Atomic Probes of New Physics

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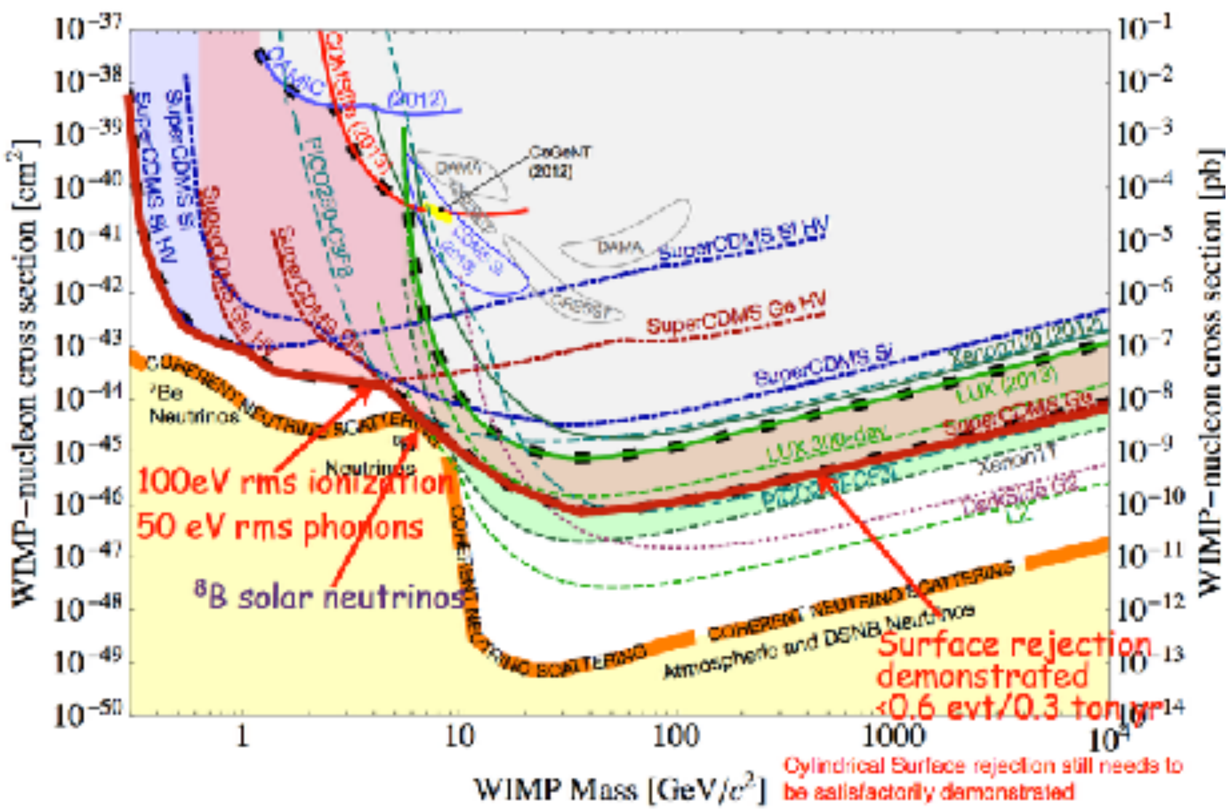
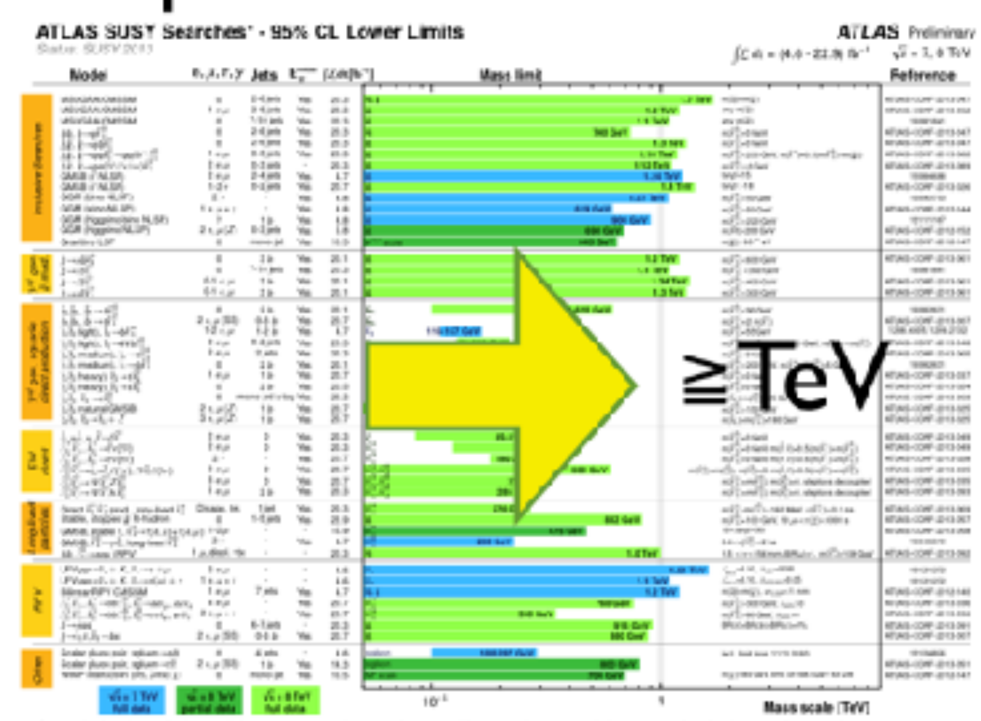
New physics is taking longer than we thought to show up.



No new particles



It is still too soon to draw clear conclusions. Time to explore alternative scenarios and question our standard paradigm.

Many new ideas have been explored in the last few years

Neutral Naturalness

Relaxion

Sub GeV dark matter

These new ideas often suggest the existence of dark sectors and possibly lead to signals beyond the LHC and standard direct detection experiments

See talks by
Choi,McCullough,Kamenik

Relaxion

A new paradigm, no partners! The Higgs was originally heavy and it then evolved to be light in the early universe.

In this scenario a light spin-0 particle plays the central role, and not new physics at the electroweak scale.

[Graham, Kaplan, Rajendran, 2014]

⇨ Naturalness problem at the “low energy frontier”

The relaxion force

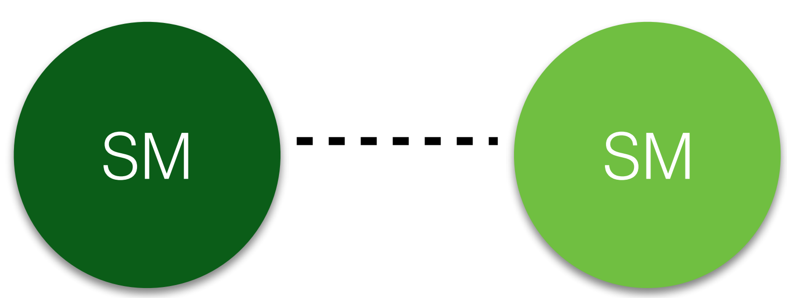
The relaxion mass is not fixed
Several orders of magnitude are possible!
Sub-eV as well as few GeV range

Crucial question: how does it interact with the visible sector?

