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Status of Precision Mass Measurements of Light Atomic Nuclei

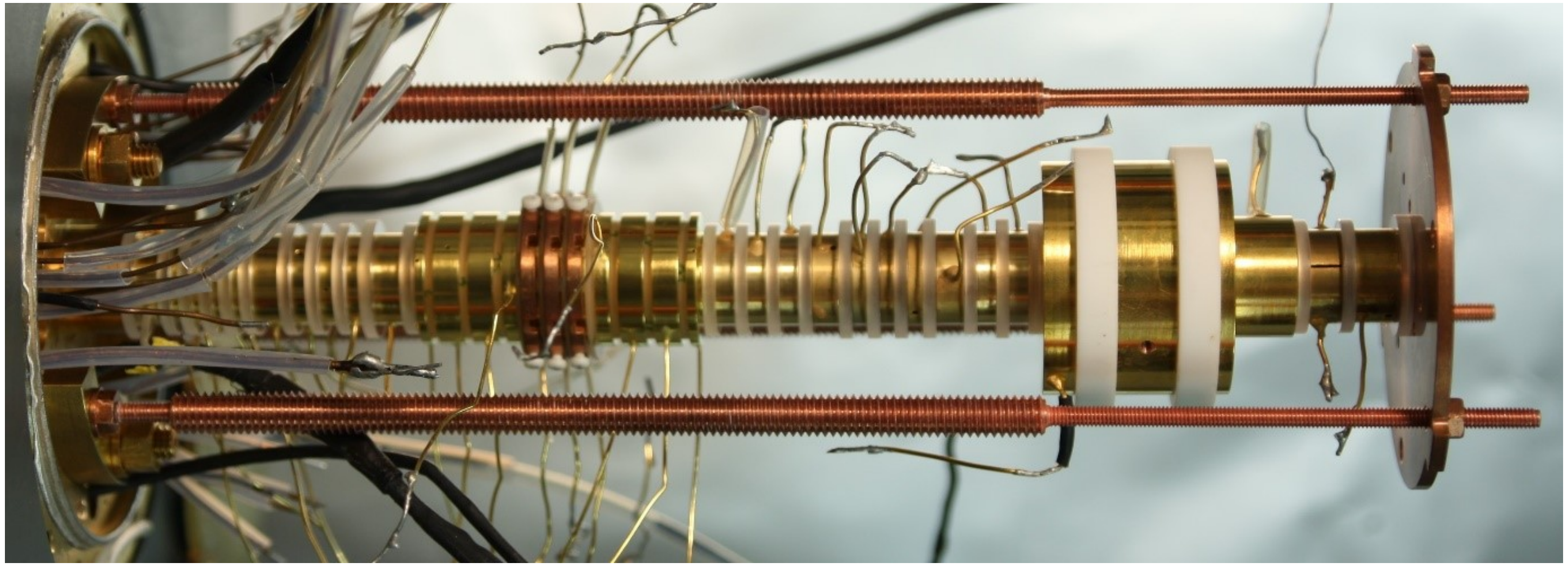
TCFS Workshop, 2022

Sangeetha Sasidharan

LION TRAP

LIONTRAP

- Acronym for **L**ight **ION TRAP** experiment.
- High precision Penning-trap mass spectrometer for light ions
- Experiments with single and stable trapped ions.
  → Reaching 11 digits of precision
- Measure directly in atomic mass units, $u = \frac{1}{12} m(^{12}C)$



Measuring light ions is difficult because of relatively small signals and high relativistic shifts

Motivation for Light Atomic Masses

- m_p and m_n are fundamental properties of the basic building blocks of matter

$$m_{Atom} = Nm_{Neutron} + Z\,m_{Proton} + Z\,m_{Electron} - \frac{B_{Atom} + B_{nucleus}}{c^2}$$

- m_d is the starting point for the determination of the atomic mass of the neutron:

$$m_\mathrm{n} = m_\mathrm{d} - m_\mathrm{p} + S_n/c^2$$
$$S_n/c^2 = 2.388\,170\,08(42) \times 10^{-3}\mathrm{u}$$

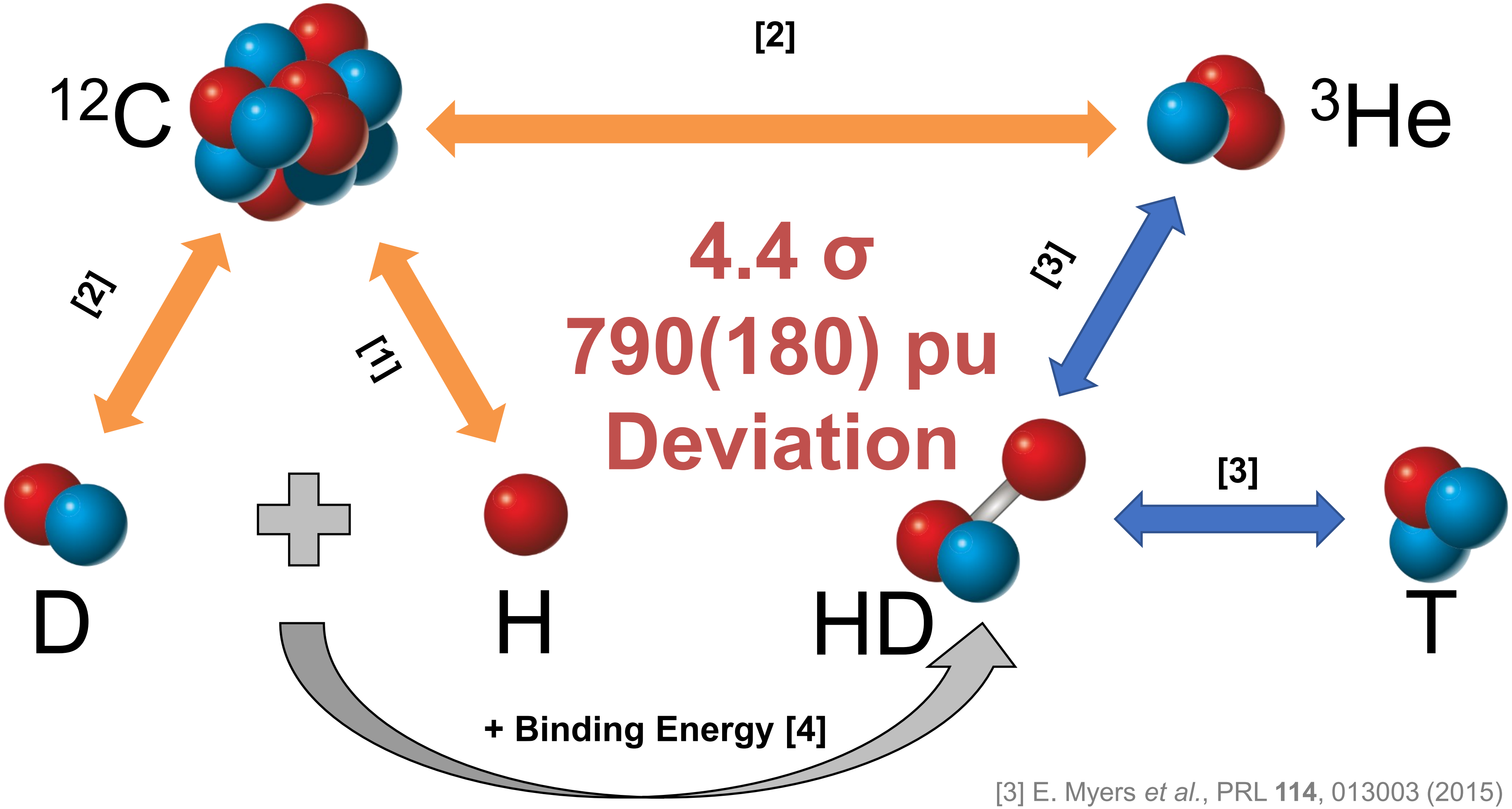
M.S. Dewey et al. Phys. Rev. C73, 044303 (2006)
S. Rau et al. Nature 585, 43–47 (2020)

- **Simple atomic systems**
  - ➢ Hydrogen spectroscopy: $\mu = \frac{m_e m_p}{m_e + m_p}$
  - ➢ Ro-vibrational spectroscopy in HD^+ molecular ions: $R_\infty \left(\frac{m_e}{m_p} + \frac{m_e}{m_d}\right)$

Puzzle of Light Atomic Masses

R.S. Van Dyck *et al.* @ UW

E. Myers *et al.* @ FSU



4.4 σ
790(180) pu
Deviation

+ Binding Energy [4]

