Physics beyond colliders

(Vietnam beyond Quy Nhon)

Michael Doser / CERN

(slightly) limiting the BSM landscape

Don't sweat the details - focus on known big problems and questions

1) dark matter

$\updownarrow$

2) fundamental symmetries

$\updownarrow$

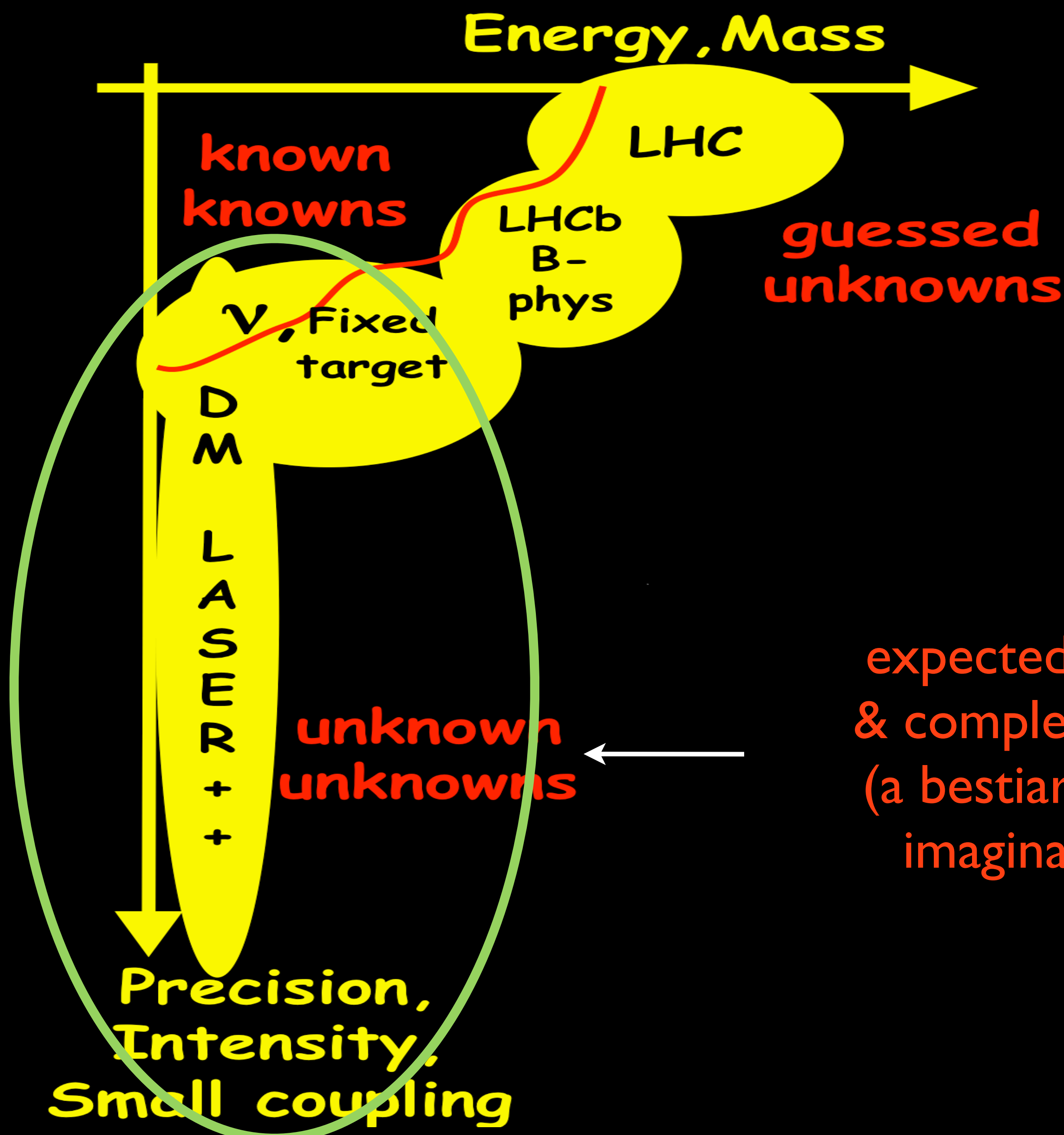
3) some smaller questions
(how well does the SM *really* work?
what is a proton?
do we fully understand gravity?)

} BSM

BSM ?

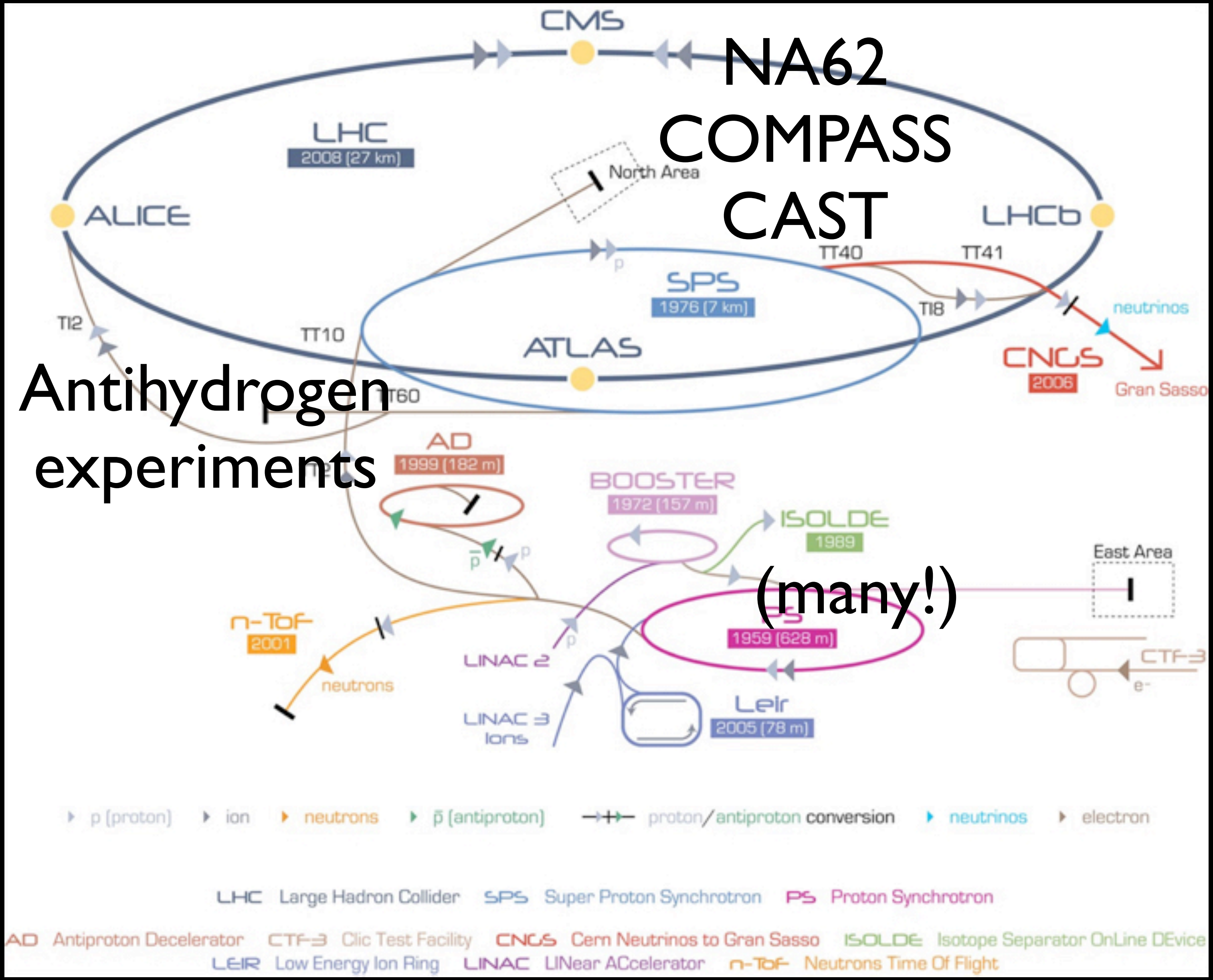
(and I'm going to *mostly* require that an accelerator be involved somewhere
... in fact, this will be a somewhat CERN-centric perspective ...)

Exploring is (at least) 2 dimensional



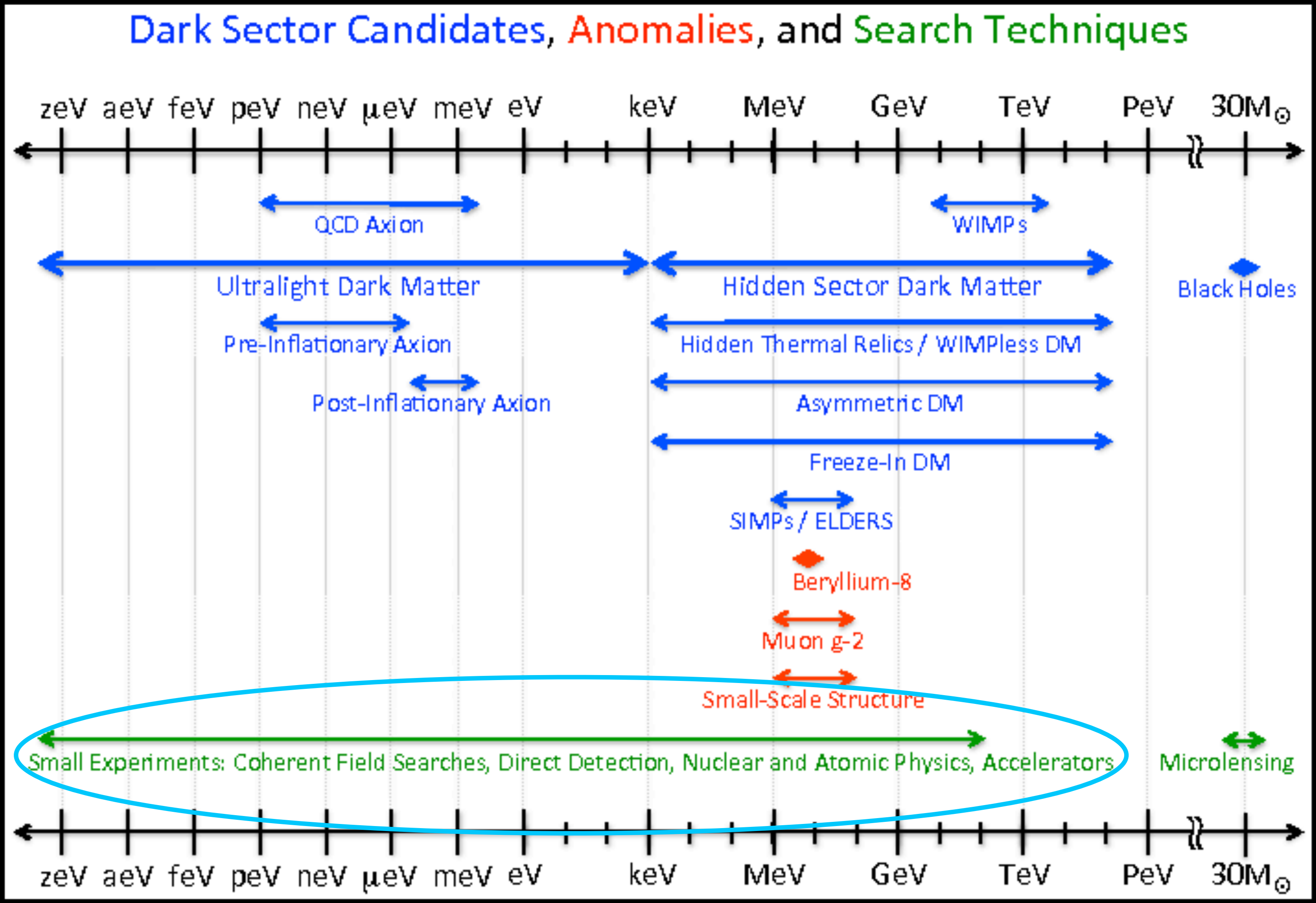
expected, hoped-for & complete surprises (a bestiary of mostly imaginary things)

Exploring at CERN (but not at a (the) collider):



1) dark matter

10^{-24} eV ⟵ Mass range covered ⟶ 10^{67} eV



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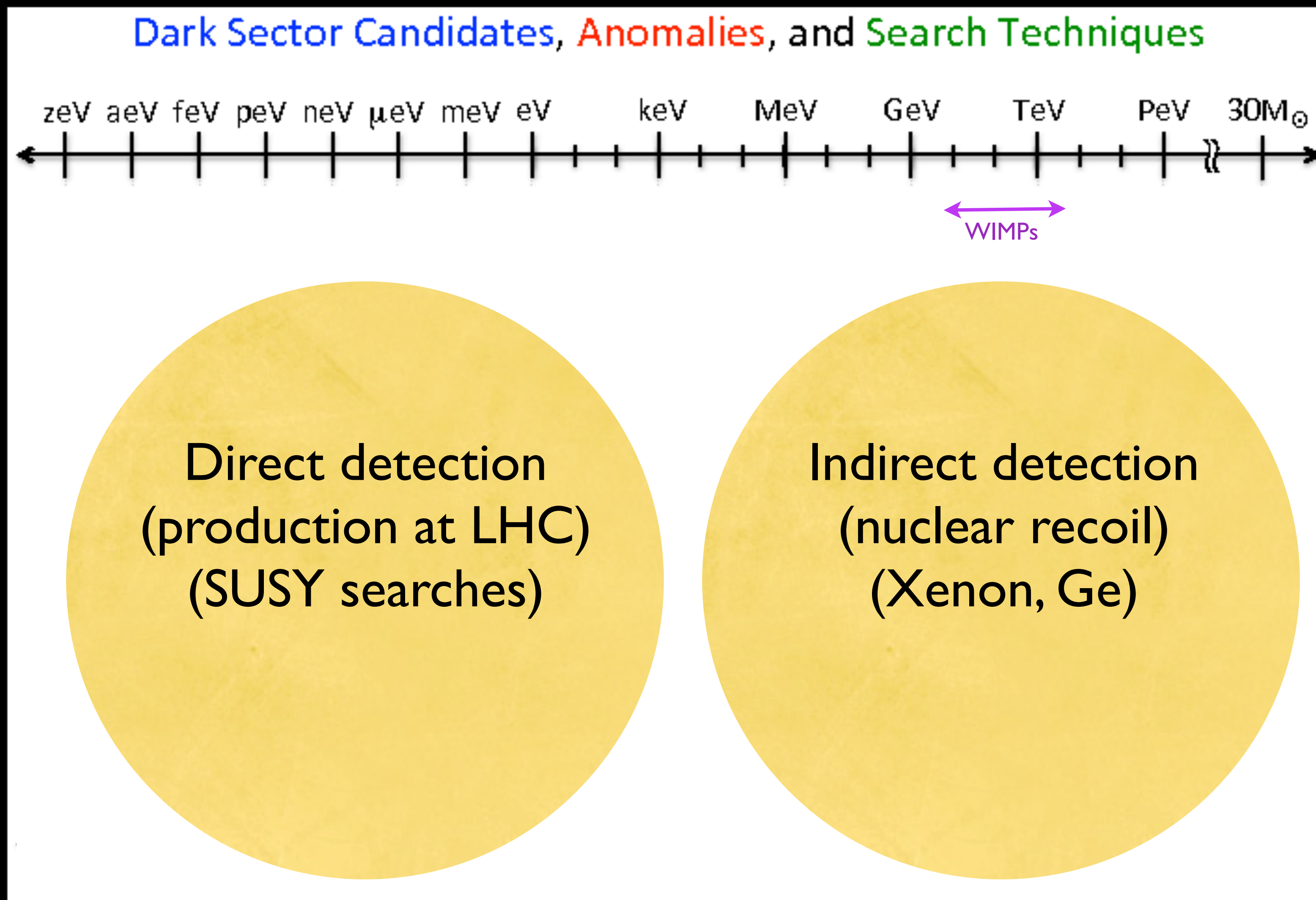

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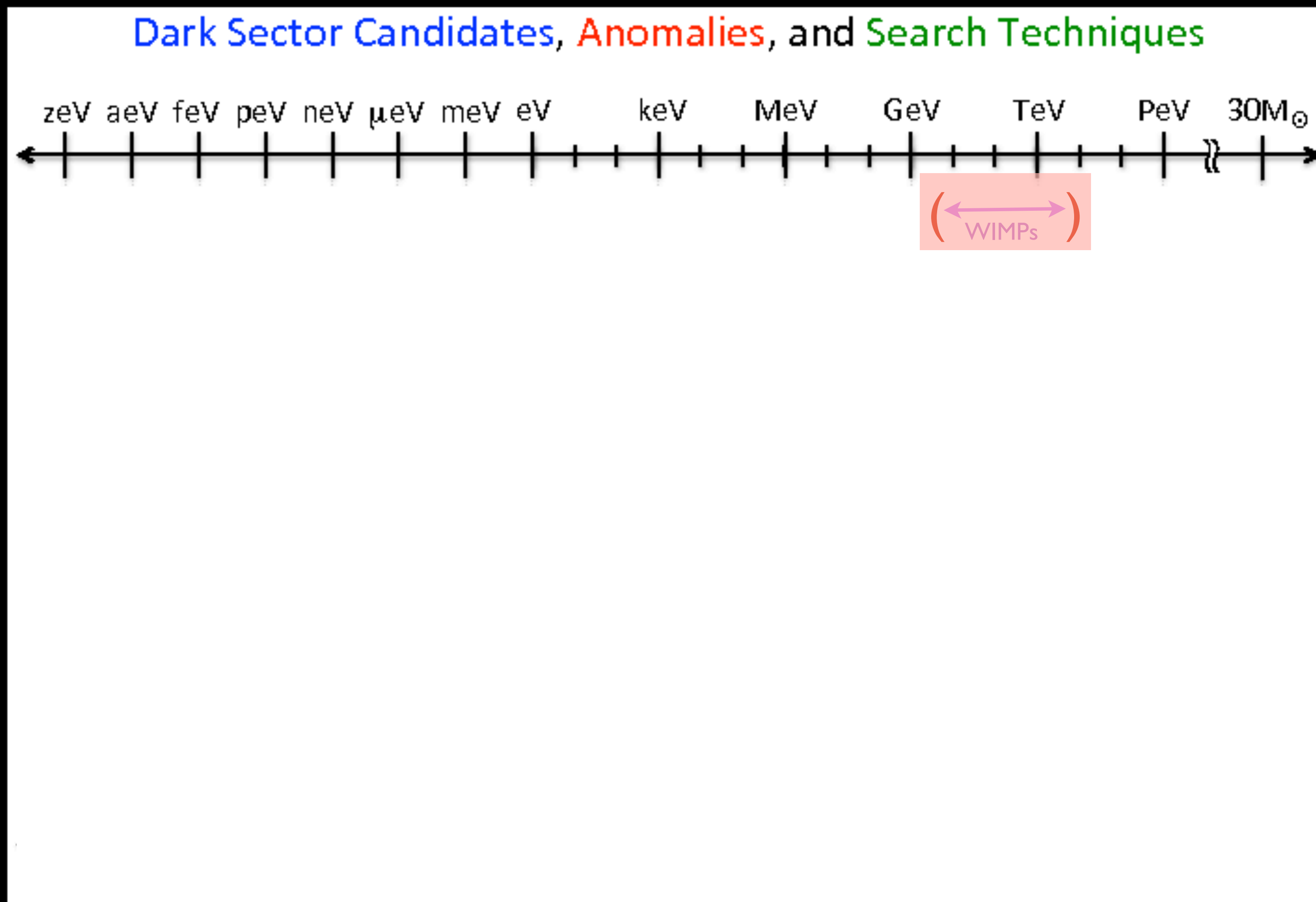
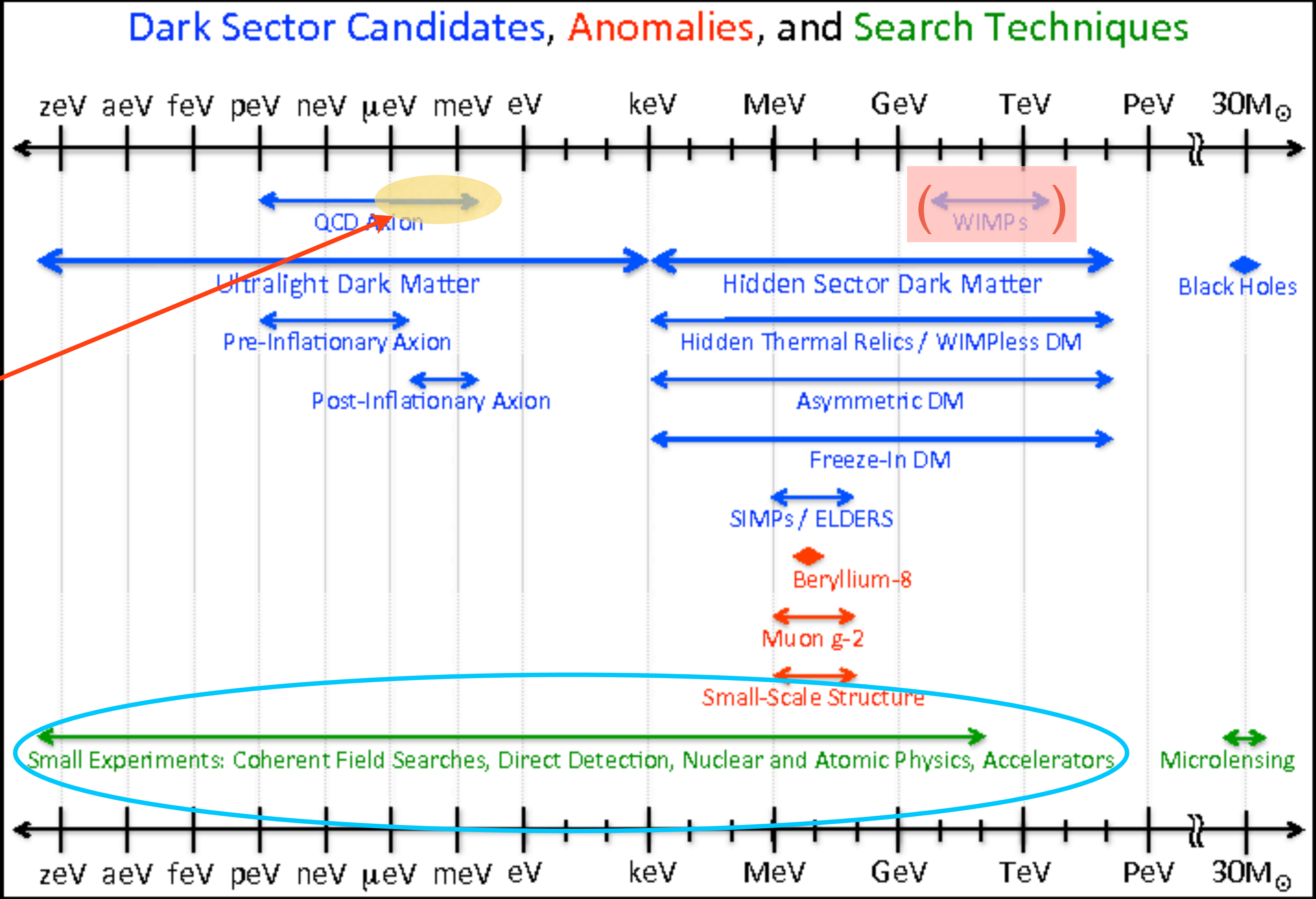


1) dark matter

- axions, wisps, chameleons
- heavy neutral leptons
- dark photons

10^{-24} eV ⟵ Mass range covers ⟶ 10^{67} eV



astrophysical limits; Gray Rybka, Physics of the Dark Universe 4(2014)14–16

1) dark matter: axions

https://www.susanjfowler.com/blog/2016/9/17/from-the-fledgling-physicist-archives-an-introduction-to-axions

CP-violation in the weak interaction, but not in the EM, strong interactions

QCD predicts possibility of CP-violation in the strong interaction (quark mass mixing)

Roberto Peccei & Helen Quinn (1977): a (new) global chiral symmetry (that is spontaneously broken at large scales f_a) that perfectly "avoids" this (potential) CP-violation.

R. D. Peccei and Helen R. Quinn, Phys. Rev. Lett. 38, 1440 – Published 20 June 1977

The observed CP invariance of the strong interactions is a natural feature of a theory such as quantum chromodynamics provided only that at least one fermion flavor acquires its mass through a Yukawa coupling to a scalar field which has a nonvanishing vacuum expectation value, and the Lagrangian originally possesses a U(1) invariance involving all Yukawa couplings.

...choice of phases (which appear in the fermion mass term) for various scalar expectation values...

