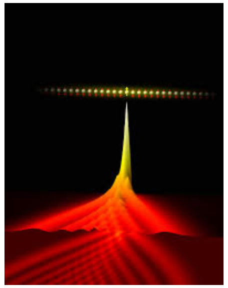
Relaxion dark matter & the precision front

Gilad Perez

Weizmann Inst.



New Paths towards New Physics, 2019

CNRS/LAPTh-Annecy mini-workshop

Outline

- Intro: brief motivation for light physics & dark matter (DM).

- Relaxion & coherent DM, \w dynamical misalignment.

- Prelim: probing heavyish-light-scalar/relaxion DM \w clocks.

- Very prelim: probing scalar-stars \w clocks (earth & space).

- Conclusions.

Introduction

♦ New particles/forces must exists as Standard Model can't account for baryon asym., dark matter (DM), Higgs-hierarchy, etc.

♦ Conventional particle-TeV-physics wisdom is challenged by the null results of the LHC & DM experiments.

♦ New paradigms recently proposed suggest alternative solutions.

"Cosmic attractors", "dynamical relaxation", "N-naturalness", "relating the weak-scale to the CC" & "inflating the Weak scale".

♦ Presence of light scalar/s is common to most.

Benchmarking-relaxion

- Relaxion-models => interesting & concrete: solves the hier' strong CP problems in a simple & computable way, \w definite Lagrangian.

Graham, Kaplan & Rajendran (15); Hook,Marques-Tavares; Gupta, Komargodski, GP & Ubaldi (16); Davidi, Gupta, GP, Redigolo & Shalit; Gupta; Nelson & Prescod-Weinstein (17)

- The relaxion is light because it is axion-like particle but due to CP violation it mixes with the Higgs => has scalar interactions.

Flacke, Frugiuele, Fuchs, Gupta & GP; Choi & Im (16)

it interacts \w atoms

its variation <=> variation of all constants

Use as benchmark to compute sensitivity of variety of exp' & compare them to scalar-new-physics.

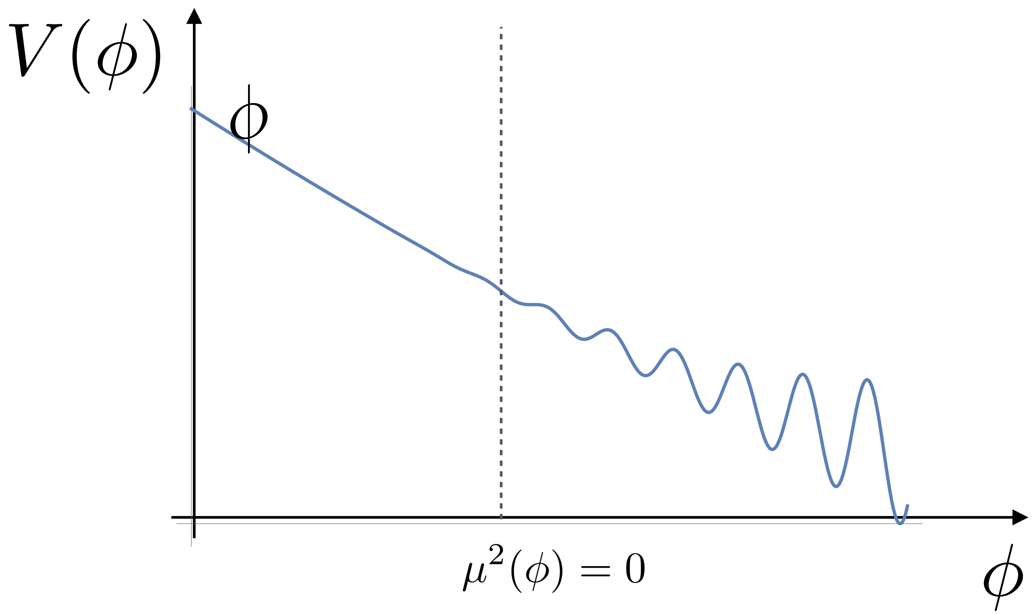
Relaxion's physics

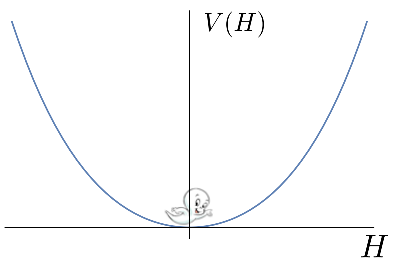
Graham, Kaplan & Rajendran (15)

- A dynamical solution/amelioration of the Higgs fine-tuning problem:

(*i*) Add a scalar (relaxion) Higgs dependent mass: $\overbrace{(\Lambda^2 - g^2\phi^2)}^{\mu^2(\phi)} H^\dagger H$

(*ii*) ϕ roles till μ^2 changes sign $\Rightarrow \langle H \rangle \neq 0 \Rightarrow$ stops rolling.





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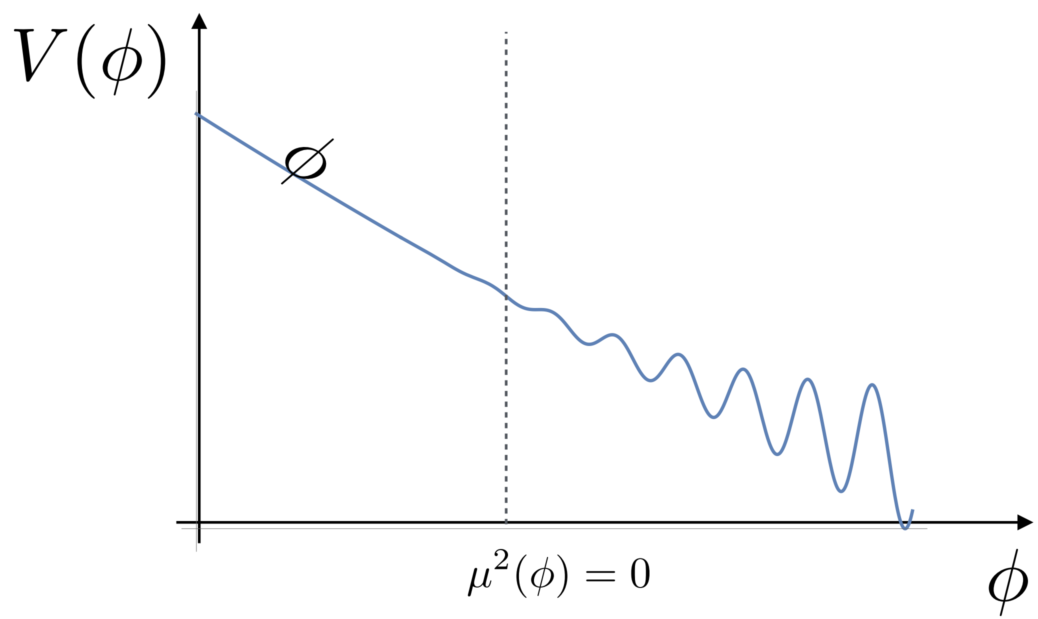

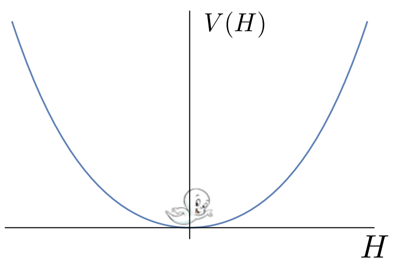

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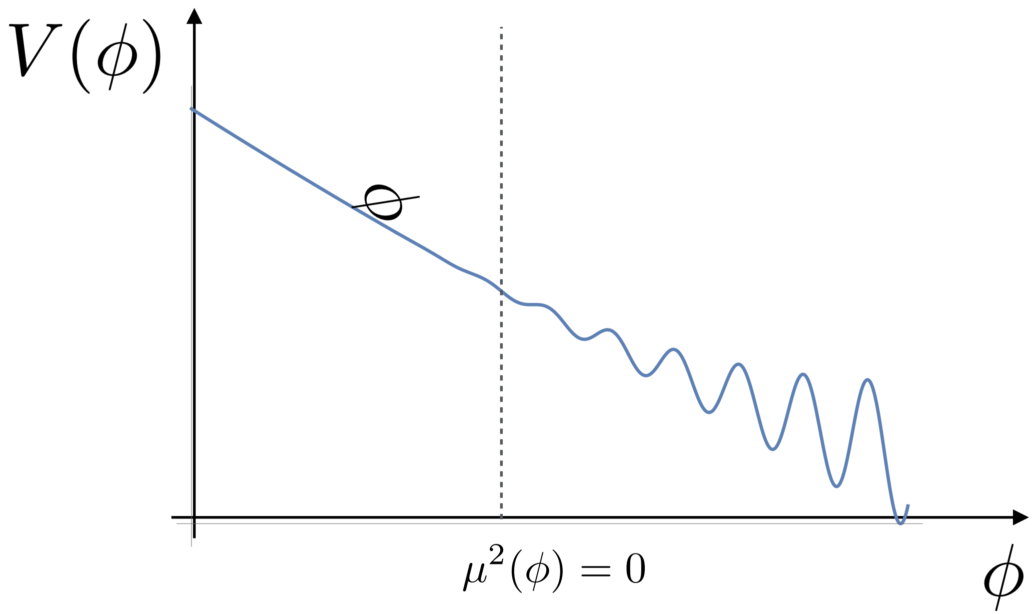

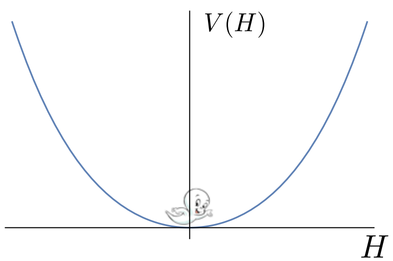

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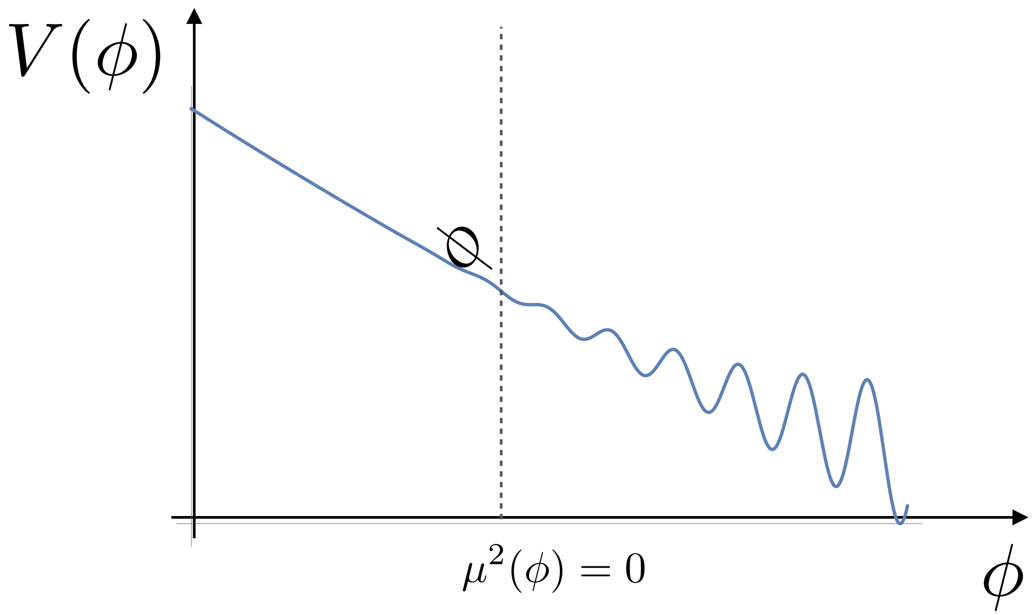

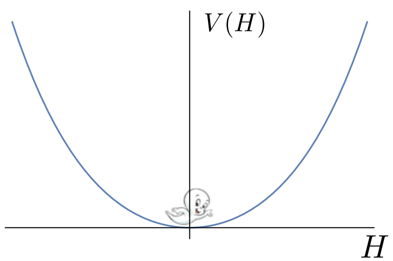

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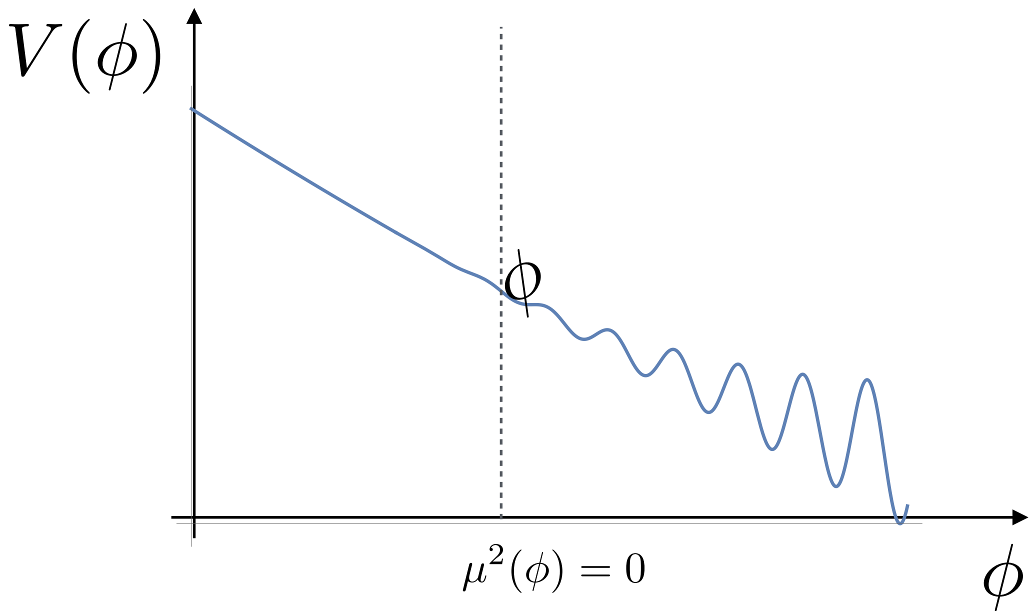

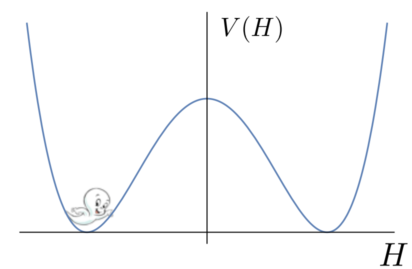

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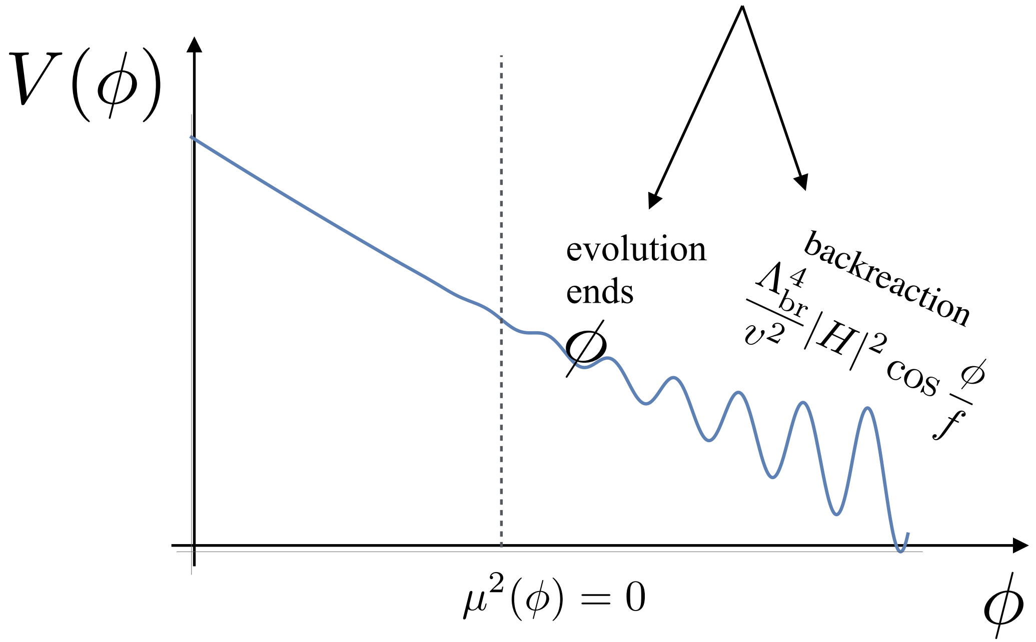

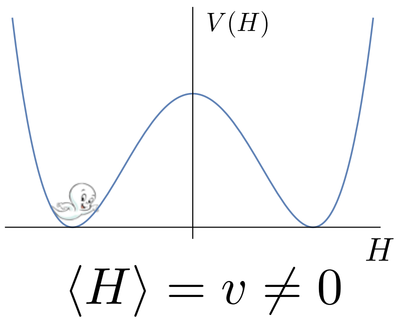

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- Focus shifts from TeV Higgs dynamics to relaxion, which is light & weakly coupled …

Motivation to hunt & compare sensitivity to broad class of scalar-new-physics in:

If it is heavy, mass >> eV

(i) can be copiously produced & detected at colliders;

(ii) can affect cosmological history + astrophysics dynamics.

