

Precision studies of astrophysical relevant nuclear structures and reactions: from MAMI to MESA and beyond (?)

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Precision across scales: from nuclei to stars

What we want to know: how hard can it be?

- Where do elements come from?
- How stars and the Universe evolve?
- What are the properties of matter under extreme conditions



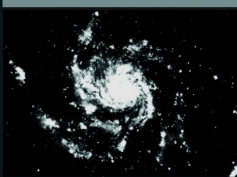
Precision across scales: from nuclei to stars

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Cauldrons in the Cosmos

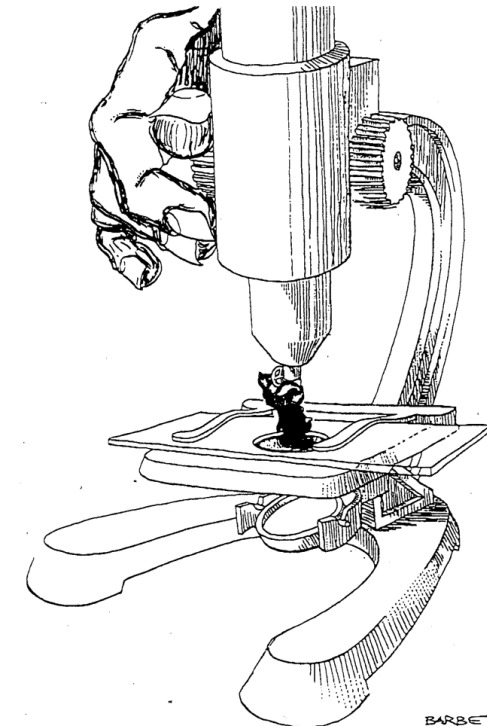
NUCLEAR ASTROPHYSICS



Claus E. Rolfs and
William S. Rodney

With a Foreword by William A. Fowler

... in the lab ...

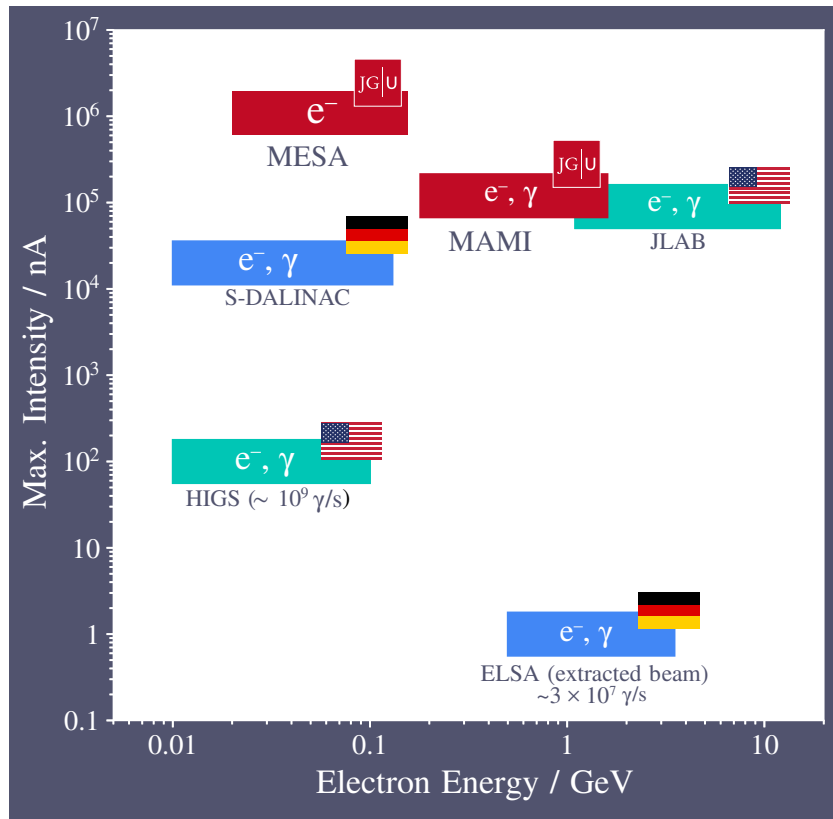


where. Thus, the ultimate goal of the field has not been attained, and much work is needed on all its aspects (experiment, theory, and observation) before the picture is complete.

Laboratory nuclear astrophysics is often a frustrating science. The desired cross sections are among the smallest measured in the nuclear laboratory, often requiring long data-collection times with painstaking attention to back-

Unlocking precision across scales

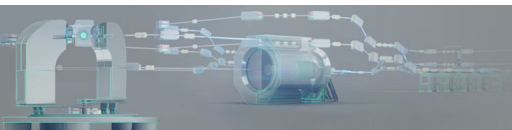
MESA - Mainz Energy-Recovering Superconducting Accelerator



Precision physics with hadrons and nuclei

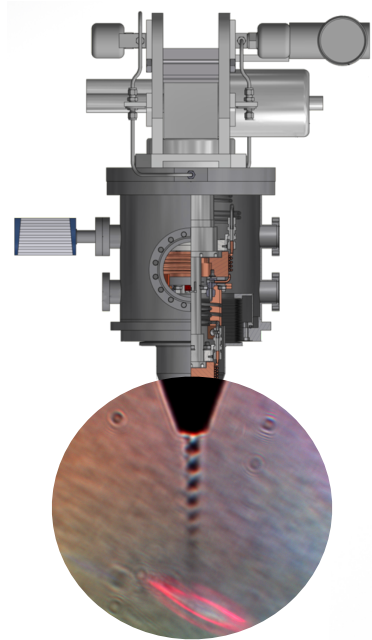
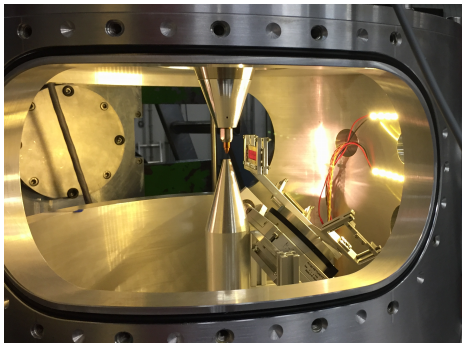
MESA - Mainz Energy-Recovering Superconducting Accelerator

- Energy-recovery mode for **high intensity** (MAGIX)
- Extracted-beam mode for **high polarisation** (P2)
- Beam dump experiment (**DarkMESA**)

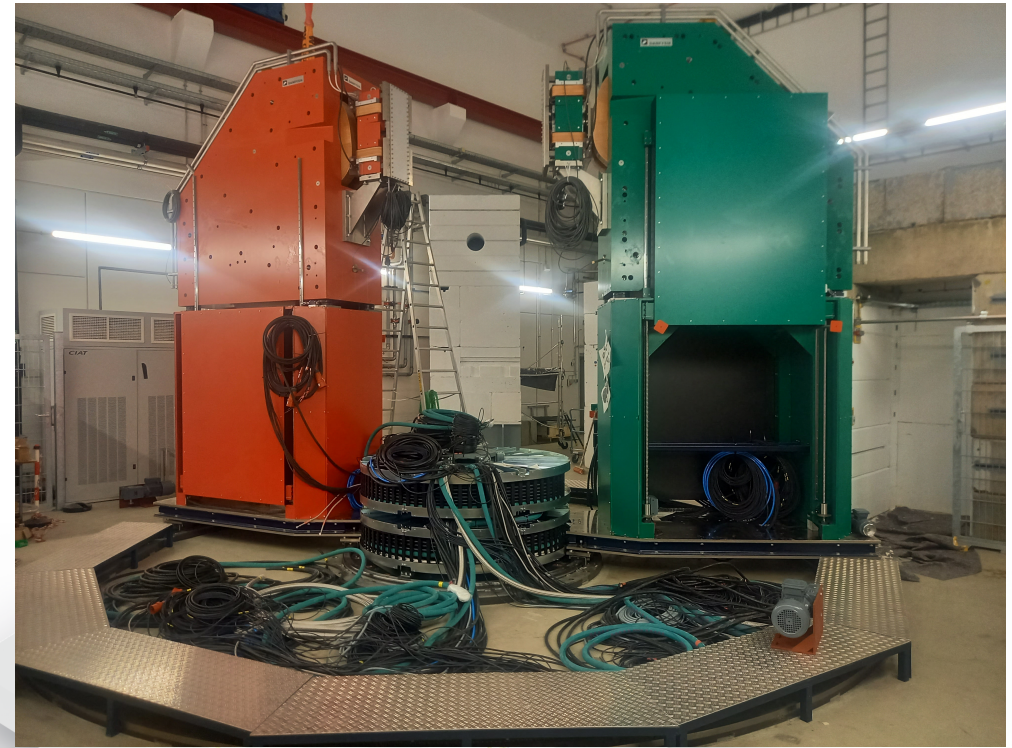


MAGIX

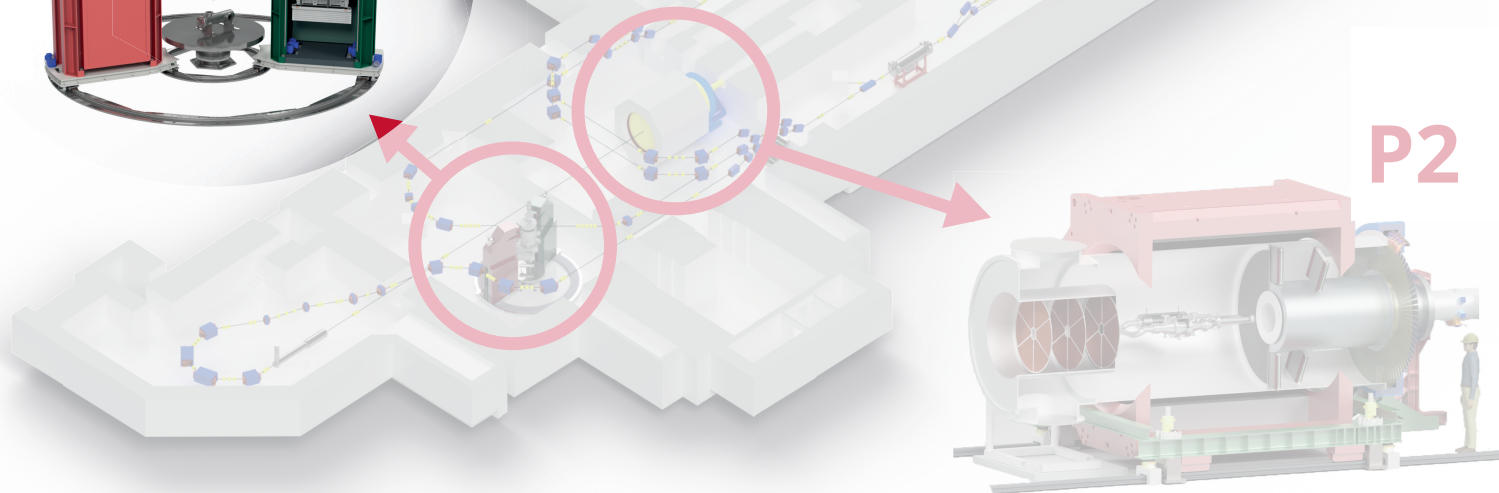
- High-resolution spectrometers ($\Delta p/p \leq 10^{-4}$)
- Cryogenic **windowless** gas-jet target



MAGIX

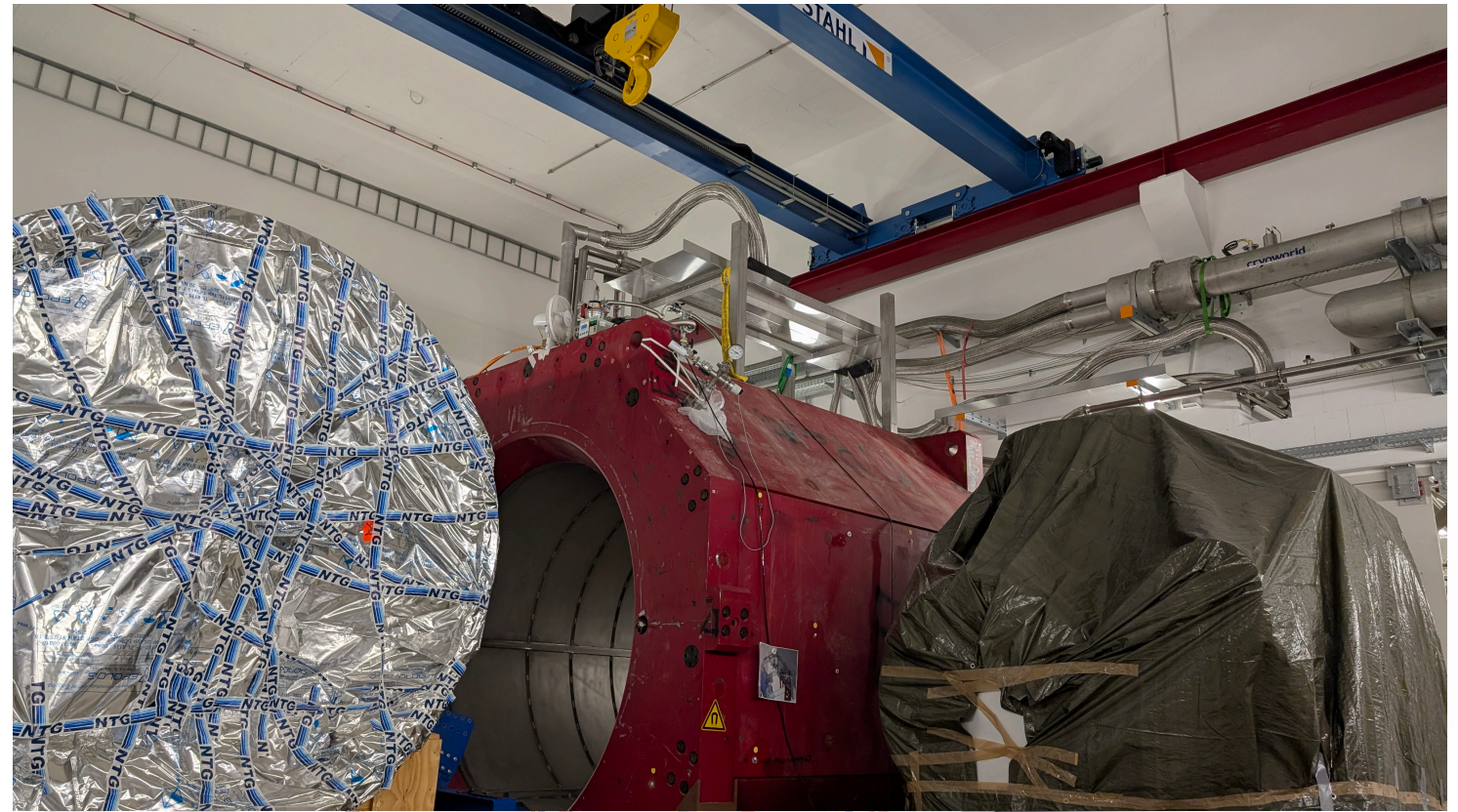


- Detection of **low-energy recoil particles**

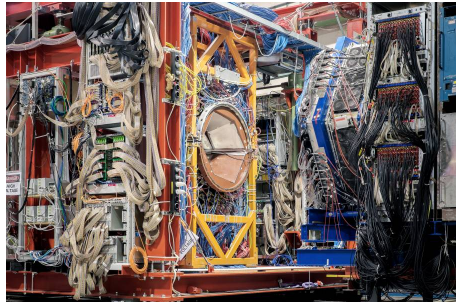


P2

- $L \approx 2.4 \cdot 10^{39} \text{ s}^{-1} \text{ cm}^{-2}$ for 60 cm H target
- **Solenoid spectrometer** with integrating Cherenkov detectors
- State of the art digitization electronics for PV experiment: **transient digitizer**
- Momentum transfer determined by **HV-MAPS tracking detectors**
- **MicroMegas** tracking detectors for asymmetry measurements at backward angles.



