Dark Matter – motivation & searches

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Bad Honnef physics school, May 13th, 2025
"Frontiers of Quantum Metrology for New Physics Searches"

WILHELM UND ELSE HERAEUS-STIFTUNG

[picture credit: Weizmann]

Leibniz Universität Hannover

QuantumFrontiers Cluster of Excellence

DQmat

DESY.

HELMHOLTZ QUANTUM

Quest for most fundamental structures

What is the Universe made of?

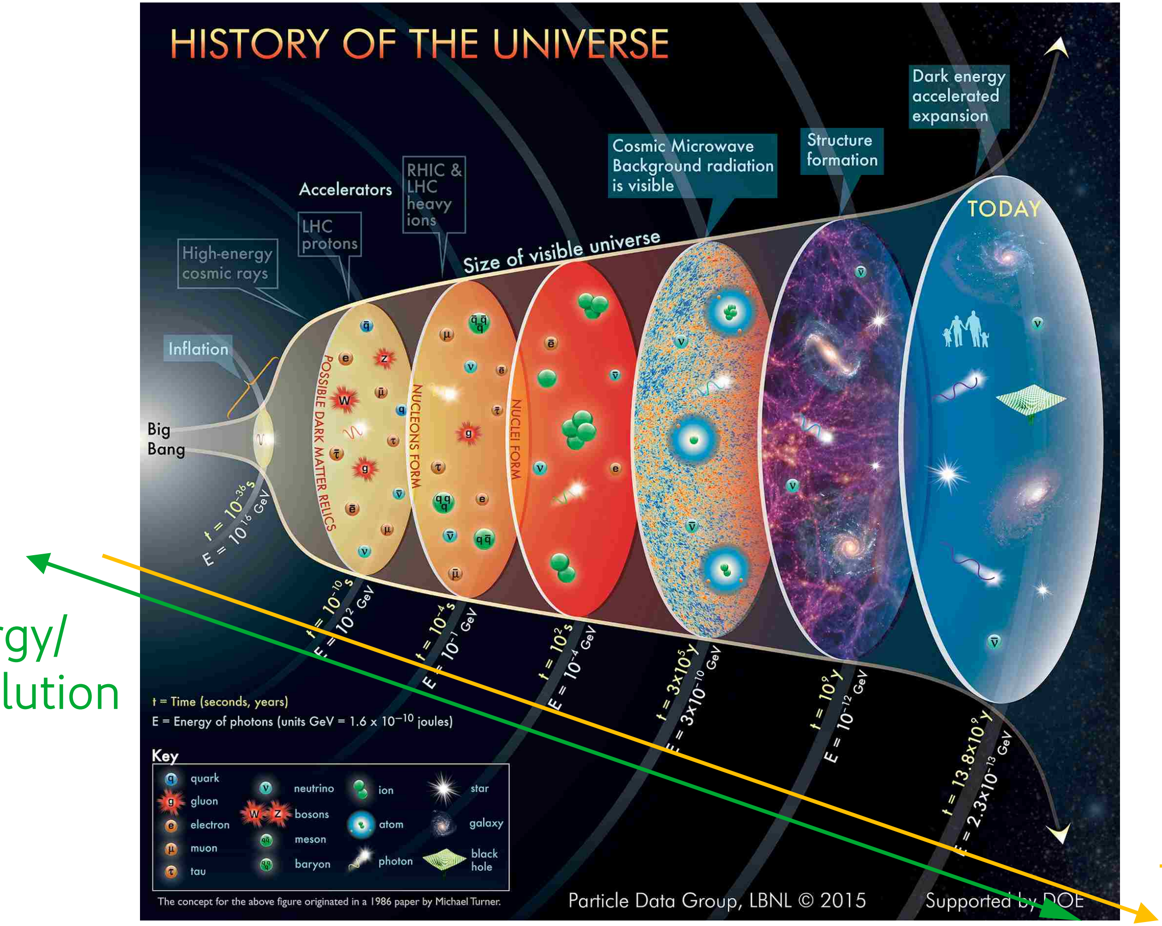
What holds the constituents together?

How can we observe invisible objects?

How can we model the dynamics of particles and the Universe and test our hypotheses?

What will bring us to the next level of understanding?

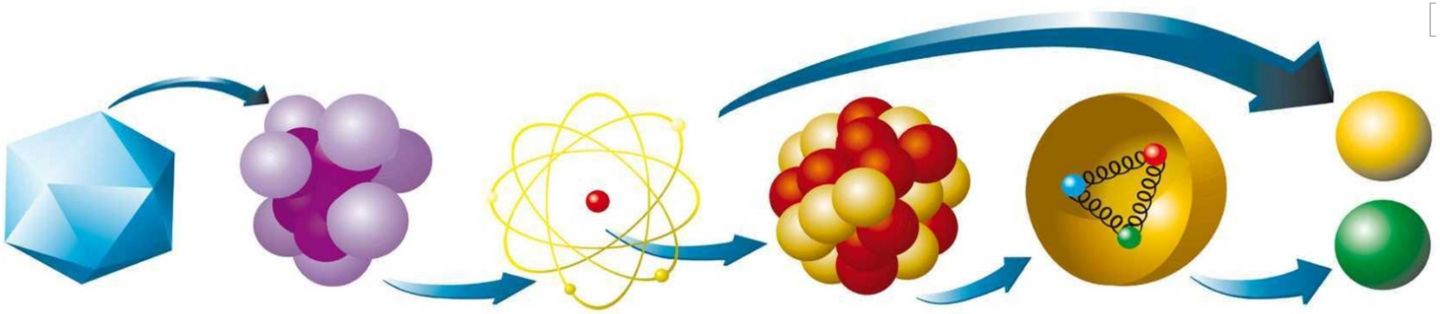
energy/
resolution



time

Building blocks of the Universe

[image credit: DESY]

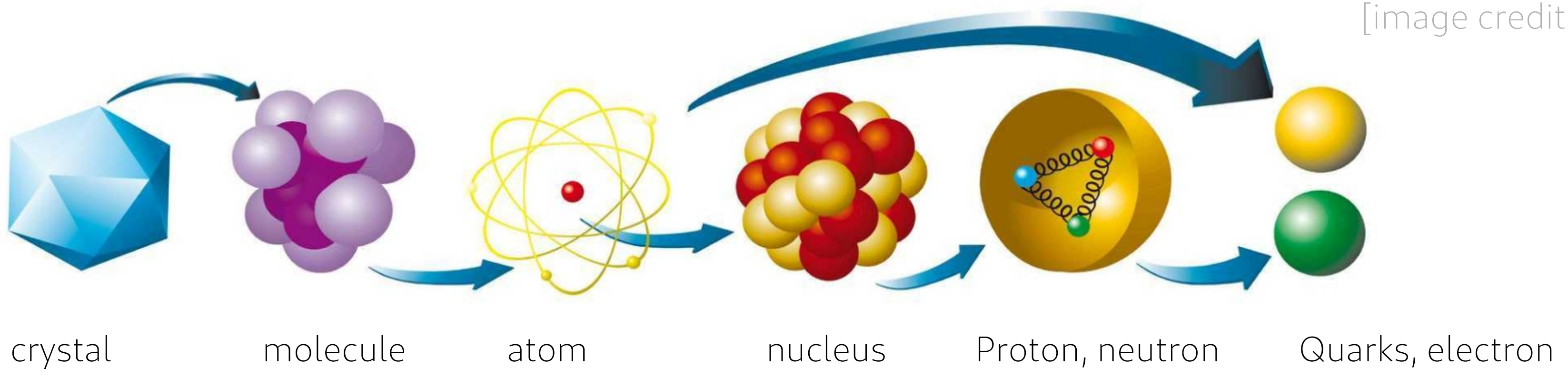


crystal molecule atom nucleus Proton, neutron Quarks, electron

The big open questions of particle physics are closely connected to the evolution of the early Universe.

Building blocks of the Universe

[image credit: DESY]



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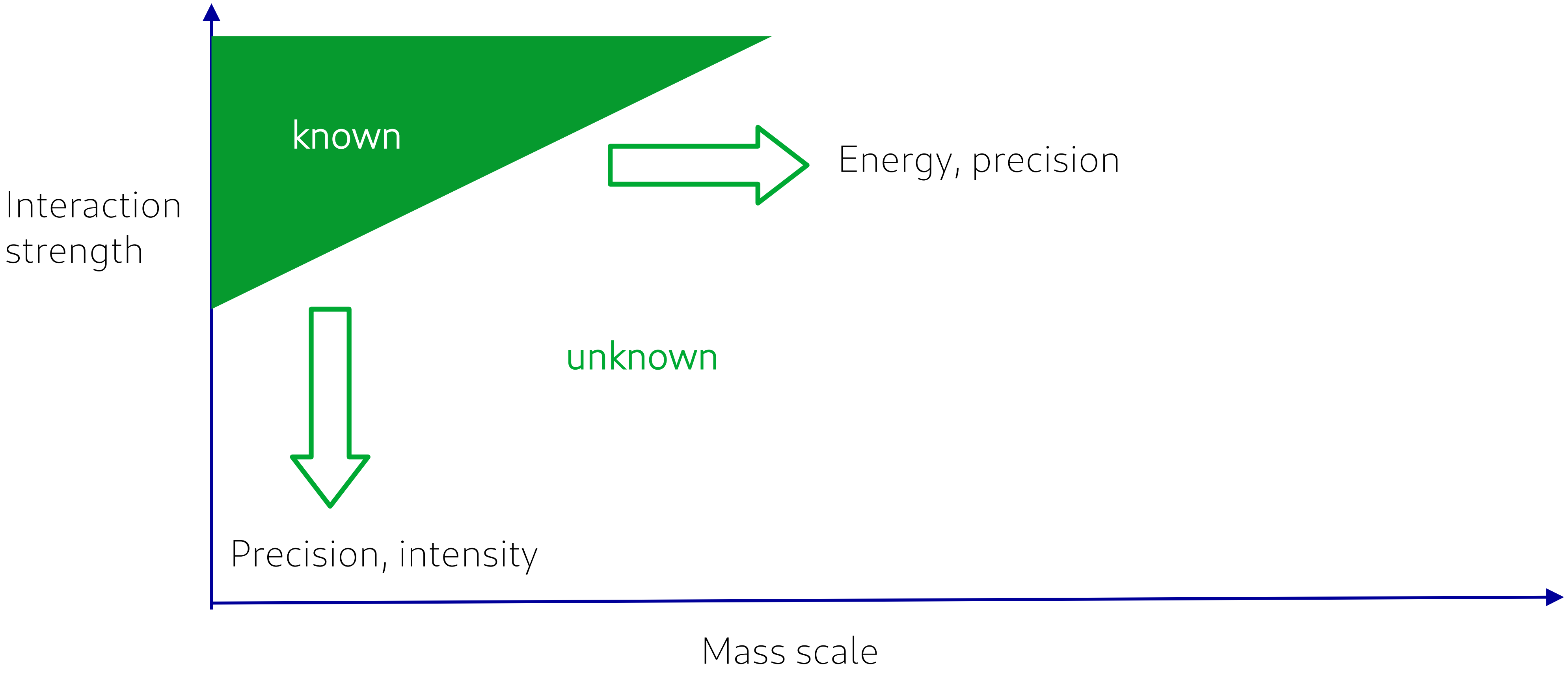
Progress towards the unknown physics



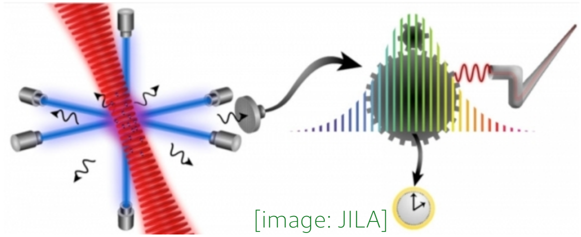
Tools to test particle physics

Colliders: LHC, Tevatron, LEP, ...

Energy:
13.6 TeV

Precision:
10^{-2} - 10^{-5}

Quantum sensors: atomic clocks

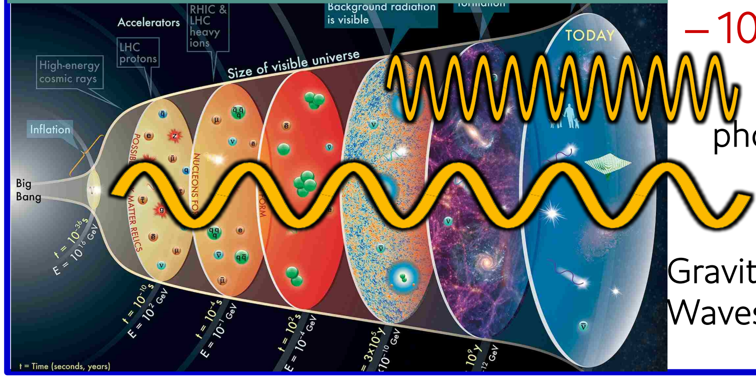


[image: JILA]

Energy:
~eV

Precision:
~10^{-18}

Cosmic messengers: CMB, GWs



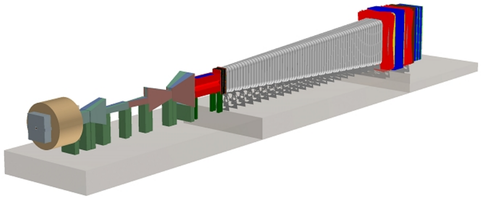
GeV
– 10^8 TeV

photons

Gravitational Waves

High-intensity experiments (to measure rare processes)

Energy:
medium
keV-GeV



Translation of units

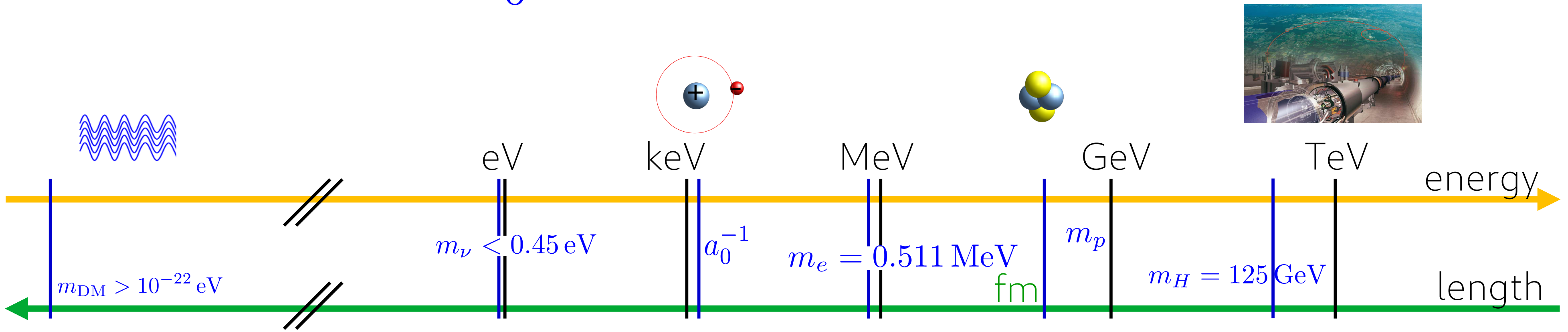
Remark: particle physicists like natural units: $\hbar = c = 1$

➜ [energy] = [momentum] = [mass]
➜ [energy] = 1/[length] = 1/[time]

Useful conversions: $1 = \hbar c = 197.3\,\text{MeV fm}$

$$\Rightarrow 1\,\text{fm}^{-1} \simeq 200\,\text{MeV}$$

$$a_0^{-1} \simeq 4\,\text{keV}$$



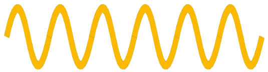
I. Particle physics today and
need for beyond the Standard Model

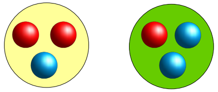
II. Models of Dark Matter

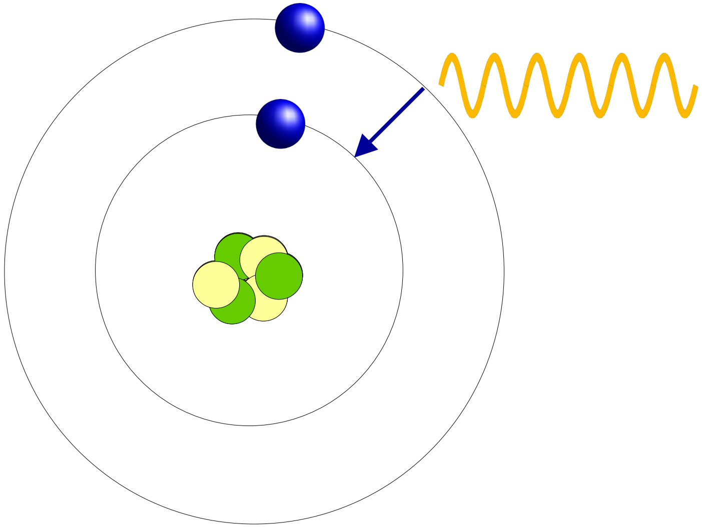
III. Atomic searches for Dark Matter/ New Physics

I. Particle physics today and
need for beyond the Standard Model

Elementary particles in atoms

- In electrodynamics and atomic physics, these particles play a leading role
  - the photon 
  - the electron 

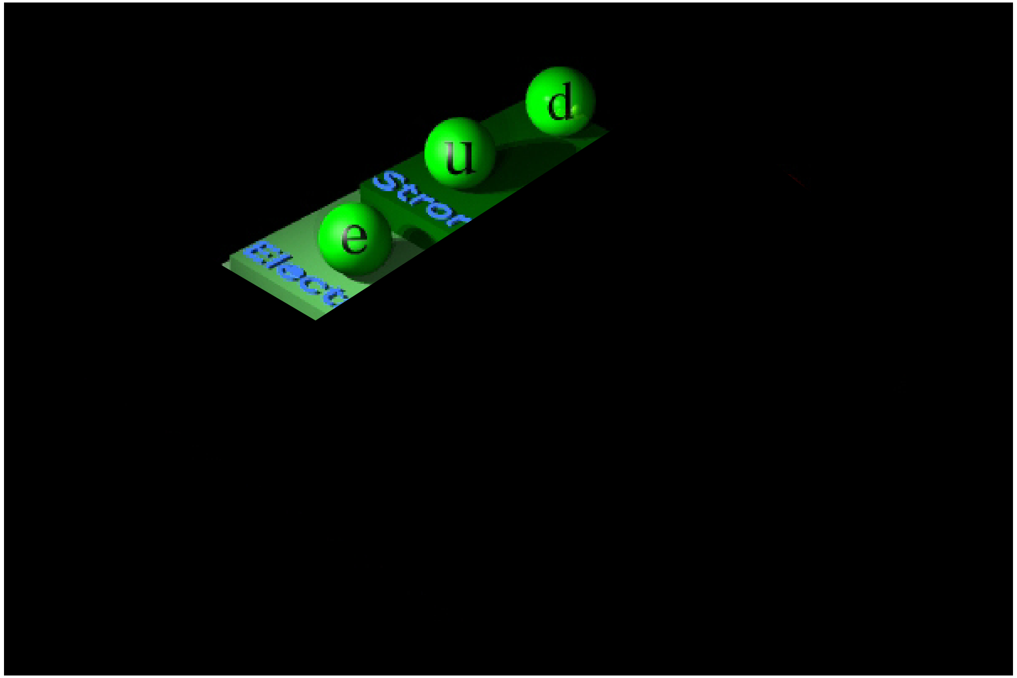
    (and its antiparticle, the positron)
  - up- and down quarks in proton, neutron 



- More subtle effects by
  - Z-boson of electroweak force → parity violation
  - Other quarks and gluons in proton, neutron
- Could new particles/ fields affect atoms/ ions/ nuclei?
  - New force carriers? → Z’ boson, dark photon, “fifth force”
  - Dark Matter? → recoil from nucleus, electron, or changing fundamental constants

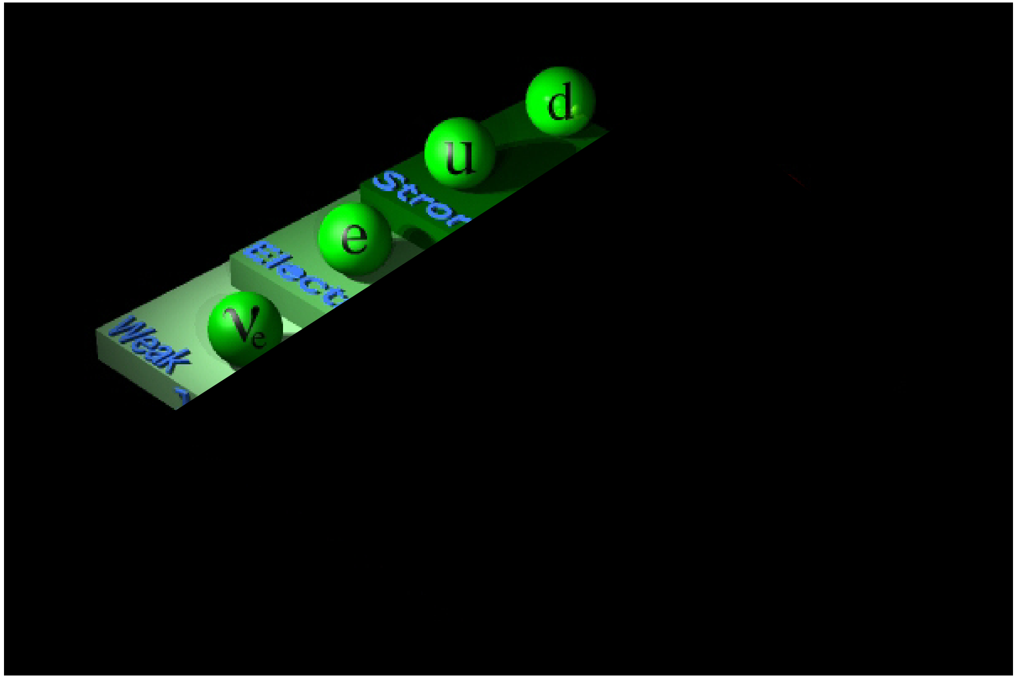
Precision measurements can probe Dark Matter & new interactions in atomic systems

The particles of the Standard Model



- Atoms mostly made of
  - electrons (charged lepton)
  - up and down quarks in the neutrons and protons

The particles of the Standard Model



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- Neutrino: neutral lepton, massless in SM

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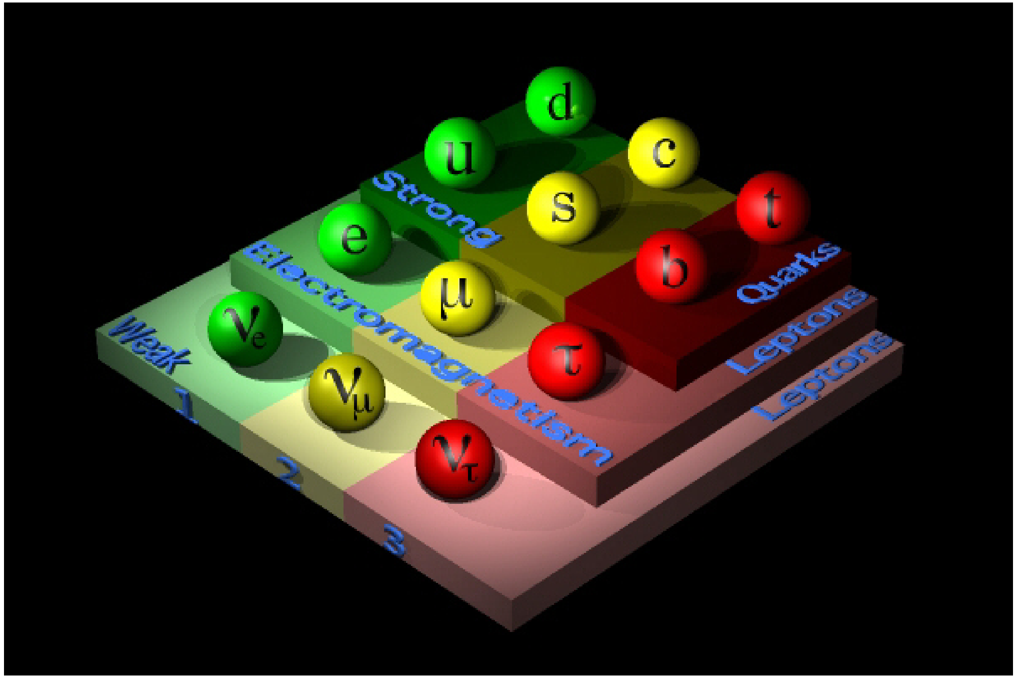

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- 2nd & 3rd generation: heavier copies of the 1st

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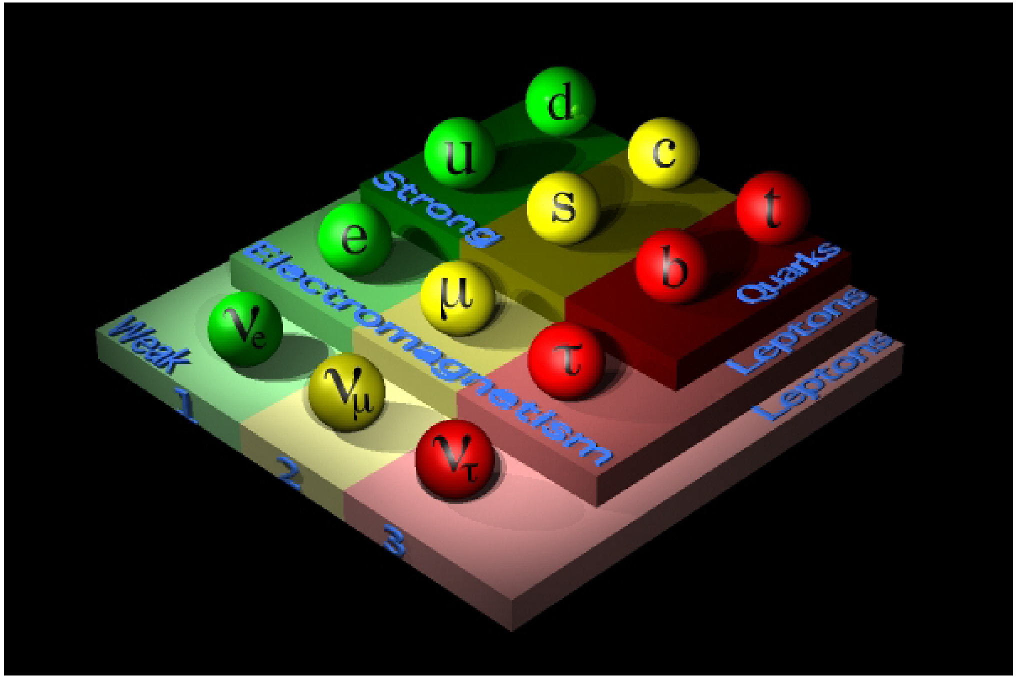

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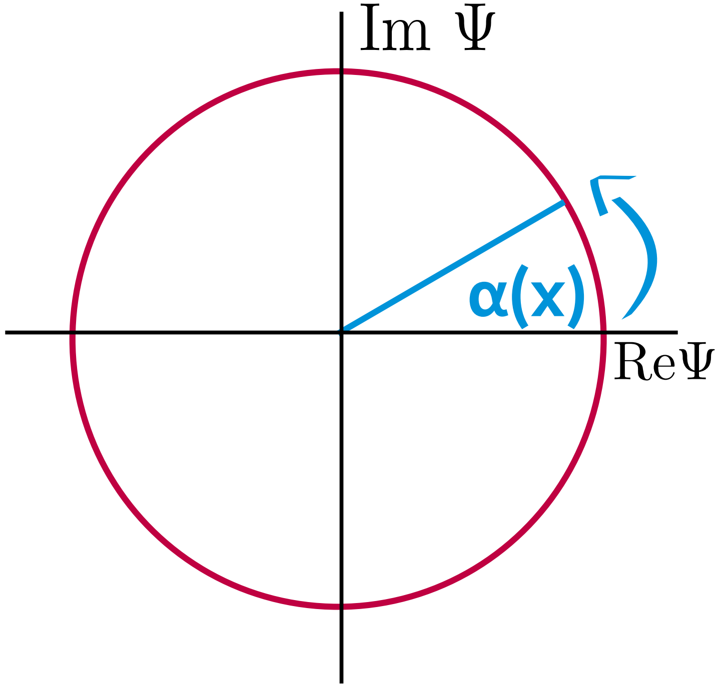
Building blocks as fermions: Matter particles (quarks and leptons) exist in 3 generations.