In general there is a mixing between the Higgs boson and the relaxion

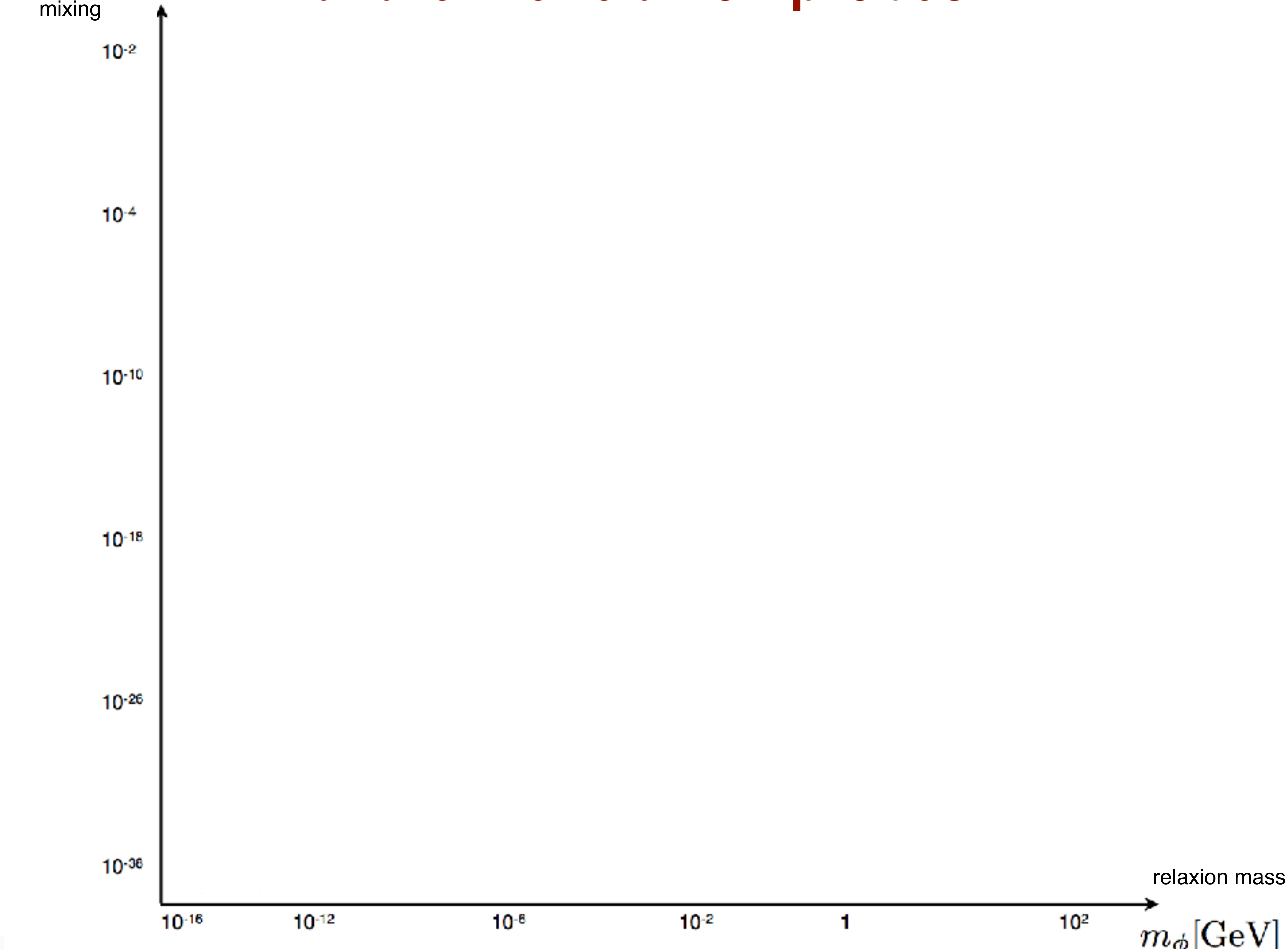
[Flacke,CF, Fuchs,Gupta,Perez 2016]

[Choi, Im 2016]



''Relaxion'' force

What are the relaxion probes?



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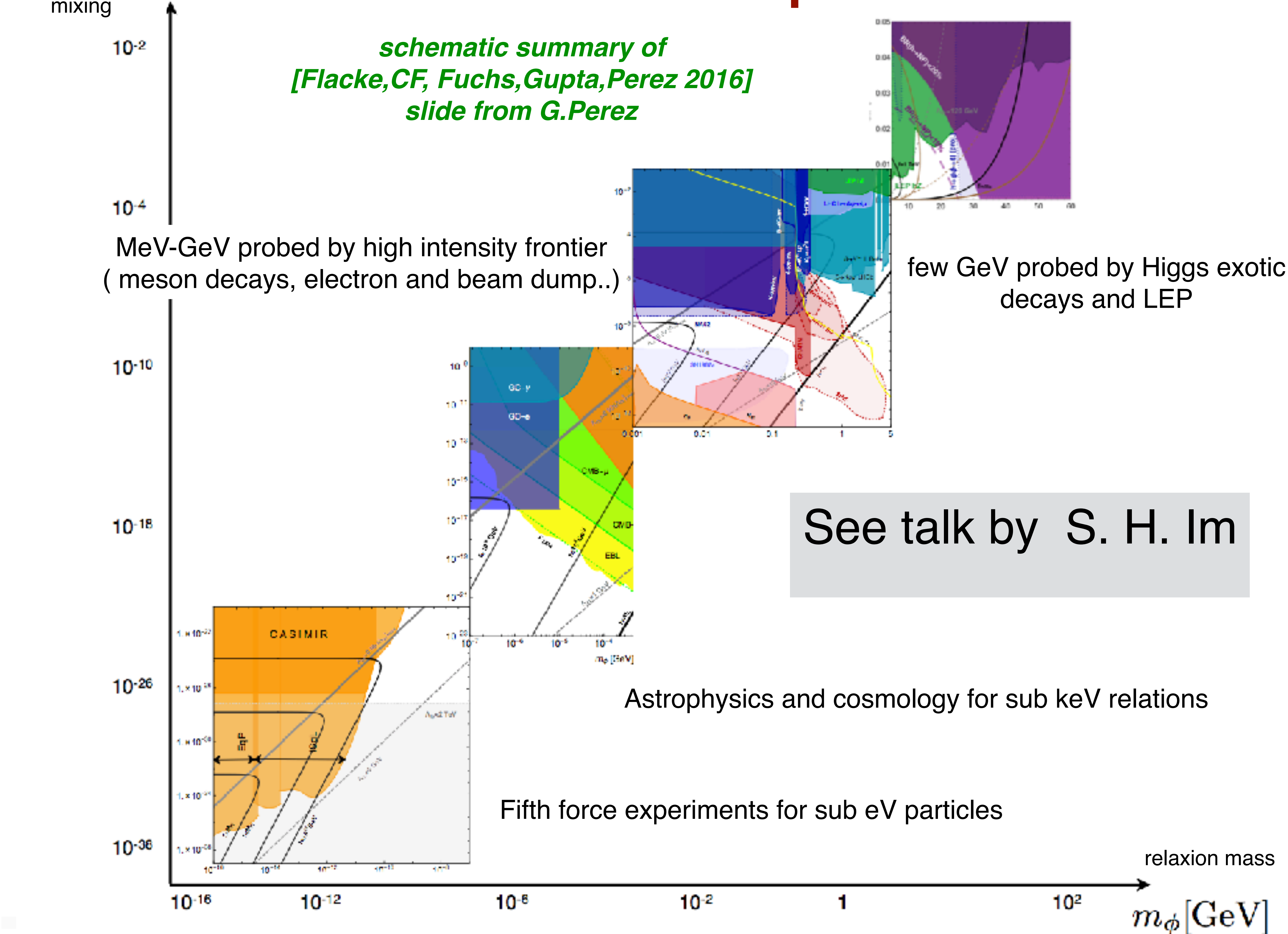


Many experiments become linked to the solution of the naturalness problem of the Higgs mass

What about new probes and ideas?

