ETH zürich

Lecture at the CHIPP Winter School 2023 - Leukerbad, Paolo Crivelli (ETHZ)

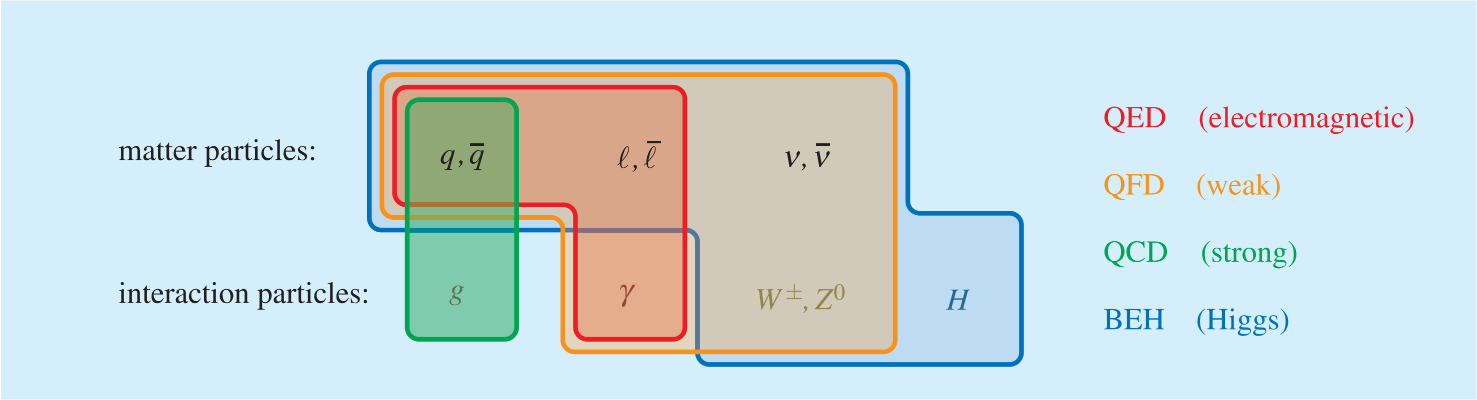
Low energy particle physics

Content of the lecture

- The limits of the Standard Model
- Low energy vs LHC physics
- Searches of SUSY and cLFV at the high intensity/low energy frontier
- Dark matter searches at the high intensity/low energy frontier
- Inspecting the matter-antimatter asymmetry with anti-hydrogen

The Standard Model

- The standard Model is a very **powerful** and **successful theory** describing the electromagnetic, weak and strong interactions between elementary subatomic particles (gravity is not included).



- It has demonstrated large and continued success in predicting experimental observables, such as the top quark, the W, Z and the Higgs bosons
  ➜ powerful predictions via radiative loops.

The short comings of the Standard Model

- **The Standard Model has fallen short in anticipating neutrino masses and oscillations, the existence of Dark Matter and the apparent Baryon- anti-Baryon asymmetry.**

- It might be perceived as having too much arbitrariness and fine-tuning (how to fix the input parameters?)
- Charge quantization unexplained (charge electron vs proton)
- Fermion masses, mixings, families unexplained
- Higgs/hierarchy problem
- Strong CP problem
- Gravity not unified

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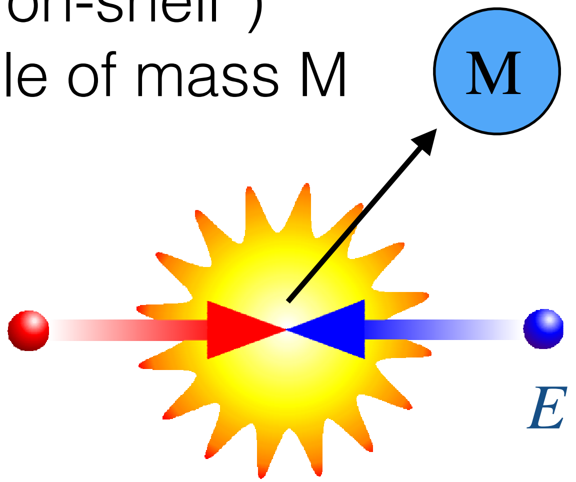
BSM Physics required!

Complementary strategies for BSM searches

High-energy collisions

real ("on-shell") particle of mass M

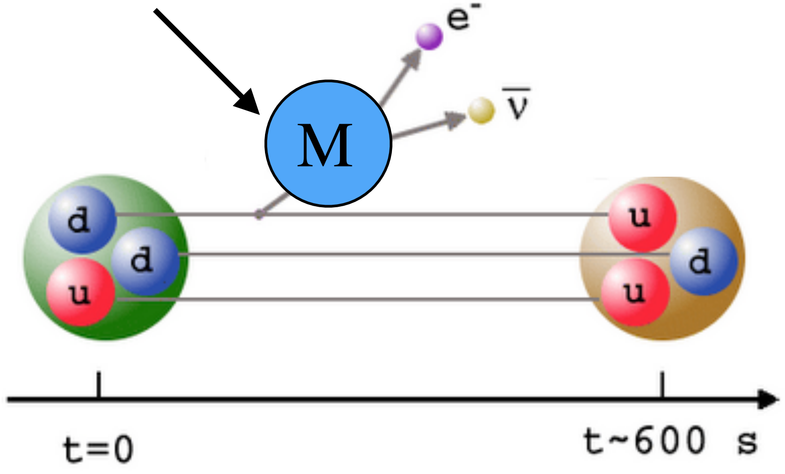


on-shell particles limited by kinematical threshold:

$$(Mc^2) < E_{cms}$$

Rare/New processes

virtual ("off-shell") particle of mass M



off-shell particles sensitivity limited by rarity of process:

$$(Mc^2)\Delta t \gtrsim \hbar$$

Some examples from the past

What was the BSM physics discovered in 1947?

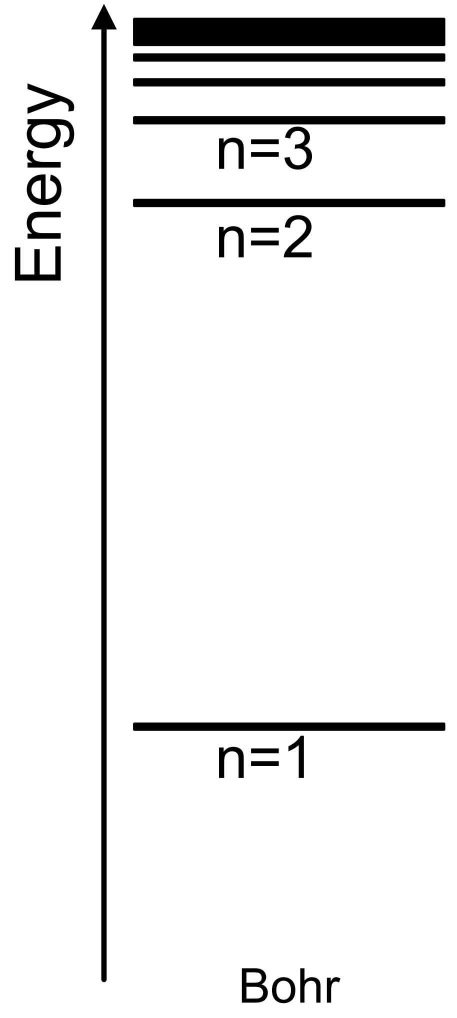
The "birth" of Quantum Electrodynamics (QED)

Dirac theory great success in predicting many phenomena of atomic physics.
Is the electron a "point-like Dirac particle" with g=2?

- Nafe, Nelson, and Rabi (1947) obtained precision measurements of the hyperfine structure intervals in hydrogen and deuterium: 0.2% discrepancy from predictions based on g = 2 → Dirac theory of the electron no longer completely satisfactory → **need to apply QED corrections**
- Lamb and Retherford (1947): measured the energy splitting between the $2S_{1/2}$ and $2P_{1/2}$ in Hydrogen (this is predicted to be zero by Dirac's theory!)

Realization that Dirac theory not sufficient BSM physics required → QED

Reminder - The hydrogen atom



- The atomic gross structure of the atomic energy levels is given by the Bohr and the **Schrödinger equation** (SEQ)

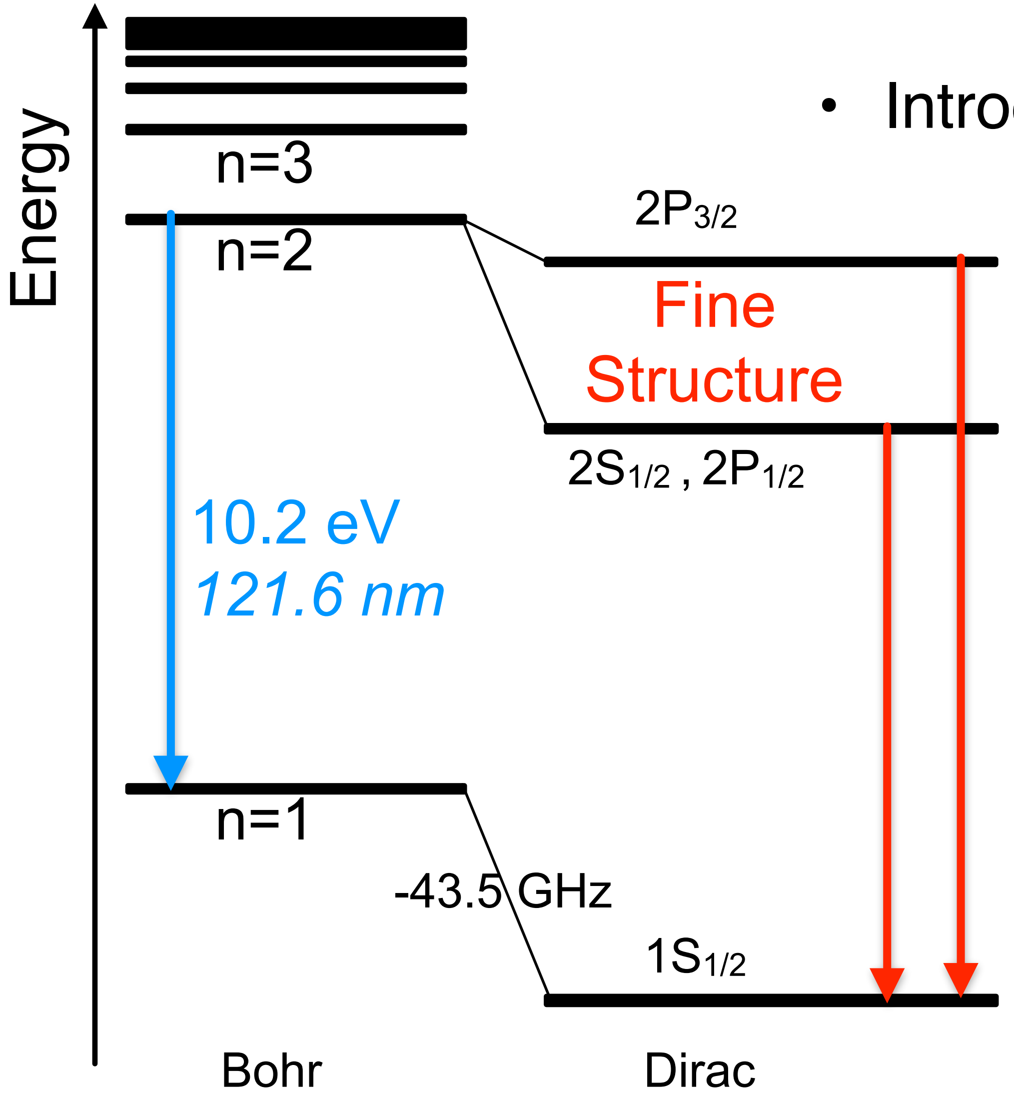
$$\frac{p^2}{2m_e} + V(r) = E \quad \rightarrow \quad \left[\frac{\hbar^2 \Delta}{2m_e} + V(r)\right]\Psi = E\Psi$$

- Coulomb-potential: $V(r) = -\frac{1}{4\pi\epsilon_0}\frac{Ze^2}{r}$

- First (non-relativistic) correction: **finite mass of the nucleus** taken into account by reduced mass: $m_R = \frac{M\,m}{M+m}$

- The gross eigenenergies are: $E_n = -\frac{(Z\alpha)^2 m_R c^2}{2n^2}$

Leading relativistic Dirac correction



- Introduces correction for angular momentum and spin

Solution of the Dirac equation

$$E_{nj} \simeq m \left[1 - \frac{Z^2\alpha^2}{2n^2} - \frac{(Z^2\alpha^2)^2}{2n^4} \left(\frac{n}{j+\frac{1}{2}} - \frac{3}{4} \right) + \dots \right]$$

Split of energy levels with same n but different total angular momentum j=l+s with l orbital angular momentum and spin

Relativistic effect→ fine structure in H atom.
The levels $2P_{3/2}$ and $2P_{1/2}$ split in energy but $2S_{1/2}$ and $2P_{1/2}$ are the same.

Spectroscopic notation

nl_j

principal quantum number

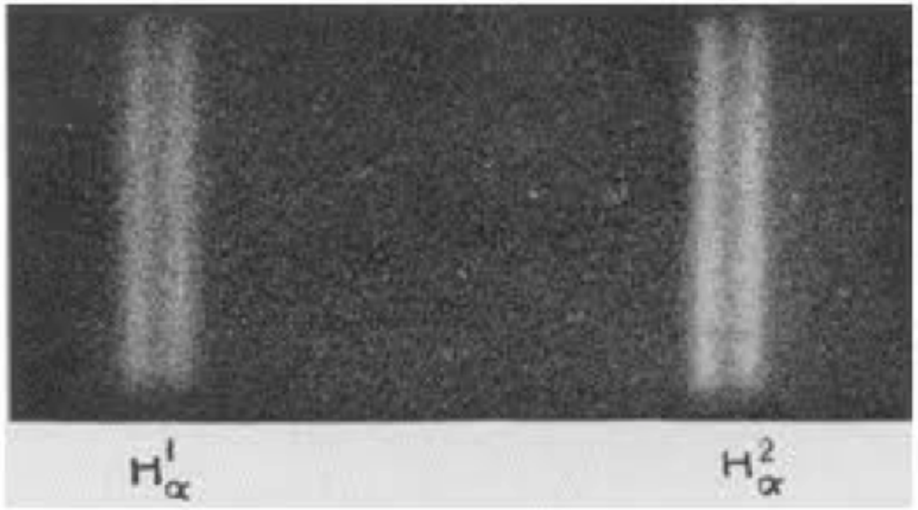
orbital angular momentum

Total angular momentum j=l+s

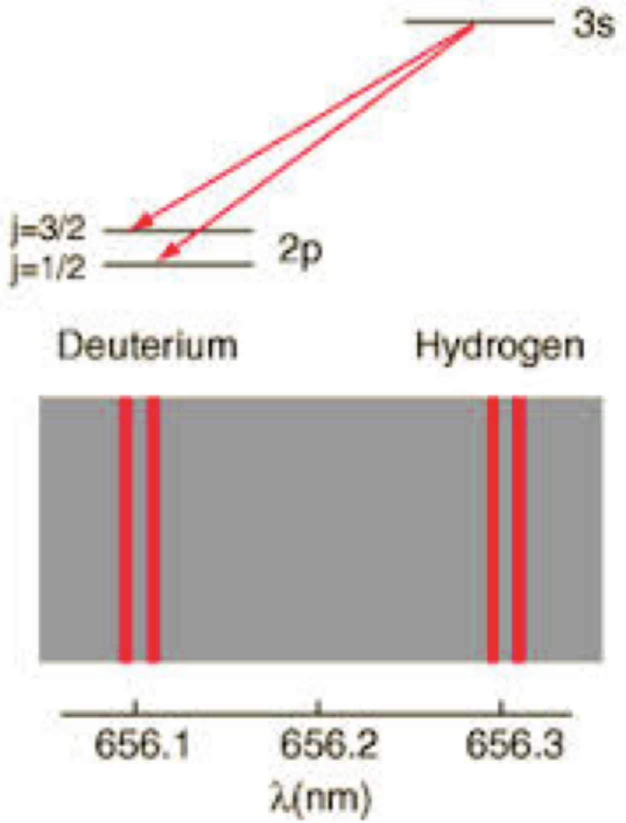
letter	name	*l*
s	**s**harp	0
p	**p**rincipal	1
d	**d**iffuse	2
f	**f**undamental	3
g		4
h		5

alphabetical

Hα/Dα Balmer absorption lines

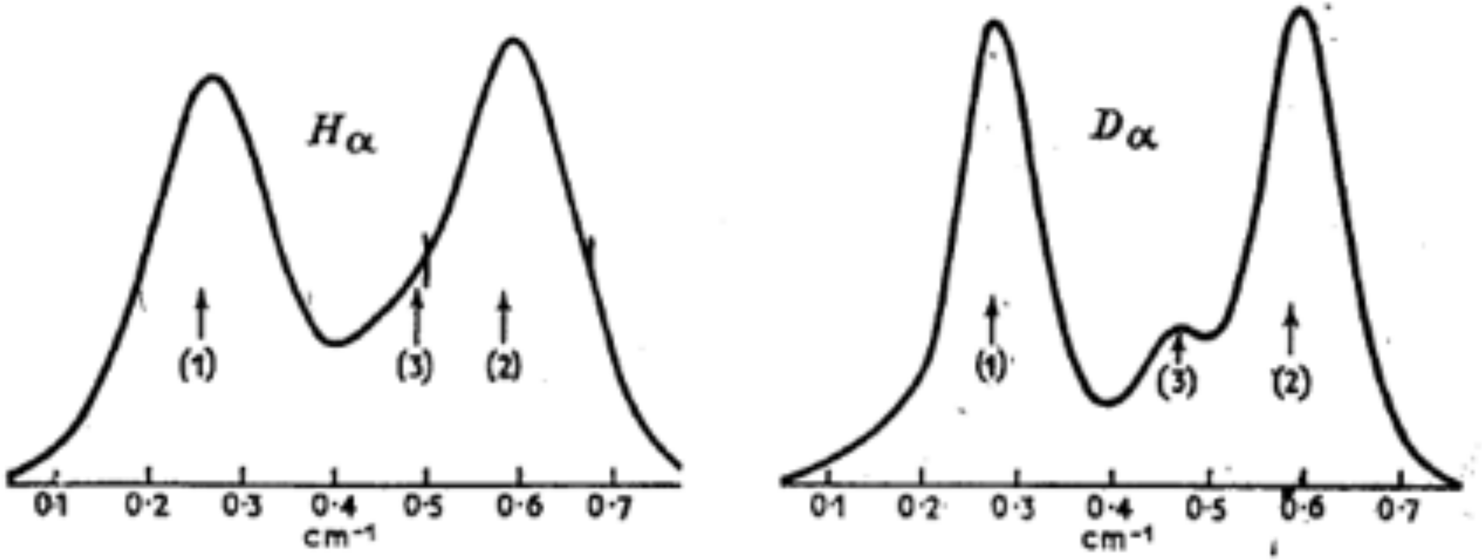


Balmer α line n=3 → n=2



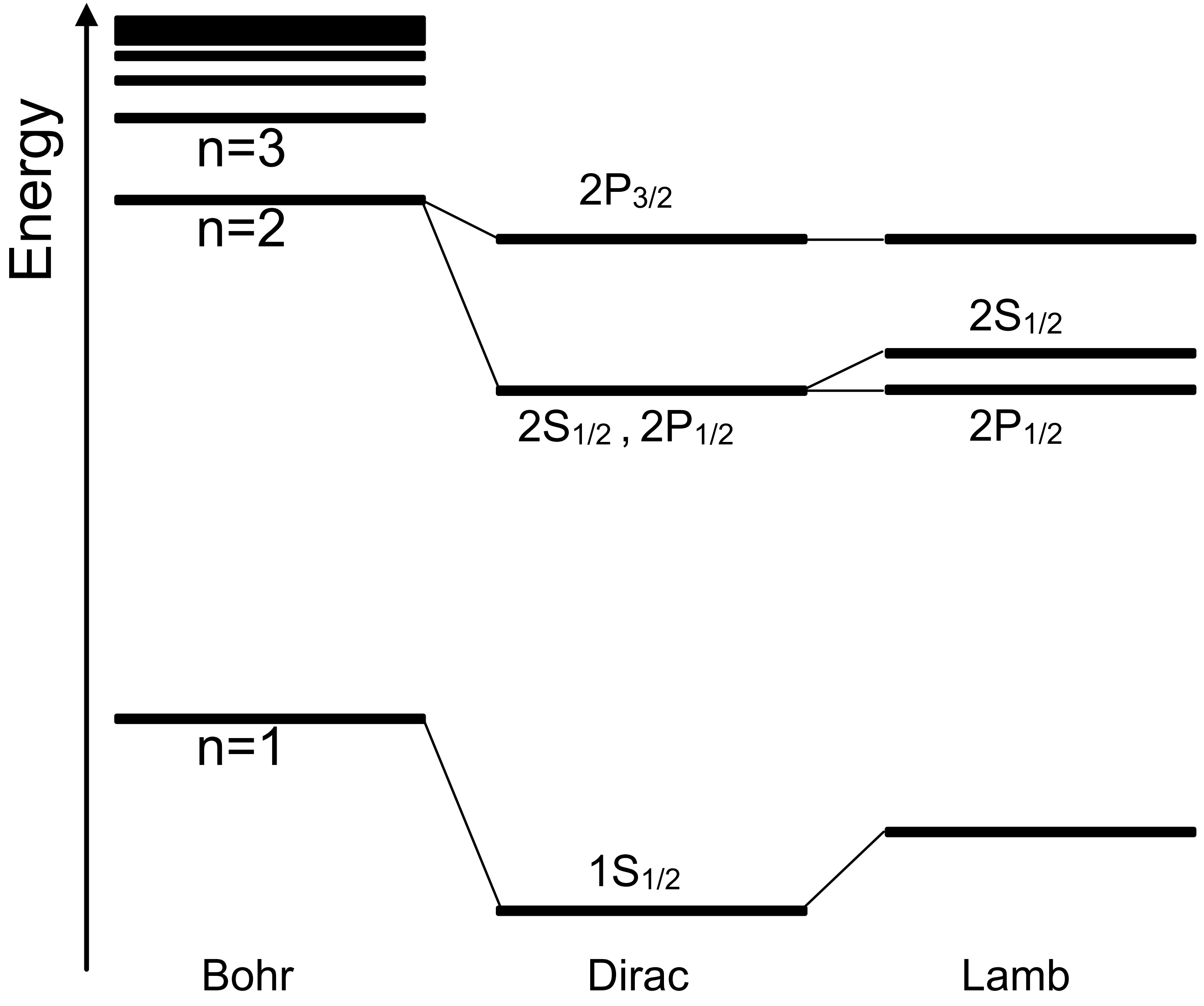
Hα/Dα Balmer absorption lines

Careful inspection of spectral lines of atomic hydrogen and deuterium obtained by **traditional absorption spectroscopy.**

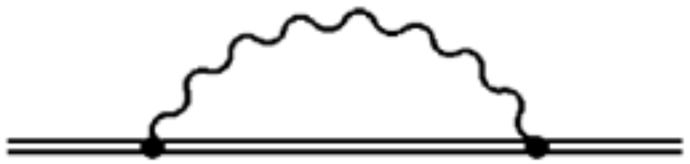


- Components **(1)** and **(2)** are from the **fine splitting**.
- The 3rd line at position **(3)** suggested that **Dirac theory must be revised** (before World War II).
- Final confirmation in 1947 using **resonant spectroscopy** (Lamb)

The Lamb shift (QED effect)



- The leading QED effect in conventional atoms is by the self energy contribution
- A virtual photon can be emitted and re-absorbed by the bound electron



- This fluctuation of the EM-field can be pictured as perturbing the electron orbit and therefore shifting the energy levels.

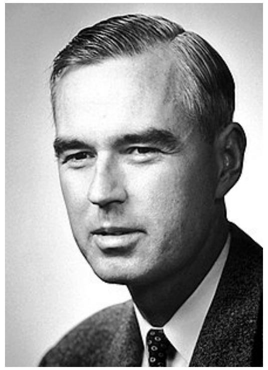
Willis Lamb

WILLIS E. LAMB, JR.

Fine structure of the hydrogen atom

Nobel Lecture, December 12, 1955

When the Nobel Prizes were first awarded in 1901, physicists knew something of just two objects which are now called « elementary particles »: the electron and the proton. A deluge of other « elementary » particles appeared after 1930; neutron, neutrino, μ meson, π meson, heavier mesons, and various hyperons. I have heard it said that « the finder of a new elementary particle used to be rewarded by a Nobel Prize, but such a discovery now ought to be punished by a $10,000 fine ».



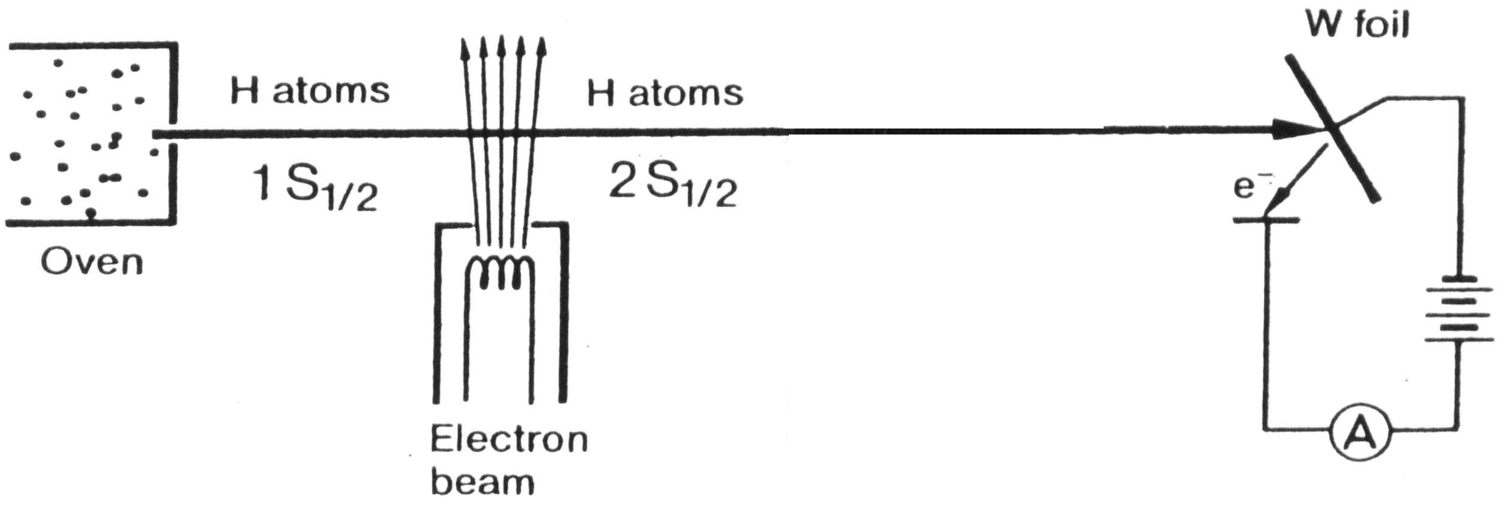
Willis Eugene Lamb
1913-2008
American physicist

http://www.nobelprize.org/nobel_prizes/physics/laureates/1955/lamb-lecture.html#

Lamb shift measurement (1947)

- **Basic idea:** produce beam of hydrogen atoms in the metastable 2S state by bombarding ground state atoms with electrons.

$$\tau_{2S} \simeq 10^8 \text{ns} = 100 \text{ ms}$$



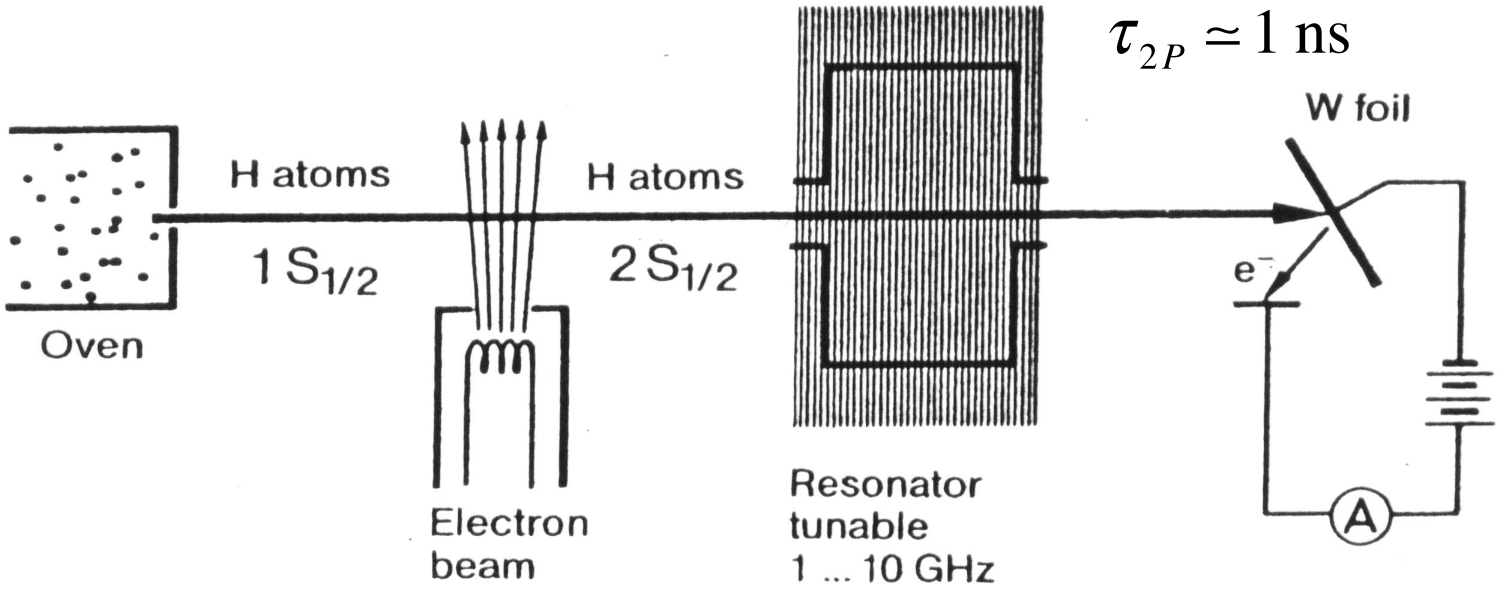
$I \propto$ "2S rate"

- The atoms in the 2S impinging on metal surface release electrons that can be detected with an electrometer while this process does not occur for the atoms in the ground state (1S).

Lamb shift measurement (1947)

- **RF field:** on resonance frequency induce transition from the 2S to the 2P state.

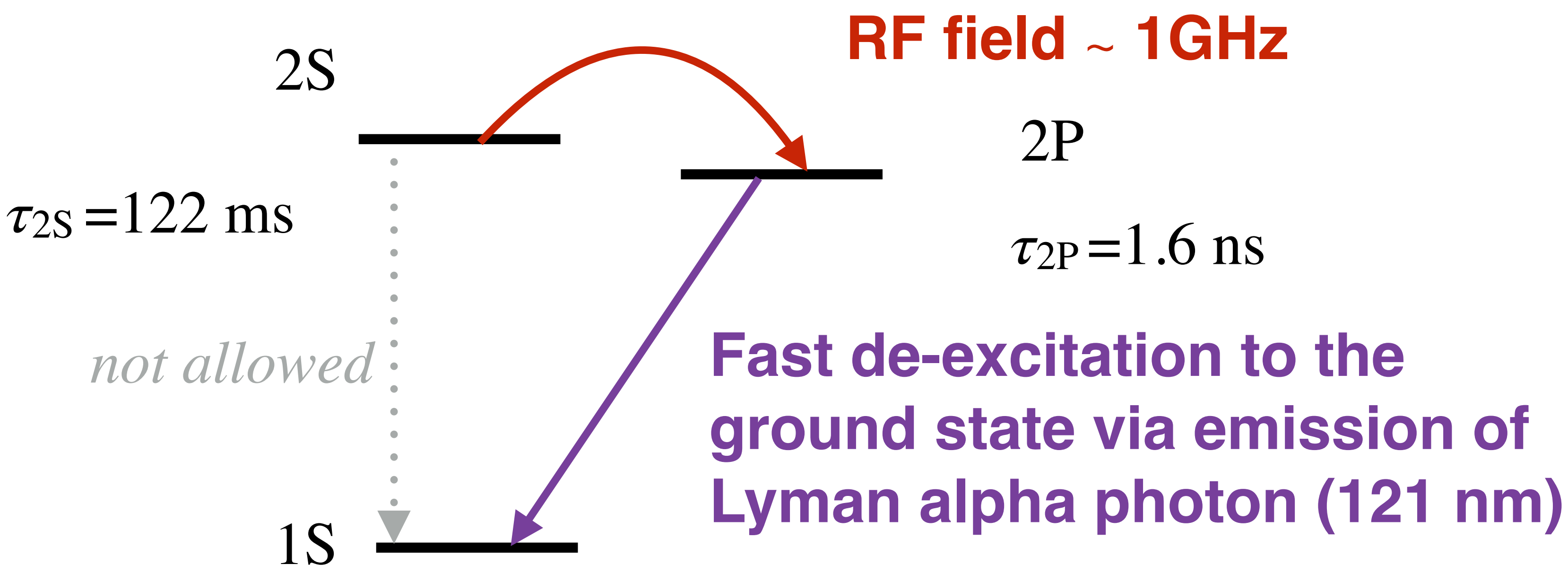
$\tau_{2P} \simeq 1$ ns



I ∝ "2S rate"

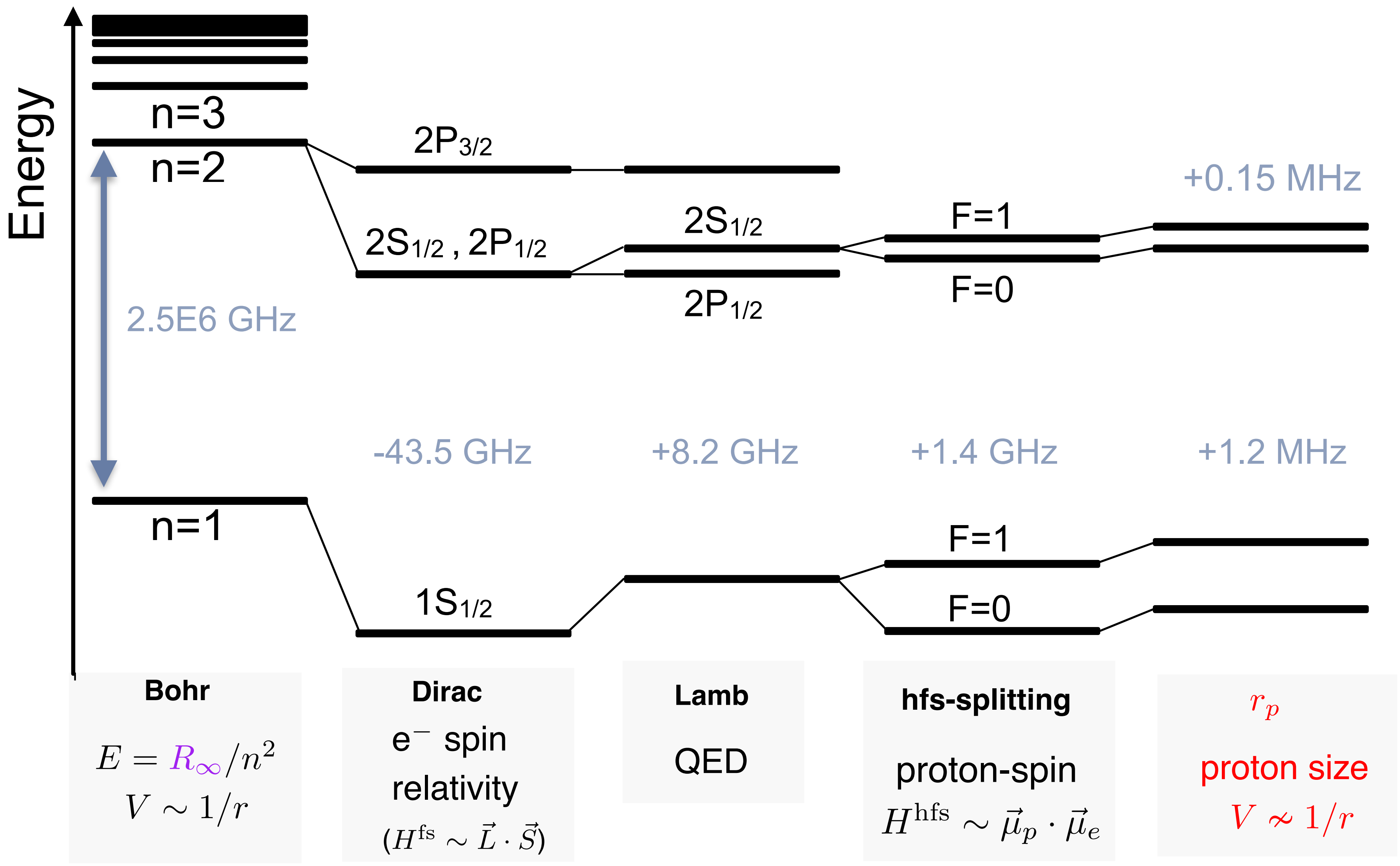
- The 2P state decays quickly to the 1S → signal in the electrometer will decrease

Lamb shift measurement (1947)



RESONANCE : Applying the correct RF field at the resonance frequency one can induce transition from the 2S to the 2P state. The 2P state decays quickly to the ground state (in about 1 ns) and therefore the signal in the electrometer will decrease.

Hyperfine splitting and nuclear effects

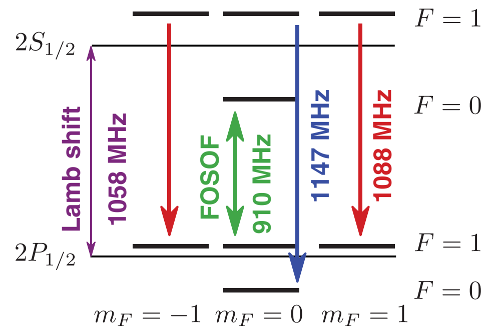


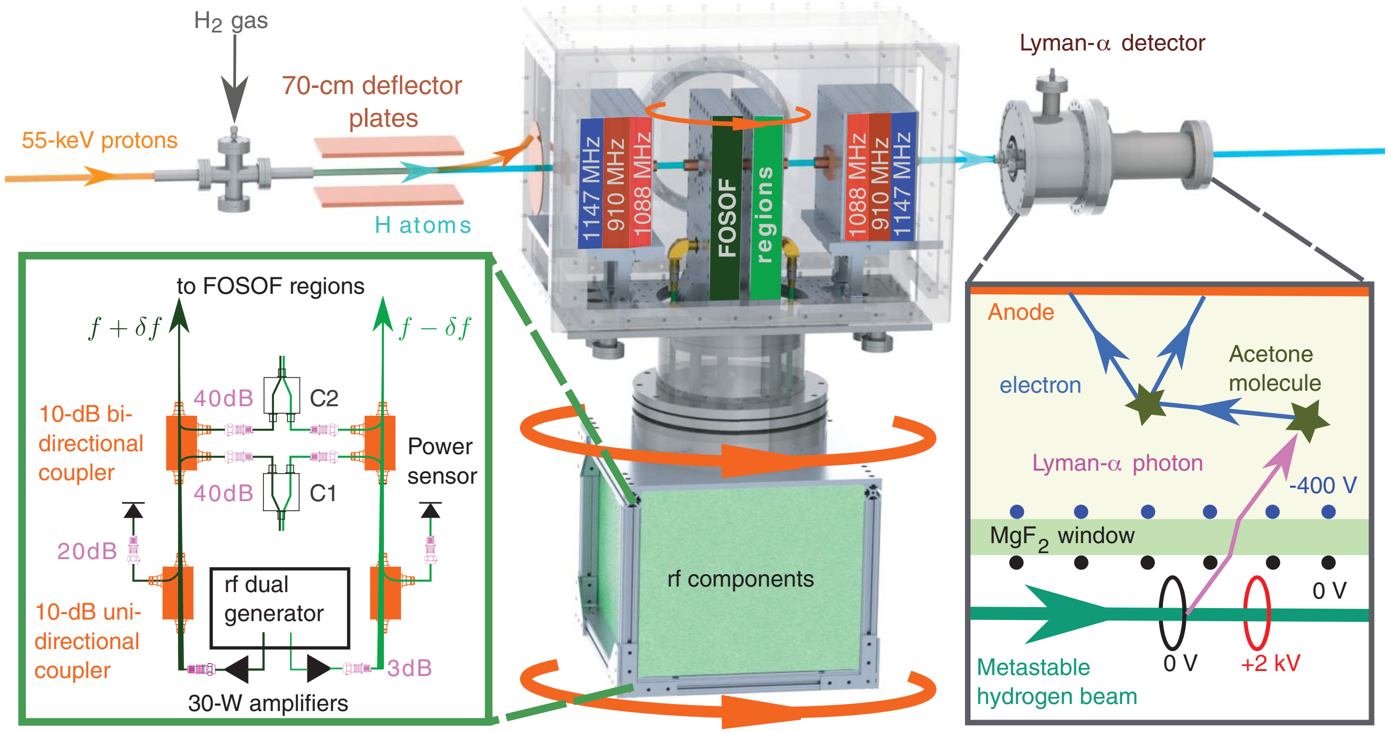
Lamb shift 2019

A measurement of the atomic hydrogen Lamb shift and the proton charge radius

N. Bezginov[1], T. Valdez[1], M. Horbatsch[1], A. Marsman[1], A. C. Vutha[2], E. A. Hessels[1,*]
+ See all authors and affiliations

Science 06 Sep 2019:
Vol. 365, Issue 6457, pp. 1007-1012
DOI: 10.1126/science.aau7807





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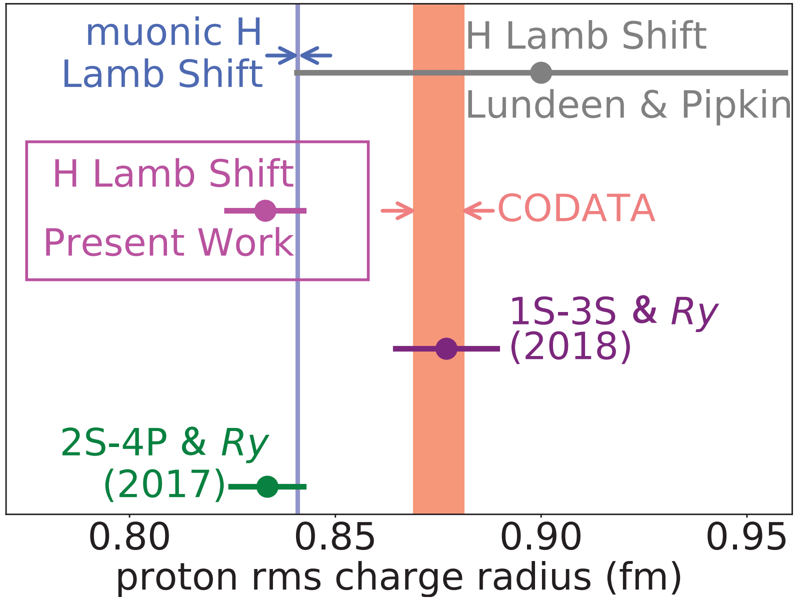
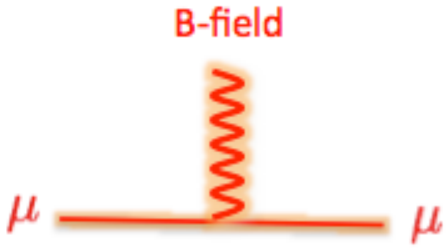


The anomalous magnetic moment

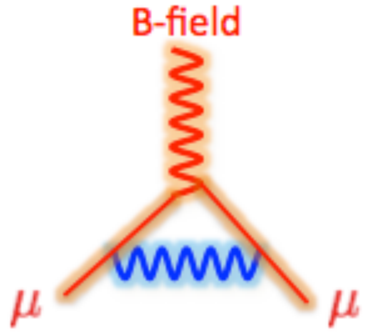
Dirac theory predicts a *g*-factor of $g_{Dirac} = 2$

Magnetic moment of a Dirac particle: $\vec{\mu}_{Dirac} = g_{Dirac}\mu_B\vec{S}$

Interaction of magnetic moment with external magnetic field $\vec{\mathrm{B}}$ with ***g* = 2:** consequence of Dirac equation



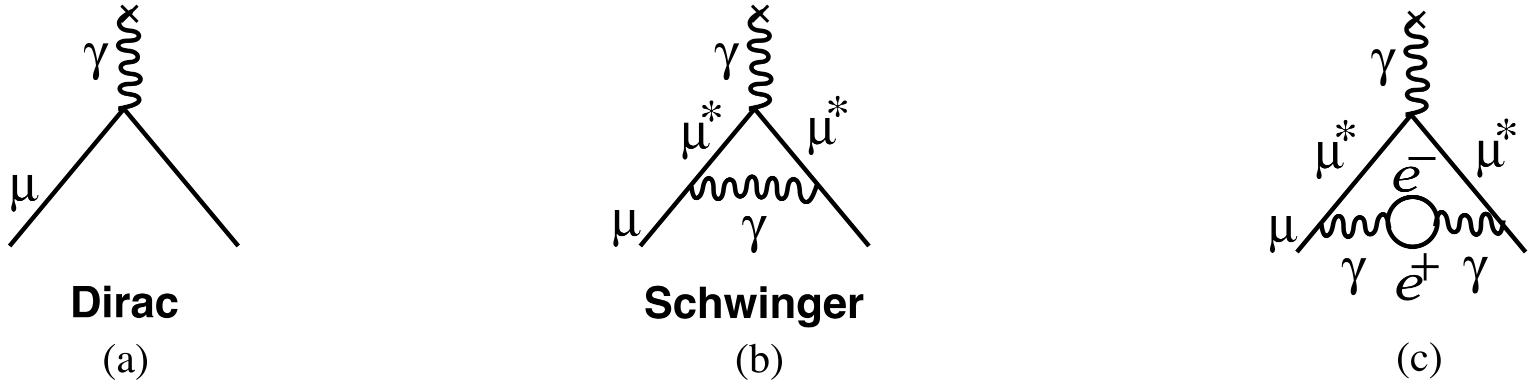
"Dirac Interaction"
g=2



QED "Schwinger Interaction"
(g-2)=α/π

BUT QED *radiative corrections alter this result* which is *true only for a "bare" point-like Dirac particle!*

Adding more corrections…

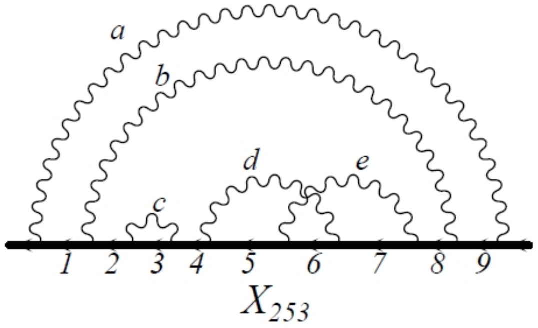


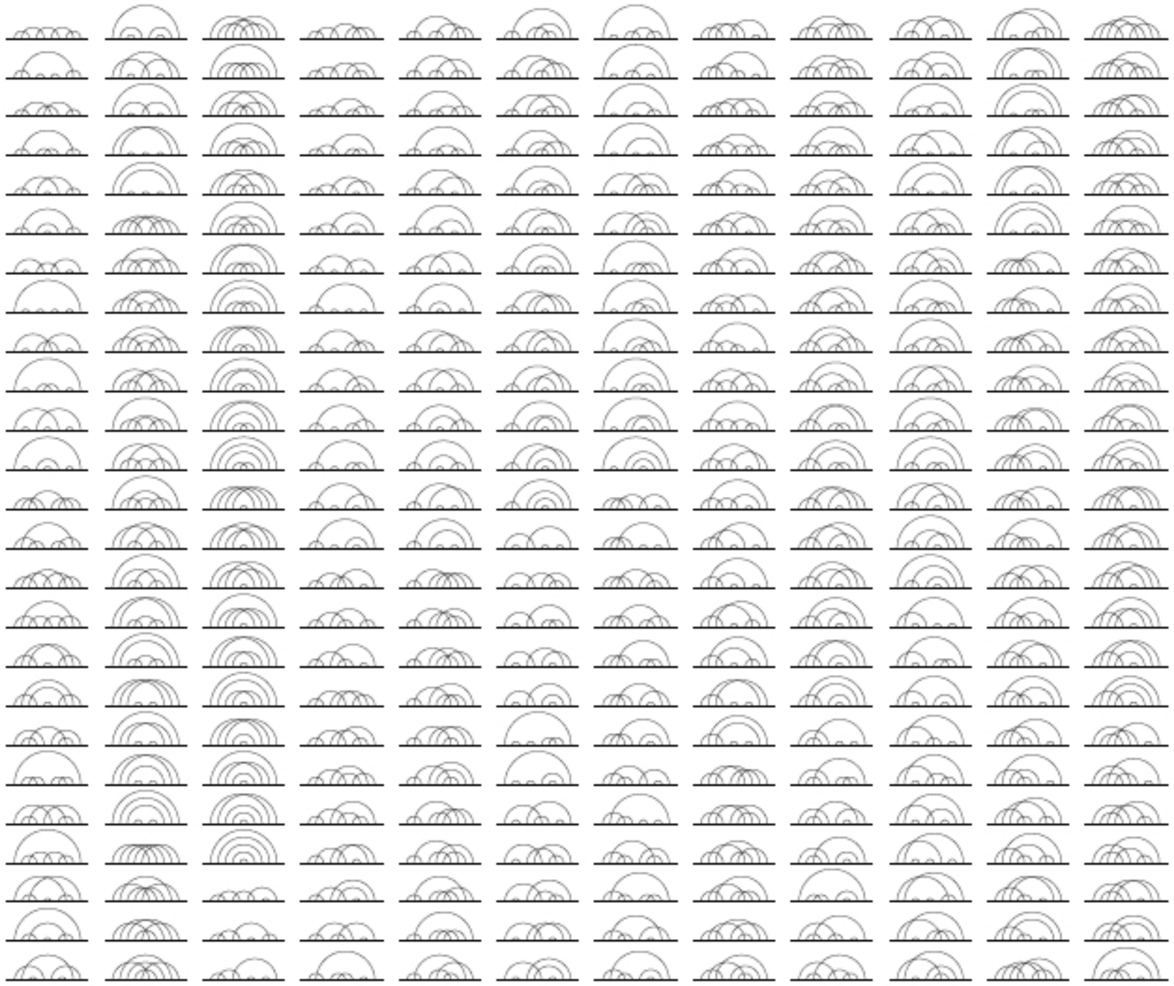
- Dyson (1949) showed that Schwinger's theory could be extended to permit calculation of higher-order corrections to the properties of quantum systems. Dyson was able to simplify the procedure, devise an unambiguous program for obtaining the nth-order contribution to **any quantity which can be calculated using QED**, and show that these contributions would remain finite to arbitrary order in α, e.g.

$$a_e(theo) = A_E\left(\frac{\alpha}{\pi}\right) + B_e\left(\frac{\alpha}{\pi}\right)^2 + C_e\left(\frac{\alpha}{\pi}\right)^3 + D_e\left(\frac{\alpha}{\pi}\right)^4 + E_e\left(\frac{\alpha}{\pi}\right)^5 + \ldots$$

…and few ten thousands more ….

For example: few of the ten thousand diagrams evaluated for the electron g-2





…and few ten thousands more ….

Physics Letters B
Volume 772, 10 September 2017, Pages 232-238

High-precision calculation of the 4-loop contribution to the electron g-2 in QED

Stefano Laporta ✉

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https://doi.org/10.1016/j.physletb.2017.06.056   Get rights and content

Abstract

I have evaluated up to 1100 digits of precision the contribution of the 891 4-loop Feynman diagrams contributing to the electron g-2 in QED. The total mass-independent 4-loop contribution is

$$a_e = -1.912245764926445574152647167439830054060873390658725345\ldots\left(\frac{\alpha}{\pi}\right)^4 .$$

I have fit a semi-analytical expression to the numerical value. The expression contains harmonic polylogarithms of argument $e^{\frac{i\pi}{3}}$, $e^{\frac{2i\pi}{3}}$, $e^{\frac{i\pi}{2}}$, one-dimensional integrals of products of complete elliptic integrals and six finite parts of master integrals, evaluated up to 4800 digits.

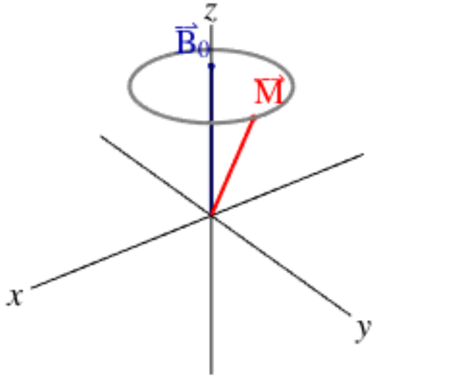
Table 1. First 1100 digits of $a_e^{(4)}$.

