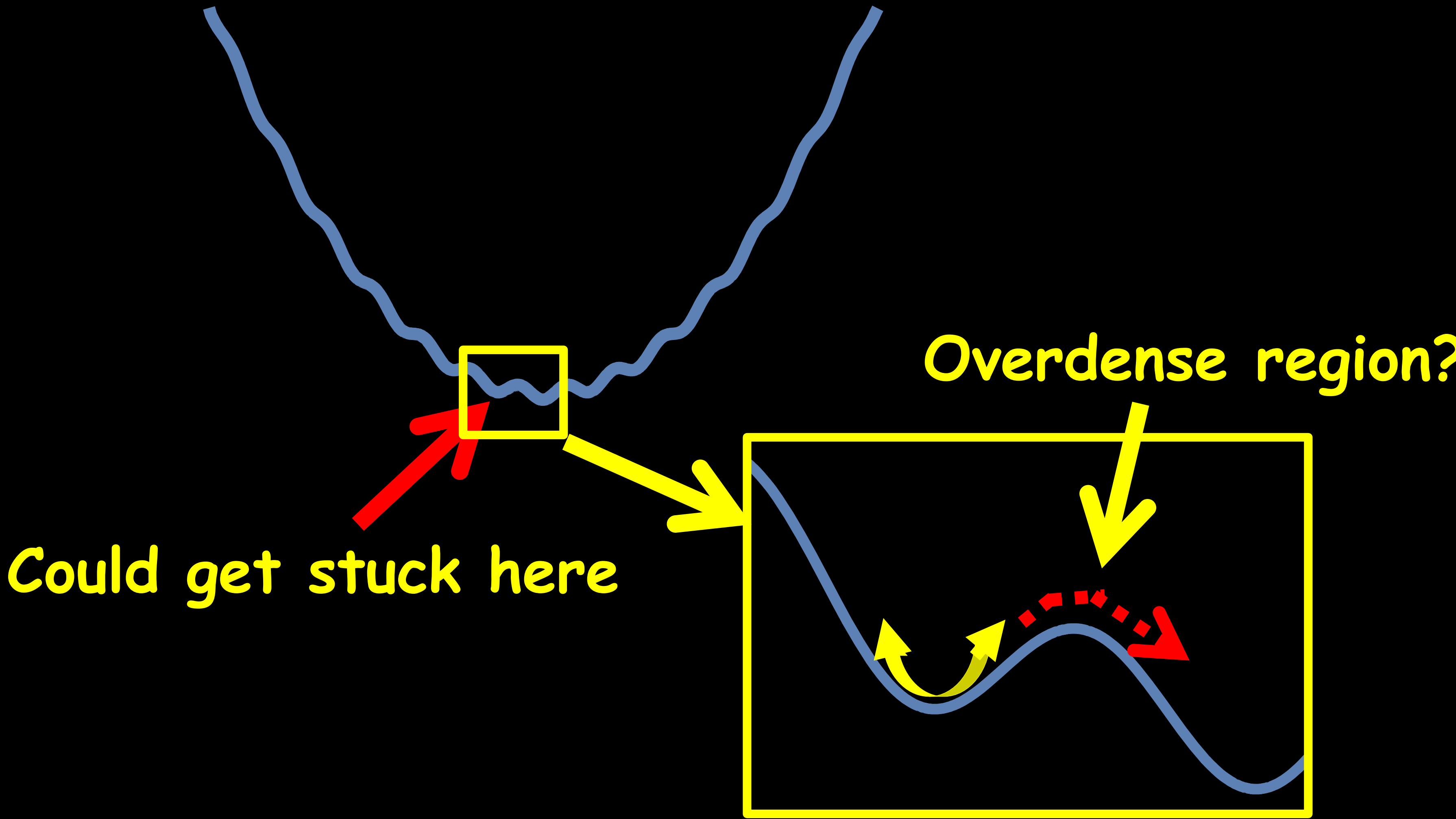

$$amplitude \sim \sqrt{DM density}$$

Side Remark:

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Tunneling from Oscillating State

Not always what you expect ;-).

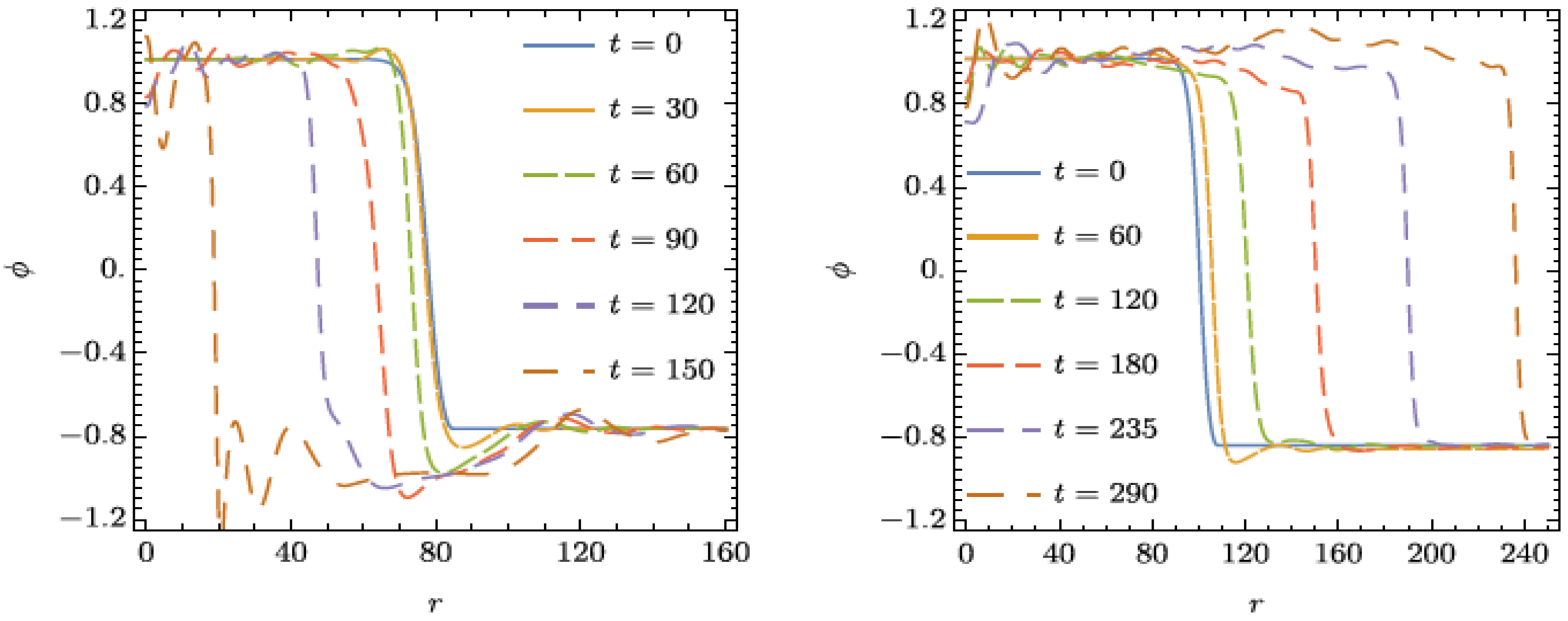

Figure 8: Field profiles showing lattice bubble evolution for oscillation reaching $1.2\sqrt{2\alpha_{\rm tw}}$ (left panel) and $0.8\sqrt{2\alpha_{\rm tw}}$ (right panel). The values defining the potential were set to $g = 1/10$, $b = 1/300$ and $c = 1$.

1704.06445 L. Darme, JJ, M. Lewicki

Interesting Phenomena??

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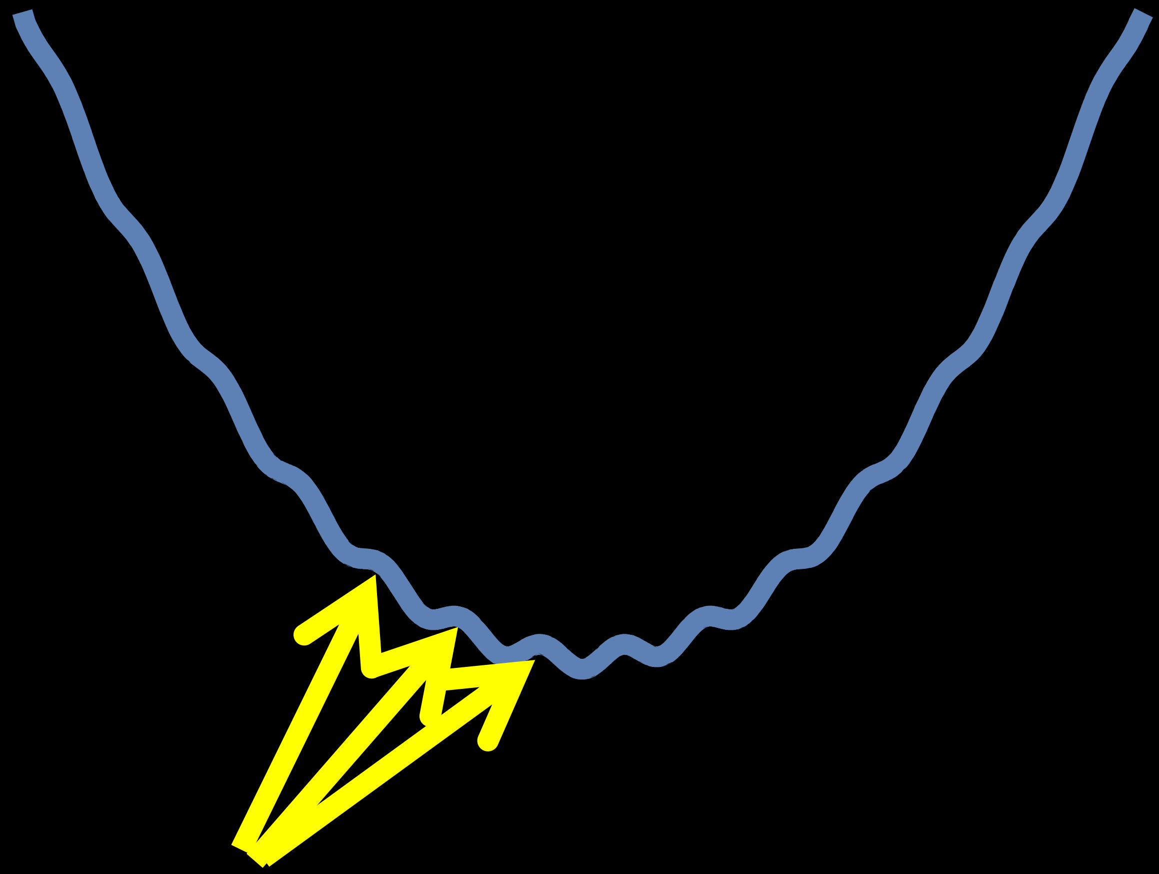

Regions with "negative mass"

Instability + Parametric Resonance
→ Particle Production with p≠0?!?