Symmetries of the theory

- Gauge symmetries:
  - Physics, i.e. action $S = \int d^4x \mathcal{L}\left(\phi(x), \partial_\mu \phi(x)\right)$ invariant under local symmetry transformations $\Psi(x) \to \Psi'(x)$
  - e.g. simplest case with one parameter $\widehat{=}\, U(1)$

$$\Psi(x) \to \Psi'(x) = e^{-i\alpha(x)}\Psi(x)$$

  - QED: conservation of electric charge



Gauge bosons as force carriers

Invariance under these symmetry transformations requires new spin-1 bosons: the gauge bosons ↔️ force carriers

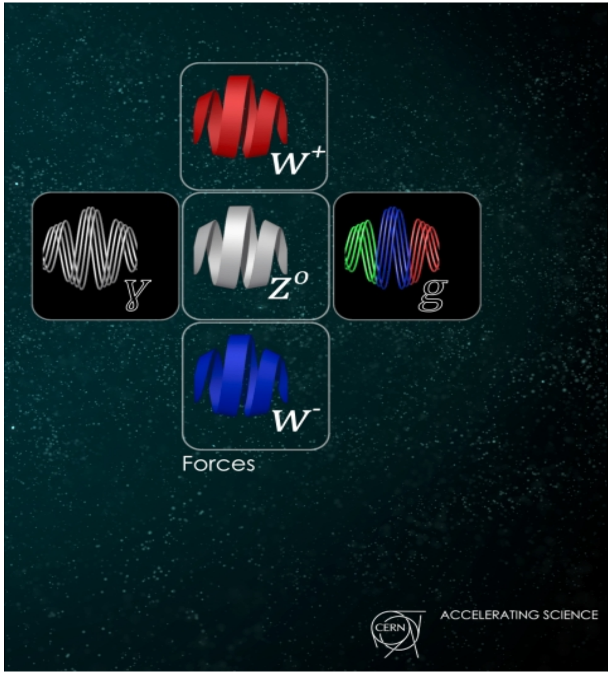
SM symmetry group and its interactions

$$G_{SM} = SU(3)_c \otimes \underbrace{SU(2)_L \otimes U(1)_Y}_{\longrightarrow U(1)_{\mathbf{em}}}$$

Strong:
Gluons g

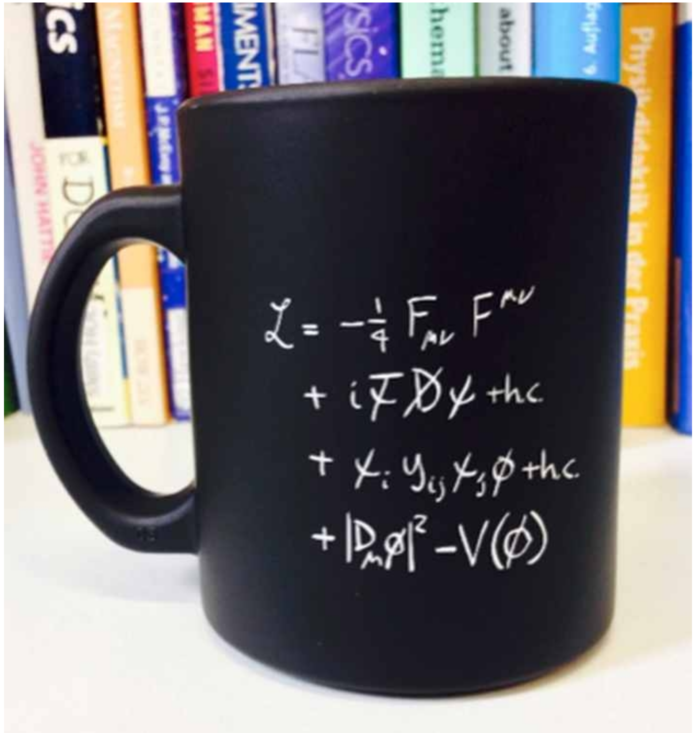
Electroweak: γ, W, Z

Symmetry breaking
→ Higgs boson H



An elegant Lagrangian

- As in mechanics, the SM is described by its Lagrangian



Observation: gauge bosons have masses, but explicit mass terms break symmetry

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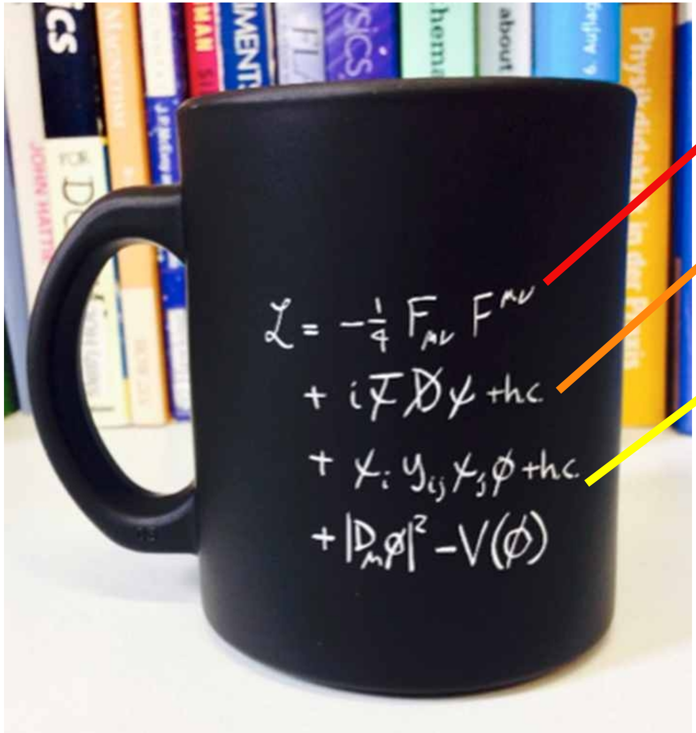

gauge bosons: self-interaction

fermions including their interaction with gauge bosons

Fermions-Higgs (Yukawa) interaction

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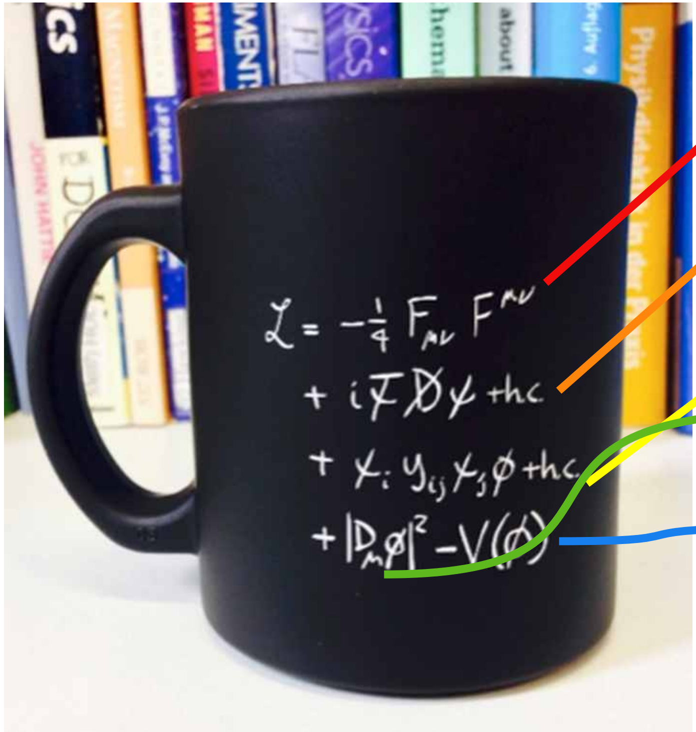

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Higgs kinetic term and its interaction with gauge bosons

Higgs potential

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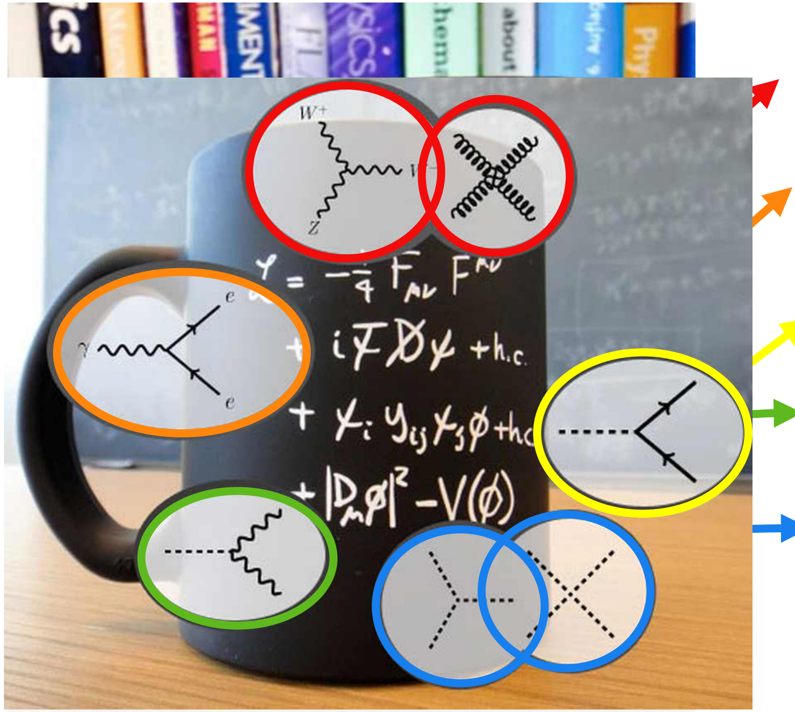

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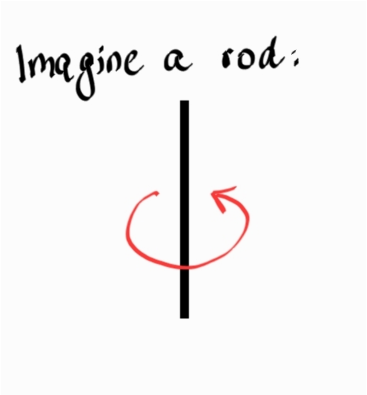
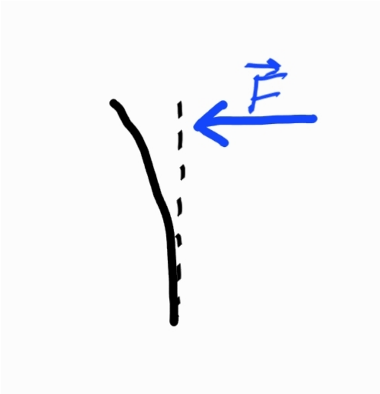
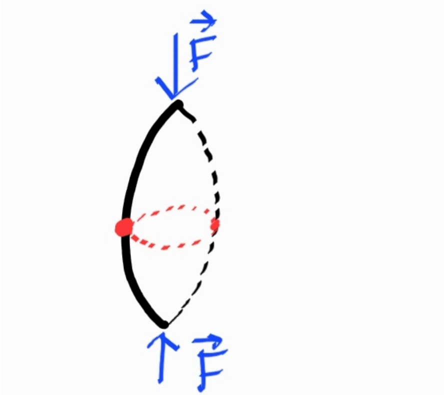
Spontaneous symmetry breaking (SSB)



Unbroken symmetry
→ rotational invariance



External force
→ bending breaks
symmetry explicitly



all directions of bending equal
→ bending breaks symmetry
spontaneously

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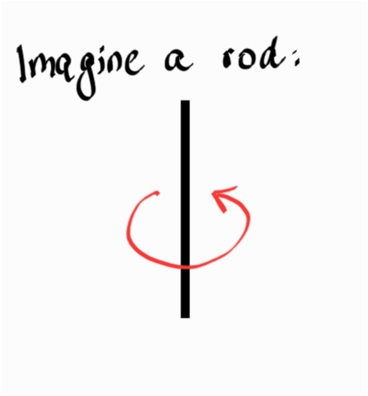

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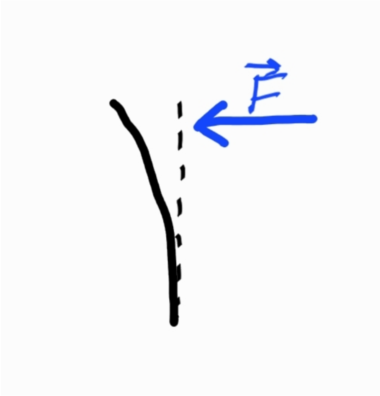

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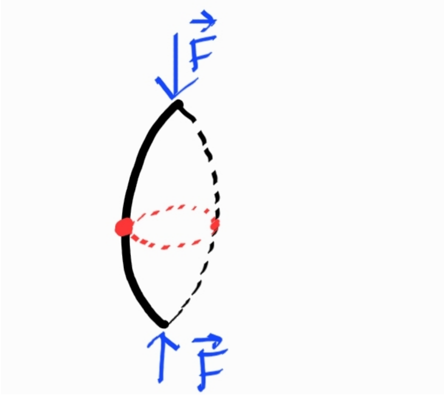

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→ bending breaks symmetry
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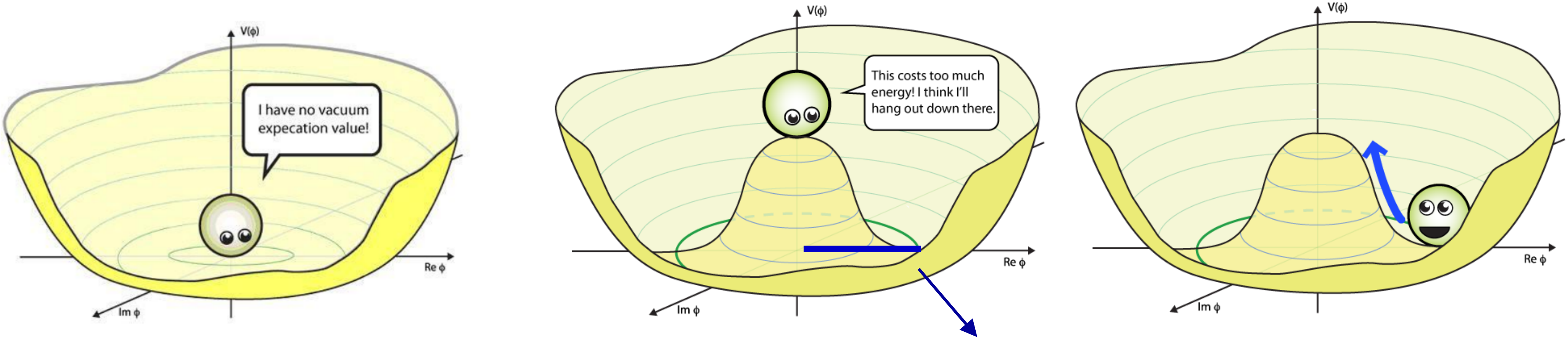
- SSB does not break the symmetry of the Lagrangian
- but the chosen ground state breaks the symmetry

The Higgs mechanism

Minimal (elegant) Higgs potential in the SM: $V(\Phi) = \frac{\lambda}{4}\left(\Phi^\dagger\Phi\right)^2 - \mu^2\left(\Phi^\dagger\Phi\right)$



[QuantumDiaries]

Vacuum expectation value **v≠0**

$$m_H = \sqrt{\lambda/2}v$$

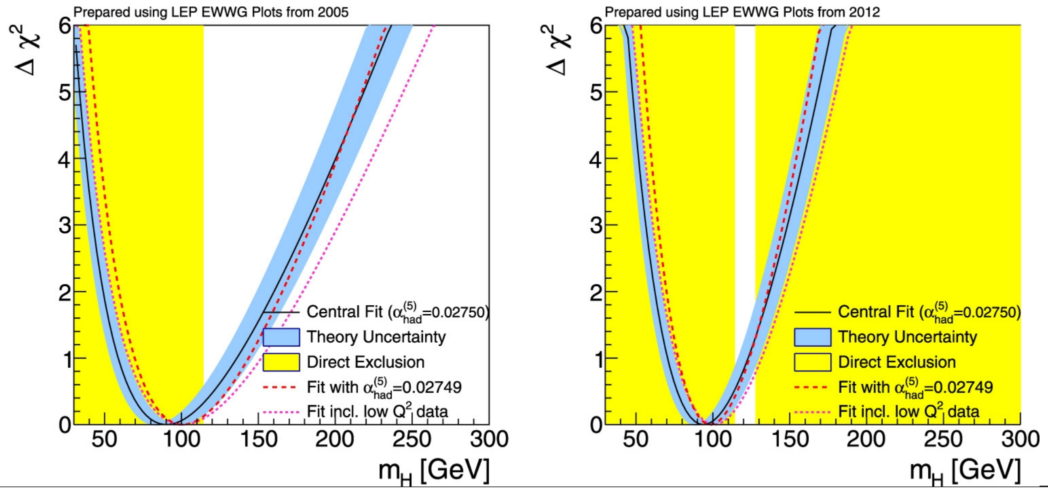
The particles obtain a **mass** proportional to the vacuum expectation value of the Higgs boson.

We observe massless and massive particles in nature. → mechanism?

Hierarchy problem of the Higgs mass

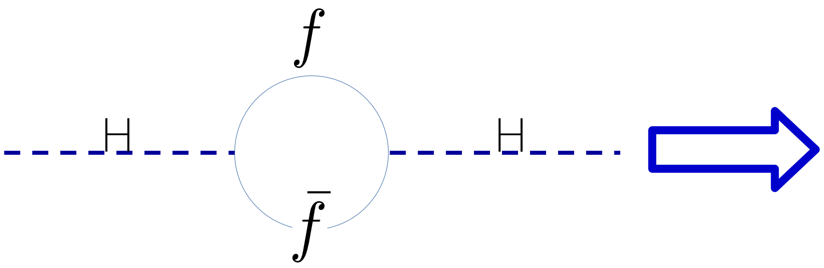
Higgs mass m_H is a free parameter of the SM.
→ needs to be measured: ATLAS & CMS @ LHC measured m_H = 125 GeV.
Ok.

Is this surprising?
No: The global fit of electroweak precision data pre-Higgs-discovery indicated the 100 GeV scale.
The W and Z boson masses were discovered around the same scale.



Hierarchy problem of the Higgs mass

Is it a problem?
Yes, at least it is unnatural.
A fundamental scalar is quadratically sensitive to the cutoff scale of the theory.



$$\Delta m_H^2 \propto -2N_f \left(A \int^{\Lambda} \frac{d^4k}{k^2} + 2m_f^2 \int^{\Lambda} \frac{dk}{k^2} \right)$$
$$\propto -2N_f \left(A\,\Lambda^2 + B\,\ln\Lambda\right)$$

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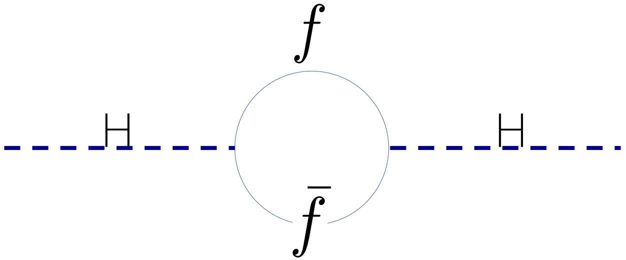

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If there is no New Physics below M_{pl}: **Λ** → M_{Pl}

Hierarchy problem → fine tuning

Explain observation: $$m_H^2 = m_{H,0}^2 + \Delta m_H^2 \stackrel{!}{=} (125\,\mathrm{GeV})^2$$

- m_H^2: physical mass
- $m_{H,0}^2$: bare mass parameter in $\mathcal{L}$
- Δm_H^2: $\propto M_{\mathrm{Pl}}^2 = 10^{38}\,\mathrm{GeV}^2$
- $(125\,\mathrm{GeV})^2$: $10^4\,\mathrm{GeV}^2$

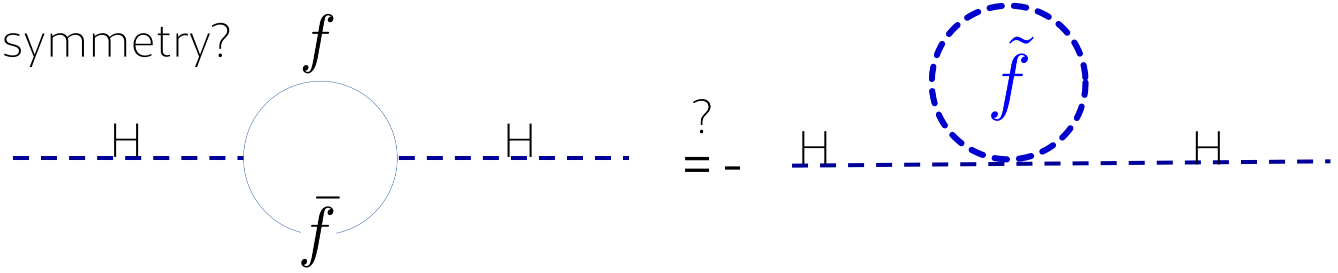
Hierarchy problem → fine tuning

Explain observation: $$m_H^2 = m_{H,0}^2 + M_{\mathrm{Pl}}^2 \stackrel{!}{=} (125\,\mathrm{GeV})^2$$

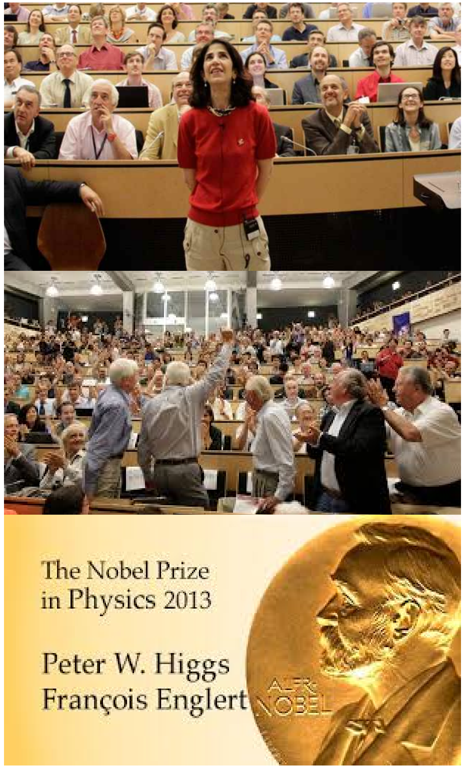
$m_{H,0}^2$: $\mathcal{O}(10^{38}\,\mathrm{GeV}^2)$ — M_{Pl}^2: $\mathcal{O}(10^{38}\,\mathrm{GeV}^2)$ — $(125\,\mathrm{GeV})^2$: $10^4\,\mathrm{GeV}^2$

Cancellation of 34 orders of magnitude needed!
34 out of 38 digits need to exactly cancel each other to yield the observed Higgs mass.
Not impossible, but calls for explanation.

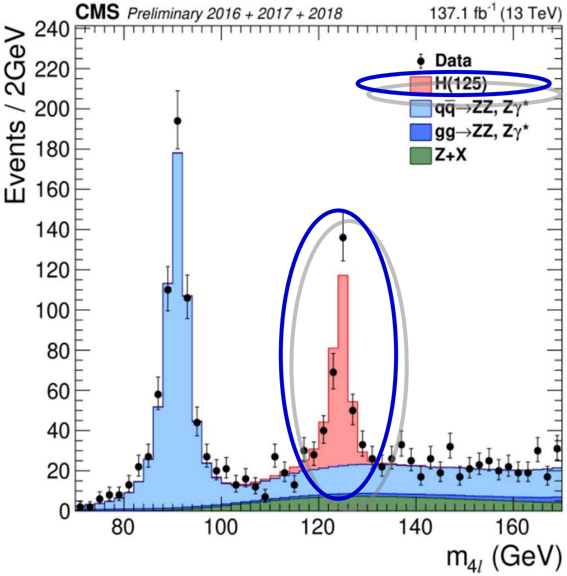
Δm_H^2 cancelled by symmetry?



Higgs under experimental scrutiny



1964 [Brout Englert] [Higgs]
[Hagen Guralnik Kibble]
2012 [ATLAS, CMS @LHC/CERN]



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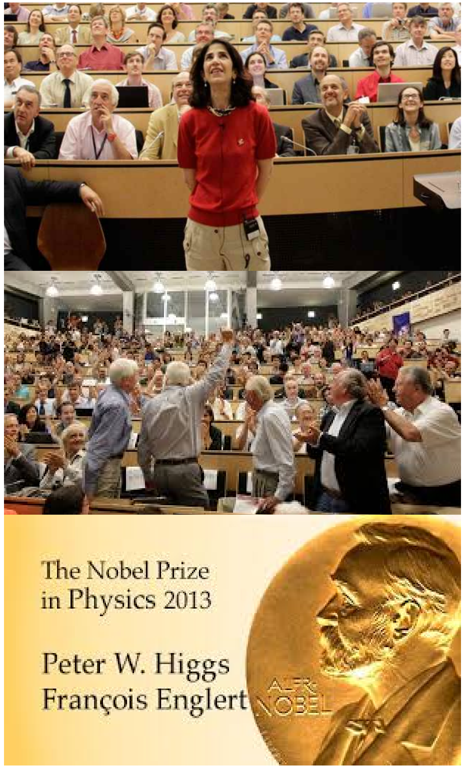

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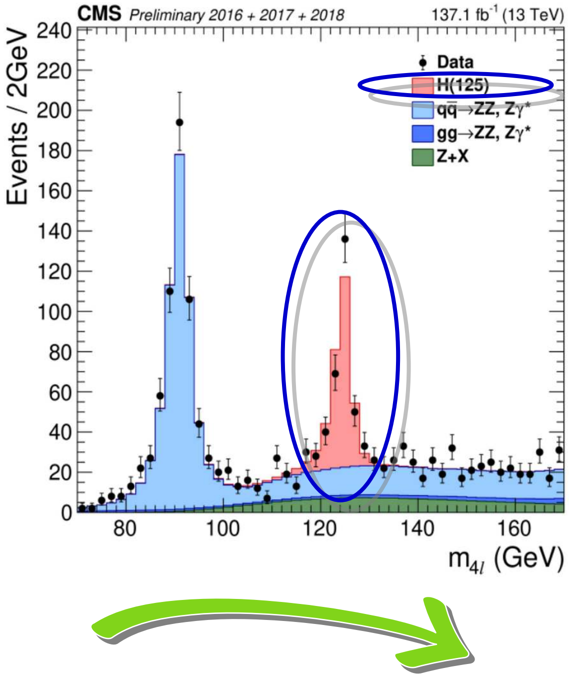
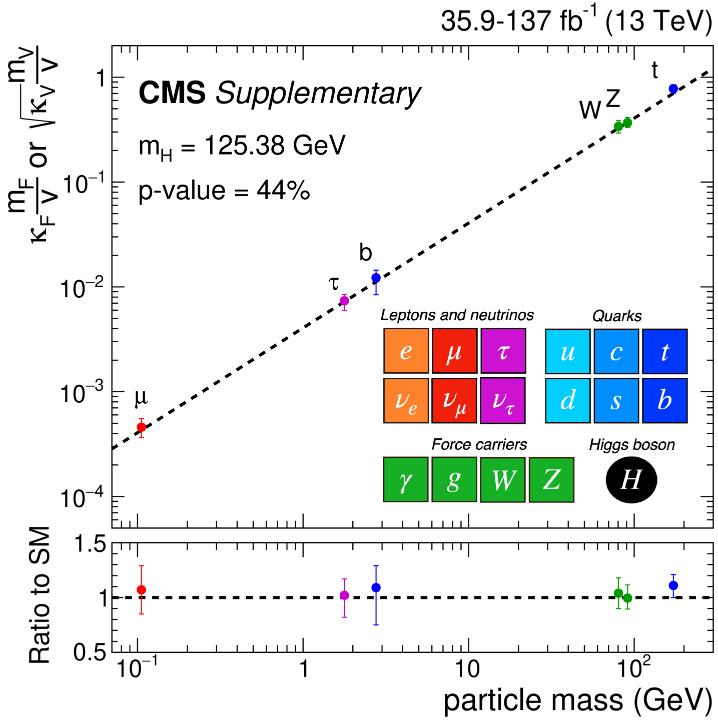




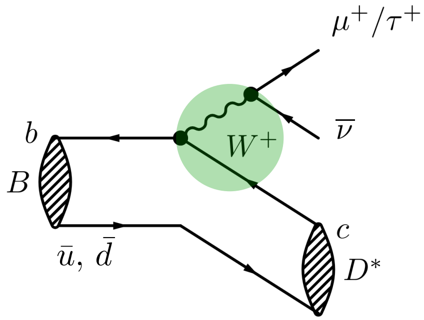
So far, its properties are compatible with the SM, but New Physics may contribute within the uncertainties. Many properties not even determined yet!

Data mostly SM-like + some deviations

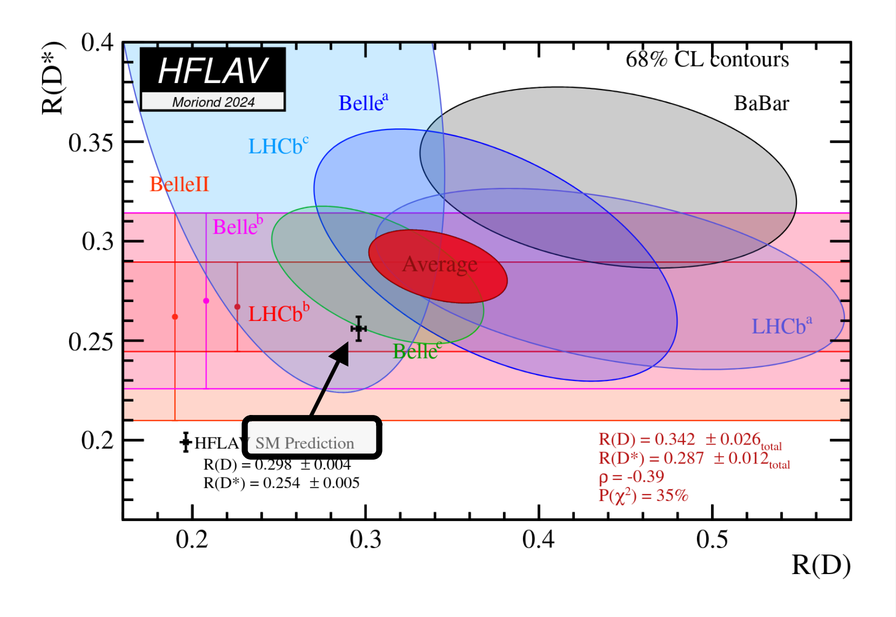
Standard Model highly successful theory, tested precisely.
But: intriguing "anomalies" (deviations from SM expectation)

An example at high energy:

$\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau/\ell^-\bar{\nu}_\ell$

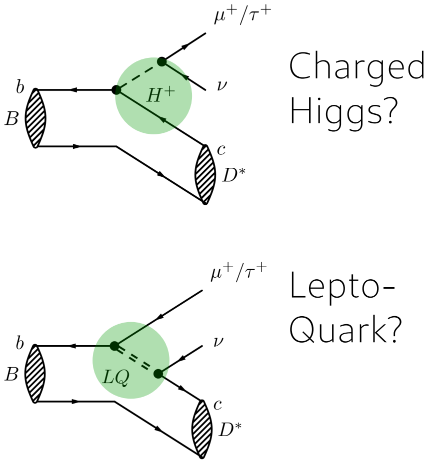


How often are 3[rd] generation leptons in final state compared to 1[st] and 2[nd] generation?



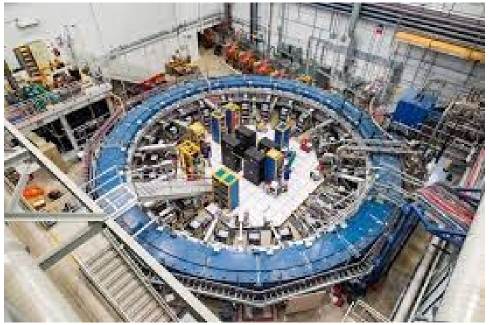
3 σ tension between data and SM

High sensitivity to NP in comparison of ratios (systematics cancel)

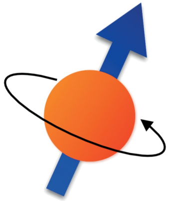


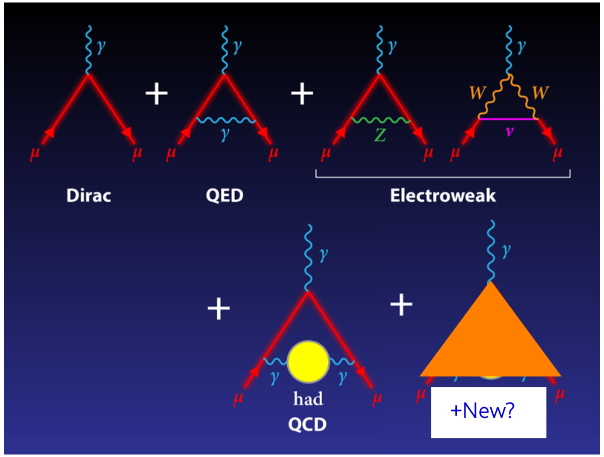
Magnetic moment of the muon (g-2)

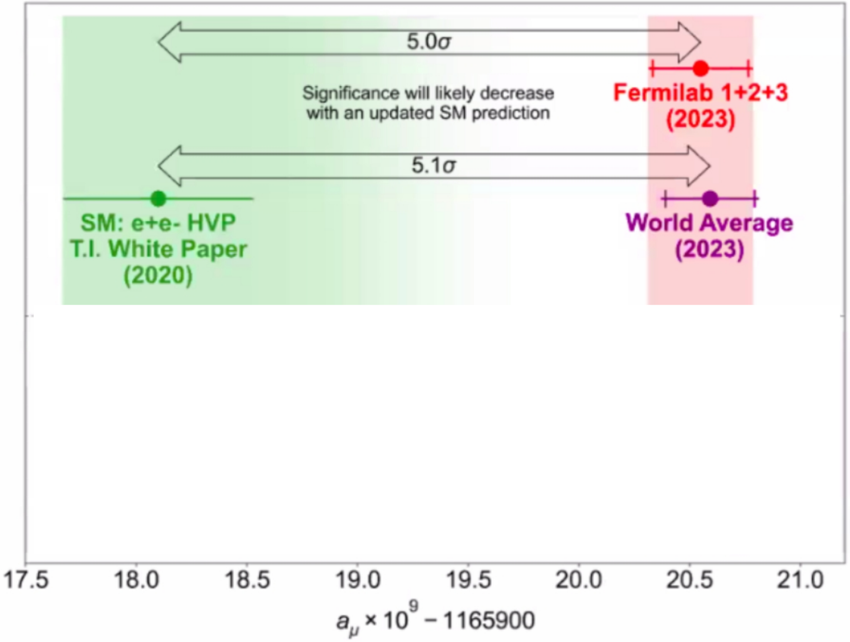
An example at lower energy & higher precision



Polarized muons in storage ring
→ measure spin precession







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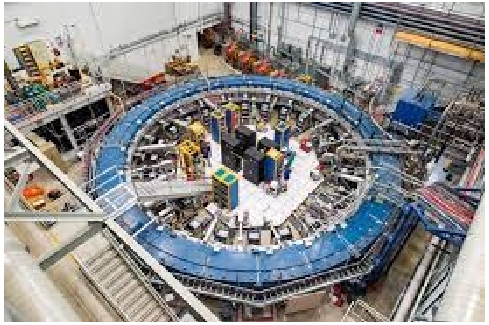

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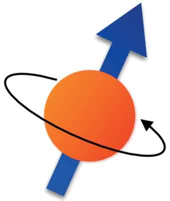
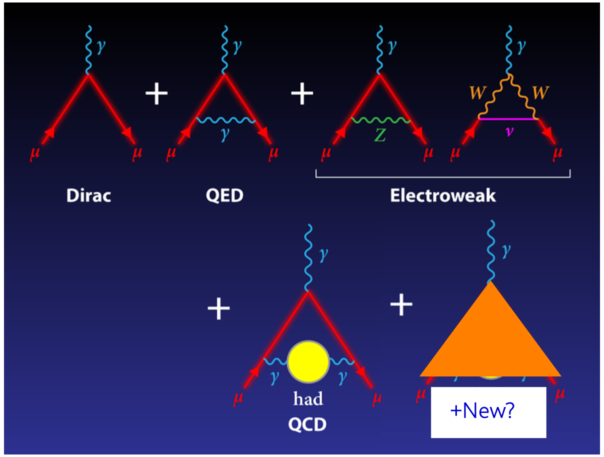
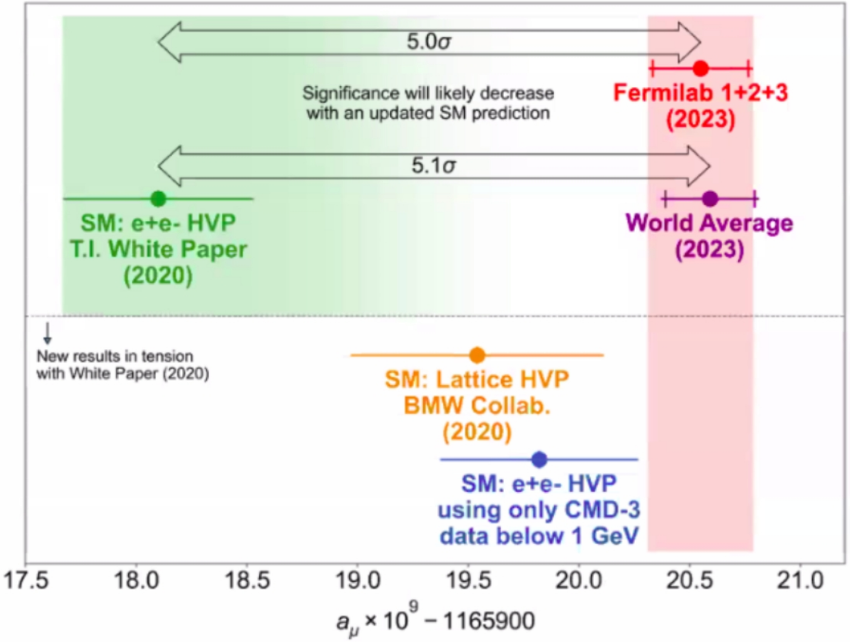


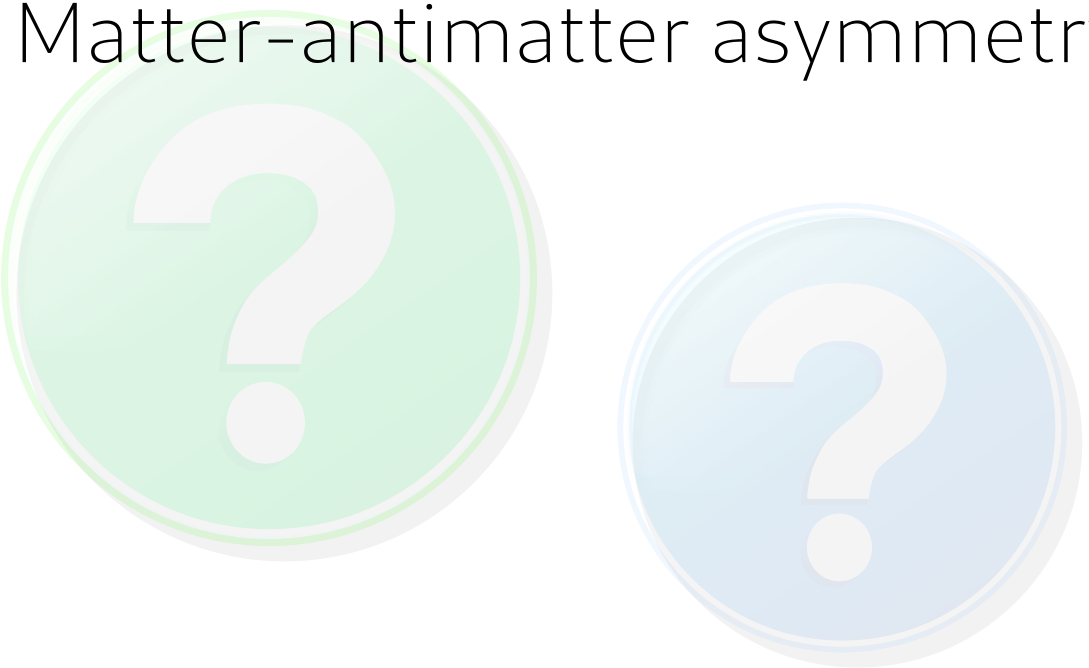


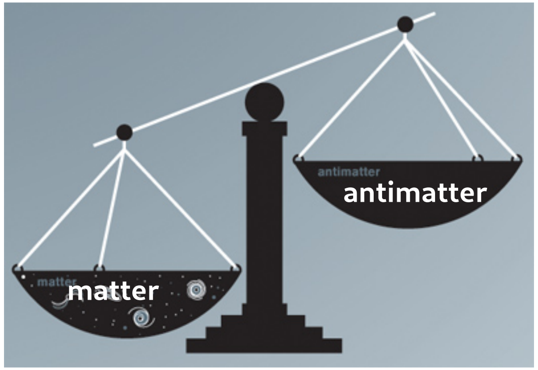


Further SM theory calculations before New Physics interpretation.

