Studies of the $^{16}O(\gamma^*,\alpha)^{12}C$ reaction for astrophysical relevance at MAGIX/MESA

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SFB School – Boppard – October 23, 2019

Topics

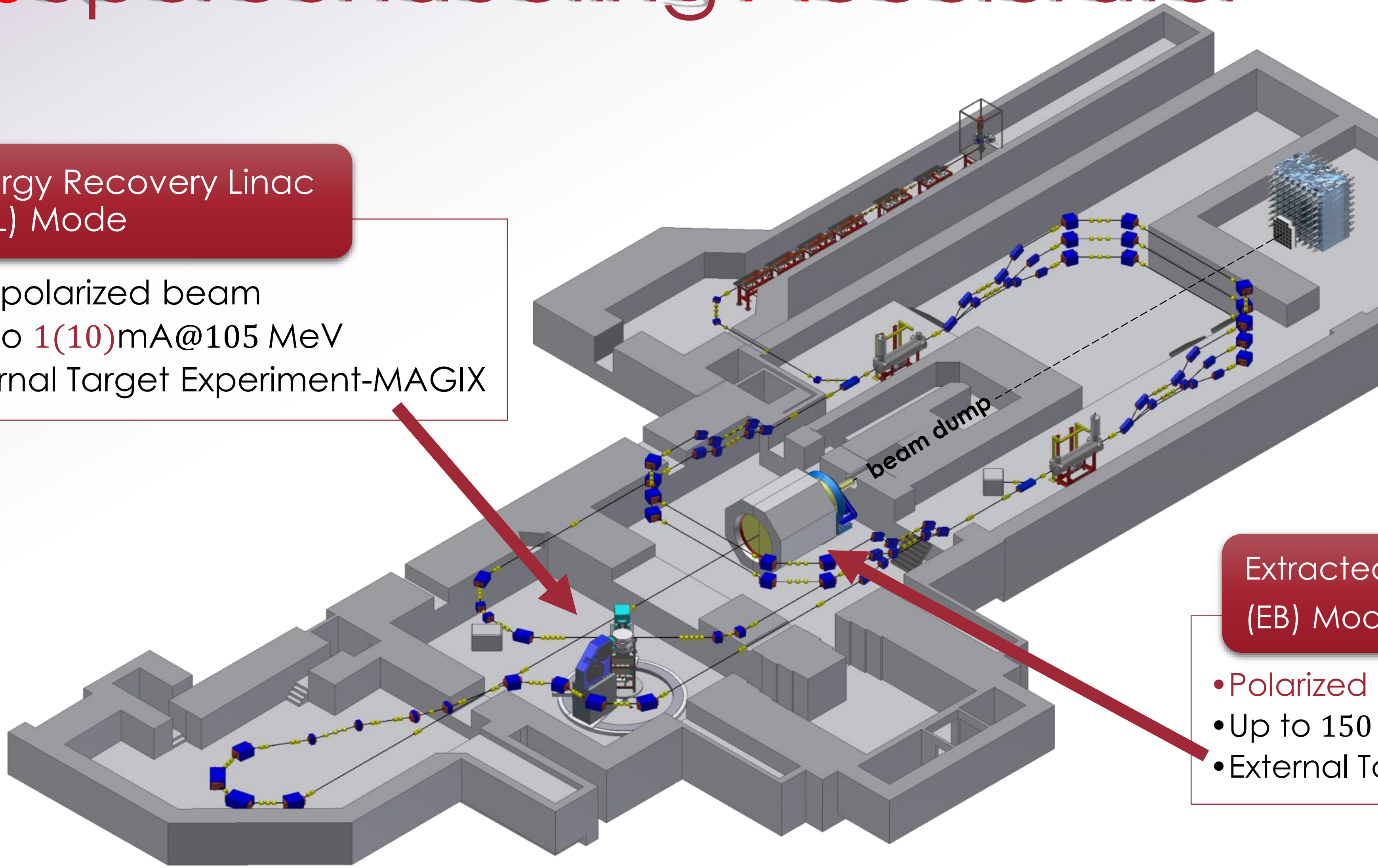
- MAGIX@MESA
- S-Factor of $^{12}C(\alpha,\gamma)^{16}O$
- Feasibility Studies
- Summary/Outlook