Fluctuations may grow rapidly

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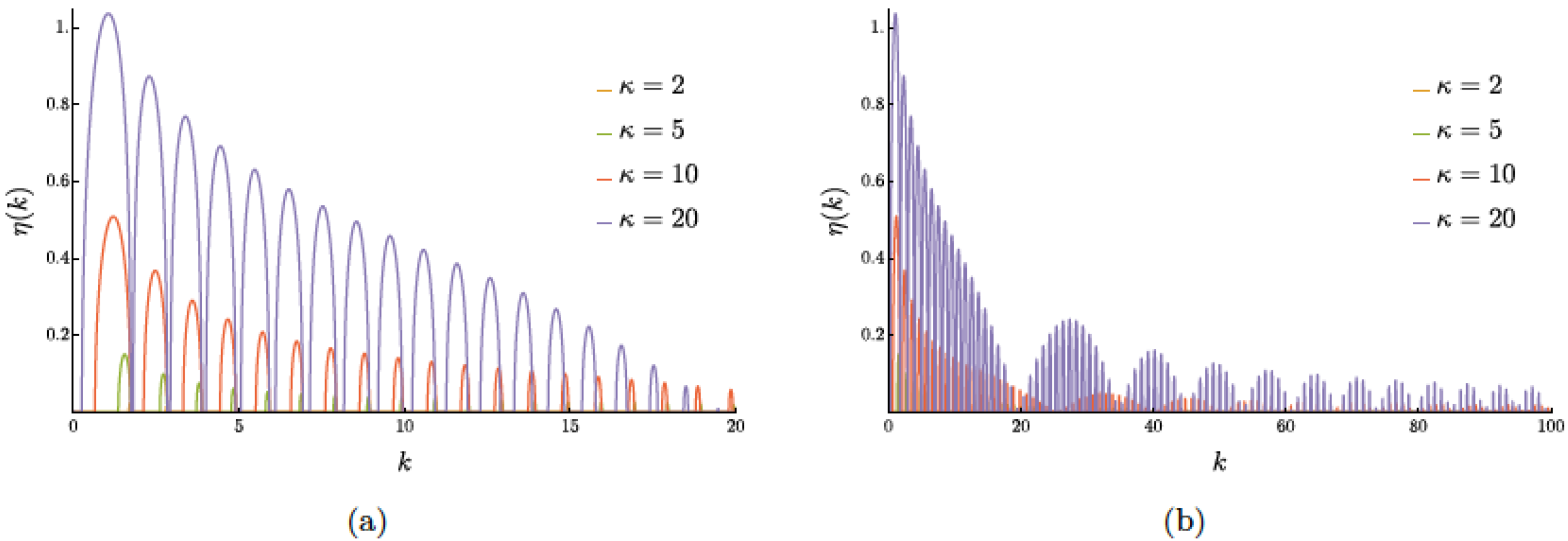

Figure 8: Combination of the plots $\eta(k)$ vs. k for $\frac{\varphi_{\text{initial}}}{2\pi} = 100$ and $\kappa = 2.0, 5.0, 10, 20$.

➔ **New initial conditions for structure formation!**

Going Beyond Dark Matter

Exploring inflationary "axions" with gravitational waves

1606.07812

A. Hebecker, JJ, F. Rompineve, L.Witkowski

Monodromy inflation

$$V(\phi) = \frac{1}{2}m^2\phi^2 + \Lambda^4 \cos\left(\frac{\phi}{f} + \gamma\right)$$