The relaxion represents a highly motivated example
for intermediate
long range hidden forces
between matter

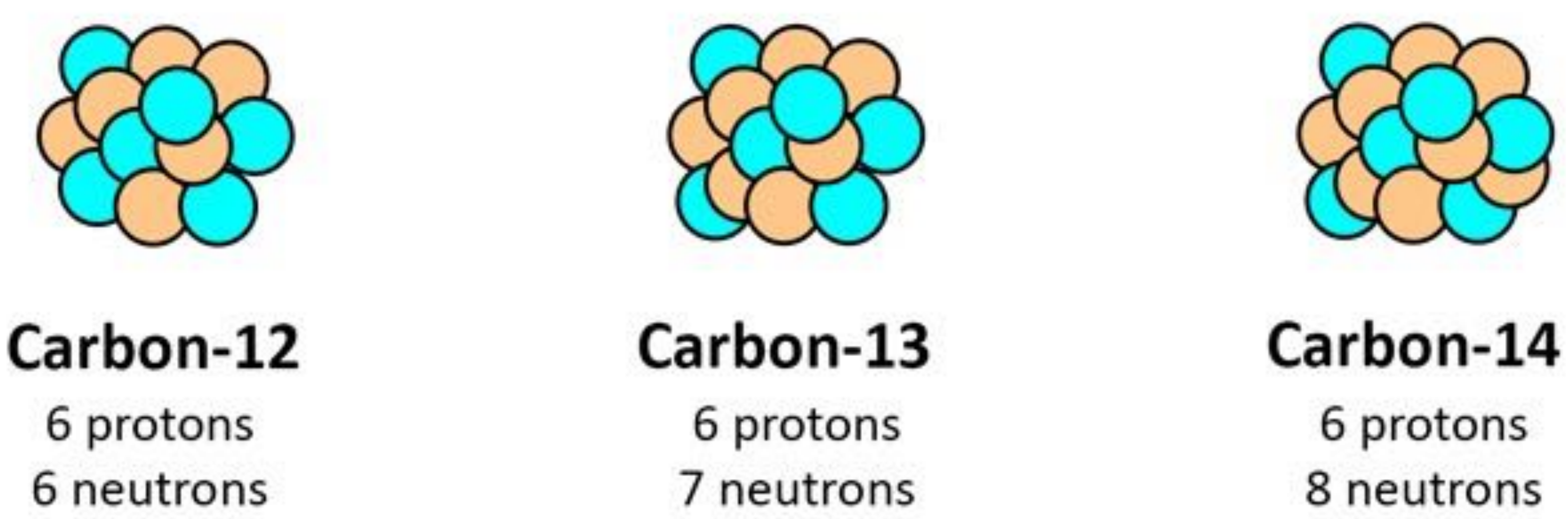
ISOTOPE SHIFT MEASUREMENTS TO PROBE DARK FORCES

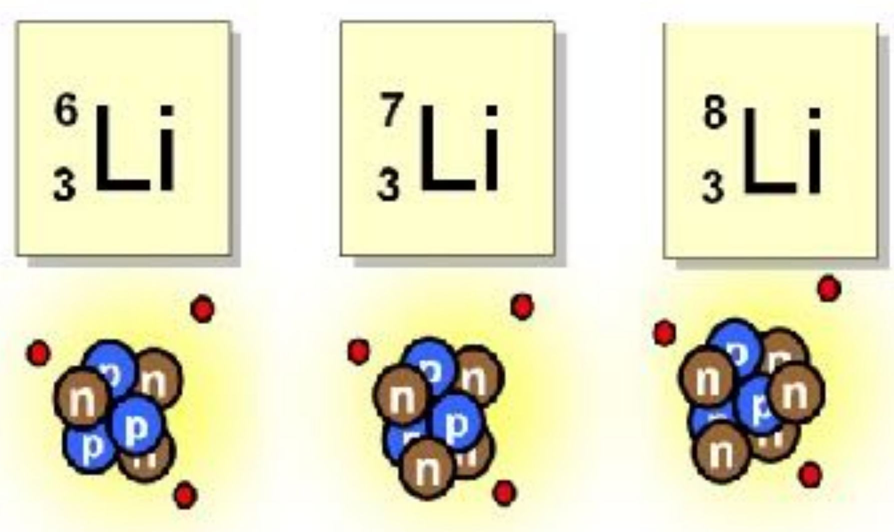
[J.C. Berengut, D. Budker, C. Delaunay, V.V. Flambaum, CF, E. Fuchs, C. Grojean, R. Harnik, R. Ozeri, G. Perez, Y.Soreq, 2017]

collaboration between atomic physicists (both experimentalists and theorists) and particle theorists

Isotopes

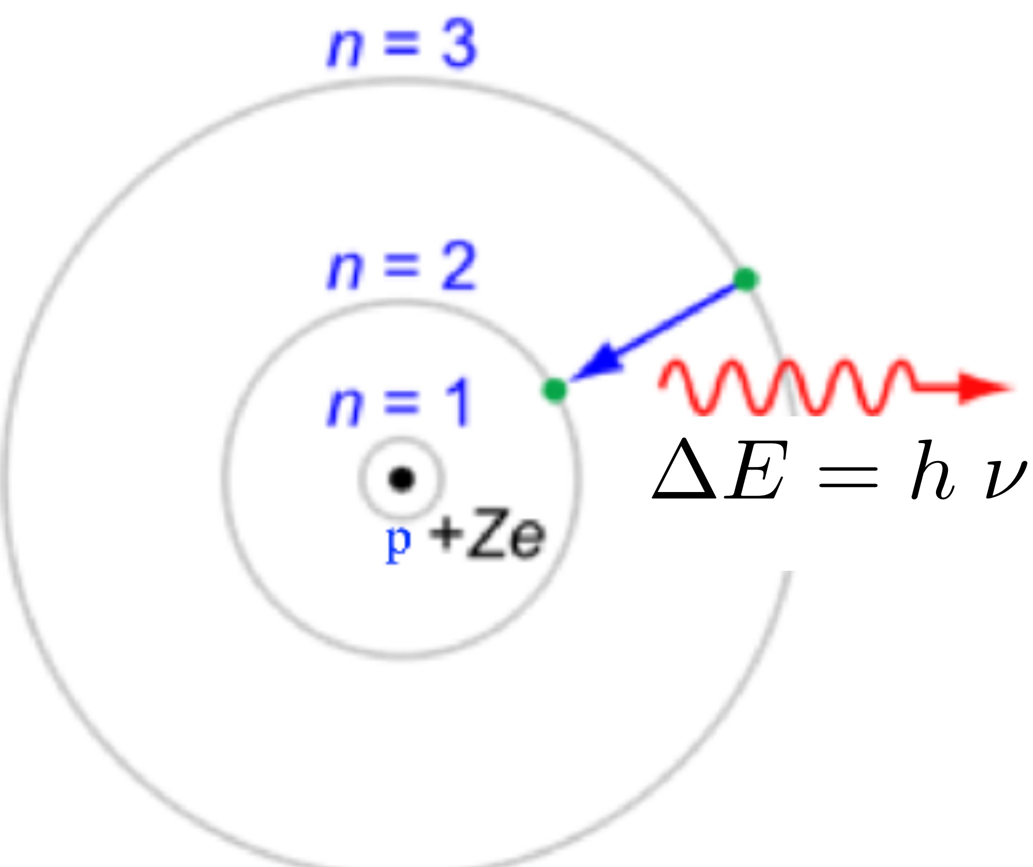
Isotopes are atoms with the same number of protons but that have a different number of neutrons.





