Exploring the Dark Matter ALPS

J. Jaeckel[**]

G. Alonso**, P. Arias, J. Berges**, D. Cadamuro, A. Chatrychan**, R. Gupta[†], V. Mehta[yy], J. Redondo[x], A. Ringwald*, M. Spannowsky[†], L. Witkowski[zz]

[**]Heidelberg U., [z]Santiago de Chile U., [†]IPPP Durham, [yy]Goettingen U., *DESY, [x]U. Zaragoza, [zz]APC Paris

Standard

ALP Dark Matter

What are ALPs?

- Axion-like particles
- Very light (sub-eV) bosons
- Very weakly coupled
- Often: Pseudo-Goldstone bosons
  (arising from spontaneous symmetry breaking at scale f_a)

Potential and mass related to SSB scale

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

- **Potential for Pseudo-Goldstones:**

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

Explicit symmetry breaking

Scale of spontaneous symmetry breaking

- **Mass:** $m_\phi = \dfrac{\Lambda^2}{f_a}$

Naturally light!
(For large f_a)

Couplings fixed by f_a

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

- Photon coupling

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

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

- Gluon coupling

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

$$g_{\phi gg} \sim \frac{\alpha_s}{2\pi f_a}$$

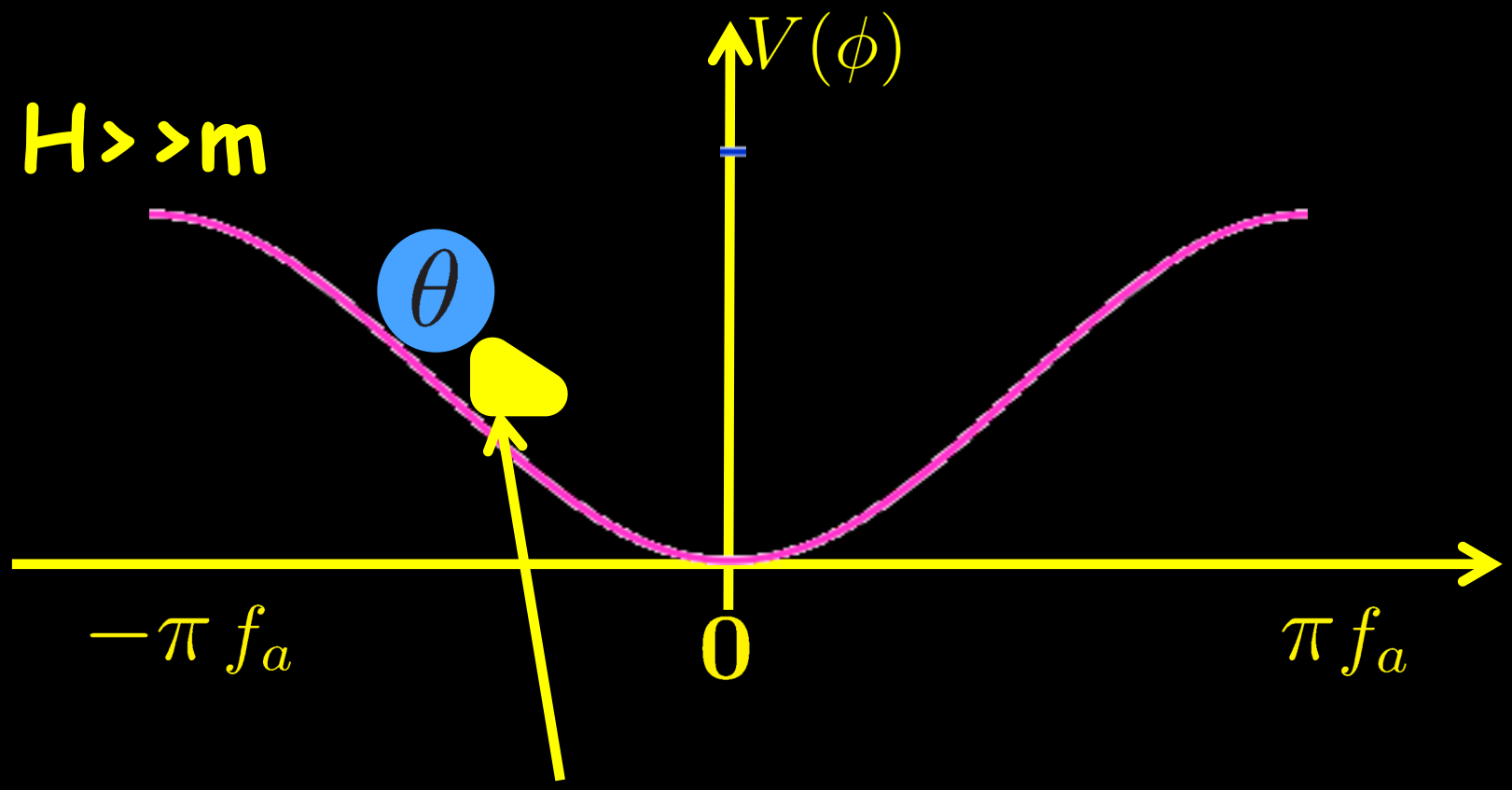
At low energies electric dipole coupling

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

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

The ALP has no clue where to start

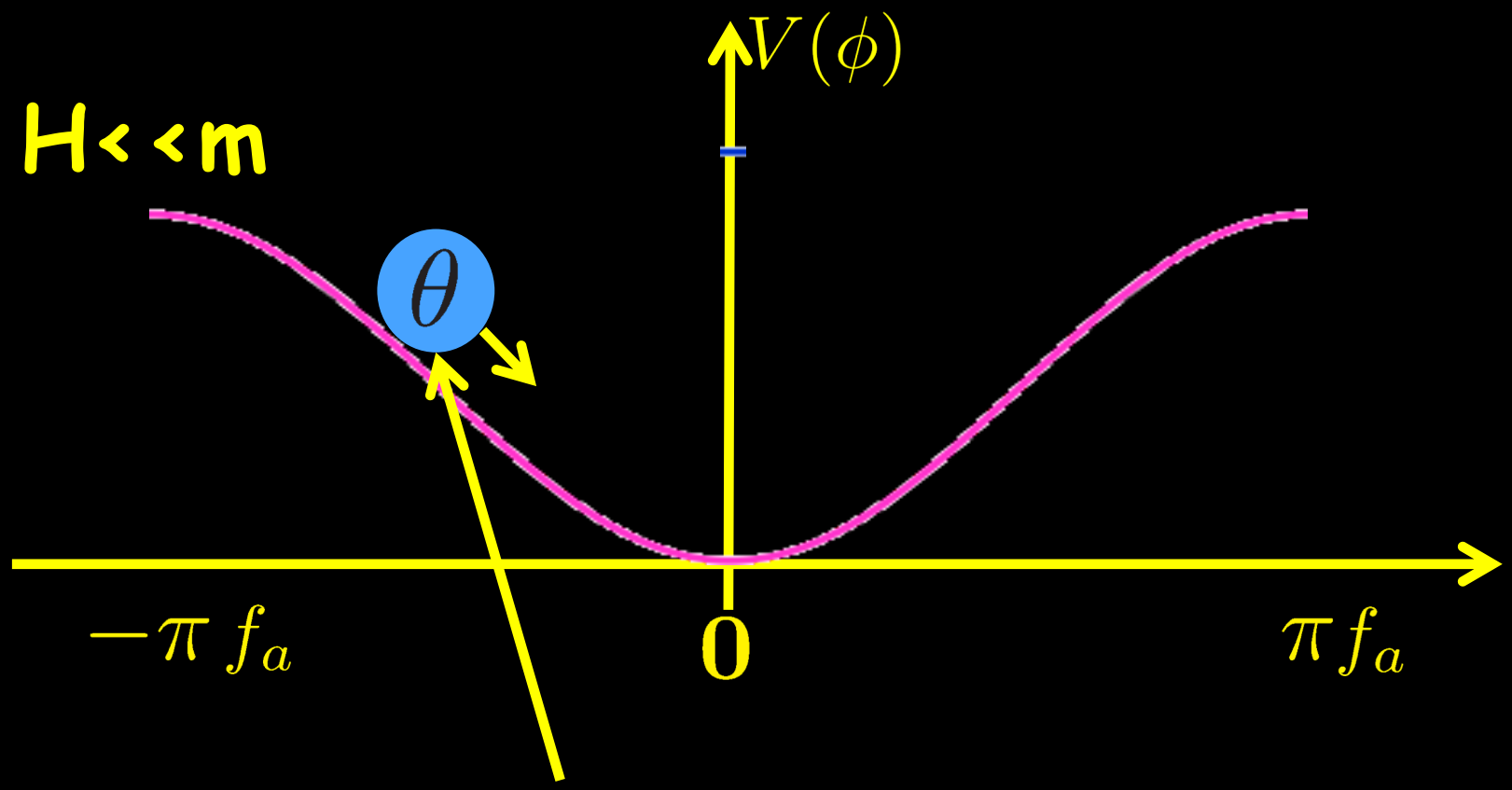
INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University



Field is stuck because of Hubble "breaking"