Field oscillations

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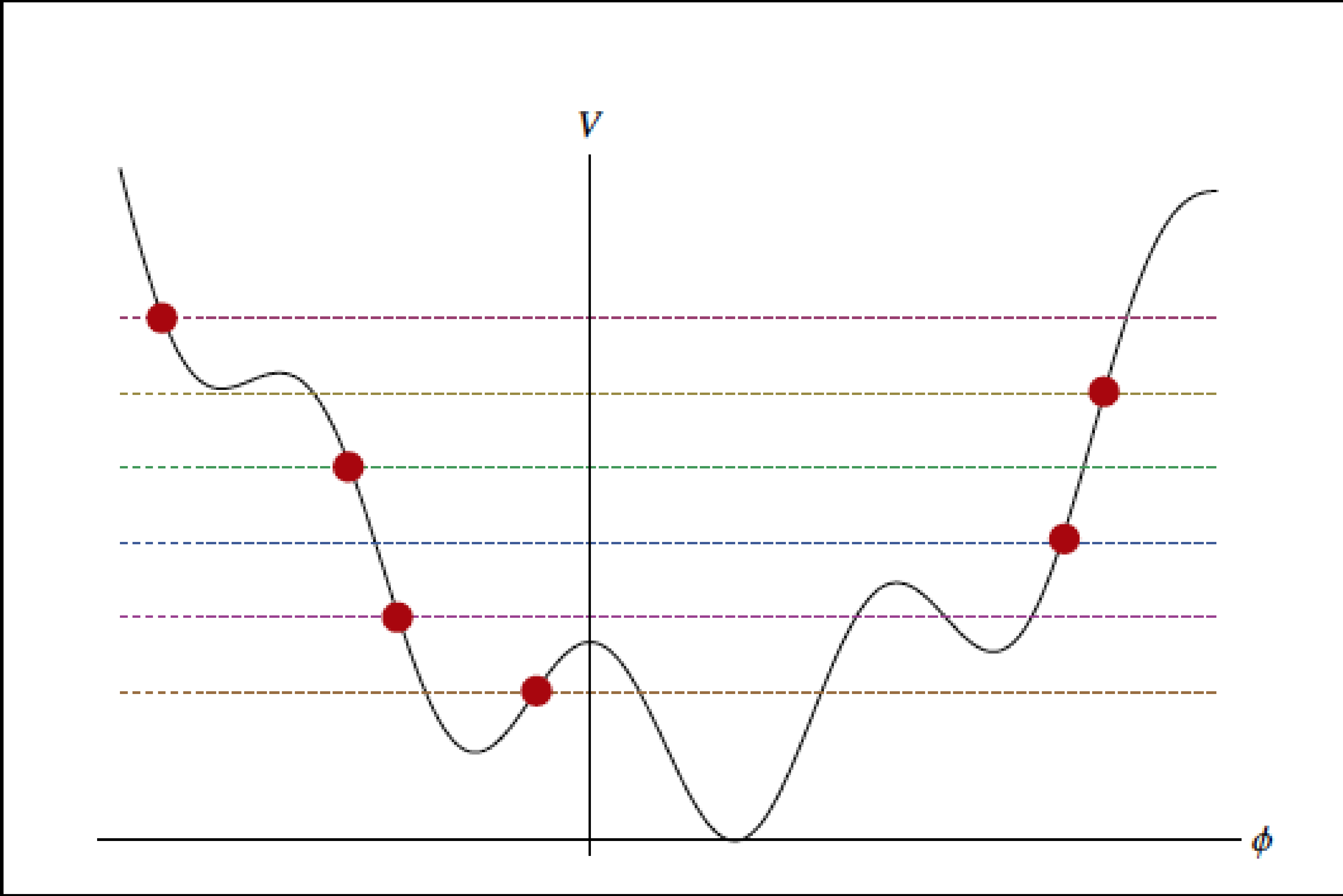
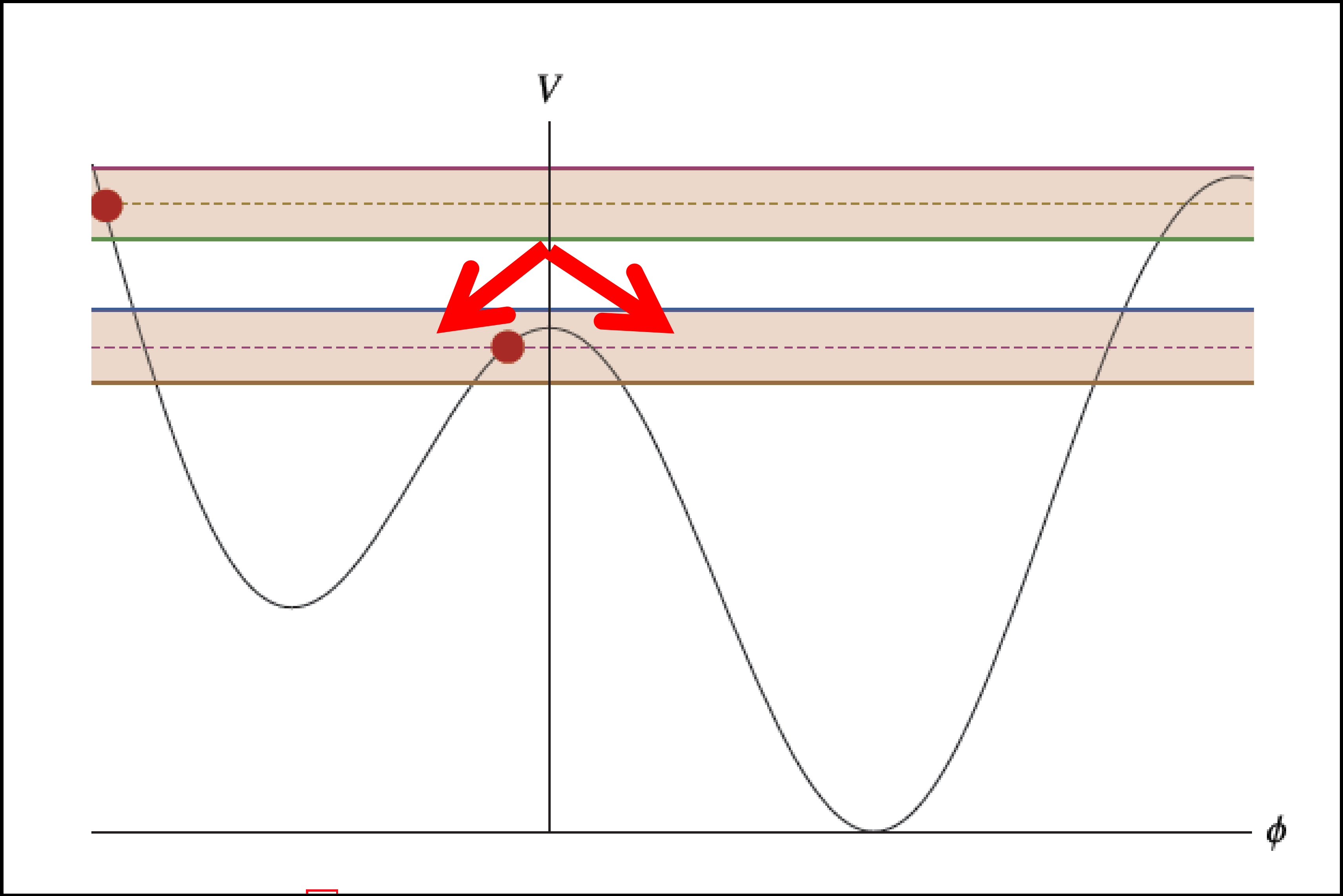
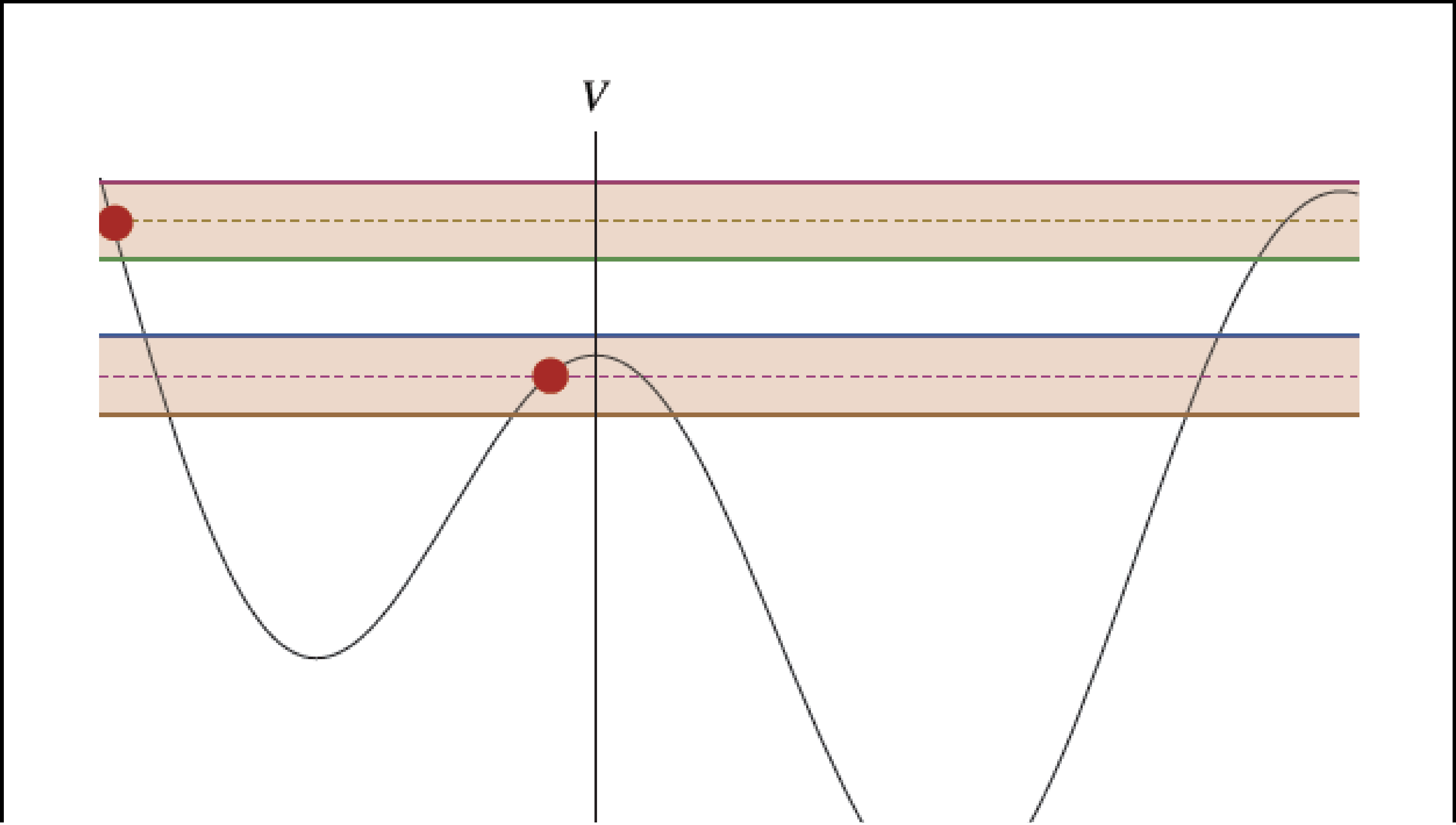


Including fluctuations



Including fluctuations



Different parts of Universe end in different minima
➔ Bubbles form
➔ GW are produced

Gravitational wave spectra

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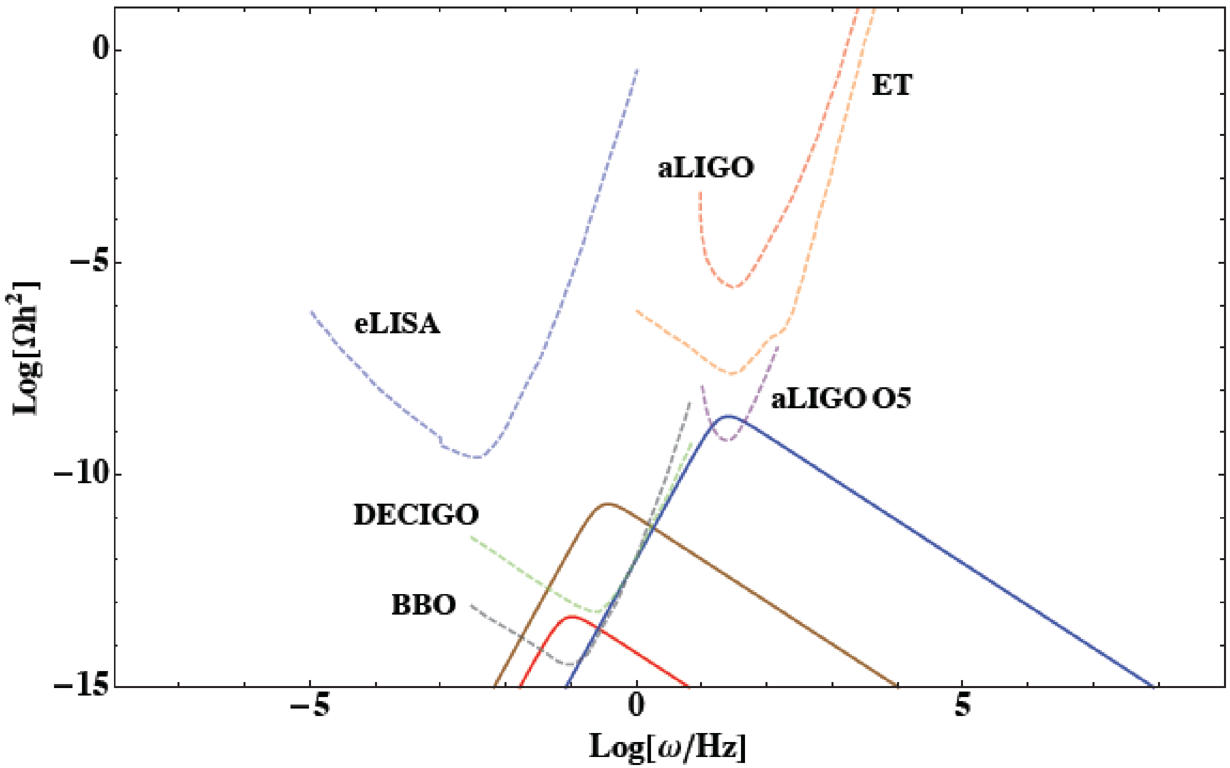

Figure 12: Gravitational wave spectra as in (5.22) with $w = 1/3$. The inflaton mass is fixed to $m \sim 10^{-5} M_p$. Spectra are shown as solid lines for different values of κ, f and T_{RH}: the blue curve is obtained for $\kappa = 5$, $f = 0.1 M_p$, $T_{RH} \sim 10^{12}$ GeV; the brown curve for $\kappa = 10$, $f = 0.01 M_p$, $T_{RH} \sim 10^{11}$ GeV; the red one for $\kappa = 70$, $f = 0.001 M_p$, $T_{RH} \sim 10^{11}$ GeV. We have also taken $w = 1/3, \theta_0 = 10^{-2}, \sigma = 10^{-1}$ in (5.22). For the values of the reheating temperature considered here, we have $g_*(T_{RH}) \sim 10^2$. Sensitivity curves of some ground- and space-based interferometers are shown for comparison as dashed curves (data taken from [74]).