Goldstone theorem: spontaneous symmetry breaking $\longrightarrow$ new particle

Nambu-Goldstone Boson (no spin, no mass, no charge)

if symmetry is not exact, mass ≠ 0 $\longrightarrow$ Pseudo-Nambu-Goldstone Boson : Axion

S. Weinberg, PRL 40 (1978) 223

The axion is extremely hard to find, because it doesn't interact with (m)any of the particles in the standard model, with the exception of photons, which it can decay to.

1) dark matter: axions (*axion-like particles*)

Couplings fixed by scale of symmetry breaking: f_a (m $\not\leftrightarrow$ g)

Photon coupling

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

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

Gluon coupling

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

$$g_{agg} \sim \frac{\alpha_s}{2\pi f_a}$$

Fermion couplings

$$\mathcal{L} \supset \frac{\partial_\mu \phi}{f_a} \bar{\psi} \gamma^\mu \gamma^5 \psi$$

main difference between axions and ALPs: mass and coupling constants are independent for ALPs

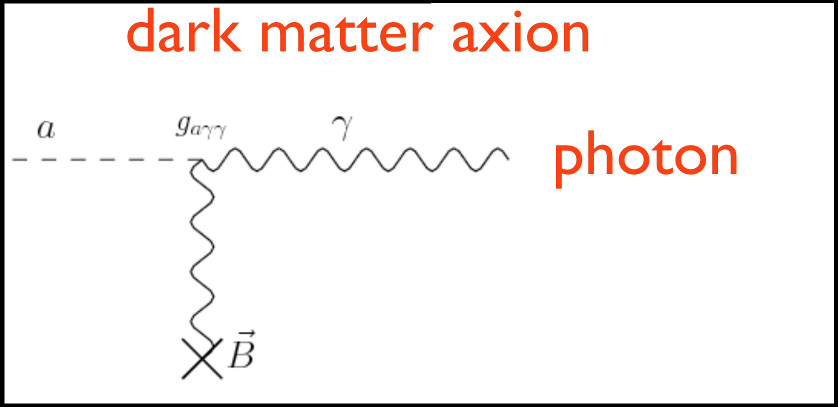
1) dark matter: wisps, ALP's

WIMP = weakly interacting massive particle

WISP = weakly interacting slim/sub-eV particle

Axions (and Axion-Like particles), in addition to being a possible solution to the strong CP problem, also arise naturally in several extension of the SM (string theory, SUSY): spin 0, very weak coupling to photons

Detection of ALPs: Primakoff effect



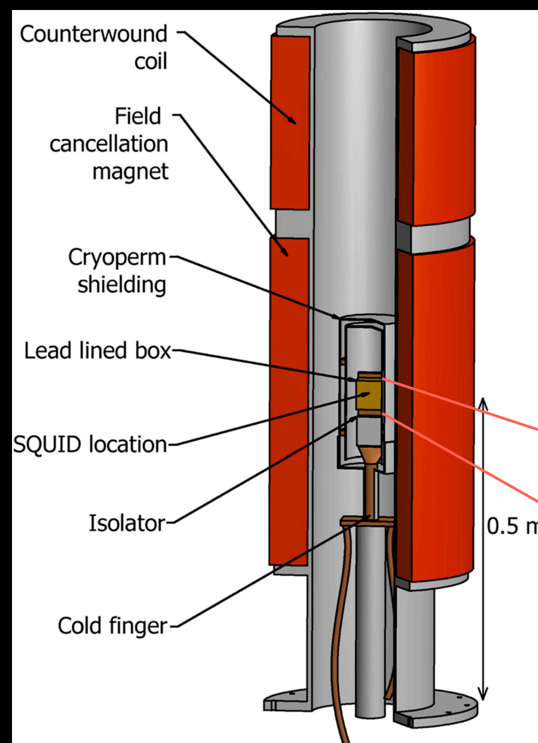
1) dark matter: wisps, ALP's

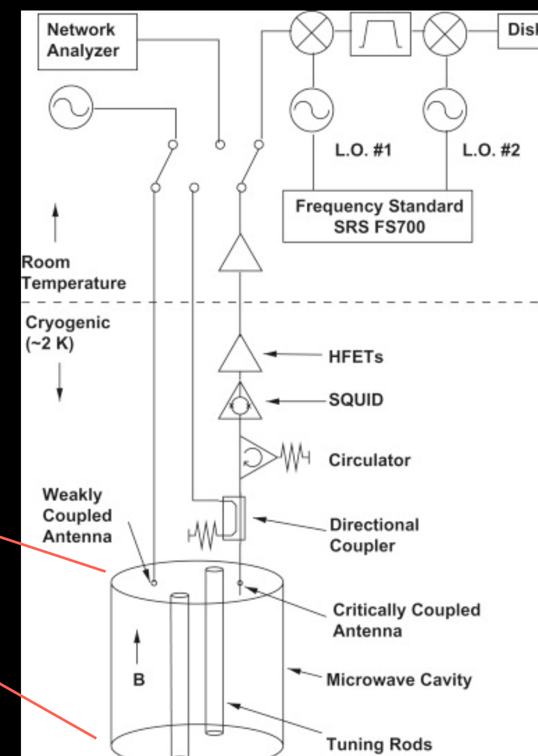
Looking for the dark matter axion wind (galactic halo)

m_a unknown $\longrightarrow$ frequency of optimal coupling unknown
on resonance, axion to photon conversion is enhanced

ADMX

4.13 μeV axion
$\downarrow$
1 GHz photon





S.J. Asztalos et al., NIM A, Volume 656, Issue 1, (2011) 39

Searching for (low energy) axions converting into microwave photons. Uses an 8 Tesla magnet and an RF cavity, and try to induce these axion-photon conversions

1) dark matter: wisps, ALP's

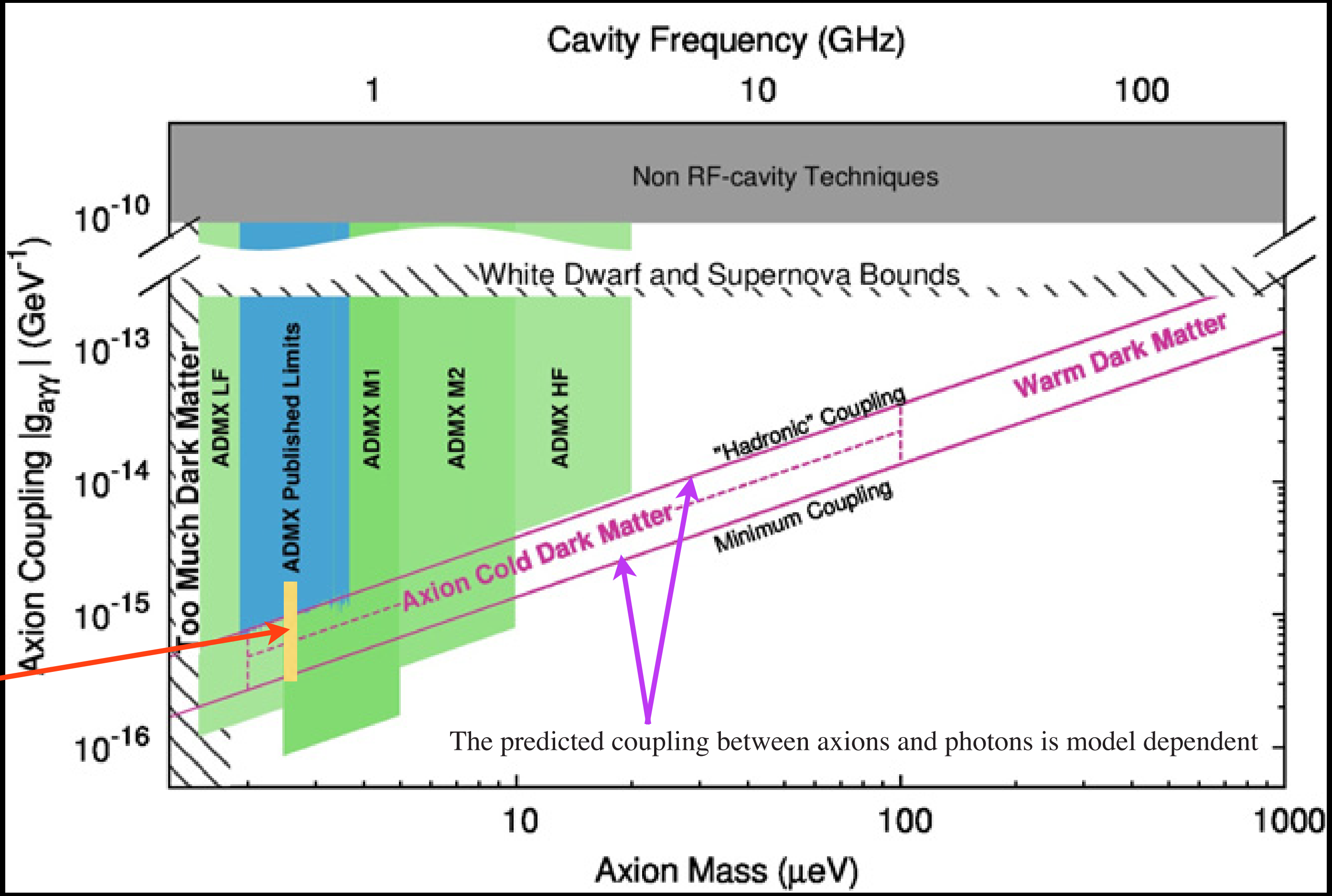
Looking for the dark matter axion wind (galactic halo)

m_a unknown ⟶ frequency of optimal coupling unknown
on resonance, axion to photon conversion is enhanced

ADMX

Gray Rybka, Physics of the Dark Universe 4(2014)14–16

N. Du et al., (ADMX), Phys. Rev. Lett. 120, 151301 (2018)



1) dark matter: wisps, ALP's

CAST

Looking for solar axions; coupling requires 90° between axion momentum and B field: use (LHC) dipole magnets

axion-to-photon conversion $p' = \frac{1}{4} g^2_{a\gamma} (BL)^2 \frac{\sin^2(qL/2)}{(qL/2)^2}$

$q = \Delta p(\text{axion,photon}) = \left| \frac{m^2_a}{2E_a} \right|$ $\qquad m_a \lesssim 0.02\text{eV}$

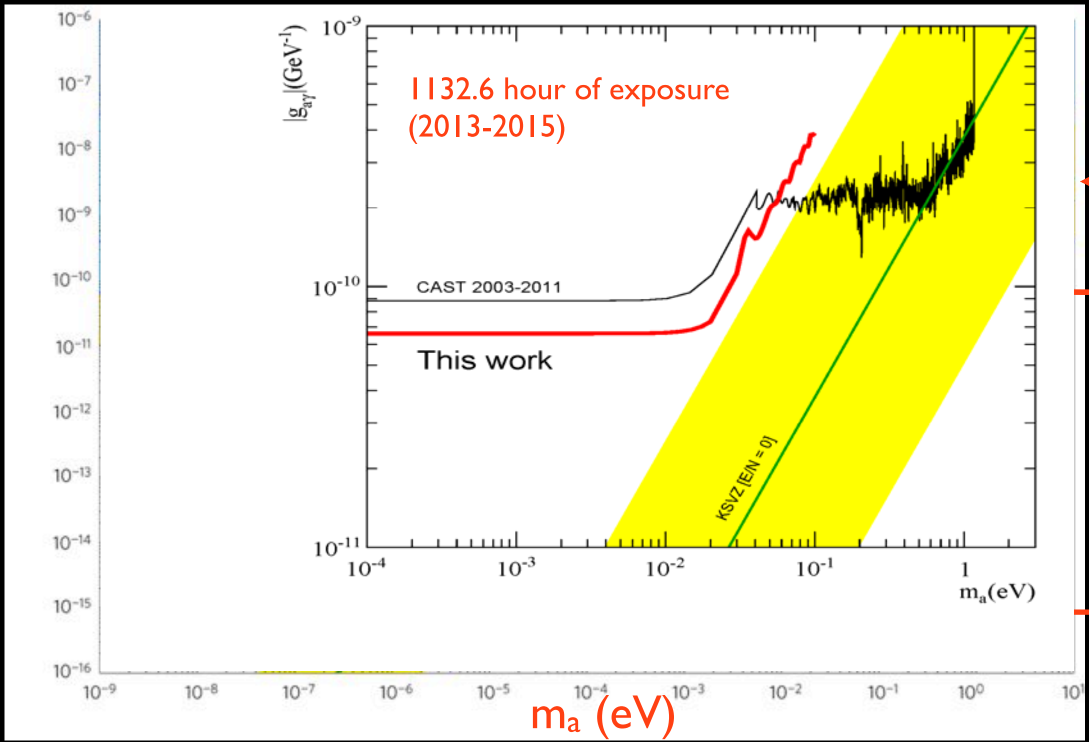
axion-mass independent limit, depends only on exposure

extend range by filling magnet volume with dilute gas:

$q = \left| \frac{m^2_\gamma - m^2_a}{2E_a} \right| \longrightarrow m_a \lesssim 1.12\text{eV}$

1) dark matter: wisps, ALP's

CAST



$|g_{a\gamma}|$ (GeV^{-1})

m_a (eV)

E(solar axion) ~ keV ⟶ X-rays

10^4-10^5 GeV

10^7-10^8 GeV

10^{12}-10^{13} GeV

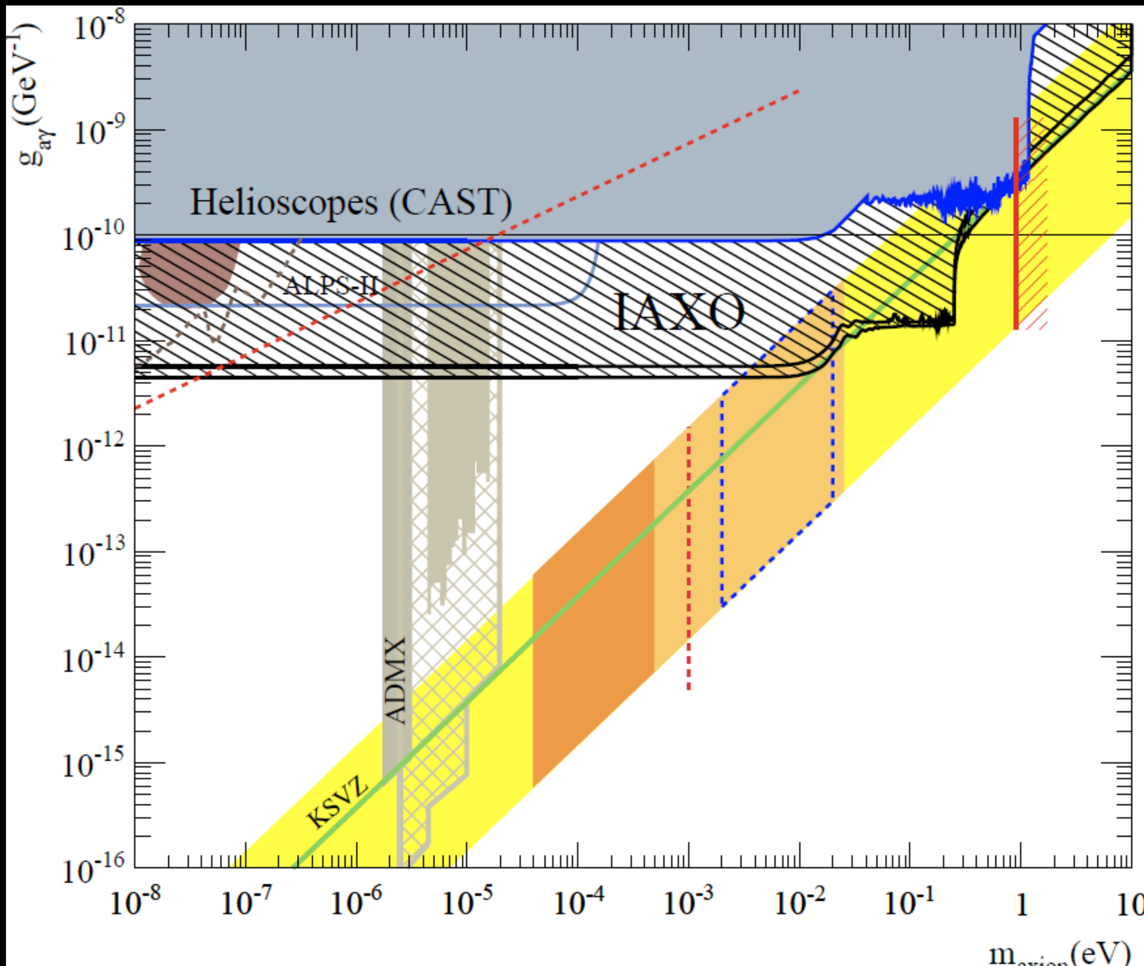
corres-ponding f_a range

>> LHC

Nature Physics **vol 13**, pages 584–590 (2017)

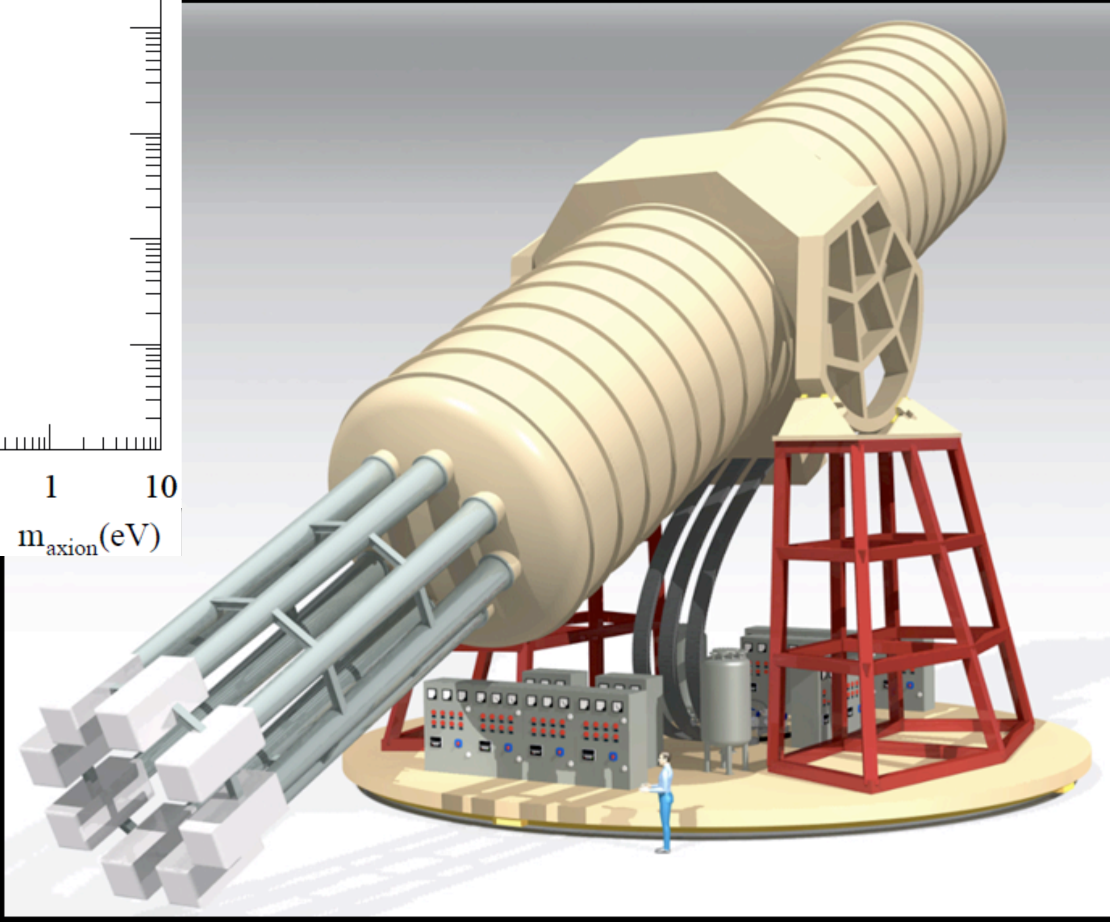
1) dark matter: wisps, ALP's

IAXO



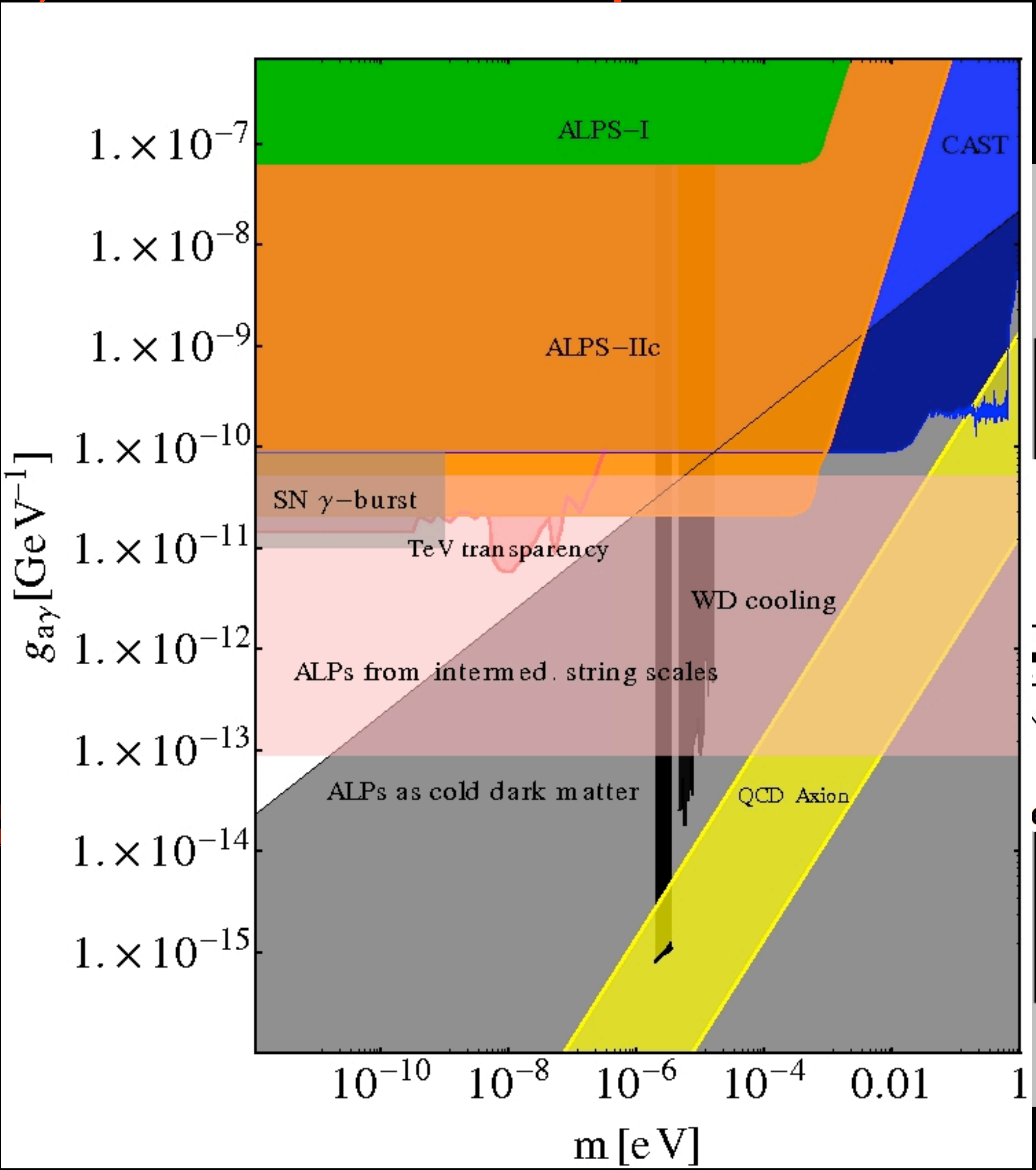
M. Pivaroff, LLNL-PRES-676942 (TAUP 2015 conference)