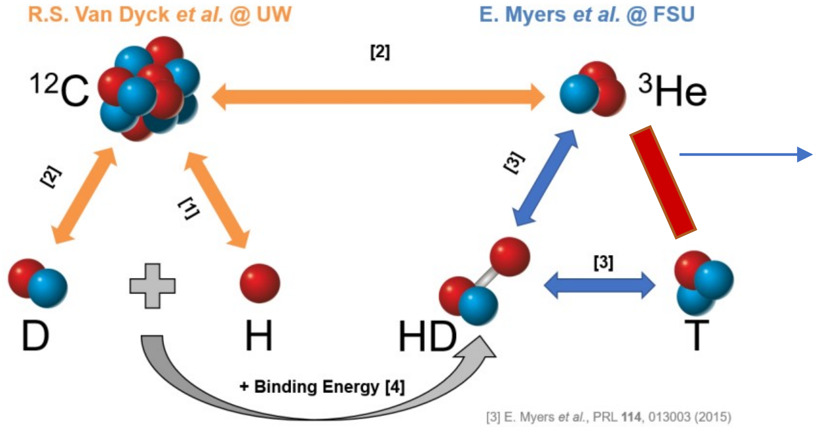
[1] R. S. Van Dyck Jr. *et al.*, AIP Conf. Proc. **457**, 101 (1999)

[2] S. L. Zafonte *et al.*, Metrologia **52**, 280 (2015)

[3] E. Myers *et al.*, PRL **114**, 013003 (2015)

[4] Yan *et al.*, PRA **67**, 062504 (2003)

Motivation for Light Atomic Masses



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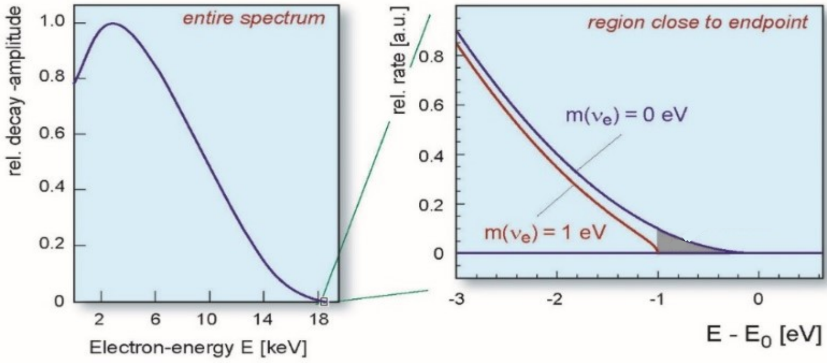
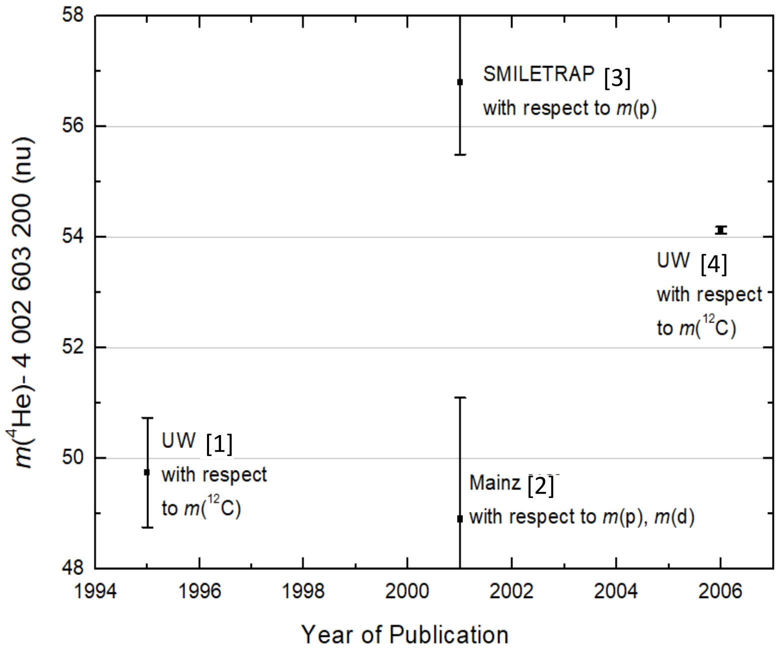


From: http://www.katrin.kit.edu



Light ion mass puzzle : discrepancies in high-precision measurements from different mass-spectrometers

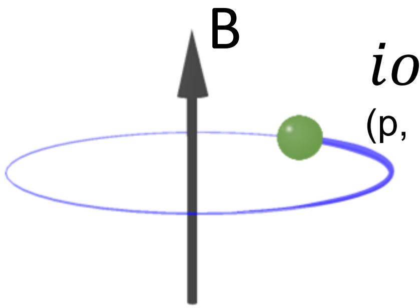
- $\Delta M = m(^{3}\mathrm{He}) - m(\mathrm{T})$ used in neutrino physics → KATRIN
- δ(ΔM)< 20meV $[{}^{\delta m}/_{m} \sim 5\ \mathrm{ppt}\ ]$

- Mass of α-particle, important in fundamental physics
- Disagreement in the past
- Support the extraction of electron's atomic mass

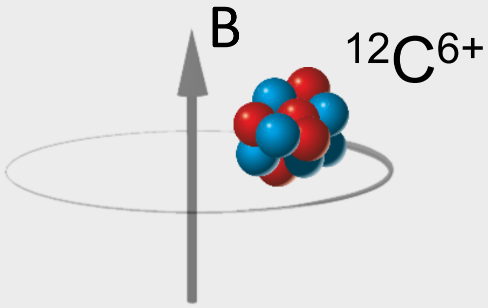
[1] R.S. Van Dyck Jr *et al.*, Phys. Scripta A T59, **134** (1995)
[2] Brunner. S *et al.*, Eur. Phys. J. D **15**, 181 (2001)
[3] T. Fritioff *et al.*, Eur. Phys. J. D **15**, 141-143 (2001)
[4] R. S. Van Dyck *et al.*, Int. J. Mass Spectrom., **251**,(2006)

Where and How Do We Measure?

Direct measurement of the atomic mass of the ion :



ion of interest
(p, d, HD$^+$, ^{3}He^{2+}, ^{4}He^{2+}...)



$$\nu_c(ion\ of\ interest) = \frac{1}{2\pi}\frac{q_{ion\ of\ interest}}{m_{ion\ of\ interest}}B$$

$$\nu_c(^{12}C^{6+}) = \frac{1}{2\pi}\frac{6\,e}{m(^{12}C^{6+})}B$$

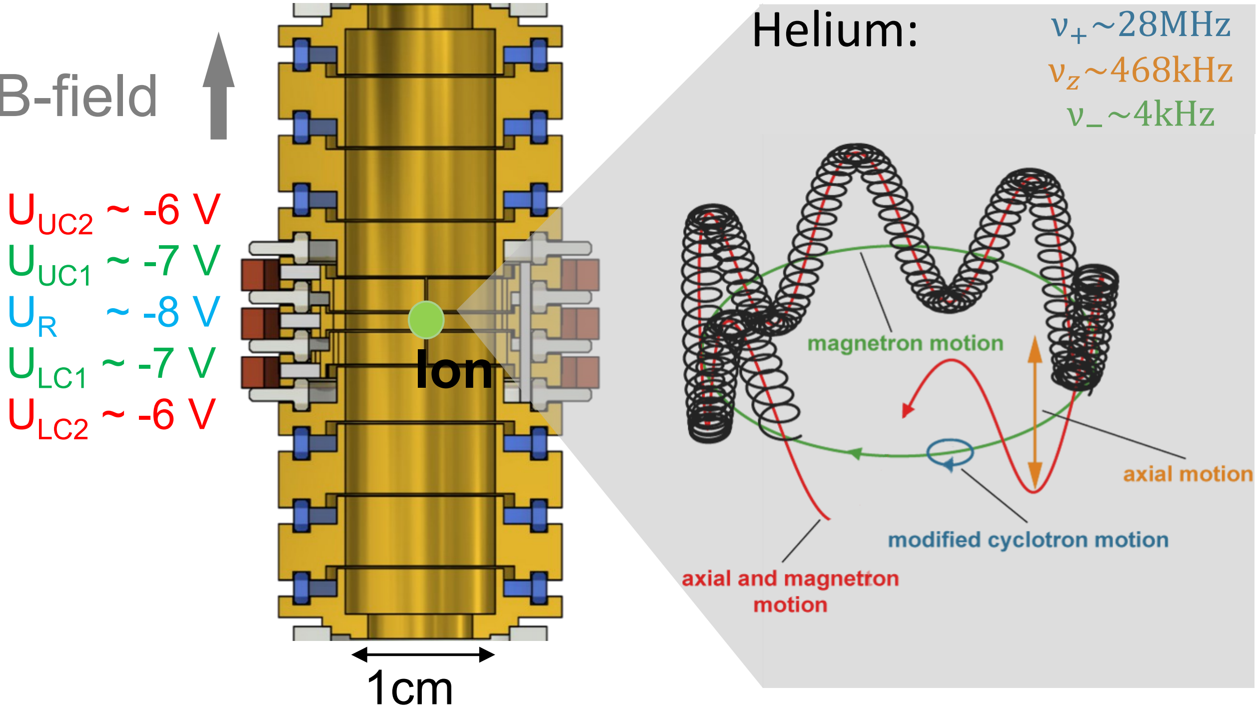
$$m_{ion\ of\ interest} = \frac{q_{ion\ of\ interest}}{6}\frac{\nu_c(^{12}C^{6+})}{\nu_c(ion\ of\ interest)}m(^{12}C^{6+})$$

$$R \equiv \frac{\nu_c(^{12}C^{6+})}{\nu_c(ion\ of\ interest)}$$

$\delta m/m(^{12}C^{6+})<8\cdot10^{-14}$

Measurement Technique

Measurement of cyclotron frequency, $\nu_C = \frac{1}{2\pi}\frac{q}{m}B$, where q is the charge, m is the mass in a homogeneous magnetic field (B).