Isotope frequency shift

Consider an **atomic optical transition**
and consider two **spin-less** isotopes of a given element A and A'



$$\nu_i^A \quad \nu_i^{A'}$$

electronic transition i

Is the frequency different? How?

$$\nu_i^{AA'} = \nu_i^A - \nu_i^{A'}$$

Mass and field shift

$$\nu_i^{AA'} = \nu_i^{A} - \nu_i^{A'}$$

electronic factors

$$\boxed{\nu_i^{AA'} \approx K_i \mu_{AA'} + F_i \lambda_{AA'}}$$

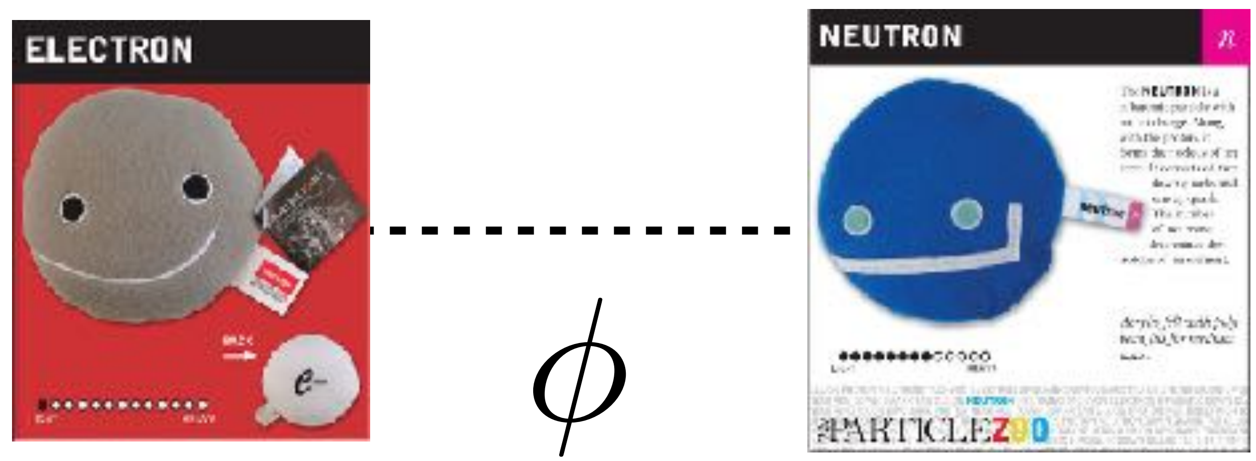
mass shift

field shift

$$\lambda_{AA'} = \delta\langle r^2 \rangle + \text{higher moments}$$

Isotopes have different nuclear volume

Hidden force
between electrons and neutrons



$$V_\phi(r) = \frac{(-1)^{s+1}}{4\pi} y_e y_N \frac{e^{-m_\phi r}}{r}$$

This will give rise to an additional contribution to the frequency shift.

$$X_i \simeq \int d^3r \, \frac{e^{-m_\phi r}}{r} \left[|\psi_b(r)|^2 - |\psi_a(r)|^2 \right]$$

electronic contribution

How do we probe this?

King Plot in atomic physics

Measure 2 transitions with the same isotopes. The 2 data-sets are linearly related

King J. Opt. Soc. Am. **53**, 638 (1963)

$$m\nu_2 = F_{21} m\nu_1 + K_{12}$$

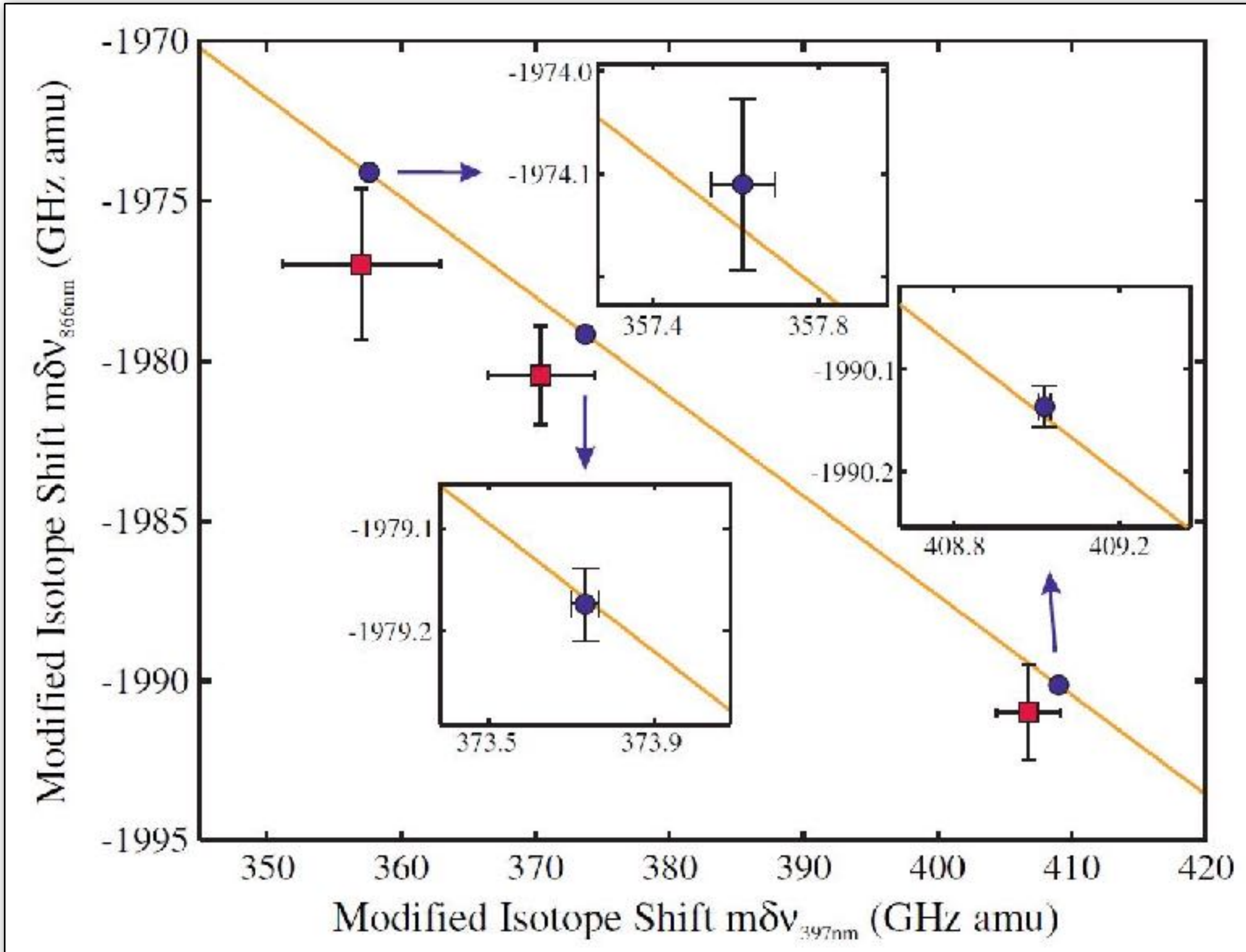
King plot is useful to extract informations on both atomic and nuclear structure in heavy atoms where theoretical precision of the calculations is limited.

King Plot in atomic physics

Calcium Z=20

[Geber et al. 2015]

Precision 0.1 MhZ
Linear King Plot



King Plot in particle physics

New goal: probing new long range interactions between electrons and neutrons!

$$V_\phi(r) = \frac{(-1)^{s+1}}{4\pi} y_e y_N \frac{e^{-m_\phi r}}{r}$$

$$m\nu_2 = F_{21} m\nu_1 + K_{12} + y_e y_N X_{12} A A'$$

$$X_i \simeq \int d^3 r \, \frac{e^{-m_\phi r}}{r} \left[|\psi_b(r)|^2 - |\psi_a(r)|^2 \right]$$

electron densities in initial/final atomic states computed using many-body perturbation theory

i: a->b

King Plot in particle physics

inter

$m\nu$,

A new intermediate long range force (sub MeV) leads
to a breaking of King linearity.

If data agrees with it we can constrain this hidden force!