Need for physics beyond the SM (BSM)

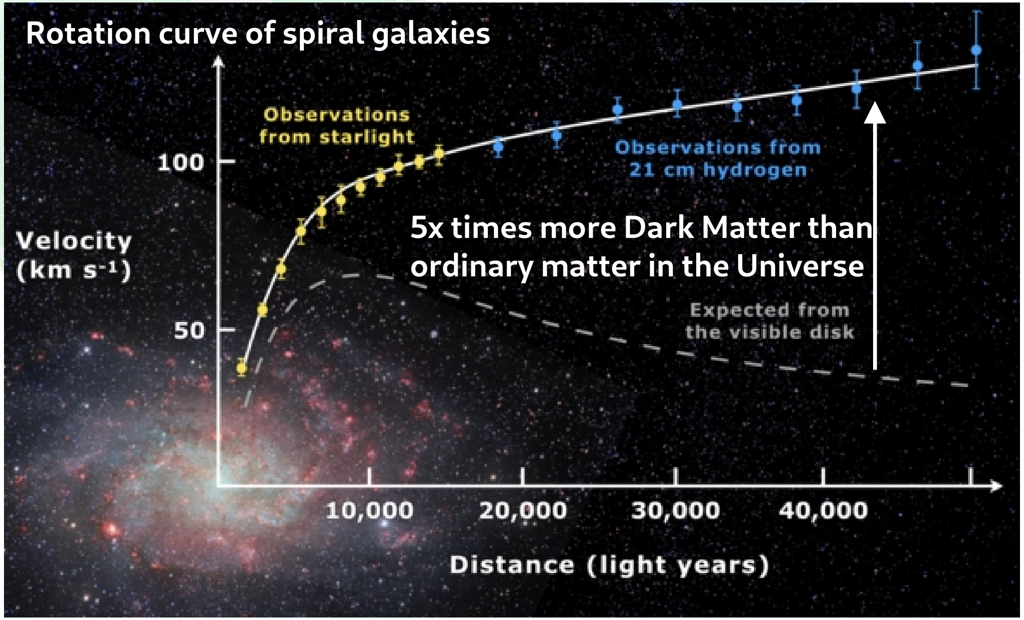
- Matter-antimatter asymmetry

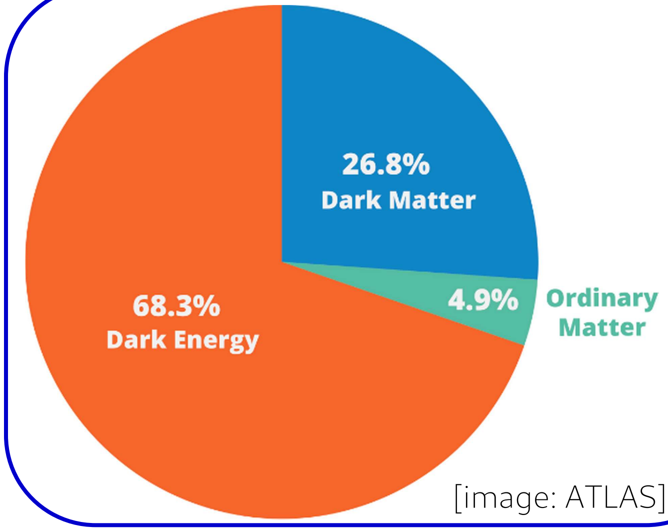




Need for physics beyond the SM

- Matter-antimatter asymmetry
- Dark Matter

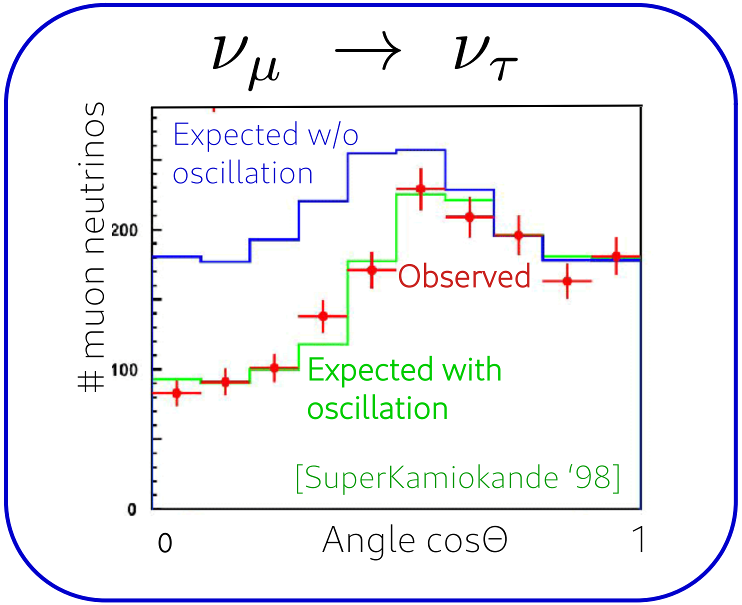




[image: ATLAS]

Need for physics beyond the SM

- Matter-antimatter asymmetry
- Dark Matter
- Neutrino masses



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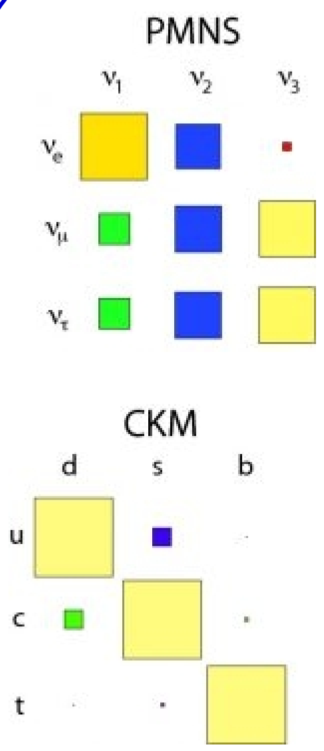

Lepton mixing across different generations sizeable

Quark mixing mostly diagonal → preferred within same generation

→ organizing principle?

Need for physics beyond the SM

- Matter-antimatter asymmetry
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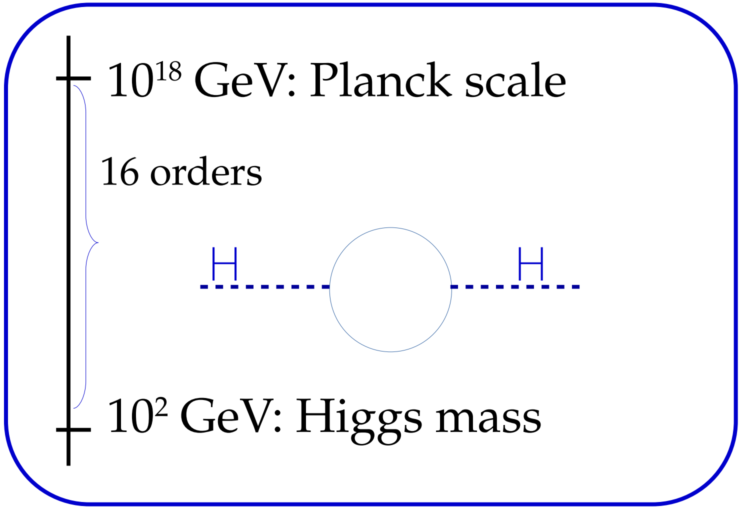
- Hierarchy problem of Higgs mass



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Why is θ parameter of strong interaction (QCD) not ~1, but limited (by the electric dipole moment of the neutron) to $<10^{-10}$?

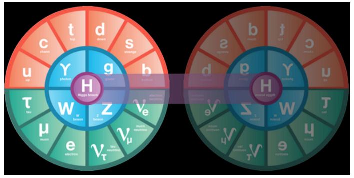
New Physics (NP) needed! → extend SM & look for new particles/ interactions/ geometry

Approaches to models beyond the SM

Based on **symmetries**

Based on **dynamics**

- Cancellation of terms due to relations between couplings or masses
- Often requires partner particles for SM particles
- Examples: supersymmetry, neutral naturalness



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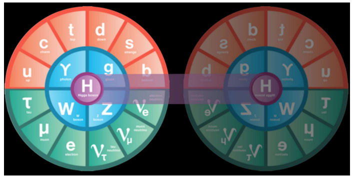
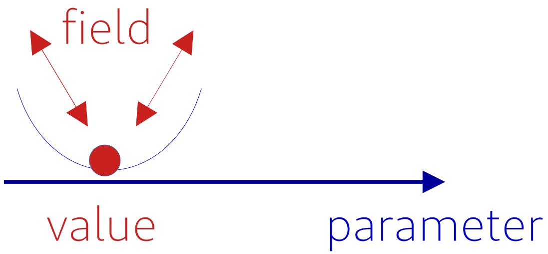


~heavy

Based on **dynamics**

- Parameter → dynamical field
- Vacuum expectation value of the field explains observed parameter
- Examples: axion, relaxion



~light

Prediction of low-mass new particles

Goldstone Theorem → massless particles

A broken symmetry* introduces a new massless scalar (spin-0) boson.

*More precisely: Every spontaneously broken generator (of a group G) of an exact global symmetry

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*More precisely: Every spontaneously broken generator (of a group G) of an exact global symmetry

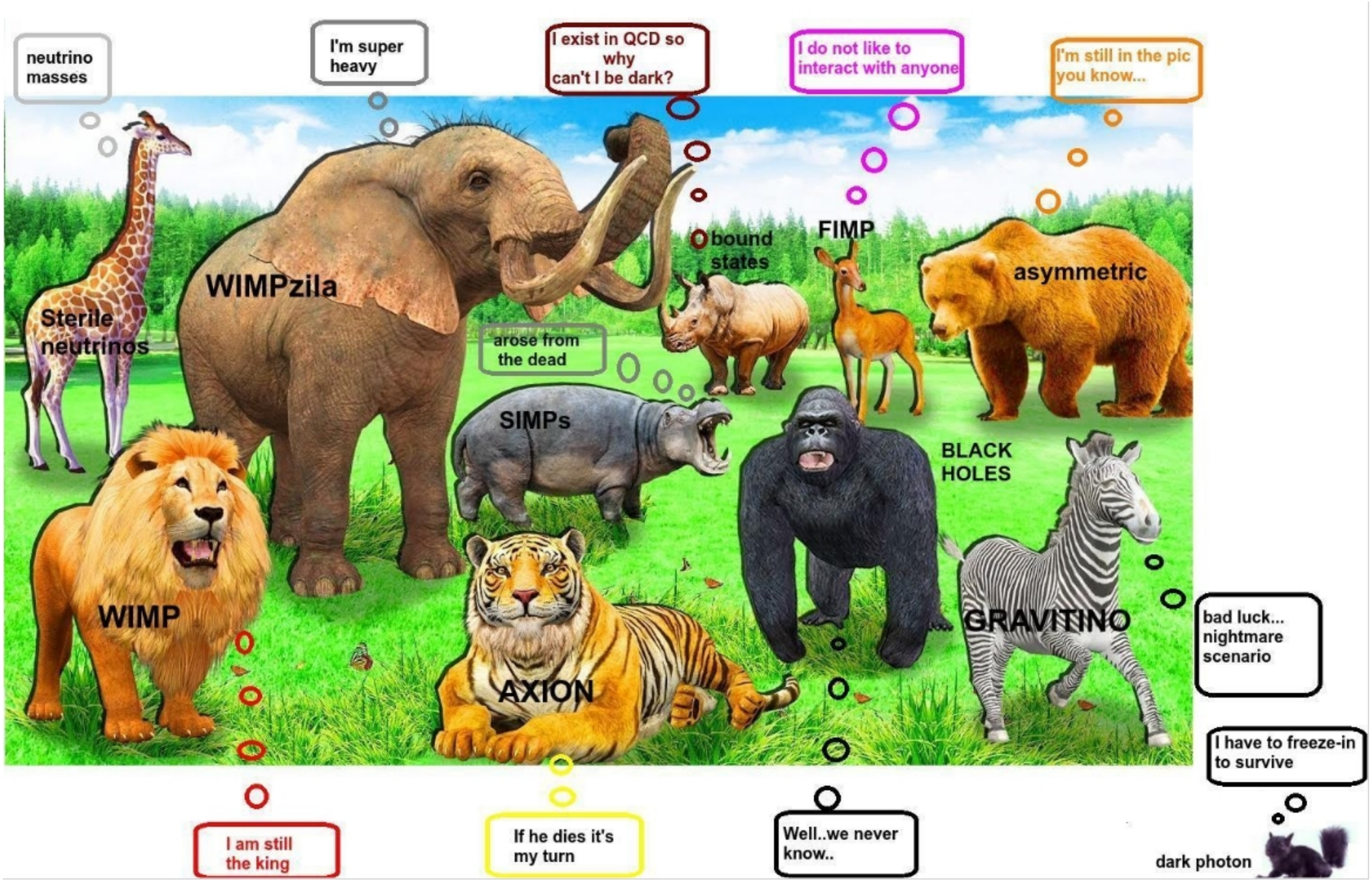
Why expect light particles?

- Spontaneously broken exact symmetry → Predict massless particles
- Spontaneously broken approximate symmetry → Predict low-mass particles

- e.g. dilaton (spin-0) from scale invariance, dark photon (spin-1) from new force, axion (spin-0 pseudoscalar) as solution to strong CP problem…
- Still insufficiently tested extensions of the SM
  - How can we search for these well-motivated new particles?
  - interplay of cosmology/ astrophysics/ intensity/ precision frontiers

II. Models of Dark Matter

Slide by Farinaldo Queiroz



But I will be quite selective: focus on (rel)axion

Landscape of DM models

Bertone & Tait, Nature volume 562, pages 51–56 (2018)

→ see Marianna Safronova's lectures

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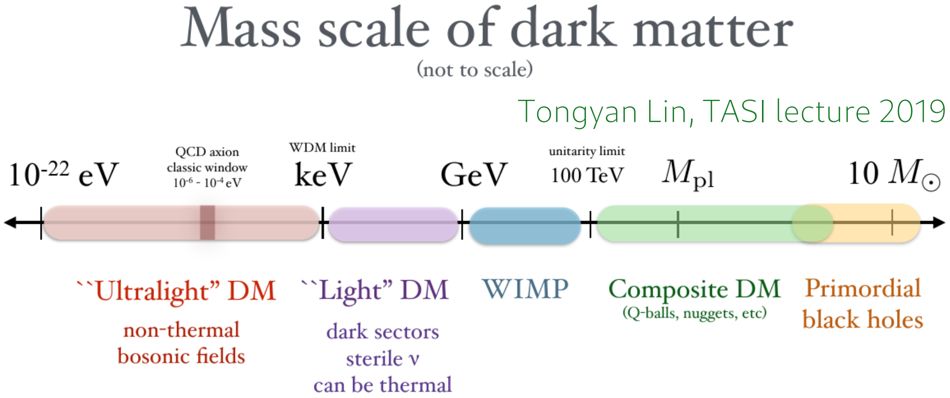


Tongyan Lin, TASI lecture 2019

→ see Marianna Safronova's lectures

Characteristics of ultralight DM

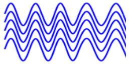
Tongyan Lin, TASI lecture 2019

Occupation number $N = \frac{\rho_{\rm DM}}{m_{\rm DM}} \lambda_{\rm dB}^3 = 75 \left(\frac{10\,{\rm eV}}{m_{\rm DM}} \right)^4$

$v \sim 10^{-3}, \rho_{\rm DM} \sim 0.4\,{\rm GeV/cm}^3$

de-Broglie wavelength: corresponds to wave-like properties of particle of given momentum

$\lambda_{\rm dB} = \frac{2\pi}{mv}$

If $N \gg 1 \Rightarrow$ DM as classical field 

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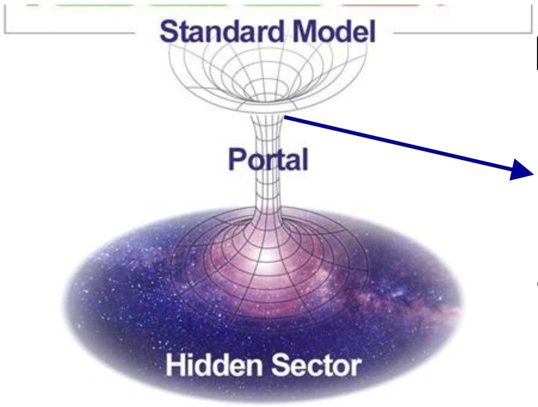
Hubble friction $H(t) = \dot{a}/a$

- $H \gg m_\phi \longrightarrow \phi(t) = \phi_0$
- $H \ll m_\phi \longrightarrow \phi(t) = \phi_0 \cos(m_\phi t)$ oscillates

Ultralight scalar can be cold DM (energy density ~ $1/a^3$)

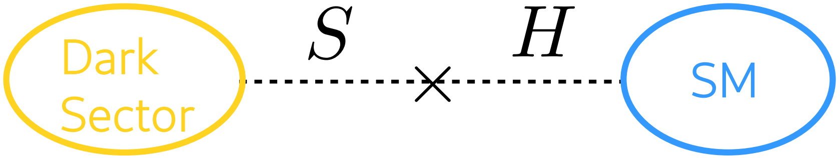
Portals to a Dark Sector



Portal: suppressed (but non-zero) interaction between SM and DM

Feeble coupling: predict **Feebly Interacting Particles (FIPS)**

→ can be new force carriers



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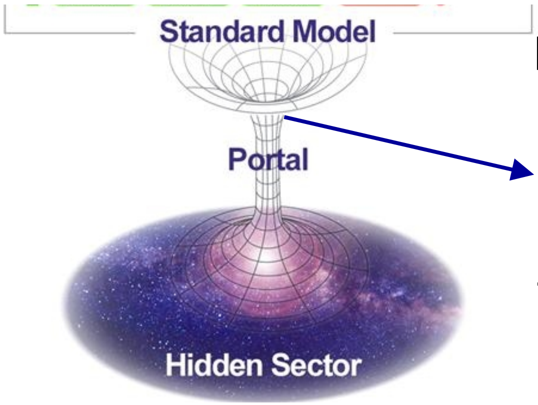

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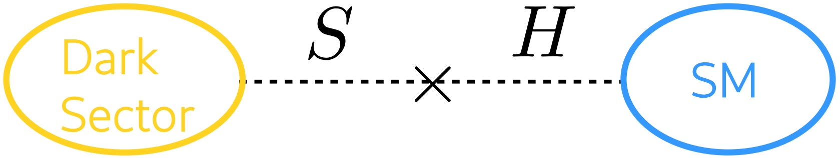
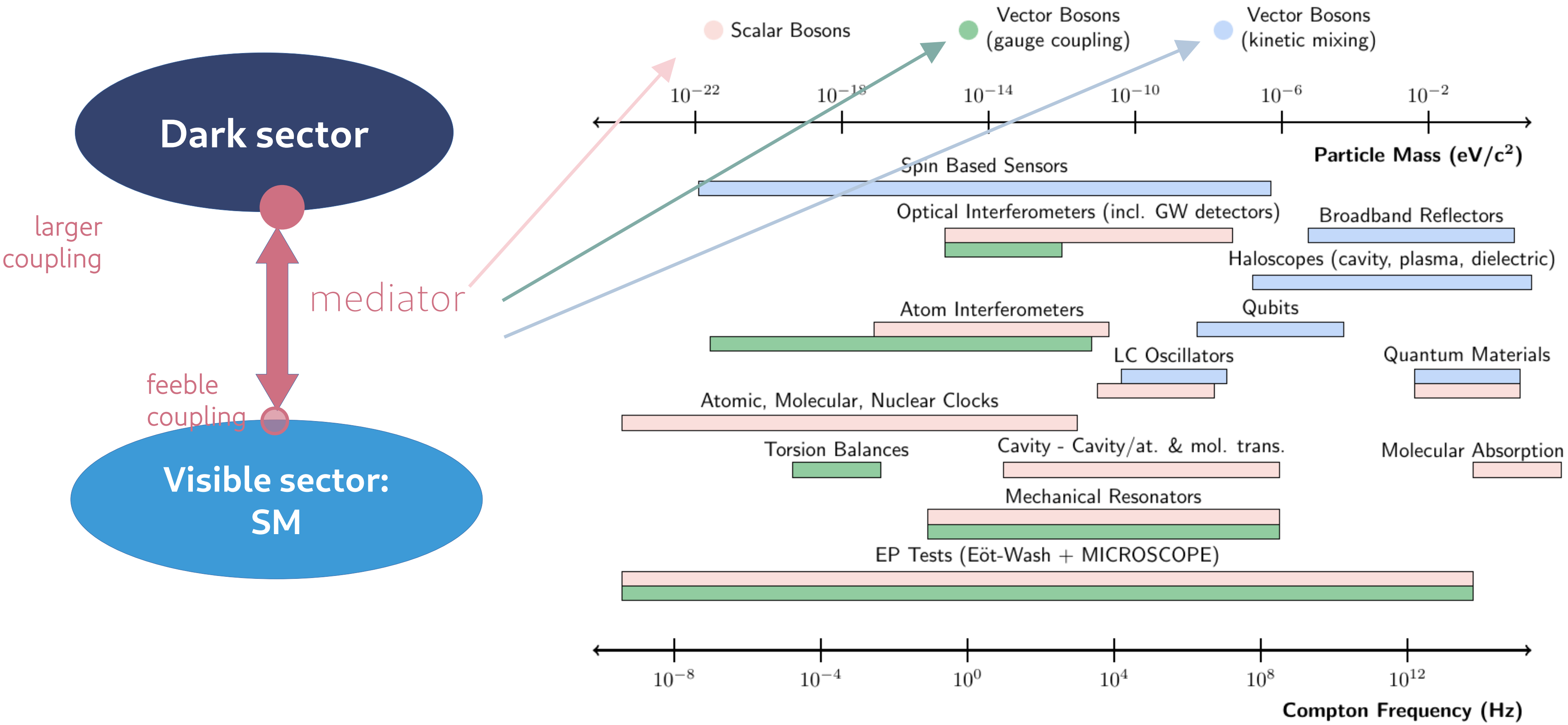


Portal	Coupling
Vector (Dark Photon, A_μ)	$-\frac{\varepsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Scalar (Dark Higgs, S)	$(\mu S + \lambda_{HS} S^2) H^\dagger H$
Fermion (Sterile Neutrino, N)	$y_N L H N$
Pseudo-scalar (Axion, a)	$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu} \tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a} \overline{\psi} \gamma^\mu \gamma^5 \psi$

Light DM and detection methods



What explains the small θ in QCD?

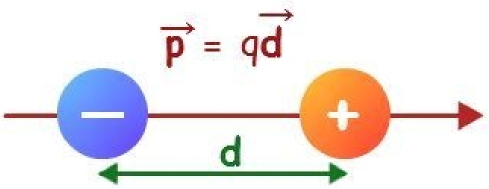
The SM contains term that violates the Charge (C) times Parity (P) symmetry

$$\mathcal{L}_{\text{SM}} \supset \theta \frac{g^2}{32\pi^2} G^a_{\mu\nu}\widetilde{G}^{a\mu\nu}$$

coefficient | coupling | Gluon field strength (tensors)

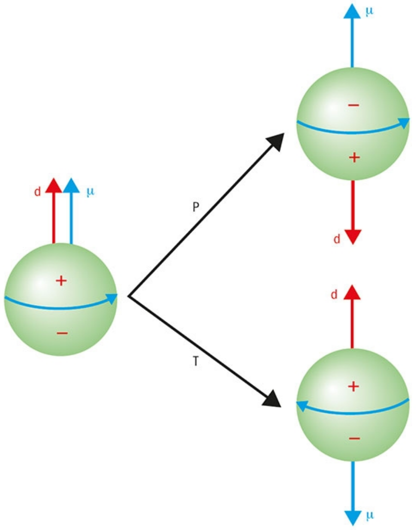
$\theta \sim \mathcal{O}(1)?$ ✗

CP violation induces Electric Dipole Moment (EDM)



Neutron EDM not detected, only upper bound ✗

$$\longrightarrow \bar{\theta} \equiv \theta - \arg \det m_q < 10^{-10}$$



Possible solution: axion

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Axion as dynamical solution

$$\frac{1}{2}\partial_\mu a \partial^\mu a + \frac{g^2}{32\pi^2}\frac{a(x)}{f_a} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

Axion minimizes potential at

$$\bar{\theta} = \frac{a(x)}{f_a} - \det\,\arg \mathrm{m_q} = 0$$

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At low energy: non-relativistic Hamiltonian → how to probe the axion couplings

$$\mathscr{H} = \sqrt{\frac{\varepsilon_0}{\mu_0}} g_{a\gamma\gamma} \int a\mathbf{E}\cdot\mathbf{B}dV + g_{aff}\hbar c \nabla a \cdot \hat{\mathbf{S}} + \sqrt{\varepsilon_0(\hbar c)^3} g_{\rm EDM} a \hat{\mathbf{S}}\cdot\mathbf{E},$$

Can the axion be Dark Matter?