Flacke, Frugiuele, Fuchs, Gupta & GP; Choi & Im (16);
Frugiuele, Fuchs, GP & Schlaffer; Fonseca, Morgante & Servant; Fonseca & Morgante(18)

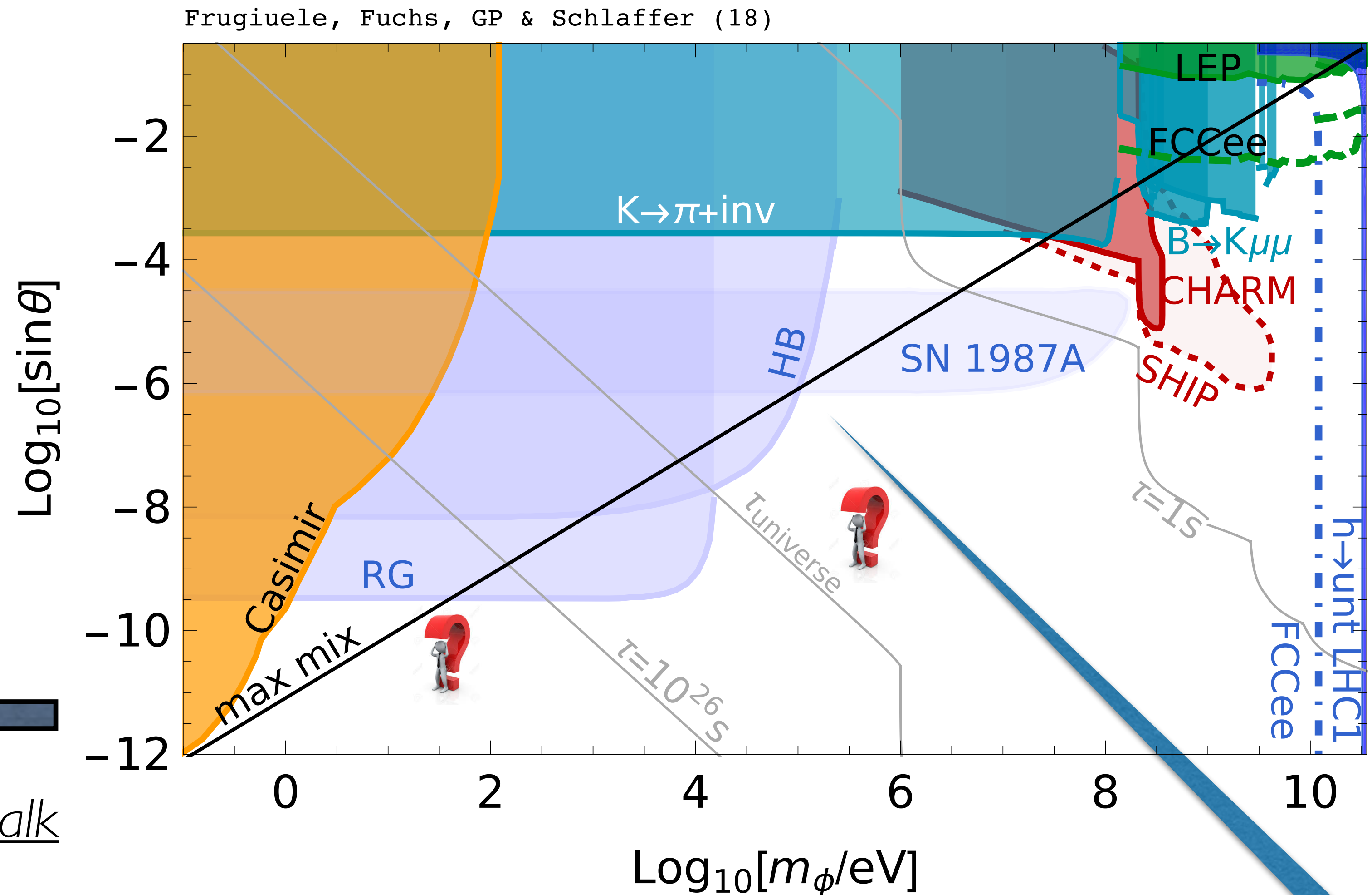
If it is ultra-light, mass < eV (*today's talk*)

(i) virtual processes searching for long-range "Yukawa" force;

(ii) time-depend. background if relaxion/scalar = dark matter (DM):

(a) for average DM density; (b) for relaxion stars.

Hunting a “heavy” relaxion/scalar-portal



today’s talk

“Physical” region: below diagonal

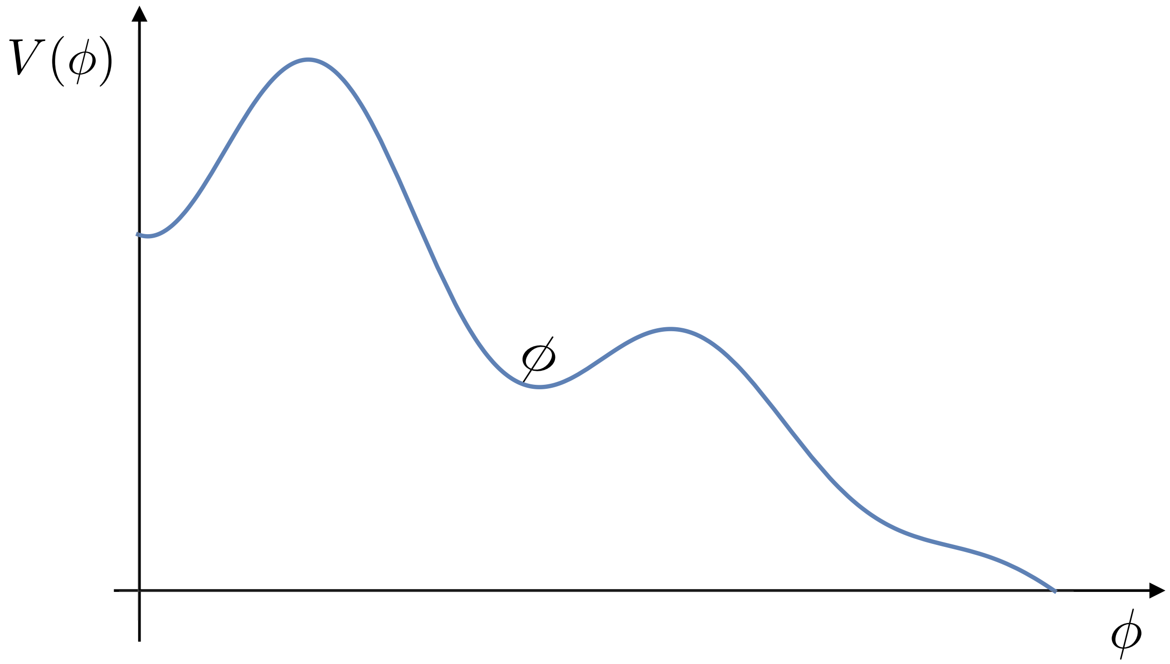
Relaxion/scalar light dark matter

Banerjee, Kim & GP (18)

Concrete ex.: relaxion dark matter (DM)

Banerjee, Kim & GP (18)

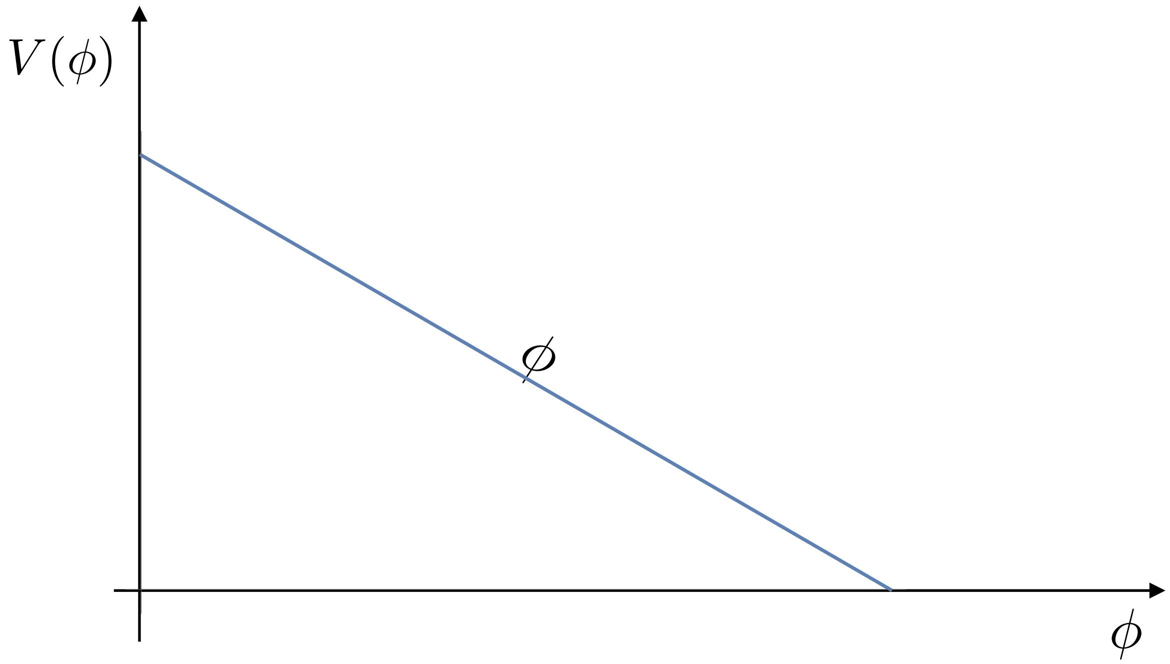
- Basic idea is similar to axion DM (but avoiding missalignment problem):



Concrete ex.: relaxion dark matter (DM)

- Basic idea is similar to axion DM (but avoiding missalignment problem):

  After reheating the wiggles disappear (sym' restoration):



Concrete ex.: relaxion dark matter (DM)

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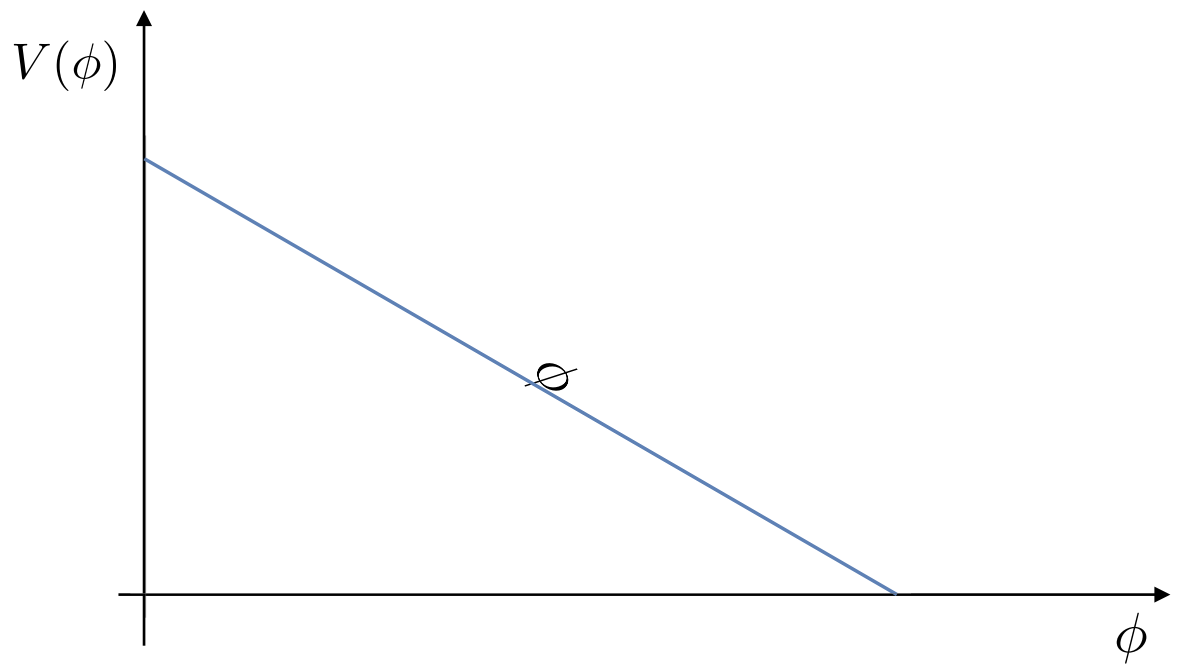
  After reheating the wiggles disappear: and the relaxion roles a bit.



