The low-energy physics frontier @Mami: Results and Perspectives

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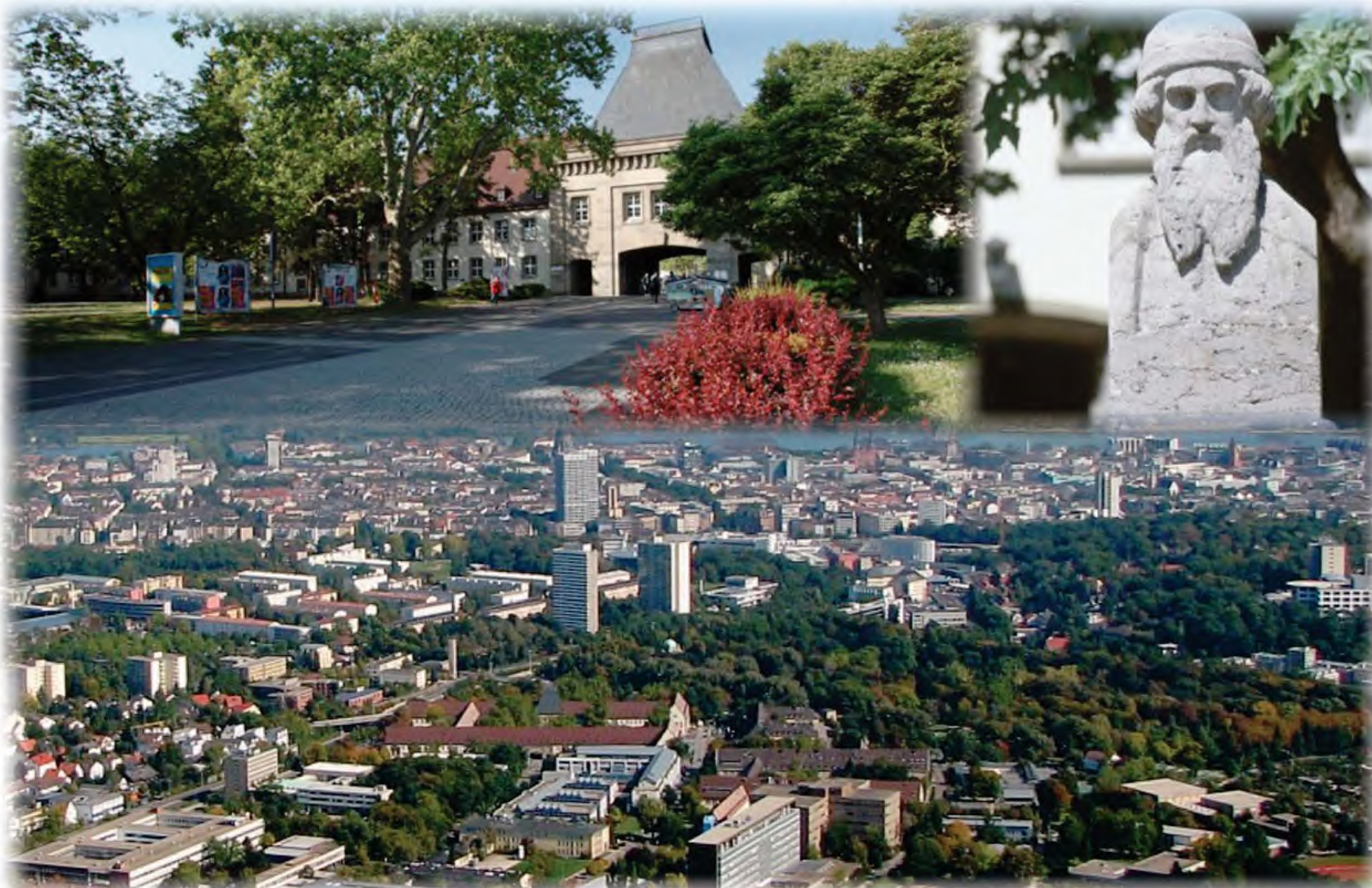


MAMI

MAMI-C

Harmonic Double Sided Microtron (2007)
up to E = 1.6 GeV

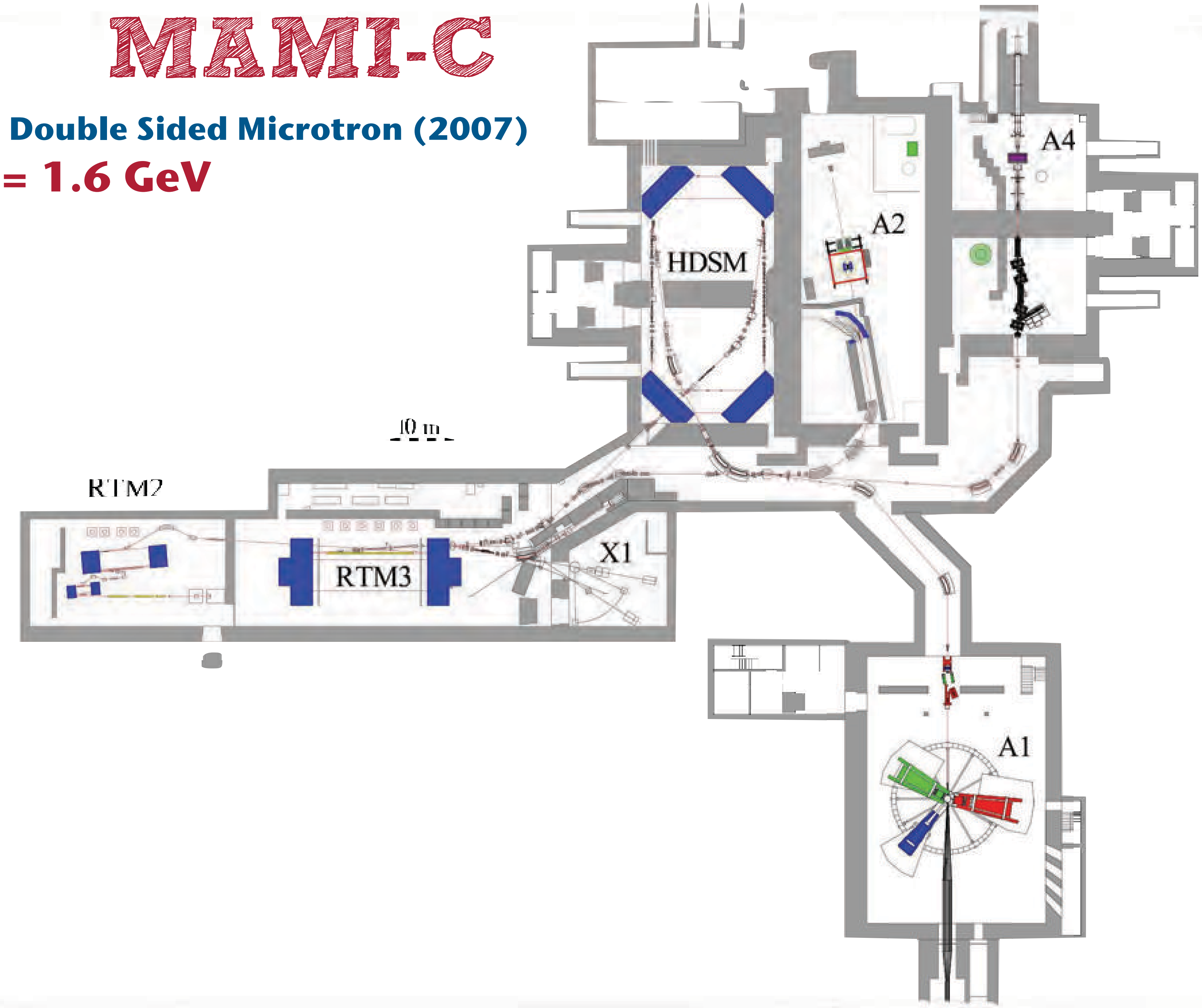
HIGH

Intensity
up to 100 μA

Resolution
σ_E < 0.100 MeV

Polarization
up to 80% @ 40μA

Reliability
85% (7000 h/y)



Three Experimental Areas

A4: Parity Violation in in ep elastic scattering

Single-Spin-Asymmetries <10^{-5}

✧ PbF_2 Calorimeter

A2: Real Photon Scattering

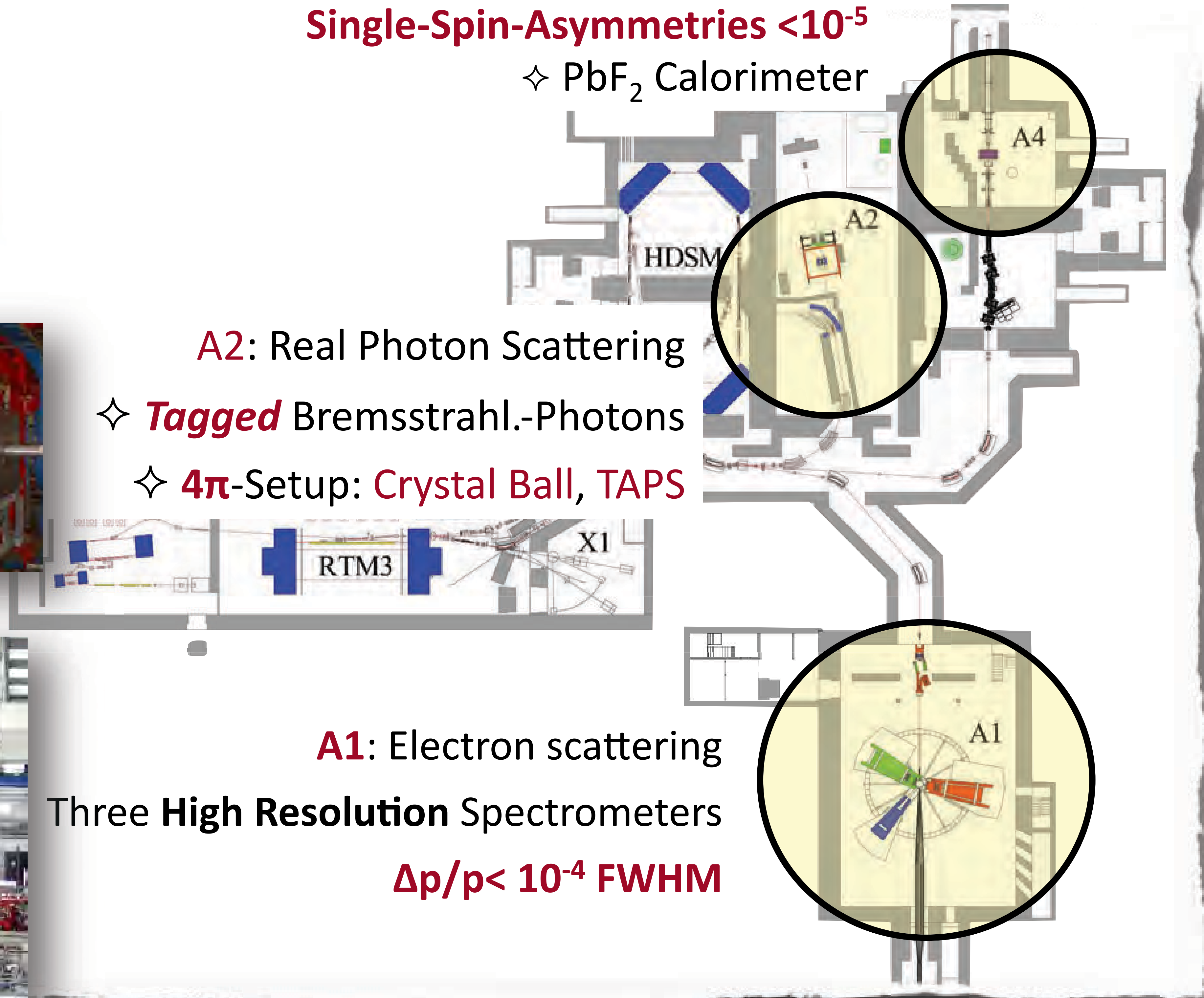
✧ ***Tagged*** Bremsstrahl.-Photons

✧ **4π**-Setup: Crystal Ball, TAPS

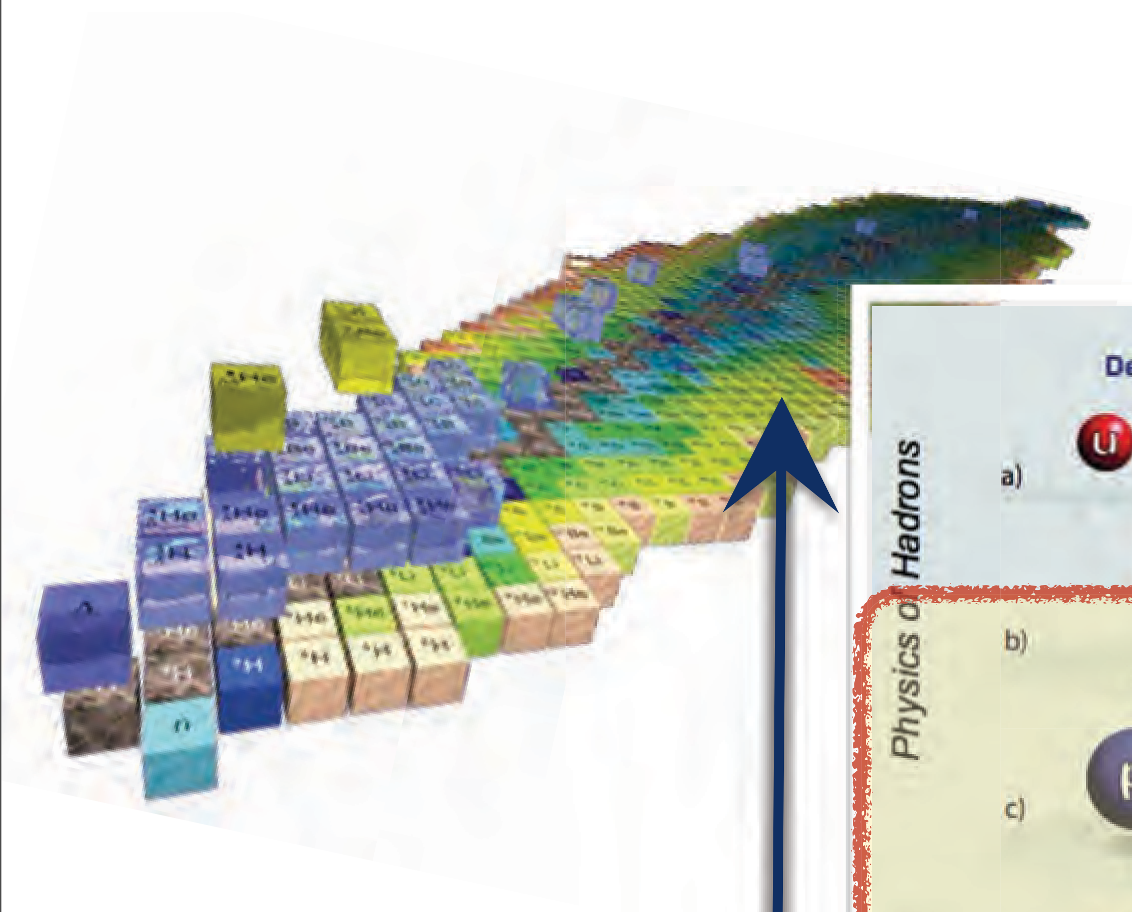
A1: Electron scattering

Three **High Resolution** Spectrometers

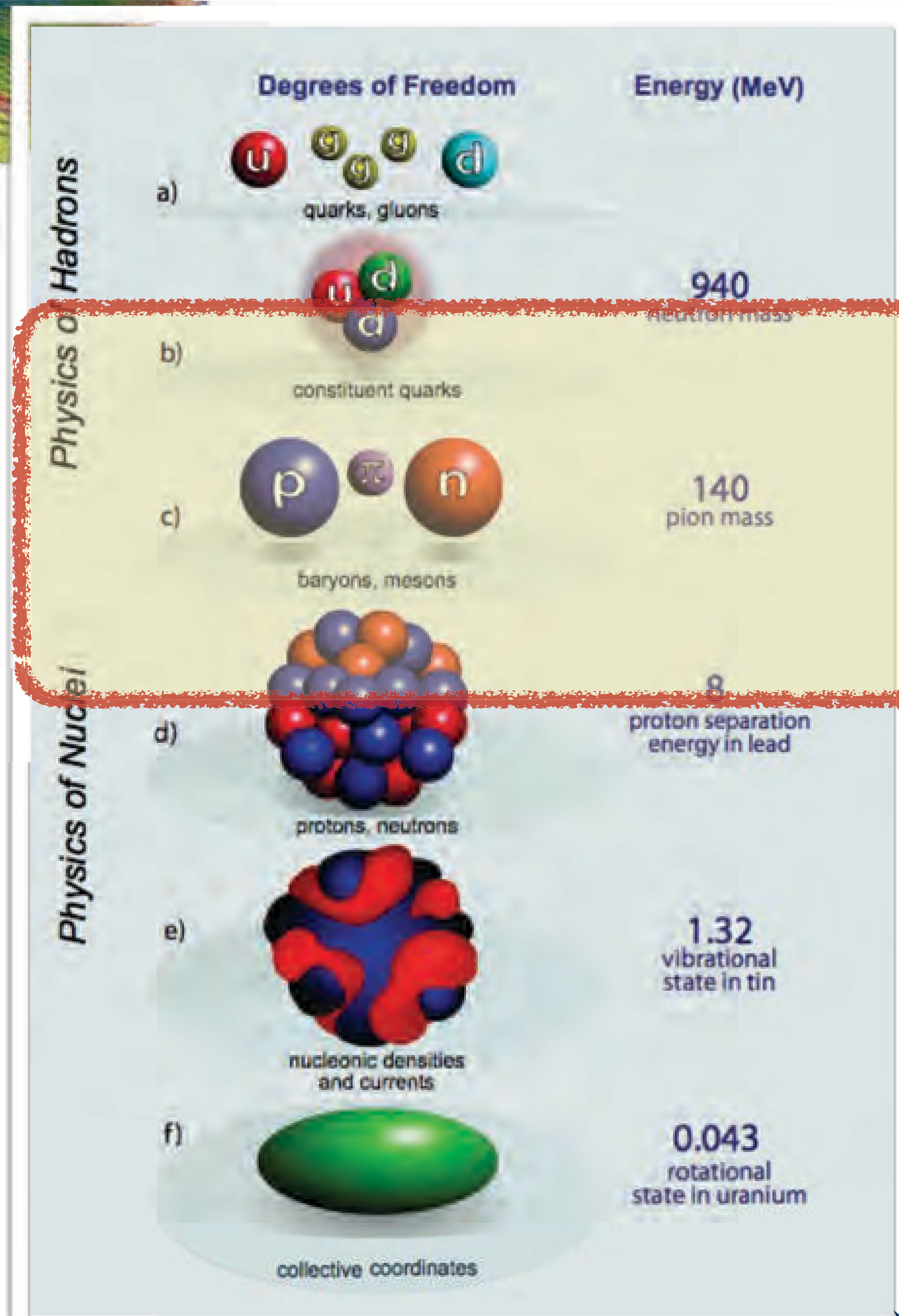
Δp/p< 10^{-4} FWHM



Medium Energy Region



Resolution



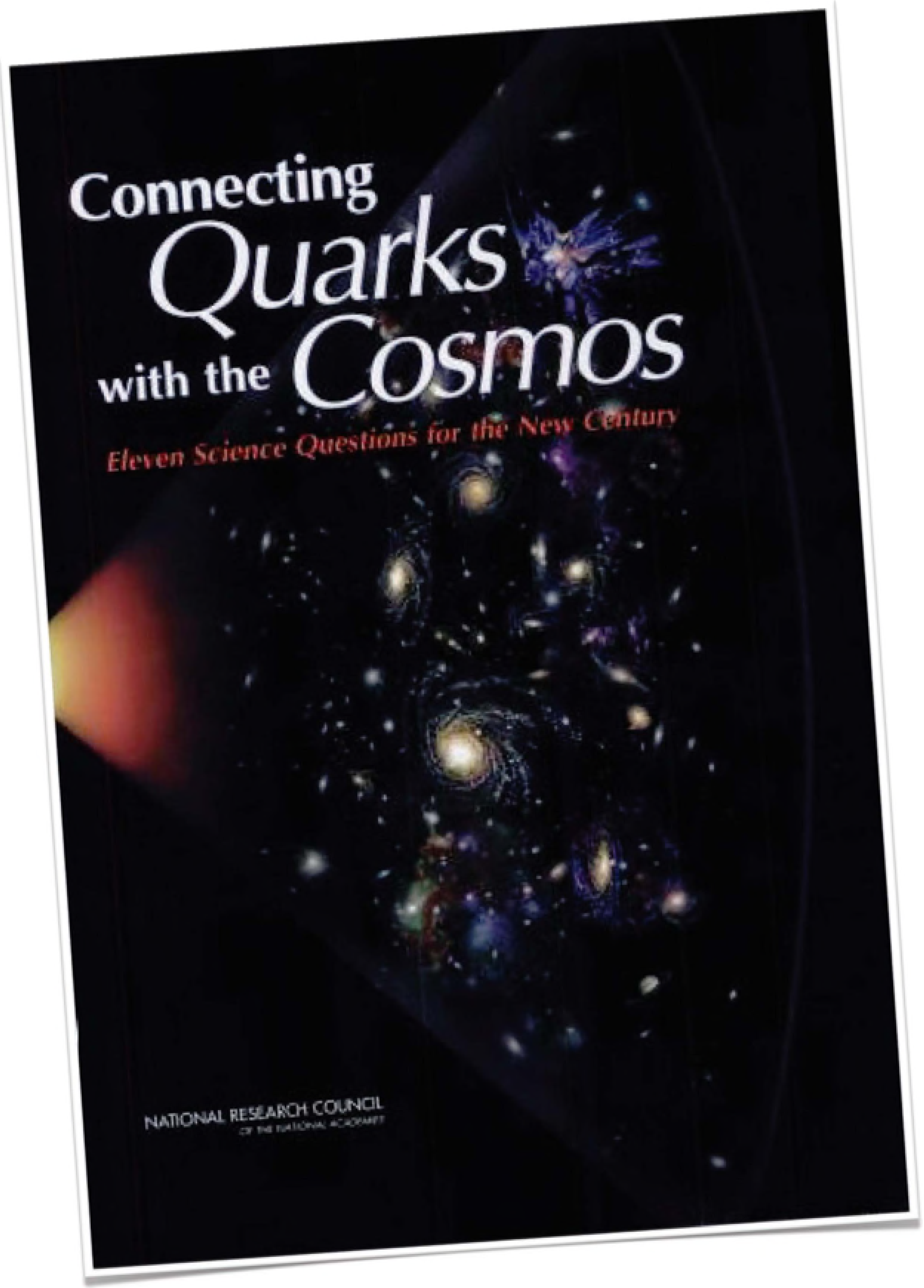
LRP Nuclear Science Advisory Committee (2008)

Simplicity

- Hot and dense quark-gluon matter
- Hadron structure
- Hadron-Nuclear interface
- Nuclear structure
- Nuclear reactions
- Nuclear astrophysics
- Applications of nuclear science

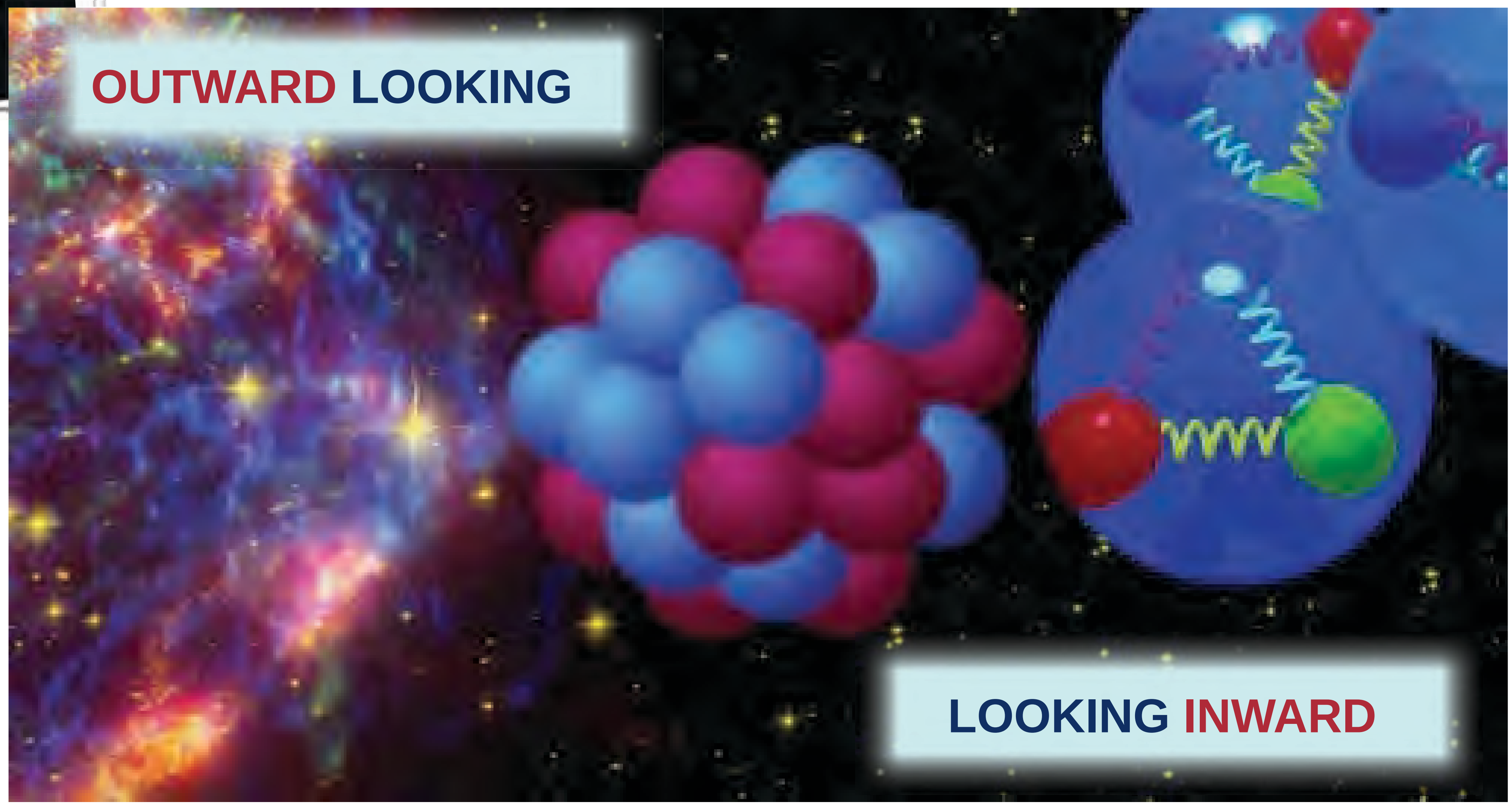
Complexity

What is it all about?