J.K. Vogel et al., Physics Procedia 61 (2015) 193 – 200

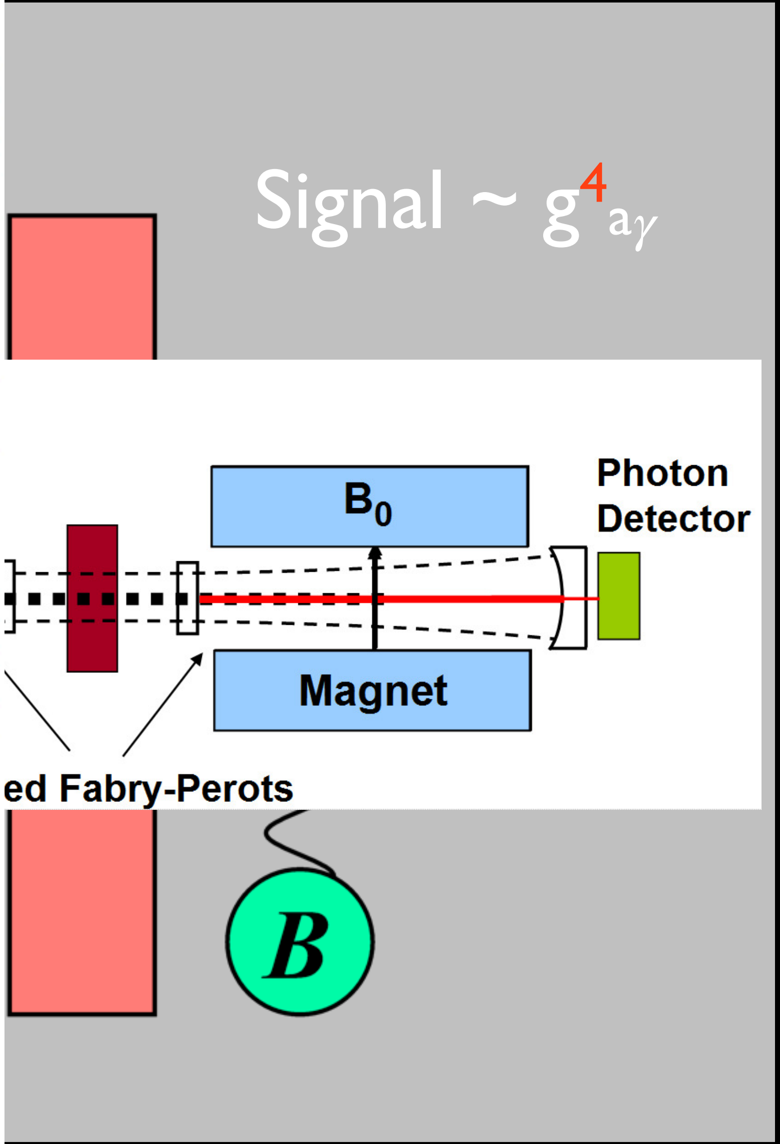


1) dark matter: wisps, ALP's

OSQAR
ALPS-III

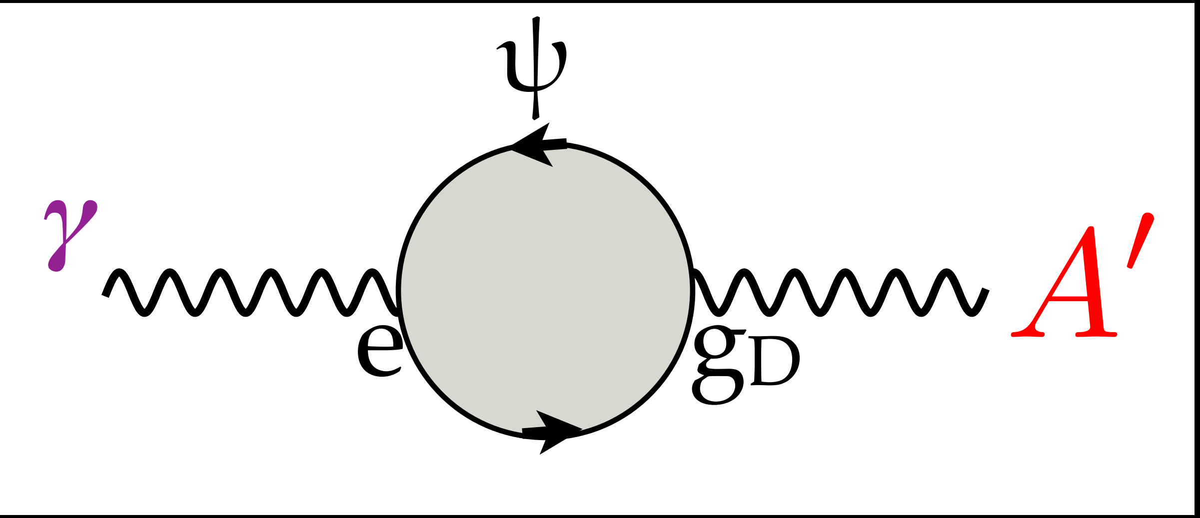


Signal ~ $g^4_{a\gamma}$



1) dark matter: paraphotons, chameleons

again, add a U(1) symmetry to the SM $\longrightarrow$ new Abelian U(1) gauge boson A' that couples very weakly to electrically charged particles with coupling strength $\alpha' = \epsilon^2 \alpha_{em}$, $\alpha_{em} = 1/137$



kinetic mixing:

via one heavy particle ψ with both EM charge e & dark charge g_D

B. Holdom, Phys. Lett. B 166 (1986) 196

Since the dark photon mixes with SM photon, A' can be produced by a similar mechanism that can generate SM photons, but with reduced rate, determined by $m_{A'}$ and ε.

The attractiveness of dark photons is that they allow self-interacting DM; they are the gauge bosons of new U(1) symmetries

https://arxiv.org/pdf/1311.0029.pdf

http://inspirehep.net/record/1338147/files/Pages_from_C14-03-15--1_219.pdf?version=1

1) dark matter: paraphotons, chameleons

expansion of the Universe:

→ massless scalar field that couples to matter with gravitational strength

→ violations of the Equivalence Principle (EP)

"chameleons" avoid this by having a density-dependent mass M (tiny in vacuum)

bounds from current tests of EP compatible with M < O(10^{-3} eV))

J. Khoury & A. Weltman, Phys. Rev. D 69, 044026 (2004)

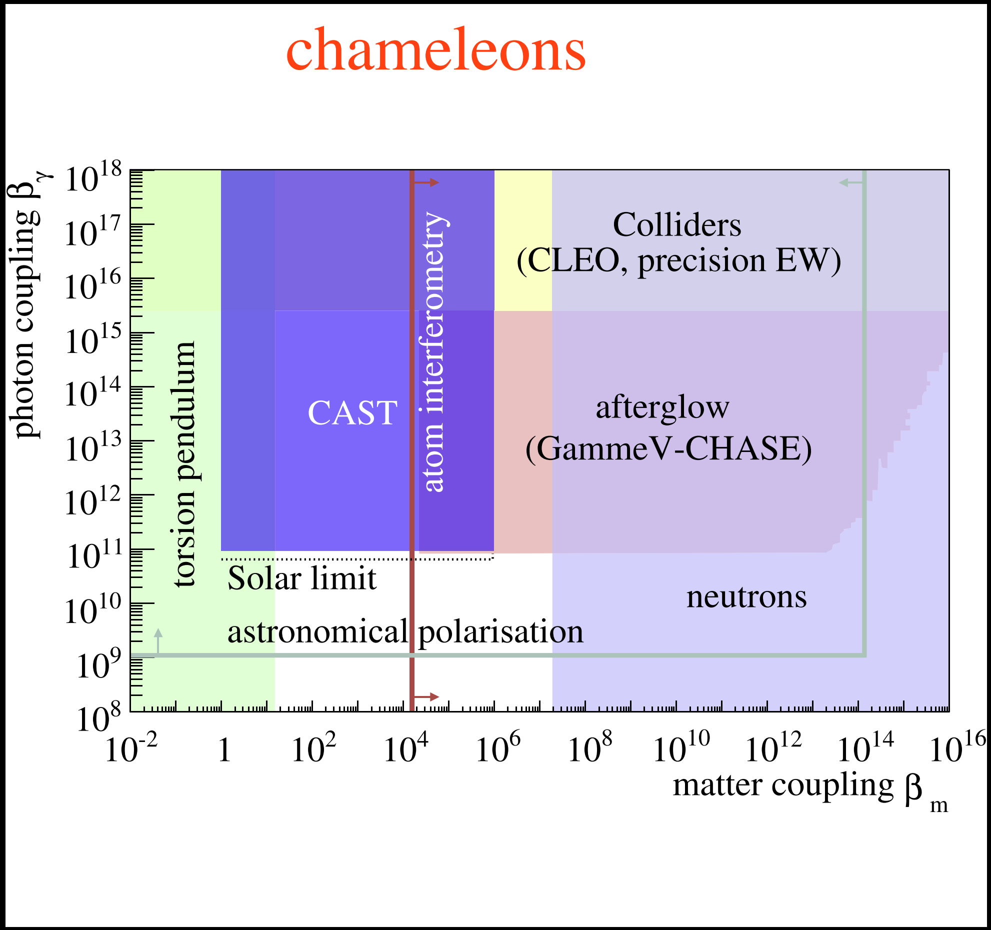
Chameleons, like axions, can be detected by the inverse Primakoff effect inside a transverse magnetic field

all these states have very similar experimental signatures; only the interpretation of (the absence of) a signal depends on the type of particle being looked for

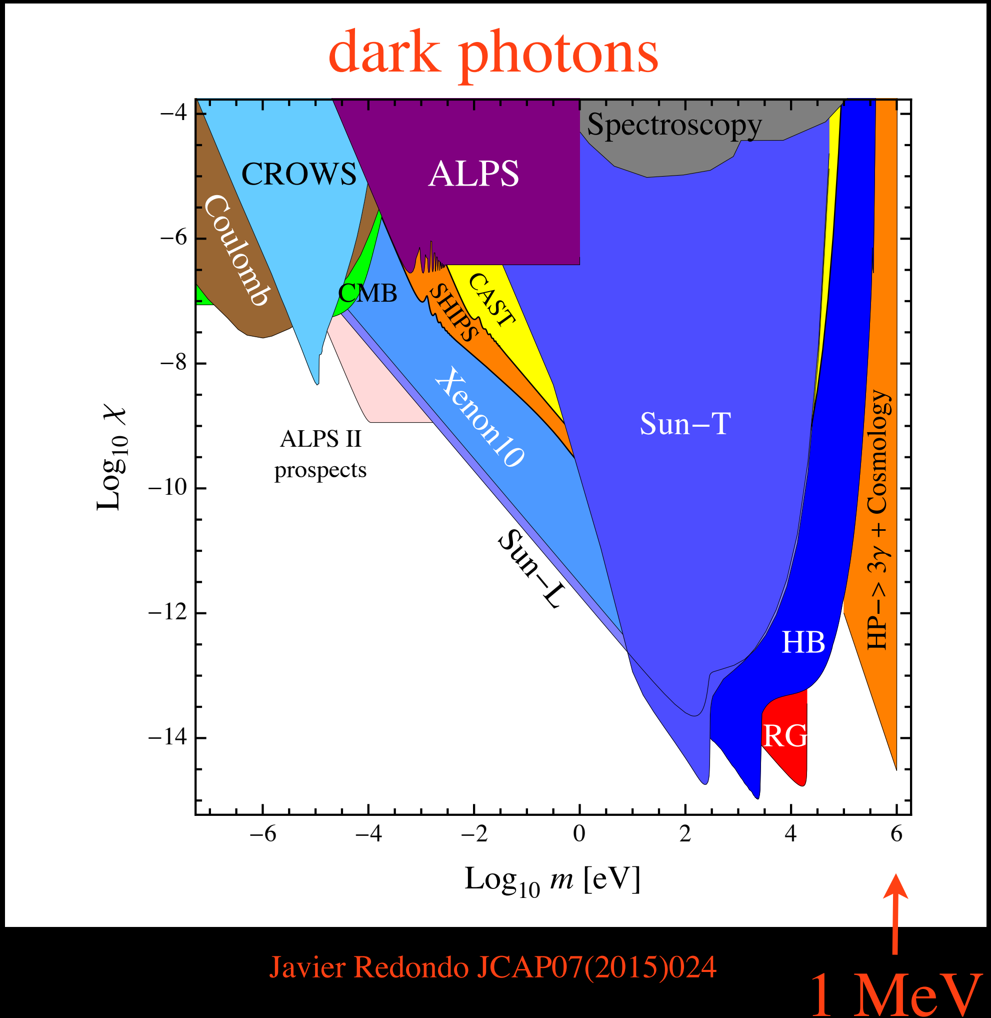
CAST

The parameter space of chameleons is determined by the coupling constants to matter β_m and radiation β_γ,

X-ray detection threshold lowered to below 400 eV, to match the expected converted solar chameleon spectrum which peaks at 600 eV.



V. Anastassopoulos et al. / Physics Letters B 749 (2015) 172–180



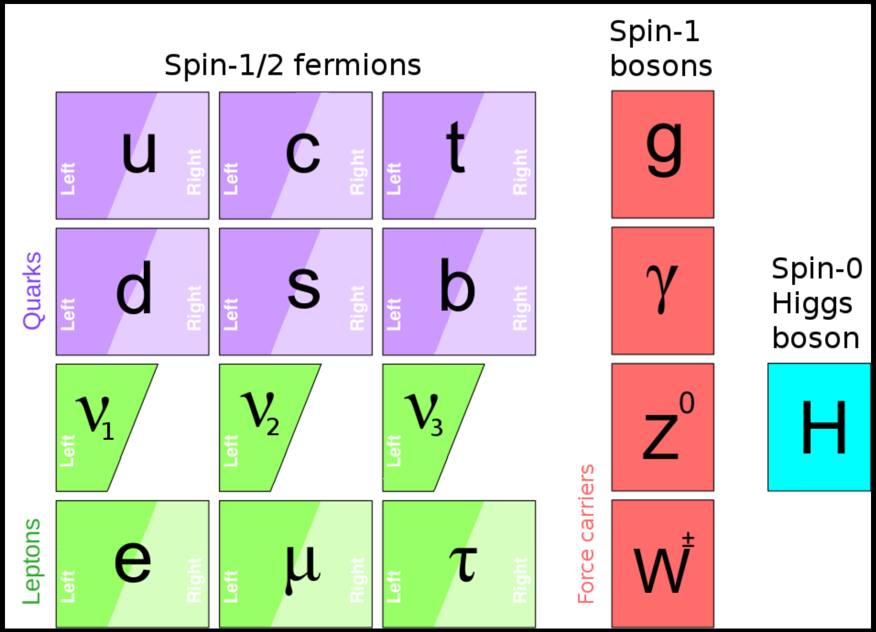
Javier Redondo JCAP07(2015)024

1) dark matter: HNL (incl. sterile neutrinos)

The νMSM, Dark Matter and Baryon Asymmetry of the Universe

νMSM = SM + 3 right-handed HNLs

Takehiko Asaka, Mikhail Shaposhnikov, Phys. Lett. B 620 (2005) 17, https://arxiv.org/abs/hep-ph/0505013

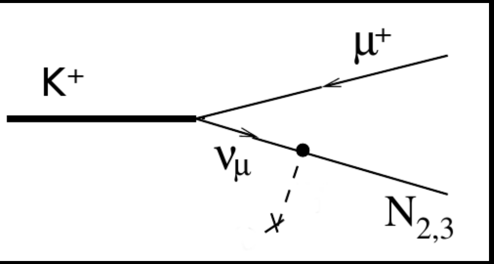


- neutrino masses (see-saw mechanism)
- baryon excess
  (if CP violation in neutrino sector)
- dark matter candidate

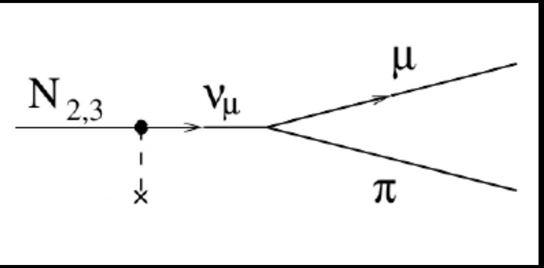
Dark matter sterile neutrino is likely to have a mass in the O(few) keV region; can be searched for in particle physics experiments by detailed analysis of the *kinematics* of β decays of different isotopes or K decays https://arxiv.org/pdf/0705.1729.pdf

F. Bezrukov and M. Shaposhnikov, Phys. Rev. D 75 (2007) 053005 [arXiv:hep-ph/0611352].

2- /3-body decays
$K^\pm \to \mu^\pm N$,
$K^\pm \to e^\pm N$
$K_{L,S} \to \pi^\pm e^\mp N$



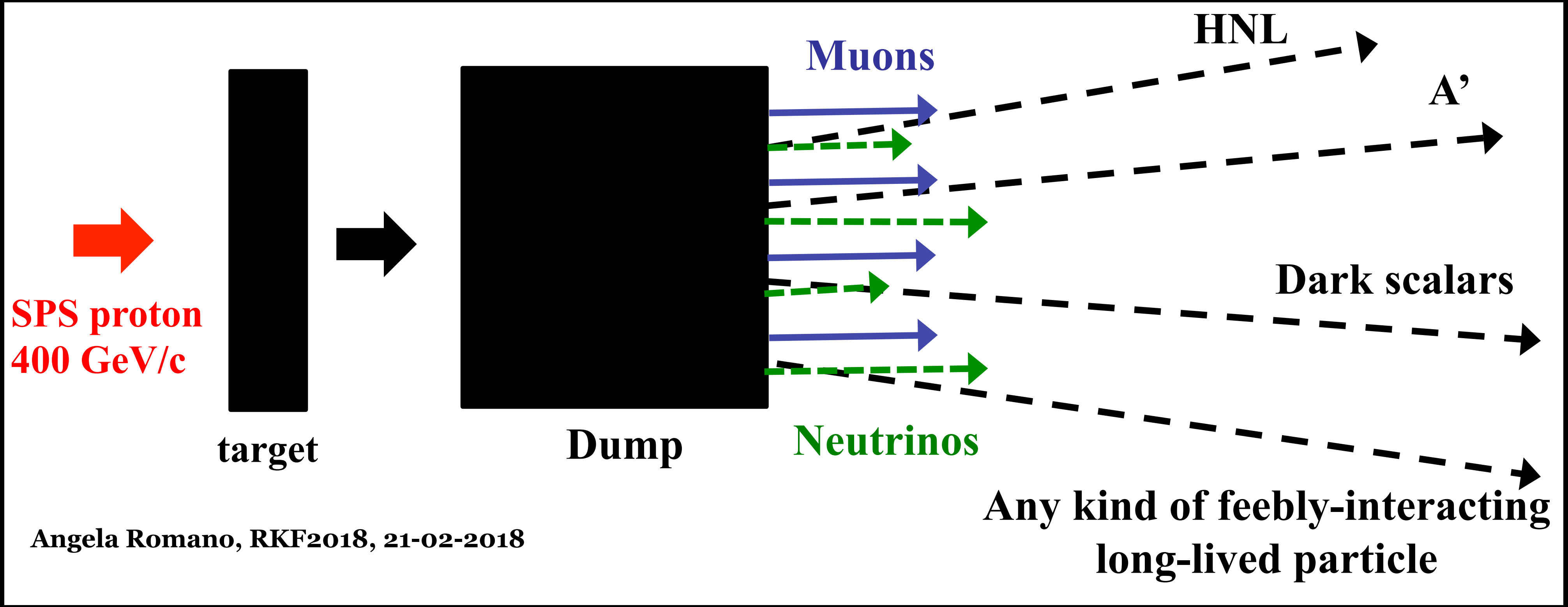
look for the decays of neutral leptons inside a detector



$M_\pi < M_N < M_D$

$M_D < M_N < M_B$

1) dark matter: at fixed target experiments NA62



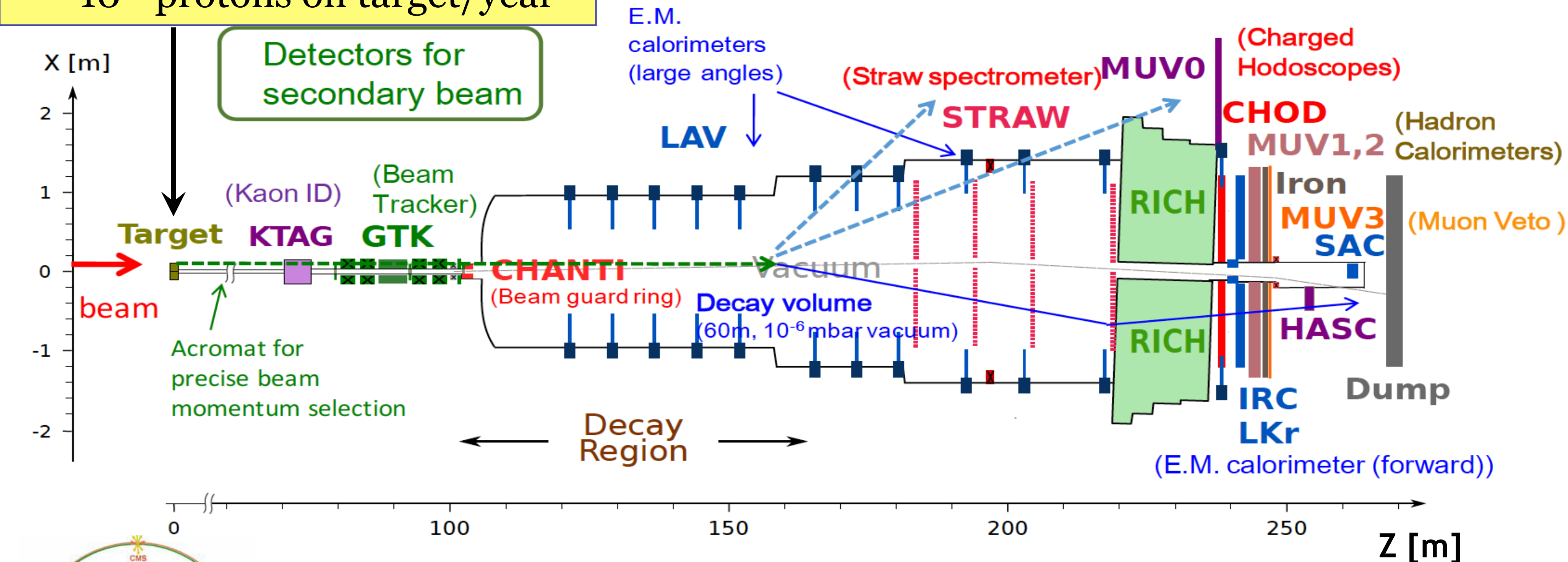
- DM-SM interactions feeble: ultra-suppressed production rate, very long lived
- requires high intensity, high energy beam for production
- requires long fiducial decay volume and subsequent excellent PID

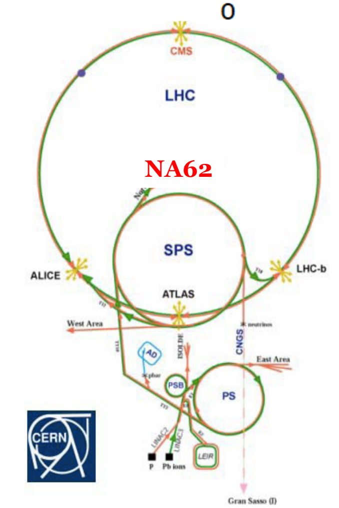
1) dark matter: at fixed target experiments NA62

SPS proton beam on Be target:
- 400 GeV/c, 3×10^{12}/spill
- $\sim10^{18}$ protons on target/year

[NA62 Detector Paper, 2017 JINST 12 P05025]