The ALP has no clue where to start

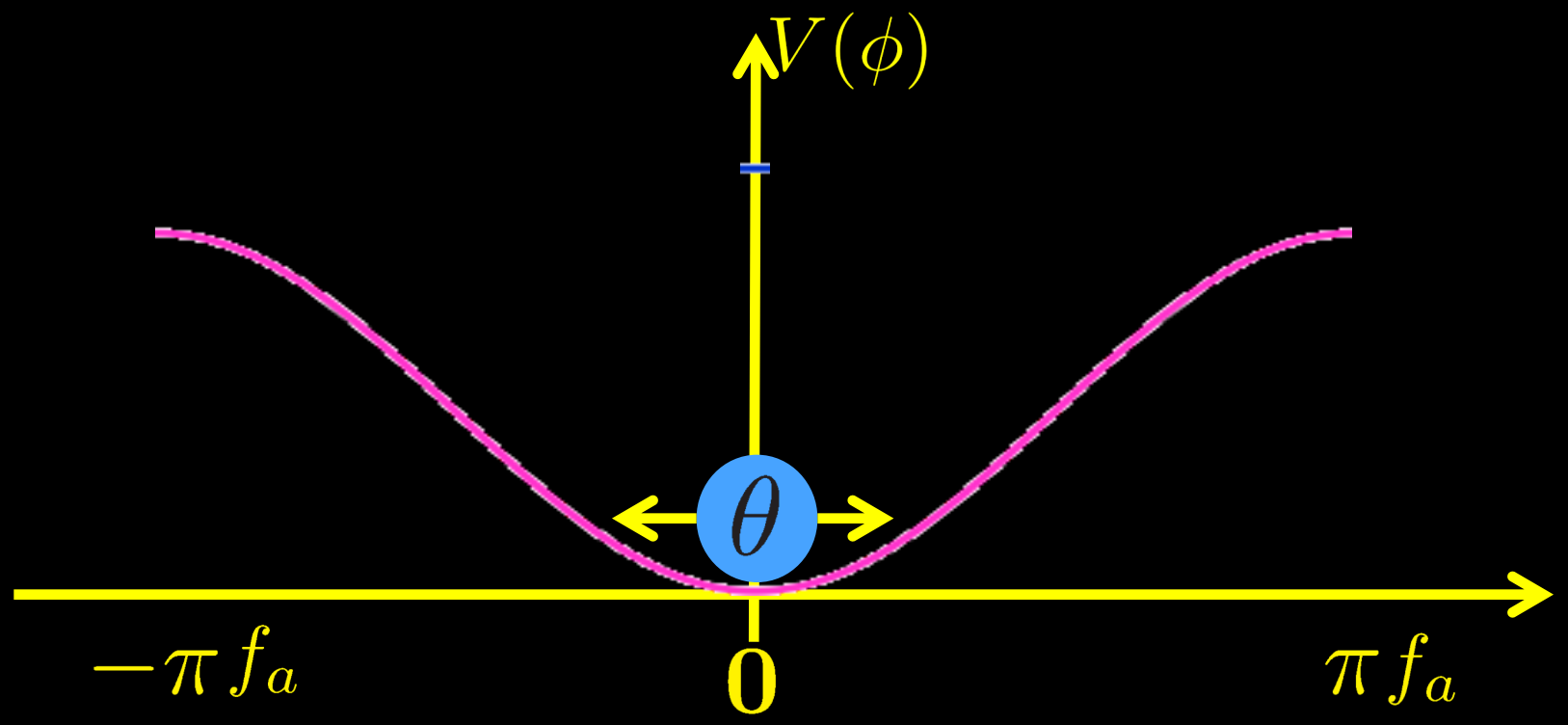
INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University



Can start moving…

ALP dark matter

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

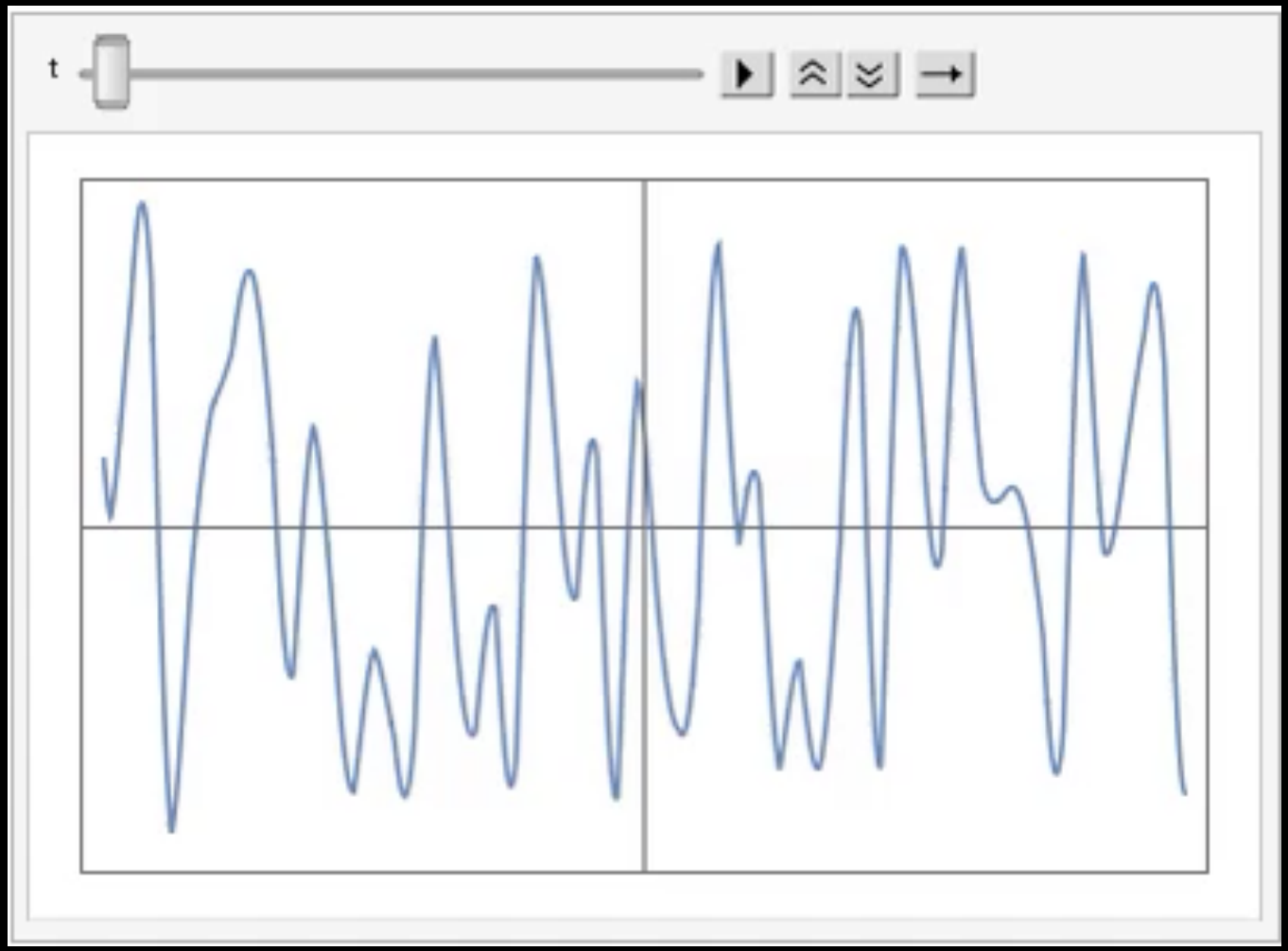


➔ Oscillations contain energy
➔ behave like non-relativistic particles (T=0)

Why Cold? Inflation!