Complementing MESA



Real Photon Scattering

A2

DarkMesa

MESA

P2

MAGIX

MESA-Hall

MAMI

10 m

RTM2

RTM3

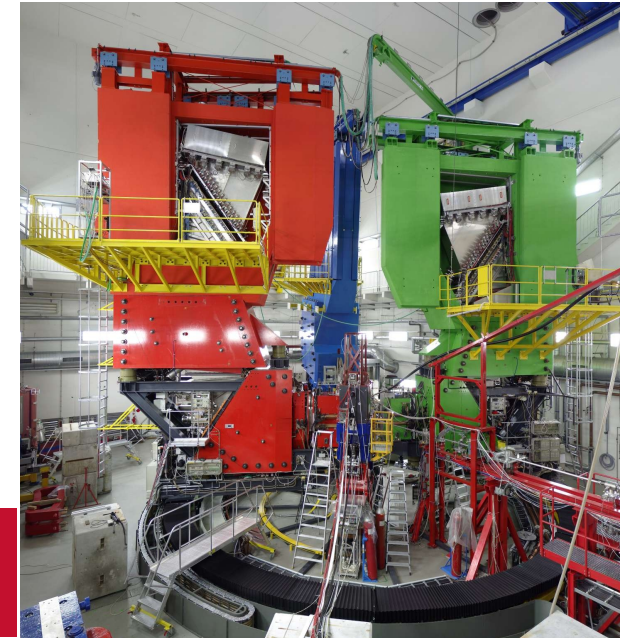
X1L

A1

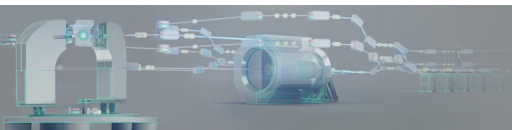
Electron Scattering - Virtual Photons

MAMI

A1



Weak radii and neutron skins



Weak radii and neutron skins

....I won't try to match any of Jorge's lectures

Heaven and Earth: connecting JLab to the cosmos

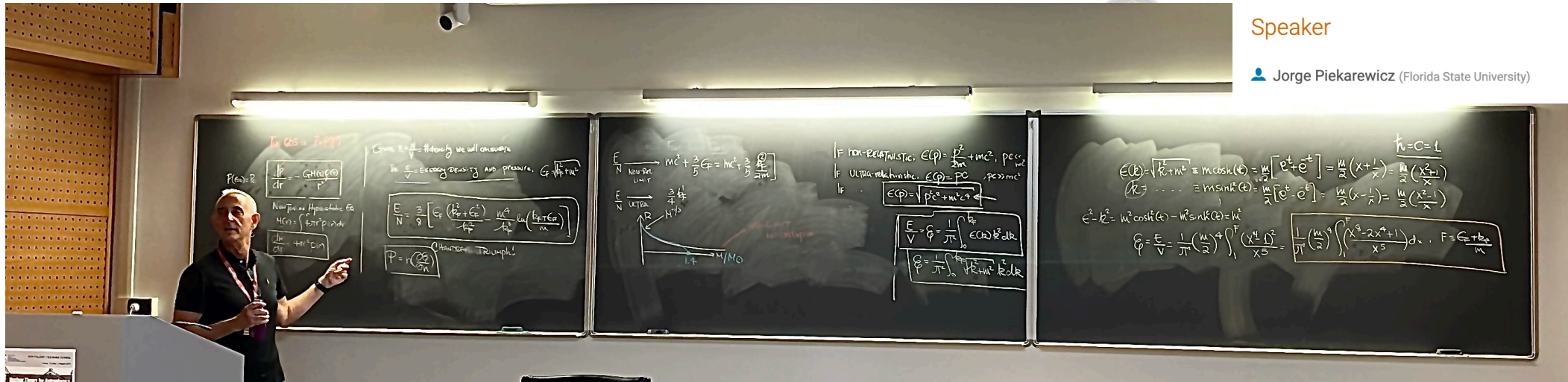
📅 Mar 24, 2026, 1:45 PM

🕒 30m

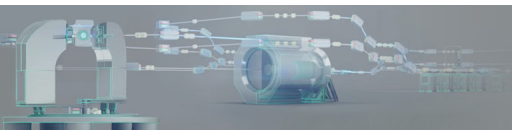
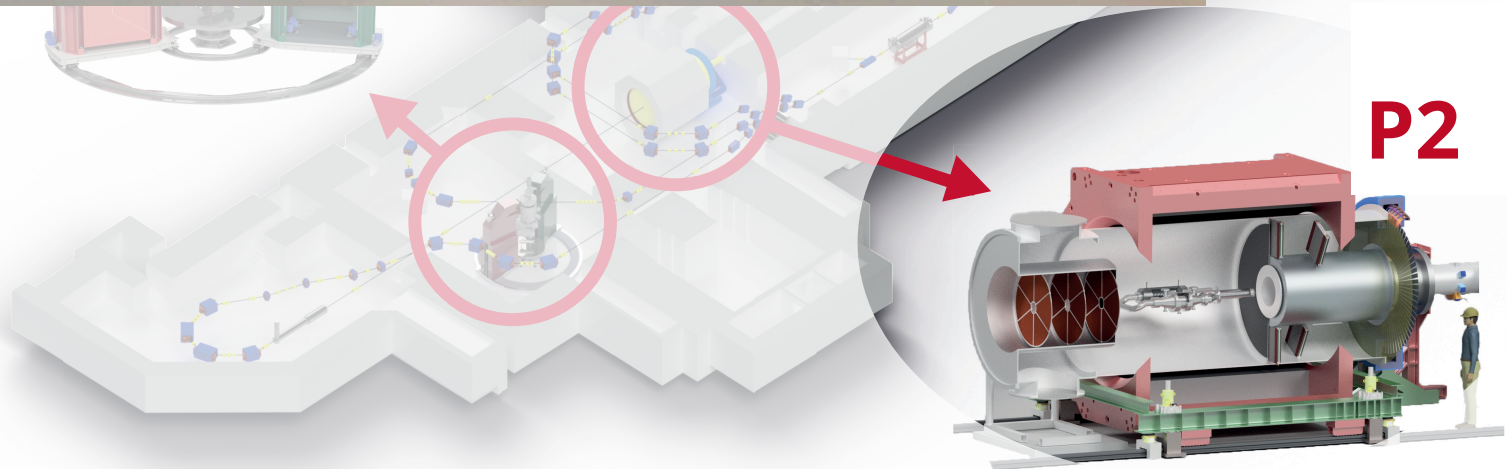
📍 F113 (CEBAF CENTER)

Speaker

👤 Jorge Piekarewicz (Florida State University)

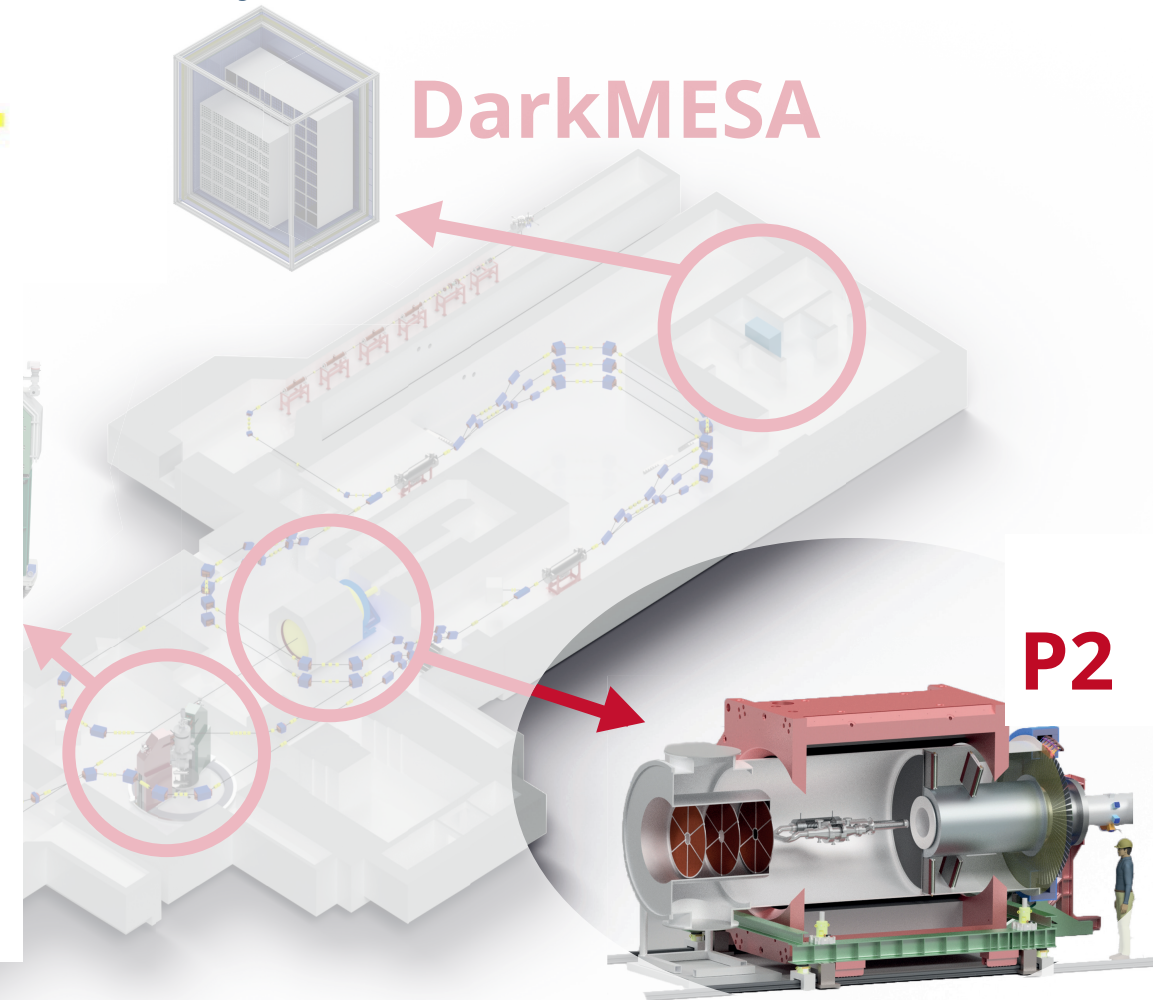
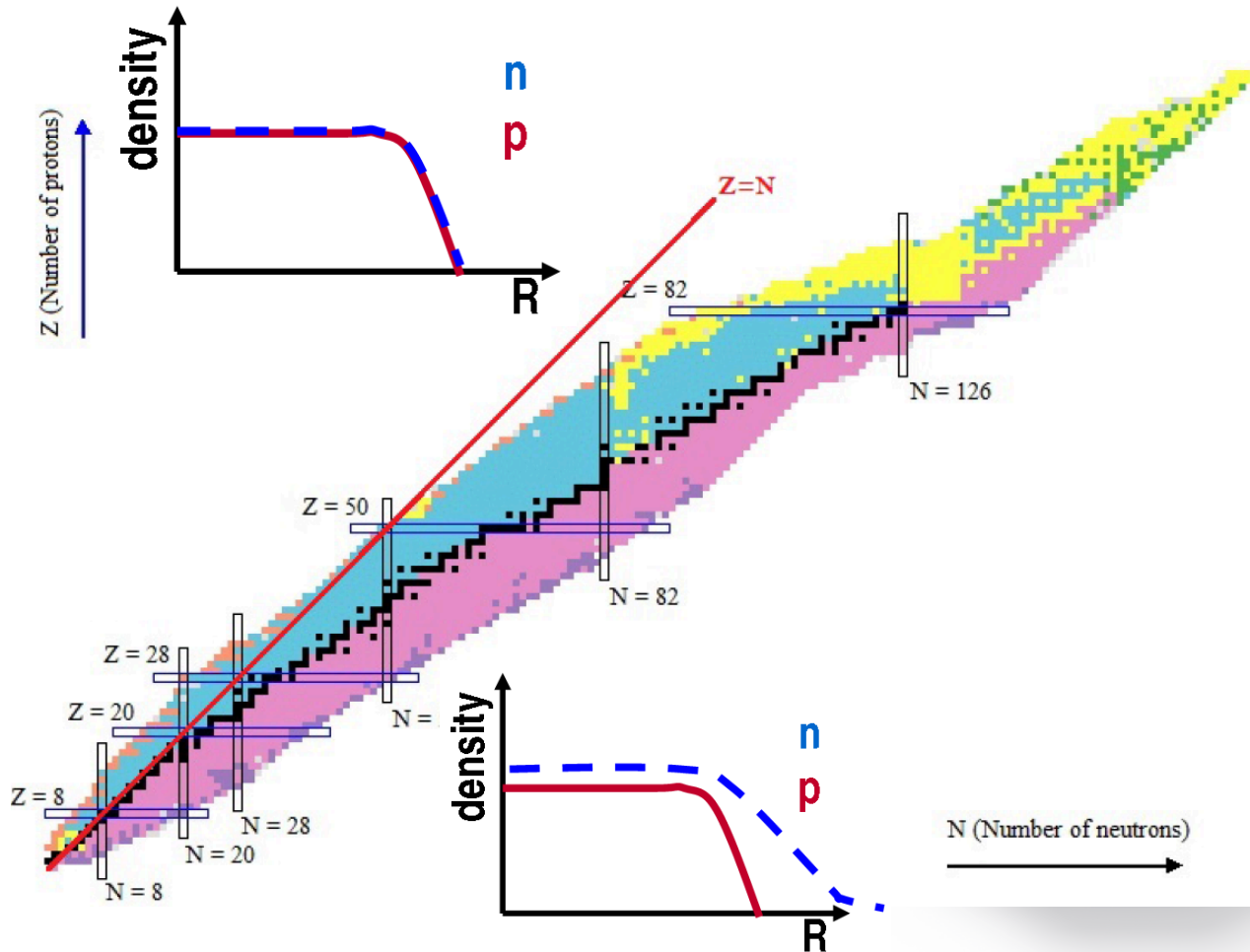