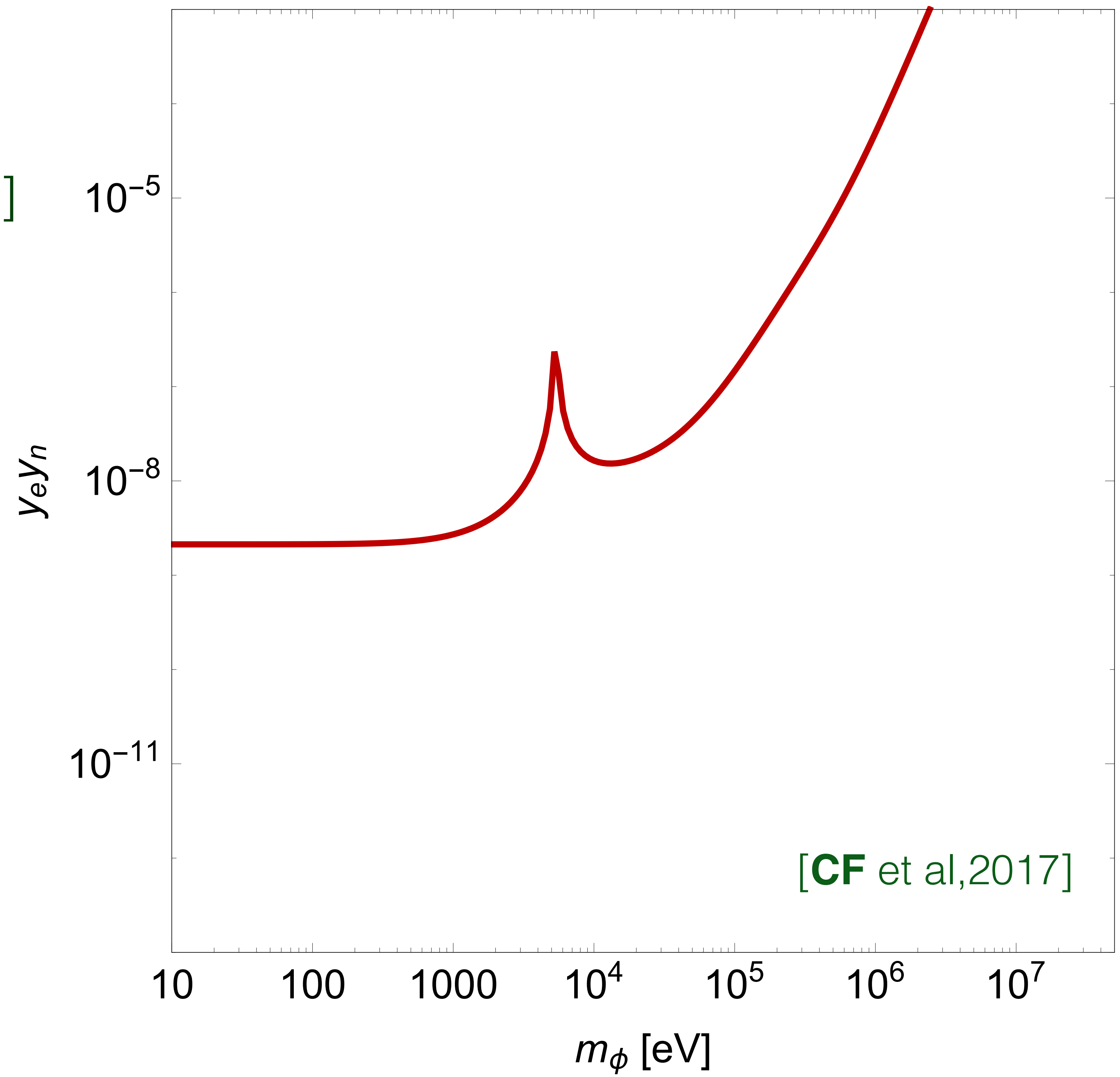
$X_i \simeq$

ele
ato
ma

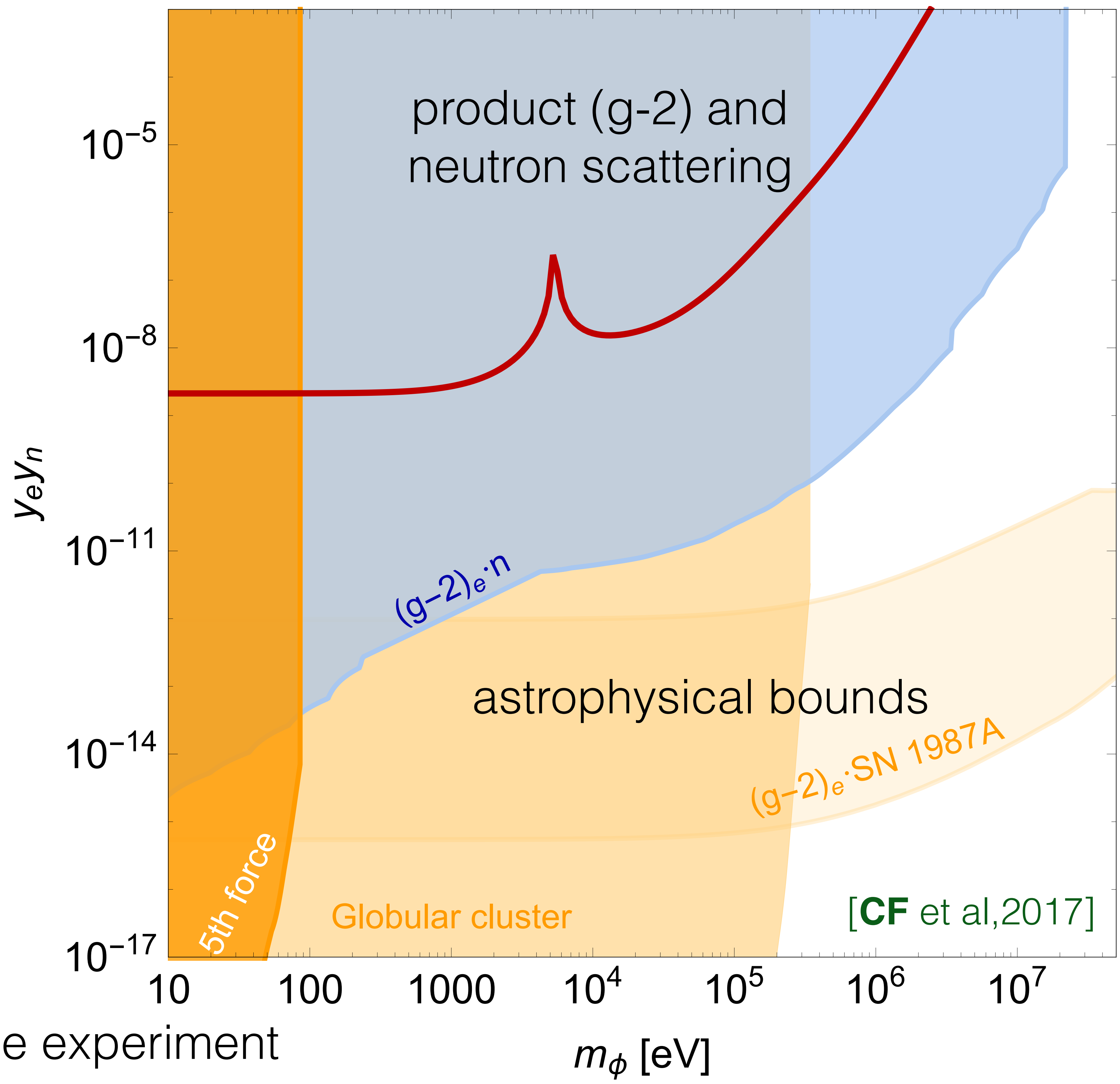
Existing data

Precision 0.1 Mhz
Linear King Plot

[Geber et al. 2015]



Probes of neutron-electron hidden forces



5th force experiment

Can we improve the reach?