Angela Romano, RKF2018, 21-02-2018





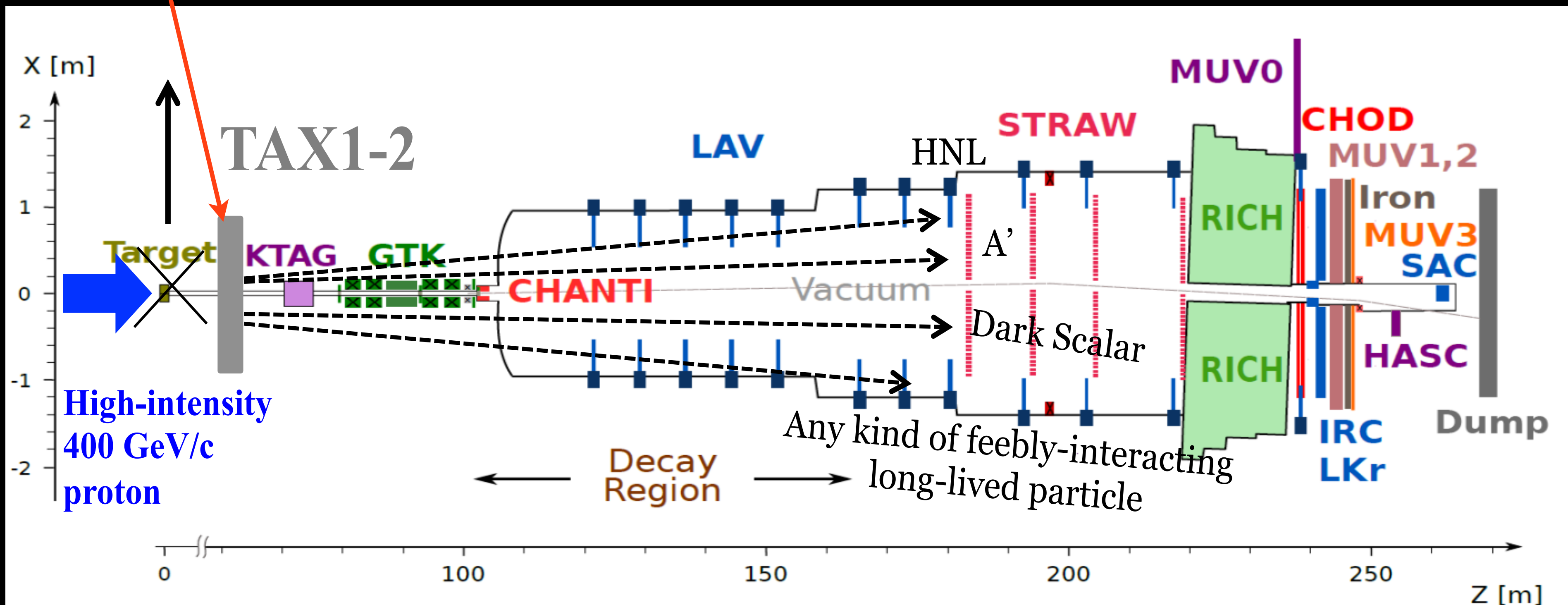
- 800 MHz beam rate @ GTK (K^+ @ 75 GeV/c, 45MHz)
- hermetic photon veto: 10^{-8} rejection of $\pi^0\rightarrow\gamma\gamma$ (E_γ>40 GeV)
- excellent timing O(100ps), PID, kinematics

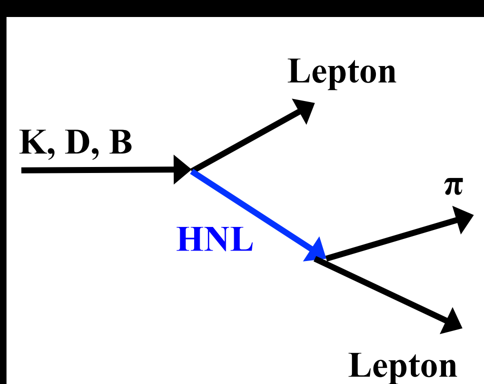
→ well suited to searching for MeV-GeV particles feebly coupled to SM via direct detection of long-lived particles

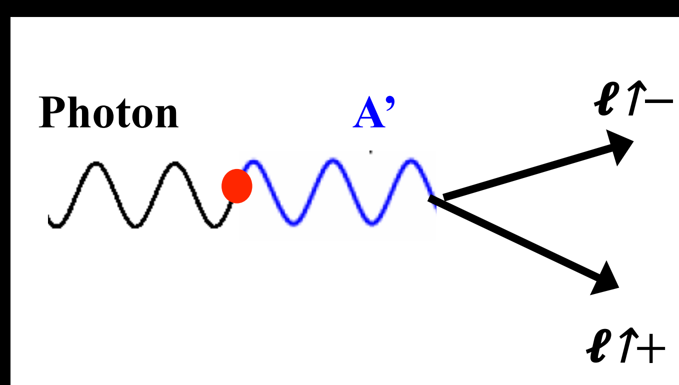
1) dark matter: at fixed target experiments NA62

Angela Romano, RKF2018, 21-02-2018

TAX1-2 = 3.2 m Cu/Fe ~ 22 λ_I = beam dump



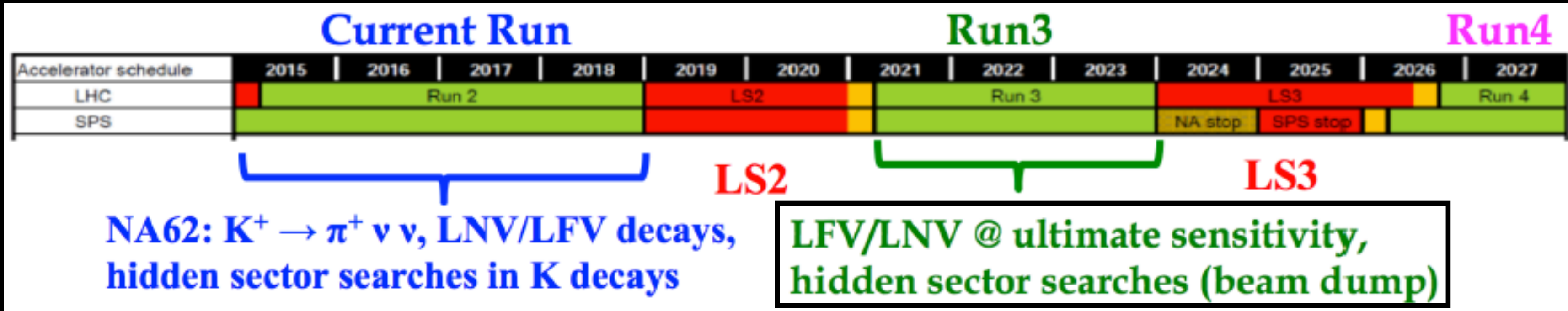


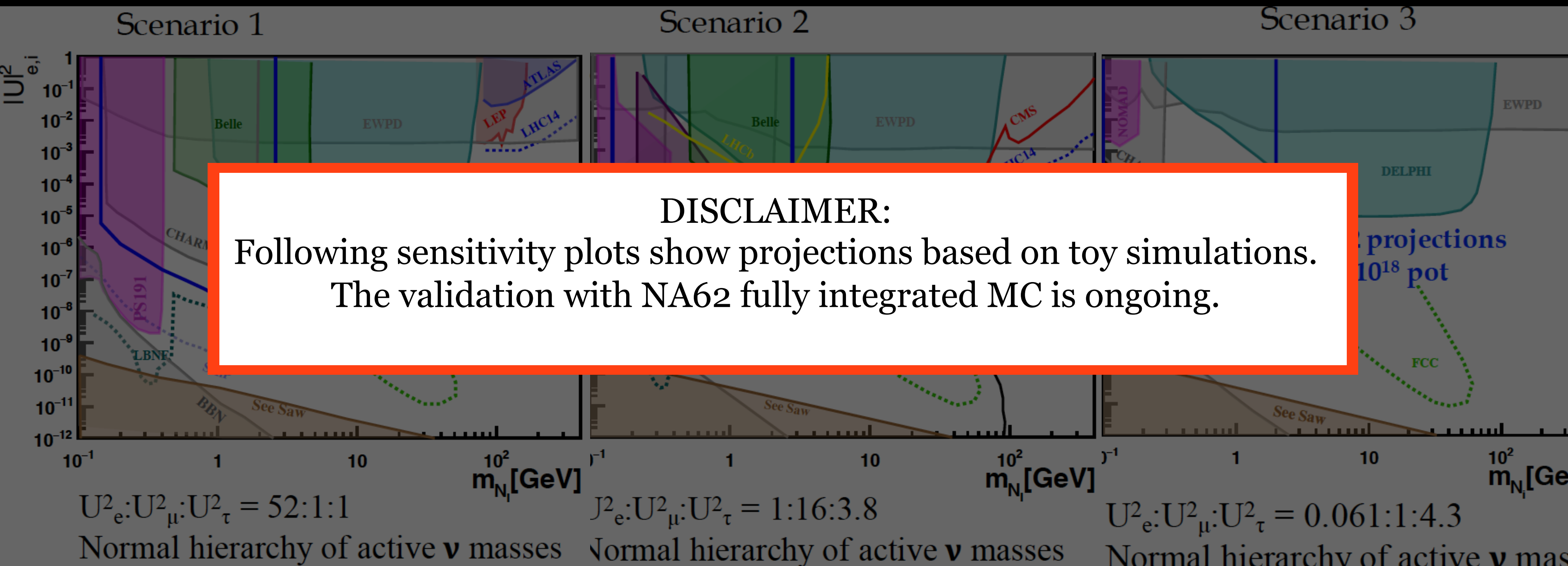


$\tau_X \sim 1/\text{coupling}^2$

long decay volume probes low values of coupling

NA62



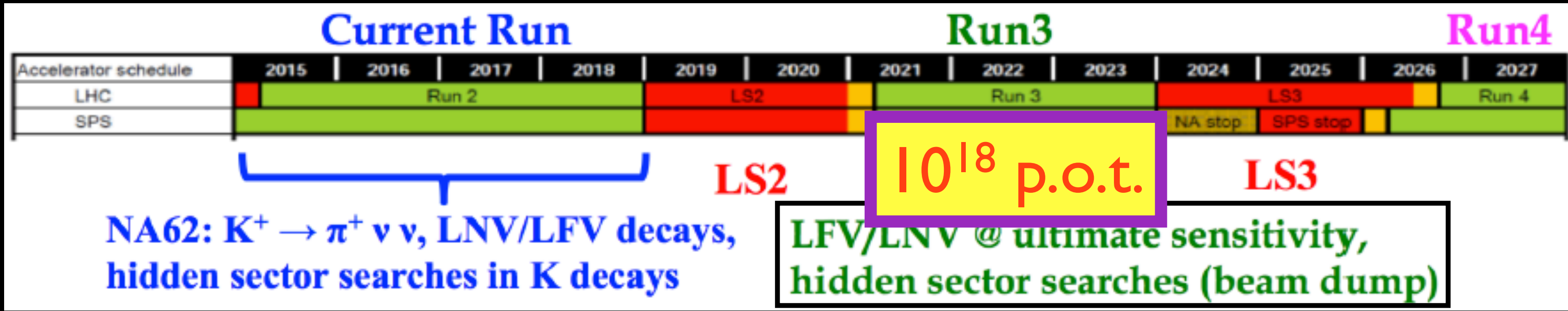


DISCLAIMER:
Following sensitivity plots show projections based on toy simulations.
The validation with NA62 fully integrated MC is ongoing.

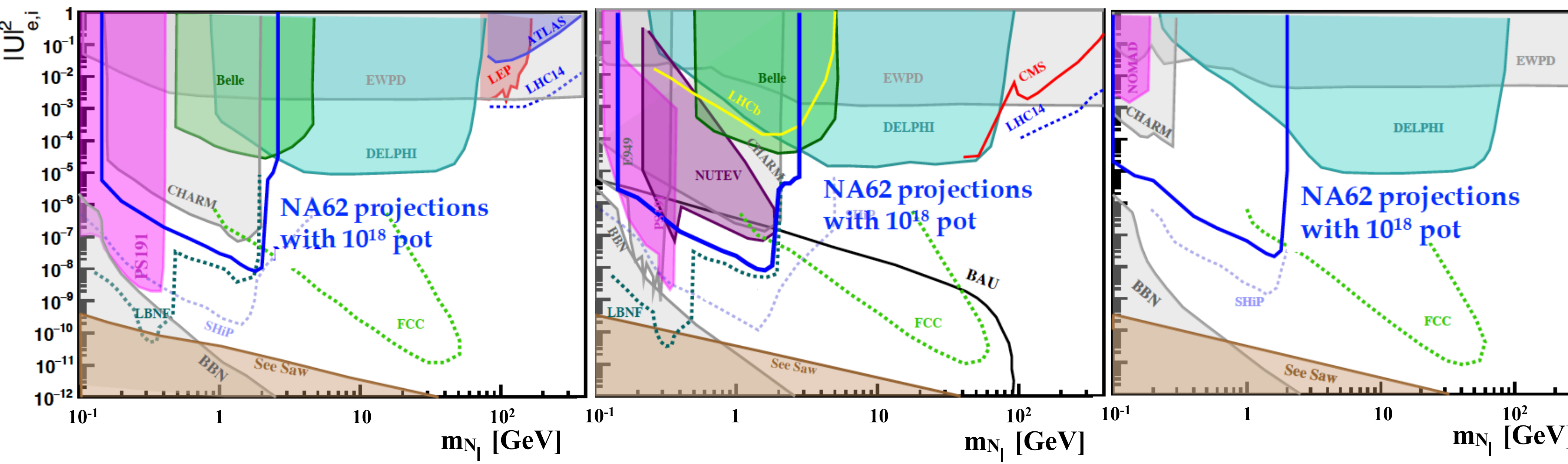
Heavy Neutral Lepton (HNL)

NA62 sensitivity with **~10^{18} 400-GeV PoT** running in “dump” mode

NA62



Scenario 1 | Scenario 2 | Scenario 3



$U^2_e:U^2_\mu:U^2_\tau = 52:1:1$
Normal hierarchy of active ν masses

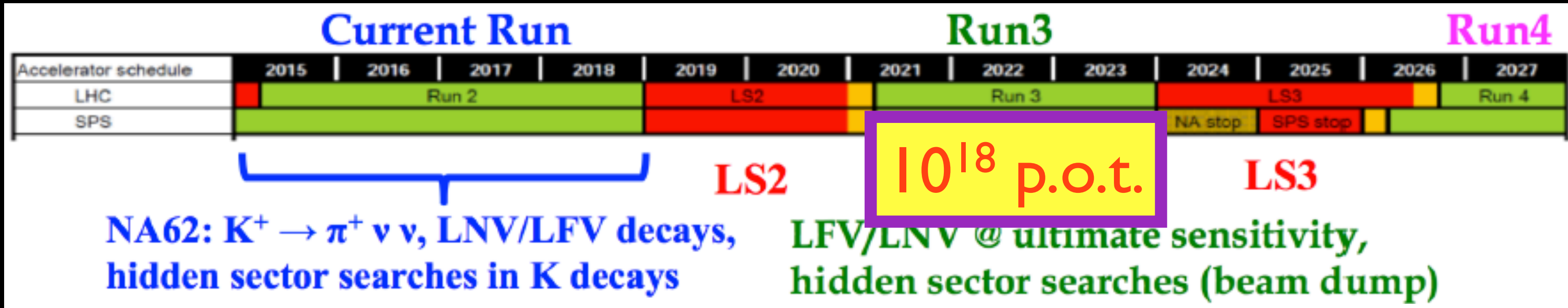
$U^2_e:U^2_\mu:U^2_\tau = 1:16:3.8$
Normal hierarchy of active ν masses

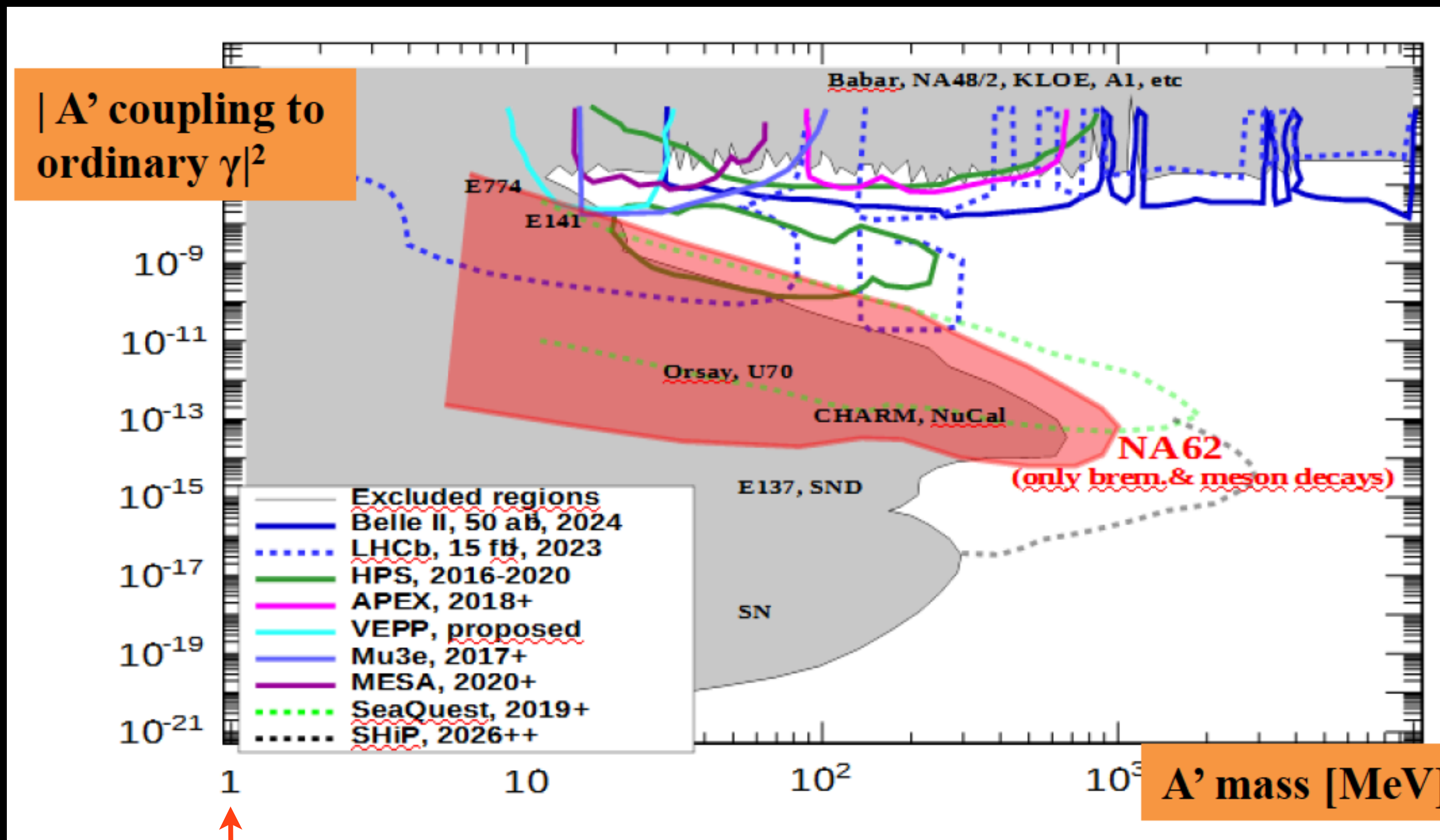
$U^2_e:U^2_\mu:U^2_\tau = 0.061:1:4.3$
Normal hierarchy of active ν masses

Heavy Neutral Lepton (HNL)

NA62 sensitivity with **~10^{18} 400-GeV PoT** running in "dump" mode

NA62



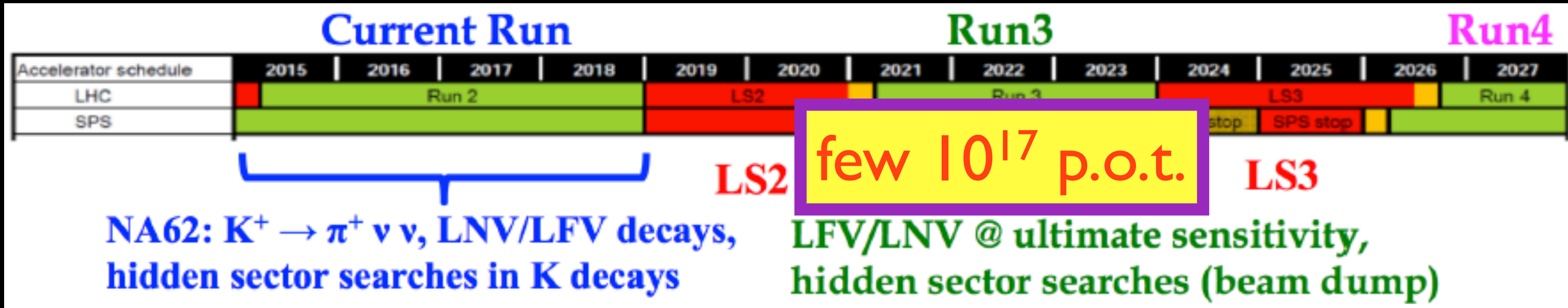


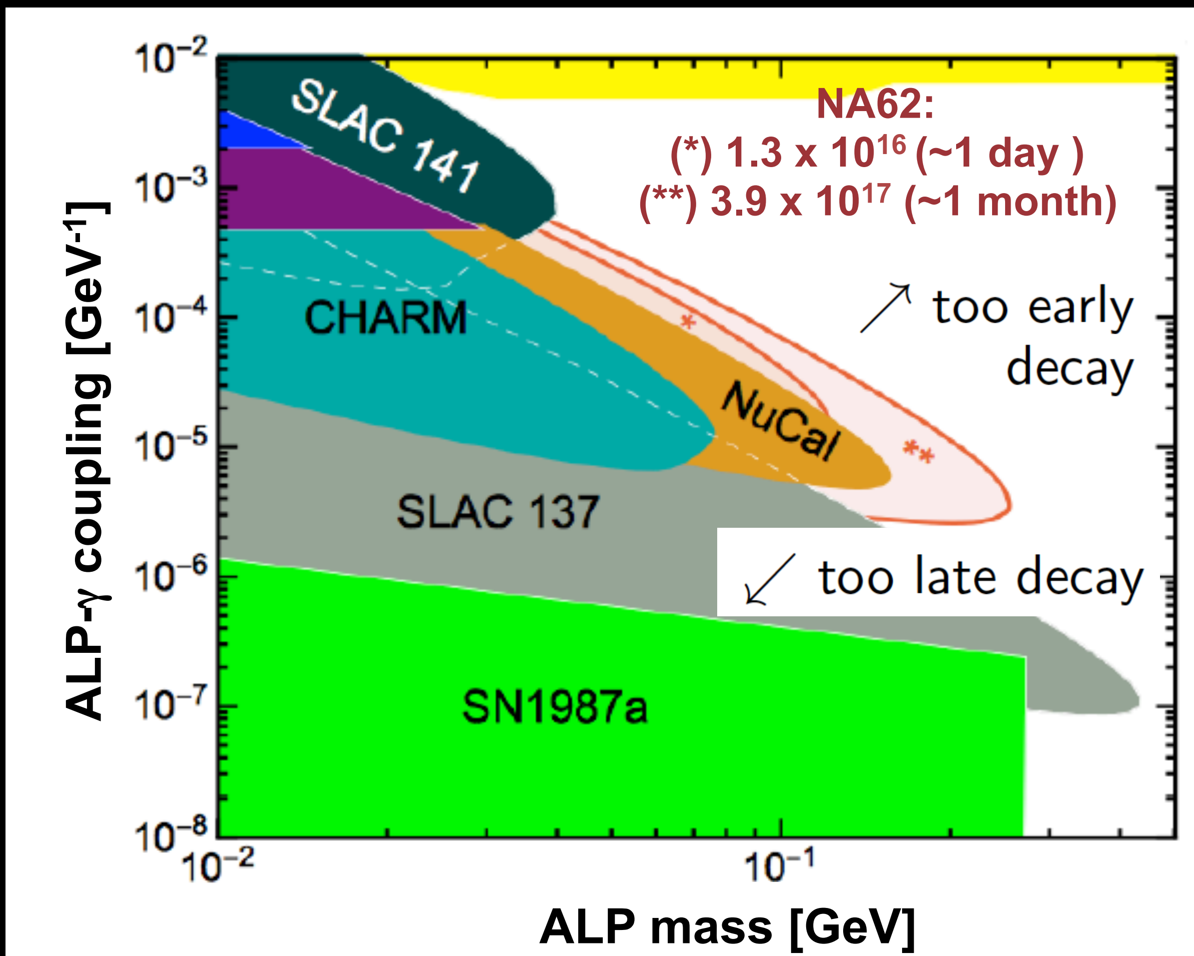
1 MeV

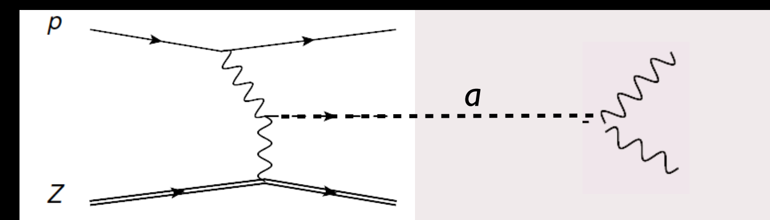
Dark Photon

NA62 sensitivity with $\sim 10^{18}$ **400-GeV PoT** running in "dump" mode

NA62







target

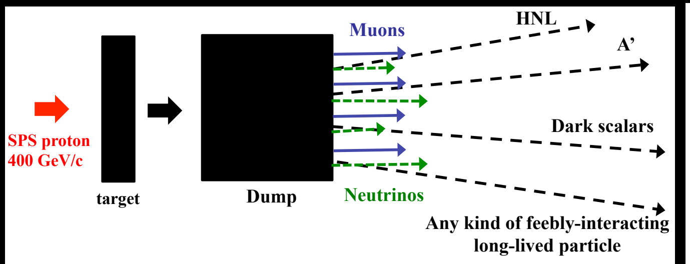
decay volume

$$\tau \sim 1/(g_{a\gamma}^2 m_a^3)$$

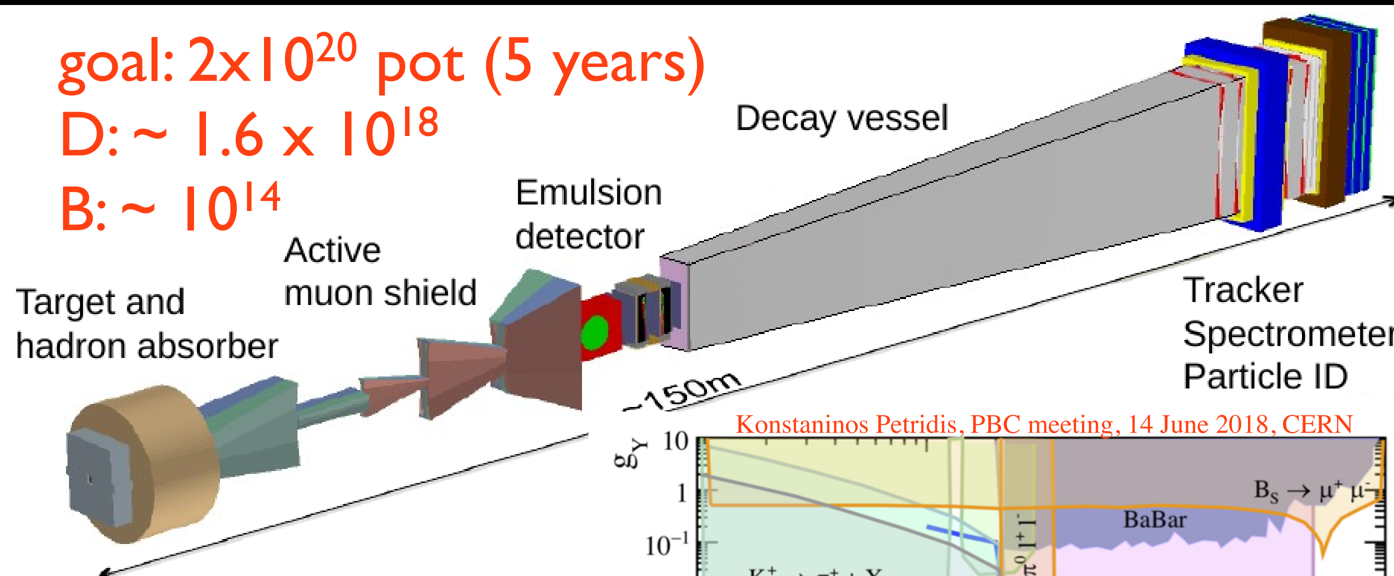
Axion-like Particle (ALP)