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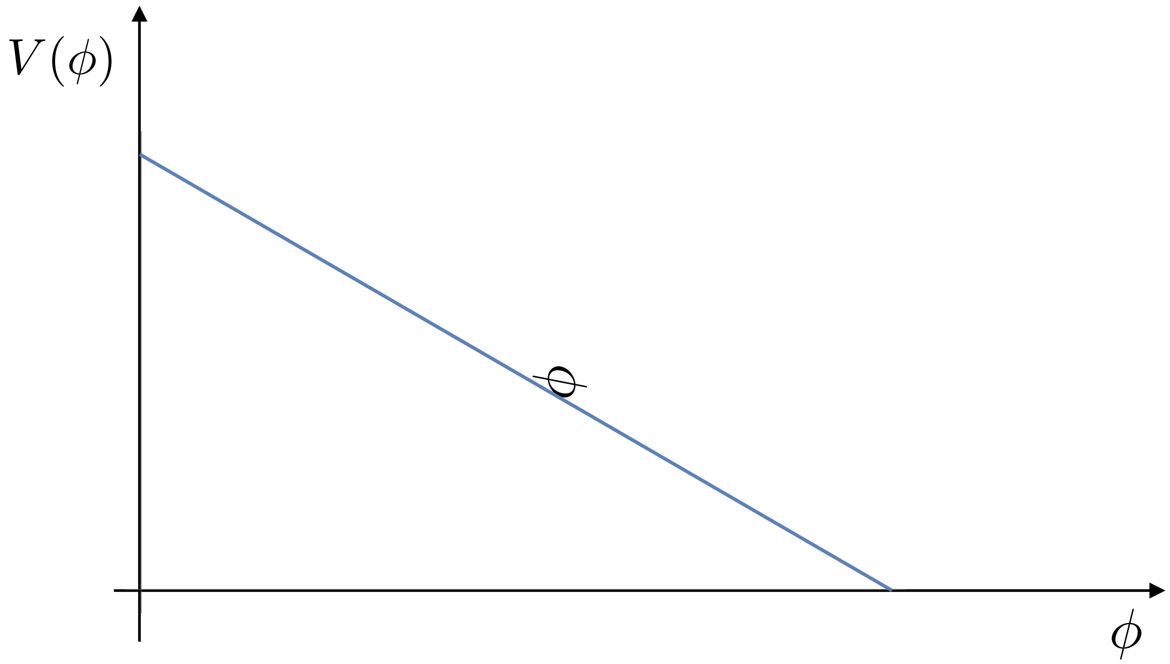
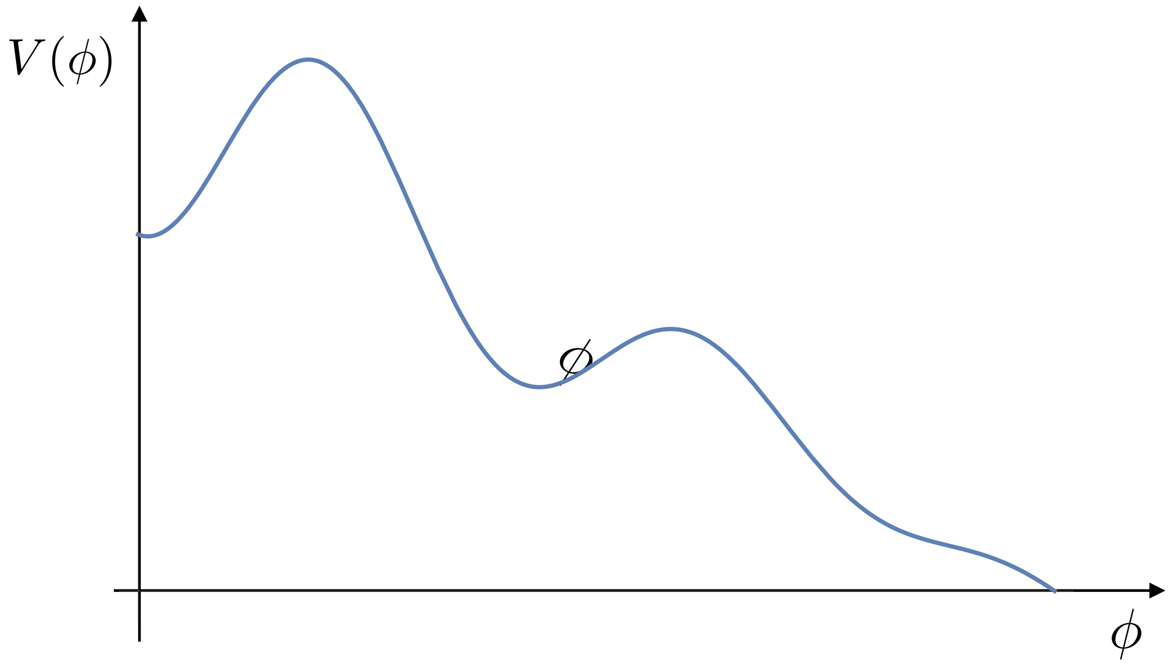


Concrete ex.: relaxion dark matter (DM)

- Basic idea is similar to axion DM (but avoiding missalignment problem):

  Now the relaxion not at the min' and start to oscillates = DM.



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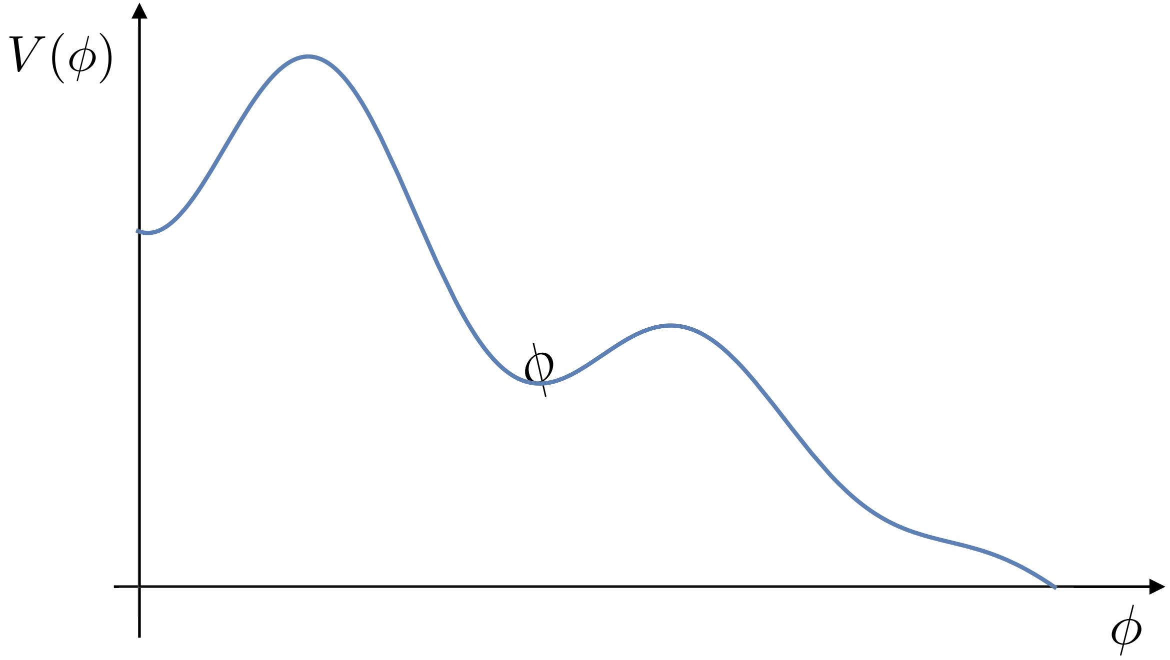

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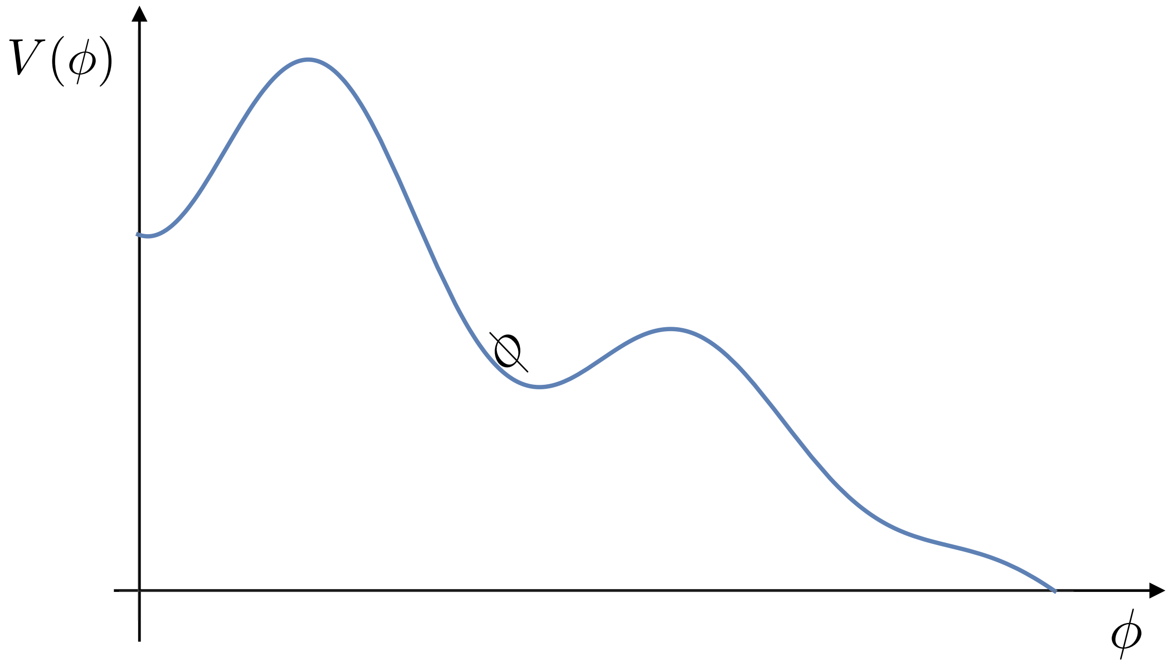

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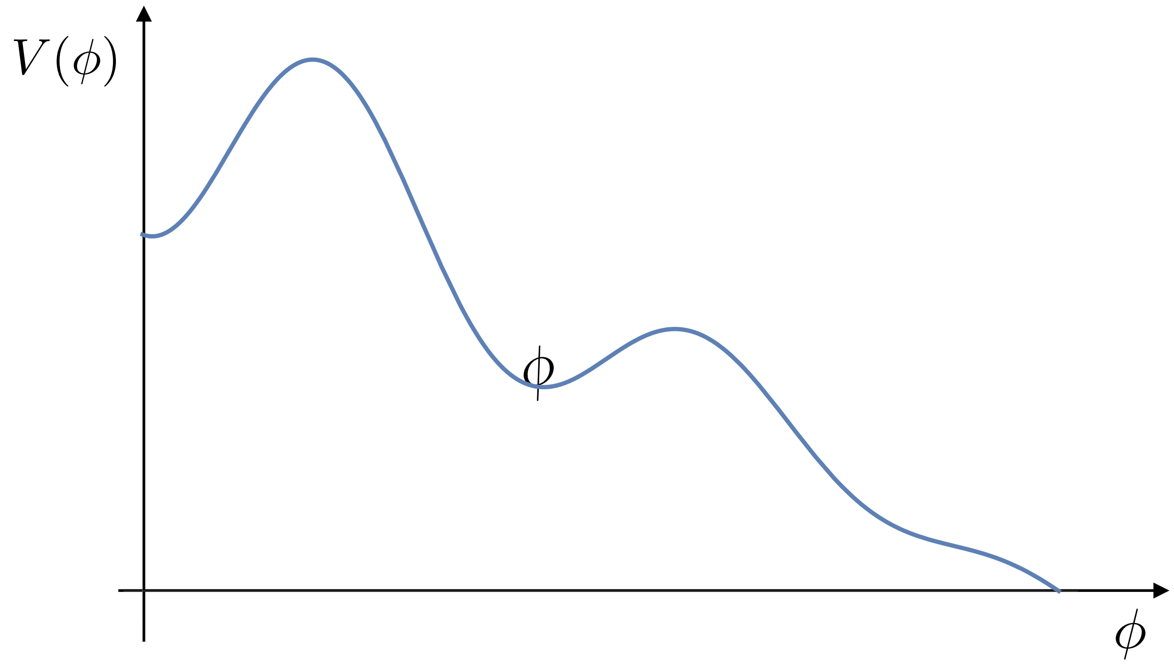

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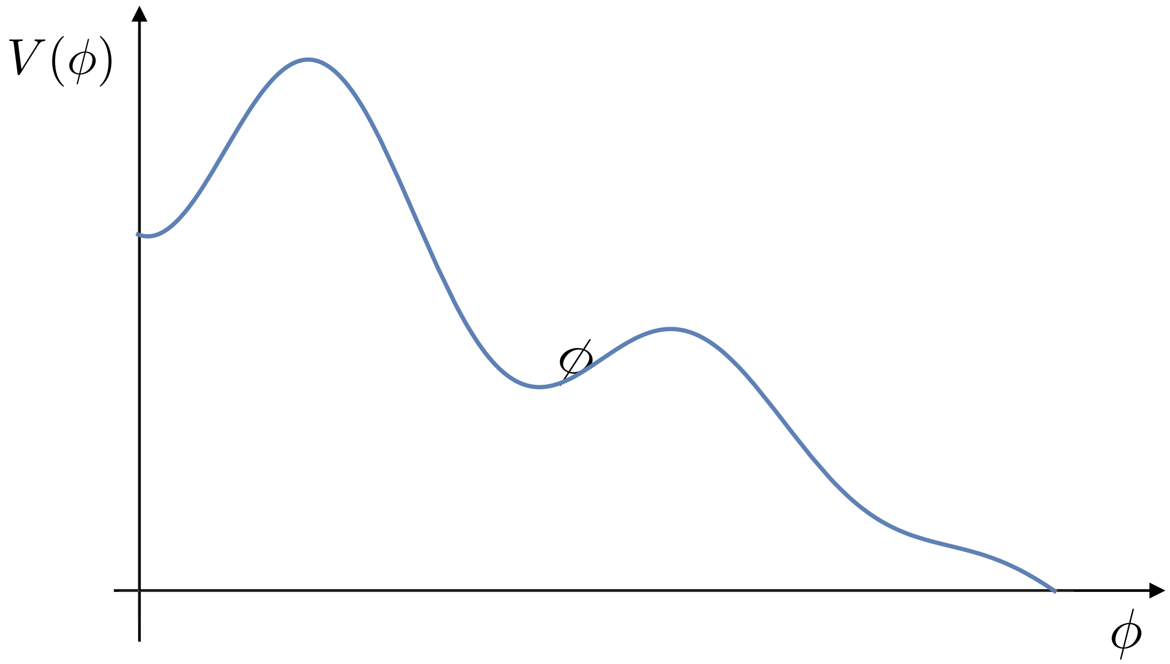


Coherent relaxion DM relic density

- Basic idea is similar to axion DM (but avoiding missalignment problem):

  Now the relaxion not at the min' and start to oscillates = DM.

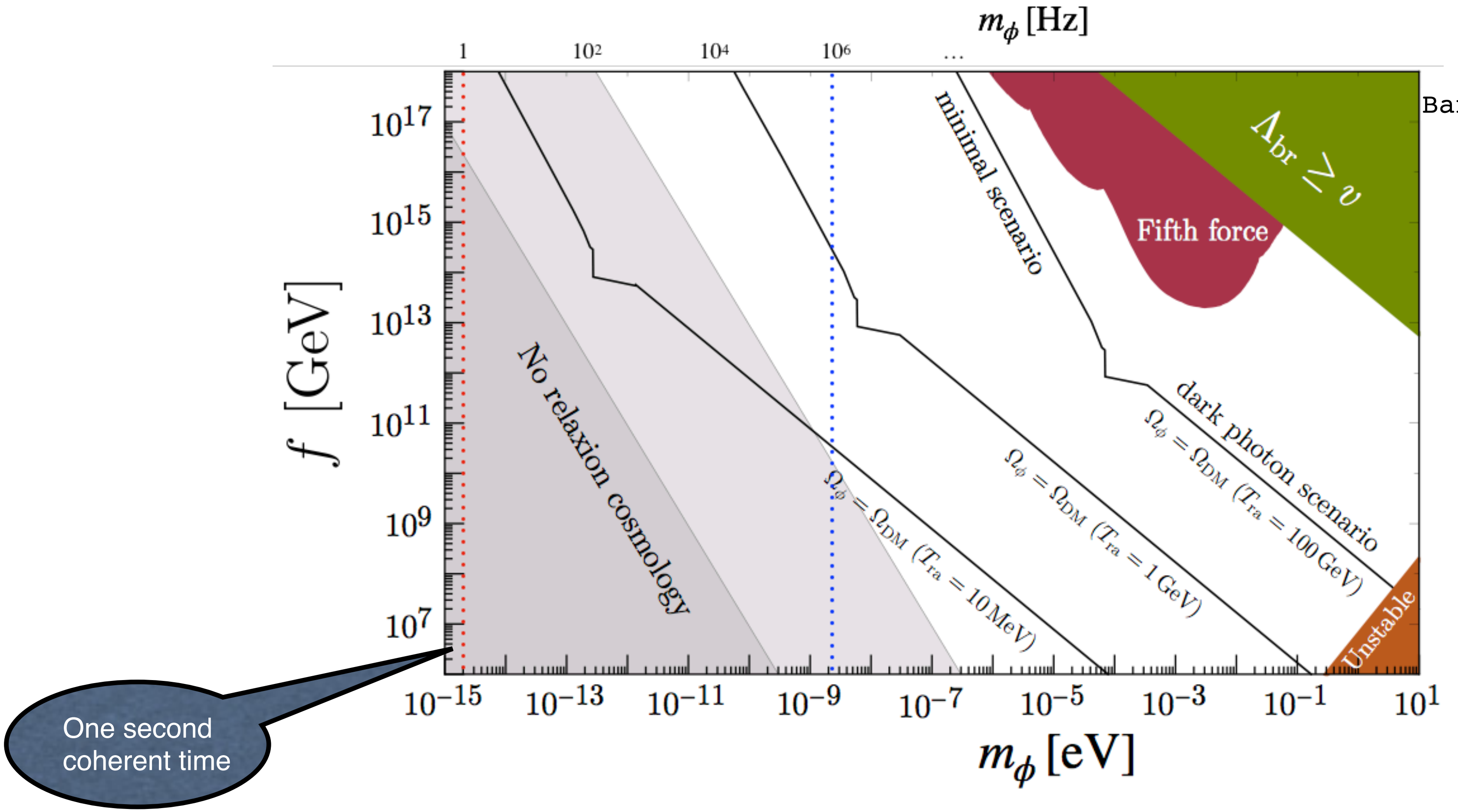
Light-coherent DM abundance: $\rho_{\rm DM}^{\rm cos} \sim m^2 \Delta\phi^2$

For $m_\phi \gtrsim H(T_{\rm ra})$: $\rho_{\rm DM}^{\rm cos} \sim \Omega_\phi h^2 \approx 3 \times (\Delta\theta)^2_{T=T_{\rm os}} \left(\frac{\Lambda_{\rm br}}{1\,{\rm GeV}}\right)^4 \left(\frac{100\,{\rm GeV}}{T_{\rm os}}\right)^3$

where the observed DM abundance is $\Omega_{\rm DM} h^2 \simeq 0.12$

For $m_\phi < H(T_{\rm ra})$: extra suppression is obtained as oscilation starts when $H(T_{\rm osc}) \sim m_\phi$.