The axion solves the strong CP problem. ✅

See e.g. TASI lecture 2018 by Anson Hook,
Axion theory lecture by Jeff Dror,
Planck 2024 talk by Geraldine Servant

Can it solve another problem? Can it account for DM? → It needs to have the correct relic density

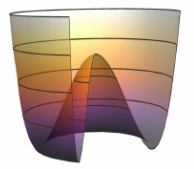
Consider complex scalar field

$$\Phi = \phi e^{i\theta}$$

charged under anomalous U(1) global symmmetry (Peccei-Quinn symmetry)

Spontaneously broken at scale f_a $V(\varphi) = \lambda \left(|\varphi|^2 - \frac{f_a^2}{2} \right)^2$

$$\langle \varphi \rangle = f_a / \sqrt{2}$$



Axion as Goldstone boson

$$\theta \to \theta + \text{const.}$$

$$\boxed{\theta = a / f_a}$$

Slide by
Geraldine Servant

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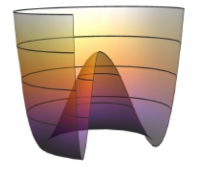

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Slide by
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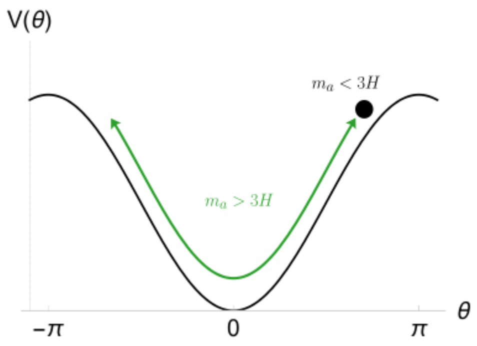
Misalignment mechanism



Topological production

Axions from strings
If $f_a \sim 10^{11}$ GeV

Axion vs. Axion-Like Particle (ALP)

Non-perturbative effects at energy $\Lambda_b \ll f_a$ break the shift symmetry and generate a potential/mass for the axion

$$V = m_a^2(T) f_a^2 [1 - \cos(\theta)]$$

$$m_a = \Lambda_b^2 / f_a$$

Slide by
Geraldine Servant

QCD axion

$m_a^2 f_a^2 \approx (76\ \text{MeV})^4$

Generic ALP

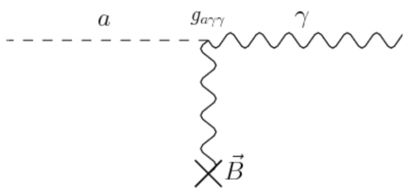
m_a **and** f_a **: free parameters**

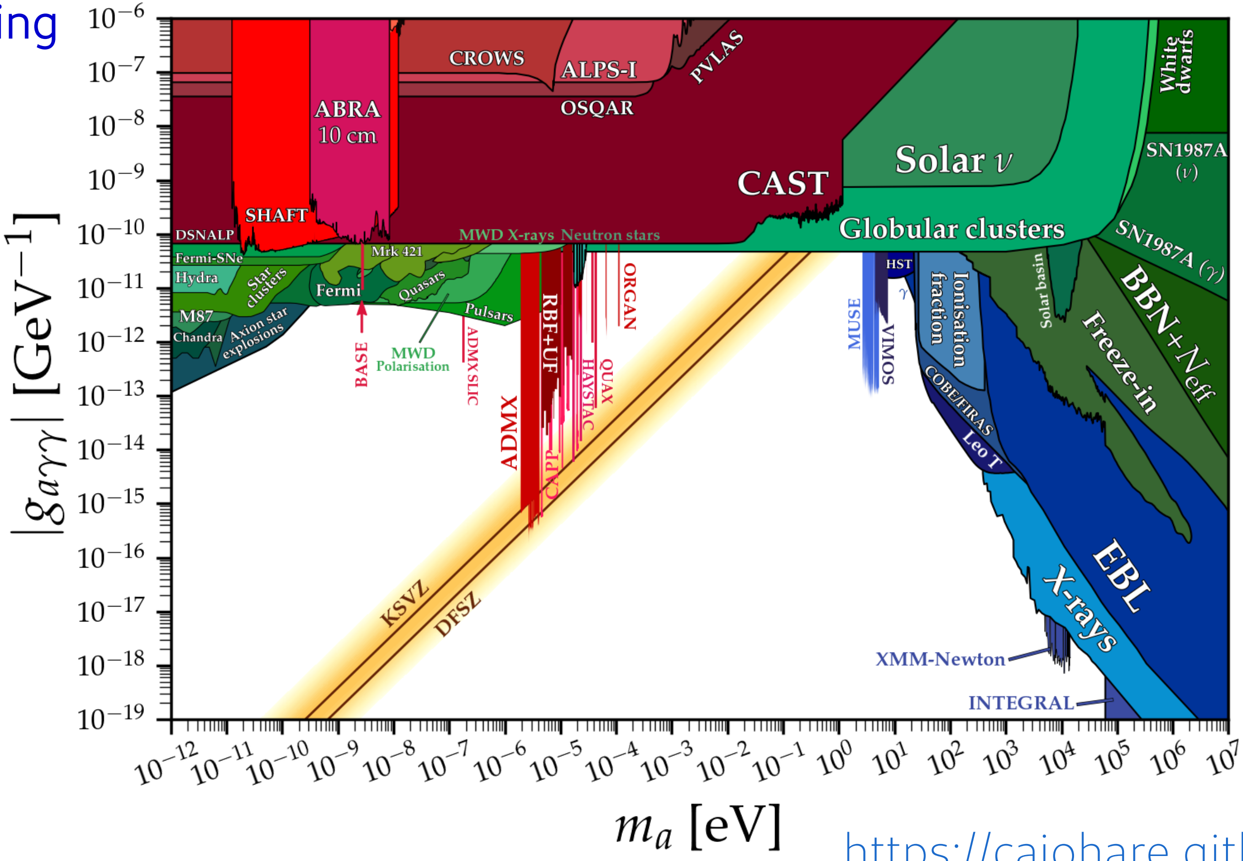
$1/f_a$: interaction strength

$[1/f_a] = [1/\text{mass}]$

Status of Light DM searches: axion

axion-photon coupling





Ciaran O'Hare

https://cajohare.github.io/AxionLimits/

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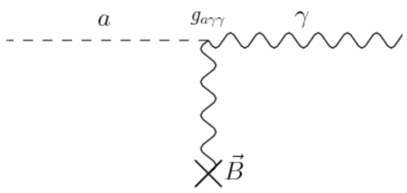
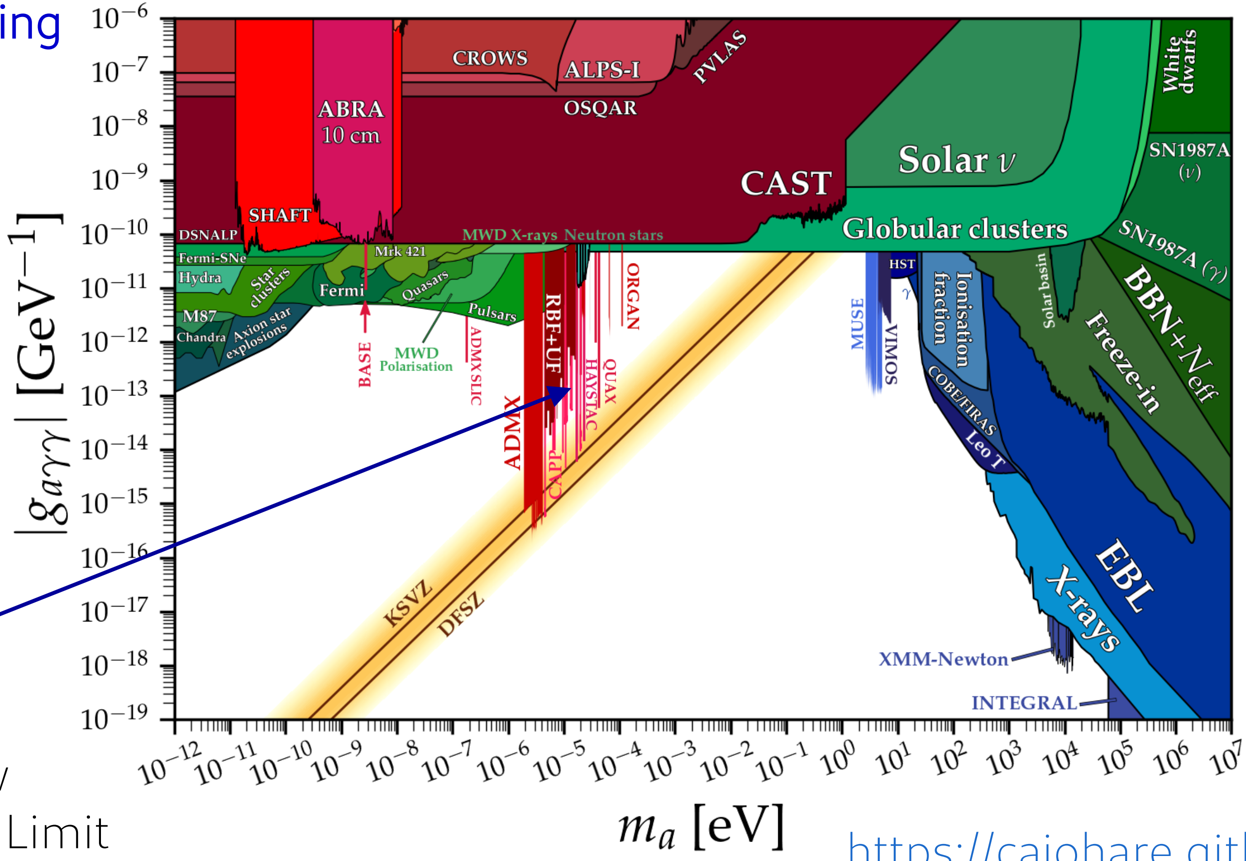




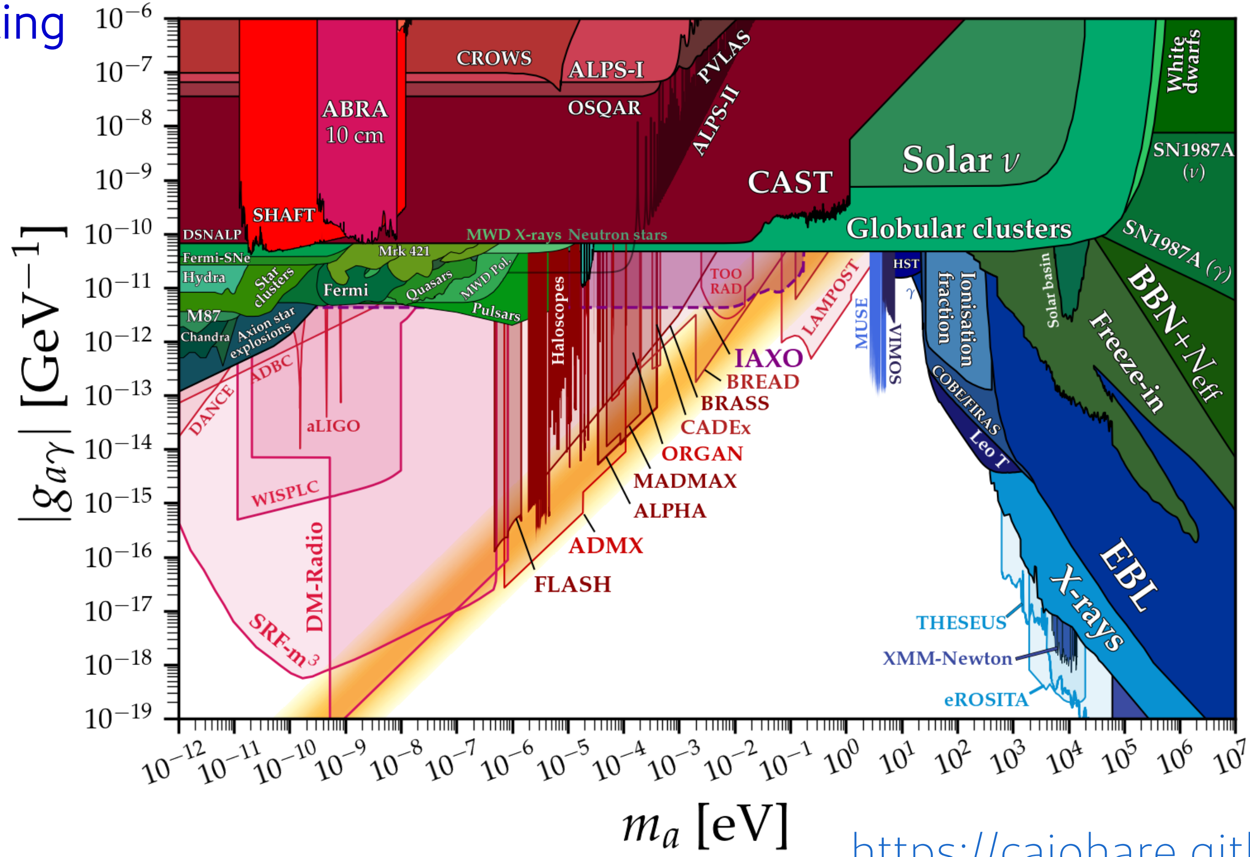
Haystac goes below Standard Quantum Limit by squeezing → faster scan

Ciaran O'Hare

https://cajohare.github.io/AxionLimits/

Axion searches: prospects

axion-photon coupling



Ciaran O'Hare

https://cajohare.github.io/AxionLimits/

SM+singlet scalar: General vs Relaxion

$$V(\Phi, H) = V_\phi + \mu^2(\phi) H^\dagger H + \lambda_h \left(H^\dagger H\right)^2$$

General renormalizable scalar singlet

special case

Relaxion (pseudoscalar)

Graham, Kaplan, Rajendran '15

$$V_\phi = t\phi + \frac{1}{2} m_0^2 \phi^2 + \frac{a_\phi}{3}\phi^3 + \frac{\lambda_\phi}{4}\phi^4$$

$$\mu^2(\phi) = -\mu_0^2 + 2a_{h\phi}\phi + \hat{\lambda}_{h\phi}\phi^2$$

$$V_\phi = g\,\Lambda^3\phi + \mathcal{O}\left(g/\Lambda\right)$$

$$\mu^2(\phi) = -\Lambda^2 + g\Lambda\phi - \tilde{M}^2 \cos\left(\phi/f\right)$$

Relaxion and Higgs potential

Graham, Kaplan, **Rajendran** '15

$$V(\Phi) = rg\Lambda^3\Phi$$

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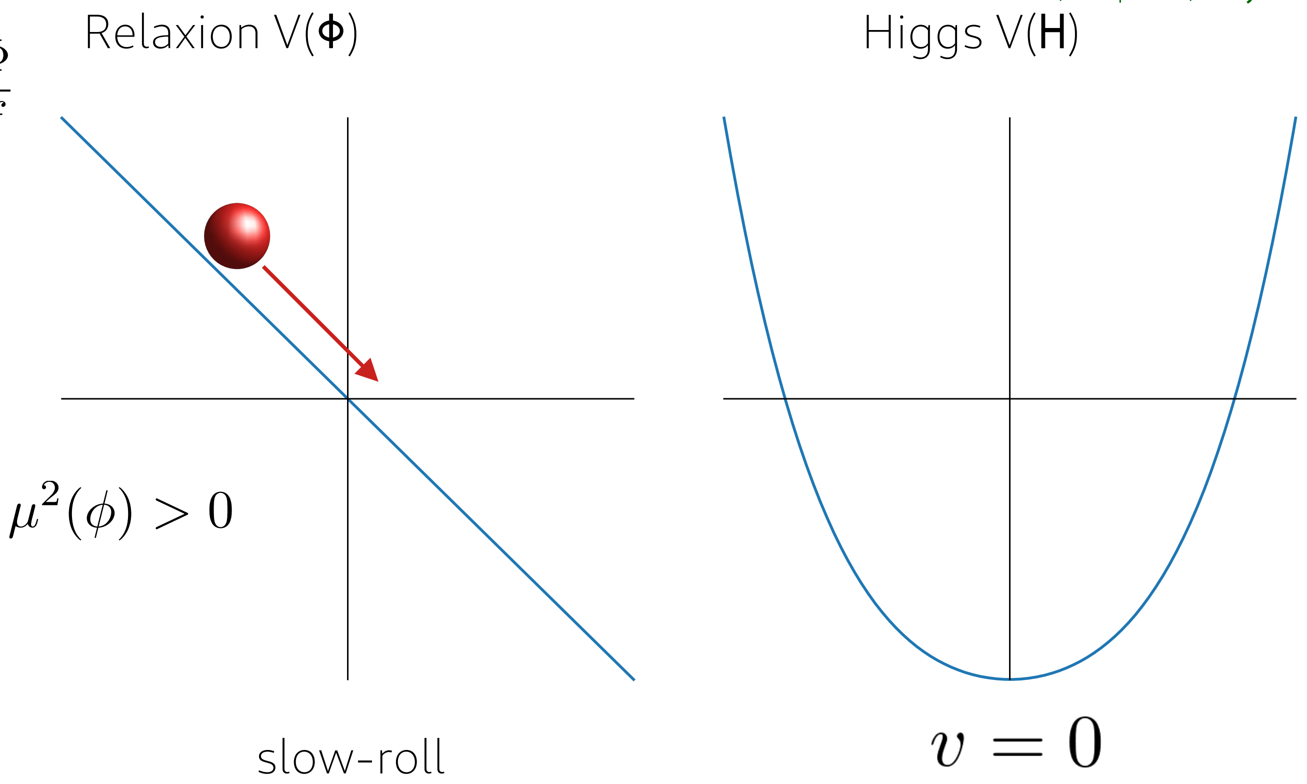

Figure by M. Schlaffer

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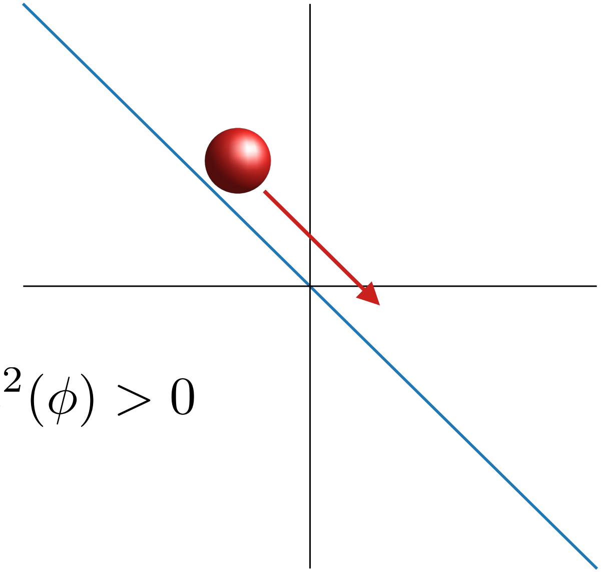
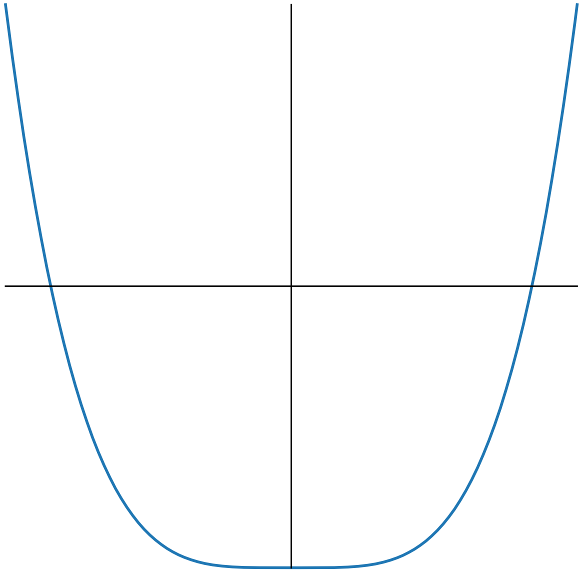
Relaxion V(**Φ**)



$\mu^2(\phi) > 0$

slow-roll

Higgs V(**H**)



$v = 0$

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Graham, Kaplan, Rajendran '15

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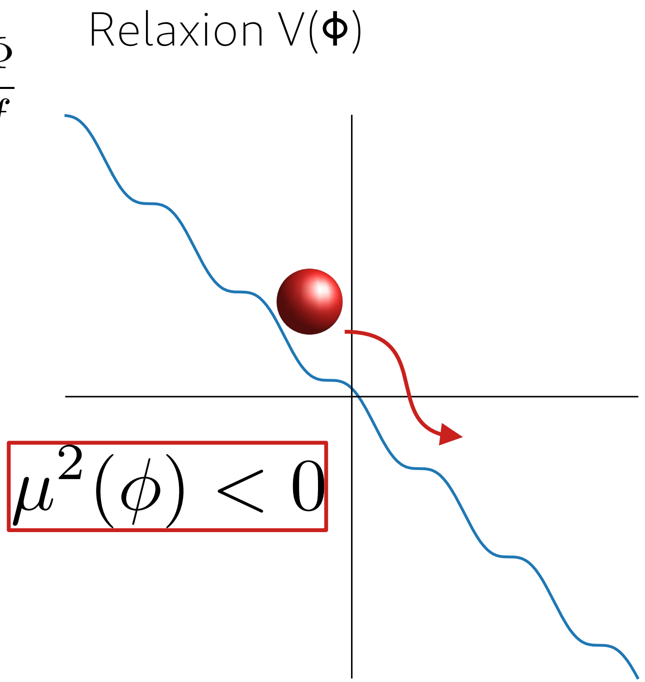
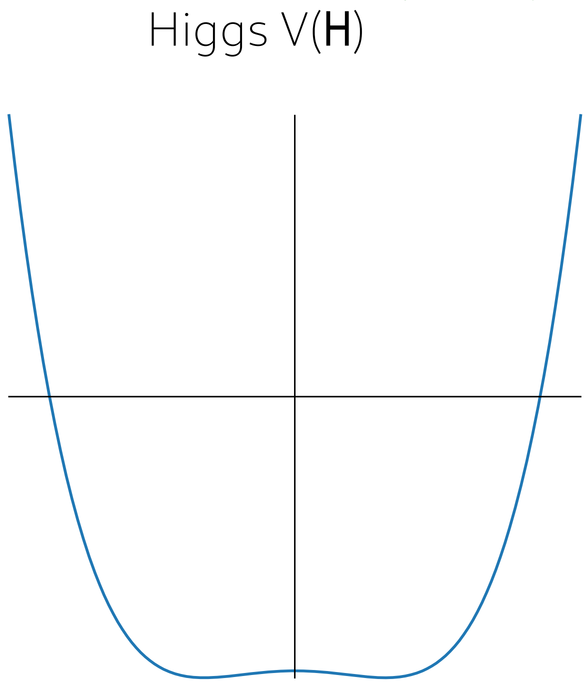




$$V_{\rm br} = \frac{1}{2}\tilde{M}^2 v^2(\phi)\cos\left(\frac{\phi}{f}\right)$$

$$v = v(\phi) \neq 0$$

Backreaction barrier→ wiggles grow

Relaxion and Higgs potential

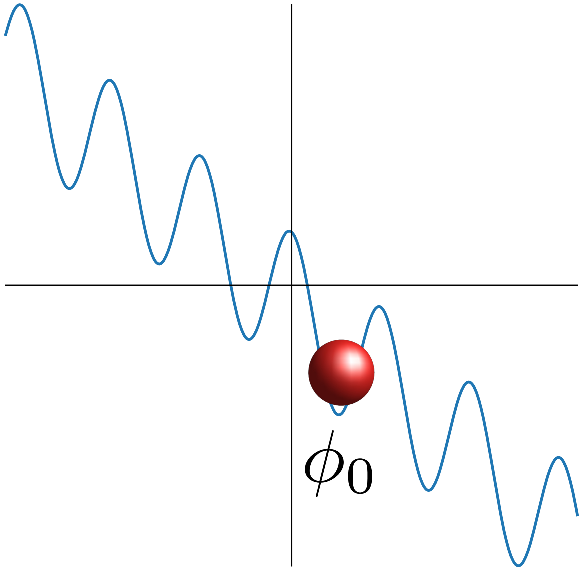
Flacke, Frugiuele, **EF**, Gupta, Perez '16
Choi, Im '16

Graham, Kaplan, Rajendran '15

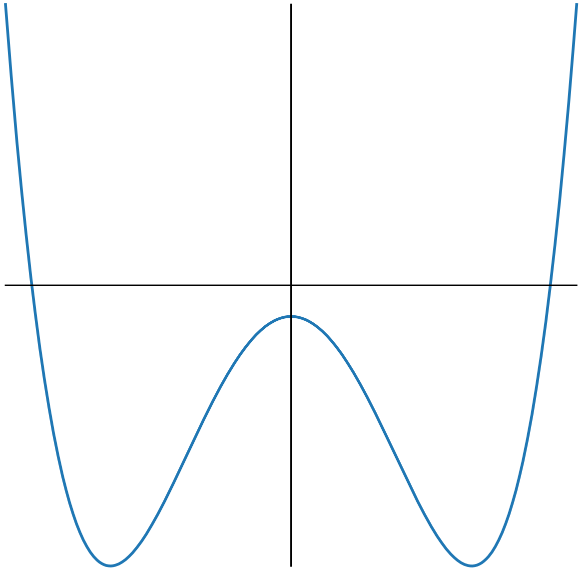
relaxion stopping point breaks CP

Relaxion & Higgs mix

Relaxion V(**Φ**)



Higgs V(**H**)



Backreaction: when
$V'_{\text{roll}} = -V'_{br}$ → relaxion stops

$v \neq 0$
$m_h = m_h^{\text{obs}}$

Relaxion and Higgs potential

Flacke, Frugiuele, **EF**, Gupta, Perez '16
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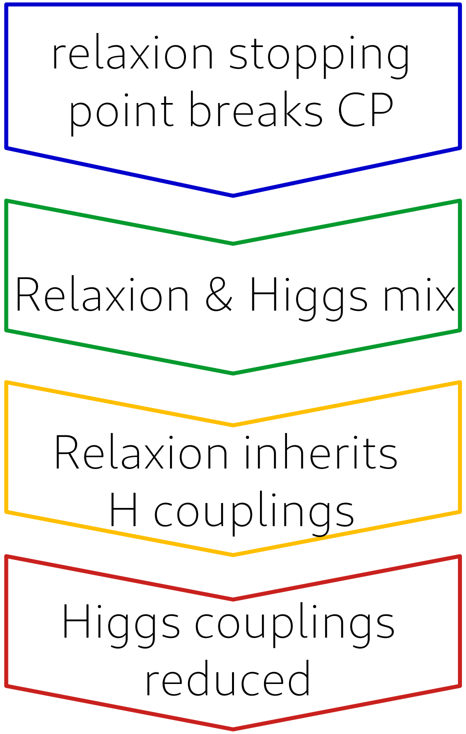
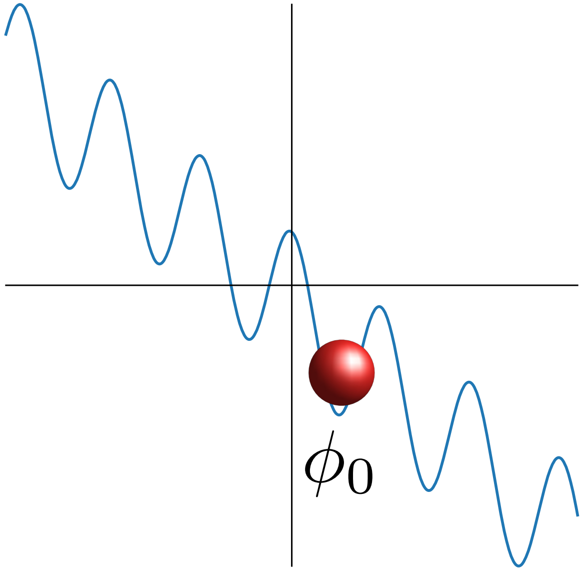
Graham, Kaplan, Rajendran '15



Relaxion V(**Φ**)



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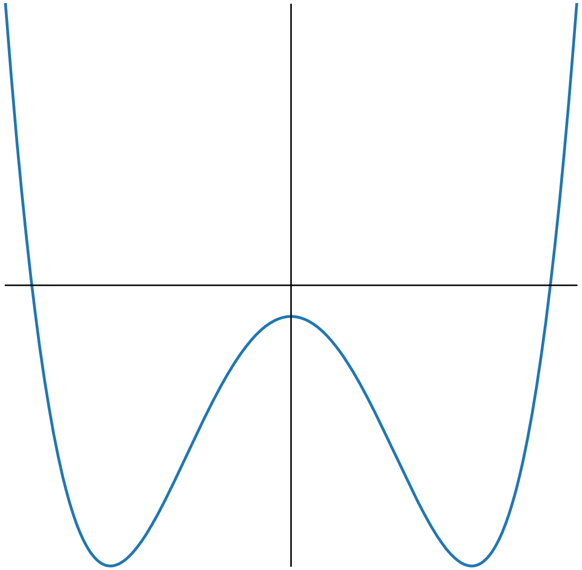
Higgs V(**H**)



$$v \neq 0$$
$$m_h = m_h^{\rm obs}$$

SM+Singlet: General vs Relaxion

$$V(\Phi, H) = V_\phi + \mu^2(\phi) H^\dagger H + \lambda_h \left(H^\dagger H\right)^2$$

General renormalizable scalar singlet → special case → **Relaxion (pseudoscalar)**

Graham, Kaplan, Rajendran '15

General renormalizable scalar singlet	Relaxion (pseudoscalar)
$V_\phi = t\phi + \frac{1}{2} m_0^2 \phi^2 + \frac{a_\phi}{3}\phi^3 + \frac{\lambda_\phi}{4}\phi^4$	$V_\phi = g\Lambda^3\phi + \mathcal{O}(g/\Lambda)$
$\mu^2(\phi) = -\mu_0^2 + 2a_{h\phi}\phi + \hat{\lambda}_{h\phi}\phi^2$	$\mu^2(\phi) = -\Lambda^2 + g\Lambda\phi - \tilde{M}^2 \cos(\phi/f)$
→ Singlet-Higgs Mixing angle $\sin\theta \approx \frac{a_{h\phi}}{v\lambda_h}$	$s_\theta \approx \frac{\tilde{M}^2}{2vf\lambda_h} \sin\left(\frac{\phi_0}{f}\right)$
	+ CP-odd couplings to SM (like axion)

Relaxion as a portal to a Dark Sector

Relaxion-Higgs mixing

→ pseudoscalar relaxion inherits scalar couplings to SM

Scalar:

$$\mathscr{L} \supset g_e \phi \, \bar{e} e + \frac{g_\gamma}{4} \phi F_{\mu\nu} F^{\mu\nu}$$

1) Fifth force experiments e.g. EP test,...

2) Oscillation of fundamental constants

$$m_e \to m_e + g_e \, \phi(t)$$
$$\alpha \to \alpha + g_\gamma \, \phi(t)$$

Probed by atomic clock experiments, nuclear transitions.....

"Dilaton-like"

Pseudo-scalar:

$$\mathscr{L} \supset \frac{g_{\phi\gamma\gamma}}{4} \phi \tilde{F}_{\mu\nu} F^{\mu\nu} + \frac{i g_d}{2} \phi \bar{N} \sigma_{\mu\nu} \gamma_5 N F^{\mu\nu} + g_{\phi NN} \partial_\mu \phi \bar{N} \gamma^\mu \gamma_5 N$$

1) Nuclear Magnetic Resonance

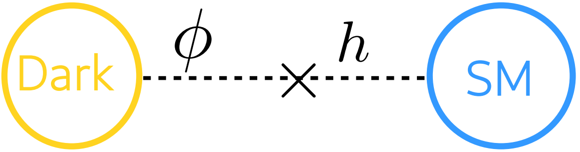
2) Resonant magnetic cavity

Probed by GNOME, CASPEr, ABRACADABRA......

Slide by Abishek Banerjee

"Axion-like"

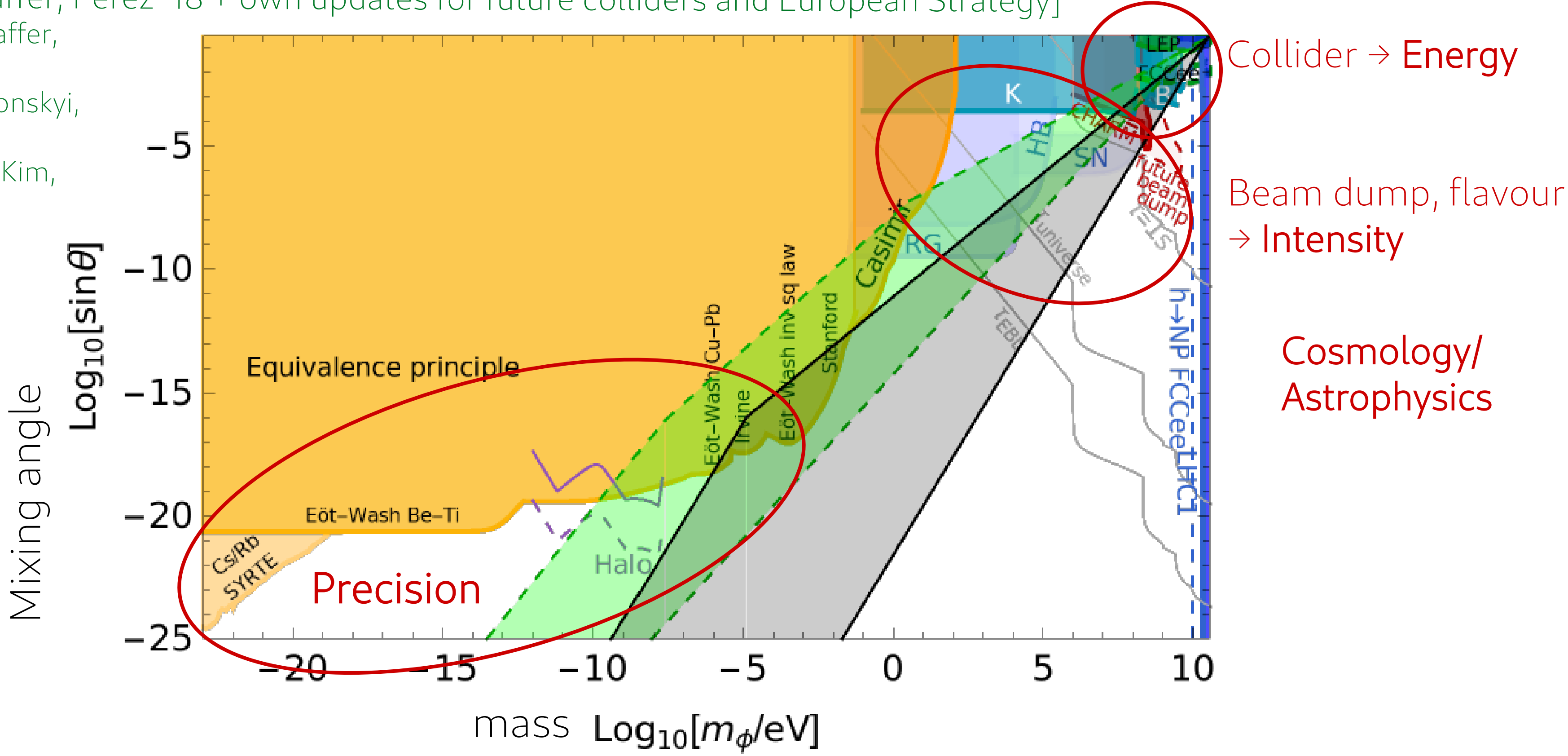
"Relaxion"



Relaxion mass and mixing space

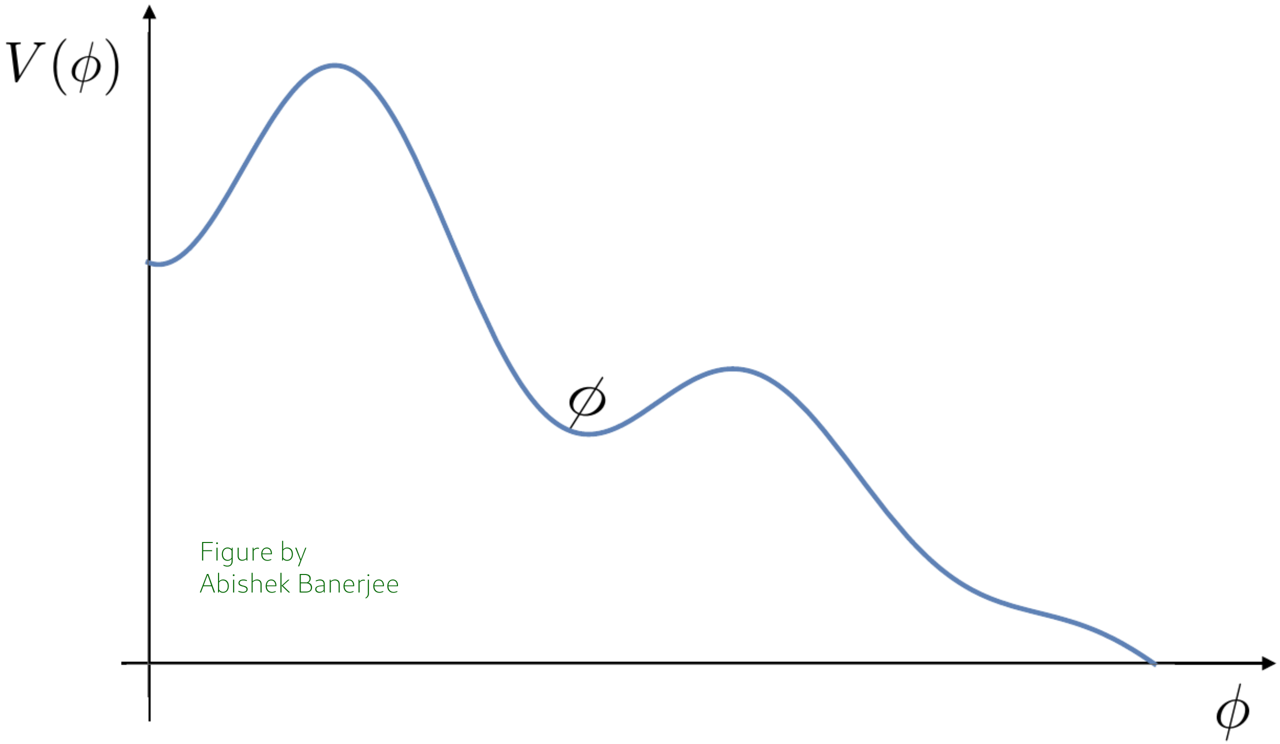
[Frugiuele, **EF**, Schlaffer, Perez '18 + own updates for future colliders and European Strategy]