- Ion stored in:
  - homogenous static magnetic field
  - electrostatic quadrupole potential for trapping

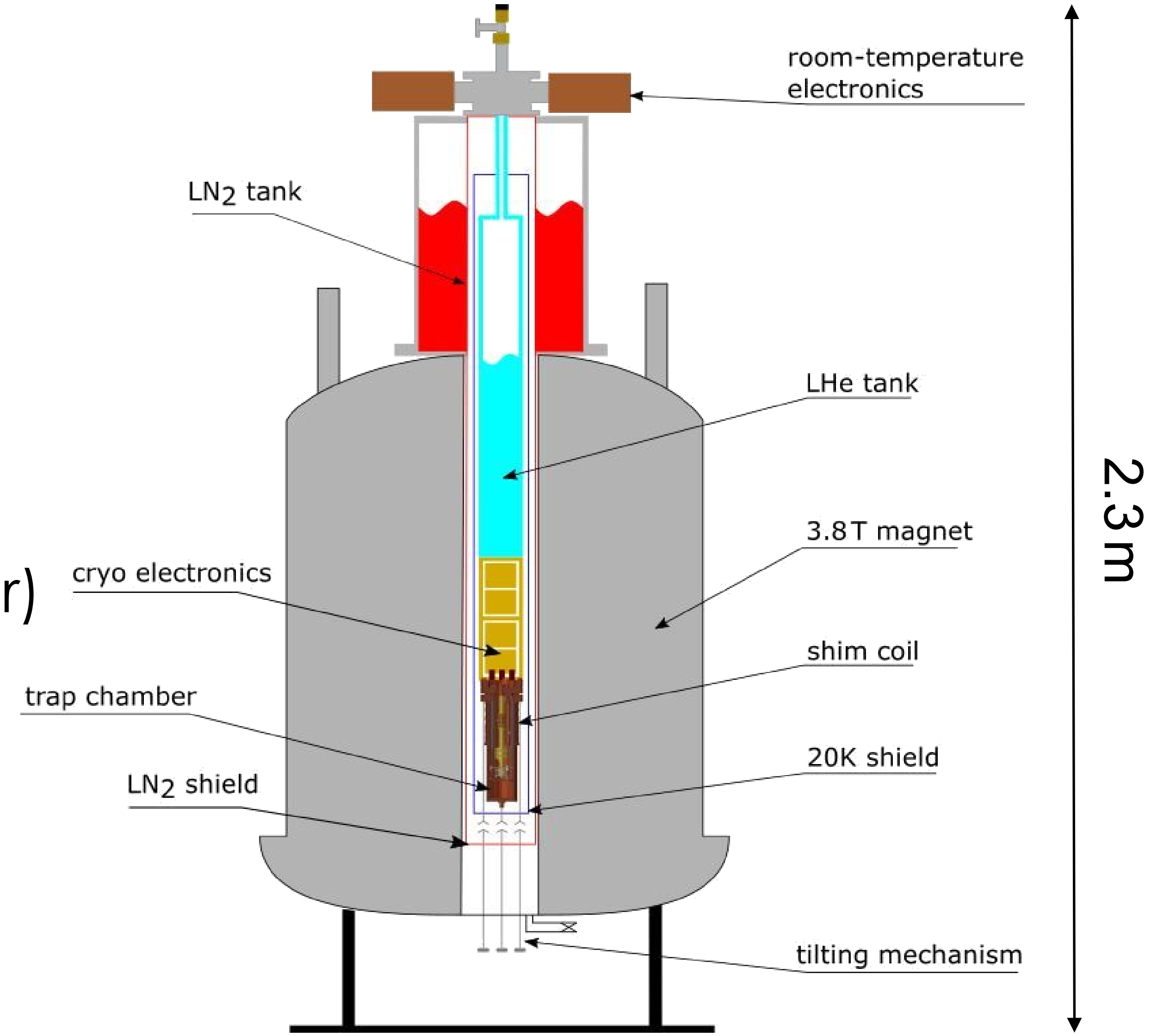
cyclotron frequency via invariance theorem [1]:

$$\nu_c = \sqrt{{\nu_+}^2 + {\nu_z}^2 + {\nu_-}^2} \qquad \nu_c \approx \nu_+ \gg \nu_z \gg \nu_-$$

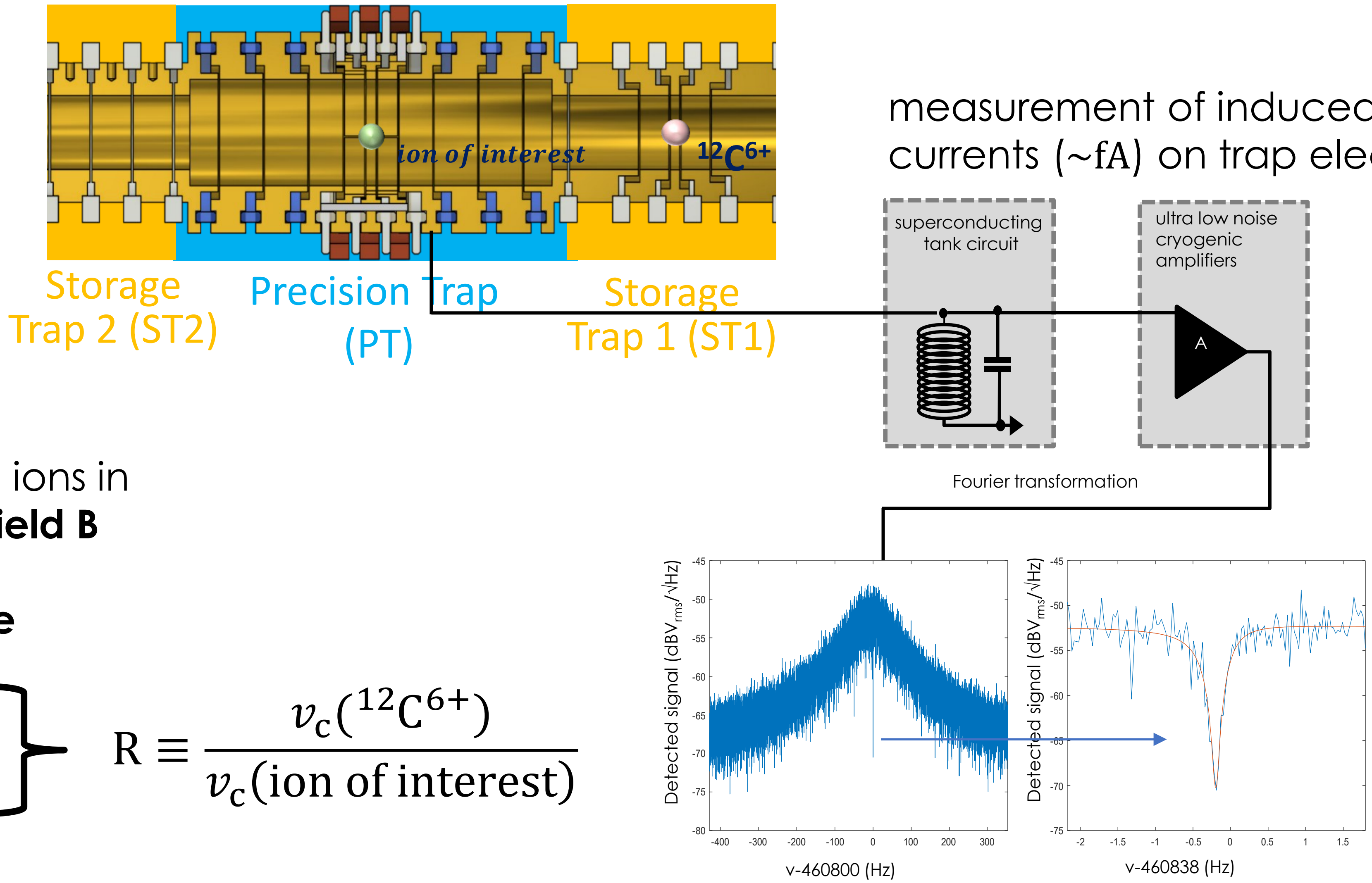
[1] L.S. Brown & G. Gabrielse, PRA 25, 2423 (1982)

Setup

- Offline experiment
- Liquid helium temperature
- Hermetically sealed trap chamber, Ultra-high vacuum (Pressure < 10^{-16} mbar)
- In situ ion creation using miniature EBIT/S