ECT* July 2024



Weak radii and neutron skins

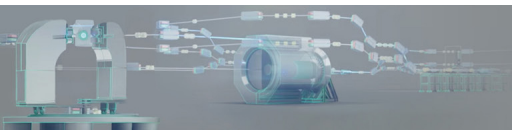
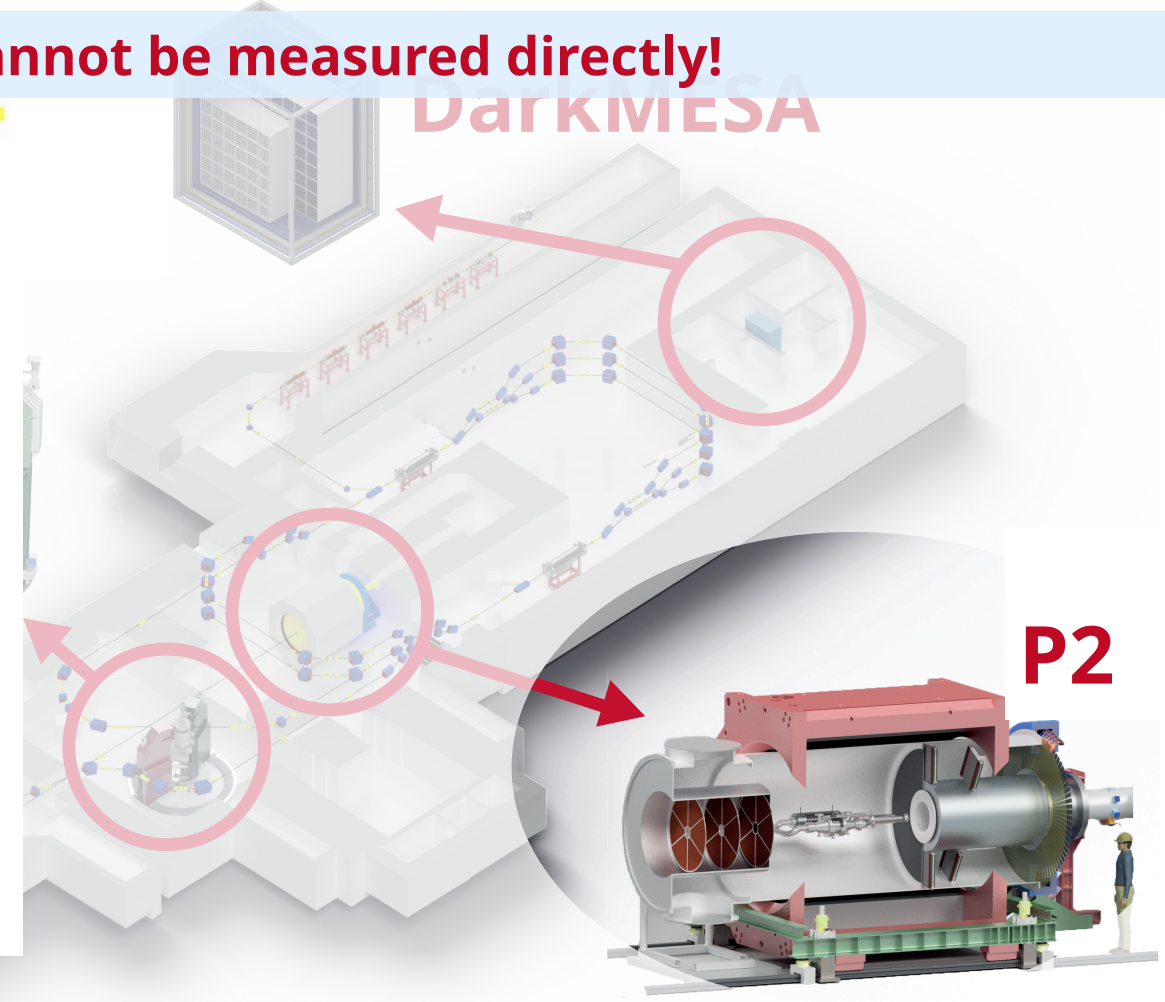
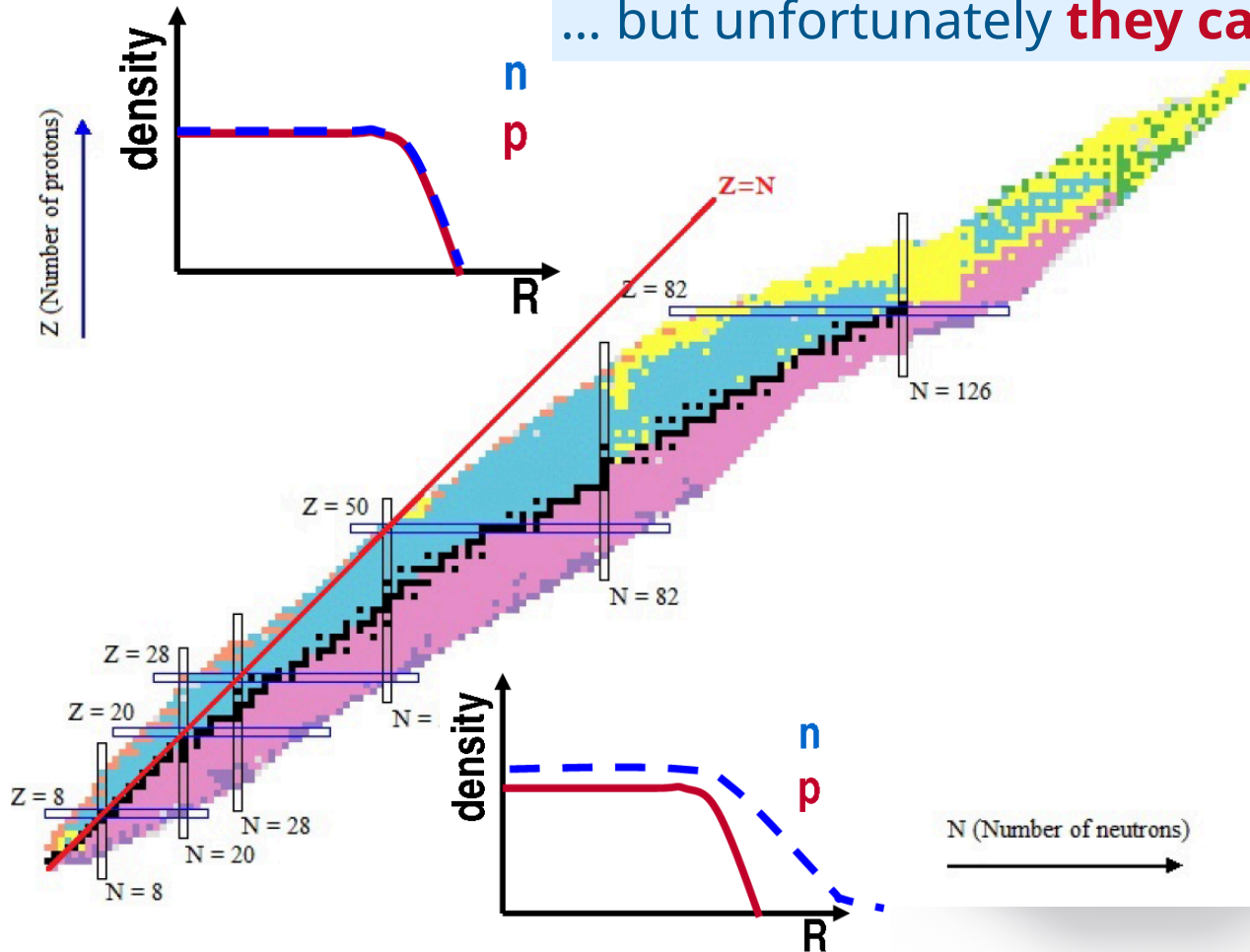
... neutron stars are awesome and neutron skins let us study them in the lab!



Weak radii and neutron skins

... neutron stars are awesome and neutron skins let us study them in the lab!

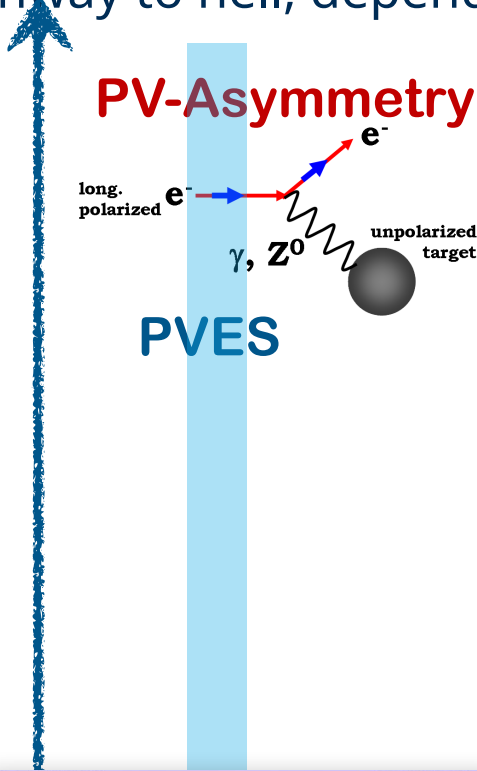
... but unfortunately **they cannot be measured directly!**



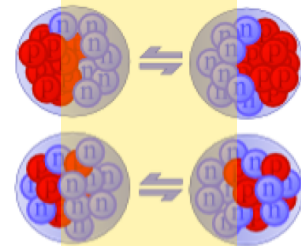
The stairway to heaven

...or the highway to hell, depending on your level of optimism...

Experimental Challenges
(in unit of frustration)

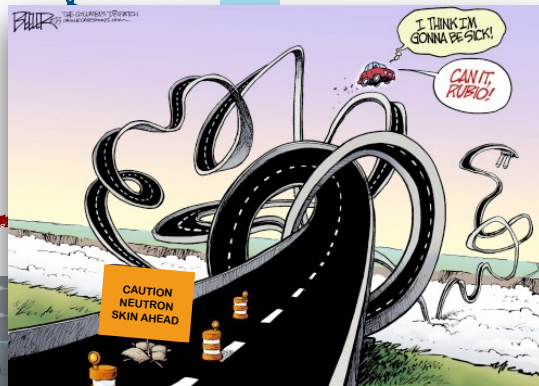
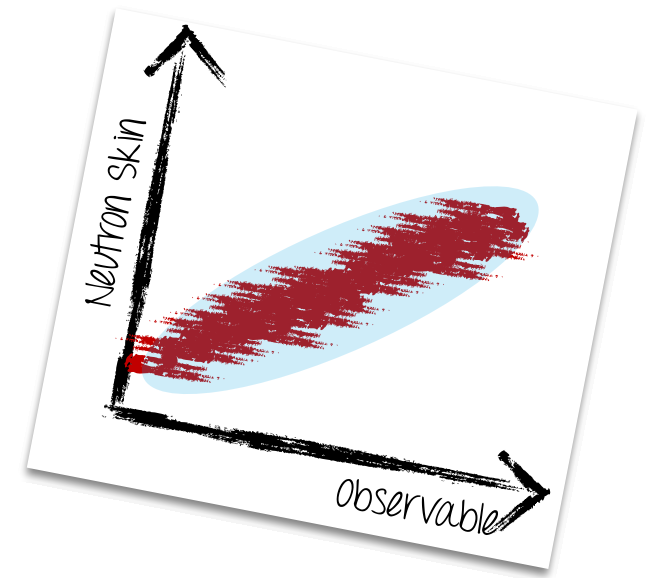
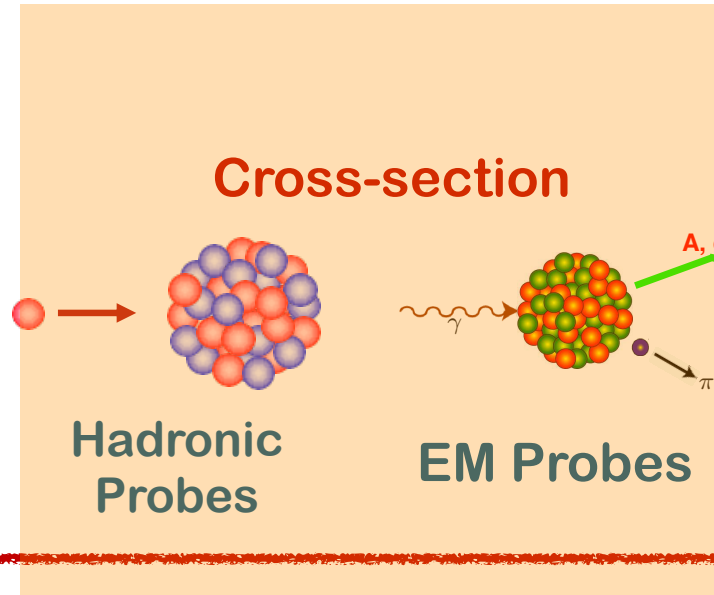


Resonance Strength



Collective Excitation

(Personal selection)