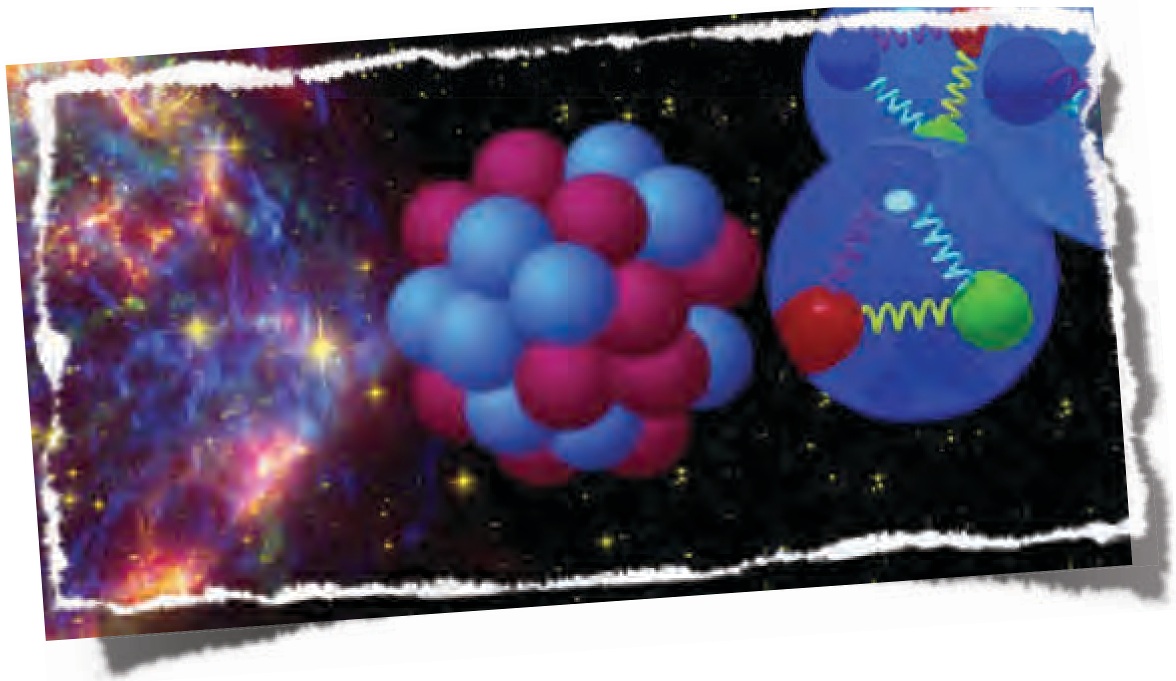


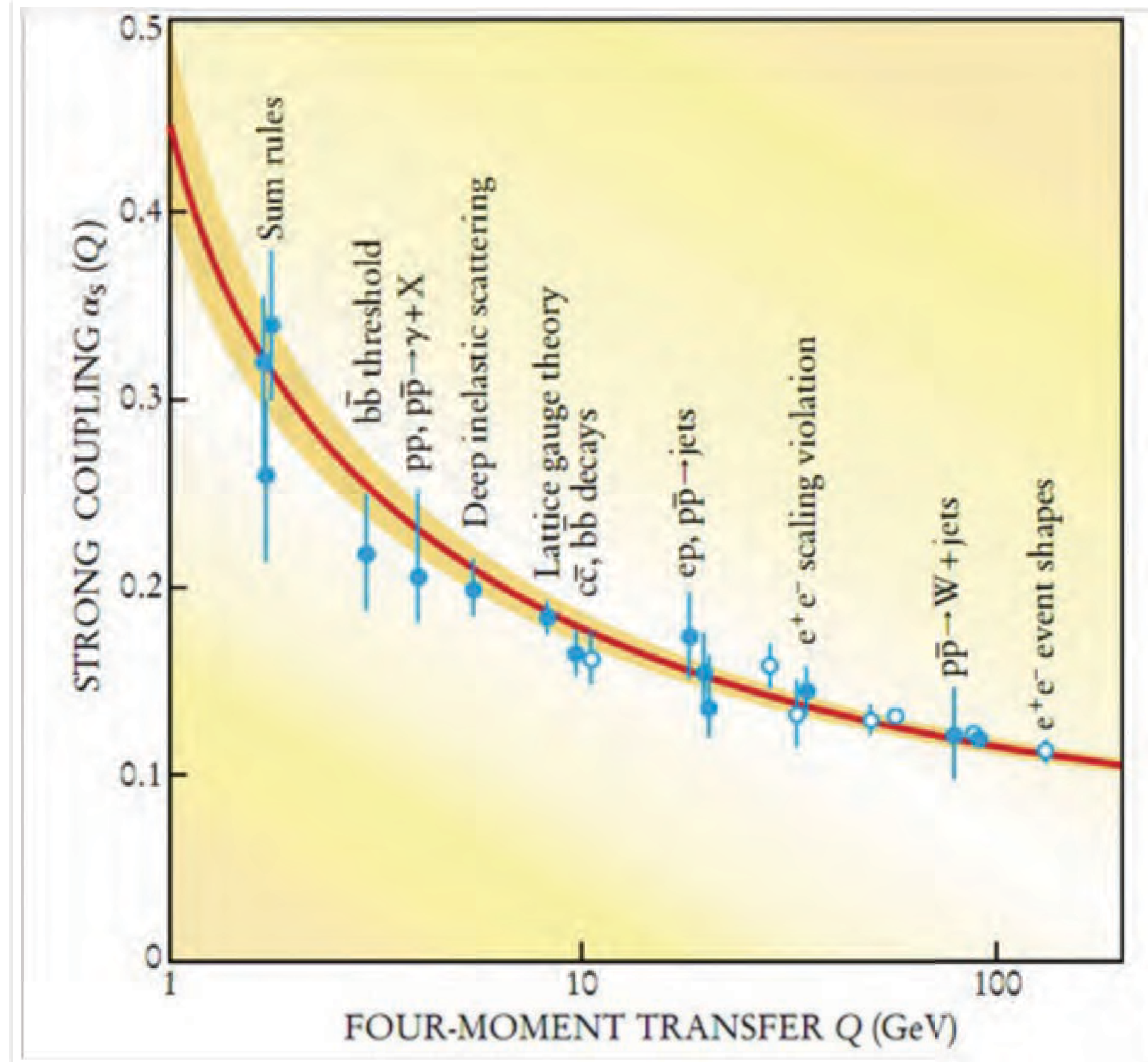
Scales and Phases of Nuclear Matter

Courtesy R.F.Carsten (WNSL)



First Constraint





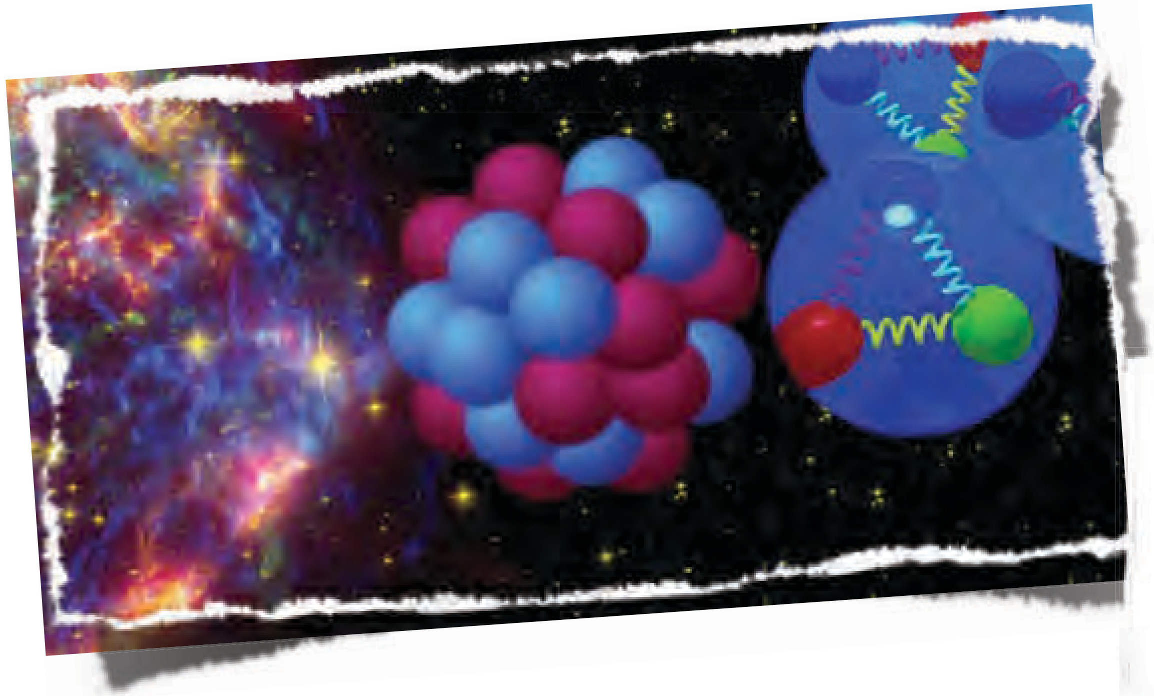
F. Wilczek "QCD made *simple*" (http://www.frankwilczek.com/)

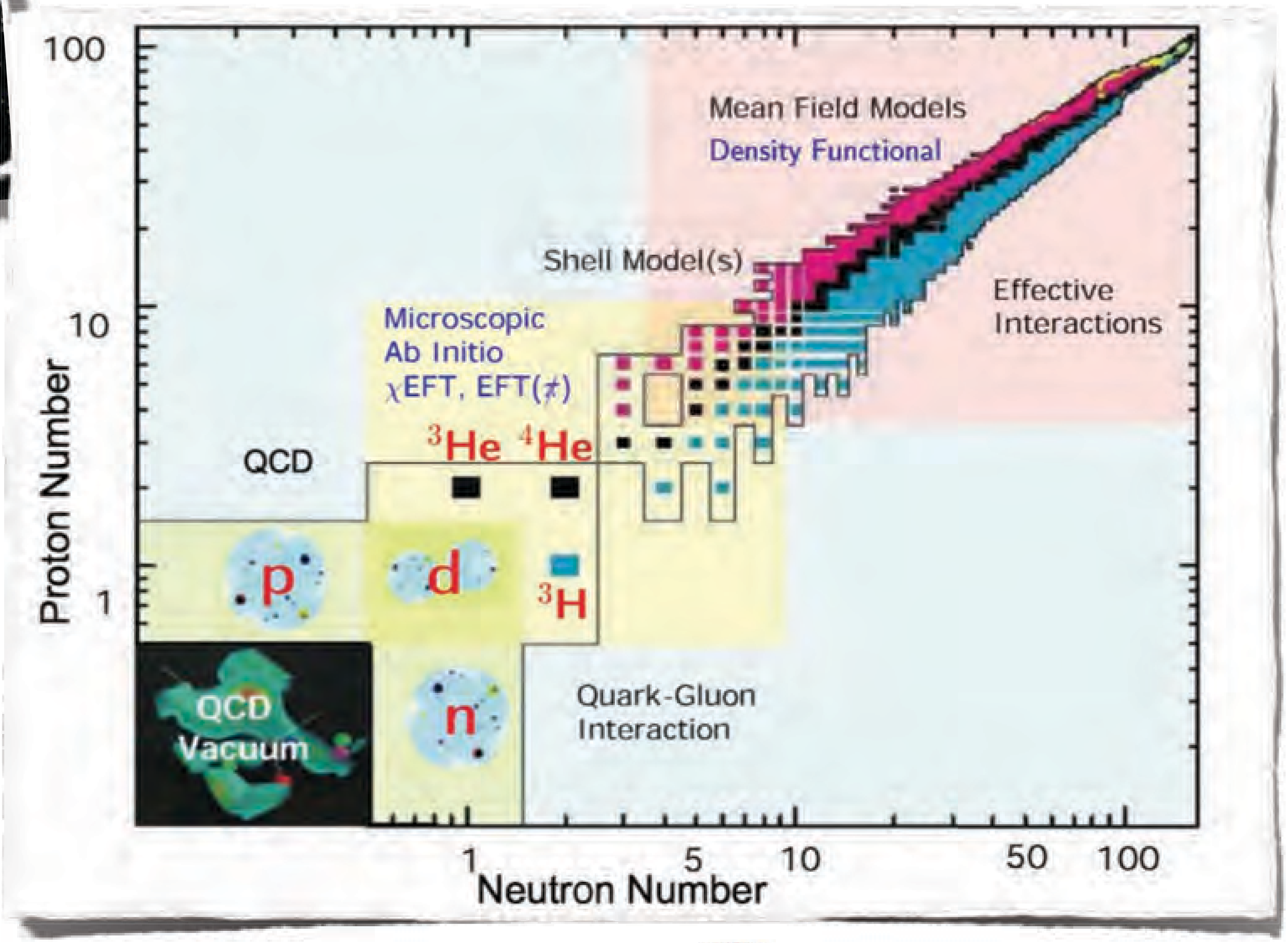
QCD in the non-perturbative regime

„If the Lord Almighty had consulted me before embarking upon creation, I would have recommended something *simpler*."

King Alphonse X. of Castille and Léon (1221-1284), on having the Ptolemaic system of epicycles explained to him

First Constraint





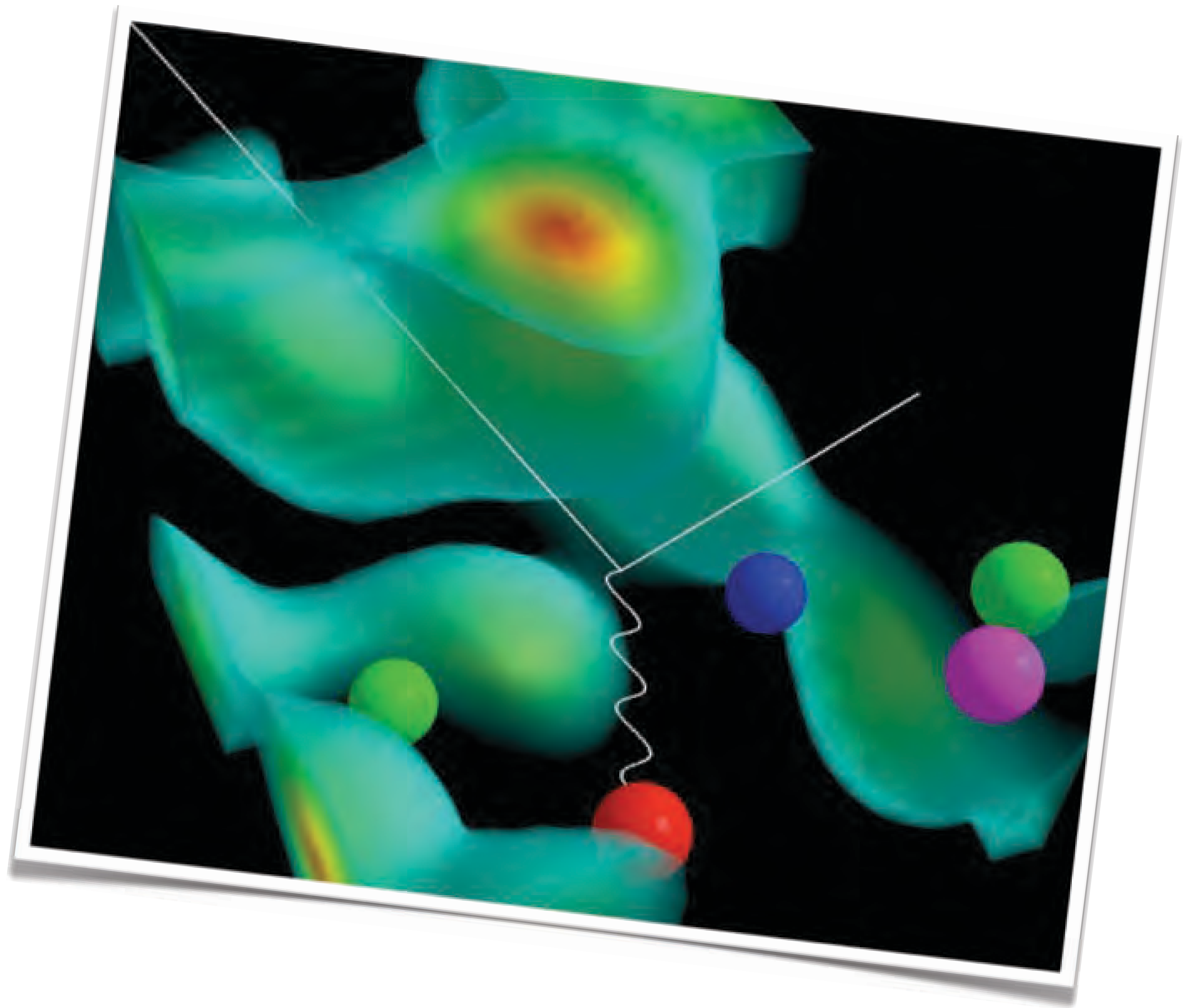
Modern nuclear physics is about…

→Linking QCD to many body systems

UNEDF SciDAC Collaboration
Universal Nuclear Energy Density Functional

The Beauty of the Electromagnetic Probe

Clean probe of hadron structure



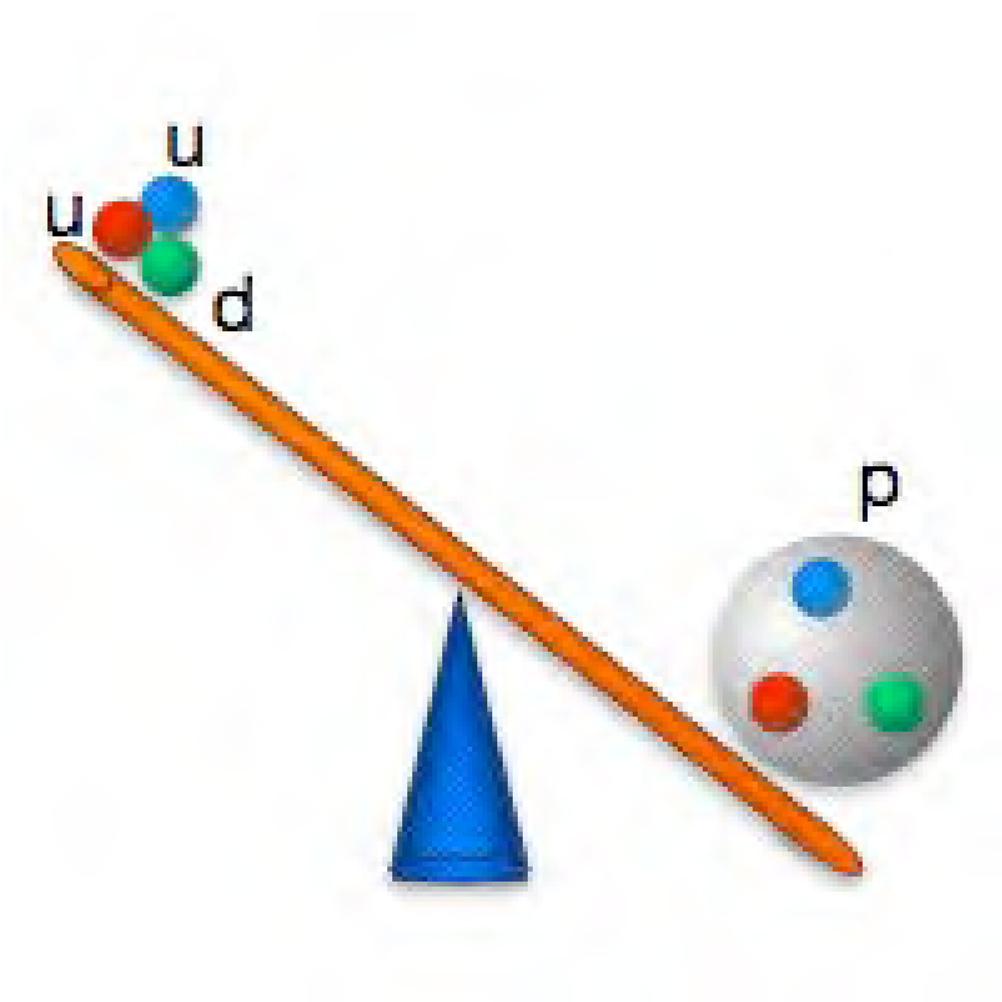
- ➢ Electron-vertex well-known from QED
- ➢ One-photon exchange dominates
- ➢ Higher-order exchange diagrams are suppressed
- ➢ Vary the wavelength of the probe to view deeper inside the hadron

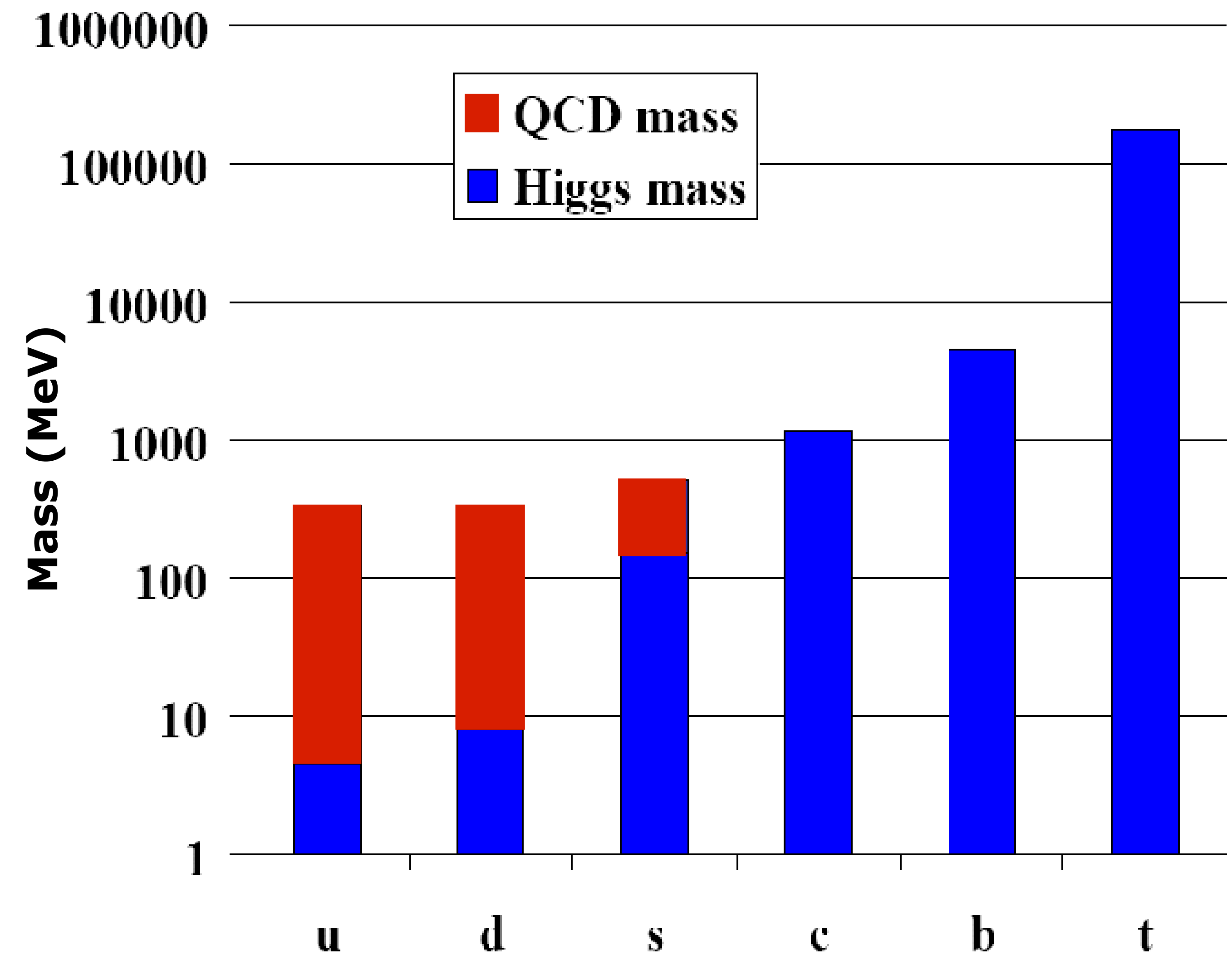
THE PROTON

One Millennium Quest
Generation of Mass

Not the elementary mass of the fermions → Higgs Sector

But the actual mass of the "Macroscopic" Hadron and its Composites





Nuclear Physics @ A=1 ≡ Nucleon Properties

mass

$$m_p = 938.272046(21)\,\mathrm{MeV/c^2}$$

Discovered by E. Rutherford (1919)

$$m_n = 939.565379(21)\,\mathrm{MeV/c^2}$$

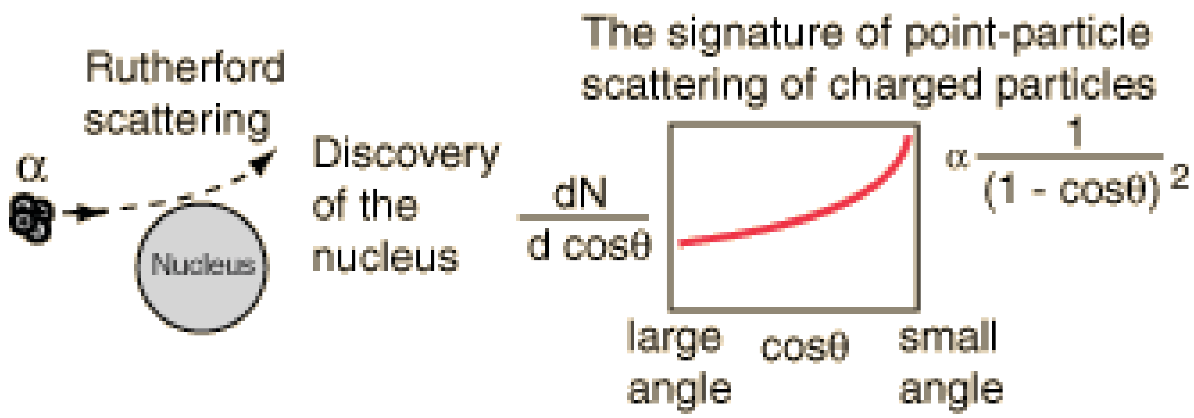
Discovered by J. Chadwick (1939)

size

moments of electric charge and magnetization distribution derived from **form factor** measurements

Form Factors are Ethernal

http://hyperphysics.phy-astr.gsu.edu/



Rutherford Scattering

$$\frac{d\sigma}{d\ \cos\theta} = \frac{\pi}{2} z^2 Z^2 \alpha^2 \left(\frac{\hbar c}{KE}\right)^2 \frac{1}{(1-\cos\theta)^2}$$