Measurement Procedure



measurement of induced image currents (~fA) on trap electrodes

- Compare cyclotron frequencies ν_c of two ions in the **same magnetic field B**
  → **same place**
  → **(almost) same time**

$$\left.\begin{array}{l}\text{(I)}\quad \nu_{\mathrm{c}}(\text{ion of interest}) \text{ in PT}\\ \text{(II)}\ \nu_{\mathrm{c}}(^{12}\mathrm{C}^{6+}) \text{ in PT}\end{array}\right\} \quad R \equiv \frac{\nu_{\mathrm{c}}(^{12}\mathrm{C}^{6+})}{\nu_{\mathrm{c}}(\text{ion of interest})}$$

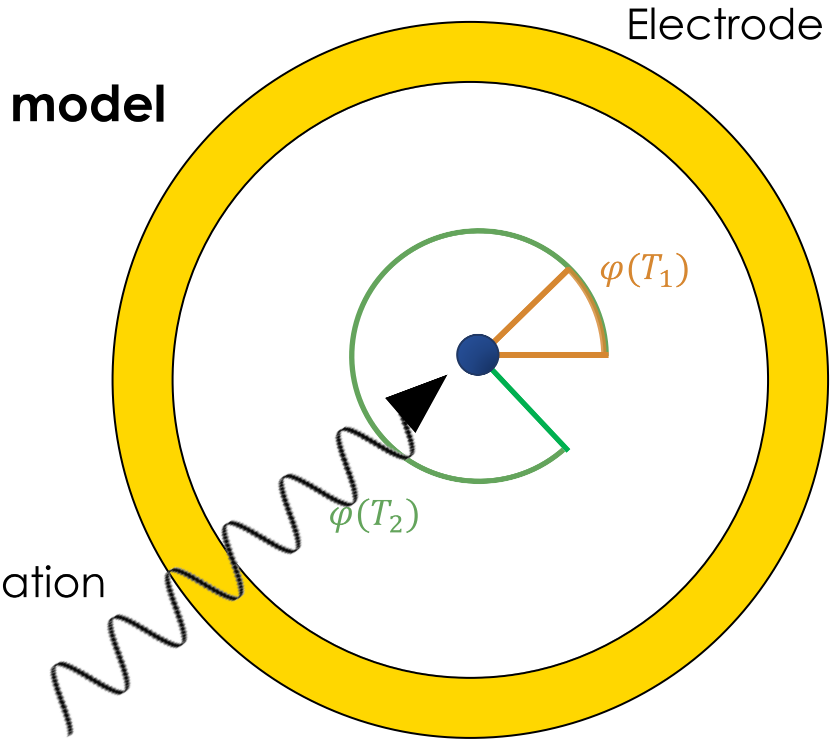
Eg Dip signal of a single deuteron

Phase-Sensitive Detection Method

- phase-sensitive measurement scheme
- phase of ν_+ mapped to ν_z by a pulse with $\nu = \nu_+ + \nu_z$
  $\rightarrow$ amplifies both modes
- the Fourier spectrum provides phase of the ion

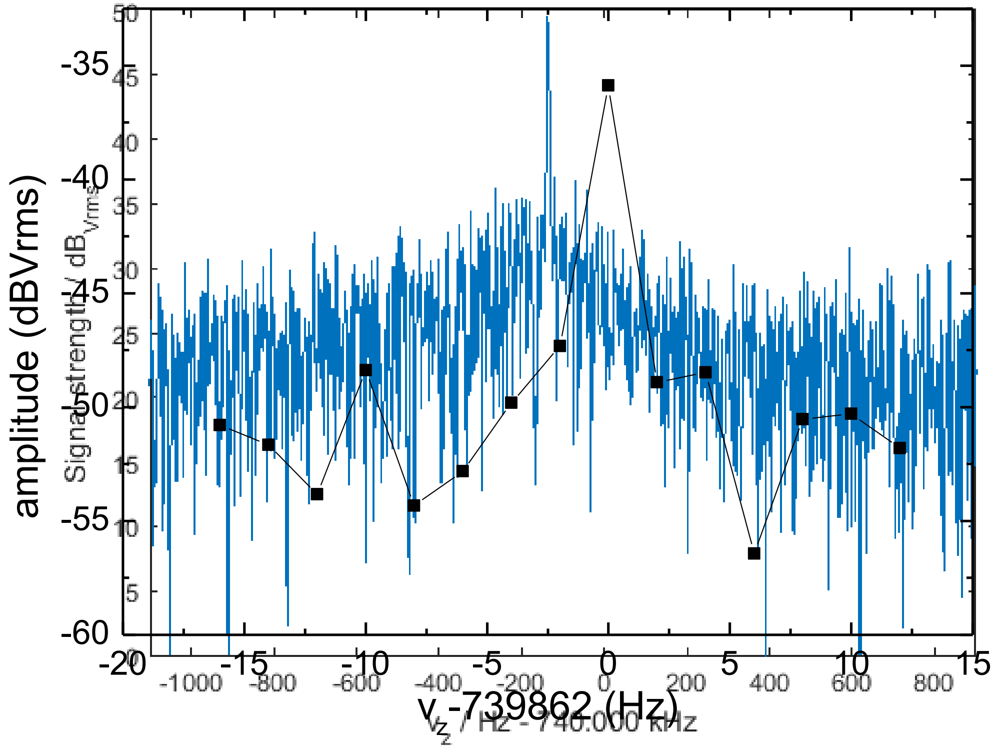
$$\nu = \frac{\varphi(T_2) - \varphi(T_1)}{360° \cdot T_{\mathrm{evol}}}$$

Advantages:
-No lineshape model needed
BUT: at (small) excited radius



$$T_{\mathrm{evol}} = T_2 - T_1$$

Peak-signal of a single proton



Previous Measurements

- Proton mass with $\frac{\delta m_\mathrm{p}}{m_\mathrm{p}} = 3.2 \cdot 10^{-11}$

$$m_\mathrm{p} = 1.007\,276\,466\,583\,\underset{\text{(stat)}}{(15)}\underset{\text{(syst)}}{(29)}\ \mathrm{u}$$

- Deuteron mass with $\frac{\delta m_\mathrm{d}}{m_\mathrm{d}} = 8.5 \cdot 10^{-12}$

$$m_\mathrm{d} = 2.013\,553\,212\,535\,\underset{\text{(stat)}}{(11)}\underset{\text{(syst)}}{(13)}\ \mathrm{u}$$

Systematics

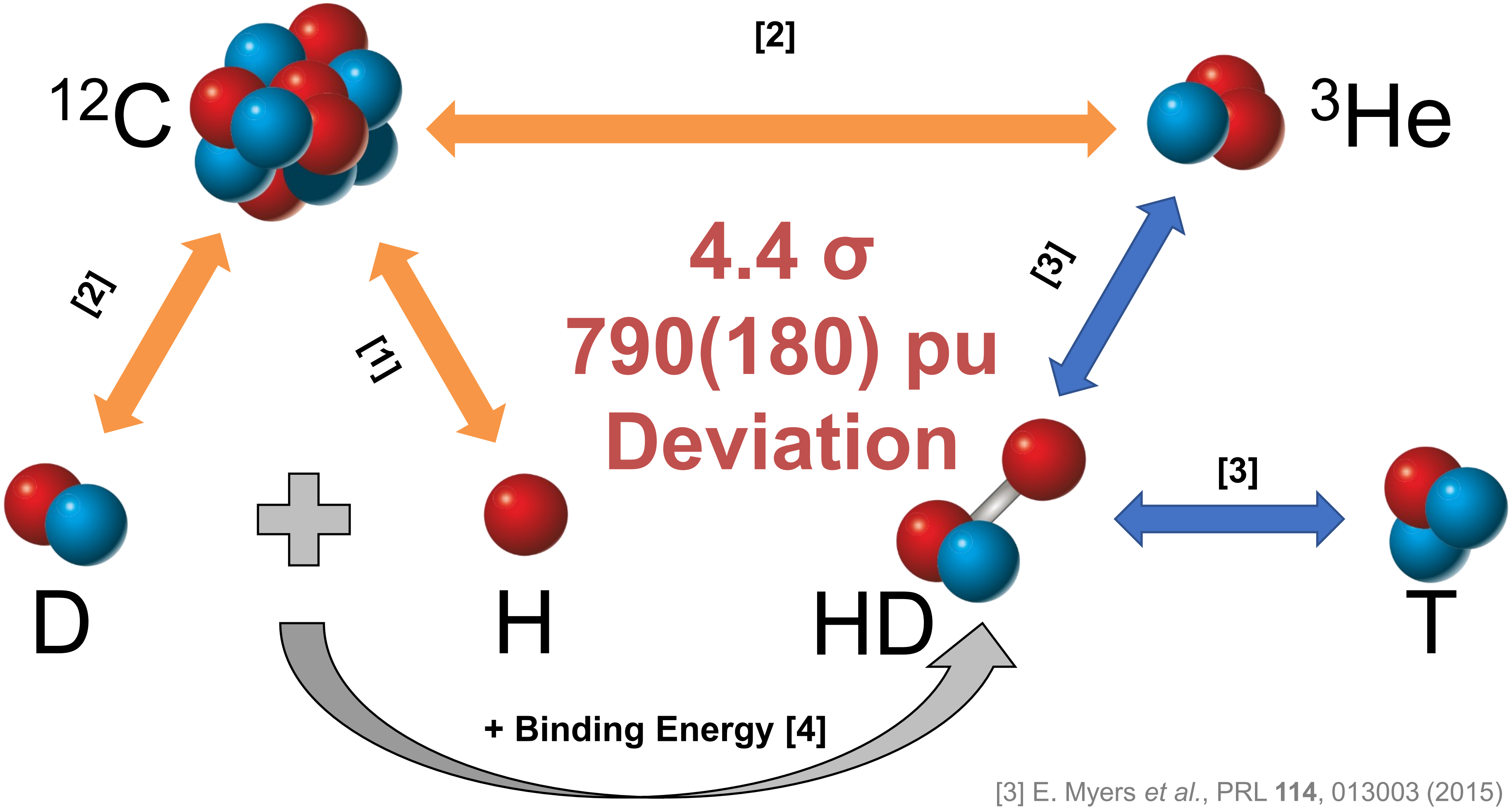
Effect	Rel. Unc. (10^{-12}) Proton Mass	Rel. Unc. (10^{-12}) Deuteron Mass
Residual Magnetostatic Inhomogeneity	**27.5**	**0.6**
Special Relativity	**7.1**	**1.2**
Image Charge	**4.6**	**4.1**
Dip Lineshape	**3**	**4.7**
Quadratic Sum	**≈29**	**≈6.5**