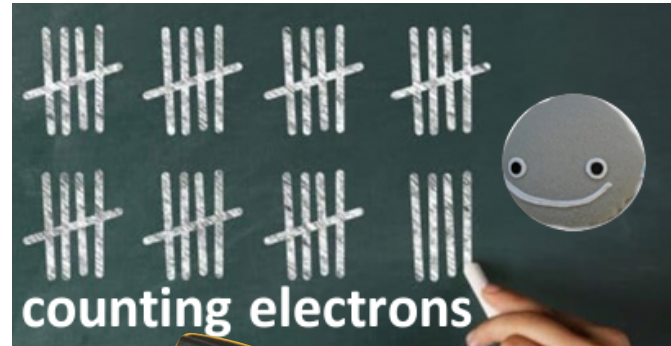


Theo. uncertainties (a.u)

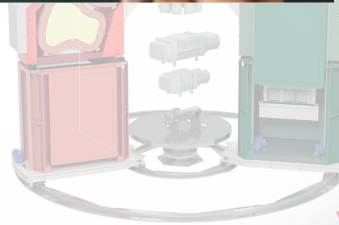
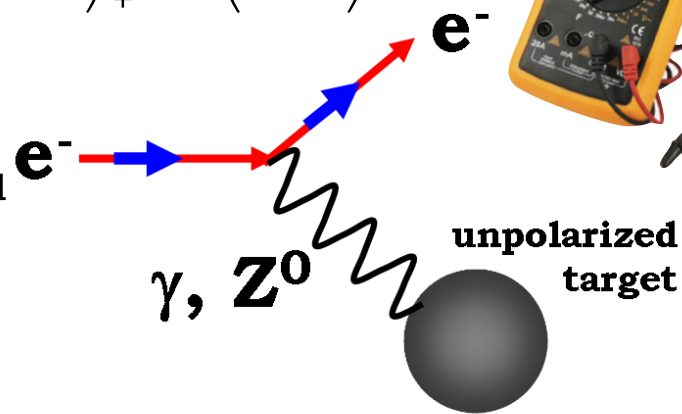


Weak radii and neutron skins

$$A_{PV} = \frac{\left(\frac{d\sigma}{d\Omega}\right)_+ - \left(\frac{d\sigma}{d\Omega}\right)_-}{\left(\frac{d\sigma}{d\Omega}\right)_+ + \left(\frac{d\sigma}{d\Omega}\right)_-}$$

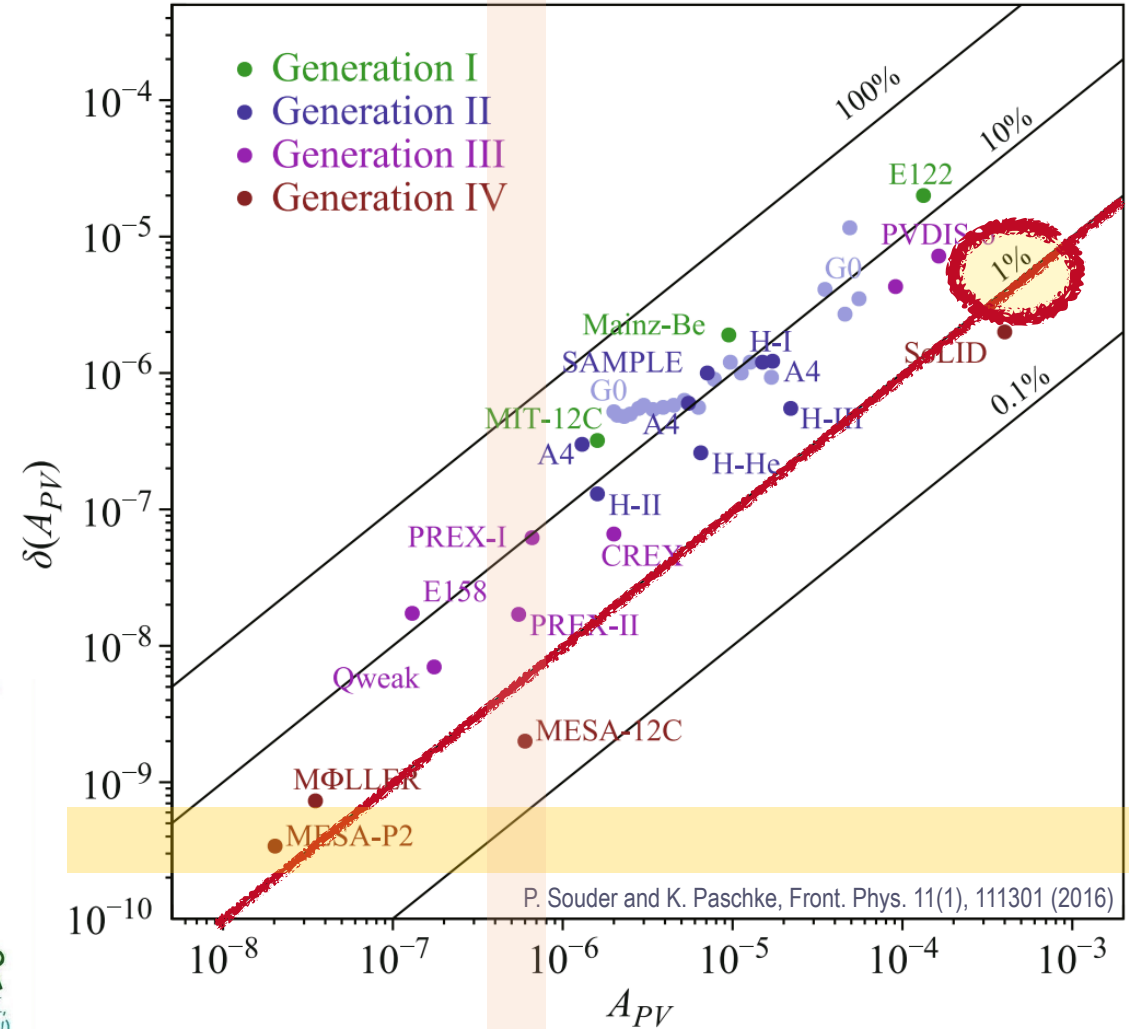


long. polarized e^-



WHAT DOESN'T
KILL YOU
MAKES YOU
CRANKY
~~STRONGER~~
PISSED OFF
~~STRONGER~~
GRUMPY
STRONGER
(IT MAY TAKE A WHILE,
BUT YOU'LL GET THERE!)

$A_{PV} (^{208}\text{Pb}) \approx 550 \text{ ppb}$

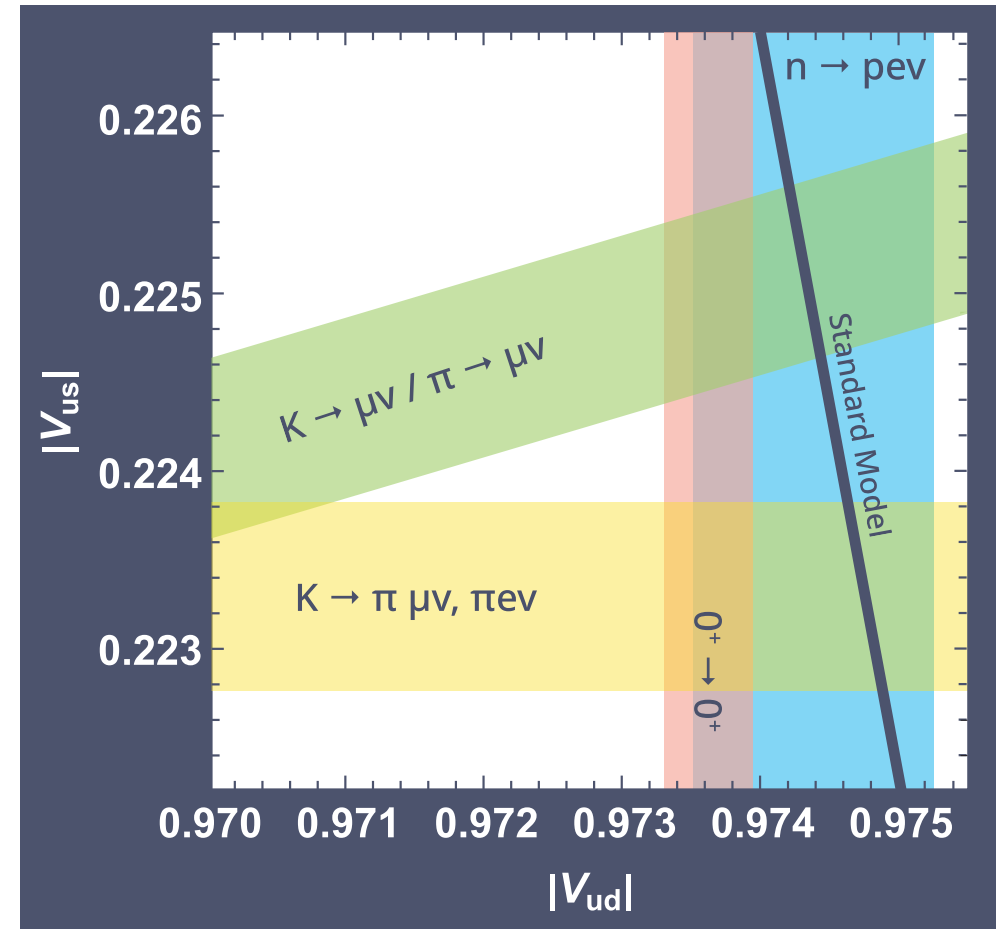
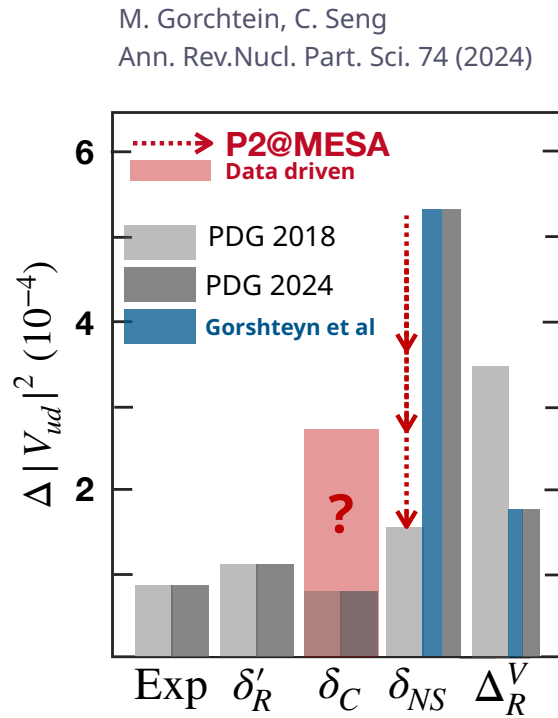


Weak radii Go Full Diva

BSM searches involving hadrons: Do we find cracks in the SM?

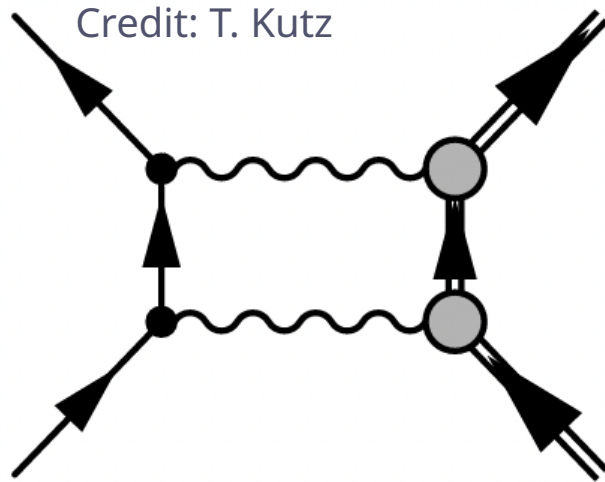
- Data driven constraints from **weak radius measurements**
- Complements precision measurement of **neutron lifetime** and improved **branching ratio of kaon decays**

Overconstraining the CKM matrix at the per mille level



BSM Searches, weak radii and neutron skins

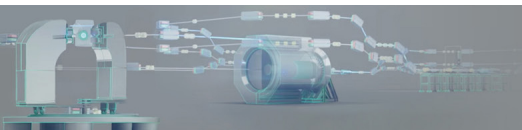
Advance precision of hadronic and nuclear processes and properties



• $\square_{\gamma\gamma}$: background to PVES

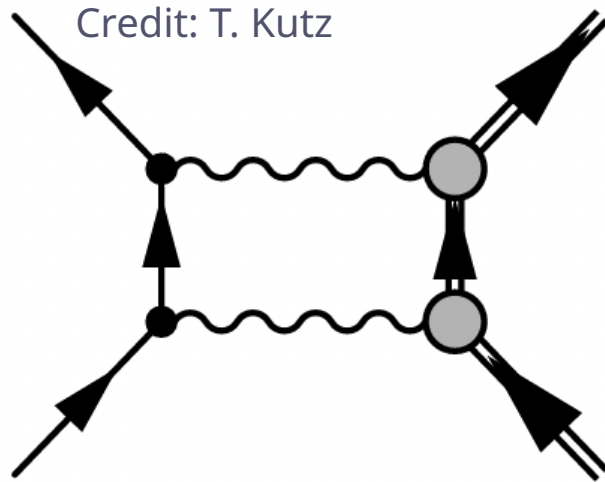
• $\square_{\gamma Z}$: weak mixing angle extractions from PVES