MAGIX@MESA

Mainz Energy-Recovering Superconducting Accelerator

Energy Recovery Linac (ERL) Mode

- (un)polarized beam
- Up to $1(10)$mA@105 MeV
- Internal Target Experiment-MAGIX



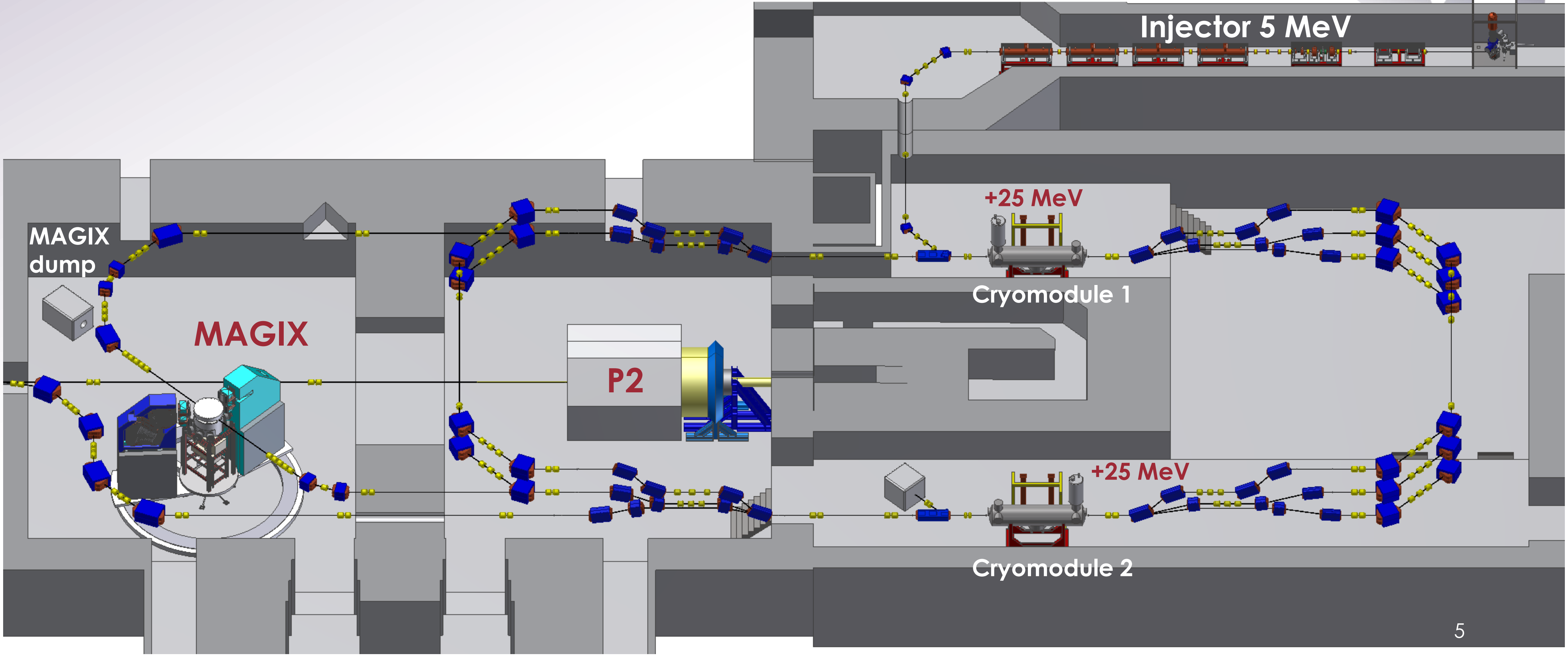
Dark MESA

- Parasitic Experiment
- Search for Dark Matter
- **Talk Manuel Mauch**

Extracted Beam (EB) Mode

- Polarized beam
- Up to $150\ \mu$A@155 MeV