+ relativistic electrons
+ nuclear recoil
+ magnetic moments

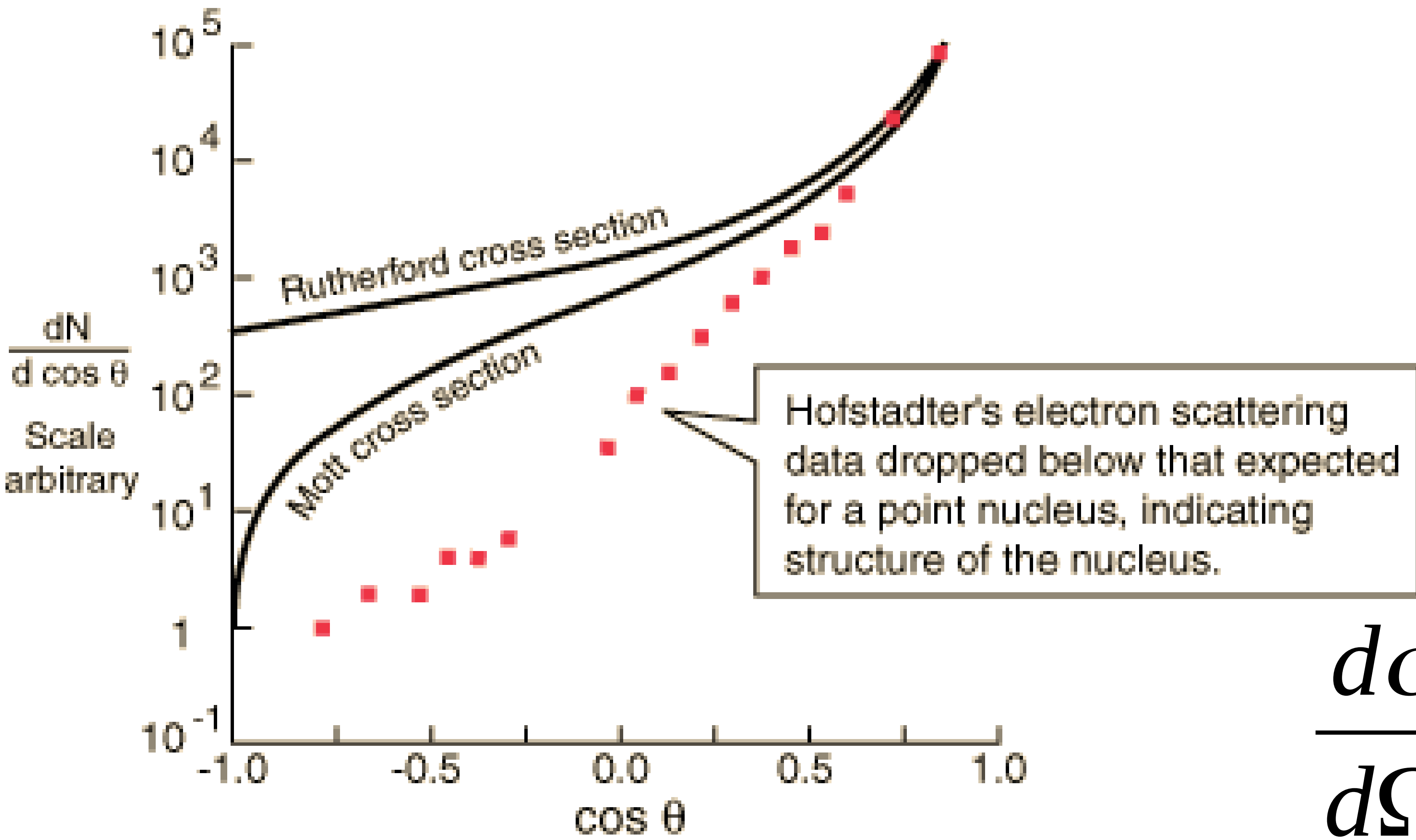
Mott Scattering

Electron Rutherford formula

Electron magnetic moment effect

$$\frac{d\sigma}{d\ \cos\theta} = \left(\frac{d\sigma}{d\ \cos\theta}\right)_R \frac{(1+\cos\theta)/2}{\left[1+\frac{(1-\cos\theta)KE}{Mc^2}\right]}$$

Nuclear recoil effect

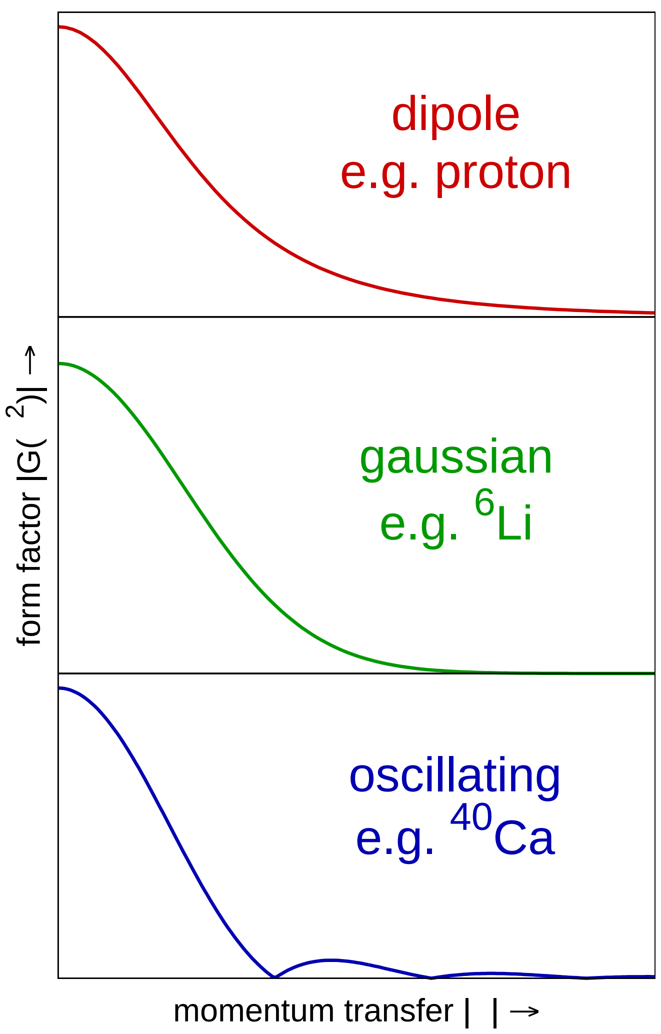


$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \cdot |G(q)|^2$$

Hofstadter, R., et al., Phys. Rev. 92, 978 (1953).

Form Factors from Elastic ep scattering

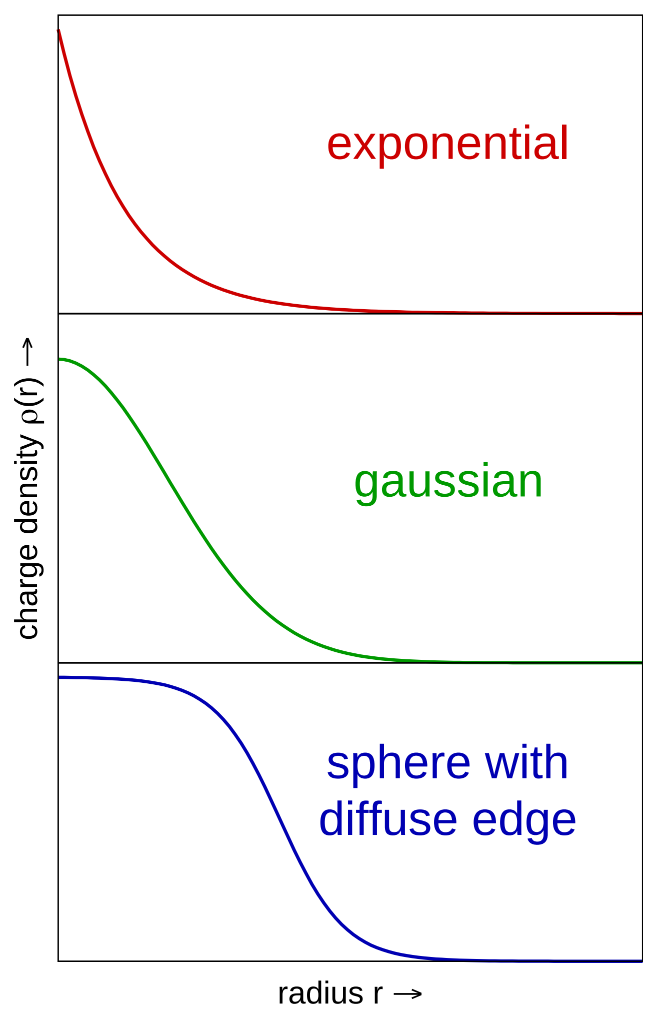
form factor: $G(q^2) = \frac{1}{e}\int_0^\infty \rho(r)\,\frac{\sin qr}{qr}\,4\pi r^2\,dr$



Fourier

⇔

Transform



charge distribution: $\rho(r) = \frac{e}{(2\pi)^3}\int_0^\infty G(q^2)\,\frac{\sin qr}{qr}\,4\pi q^2\,dq$

The latest MAMI measurement

The experiment designed for ...
high precision by redundancy


PRL 105, 242001 (2010) PHYSICAL REVIEW LETTERS 10 DECEMBER 2010

High-Precision Determination of the Electric and Magnetic Form Factors of the Proton

J. C. Bernauer,[1,*] P. Achenbach,[1] C. Ayerbe Gayoso,[1] R. Böhm,[1] D. Bosnar,[2] L. Debenjak,[3] M. O. Distler,[1,†] L. Doria,[1] A. Esser,[1] H. Fonvieille,[4] J. M. Friedrich,[5] J. Friedrich,[1] M. Gómez Rodríguez de la Paz,[1] M. Makek,[2] H. Merkel,[1] D. G. Middleton,[1] U. Müller,[1] L. Nungesser,[1] J. Pochodzalla,[1] M. Potokar,[3] S. Sánchez Majos,[1] B. S. Schlimme,[1] S. Širca,[6,3] Th. Walcher,[1] and M. Weinriefer[1]

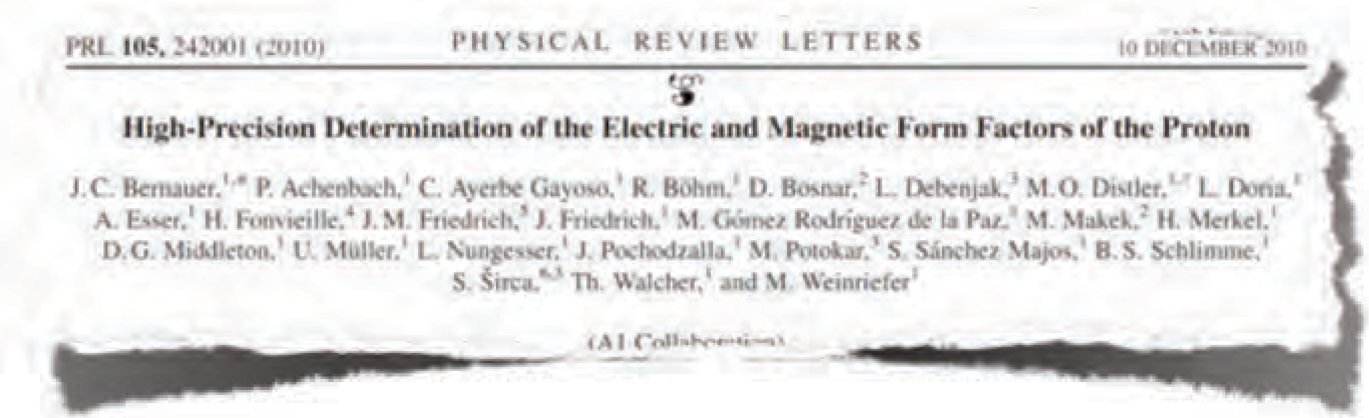
(A1 Collaboration)

- Statistical precision $\sigma < 0.1\%$
- $\delta\theta < 0.5$ mrad vertical and horizontal
- Control of luminosity and systematic errors

➛ All quantities measured by more than one method

Rosenbluth with a twist

"Super-Rosenbluth Separation": fit of form factor models **DIRECTLY to cross sections**



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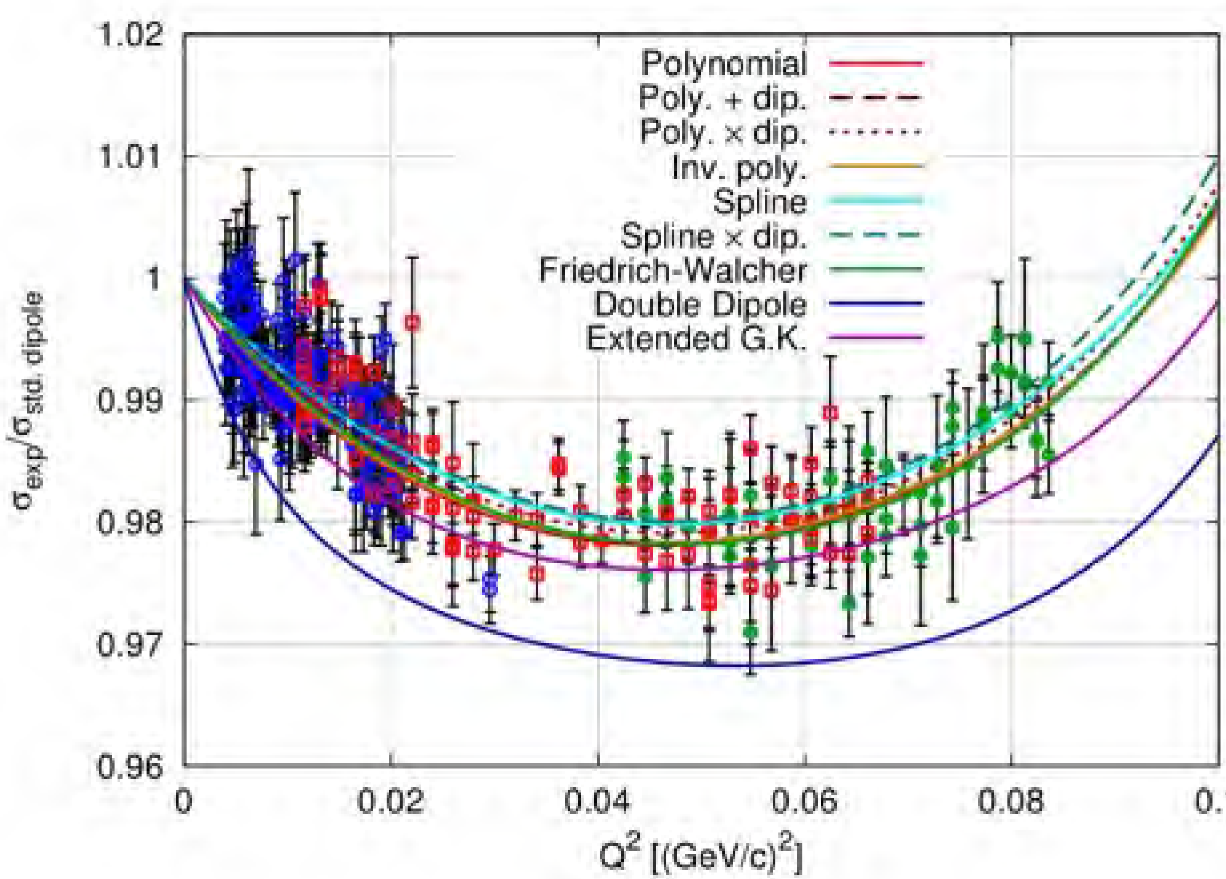
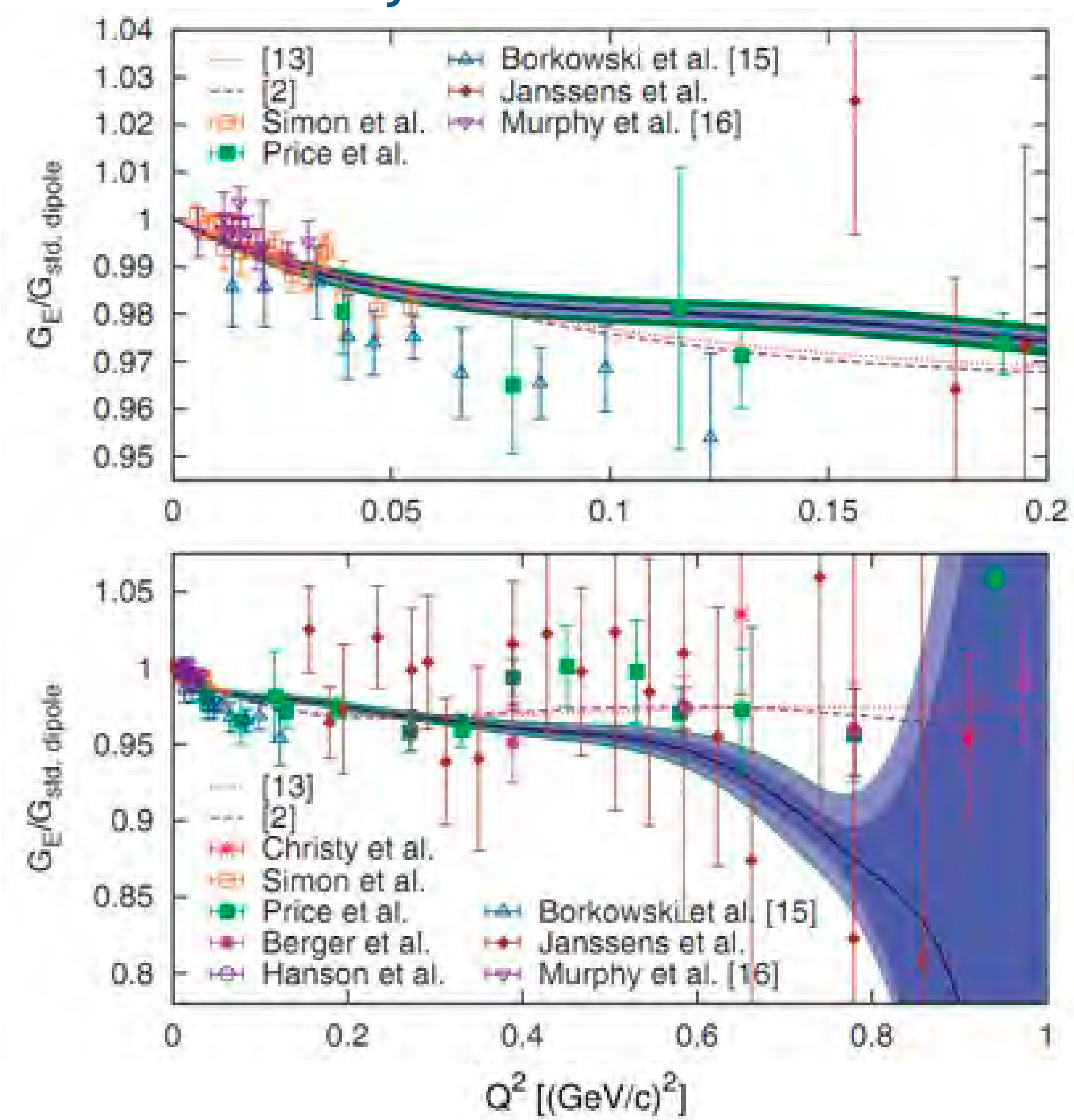
(A1 Collaboration)

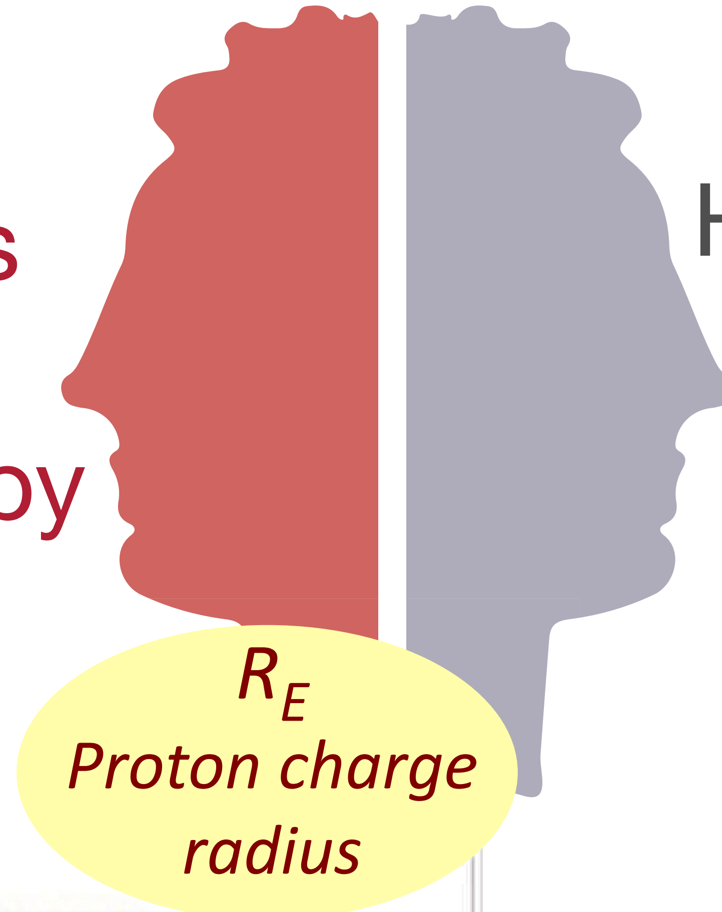
- All Q^2 and ε data are used in one fit
- No projection to constant Q^2
  - ➛ no limit of kinematics
- One "estimator"
  - ➛ stat. theory "robust estimator"



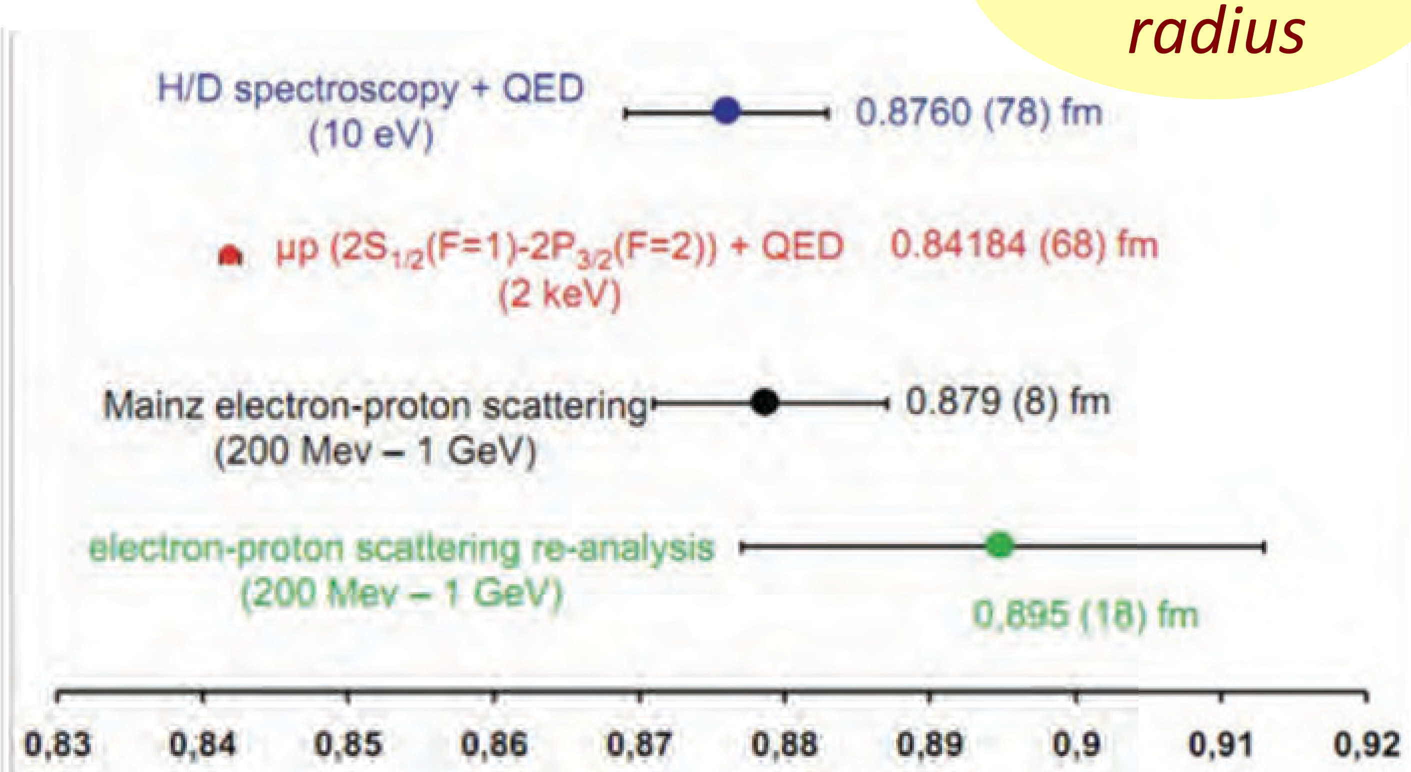


The Low Energy Frontier

Strong Interactions
Hadron Structure
Hadron Spectroscopy



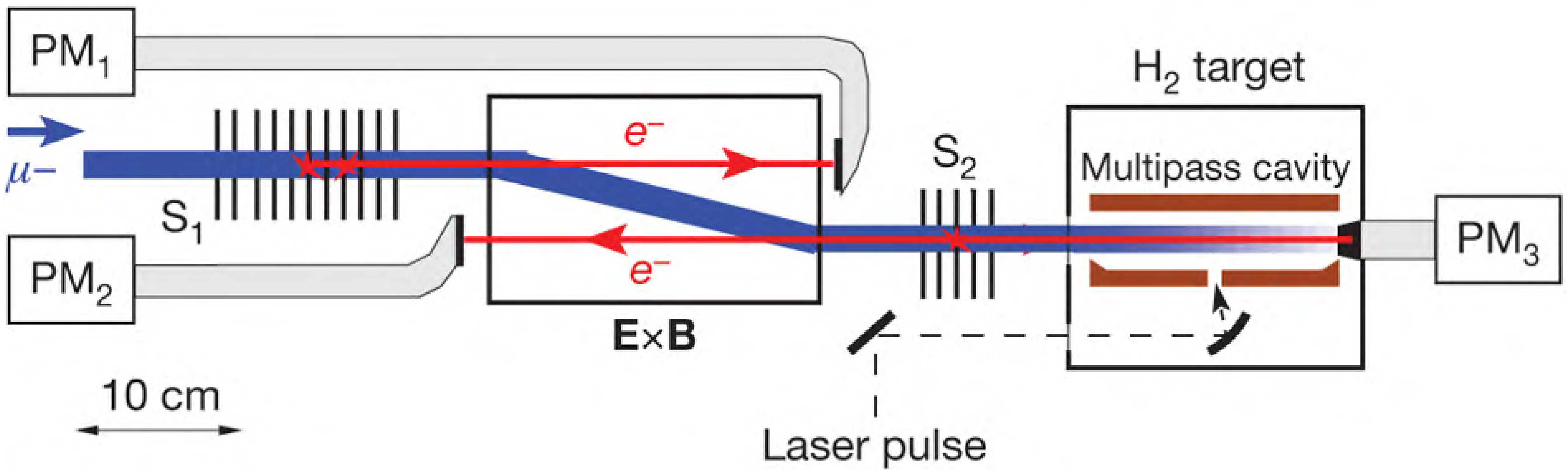
High-Energy Physics
Precision Physics
Atomic Physics
Astrophysics