–1.9122457649264455741526471674398300540608733906587253451713298480060
3844398065170614276089270000363158375584153314732700563785149128545391
9028043270502738223043455789570455627293099412966997602777822115784720
3390641519081665270979708674381150121551479722743221642734319279759586
0740500578373849607018743283140248380251922494607422985589304635061404
9225266343109442400023563568812806206454940132249775943004292888367617
4889923691518087808698970526357853375377696411702453619601349757449436
1268486175162606832387186747303831505962741878015305514879400536977798
3694642786843269184311758895811597435669504330483490736134265864995311
6387811743475385423488364085584441882237217456706871041823307430517443
0557394596117155085896114899526126606124699407311840392747234002346496
9531735482584817998224097373710773657404645135211230912425281111372153
0215445372101481112115984897088422327987972048420144512282845151658523
6561786594592600991733031721302865467212345340500349104700728924487200
6160442613254490690004319151982300474881814943110384953782994062967586
7875385249781946989793132162197975750676701142904897962085050785592…

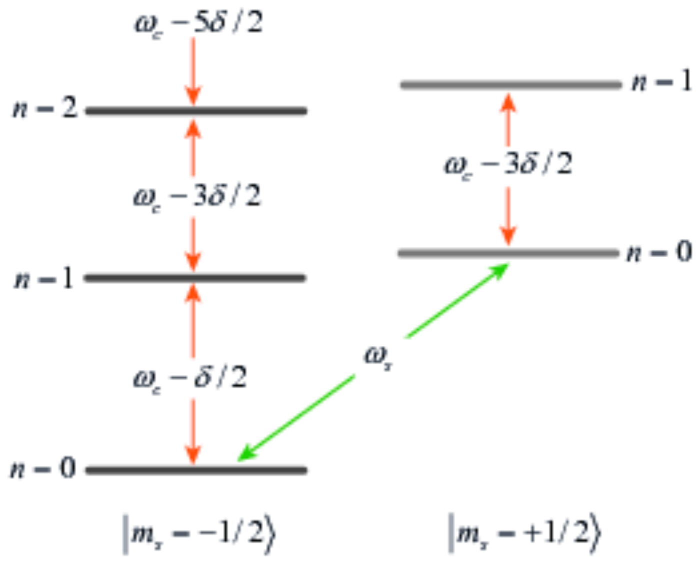
Measurement of the anomalous magnetic moment

Two distinct experimental techniques developed to precisely measure the g-factor:

(1) **“precession experiments”**: direct observation of spin precession of polarized electrons or **muons** in a magnetic field;



(2) **“resonance experiments”:** oscillating electromagnetic field inducing transitions between energy levels of the **electron** interacting with a static magnetic field.



Precession experiments

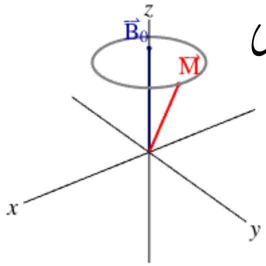
Particle of rest mass *m* and charge *e* moves with velocity $\vec{v}$ in a constant magnetic field $\vec{B}$. The **orbital motion** is a uniform rotation at the **cyclotron frequency**

$$\omega_c \equiv \frac{\omega_0}{\gamma} \quad \text{where} \quad \omega_0 \equiv \frac{eB}{m}$$

relativistic correction

Joseph Larmor (1857-1942) Northern Irish physicist and mathematician

Spin motion, as viewed from the laboratory frame, is a **uniform Larmor precession** at the frequency



$$\omega_s = \frac{g}{2}\gamma\omega_c + (1-\gamma)\omega_c$$

precession for a particle at rest

Thomas precession frequency due to acceleration of the circular motion.

Llewellyn Hilleth Thomas (1903-1992), British physicist and applied mathematician

Precession experiments - relative precession

- We consider the **relative precession frequency** of the spin relative to the cyclotron:

spin cyclotron

$$\omega_D \equiv \omega_s - \omega_c$$

- We have: $$\omega_D = \frac{g}{2}\gamma\omega_c + (1-\gamma)\omega_c - \omega_c = \left(\frac{g}{2} - 1\right)\gamma\omega_c$$

- Using $\omega_c \equiv \frac{\omega_0}{\gamma}$ we have: $$\omega_D = \left(\frac{g}{2} - 1\right)\gamma\frac{eB}{\gamma m} \equiv a\omega_0$$

where we define the **anomalous magnetic moment:**

$$a \equiv \frac{g}{2} - 1 = \frac{(g-2)}{2}$$

No Lorentz factor!

Anomalous magnetic moment

- We have found that the **anomalous magnetic moment** can be measured from the relative precession frequency:

$$\omega_D \equiv a\omega_0 \qquad\qquad a \equiv \frac{g}{2} - 1 = \frac{(g-2)}{2}$$

For a point-like Dirac particle: g = 2 → a_{Dirac} = 0!

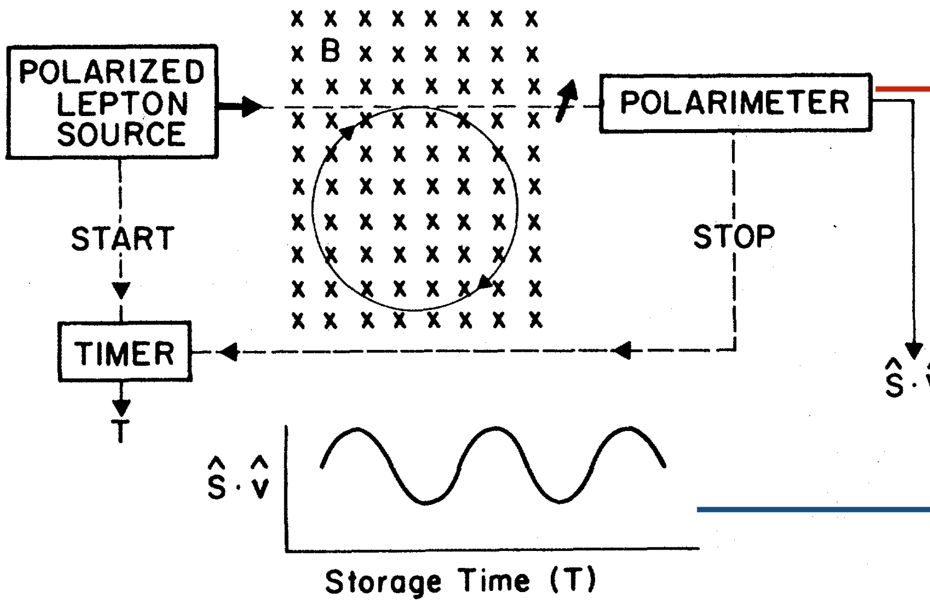
This is great but what makes this result even more fantastic is that the relative precession frequency is **independent of γ** → ***a*** **can be measured without first order correction to the velocity.**

$$\omega_0 \equiv \frac{eB}{m}$$

Lorentz factor affects identically cyclotron and spin precession!

Schematic of a precession experiment

Polarized source of electrons stored in constant magnetic field for a time T after which they are analysed by a polarimeter.



measures the amount of polarization $\vec{S}\cdot\vec{n}$ relative to fixed direction $\vec{n}$.

Output of the polarimeter oscillates as a function $\sim \cos\omega_D T \rightarrow \omega_D$

Accuracy $\sim T \rightarrow$ increase time particle spends in $\vec{B}$ field. In a real experiment, $\vec{B}$ never "exactly constant" and $\vec{E}$ fields necessary to guide particles in desired direction. Trajectory: Lorentz force plus spin precession (Bargmann-Michel-Telegdi equations)

Theory vs Experiment - electron

In order to match the current experimental precision $a_e(\alpha_{LKB2020}) = \frac{g_e - 2}{2} = 1{,}159{,}652{,}180.252\,(95) \times 10^{-12}.$

→ theoretical value up to fifth term in the Dyson expansion since $(\alpha/\pi)^5 \simeq 0.07 \times 10^{-12}$.

At this level of precision contributions from three types of interactions: **electromagnetic, hadronic, and electroweak**.

4th term: 891 Feynman diagrams , 5th term: 12672 diagrams (evaluated numerically)

$$a_e(theo) = 0.001159652181643(25)_{D_e}(23)_{E_e}(16)_{hadr+EW}(763)_{\alpha}$$

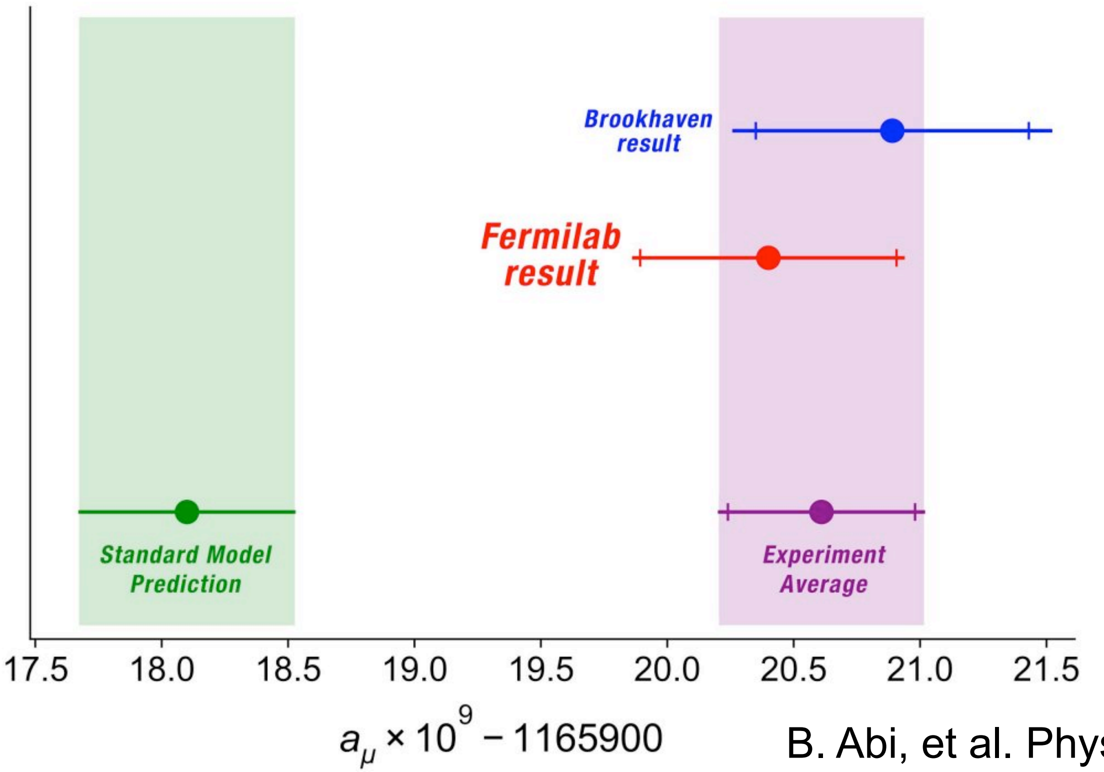
uncertainty from 5th order QED calculations

hadronic and weak contributions

uncertainty from determination of α

Today theory and experiment are in good agreement at this fantastic precision! Maybe with more precision some deviations from QED could hint at new physics at very high energy. But so far this is not the case.

Theory vs Experiment - muon



For the muon there is a 4 sigma discrepancy between the theoretical predictions and the experimental value.

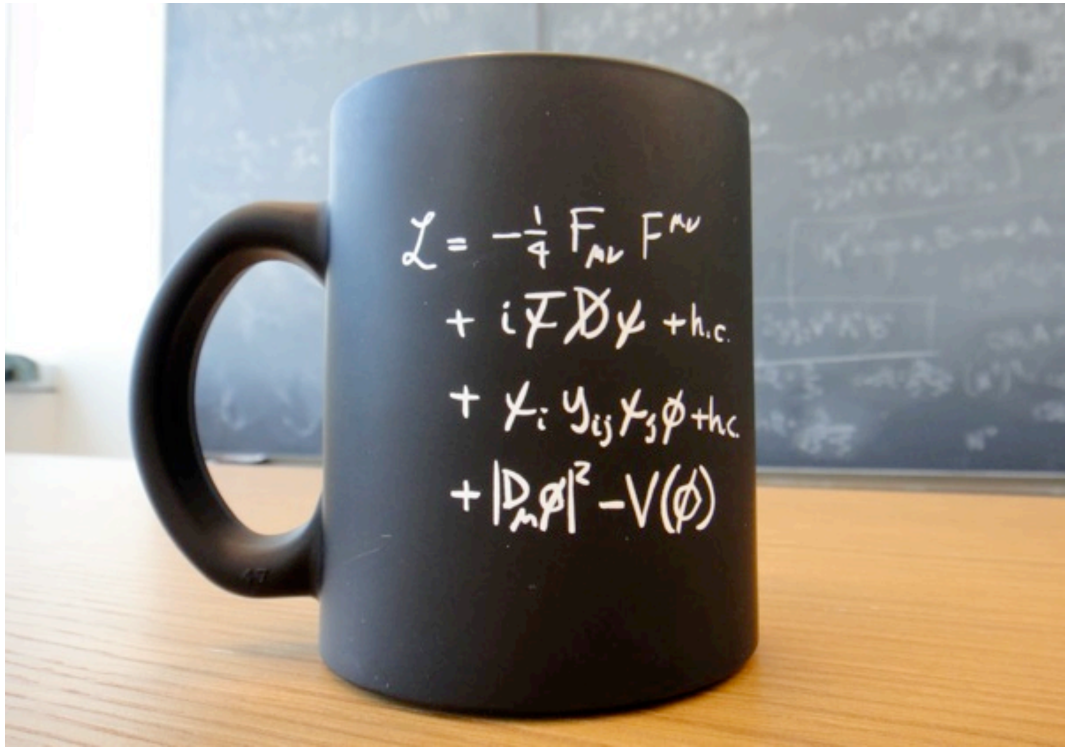
TO NOTE: Lattice QCD calculations S. Borsanyi et al. Nature 593 (2021) reduce discrepancy.

B. Abi, et al. Phys. Rev. Lett. 126, 141801 (2021)

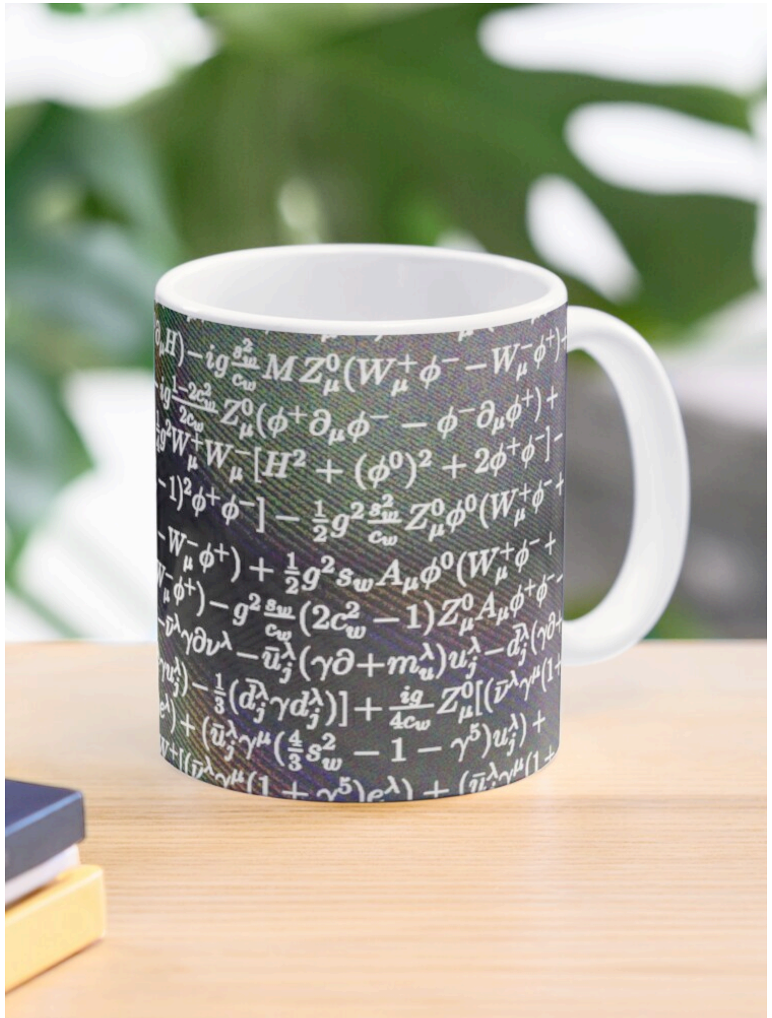
New physics (see later) or problem with calculation of hadronic corrections*?

*Hadronic corrections to be directly measured by MUonE EXP @ CERN G. Abbiendi. PoS ICHEP2020, 223 (2021)

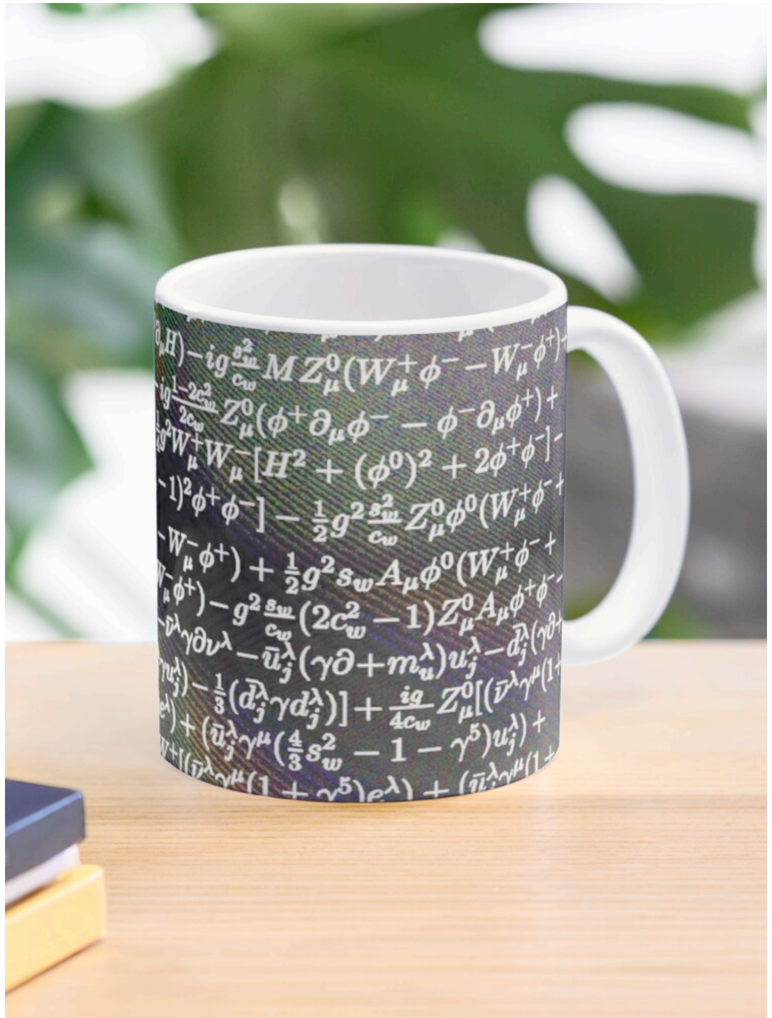
Back to the Standard Model…



How to fix the input parameters?



How many free parameters do we have in the Standard Model?



A) 18
B) 12
C) 26
D) 32

Free parameters in the Standard Model

- 6 quark masses
- 6 lepton masses
- Higgs mass + vacuum expectation value (v)
- 3 gauge couplings (e, $\sin^2\theta_W$, g_s),
- 3 CKM rotation angles, 1 CP violation phase,
- 3 PNMS rotation angles, 1 CP violation phase,
- θ parameter [strong CP violation]

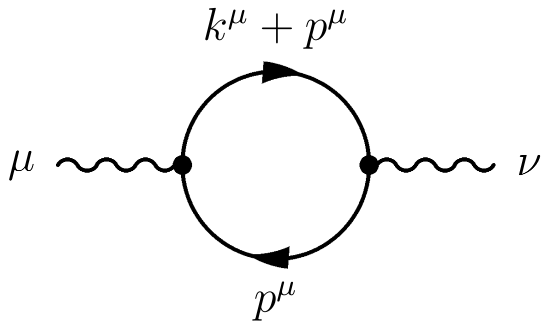
TOTAL: 26

Those **parameters are not predicted by the theory but need to be determined experimentally**! Many of them through low energy particle physics experiments!

Charge renormalization -> Running of the coupling of constants

- Problem for evaluation of loop or higher order diagrams → **divergent amplitudes**

E.g. photon propagator in QED



$$\Pi_{1L}^{\alpha\beta}(k) \propto \int d^4p \frac{p^2}{p^4} \propto \int d^4p \frac{1}{p^2} \propto \int p^3 \mathrm{d}p \frac{1}{p^2} \propto p^2 \to \infty$$

This is called the **ultra-violet divergence of QED**

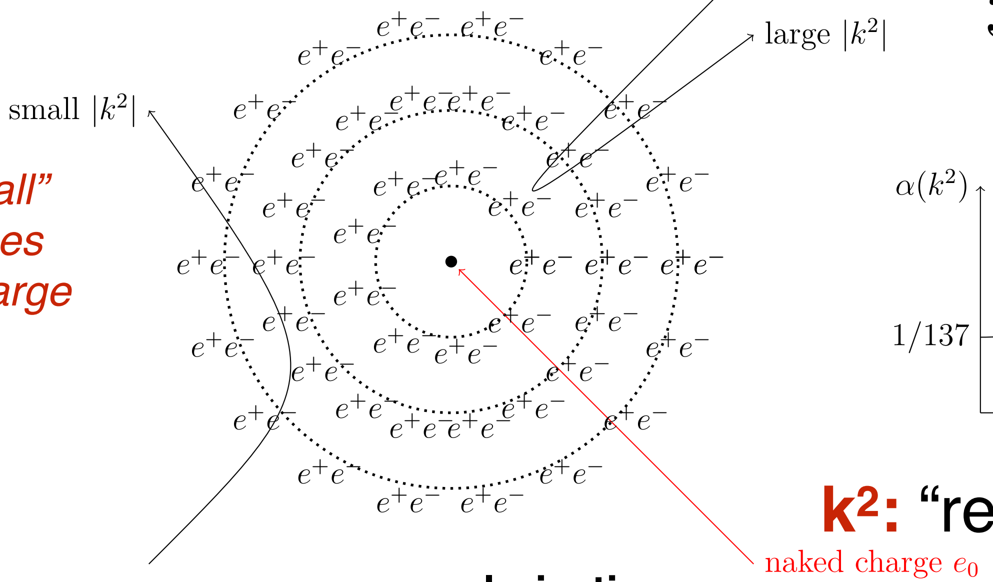
Running of the coupling of constant in QED

- **Renormalization:** divergent integrals regularized by absorbing them into definition of bare parameters of theory → new scale μ and higher order corrections for given scale Q^2 relative to μ

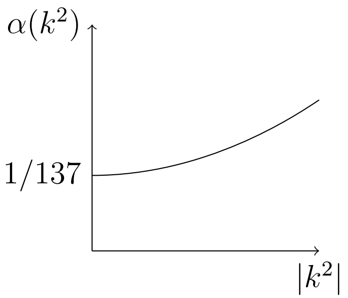
QED **Running of** α

$$\alpha(Q^2) = \frac{\alpha(\mu^2)}{1 - \frac{\alpha(\mu^2)}{3\pi}\ln\left(\frac{Q^2}{\mu^2}\right)}$$

At relatively "small" |k²|, photon probes the shielded charge



vacuum polarization



At "larger" |k²|, photon probes more of naked charge → electric charge we see increases with k²

k²: "resolution" of the probing photon ($\lambda \sim 1/p$)

Running of the coupling of constant in QED

Verified experimentally

★ In QED, running coupling **increases** very slowly

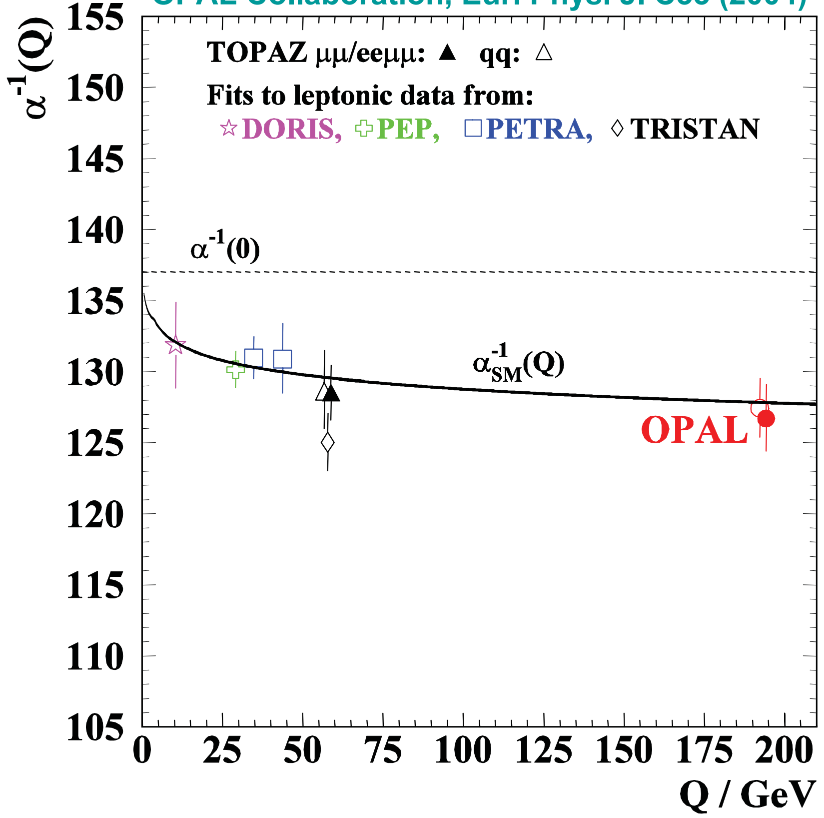
- Atomic physics: $Q^2 \sim 0$

$$1/\alpha = 137.03599976(50)$$

- High energy physics:

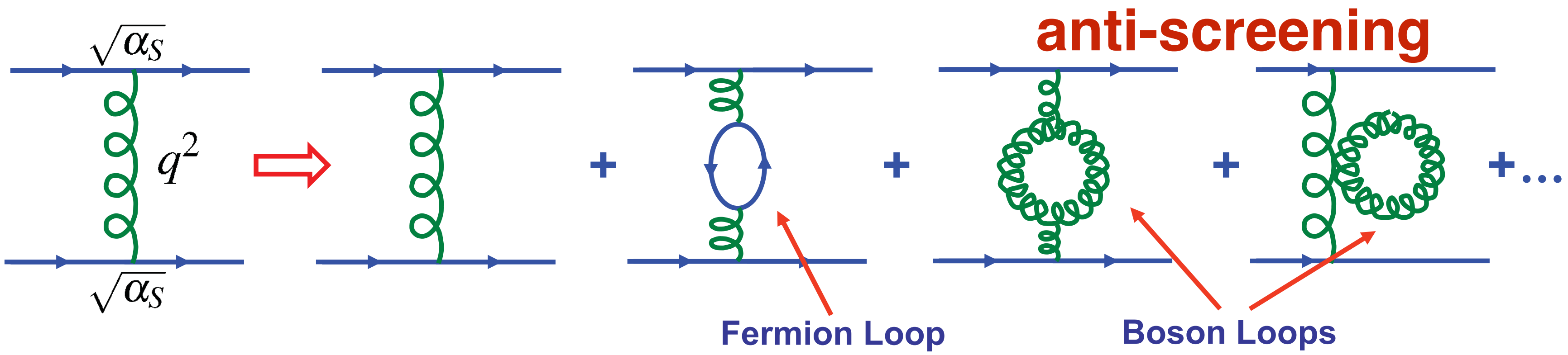
$$1/\alpha(193\,\mathrm{GeV}) = 127.4 \pm 2.1$$

OPAL Collaboration, Eur. Phys. J. C33 (2004)



Running of the coupling of constant in QCD

QCD Similar to QED but also have gluon loops



- **Fermionic and bosonic enter with opposite sign! Competing contributions in total amplitude!**

Running of α_s

$$\alpha_s(Q^2) = \frac{\alpha_s(\mu^2)}{1 + \alpha_s(\mu^2)\frac{\beta_0}{4\pi}\ln\left(\frac{Q^2}{\mu^2}\right)}$$

$$\beta_0 = \frac{11N_C - 2N_f}{3}$$

N_c = no. of colours
N_f = no. of quark flavours

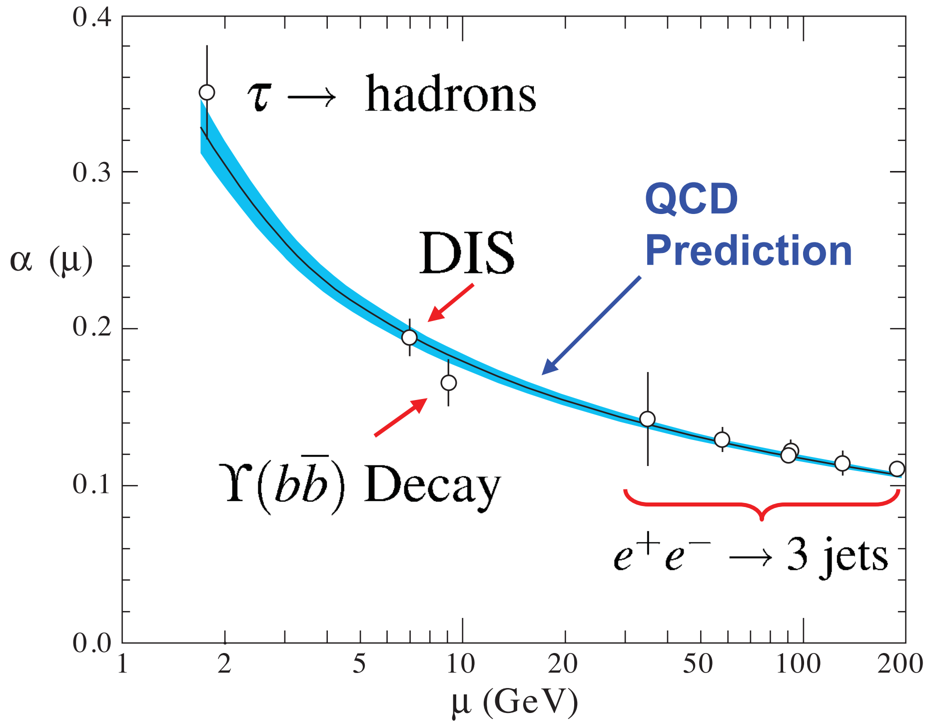
Running of the coupling of constant in QCD

For $N_C = 3$ and $N_f \leq 16$ quarks, $\beta_0 > 0$ and hence α_s *decreases* with increasing Q^2. This is also very well experimentally verified.

★ **Measure α_s in many ways:**

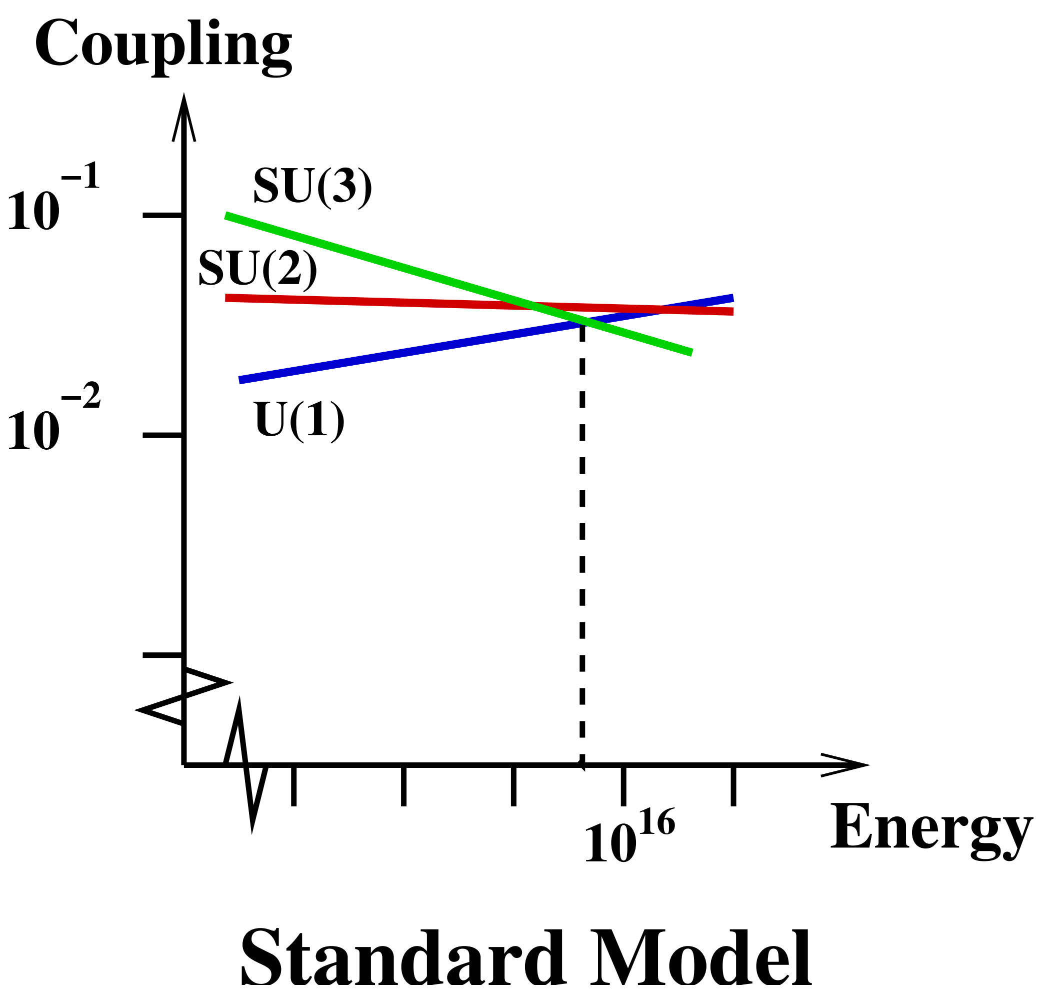
- **jet rates**
- **DIS**
- **tau decays**
- **bottomonium decays**
- **+…**

✶ **As predicted by QCD, α_s decreases with Q^2**



Running of the coupling of constants

- QED coupling constant grows with energy
- Other forces (strong and weak) behave in an opposite way, due to self gauge couplings (they are asymptotically free)
- Opens the possibility that coupling constants “merge” (unify!) at high energy and be represented by a single unified force.



Einstein's dream: unify all forces!

VOLUME 32, NUMBER 8 PHYSICAL REVIEW LETTERS 25 FEBRUARY 1974

Unity of All Elementary-Particle Forces

Howard Georgi* and S. L. Glashow
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 10 January 1974)

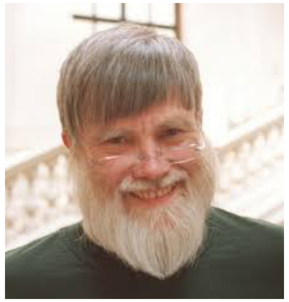
Strong, electromagnetic, and weak forces are conjectured to arise from a single fundamental interaction based on the gauge group SU(5).

It makes just one easily testable prediction, $\sin^2\theta_w = \frac{3}{8}$. It also predicts that the proton decays—but with an unknown and adjustable rate.

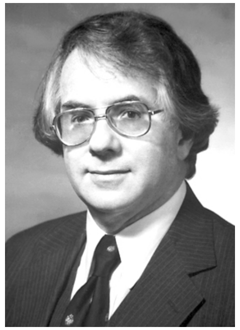
Other work of this era:

Pati and Salam: Is Baryon Number Conserved? PRL 31, 661 (1973)

Georgi, Quinn, and Weinberg: PRL 33, 451 (1974) proton lifetime ~ 6×10^{31} years.



Howard Mason Georgi
Born 1947



Sheldon Lee Glashow
Born 1932

Grand Unified Theory (GUT)

- Invariance under $G \supset SU(3) \times SU(2) \times U(1) \rightarrow 1$ gauge coupling
  $\rightarrow \sin^2\theta_W$ fixed

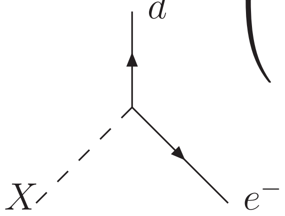
  Predictions: $\sin^2\theta_W = 0.20 \ldots 0.25$ & charge quantisation: $Q_{e^-} - 3Q_d = 0$

- Invariance: Leptons->Quarks and Quarks->Leptons

- All fermions in the same multiplet

$$5^* = \begin{pmatrix} d_1^c \\ d_2^c \\ d_3^c \\ --- \\ e^- \\ -\nu_e \end{pmatrix}_L \quad \begin{array}{l} \text{color–antitriplet} \\ \text{isosinglet} \\ \\ \text{color–singlet} \\ \text{isodoublet} \end{array}$$

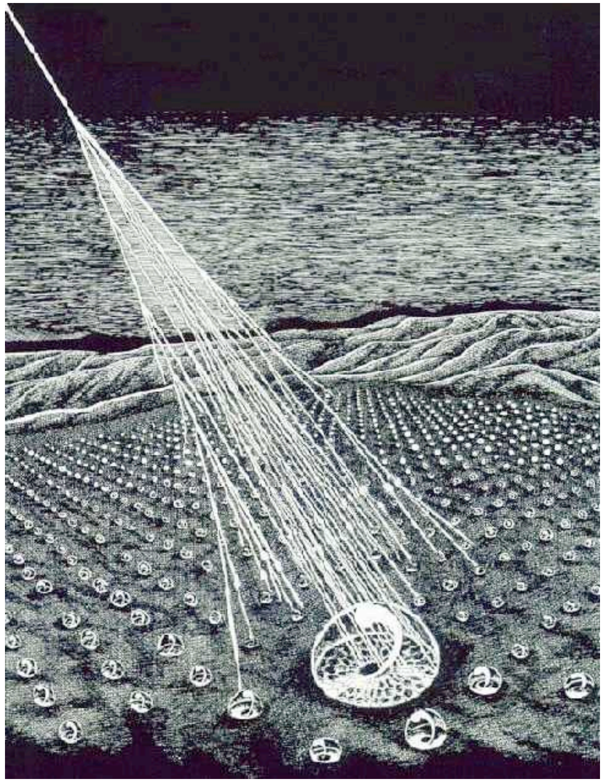
$$\left(\begin{array}{ccc|cc}
\frac{G^3}{\sqrt{2}} + \frac{G^8}{\sqrt{6}} - \frac{2B}{\sqrt{30}} & \frac{G^{1-i2}}{\sqrt{2}} & \frac{G^{4-i5}}{\sqrt{2}} & X_1^\dagger & Y_1^\dagger \\
\frac{G^{1+i2}}{\sqrt{2}} & -\frac{G^3}{\sqrt{2}} + \frac{G^8}{\sqrt{6}} - \frac{2B}{\sqrt{30}} & \frac{G^{6-i7}}{\sqrt{2}} & X_2^\dagger & Y_2^\dagger \\
\frac{G^{4+i5}}{\sqrt{2}} & \frac{G^{6+i7}}{\sqrt{2}} & -\sqrt{\frac{2}{3}}G^8 - \frac{2B}{\sqrt{30}} & X_3^\dagger & Y_3^\dagger \\
\hline
X_1 & X_2 & X_3 & \frac{W^3}{\sqrt{2}} + \frac{3B}{\sqrt{30}} & W^+ \\
Y_1 & Y_2 & Y_3 & W^- & -\frac{W^3}{\sqrt{2}} + \frac{3B}{\sqrt{30}}
\end{array}\right)$$



- New bosons $m_X = 10^{16}$ GeV

Can we reach GUT scale energies?

100 EeV Cosmic Ray

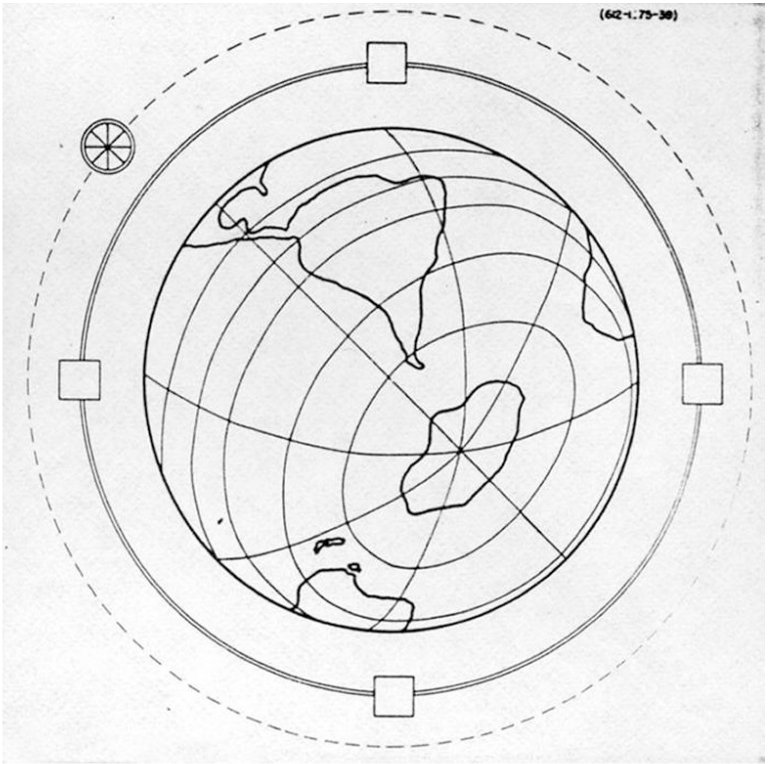


$E_{cm} = \sqrt{2 E m}$

$E \sim \sqrt{10^{20}\ \text{eV} \times 1\ \text{GeV}}$

$E \sim 10^6$ GeV

Enrico Fermi's Globatron



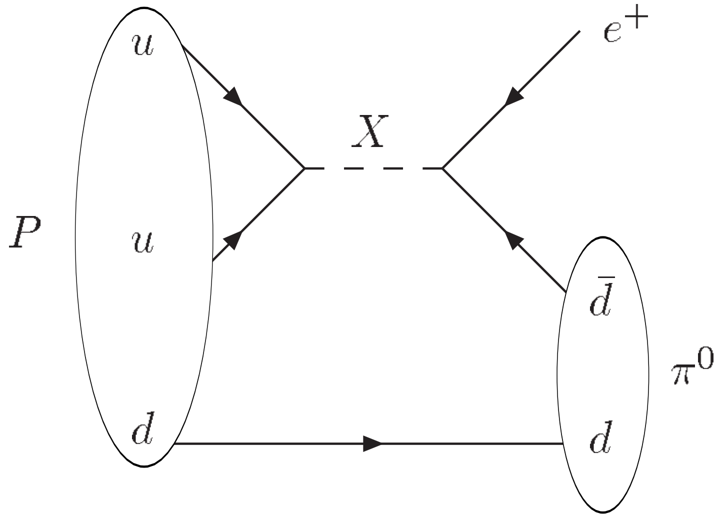
$p = 0.3\ B[T]\ r[m]$

$p \sim 100\ T \times 10^6\ m$

$E \sim 10^8$ GeV

Grand Unified Theory (GUT) -> Proton decay

- A possible proton decay



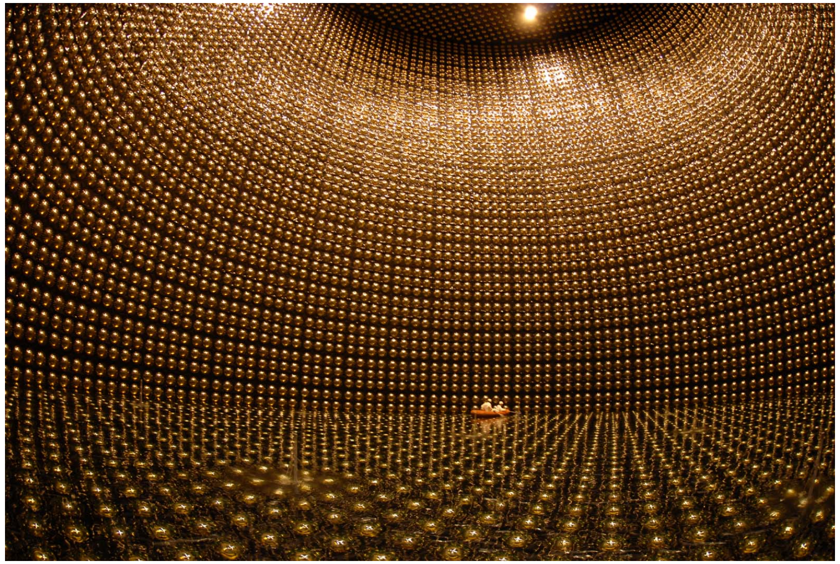
- Current experimental limit:

$\tau(N \to e^+ \pi)$

LIMIT (10^{30} years)	PARTICLE	CL%	EVTS	BKGD EST	DOCUMENT ID		TECN
>24000	p	90	0	0.59	[1] TAKENAKA	20	SKAM

From https://pdg.lbl.gov

- Superkamiokande (1996-): water Cherenkov detector with 22.5 kton fiducial volume: 7.5×10^{33} p

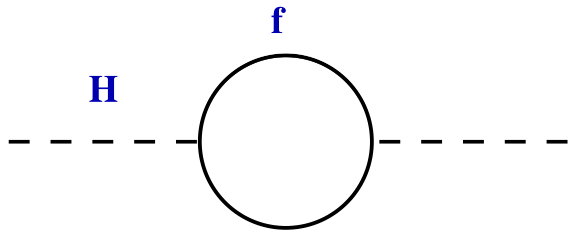


τ_1

Hierarchy Problem, fine tuning and naturalness

- The SM is only valid up at some energy scale Λ. Candidates for this scale are: O(10^{16} GeV) in GUT or the Planck scale O(10^{19}GeV).
- The one loop radiative corrections to the Higgs boson mass

$$\Delta m_H^2 = m_H^2 - m_{bare}^2 = \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \ldots$$



has a quadratic divergence ~ Λ^2 which can only be canceled by fine-tuning the bare mass term

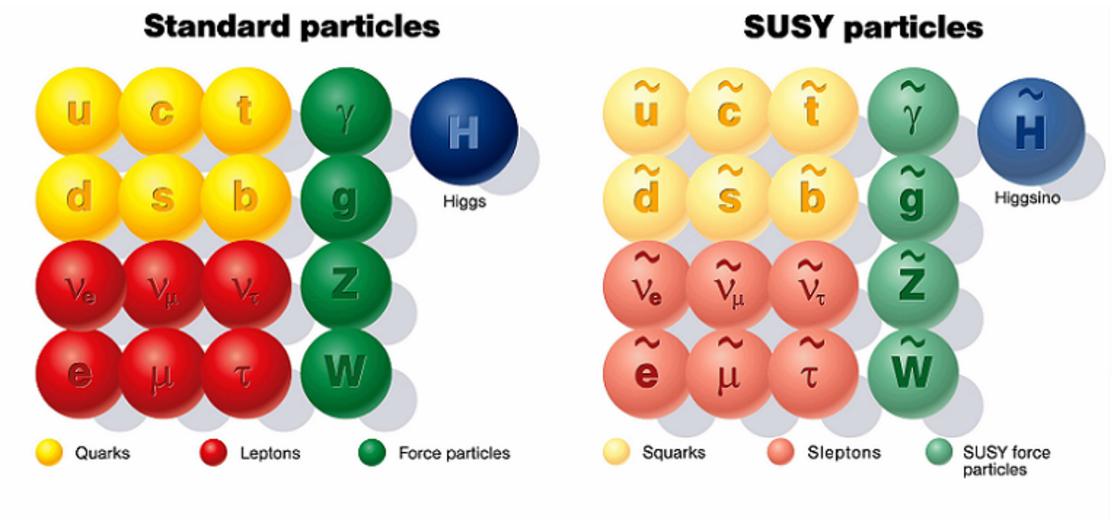
- For Λ at the Planck scale to get the measured Higgs mass of M_H=125 GeV, the bare mass should be 10^{34} x M_H
This fine-tuning seems to be unnatural and suggests new physics might play a role in compensating for the large corrections.

Supersymmetry (SUSY)

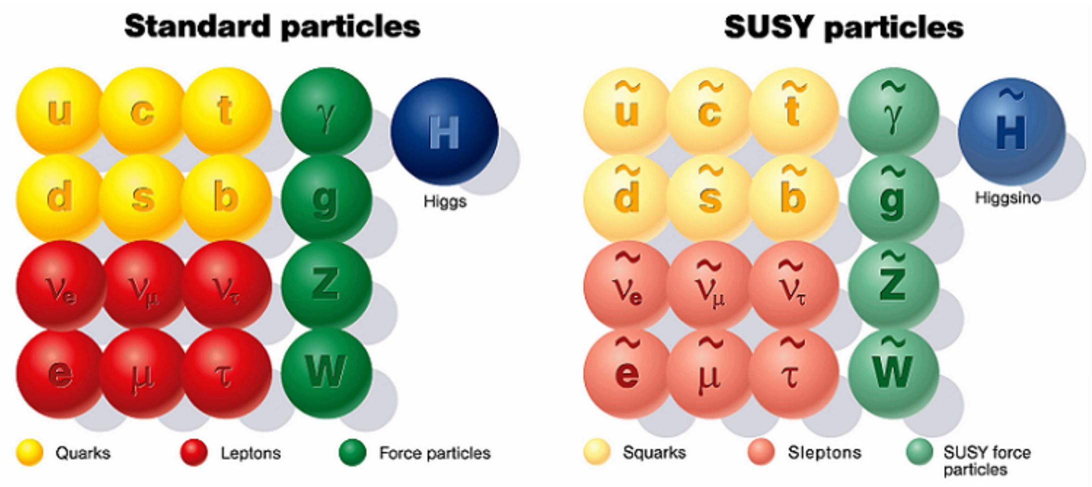
- SUSY: space-time symmetry mapping particles and fields of integer spin (bosons) into particles and fields of half integer spin (fermions), and viceversa.
  The generators Q act as

$$Q\,|fermion\rangle = |boson\rangle \qquad Q\,|boson\rangle = |fermion\rangle$$

  - Generators change the spin of a particle
  - Each particle has a super-partner



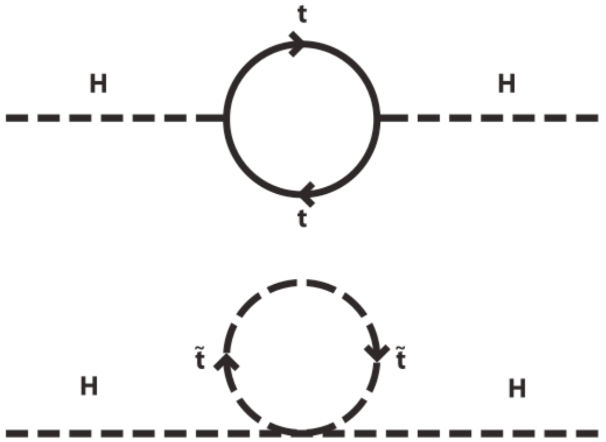
Supersymmetry (SUSY)



- **Doubling the number of elementary particles to solve problems seems to be unnatural** … but … **it is been done before!**
- The marriage of relativity and QM conceived **anti-matter**. As a result, the number of elementary particles doubled (Dirac and QFT).
- **Why is anti-matter needed in the Universe?**

Supersymmetry (SUSY) & the hierarchy problem

- **SUSY cures the hierarchy problem** in the following way: if SUSY were exact, radiative corrections to the scalar masses squared would be absent because the contribution of fermion loops exactly cancels against the boson loops



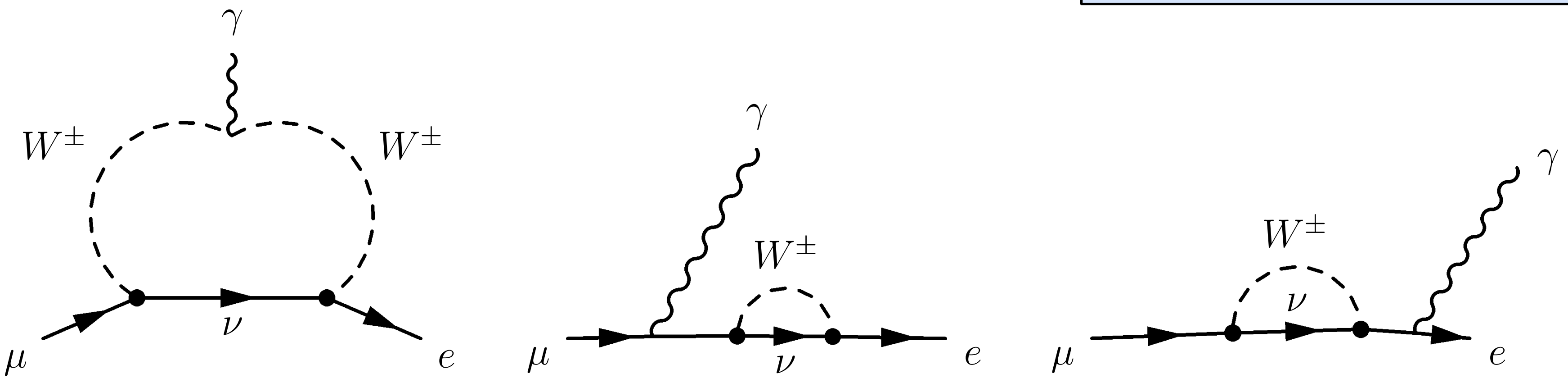
- Solution of hierarchy problem by low-energy SUSY masses **< O(1 TeV) + lightest supersymmetric particle (LSP) is stable, weakly interacting ➜ ideal DM candidate (see later…)**

- BUT sofar no signs of SUSY neither at LHC nor in direct detection experiments…..