- External Target Experiment – P2

Mainz Energy-Recovering Superconducting Accelerator



MesA Gas Internal target eXperiment - MAGIX

Internal Gas-Target

- Low energy high precision electron scattering
- Different gas types possible

Spectrometer

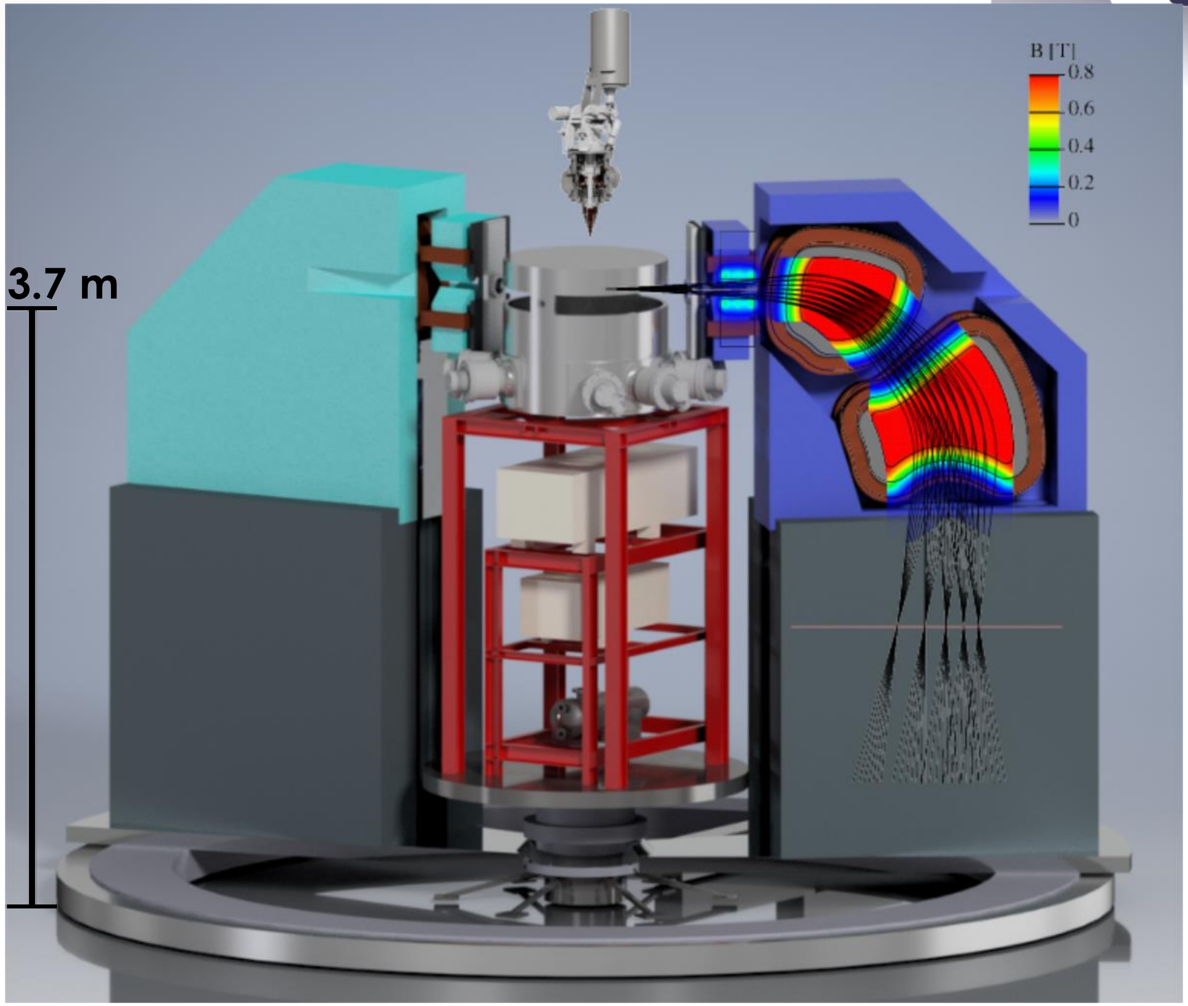
- High momentum resolution $\frac{\Delta p}{p} < 10^{-4}$
- Angular resolution $\Delta\theta < 0.05°$