→ Superconducting B_2-shim coil

Puzzle of Light Atomic Masses

R.S. Van Dyck *et al.* @ UW

E. Myers *et al.* @ FSU



4.4 σ
790(180) pu
Deviation

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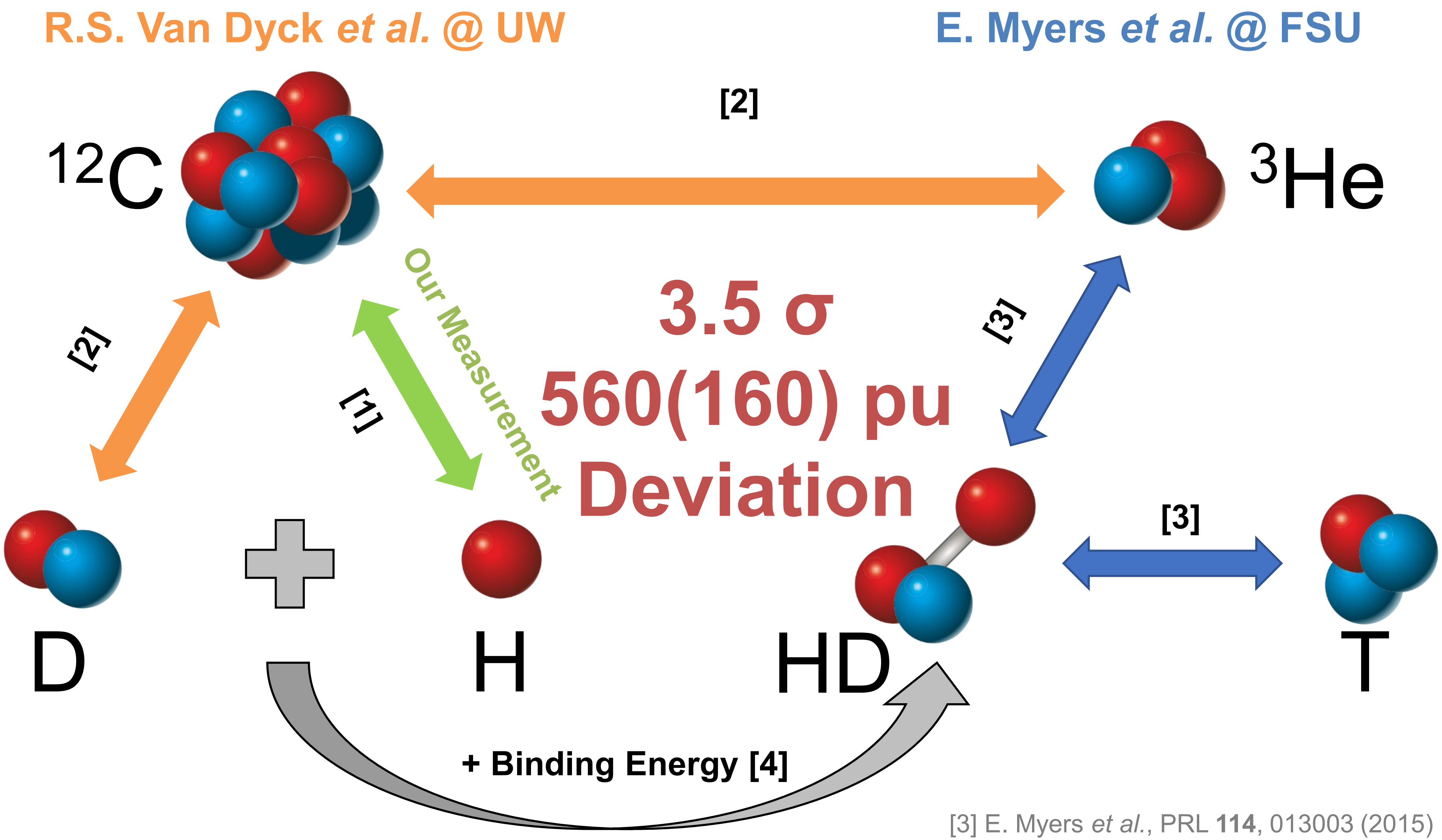
[4] Yan *et al.*, PRA **67**, 062504 (2003)

Puzzle of Light Atomic Masses



R.S. Van Dyck *et al.* @ UW

E. Myers *et al.* @ FSU

^{12}C

^{3}He

[2]

[2]

[1]

Our Measurement

[3]

[3]

3.5 σ

560(160) pu

Deviation

D

H

HD

T

+ Binding Energy [4]

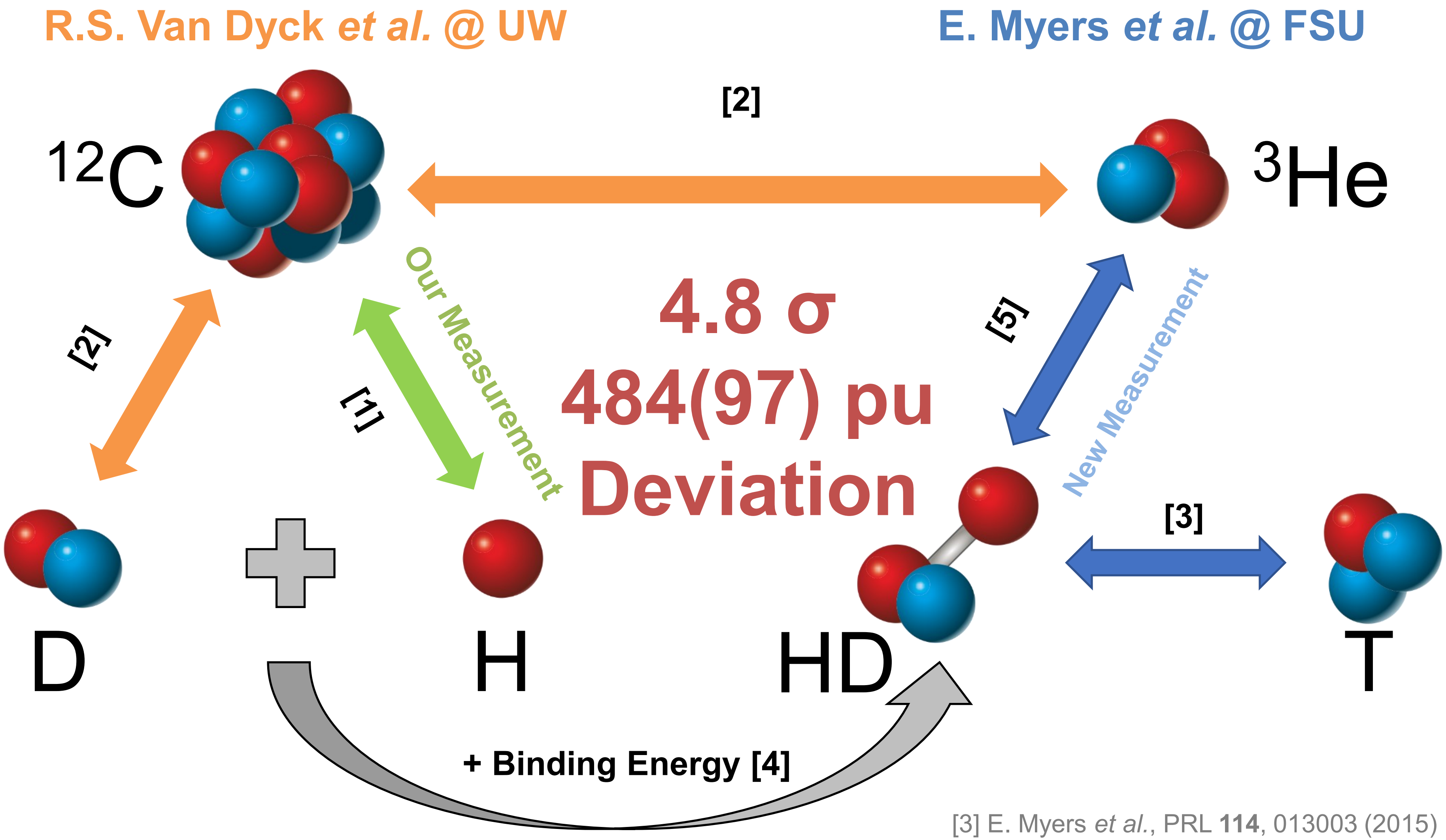
[1] F. Heiße *et al.*, PRL **119**, 033001 (2017)