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

Field value



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

Dark Matter Density

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

- Depends on the initial field value

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

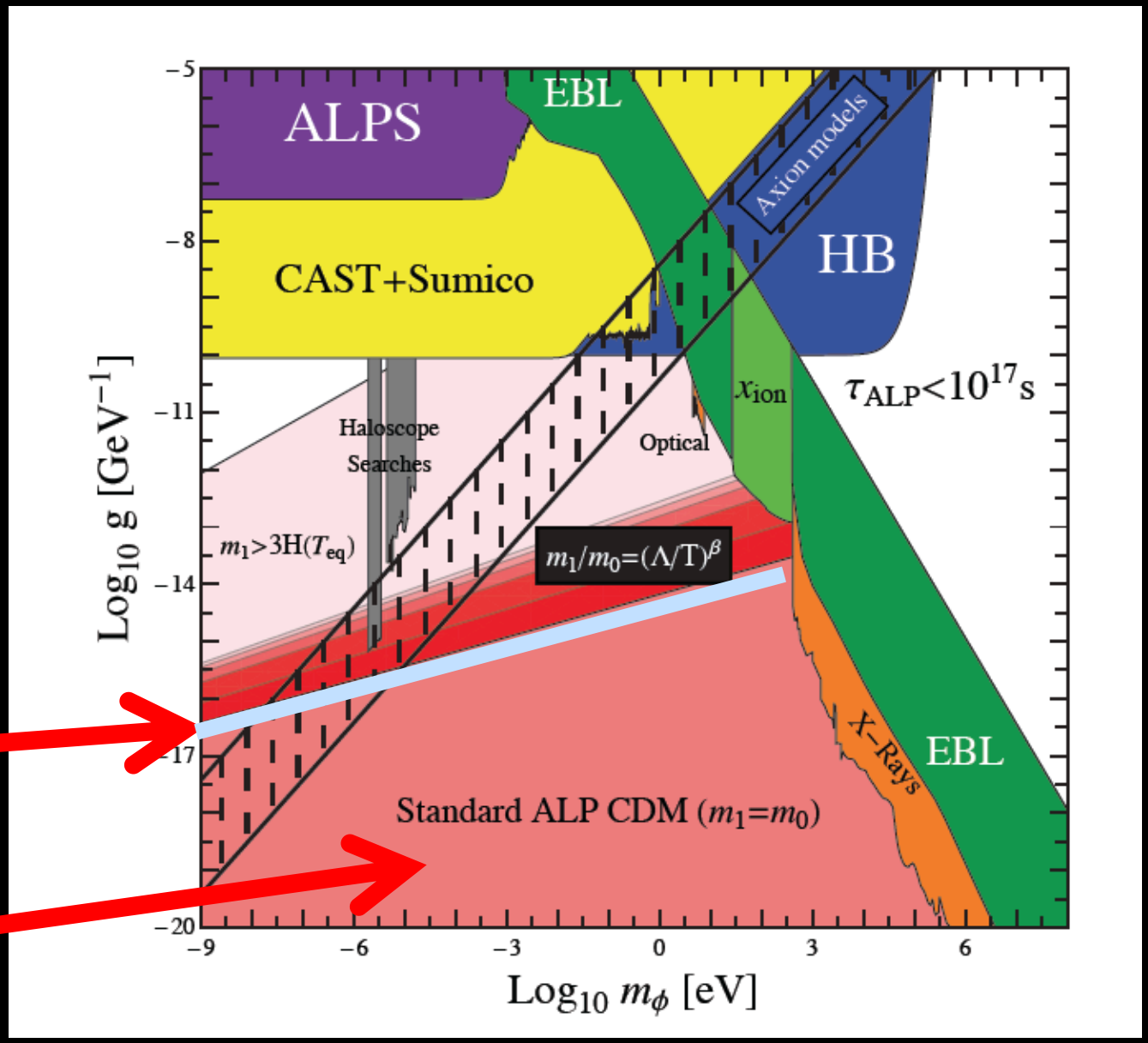
- Pseudo-Goldstone

➔ Field value $\phi_1 \leq \pi f_a$

Naturally $\phi_1 \sim \pi f_a$

Axion(-like particle) Dark Matter

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

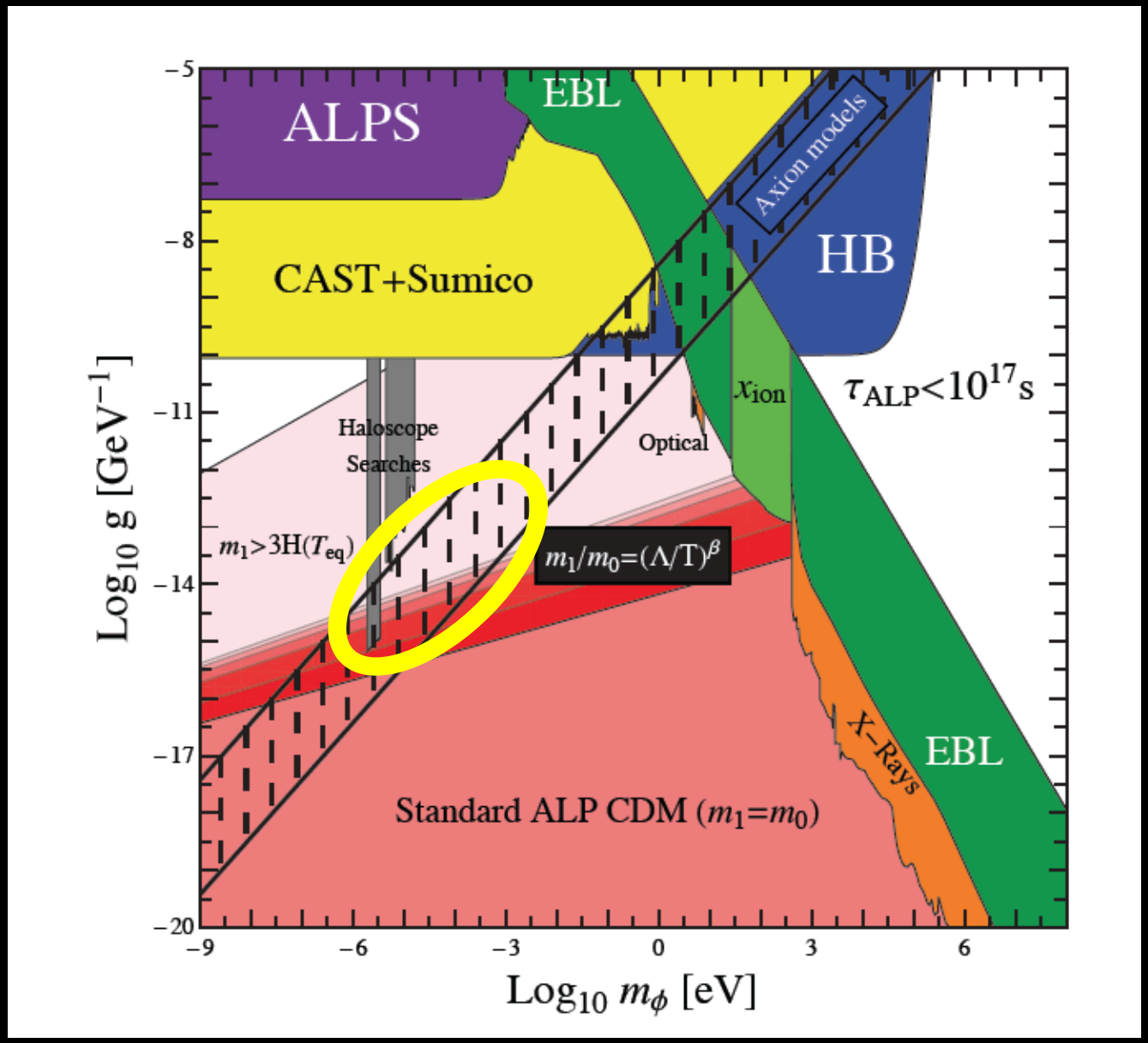


Natural

Possible

Axion Dark Matter

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University



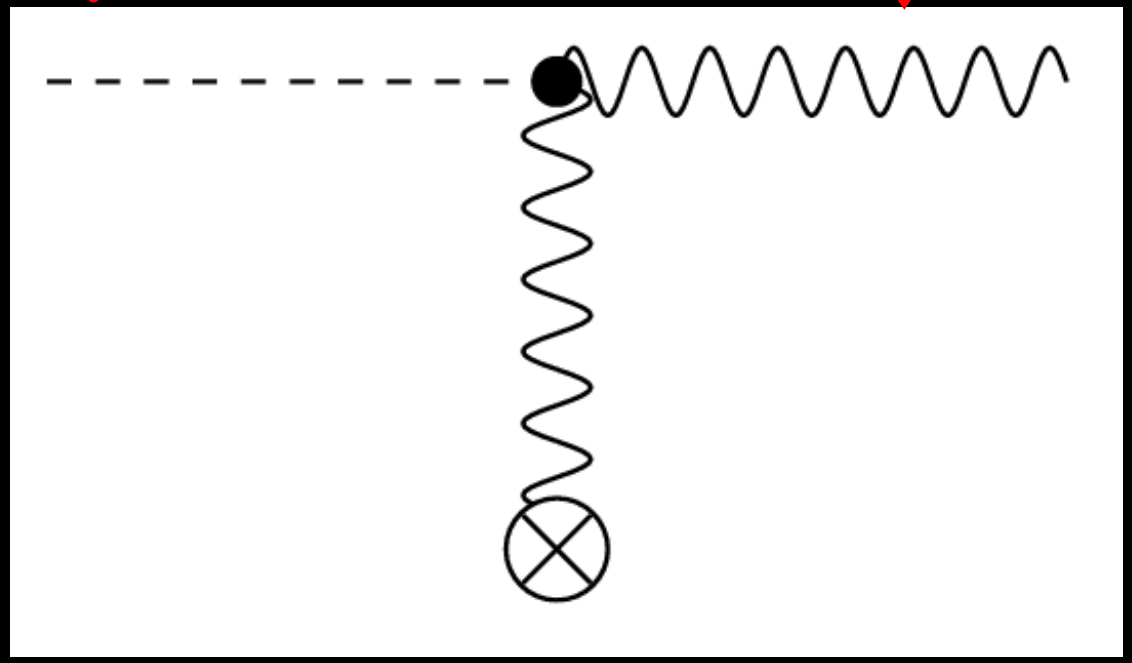
Detecting WISPy DM

Use a plentiful source of axions

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

- Photon Regeneration

Photon
(amplified/detection)



ALP
(dark matter)

Many efforts underway ☺

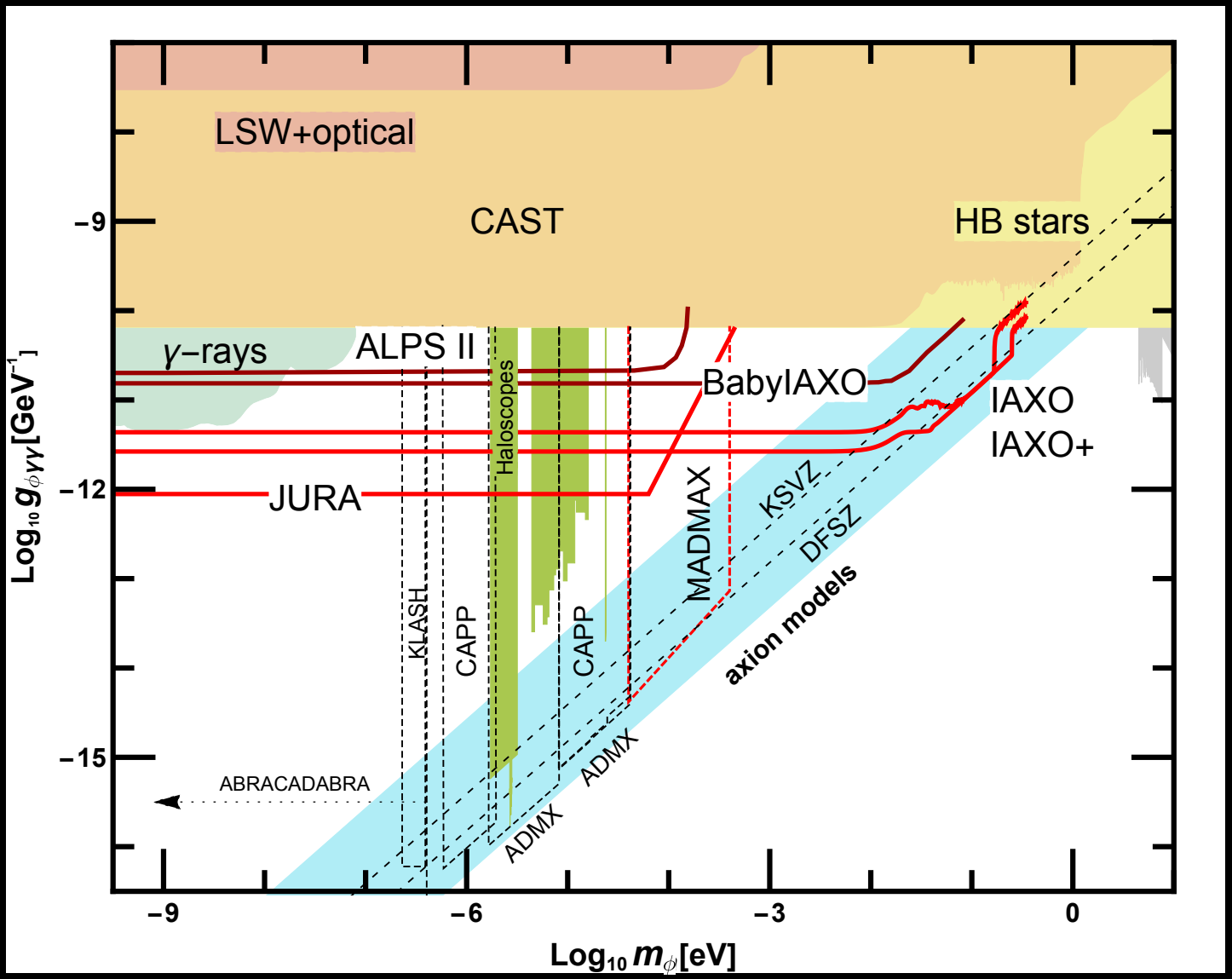
- ADMX
- MadMax
- CAPP-CULTASK
- + Many more: Abracadabra, Alps, Ariadne, Casper, EDM ring, FUNK, Haystac, HeXeniA Iaxo, Organ, Rades, Sensei, Quax….