• $\square_{\gamma W}$: CKM matrix elements from β -decay



BSM Searches, weak radii and neutron skins

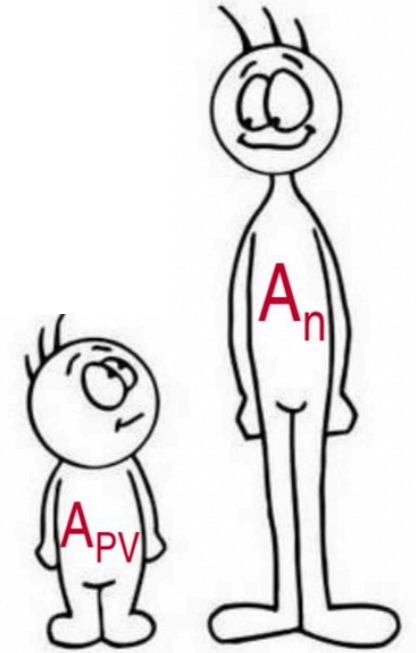
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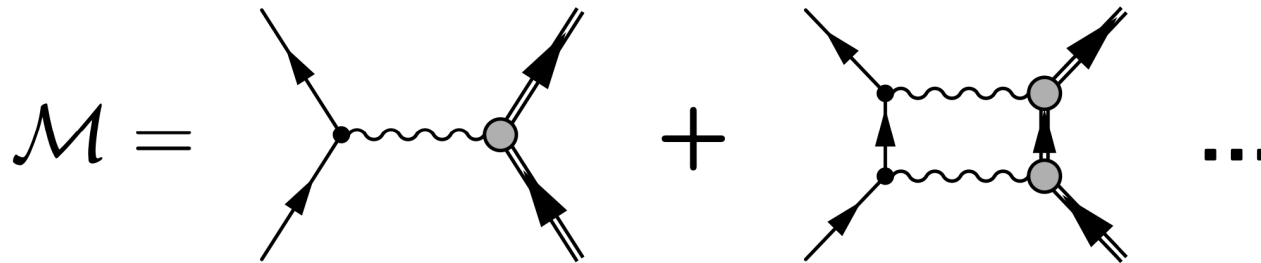
• $\square_{\gamma\gamma}$: background to PVES

• $\square_{\gamma Z}$: weak mixing angle extractions from PVES

• $\square_{\gamma W}$: CKM matrix elements from β -decay



Can observe interference between 1- and 2 γ exchange

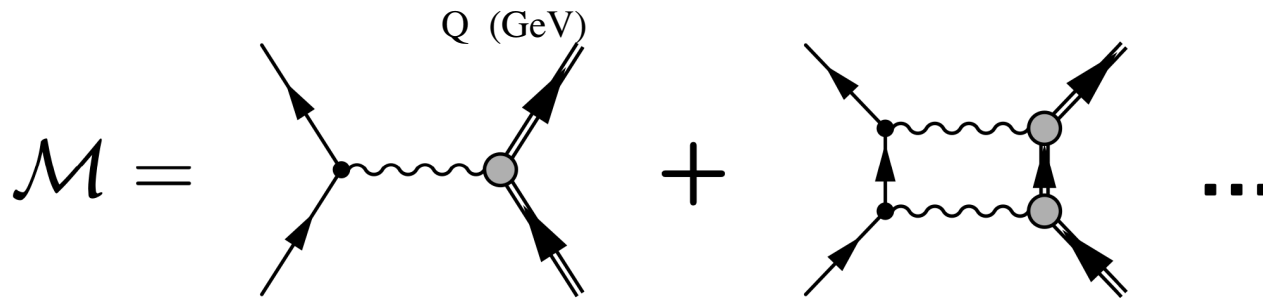
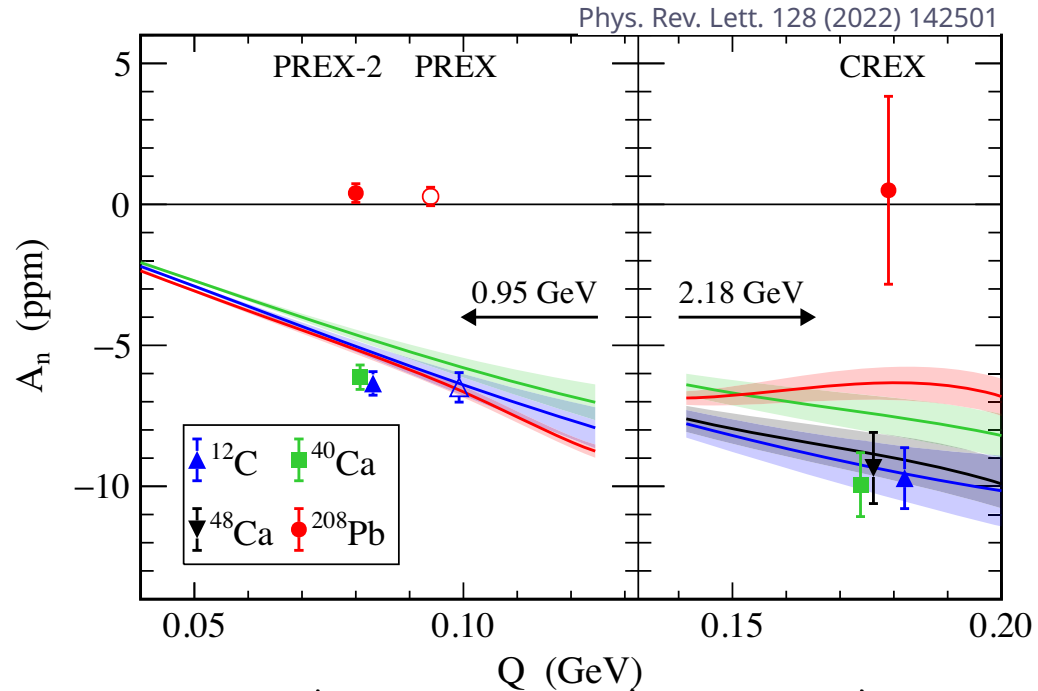


$$A_n = \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow} = \frac{2\mathcal{I}(\mathcal{M}_{1\gamma}\mathcal{M}_{2\gamma}^*)}{|\mathcal{M}_{1\gamma}|^2}$$

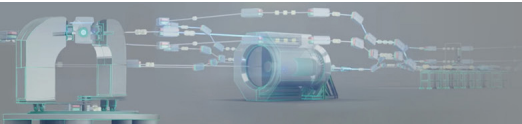


BSM Searches, weak radii and neutron skins

Advance precision of hadronic and nuclear processes and properties

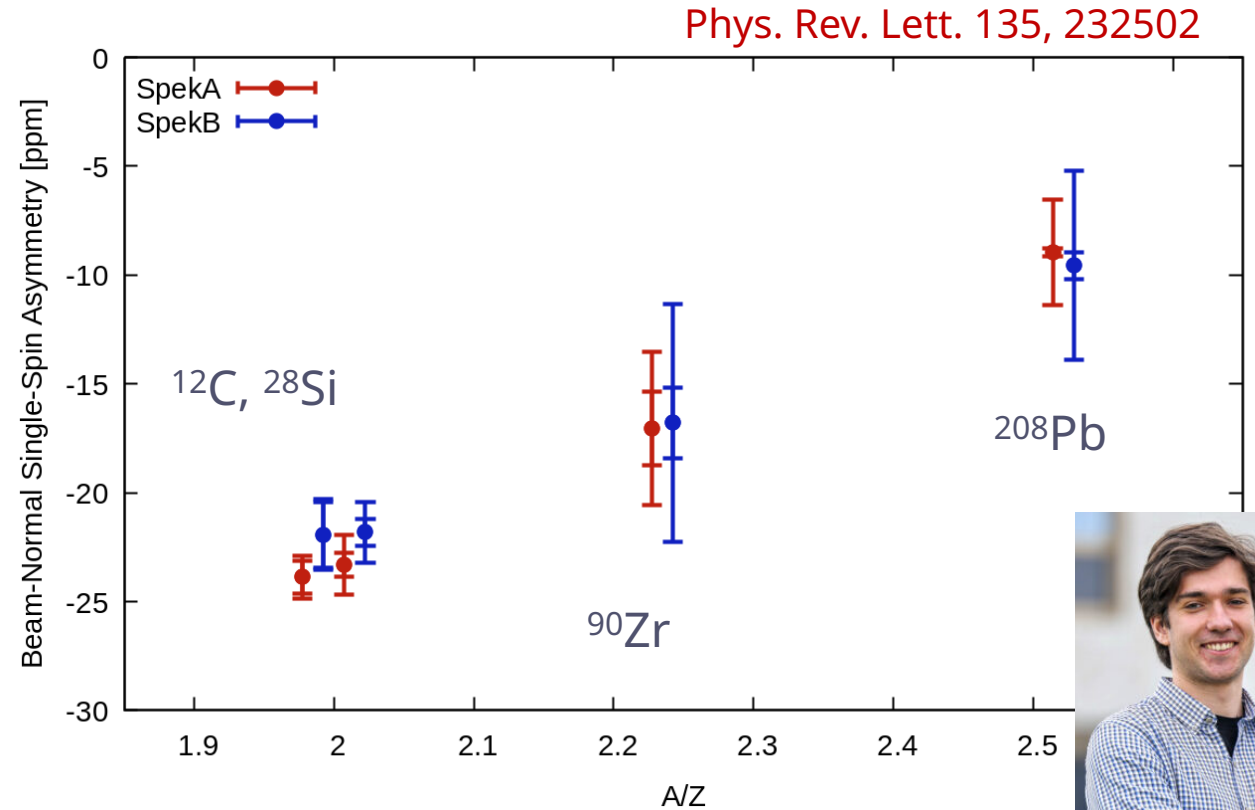
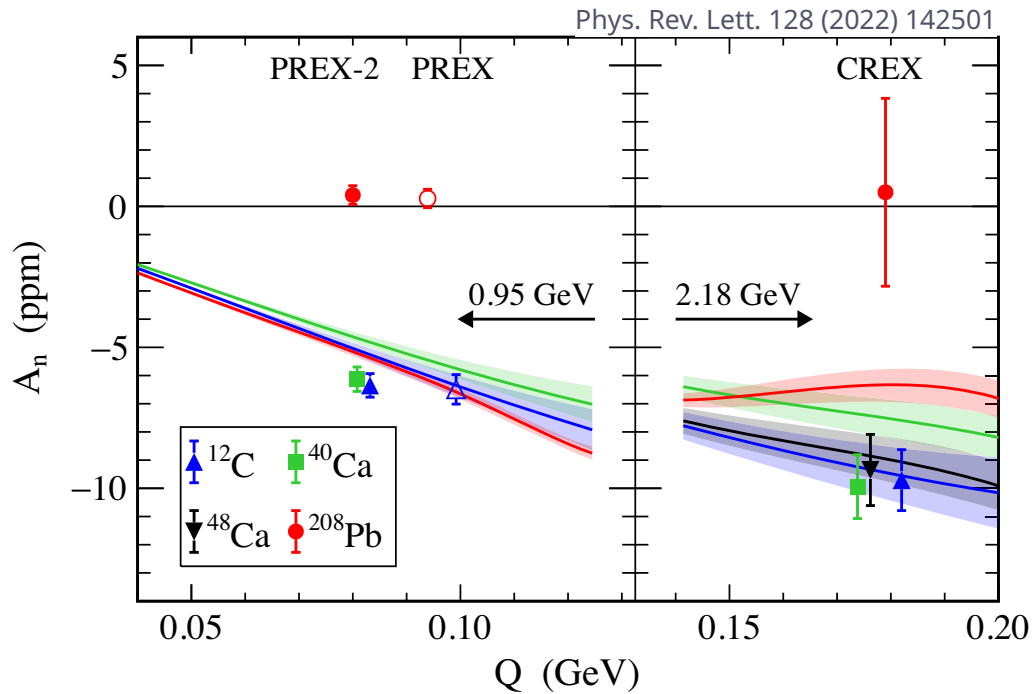


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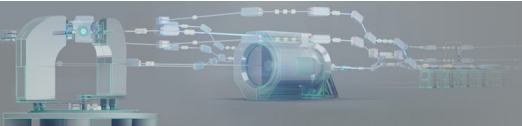


BSM Searches, weak radii and neutron skins

Advance precision of hadronic and nuclear processes and properties



True discrepancy or insufficient understanding?



Low energy positrons won't solve the puzzle ...

...but they could make sure we have a puzzle in the first place!

Leading expectation: $A_n(e^-) \approx A_n(e^+)$

1 γ amplitude flips sign, 2 γ does not

Differences could arise from:

- Higher-order effects (beyond 2 γ)
- Coulomb distortions (e^- vs e^+) relevant for heavy nuclei and low energies
- Nuclear structure: inelastic states in TPE

e^+ vs e^- comparison becomes a diagnostic tool

Treatment of inelastic intermediate states and tests Coulomb distortion modelling



From nuclear structure to stellar reactions

The making of the elements...

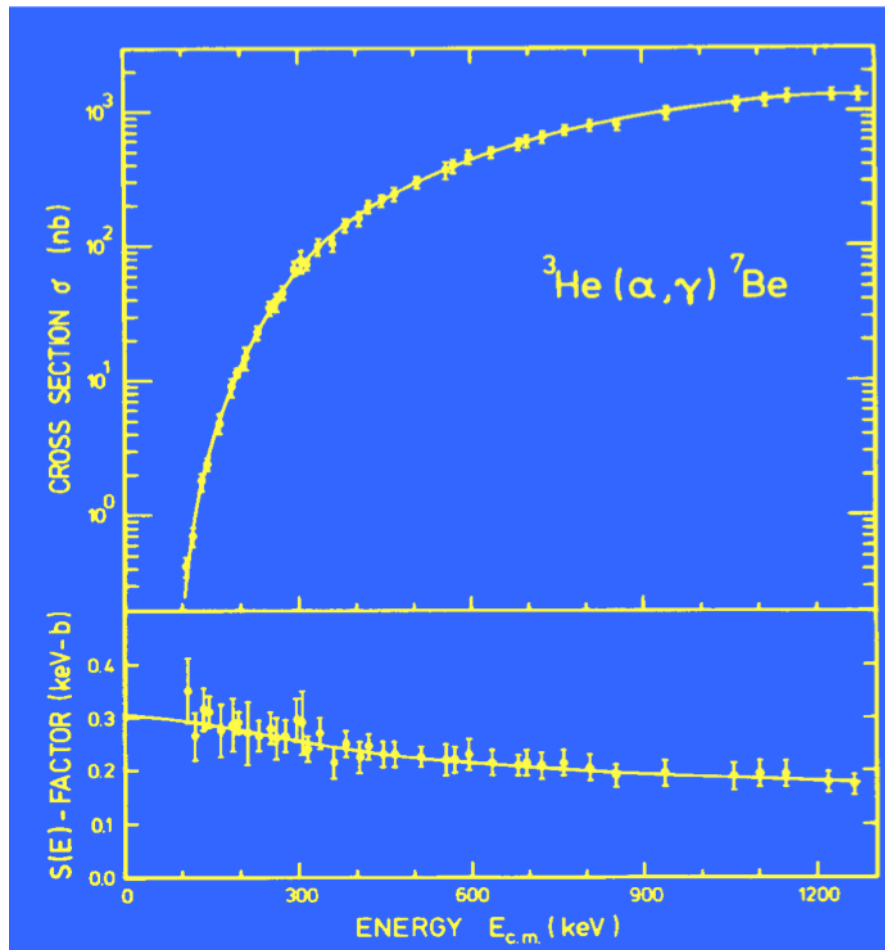
Credit: NASA

The image is a composite illustrating the origin of elements. On the left is a periodic table where each element's cell contains a small image of the element. In the center, a diagram shows various stellar processes: 'The big bang' (Hydrogen), 'Dying low-mass stars' (Helium), 'White dwarf supernovae' (Carbon, Nitrogen, Oxygen), 'Radioactive decay' (Uranium), 'Cosmic ray collisions' (Lithium, Beryllium), 'Dying high-mass stars' (Iron, Nickel, Cobalt, Nickel, Copper, Zinc), and 'Merging neutron stars' (Gold, Silver, Platinum, Gold, Mercury). On the right, a starry night sky features the text 'we are ALL made of Stardust' in a glowing font, with silhouettes of a family (two adults and two children) standing on a hill looking up at the stars.