Relaxion dark matter, parameter space



Banerjee, Kim & GP (18)

♦ If the relaxion oscillates due to its mixing with the Higgs all constants of nature + masses now oscillates.

Banerjee, Kim & GP (18)

$$\frac{\delta m_e}{m_e} \lesssim y_e \sin_{\phi h} \frac{\sqrt{\rho_{\rm DM}}}{m_e m_\phi} \sin(m_\phi t)$$

Arvanitaki, Huang & Van Tilburg (15)

Two relevant questions

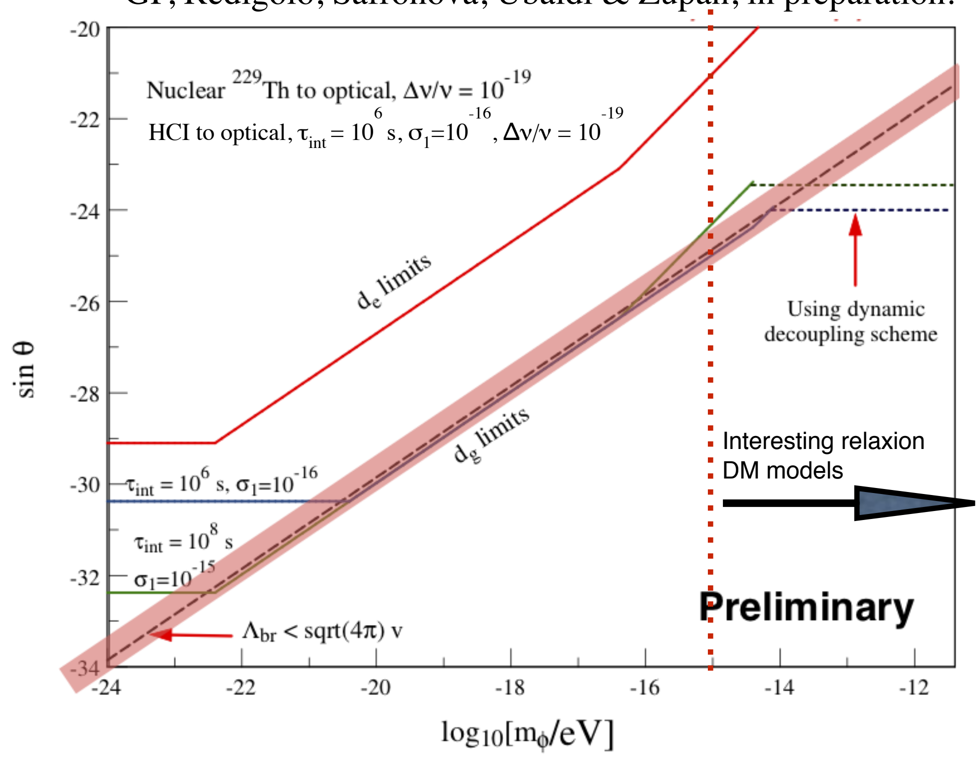
(i) Notice that relevant models have osc. freq. 1 - 10^{14} Hz. Can we probe these?

(ii) Is the amplitude large enough to probe meaningful models?

Constraining sub-Hz relaxion DM

Graham, Kaplan, Mardon, Rajendran & Terrano; Arvanitaki, Dimopoulos & Van Tilburg; Van Tilburg, Leefer, Bougas & Budker (15)

GP, Redigolo, Safronova, Ubaldi & Zupan, in preparation.



$$\left(d_{e,\alpha} \sim \delta m_e, \delta\alpha / m_e, \alpha\right)$$

d_e stands for the time dependent component of the fine coupling constant, the bound on d_g (the coefficient of the time dependent component of α_s, the strong coupling) assumes a working ^{229}Th nuclear clock with a 1 : 10^{19} precision, τ_{int} stands for the total assumed integration time and σ_1 stands for the corresponding stability. The dashed-red line on the diagonal corresponds to the maximal mixing allowed in this scenario, Λ_{br} corresponds to a coupling in the relaxion model.

Back to our 2 questions

(i) Notice that relevant models have osc. freq. 1 - 10^{14} Hz.
Can we probe these? 

(ii) Is the amplitude large enough to probe meaningful models?

However, gravity can help: dark matter might form “relaxion-planets” that might be trapped around earth-gravitational field.

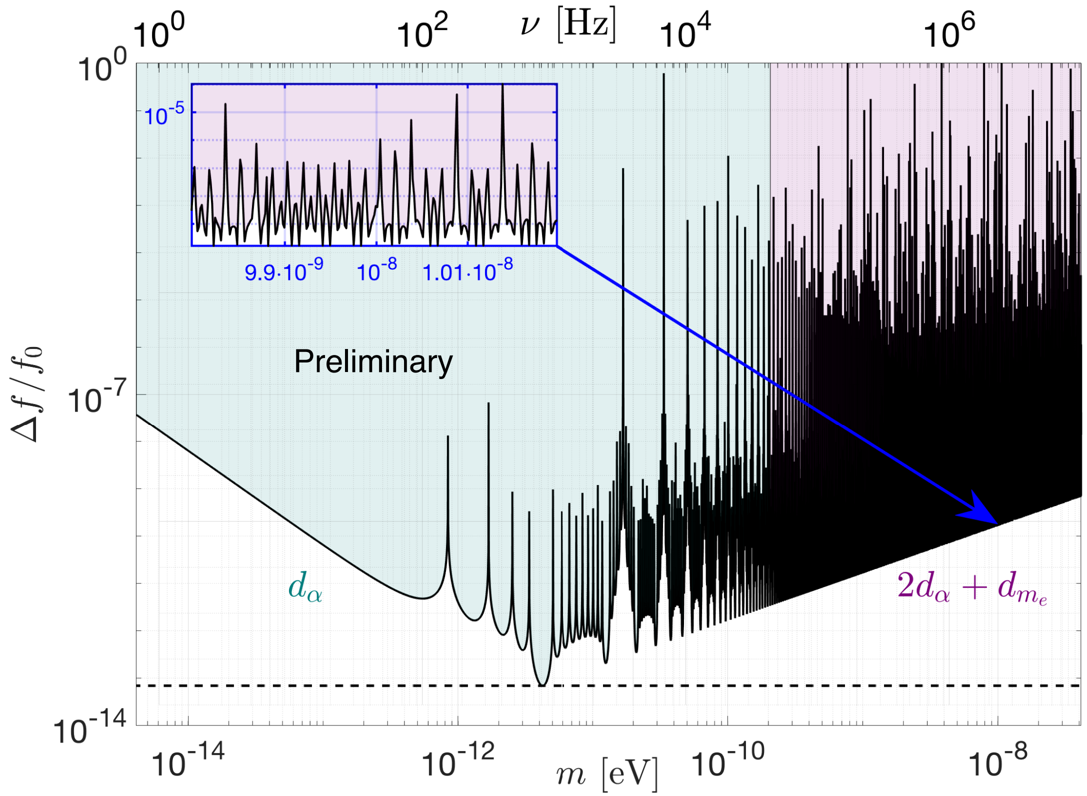
Banerjee, Budker, Eby, Kim, GP, in Prep.

(similar to axion-stars requiring stability and assuming capturing & coherence)

Kimball, et al. (17)

Beyond 1Hz DM mass \w dynamical decoupling (DD)

Aharony, Akerman, Ozeri, GP & Shaniv & Savoray, in prep. (ion-cavity comparison)



Current bound on the relative modulation of the transition frequency from a DD experiment, placed at 95% CL. The dashed line marks the current sensitivity reach, corresponding to scanning over ν_m. The inset is a magnified view of $m \sim 10^{-8}$eV.

Beyond 1Hz DM mass \w dynamical decoupling

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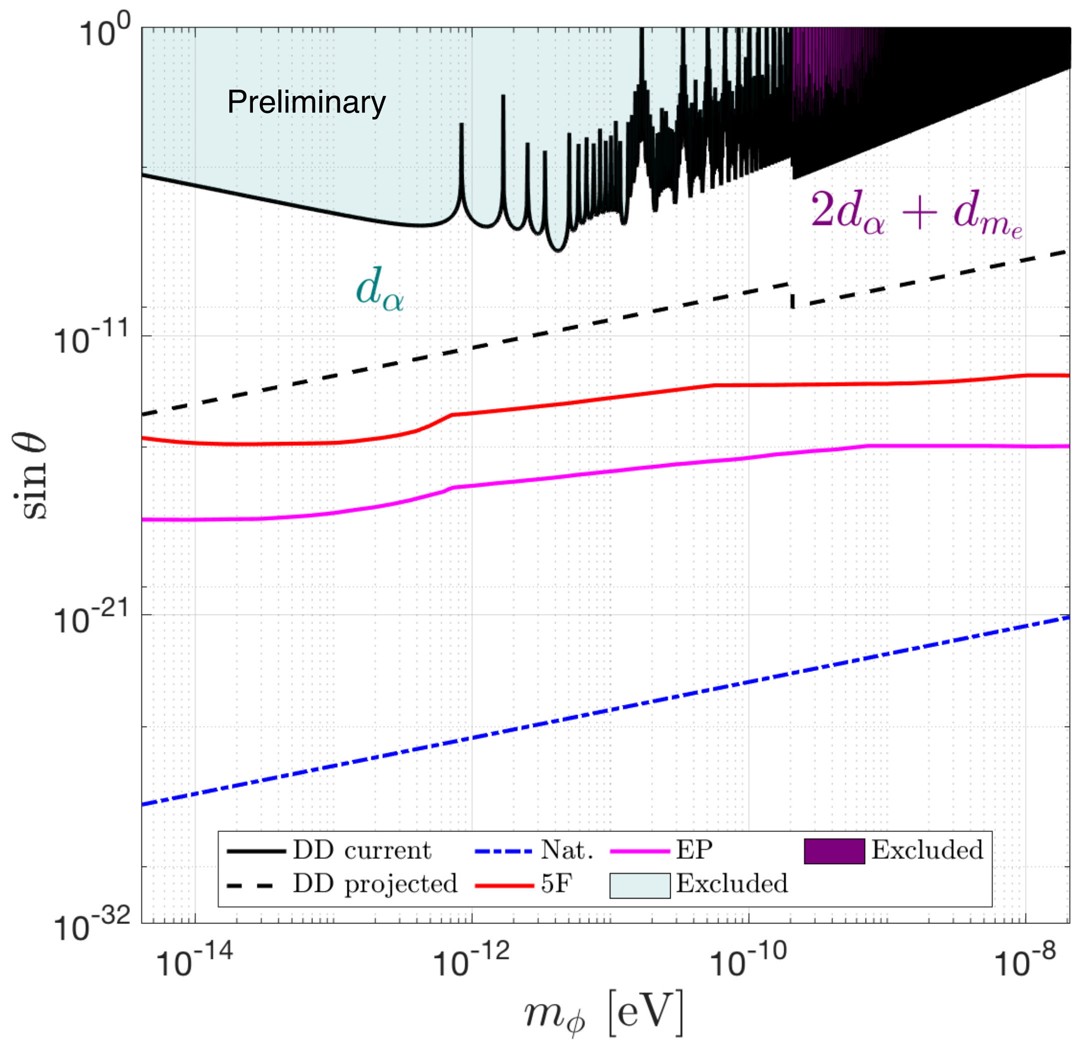


The bounds on the mixing angle of a relaxion DM: Black – current and projected bounds from DD experiments at 95% CL. Red – Bounds from fifth force experiments. Magenta – EP-tests bounds. Dash-dotted – Bounds from Naturalness.

Searching for a relaxion DM planet around us

Assume small DM density & large radius => mass-radii relation:

$$R_{\rm star} \approx \frac{M_{\rm Pl}^2}{m_\phi^2}\frac{1}{M_{\rm Earth}} \qquad (M_* \ll M_{\rm Earth})\,.$$

Eby, Leembruggen, Street, Suranyi & Wijewardhana (18);

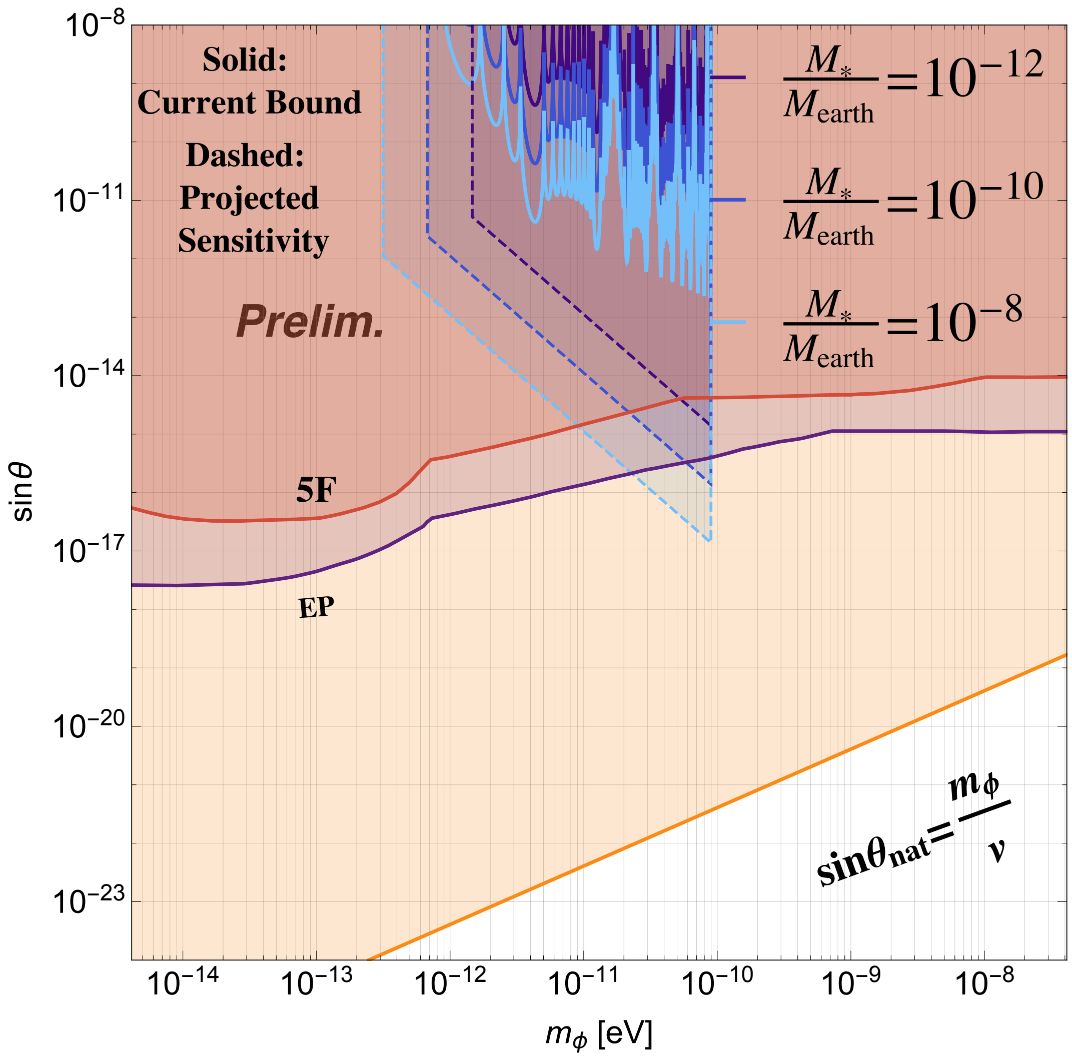
Banerjee, Budker, Eby, Kim, GP, in Prep.