Thin Target - High Beam Current

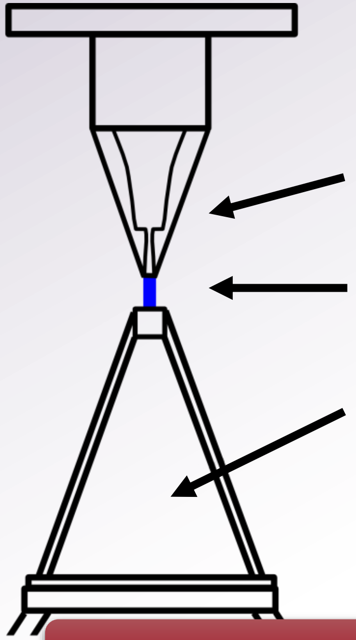
- High luminosity $\mathcal{L} \sim 10^{35}$ cm^{-2} s^{-1}

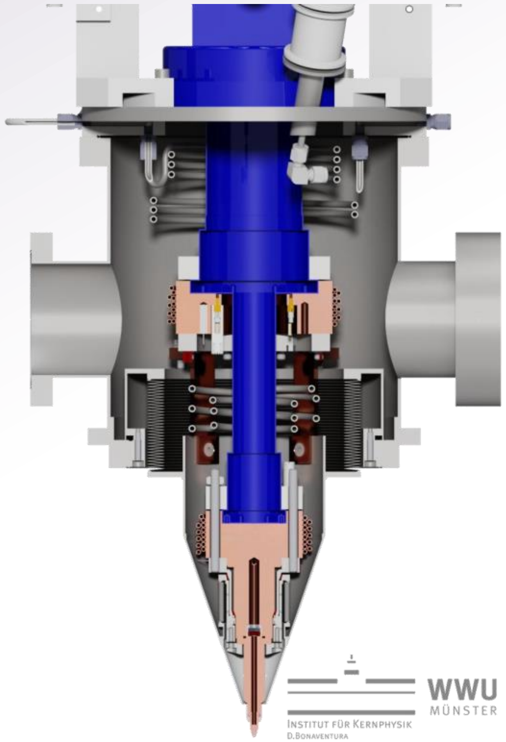
Physics

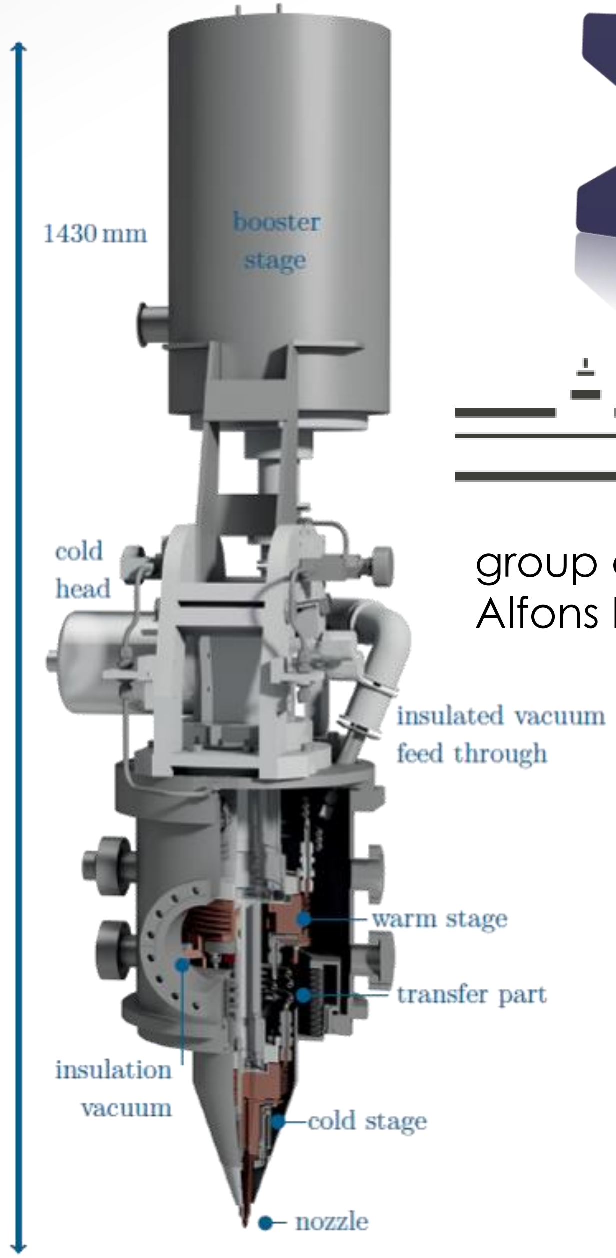
- e.-m. form factor measurements
- Search for messenger particles of the dark sector