From nuclear structure to stellar reactions

Thermonuclear reactions in stars occur by tunnel effect!



$$\text{Yield} = N_p \times N_t \times \sigma \times \eta$$

$$N_p = 10^{14} \text{ pps } (\sim 100 \mu\text{A } q=1+)$$

$$N_t = 10^{19} \text{ atoms/cm}^2$$

$$\sigma \sim 10^{-15} \text{ barn } (10^{-39} \text{ cm}^2)$$

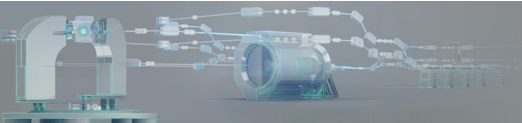
$$\eta = 1 - 100\%$$

$$Y = 0.3 - 30 \text{ events/year}$$

Credit: M Aliotta

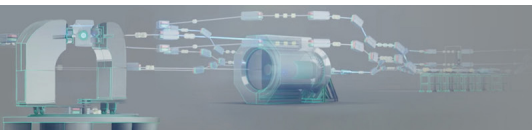


~ 1.2-120 counts/PhD



From nuclear structure to stellar reactions

Counts per PhD: can we do better?



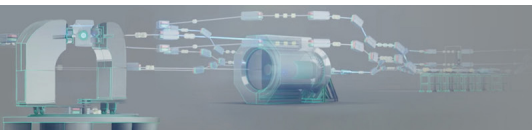
From nuclear structure to stellar reactions

Counts per PhD: can we do better?

- reducing “noise” (i.e. background)



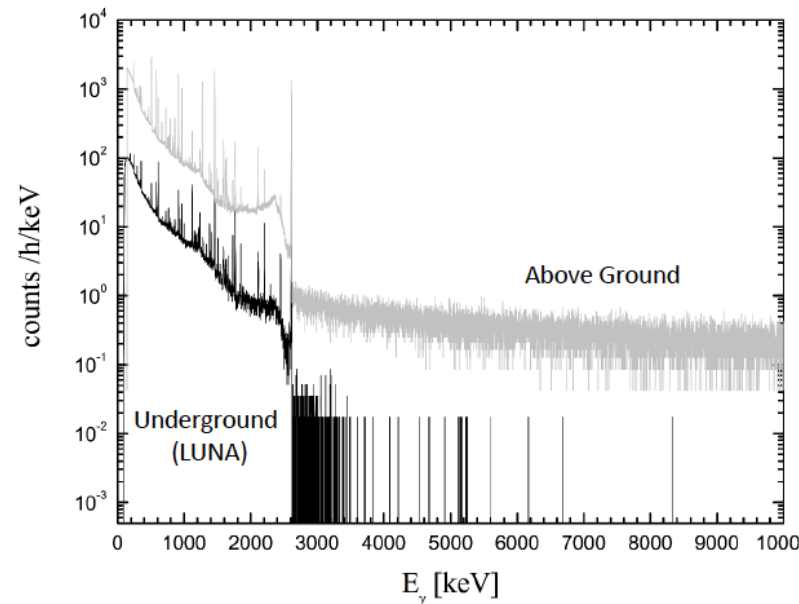
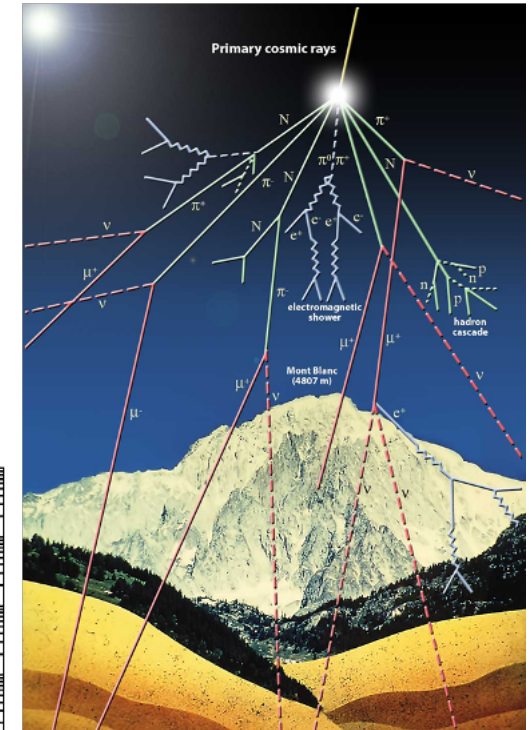
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From nuclear structure to stellar reactions

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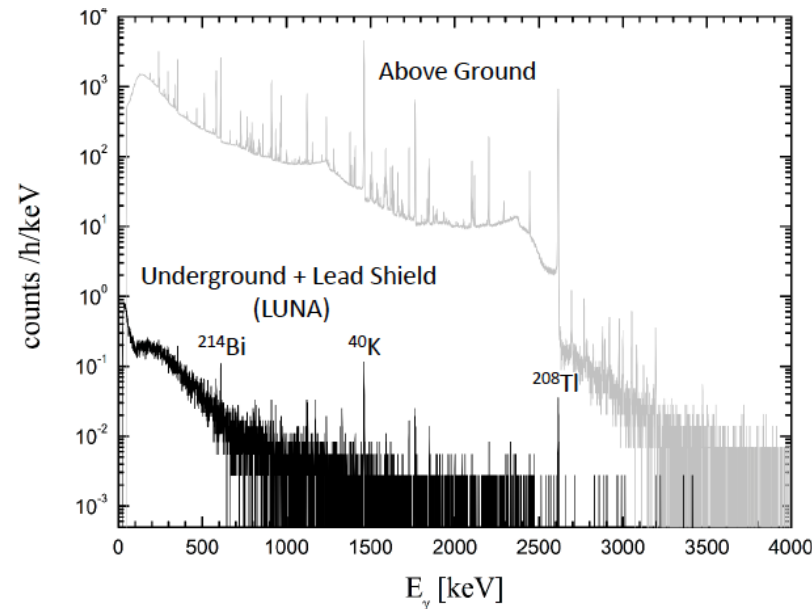
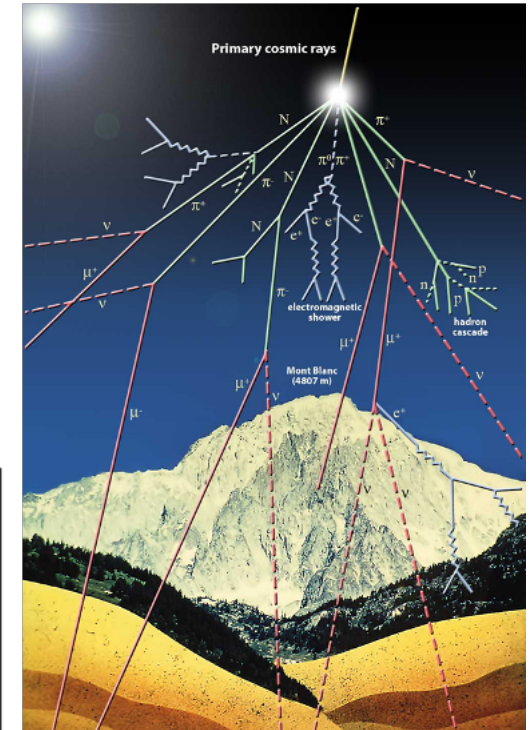
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From nuclear structure to stellar reactions

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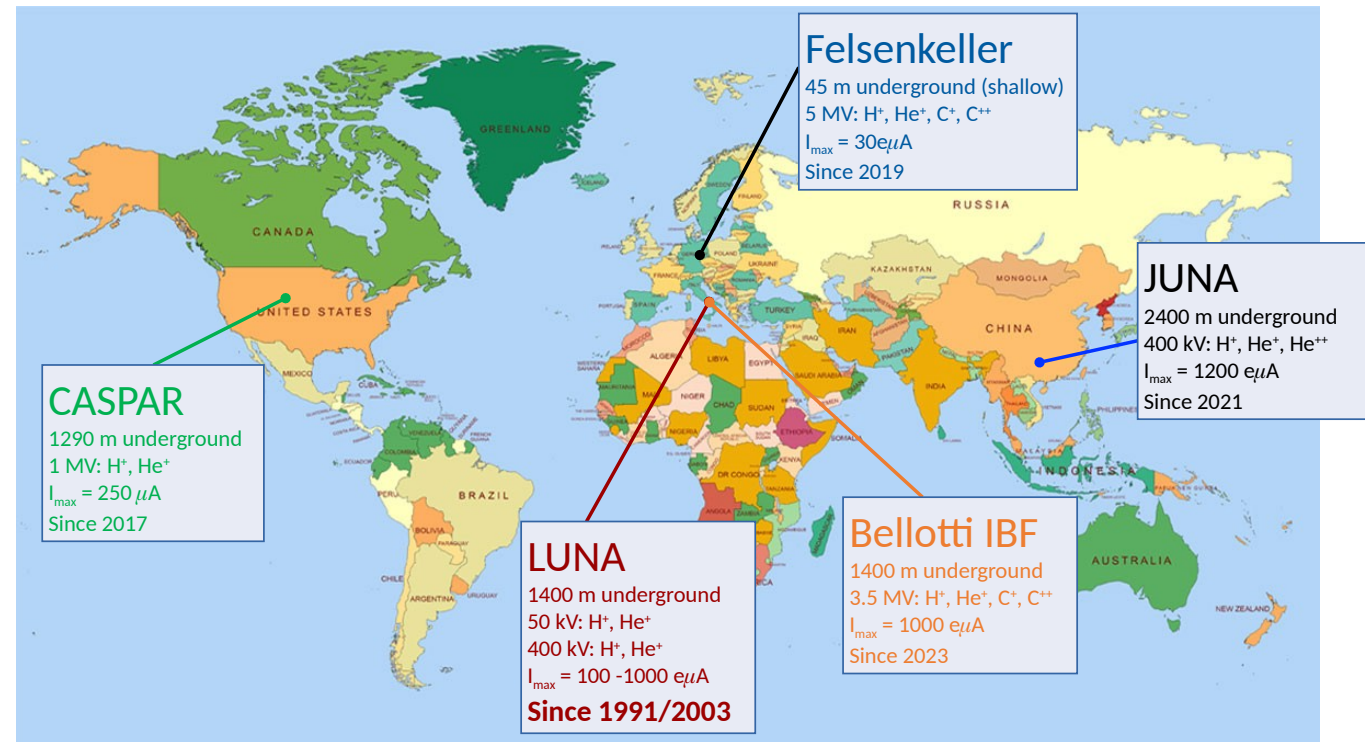


From nuclear structure to stellar reactions

Counts per PhD: can we do better?

- reducing “noise” (i.e. background)
- improving “signal” (e.g. beam currents, target density, efficiency)
 - Quiescent burning → stable beams
 - Direct measurements limited → indirect approaches!