Many efforts underway ☺

- ADMX
- MadMax
- CAPP-CULTASK
- + Many more: Abracadabra, Alps, Ariadne, Casper, EDM ring, FUNK, Haystac, HeXeniA Iaxo, Organ, Rades, Sensei, Quax….

A Bright Future

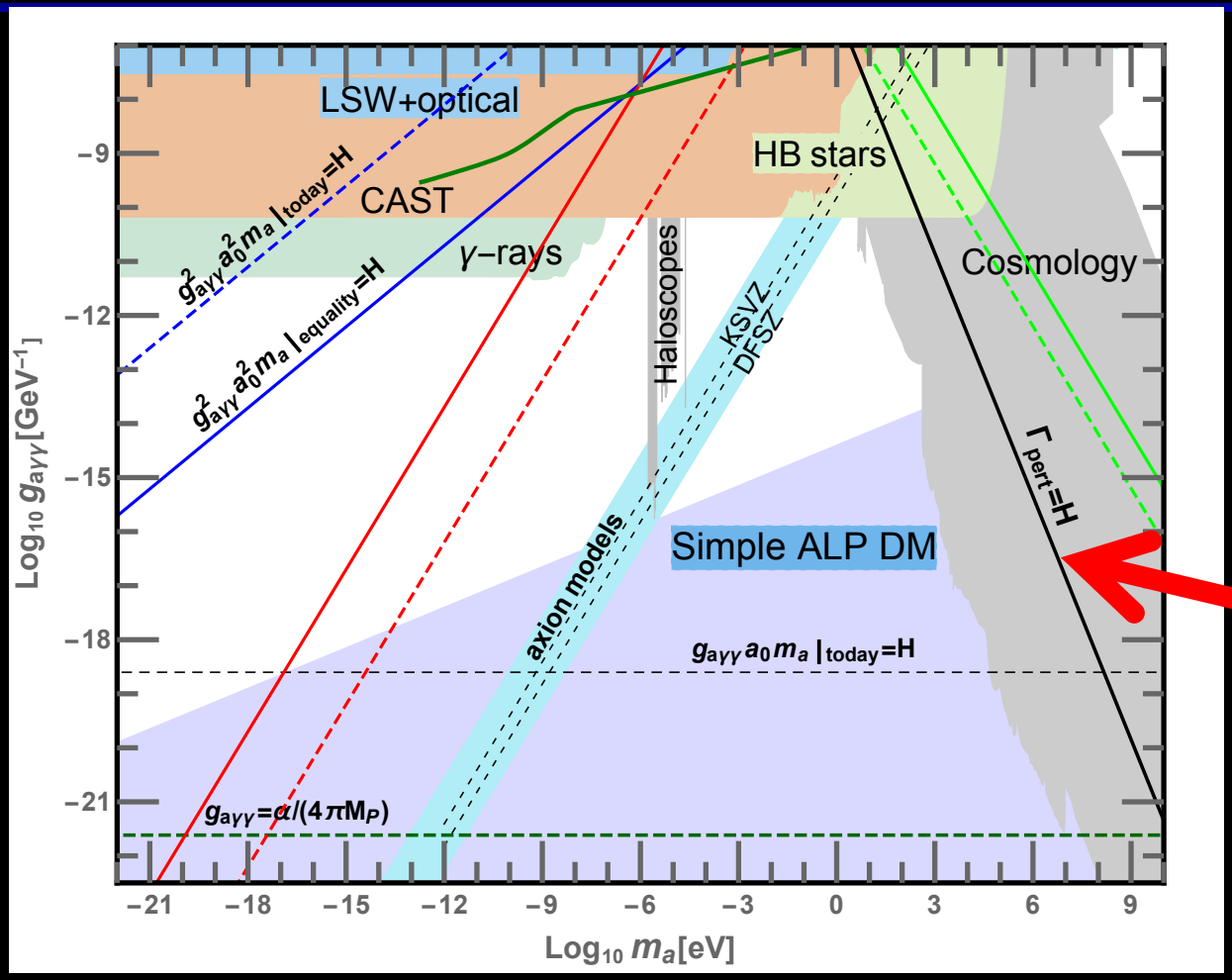
INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University