NA62 sensitivity with **1.3 x 10[16] (3.9 x 10[17]) 400-GeV PoT** corresponding to 1 day (1 month) of runs in "dump" mode

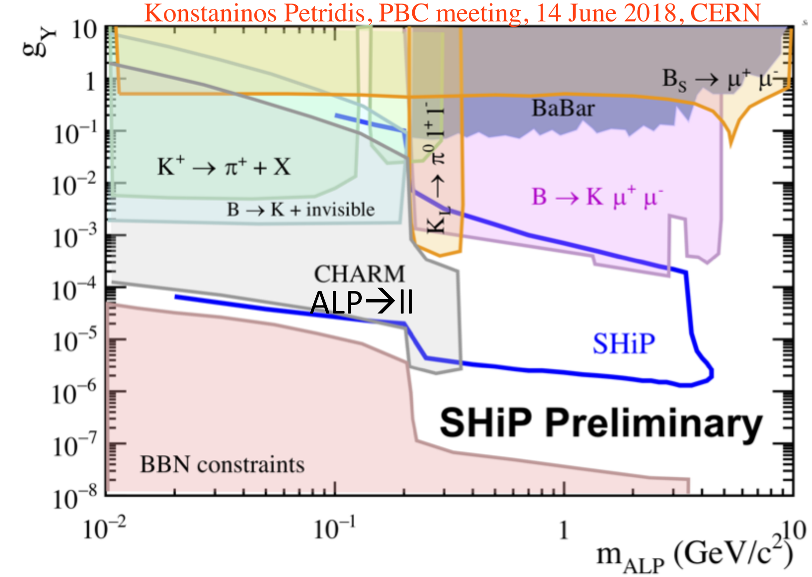
1) dark matter: at fixed target experiments SHiP

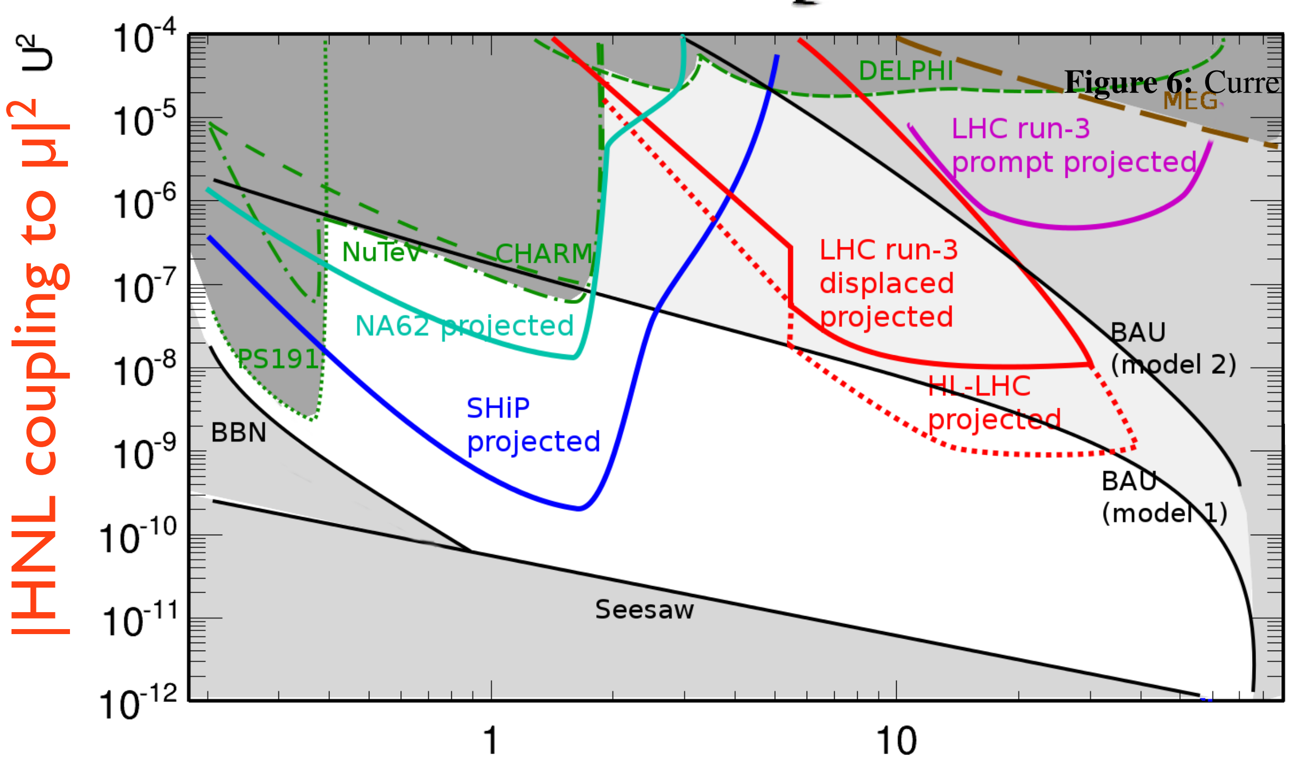


goal: 2×10^{20} pot (5 years)
D: ~ 1.6×10^{18}
B: ~ 10^{14}

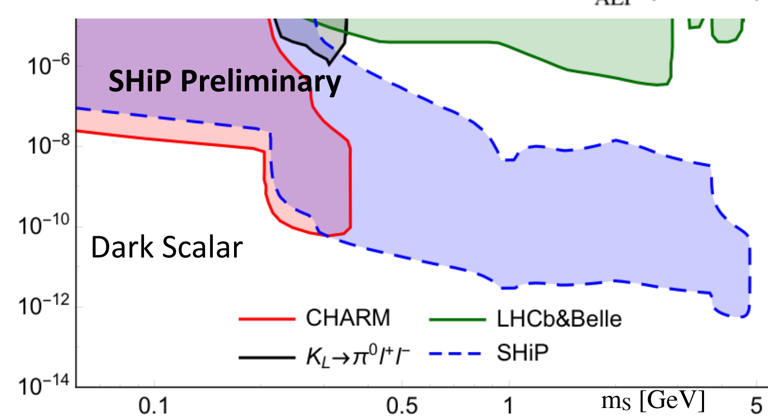


Konstaninos Petridis, PBC meeting, 14 June 2018, CERN





Philippe Mermod, arXiv:1712.01768v1 [hep-ex] 5 Dec 2017



2) broken* symmetries?

look at the following symmetries:

LFV
CPT
WEP
Lorentz invariance

* νMSM is a potential solution to the baryon asymmetry of the Universe, by moving the problem to the lepton sector; alternatively, $\not{CP}$, but no sign of baryon number violation yet

fundamental symmetries: CPT, Lorentz invariance

CPT is part of the "standard model", but the SM can be extended to allow CPT violation

CPT violation and the standard model

Don Colladay and V. Alan Kostelecký
Department of Physics, Indiana University, Bloomington, Indiana 47405
Phys. Rev. D 55, 6760–6774 (1997)

CPT & Lorentz violation

Modified Dirac eq. in SME

$$(i\gamma^{\mu}D_{\mu} - m_e - \boxed{a^e_{\mu}\gamma^{\mu} - b^e_{\mu}\gamma_5\gamma^{\mu}}$$
$$- \boxed{\tfrac{1}{2}H^e_{\mu\nu}\sigma^{\mu\nu} + ic^e_{\mu\nu}\gamma^{\mu}D^{\nu} + id^e_{\mu\nu}\gamma_5\gamma^{\mu}D^{\nu}})\psi = 0\,.$$

Lorentz violation

- Spontaneous Lorentz symmetry breaking by (exotic) string vacua
- Note: there is a preferred frame, sidereal variation due to earth rotation may be detectable

fundamental symmetries: WEP

- General relativity is a classical (non quantum) theory;
- EEP violations may appear in some quantum theory
- New quantum scalar and vector fields are allowed in some models (Kaluza Klein ….)

Einstein field: tensor graviton (Spin 2, “Newtonian”)

+ Gravi-vector (spin 1)

+ Gravi-scalar (spin 0)

- These fields may mediate interactions violating the equivalence principle

M. Nieto and T. Goldman, Phys. Rep. 205, 5 221-281,(1992)

$$V = -\frac{G_\infty}{r} m_1 m_2 \left(1 \mp a\, e^{-r/v} + b\, e^{-r/s} \right)$$

Phys. Rev. D 33 (2475) (1986)

Cancellation effects in matter experiment if a ≈ b and v ≈ s

fundamental symmetries:

antimatter experiments (all at CERN)

precision antiproton measurements

q, m, μ

ATRAP, BASE

precision antihydrogen & antiprotonic atom spectroscopy

ALPHA, ATRAP, ASACUSA

gravity w/ antihydrogen

and other antimatter-containing systems

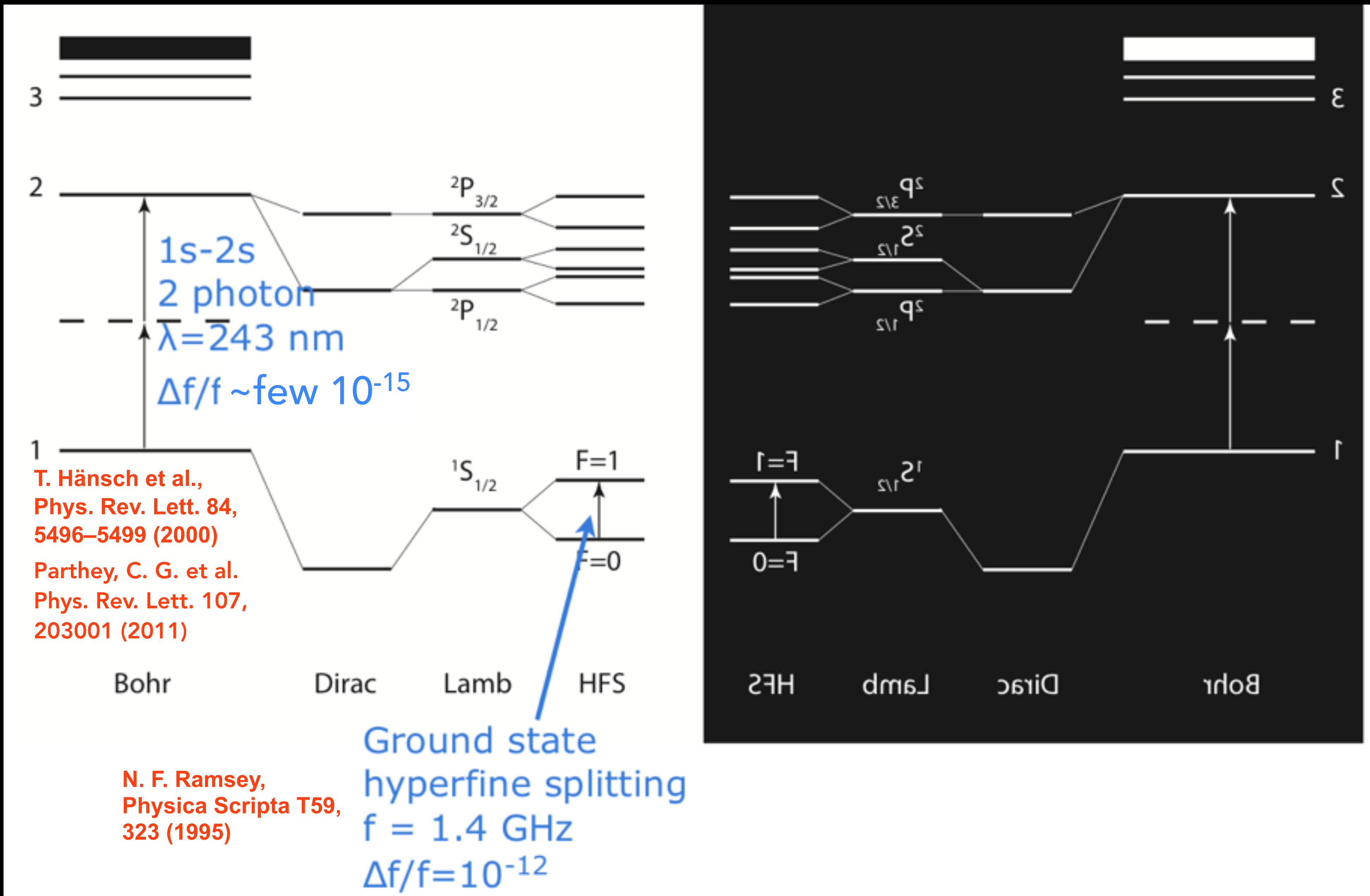
AE$\bar{g}$IS, ALPHA, GBAR

spectroscopy / ALPHA / antihydrogen formation

precision
antihydrogen &
antiprotonic atom
spectroscopy
ALPHA, ATRAP,
ASACUSA

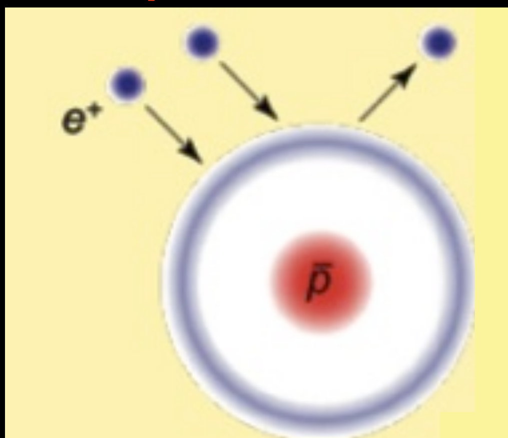
experimentally:

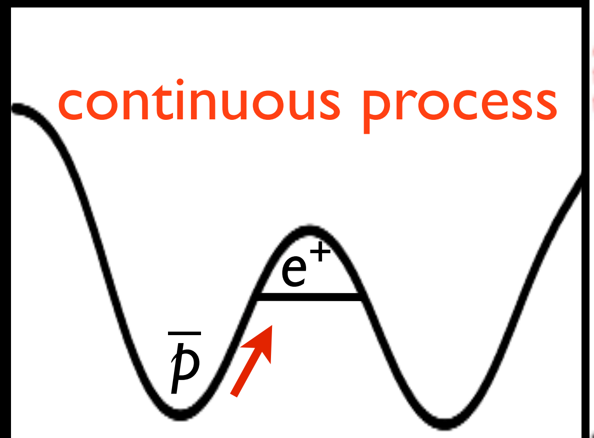
HYDROGEN **ANTIHYDROGEN**



ALPHA: antihydrogen formation & trapping

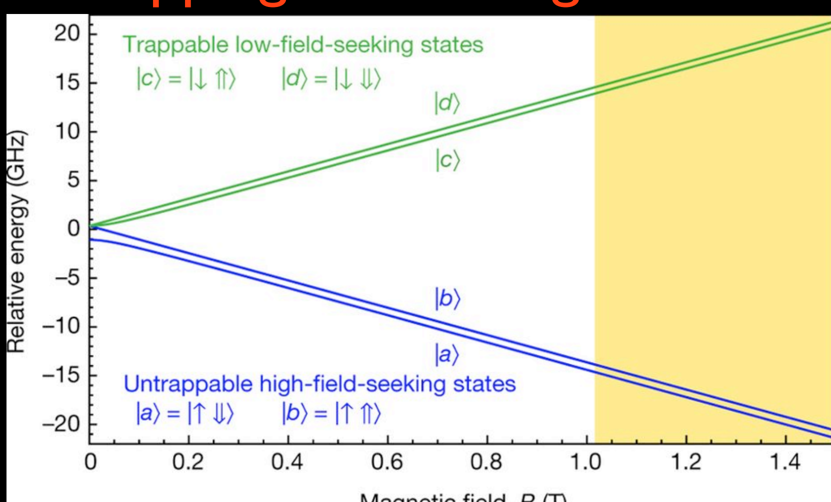
3-body recombination

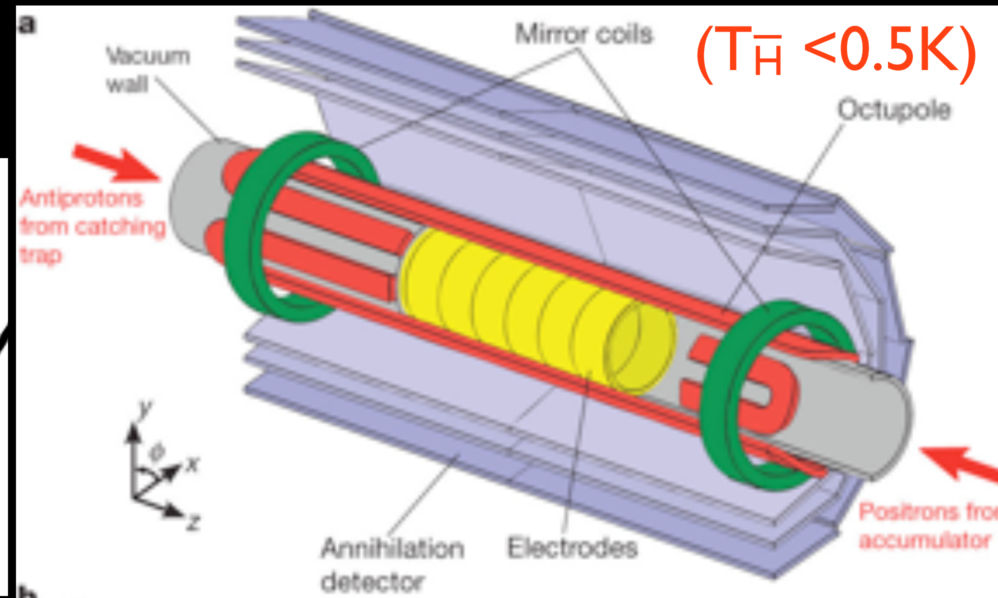


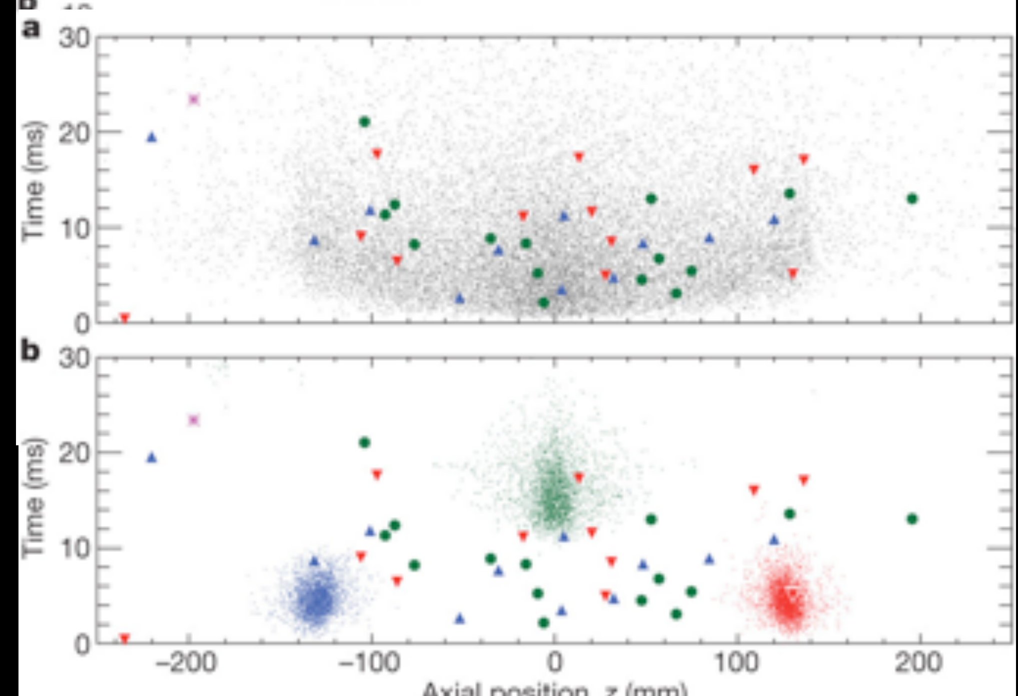


$v_{\bar{H}} \sim v_{e^+}$ ($T_{\bar{H}} >> T_{e^+}$)

trapping in B-field gradient



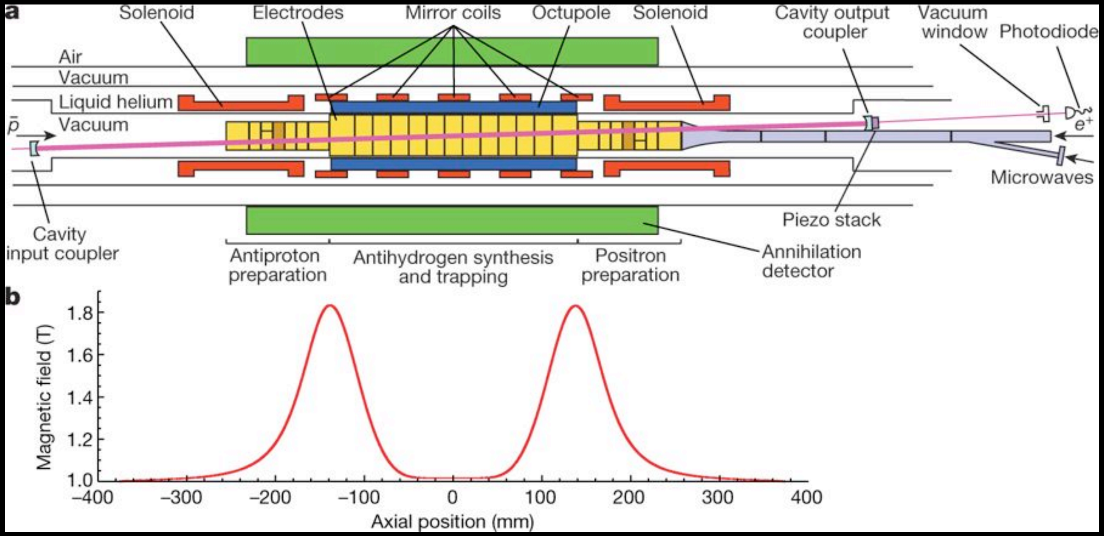




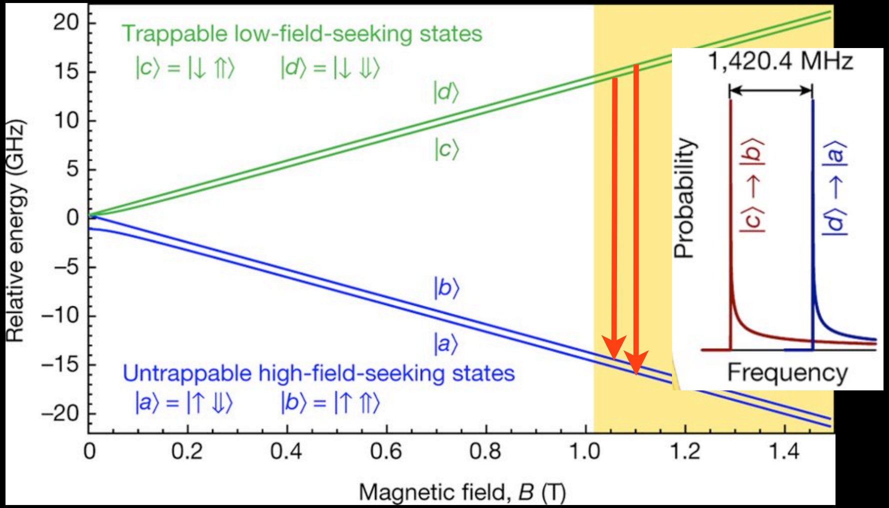
G. B. Andresen et al., Nature 468, 673–676 (02 December 2010)