Can obtain large density enhancement:

$$r \equiv \frac{\rho_{\rm star}}{\rho_{\rm loc-DM}} \sim \xi \frac{M_{\rm Earth}^4\, m_\phi^6}{M_{\rm Pl}^6\, \rho_{\rm loc-DM}} \sim \xi \times 10^{28} \times \left(\frac{m_\phi}{10^{-10}}\right)^6 \qquad \xi \equiv M_{\rm star}/M_{\rm Earth}$$

Large star DM density => visible effect

Aharony, Akerman, Ozeri, GP & Shaniv & Savoray, in prep. (ion-cavity comparison); Banerjee, Budker, Eby, Kim, GP, in Prep.



Bounds for a relaxion star centered around earth.

Conclusions

- Null-LHC + new paradigms + incredible sensitivity => new era!

- Relaxion-benchmarking allows to compare sensitivities.

- Relaxion-DM: dynamic decoupling -> strong bounds but cannot compete \w 5th force & can't probe physical region.

- Relaxion-DM-stars: table-top probe physical region, stronger than 5th force & can/should compare \w space.

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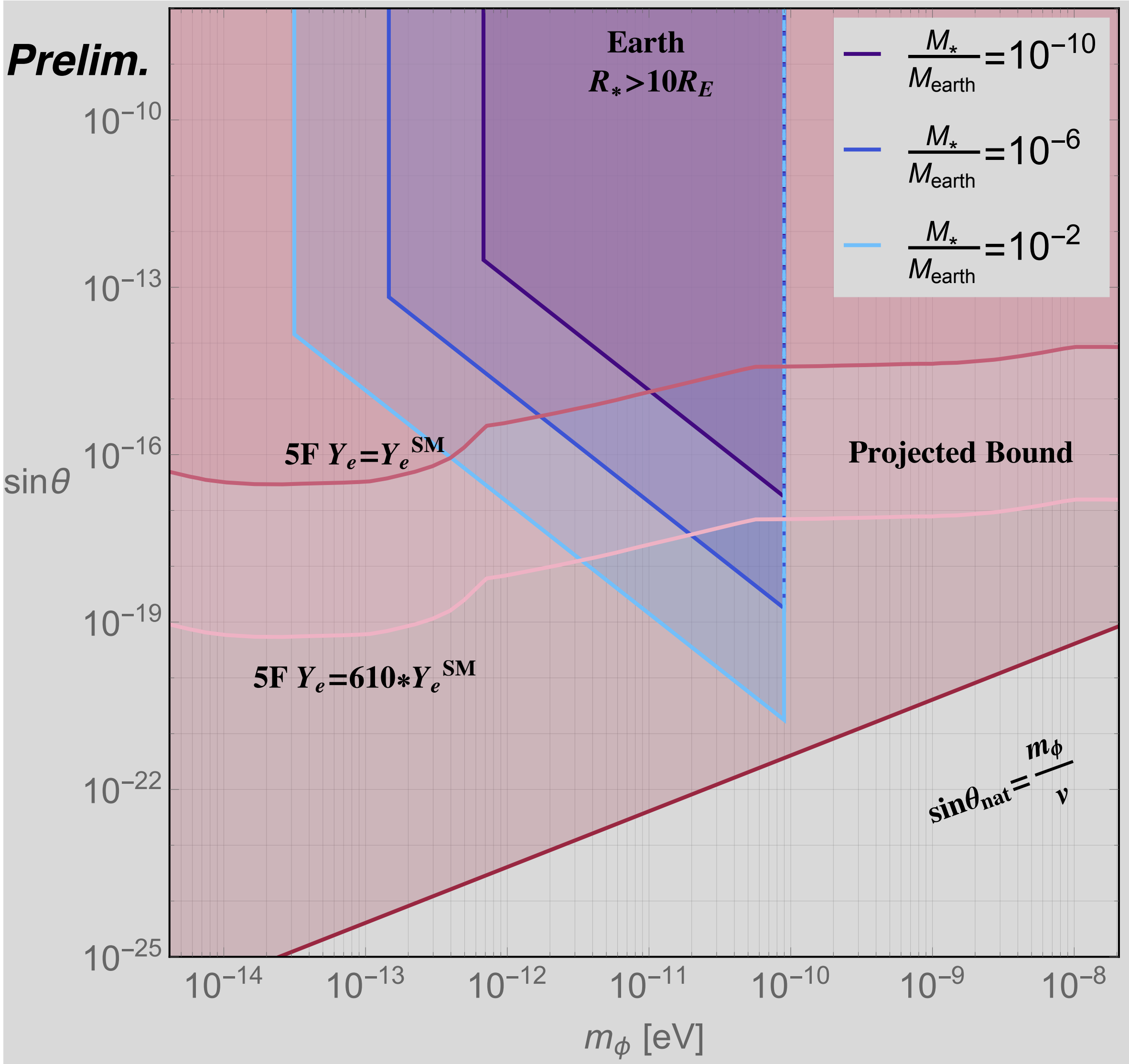

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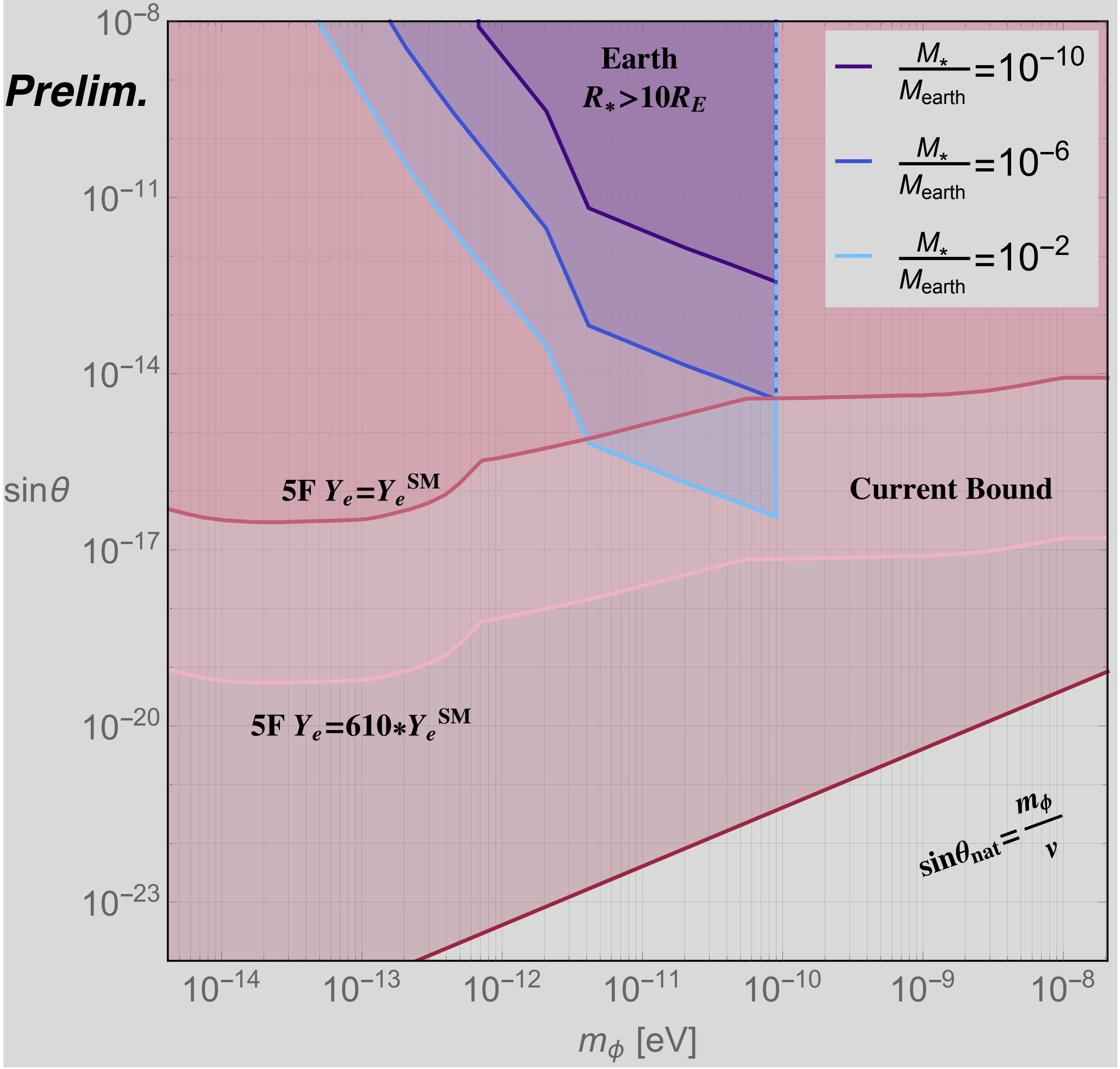
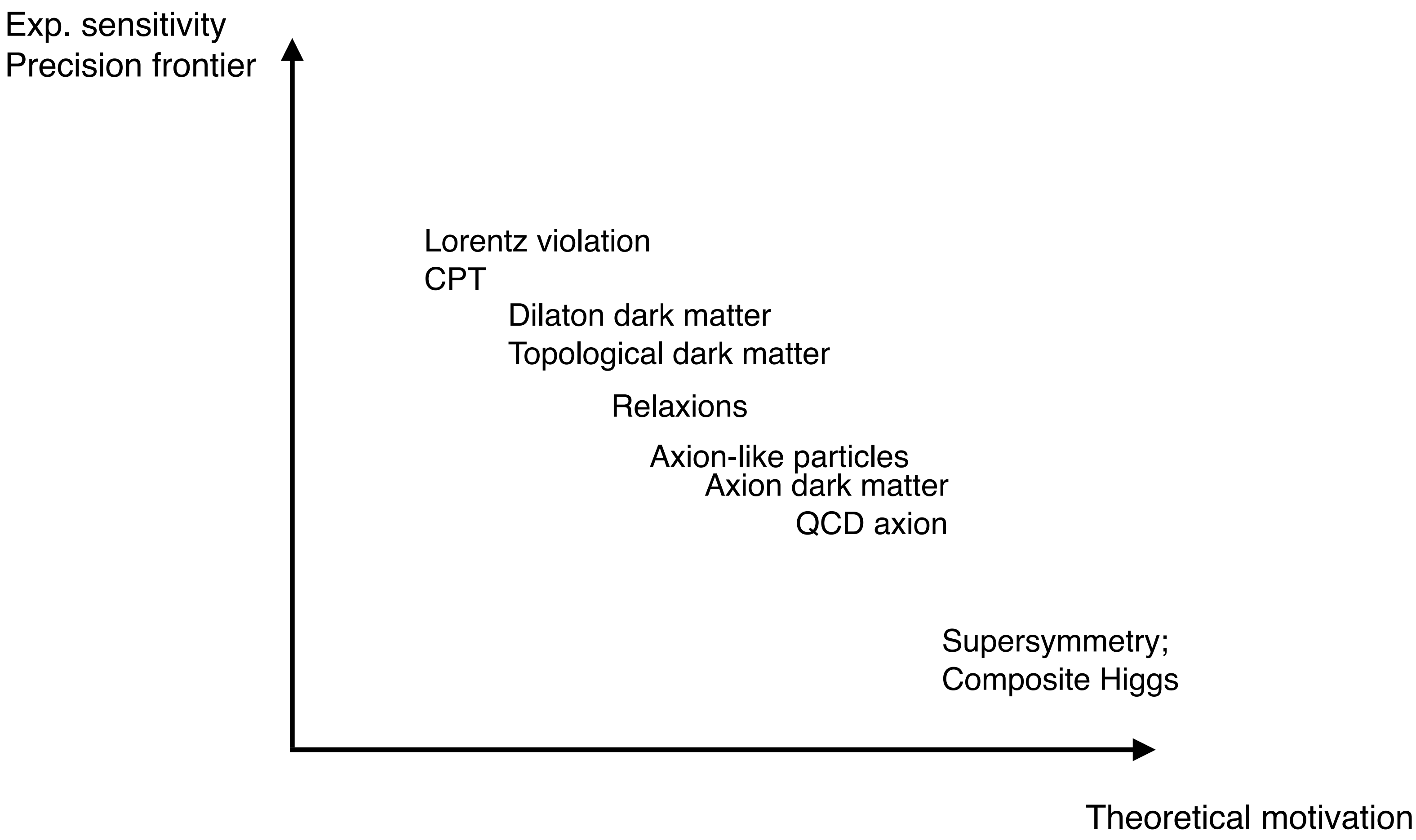


Backups

Subjective particle physicist perspective



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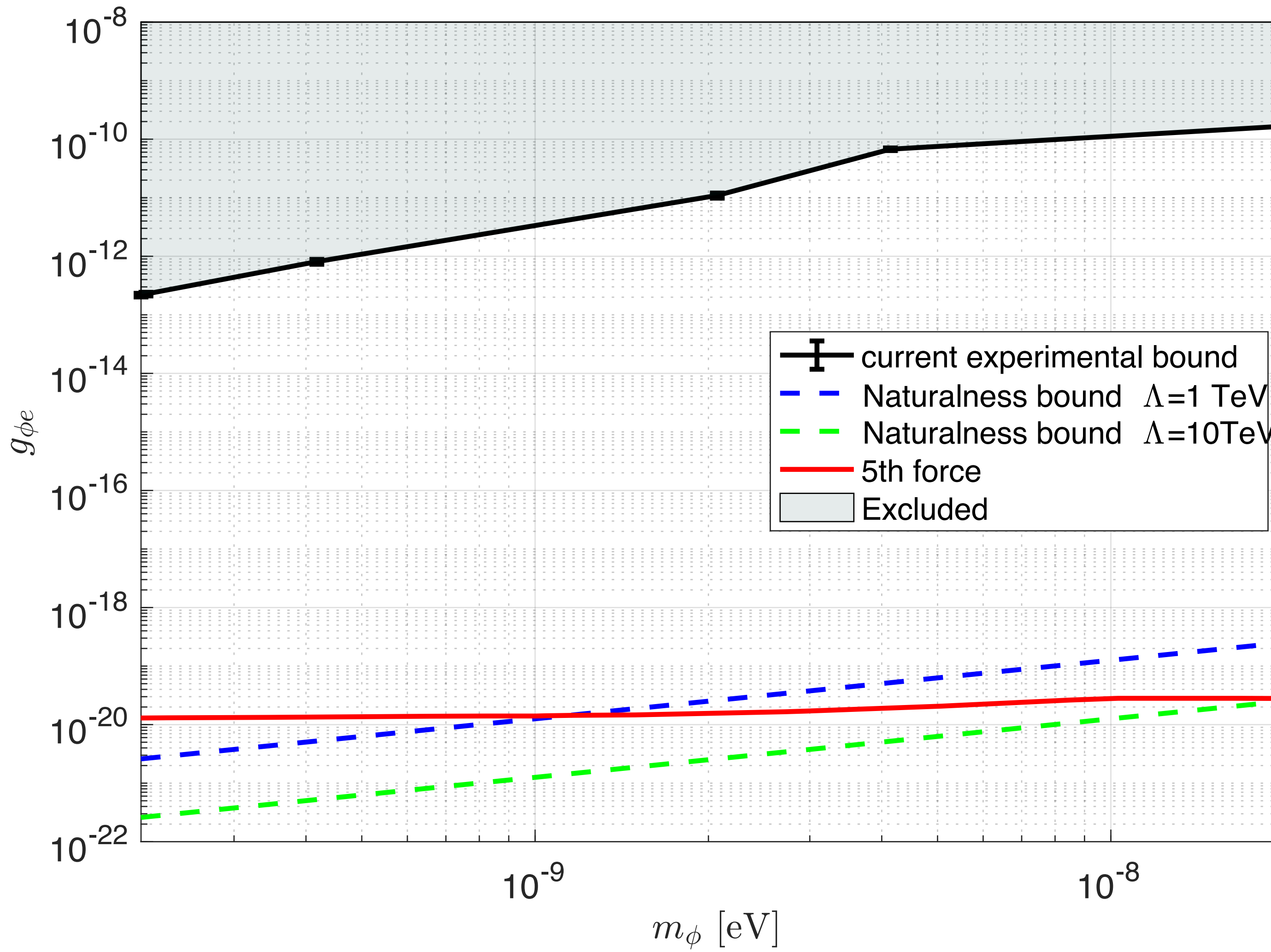