A little surpising stability

Axion Dark Matter

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

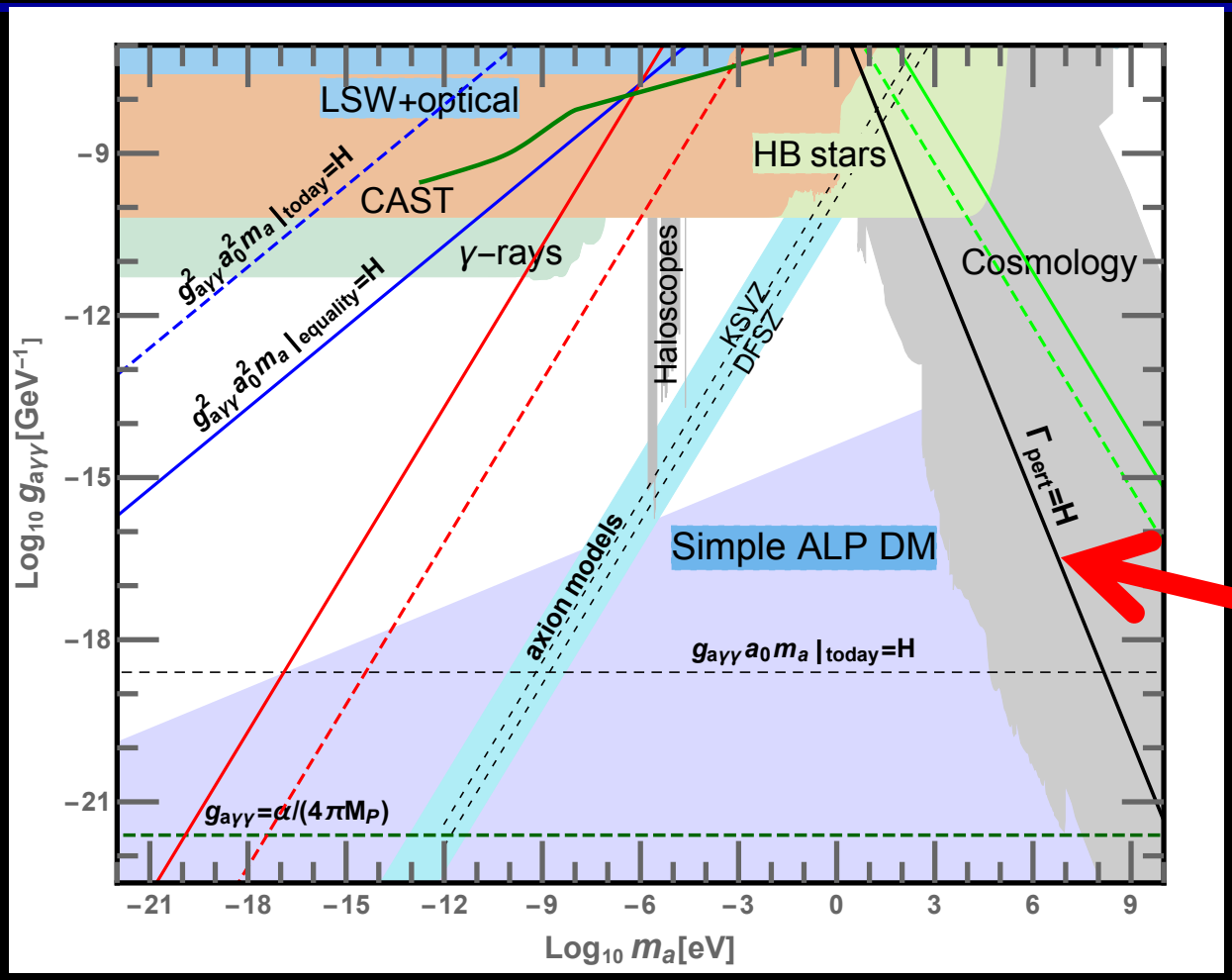


Standard Stability bound

$$\Gamma_{\rm pert} = \frac{g_{\phi\gamma\gamma}^2 m_\phi^3}{64\pi}$$

Axion Dark Matter

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University



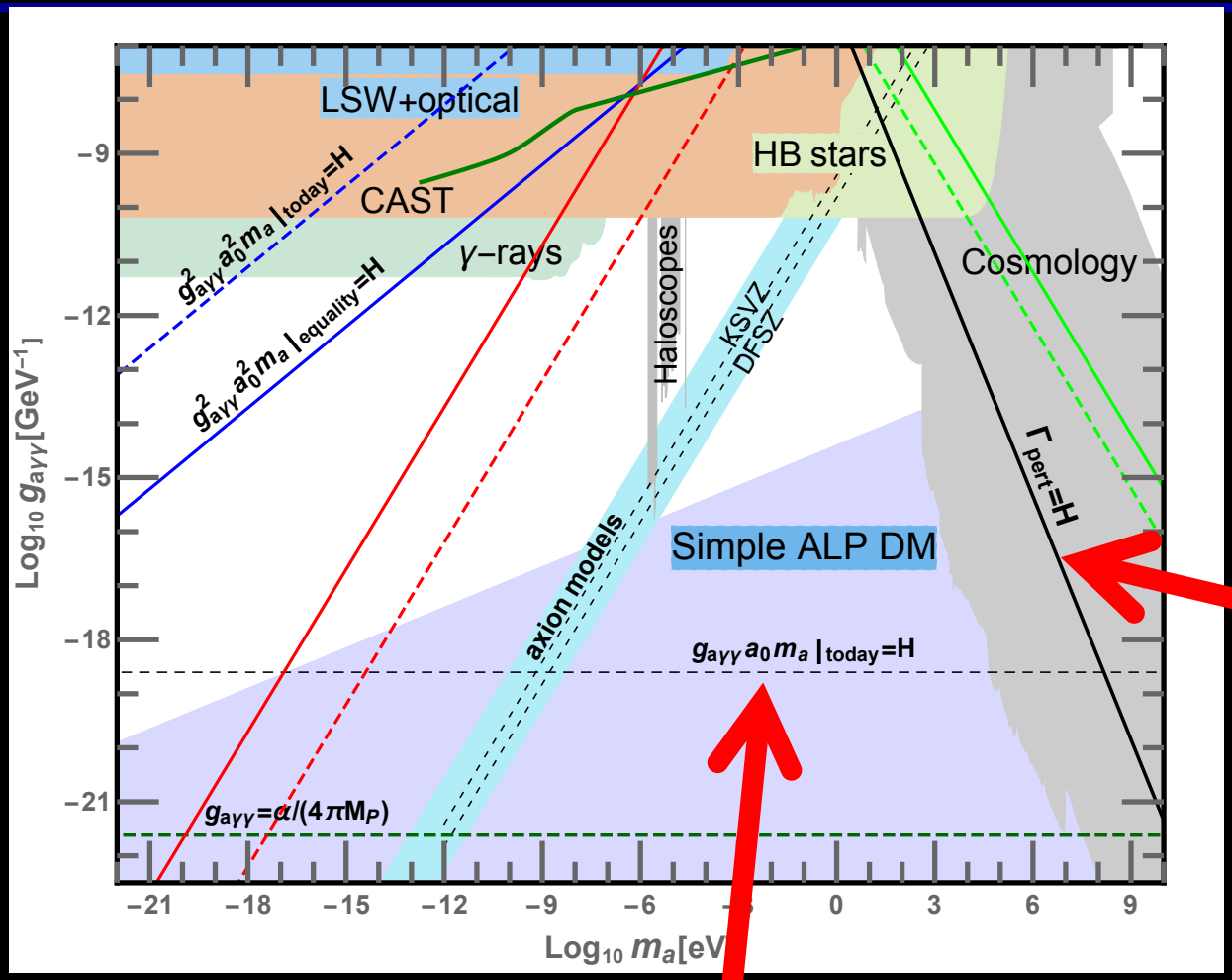
Standard Stability bound

$$\Gamma_{\rm pert} = \frac{g^2_{\phi\gamma\gamma} m^3_\phi}{64\pi}$$

However: ALP field is extremely coherent
➔ Bose enhancement possible

Axion Dark Matter

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University



Standard Stability bound

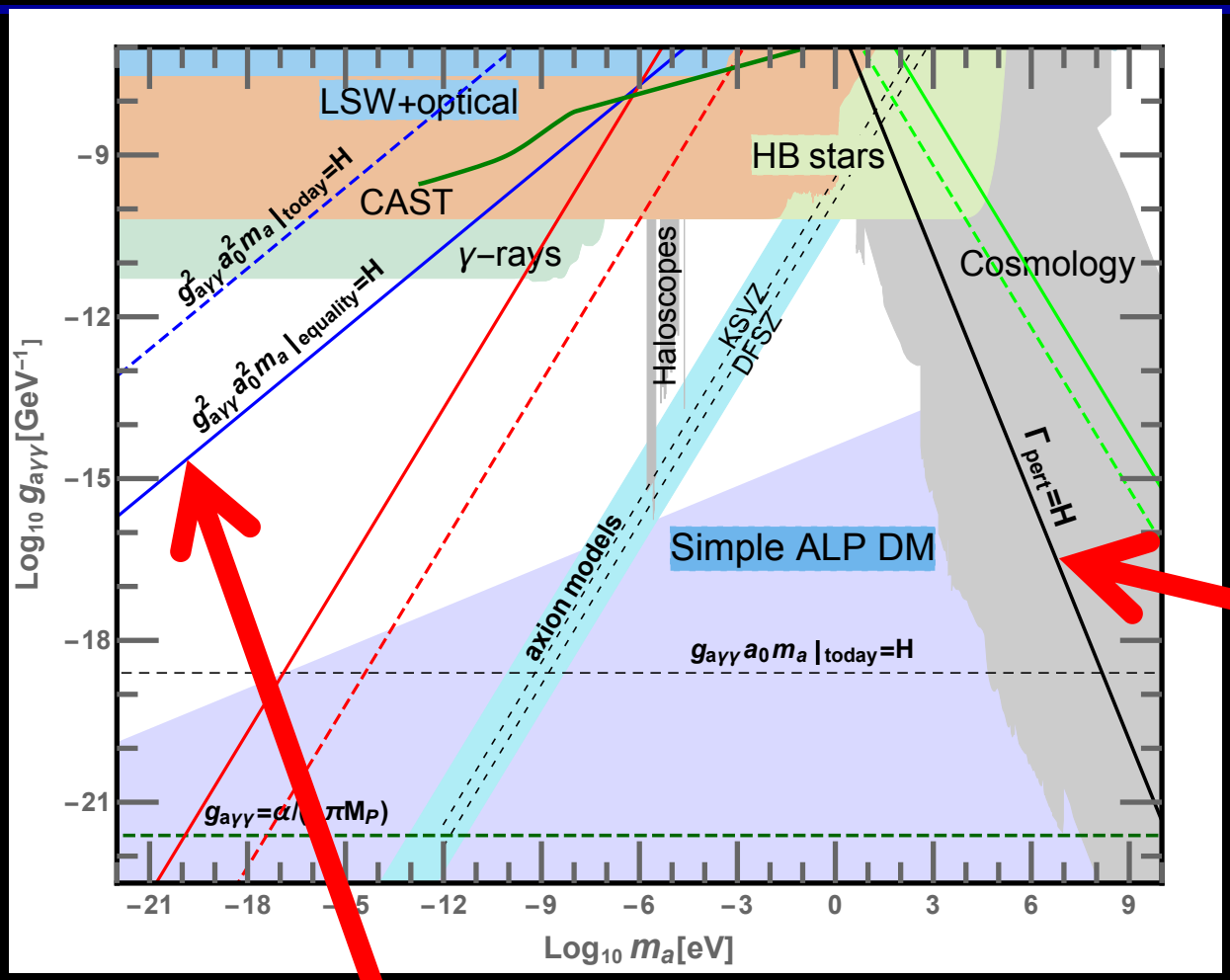
$$\Gamma_{\rm pert} = \frac{g^2_{\phi\gamma\gamma} m^3_\phi}{64\pi}$$

Without expansion/structure this would set a limit

(basically one ALP has to decay in the Universe for Bose enhancement to start)

Axion Dark Matter

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University



Standard Stability bound

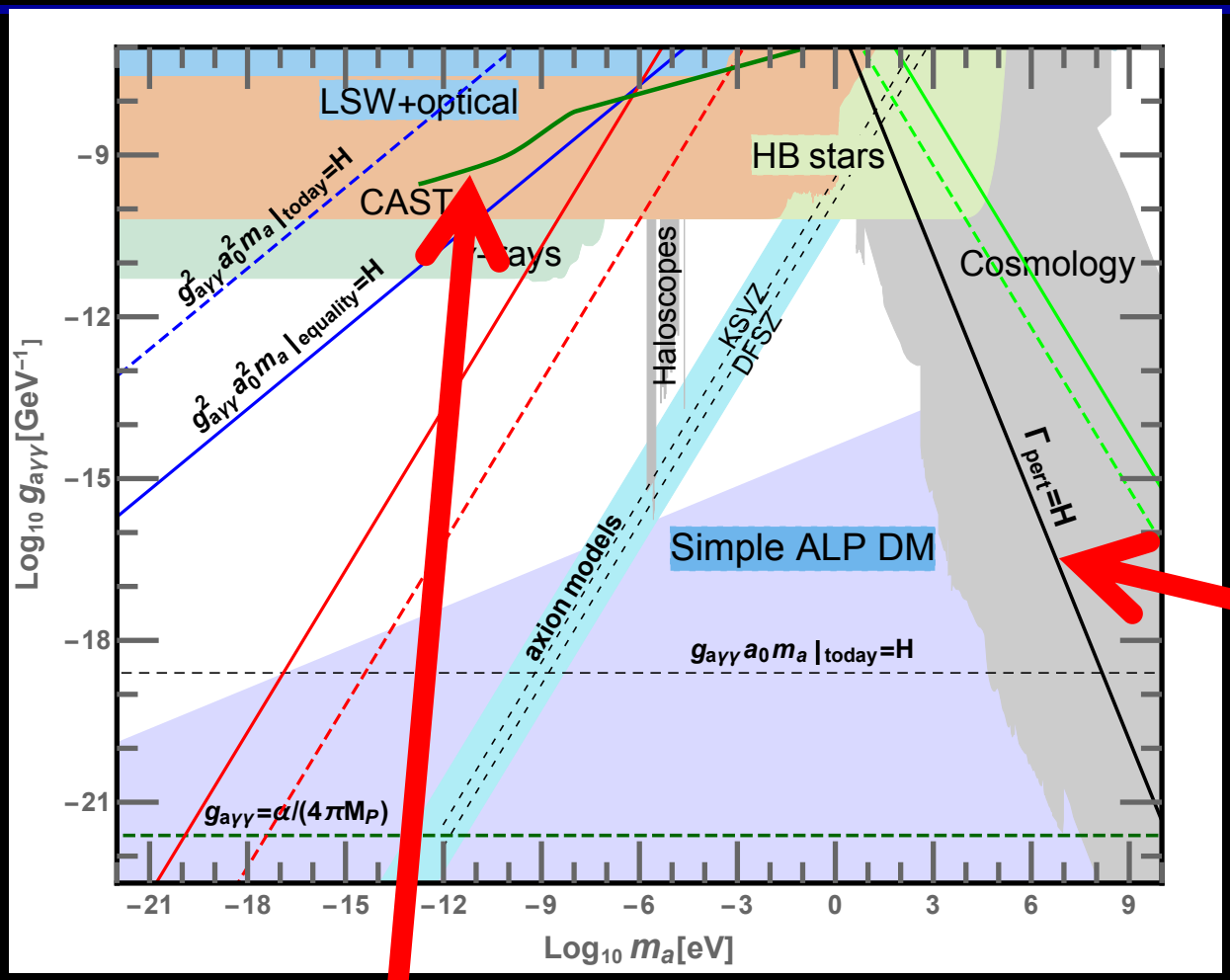
$$\Gamma_{\rm pert} = \frac{g^2_{\phi\gamma\gamma} m^3_\phi}{64\pi}$$

Including expansion

(a second ALP has to decay before the photons from the first have red-shifted sufficiently)

Axion Dark Matter

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University



Standard Stability bound

$$\Gamma_{\rm pert} = \frac{g_{\phi\gamma\gamma}^2 m_\phi^3}{64\pi}$$

Photons have mass in Plasma

➔ Prevents decay if $m_\phi \lesssim 2m_\gamma$

Exploring Beyond the Standard Scenario

Going Monodromic

Monodromy potential

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

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

Monodromy add-on

"Axion" potential
(pseudo-Goldstone pot.)