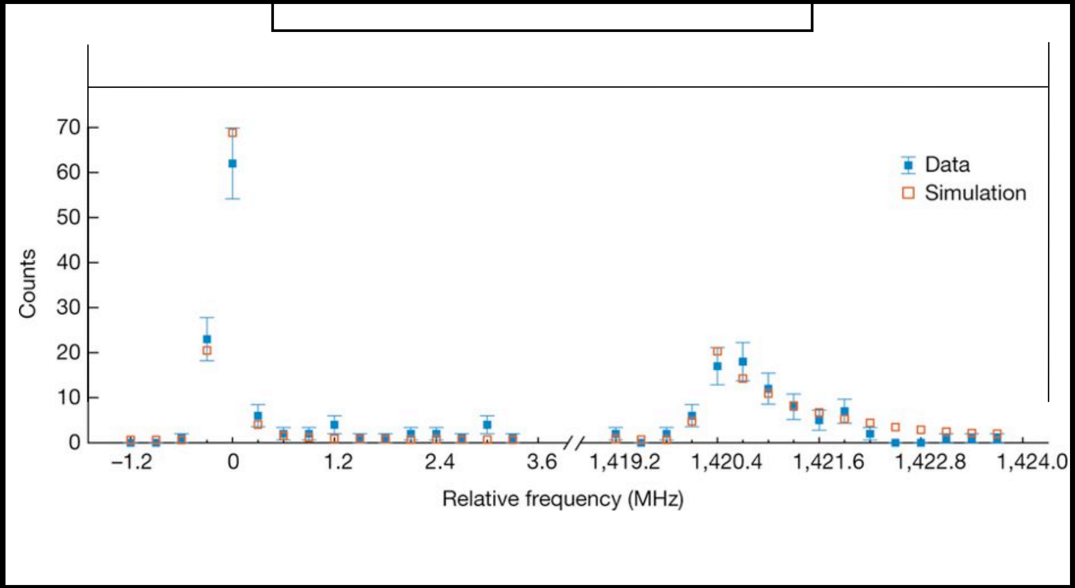
ALPHA: antihydrogen hyperfine splitting

M. Ahmadi et al., Nature 548, 66–69 (03 August 2017)



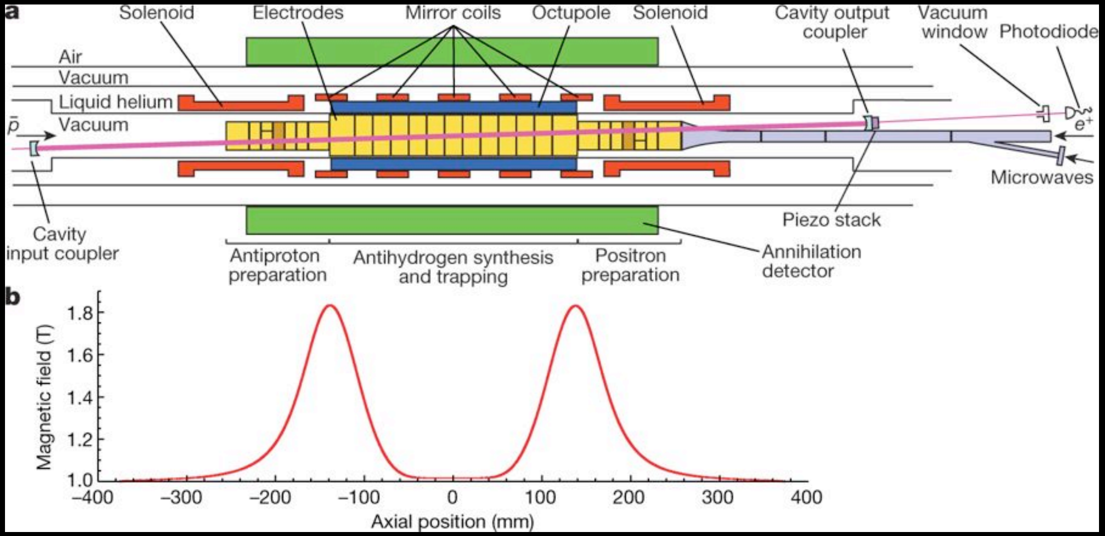
HFS$_H$ = 1,420.4 ± 0.5 MHz





ALPHA: antihydrogen precision spectroscopy

M. Ahmadi et al., Nature 557, 71–75 (2018)



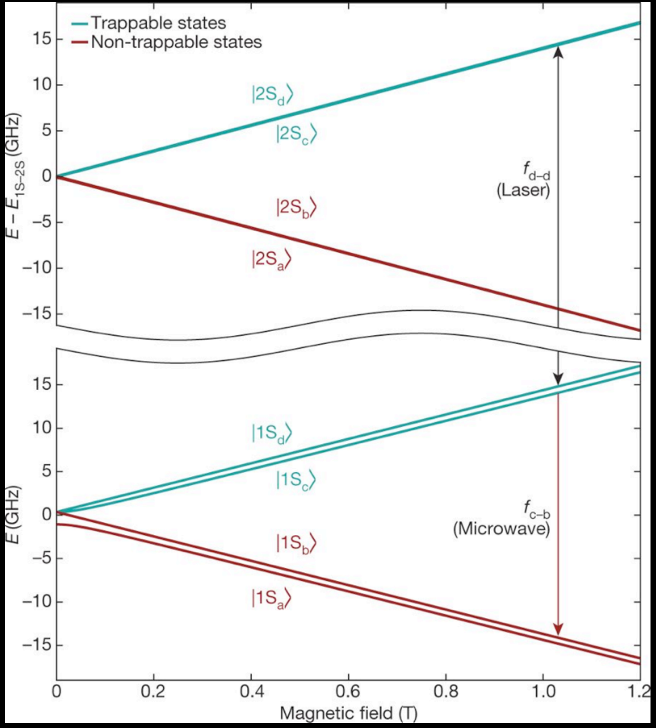
initial population 50:50 $1S_c$ and $1S_d$

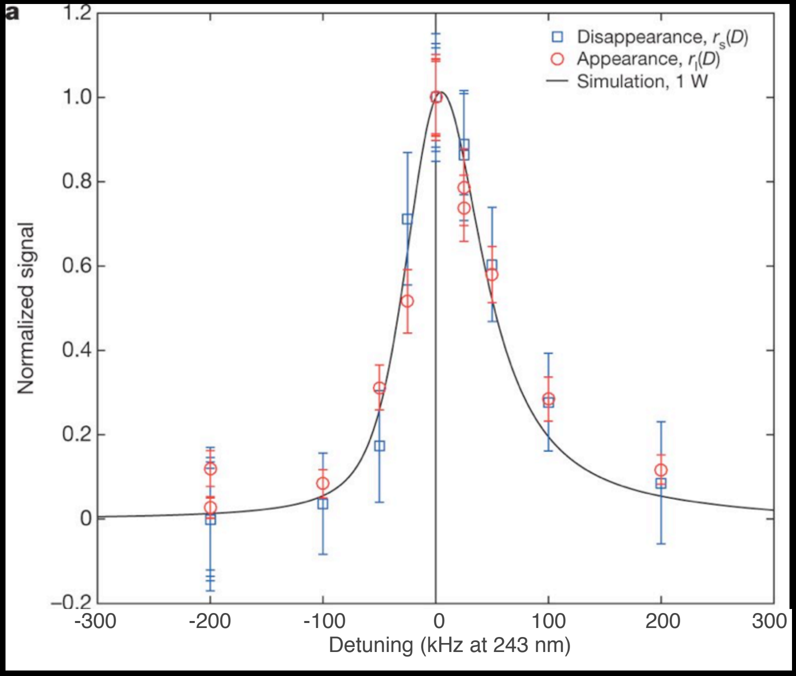
count $1S_d$ population: 2γ excite into $2S_d$

- photo-ionize $2S_d$ with 3rd γ
- decay into (untrapped)

count $1S_c$ population: μwave into $1S_b$

count remaining $1S_d$ population: dump





1S-2S to 10^{-12}

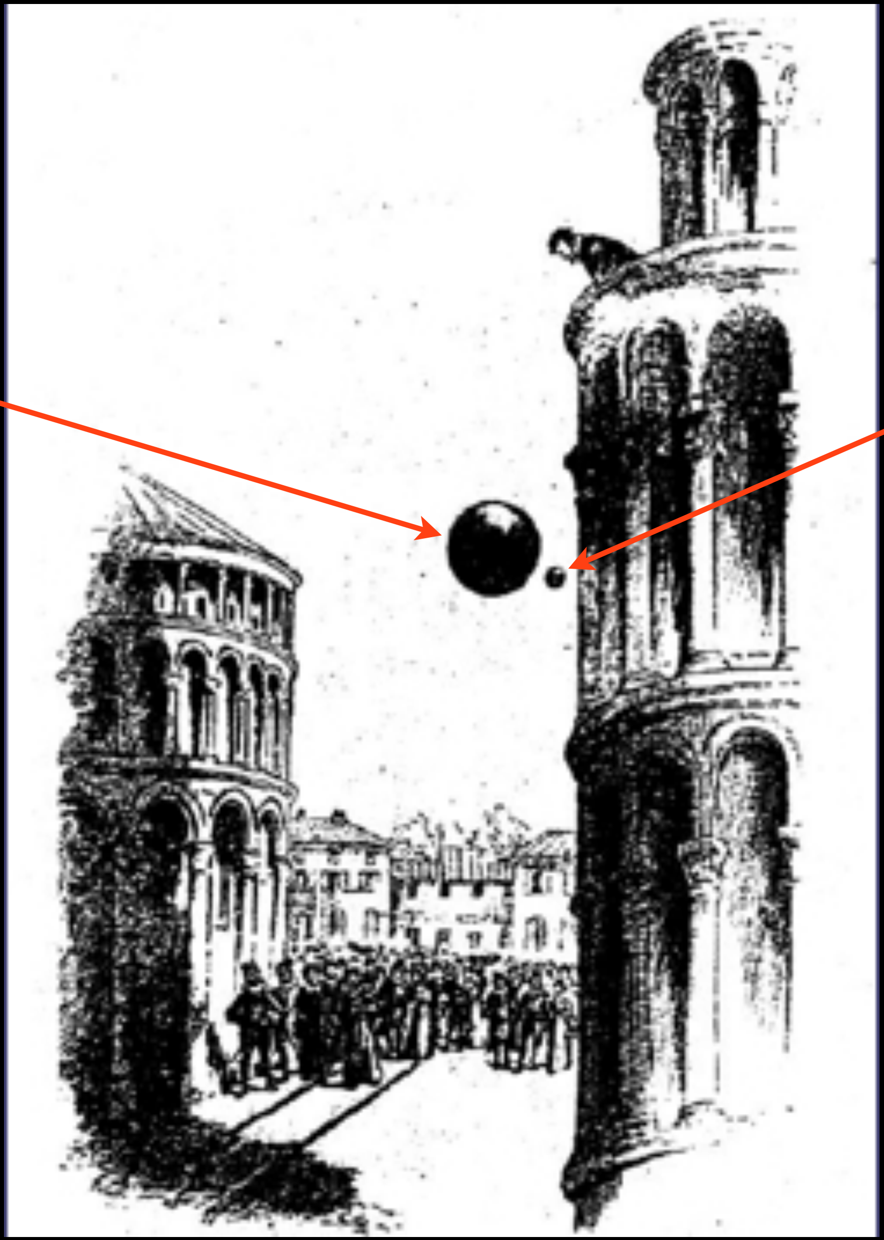
testing gravity with antimatter

gravity
w/ antihydrogen
and other antimatter-
containing systems

AE$\bar{g}$IS, ALPHA,
GBAR

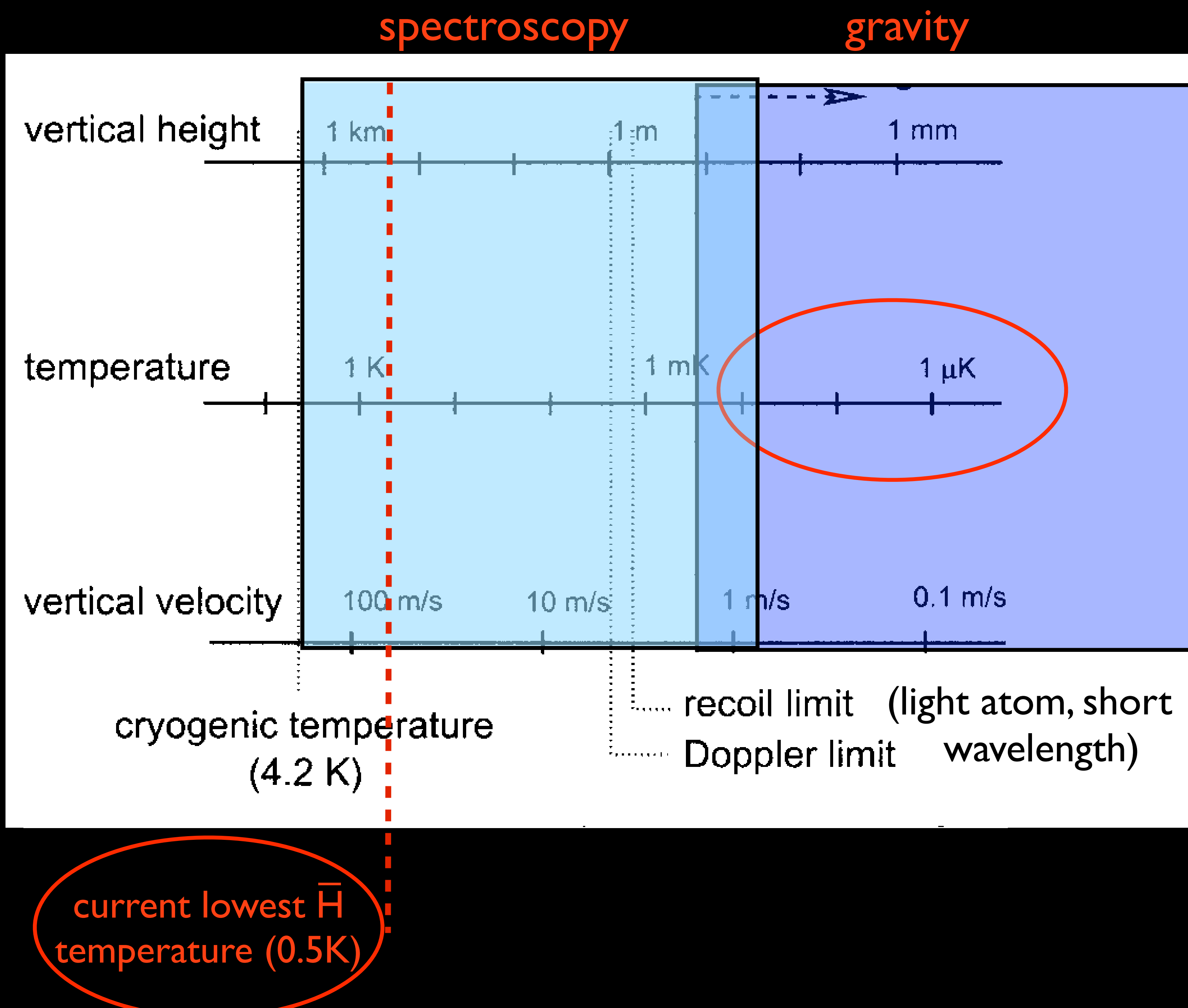
experimentally:

ANTIHYDROGEN



HYDROGEN

the importance of working at low temperature



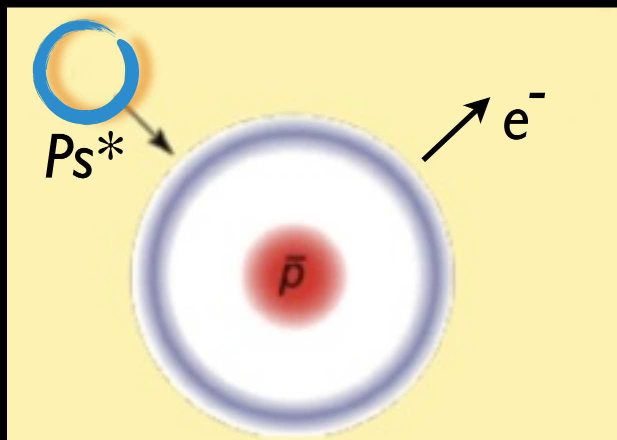
AE$\bar{g}$IS

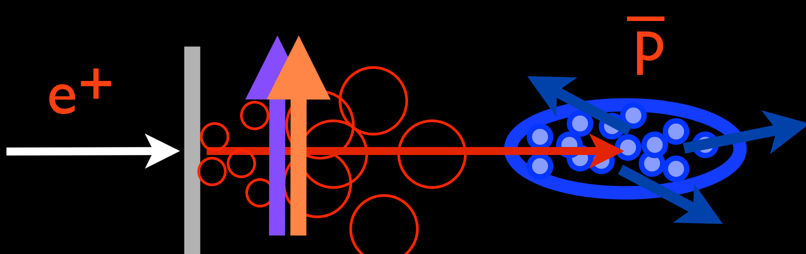
pulsed process

$v_{\bar{H}} \sim v_{\bar{p}} \quad (T_{\bar{H}} = T_{\bar{p}})$

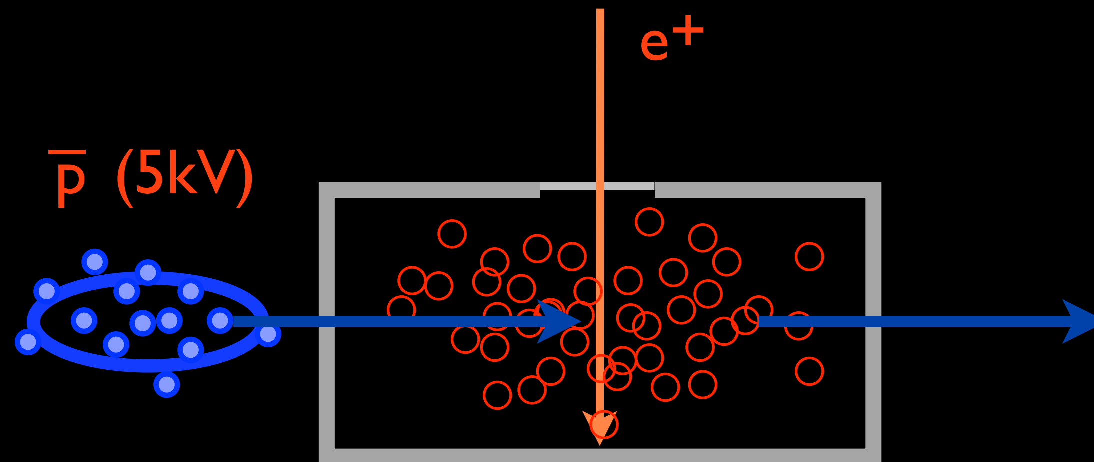
GBAR

charge exchange





$$Ps^* + \bar{p} \rightarrow \bar{H}^* + e^-$$



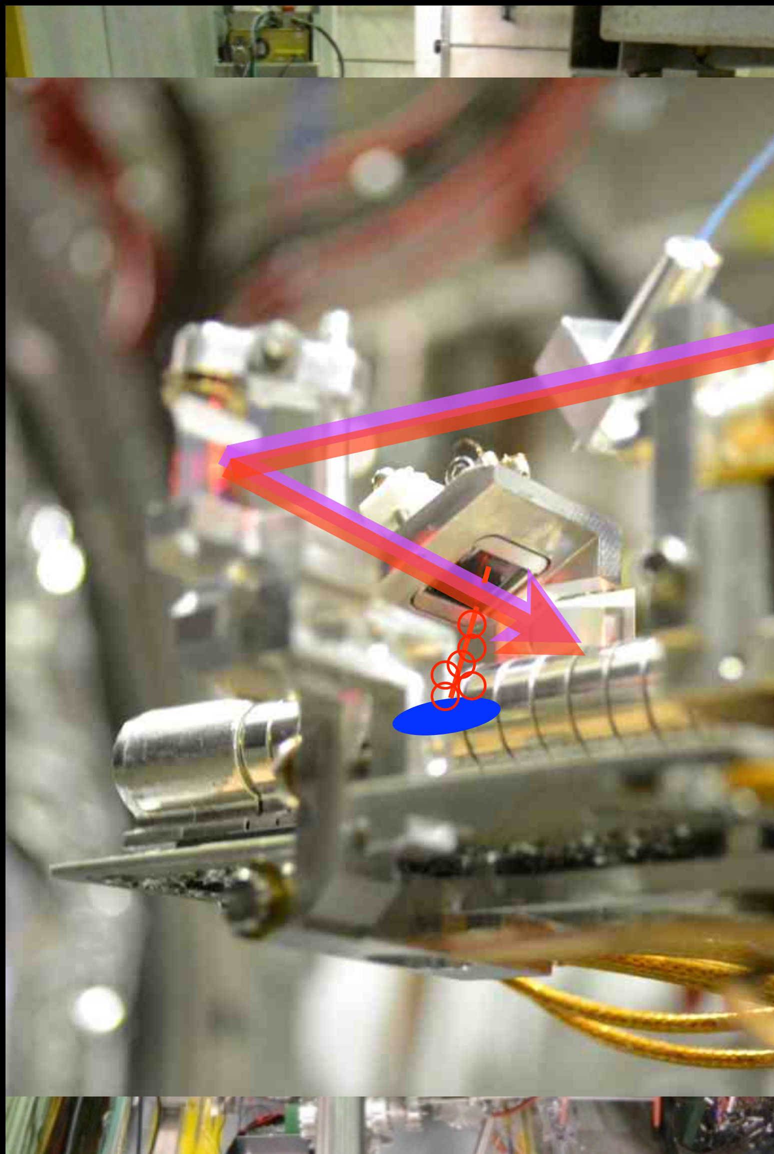
$$Ps + \bar{p} \rightarrow \bar{H} + e^-$$

$$Ps + \bar{H} \rightarrow \bar{H}^+ + e^-$$

launch horizontally;
measure parabolic trajectory

sympathetic cooling with Be+
photodetach e+; measure t_{drop}

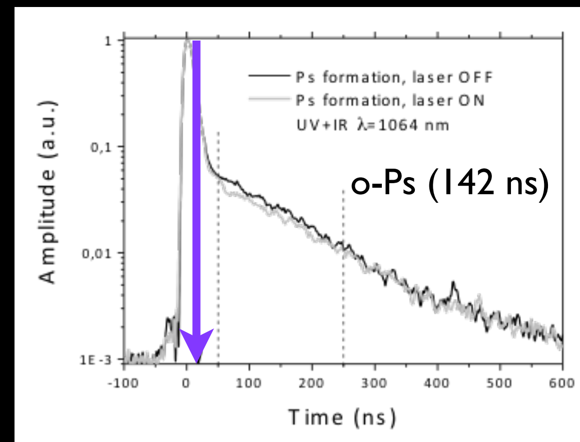
AEḡIS

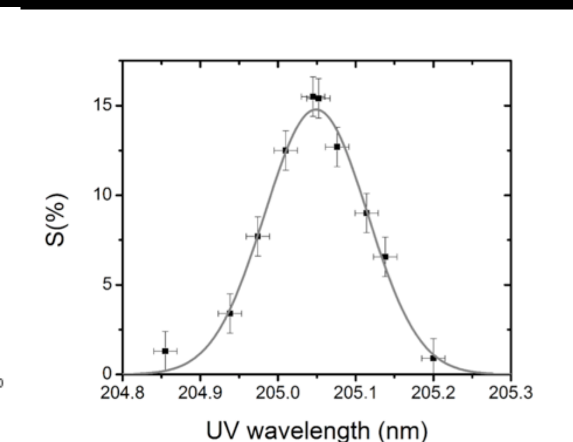


positronium excitation

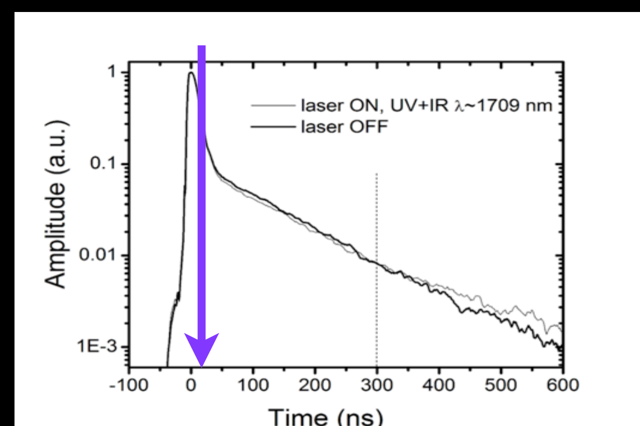
$1 \xrightarrow{205\text{ nm}} 3 \xrightarrow{1064\text{ nm}}$ continuum