[**EF**, Matsedonskii, Schlaffer, Savoray '20]
[Banerjee, Kim, Matsedonskyi, Perez, Safronova '20]
[Banerjee, Budker, Eby, Kim, Perez '19]
[Flacke, Frugiuele, **EF**, Gupta, Perez '16]



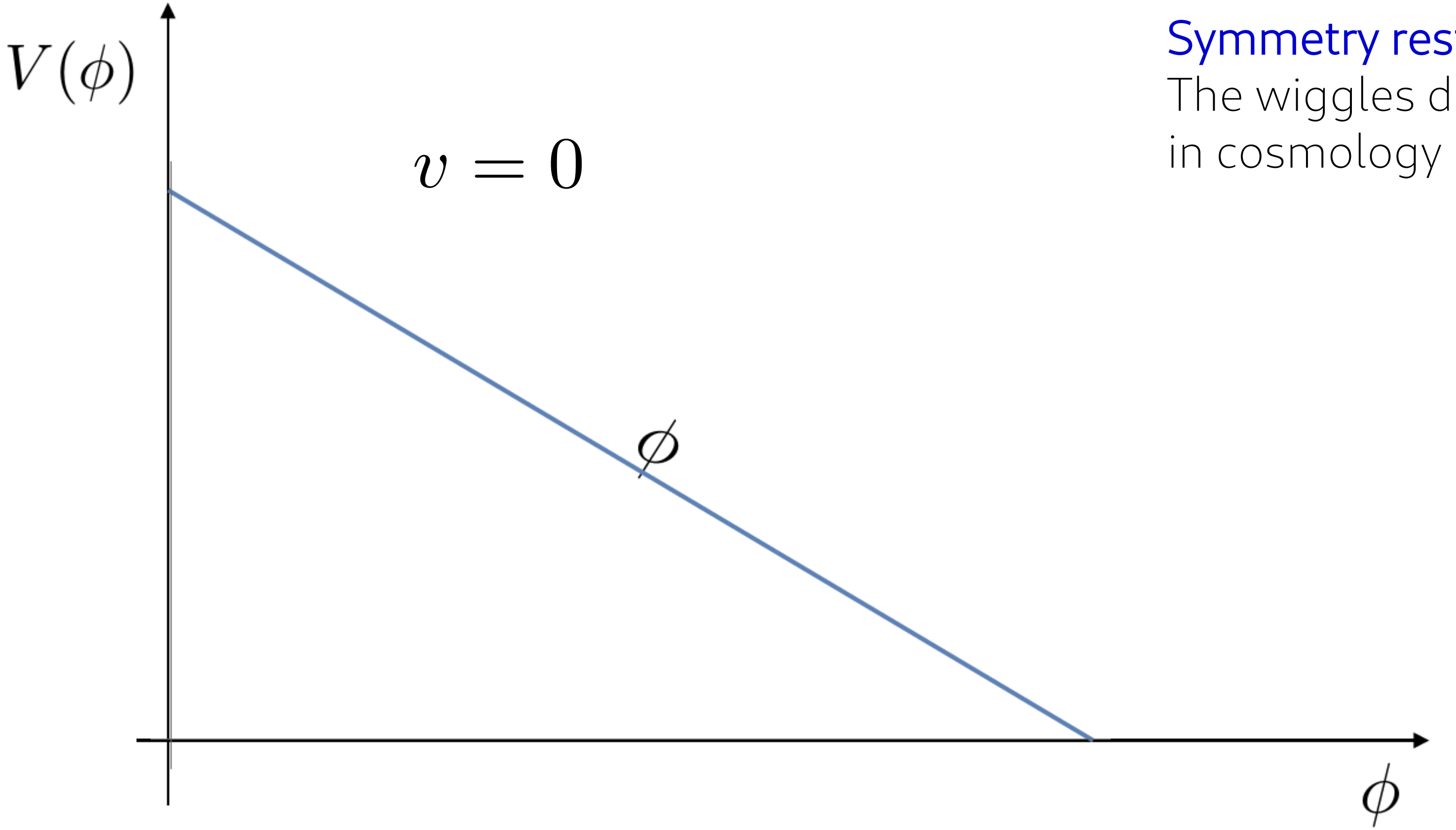
Several methods needed to probe broad range of unknown mass/coupling

Can the relaxion be Dark Matter?



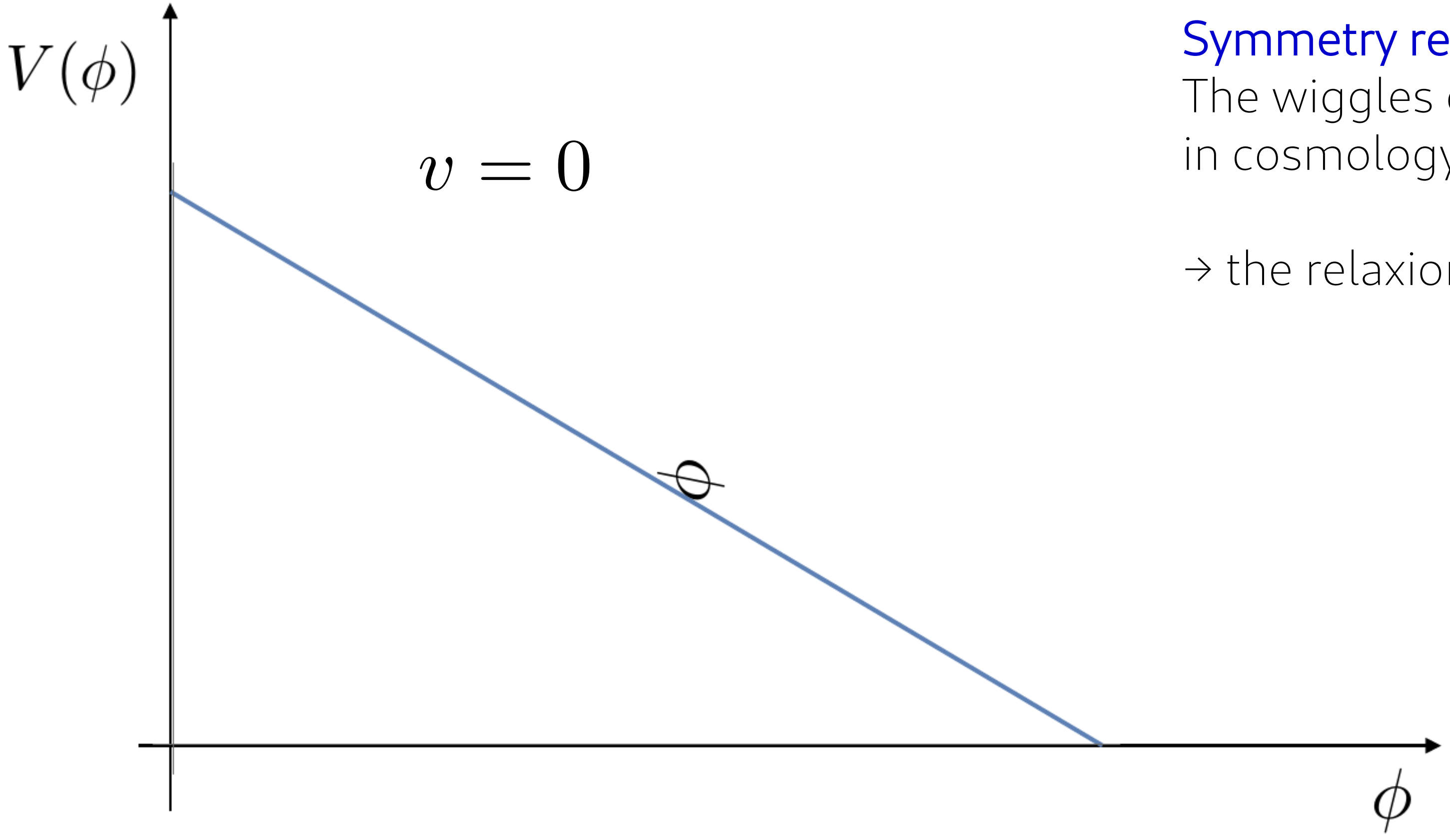
Can the relaxion oscillate like axion DM?

Can the relaxion be Dark Matter?



Symmetry restoration:
The wiggles diappear after reheating in cosmology

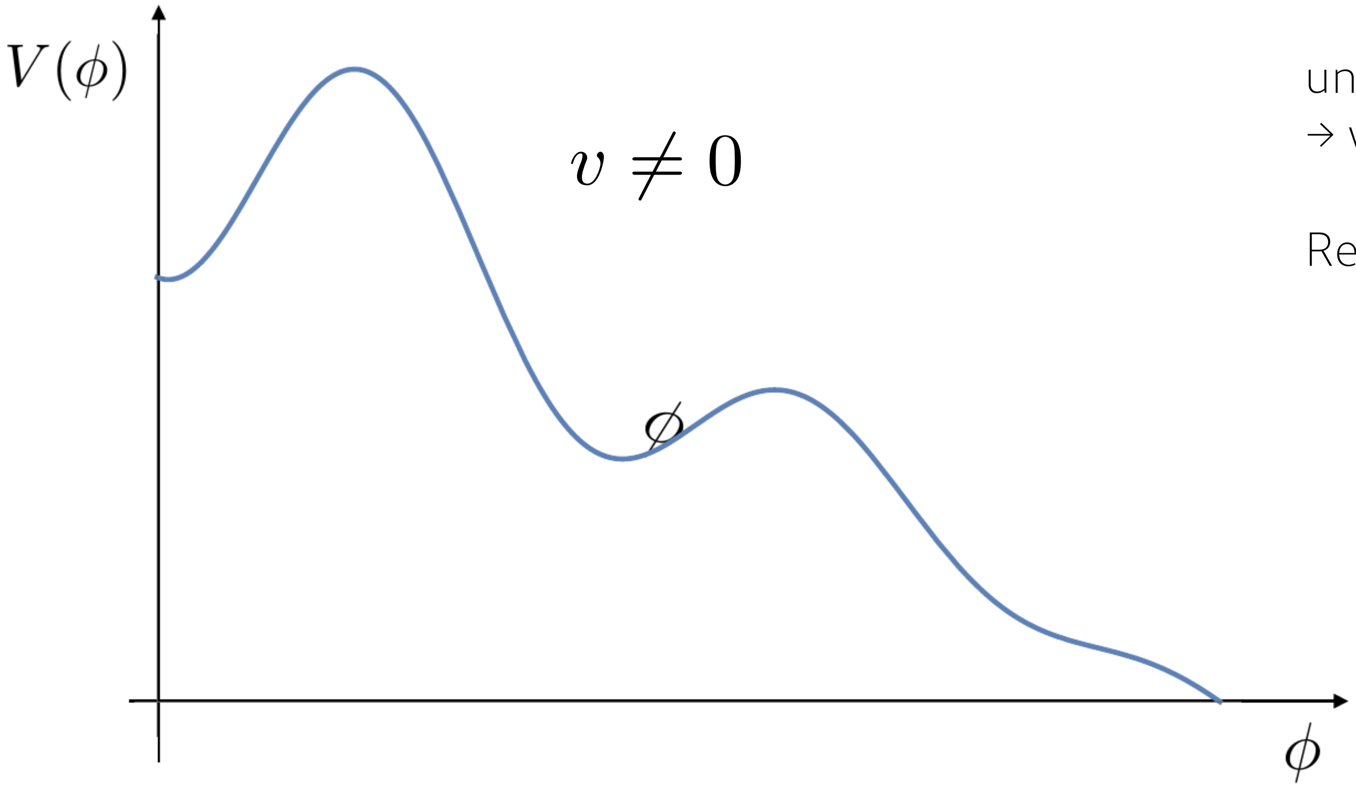
Can the relaxion be Dark Matter?



Symmetry restoration:
The wiggles diappear after reheating in cosmology

→ the relaxion keeps rolling down

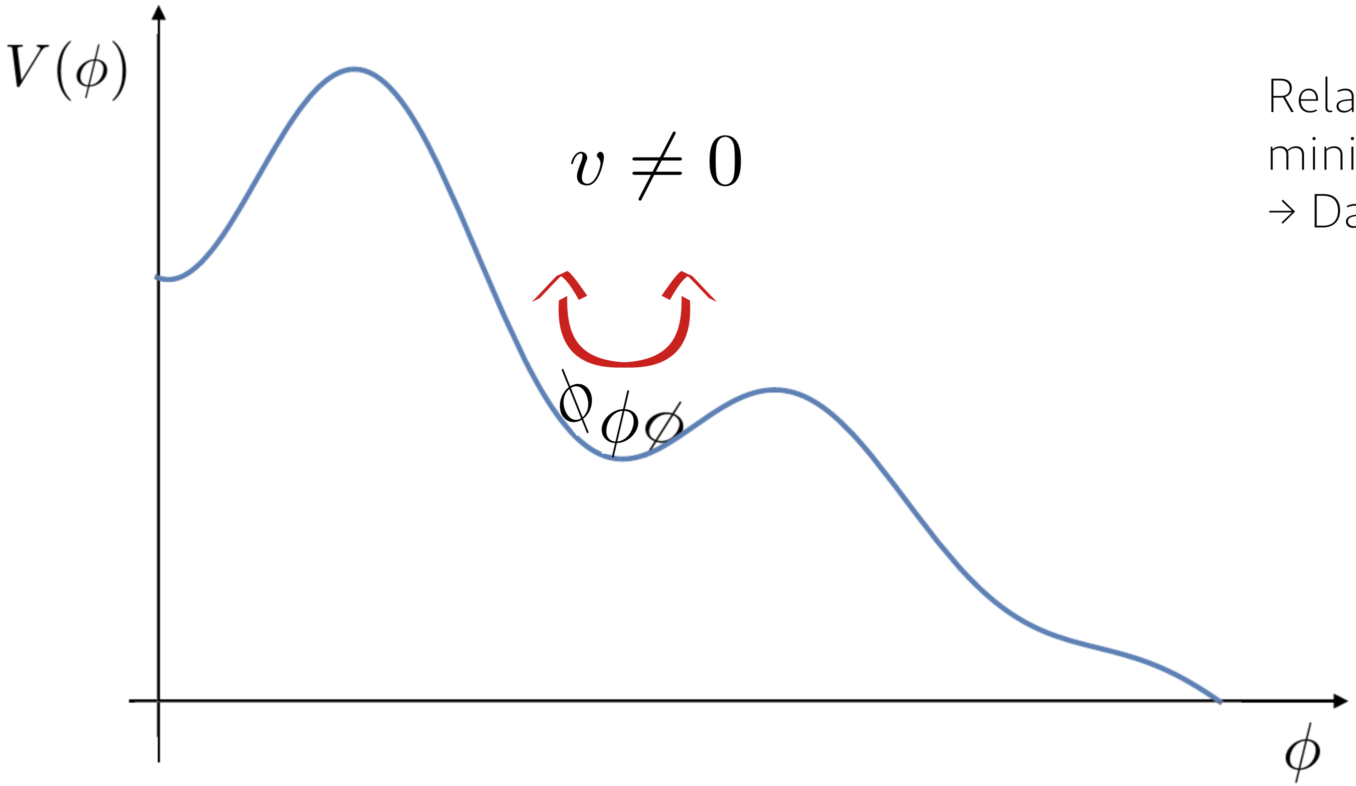
Can the relaxion be Dark Matter?



universe cools down
→ wiggles re-appear

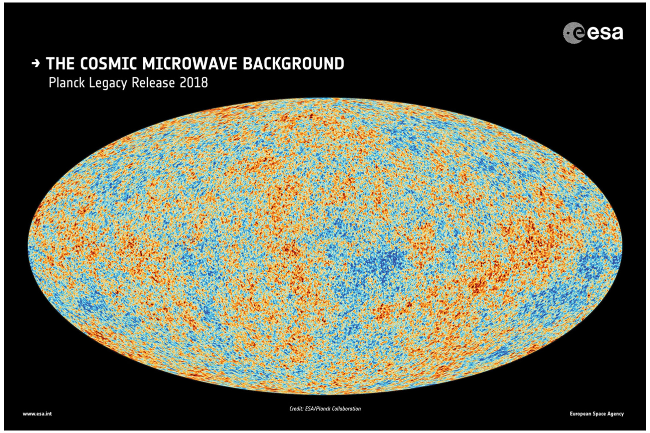
Relaxion trapped in minimum

Can the relaxion be Dark Matter?



Relaxion oscillates around minimum
→ Dark Matter as axion

Constraints on relaxion Dark Matter

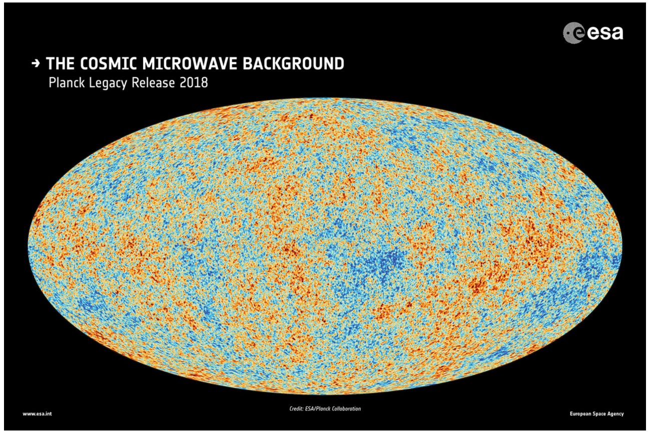


1) DM decaying into relativistic particles perturbs cosmic microwave background

→ relaxion lifetime needs to be long enough:

$$\Gamma_\phi > 160\,\mathrm{Gyr}$$

Constraints on relaxion Dark Matter



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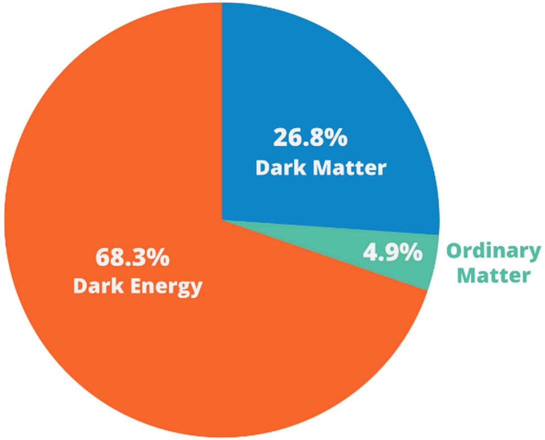


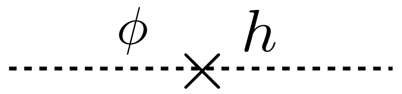
2) Relaxion needs to produce DM relic density

$$\Omega_\phi h^2 \stackrel{!}{=} \Omega_{\mathrm{DM}} h^2 = 0.12$$

with $$\Omega_\phi \propto \frac{m_\phi^2 f^2}{T_{\mathrm{osc}}^3} (\Delta\theta)^2$$

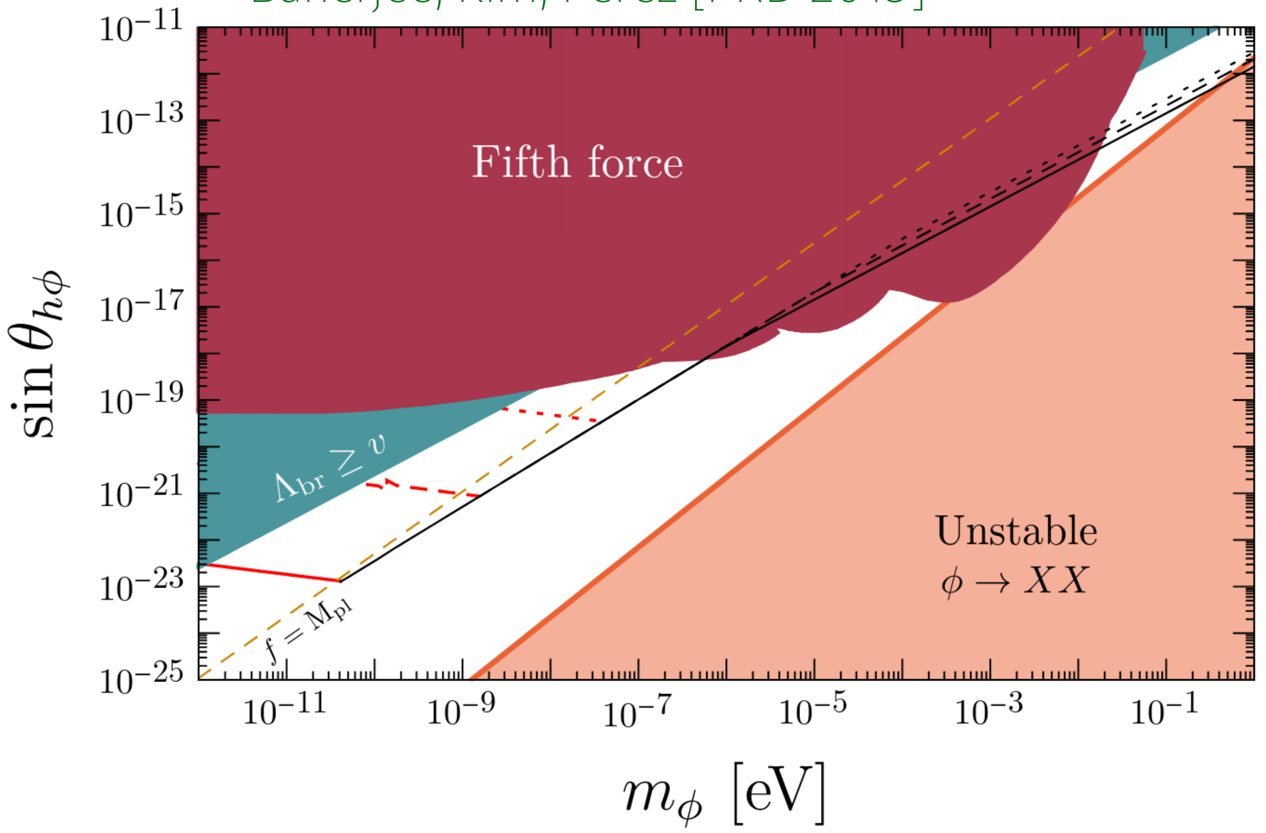
Relaxion Dark Matter

Relaxion-Higgs mixing angle from mass diagonalization



3) Fifth-force searches probe large parameter space

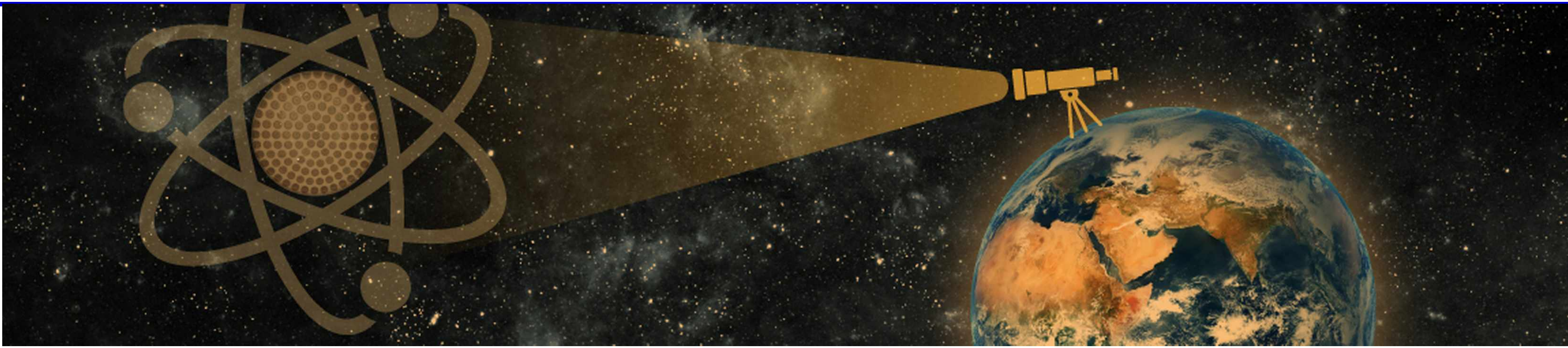
Banerjee, Kim, Perez [PRD 2019]



[Image: QuantumFrontiers]

III. Atomic searches for Dark Matter/ New Physics

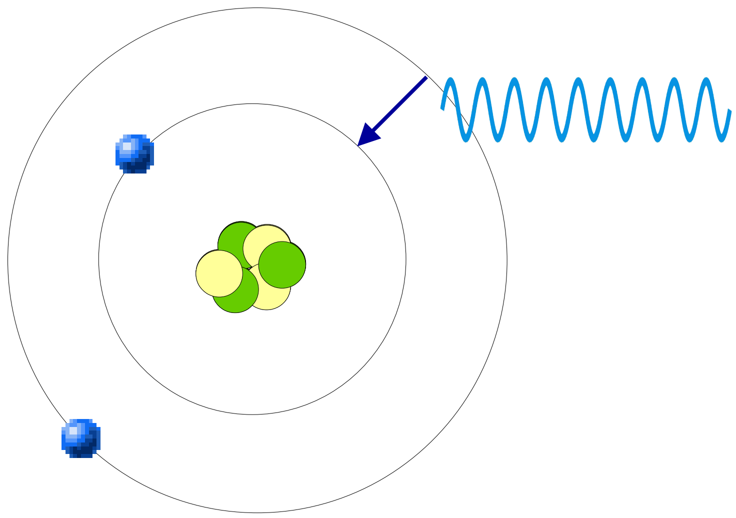
Search for NP-SM interaction



- How can we detect light, feebly interacting new particles?
- Detect interaction with known matter (SM).
- Quantum sensors: in particular interactions with
  - Photons
  - Electrons
  - Neutrons, protons
  - Gluons
  - nucleus
  - Electric fields
  - Magnetic fields
  - gravity
- Feeble effects → goal to lower detection threshold, control uncertainties

Light scalar in atomic spectrum?

- Motivation: search for light new boson Φ that couples to electrons and the nucleus
- Φ perturbs electron levels → only tiny frequency change



Light scalar in atomic spectrum?

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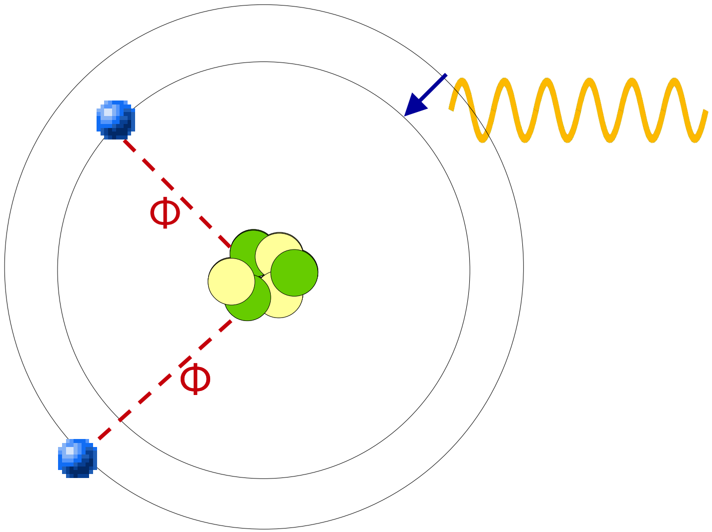
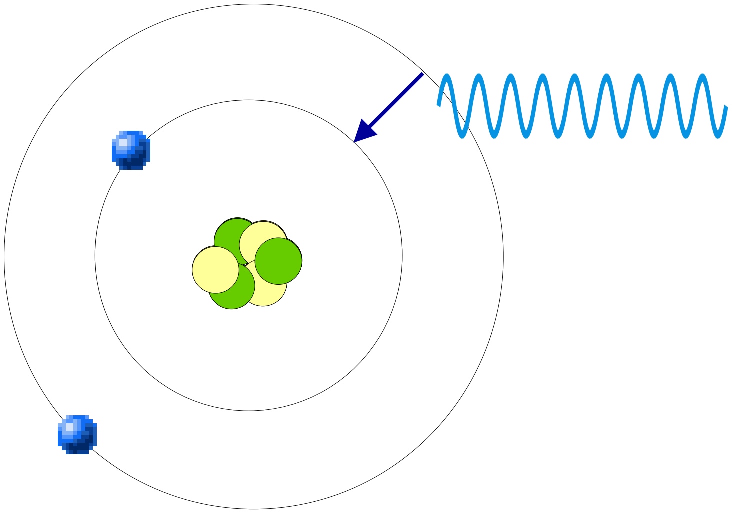


Can this change the rate of clocks?

Light scalar in atomic spectrum?

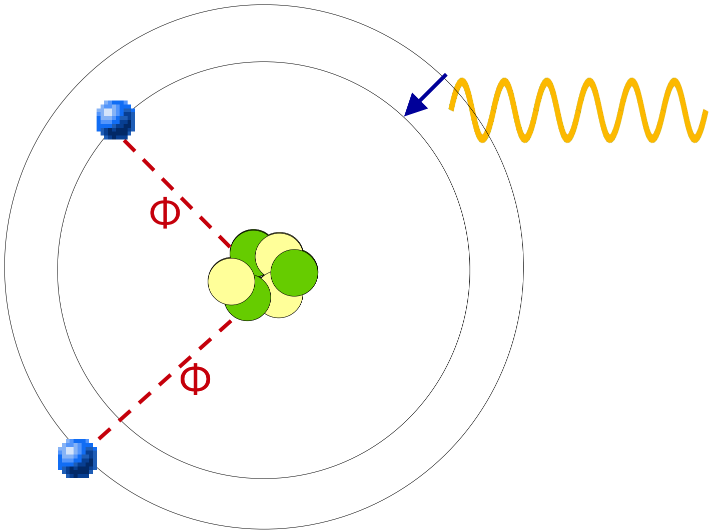
- Motivation: search for light new boson Φ that couples to electrons and the nucleus
- Φ perturbs electron levels → only tiny frequency change



Light scalar in atomic spectrum?