The decay: $\mu \to e\gamma$

- **G. Feinberg (1963)**: but if $W^{\pm}$ boson exists →

$$Br(\mu \to e\gamma) \approx 10^{-4}$$



However, these processes would not happen if neutrinos associated to muons are different than neutrinos associated to electrons

$$\nu_e \neq \nu_\mu ?$$

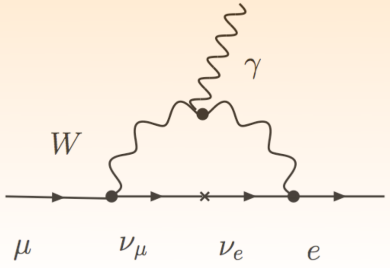
are there different types of neutrinos?

This pointed to a more "complex" scenario - not simply naive addition of IVB

μ→ eγ with neutrino oscillation

- In SM + ν-oscillation framework

$$\mathcal{P}_{\nu_l \to \nu_{l'}} = \quad |\langle \nu_{l'} | \nu_l \rangle|^2 = \left| \sum_i V_{li} V^*_{l'i} e^{-i(m_i^2/2E_i)/L} \right|^2 \neq 0$$



SM with massive neutrinos (Dirac)

$$\Gamma(\mu \to e\gamma) = \quad \approx \frac{G_F^2 m_\mu^5}{192\pi^3} \frac{\alpha}{2\pi} \sin^2 2\theta \, sin^2 \left(\frac{\Delta m^2 L}{4E} \right)$$

$$B(\mu^+ \to e^+\gamma) \approx 10^{-54}$$

- $\mu \to e\gamma$ not allowed in SM
  lepton flavor (number) conservation.

- ν-mixing gives rise to
  very small BR
  (BR not measurable)

[A. Antognini]

μ→ eγ : SUSY searches at the high intensity/low energy frontier

● In SUSY framework

- SU(5) SUSY-GUT and SO(10) SUSY-GUT models predict measureble LFV decay BR
- Null results
  - precise test of established model
  - ruled out of speculative model

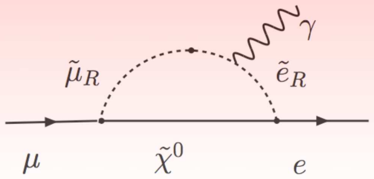
$$\Gamma(l_1 \to l_2\gamma) = \frac{\alpha G_F^2 m_{l_1}^5}{2048\pi^4}(|D_R|^2 + |D_L|^2)$$

$$D_R = D_L \approx \frac{1}{G_F \Lambda^2}$$

$$\Lambda \geqslant 340 \text{ TeV}$$

with current BR ($\mu^+ \to e^+ \gamma$)

SU(5) SUSY-GUT o SO(10) SUSY-GUT



$$10^{-14} < B(\mu^+ \to e^+\gamma) < 10^{-11}$$

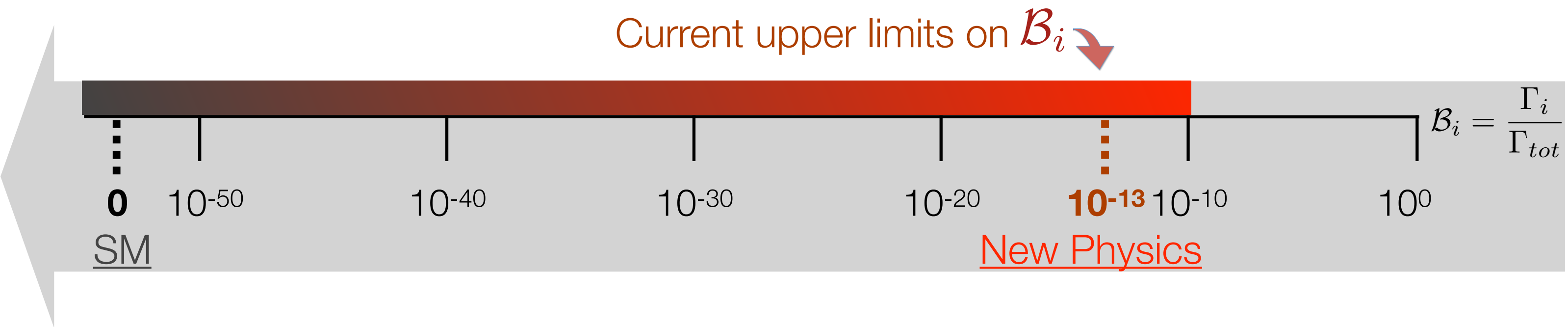
- In SUSY models BR may be measurable

Sensitivity up to 500 TeV

Very rare events:

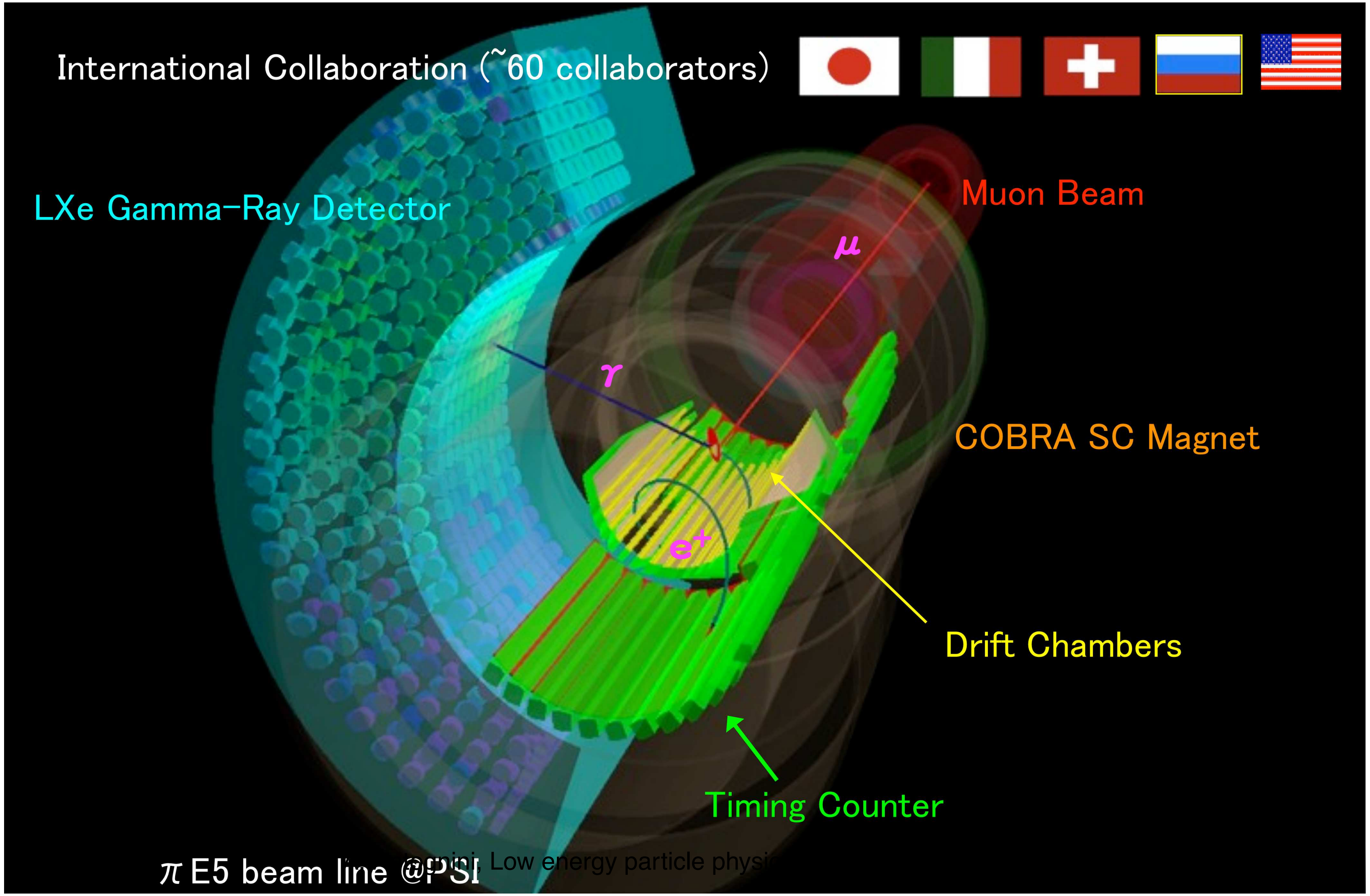
if BR$\sim 10^{-11} \to\sim 10^{13}$ μ^+ needed

$\to$ Intensity frontier

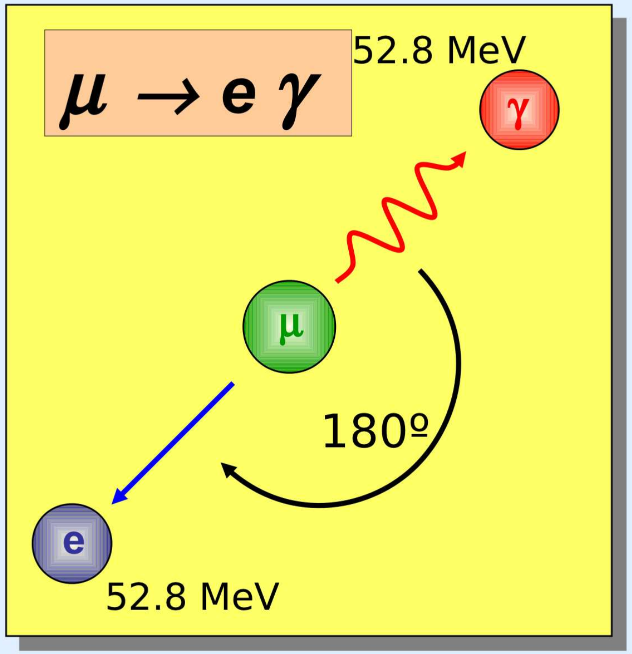


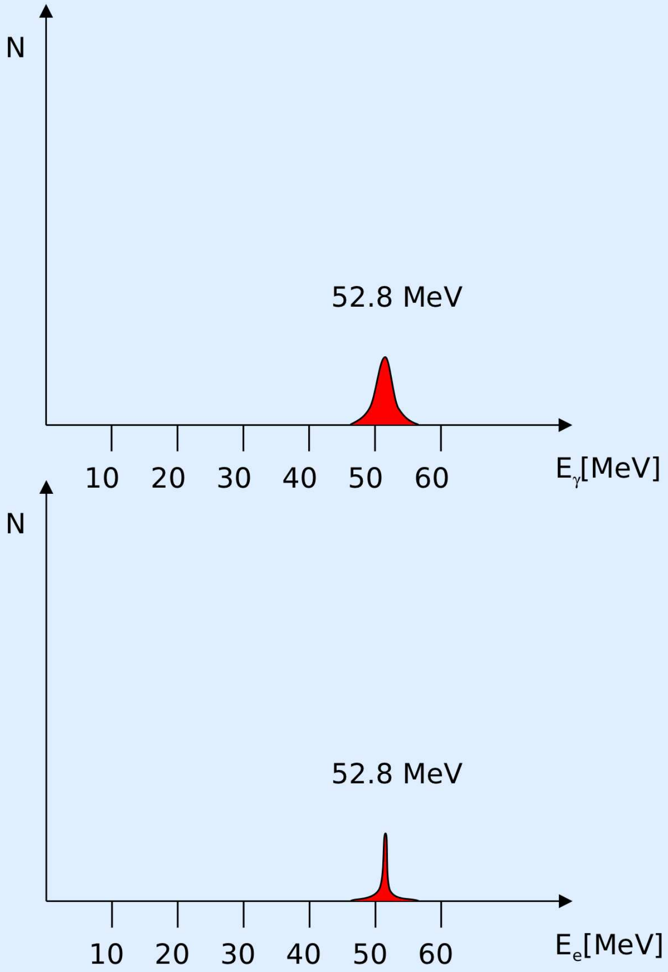
[A. Antognini]

The MEG experiment at PSI



MEG- Decay topology





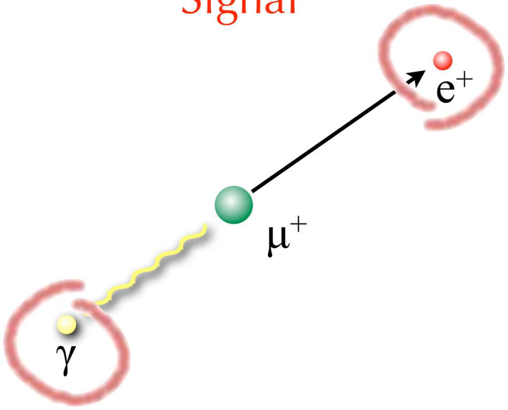
μ → e γ signal very clean

- $E_g = E_e$ = 52.8 MeV
- $\theta_{\gamma e}$ = 180º
- e and γ in time

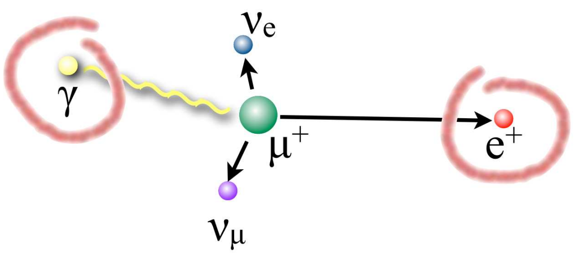
[S. Ritt]

MEG- Signal vs BKG decay topology

"Signal"

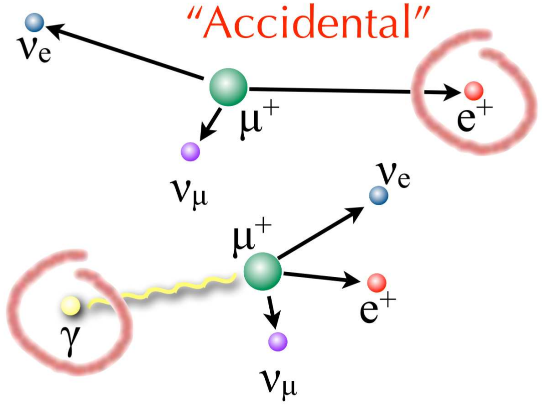


"RMD"



$$\mu \to e\bar{\nu}\nu\gamma$$

"Accidental"



$$\mu \to e\bar{\nu}\nu$$

$$\mu \to e\bar{\nu}\nu\gamma$$

$$e\mathcal{N} \to e\mathcal{N}\gamma$$

$$e^+e^- \to \gamma\gamma$$

Ee = Eγ = 52.8 MeV

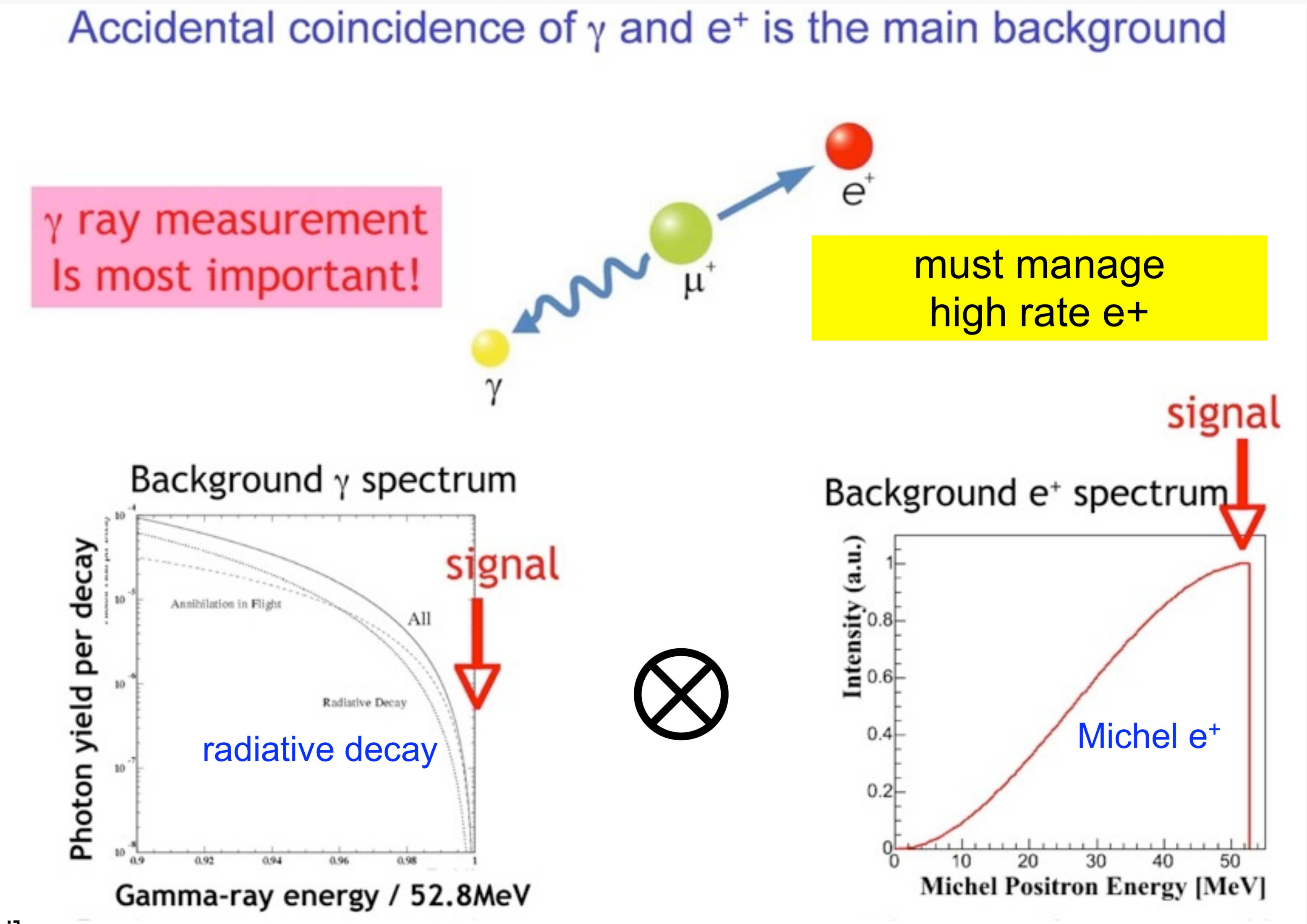
$\theta_{e\gamma} = 180^o$

$t_{e\gamma} \sim 0$

$$B_{\text{prompt}} \approx 0.1 \times B_{\text{acc}} \qquad B_{\text{acc}} \approx R_\mu^2 \Delta E_e \Delta E_\gamma^2 \Delta\theta^2 \Delta t$$

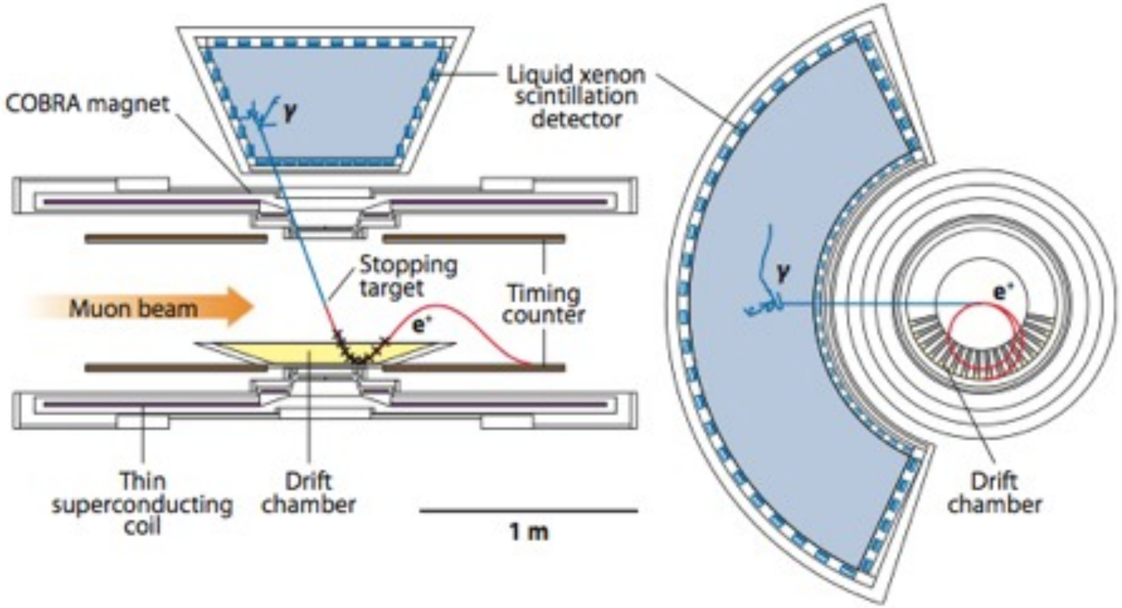
The accidental background is dominant and it is determined by the experimental resolutions

Accidental background



[T. Mori]

MEG setup



Detector OUTLINE

- **μ decay** at **rest**
  - *Beam rate:* ***3×10⁷ μ/s***
  - *μ stopped in* ***205 μm target***

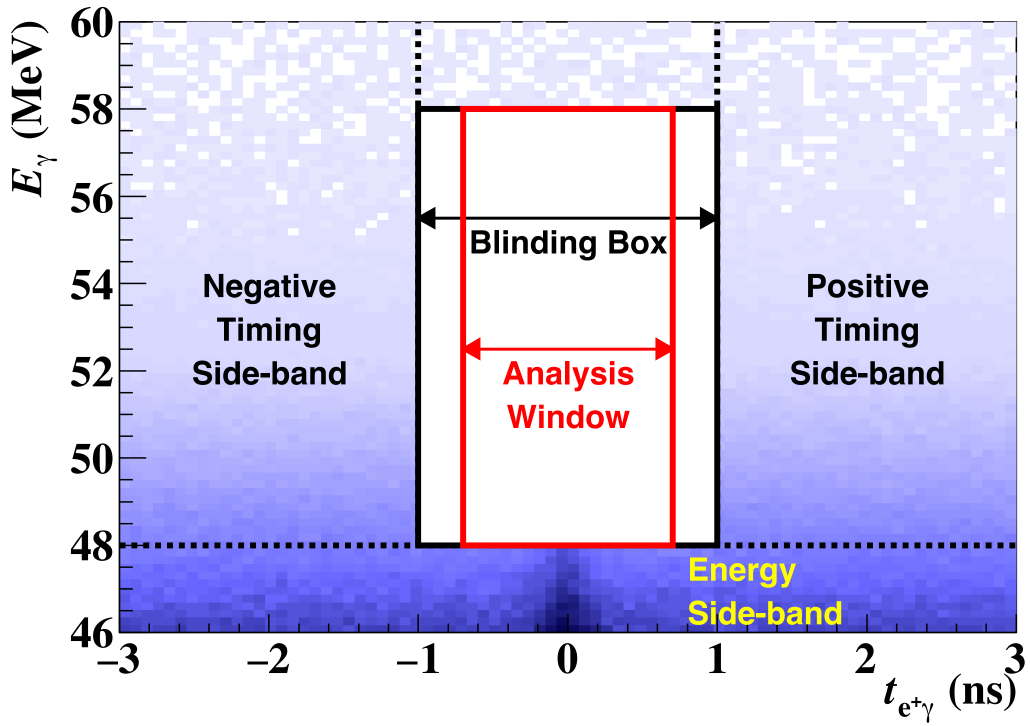
γ detection

- ***Liquid Xenon*** *calorimetry with* ***scintillation light***
  - **fast**: 4/22/45 ns
  - **high LY**: ~0.8 NaI
  - **short X_0**: 2.77 cm

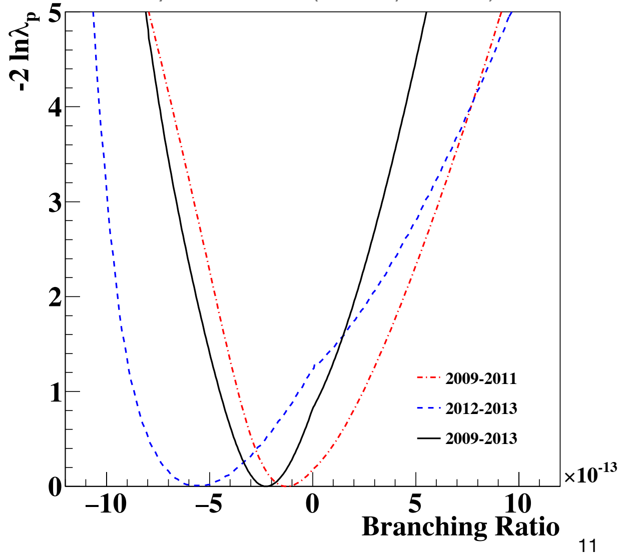
e^+ detection

- ***magnetic spectrometer***
  - **non-uniform B field → constant bending radius** and **e^+ swept rapidly away**
  - **ultra-thin drift chambers** to **limit matter effects (X_0 ~ 0.0003 per module)**
- ***TC detector***
  - **time of flight** with **plastic scintillator counters**
  - **transverse scintillation fibers → hit position**

MEG- Results



A. M. Baldini et al. (MEG Collaboration), Eur. Phys. J. C76 (2016) no. 8, 434



Full data sample: 2009-2013
Best fitted branching ratio at 90% C.L.:

$$\mathcal{B}(\mu^+ \to e^+\gamma) < 4.2 \times 10^{-13}$$

From MEGA to MEG:
improvement by a factor ~ 30

Systematic uncertainties: Target “alignment”: 5%
Other sources: < 1%

MEG upgrade

The MEGII experiment

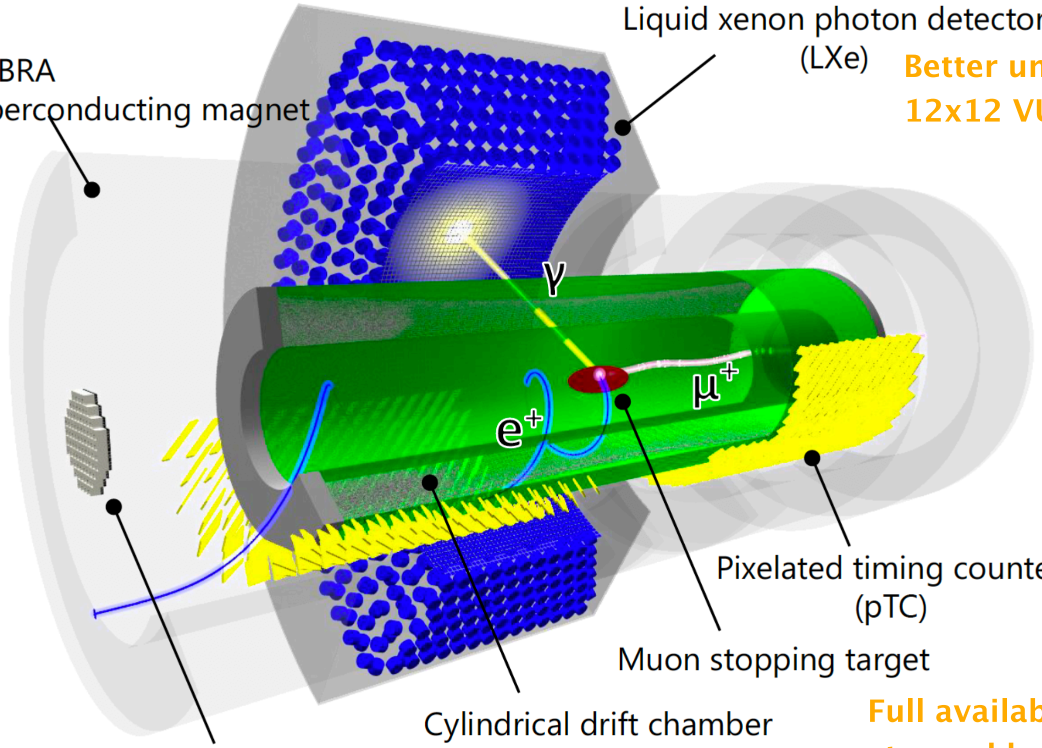
New electronics:
Wavedream

~9000 channels at 5GSPS

x2 Resolution everywhere

Updated and new Calibration methods

Quasi mono-chromatic positron beam



Better uniformity w/ 12x12 VUV SiPM

x2 Beam Intensity

35 ps resolution w/ multiple hits

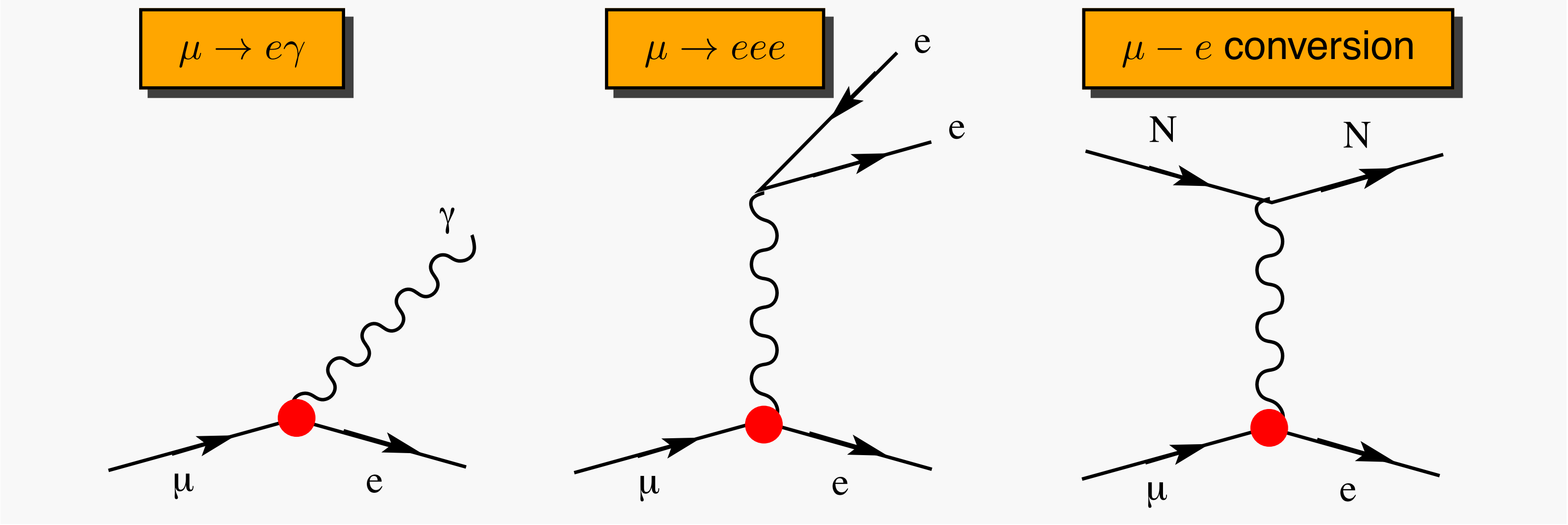
Full available stopped beam intensity 7×10^7

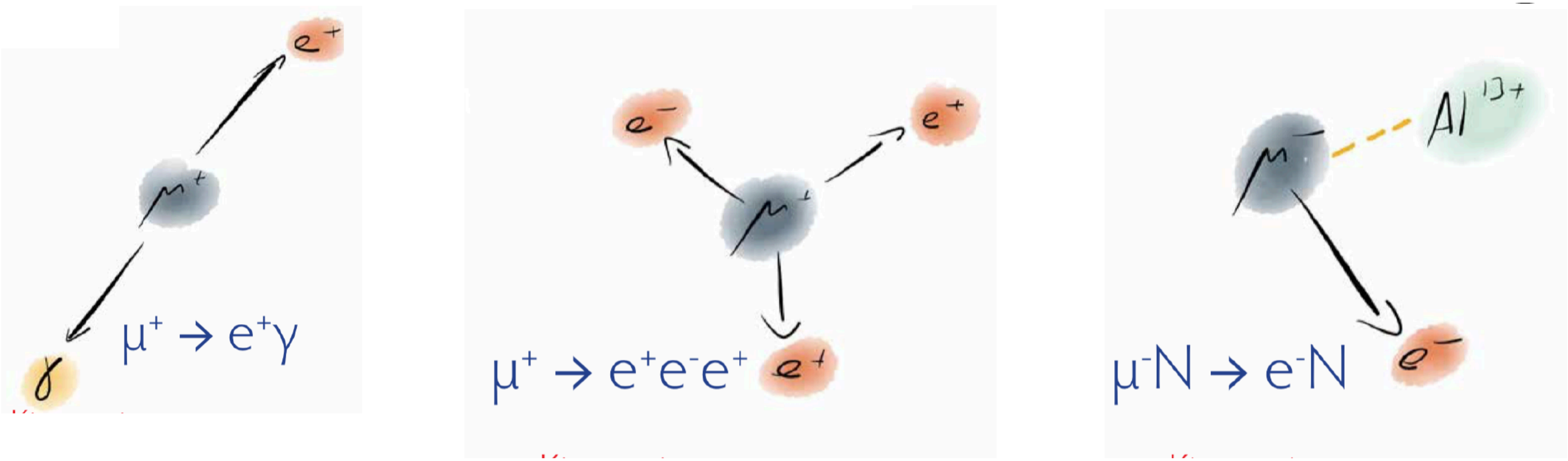
Background rejection

Single volume $He:iC_4H_{10}$

A.M. Baldini et al. (MEGII collab.) Eur. Phys. J. 78 (2018) 380

Three possible charge Lepton Flavour Violating Process (cLFV)

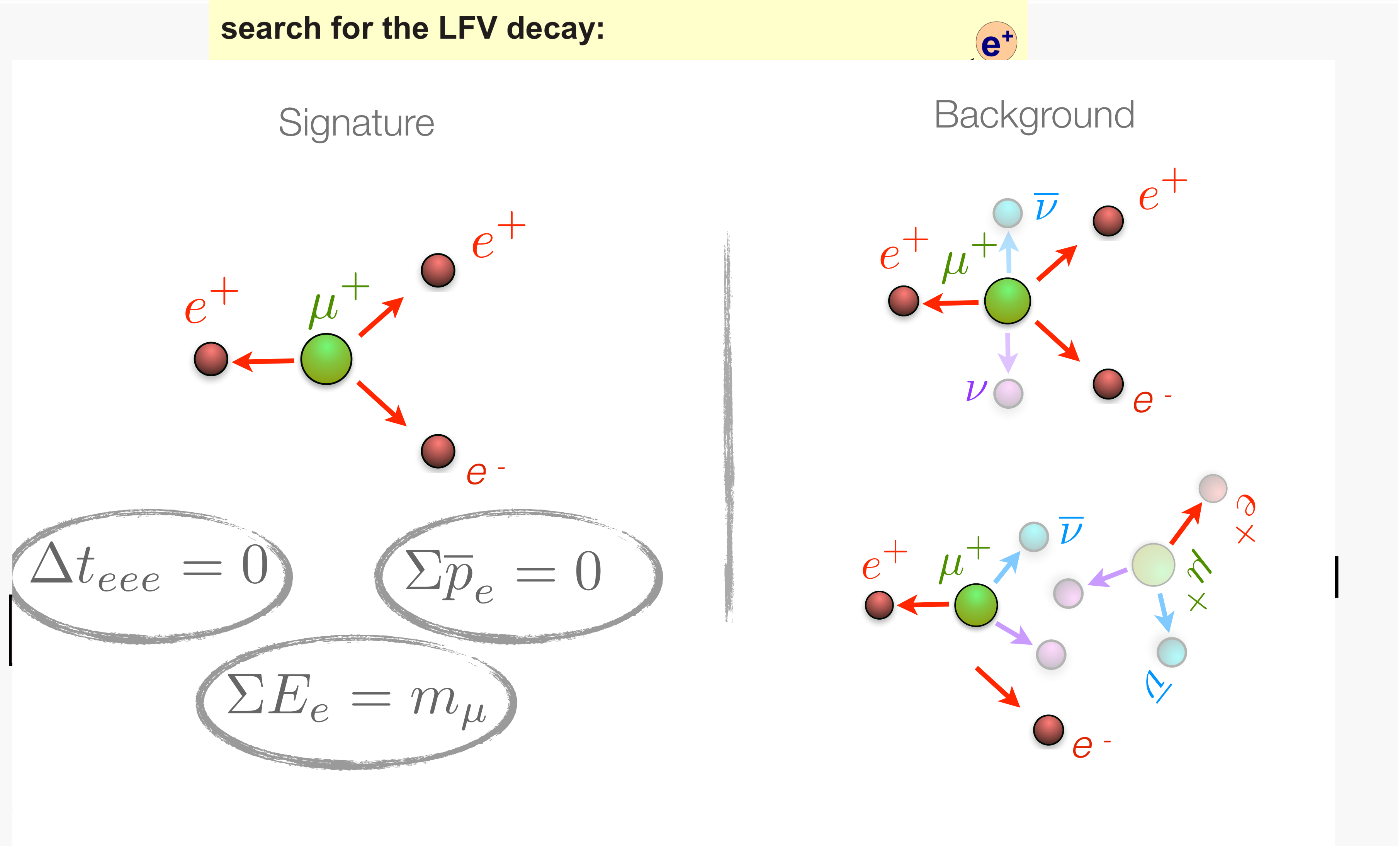




The μ → eee at PSI

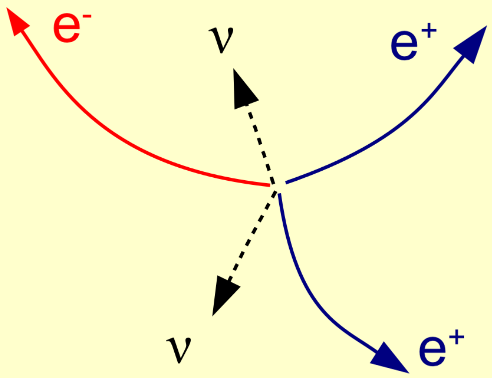
The Mu3e: signal vs BKG

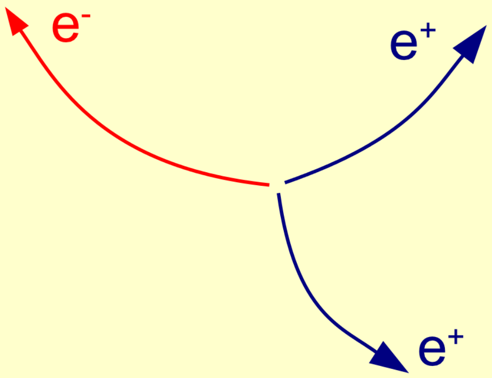
search for the LFV decay:



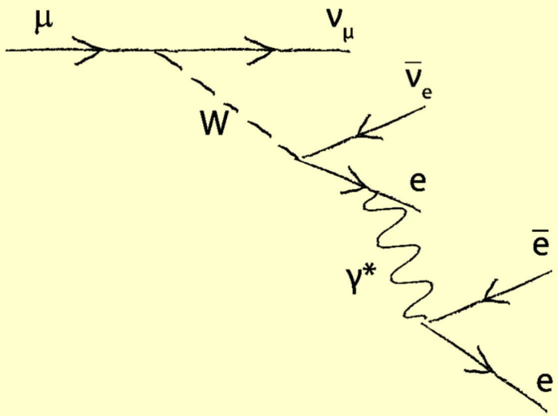
Background from internal conversion

Irreducible BG: radiative decay with internal conversion





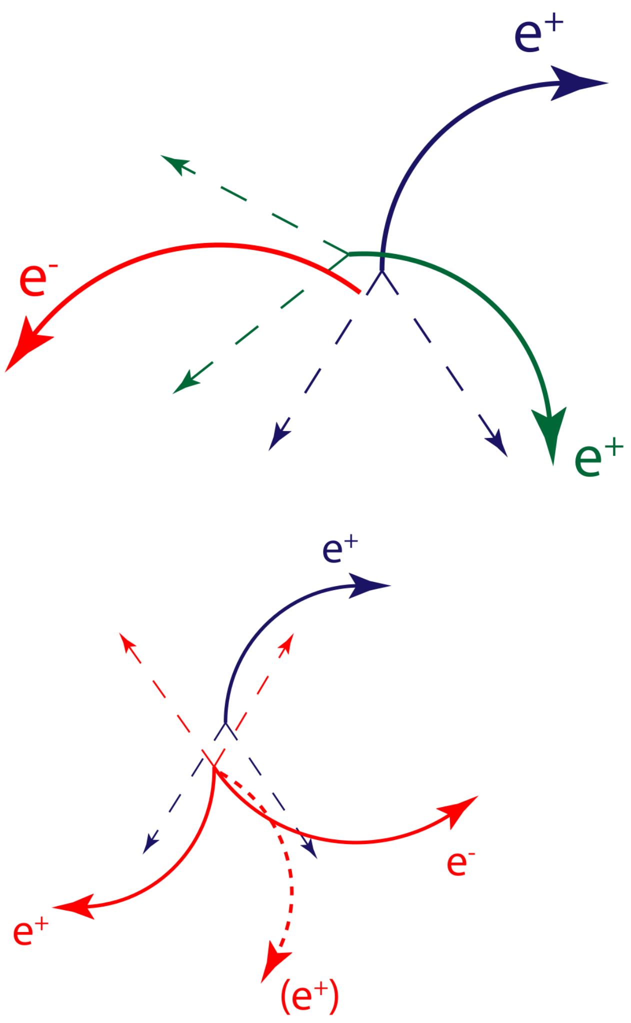
$B(\mu^+ \rightarrow e^+e^+e^- \nu\nu) = 3.4 \cdot 10^{-5}$



$$\sum_i E_i = m_\mu$$
$$\sum_i \vec{p}_i = 0$$

[A. Schöning]

Accidental Background

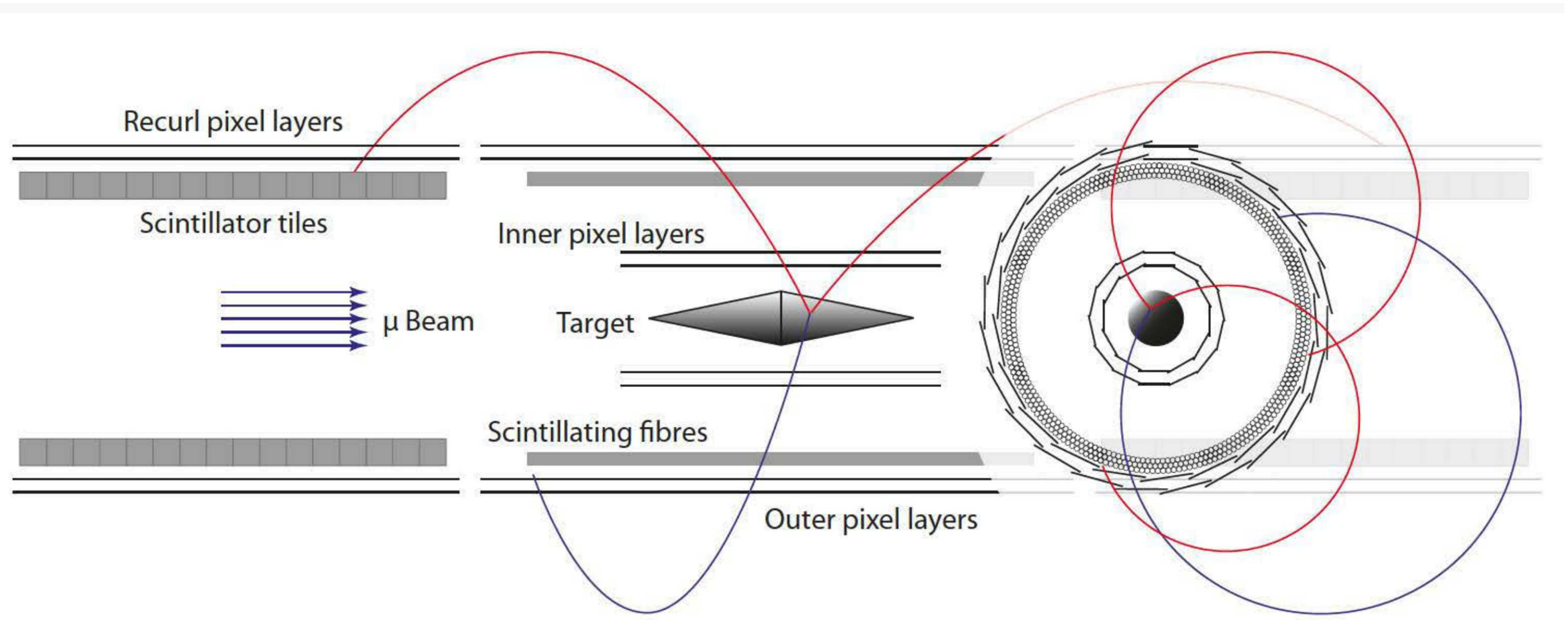


- Overlays of two normal muon decays with an electron
- Electrons from Bhabha-scattering, photon conversion, mis-reconstruction

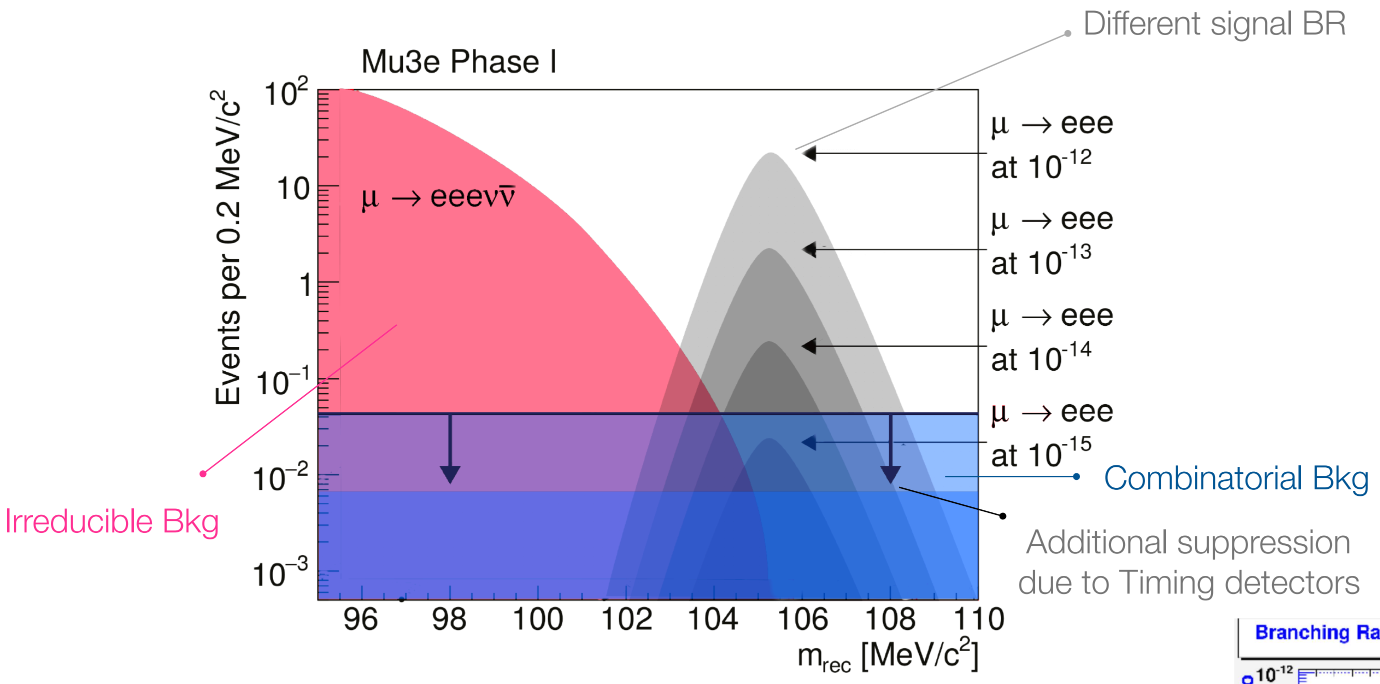
Need excellent:

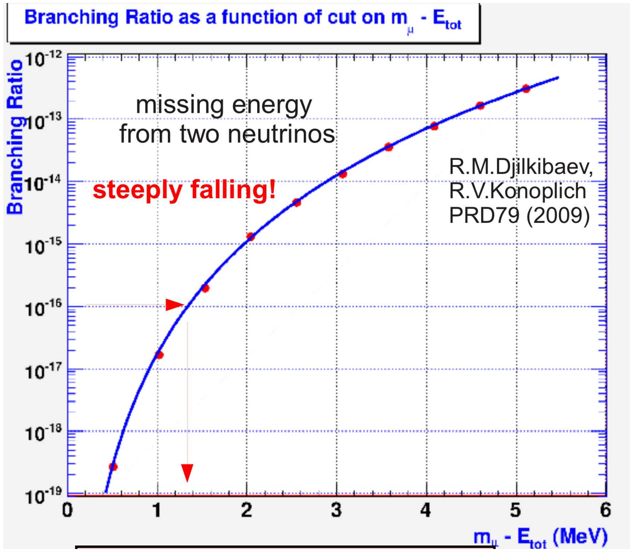
- Vertex resolution
- Timing resolution
- Kinematics reconstruction

Mu3e experimental setup



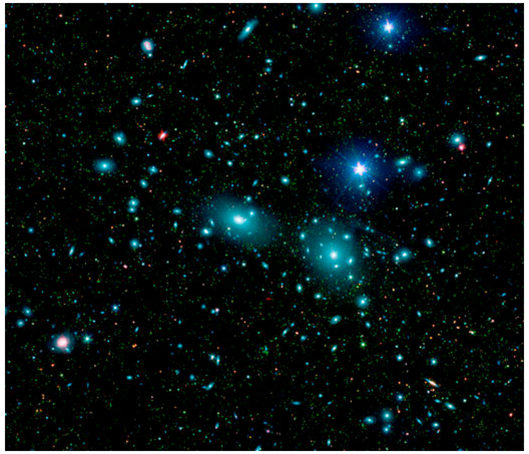
Sensitivity





Dark Matter

The first evidence for “die dunkle Materie”



Coma Cluster (**Abell 1656**) is a large cluster of galaxies that contains over 1,000 identified galaxies.