Credit: E. Masha - Bormio 2026



From nuclear structure to stellar reactions

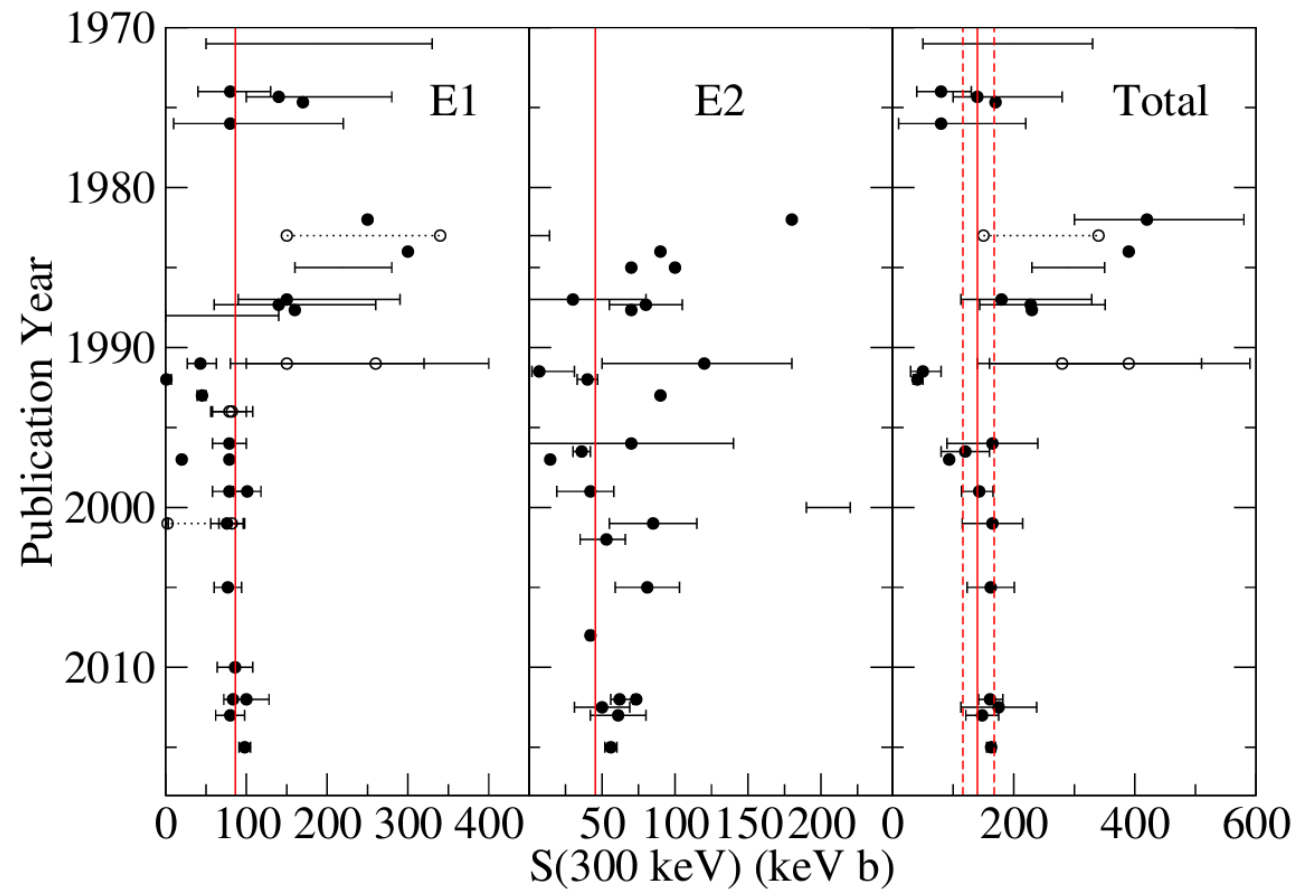
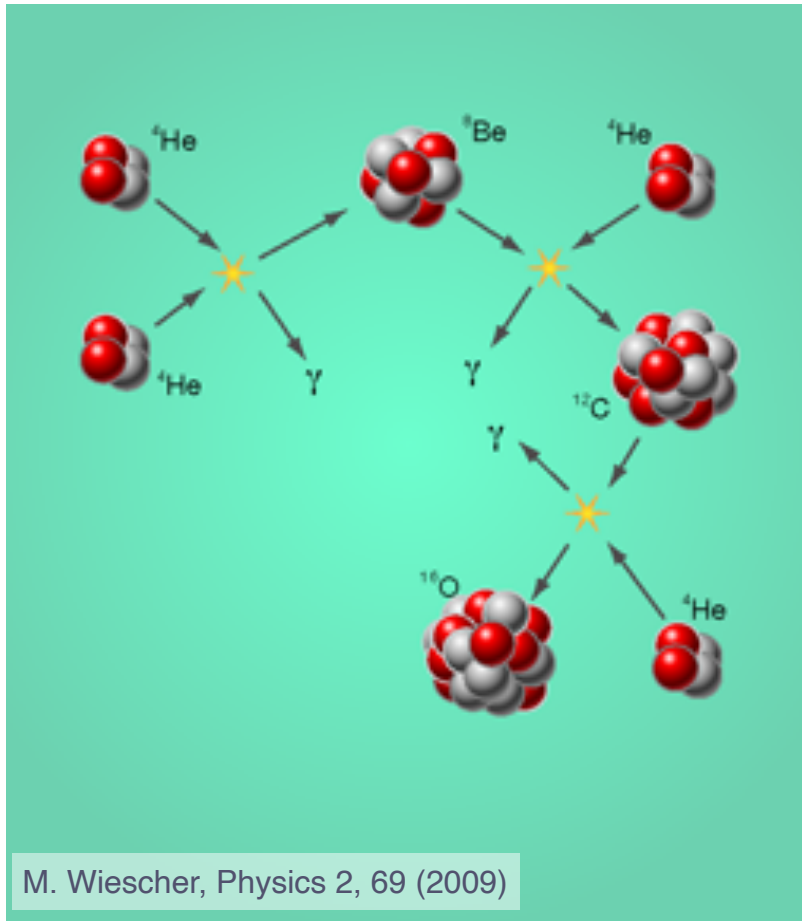
Counts per PhD: can we do better?

- reducing “noise” (i.e. background)
- improving “signal” (e.g. beam currents, target density, efficiency)
 - Quiescent burning → stable beams
 - Direct measurements limited → indirect approaches!
 - Indirect methods (with their own highway)
 - transfer reaction - elastic scattering - Coulomb dissociation - time-inverse
 - **MESA: novel time-inverse idea**



The Quest for the Grail

...50+ years of experiment, still extrapolating!

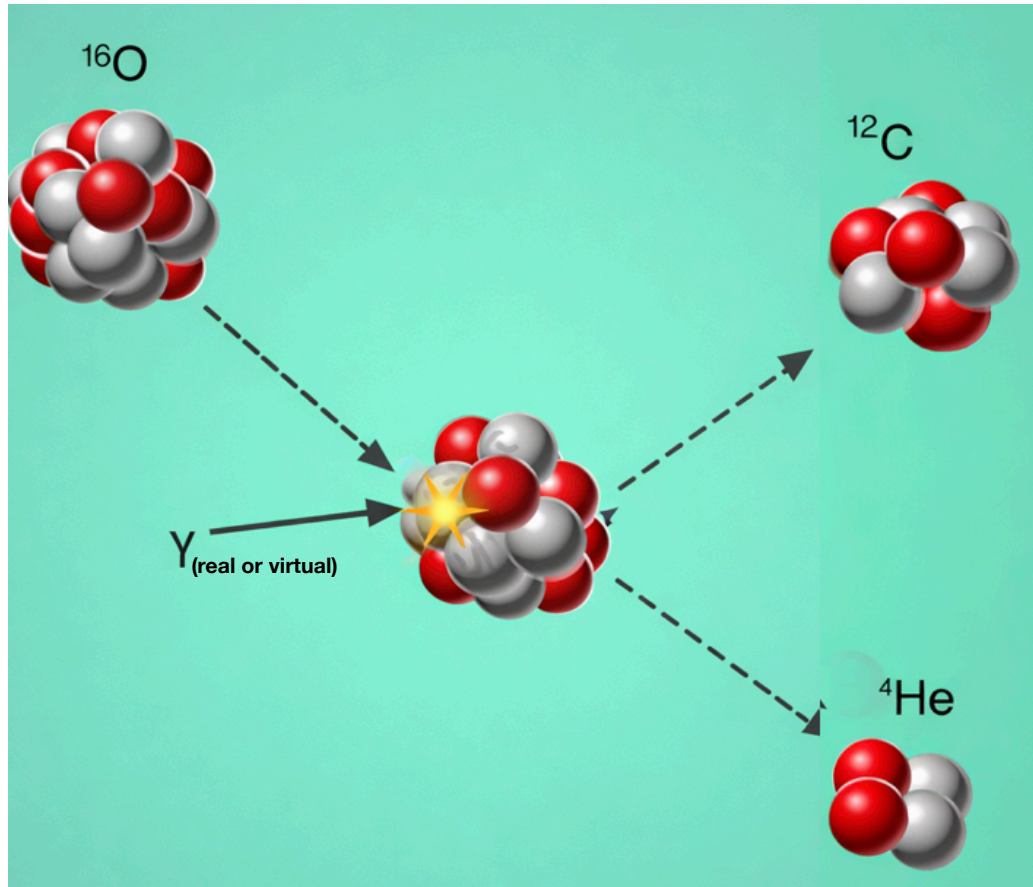


R.J. deBoer et al., Rev. Mod. Phys. 2017



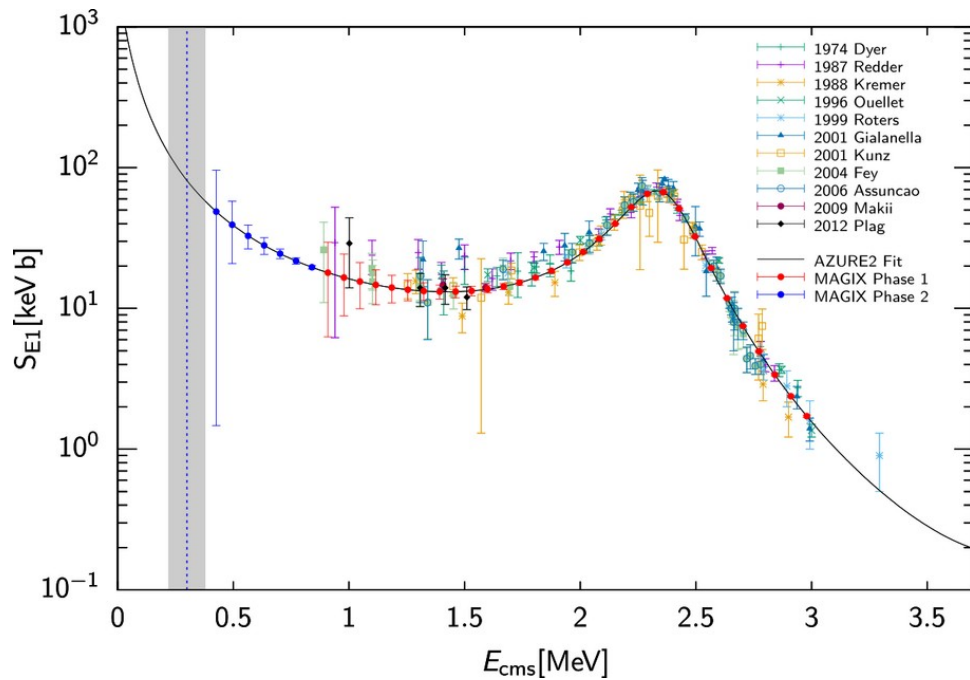
The Quest for the Grail

→ liarG eht rof tseuQ ehT

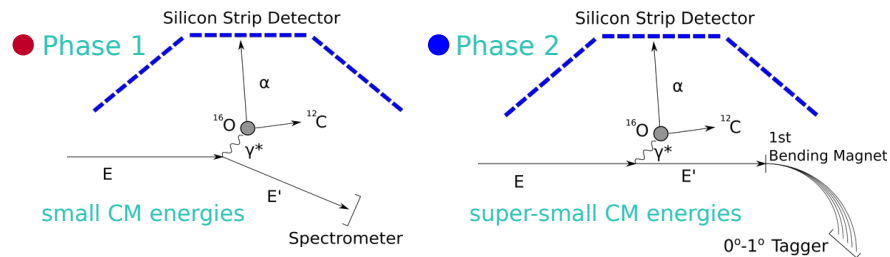


The Quest for the Grail

ERL + gas jet target at their best



Stefan Lunkenheimer

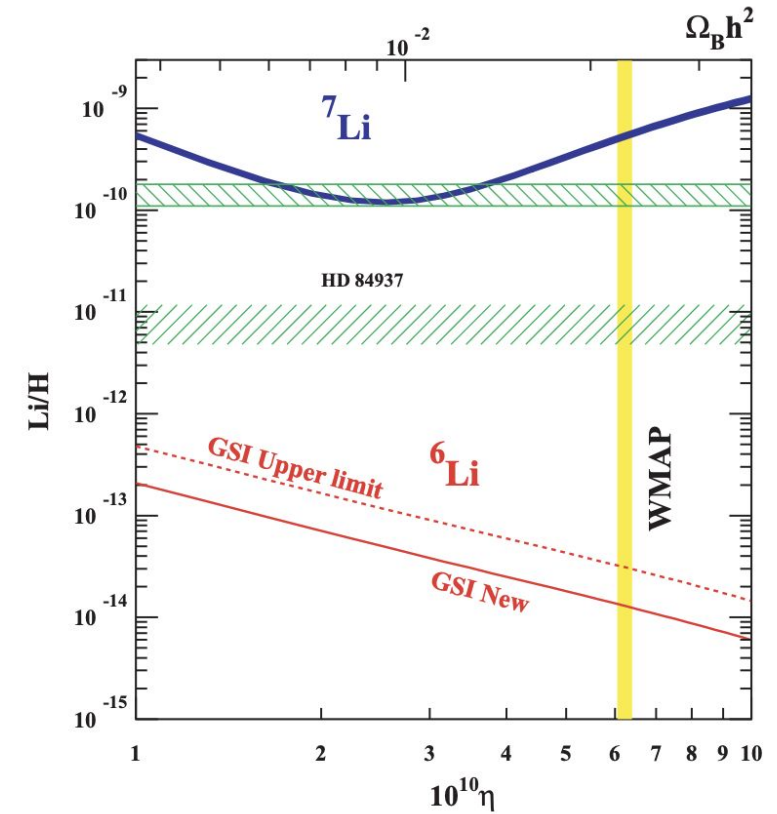
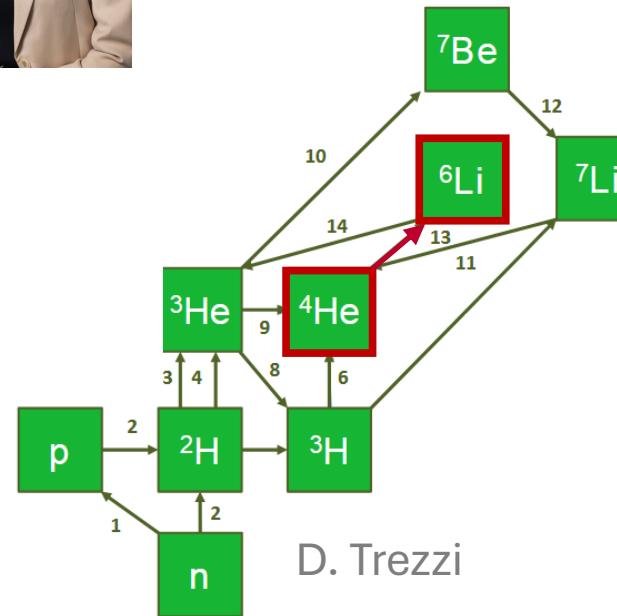


Will it work?