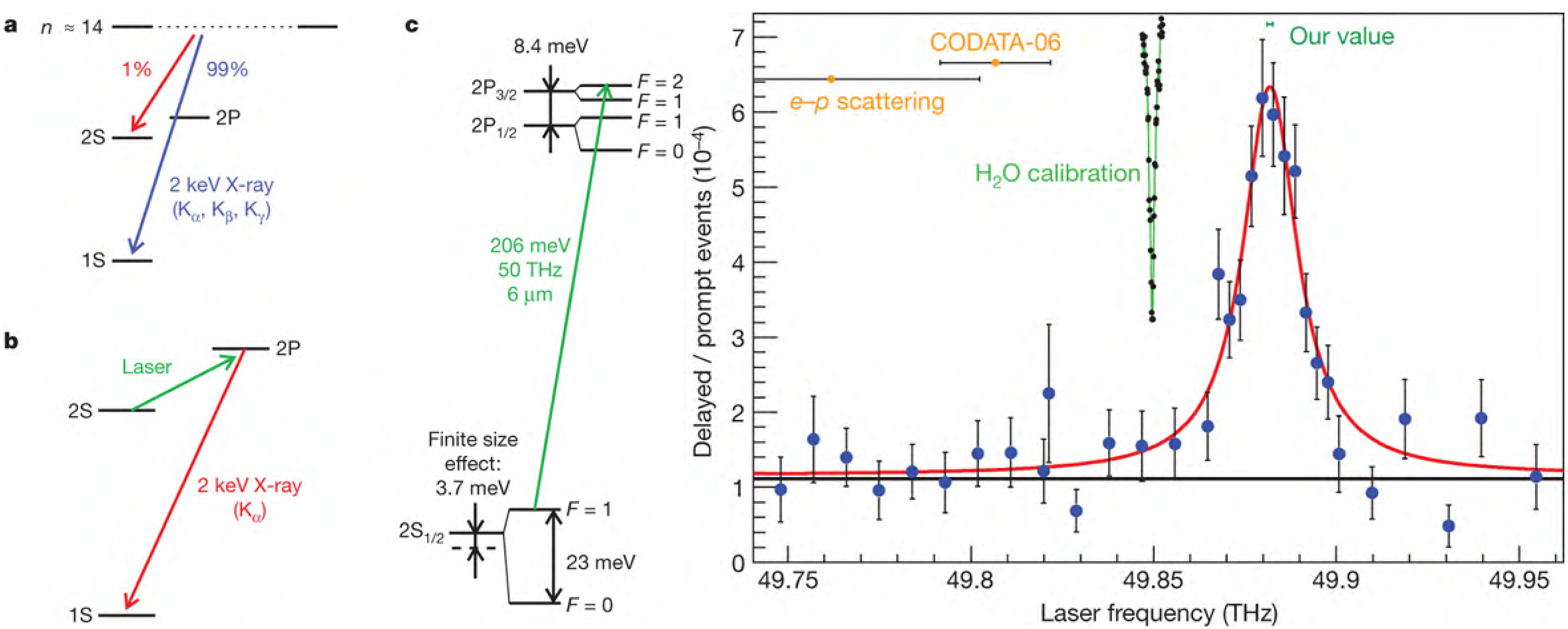


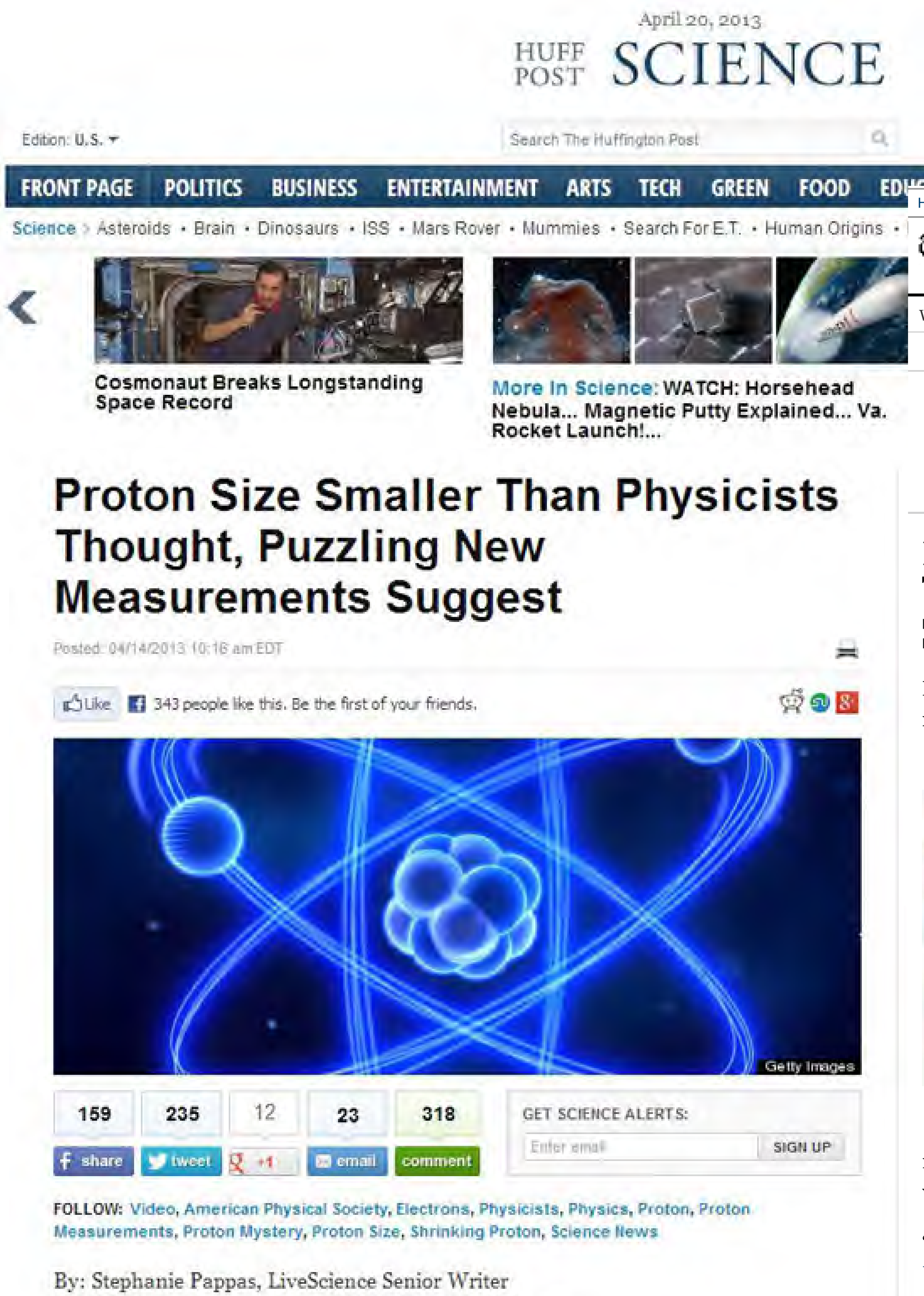
...the Atomic Physics frontier

The Low Energy Frontier

Nature **466**, 213-216 (8 July 2010)







April 20, 2013

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Proton Size Smaller Than Physicists Thought, Puzzling New Measurements Suggest

Posted: 04/14/2013 10:16 am EDT

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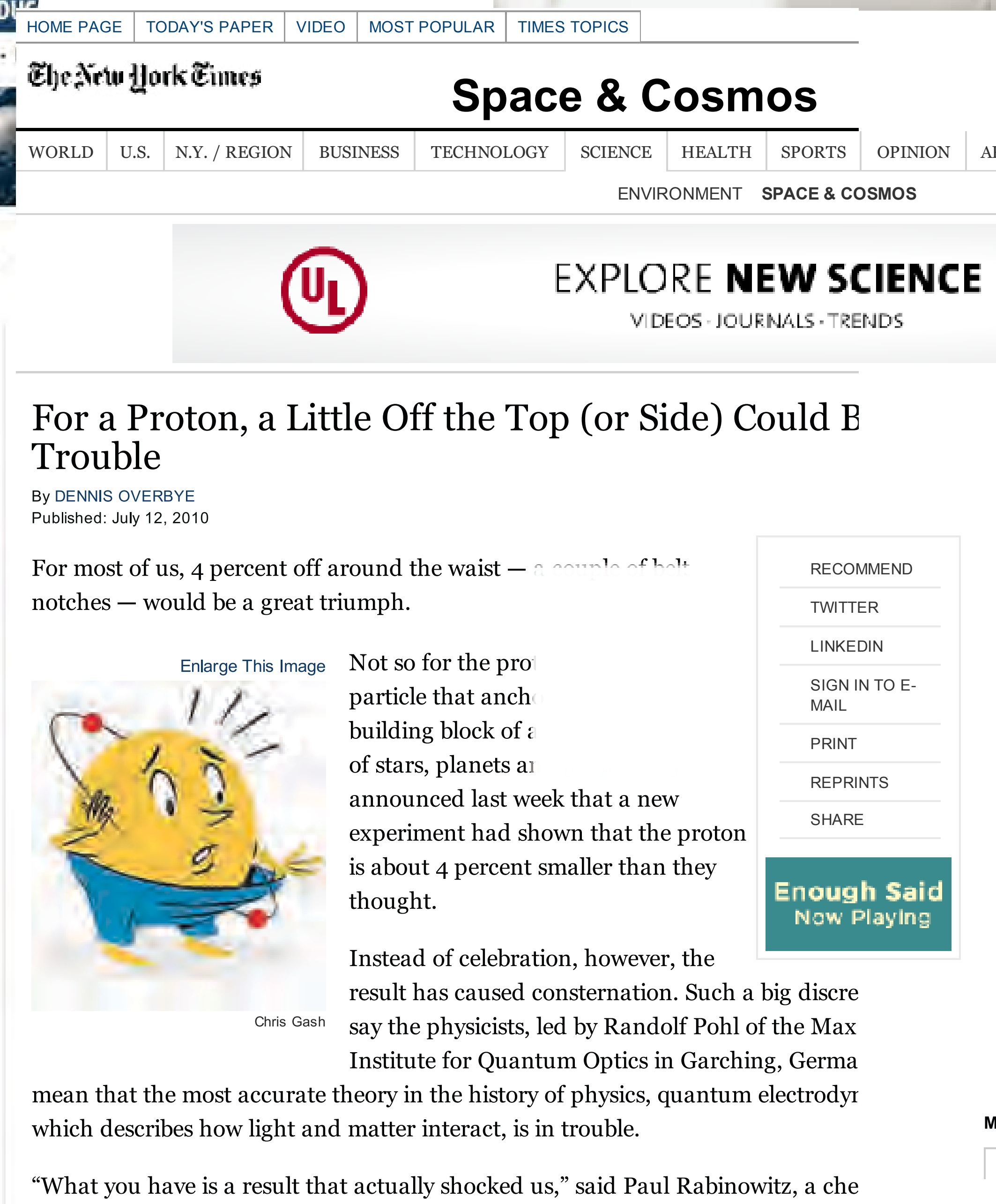

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For a Proton, a Little Off the Top (or Side) Could B Trouble

By DENNIS OVERBYE
Published: July 12, 2010

For most of us, 4 percent off around the waist — notches — would be a great triumph.

Enlarge This Image

Chris Gash

Not so for the pro particle that anch building block of of stars, planets a announced last week that a new experiment had shown that the proton is about 4 percent smaller than they thought.

Instead of celebration, however, the result has caused consternation. Such a big discre say the physicists, led by Randolf Pohl of the Max Institute for Quantum Optics in Garching, Germa mean that the most accurate theory in the history of physics, quantum electrody which describes how light and matter interact, is in trouble.

"What you have is a result that actually shocked us," said Paul Rabinowitz, a che

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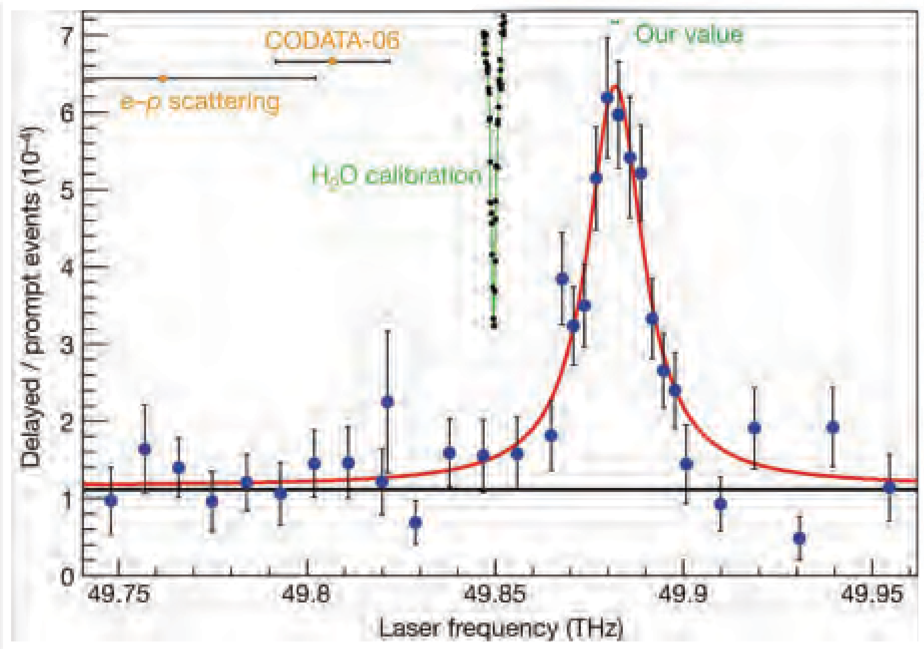
Enough Said Now Playing

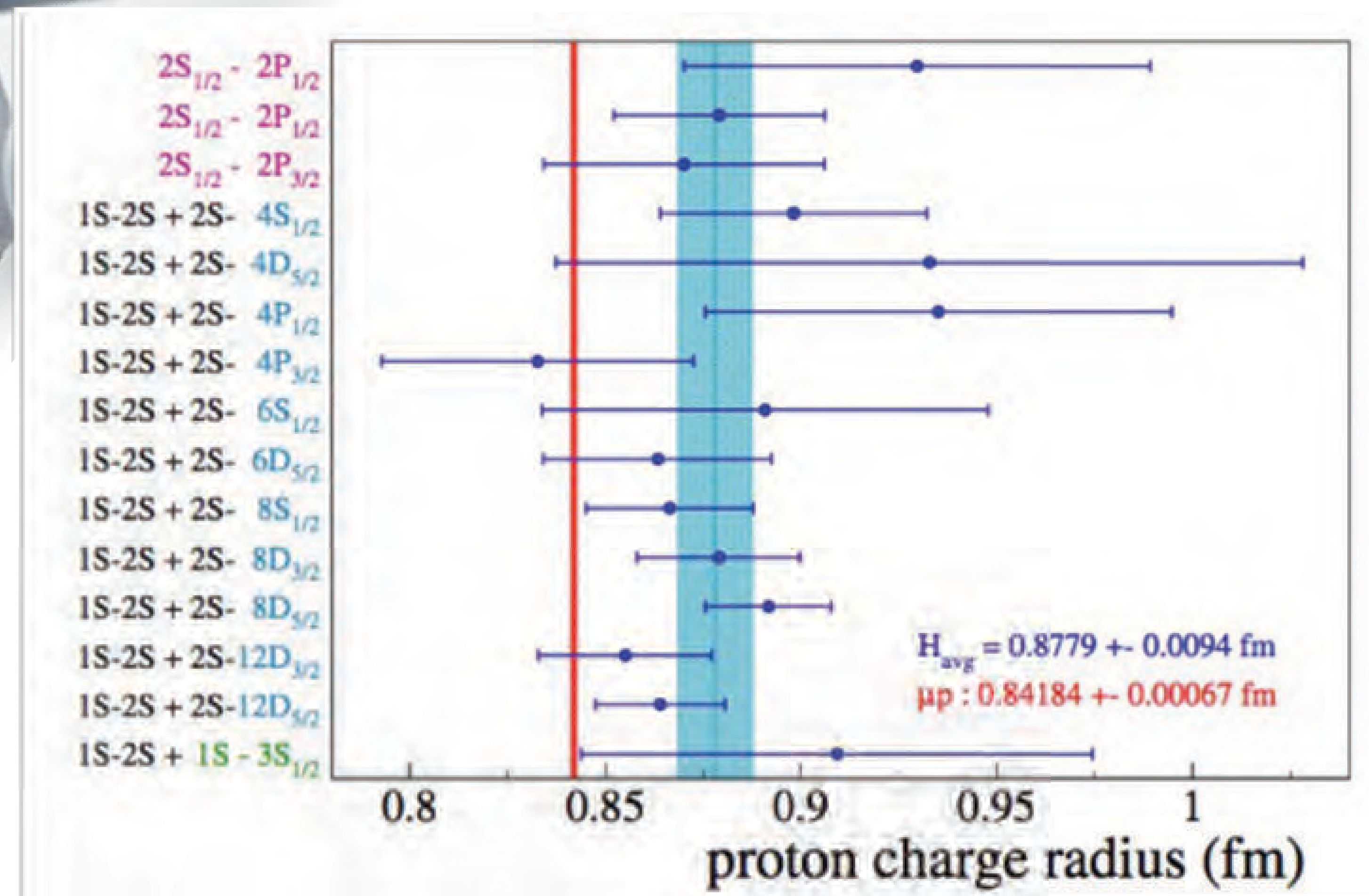
....not just interesting:

- ➔ Tests our theoretical understanding of proton
- ➔ Radius of proton is dominant uncertainty in many QED processes

The Radius Puzzle

R. Pohl et al., Nature 466, (2010) 213

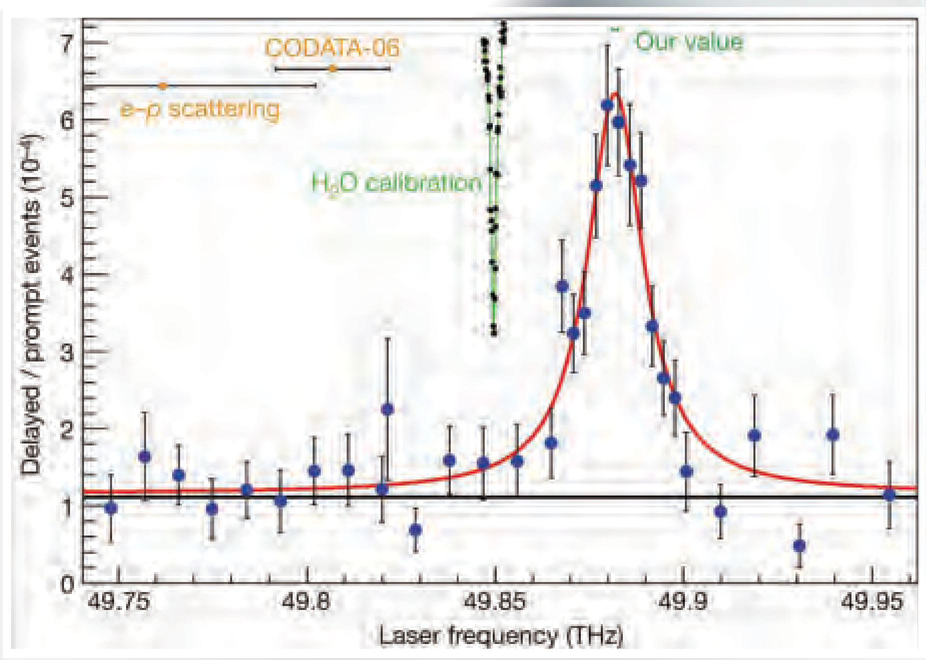




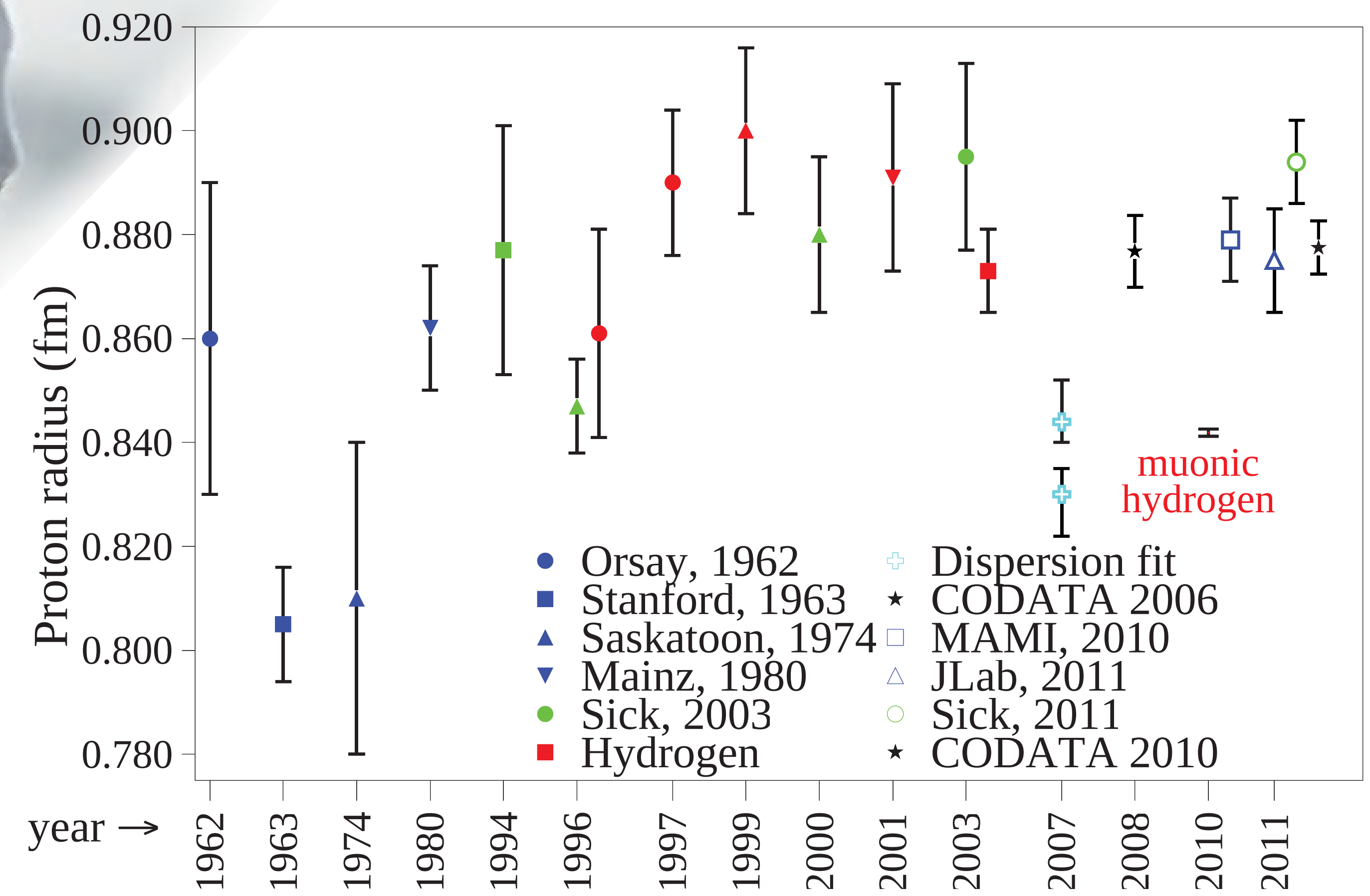
Discrepancy is between muonic and electronic measurements (atomic)

The Radius Puzzle

R. Pohl et al., Nature 466, (2010) 213



Pohl, Gilman, Miller, Pachucki review, arXiv:1301.0905,



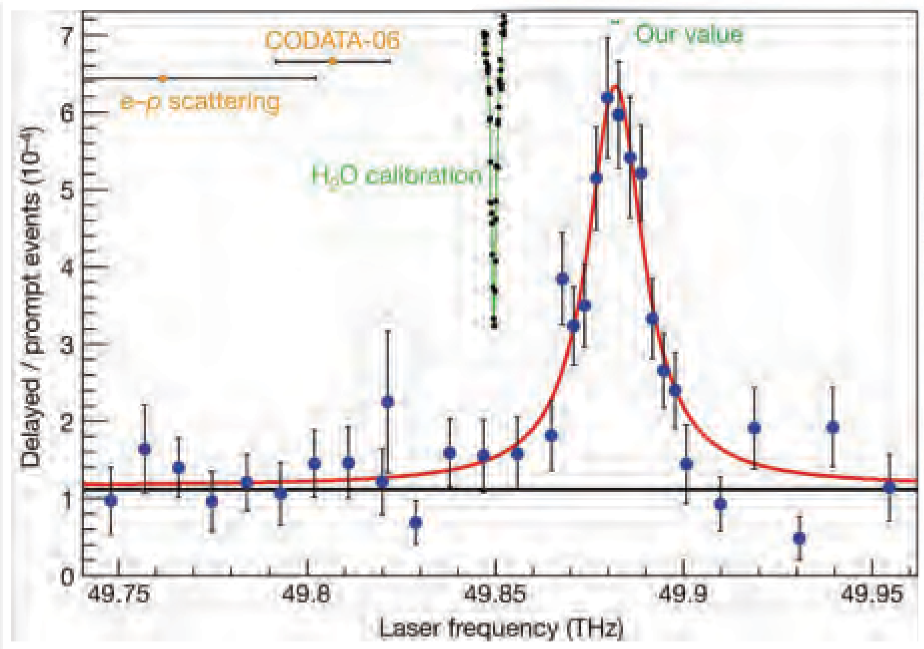
Discrepancy is between muonic and electronic measurements (scattering)

Novel beyond SM physics?
Novel hadron physics?

already excluded: missing atomic physics, structures in FF, anomalous 3rd Zemach radius

The Radius Puzzle

R. Pohl et al., Nature 466, (2010) 213



Discrepancy is between muonic and electronic measurements (both types)

New data are needed and they are coming ...