[2] S. L. Zafonte *et al.*, Metrologia **52**, 280 (2015)

[3] E. Myers *et al.*, PRL **114**, 013003 (2015)

[4] Yan *et al.*, PRA **67**, 062504 (2003)

Puzzle of Light Atomic Masses



R.S. Van Dyck *et al.* @ UW

E. Myers *et al.* @ FSU

[2]

^{12}C

^{3}He

[2]

[1]

Our Measurement

4.8 σ

484(97) pu

Deviation

[5]

New Measurement

[3]

D

H

HD

T

+ Binding Energy [4]

[1] F. Heiße *et al.*, PRL **119**, 033001 (2017)

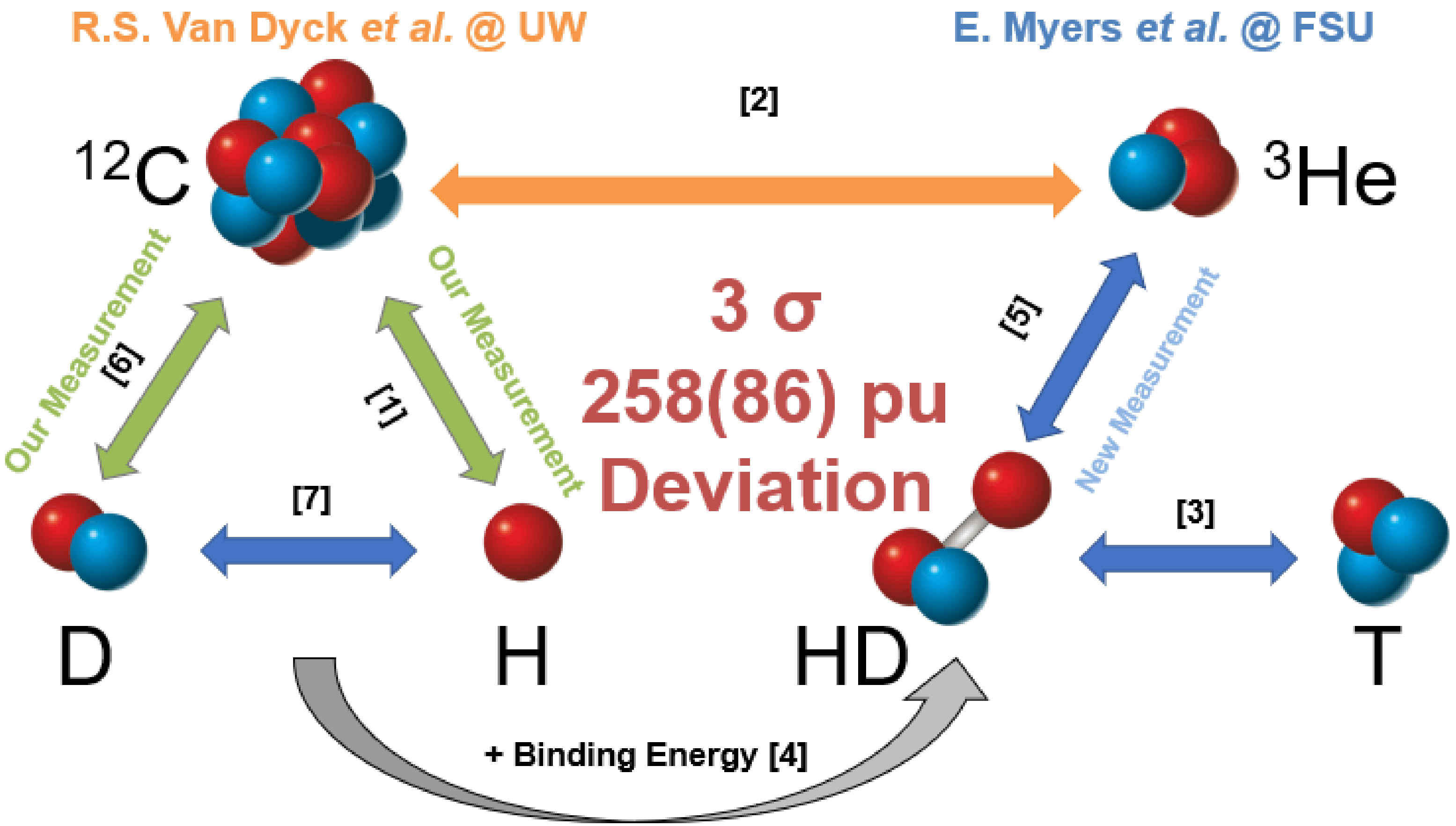
[2] S. L. Zafonte *et al.*, Metrologia **52**, 280 (2015)

[3] E. Myers *et al.*, PRL **114**, 013003 (2015)

[4] Korobov *et al.*, PRL. 118, 233001 (2017)

[5] S. Hamzeloui *et al*, PRA **96**, 060501 (2017)

Light Ion Mass Puzzle



🟧 UW
🟦 FSU
🟩 MPIK

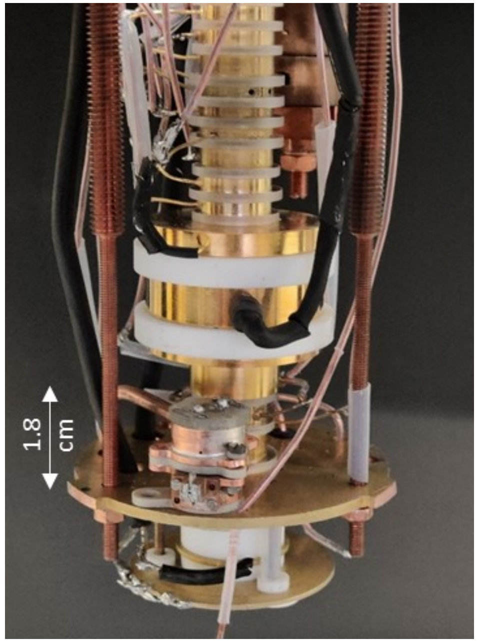
- An inconsistency in the values of light masses from different world-leading experiments
- Measurements performed by our group: **proton**[3], **deuteron** and **HD$^+$**
- Compare with deuteron-to-proton mass ratio reported by the FSU [7]:

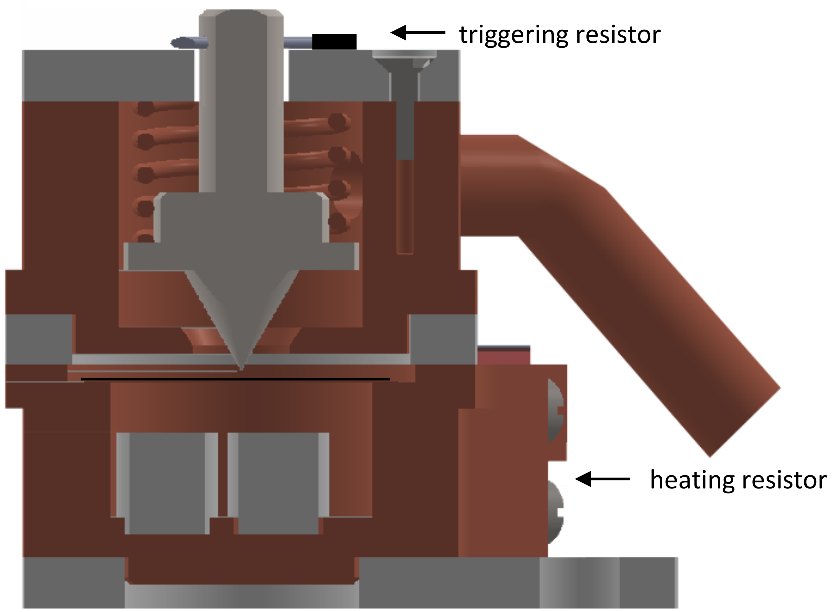
$$\frac{m_d}{m_p}(\text{FSU}) - \frac{m_d}{m_p}(\text{MPIK}) = 46(73) \times 10^{-12}\ \text{u}$$