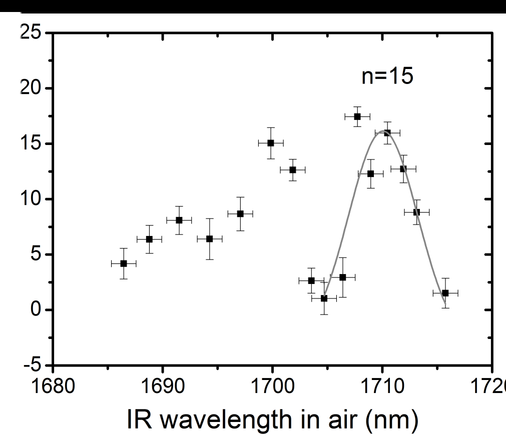
3P excitation line centered at 205.05±0.02 nm





$1 \xrightarrow{205\text{ nm}} 3 \xrightarrow{1700\text{ nm}}$ nS ($\tau \sim \mu s$)

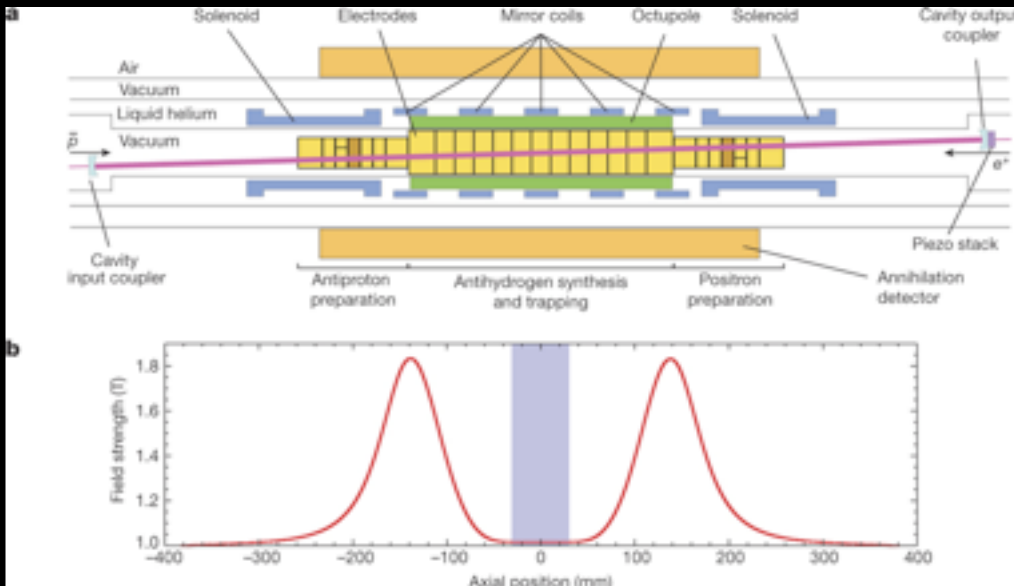


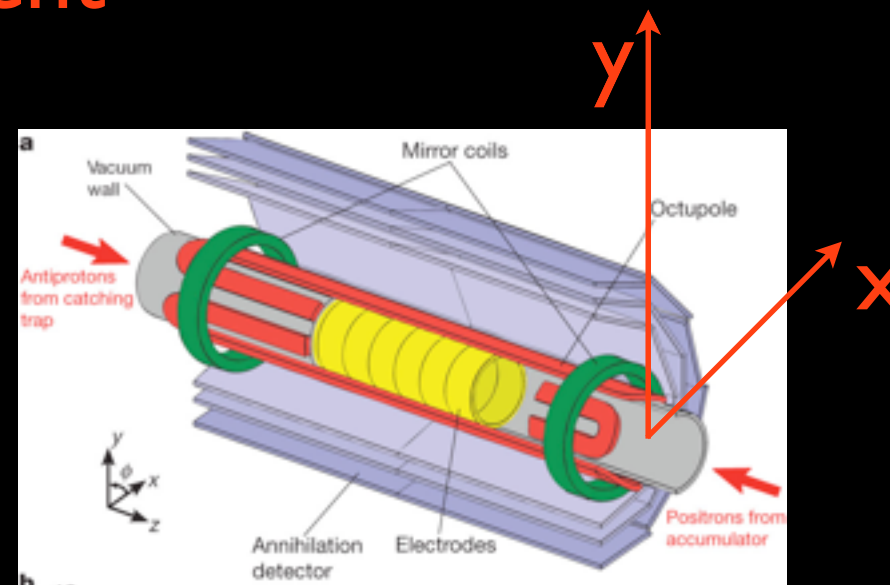


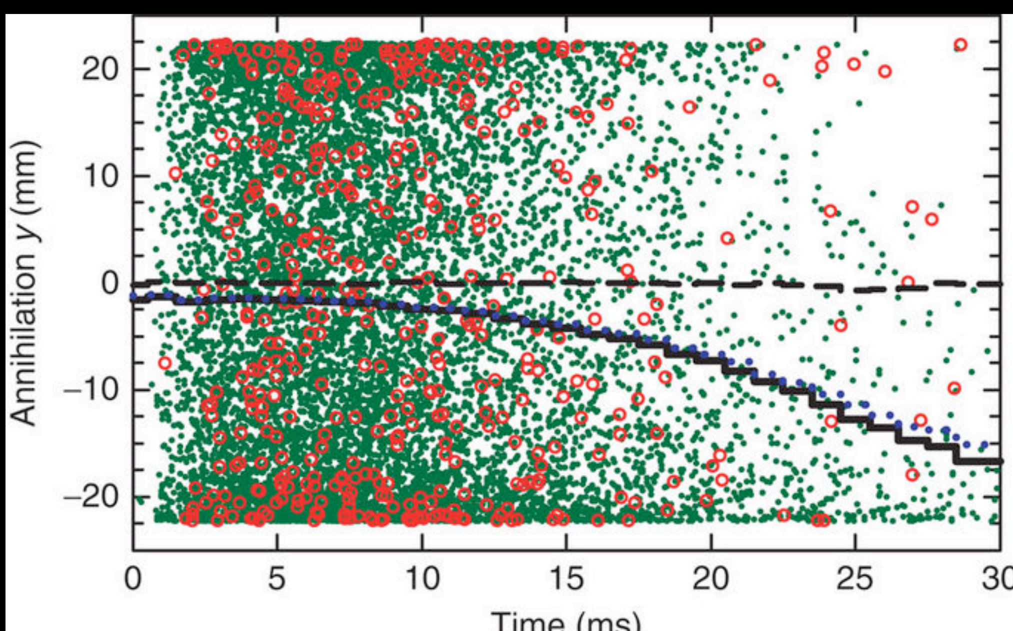
precision (QED) tests with Ps in future?

ALPHA: gravity measurement

M. Ahmadi et al., Nature Communications 4, Article number: 1785 (2013)







$F \equiv M_g / M$ $\qquad$ $F_{\bar{H}} < 110$

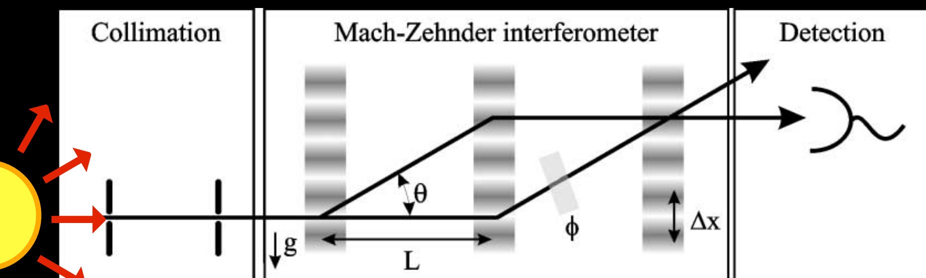
"… cooling the anti-atoms, perhaps with lasers, to 30 mK or lower, and by lengthening the magnetic shutdown time constant to 300 ms, we would have the statistical power to measure gravity to the $F = \pm 1$ level …"

dedicated apparatus being installed

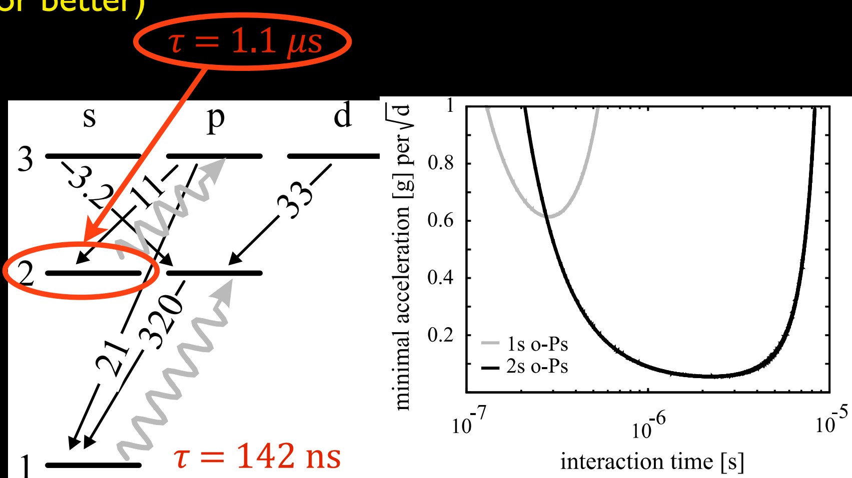
testing gravity with antimatter (other systems)

positronium (purely leptonic system)

M. Oberthaler, Volume 192, Issues 1–2, (2002) 129



Ps source
(2π or better)

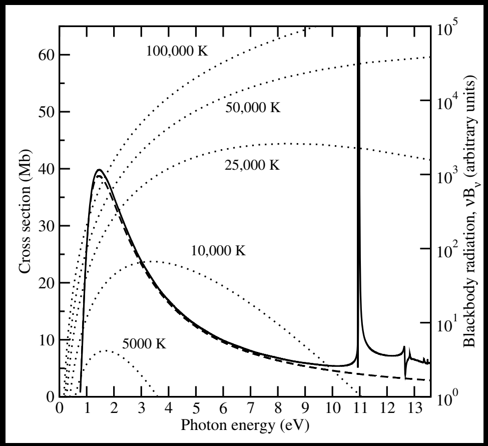


measurement of g
to 20% imaginable

protonium (purely baryonic system)

pulsed formation via co-trapped $\bar{p}$ and H^-

- photo-ionize $H^- \rightarrow H + e^-$
- charge exchange $H + \bar{p} \rightarrow p\bar{p}(40) + e^-$



very high
cross-section

H. Sadeghpour, A. Dalgarno, R. Forrey, The Astrophysical Journal Letters, 709:L168–L171, 2010

long-lived cold Rydberg protonium
→ trap / beam

gravity measurement
precision spectroscopy (QCD)

3) other questions: how well does the SM *really* work

rare K decays / complementary to B-factories

what is the proton, and what is its radius?

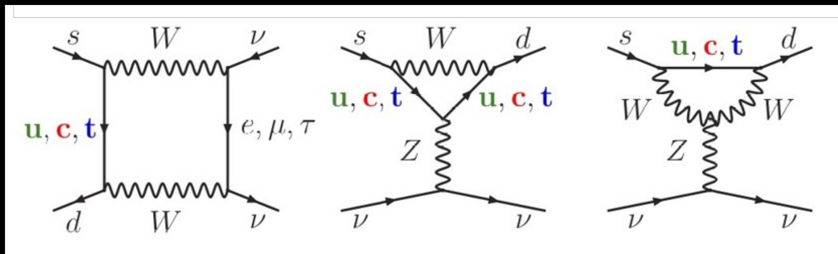
deviations from SM in nuclear transitions?

NA62
COMPASS
ISOLDE

NA62: the FCNC $K^+ \to \pi^+ \nu\bar{\nu}$

on the way to $K_L \to \pi^0 \nu\bar{\nu}$

→ 10 % meas^t of CKM parameter $|V_{td}|$

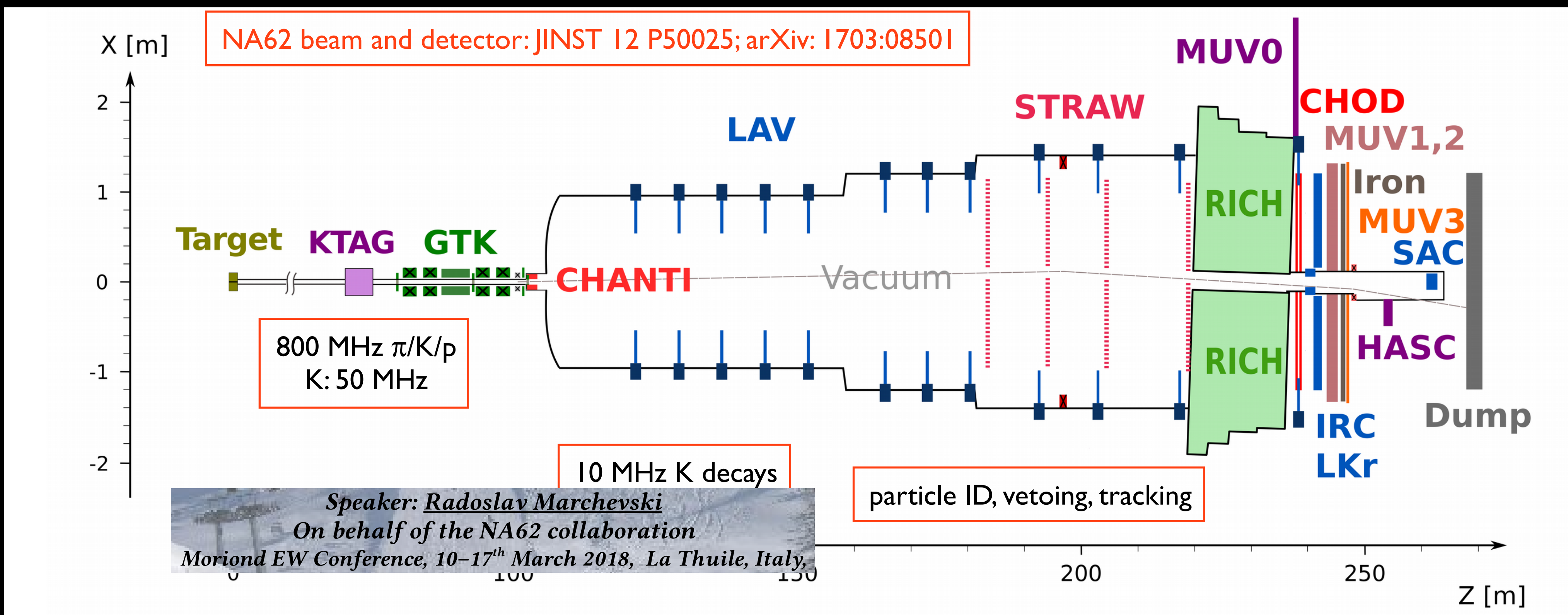


SM predictions: [Brod, Gorbahn, Stamou, Phys. Rev.D 83, 034030 (2011)],[Buras. et. al., JHEP11(2015)033]

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (8.39 \pm 0.30) \times 10^{-11} \left(\frac{|V_{cb}|}{0.0407}\right)^{2.8} \left(\frac{\gamma}{73.2^\circ}\right)^{0.74} = (8.4 \pm 1.0) \times 10^{-11}$$

Experimental result: [Phys. Rev. D 79, 092004 (2009)]

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (17.3^{+11.5}_{-10.5}) \times 10^{-11} \text{ (BNL, "kaon decays at rest")}$$



Speaker: Radoslav Marchevski
On behalf of the NA62 collaboration
Moriond EW Conference, 10–17th March 2018, La Thuile, Italy,

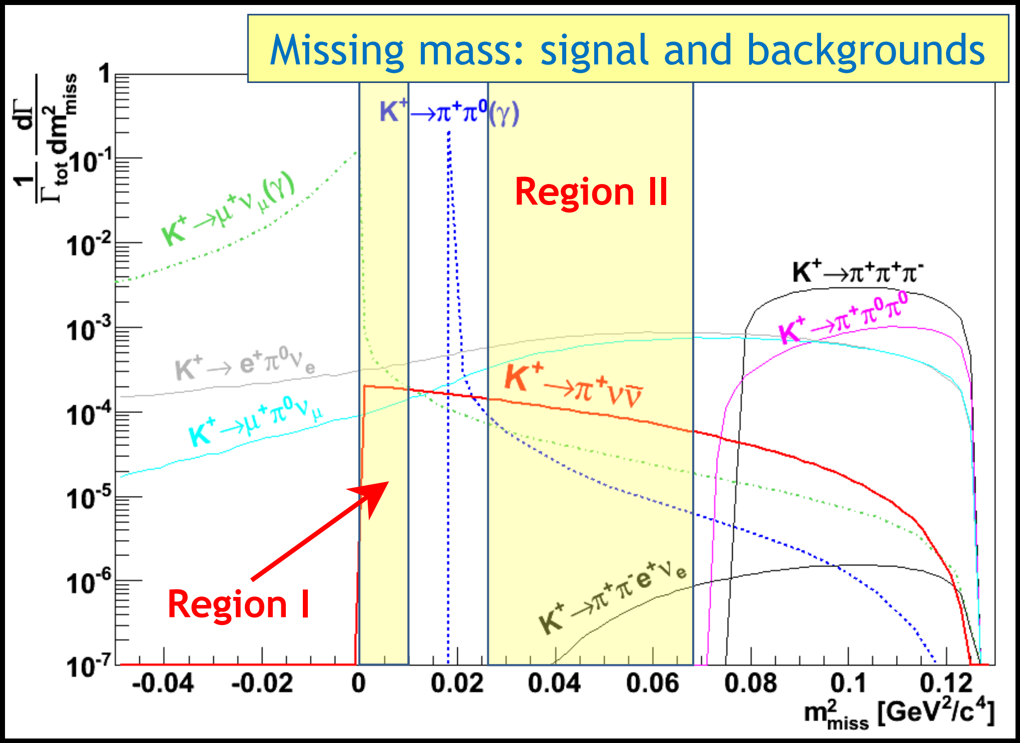
material for NA62 slides from:

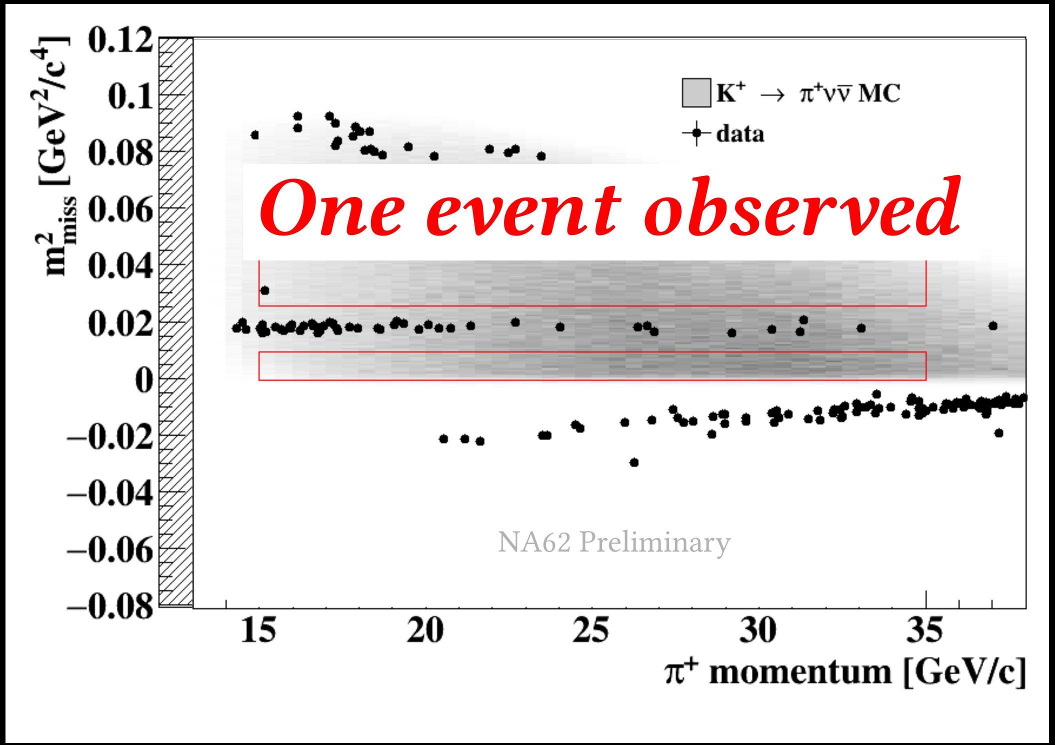
Radoslav Marchevski:
https://indico.in2p3.fr/event/16579/contributions/60808/attachments/47182/59257/Moriond_rmarchev.pdf
Cristina Lazzeroni:
https://conference.ippp.dur.ac.uk/event/625/contributions/3457/attachments/2936/3191/Lazzeroni_PPAP2017_5.pdf

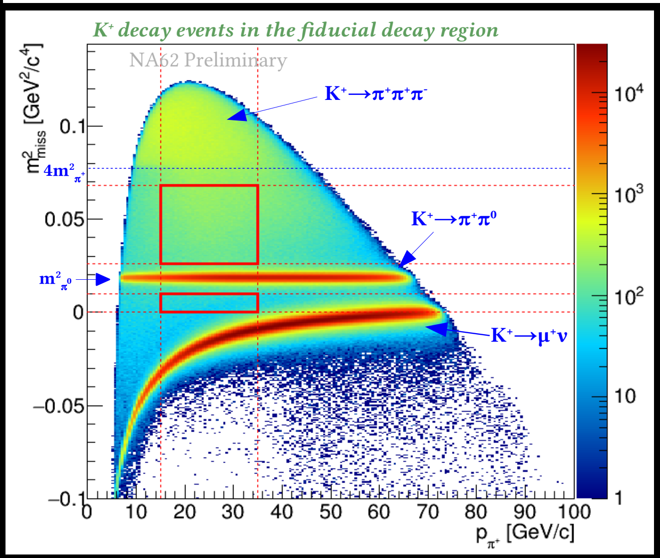
NA62: the FCNC $K^+ \to \pi^+ \nu\nu$

the challenge:

2016 data set (1%)







need to reduce back^{gd} by >10 orders of magnitude

need to understand background at $<10^{-11}$ level

such precision requires *enormous* care!

but the prize is sensitivity to BSM!

Hints by LHCb of LFV in B decays ($b \to s\mu^+\mu^-$)...