- Reaction studies of astrophysical relevance
- Few Body reactions
- …



Jet-Target







WWU MÜNSTER

group of
Alfons Khoukaz

Gas-Jet

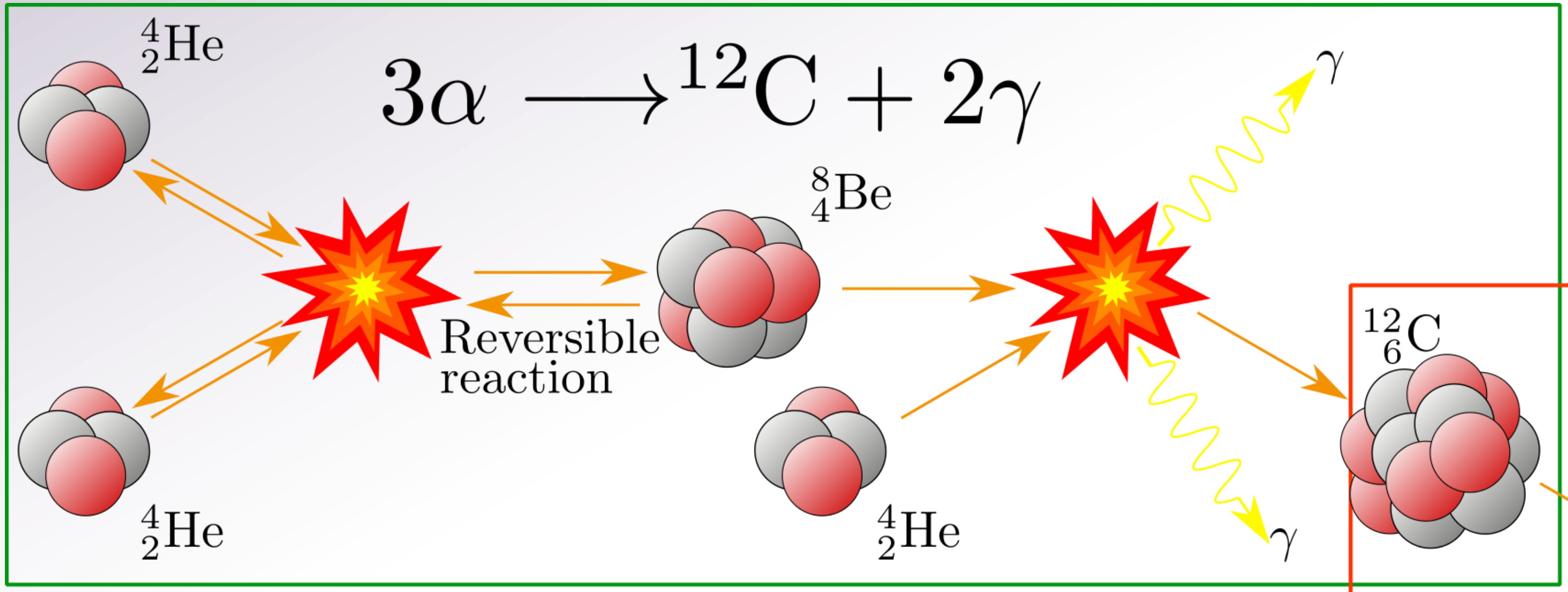
- Directive gas beam in vacuum
- ~Point-like (Diameter ~3 mm)
- $>10^{18}$ atoms / cm²