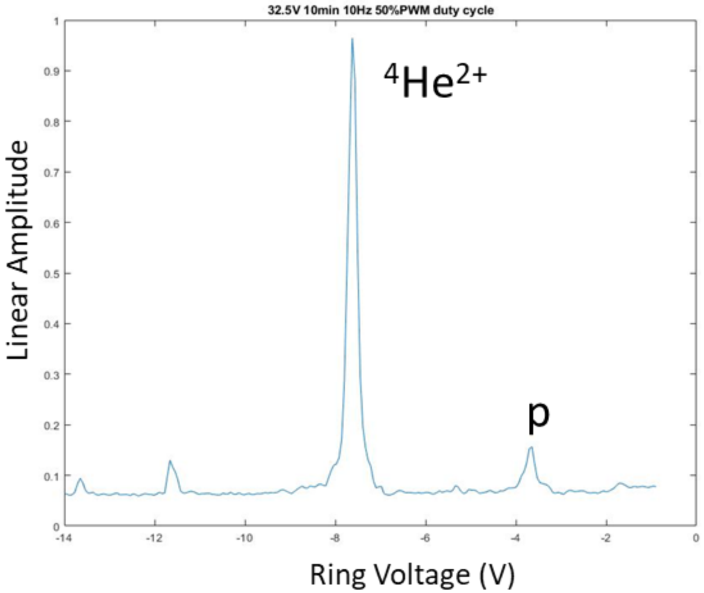
- **Remaining discrepancy**: $258(86)\text{pu}$, $\boldsymbol{3\sigma}$→ motivation for ^{3}He mass measurement

[1] F. Heiße *et al.*, PRL **119**, 033001 (2017)
[2] S. L. Zafonte *et al.*, Metrologia **52**, 280 (2015)
[3] E. Myers *et al.*, PRL **114**, 013003 (2015)
[4] V. Korobov *et al.*, PRL. 118, 233001 (2017)
[5] S. Hamzeloui *et al*, PRA **96**, 060501 (2017)
[6] S. Rau *et al., Nature* **585,** 43–47 (2020)
[7] D. J. Fink *et al.*, PRL **124**, 013001 (2020)

Source for $^{3}\mathrm{He}$ / $^{4}\mathrm{He}$





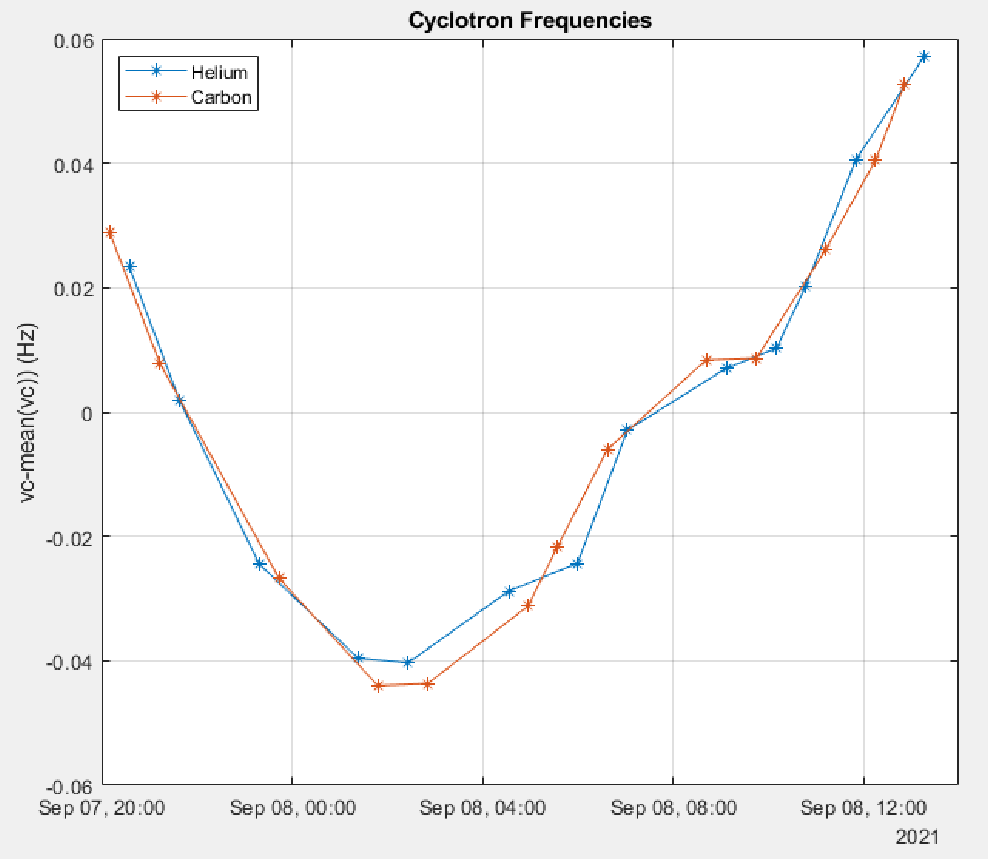


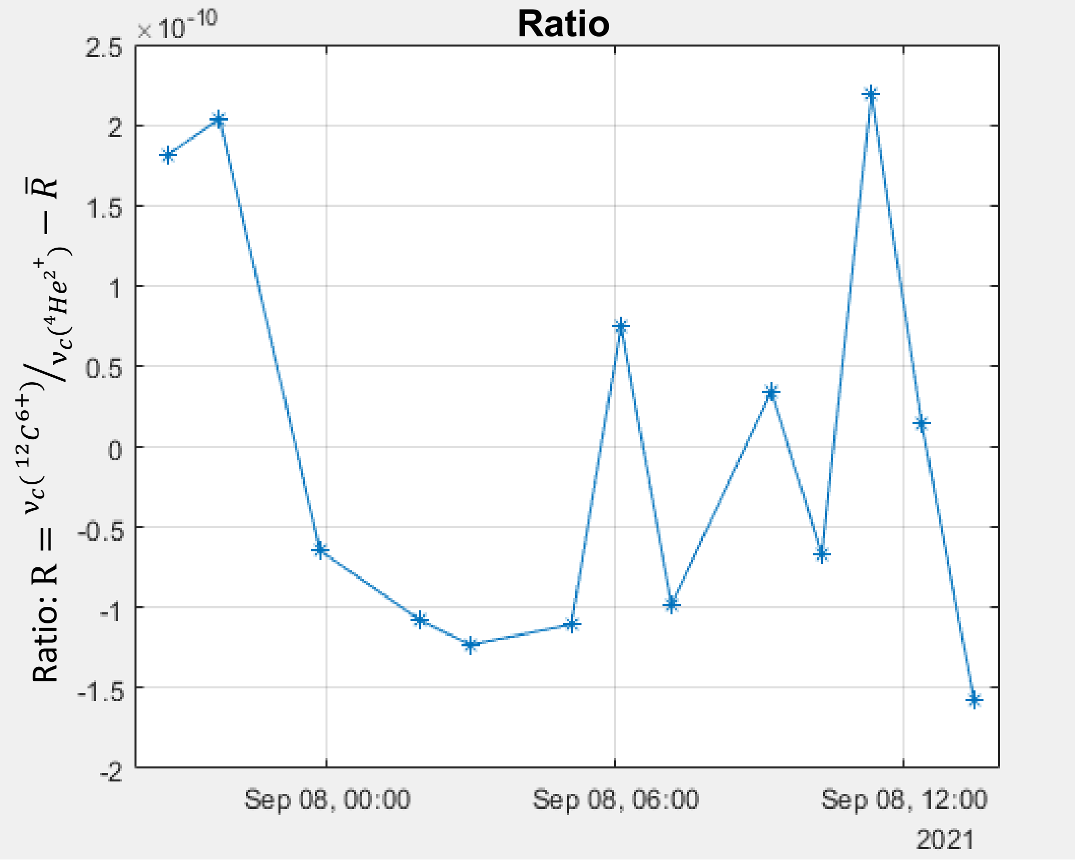
Mass spectrum after cleaning

- In-situ ion production method.
- Weak bonding capability of He.
- Activated charcoal as an adsorption agent, He adsorbed at 4K.