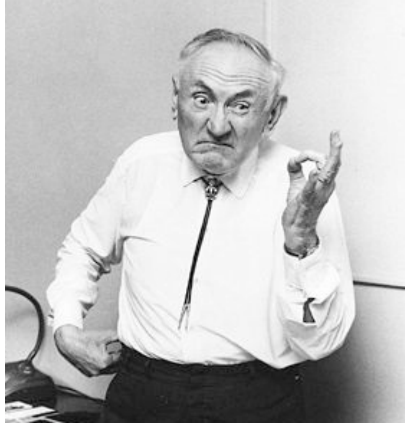
Using the virial theorem and assuming a uniform distribution of the **cluster total mass** in a sphere of radius R_{tot}, Zwicky (1933) got

$$M_{\text{tot}} \approx \frac{R_{\text{tot}}\bar{v}^2}{5G_N}$$

Plugging in the **observed average “nebulae” velocity**

$$M_{\text{tot}} \gtrsim 9 \times 10^{43}\text{kg} = 4.5 \times 10^{13} M_{\odot}$$

From observation they knew that a typical nebula would contain about **8.5 x 10^7 sunlike stars.**



Fritz Zwicky (1898-1974) was a Swiss astronomer He studied at ETH (1916-1922)

The galactic rotation curves

With the advent of **radio-telescopes** it became possible to **measure the velocity as a function of radius** of gas circling around cylindrical symmetric systems such as spiral galaxies.

$$v_c^2(r) = \frac{G_N M(r)}{r}$$

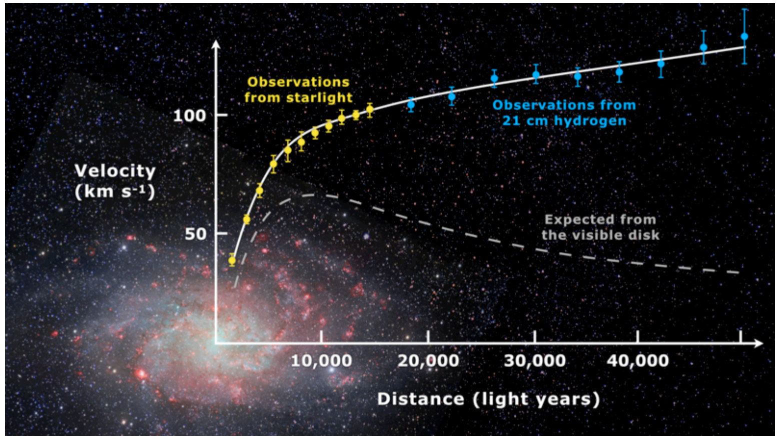
Vera Rubin (1926-2016) was a US astronomer

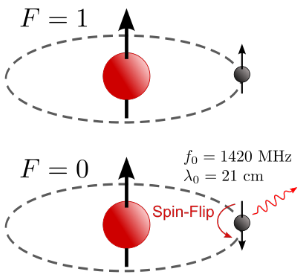
For a Galaxy as an homogenous sphere of radius R and constant density

$$v_c(r) = \sqrt{\frac{4\pi G_N \rho}{3}} r, \ (r \leq R)$$

Outside any spherical symmetric distribution of mass M

$$v_c(r) = \sqrt{\frac{G_N M}{r}}, \ (r \geq R)$$



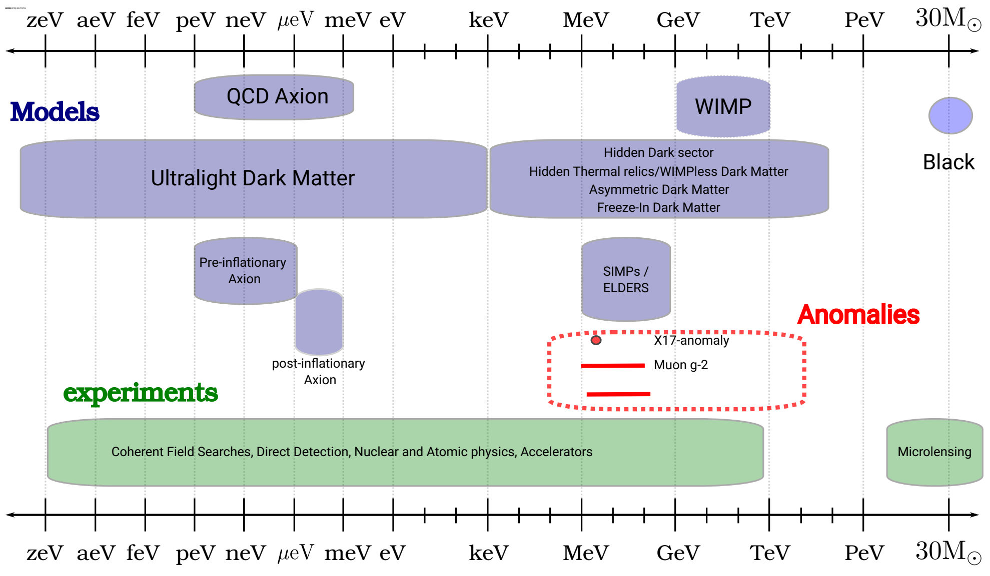


The galactic rotation curves

This observation necessitates at least one of the following:

1) There exists in galaxies large quantities of unseen matter which boosts the stars' velocities beyond what would be expected on the basis of the visible mass alone, or
2) Newton's Laws do not apply to galaxies.

Option (1) leads to the **dark matter hypothesis;**



From E. Depero PhD Thesis (ETH 2020)

option (2) leads to **MOdified Newtonian Dynamics (MOND).**

MOdified Newtonian Dynamics (MOND)

Milgron's idea: **Newton's laws** extensively tested in high-acceleration environments (in the Solar System and on Earth) but **have not been verified for objects with extremely low acceleration**, such as stars in the outer parts of galaxies.
This led Milgrom to postulate a new effective gravitational force law:

$$F_N = maf(x) \quad \text{where} \quad f(x) = f\left(\frac{a}{a_0}\right) \begin{cases} f(x) \to 1 & \text{for } x \gg 1 \\ f(x) = x & \text{for } x \ll 1 \end{cases}$$

Thus, in the **deep-MOND regime** $a \ll a_0 \Longrightarrow \quad F_N = m\frac{a^2}{a_0}$

$$\frac{GMm}{r^2} = m\frac{\left(\frac{v^2}{r}\right)^2}{a_0} \quad \Longrightarrow \quad v^4 = GMa_0$$

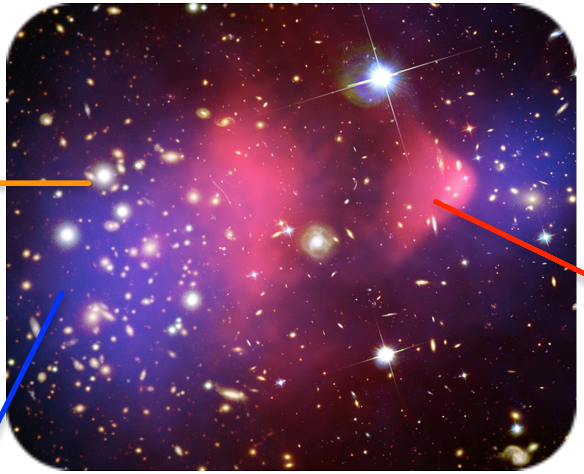
Mordehai Milgrom
(1946-)
Israeli astrophysicist

→ the star's rotation velocity is independent of *r*, its distance from the centre of the galaxy, the rotation curve is flat, as required. By fitting his law to rotation curve data, Milgrom found $a_0 \approx 1.2 \times 10^{-10} \mathrm{ms}^{-2}$

The bullet cluster

The Bullet Cluster (1E 0657-56) consists of two colliding clusters of galaxies.

The stars of the galaxies, observable in visible light, not greatly affected by the collision, and most passed right through, gravitationally slowed but not otherwise altered.

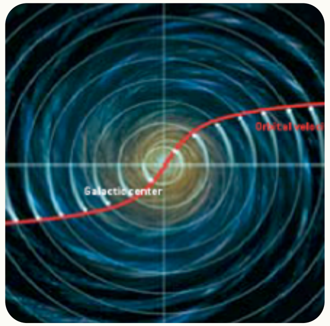


Chandra X-ray Observatory (CXO)

The hot gas of the two colliding components. The gases of the Intracluster medium interact electromagnetically, causing the gases of both clusters to slow much more than the stars.

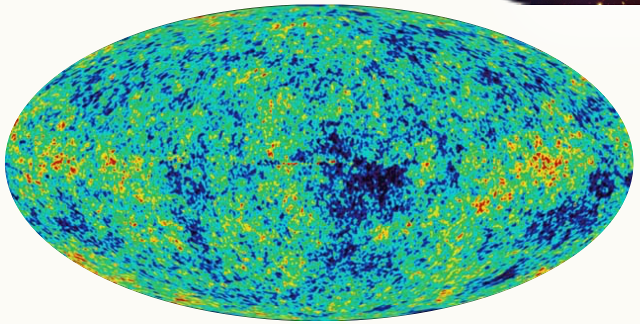
Dark matter, was detected indirectly by the gravitational lensing of background objects. In MOND, the lensing would be expected to follow the baryonic matter; i.e. the X-ray gas. However, the lensing is strongest in two separated regions near (possibly coincident with) the visible galaxies. This provides support for the idea that most of the gravitation in the cluster pair is in the form of two regions of dark matter, which bypassed the gas regions during the collision. This accords with predictions of dark matter as only gravitationally interacting, other than weakly/feebly interacting.

Dark Matter: Astro + Cosmology through Gravitational effects



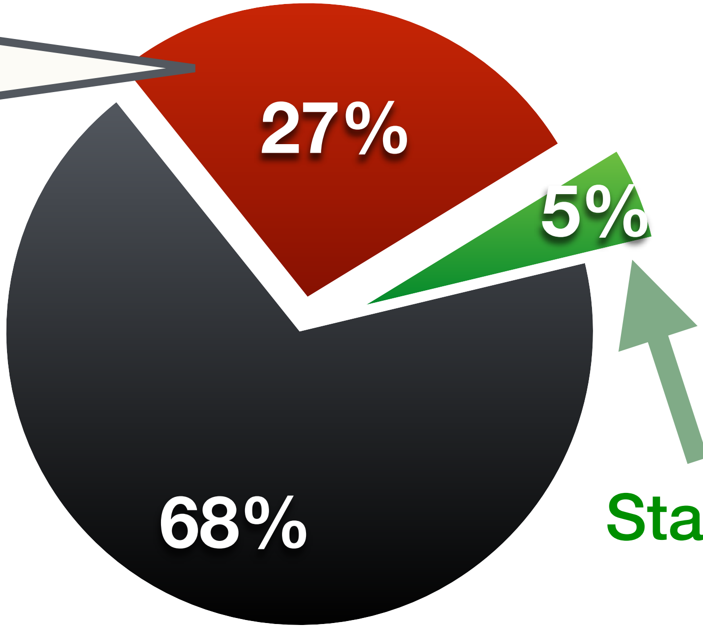
GALACTIC
ROTATION CURVES

GRAVITATIONAL
LENSING



COSMIC MICROWAVE BACKGROUND

ΛCDM (Lambda Cold Dark Matter)



Standard Model

Dark Energy

Interaction DM-SM other than gravity? If so very weak…

Only gravitationally? Nightmare scenario from a particle physicist point of view.

$$\Omega_{DM} \sim 5\Omega_{SM}$$

Relic densities of Standard Matter (SM) and Dark Matter (DM) are “similar”

SUGGESTS COMMON ORIGIN BETWEEN SM and DM.

Can those be related with **A SINGLE THEORY?**

Weakly Interacting Massive Particles (WIMPs)

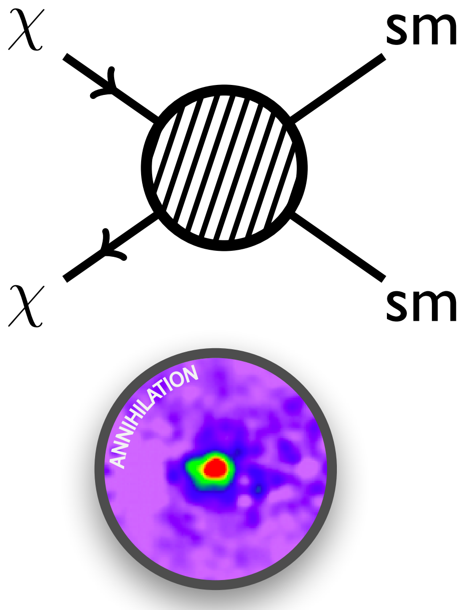
INTERACTS VIA WEAK FORCE (**W** and **Z** BOSONS)

Dark Matter — WEAK FORCE? — **Standard Model**

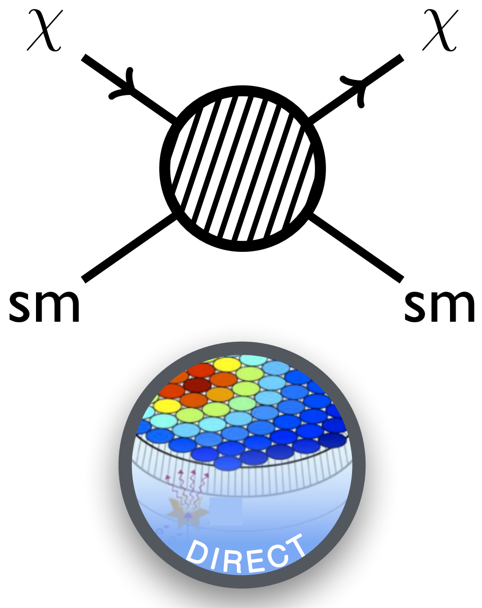
$$\sigma \sim G_F^2 m_X^2$$

Dark matter searches related by crossing symmetry:

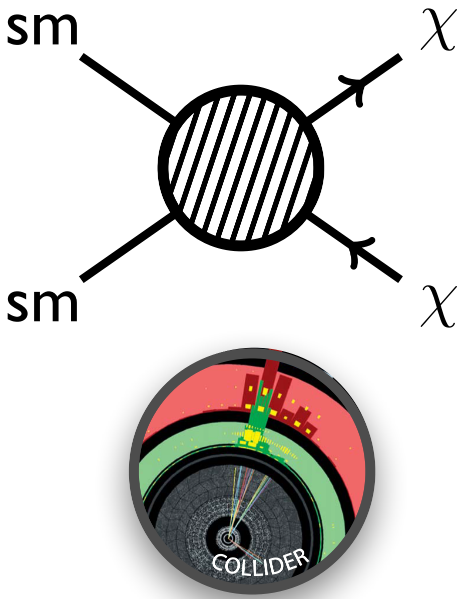
INDIRECT



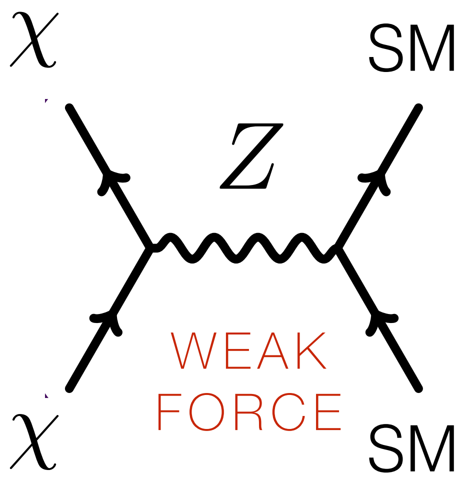
DIRECT



COLLIDER



The WIMP miracle



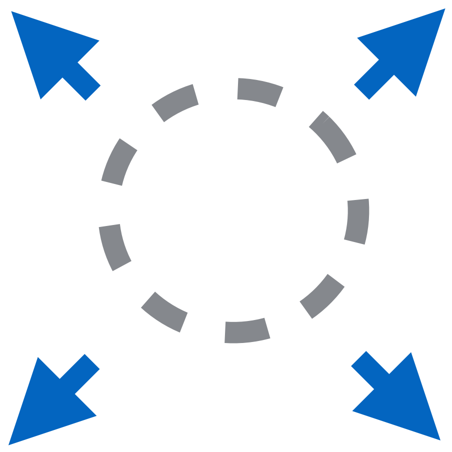
annihilation

OBSERVED **AMOUNT OF DARK MATTER** TODAY

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

Thermal averaged **ANNIHILATION** RATE

vs.



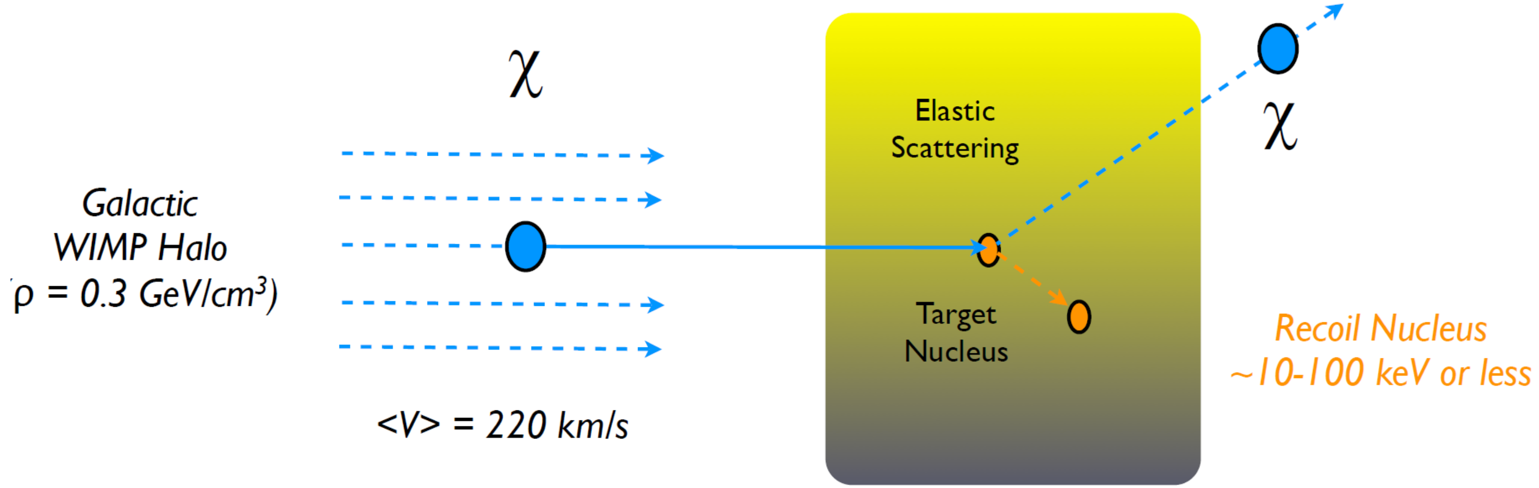
expansion of universe

"WEAK SCALE" MASS

$m_X \sim 100$ GeV, $g_X = g_{WEAK}$

IDEAL CANDIDATE:
Lightest Super-symmetrical Particle

Direct WIMP searches (Method)

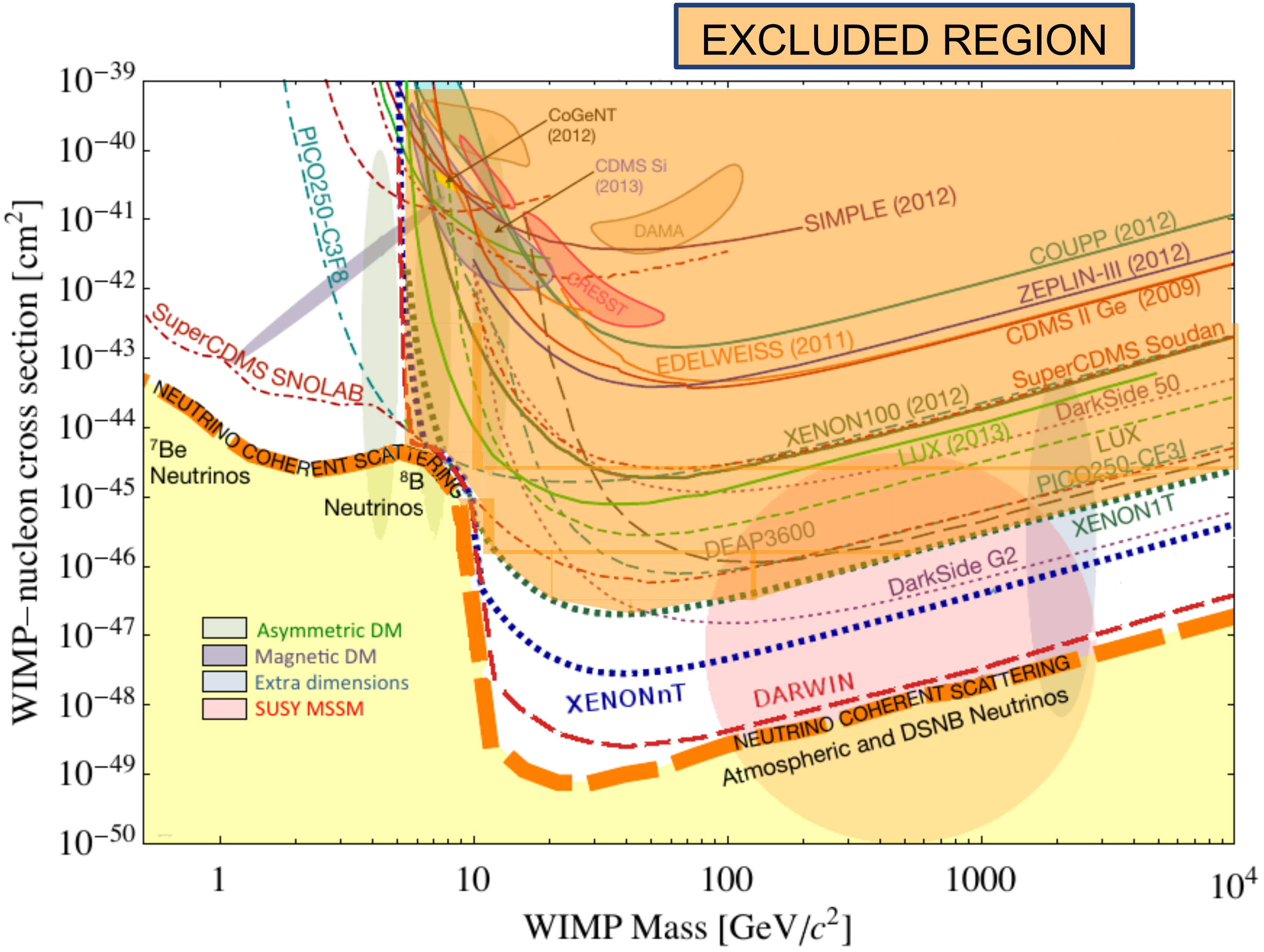


- The total event rate is $$R \propto N_T \frac{\rho_0}{m_X} \sigma \langle v \rangle$$

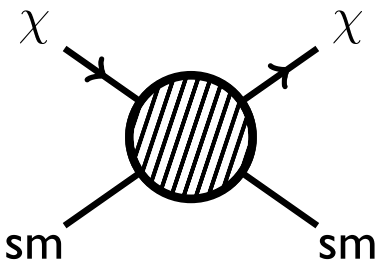
where N_T is the number of nuclei in the target (Detector physics input), $\sigma = \sigma_{XN}$ is the WIMP-nucleus elastic scattering cross section (Particle physics input), and $<v>$ is the average WIMP velocity in the lab frame (Astrophysics input).

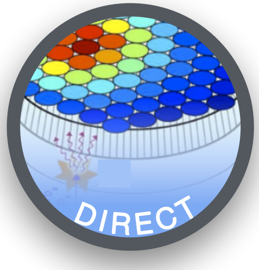
$$\langle v \rangle = \int_0^\infty v\, f(v)\, dv$$

Status of direct Searches

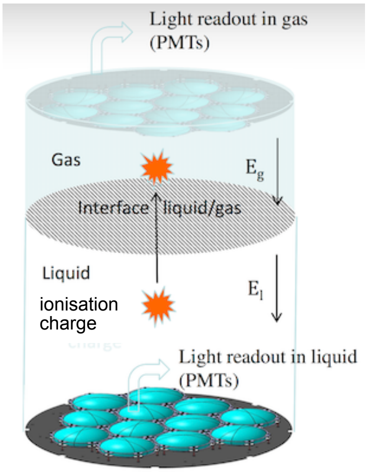


M. Klasen et al. et al. Prog.Part.Nucl.Phys. 85 (2015) 1-32



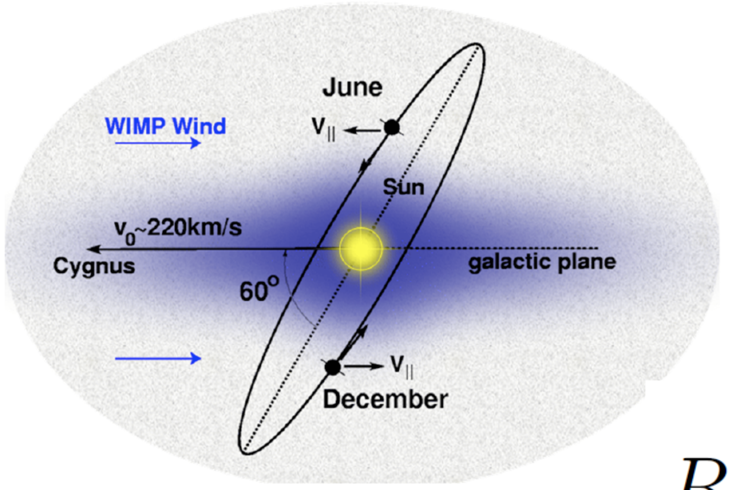


MEASURE NUCLEAR RECOIL e.g. in liquid Argon or Xenon



Annual modulation

K. Freese, J. Frieman and A.Gould, Phys. Rev. D37, 3388 (1988)



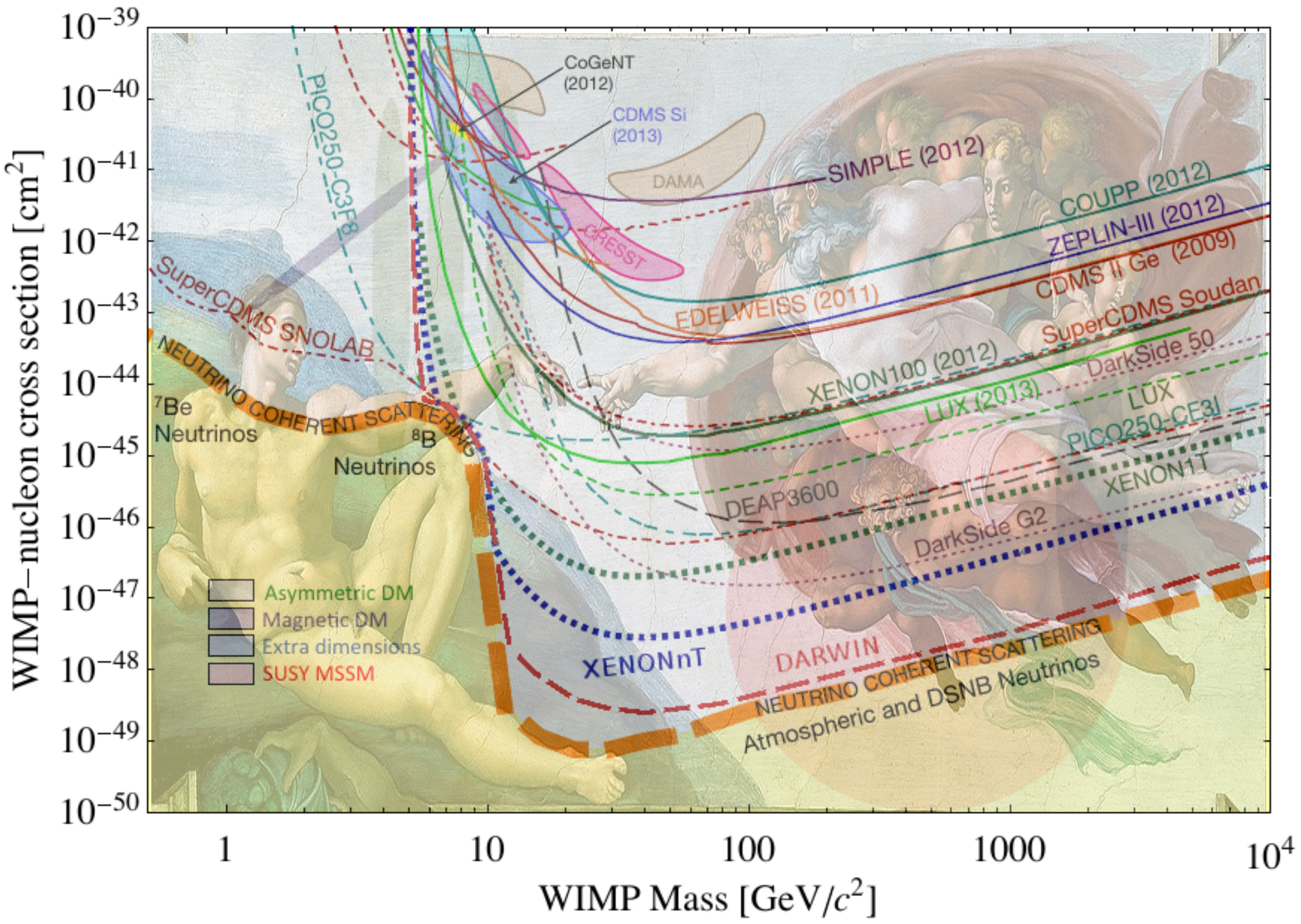
$$v_E(t) = v_\odot + v_\oplus \cos\gamma \cos\omega(t - t_0)$$
$$= v_\odot + \Delta v_E \cos\omega(t - t_0)$$

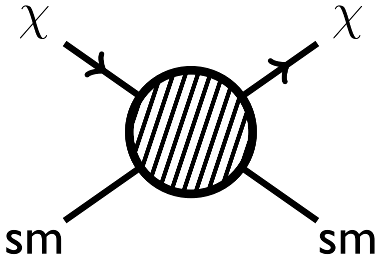
$$R(v_E) = R(v_\odot) + \left(\frac{\partial R}{\partial v_E}\right)_{v_\odot} \Delta v_E \cos\omega(t - t_0)$$

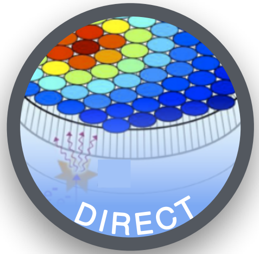
where $v_\odot = v_{rot} + 12$ km/s is the sun's velocity with respect to the galactic halo and $\Delta v_E \simeq 15$ km/s, $\omega \equiv 2\pi/T$ $(T = 1$ year$)$ with $t_0 = 152.5$ days

Phase and period are both predicted!

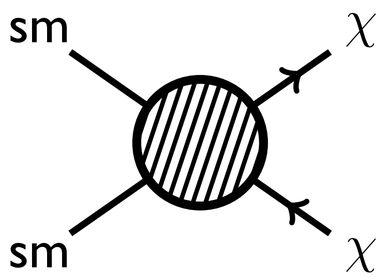
Tough times for the WIMP miracle?

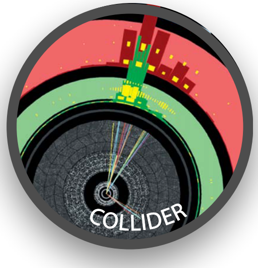






+





So far no WIMP/SUSY

M. Klasen et al. et al. Prog.Part.Nucl.Phys. 85 (2015) 1-32 & MICHELANGELO

Light Mediators searches complementary to WIMPs

recent review https://arxiv.org/pdf/1707.04591.pdf

OBSERVED **AMOUNT OF DARK MATTER** TODAY

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

The WIMP miracle

$$(m_X, g_X) \sim (m_{\text{weak}}, g_{\text{weak}})$$

The WIMPless MIRACLE

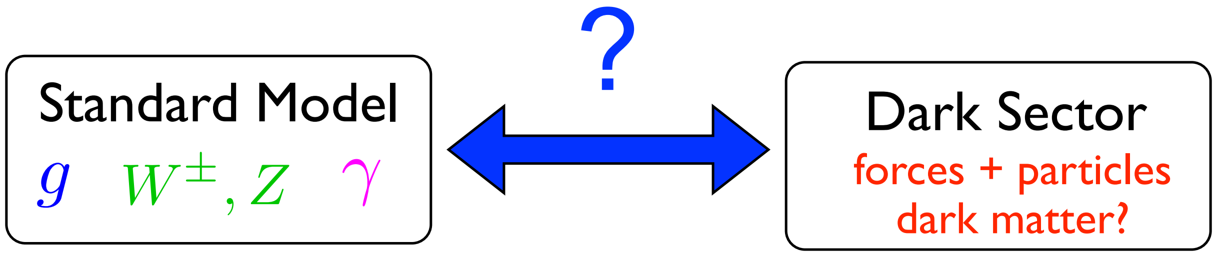
$$\frac{m_X}{g_X^2} \sim \frac{m_{\text{weak}}}{g_{\text{weak}}^2}$$

J. Feng and J. Kumar Phys.Rev.Lett.101:231301,2008

Large range for g_X and m_X

Renormalizable Portals

B. Batell, M. Pospelov and A. Ritz, Phys. Rev. D80 (2009) 095024.



• "Axion"	$\frac{1}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu} a$	axions & axion-like particles (ALPs)
• "Vector"	$\epsilon\, F^{Y,\mu\nu} F'_{\mu\nu}$	dark photon A′
• "Higgs"	$\lambda\, H^2 S^2 + \mu\, H^2 S$	exotic Higgs decays?
• "Neutrino"	$\kappa\, (HL) N$	sterile neutrinos?

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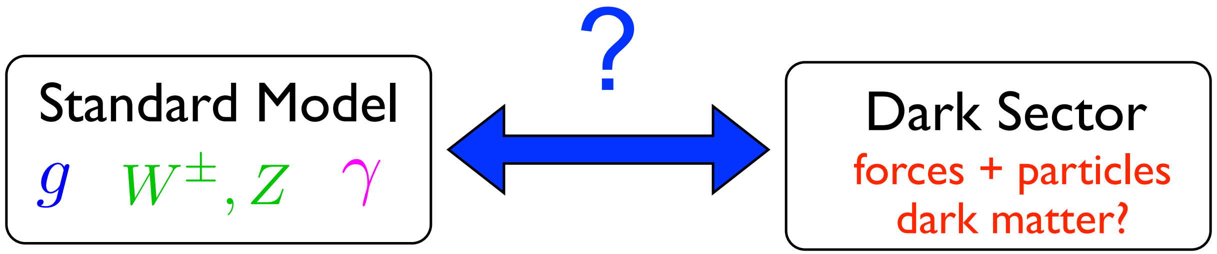

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The Axion portal - CP violation in QCD

CP violating term in QCD Lagrangian:

$$\mathcal{L}_{\mathrm{QCD}} \propto \bar{\theta}\,\frac{\alpha_s}{8\pi^2} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Where $$\bar{\theta} = \theta - \arg\det(Y_u Y_d)$$

Random phase from QCD Θ-vacuum

Phases from Yukawa coupling: CKM matrix

CP violating phase through CKM matrix

→ Physically observable CP violation in strong interaction expected but so far no evidence

The Axion portal - the strong CP problem

CP violating term in QCD induces neutron electric dipole moment (EDM)

$$d_N = (5.2 \times 10^{-16} \mathrm{e} \cdot \mathrm{cm})\bar{\theta}$$

Current experimental bound: $d_N > 2 \times 10^{-26} \mathrm{e} \cdot \mathrm{cm}$

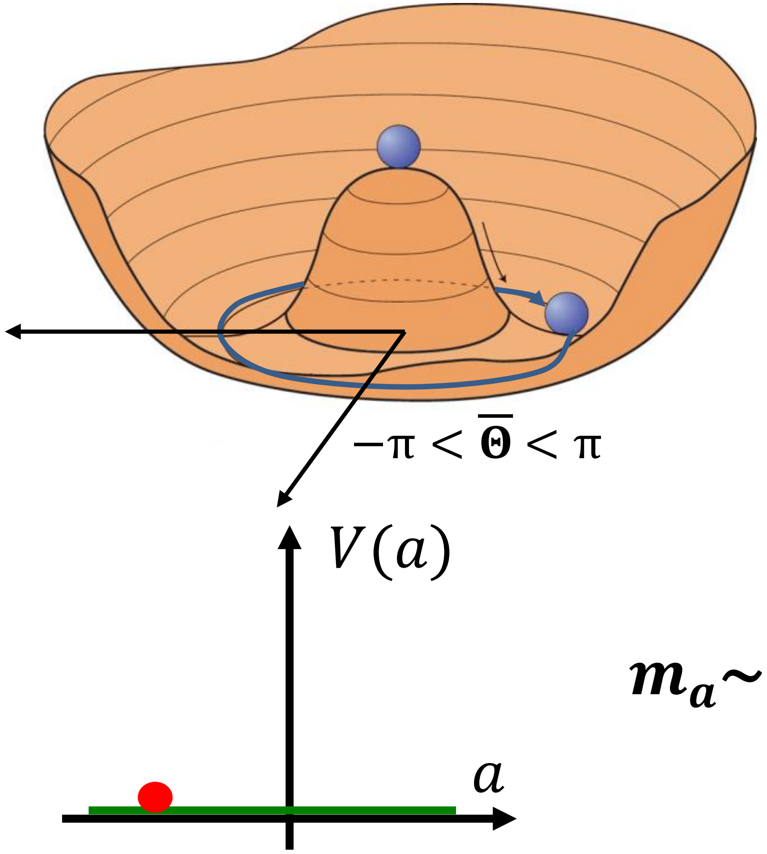
$$\Rightarrow \quad \bar{\theta} < 10^{-10}$$

Two seemingly independent terms cancel each other at the level of 10^{-10}

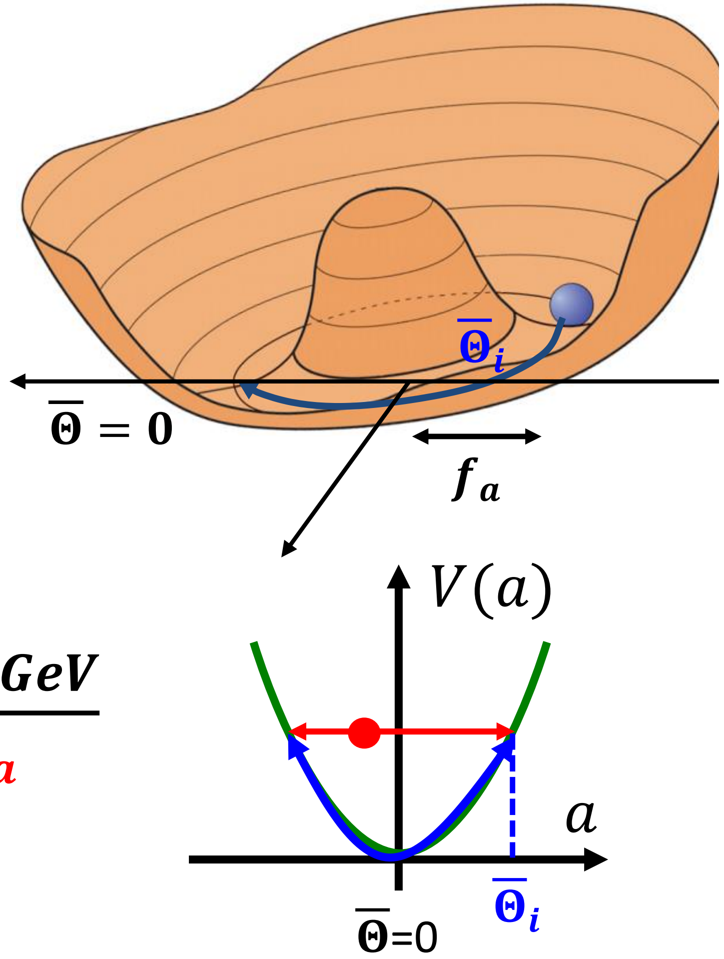
$\Rightarrow$ Strong CP problem

Axions as a solution to the strong CP problem

Make $\bar{\Theta}$ dynamical → U(1) with spontaneous Peccei Quinn symmetry breaking



QCD: explicit symmetry breaking



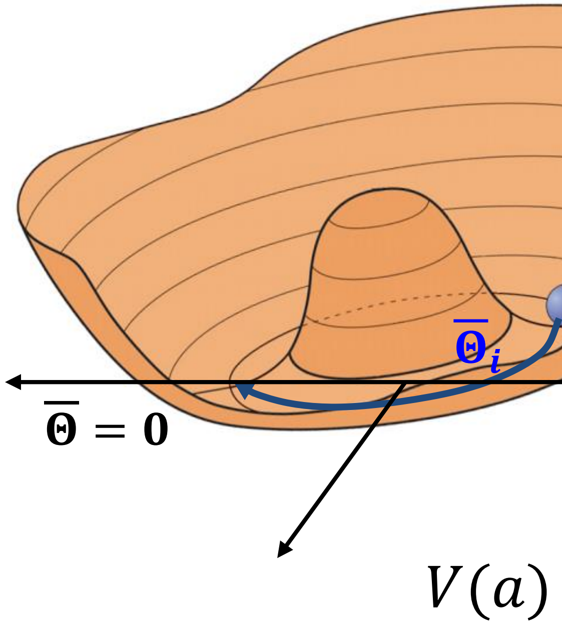
$$m_a \sim 5.7\mu eV \, \frac{10^{12} GeV}{f_a}$$

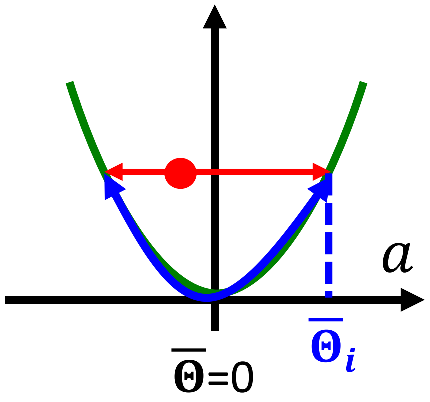
Axions as a solution to the strong CP problem

If axion exists:

→ Contribution to Dark Matter:

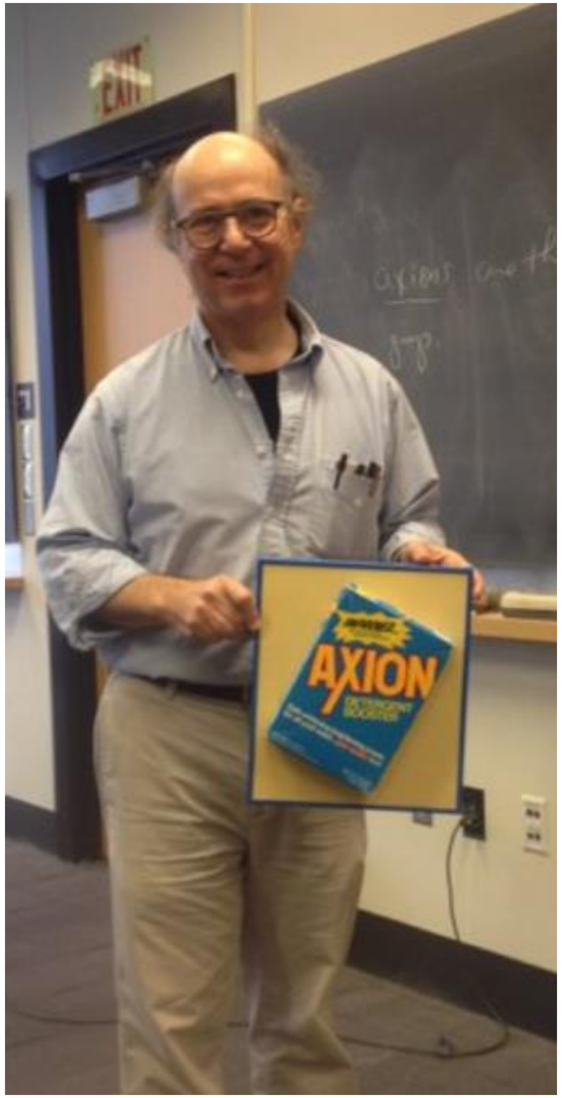
as relic oscillations of $\bar{\Theta}$ around minimum





Oscillations amplitude (particle density)
damped by expansion of universe H(t)
Damping depends on ratio
oscillation frequency (m_a) to H(t)

Axions as a solution to the strong CP problem



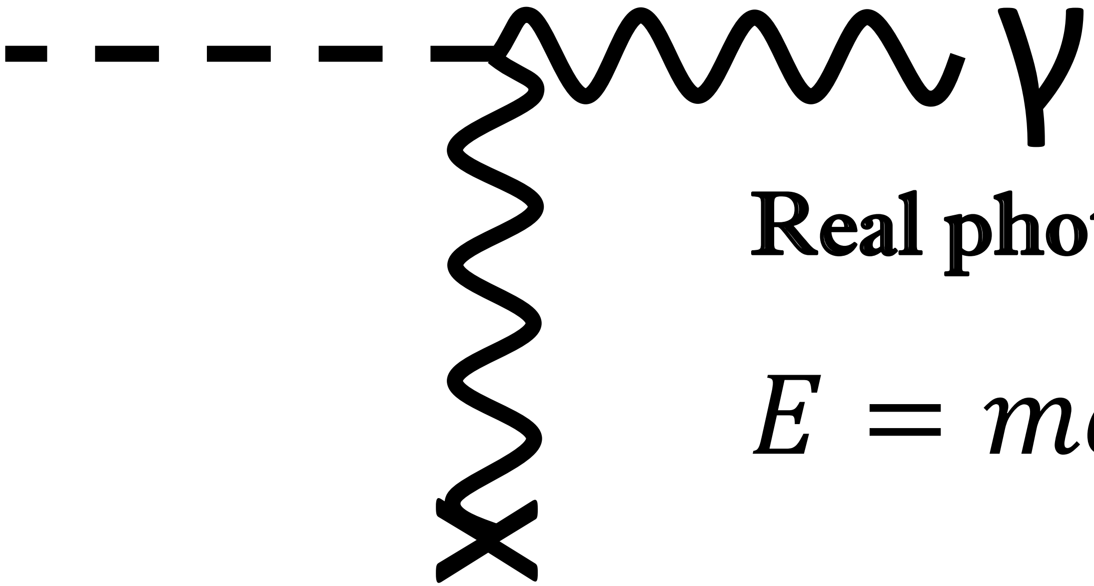
R. Peccei und *H. Quinn*,
Phys. Rev. Lett. **38**, 1440 (1977)
S. Weinberg, Phys. Rev. Lett. **40**, 223 (1978);
F. Wilczek, Phys. Rev. Lett. **40**, 279 (1978)

The Birth of Axions

Frank Wilczek
Institute for Advanced Study
Princeton, NJ 08540

usual, very light particle. I called this particle the *axion*, after the laundry detergent, because that was a nice catchy name that sounded like a particle and because this particular particle solved a problem involving *axial* currents.

Detection of Axions coupling to photons - Primakoff effect



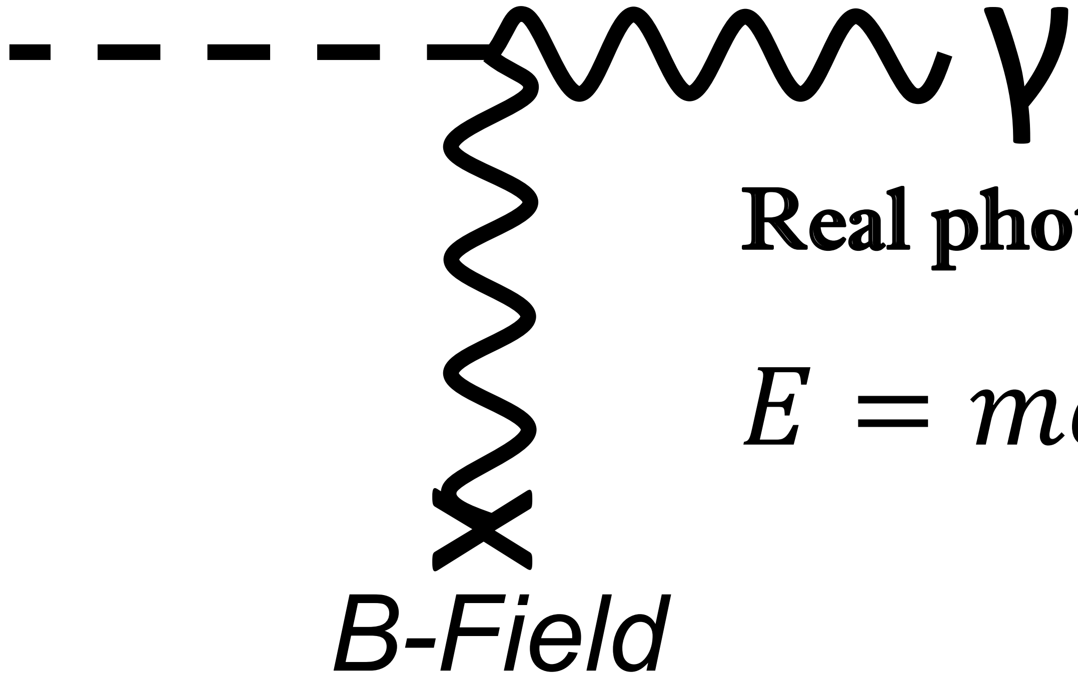
Real photon

$$E = mc^2 = h\boldsymbol{\nu}$$

Suppressed by $\frac{1}{f_a}$

$$\mathcal{L}_{a\gamma} = \frac{\alpha}{2\pi} C_{a\gamma} \frac{a(t)}{f_a} \boldsymbol{E} \cdot \boldsymbol{B}$$

Detection of Axions coupling to photons - Primakoff effect



Real photon

$$E = mc^2 = h\nu$$

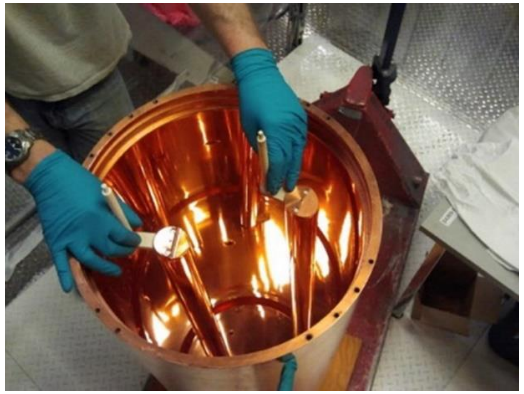
→ **Axion in B-field sources E-field oscillations!**

Suppressed by $\frac{1}{f_a}$

Axions detection - cavities in B-field

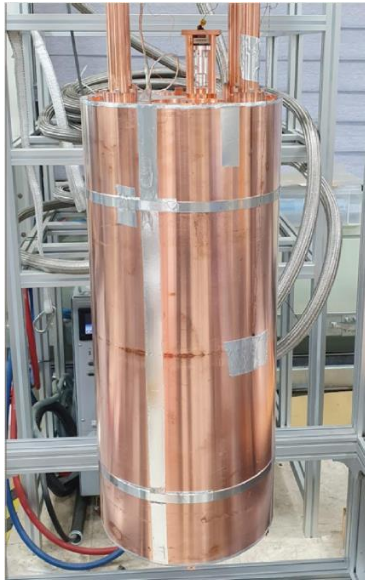
→ Use resonator to "pump cavity"

Adjusting resonance frequency: "Tuning Rod"



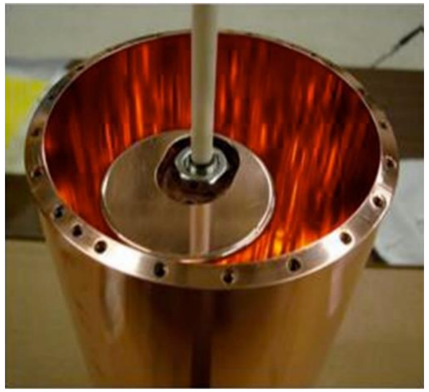
ADMX

U Washington, USA



CAPP

IBS, S. Korea



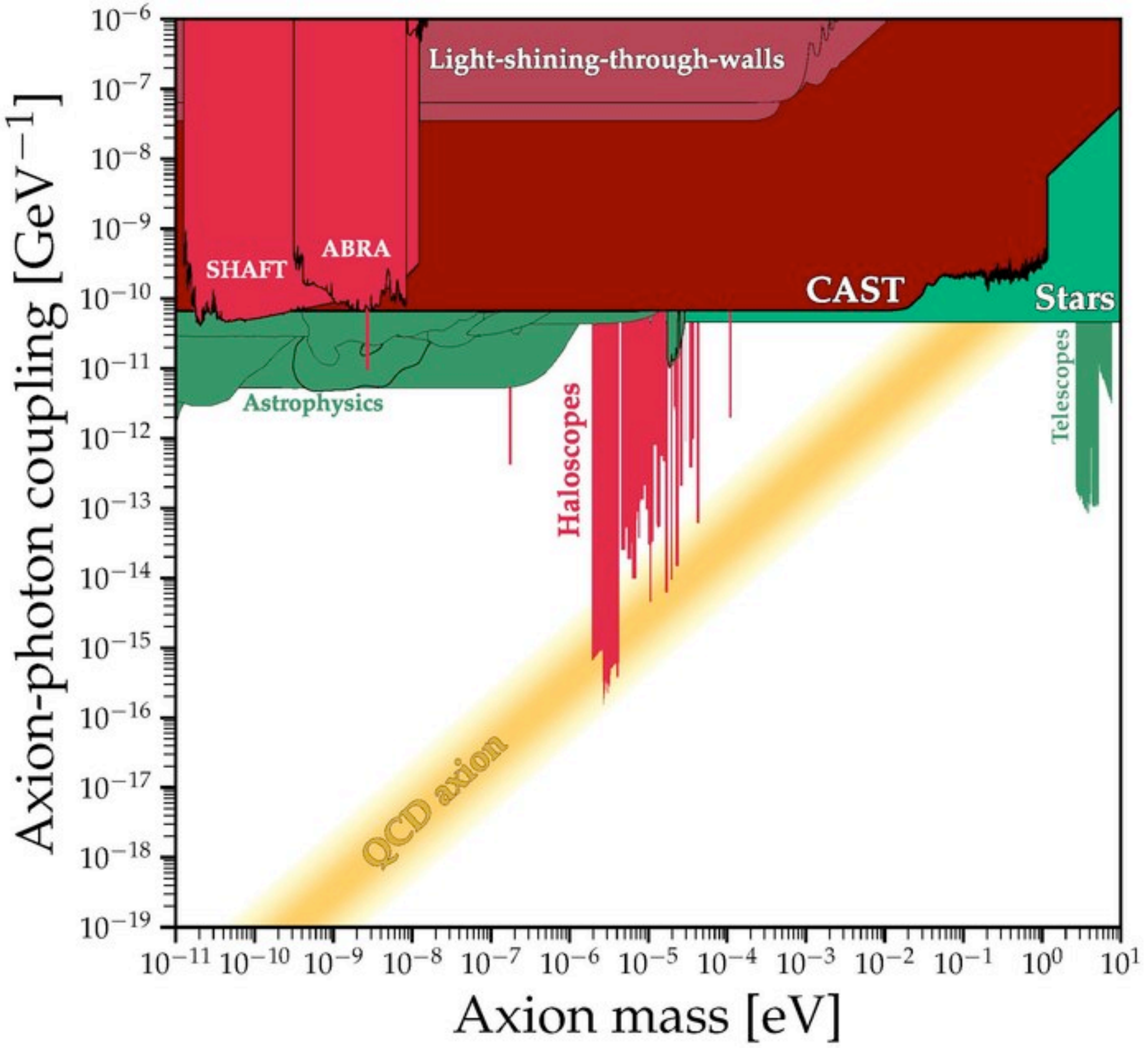
HAYSTAC

Yale University, USA

$$P_{sig} \propto B^2 V\, Q_{cav}$$

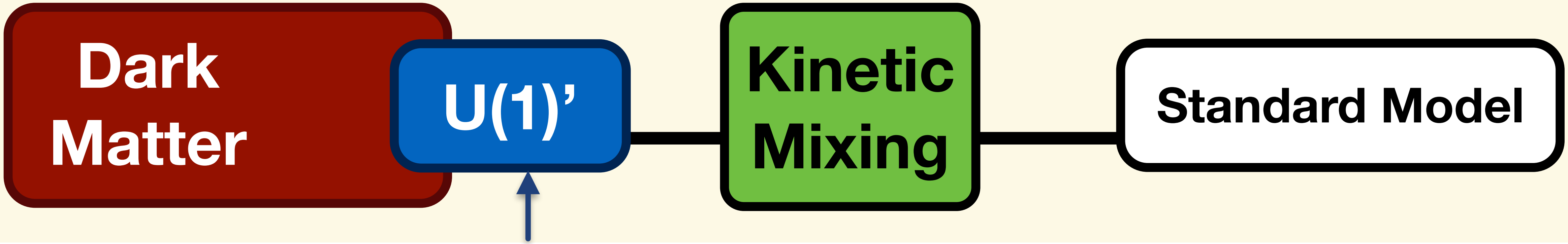
$$P_{sig}(B{=}6.8\ T,\ V{=}136\ l,\ Q{=}10^5) \sim 2 \cdot 10^{-22}\ W$$

Status of current searches



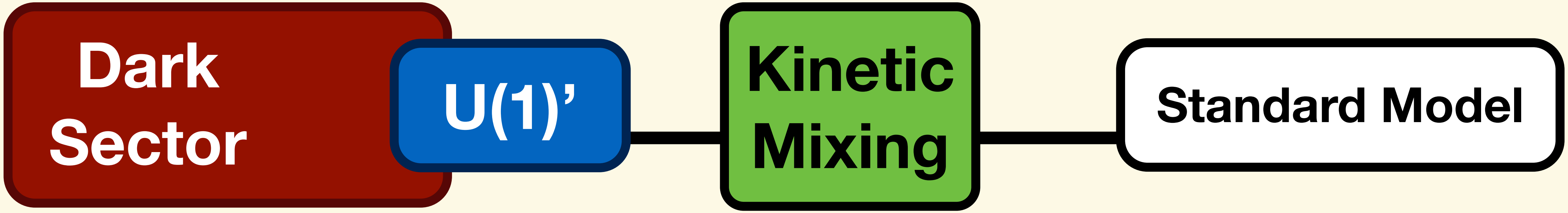
The Vector portal - the Dark Photon

- "Axion" — $\frac{1}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu} a$ — axions & axion-like particles (ALPs)
- "Higgs" — $\lambda H^2 S^2 + \mu H^2 S$ — exotic Higgs decays?
- "Vector" — $\epsilon F^{Y,\mu\nu} F'_{\mu\nu}$ — dark photon A′
- "Neutrino" — $\kappa (HL) N$ — sterile neutrinos?