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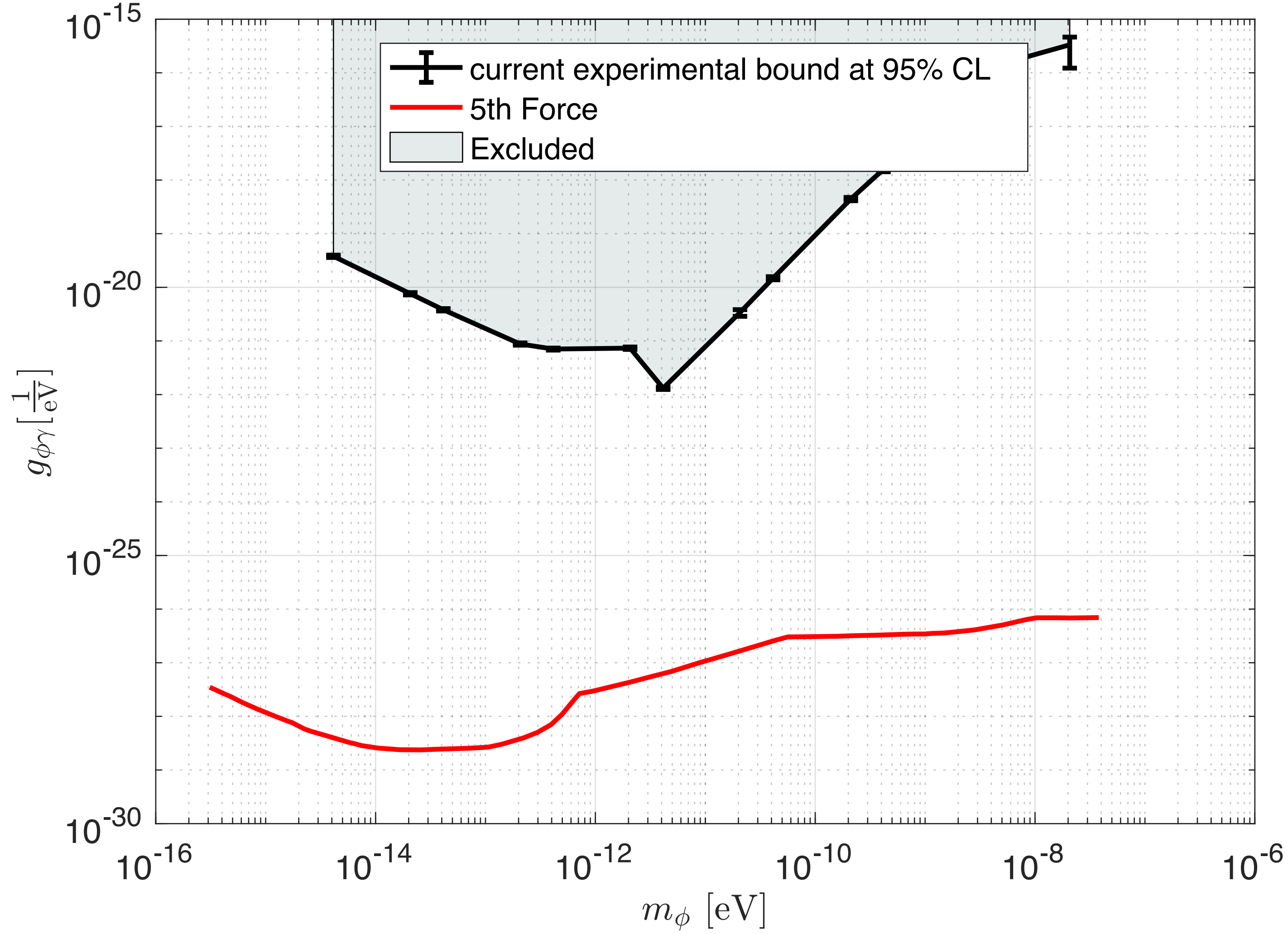
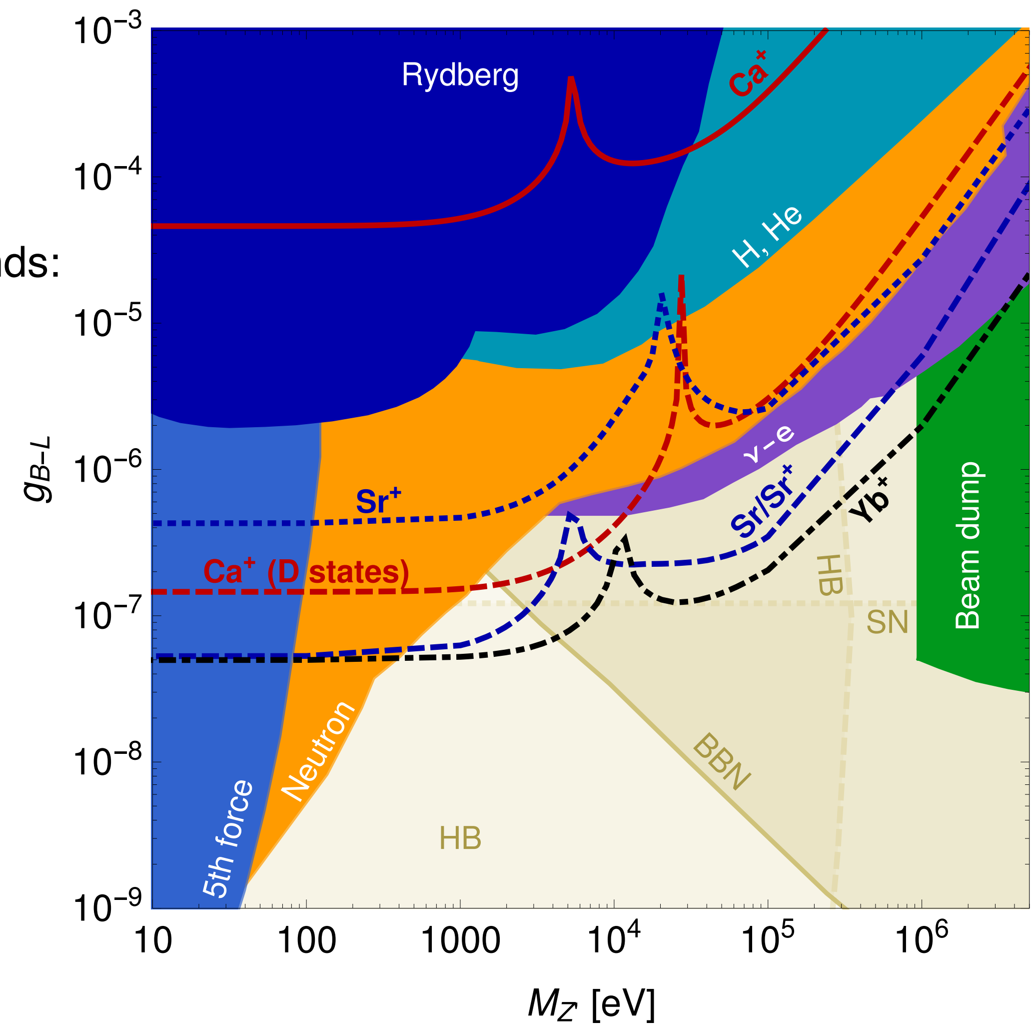


$U(1)_{B-L}$

Frugiuele, Fuchs, GP & Schlaffer (16)

Complementarity with astro/cosmo' bounds:

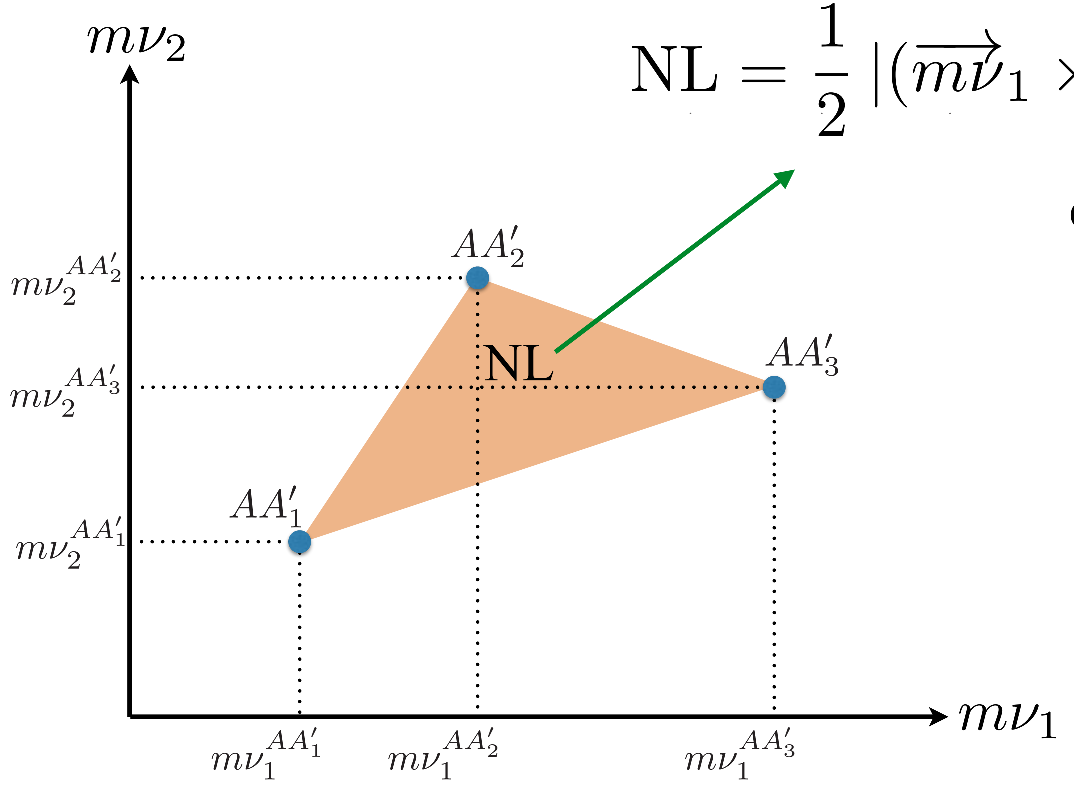


King comparison

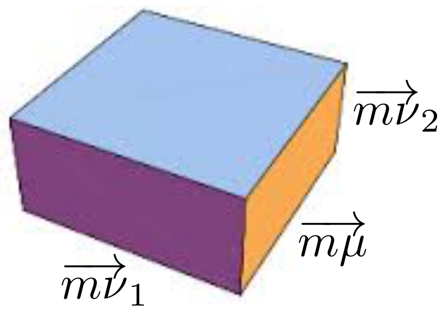
- Level of linearity can be quantified by comparing area of triangle to that of a cube: $\mathrm{NL}/|\overrightarrow{m\nu}_2||\overrightarrow{m\nu}_1| \ll 1\,.$

$$\overrightarrow{m\mu} \equiv (1,1,1)\,.$$

$$\mathrm{NL} = \frac{1}{2}\,|(\overrightarrow{m\nu}_1 \times \overrightarrow{m\nu}_2)\cdot\overrightarrow{m\mu}|\,.$$



Or volume of prallelepiped:



King linearity implications

♦ Linearity implies that $\overrightarrow{m\nu}_2$ & $\overrightarrow{m\nu}_1$ must be linearly dependent:

$$\overrightarrow{m\nu}_2 = K_2\,\overrightarrow{m_\mu} + F_2\,\vec{v} + \mathcal{O}\left(10^{-4}\right)$$
$$\overrightarrow{m\nu}_1 = K_1\,\overrightarrow{m_\mu} + F_1\,\vec{v} + \mathcal{O}\left(10^{-4}\right)$$

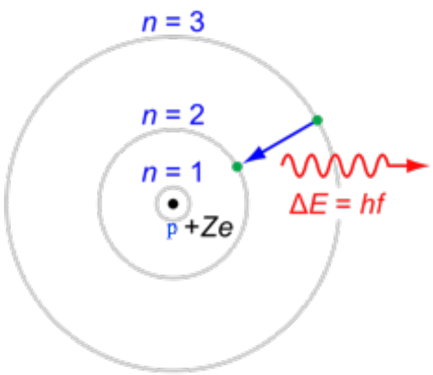
$$\overrightarrow{m\nu}_2 \cong K_{21}\,\overrightarrow{m\mu} + F_{21}\,\overrightarrow{m\nu}_1\,,$$

with $F_{21} \equiv F_2/F_1$ and $K_{21} \equiv K_2 - F_{21}K_1$.

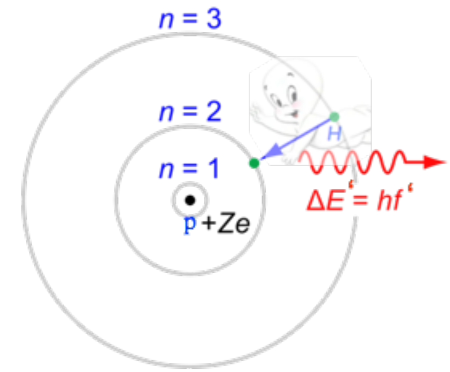
F_i & $\vec{v}$ are unknown but F_{21} & K_{21} can be measured precisely.