Improvements on Proton Radius

Possible experiments include:

- Redoing atomic hydrogen
- Light muonic atoms for radius comparison in heavier systems
- Electron scattering at lower Q^2
  (JLAB, MAMI)
- Muon scattering (MUSE@PSI)

Second constraint

It's always *just* water

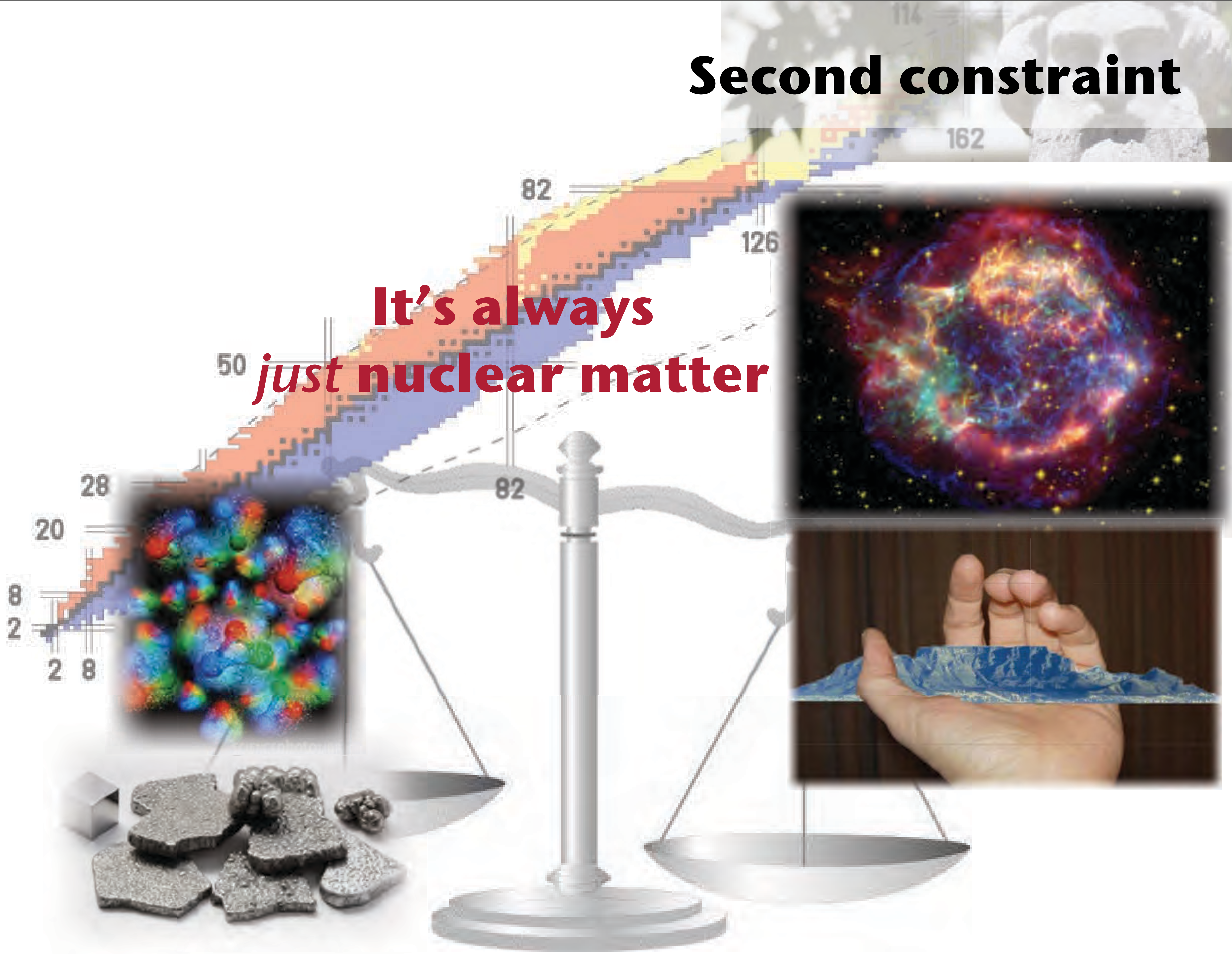
© Corgi Lane

© ryandury

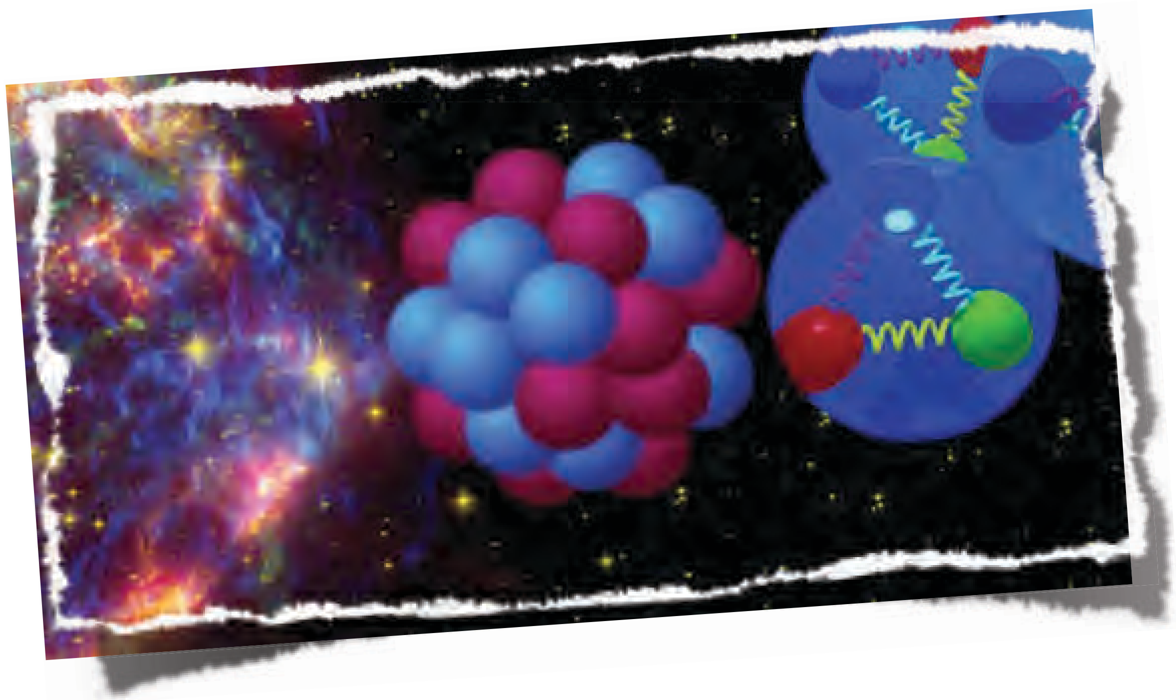
© Jens Rydén

Second constraint

It's always
***just* nuclear matter**

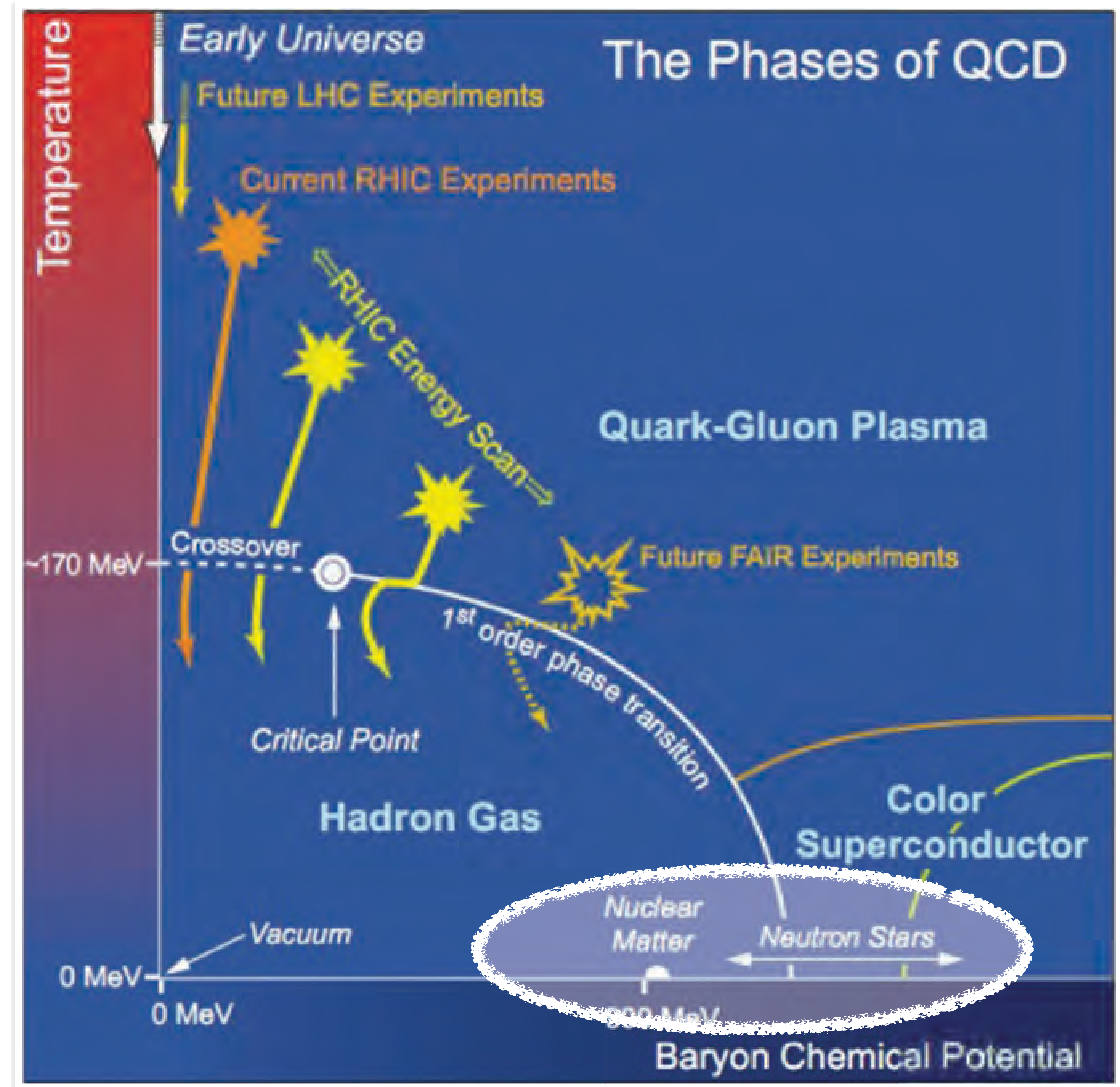


Second constraint



Modern nuclear physics is about…

➜Unravelling the phases of nuclear matter

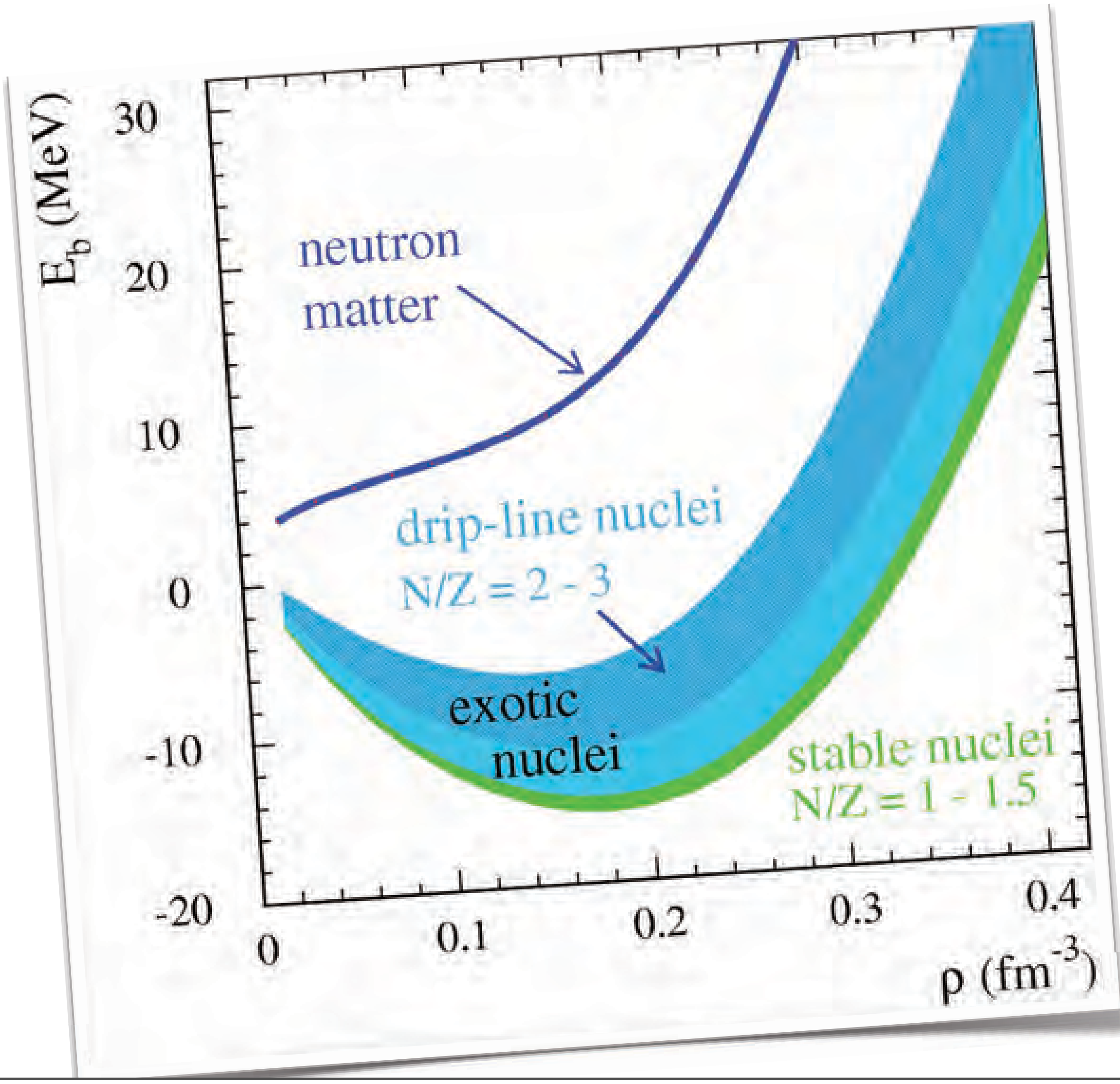


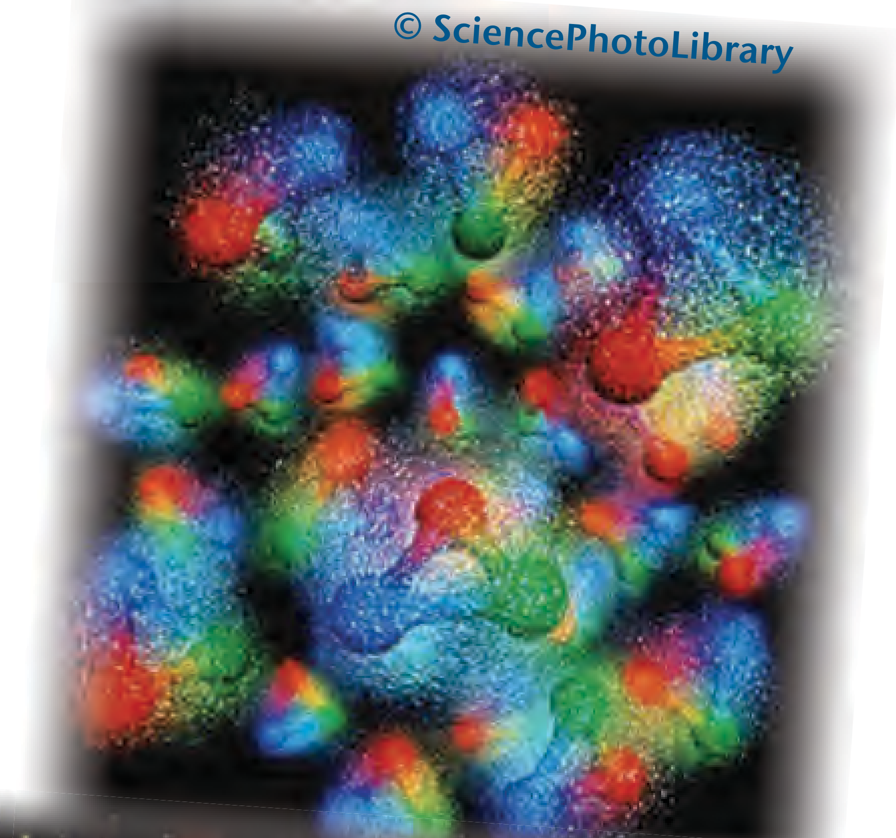
LRP Nuclear Science Advisory Committee(2008)

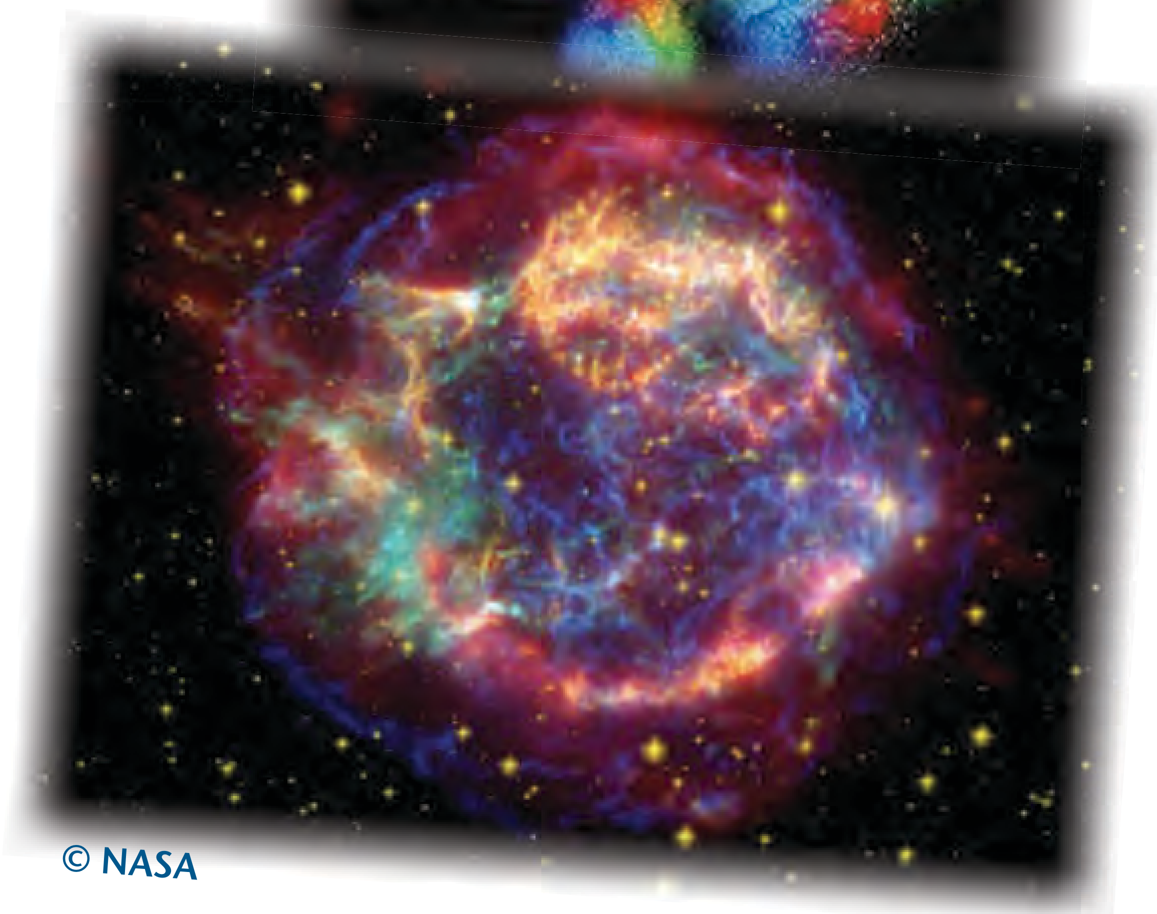
The Equation of State of Nuclear Matter

A heavy nucleus (like ^{208}Pb) is 18 orders of magnitude smaller and 55 orders of magnitude lighter than a neutron star

Yet bounded by the same EOS







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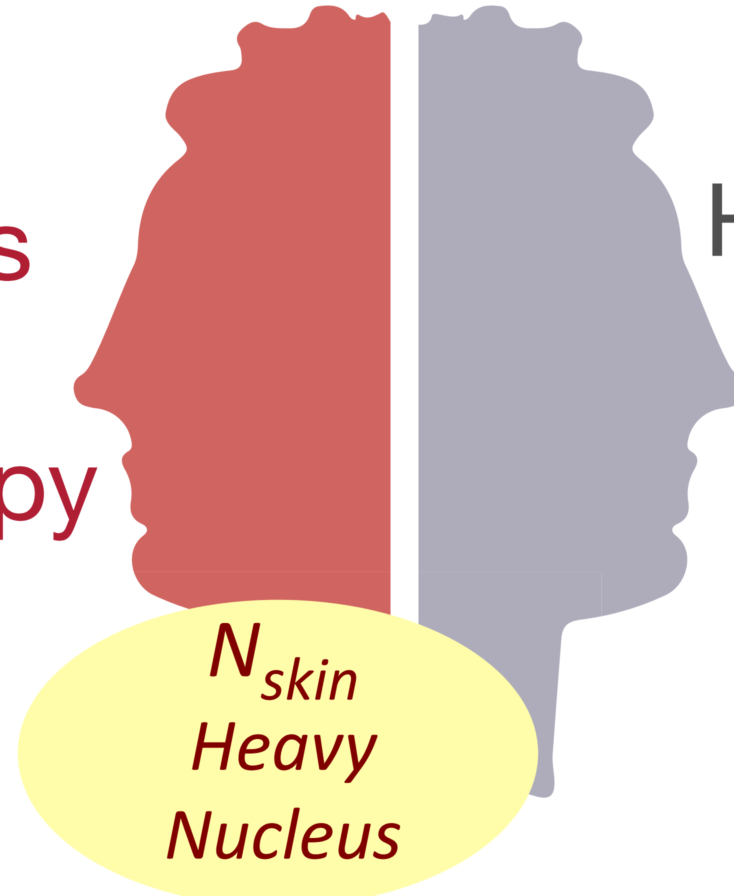

High-Energy Physics
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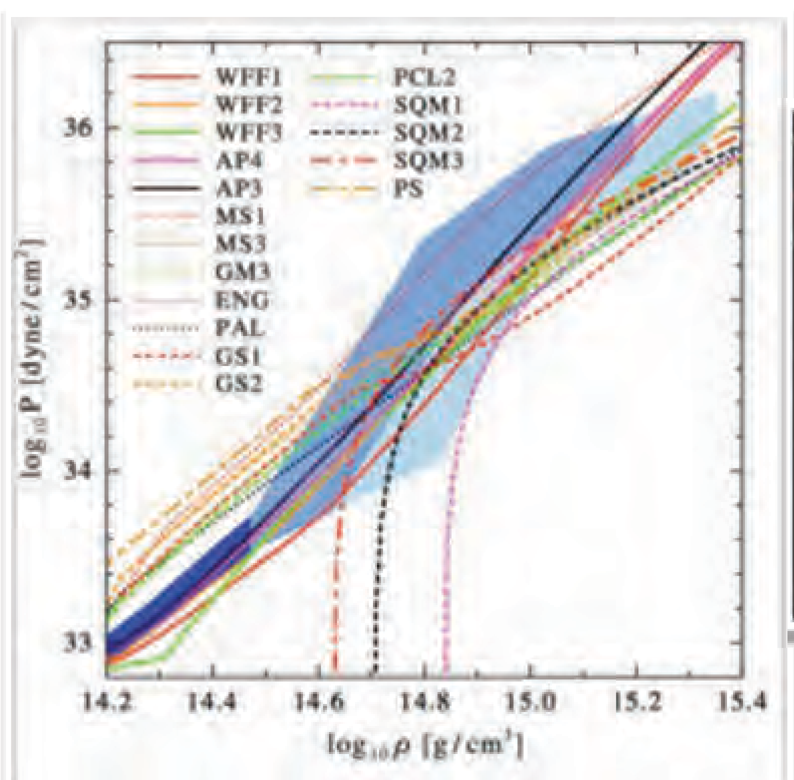
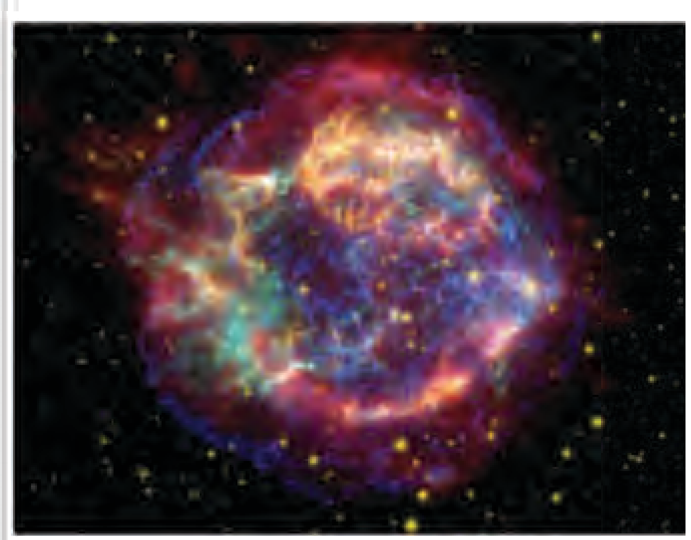
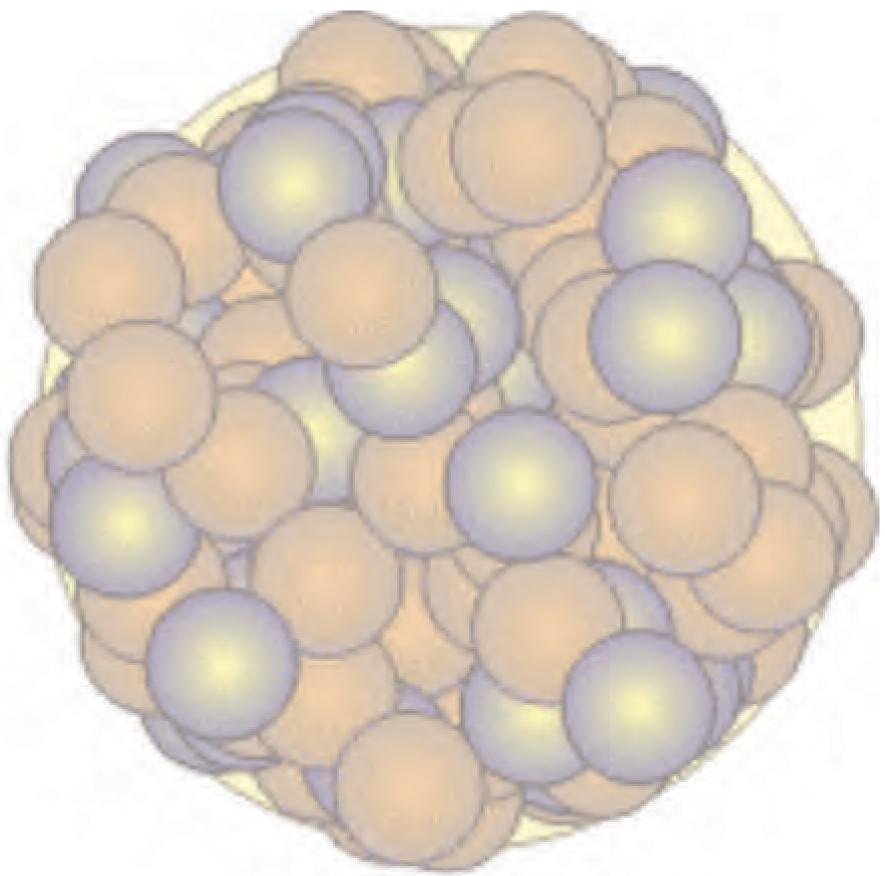


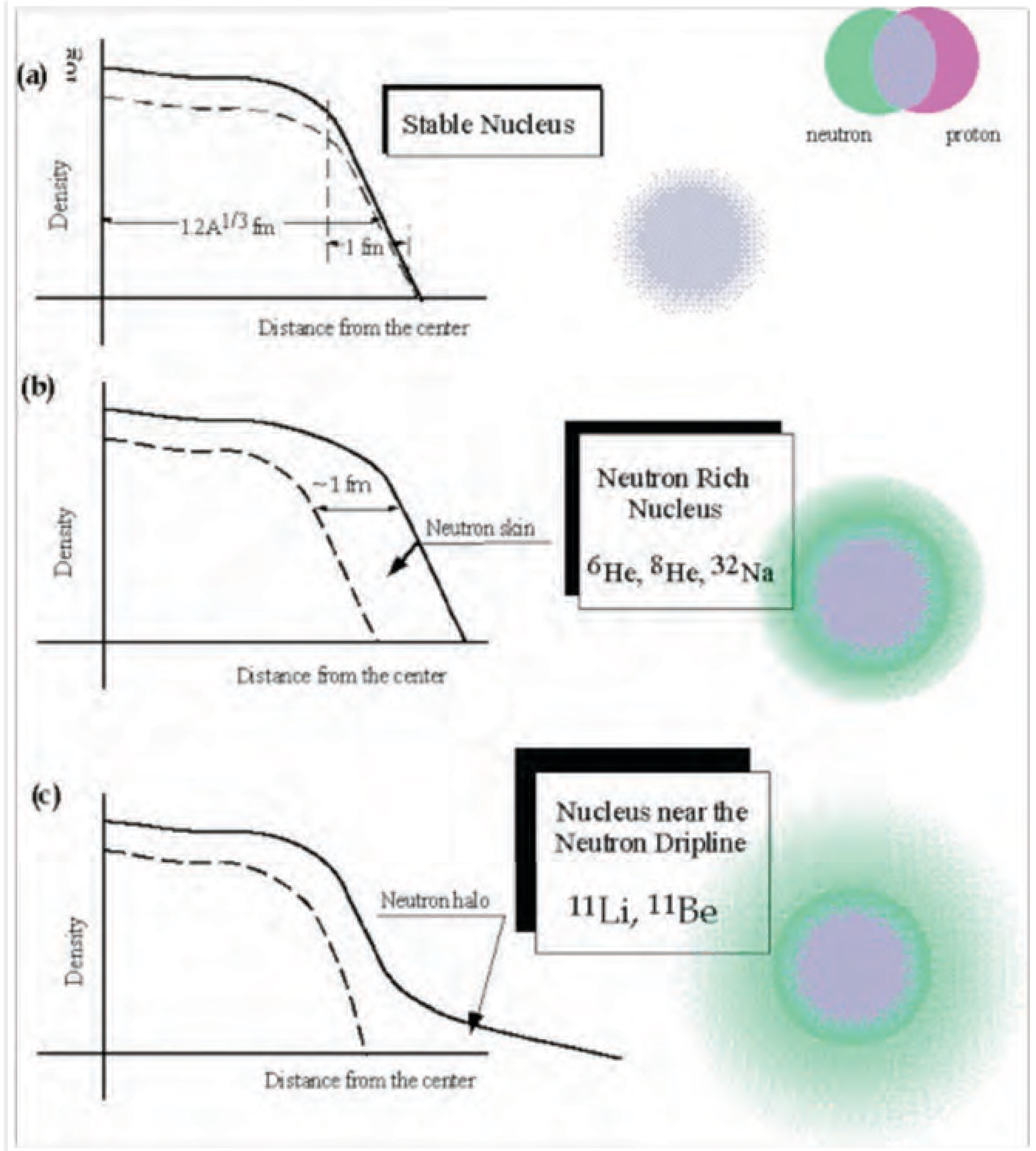


...the
Astrophysics
frontier

Neutron Skin Measurements

Where do the neutrons go?