Populating parameter space

+

Evading cosmological limits

G. Alonso, JJ

Non Standard Kinetic Terms

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$$\mathcal{L} = \frac{1}{2} K^2(\phi) \partial^\mu \phi \partial_\mu \phi - V(\phi)$$

$$V(\phi) = \Lambda^4 \left(1 - \cos \frac{\phi}{f_a} \right)$$

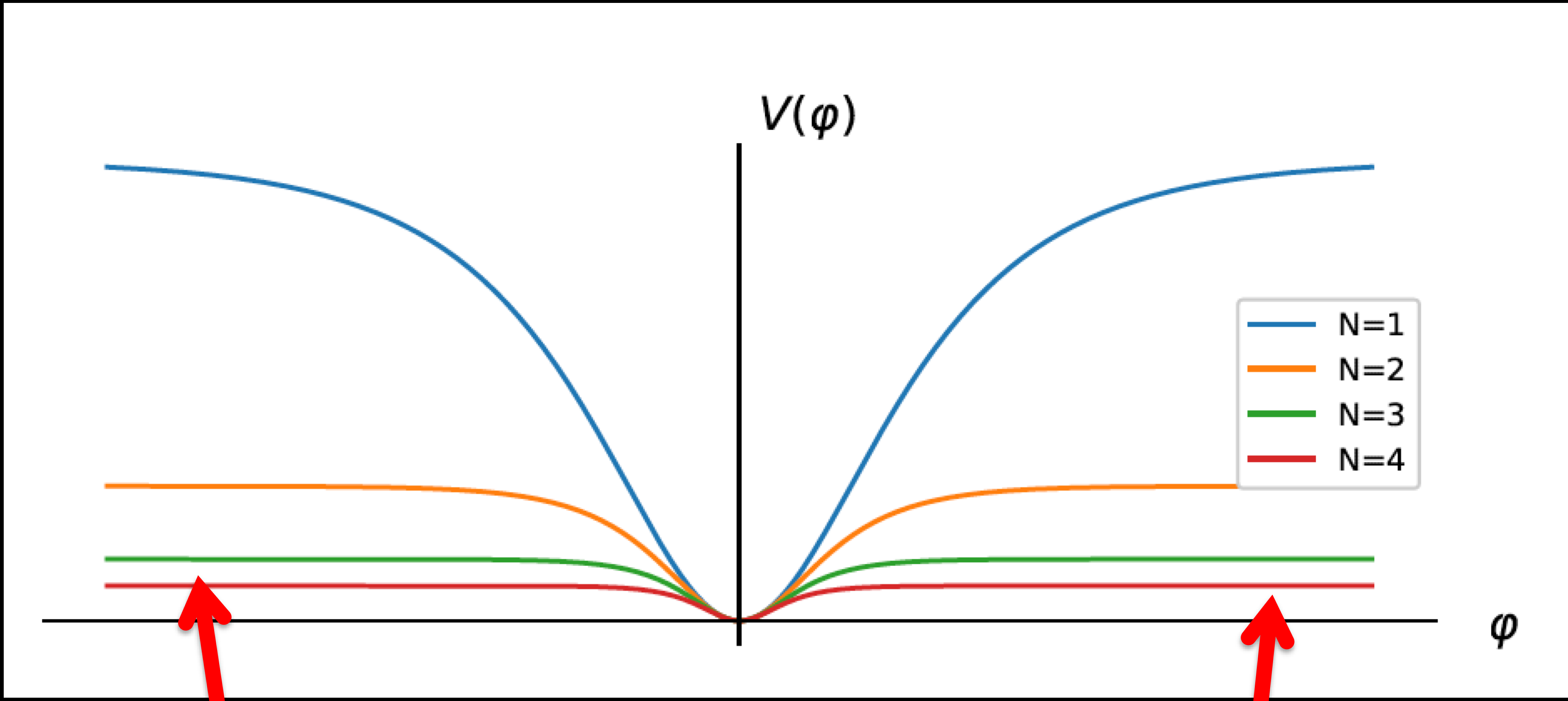
Use weird kinetic term →

$$K(\phi) = \frac{1}{\cos\left(\frac{N\phi}{f_a}\right)}$$

Canonically normalized

$$\mathcal{L} = \frac{1}{2} \partial^\mu \varphi \partial_\mu \varphi - \Lambda^4 \left[1 - \cos \left(\frac{2}{N} \arctan \left(\tanh \frac{N \varphi}{2 f_a} \right) \right) \right] .$$

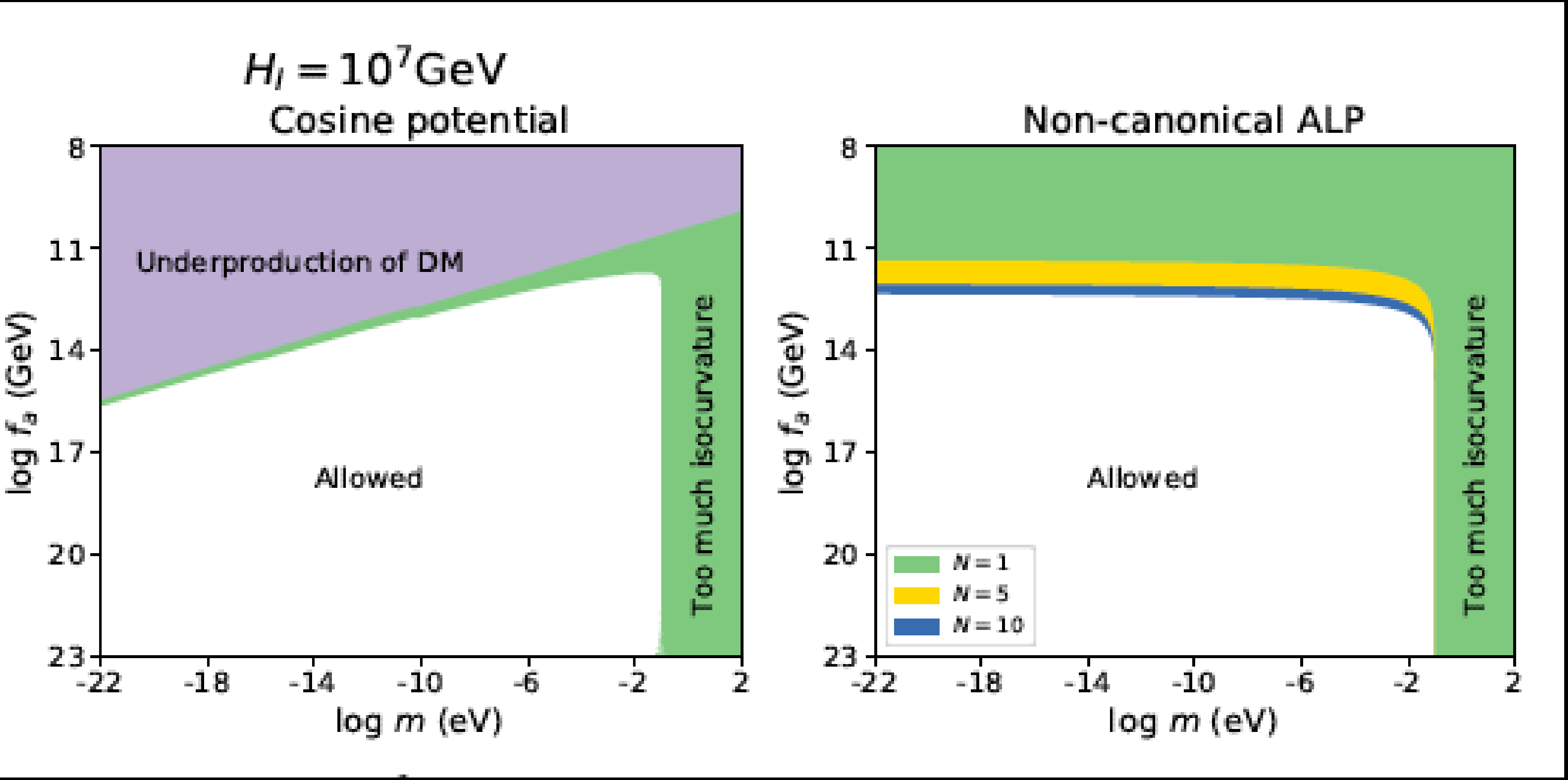
New potential



Field range infinite

Potential flatter at large field values

New regions available



Conclusions

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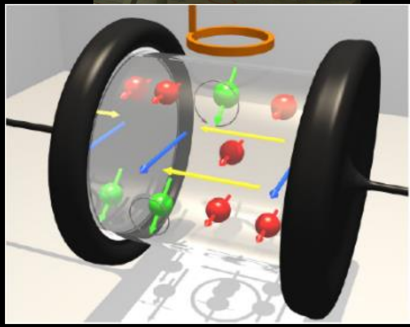
Conclusions

- Dark Matter may be Axiony/WISPy ☺
  - ➔ New Search opportunities!
  - ➔ Searches ongoing!