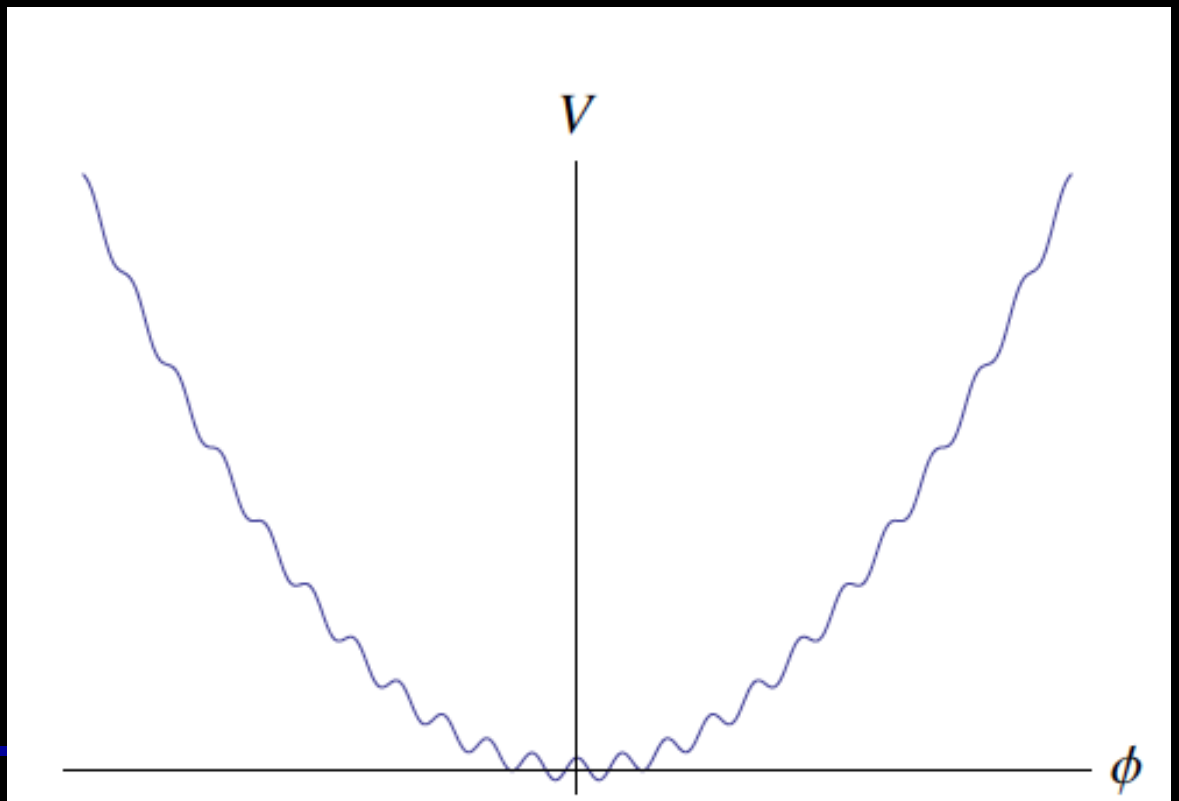
Monodromy potential

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

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

Funny potential

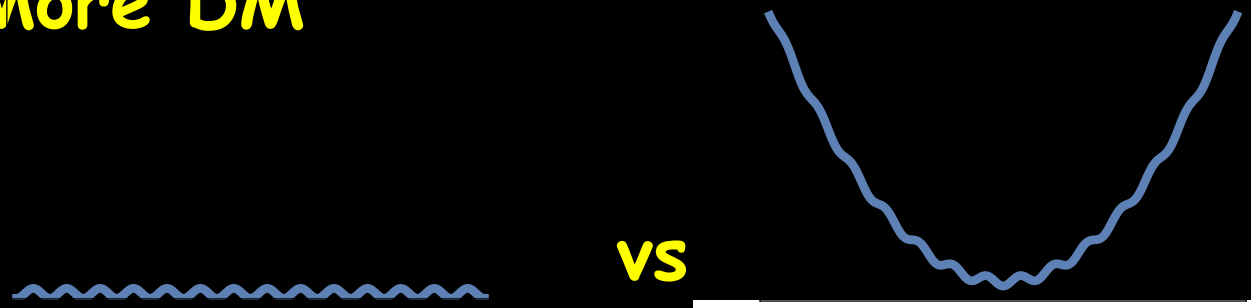
+ enlarged field range



Advantages

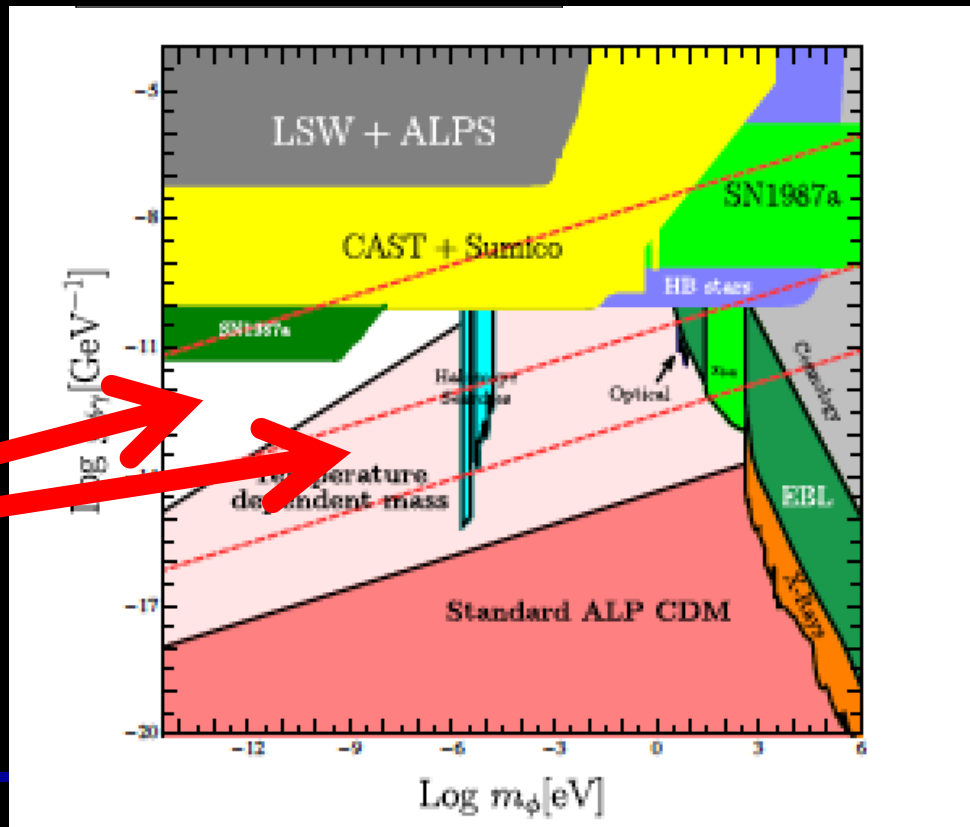
INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

- Allows to start with higher energy density
  ➔ More DM



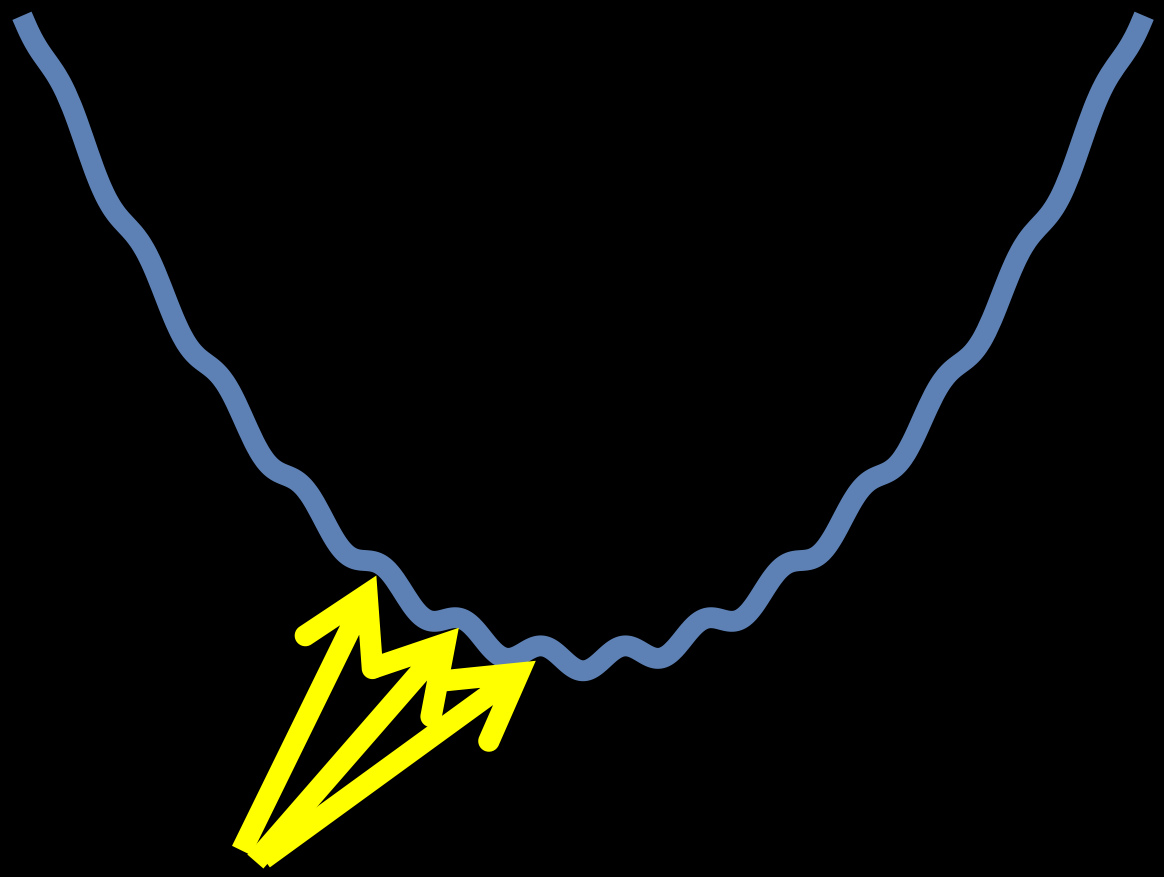
vs

Models
in this region!