Adding light new physics (NP)

New forces acts on electron & quarks leads to change of energy levels.



$$+ \quad \mathcal{L}_\phi = \phi(y_e \bar{e} e + y_n \bar{n} n) \quad \Longrightarrow$$



- New physics part known, precisely calculated:

CI+MBPT: Dzuba, Flambaum & Kozlov (96) Berengut, Flambaum & Kozlov (06);
GRASP2K: Jonsson, Gaigalas, Biero, Fischer & Grant (2013)

(Combination of the many-body perturbation theory with the configuration-interaction method)

$$\overrightarrow{m\nu}_i = K_i \, \overrightarrow{m_\mu} + F_i \, \vec{v} + \boxed{y_e y_n X_i \vec{h}},$$

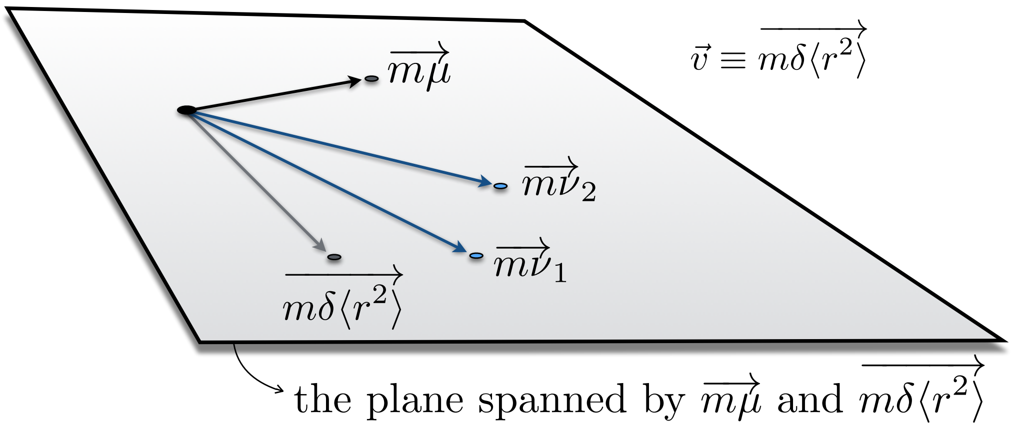
Delaunay, Ozeri, GP & Soreq (16)

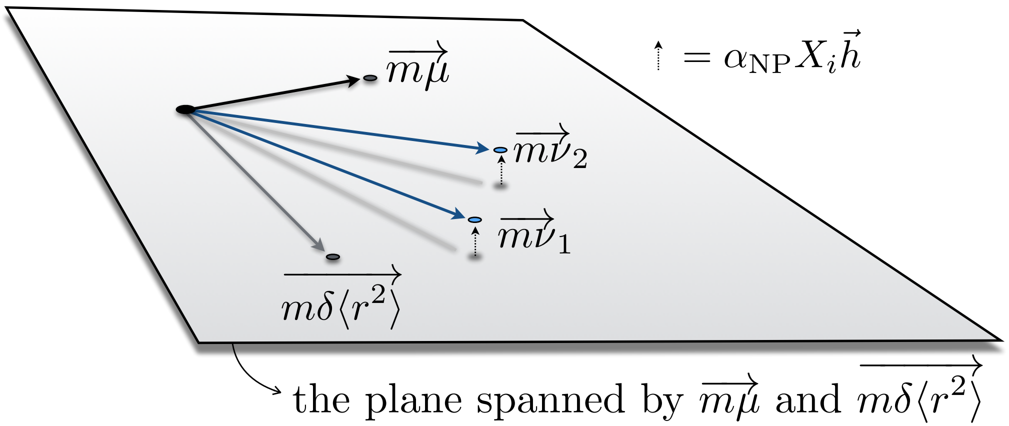
$$\Downarrow$$

$$\overrightarrow{m\nu}_2 = K_{21} \overrightarrow{m\mu} + F_{21} \overrightarrow{m\nu}_1 + \alpha_{\rm NP} \vec{h} X_1 \left(X_{21} - F_{21} \right) ,$$

and $X_{21} \equiv X_2 / X_1$.

Illustration: adding light new physics (NP)





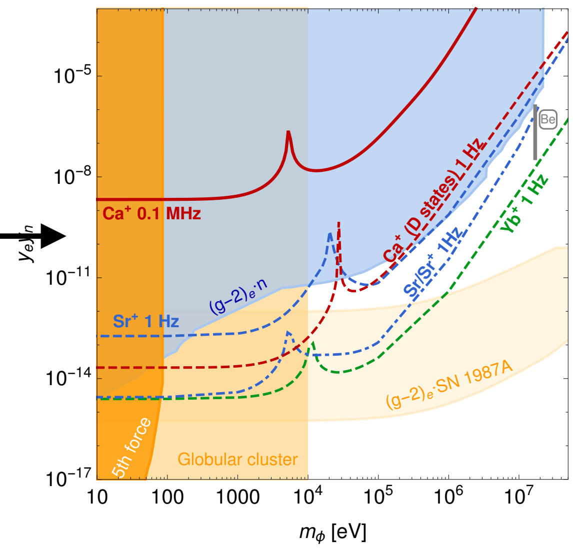
Light mediators

If mediator's mass, m_X, is smaller than inverse of outer electrons than the potential is Coulombic.

If mediator's mass is smaller than inverse distance of most inner electron from the nucleus then the full Yukawa potential is required.

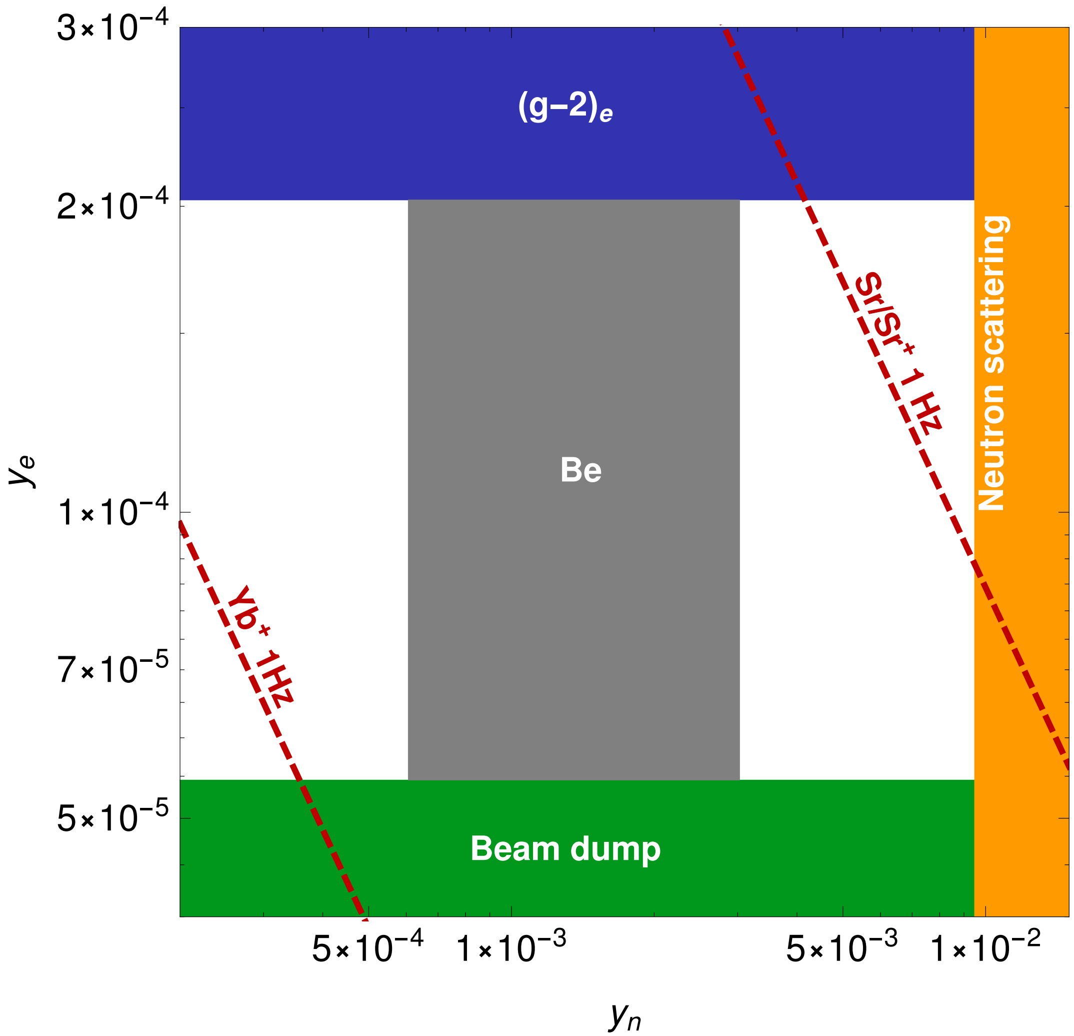
Otherwise the potential is described via a delta function.

$$V(r) = \begin{cases} \frac{1}{r} & \text{for} \quad m_X \lesssim \alpha m_e \,, \\ \frac{e^{-r m_X}}{r} & \text{for} \quad \alpha m_e \lesssim m_X \lesssim \alpha m_e Z \,, \\ \frac{1}{m_X^2} \, \delta^3(r) & \text{otherwise} \,. \end{cases}$$

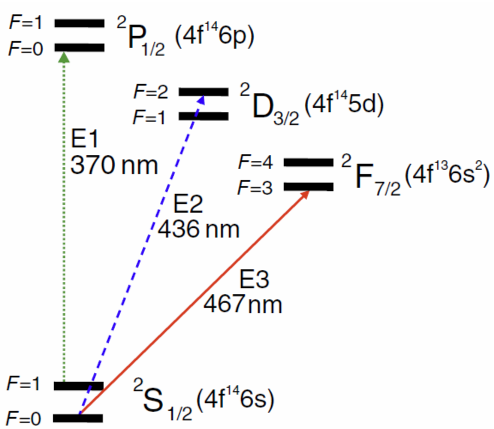


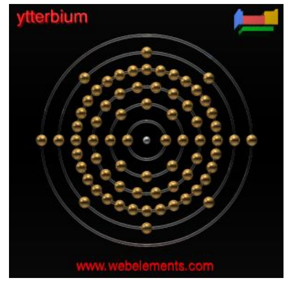
Be 17 MeV anomaly

Frugiuele, Fuchs, GP & Schlaffer v2 (16)

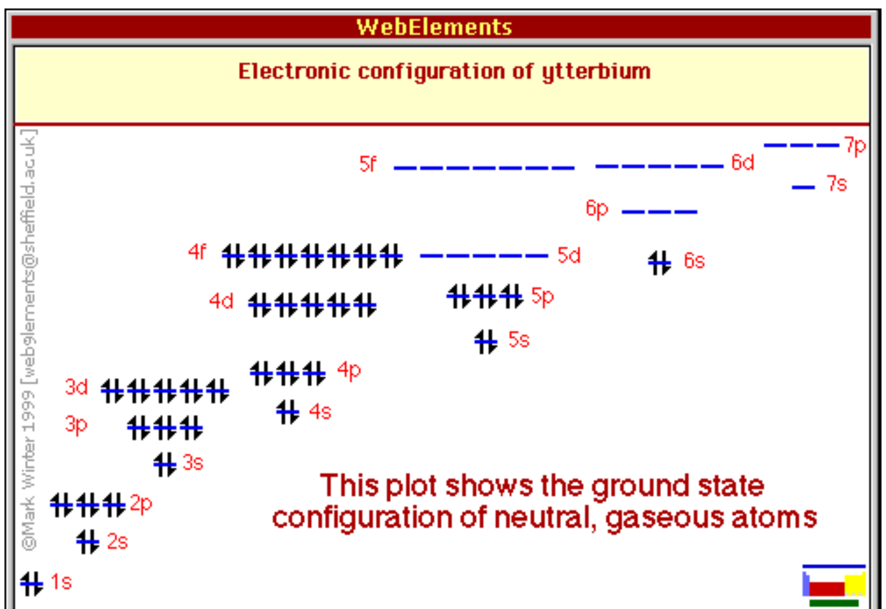


Ex.: Yb^{+} with Z=70, n=6 and A=168(4)-174(6).





The Kossel shell structure of ytterbium.



The electronic configuration of ytterbium.

nuclide symbol	Z(p)	N(n)	isotopic mass (u)	half-life	decay mode(s)[2][n 1]	daughter isotope(s)[n 2]	nuclear spin	representative isotopic composition (mole fraction)	range of natural variation (mole fraction)
	excitation energy								
^{148}Yb	70	78	147.96742(64)#	250# ms	β^+	^{148}Tm	0+		
^{149}Yb	70	79	148.96404(54)#	0.7(2) s	β^+	^{149}Tm	(1/2+,3/2+)		
^{150}Yb	70	80	149.95842(43)#	700# ms [>200 ns]	β^+	^{150}Tm	0+		
^{151}Yb	70	81	150.95540(32)	1.6(5) s	β^+	^{151}Tm	(1/2+)		
					β^+, p (rare)	^{150}Er			
^{151m1}Yb	750(100)# keV			1.6(5) s	β^+	^{151}Tm	(11/2−)		
					β^+, p (rare)	^{150}Er			
^{151m2}Yb	1790(500)# keV			2.6(7) μs			19/2−#		
^{151m3}Yb	2450(500)# keV			20(1) μs			27/2−#		
^{152}Yb	70	82	151.95029(22)	3.04(6) s	β^+	^{152}Tm	0+		
					β^+, p (rare)	^{151}Er			
^{153}Yb	70	83	152.94948(21)#	4.2(2) s	α (50%)	^{149}Er	7/2−#		
					β^+ (50%)	^{153}Tm			
					β^+, p (.008%)	^{152}Er			
^{153m}Yb	2700(100) keV			15(1) μs			(27/2−)		
^{154}Yb	70	84	153.946394(19)	0.409(2) s	α (92.8%)	^{150}Er	0+		
					β^+ (7.119%)	^{154}Tm			
^{155}Yb	70	85	154.945782(18)	1.793(19) s	α (89%)	^{151}Er	(7/2−)		
					β^+ (11%)	^{155}Tm			
^{156}Yb	70	86	155.942818(12)	26.1(7) s	β^+ (90%)	^{156}Tm	0+		
					α (10%)	^{152}Er			
^{157}Yb	70	87	156.942628(11)	38.6(10) s	β^+ (99.5%)	^{157}Tm	7/2−		
					α (.5%)	^{153}Er			
^{158}Yb	70	88	157.939866(9)	1.49(13) min	β^+ (99.99%)	^{158}Tm	0+		
					α (.0021%)	^{154}Er			
^{159}Yb	70	89	158.94005(2)	1.67(9) min	β^+	^{159}Tm	5/2(−)		
^{160}Yb	70	90	159.937552(18)	4.8(2) min	β^+	^{160}Tm	0+		
^{161}Yb	70	91	160.937902(17)	4.2(2) min	β^+	^{161}Tm	3/2−		
^{162}Yb	70	92	161.935768(17)	18.87(19) min	β^+	^{162}Tm	0+		
^{163}Yb	70	93	162.936334(17)	11.05(25) min	β^+	^{163}Tm	3/2−		
^{164}Yb	70	94	163.934489(17)	75.8(17) min	EC	^{164}Tm	0+		
^{165}Yb	70	95	164.93528(3)	9.9(3) min	β^+	^{165}Tm	5/2−		
^{166}Yb	70	96	165.933882(9)	56.7(1) h	EC	^{166}Tm	0+		
^{167}Yb	70	97	166.934950(5)	17.5(2) min	β^+	^{167}Tm	5/2−		
^{168}Yb	70	98	167.933897(5)	Observationally Stable[n 3]			0+	0.0013(1)	
^{169}Yb	70	99	168.935190(5)	32.026(5) d	EC	^{169}Tm	7/2+		
^{169m}Yb	24.199(3) keV			46(2) s	IT	^{169}Yb	1/2−		
^{170}Yb	70	100	169.9347618(26)	Observationally Stable[n 4]			0+	0.0304(15)	
^{170m}Yb	1258.46(14) keV			370(15) ns			4−		
^{171}Yb	70	101	170.9363258(26)	Observationally Stable[n 5]			1/2−	0.1428(57)	
^{171m1}Yb	95.282(2) keV			5.25(24) ms	IT	^{171}Yb	7/2+		
^{171m2}Yb	122.416(2) keV			265(20) ns			5/2−		
^{172}Yb	70	102	171.9363815(26)	Observationally Stable[n 6]			0+	0.2183(67)	
^{173}Yb	70	103	172.9382108(26)	Observationally Stable[n 7]			5/2−	0.1613(27)	
^{173m}Yb	398.9(5) keV			2.9(1) μs			1/2−		
^{174}Yb	70	104	173.9388621(26)	Observationally Stable[n 8]			0+	0.3183(92)	
^{175}Yb	70	105	174.9412765(26)	4.185(1) d	β^-	^{175}Lu	7/2−		
^{175m}Yb	514.865(4) keV			68.2(3) ms			1/2−		
^{176}Yb	70	106	175.9425717(28)	Observationally Stable[n 9]			0+	0.1276(41)	
^{176m}Yb	1050.0(3) keV			11.4(3) s			(8)−		
^{177}Yb	70	107	176.9452608(28)	1.911(3) h	β^-	^{177}Lu	(9/2+)		
^{177m}Yb	331.5(3) keV			6.41(2) s	IT	^{177}Yb	(1/2−)		
^{178}Yb	70	108	177.946647(11)	74(3) min	β^-	^{178}Lu	0+		
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Precision mass measurements: 10^{-10}

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The most precise atomic mass measurements in Penning traps

Edmund G. Myers*

Florida State University, Department of Physics, Tallahassee, FL 32306-4350, USA

Table 10
Atomic masses of the most abundant isotopes of strontium and ytterbium measured at FSU [109].