NEW FORCE CARRIED BY MASSIVE **VECTOR** BOSON: **DARK PHOTON**

DARK SECTORS - THE VECTOR PORTAL



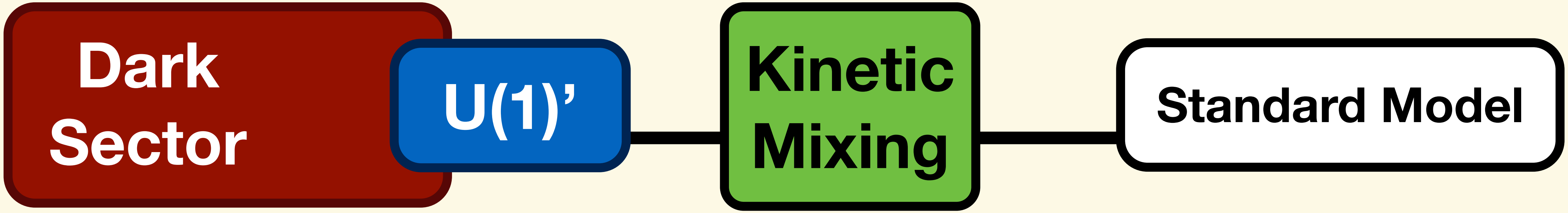
DARK SECTOR (DS) charged under a new U(1)' gauge symmetry and interacts with SM through kinetic mixing (ε) of a MASSIVE VECTOR MEDIATOR (A') with our photon.

Dark matter with mass (m_χ), part of DS.

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu} + \frac{m^2_{A'}}{2} A'_\mu A'^\mu + i\bar{\chi}\gamma^\mu \partial_\mu \chi - m_\chi \bar{\chi}\chi - e_D \bar{\chi}\gamma^\mu A'_\mu \chi,$$

Four parameters: $m_{A'}$, m_χ, $\alpha_D = e_D^2/4\pi$, ε

DARK SECTORS - THE VECTOR PORTAL



In this framework DM can be produced thermally in the early Universe

OBSERVED **AMOUNT OF DARK MATTER** TODAY

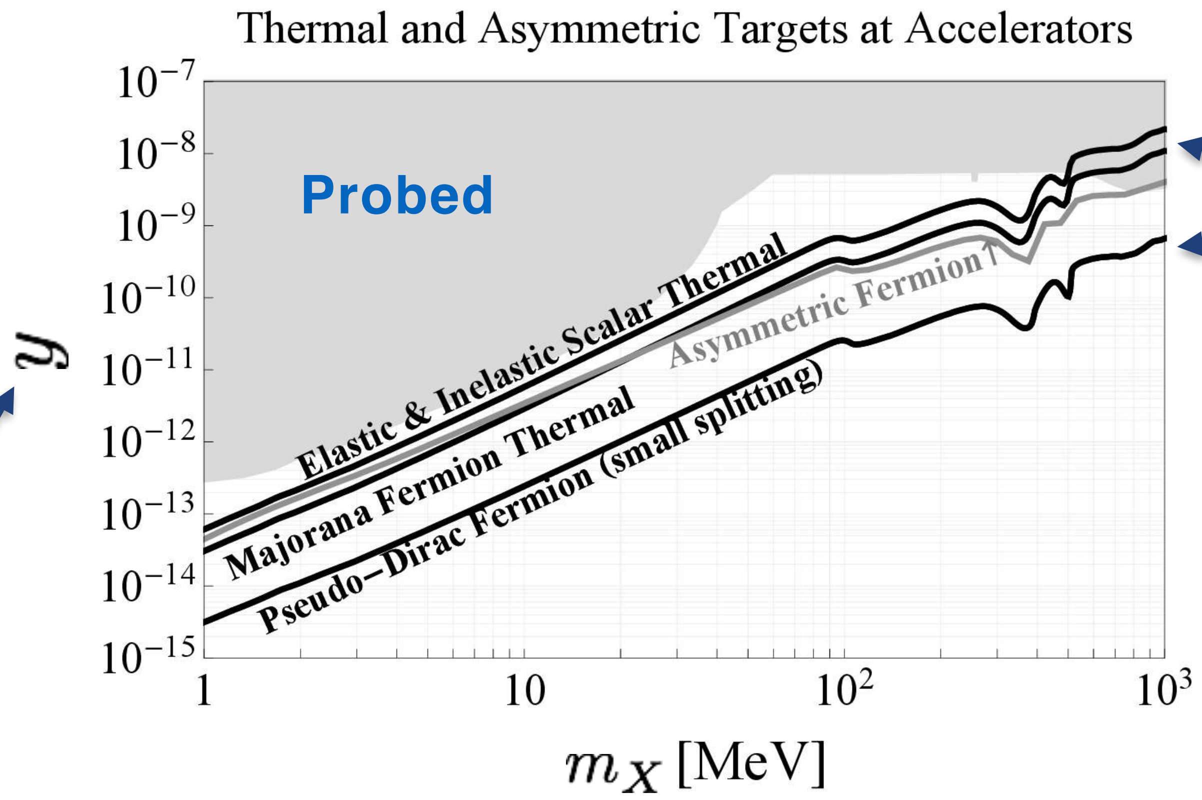
$$\Omega_X \propto \frac{1}{< v\sigma >} \sim \frac{m_X^2}{y}$$

WHERE

$$y = \epsilon^2 \alpha_D \left(\frac{m_X}{m_{A'}}\right)^4$$

The (y,mX) DM PARAMETER SPACE

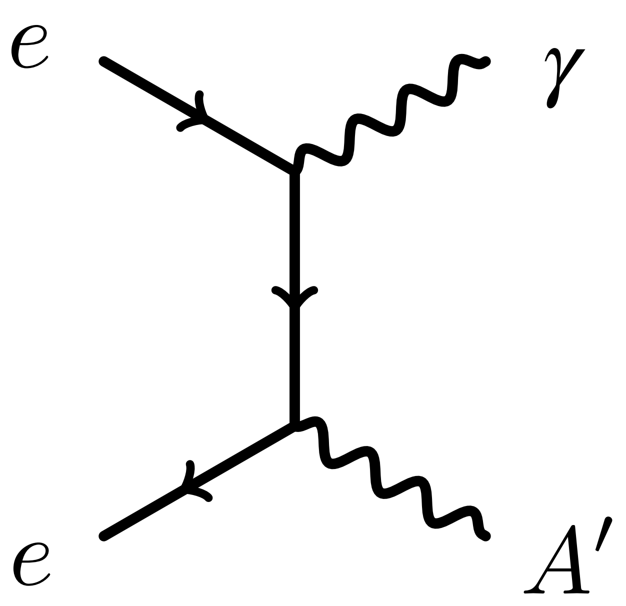
For a review see e.g https://arxiv.org/pdf/1707.04591.pdf



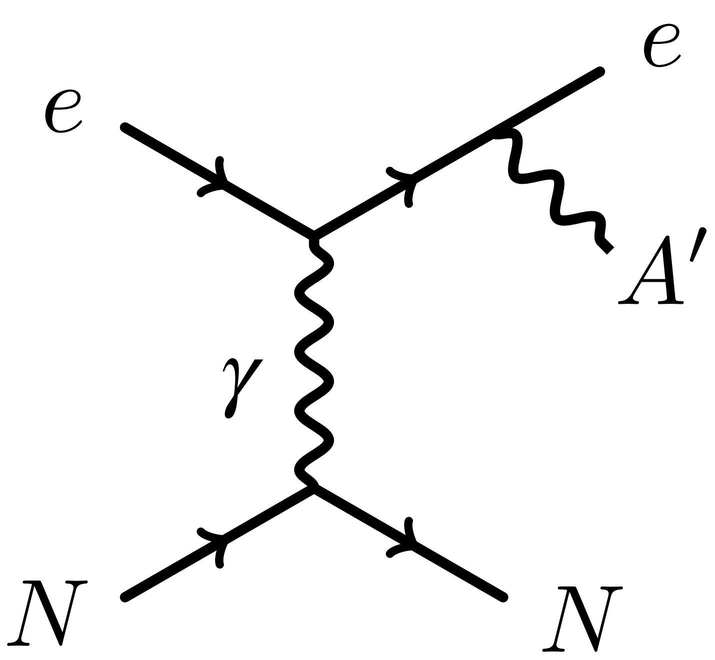
Solid lines predictions from DM relic abundance

DM -> SM annihilation rate is ~ y,
useful variable to compare exp. sensitivities

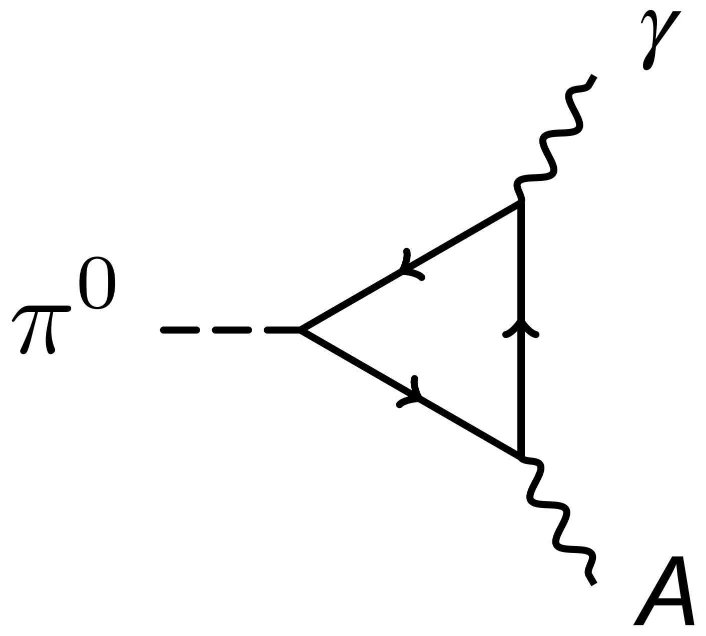
Production of Dark Photons



annihilation



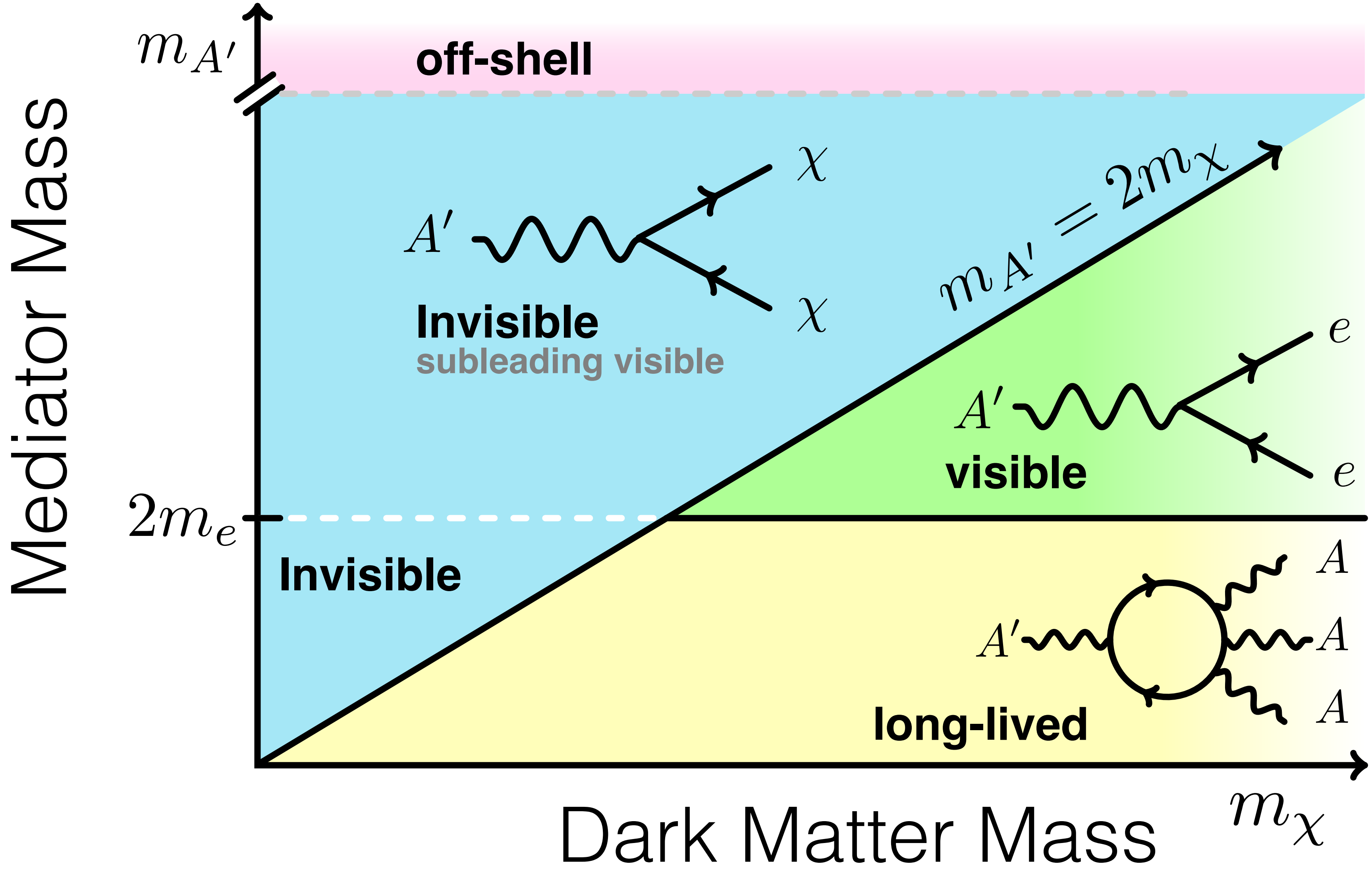
bremsstrahlung



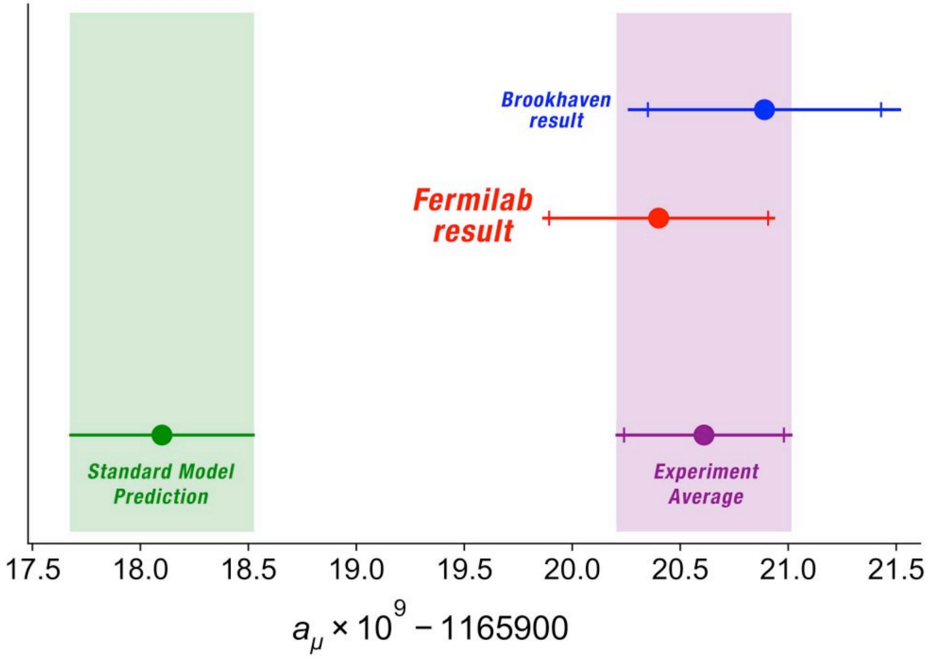
meson decay

Decays of Dark Photons

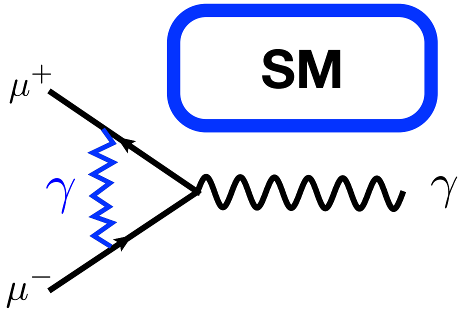
Adapted from Natalia Toro, Dark Sectors 2017 (1608.03591)



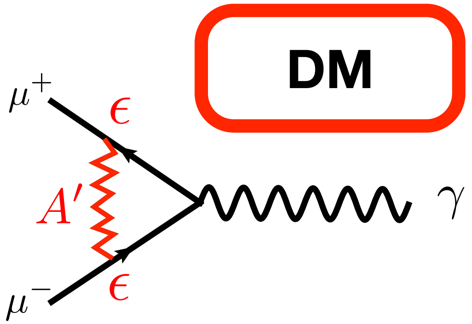
The muon (g-2): an additional motivation to search for dark photons



B. Abi, et al. Phys. Rev. Lett. 126, 141801 (2021)

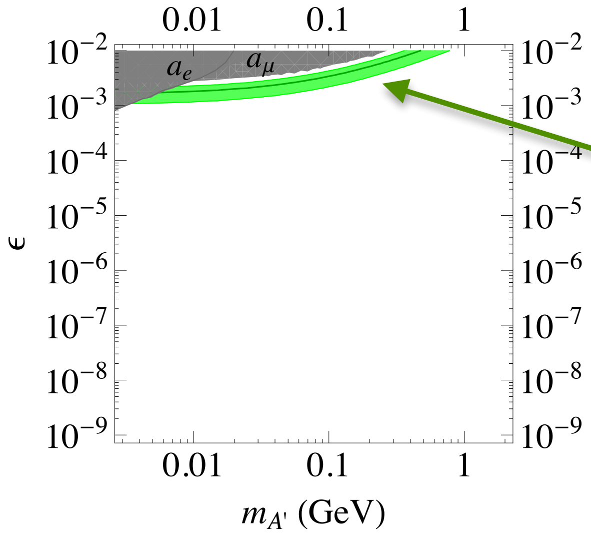


$$(g_s - 2)^{\gamma}_{\mu} \simeq \frac{\alpha}{2\pi}$$
$$\simeq 10^{-3}$$



$$(g_s - 2)^{A'}_{\mu} \simeq \frac{\alpha}{2\pi} \times \epsilon^2 \qquad (m_{A'} \ll m_\mu)$$
$$\simeq 10^{-3} \times \epsilon^2$$

M. Pospelov, A. Ritz and M. B. Voloshin, Phys. Lett. B 662, 53 (2008)

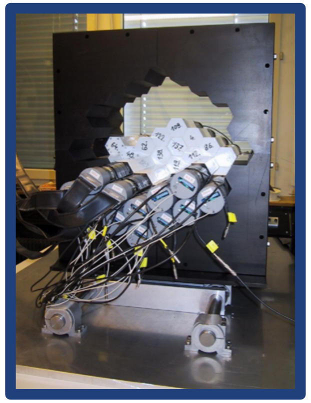


A' may explain observed anomaly

Searches for dark photons: David and Goliath

IPA ETH zürich

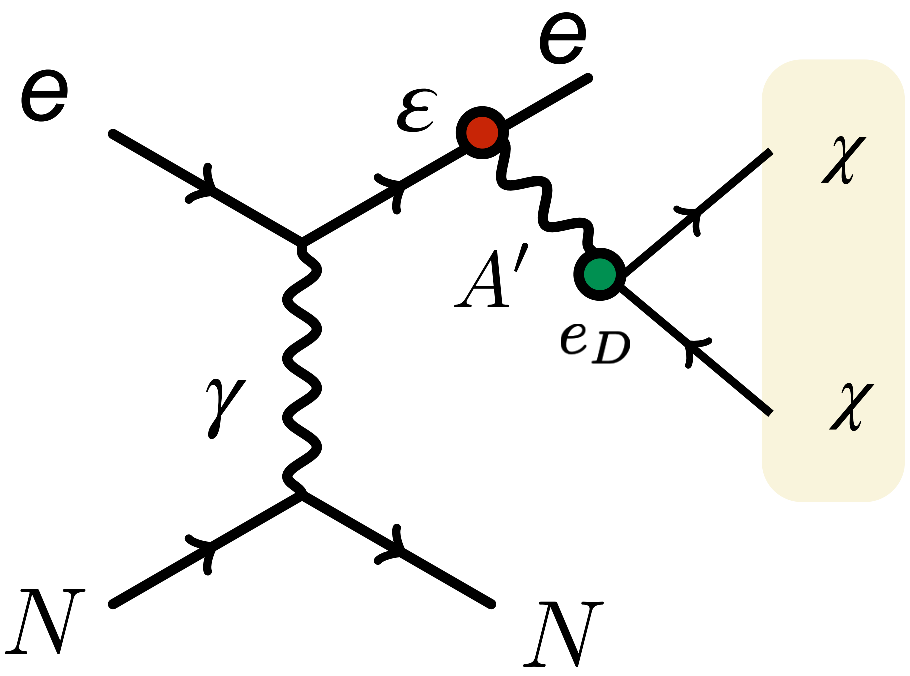
CERN



At rest vs 100 GeV

The NA64 search for A' → $\chi\bar{\chi}$

INVISIBLE DECAY MODE $m'_A > 2m_X$



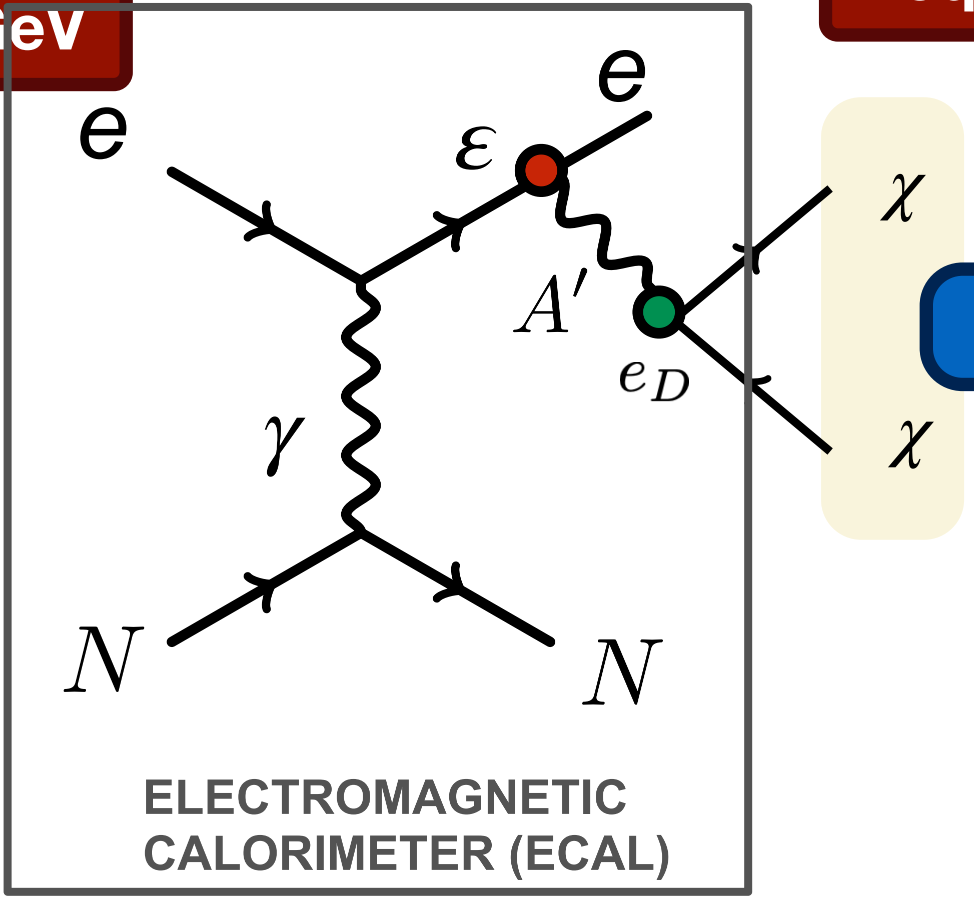
Missing Energy/momentum

The NA64 method to search for A’ $\rightarrow \chi\bar{\chi}$

TAGGED 100 GeV

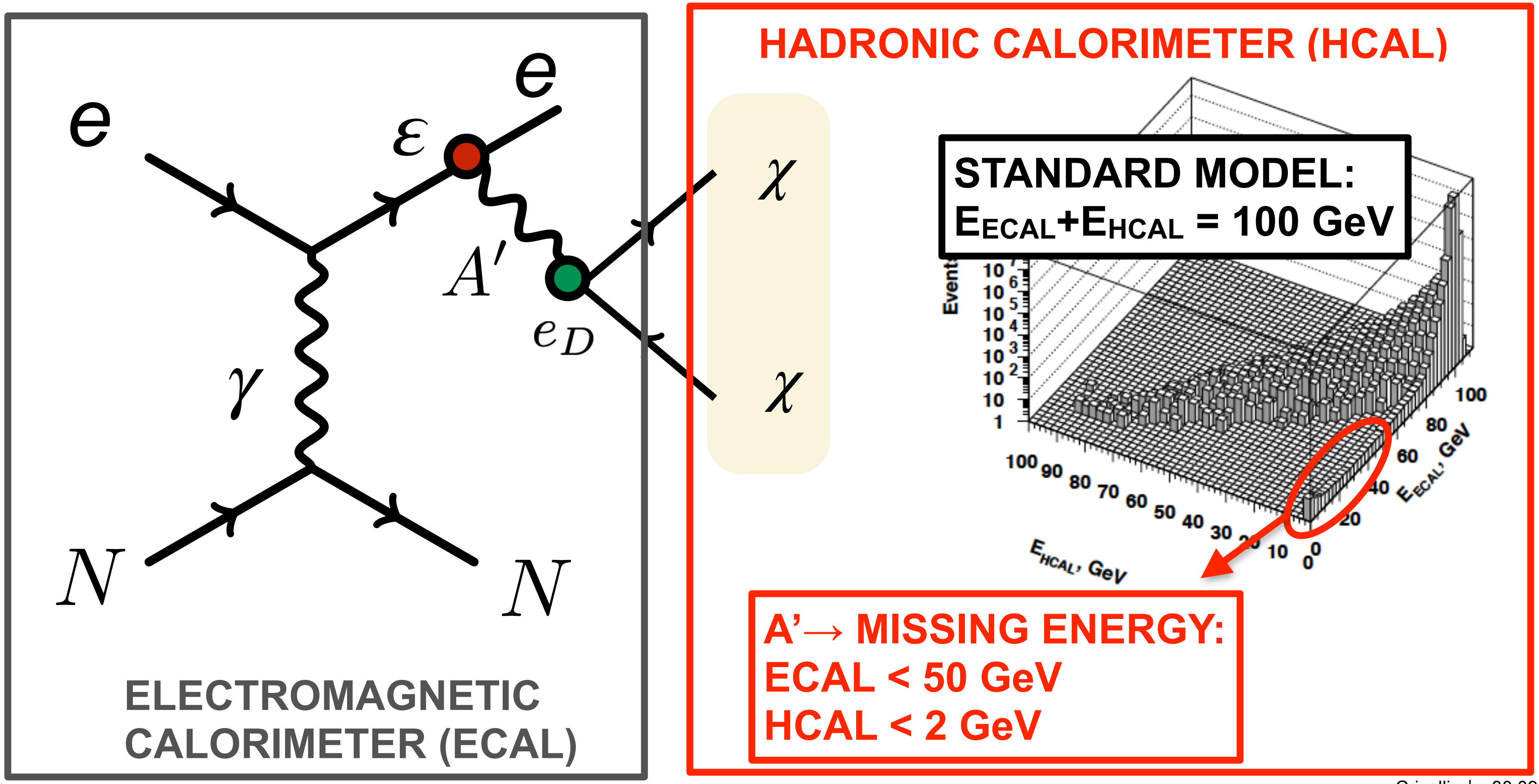
Requested ECAL ENERGY < 50 GeV

Active Dump

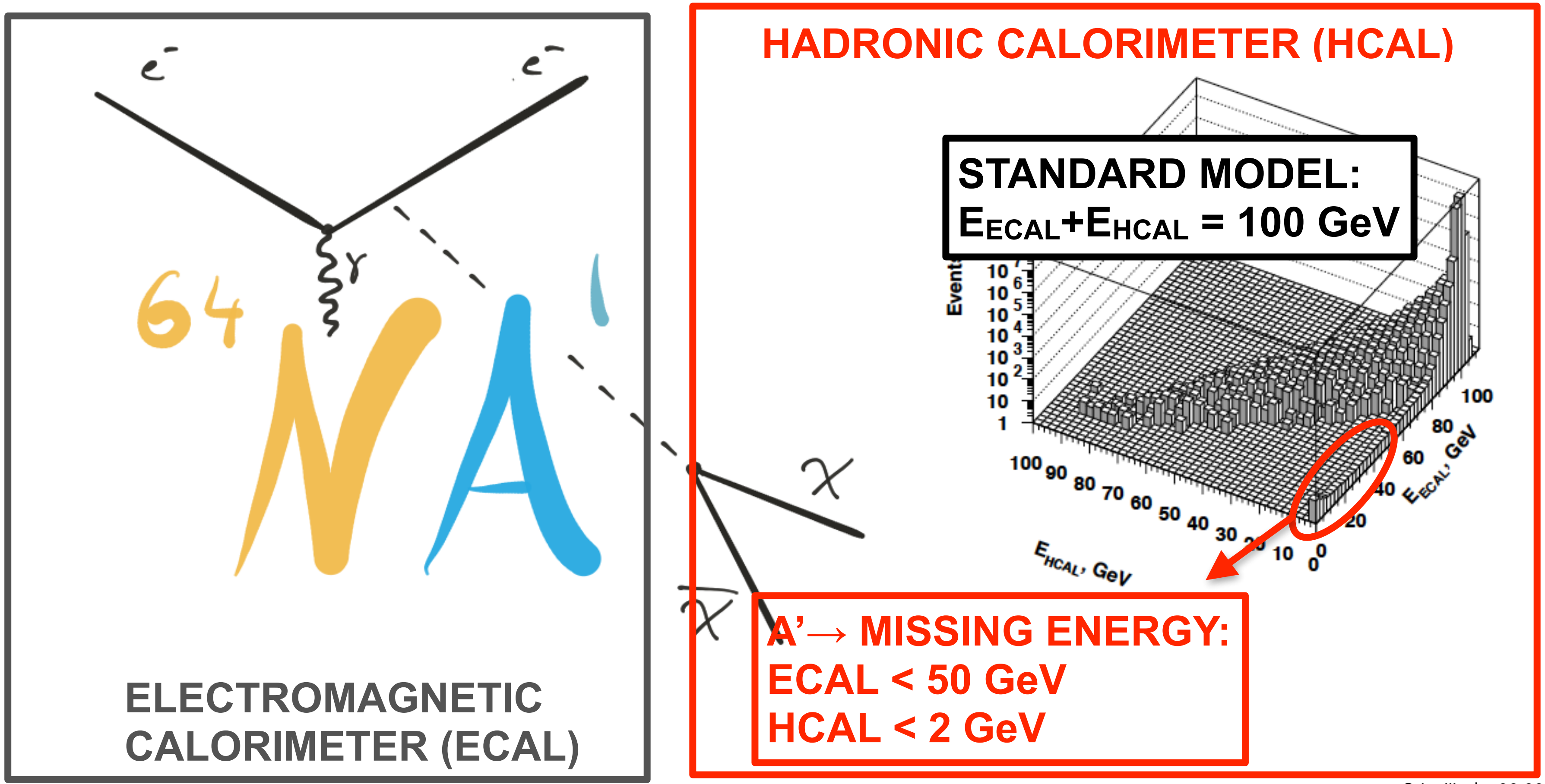


“BREMSSTRAHLUNG” OF A’

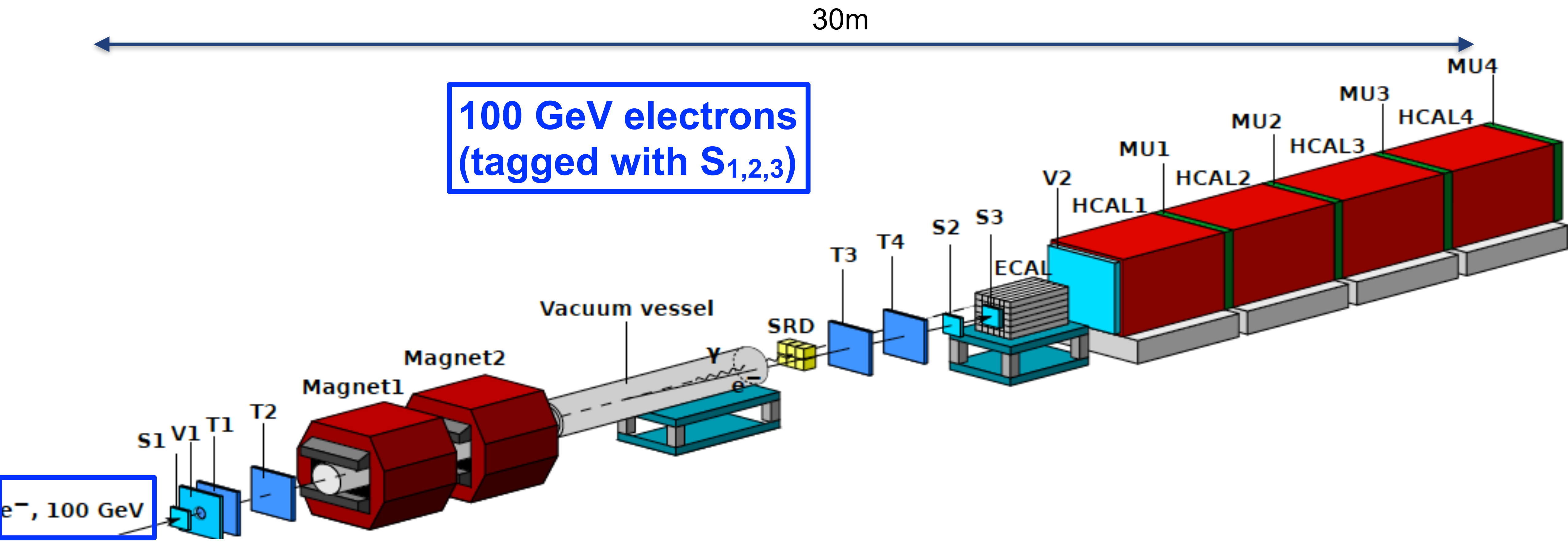
The NA64 method to search for A’ → $\chi\bar{\chi}$



The NA64 method to search for A’ $\rightarrow \chi\bar{\chi}$



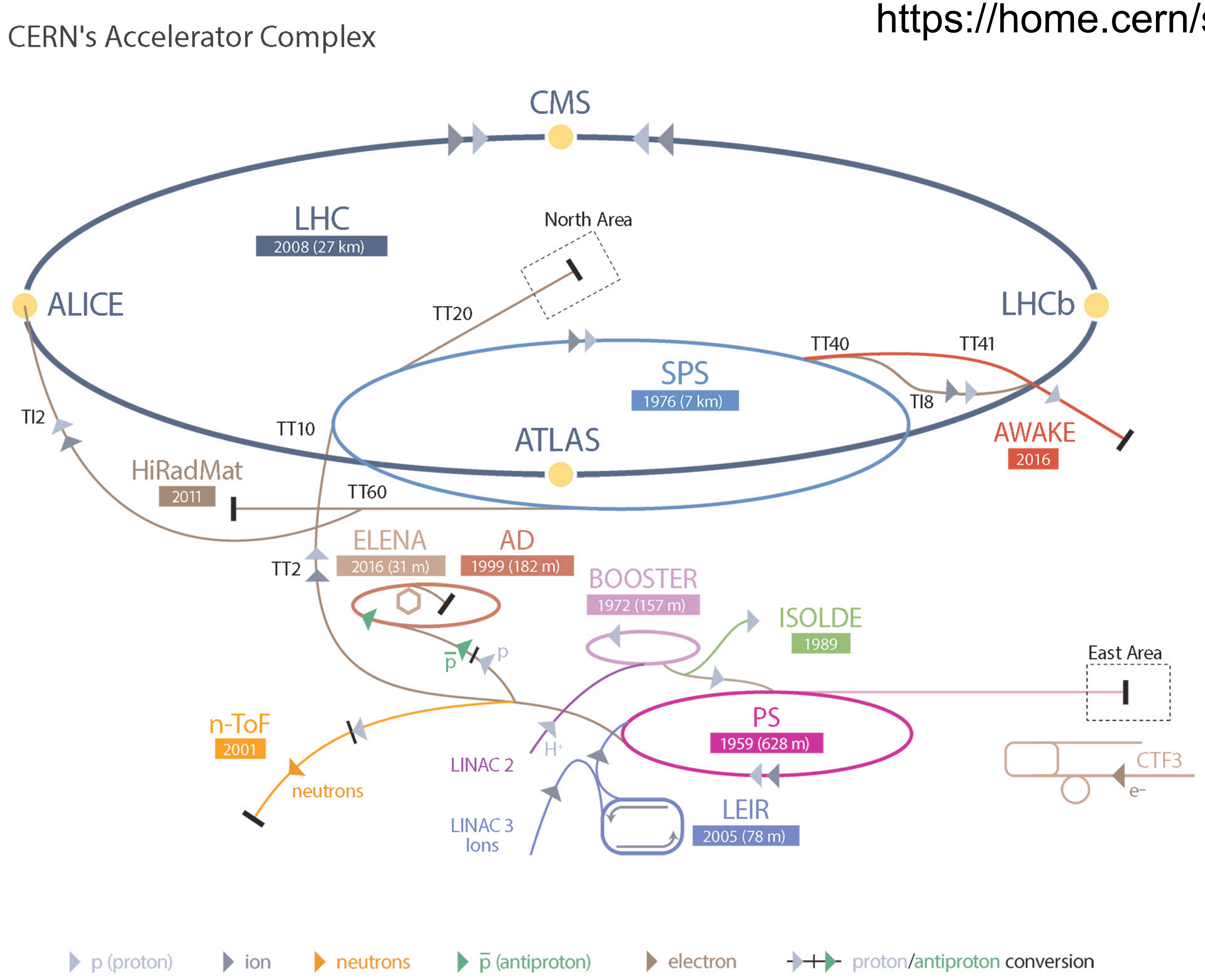
The CERN SPS H4 electron beam



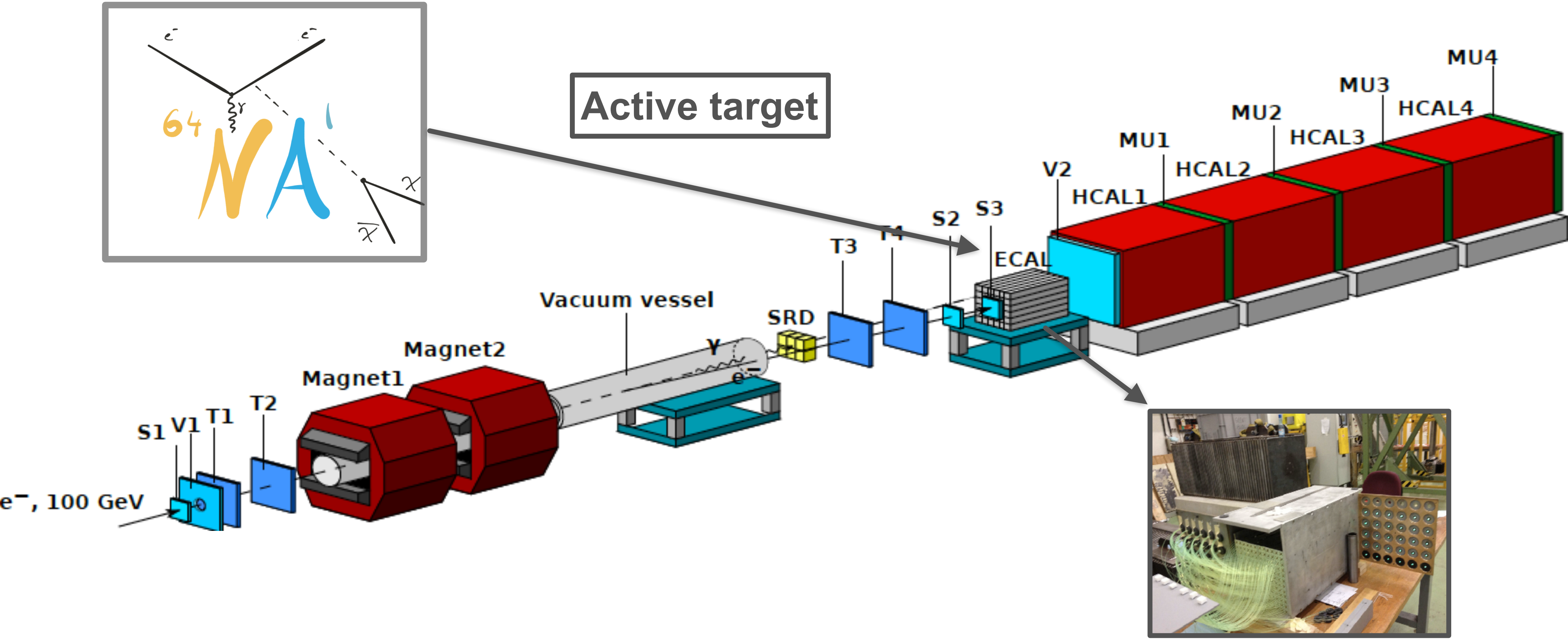
- Up to 7×10^{6} e^{-}/spill, 2-4 spill/min, spill duration 5s
- Low contamination: π (<1%), μ/K (0.1%)
- Low energy tails (<1%)
- Beam spot of 1.5 cm (FWHM)

The CERN SPS H4 electron beam

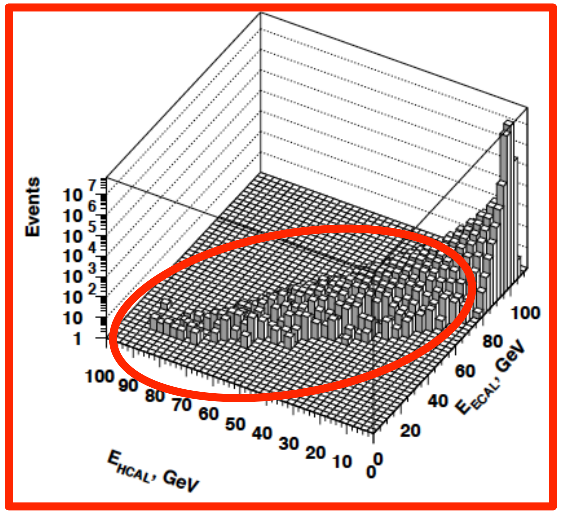
https://home.cern/science/accelerators



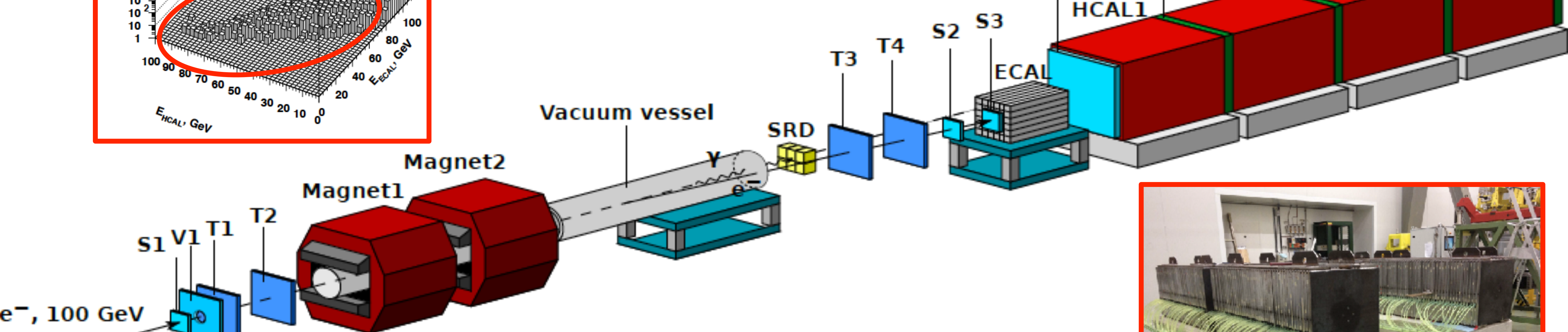
The Electromagnetic Calorimeter (ECAL)



The Hadronic Calorimeter (HCAL)



High hermeticity

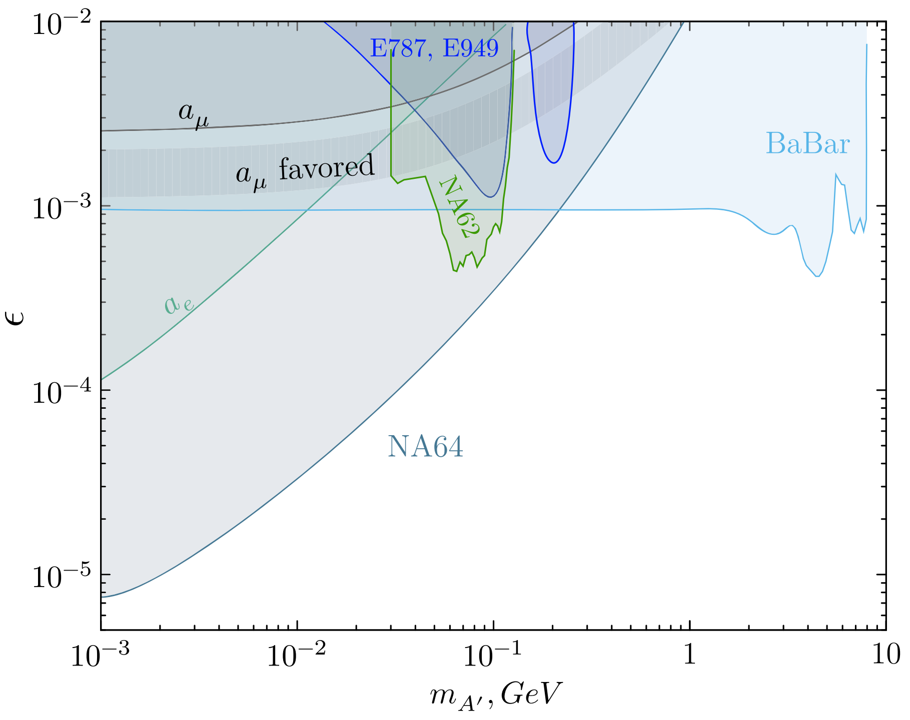


- High hermeticity : 4 HCAL (~7 λ/module)
- FeSc sandwich 3x3 matrix, cells 19.4x19.2x150 cm^3
- WLS fibers in spiral→ suppress energy leaks
- Energy resolution ~ 60%/√(E[GeV])

The NA64 search for A' → $\chi\bar{\chi}$ - *results combined analysis 2016-2018*

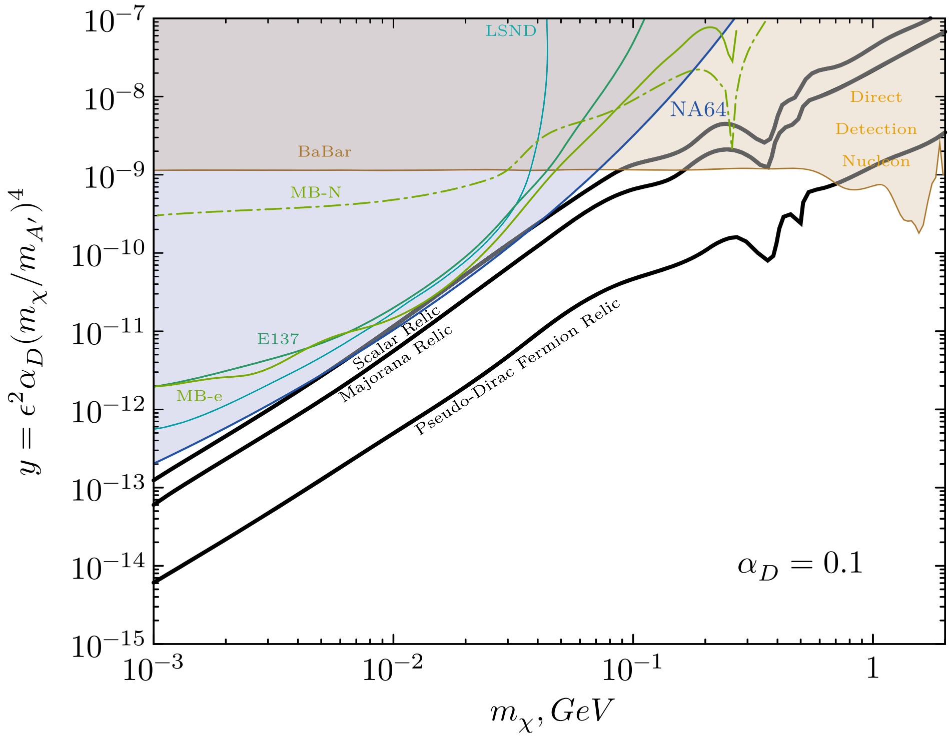
2.8 x 10^{11} electrons on target

COUPLING ε



MASS OF THE DARK PHOTON

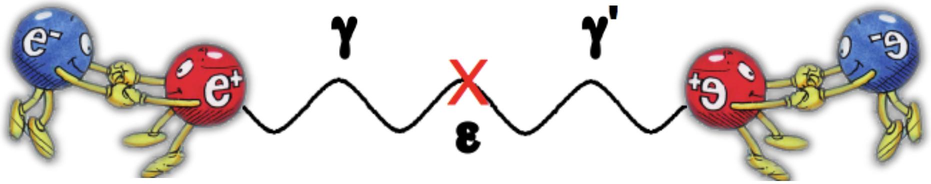
Y parameter



MASS OF THE DARK PHOTON

NA64 collaboration, Phys. Rev. Lett. 118, 011802 (2017)
NA64 collaboration, Phys. Rev. Lett. 123, 121801 (2019)