Interesting Phenomena??

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

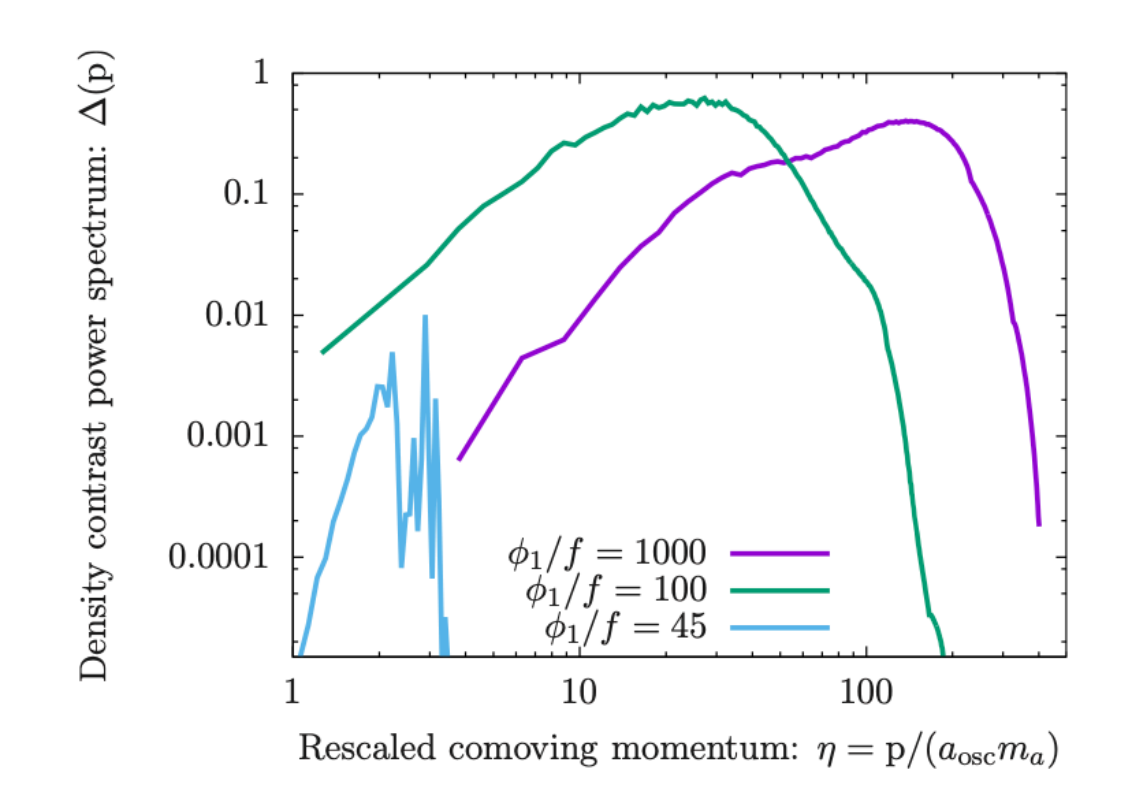


Regions with "negative mass"

Instability + Parametric Resonance
➔ Particle Production with $p \neq 0$?!?

Large O(1) fluctuations

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University



Fluctuations on small scales

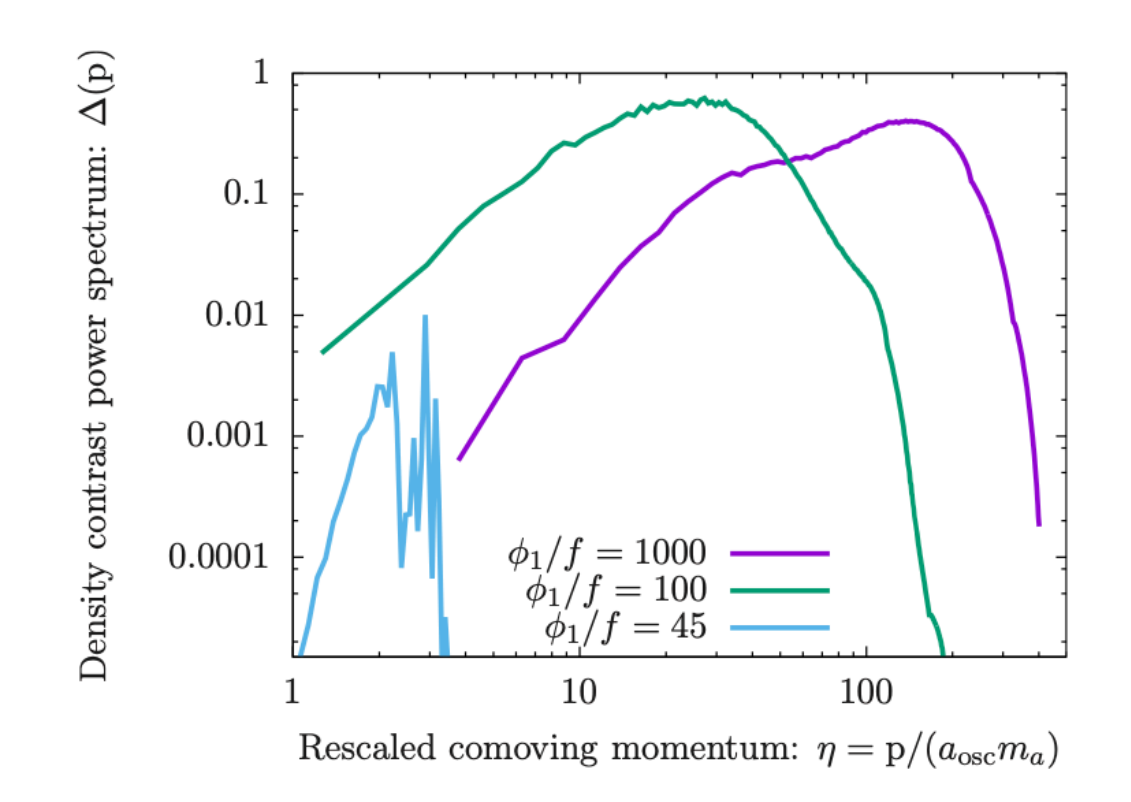
→no problem with isocurvature

→Too small to collapse into miniclusters

$$R_{\mathrm{today}}^{\mathrm{in\ structure}} \sim (10^5 - 10^6)\mathrm{km}\sqrt{\frac{\mathrm{eV}}{m_a}}\frac{a_{\mathrm{structure}}}{a_{\mathrm{today}}},$$

Large O(1) fluctuations

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University



Fluctuations on small scales

→no problem with isocurvature)

→Too small to collapse into miniclusters

$$R_{\mathrm{today}}^{\mathrm{in\ structure}} \sim (10^5 - 10^6)\mathrm{km}\sqrt{\frac{\mathrm{eV}}{m_a}}\frac{a_{\mathrm{structure}}}{a_{\mathrm{today}}},$$

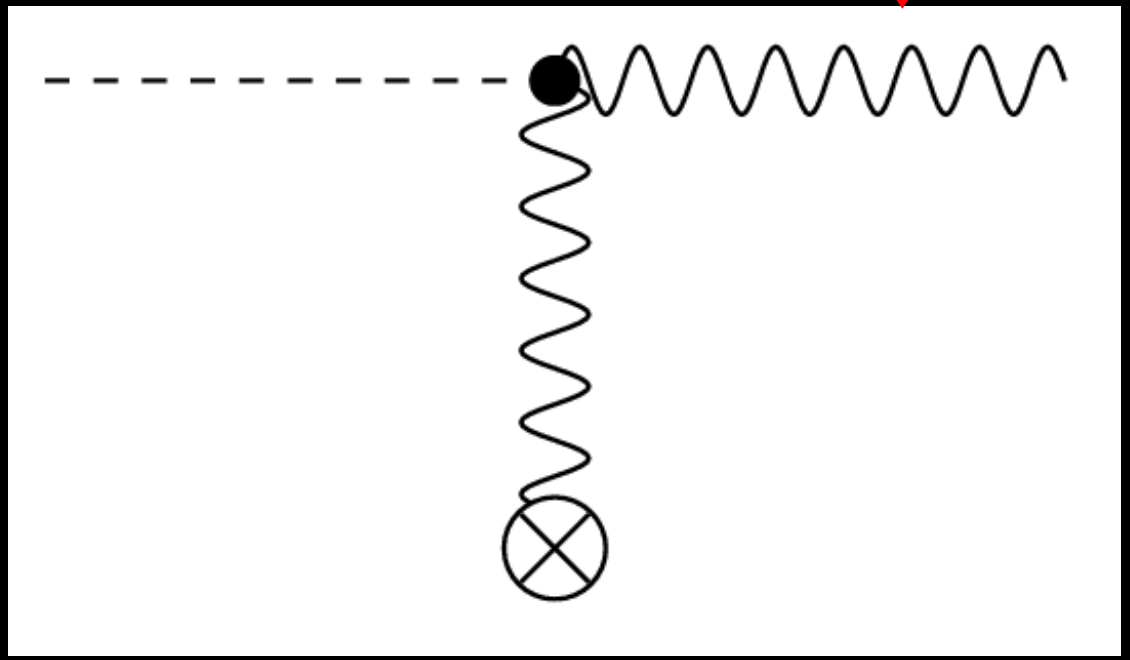
-Can we see such structures?