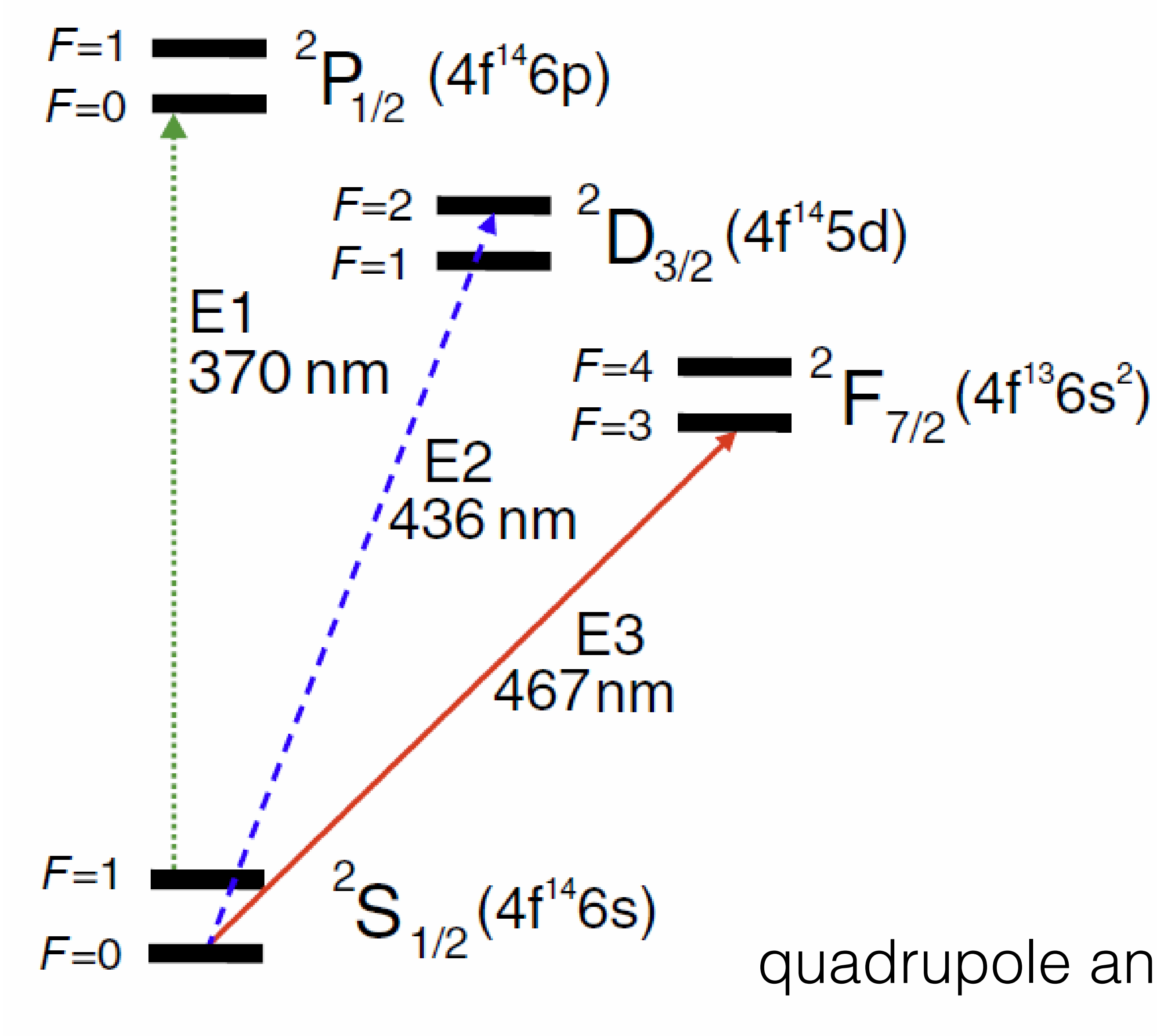
- Several other systems: the precision is comparable to Calcium data and so it is the reach.
- We can improve it performing NEW measurements for instance for **dipole-forbidden transitions** where higher precision can be achieved.

Expected accuracy of sub-Hz, better than $1{:}10^{16}$

Dipole-forbidden transitions

Yb⁺ ion-clock

Two working experiments:
PTB Germany, NPL UK



New Journal of Physics
The open-access journal for physics

Absolute frequency measurement of the $^2S_{1/2}$–$^2F_{7/2}$ electric octupole transition in a single ion of $^{171}Yb^+$ with 10^{-15} fractional uncertainty

S A King[1,2,3], R M Godun[1], S A Webster[1], H S Margolis[1], L A M Johnson[1], K Szymaniec[1], P E G Baird[2] and P Gill[1,2]
[1] National Physical Laboratory, Hampton Road, Teddington, TW11 0LW, UK
[2] Clarendon Laboratory, University of Oxford, Parks Road, Oxford OX1 3PU, UK
E-mail: steven.king@npl.co.uk

Selected for a Viewpoint in *Physics*
PRL **113,** 210802 (2014) PHYSICAL REVIEW LETTERS week ending 21 NOVEMBER 2014

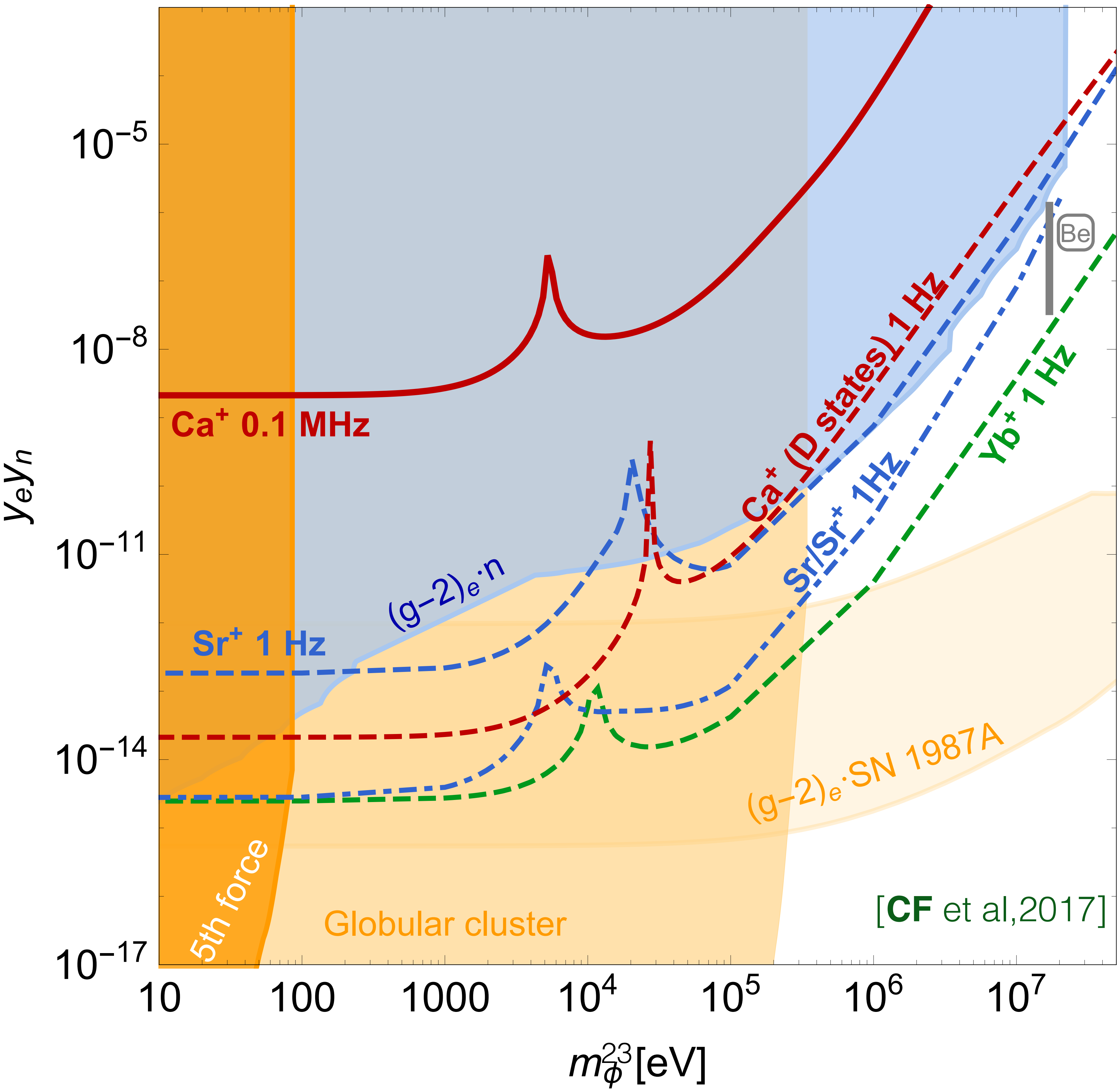
Improved Limit on a Temporal Variation of m_p/m_e from Comparisons of Yb^+ and Cs Atomic Clocks