NA62: SM tests, BSM: LFV/LNV

Decay mode	SM violation	Limits on BR	Experiment
$K^+ \to \pi^-\mu^+\mu^+$	LNV	8.6×10^{-11}	CERN NA48/2 [5]
$K^+ \to \pi^-e^+e^+$	LNV	6.4×10^{-10}	BNL E865/CERN NA48/2 [6]
$K^+ \to \pi^-\mu^+e^+$	LNV	5.0×10^{-10}	BNL E865/CERN NA48/2 [6]
$K^+ \to \pi^+\mu^-e^+$	LFV	5.2×10^{-10}	BNL E865/CERN NA48/2 [6]
$K^+ \to \pi^+\mu^+e^-$	LFV	1.3×10^{-11}	BNL E777/E865 [7]

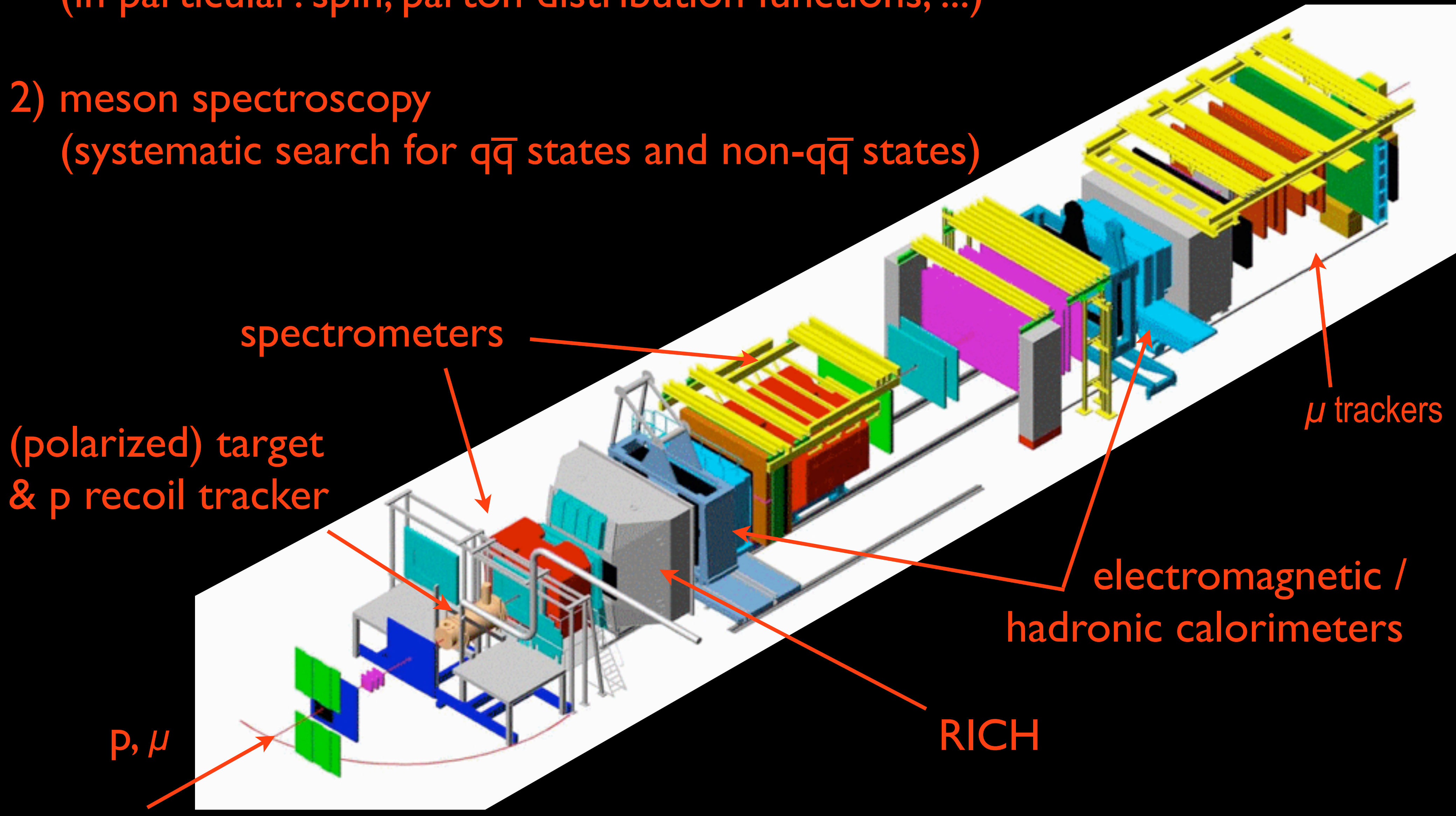
incorporating massive neutrinos into the SM results in a prediction of LFV and LNV decays with an unobservably low branching ratios. Therefore, an observation of any of the $K^+ \to \pi^\pm ll$ processes above would serve as a clear indication of physics beyond the SM, such as supersymmetry, Little Higgs models, extra dimensions, Z' vector bosons

COMPASS

Goals:

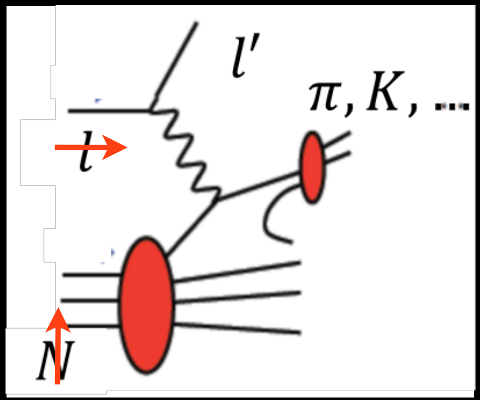
1) understanding nucleon via deep inelastic scattering (*μp, μd*)
(in particular: spin, parton distribution functions, ...)

2) meson spectroscopy
(systematic search for $q\bar{q}$ states and non-$q\bar{q}$ states)



COMPASS

many years of detailed studies of parton distribution functions via (semi-inclusive) deep inelastic scattering (μ^+ beam, 160 GeV/c, -80% long. polarization) (& of QCD $q\bar{q}$ and non-$q\bar{q}$!)

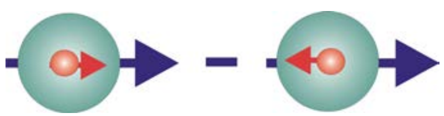


all 3 of equal importance

$q(x)$ or $f_1^q(x)$

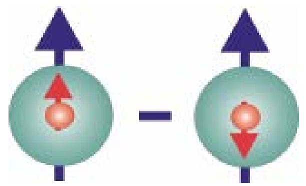
unpolarized PDF
quark with momentum xP in a nucleon

$\Delta q(x)$ or $g_1^q(x)$



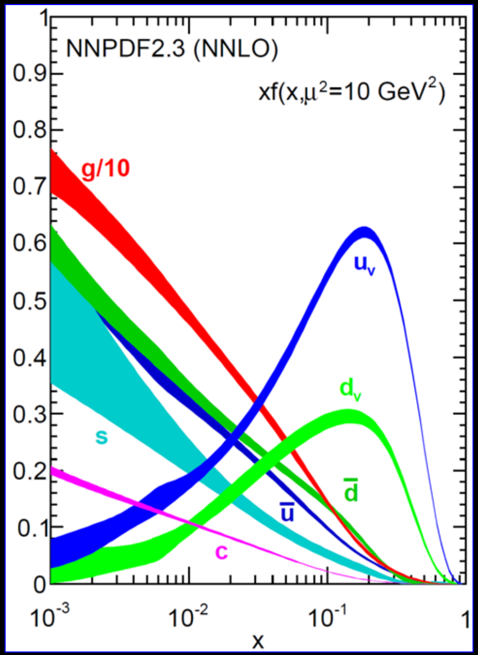
helicity PDF
quark with polarization parallel to the nucleon longitudinal polarization

$\Delta_T q(x)$ or $h_1^q(x)$



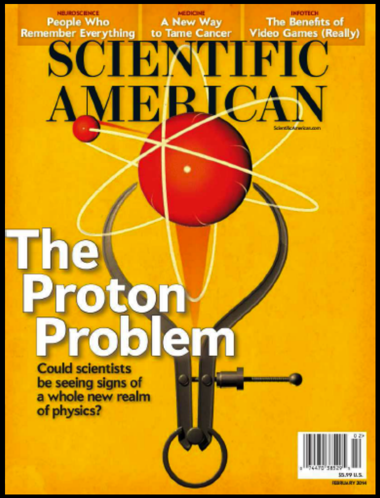
transversity PDF
quark with polarization parallel to the nucleon transverse polarization

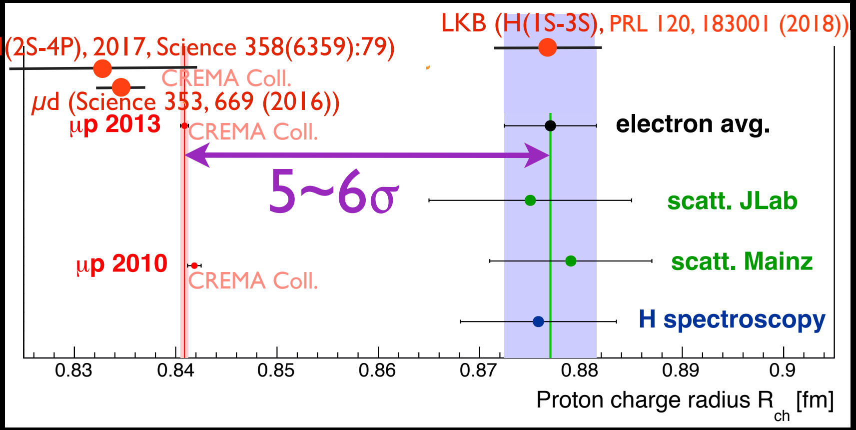
The 3D structure of the nucleon is still not fully understood; requires further experimental input

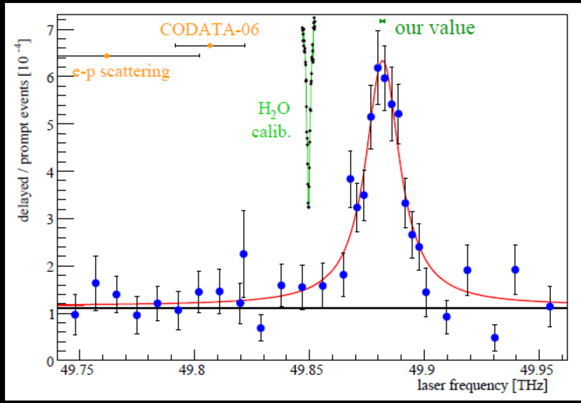


COMPASS

How to measure the proton radius







μp atomic spectroscopy very solid; need much better scattering data;
preferably μp (μ-coupling >> e-coupling?! NP!!) → MUSE experiment @ PSI, COMPASS @ CERN?

μ elastic scattering:

$$\frac{d\sigma}{d\Omega} \propto G_E^2(Q^2) + \frac{\tau}{\varepsilon} G_M^2(Q^2)$$
$$[\tau = Q^2/4m_p^2 \; ; \quad 1/\varepsilon = 1 + 2(1+\tau)\tan^2(\theta_e/2)]$$

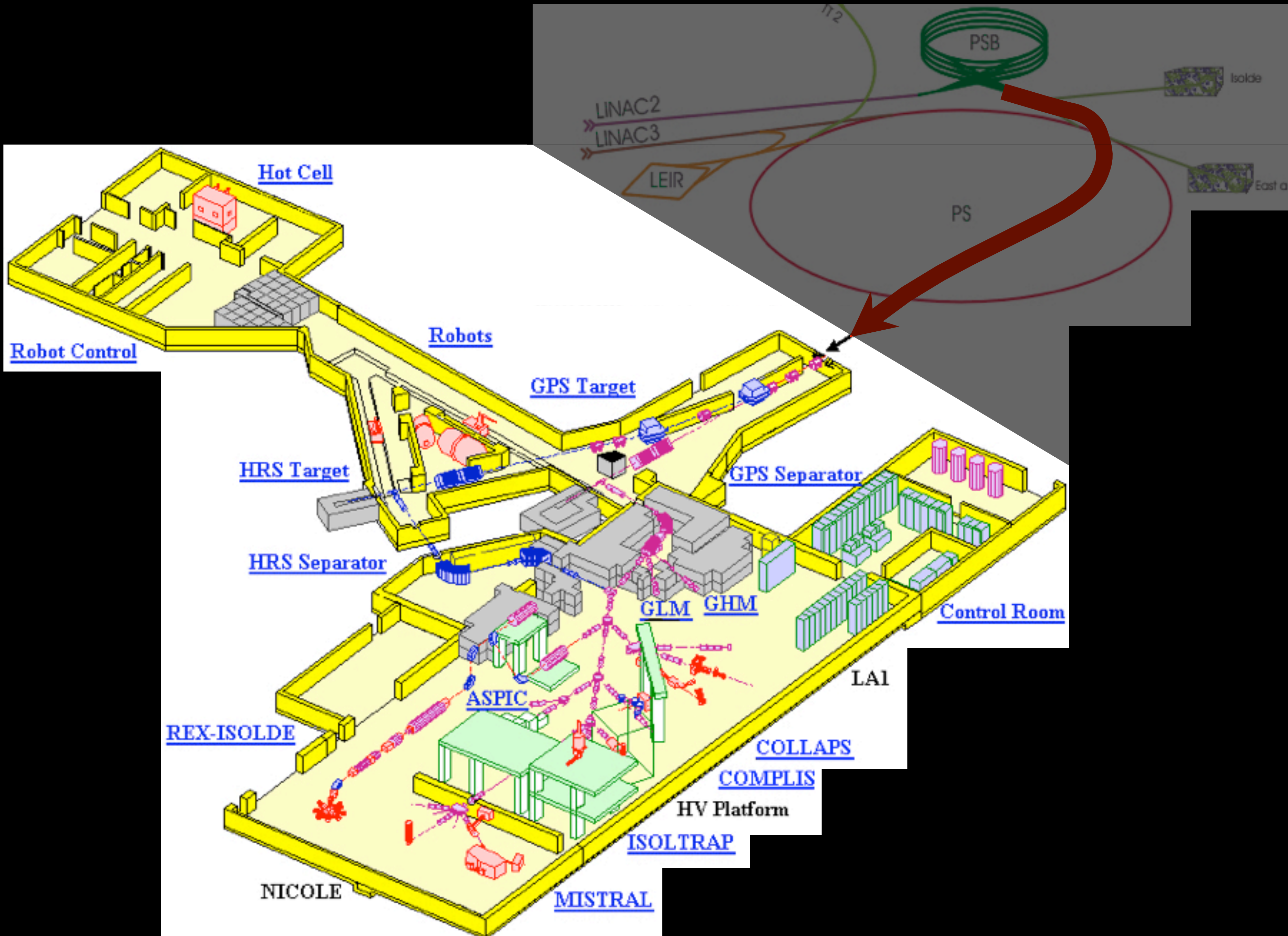
$$\boxed{R_E^2 = -6\left(dG_E/dQ^2\right)_{Q^2=0}}$$

COMPASS: smaller Coulomb corrections for high energy μ beam
measure recoil proton [high pressure TPC as target],
scattering angle O(100 μrad) of muon [silicon tracking detectors]

achieving uncertainty on $\sqrt{\langle r_E^2 \rangle}$ ~ 0.01fm requires one year of data taking

Jan Bernauer, IWHSS 2018 - International Workshop on Hadron Structure and Spectroscopy
Sebastian Uhl, IWHSS 2018 - International Workshop on Hadron Structure and Spectroscopy

ISOLDE



PSB
LINAC2
LINAC3
LEIR
PS
Isolde
Hot Cell
Robot Control
Robots
GPS Target
HRS Target
GPS Separator
HRS Separator
GLM
GHM
Control Room
LA1
ASPIC
REX-ISOLDE
COLLAPS
COMPLIS
HV Platform
ISOLTRAP
NICOLE
MISTRAL

ISOLDE (and other radioisotope facilities)

- weak interactions and nuclear physics

(examples: nuclear shapes, lifetimes, beta-decay & EW interactions

Low energy precision tests of supersymmetry, M.J. Ramsey-Musolf, S. Su / Physics Reports 456 (2008) 1–88
Weak interaction physics at ISOLDE, N Severijns and B Blank, *Journal of Physics G: Nuclear and Particle Physics*, **44**, 7, (074002), (2017)

- solid state physics

(example: implantation of radioisotopes in semi-conductors)

- astrophysics

(examples: triple-alpha to ^{12}C rate (star formation), nuclear processes occurring during supernovae)

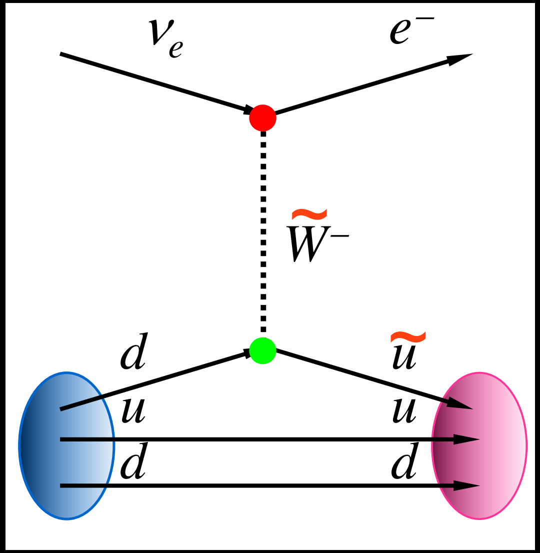
- biological systems, medical applications

(example: detoxification of mercury in plants, sensitive diagnostics)

ISOLDE (and other radioisotope facilities)

the effective mass scale probed by low energy experiments ($M \gtrsim M_W$) overlaps with that probed by the LHC (compare via EFT):

V. Cirigliano, J. Jenkins, and M. Gonzalez-Alonso, Nucl. Phys. B830, 95(2010)



$$\mathcal{L}_{\rm SM} = -\frac{G_F V_{ud}}{\sqrt{2}} \bar{e}\gamma_\mu(1-\gamma_5)\nu_e \cdot \bar{u}\gamma^\mu(1-\gamma_5)d$$

"In the minimal supersymmetric standard model (MSSM), one-loop box graphs containing superpartners can give rise to non-(V−A)⊗(V−A) four-fermion operators in the presence of left-right or flavor mixing between sfermions."

Supersymmetric contributions to weak decay correlation coefficients, S. Profumo, M. J. Ramsey-Musolf, and S. Tulin, Phys. Rev. D 75, 075017

⟶ Search for S, T terms in addition to vector/axial vector currents

⟶ Measure precisely the CKM matrix element V_{ud} & test unitarity

can "precision" compete with energy? yes, but ... precision $\overset{!}{<}$ 0.1%

ion traps are much hotter and less well-localized than MOTs are. Also as opposed to MOTs, the ions interact via the Coulomb interaction, leading to space charge effects

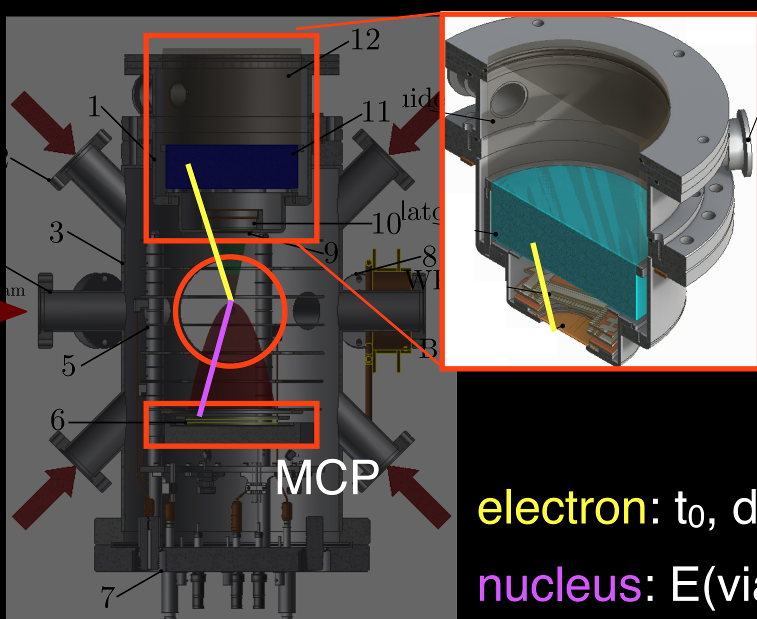
ISOLDE (and other radioisotope facilities)

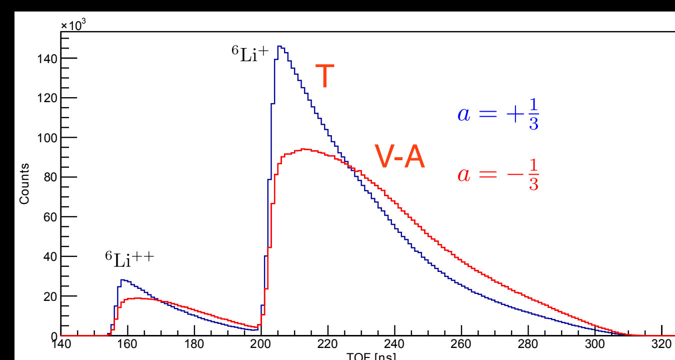
can “precision” compete with energy? yes, but ... not for every coupling

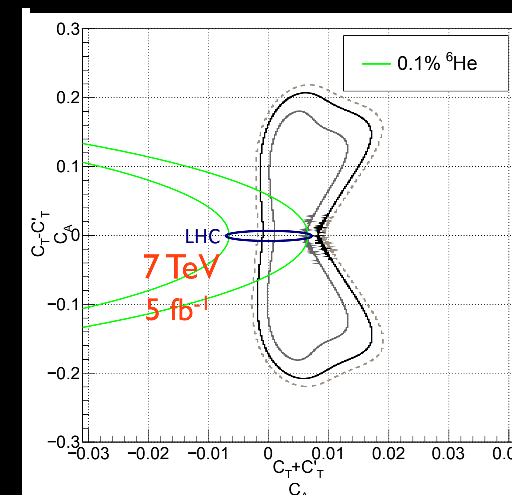
- precision $\overset{!}{<}$ 0.1% ~ mass range around few TeV
- scalar and tensor interactions (through e.g. SUSY particles) : low-energy searches with 10^{-4} sensitivity would have unmatched constraining potential, even in the LHC era.

Example: the pure Gamow-Teller decay of ^{6}He will probe ϵ_T in the 5×10^{-4} range.

Experimentally: measure the beta-neutrino angular correlation $\alpha_{\beta\nu}$ in ^{6}He trapped in a MOT or an ion trap: measure electron, recoiling daughter $\rightarrow$ reconstruct kinematics







fit

electron: t_0, direction, E

nucleus: E(via TOF), direction

~ 4x better w/ 13 TeV 50 fb^{-1}
~ 2017 ATLAS+CMS

D. Zumwalt, PhD thesis 2015, https://digital.lib.washington.edu/researchworks/handle/1773/34137
CENPA, Univ. of Washington

ISOLDE (and other radioisotope facilities)

$$\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

test of the unitarity of the CKM matrix:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 \overset{?}{=} 1$$

unitarity contribution

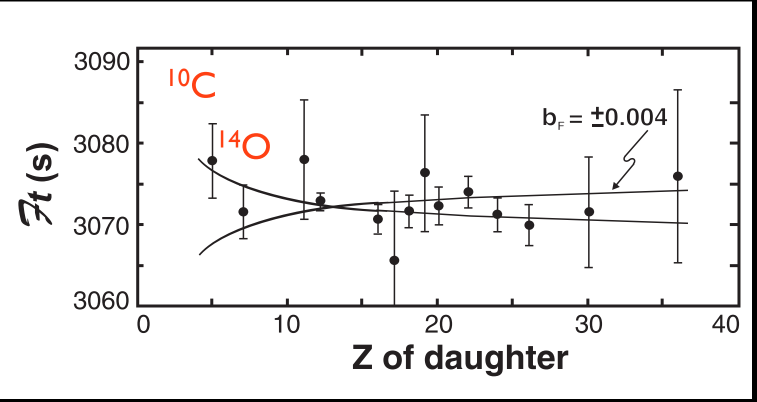
V_{ud} (nuclear β-decay) = 0.97417(21)
V_{us} (kaon-decay) = 0.2253(14)
V_{ub} (B meson decay) = 0.0037(5)

Hardy&Towner, Phys. Rev. C 91 (2015) 025501

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.99978(55)$$

V_{ud} : 220 independent measurements covering 14 separate transitions, each with a Q_{EC} value, half-life, and branching ratio that has been determined, in most cases, multiple times.

Improved sensitivity:
V_{us} (determined from K decays) has slight inconsistencies;
main uncertainty on V_{ud} now theoretical (radiative corrections);
main gains on limits on a scalar interaction from ^{10}C and ^{14}O



Many tests of the standard model, and searches for beyond-the-standard-model physics are taking place at CERN.

Even outside the LHC.

thank you for your attention!