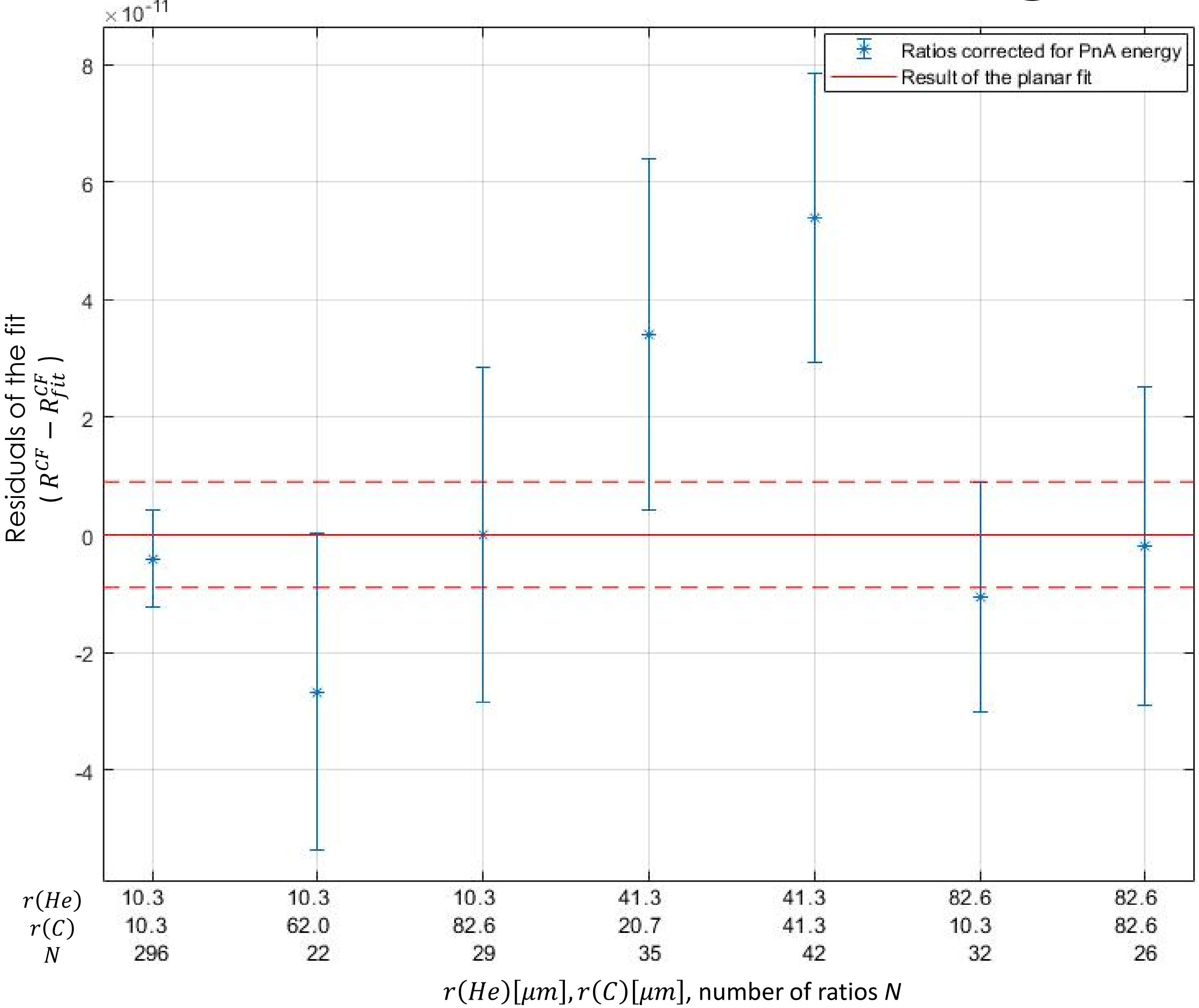
Preliminary Results

example run from 07.09.2021 6 p.m. to 08.09.2021 1 p.m.





Treatment of energy dependent shifts



Apply a global planar fit

$$R_i = R_0 + a \times E_i({}^4He^{2+}) + b \times E_i({}^{12}C^{6+}) ,$$

where: i is the run number and R_0, a and b are fit parameters, E is the excitation energy

Vary excitation energy in a range between $10\mu m$ to $80\mu m$

$$\delta R_0 / R_0 \approx 9 \times 10^{-12}$$

Estimated Error Budget Helium-4

Preliminary result !

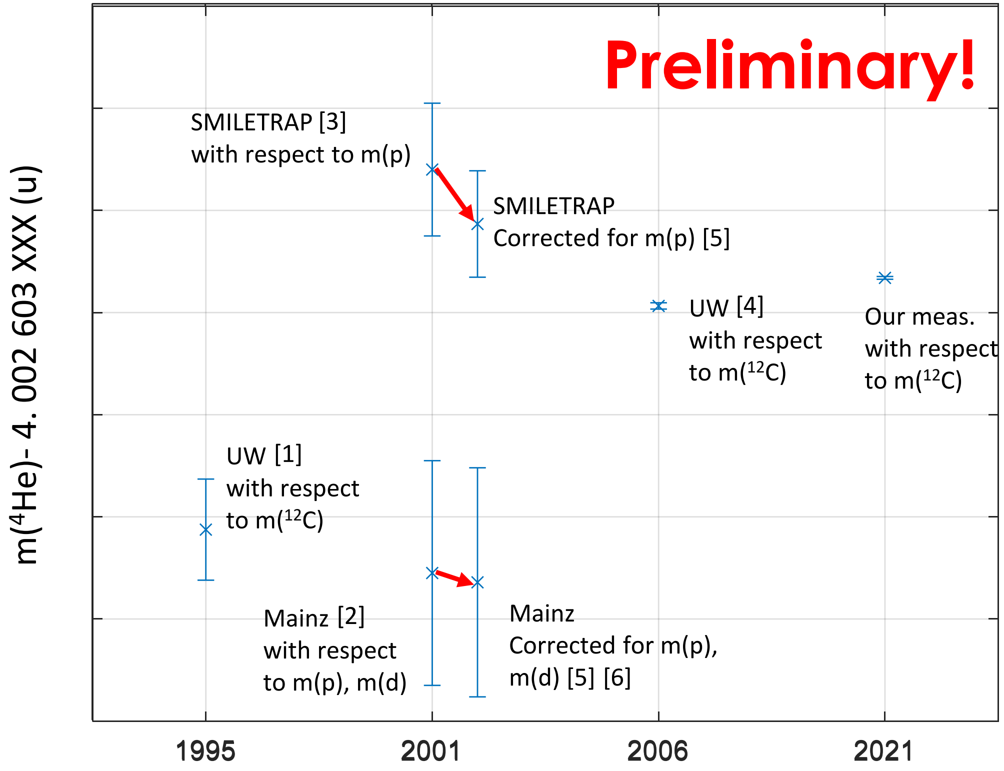
Systematic Error

Effect	Rel. Unc. (10^{-12}) Helium-4 Mass
Residual Magnetostatic Inhomogeneity	**0.3**
Special Relativity	**0.6**
Image Charge	**3.3**
Dip Lineshape	**7**
Quadratic Sum	**≈8**

Statistical Error

$$\delta R_0 / R_0 \approx 9 \times 10^{-12}$$

Preliminary Results – Discrepancy

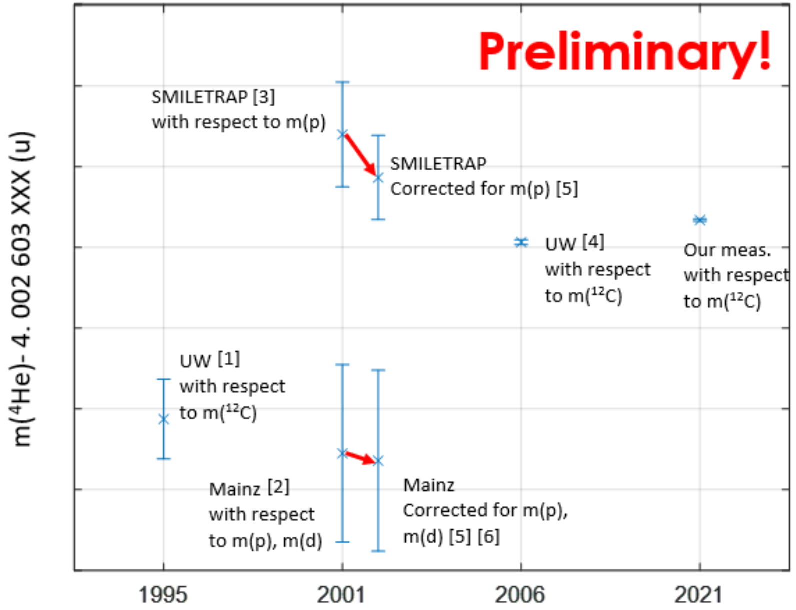


The preliminary value for total uncertainty in the cyclotron frequency ratio measurement is around 12ppt .

[1] R.S. Van Dyck Jr *et al.*, Phys. Scripta A T59, **134** (1995)
[2] Brunner. S *et al.*, Eur. Phys. J. D **15**, 181 (2001)
[3] T. Fritioff *et al.*, Eur. Phys. J. D **15**, 141-143 (2001)
[4] R. S. Van Dyck *et al.*, Int. J. Mass Spectrom., **251**,(2006)
[5] NIST Standard Reference Database http://physics.nist.gov/constants (2019)
[6] S. Rau, et al., Nature 585, 43–47 (2020)

Summary

- Estimated systematic uncertainty for He-4 to be around 8×10^{-12}
- Ongoing measurement, statistical error around 9×10^{-12}



Future projects

^{3}He Measurement

- Alternate ideas for the source
- In direct atomic mass unit
- In comparison to ^{3}T (indirect)

^{3}T Measurement

The trap design or the production mechanism needs to be modified to avoid decay electrons accumulations.

Acknowledgement

Work Group: Sangeetha Sasidharan[1,2], Olesia Bezrodnova[1], Sascha Rau[1], Wolfgang Quint[2], Sven Sturm[1] and Klaus Blaum[1]

[1] *Division of Stored and Cooled Ions at MPIK, Heidelberg*

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[2] *Atomic Physics Division at GSI Helmholtzzentrum, Darmstadt*

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