N. Huntemann, B. Lipphardt, Chr. Tamm, V. Gerginov, S. Weyers, and E. Peik*
Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany
(Received 16 July 2014; published 17 November 2014)

Accurate measurements of different transition frequencies between atomic levels of the electronic and hyperfine structure over time are used to investigate temporal variations of the fine structure constant α and the proton-to-electron mass ratio μ. We measure the frequency of the $^2S_{1/2} \rightarrow {}^2F_{7/2}$ electric octupole ($E3$) transition in $^{171}Yb^+$ against two caesium fountain clocks as $f(E3) = 642\,121\,496\,772\,645.36$ Hz with an improved fractional uncertainty of 3.9×10^{-16}. This transition frequency shows a strong sensitivity to changes of α. Together with a number of previous and recent measurements of the $^2S_{1/2} \rightarrow {}^2D_{3/2}$ electric quadrupole transition in $^{171}Yb^+$ and with data from other elements, a least-squares analysis yields $(1/\alpha)(d\alpha/dt) = -0.20(20) \times 10^{-16}$/yr and $(1/\mu)(d\mu/dt) = -0.5(1.6) \times 10^{-16}$/yr, confirming a previous limit on $d\alpha/dt$ and providing the most stringent limit on $d\mu/dt$ from laboratory experiments.

quadrupole and octupole Yb⁺ transitions

Projections



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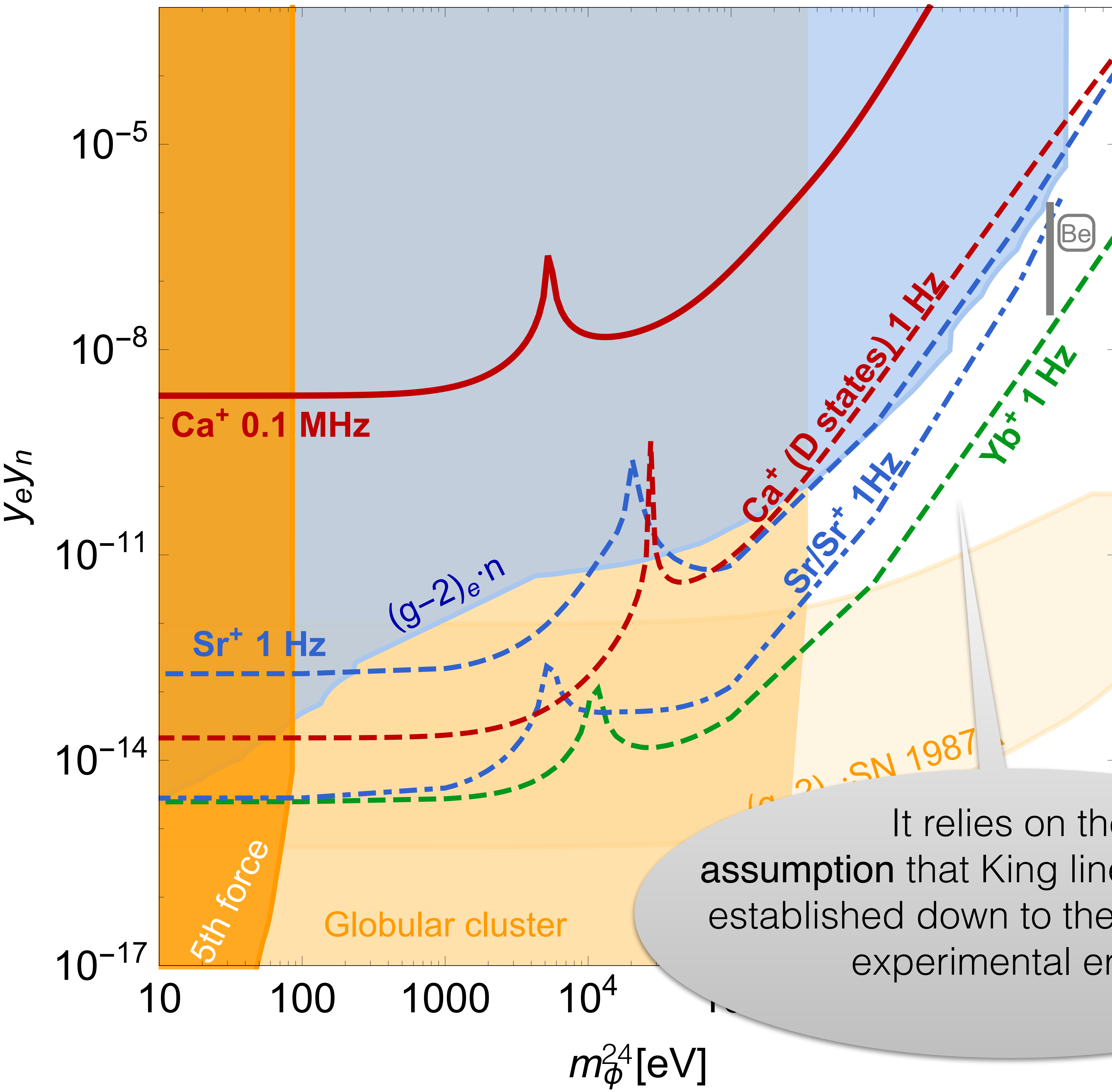

It relies on the **assumption** that King linearity will be established down to the achievable experimental error.

What about lighter atoms ?

[Delauney,CF,Fuchs,Soreq (in progress)]

Case study: **Helium**

Theory predictions sub kHz level

$$\nu_{IS}^{AA'} = \tilde{\nu}_{IS}^{AA'} + C(\delta r^2)^{AA'}$$

point-like nucleus

calculated from theory

QED calculation more precise than the experimental error

[Pachucki,,Yerokhin 2015][Pachucki,Patkos,Yerokhin 2017]

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Helium A=3 A’= 4

How is the (difference in) charge radius measured?