- Motivation: search for light new boson Φ that couples to electrons and the nucleus (here neutrons)
- Φ perturbs electron levels → only tiny frequency change

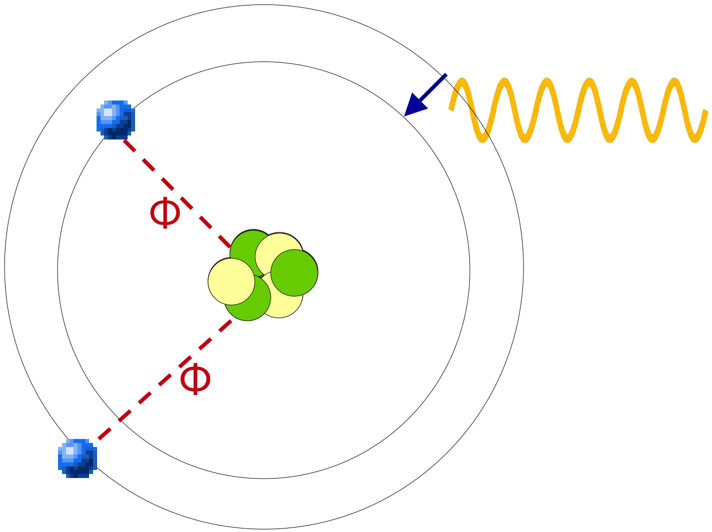
$$V_{\mathrm{NP}} = \frac{y_e y_n}{4\pi r} e^{-m_\phi r}$$



Challenge of theory-exp comparison

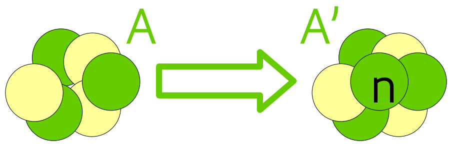
- Motivation: search for light new boson Φ that couples to electrons and neutrons
- Φ perturbs electron levels → only tiny frequency change
- Challenge: theory, nuclear uncertainties >> uncertainties of frequency measurements

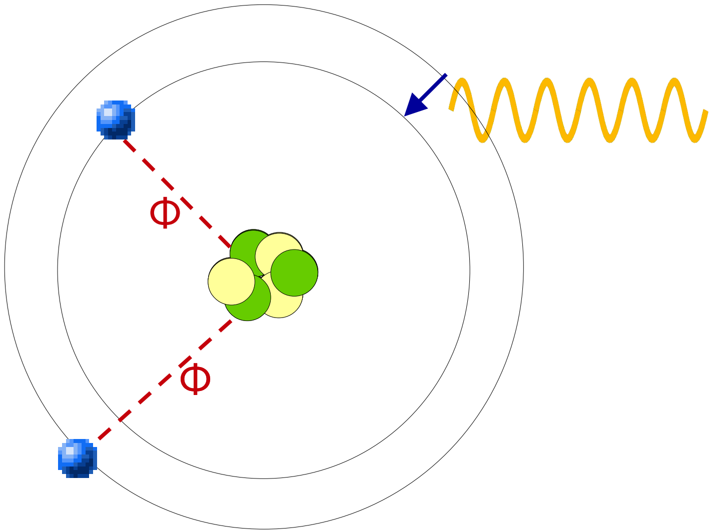
$$V_{\mathrm{NP}} = \frac{y_e y_n}{4\pi r} e^{-m_\phi r}$$



Data-driven atomic search for light scalar

- Motivation: search for light new boson Φ that couples to electrons and neutrons
- Φ perturbs electron levels → only tiny frequency change
- Challenge: theory, nuclear uncertainties >> uncertainties of frequency measurements
- Our method: Measure 2 transitions, 3 isotope pairs very precisely



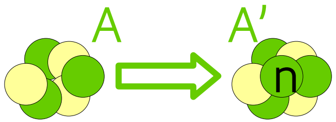


Berengut, Budker, Delaunay, Flambaum, Frugiuele, EF, Grojean, Harnik, Ozeri, Perez, Soreq; PRL 120 (2018) 091801

King plot of Isotope Shifts

Mass shift (MS) Field shift (FS)

$$\nu_i^{AA'} \equiv \nu_i^{A} - \nu_i^{A'} = K_i\, \mu_{AA'} + F_i\, \delta\langle r^2\rangle_{AA'}$$



electronic

nuclear

Poorly known nuclear charge radius

King plot of Isotope Shifts

Mass shift (MS) Field shift (FS)

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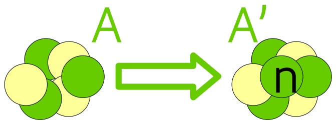


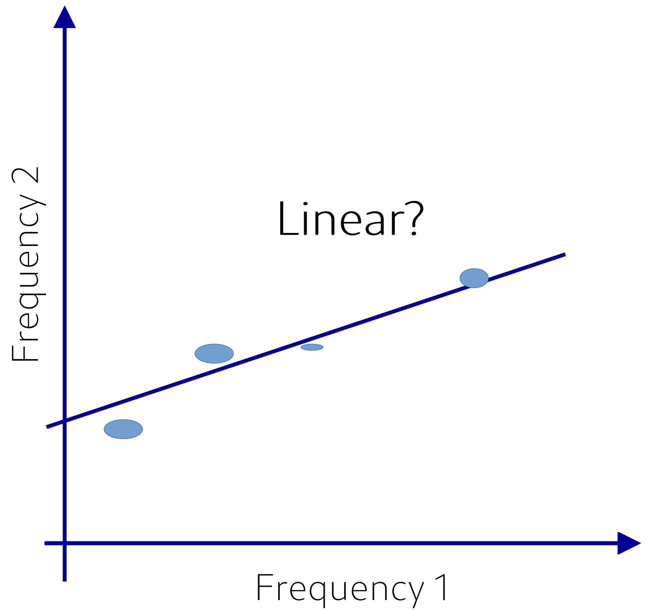
electronic
nuclear

Poorly known nuclear charge radius

2^{nd} transition to eliminate charge radius

Linear King relation (at leading order):

$$m\nu_2 = F_{21} m\nu_1 + K_{21}$$



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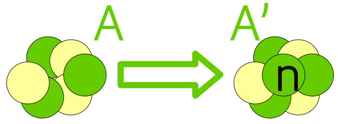


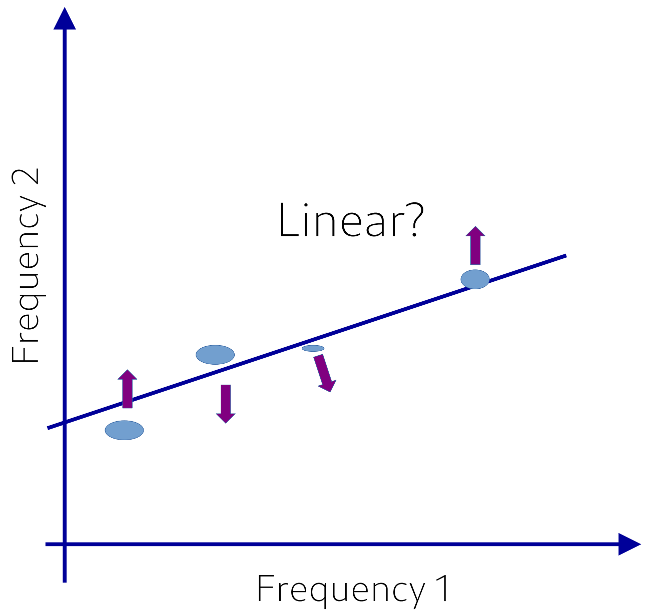
electronic
nuclear

Poorly known nuclear charge radius

2nd transition to eliminate charge radius

Linear King relation (at leading order):

$$m\nu_2 = F_{21} m\nu_1 + K_{21}$$ +NP($y_e y_n$)



King plot of Isotope Shifts

Mass shift (MS) Field shift (FS)

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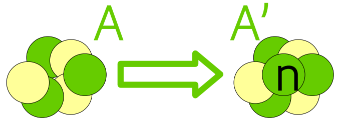


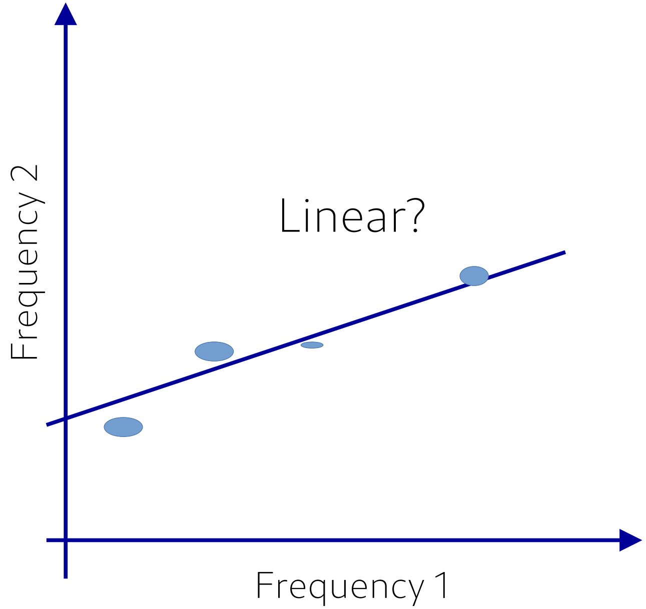
electronic
nuclear

Poorly known nuclear charge radius

2nd transition to eliminate charge radius

Linear King relation (at leading order):

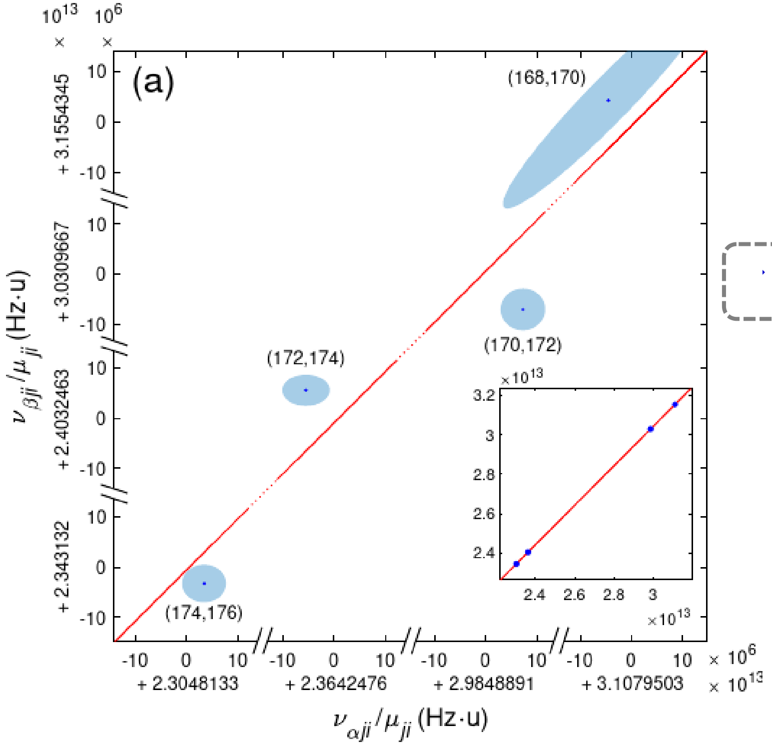
$$m\nu_2 = F_{21} m\nu_1 + K_{21} \quad \text{+NP}(y_e y_n)$$



check if 3 points (= 3 isotope pairs) on straight line

Nonlinearity in Yb^+ isotope shifts

[Counts, Hur, Craik, Jeon, Leung, Berengut, Geddes, Kawasaki, Jhe, Vuletić, PRL 125, 123003 (2020)]
+updates MIT '22, Mainz '22,
PTB/Heidelberg/Hannover/Darmstadt/Sydney 2024:
[Door, Yeh,… EF, Mehlstäubler, PRL 134(2025)6, 063002]



- significant nonlinearity (NL)

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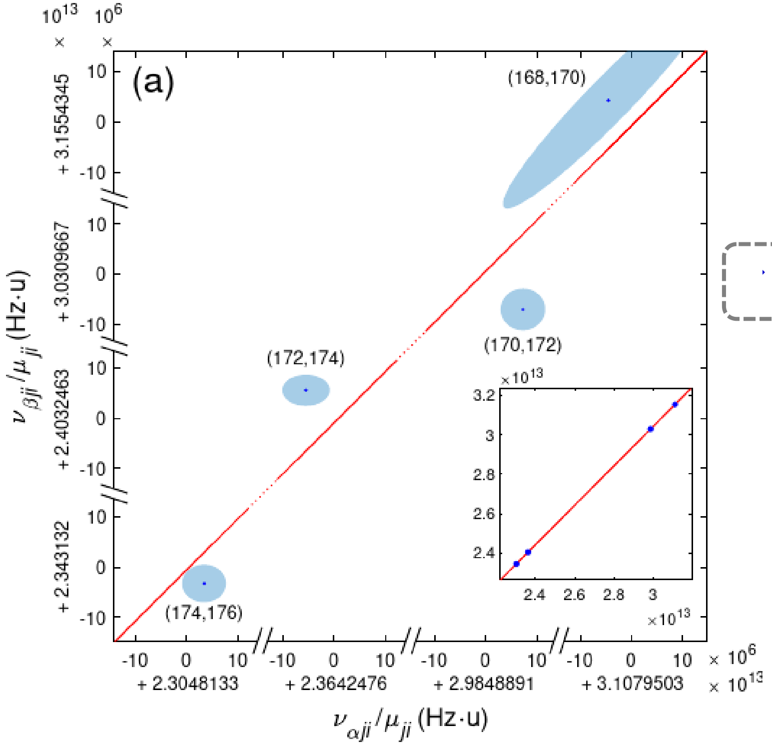
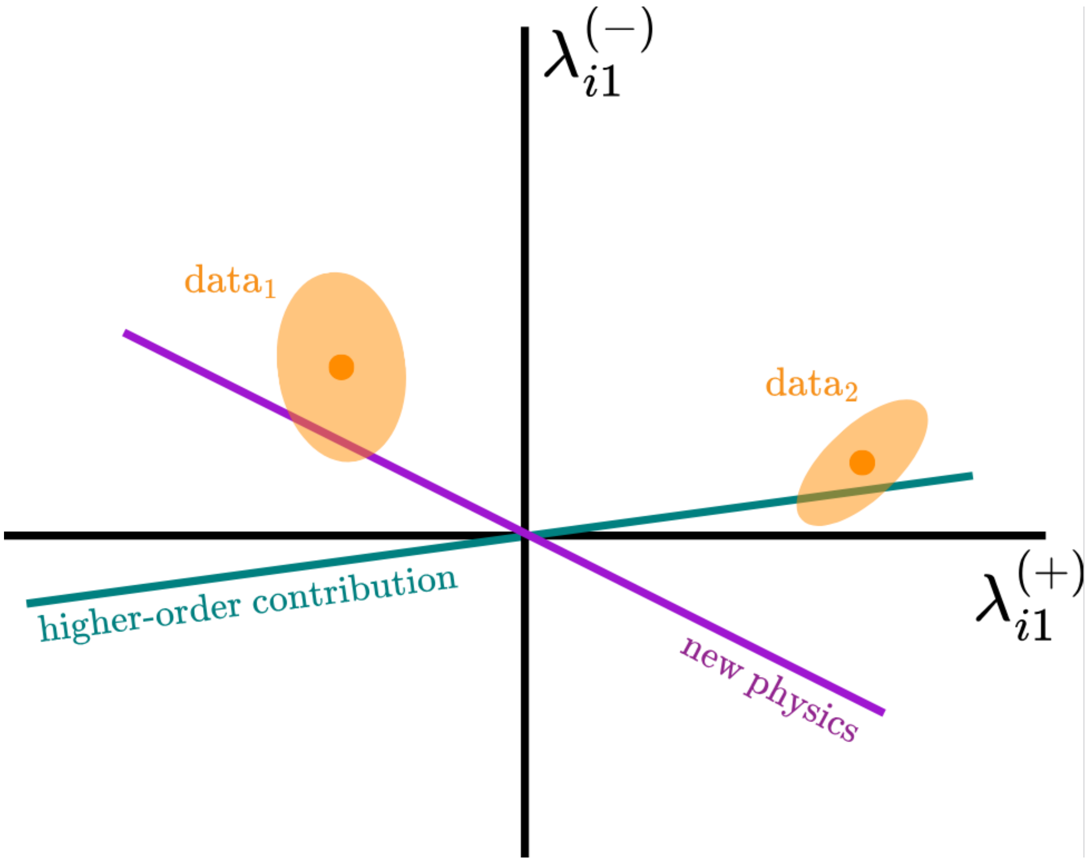


significant nonlinearity (NL)

BSM or nuclear physics?

Strategy: consider expected SM NL and constrain residual NL

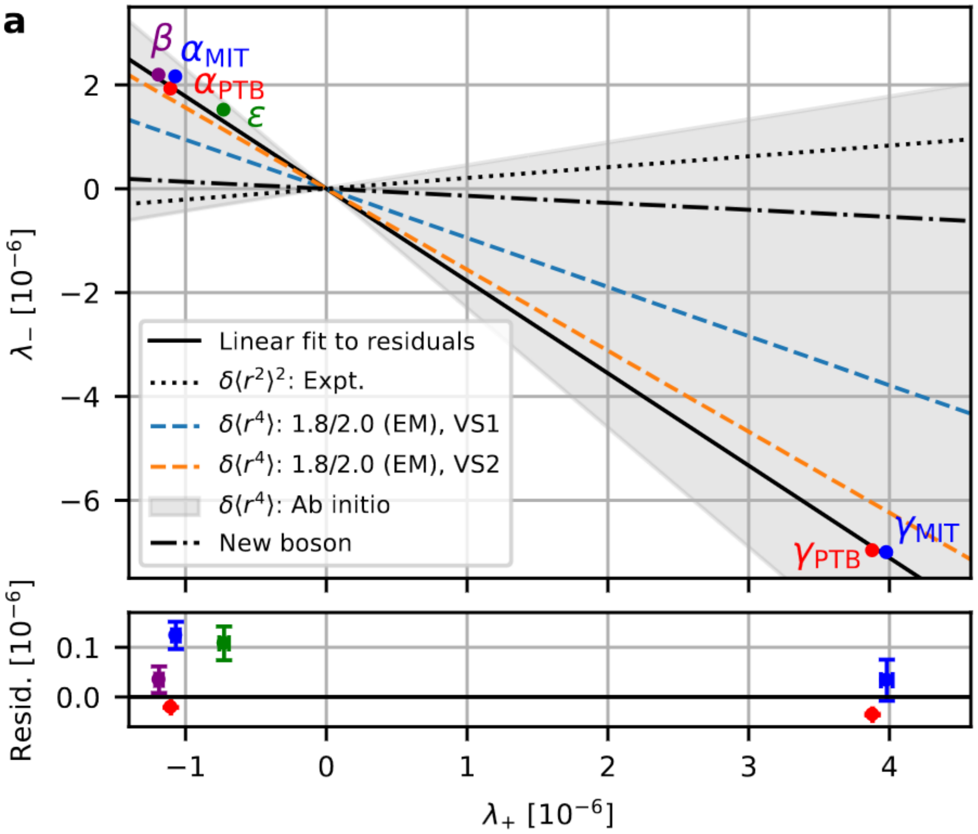
Disentangle SM from BSM



Nonlinearity decomposition plot:
→ is data compatible with higher-order SM terms or New Physics?

Disentangle SM from BSM: Yb

Door, Yeh, Heinz, Kirk, Lyu, Myagi, …EF,… Mehlstäubler. et al, PRL 134 (2025) 6, 063002



5 precise transitions in Yb/ Yb+

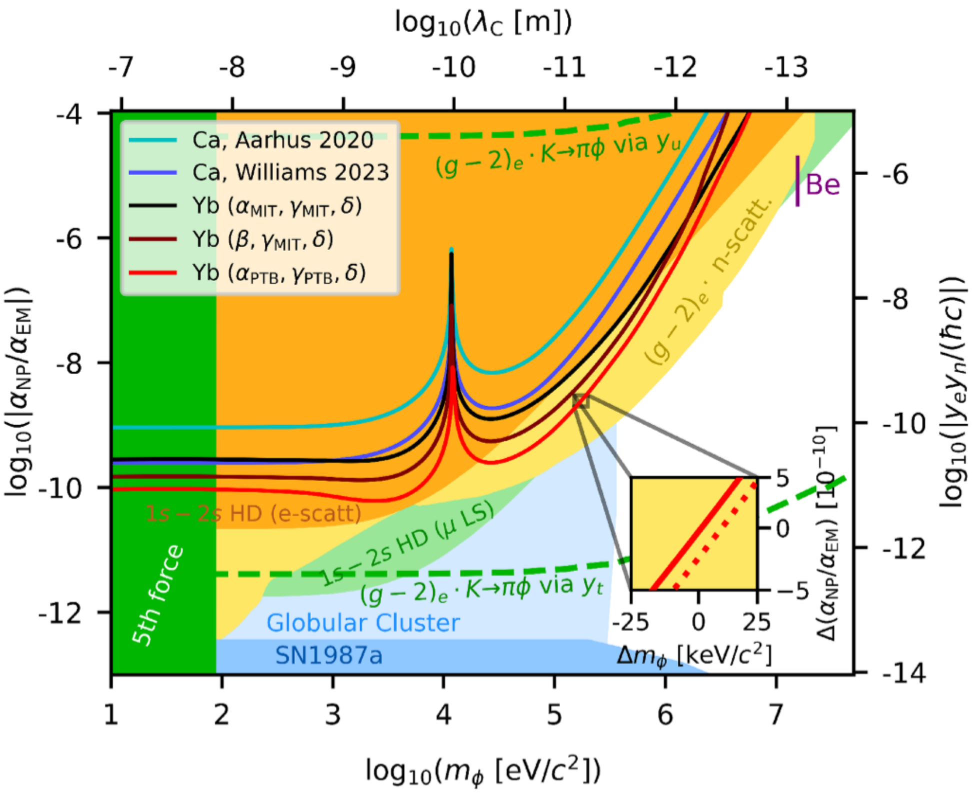
Notation	Transition	λ [nm]
$\alpha_{\mathrm{MIT}}, \alpha_{\mathrm{PTB}}$	$^2S_{1/2} \to {}^2D_{5/2}$ E2 in Yb$^+$	411
β	$^2S_{1/2} \to {}^2D_{3/2}$ E2 in Yb$^+$	435
$\gamma_{\mathrm{MIT}}, \gamma_{\mathrm{PTB}}$	$^2S_{1/2} \to {}^2F_{7/2}$ E3 in Yb$^+$	467
δ	$^1S_0 \to {}^3P_0$ in Yb	578
ϵ	$^1S_0 \to {}^1D_2$ in Yb	361

Several sources of nonlinearity needed.

- Nuclear shape effect ($\delta\langle r^4\rangle$) compatible with theory (gray)
- New boson still possible contribution

Dark boson bounds from Yb

PTB/Heidelberg/Hannover/Darmstadt/Sydney, Door, Yeh, Heinz, Kirk, Lyu, Myagi, …EF,... Mehlstäubler. et al, PRL 134 (2025) 6, 063002



here: 3 transitions and 4 isotope pairs

→ taking one SM nonlinearity into account

⇩

Best isotope-shift based bound so far

Highly Charged Ions (HCI)

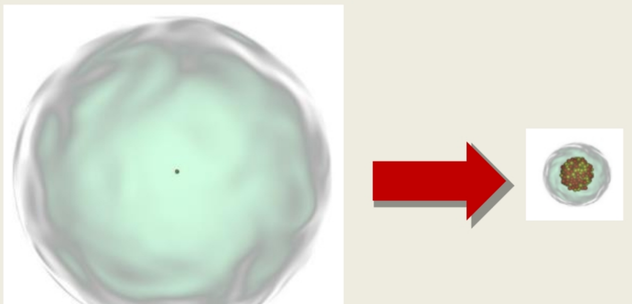


Figure: P. Schmidt

→ see Piet Schmidt's lectures

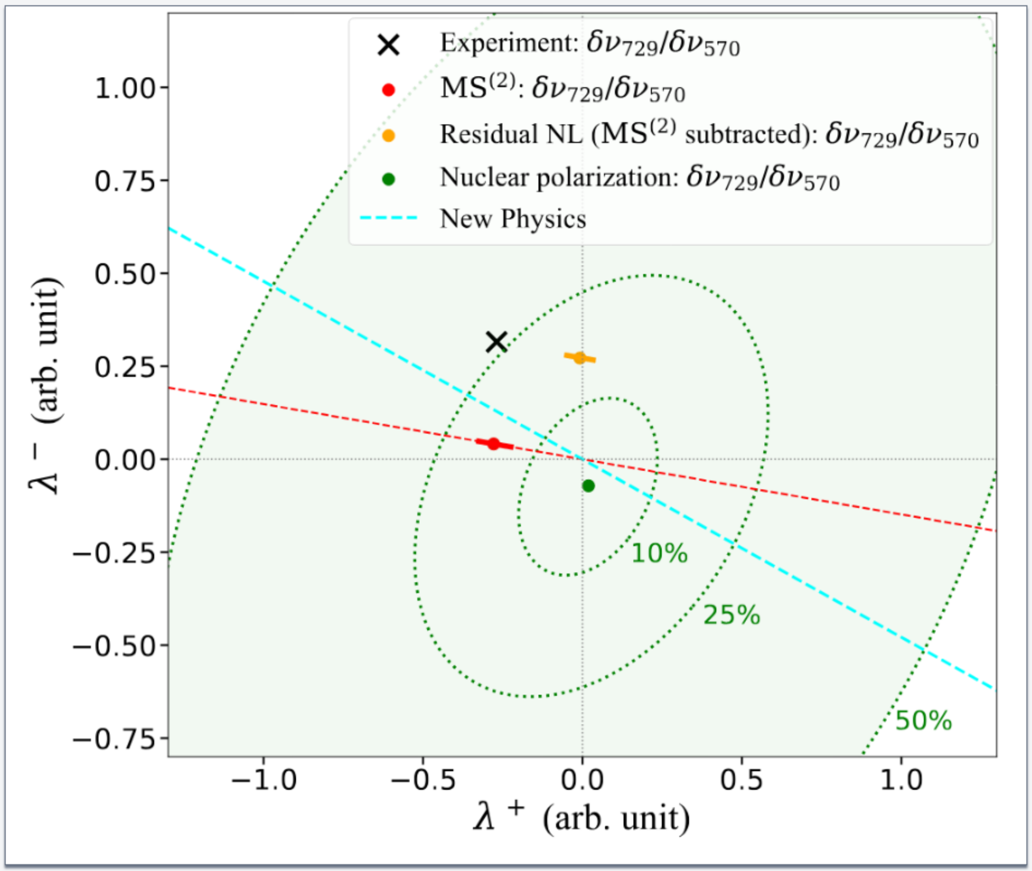
- Electrons removed → less multi-body effects
- QED effects amplified $\sim Z^4$
- Systematic shifts reduced, Stark shifts $\sim Z^{-6}$
  → high accuracy in traps
- electrons more closely bound
  → test shorter interaction range?

✅ Very sensitive to time-variation of fundamental constants ↔️ test ultralight DM
✅ Precise optical clock, e.g. Ar^{13+} (2×10^{-17}) [PTB&MPIK, King et al Nature '22]
✅ Precise isotope shift measurements possible ↔️ test light mediators

Ca isotope shifts: HCI and Ca^+

- PTB: Ca^{14+} $P_0 \to P_1$ @0.1 Hz precision
- ETH Zurich: Ca^+ $S \to D_{5/2}$ @0.1 Hz
- combined with D-fine splitting transition

Wilzewski, Huber, Door, Mariotti, Richter,… Blaum, Craik, Crespo, Schmidt, EF,
arXiv: 2412.10277 [physics.atom-ph], accepted by PRL



- Explaining the data requires more than 2nd-order mass shift & NP
- **Mass shift calculated** at 10% uncertainty → subtracted
- 1 more nonlinearity included → linear → compatible with calculated **nuclear polarization**

Ca isotope shifts: HCI and Ca^+

- PTB: Ca^{14+} $P_0 \to P_1$ @0.1 Hz precision
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- combined with D-fine splitting transition

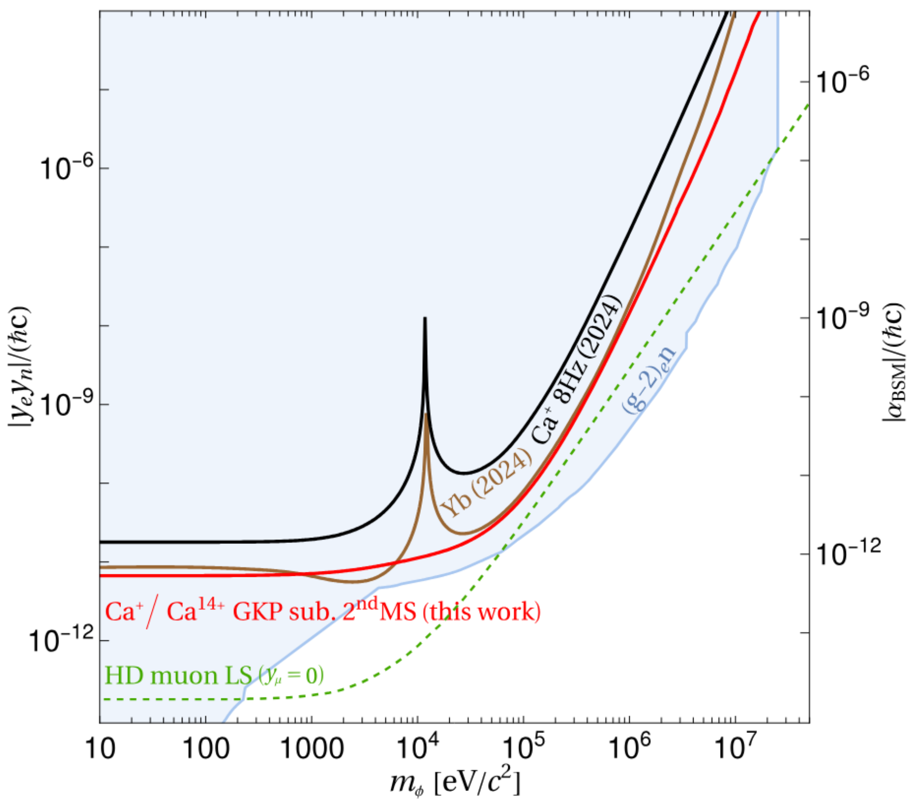
Wilzewski, Huber, Door, Mariotti, Richter,… Blaum, Craik, Crespo, Schmidt, EF, arXiv: 2412.10277 [physics.atom-ph], accepted by PRL

First nonlinearity in Ca observed

Theory input

Nuclear shape

Improved bound on dark boson



Variation of fundamental constants

Antypas et al, Snowmass 2203.14915

Scalar ultralight DM ϕ

$$\mathcal{L}_{\text{int}}^{\text{lin}} = \kappa\phi \left\{ \left[\frac{d_e F_{\mu\nu}F^{\mu\nu}}{4} - d_{m_e} m_e \bar{\psi}_e \psi_e \right] - \left[\frac{d_g \beta_3 G^a_{\mu\nu} G^{a\mu\nu}}{2 g_3} + \sum_{q=u,d,s} \left(d_{m_q} + \gamma_m d_g \right) m_q \bar{\psi}_q \psi_q \right] \right\}$$

→ induces **oscillations** of $\alpha_{\mathbf{em}}$ and fermion masses:

$$\phi(t) \approx \phi_0 \cos(m_\phi t)$$

$$\alpha \to \frac{\alpha}{1 - g_\gamma \phi} \approx \alpha(1 + g_\gamma \phi)\,, \quad m_\psi \to m_\psi + g_\psi \phi$$

→ see lecture by M. Safronova

Yb, Yb/Sr clock comparison

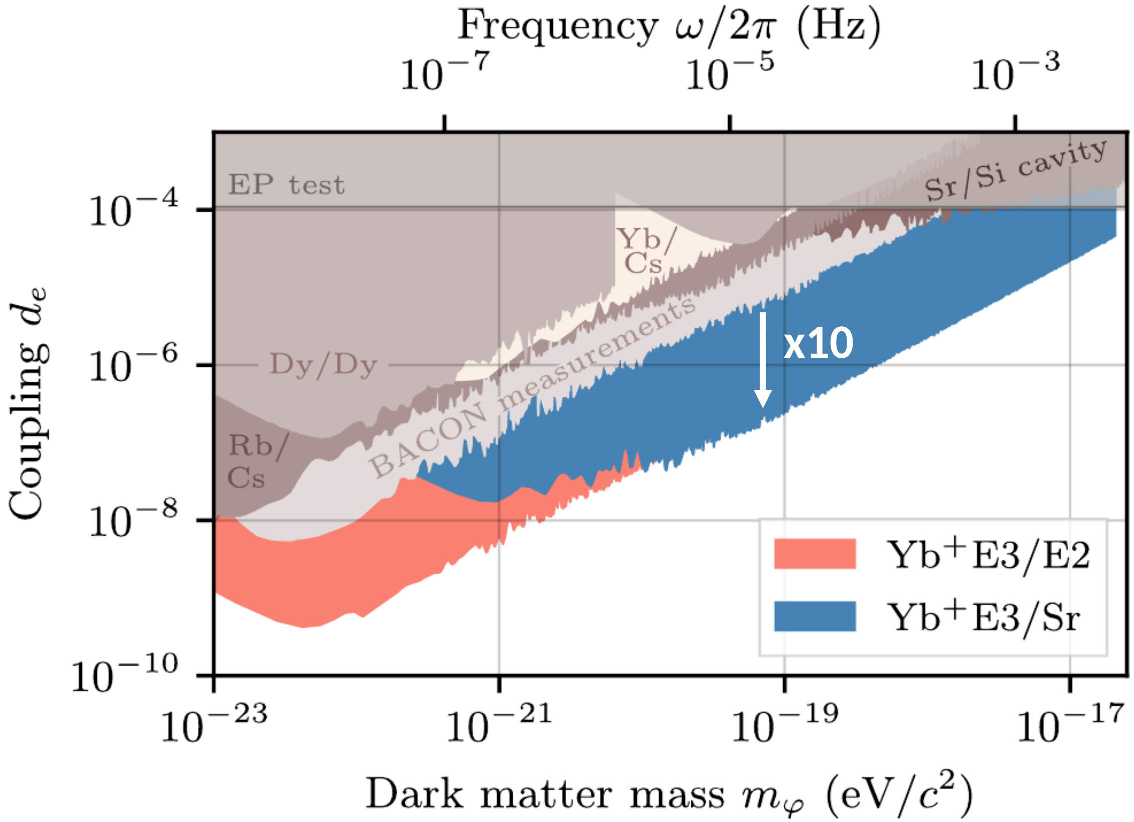
Record precision of Yb and Sr clock transitions at PTB