Pressure forces neutrons out against surface tension

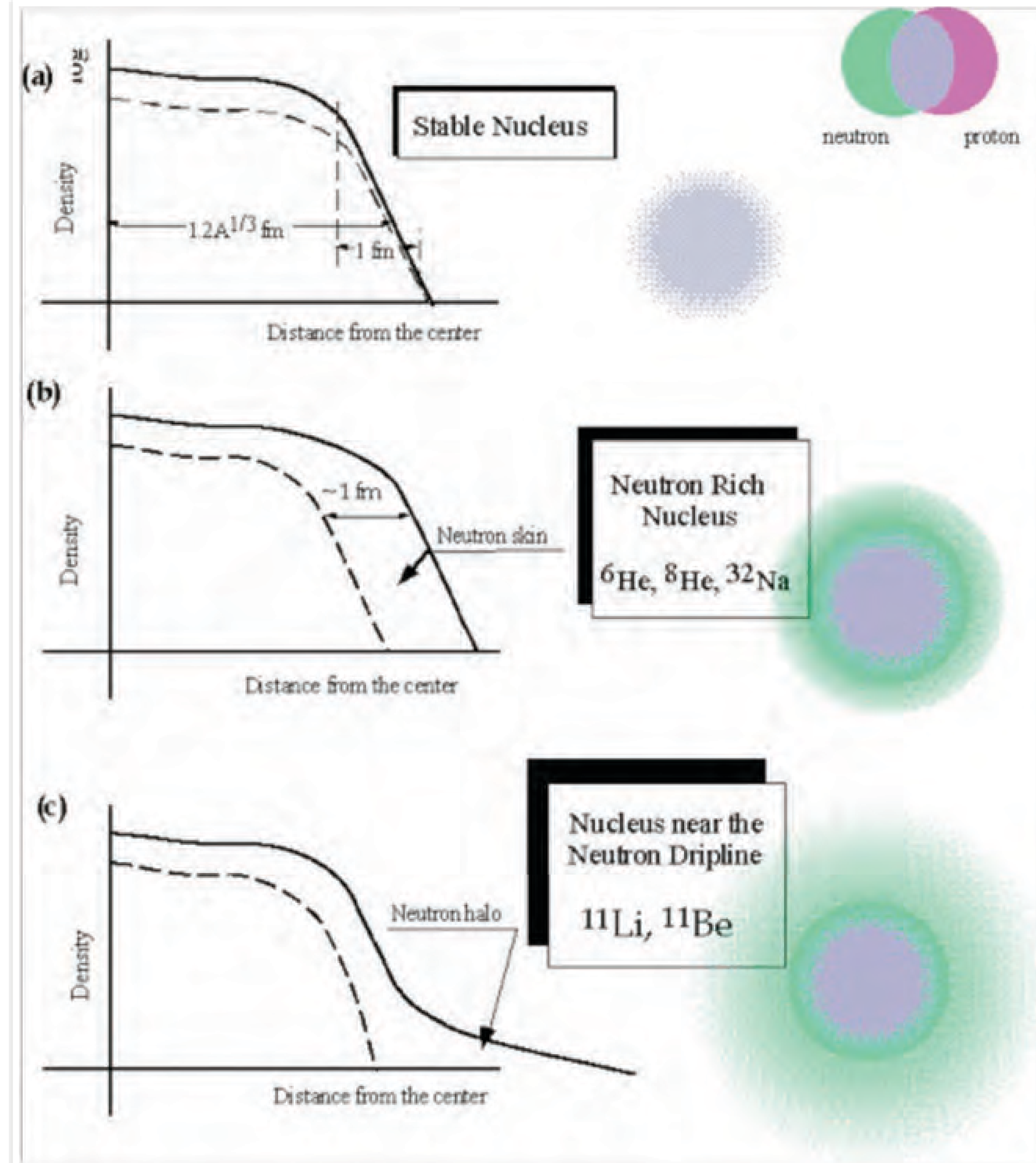
→ **EOS**

Neutron Skin Measurements

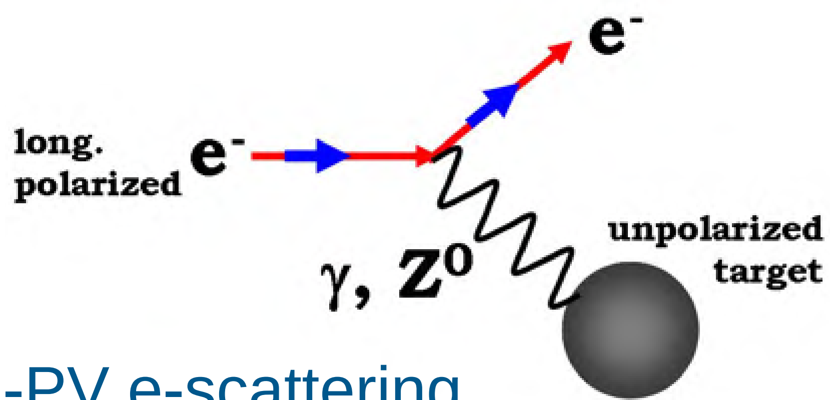
Where do the neutrons go?

Pressure forces neutrons out against surface tension

→ **EOS**



PV: the view in the mirror



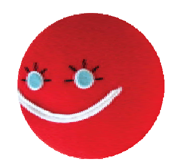
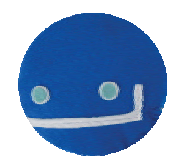
Non-PV e-scattering

Electron scattering γ exchange provides R_p through nucleus FFs

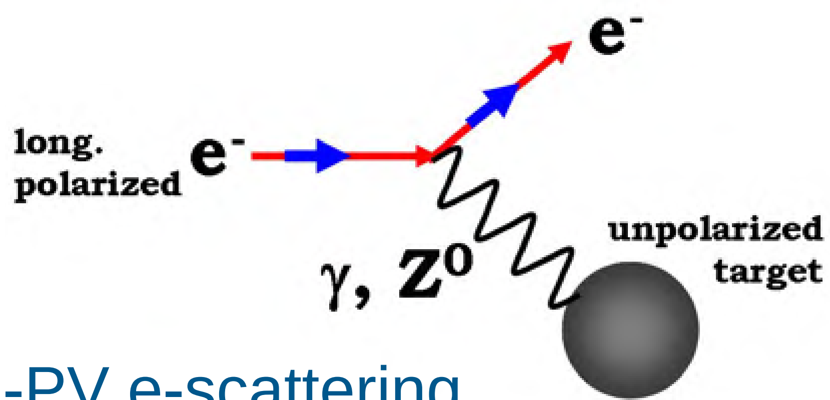
PV e-scattering

Electron also exchange Z, which is parity violating

Primarily couples to neutron

		
electric charge	**1**	**0**
weak charge	**≈0.07**	**1**

PV: the view in the mirror



Non-PV e-scattering

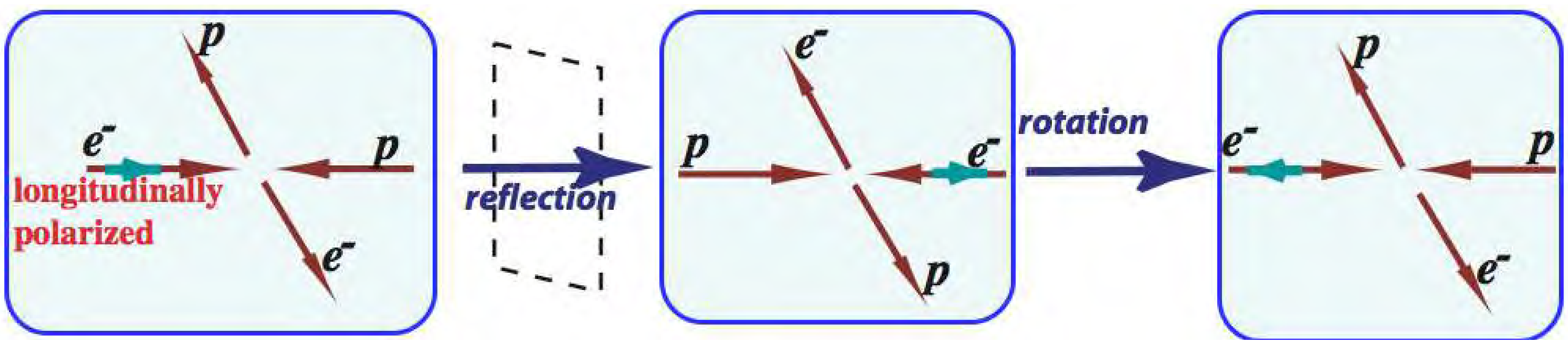
Electron scattering γ exchange provides R_p through nucleus FFs

PV e-scattering

Electron also exchange Z, which is parity violating

Primarily couples to neutron

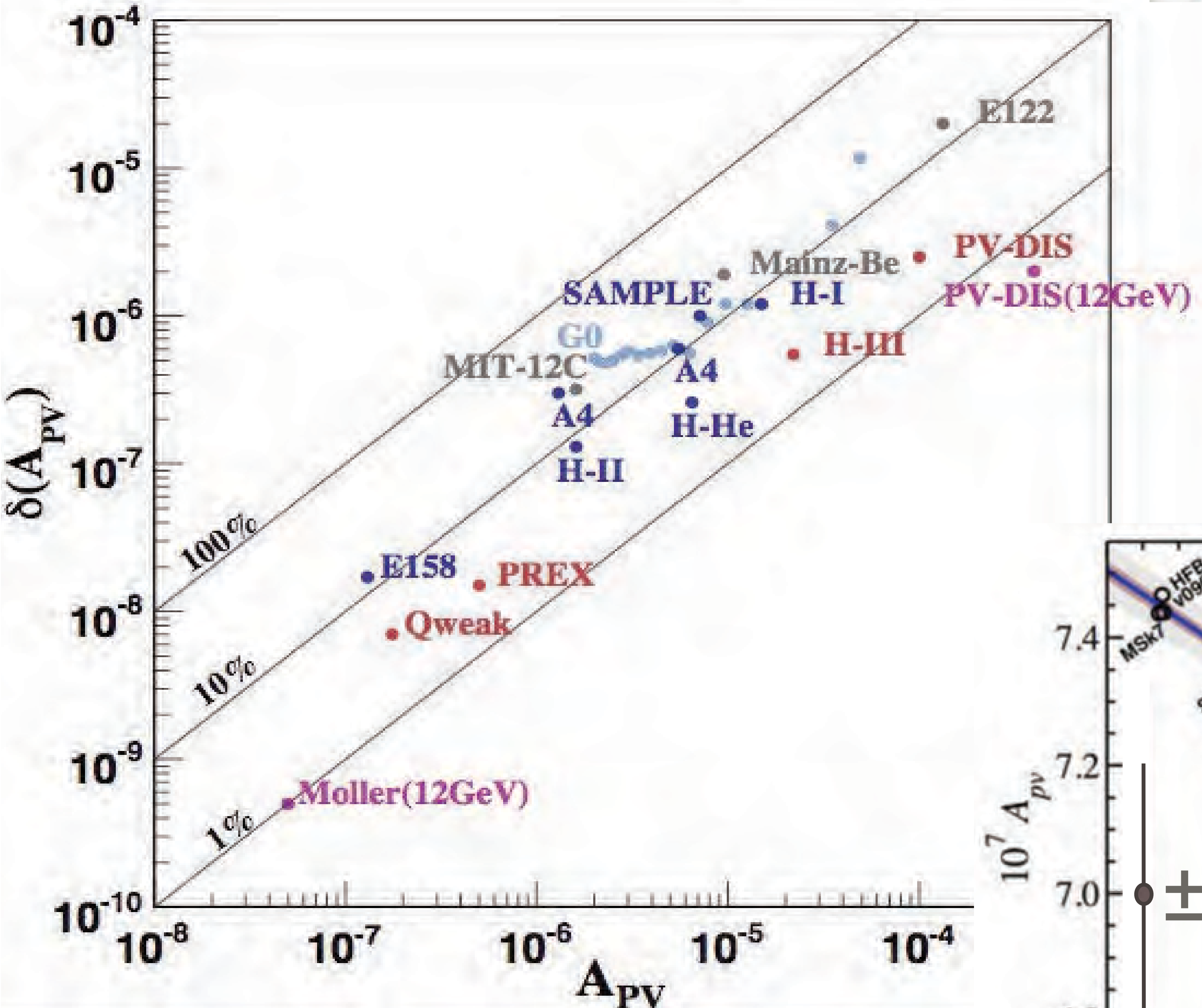
Detectable in PV asymmetry of electrons with different helicity



$$A_{\rm PV} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\left[1 - 4\sin^2\theta_W - \frac{F_n(Q^2)}{F_p(Q^2)}\right]$$

Hard, harder, PV Experiments

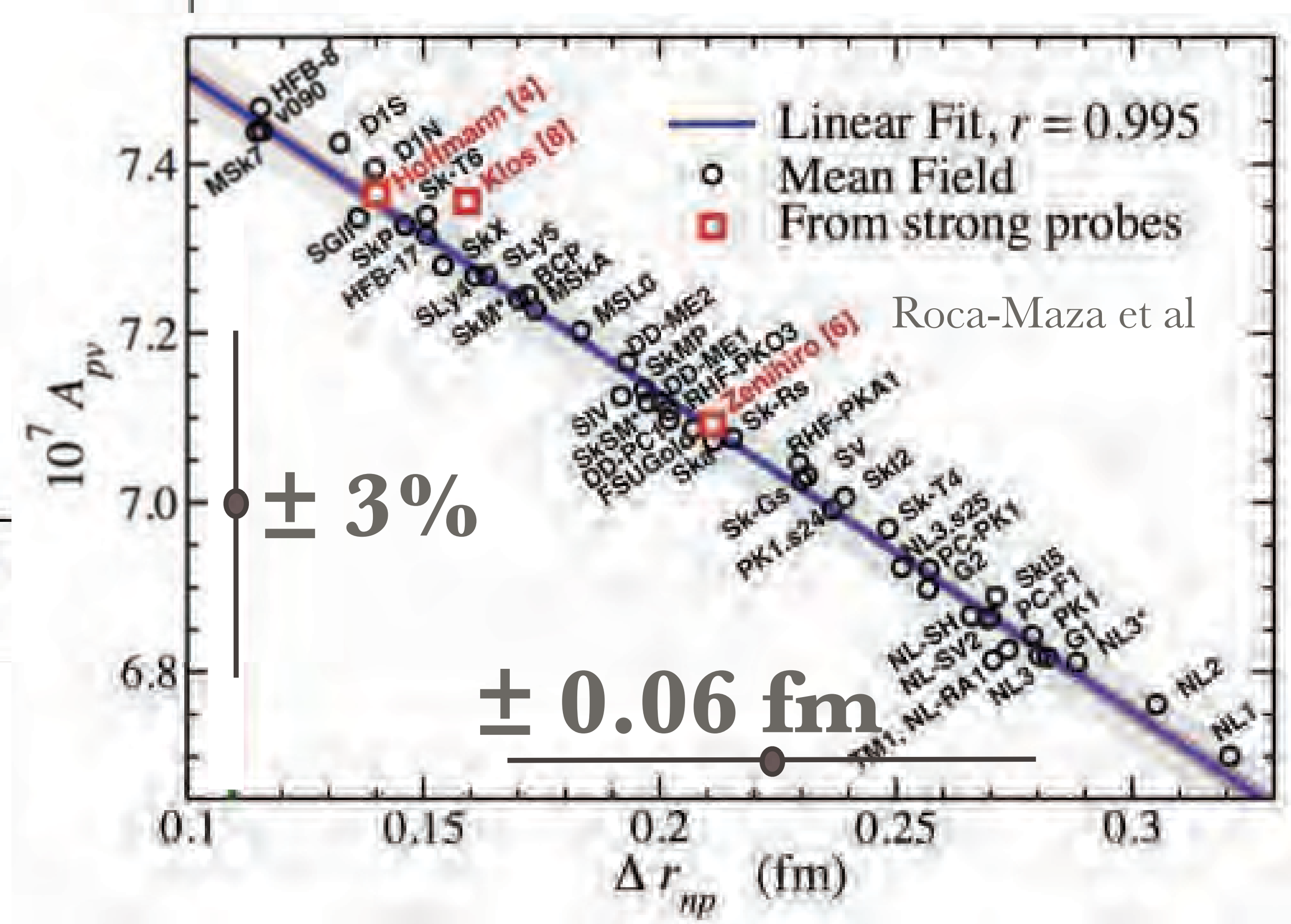
3 Decades of Progess



State-of-the-art:

sub-part per billion statistical reach and systematic control

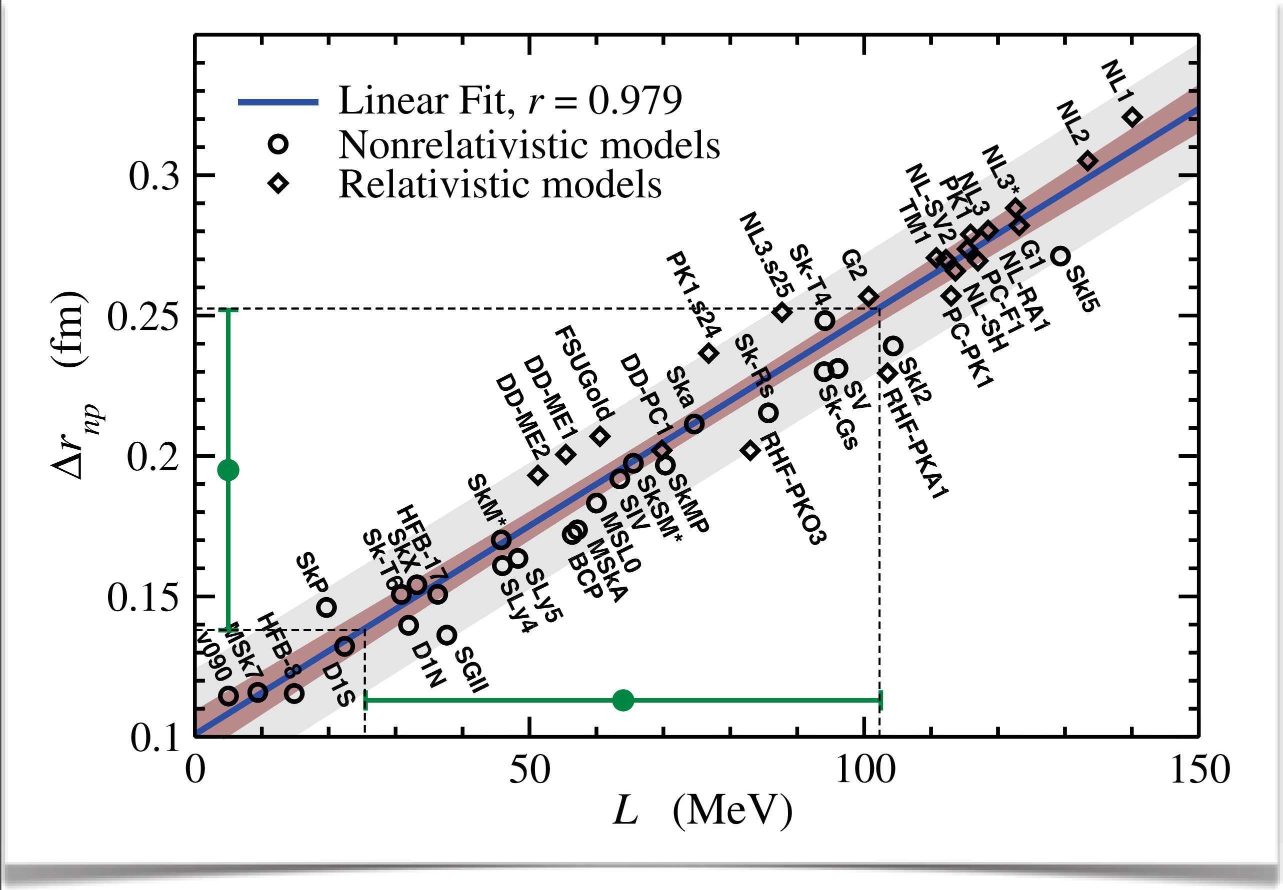
sub-1% normalization control



PV Measurements@A1

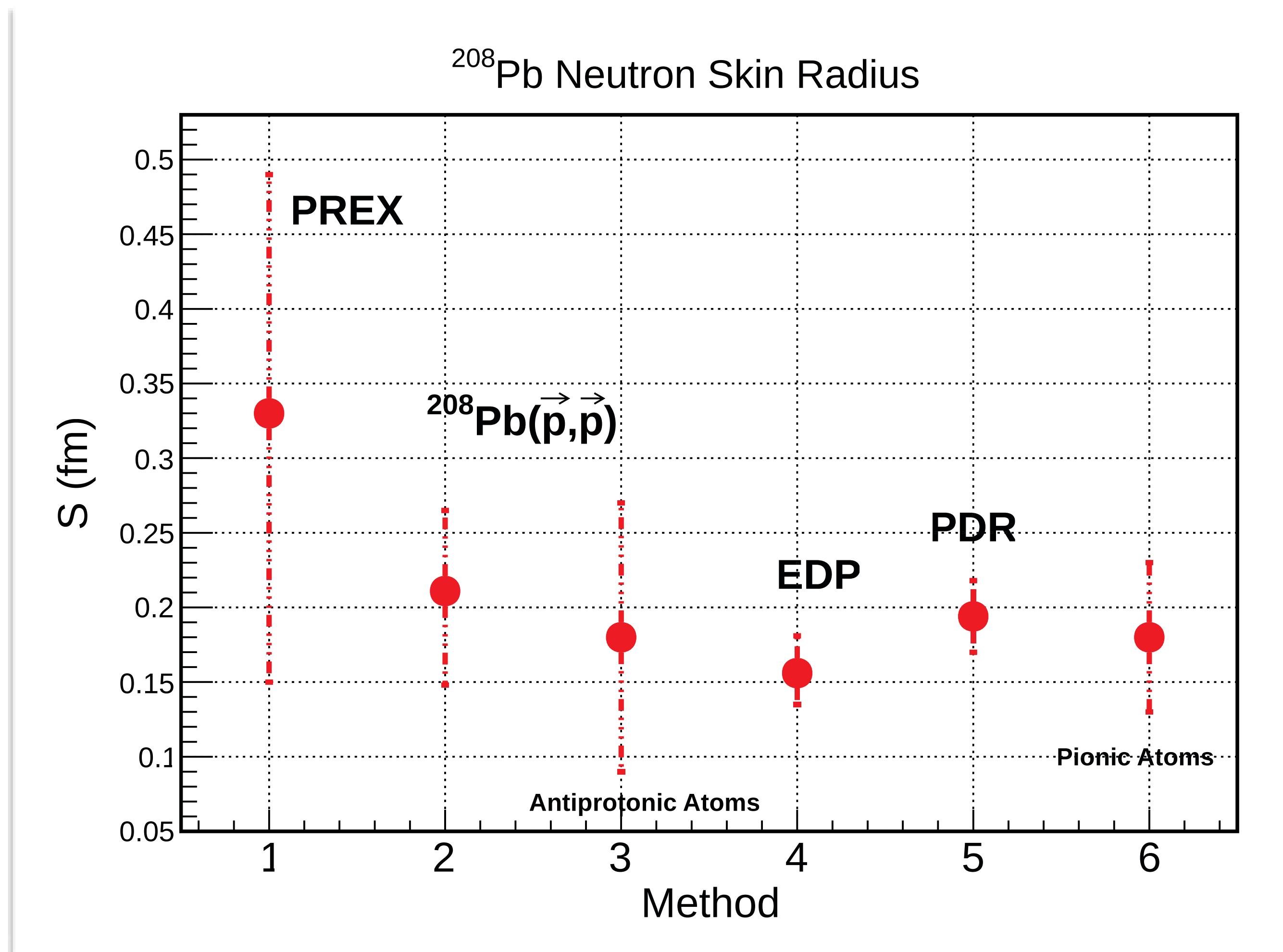
(commissioning in Spring 2014 - ^{12}C)

Neutron skin Radii: Where are we?