The Massless Dark photon case - Positronium

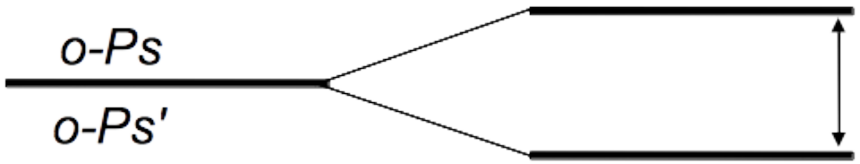


S. L. Glashow, Phys. Lett. B167, 35 (1986)

Coupling between oPs and oPs' ⇒ breaking of degeneracy

•

$$o-Ps^{+}=\frac{1}{\sqrt{2}}\left(o-Ps+o-Ps'\right)$$



$$\Delta E = 2h\varepsilon\nu$$

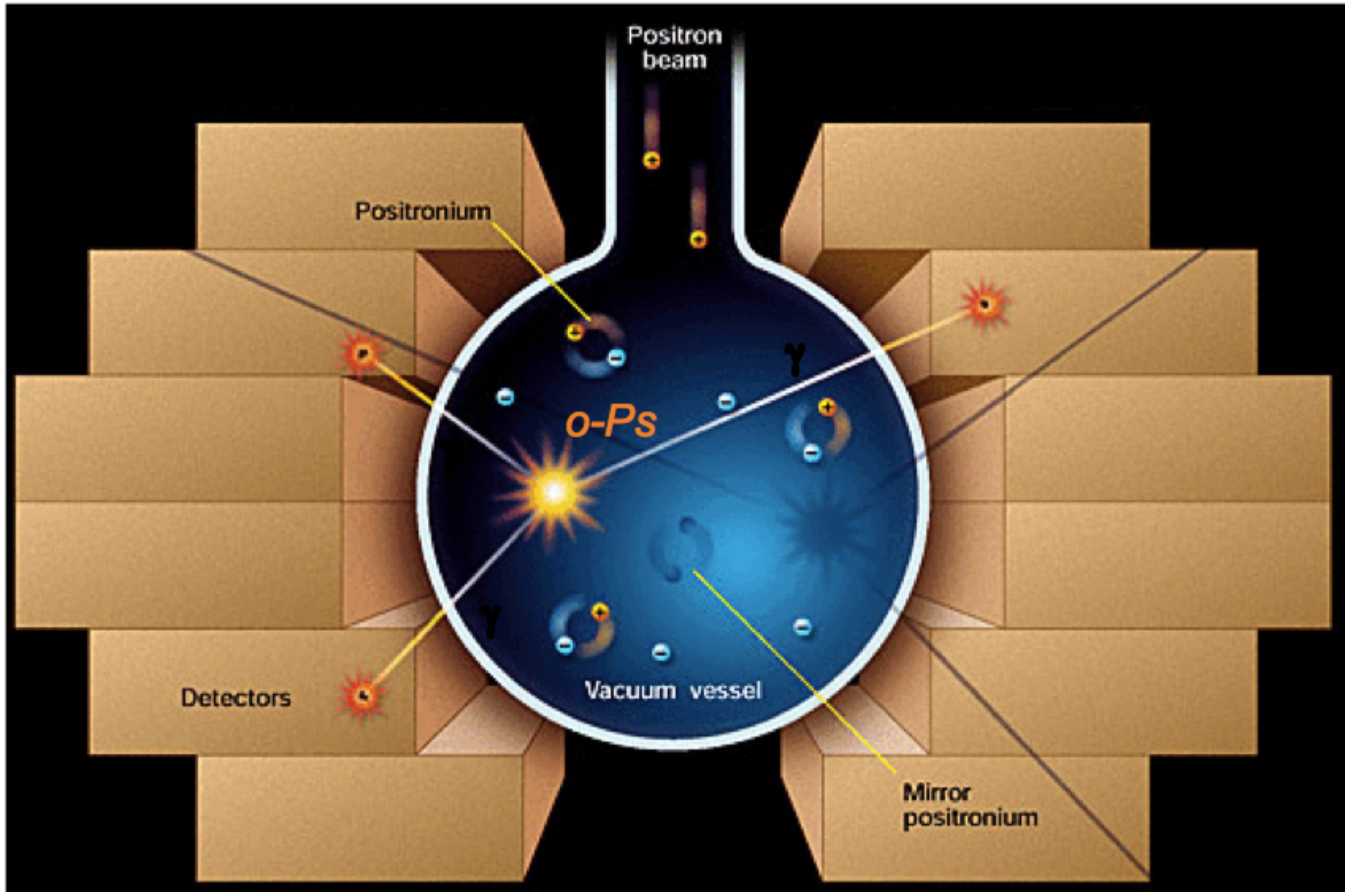
Energy splitting

$$o-Ps^{-}=\frac{1}{\sqrt{2}}\left(o-Ps-o-Ps'\right)$$

Rabi oscillation:

$$P\left(o-Ps \rightarrow o-Ps'\right)=\sin^{2}\left(2\pi\varepsilon\nu t\right)$$

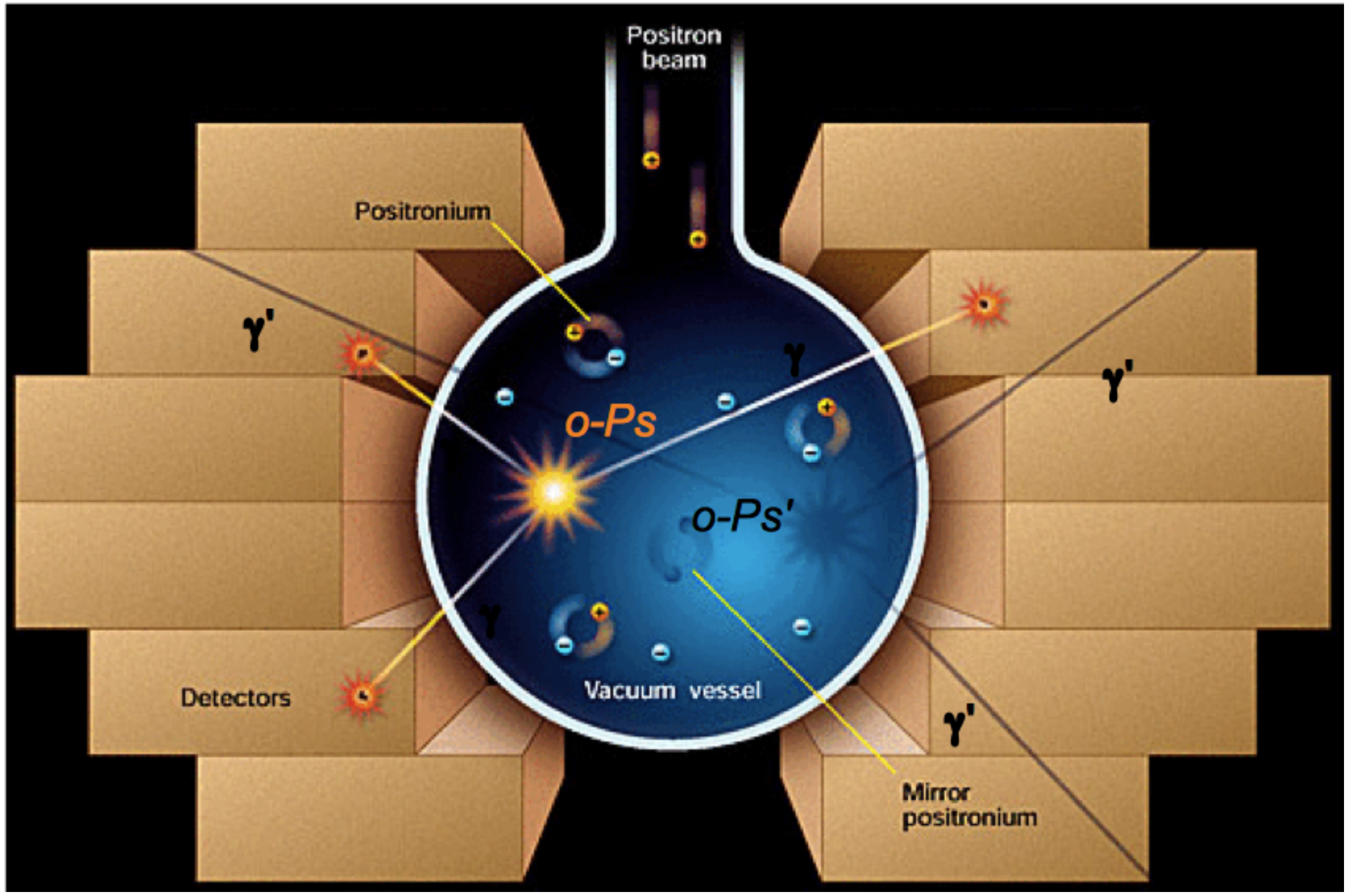
Experimental signature: oPs → invisible decay (missing energy)



Standard model decay: o-Ps → 3γ

→ energy deposition of 1022 keV (Ps mass, $E = mc^2$)

Experimental signature: oPs → invisible decay (missing energy)



Invisible decay: o-Ps → oPs' → 3γ'

→ no energy deposition (event compatible with 0 energy)

Results and Outlook for massless dark photon searches with oPs

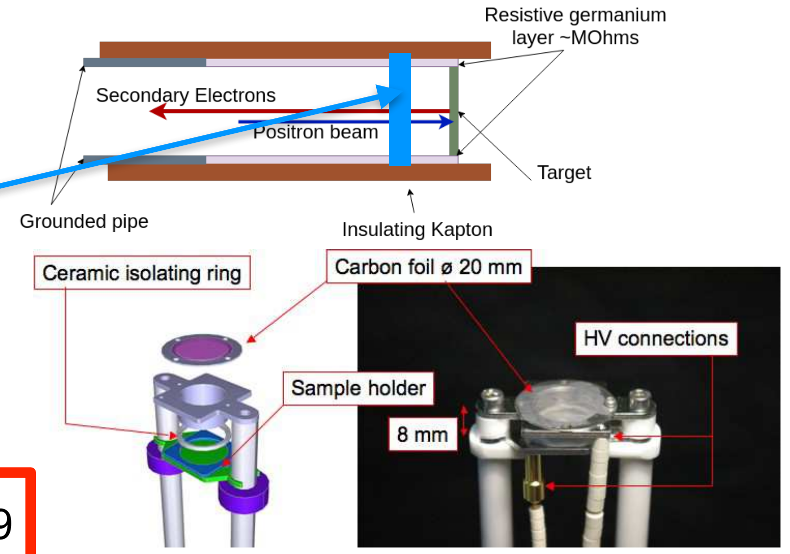
- Latest results: no excess above expected background observed
  → for the first time limit comparable to constraints from cosmology.

C. Vigo, P. Crivelli et al., PRL 124,101803 (2020)

- **Main limitations:** accidental triggers, positronium escaping the detection region

Possible improvements

- Higher e+ flux (Neon moderator) and better energy spread (Ni/W remoderator)
- Implementation of 10-20 nm carbon foil to block Ps escaping the detection region

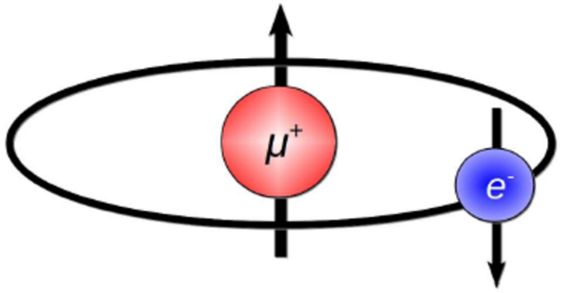


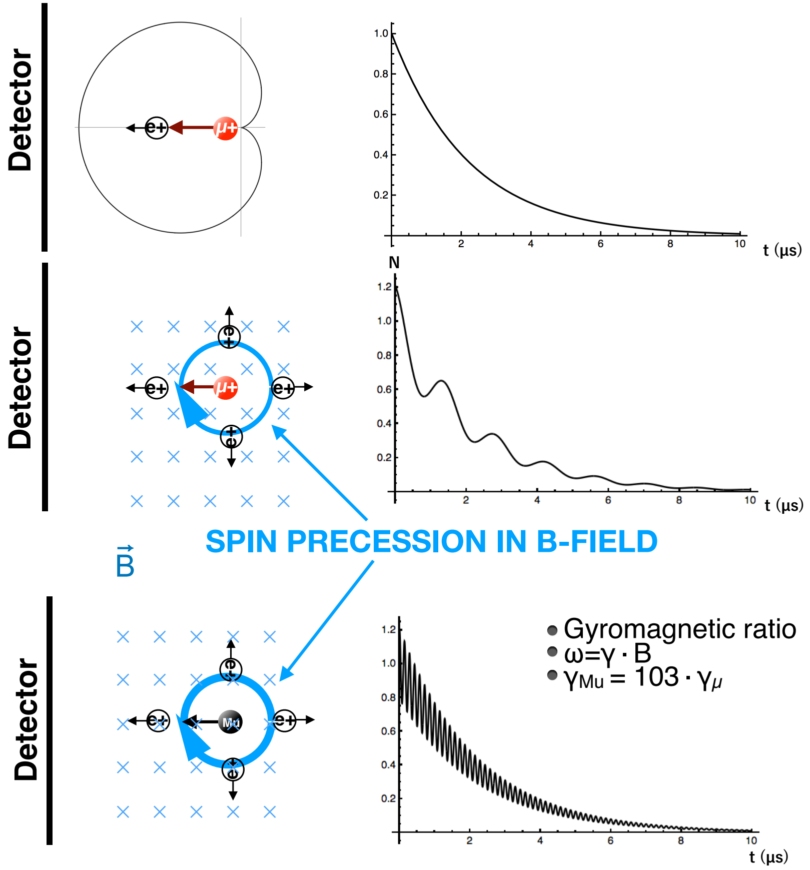
- GOAL: reach a sensitivity on mixing strength of $\epsilon \sim 10^{-9}$

(not excluded by cosmology, motivated by BSM theories…)

Another way to search for new bosons - muonium (M) atom

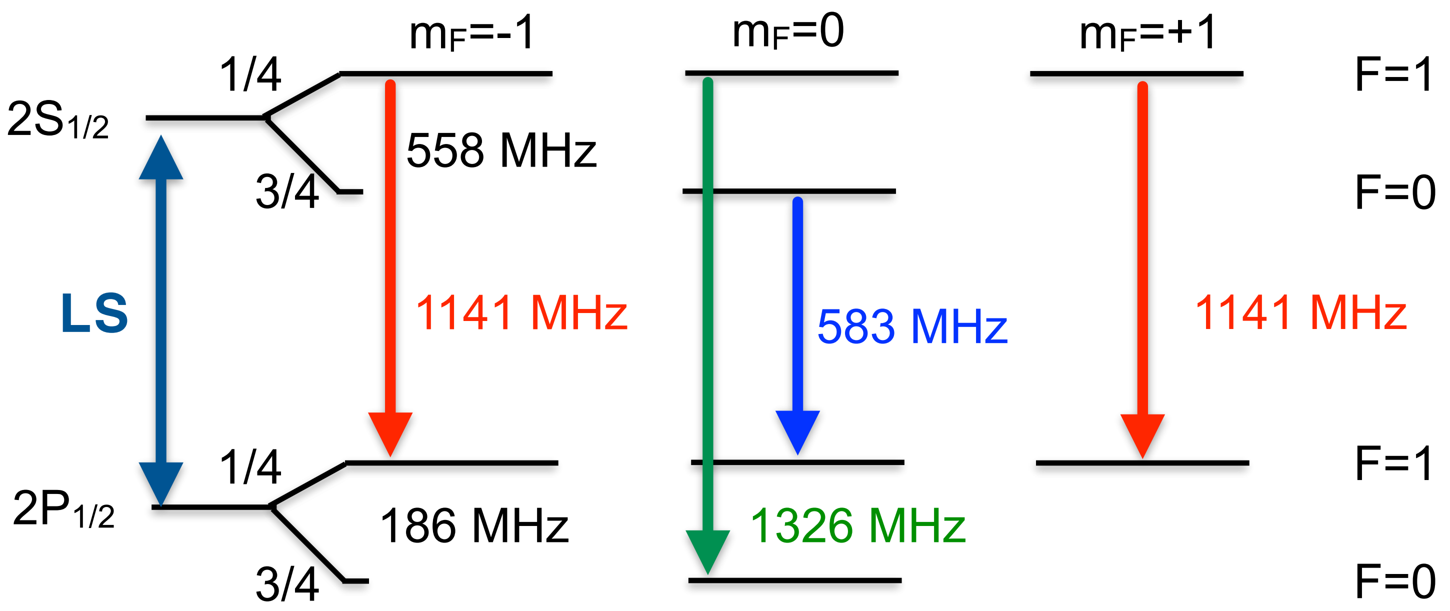
M (positive muon-electron bound state)
Predicted in 1957 (Friedmann, Telegdi, Hughes)
Unstable with lifetime of 2.2 μs.
Main decay channel: $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$





Discovered in 1960 (Hughes) by detecting muonium spin (Larmor) precession in an external magnetic field perpendicular to the spin direction.

Muonium Lamb shift



THEORY $(E(2S_{1/2}) - E(2P_{1/2}))^{\text{th}}_{\text{Mu}} = 1047.498(1)\ \text{MHz}.$

G. Janka, B. Ohayon and P. Crivelli, arXiv:2111.13951 (2021)
V. Yerokhin et al. ,Annalen der Physik 531, 1800324 (2019)
M. I. Eides, H. Grotch, and V. A. Shelyuto, Phys. Rep. 342, 63 (2001).
W. Liu, M. Boshier, S. Dhawan et al., Phys. Rev. Lett. 82, 711 (1999).

EXPERIMENT $(E(2S_{1/2}) - E(2P_{1/2}))^{\text{exp}}_{\text{Mu}} = 1042(22)\ \text{MHz}.$

C .J. Oram et al. Phys. Rev. Lett. 52, 910 (1984). DOI 10.1103/PhysRevLett.52.910. @ TRIUMF
K. Woodle, et al., Phys. Rev. A 41, 93 (1990). DOI 10.1103/ PhysRevA.41.93 @ LAMPF

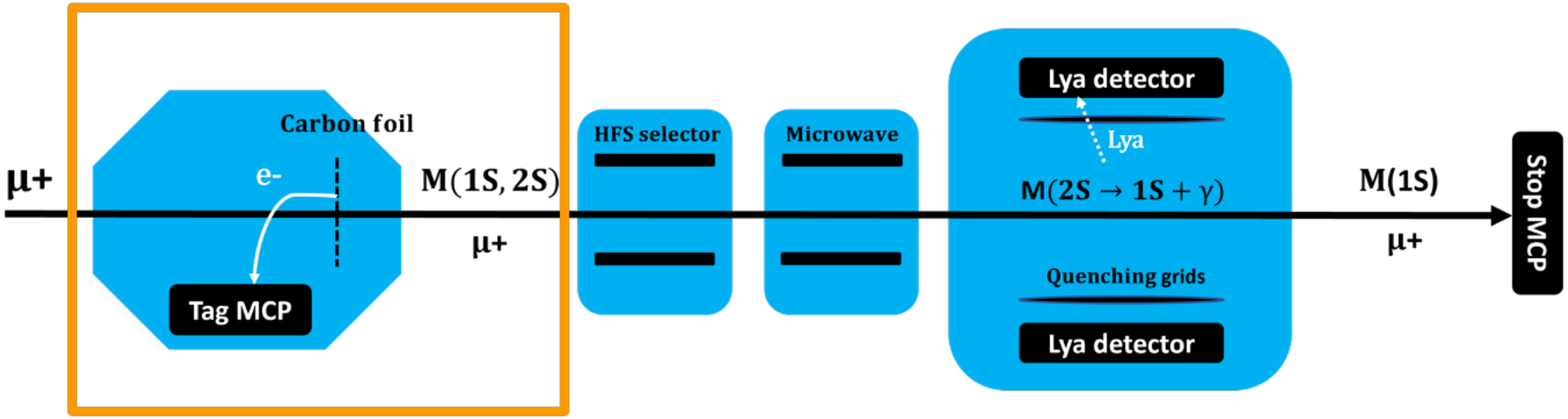
Measurement of M the Lamb shift

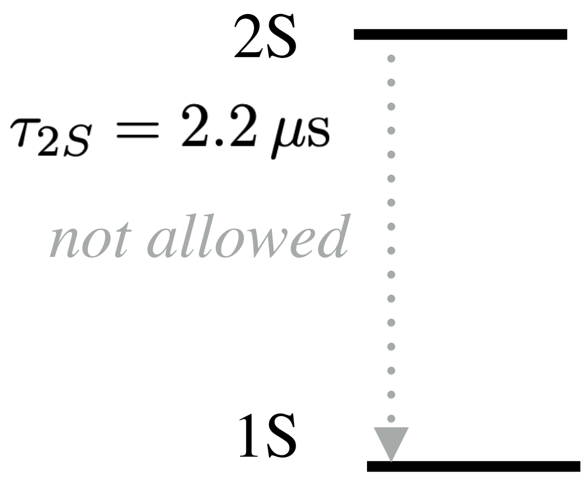
LEM beamline

10 kHz/
10 keV

PAUL SCHERRER INSTITUT
PSI

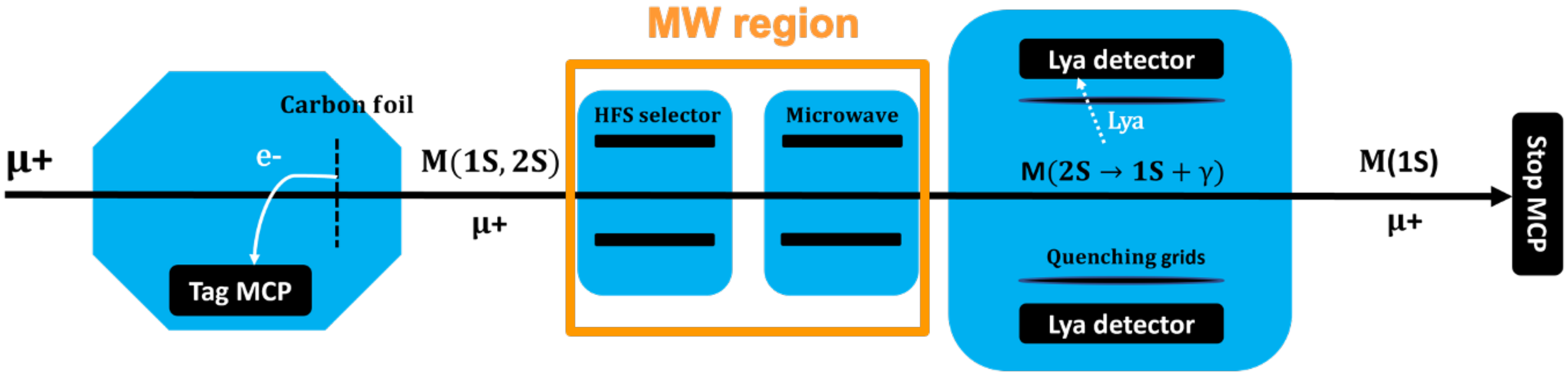
M(2S) formation & tagging

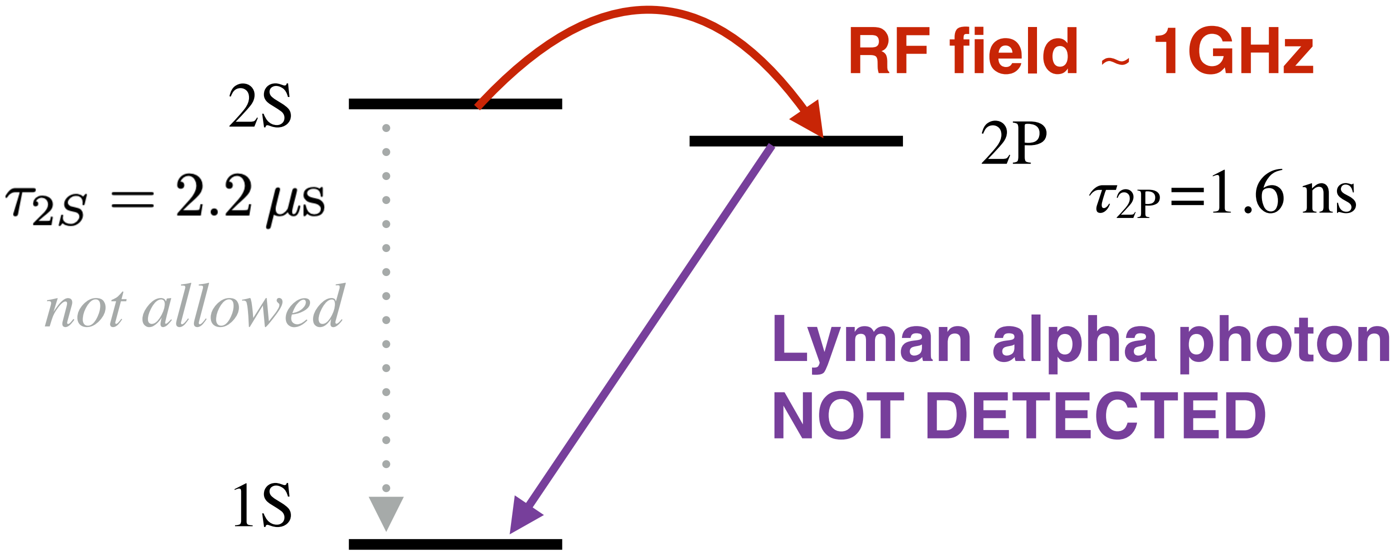




MU-MASS

Measurement of M the Lamb shift

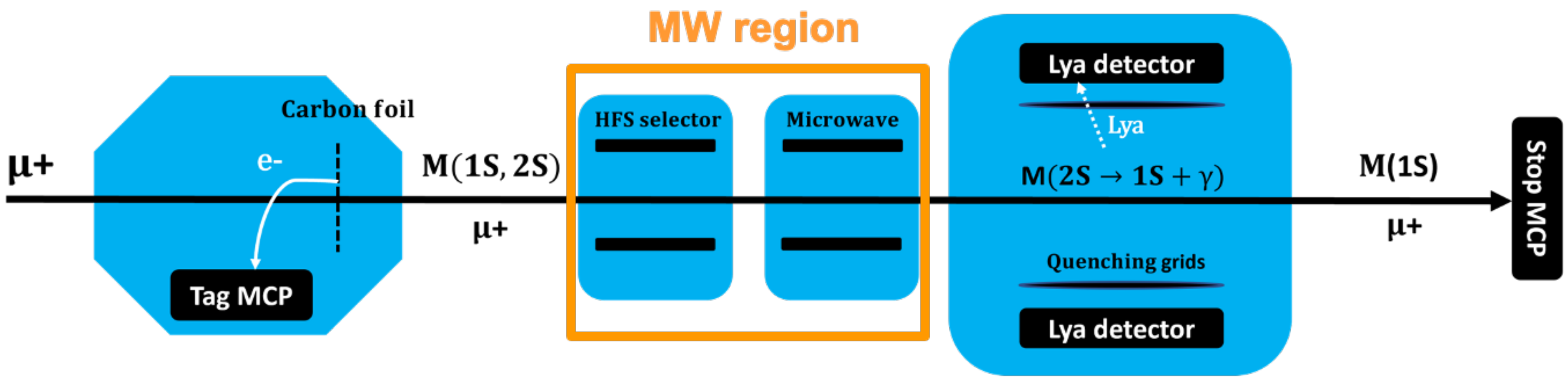


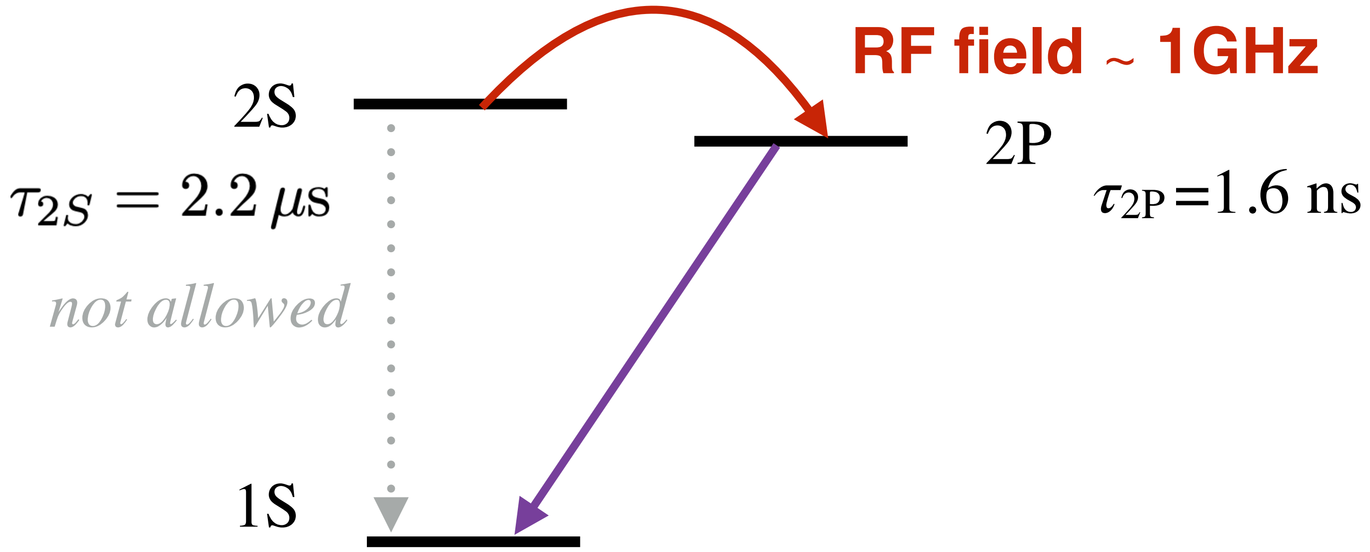


RF field ~ 1GHz

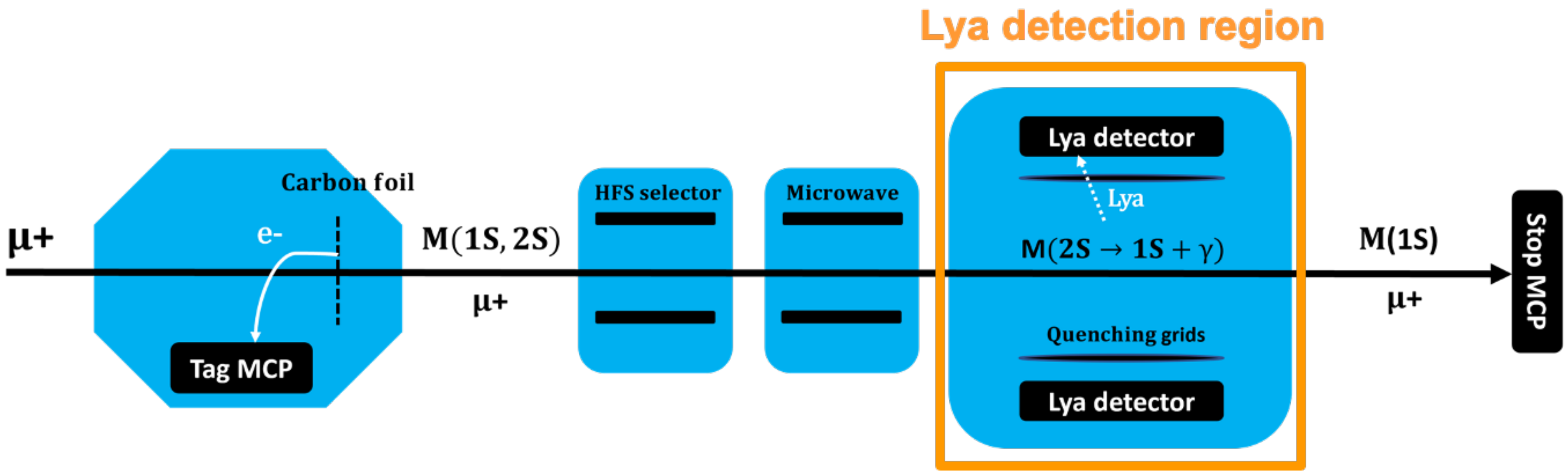
Lyman alpha photon (121 nm)
NOT DETECTED

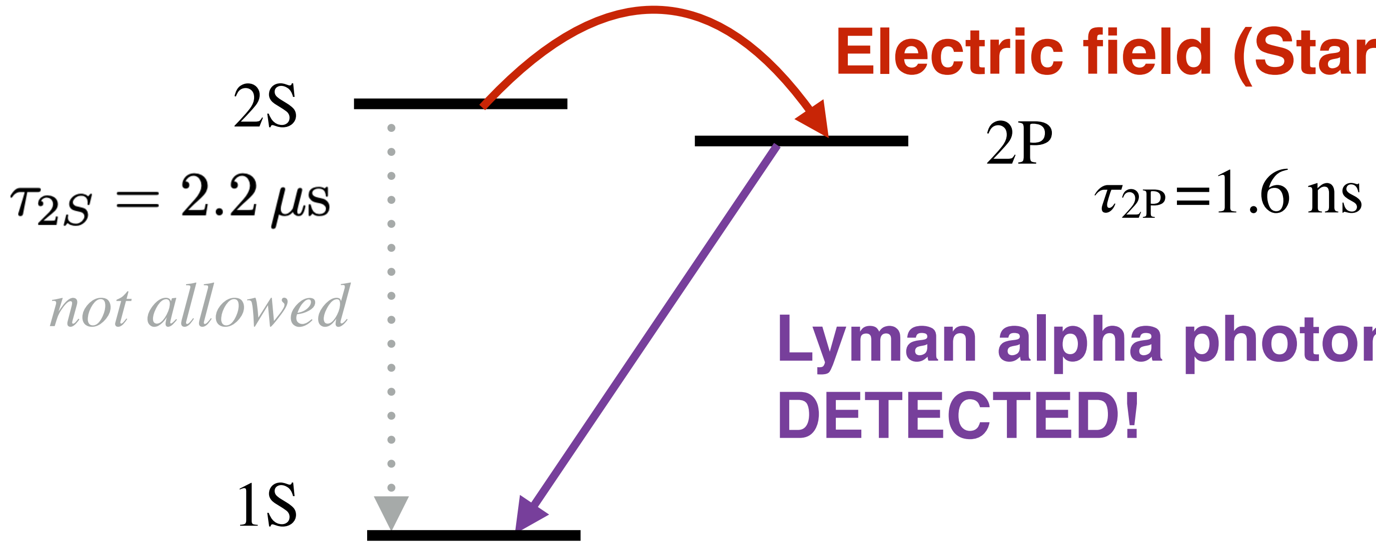
Measurement of M the Lamb shift





Measurement of M the Lamb shift

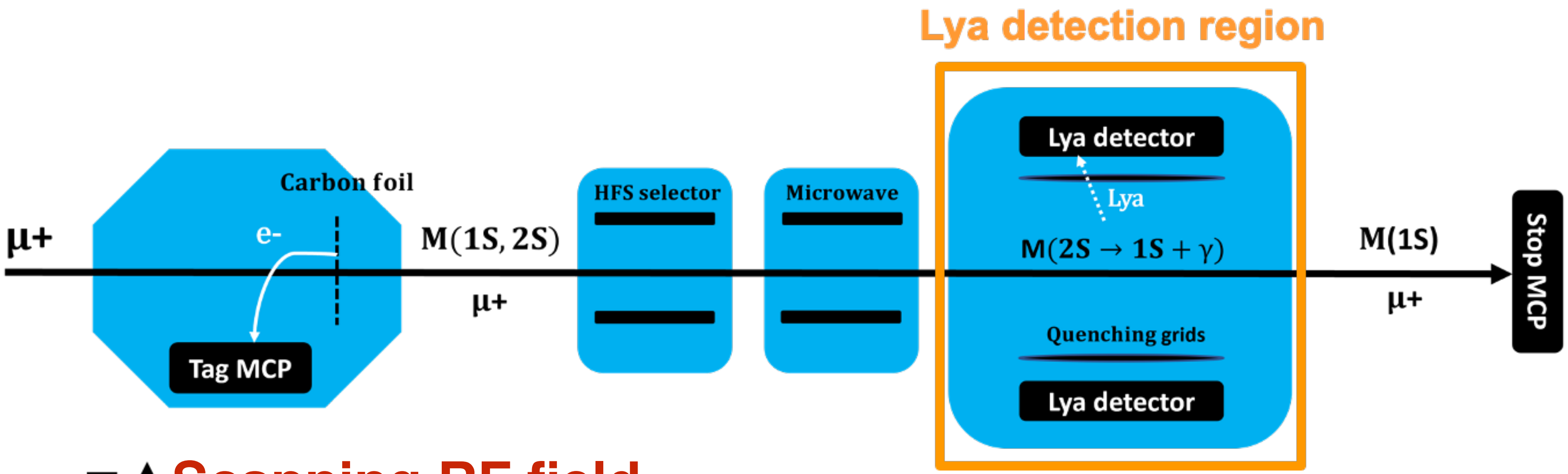


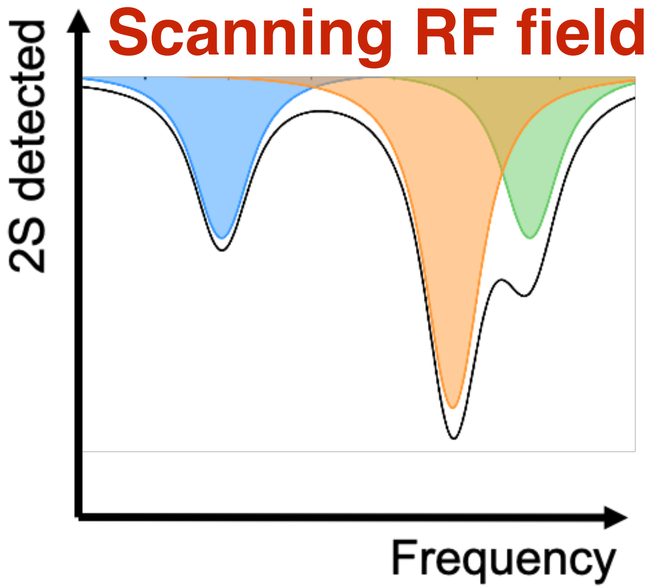


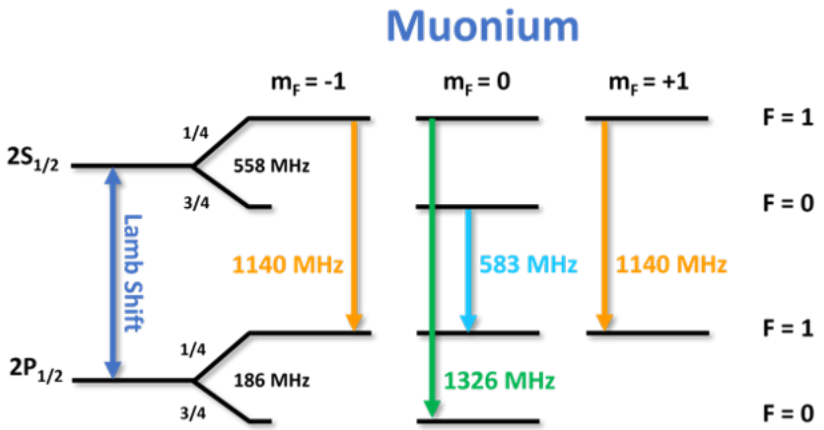
Electric field (Stark mixing)

Lyman alpha photon (121 nm) DETECTED!

Measurement of M the Lamb shift



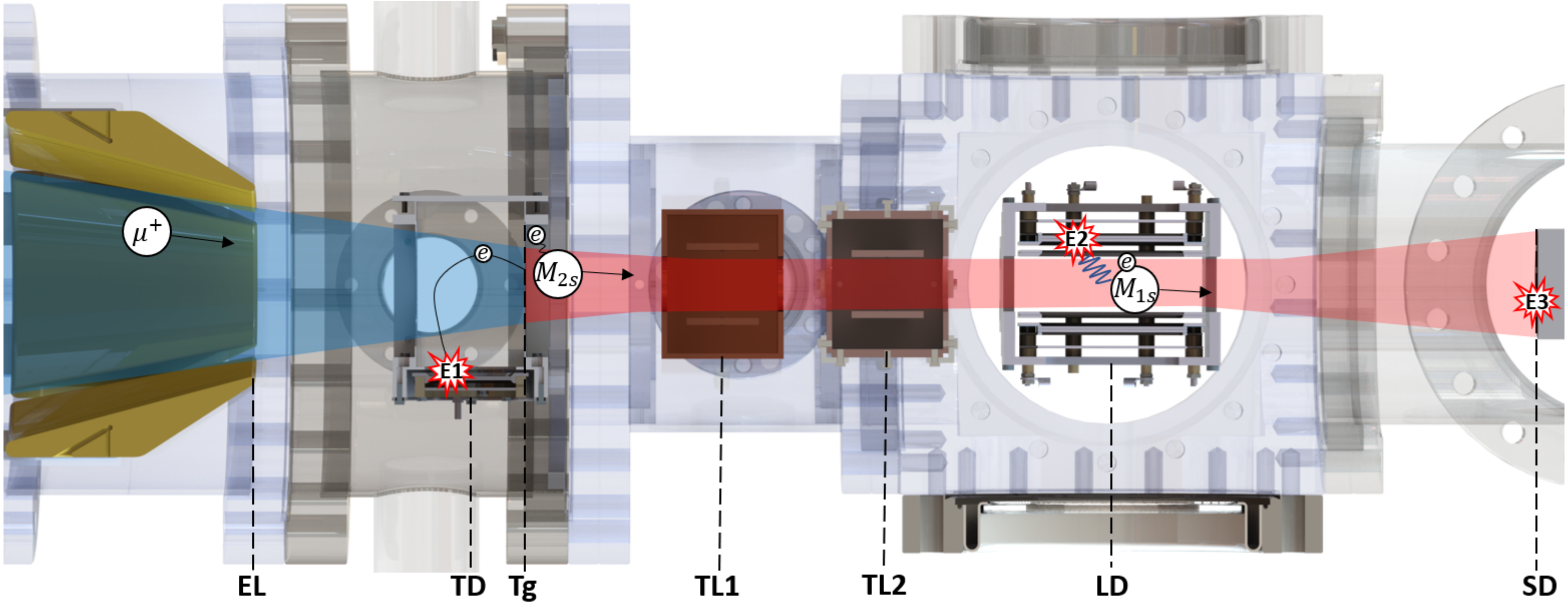




Measurement of M the Lamb shift

LEM beamline T. Prokscha et al., NIMA 595, 317 (2008)

LYMAN-ALPHA DETECTOR



TAGGING+M(2S) FORMATION

MW REGION (HFS SELECTOR + MW TRANSITION)

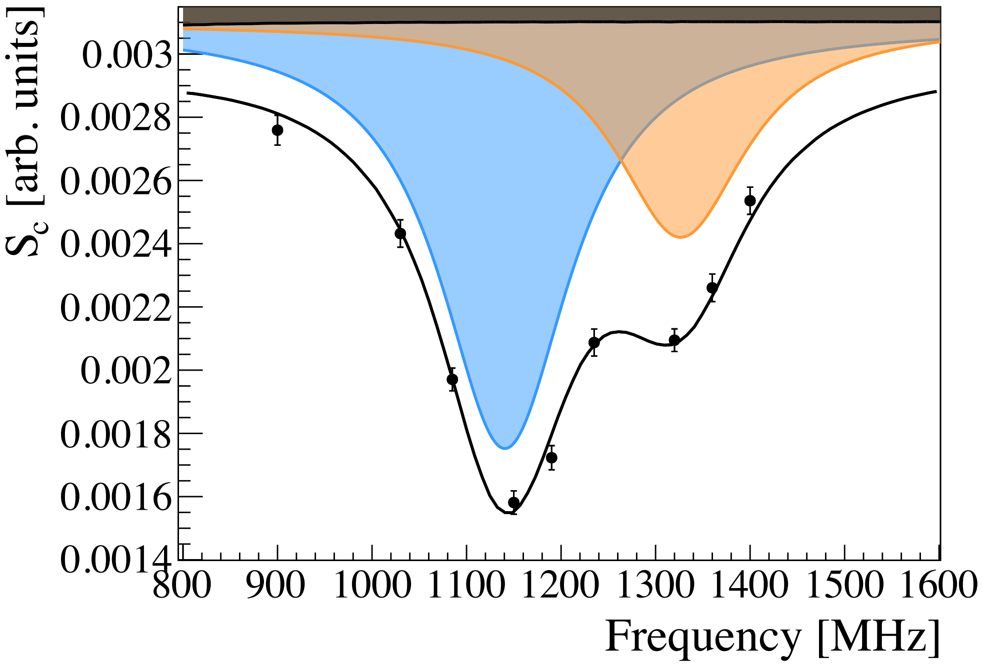
STOP DETECTOR

MU-MASS

Results of the M Lamb shift

B. Ohayon, P.Crivelli, et al. Phys. Rev Lett. 128, 011802 (2022)

48 HOURS DATA TAKING (100x statistics compared to previous measurements)



	Central Value	Uncertainty
Fitting	1139.9	2.3
4S contribution		< 1.0
MW-Beam alignment		< 0.32
MW field intensity		< 0.04
M velocity distribution		< 0.01
AC Stark $2P_{3/2}$	+0.26	< 0.02
2^{nd}-order Doppler	+0.06	< 0.01
Earth's Field		< 0.05
Quantum Interference		< 0.04
$2S_{F=1}-2P_{1/2,F=1}$	1140.2	2.5
Hyperfine	−93.0	0.0
Lamb Shift	1047.2	2.5
Theoretical value	1047.47	0.02

Results in **agreement with theoretical calculations**. Precision not enough to test b-QED but can be used to constraint new physics.

Searches for new bosons via positronium/muonium spectroscopy

- New bosons could mediate new forces resulting in shifts of Ps and M energy levels.

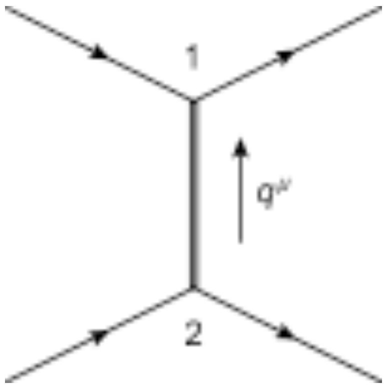
C Frugiuele et al., Phys. Rev. D100, 015010 (2019)

- Scattering between two fermions described by different potentials (scalar-scalar, vector-vector…)

P.Fadeev et al.,Phys. Rev. A 99, 022113 (2019)

We focus on the scalar-scalar potential:

$$V_{ss}(\vec{r}) = -g_1^s g_2^s \frac{e^{-Mr}}{4\pi r}$$



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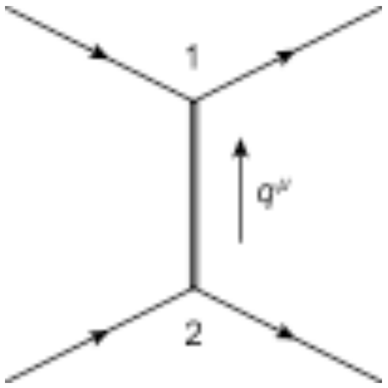


- Do you have an idea on how we could calculate the shift on the M energy levels induced by such a new scalar boson?