↓

No oscillation of frequency ratio detected

↓

Improved sensitivity to ultralight dark matter by factor 10



→ see lecture by M. Safronova

Filzinger,… Huntemann, **PRL 130**, 253001 (2023)

Choose sensitive system of clocks

$$\frac{\Delta\omega}{\omega} = K \frac{\Delta\alpha}{\alpha}$$

change in frequency

sensitivity

change in α

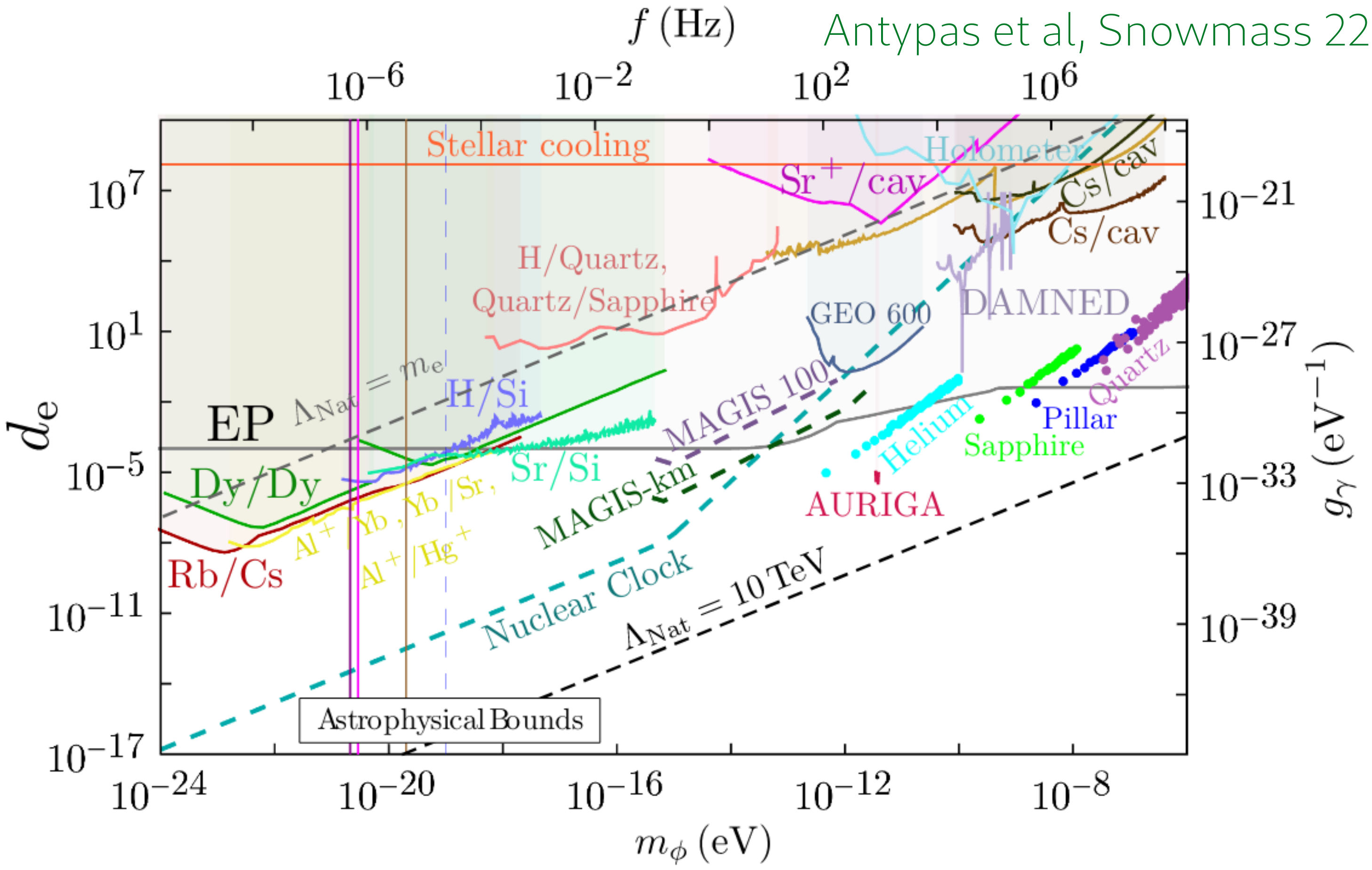
Clever choice of system

System	K	[nm]
Sr	0.06	699
Yb^{+} E2	**0.91**	436
Yb^{+} E3	**-6**	467
Al^{+}	0.01	267
In^{+}	<0.1	237

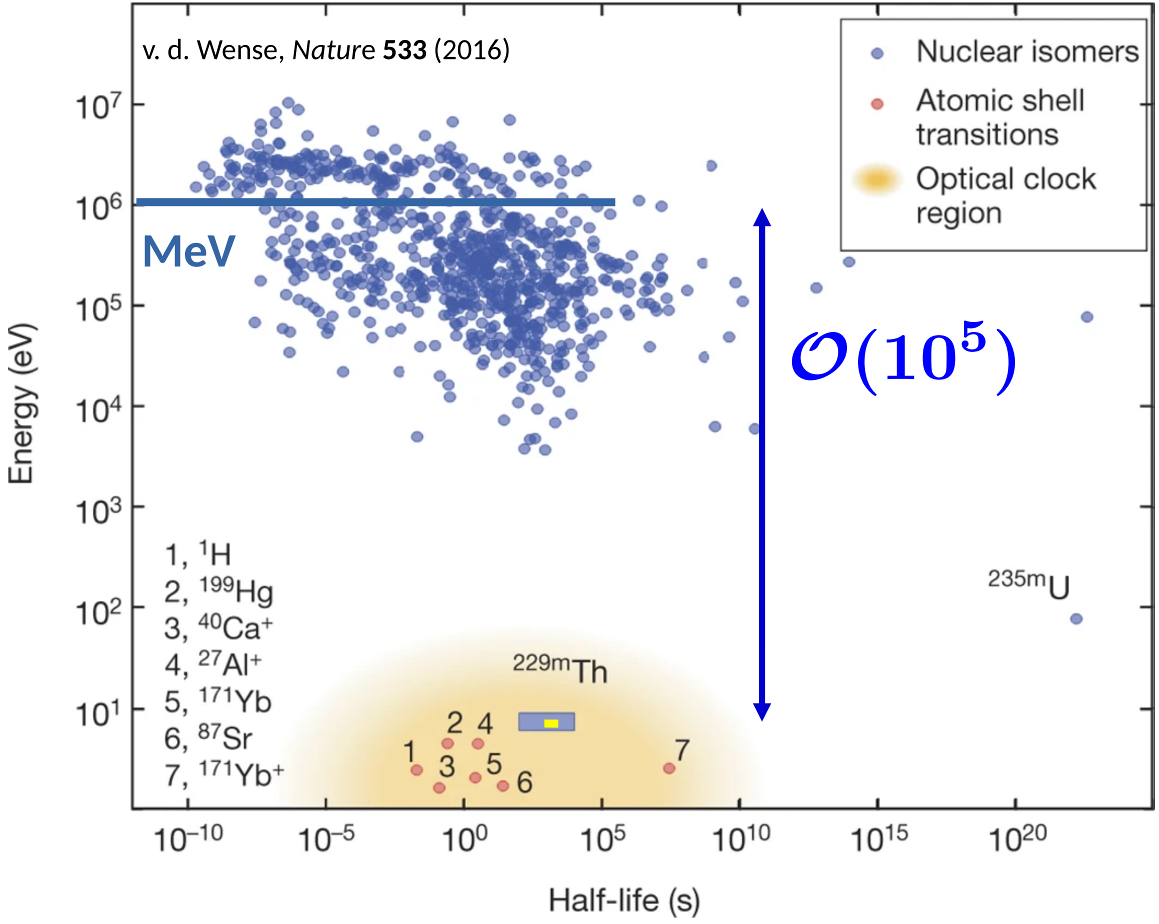
Ultralight scalar DM-photon coupling

$$\kappa \frac{d_e}{4} \phi F_{\mu\nu} F^{\mu\nu}$$

Antypas et al, Snowmass 2203.14915



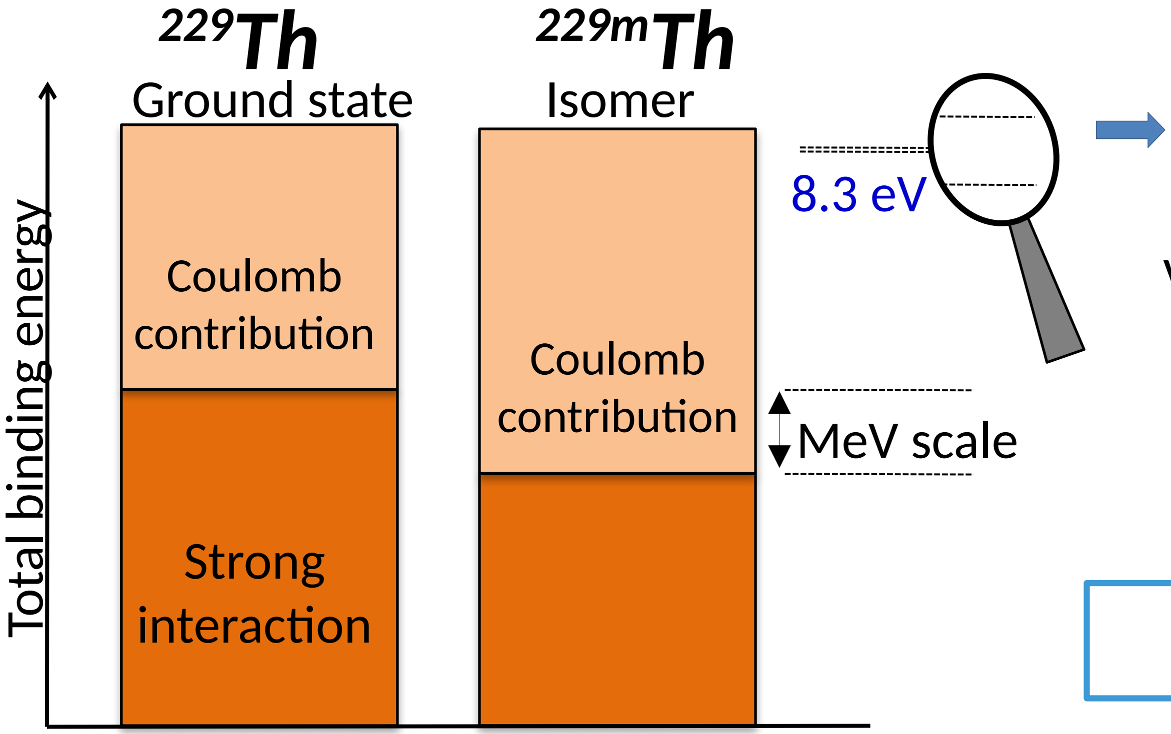
Towards a nuclear clock



^{229}Th: the only suitable system for an optical nuclear clock

Other nuclear transition in MeV range
→ inaccessible to lasers

Rare cancelation of 1:10^5



148 nm optical transition

in fact, VUV

VUV laser: Thielking et al New J. Phys. **25** (2023)

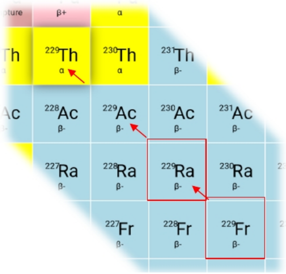
New physics sensitivity:
K ~ 10^4 (estimated)

Peik et al, Quantum Sci. Technol. **6** (2021)

20 years searches → discovery 2024

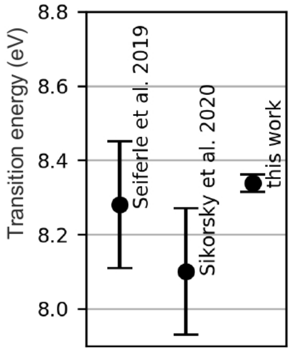
2003 ... 2023

Proposal [Peik, Thamm]



New pathway of producing the Th isomer at ISOLDE @CERN

Fr→ Ra→ Ac→ ^{229}Th



δf

δf/f % 10^{-4}

20 years searches → discovery 2024

2003 ... 2023 02/24

Proposal [Peik, Thamm]

New pathway of producing the Th isomer at ISOLDE @CERN
Fr→ Ra→ Ac→ ^{219}Th

Discovery @PTB
First laser excitation of nucleus [Peik]
Crystal from Vienna
Broadband VUV laser

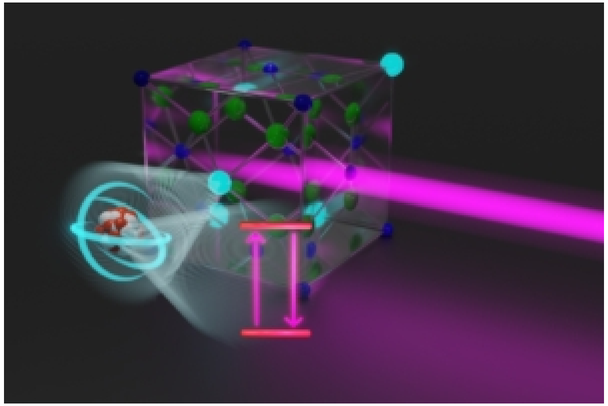


Figure: TU Vienna

f=2020.409 THz

δf			7 GHz
δf/f	%	10^{-4}	3×10^{-6}

20 years searches → discovery 2024

2003	...	2023	02/24	04/24	06/24	outlook
Proposal [Peik, Thamm]	New pathway of producing the Th isomer at ISOLDE @CERN Fr→ Ra→ Ac→ ^{219}Th		Discovery @PTB First laser excitation of nucleus [Peik] Crystal from Vienna Broadband VUV laser	@UCLA Improved precision [Hudson]	@JILA Boulder VUV frequency comb [Ye]	

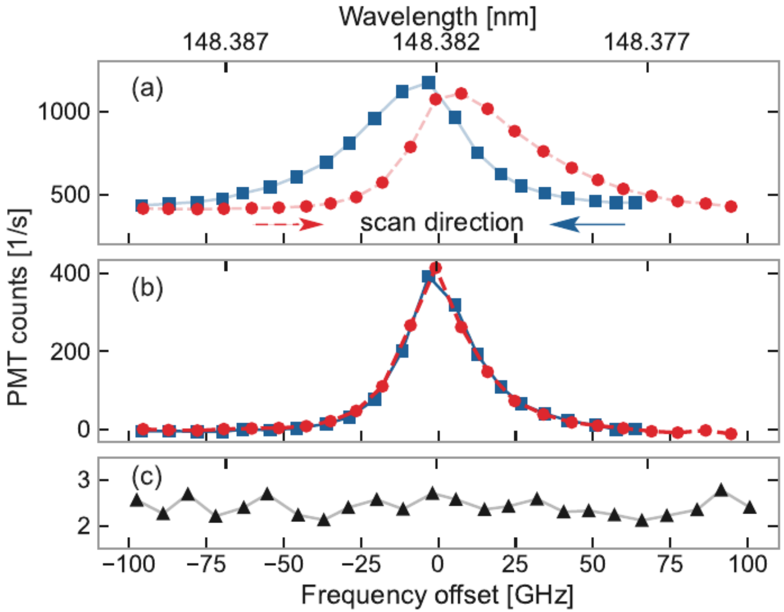
f=2020.409 THz

δf			7 GHz	3 GHz	300 kHz	
δf/f	%	10^{-4}	3×10^{-6}	1.5×10^{-6}	10^{-10}	

Lessons for DM from Th lineshape

Lineshape of nuclear Th resonance [PTB]

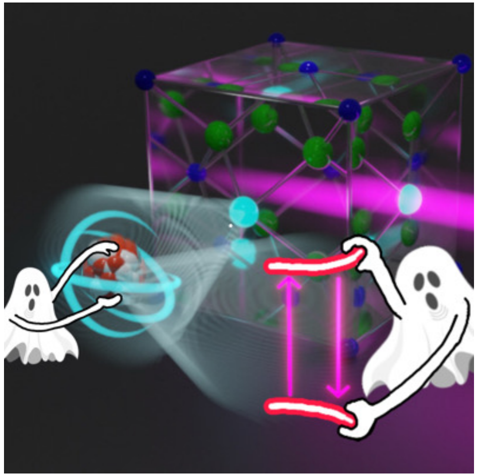
Tiedau, ..., Peik, ..., Schumm [PRL 2024]



What if there is oscillating, light Dark Matter?

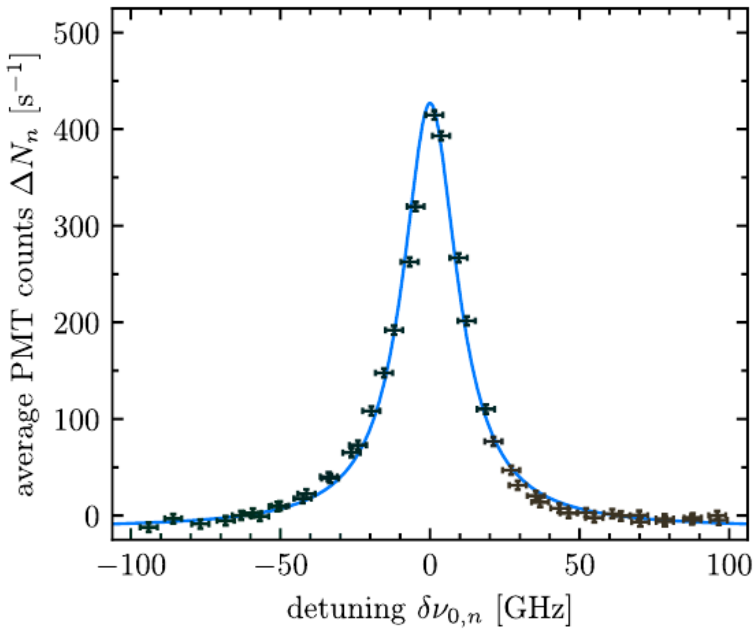
→ How much would it broaden the resonance?

→ bound on DM parameter space



Nuclear lineshape analysis

$\nu(t) \simeq \nu_0$



- In absence of DM,
  $I(\nu) = \delta(\nu - \nu_0)$

Fuchs, Kirk, Madge, Paranjape, Peik, Perez, Ratzinger, Tiedau (PTB/Hannover/Weizmann, theory & exp)
Accepted by PRX

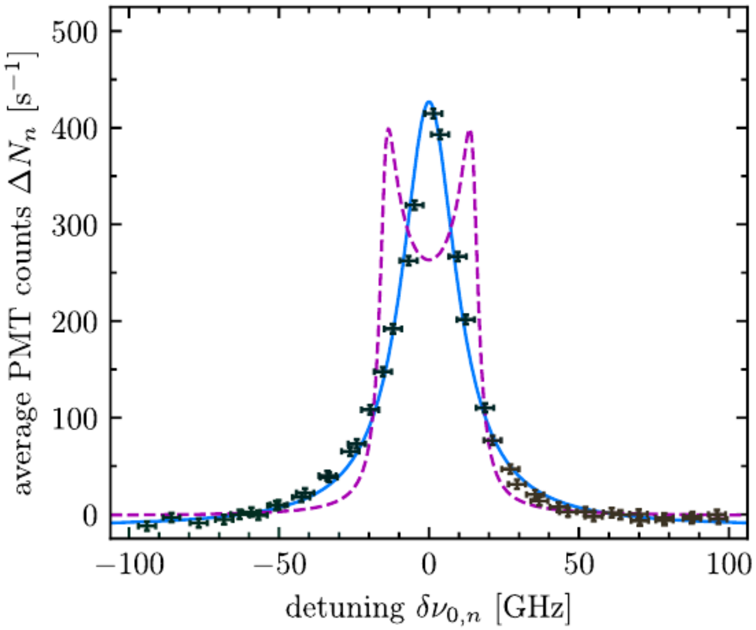
Slide by Fiona Kirk

(Convolved with resonance lineshape)

Nuclear lineshape analysis

$$\nu(t) \simeq \nu_0 + \delta\nu_{DM} \cos(2\pi\nu_{DM} t + \varphi_{DM})$$

Fuchs, Kirk, Madge, Paranjape, Peik, Perez, Ratzinger, Tiedau (PTB/Hannover/Weizmann, theory & exp)
Accepted by PRX



- In absence of DM, $I(\nu) = \delta(\nu - \nu_0)$
- In presence of DM, average over $T_{DM} = 1/\nu_{DM}$:

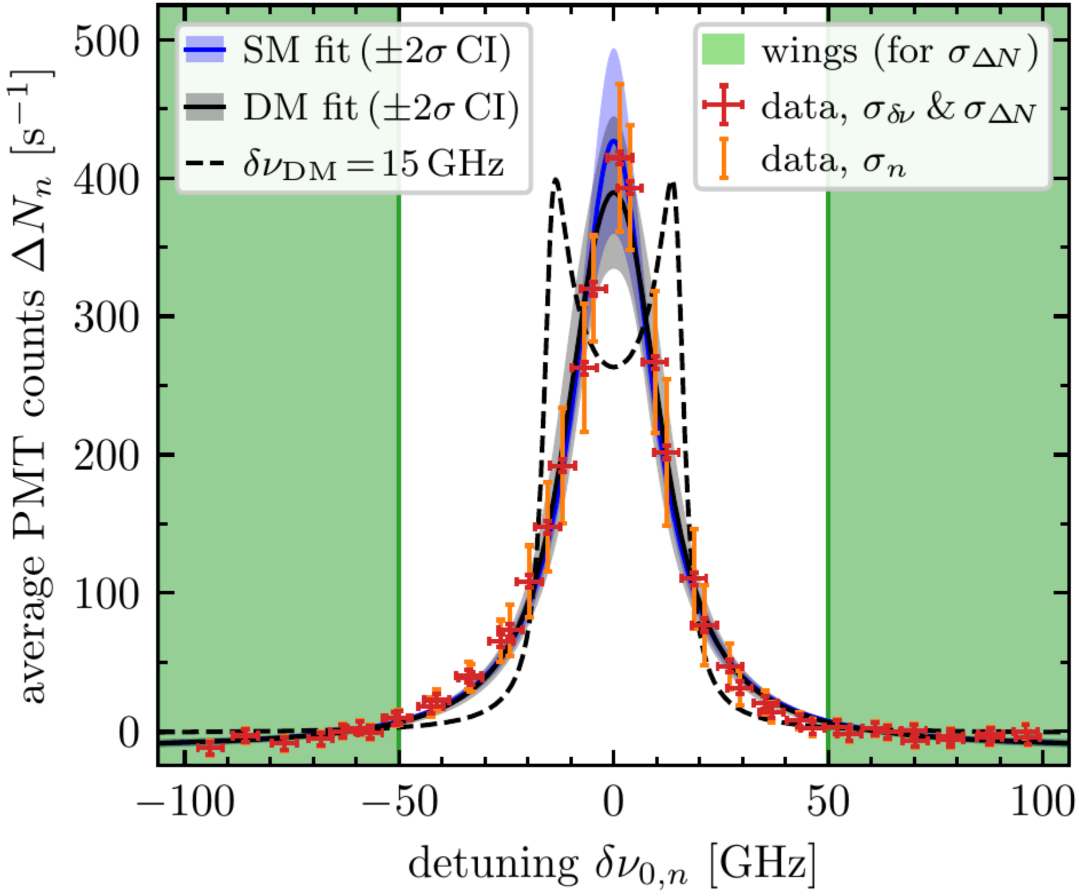
$$\langle I(\nu)\rangle_{T_{DM}} = \int_0^{T_{DM}} \frac{dt}{T_{DM}} \delta(\nu - \nu(t))$$

$$= \frac{\theta\left(1 - \left|\frac{\nu-\nu_0}{\delta\nu_{DM}}\right|\right)/\pi}{\sqrt{\delta\nu_{DM}^2 - (\nu - \nu_0)^2}}$$

Slide by Fiona Kirk

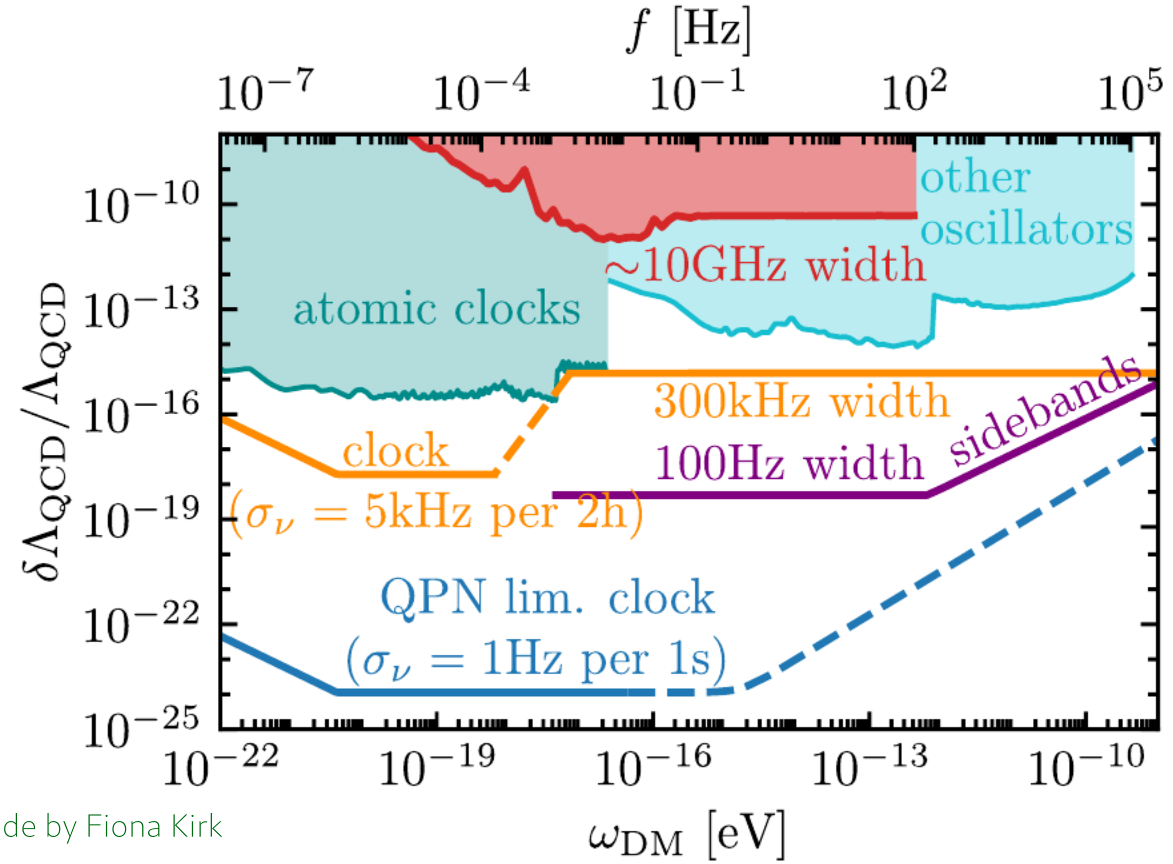
(Convolved with resonance lineshape)

SM vs DM fit to Th data



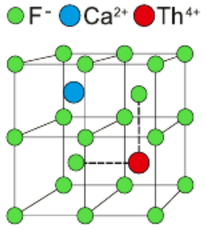
Fuchs, Kirk, Madge, Paranjape, Peik, Perez, Ratzinger, Tiedau (PTB/Hannover/Weizmann, theory & exp)
Accepted by PRX

Th probes QCD scale



Our bound, based on data published in PRL 132 (2024) 18, 182501

Projection, based on data published in Nature 633 (2024) 8028

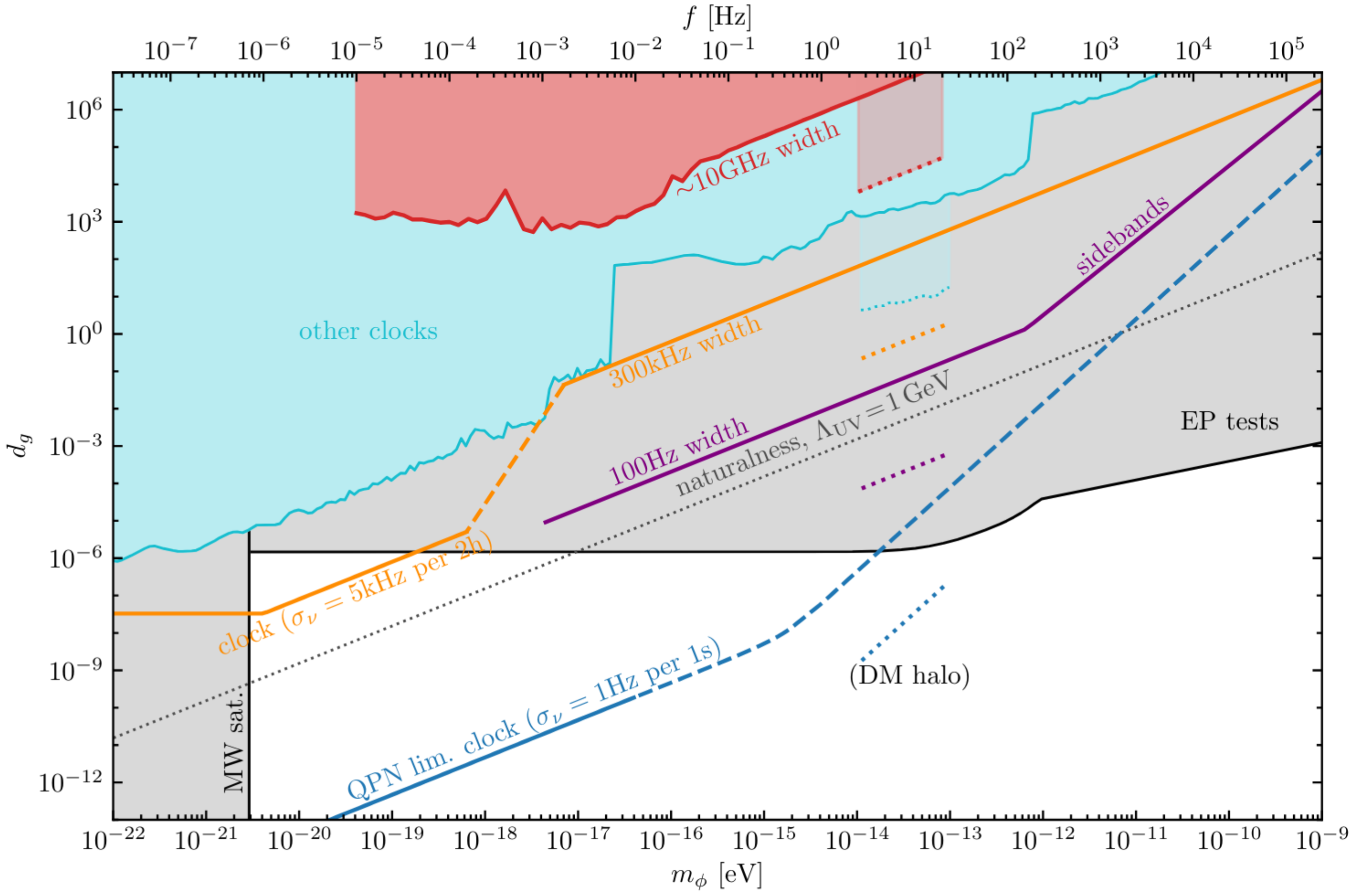


Prospective reach of a lineshape analysis limited by host crystal

Projection for a future single-ion nuclear clock (quantum-projection noise-limited)

Slide by Fiona Kirk

Bounds on DM from nuclear transition



Fuchs, Kirk, Madge, Paranjape, Peik, Perez, Ratzinger, Tiedau (PTB/Hannover/Weizmann, theory & exp)
Accepted by PRX

Potential for "nuclear superiority"
= nuclear clock can soon become more sensitive to DM than atomic clocks