-Account for it in direct detection strategy

Charging it

No conserved charge
➔ absorption possible

Photon
„absorbed in detector“

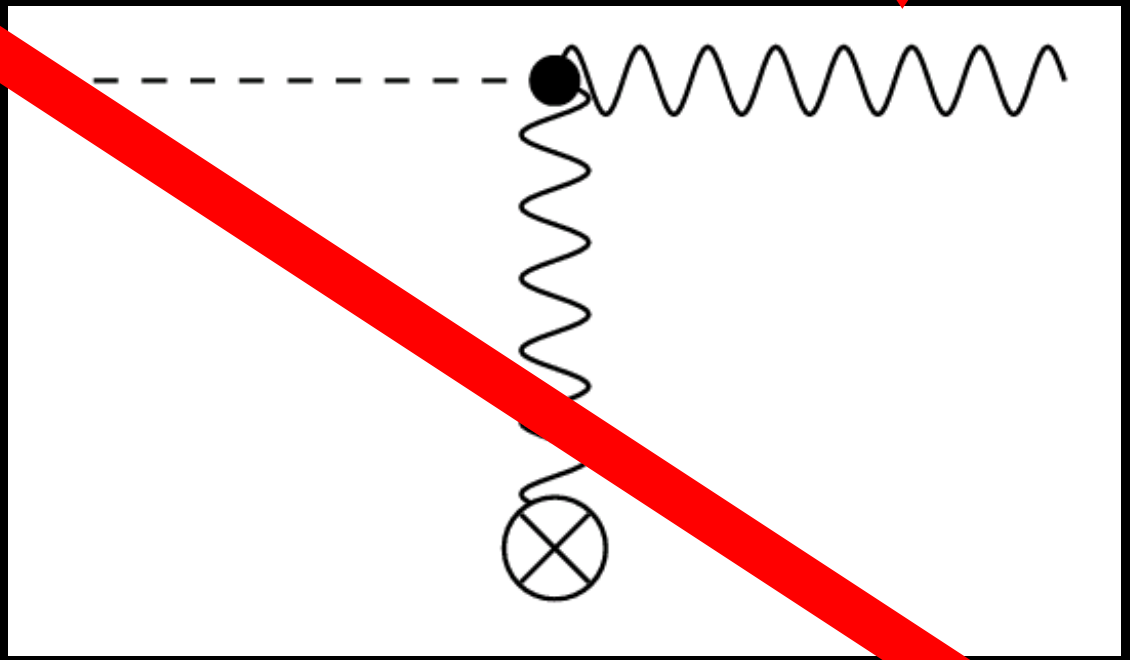


ALP
(dark matter)

With conserved charge

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

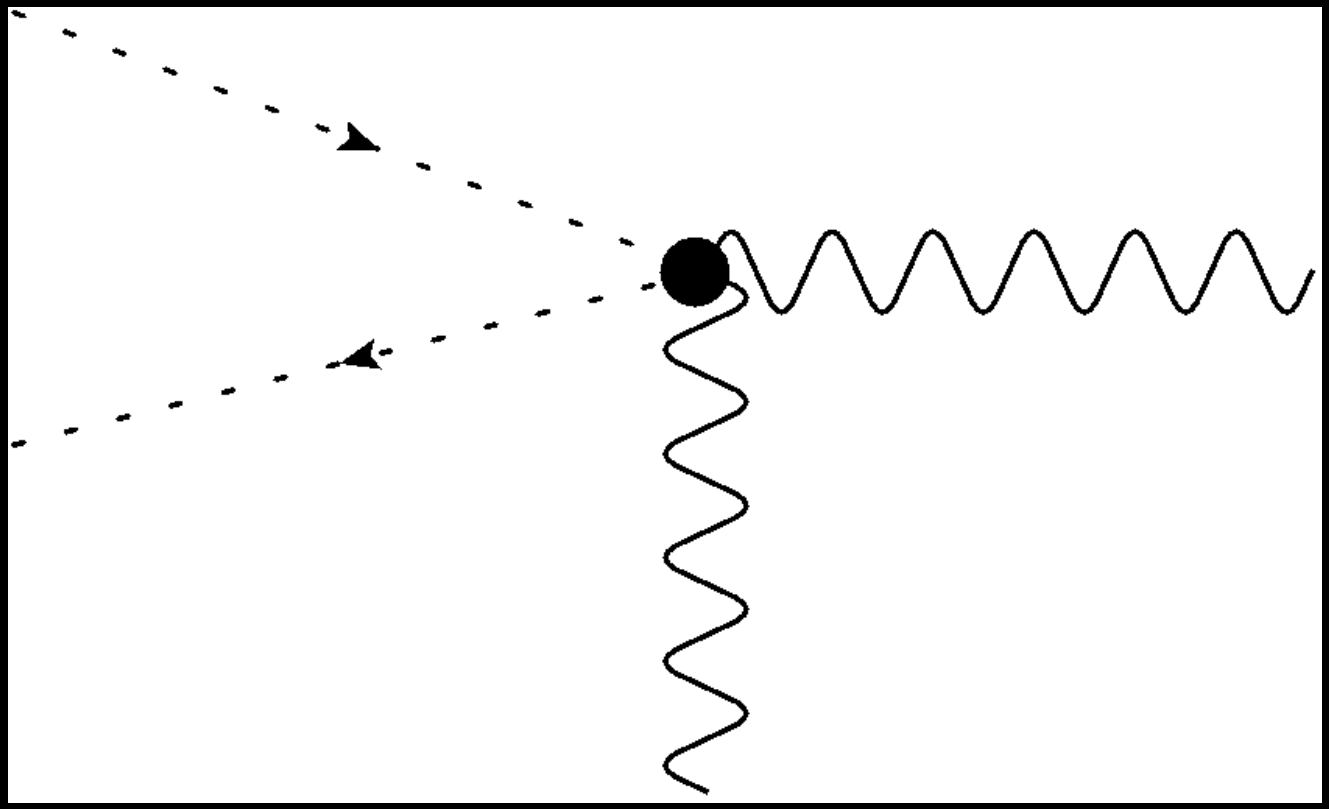
Photon
„absorbed in detector"



ALP
(dark matter)

With conserved charge

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University



Need particle and antiparticle to combine ➔ suppressed

Higher order interaction ➔ suppressed

➔ Need new methods for detection!

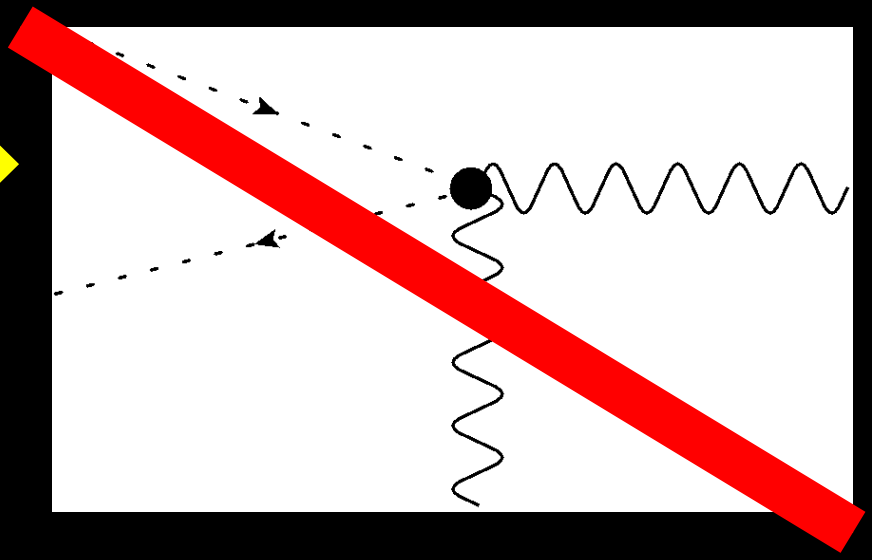
Assymmetric Charge

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

- DM could (mostly) consist of only one type of charge
- Natural mechanism Affleck-Dine

➔ No antiparticles

➔



➔Need new methods for detection!

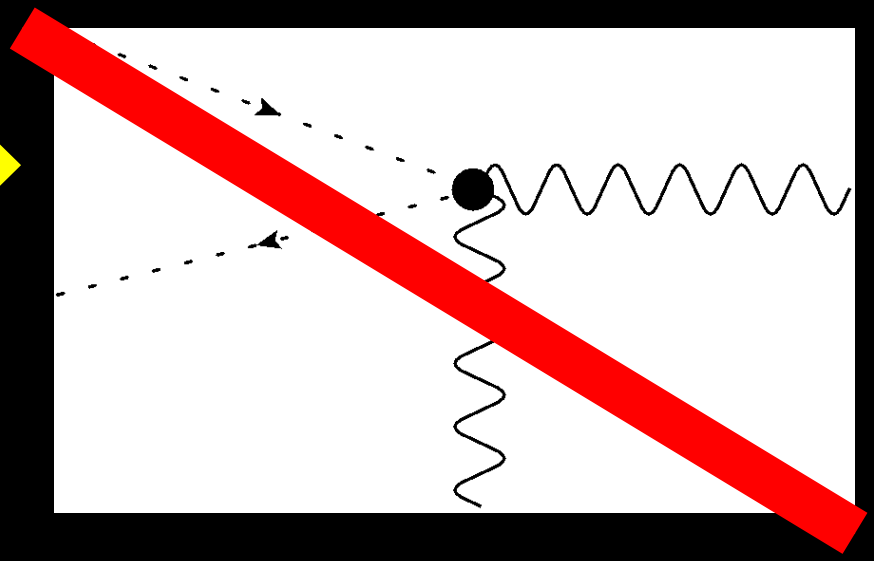
Assymmetric Charge

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

- DM could (mostly) consist of only one type of charge
- Natural mechanism Affleck-Dine

➔ No antiparticles

➔



➔Need new methods for detection!

➔Possibility for new large structures: Q-Balls

Conclusions

Conclusions

- Dark Matter may be ALPy ☺
  - ➔ New Search opportunities!
  - ➔ Searches ongoing!

  - ➔ Unusual places may be viable
  - ➔ Crazy things to explore!
  - ➔ Novel Detection techniques required

Conclusions

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

- Dark Matter may be Axiony/WISPy ☺
  - ➔ New Search opportunities!
  - ➔ Searches ongoing!
  - ➔ Unusual places may be viable
  - ➔ Crazy things to explore!
  - ➔ Novel Detection techniques required

Columbus' Theory: Tenerife – Jakarta ~ 3000 miles
Actual distance: ~ 7300 miles

https://spectrum.ieee.org/tech-talk/at-work/test-and-measurement/columbuss-geographical-miscalculations

Lesson:
Theory doesn't have to be correct
in order to find something ;-).
➔Go Explore + Be prepared
for surprises