"Lithium or die" (L. Fahrian)



- ▶ Light elements up to Be produced in first 20 mins after Big Bang
- ▶ Observations and model predictions do not agree for abundances of ${}^6\text{Li}$ and ${}^7\text{Li}$ (*primordial Lithium problem*)
- ▶ BBN models rely on precise cross section data

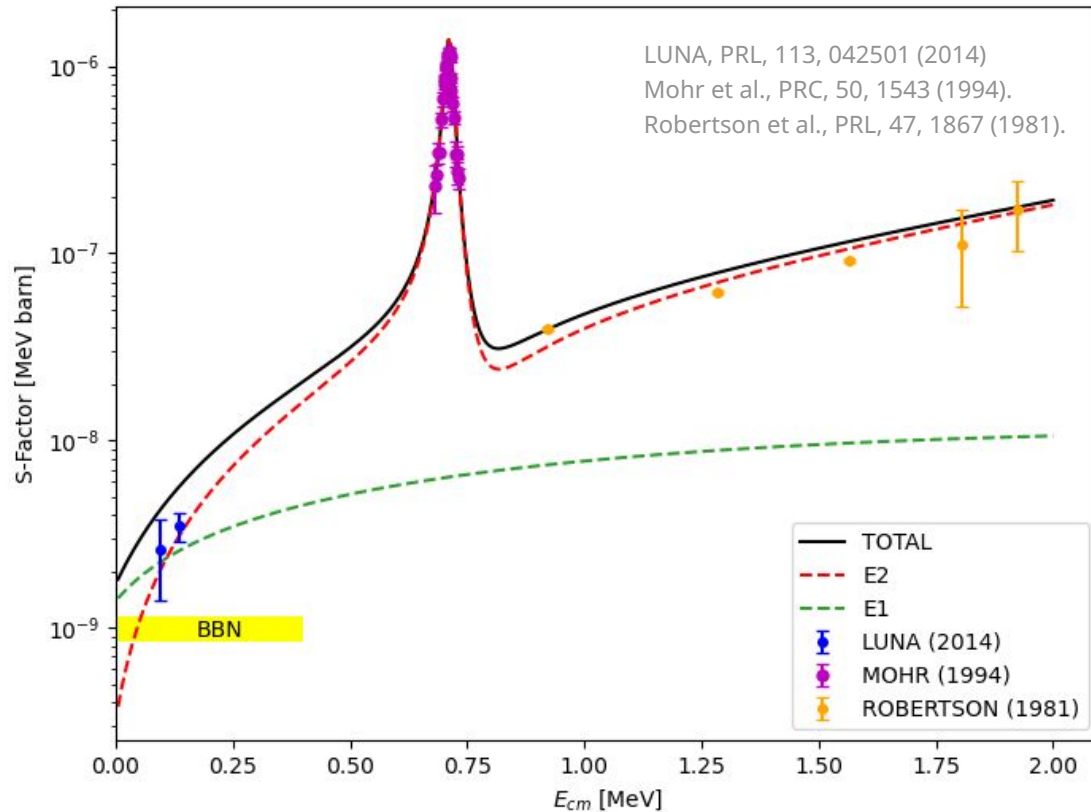


From Hammache et al., PRC, 82, 065803 (2010)



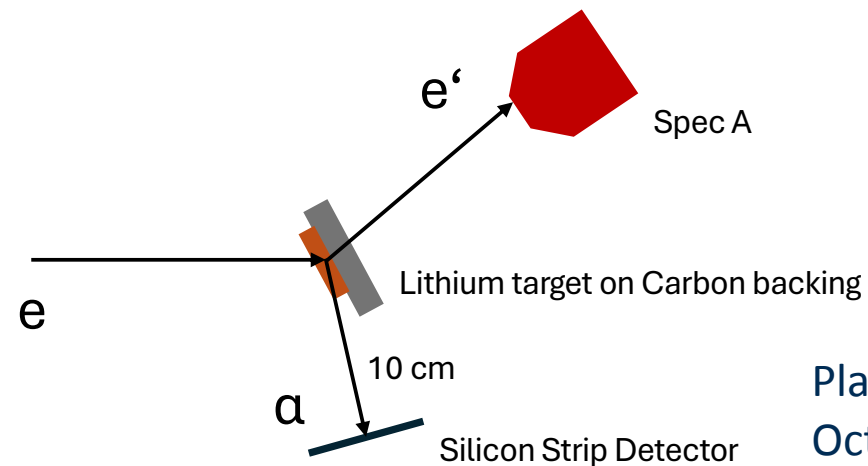
Will it work?

“Lithium or die” (L. Fahrian)



- ▶ Directly measured by LUNA collaboration in 2014
- ▶ Theoretical calculations available (M. Sanjinez)
- ▶ Low nuclear backgrounds

→ **Ideal reaction for a proof-of-principle measurement**



Planned at A1@MAMI in
October 2026

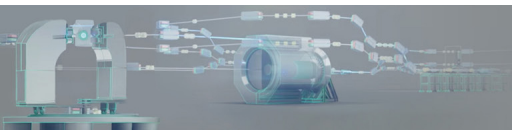


Are low energy positrons interesting?



Positrons are not a game changer here:

- ⊖ NO new reaction channels
- ⊖ NO direct access to astrophysical cross sections
- ⊖ NO dramatic reduction of uncertainties



Are low energy positrons interesting?



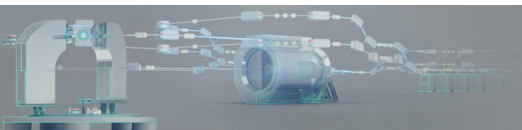
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Coulomb distortions (e^- vs e^+)

Negligible for light nuclei → potentially relevant for heavier systems (Gd/Sm, Mo/Ru)



Are low energy positrons interesting?



Positrons are not a game changer here:

- ⊖ NO new reaction channels
- ⊖ NO direct access to astrophysical cross sections
- ⊖ NO dramatic reduction of uncertainties

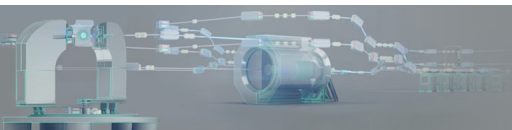


Coulomb distortions (e^- vs e^+)

Negligible for light nuclei → potentially relevant for heavier systems (Gd/Sm, Mo/Ru)

Benchmark reaction model (e^- vs e^+)

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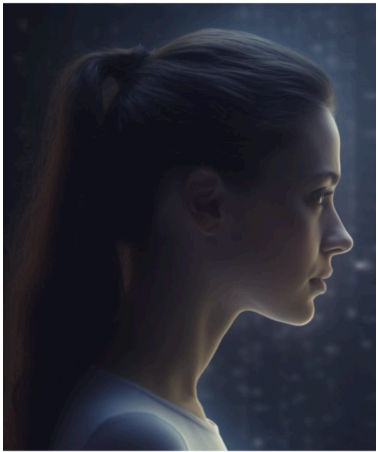


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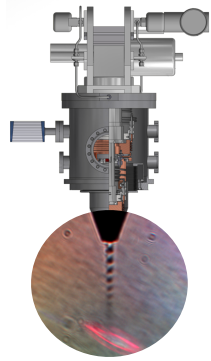
...BUT



The only two knobs...

Counts per PhD: can we do better?

- reducing “noise” (i.e. background)



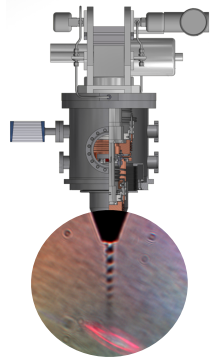
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- improving “signal” (e.g. beam currents, target density, efficiency)

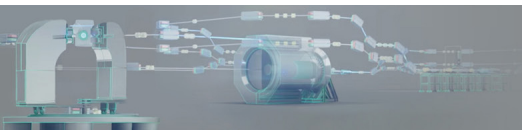


ERL-operation: up to 10 mA @ 105 MeV



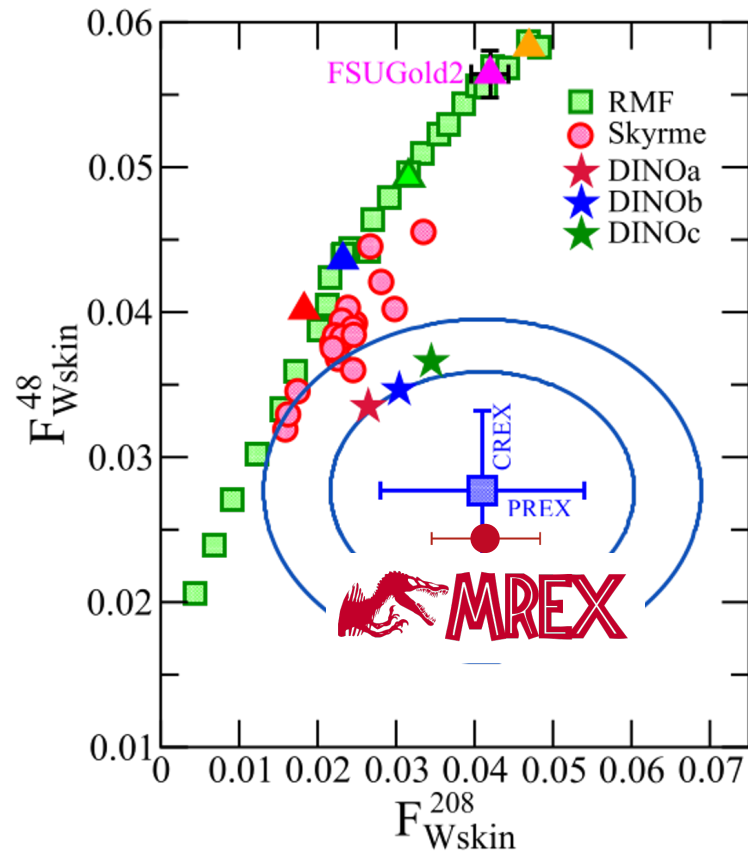
Precision across scales: from nuclei to stars

Different questions, **same frustration**: the physics changes the limitation do no!



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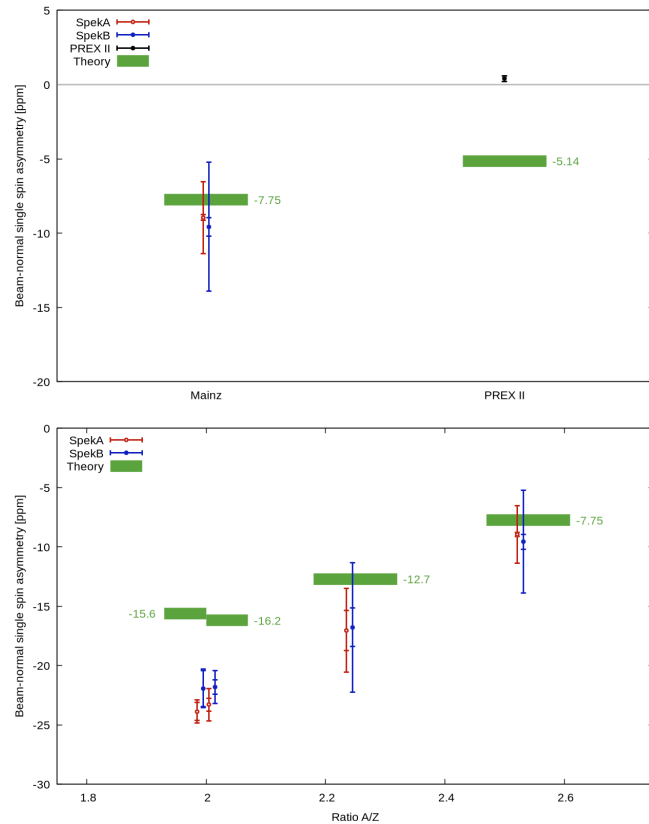


► P2 may finally resolve the “CREX/PREX Dilemma” (cit. JP)

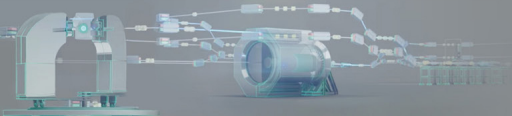


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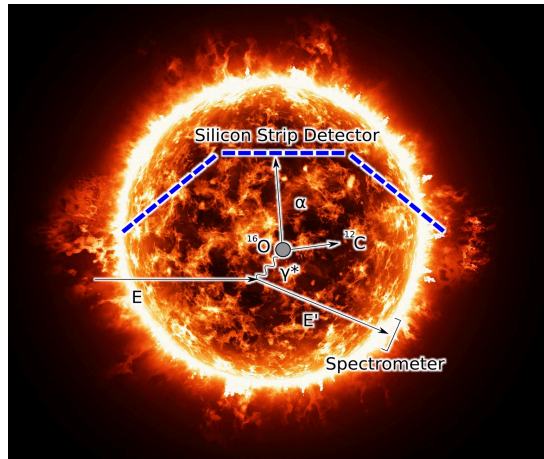


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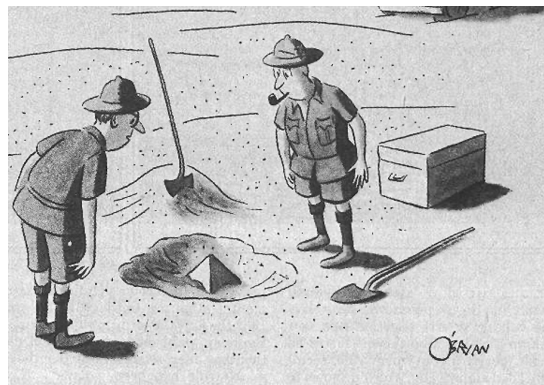


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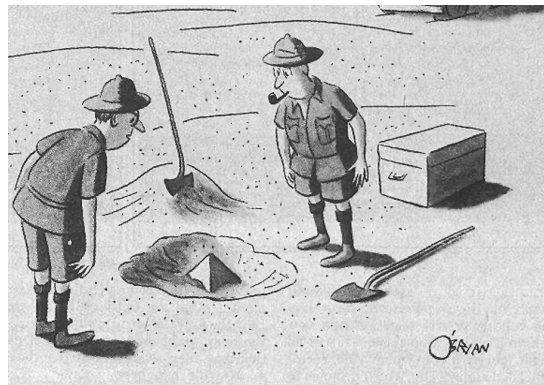
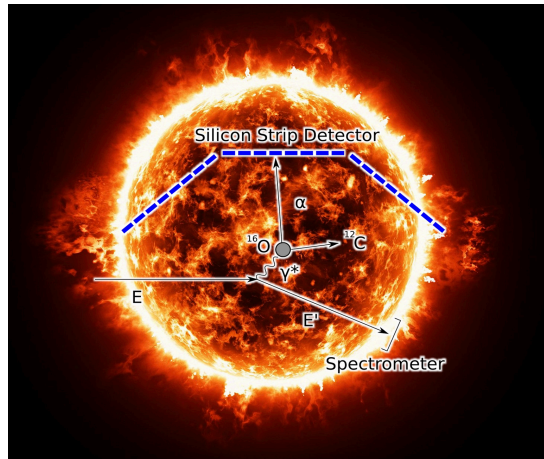


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«True art is due to 10% inspiration and 90% perspiration»