Atom	FSU mass (u)	σ_m/m (ppt)
^{86}Sr	85.909 260 730 9(91)	105
^{87}Sr	86.908 877 497 0(91)	105
^{88}Sr	87.905 612 257 1(97)	110
^{170}Yb	169.934 767 241(18)	105
^{171}Yb	170.936 331 514(19)	110
^{172}Yb	171.936 386 655(18)	105
^{173}Yb	172.938 216 213(18)	105
^{174}Yb	173.938 867 539(18)	105
^{176}Yb	175.942 574 702(22)	125

Partial solution, comparing different isotope shift, searching of nonlinearity in "King plot"

King's factorisation formula (King, 1963):

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

only depend on e-transition

($\mu_{AA'} \equiv 1/m_A - 1/m_{A'} = (A'-A)/(AA')\,\text{amu}^{-1}$, where amu ≈ 0.931 GeV)

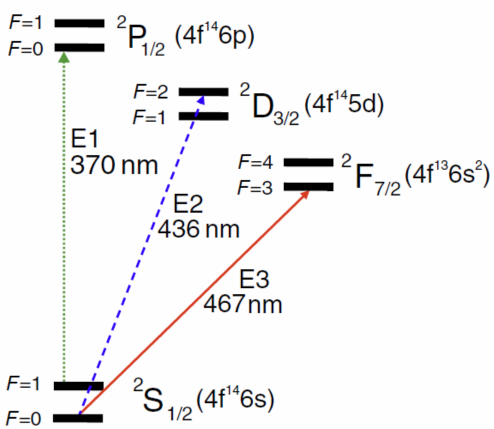
only depend on nucleus

We can solve for $\delta\langle r^2\rangle_{AA'}$ to get a linear relation:

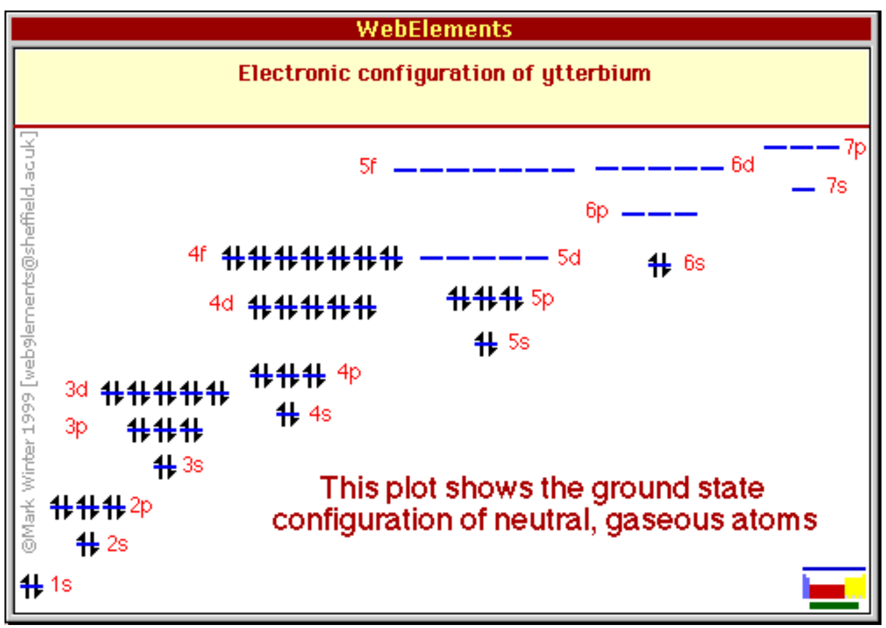
$$m\delta\nu^2_{AA'} = F_{21} m\delta\nu^1_{AA'} + K_{21}\,,$$

(with $K_{21} \equiv (K_2 - F_{21}K_1)$ and $F_{21} \equiv F_2/F_1$ and $m\delta\nu^i_{AA'} \equiv \delta\nu^i_{AA'}/\mu_{AA'}$.)

Ex.: Yb^+ with Z=70, n=6 and A=168(4)-174(6).



The Kossel shell structure of ytterbium.



The electronic configuration of ytterbium.

nuclide symbol	Z(p)	N(n)	isotopic mass (u)	half-life	decay mode(s)[2][n 1]	daughter isotope(s)[n 2]	nuclear spin	representative isotopic composition (mole fraction)	range of natural variation (mole fraction)
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^{176}Yb	70	106	175.9425717(28)	Observationally Stable[n 9]			0+	0.1276(41)	
^{176m}Yb	1050.0(3) keV			11.4(3) s			(8)−		
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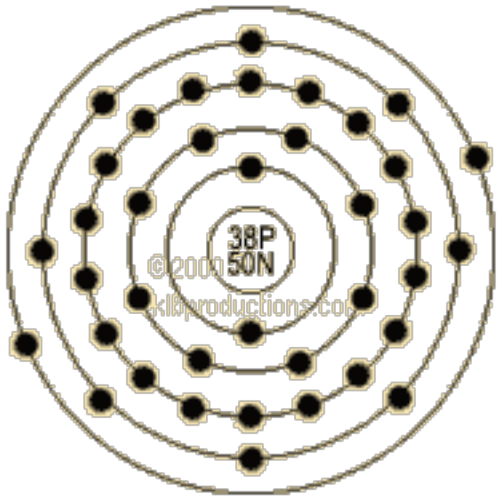
^{177m}Yb	331.5(3) keV			6.41(2) s	IT	^{177}Yb	(1/2−)		
^{178}Yb	70	108	177.946647(11)	74(3) min	β^-	^{178}Lu	0+		
^{179}Yb	70	109	178.95017(32)#	8.0(4) min	β^-	^{179}Lu	(1/2−)		

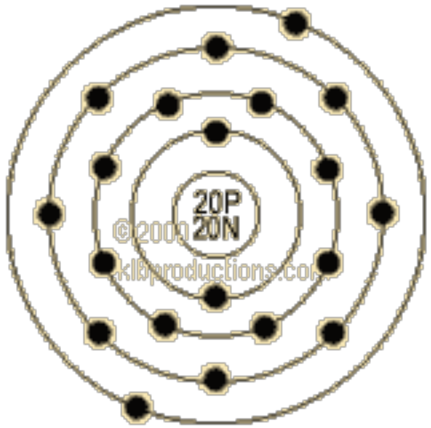
Ex.: $Sr^{(+)}$ with Z=38, n=5 and A=84-88 (90).

- **Electron Configuration:** $1s^2\ 2s^2p^6\ 3s^2p^6d^{10}\ 4s^2p^6\ 5s^{2(1)}$
- **Electrons per Energy Level:** 2,8,18,8,2(1)

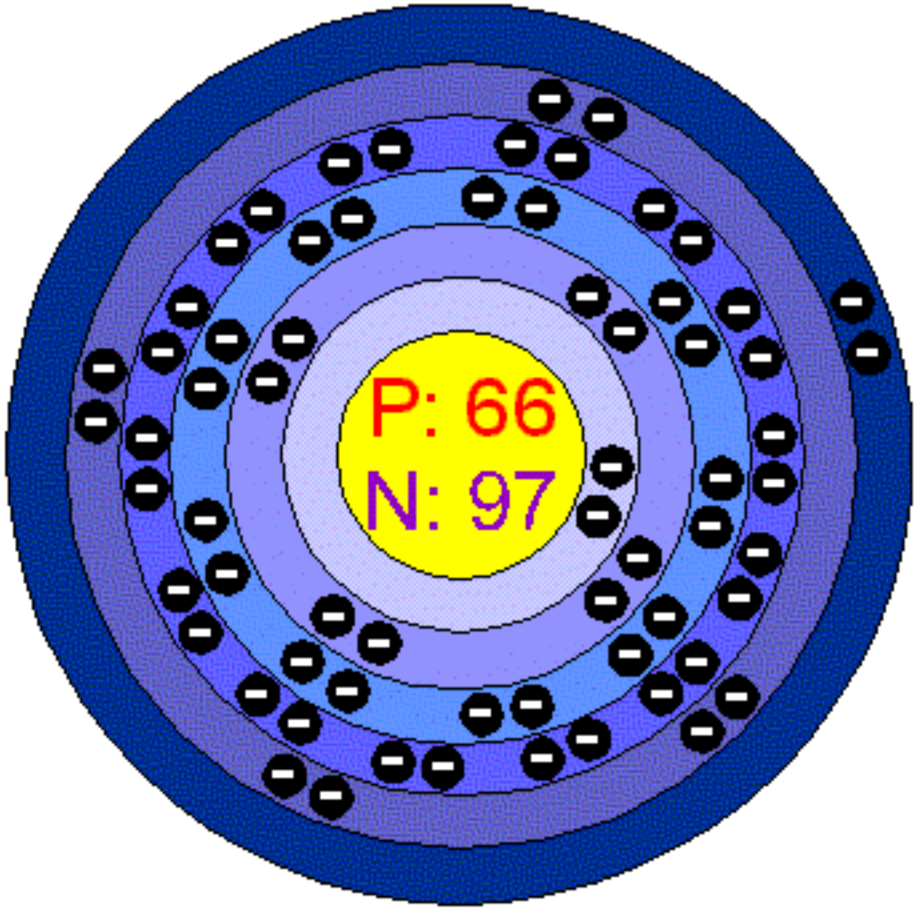


Ex.: $Ca^{(+)}$ with Z=20, n=4 and A=40-48.

- **Electron Configuration:** $1s^2\ 2s^2p^6\ 3s^2p^6\ 4s^1$
- **Electrons per Energy Level:** 2,8,8,2(1)
-



Ex.: Dy with Z=66, n=6 and A=158-164.



Number of Energy Levels: 6
First Energy Level: 2
Second Energy Level: 8
Third Energy Level: 18
Fourth Energy Level: 28
Fifth Energy Level: 8
Sixth Energy Level: 2

The observables

- We have 3 isotope shifts $(AA'_{1,2,3})$ for 2 transitions (i=1,2):

$$\overrightarrow{m\nu}_i \equiv \left(m\nu_i^{AA'_1}, m\nu_i^{AA'_2}, m\nu_i^{AA'_3}\right)$$

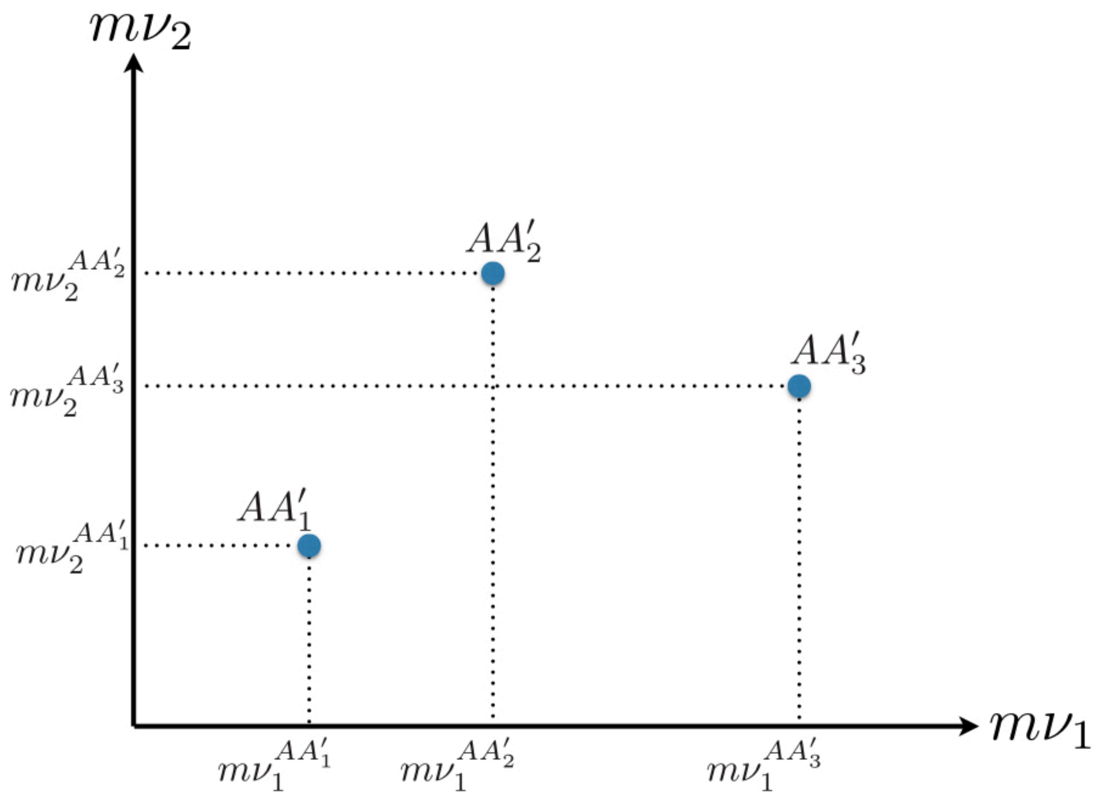
$$\nu_i^{AA'} \equiv \nu_i^{A} - \nu_i^{A'}\,. \qquad m\nu_i^{AA'} \equiv \nu_i^{AA'}/\mu_{AA'}$$

$$\mu_{AA'} \equiv m_A^{-1} - m_{A'}^{-1}$$

Target accuracy: $\Delta m\nu_i^{AA'}/m\nu_i^{AA'} \lesssim 10^{-6}$.
(currently: 10^{-4}, projected $< 10^{-9}$)

The observable: King comparison (1964)

- What would be the generic form of $\overrightarrow{m\nu}_2$ vs. $\overrightarrow{m\nu}_1$?
- 3 ISs - $m\nu_2 = am\nu_1^2 + bm\nu_1 + c$:



What about existing data ?

Limitation of method

$$\alpha_{\rm NP} = \frac{(\overrightarrow{m\nu}_1 \times \overrightarrow{m\nu}_2)\cdot \overrightarrow{m\mu}}{(\overrightarrow{m\mu}\times \vec{h})\cdot (X_1\, \overrightarrow{m\nu}_2 - X_2\, \overrightarrow{m\nu}_1)}$$

Berengut, Budker, Delaunay, Flambaum, Frugiuele, Fuchs, Grojean, Harnik, Ozeri, GP & Soreq (17)

- Only useful to bound new physics (barring cancellation).
- Short range NP: $X_i \propto F_i \;\Rightarrow\; \vec{v}$ is redefined to absorb NP; requires extra carefulness when approaching this limit.
- As long as linearity holds bounds are limited by exp' accuracy:

$$\alpha_{\rm NP} \lesssim \sigma_{\alpha_{\rm NP}} = \sqrt{\Sigma_k (\partial \alpha_{\rm NP}/\partial O_k)^2 \sigma_k^2}\,,$$

(O_K various exp' observables.)

- Once non-linearity observed bound will be set by observation.