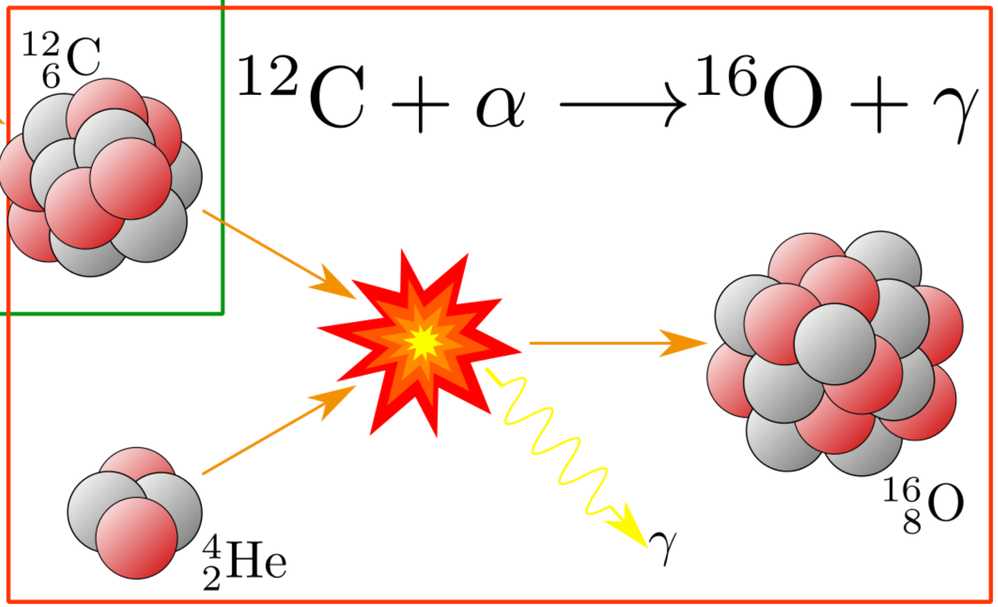
Three stages of cooling

- Precooling (Booster)
- 1st main stage: down to 28 K
- 2nd main stage: down to 8 K