1) Electron Helium scattering (5%)
2) Isotope shift measurements
3) Muonic Helium measurements (in progress)

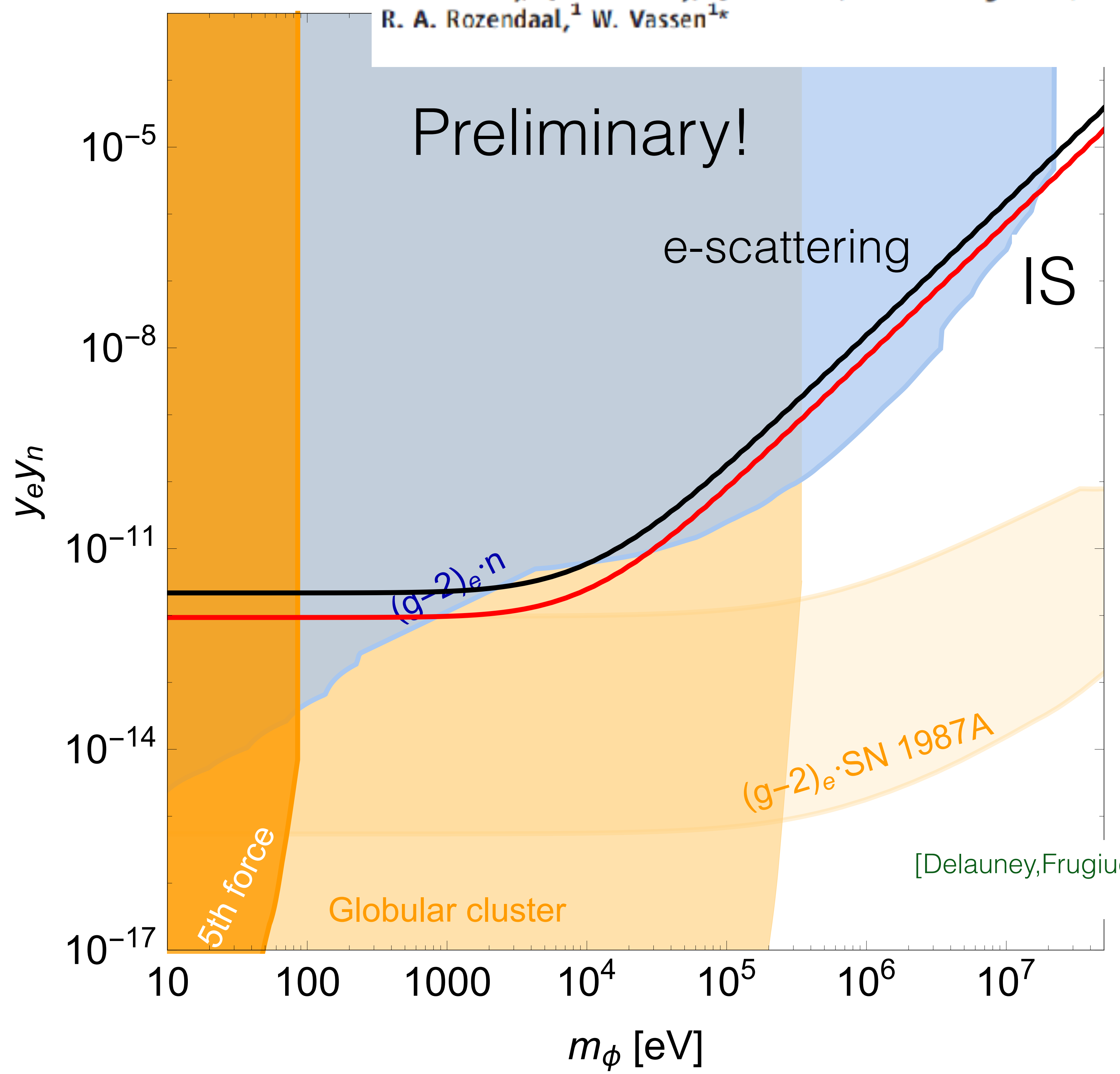
→ Prediction for $(\nu_{AA'})_{\rm IS}$!

the precision is given by the charge radius measurements

We can constraint new physics !

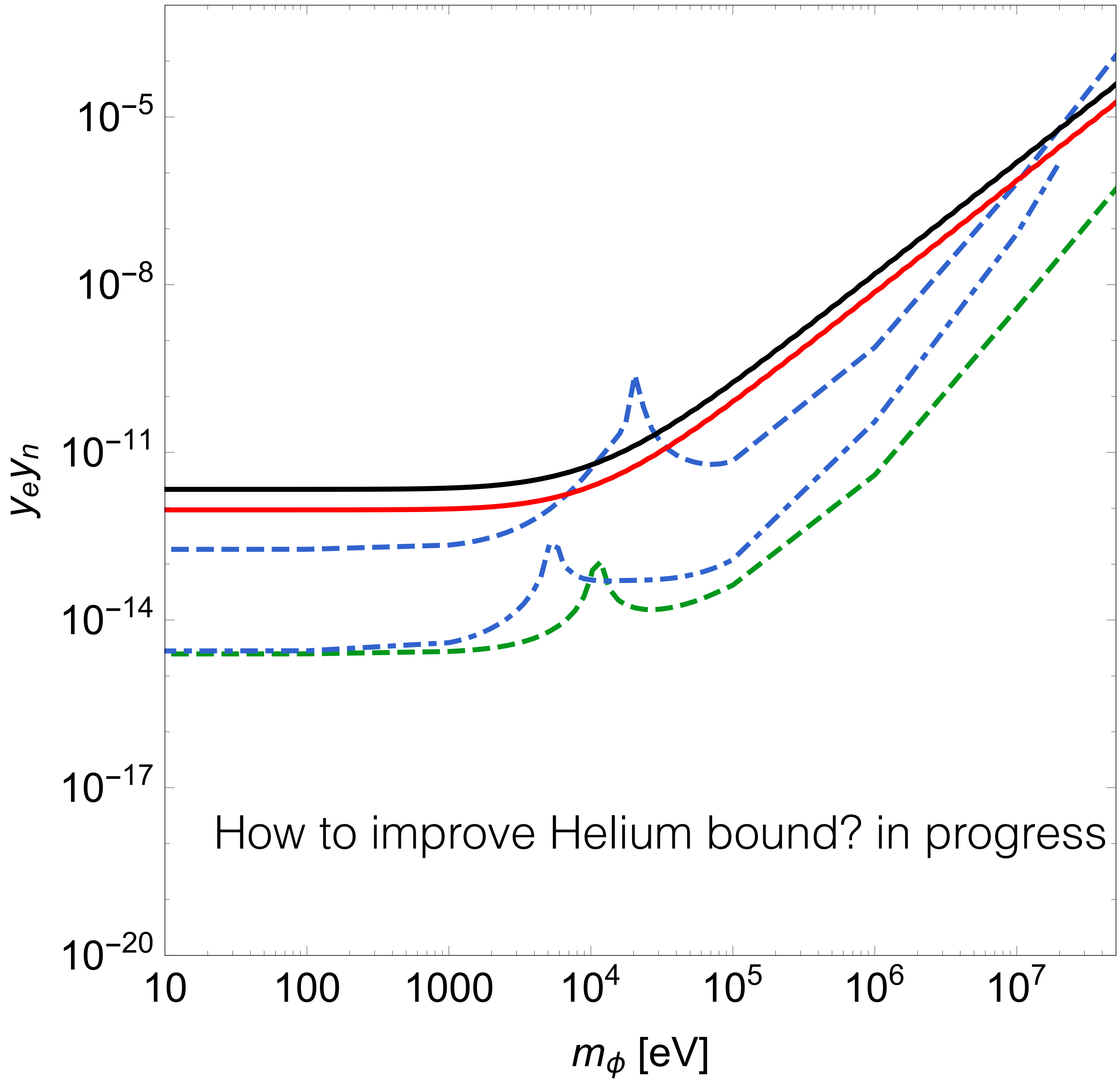
Frequency Metrology in Quantum Degenerate Helium: Direct Measurement of the 2 $^3S_1 \rightarrow$ 2 $^1S_0$ Transition

R. van Rooij,[1] J. S. Borbely,[1] J. Simonet,[2] M. D. Hoogerland,[3] K. S. E. Eikema,[1]
R. A. Rozendaal,[1] W. Vassen[1*]



[Delauney,Frugiuele,Fuchs,Soreq (in progress)]

Comparison with Kings violation



Outlook

Joint effort between atomic and particle physics community!

A lot still to explore!

What about testing spin dependent interactions with IS?

What about muonic atoms?

Possible good probe of relaxion force!