Searches for new bosons via positronium/muonium spectroscopy

- Using perturbation theory and plugging in the hydrogen wave functions (for positronium one needs to correct for the reduced mass, i.e $m_e \rightarrow m_e/2$

- Leading order corrections:

$$\langle V_{ss} \rangle = -\frac{g_1^s g_2^s}{4\pi} F_{n,l}^1(M)$$

$$F_{n,l}^k(M) = \langle \frac{e^{-Mr}}{r} \rangle_{n,l} \,, \; k = 1$$

	$l = 0$	$l = 1$	$l = 2$
$n = 1$	$\frac{4}{a_0(Ma_0+2)^2}$	X	X
$n = 2$	$\frac{2M^2a_0^2+1}{4a_0(Ma_0+1)^4}$	$\frac{1}{4a_0(Ma_0+1)^4}$	X
$n = 3$	$\frac{4(243M^4a_0^4+216M^2a_0^2+16)}{9a_0(3Ma_0+2)^6}$	$\frac{64(9M^2a_0^2+1)}{9a_0(3Ma_0+2)^6}$	$\frac{64}{9a_0(3Ma_0+2)^6}$

Searches for new bosons via positronium/muonium spectroscopy

- Perturbations

$$\Delta E_{ss}(2S^0 \to 1S^0) = \frac{g_1^s g_2^s}{4\pi}\left(\frac{4}{a_0(Ma_0+2)^2} - \frac{2M^2a_0^2+1}{4a_0(Ma_0+1)^4}\right)$$

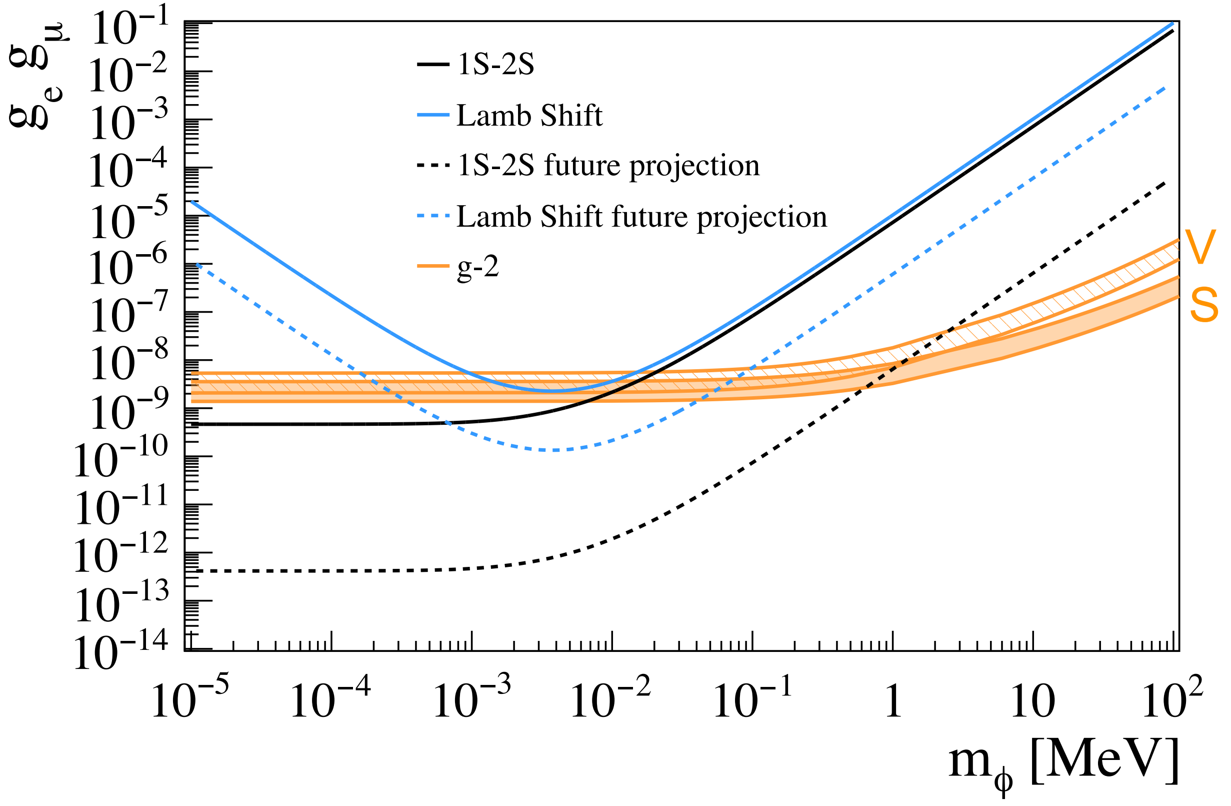
$$\Delta E_{ss}(2S^0 \to 2P^0) = \frac{g_1^s g_2^s}{4\pi}\left(\frac{1}{4a_0(Ma_0+1)^4} - \frac{2M^2a_0^2+1}{4a_0(Ma_0+1)^4}\right)$$

- To set a bound calculate the minimal value for a given M to exceed 2σ of theoretical result

$$g_\zeta^1 g_\zeta^2 > \frac{h \max_{\pm}\left|(\nu_{exp}-\nu_{the}) \pm 2\rho_{the,exp}\right|}{C_{transition}(M)}$$

where $\rho_{the,exp} = \sqrt{\rho_{the}^2 + \rho_{exp}^2}$ and $C_{transition}(M) = \frac{\Delta E_{\zeta\zeta}(transition)}{g_\zeta^1 g_\zeta^2}$

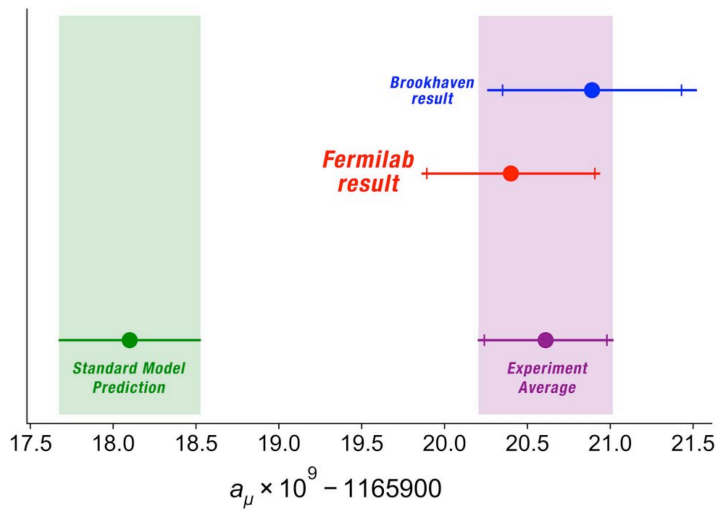
Muonium spectroscopy as a probe for new muonic forces

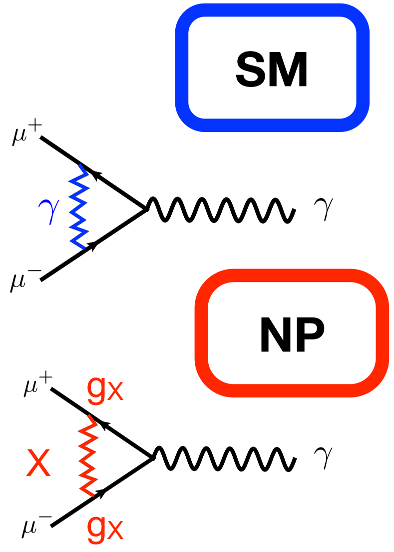


B. Ohayon, P.Crivelli, et al. Phys. Rev Lett. 128, 011802 (2022)

Bands: region suggested by **$(g\text{-}2)_\mu$**

B. Abi, et al. Phys. Rev. Lett. 126, 141801 (2021)





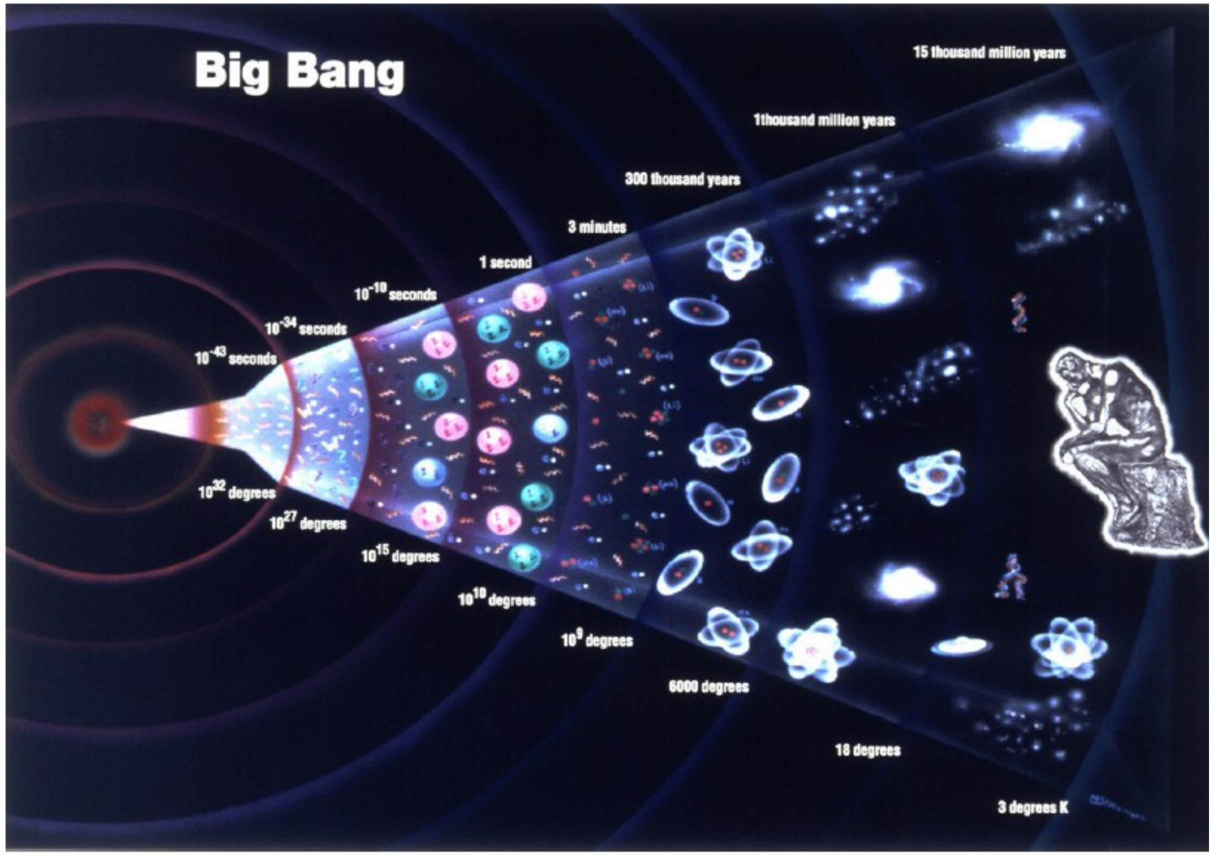
combined with bound from **$(g\text{-}2)_e$**

L. Morel et al, Nature 588, 61 (2020),
R. H. Parker et al., Science 360, 191 (2018).
D. Hanneke et al. e Phys. Rev. Lett. 100, 120801 (2008)

Baryon/anti-baryon asymmetry

Baryon/anti-baryon asymmetry

- **Why does the universe contain matter?**
  - After the Big Bang there should have been equal amounts of matter and anti-matter
- **Where did all the anti-matter go?**
  - We (matter) have annihilated anti-matter.
  - We won at the expense of a billion of twins.
  - Why was there a tiny asymmetry such that we could survive?



How do we know that there are no anti-stars/anti-galaxies out there and that we leave in a matter dominated region of the Universe?

How to generate such an asymmetry?

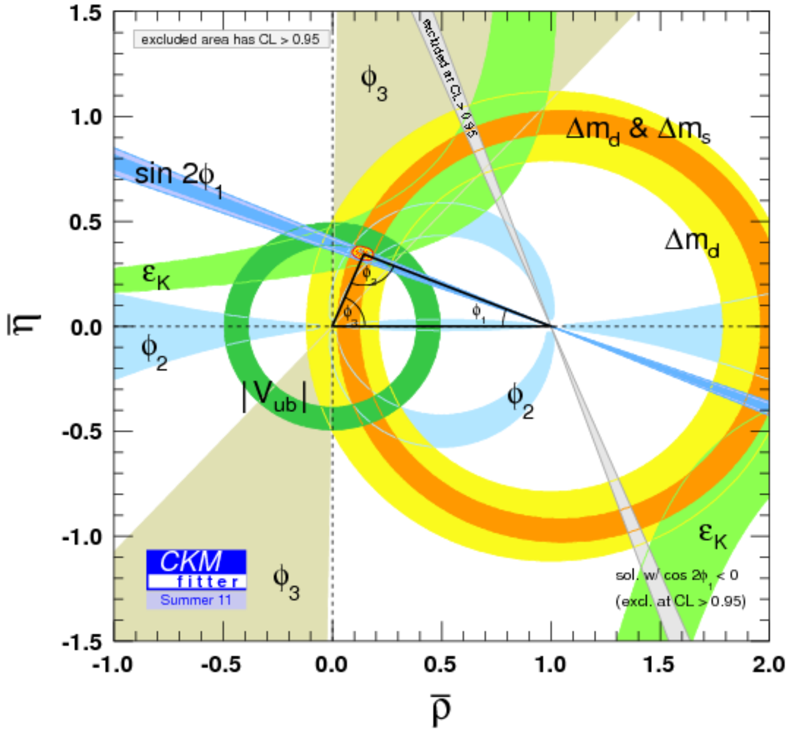
Three necessary conditions to generate Baryon-Antibaryon-Asymetry (BAU)

Andrei Sakharov
1921-1989
Russian physicist

(1) Baryon number B violation;
(2) C-symmetry and CP-symmetry violation; needed so that interactions producing more baryons than anti-baryons are not counterbalanced by interactions producing more anti-baryons than baryons.
(3) Interactions out of thermal equilibrium; otherwise, CPT symmetry would assure compensation between processes increasing and decreasing the baryon number.

The Standard Model is not enough

- CP violation well established in the quark sector (described by phase of CKM matrix)
  - Too small to explain baryon asymmetry (SM only explains 10^{-10} of what we need!)
- Need new phenomena such as:
  - **CP violation in the leptonic sector**
  - **Lorentz/CPT violation**



$$\bar{\rho} + i\bar{\eta} = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$

The Standard Model Extension (SME)

$$\mathfrak{L}_{\mathrm{SME}} = \underbrace{\mathfrak{L}_{\mathrm{SM}} + \mathfrak{L}_{\mathrm{GR}}}_{\text{Conventional physics}} + \underbrace{\mathfrak{L}_{\mathrm{LV}}}_{\text{Lorentz violation}}$$

Colladay and Kostelecky., PRD **55**, 6760 (1997)
Colladay and Kostelecky., PRD **58**, 116002 (1998)
Kostelecky., PRD **69**, 105009 (2004)

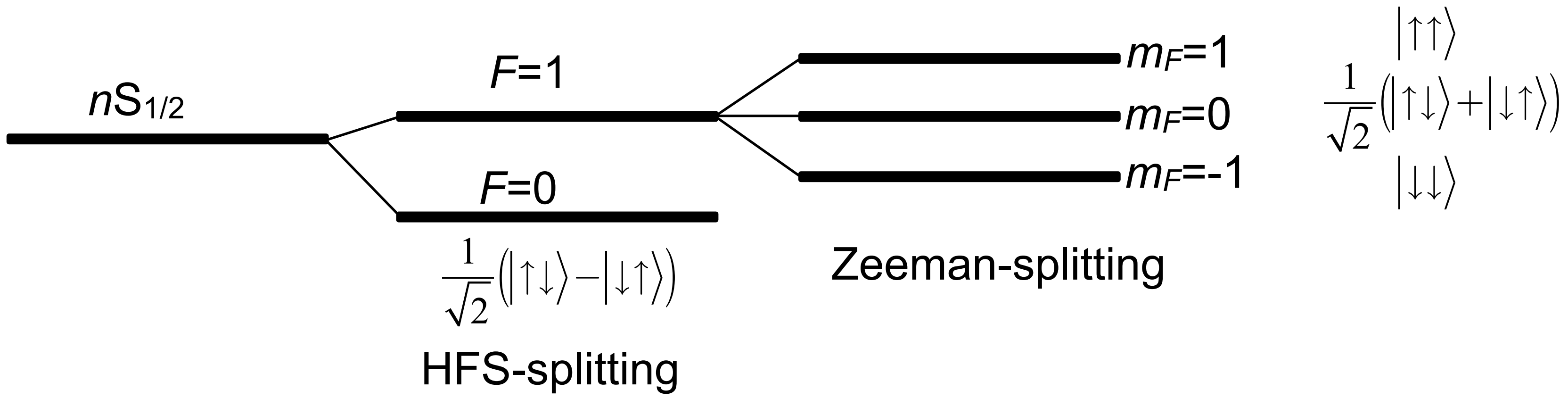
High precision spectroscopy as a sensitive test

$$\epsilon = \epsilon_0 + \delta\epsilon$$

Conventional case (→ ϵ_0)

Lorentz-violating contribution (→ $\delta\epsilon$)

Conventional case

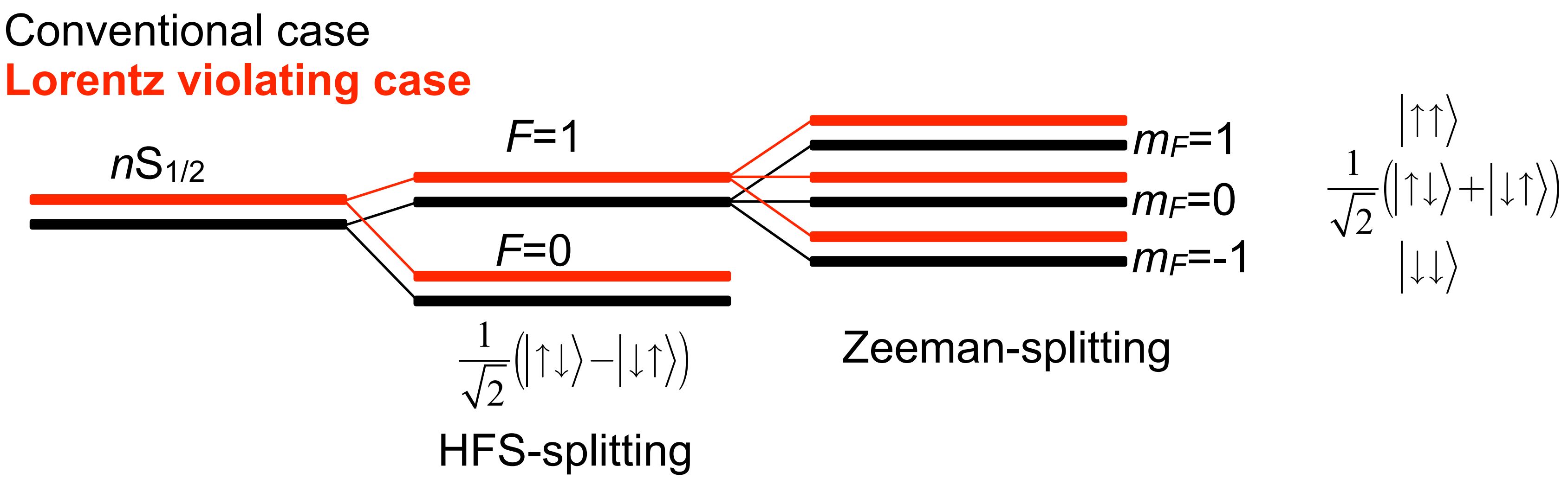


High precision spectroscopy as a sensitive test

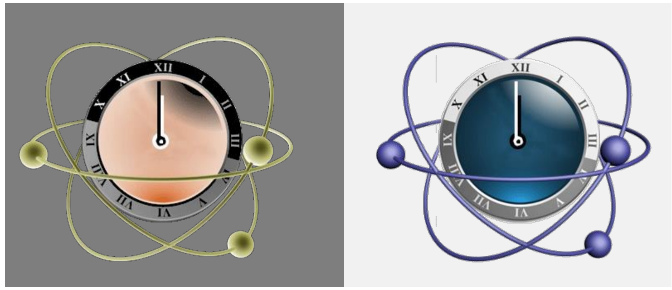
$$\epsilon = \epsilon_0 + \delta\epsilon$$

Conventional case (ϵ_0)

Lorentz-violating contribution ($\delta\epsilon$)



High precision spectroscopy of anti hydrogen as a sensitive test



- Lorentz-violating energy shift for matter

$\neq$

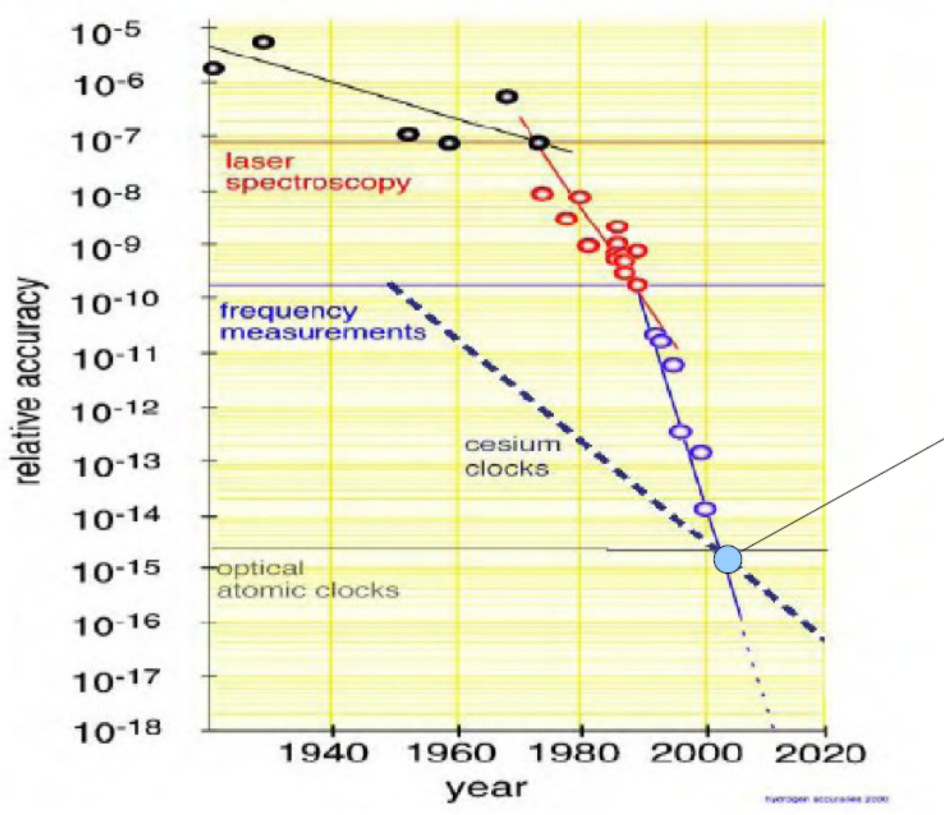
- Lorentz-violating energy shift for anti-matter

Anti-hydrogen - hydrogen comparison

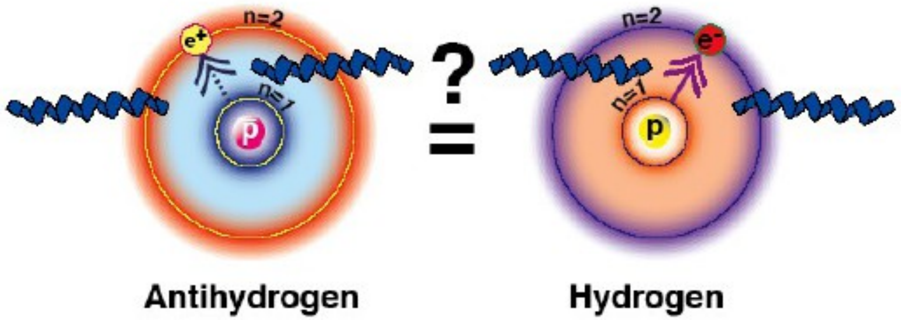
An extremely well measured number in atomic physics

2 466 061 413.187035(10) MHz

Hydrogen spectroscopy is now at a relative accuracy of 10^{-15}



Partney et al., Phys. Rev. Lett. 107, 203001 (2011)

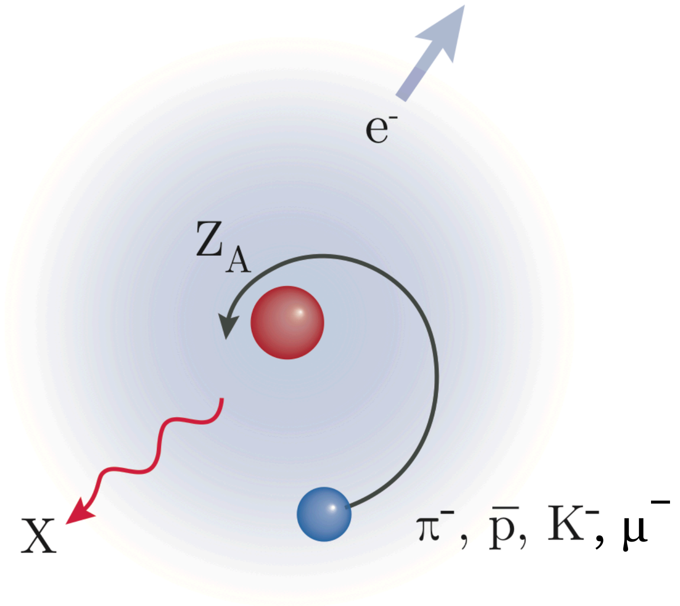


Challenges of creating antihydrogen

Hard! A bound system occupies small part of the phase-space

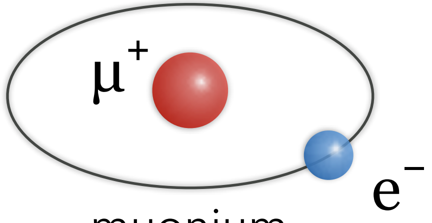
Negative particle

muonic / pionic / antiprotonic… atom

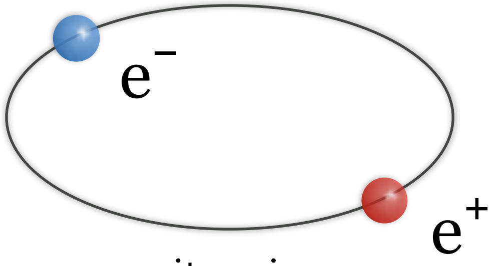


Positive particle

In matter



muonium

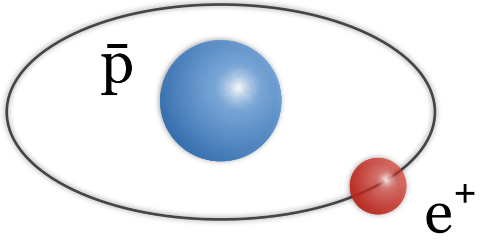


positronium

True onium! (particle-antiparticle)

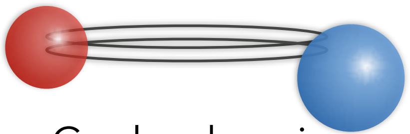
Both exotic

In trap



anti-atoms

In accelerator



Coulomb-pairs (protonium, pion-kaon…)

Formation of antihydrogen

1) Direct spontaneous radiative recombination

$$\mathrm{\bar{p}} + \mathrm{e}^+ \rightarrow \mathrm{\bar{H}} + \mathrm{h}\nu, \quad \Gamma_{\mathrm{srr}} \sim n_e T_e^{-0.63}$$

Dipole allowed free-bound transition that favours capture into strongly bound state.

2) Three body recombination

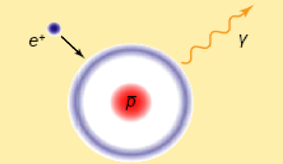
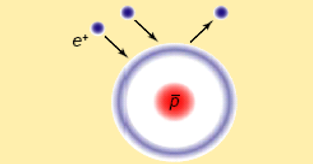
$$\mathrm{\bar{p}} + \mathrm{e}^+ + \mathrm{e}^+ \rightarrow \mathrm{\bar{H}} + \mathrm{e}^+, \quad \Gamma_{\mathrm{tbr}} \sim n_e^2 T_e^{-4.5}$$

Elastic encounter of 2 e^+ in the $\bar{p}$ continuum thus energy transfer around kT_e -> capture into weakly bound state

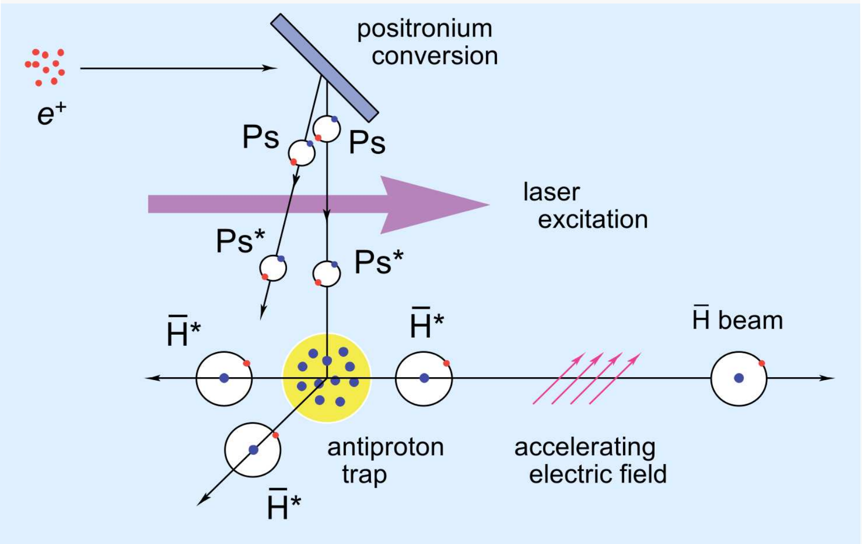
3) Charge- exchange with Ps

$$\bar{p} + Ps^* \rightarrow \bar{H}^* + e^- \qquad \sigma \sim \pi a_o^2 n_{Ps}^4$$

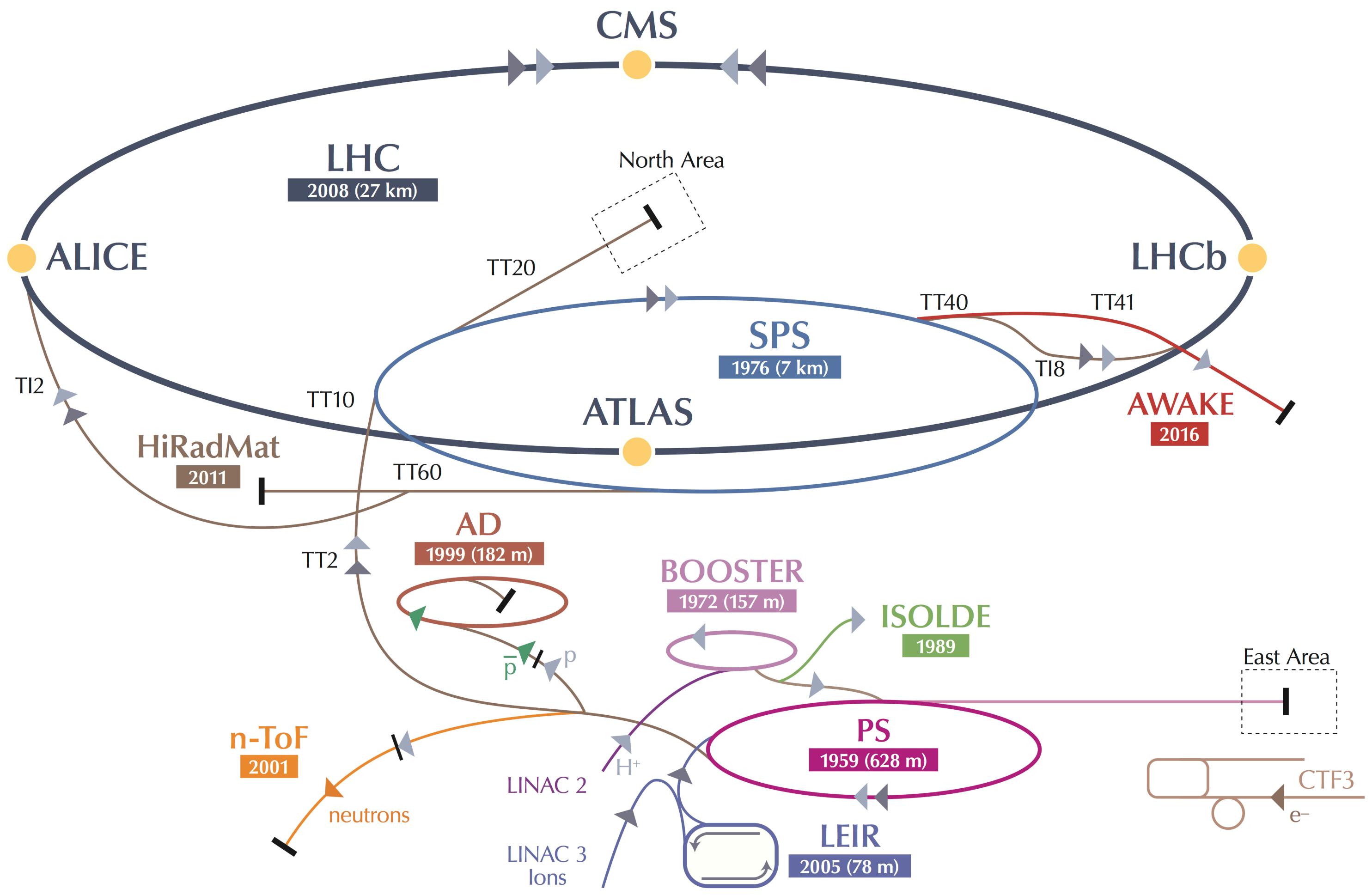
Necessary ingredients: high density, low energy antiprotons and positrons

	Radiative Recombination	Three-Body Recombination
Principle		
Temperature depend.	$\propto T^{-2/3}$	$\propto T^{-9/2}$
e^+ density dependence	$\propto n_e$	$\propto n_e^2$
Final internal states	$n < 10$	$n >> 10$
Expected rates	few 10 Hz	unknown

[J. Stevefelt *et al.*, PRA **12** (1975) 1246] [M. E. Glinsky *et al.*, Phys. Fluids B **3** (1991) 1279]

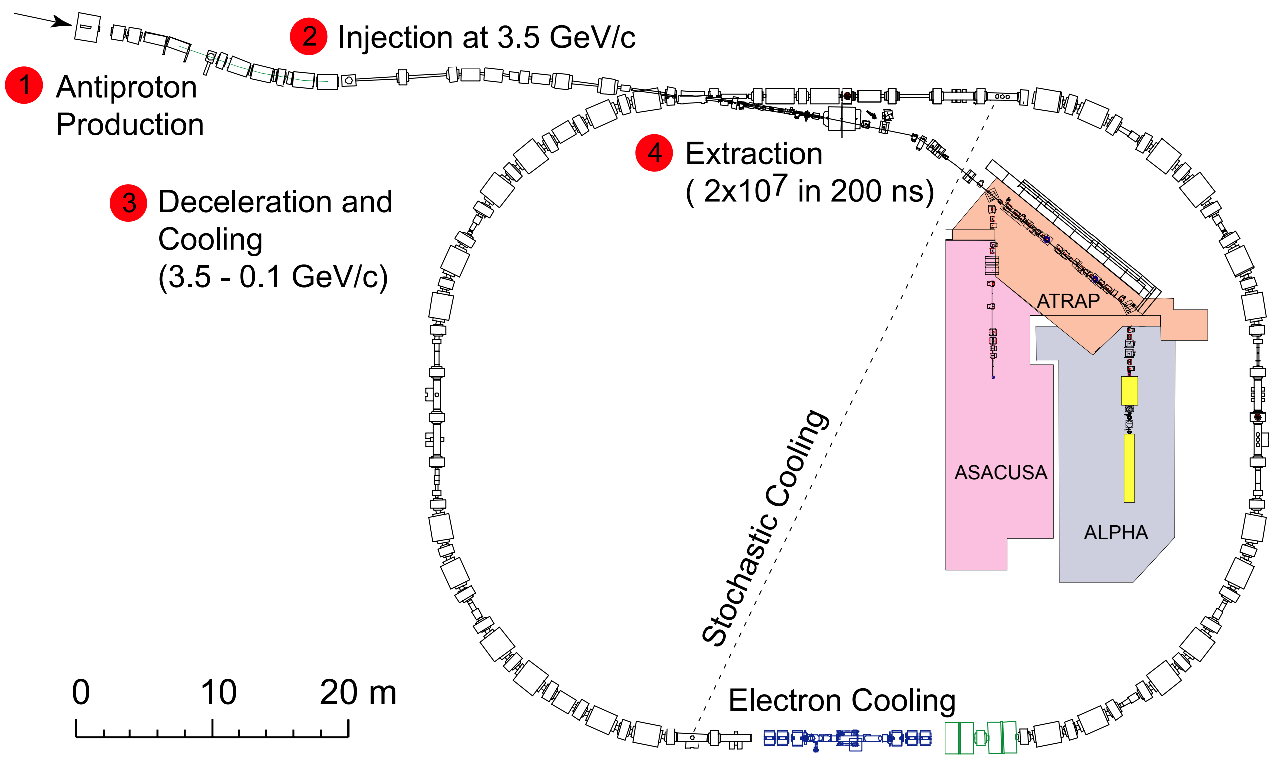


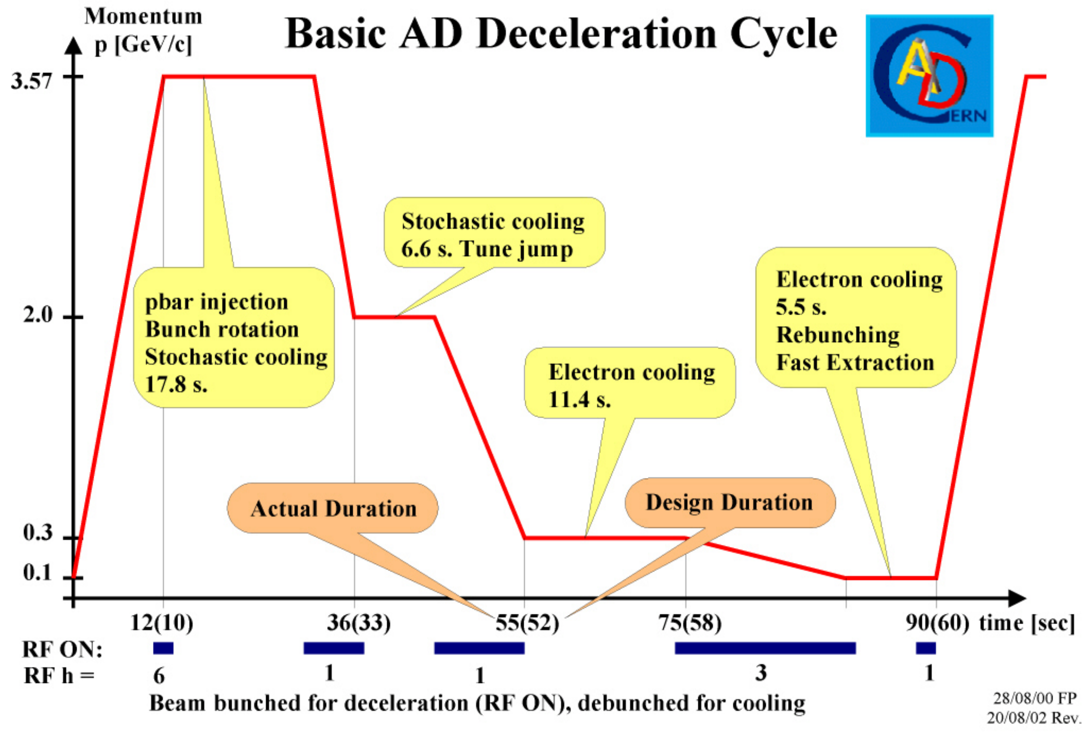
CERN facilities - creating antiprotons



The Antiproton Decelerator at CERN

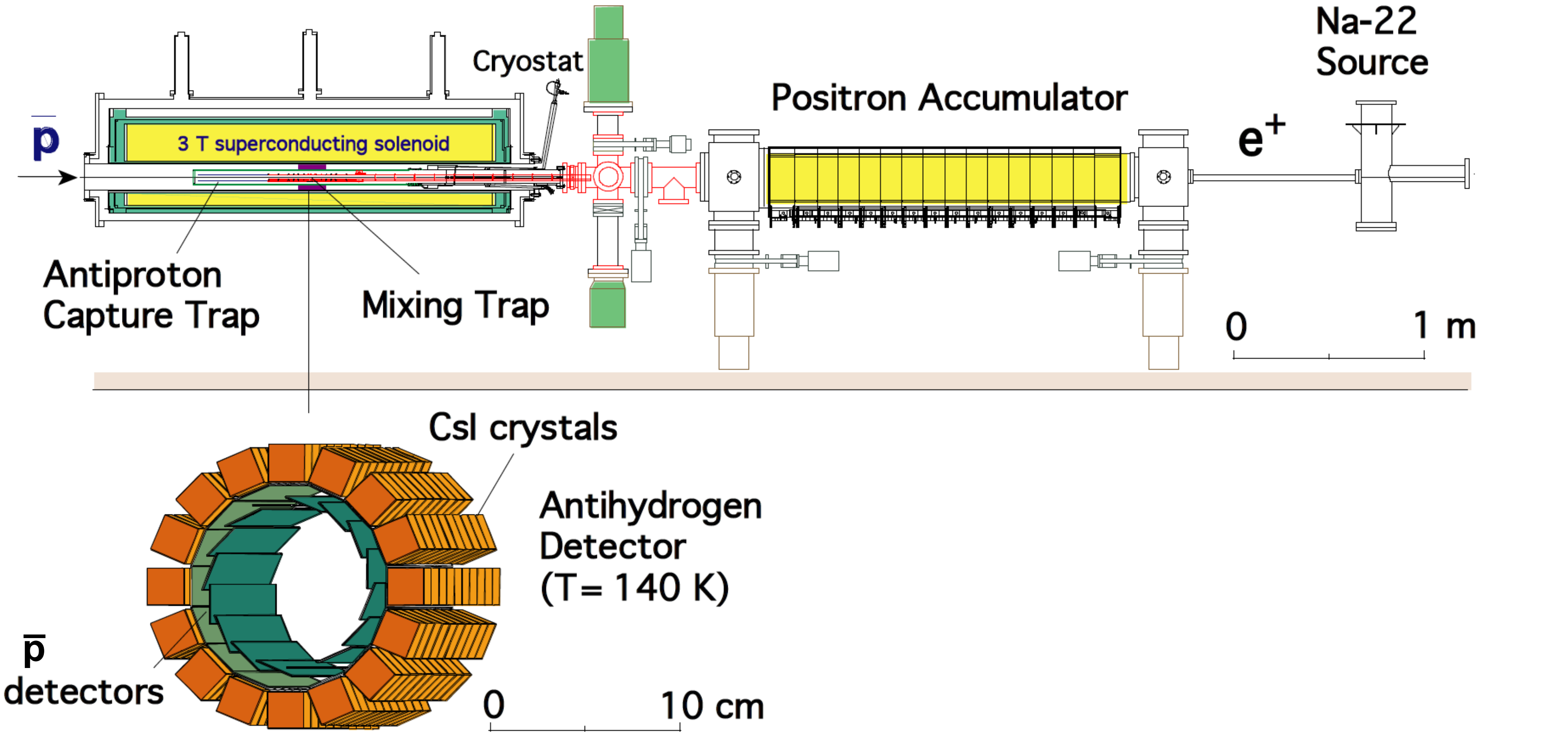
$$p(\text{beam}) + p(\text{target}) \rightarrow p + p + p + \bar{p}$$



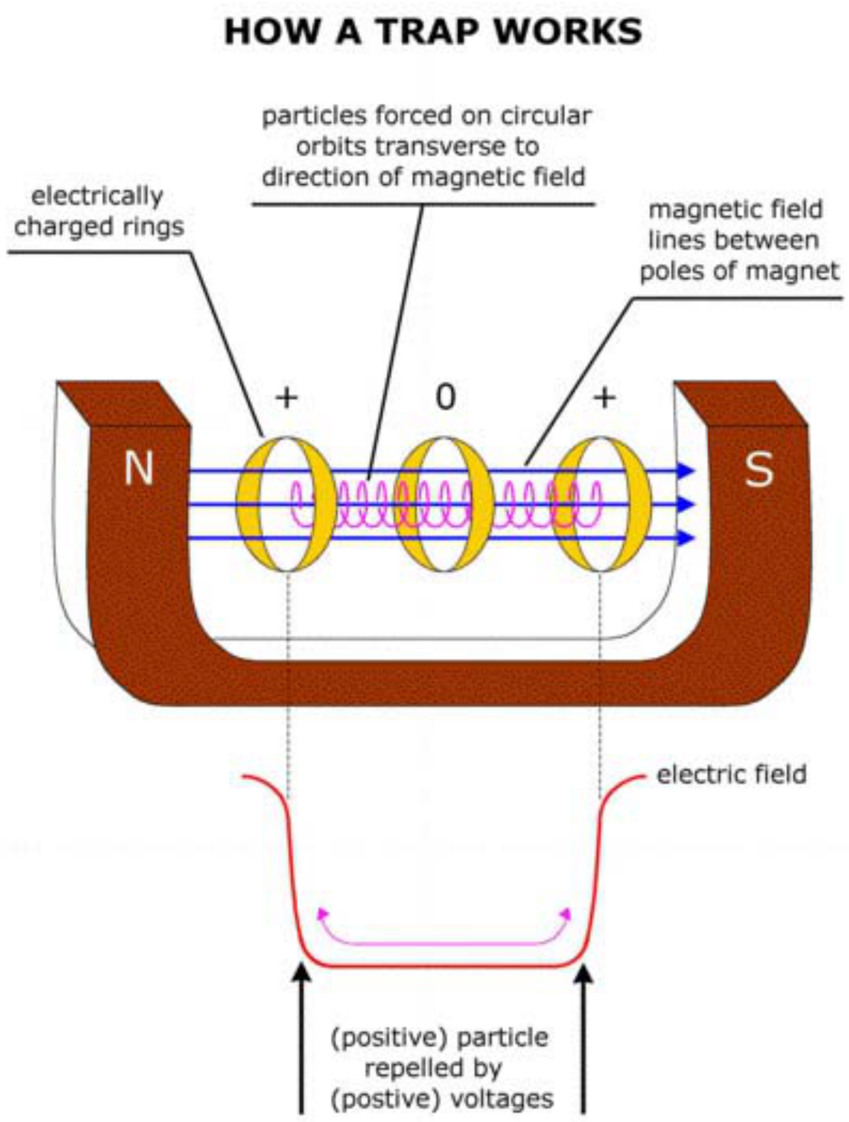


- Operation cycle is long: 100 s storage is needed
- Multiple stages of deceleration in RF cavities
- Deceleration from 3.5 GeV/c to 100 MeV/c (5.3 MeV kinetic energy)
- Needs active cooling of the beam, otherwise compressing the phase-space in the longitudinal direction results in blow-up in the transverse direction (Liouville-theorem)

Production of low energy anti-hydrogen ATHENA&ATRAP (2002)

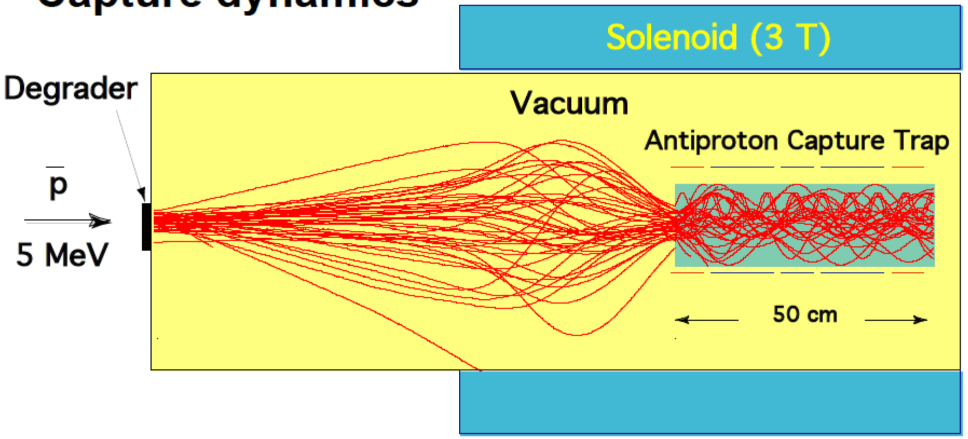


Penning-Malberg trap working principle

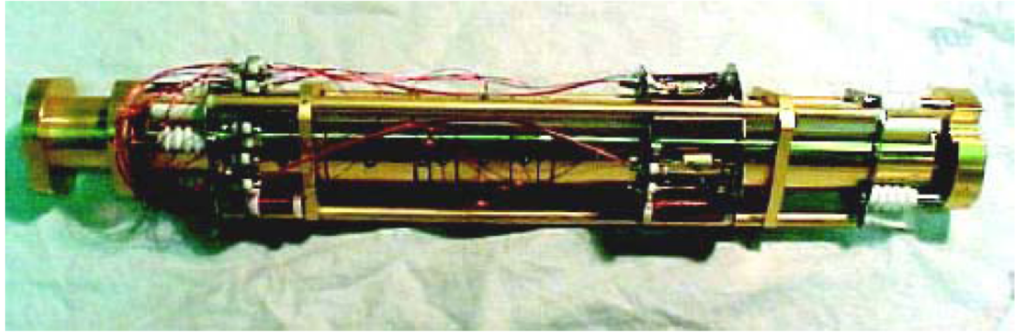


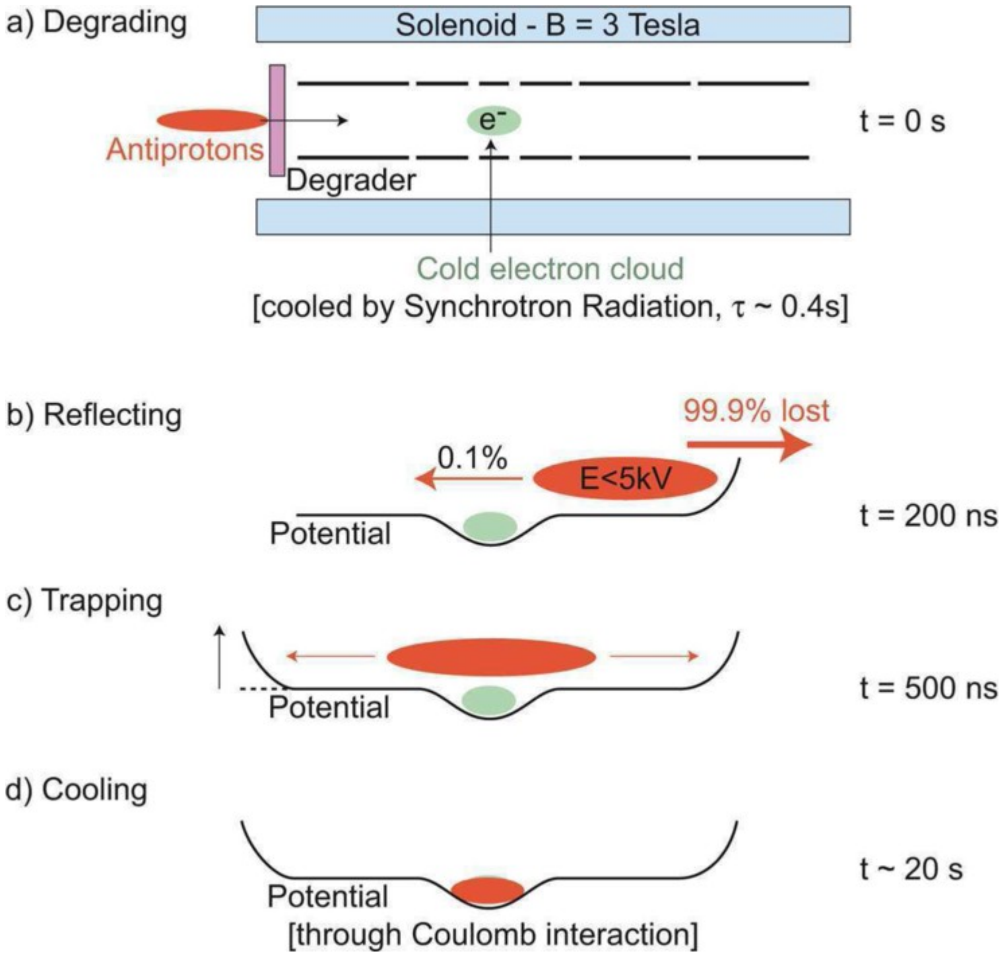
Trapping of antiprotons

- **Capture dynamics**



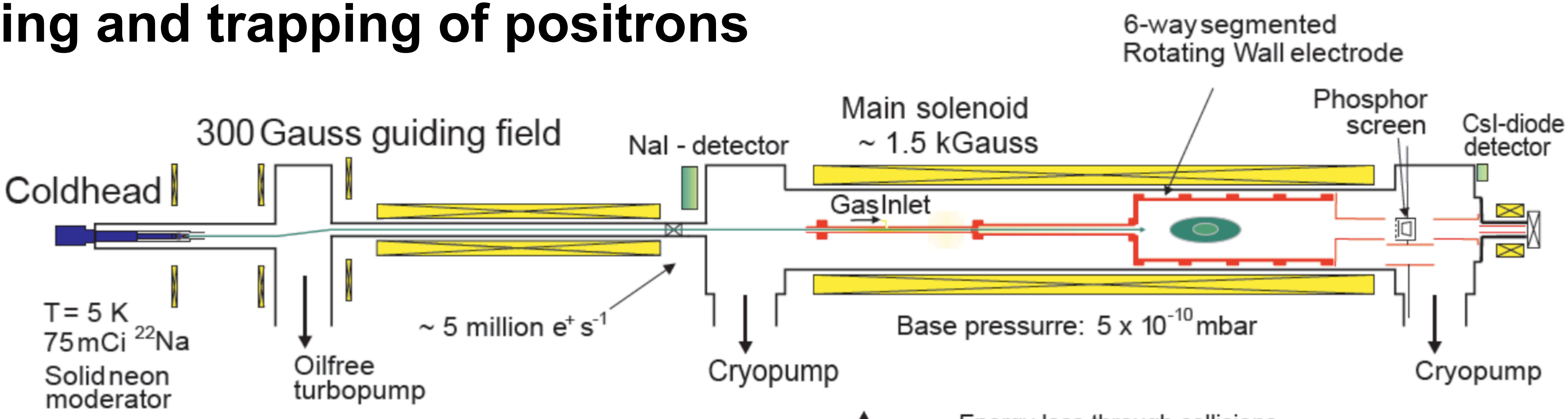
- **Capture trap (50 cm)**

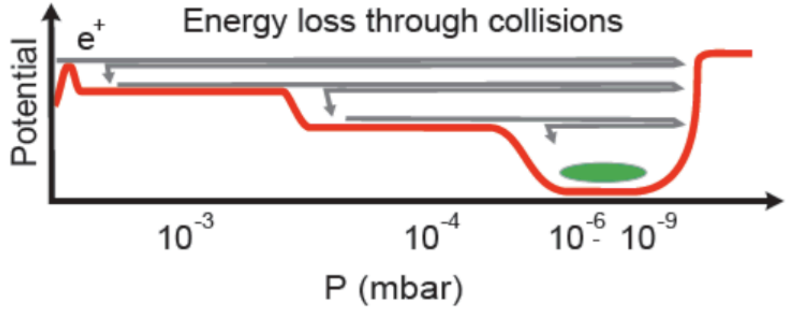




Stacking up to 10^5 antiprotons

Cooling and trapping of positrons





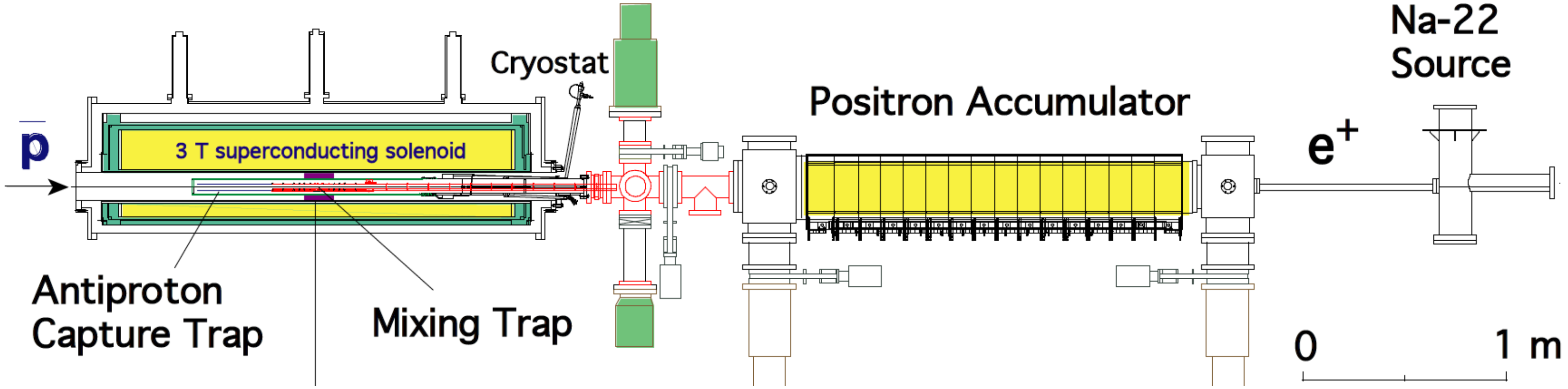
Few million e+ / sec

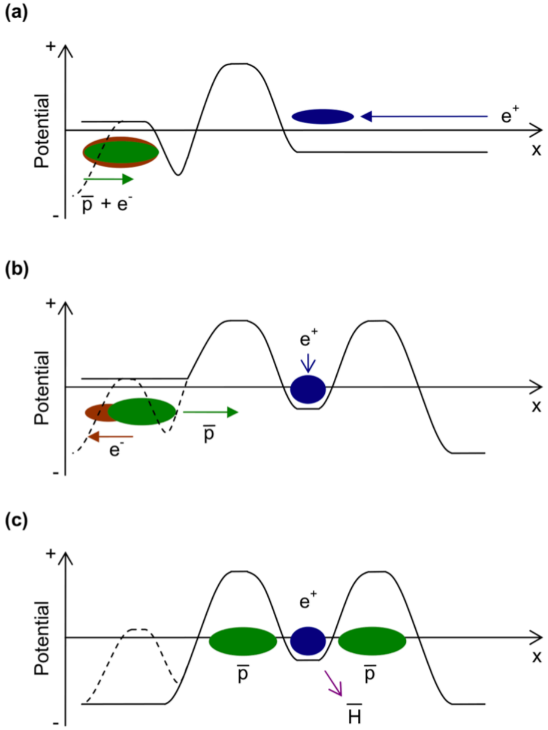
(1) Source: Na-22, 545 keV, but moderation on solid neon