  - ➔ Unusual places may be viable
  - ➔ Crazy things to explore!

- ALPs may help with Inflation ➔ Grav. waves

More fiddling with the density:

2 periods of inflation

S. Hoof, JJ

One could also want less DM…

- E. g. for QCD axions

$$\Omega^{\rm std}_{A,o}h^2 \sim 0.09\,\theta_{\rm i}^2\left(\frac{76}{g_{\rm osc}}\right)^{0.41}\left(\frac{f_A}{10^{12}\,{\rm GeV}}\right)^{1.19}$$

- Too much DM for £$_i$» 1 and f_a& 10^{12} GeV
- In post inflation scenario £$_i$ can't even be tuned

Let's recycle an old idea…

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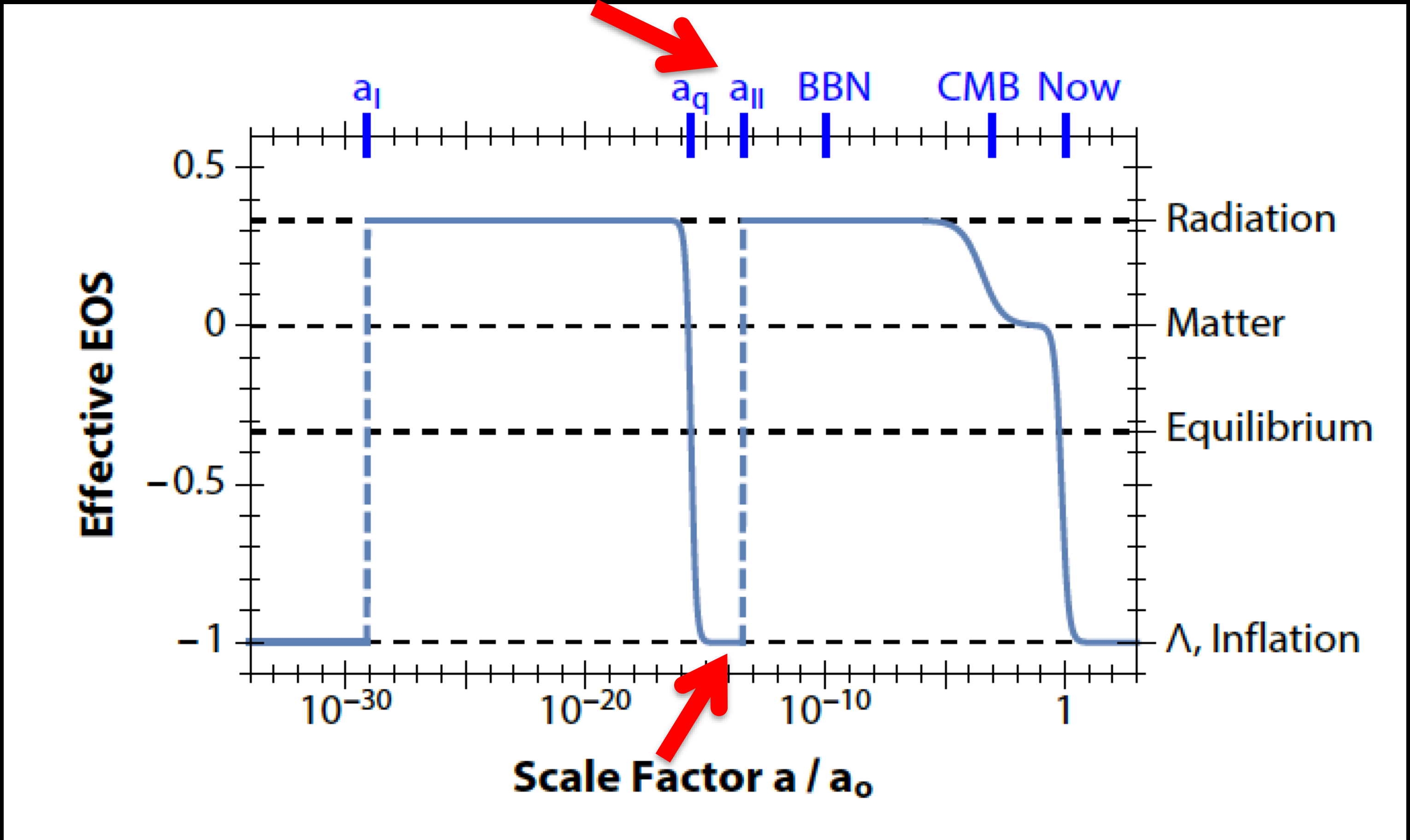
→Introduce second period of low scale inflation



Not just late inflation

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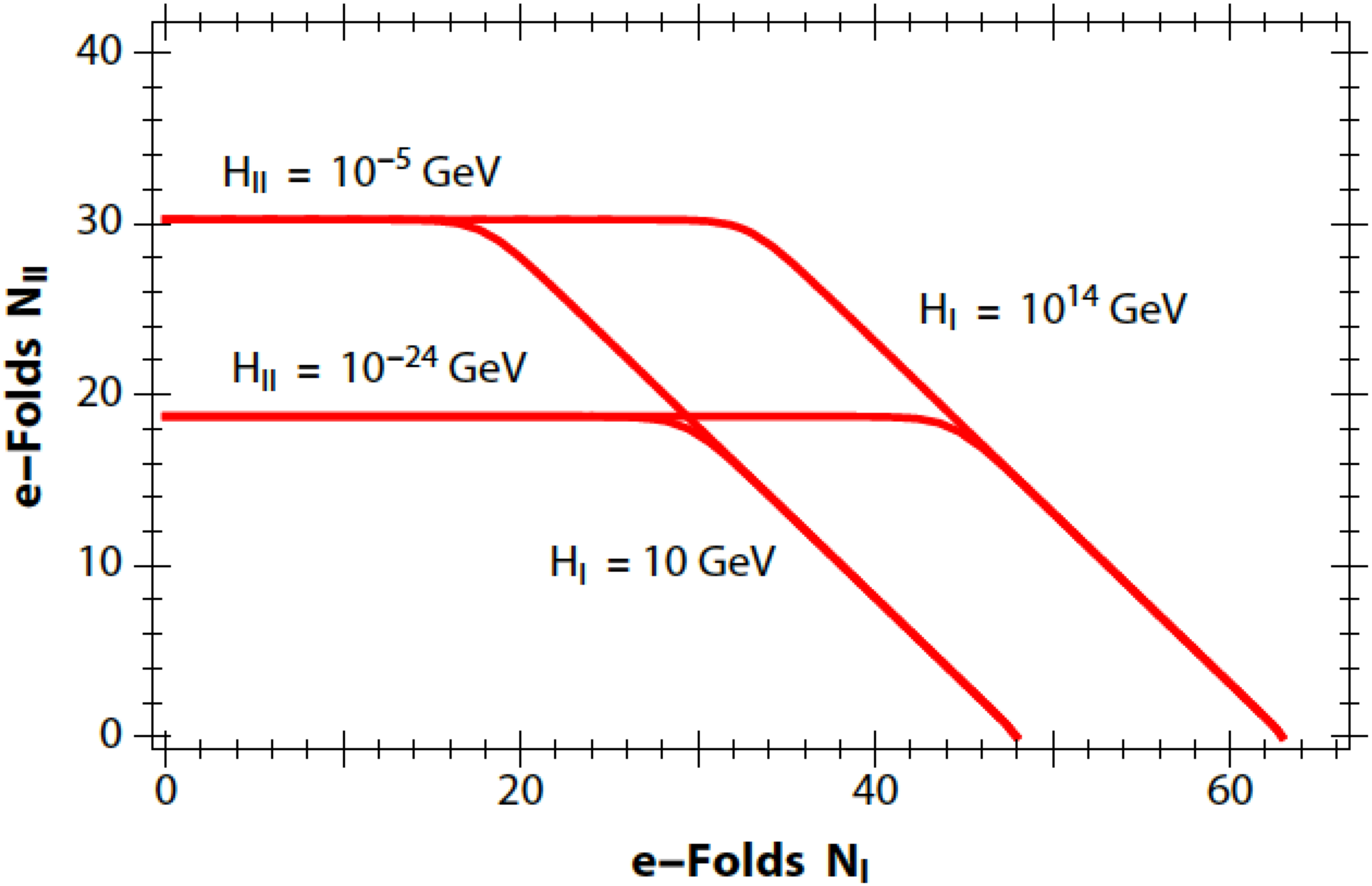

Dilution…

- If axion behaves like matter during the second inflation, i.e. $m_a > H_{inflation,\,II}$