Precise determination of N_{Skin} in ^{208}Pb set a basic constraint on the nuclear symmetry energy

X. Roca-Maza, at al. Phys. Rev. Lett. 106, 252501 (2011)

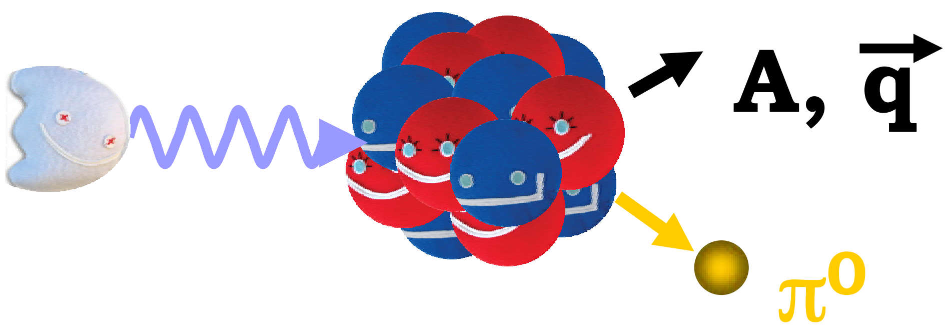


Diverse experiments but consistent results

☠ Too many model dependent observables

At A2 we *shine light* **on the nucleus!**

coherent π^0 photoproduction @ A2



$$\gamma + A_{(g.s.)} \rightarrow \pi^0 + A_{(g.s.)}$$
$$\hookrightarrow \gamma\gamma$$

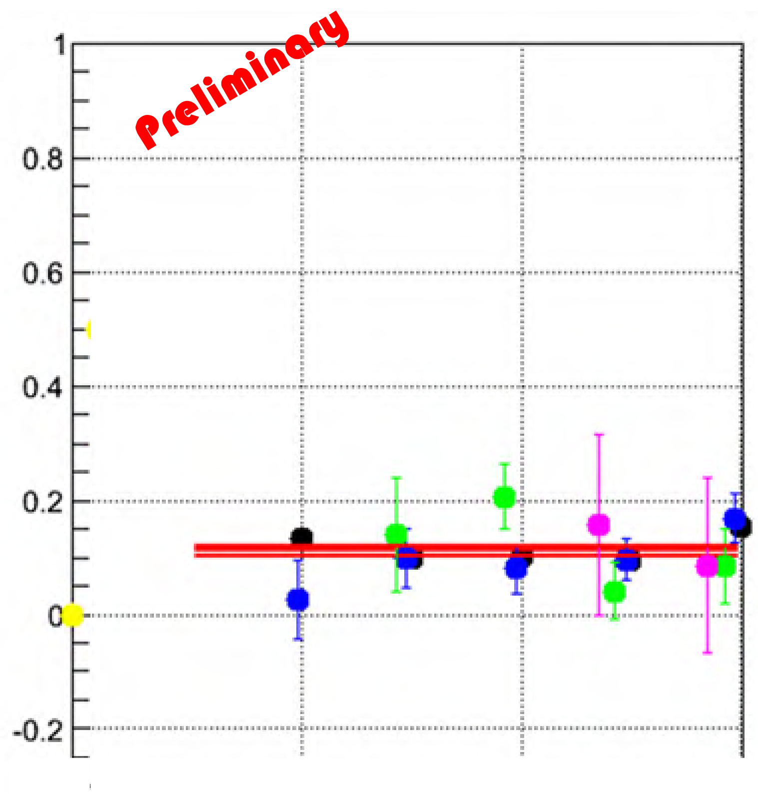
π^0 produced with equal probability on protons and neutrons

Most simple - **Plane Wave Impulse Approximation:**

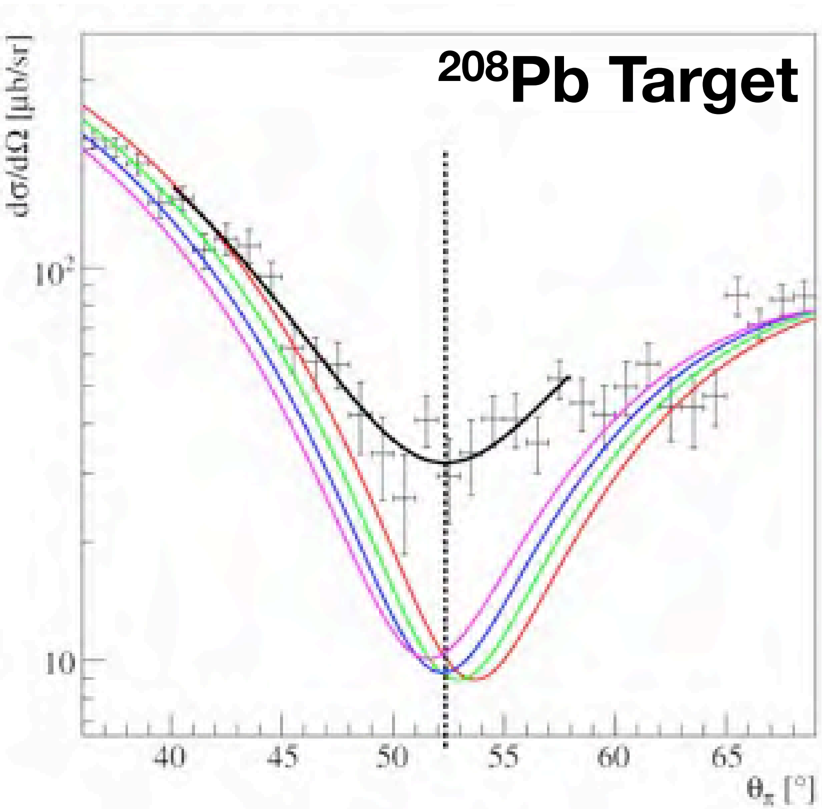
$$\frac{d\sigma}{d\Omega}(\mathbf{PWIA}) = \frac{s}{m_N^2} \times \frac{1}{2}\frac{q_\pi^*}{k^*}\left|F_2\left(E_\gamma^*, \theta_\pi^*\right)\right|^2 \sin^2\left(\theta_\pi^*\right) \times A^2 F^2\left(q\right)$$

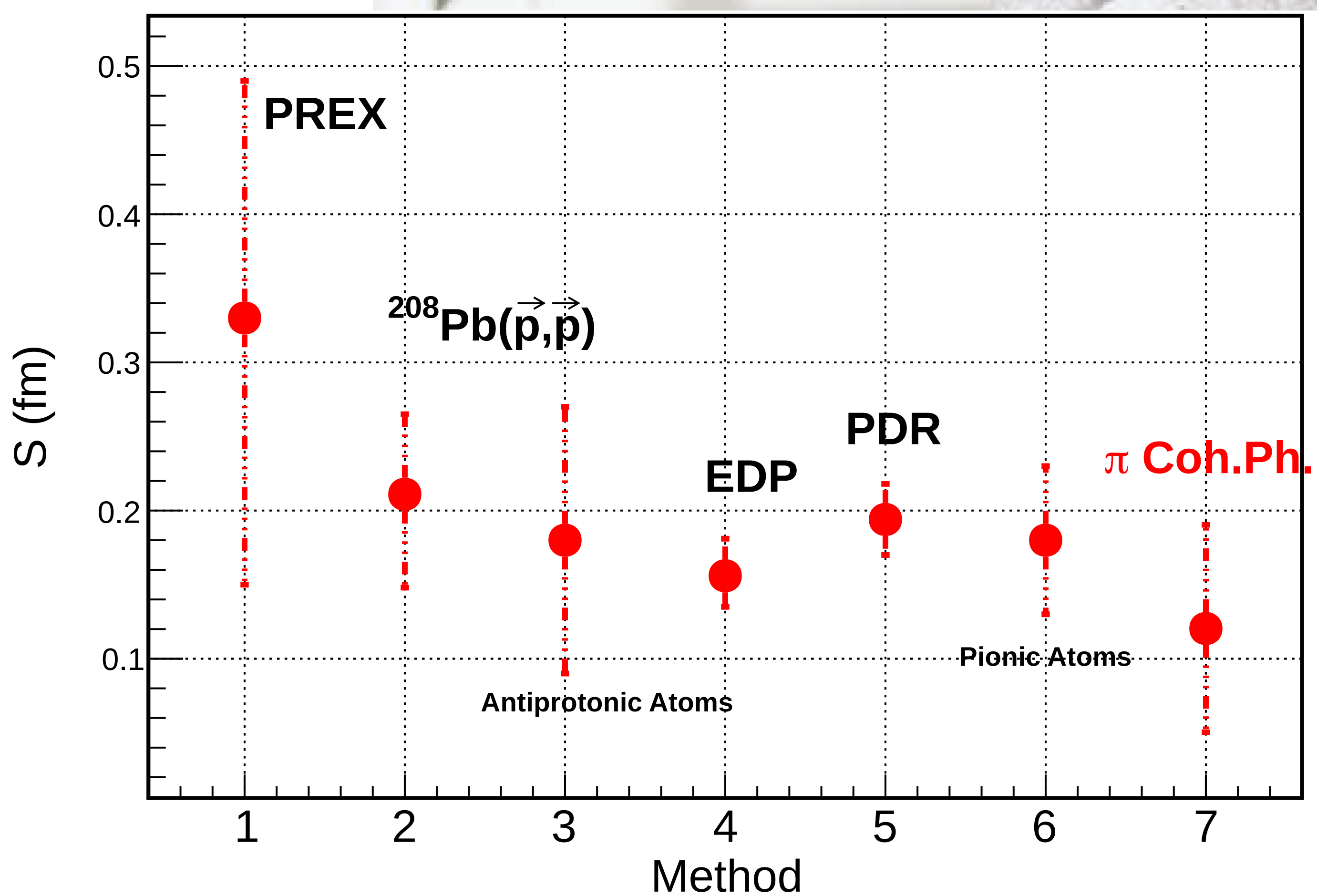
Matter Form Factor → r.m.s. matter radius

^{208}Pb neutron skin from Coherent π^0



D. Watts, et al,EPJ Web of Conferences 37, 01027 (2012)





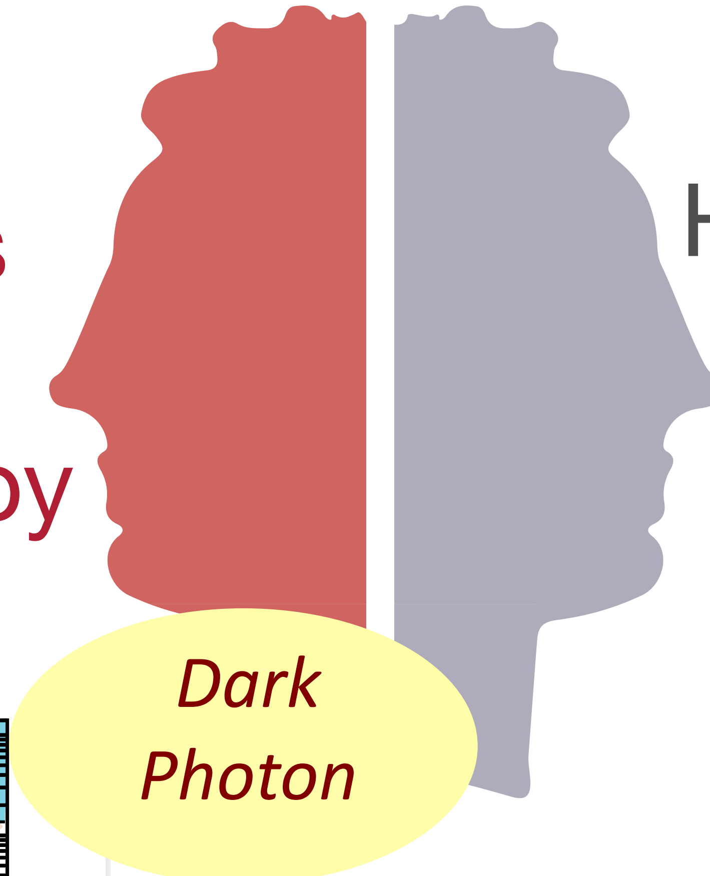
New experimental campaign@A2

(October 2012)

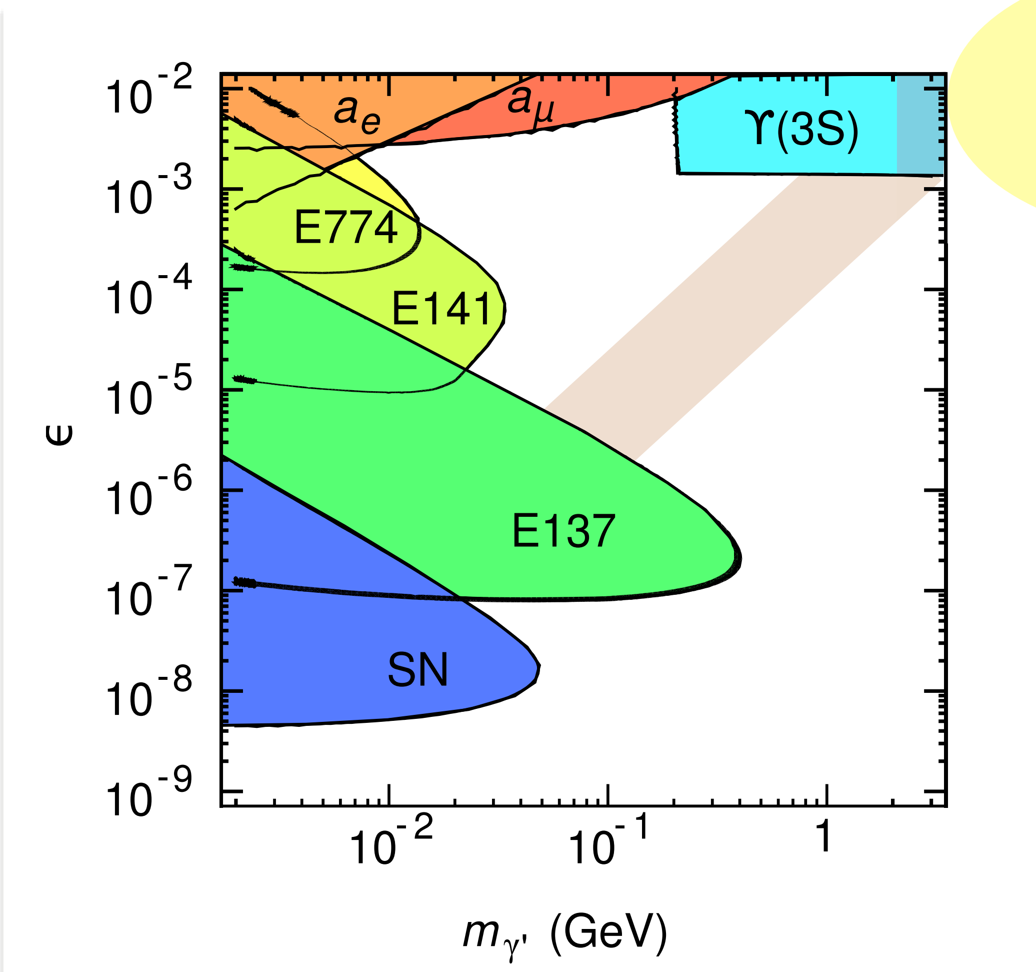
^{116,120,124}Sn, ^{58}Ni, ^{208}Pb

The Low Energy Frontier

Strong Interactions
Hadron Structure
Hadron Spectroscopy



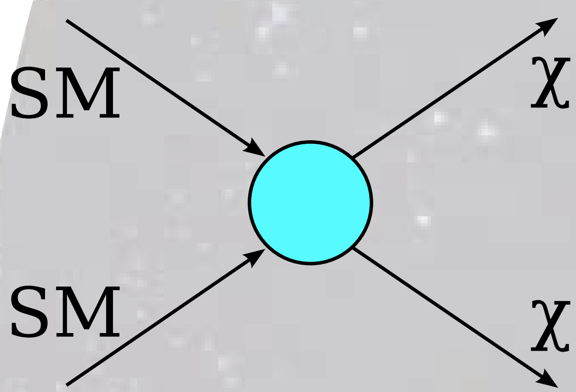
High-Energy Physics
Precision Physics
Atomic Physics
Astrophysics



...the
discovery
(HE, Precision, Astroparticle)
frontier

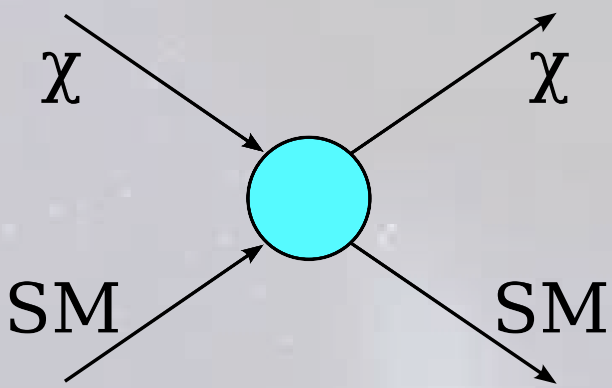
Conventional strategies for DM searches

A bottom up approach: Looking for interacting particles



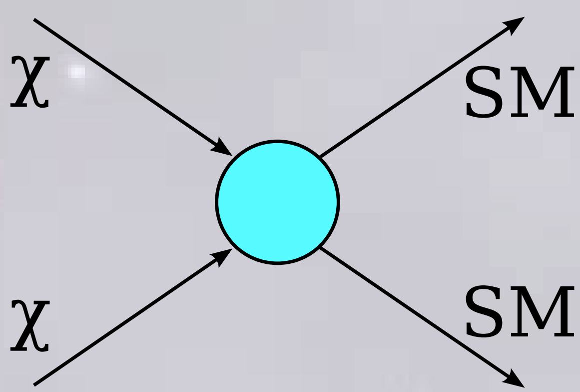
Direct Production:

Tevatron, LHC



Direct Search:

CDMS, DAMA/LIBRA,
XENON, CRESST, LUX,
COUPP, KIMS, ...

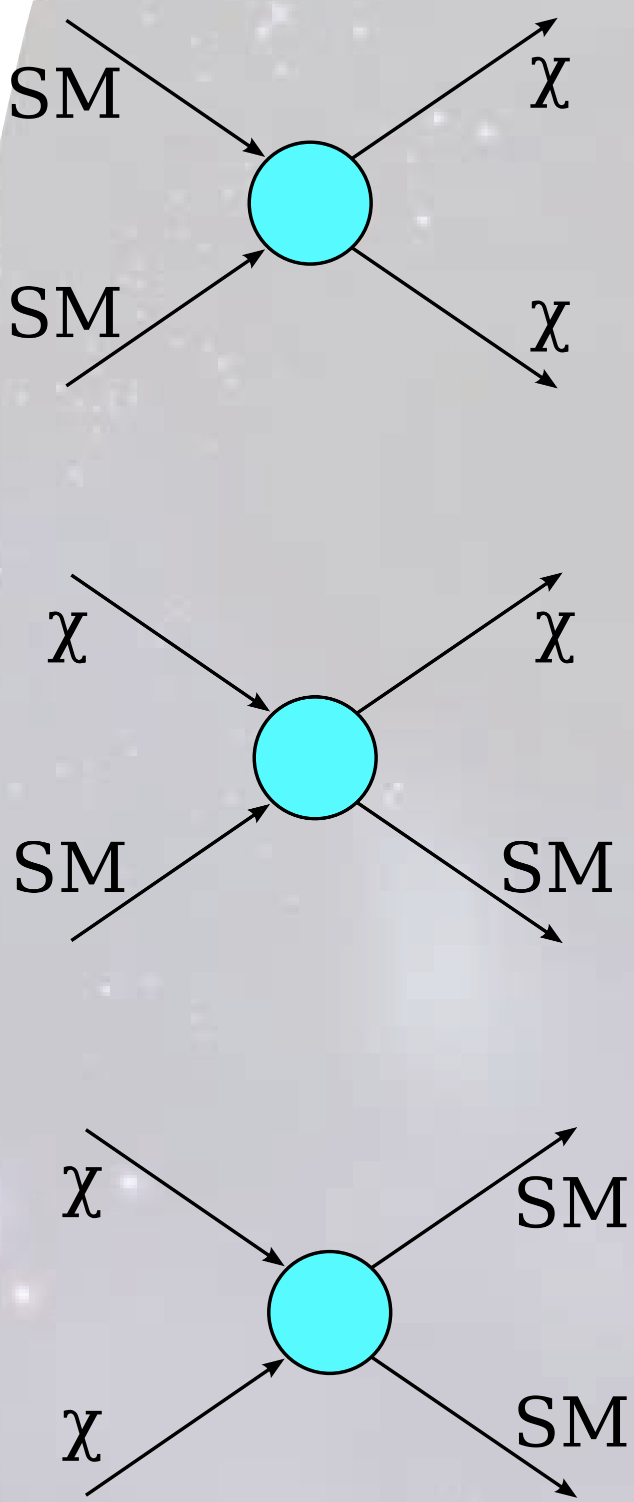


Indirect Search:

PAMELA, Fermi, HESS,
ATIC, WMAP, ...

Conventional strategies for DM searches

A bottom up approach: Looking for interacting particles



Assumptions:

There is dark matter (SUSY or something else)

Dark matter interacts with Standard Model matter (besides gravity)

Dark matter interacts via a “dark force”

Question:

What is the character of this “dark force”?

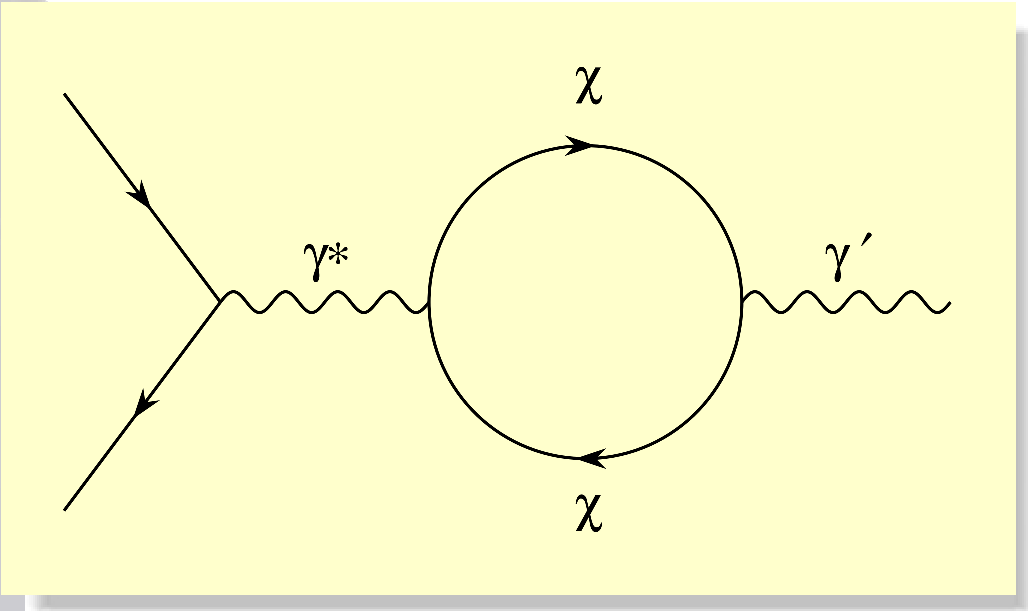
Scalar, pseudo-scalar, vector bosons?

Massive or mass-less? Mass range?

Size of the coupling constant?

A top down motivation

- Extra U(1) gauge bosons ubiquitous in extension of SM
- U(1) gauge bosons may be hidden (no interaction with SM)
- No reason for U(1) boson to be heavy
- Dark matter couples to U(1) bosons γ and γ'



- Mixing parameter ε of γ/γ' mixing
- Boson mass $m_{\gamma'} > 0 \Rightarrow$ decay suppressed, macroscopic lifetime

$\Rightarrow$ Look for χ at high energies OR for γ' at low energies!

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

Probing Dark Forces @ GeV Scale

Dark Photon

Light weakly coupled U(1) gauge boson

N. Arkani-Hamed, et al., Phys. Rev. D 79 (2009) 015014

...it explains ...

terrestrial anomalies
(DAMA, CDMS, XENON)
satellite anomalies
(PAMELA, FERMI)

$(g\text{-}2)_\mu$ anomaly

M. Pospelov, Phys. Rev. D80 (2009) 095002

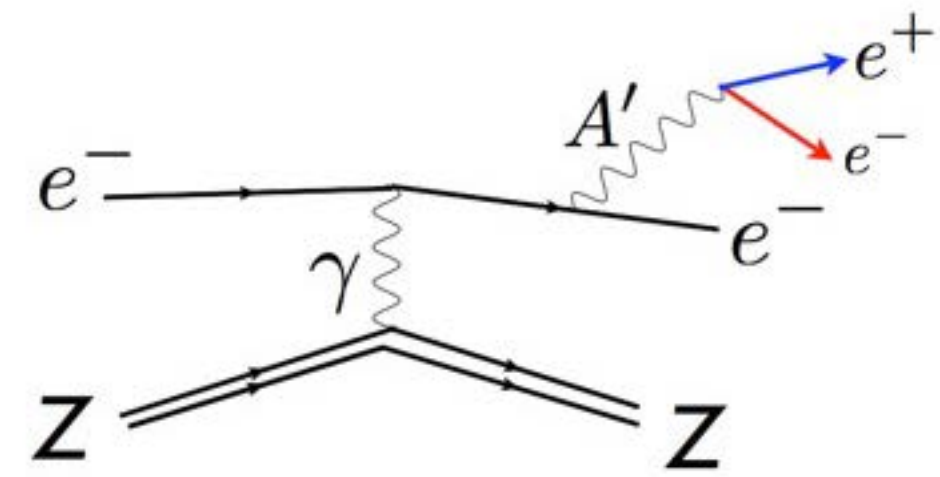
Proton Radius Puzzle

D. Tucker-Smith and I. Yavin Phys. Rev. D83 (2011) 101702

PHYSICAL REVIEW D **80**, 075018 (2009)

New fixed-target experiments to search for dark gauge forces

James D. Bjorken,[1] Rouven Essig,[1] Philip Schuster,[1] and Natalia Toro[2]
[1]*Theory Group, SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA*
[2]*Theory Group, Stanford University, Stanford, California 94305, USA*
(Received 20 July 2009; published 28 October 2009)



➠ World wide effort (CERN, DESY, JLAB, MAMI, all e^+e^- colliders, ...)