Particle questions ↔️ Quantum sensing

Baryon Asymmetry

Dark Matter

Strong CP problem

Hierarchy problem

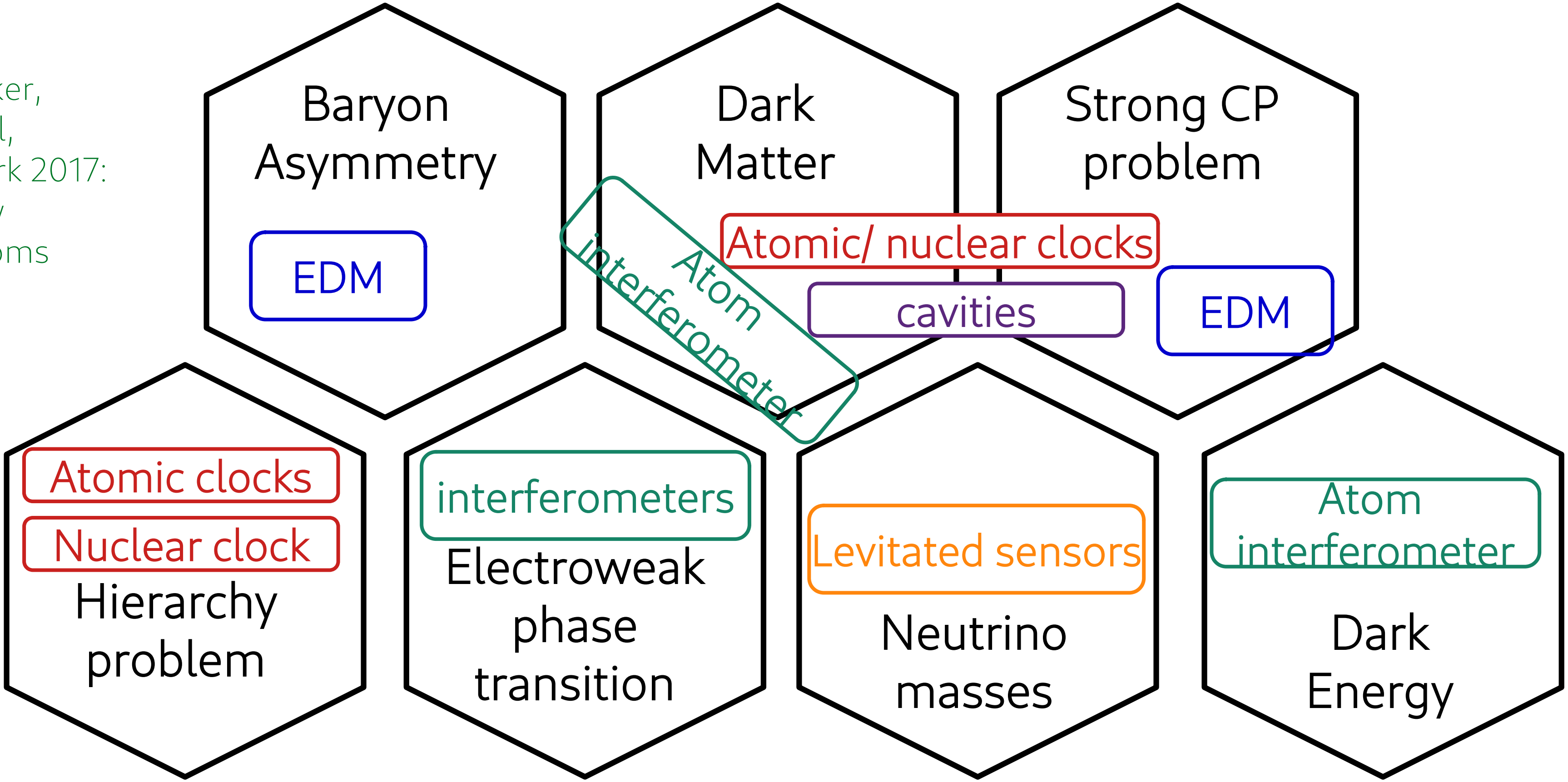
Electroweak phase transition

Neutrino masses

Dark Energy

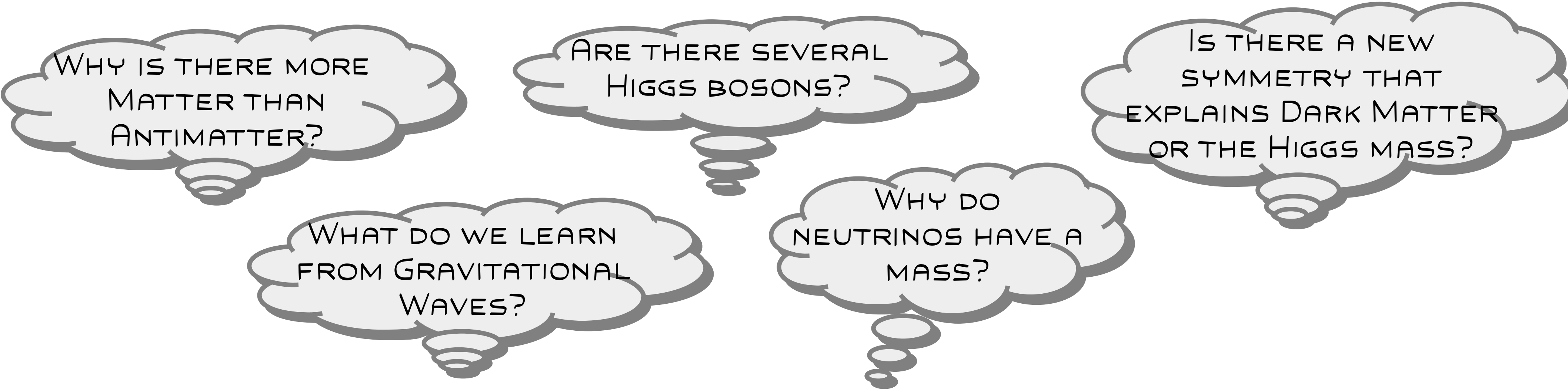
Particle questions ↔️ Quantum sensing

Review:
Safronova, Budker, DeMille, Kimball, Derevianko, Clark 2017: "Search for New Physics with Atoms and Molecules"



Many open questions

- Many questions create new questions – on a more fundamental level.



➡ A lot to do for young scientists! Real impact of quantum technologies likely.

Conclusion

→ Well-motivated scenarios with light or heavy New Physics require novel searches

→ Goal in model building: solve several question at once: e.g. axion, relaxion

→ Atomic clocks are sensitive NP sensors, new systems explored: HCI, nuclear clock

→ Isotope shifts: unprecedented precision tests nucleus and Dark Bosons

→ Detection challenges: feeble couplings, broad mass range → quantum enhancement

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Thank you!

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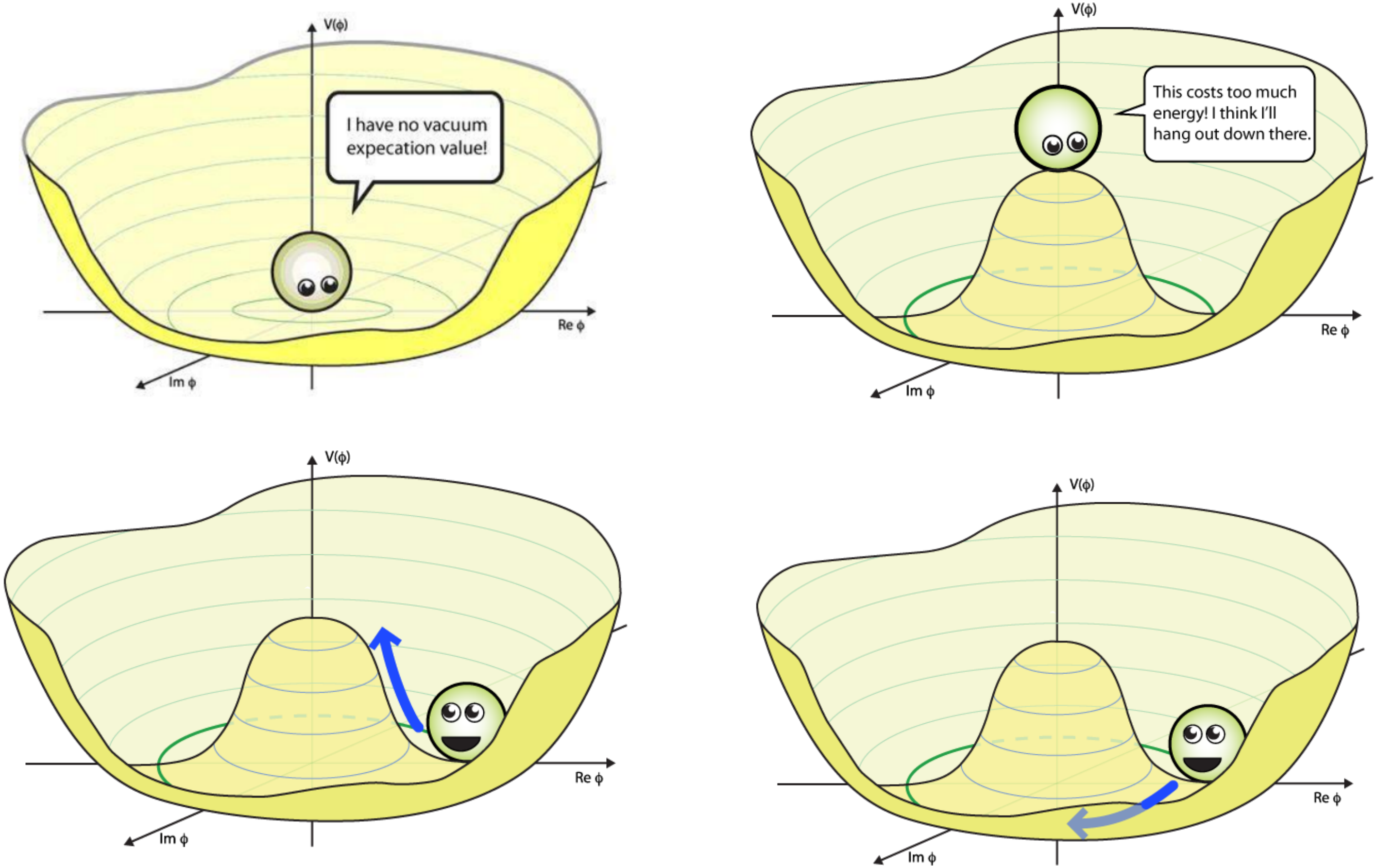
BACKUP

The Higgs mechanism

SM Higgs potential

$$V(\Phi) = \mu^2|\Phi|^2 + \lambda|\Phi|^4$$

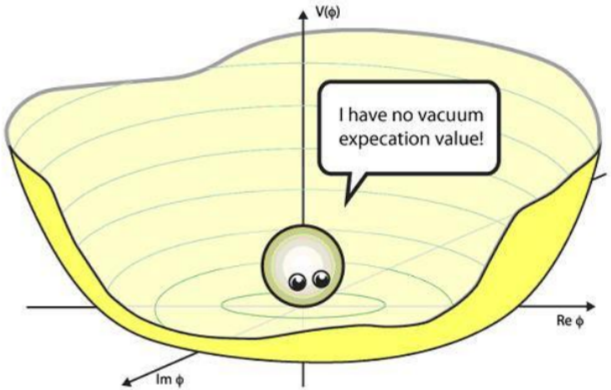
$\boxed{\mu^2 < 0}$



The Higgs potential

$\Phi = \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$ is the Higgs boson:

a complex, 2-component field
→ 4 real degrees of freedom



SM Higgs potential

$$V(\Phi) = \mu^2|\Phi|^2 + \lambda|\Phi|^4$$

- If $\mu^2, \lambda \geq 0$
  - minimum at $\langle\Phi\rangle = 0$
- If $\mu^2 < 0$
  - minimum a $\langle\Phi\rangle \neq 0$

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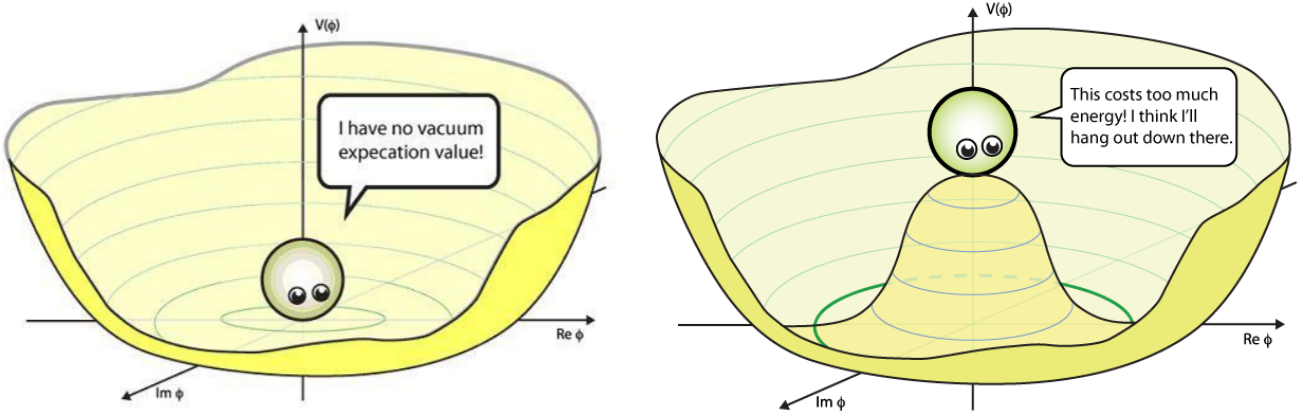

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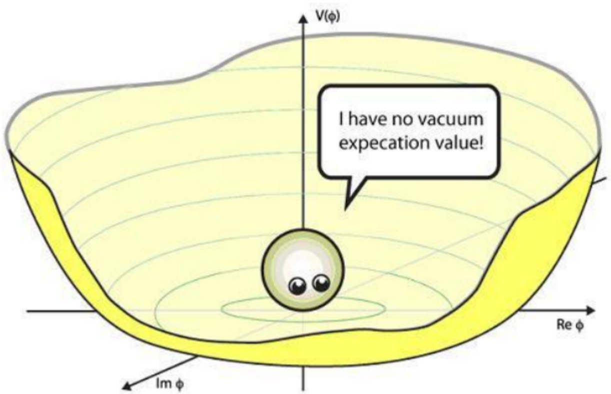

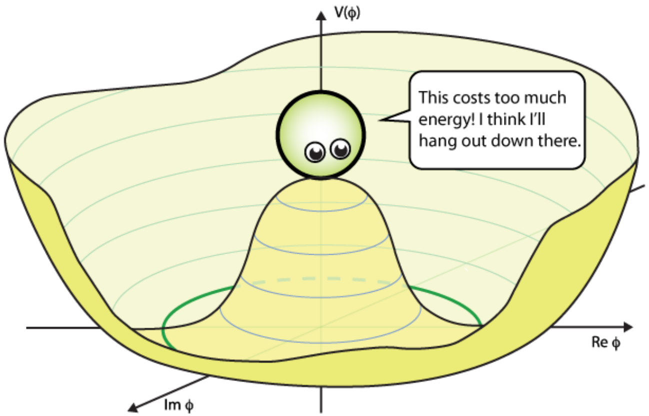

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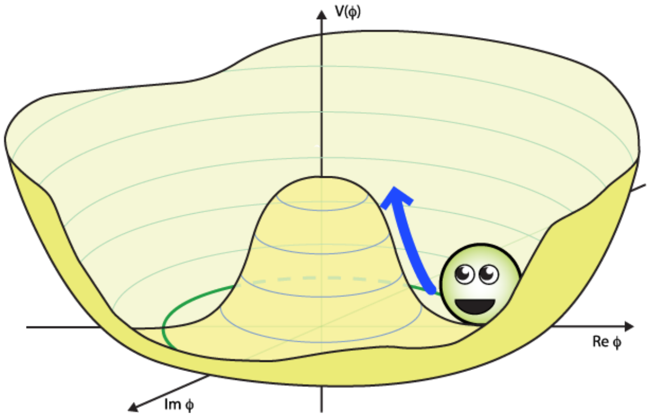

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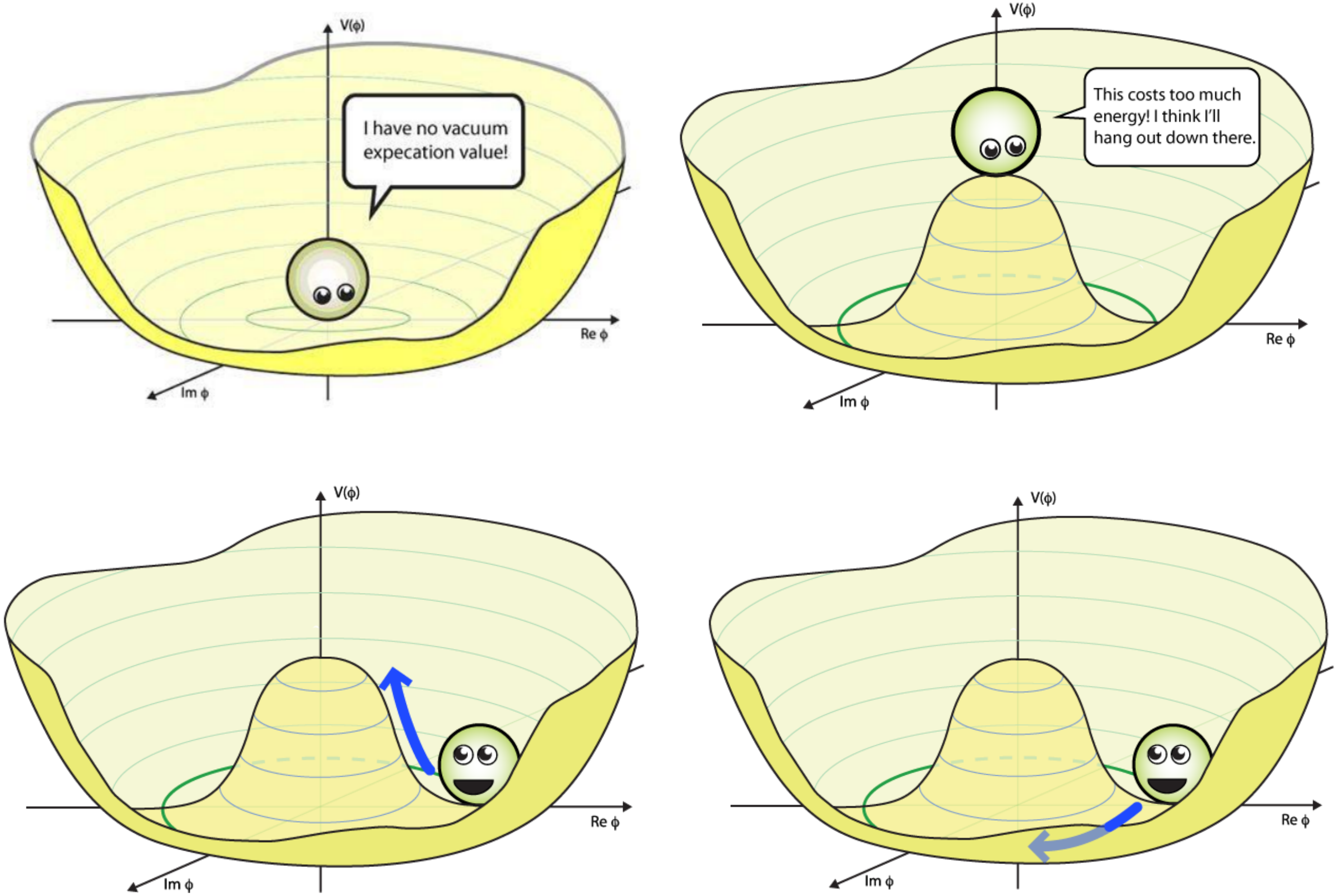
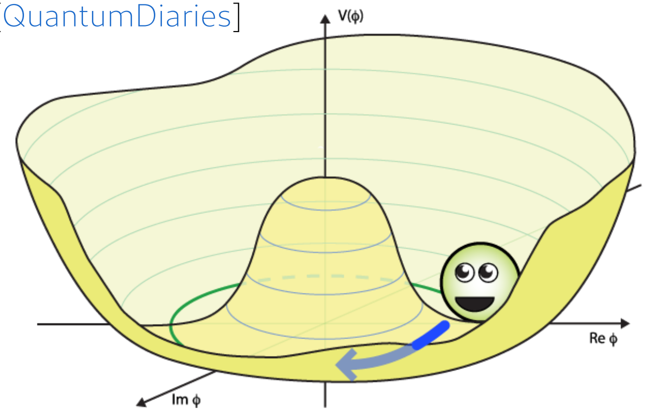
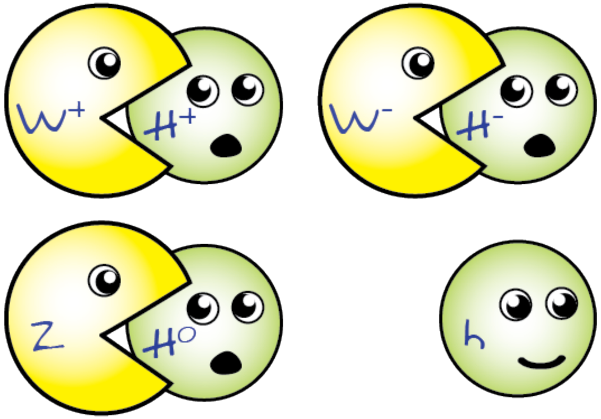


Masses of the gauge bosons

[QuantumDiaries]





The originally massless electroweak gauge bosons W±, Z “eat” 3 degrees of freedom of
They become massive:

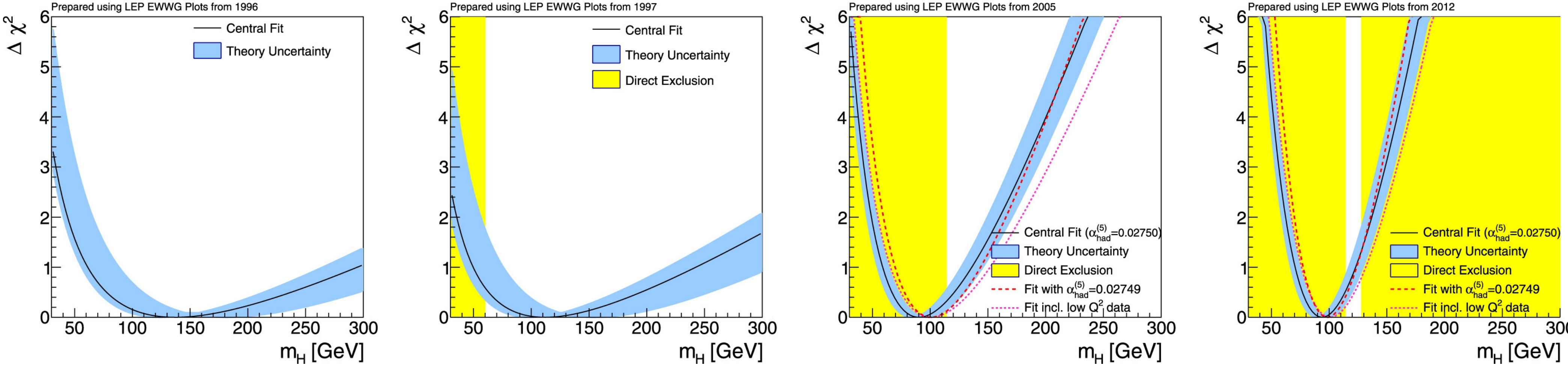
$$M_W = \frac{v}{2} g \simeq (80.379 \pm 0.012)\,\mathrm{GeV}$$

$$M_Z = \frac{v}{2}\sqrt{g^2 + g'^2} \simeq (91.1876 \pm 0.002)\,\mathrm{GeV}$$

They have an additional polarization: from 3*2 d.o.f (massless) to 3*3 d.o.f. (massive)

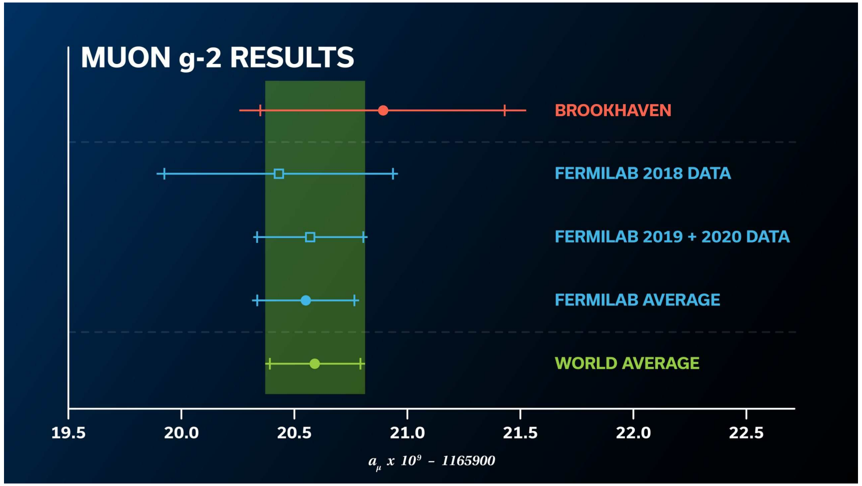
Electroweak fit of Higgs mass

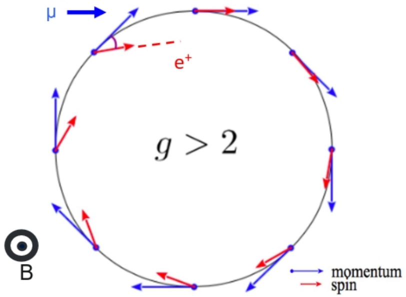
Erler, Schott, 2019



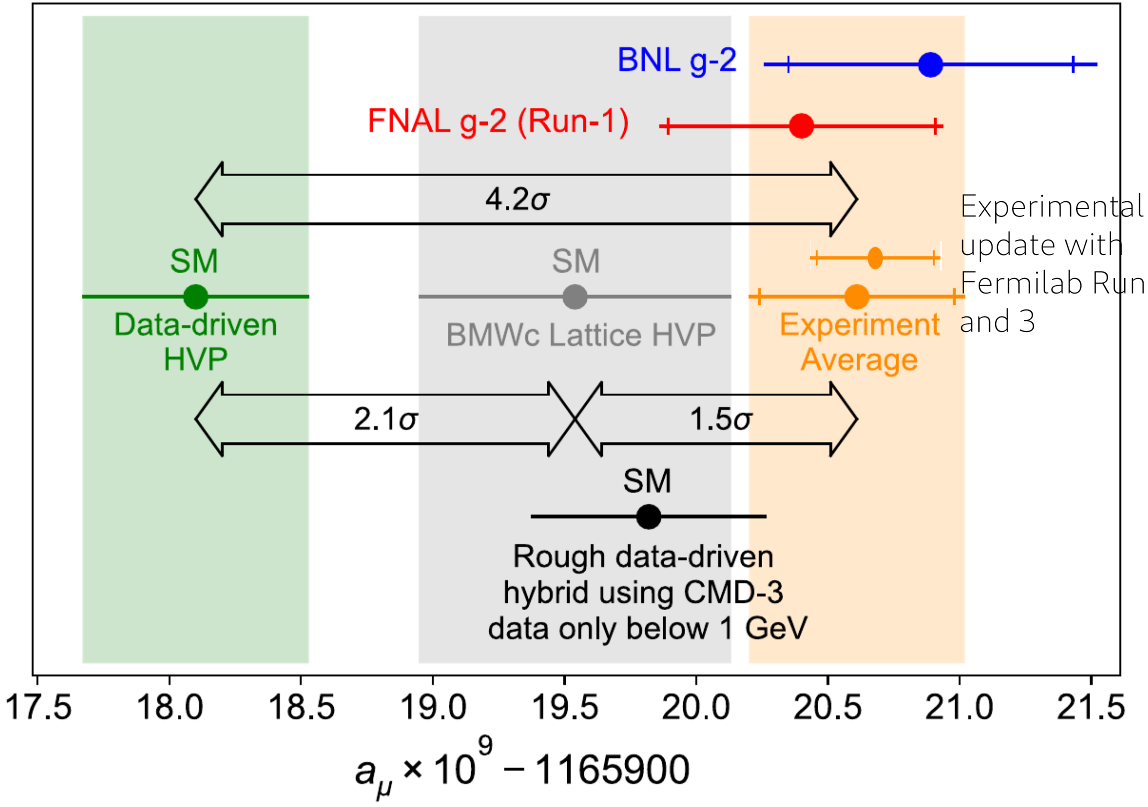
Measured muon magnetic moment

Update from 08/2023, PHYSICAL REVIEW LETTERS 131, 161802 (2023)



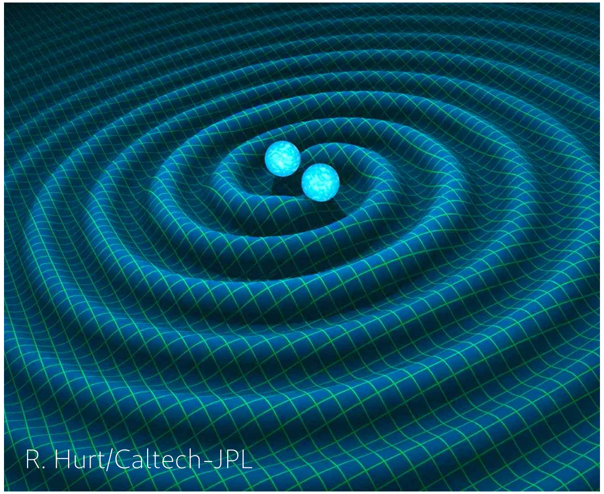


Polarized muons in storage ring. g>2 → spin precesses faster than momentum.



Experimental update with Fermilab Run-2 and 3

Gravitational waves as messengers



What can **gravitational waves** tell us about

- Processes in the early universe?
- Phase transitions, e.g. from the unbroken electroweak symmetry to the spontaneously broken phase where the gauge bosons get a mass?

How can we detect them, especially in undetected frequency ranges?

Analogy of axion/ GW detection

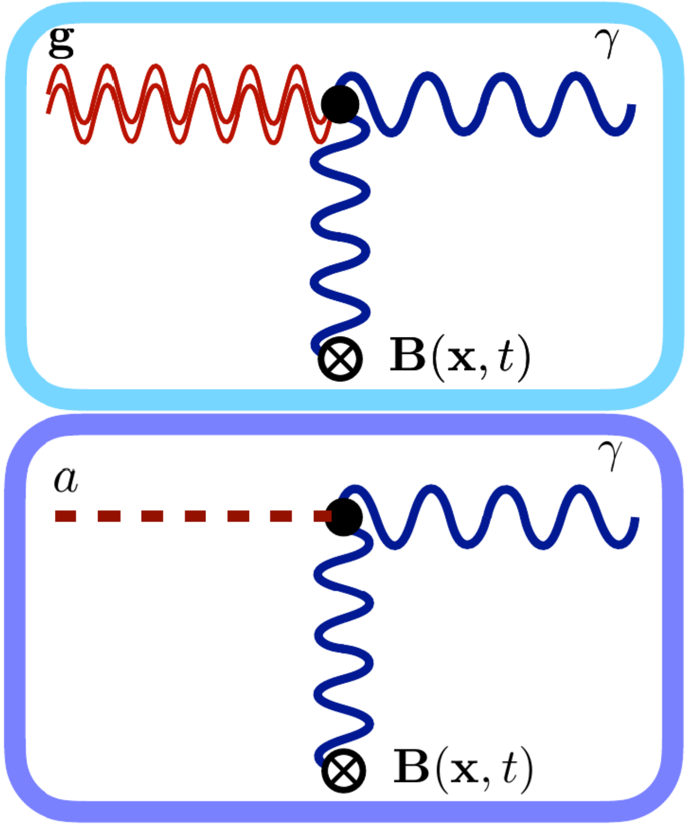


Figure by Sebastian Ellis (U Geneva) @ UHFGW workshop at CERN, 12/2023

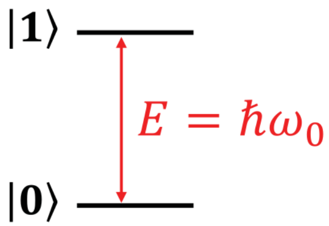
Quantum Sensors

i) Discrete, resolvable energy levels, typically 2-level system

ii) quantum system initialized in known state & read out

iii) quantum system can be coherently manipulated

Degen, Reinhard, Cappallaro '16



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iv) interaction with external field
→ energy shift or transition between levels

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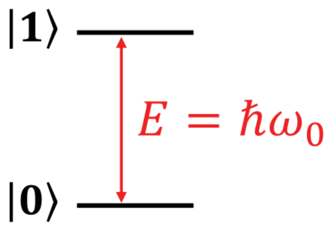

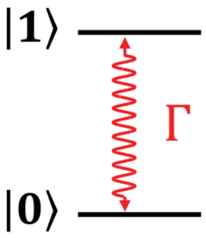

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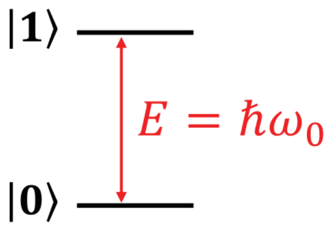

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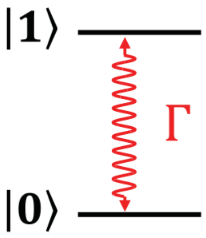

quantum objects: atoms, ions, clocks, Rydberg states, superconducting circuits, cavities, interferometers, …
& quantum techniques: entanglement/ squeezing/ non-demolition
→ well suited for light DM/NP, GWs, also for HEP detectors