- Expect dilution by volume factor
  ➔ get anything you like…

Often true… but not always

Reheating plays a role

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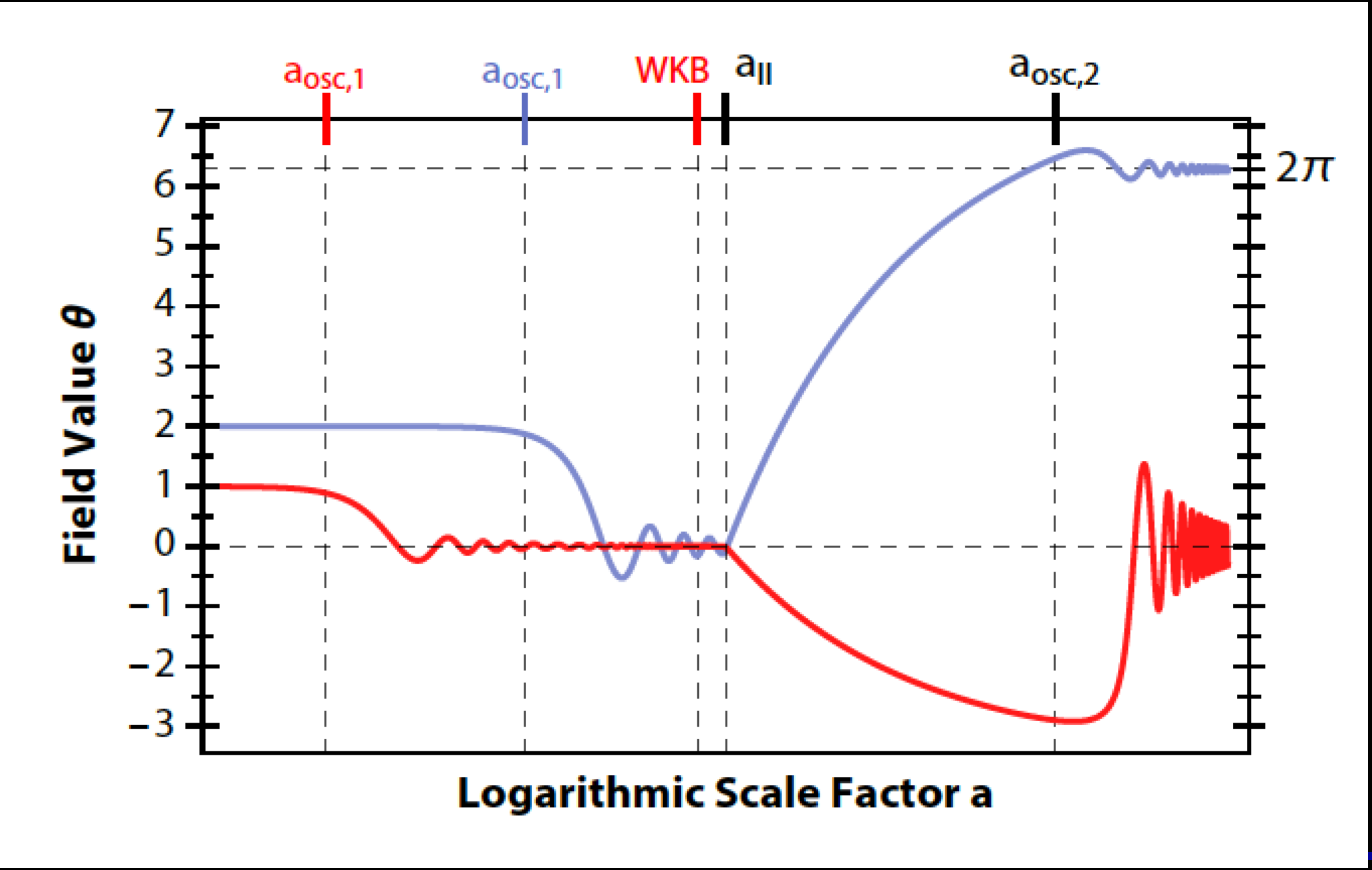
- Axions mass drops considerably if reheating temperature $>> T_{QCD}$



Funny dependence

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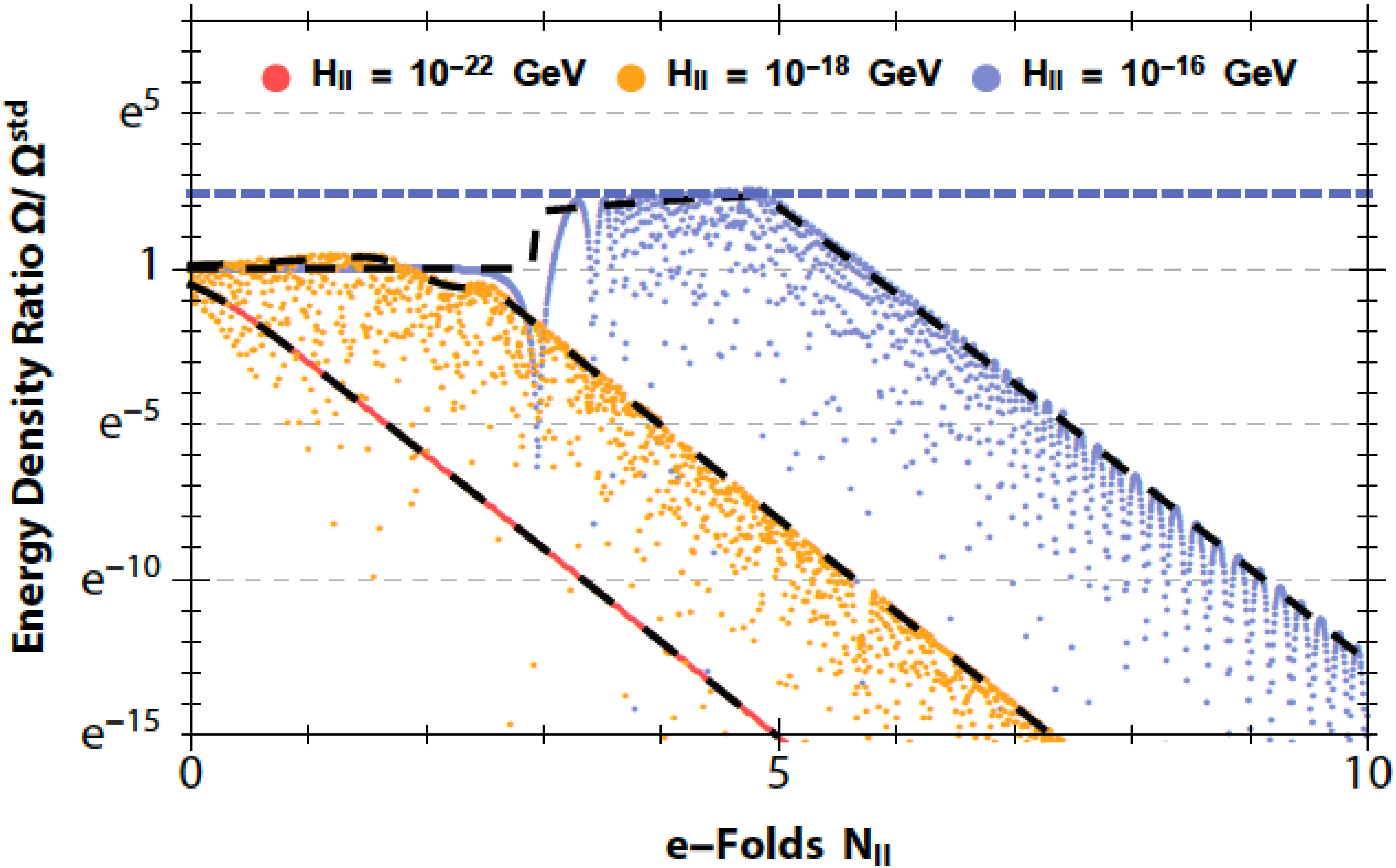
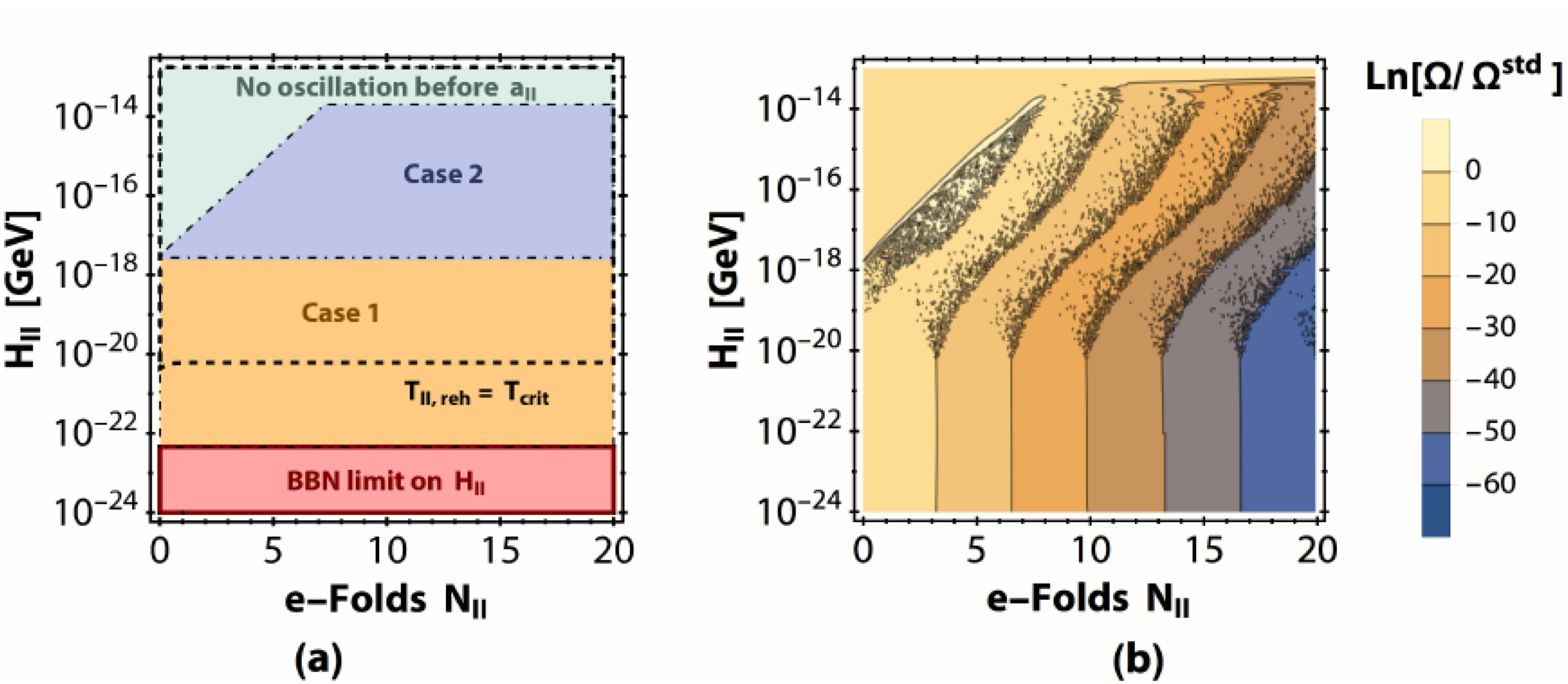