(2) Transport to main solenoid

(3) In main solenoid: 3 regions of decreasing density N2 buffer gas and potential:
- The gas provides the dissipation mechanism. To prevent annihilation: differential pumping.
- Rotating wall: makes the plasma spin faster, and squeeze axially (angular momentum conservation)
- Lowering the electrode voltage evaporative cooling: plasma reaches several 10’s of degree Kelvin

Transfer to mixing trap



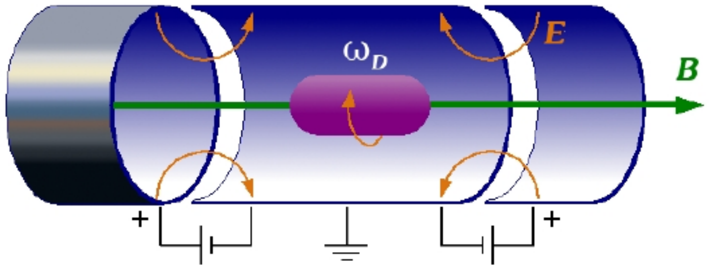


Transfer efficiency ~ 35%:
50 x 10^6 in mixing trap

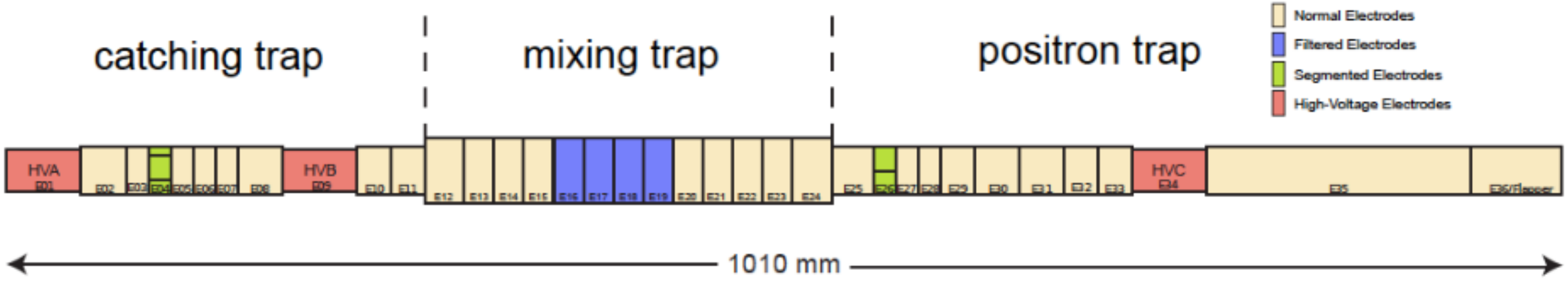
Positron plasma :
r~2mm, l~32mm,
n~2.5 x 10^8 / cm^3

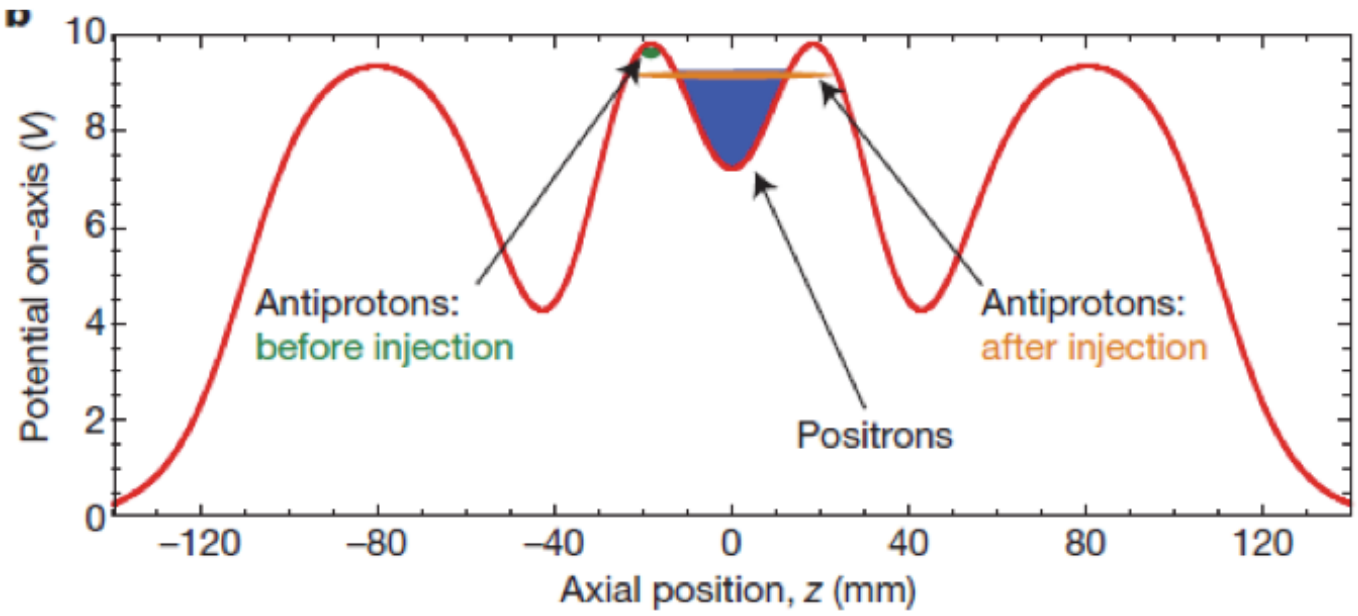
Lifetime: ~hours

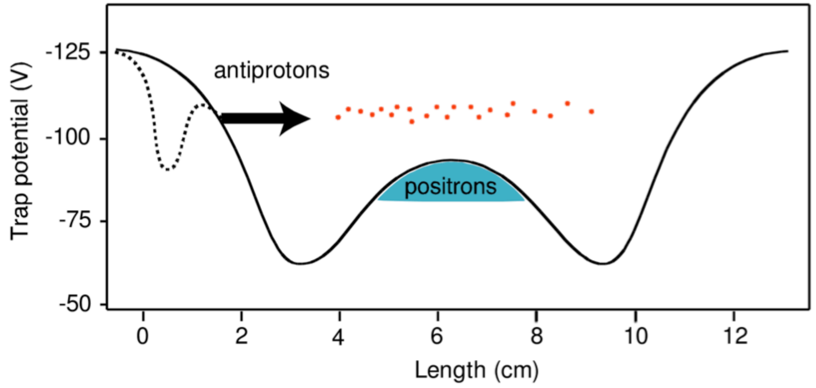
Penning-Malberg trap



Positron-antiproton mixing

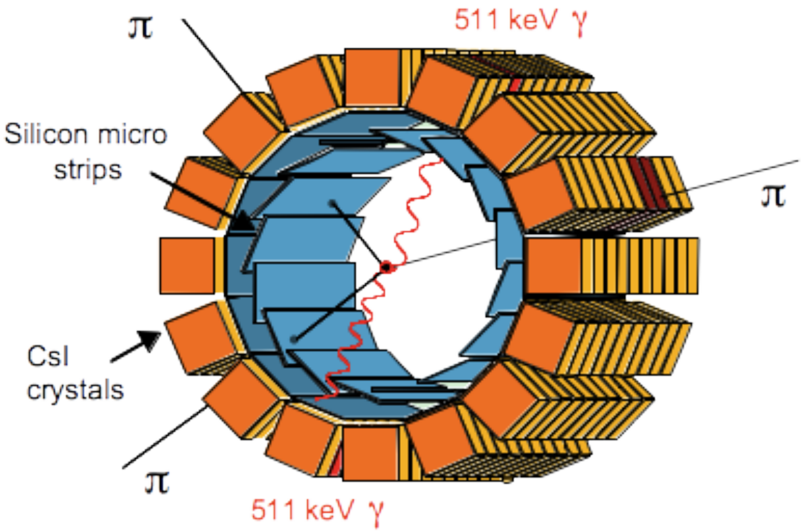




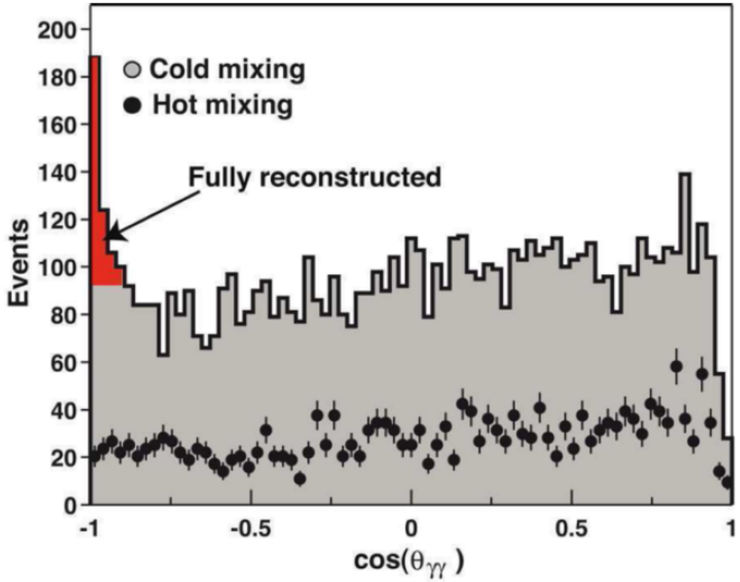


Oscillating RF field excite the p̄ so that it overlaps with the e^+

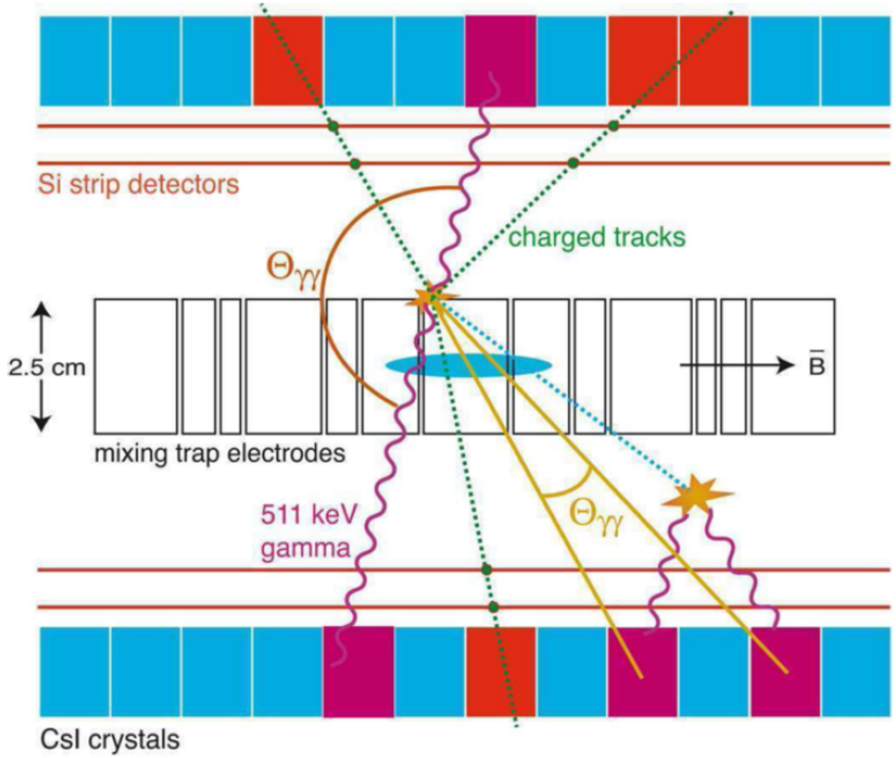
Antihydrogen detection - ATHENA (2002)



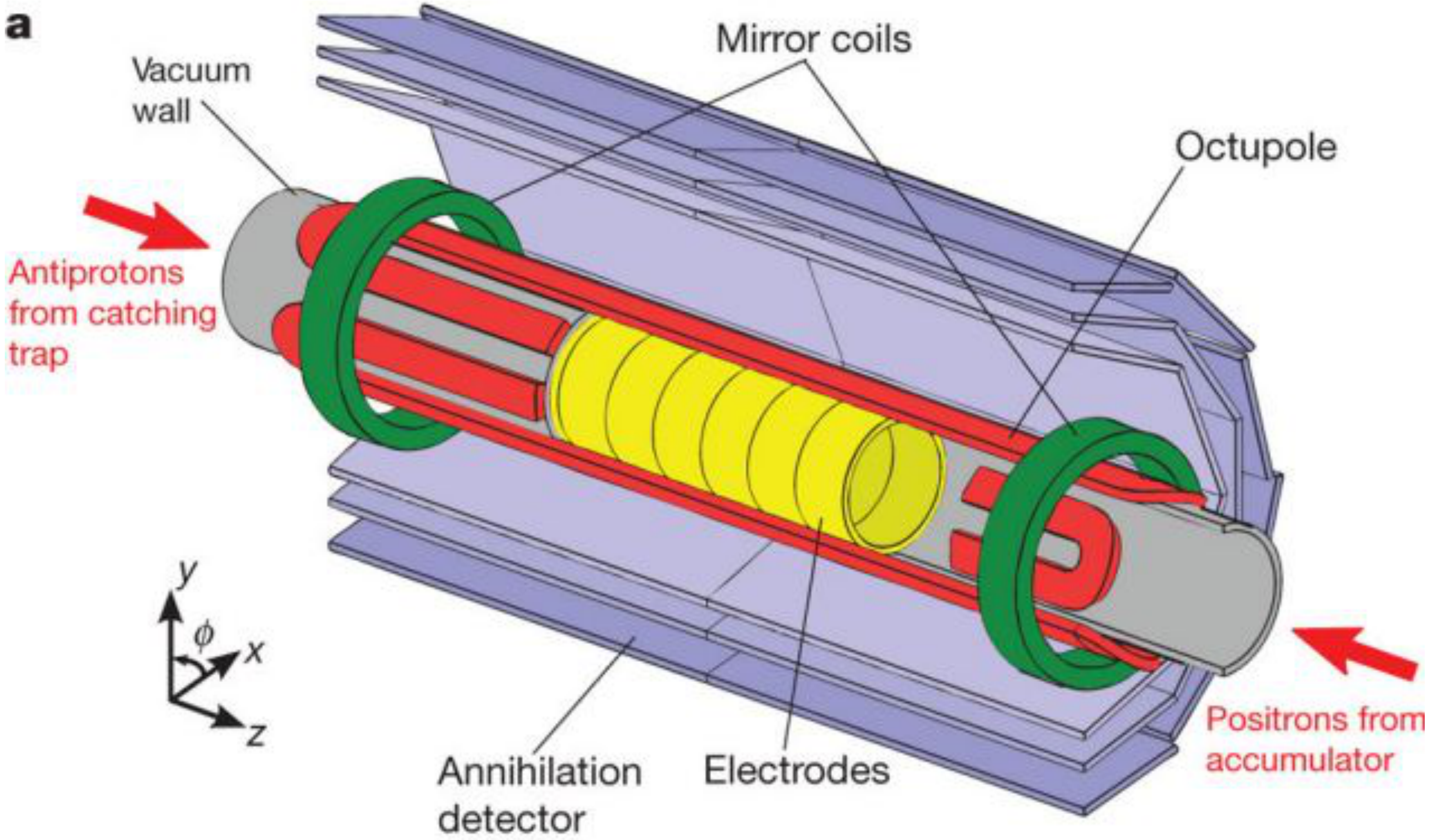
Vertex rec. eff.:	50%
Position resolution (σ):	4 mm
Silicon trigger efficiency:	(85 +-10)%
Photon energy resolution:	24% (FWHM) @ 511KeV
Photon detection efficiency:	20%



Opening angle distribution



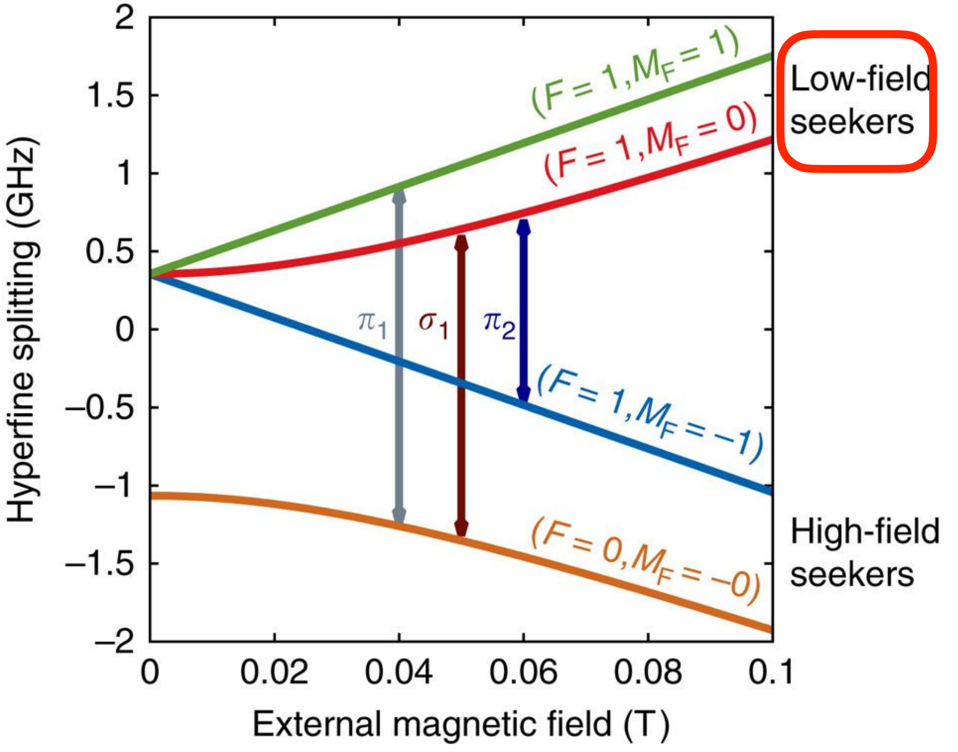
The ALPHA experiment (2006) - magnetic trapping



Magnetic trap for neutral (anti-) atoms

Atoms with magnetic moment acquire a potential in a magnetic field according to the formula:

$$U = -\vec{\mu} \cdot \vec{B} \quad \Rightarrow \quad \textbf{Force} \quad \vec{F} = \vec{\mu} \nabla \vec{B}$$



Zeeman-splitting, Breit-Rabi diagram

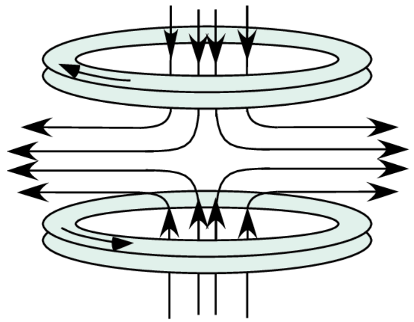
Trappable states

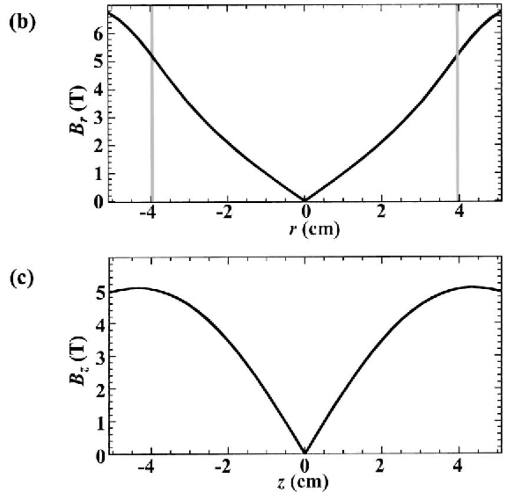
Trapping condition

$$\mu B \geq k_B T$$

Requires cold atoms: 0.6 K for 1T field

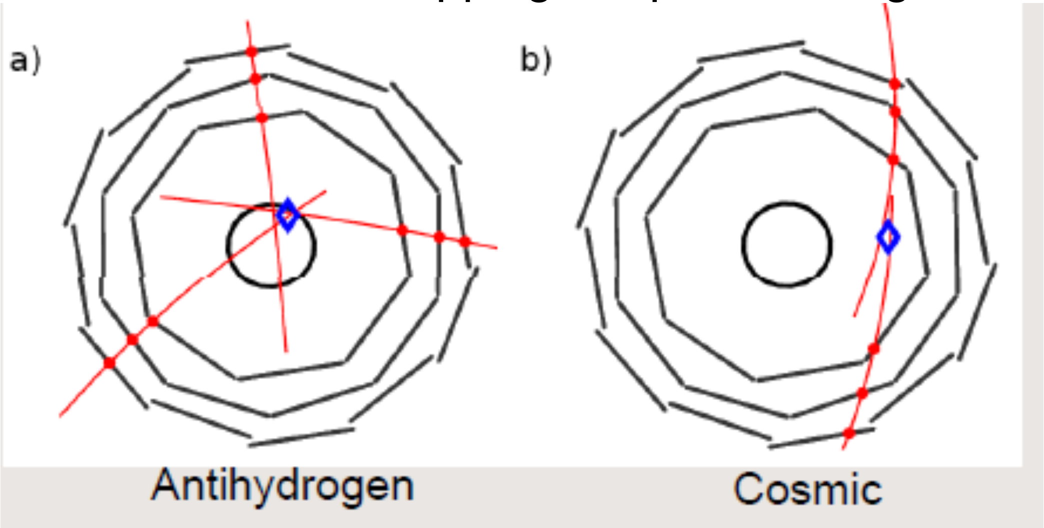
Anti-Helmholtz coil configuration - magnetic quadrupole field



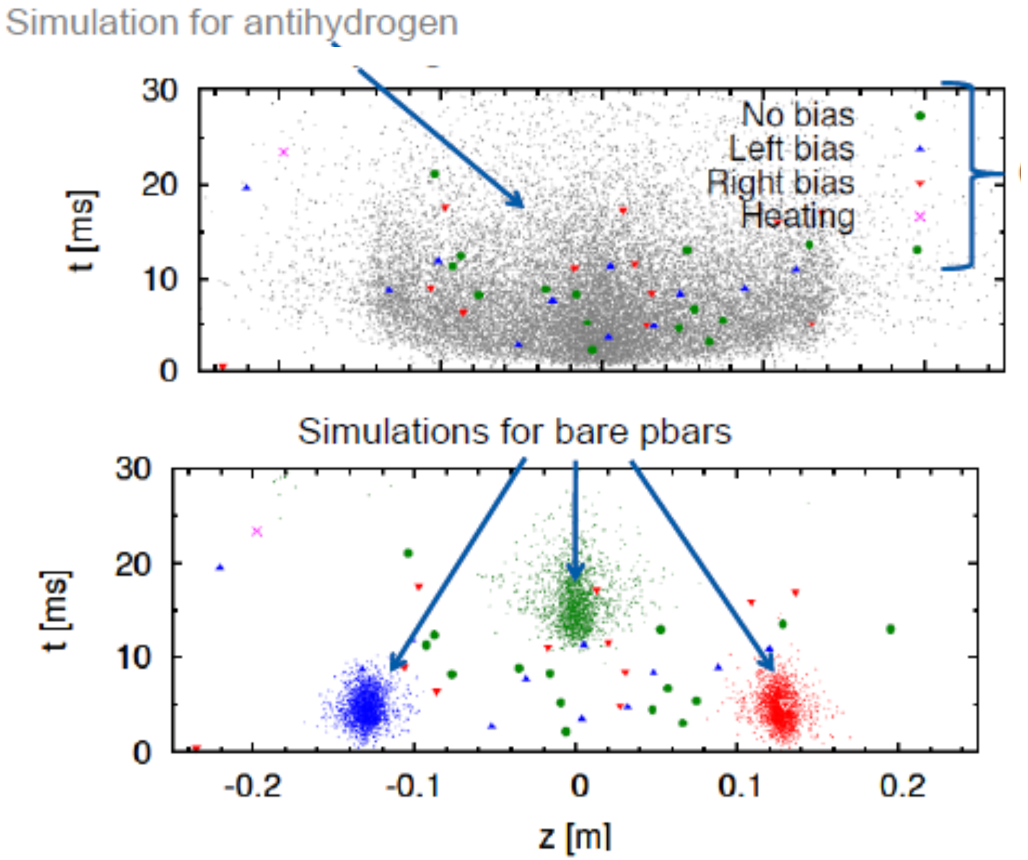


The ALPHA experiment (2009)

To demonstrate trapping ramp down magnetic field and look for annihilations on the beam pipe



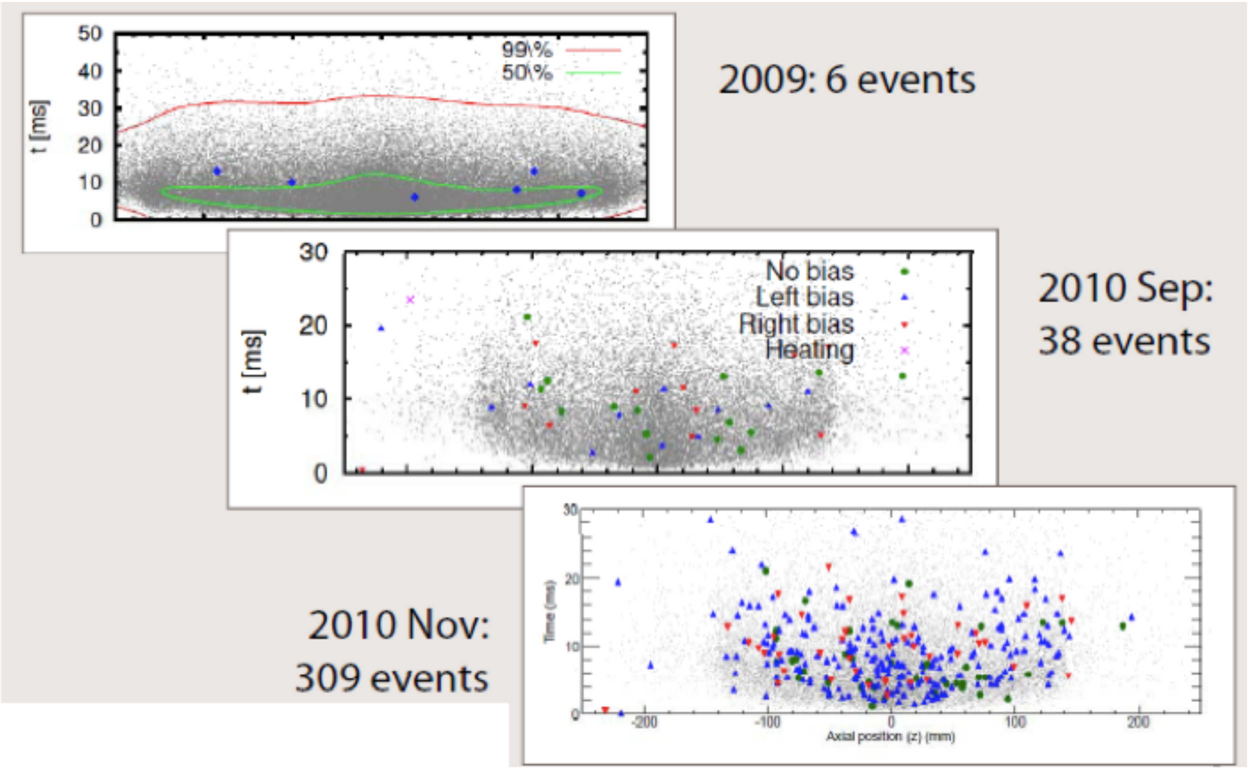
- Background from cosmics: rejected by topology

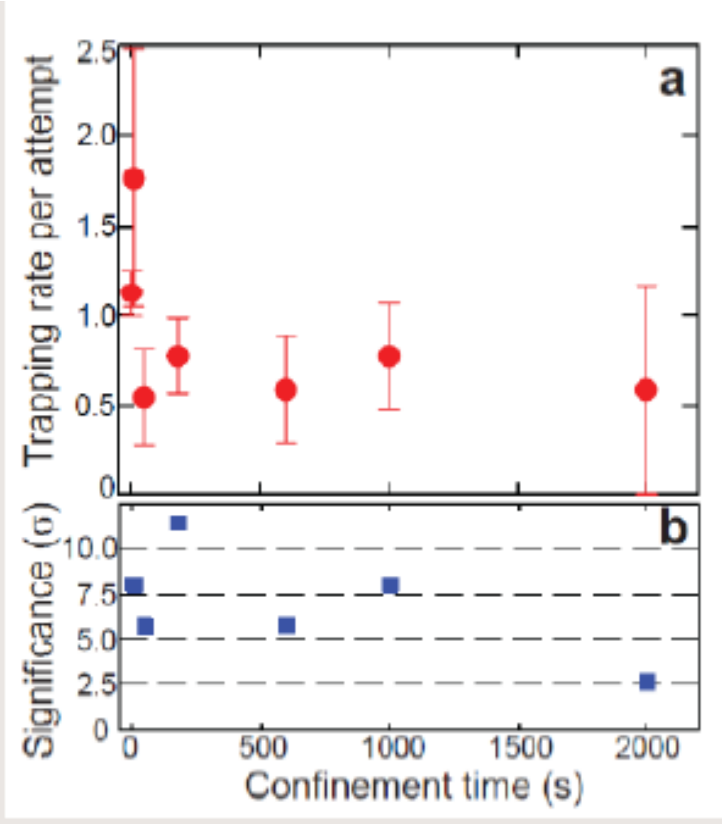


- Potential problem: „mirror trapping“ of bare $\bar{p}$ in homogenous B field —> Solution:

- Mixing with heated e+ (suppresses anti-H production)
- Release anti-H while applying E field: pbars would be deflected

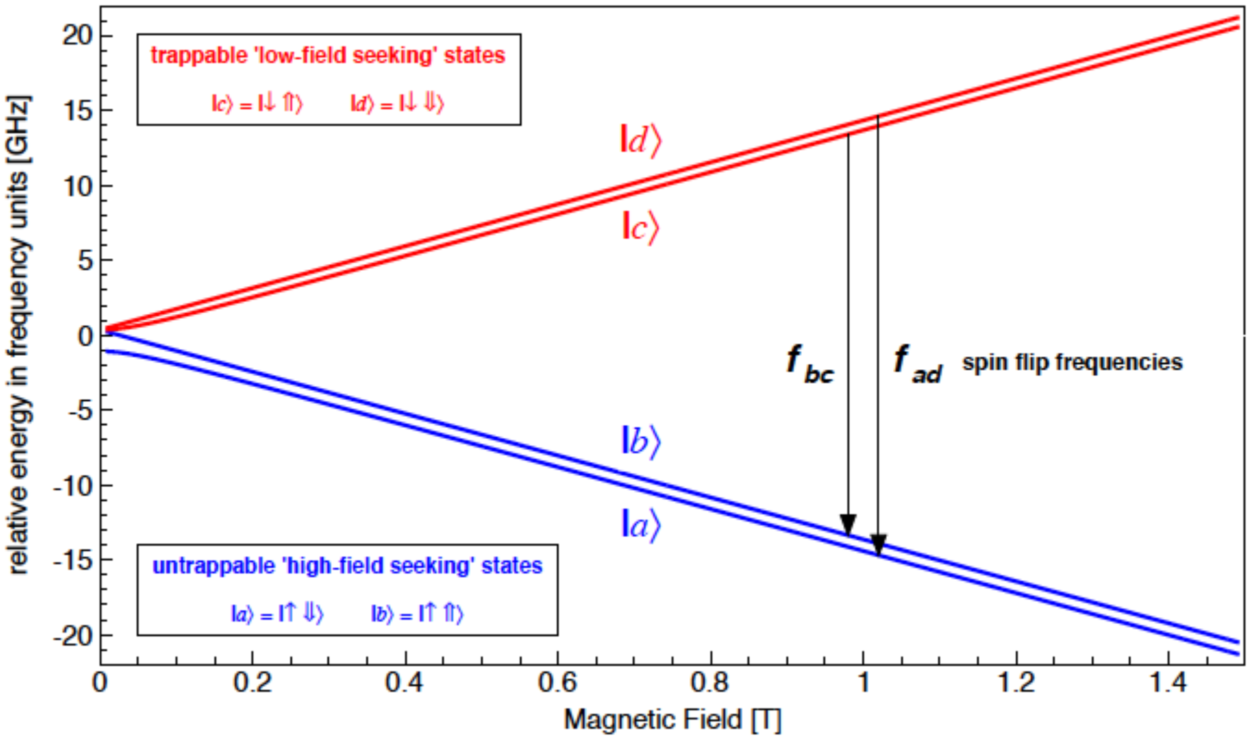
Antihydrogen trapping rates and confinement time

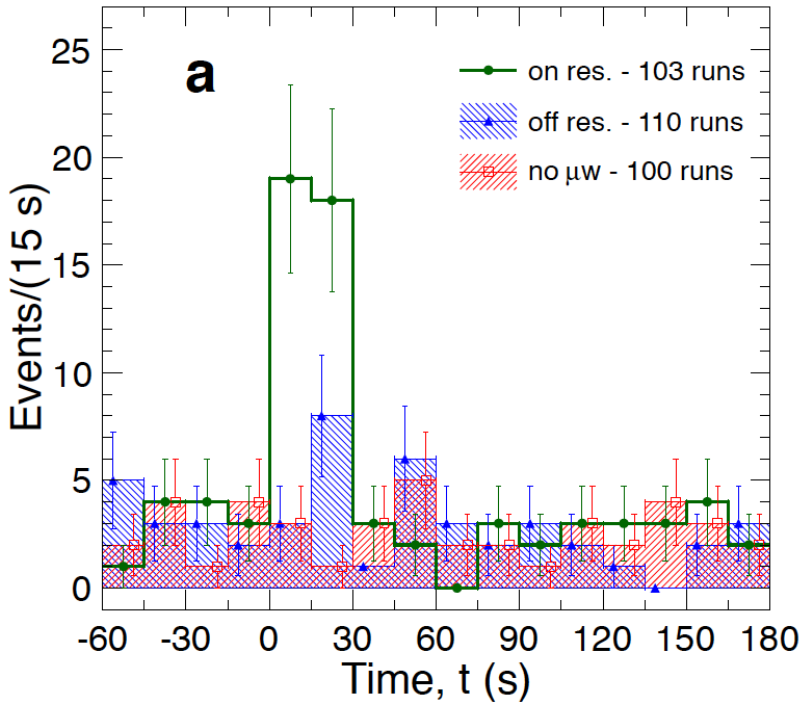




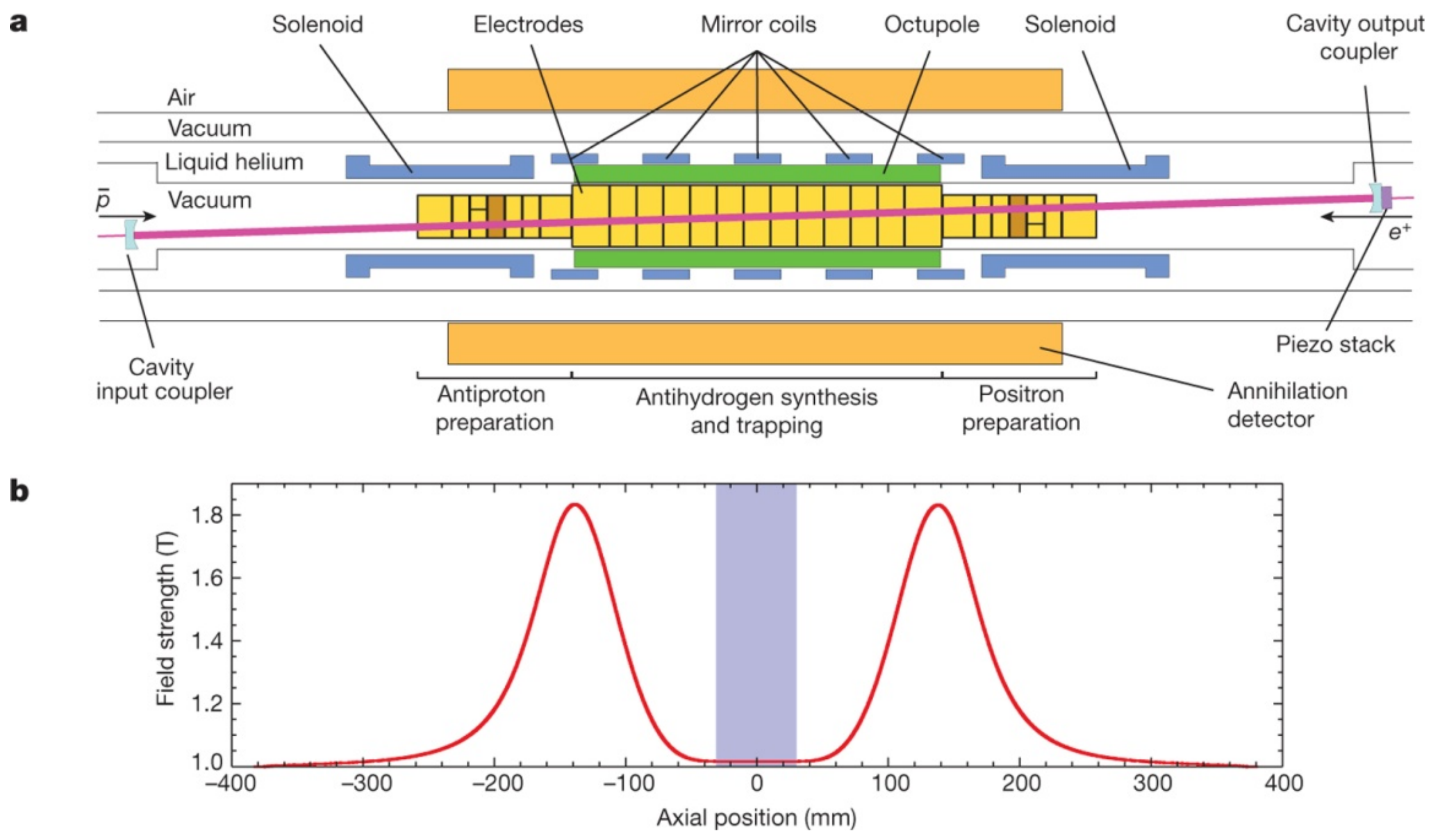
Confinement time up to 1000 s -> allows for precision spectroscopy of anti-hydrogen:
- $\bar{H}$ in the ground state (remember $\bar{H}$ formed in highly excited Rydberg state takes about 1 second to de-excite to ground state)
- Present numbers: ~20 antihydrogen atoms every 4 minutes, accumulating more than 1000 $\bar{H}$ in 8 hours

First interaction of Antihydrogen with radiation





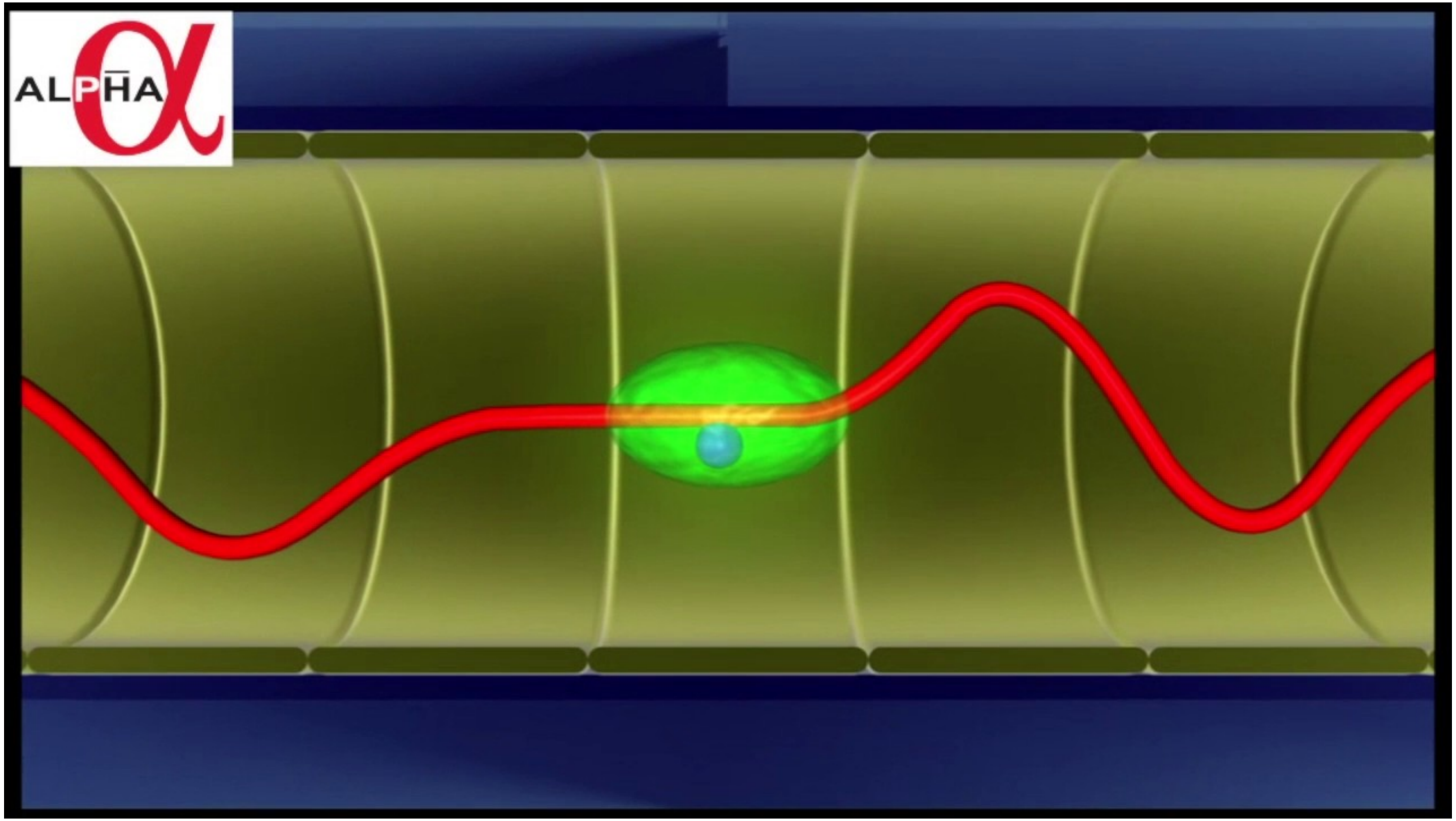
ALPHA-2: First detection of the 1S-2S transition



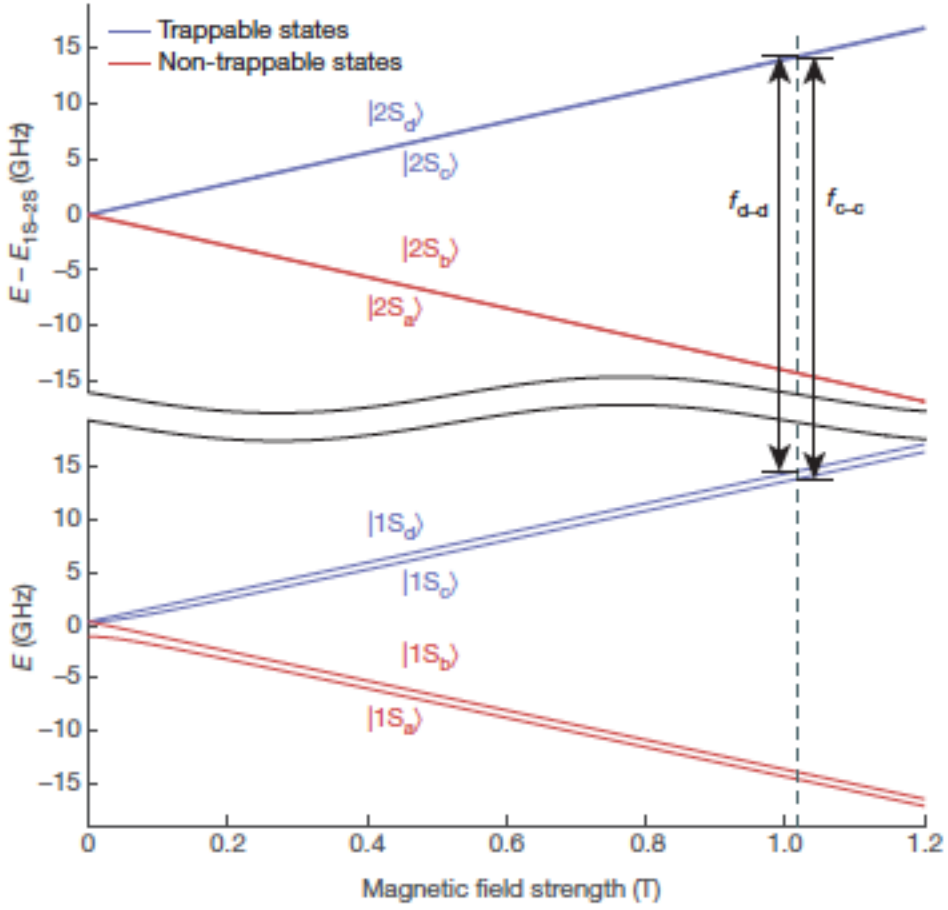
Two-photon transition at 243-nm driven by a resonant cavity locked to the frequency, passing through the centre of the trap

M Ahmadi *et al. Nature* **541,** 506–510 (2017) doi:10.1038/nature21040

Question: detection of the 1S-2S transition



ALPHA-2: First detection of the 1S-2S transition



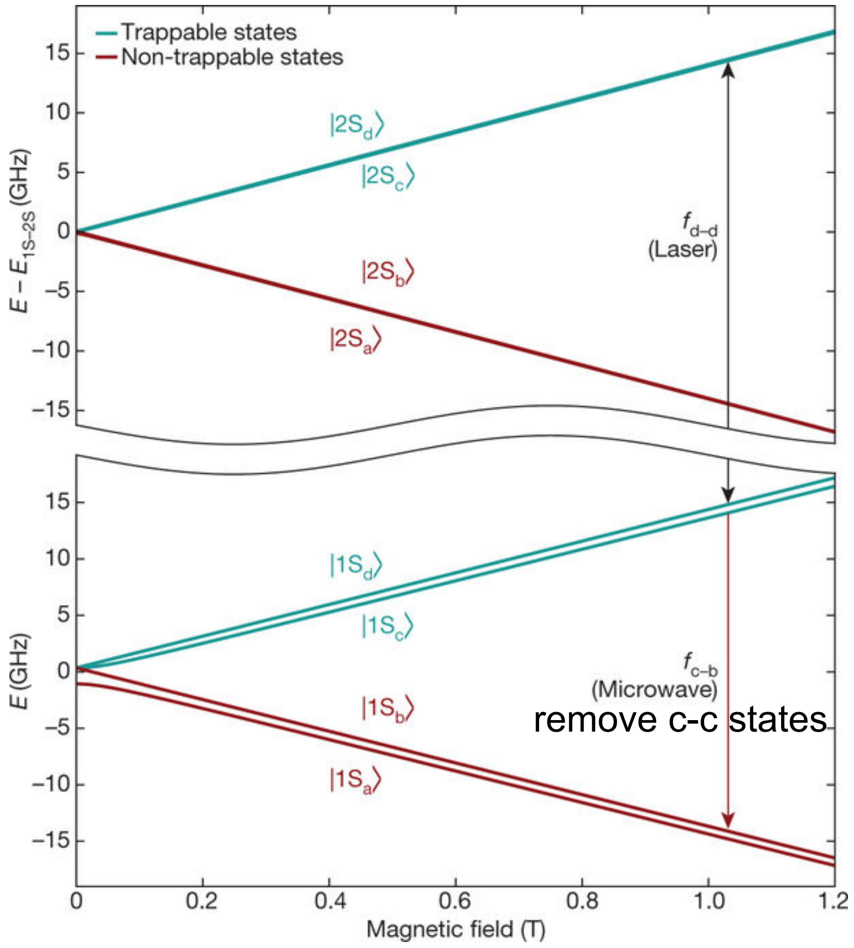
When laser on resonance —> number of trapped $\bar{H}$ depleted because of photoionisation of atoms in the same excitation laser.

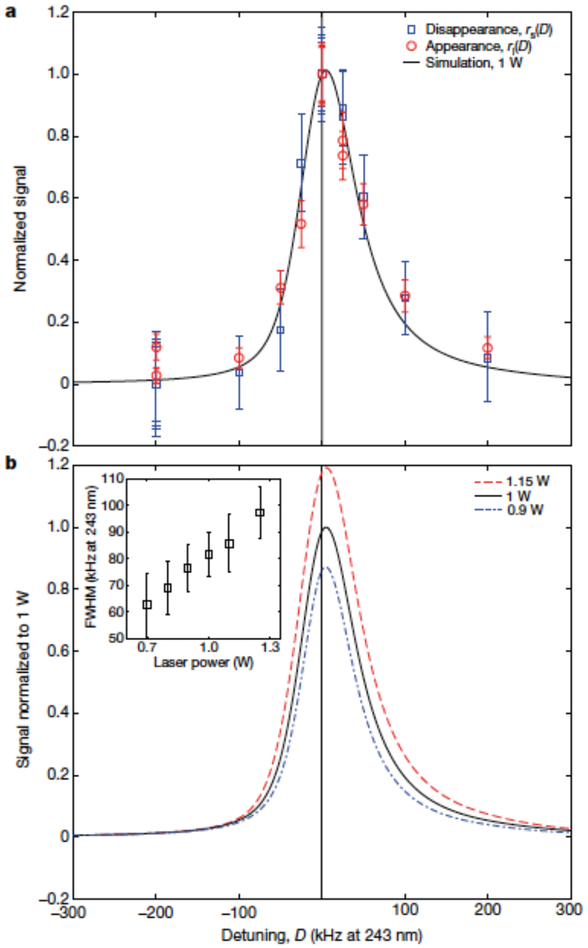
Type	Number of detected events	Background	Uncertainty
Off resonance	159	0.7	13
On resonance	67	0.7	8.2
No laser	142	0.7	12

$$f_{\mathrm{d-d}} = 2{,}466{,}061{,}103{,}064(2)\ \mathrm{kHz}$$
$$f_{\mathrm{c-c}} = 2{,}466{,}061{,}707{,}104(2)\ \mathrm{kHz}$$

No difference between hydrogen and antihydrogen transition frequency at the level of 10^{-10}

Measurement of the 1S-2S line shape





Laser drives 1S-2S transition (2-photon)
A third photon drives it to continuum: lost in the trap
Microwave removes 1Sc states, then ramping down the magnet probes 1Sd atoms

Measured transition:

$$f_{d-d} = 2{,}466{,}061{,}103{,}079.4(5.4)\,\mathrm{kHz}$$

Calculation for hydrogen in 1T field

$$f_{d-d} = 2{,}466{,}061{,}103{,}080.3(0.6)\,\mathrm{kHz}$$

Results in agreement within

$$2 \times 10^{-12}$$

Prospects: laser cooling to decrease the temperature —> narrower line

Summary

- Low-energy particle physics addresses fundamental questions of the standard model and can be sensitive to BSM physics at very large energy.
- Low-energy, precision experiments are complementary to high-energy physics
- Low-energy particle physics can do more than BSM searches:
  determination of fundamental constant, QCD at low energy, hadron structure, nuclear structure test of QED, bound-state QED, gravity, fundamental symmetry tests and technology development …..