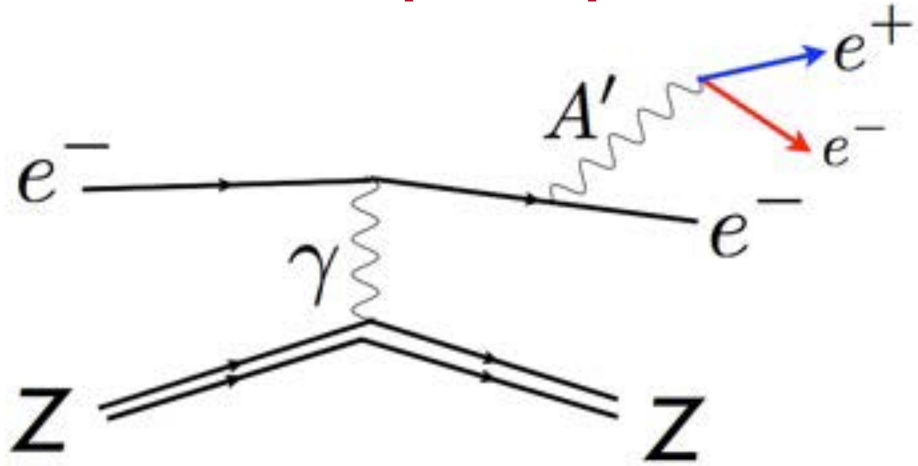
Prediction are testable:

Large cross section in leptons

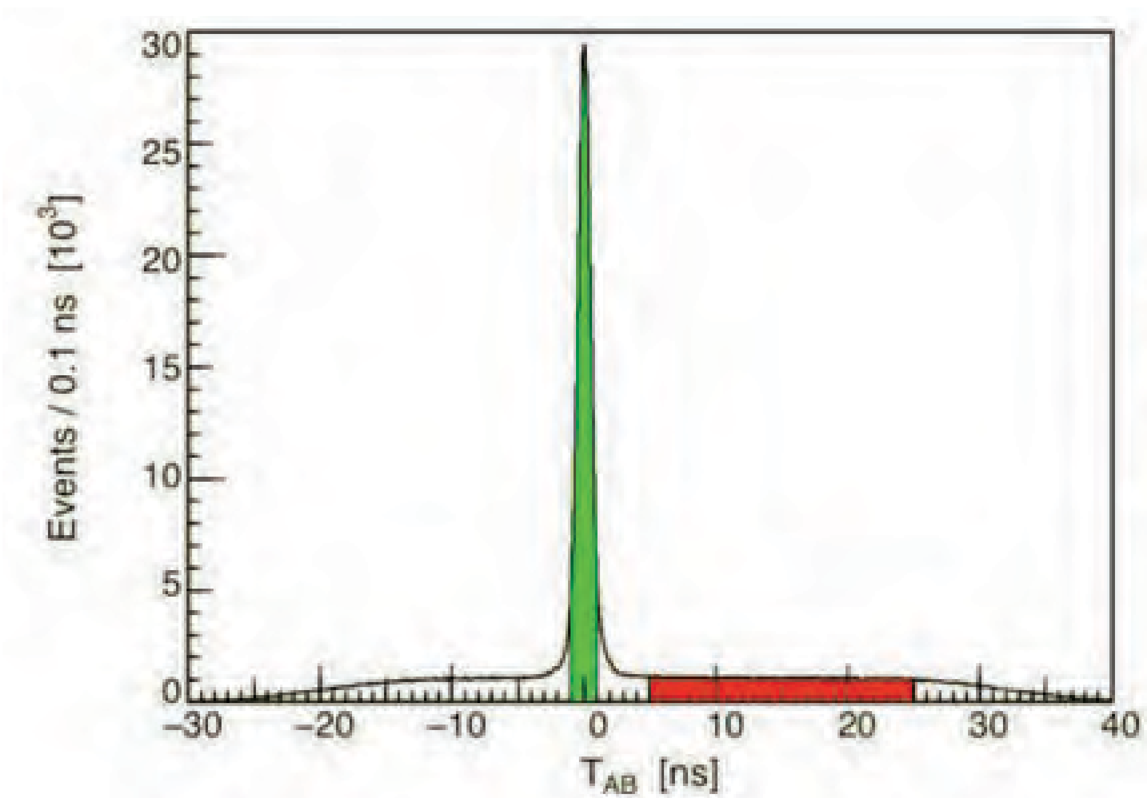
Search for the Dark Photon @ MAMI

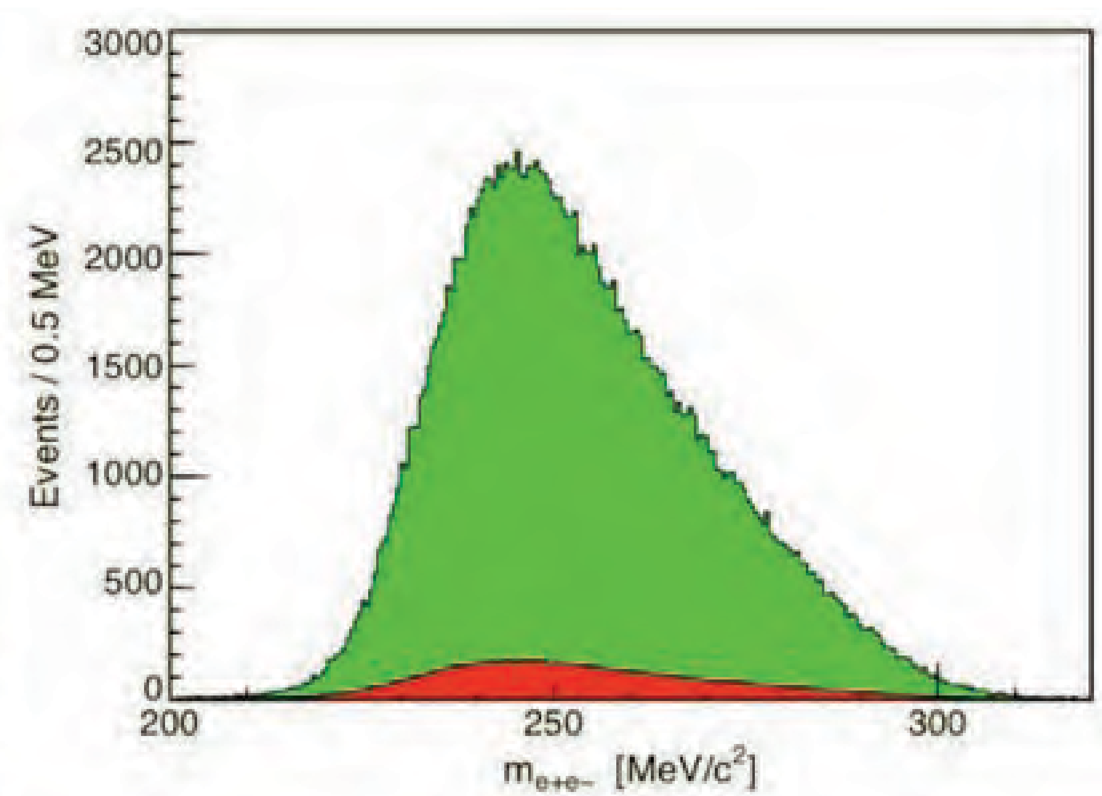
H. Merkel et al., Phys. Rev. Lett. 106 (2011) 251802

Bump Hunt: Quasi-photoproduction off ^{181}Ta target



Beam current: 100μA
Luminosity: $L = 1.7 \cdot 10^{35}$ $(s \cdot cm^2)^{-1}$
Minimal angles for spectrometers
Geometry as symmetric as possible (background reduction)





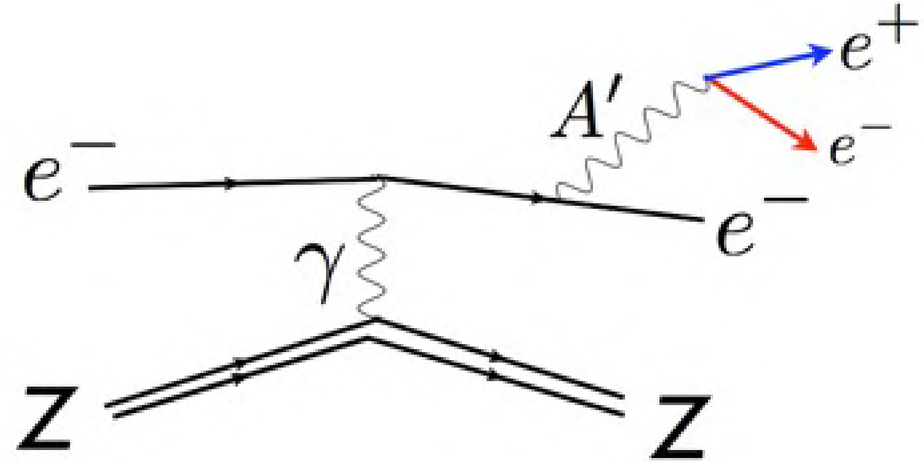
Coincidence time resolution ≈ **1 ns FWHM**
Very small **accidental background** ≈ **5%**
Above background: only coincident e^+e^- pairs!

$\delta m_{e+e-} < 0.5 MeV/c^2$

Search for the Dark Photon @ MAMI

H. Merkel et al., Phys. Rev. Lett. 106 (2011) 251802

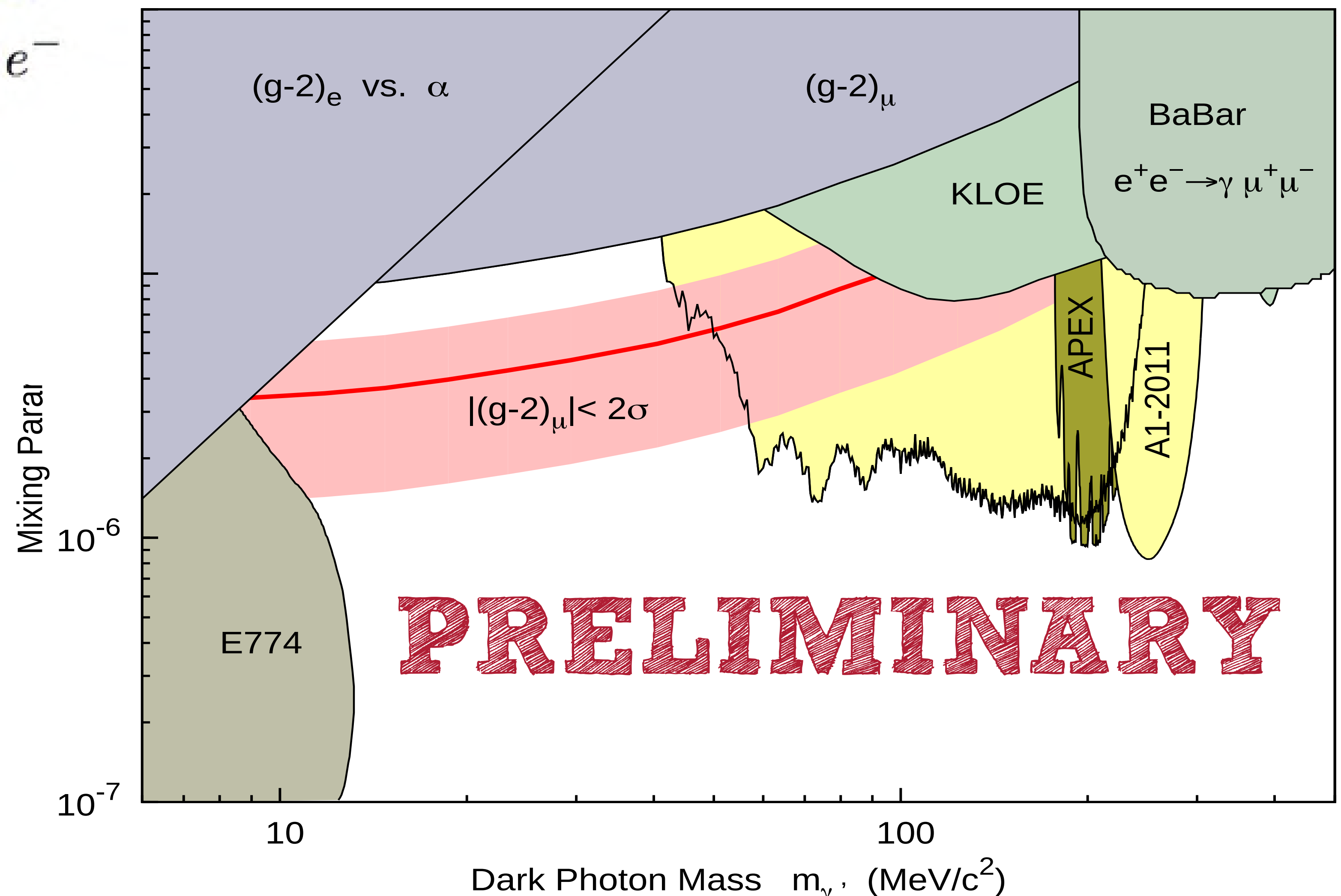
Bump Hunt: Quasi-photoproduction off ^{181}Ta target



➛ **Fight background ....**

... with high intensity ...

... and resolution.



APEX: S. Abrahamyan et al., Phys. Rev. Lett. 107 (2011) 191804
KLOE: F. Archilli et al., Phys. Lett. B. 706 (2012) 251

Feasibility:

Background (within 1%)
First exclusion limits 10^{-3}

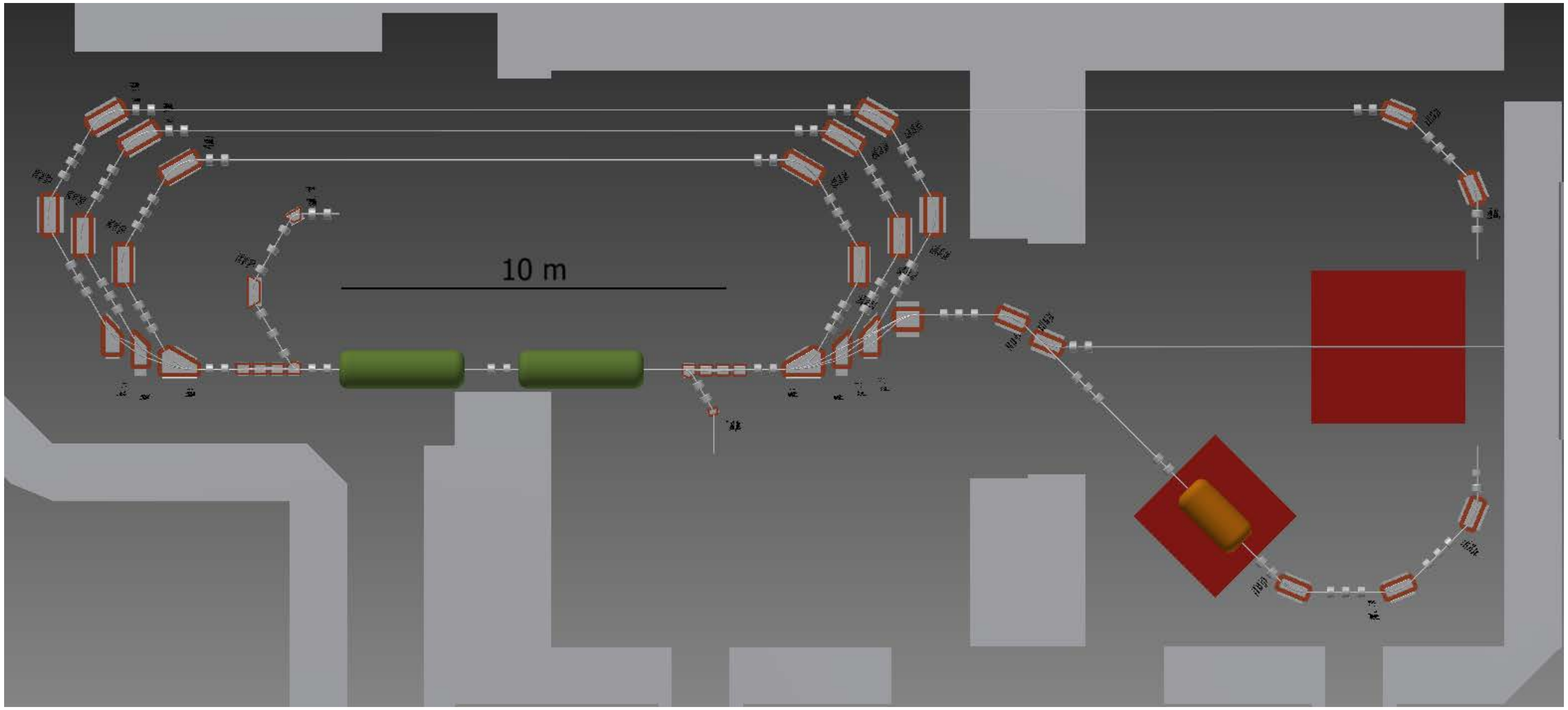
4 days beam time!!

New $\varepsilon/m_{\gamma'}$ scan

Future: Low mass region <50 MeV/c^2 and small dark photon coupling ε^2

... MESA beyond MAMI ...

Mainz Energy recovering Superconducting Accelerator

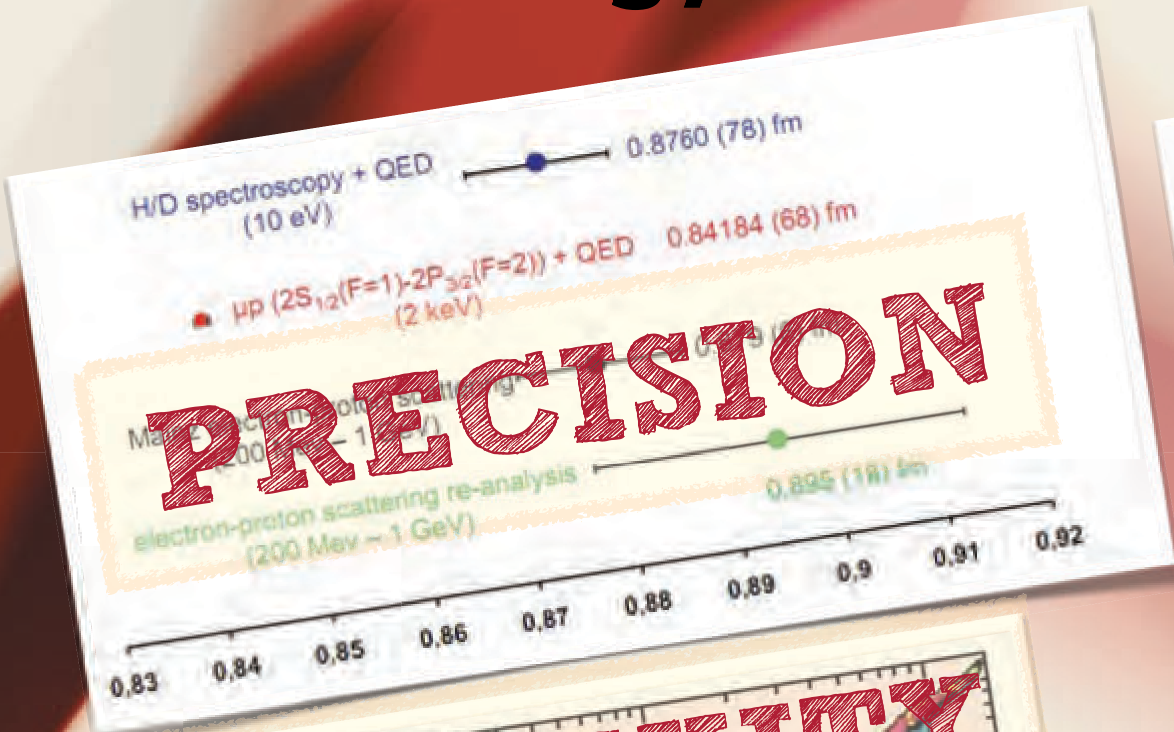


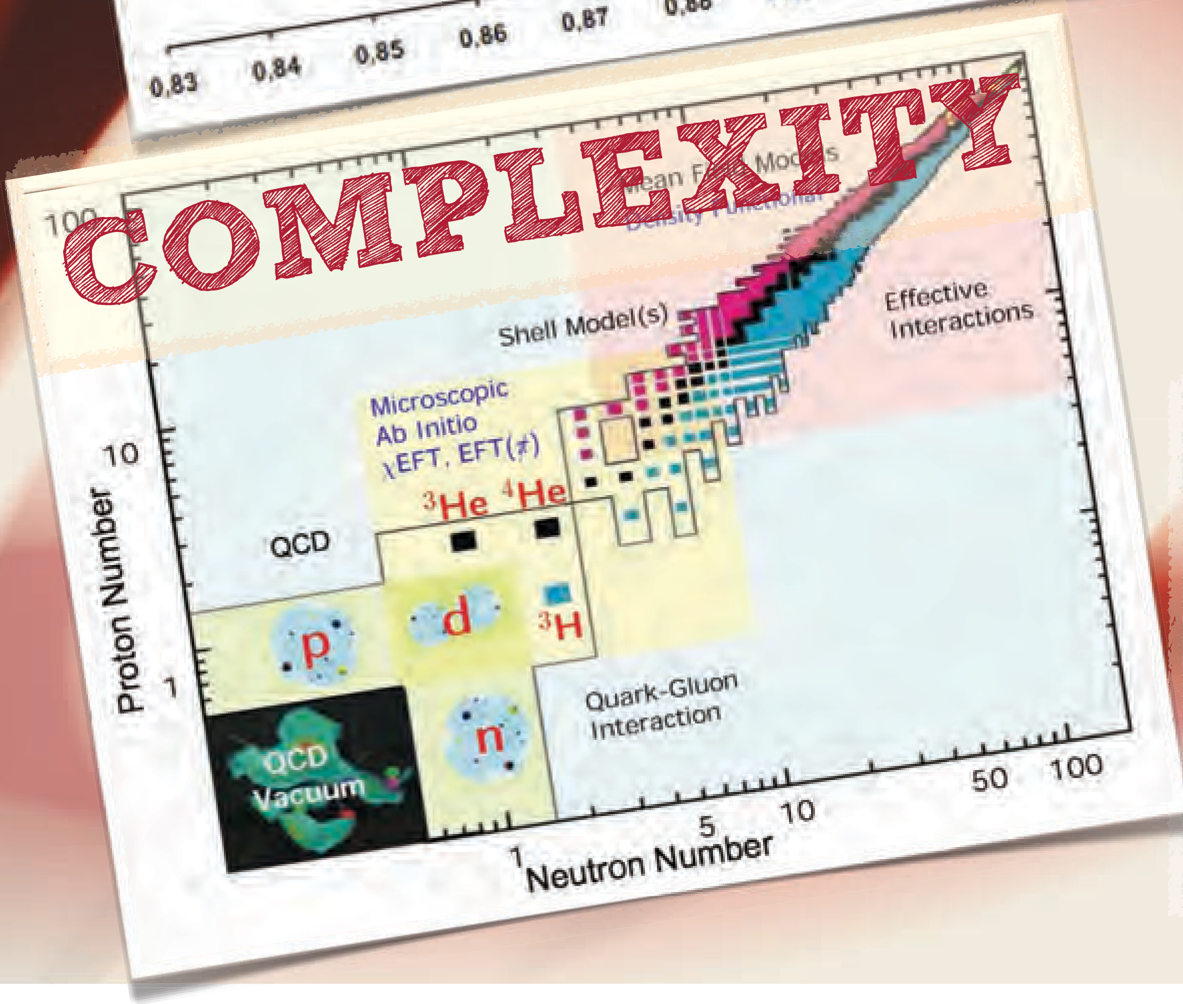
- Superconducting LINAC
- Three recirculation arcs for external beam
  high external current for “next generation” parity violation experiments
- Energy recovery mode (half wave-length recirculation) for *internal target* experiments

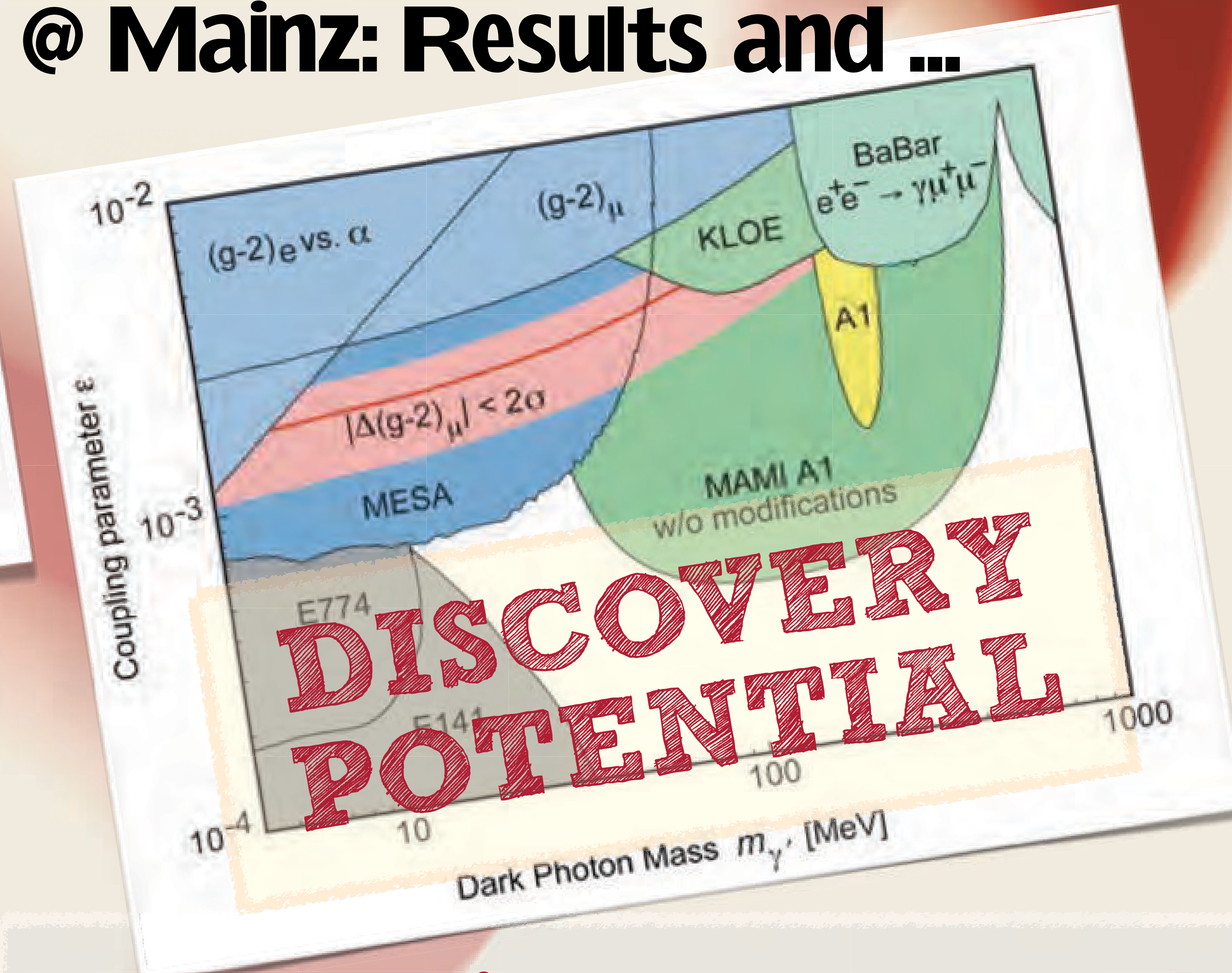
	Current	Energy	Luminosity
External Beam Mode:	150 μA	200 MeV	10^{39} cm^{-2}s^{-1}
Energy Recovery Mode:	10 mA	150 MeV	10^{36} cm^{-2}s^{-1}

Cluster of Excellence Precision Physics, Fundamental Interactions and Structure of Matter
PRISMA

The Low Energy Frontier @ Mainz: Results and ...







...perspective are excellent!

Near future (2014 - 2016) ....

Radius Puzzle: ISR and d-FF
Neutron form factor: new neutron detector
Nucleon polarizabilities with real photons
High resolution pion spectroscopy of light hypernuclei