More generally



More interesting things may happen…

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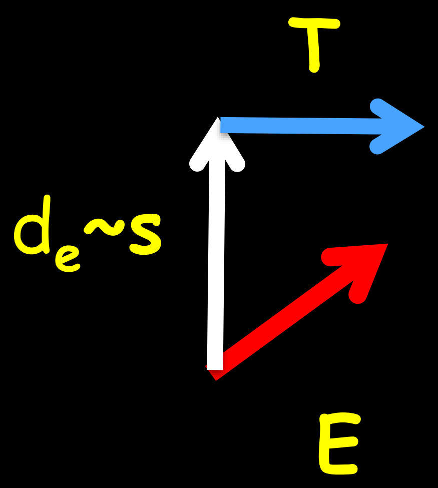
Post inflation scenario for axions…

- Blown up miniclusters

- Reduced strings/domain walls
  (maybe close to true average model)

In an electric field



Energy in an electric field

$$H = -\mathbf{d} \cdot \mathbf{E} = -c_E \mathbf{s} \cdot \mathbf{E}.$$

Torque tries to tilt dipole moment/spin

$$\mathbf{T} = \mathbf{d} \times \mathbf{E} = c_E \mathbf{s} \times \mathbf{E}.$$

Dealing with oscillation

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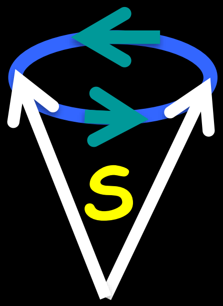
Problem: the dipole moment is rapidly oscillating $\sim m_a$

➔ Danger of cancellation

Solution: Rotate spin to compensate

➔ Use Spin Precession in magnetic field

$$\omega_L = 2\mu B$$



Resonance when $\omega_L = m_a$

Increased DM density

- In flat regions the field starts to roll much later

  → dilution delayed

  → density increased

$$\rho_\varphi(T_0) \simeq 0.162\,\frac{\mathrm{keV}}{\mathrm{cm}^3}\cdot\sqrt{\frac{m}{1\ \mathrm{eV}}}\left(\frac{f_a}{10^{11}\ \mathrm{GeV}}\right)^2\mathcal{F}(T_s)\cdot\left(2N\sin\frac{\pi}{2N}\right)^{-3/4}\,\mathrm{e}^{\frac{3}{4}N\psi_0}$$

BBN limits

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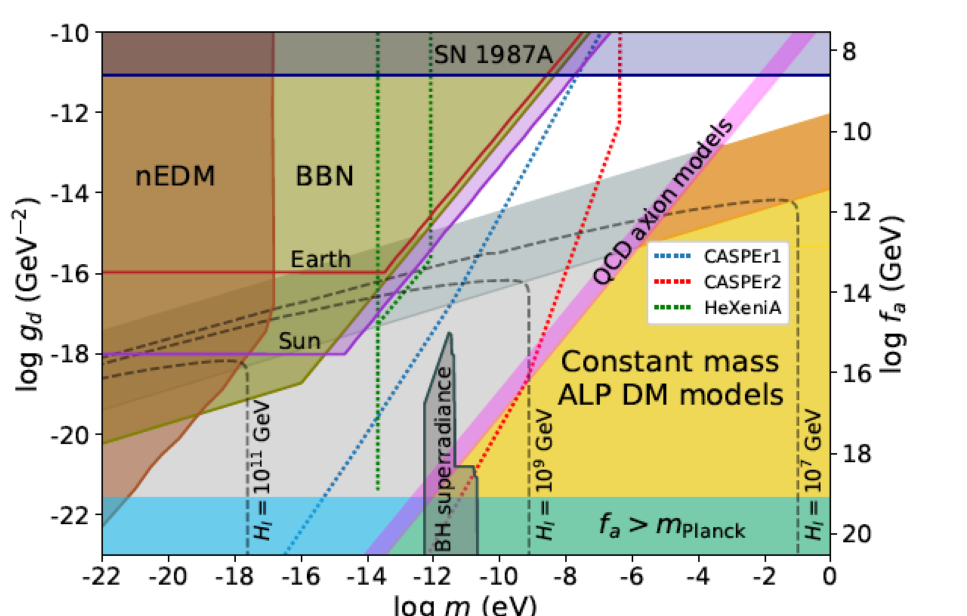
Proton-neutron mass difference depends on $\mathcal{L}_{QCD}$

$$m_n - m_p = 0.37\mathrm{MeV}\left(\frac{\phi}{f_a}\right)^2$$

Depending on f_a this can be O(1) at BBN
➔ Helium production changed



Constraining Axion Dark Matter with Big Bang Nucleosynthesis
Kfir Blum, Raffaele Tito D'Agnolo (Princeton, Inst. Advanced Study), Mariangela Lisanti, Benjamin R. Saf
Published in Phys.Lett. B737 (2014) 30-33
DOI: 10.1016/j.physletb.2014.07.059
e-Print: arXiv:1401.6460 [hep-ph] | PDF

Avoiding BBN limits

- Kinetic term

$$K(\phi) = \frac{1}{\cos\left(\frac{N\phi}{f_a}\right)}$$

Singularities at ¼/(2N)

➔ Á/f_a does not cross ¼/(2N), i.e. Á/f_a · ¼/(2N)

➔ No problem with BBN if N>~10

One more difficulty…

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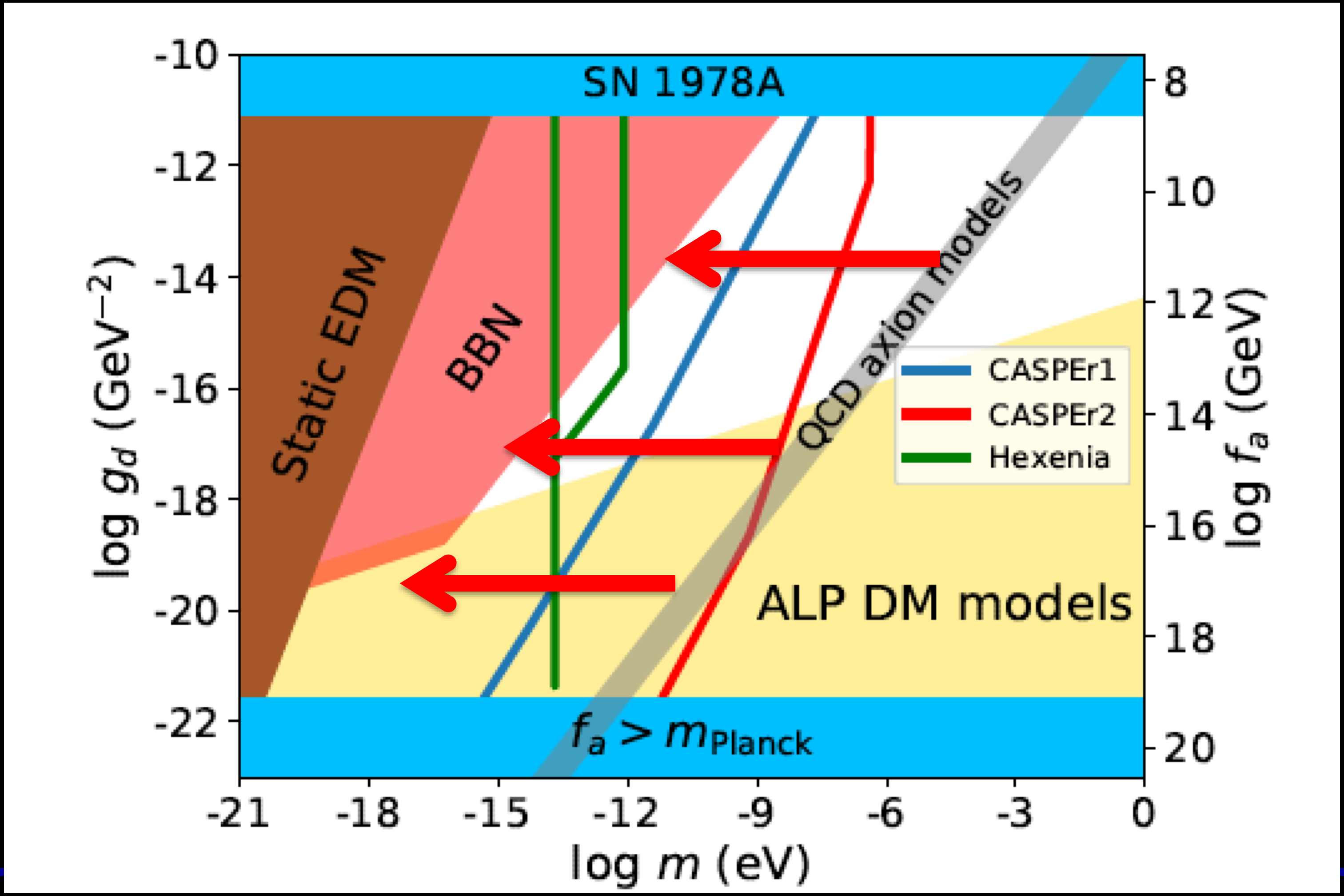
- QCD coupling generates "minimal" mass
  - ➔ difficult to be lighter than QCD axion



Do some fine-tuning…

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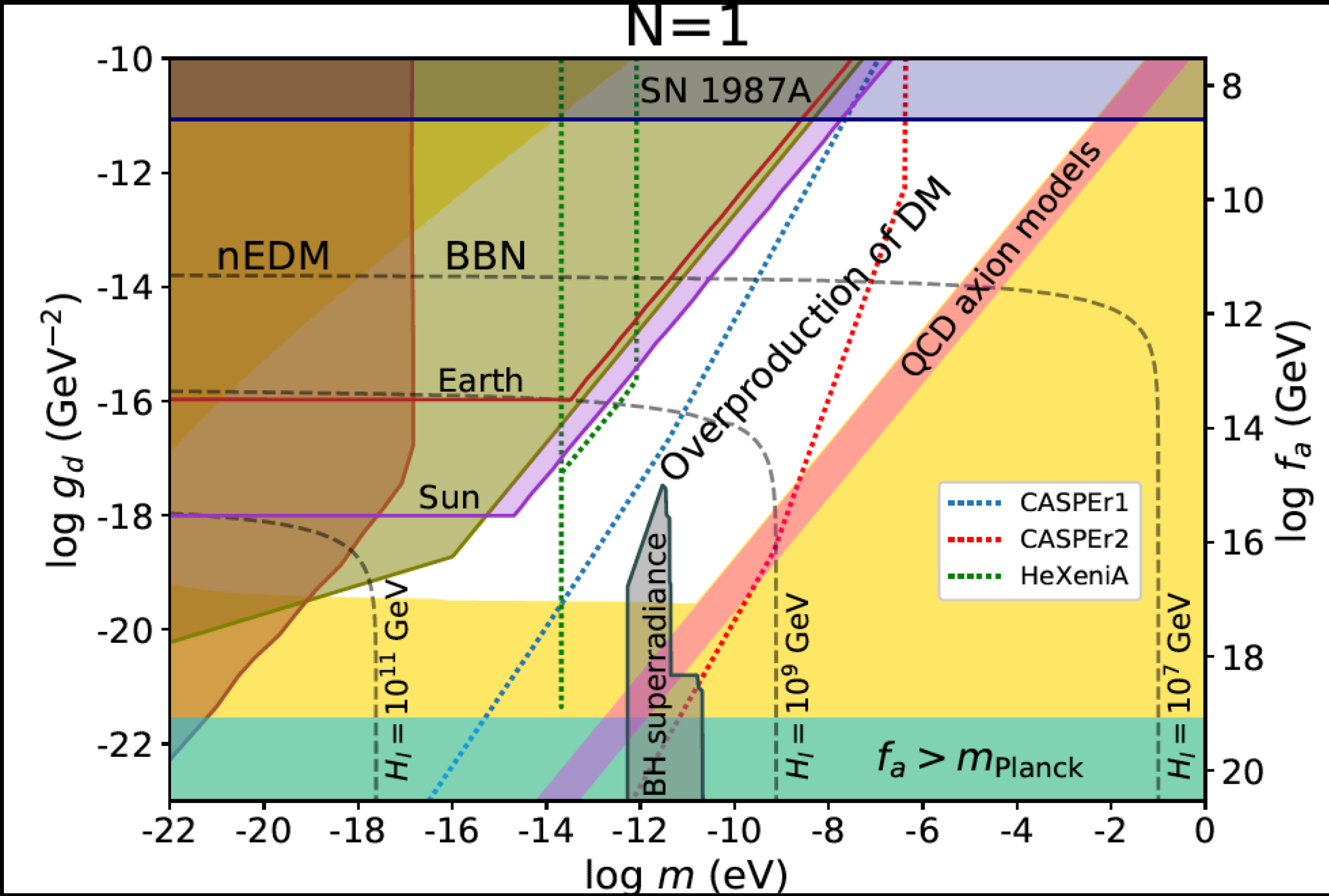
$$V(\phi) = \Lambda_{\mathrm{QCD}}^4 \left(1 - \cos\frac{\phi}{f_\phi}\right) + \Lambda_0^4 \left(1 - \cos\left(\frac{\phi}{n f_\phi} + \alpha\right)\right)$$

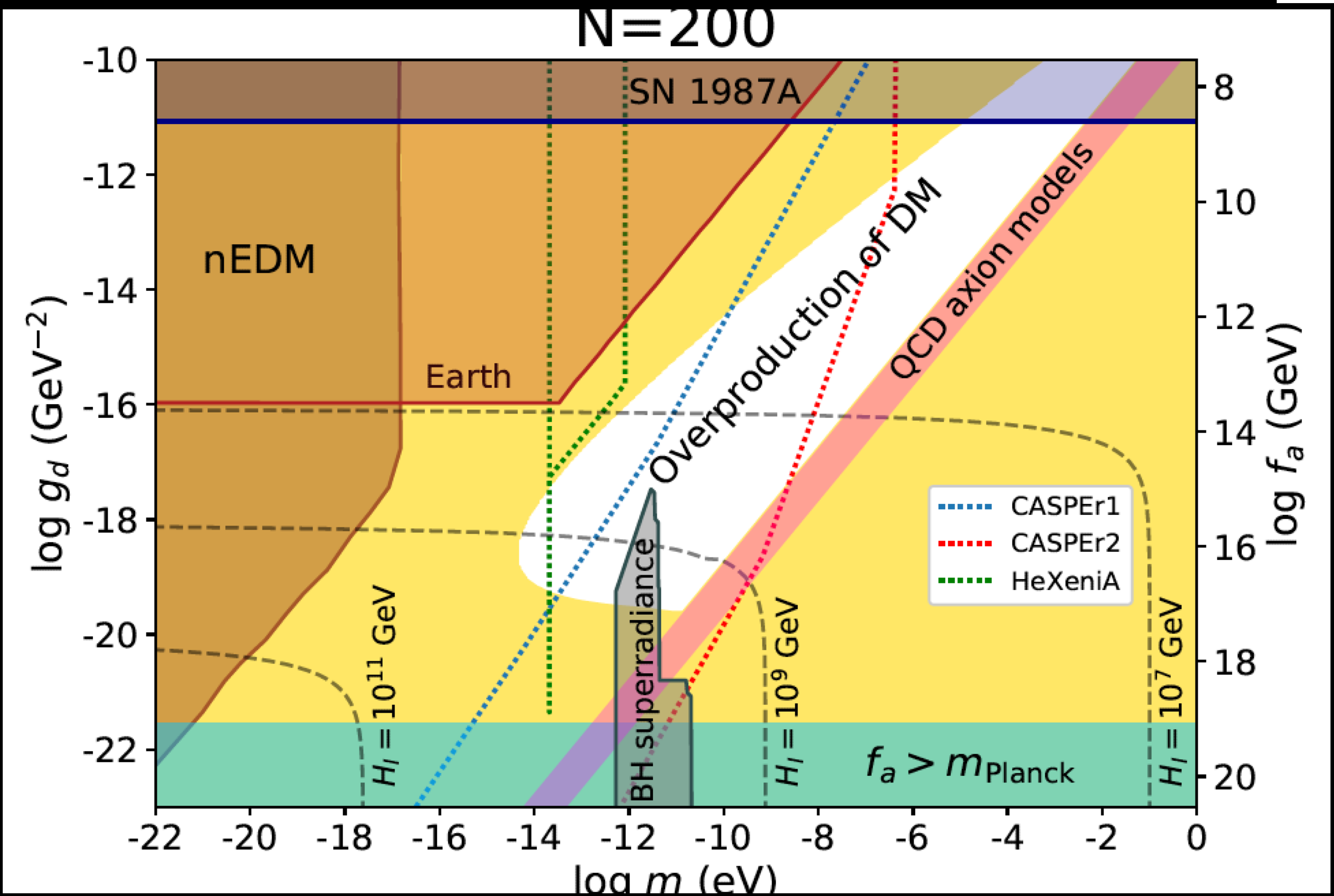
Some funny temperature dependence appears

$$m_\phi^2(T) = \begin{cases} m_{\mathrm{ALP}}^2 & , T < T_{\mathrm{crit}} \\ -m_a^2(0) & , T > T_{\mathrm{crit}} \end{cases}$$

New regions available



New regions available



Couplings fixed by f_a

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- Photon coupling

$$\mathcal{L} \supset \frac{1}{4} g_{a\gamma\gamma} F^{\mu} \tilde{F}_{\mu\nu}$$

$$g_{a\gamma\gamma} \sim \frac{\alpha}{4\pi f_a}$$

- Gluon coupling

$$\mathcal{L} \supset \frac{1}{4} g_{agg} G^{\mu} \tilde{G}_{\mu\nu}$$

$$g_{agg} \sim \frac{\alpha_s}{2\pi f_a}$$

At low energies electric dipole coupling

$$\mathcal{L} \supset -\frac{i}{2} g_d \phi \bar{N} \sigma_{\mu\nu} \gamma^5 N F^{\mu\nu}$$

$$g_d \sim 10^{-6}\,\mathrm{GeV}^2 \left(\frac{10^{10}\,\mathrm{GeV}}{f_a} \right)$$

Couplings fixed by f_a

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- **Photon coupling**

$$\mathcal{L} \supset \frac{1}{4} g_{a\gamma\gamma} F^{\mu} \tilde{F}_{\mu\nu}$$

$$g_{a\gamma\gamma} \sim \frac{\alpha}{4\pi f_a}$$

- **Gluon coupling**

$$\mathcal{L} \supset \frac{1}{4} g_{agg} G^{\mu} \tilde{G}_{\mu\nu}$$

$$g_{agg} \sim \frac{\alpha_s}{2\pi f_a}$$

- **Fermion couplings**

$$\mathcal{L} \supset \frac{\partial_\mu \phi}{f_a} \bar{\psi} \gamma^\mu \gamma^5 \psi$$

New potential

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