S-Factor of $^{12}C(\alpha,\gamma)^{16}O$

Helium Burning in Red Giants

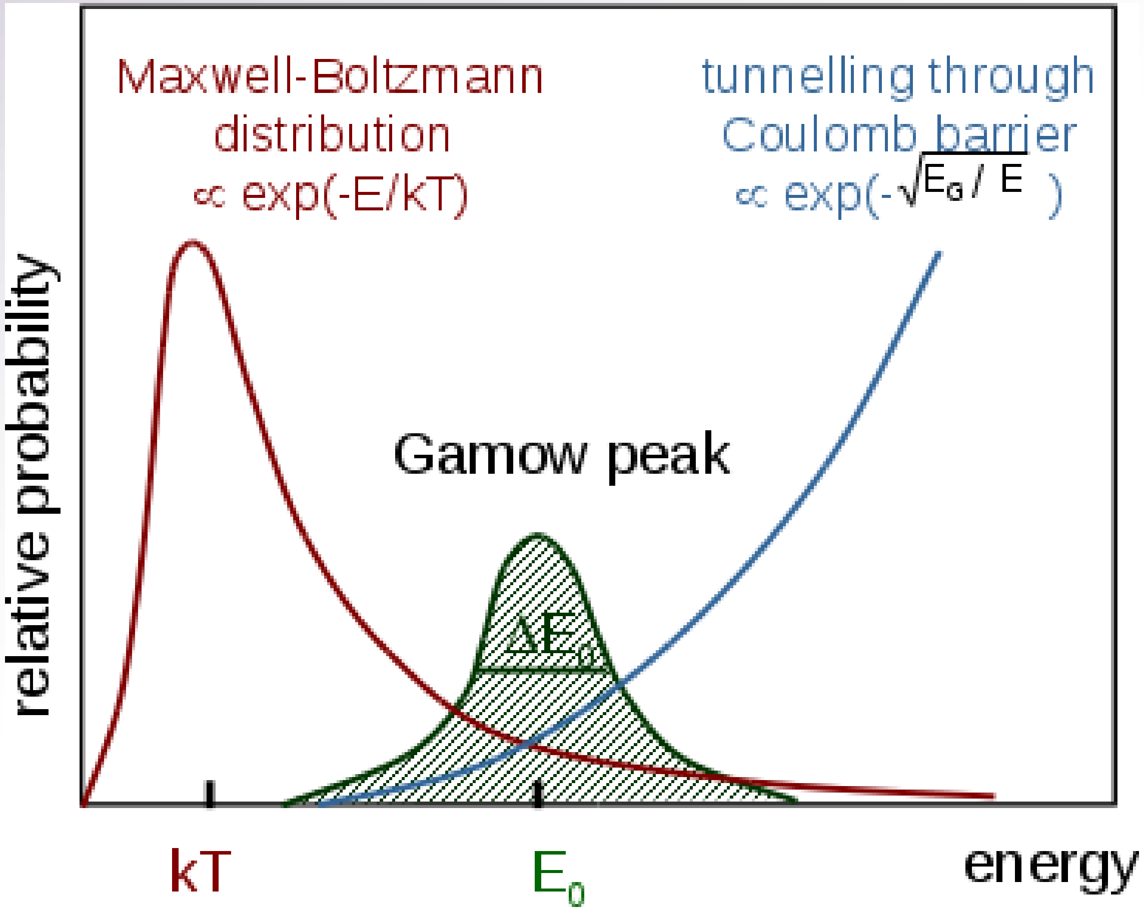




$^{12}C/^{16}O$ abundance ratio

- Descripe Further Burning states
- Nucleosynthesis in massive stars

Gamow-Peak



Maxwell-Boltzmann distribution

- Energy distribution in hot gas

$$\propto \mathbf{exp}(-\frac{\boldsymbol{E}}{\boldsymbol{kT}})$$

- $kT \sim 15\ \mathrm{keV}\ @\ T = 2 \cdot 10^8\mathrm{K}$

Coulomb penetration factor

- Tunnelling probability
- $\propto \mathbf{exp}(-\sqrt{\boldsymbol{E_0/E}}\,)$

Gamow-Peak

- $E_0 = \left(\frac{1}{2} b \cdot k \cdot T\right)^{\frac{2}{3}} \approx 300\ \mathrm{keV}$ $@\ T \approx 2 \cdot 10^8\ \mathrm{K}$

  $b = \pi\alpha Z_1 Z_2 \sqrt{2\mu c^2}$ with μ = reduced mass

Cp. Marialuisa Aliotta: Exotic beam studies in Nuclear Astrophyiscs

S-Factor of $^{12}C(\alpha,\gamma)^{16}O$

$$\sigma(E) = \frac{1}{E} e^{-\frac{2\pi Z_1 Z_2 \alpha c}{v}} \cdot S(E)$$

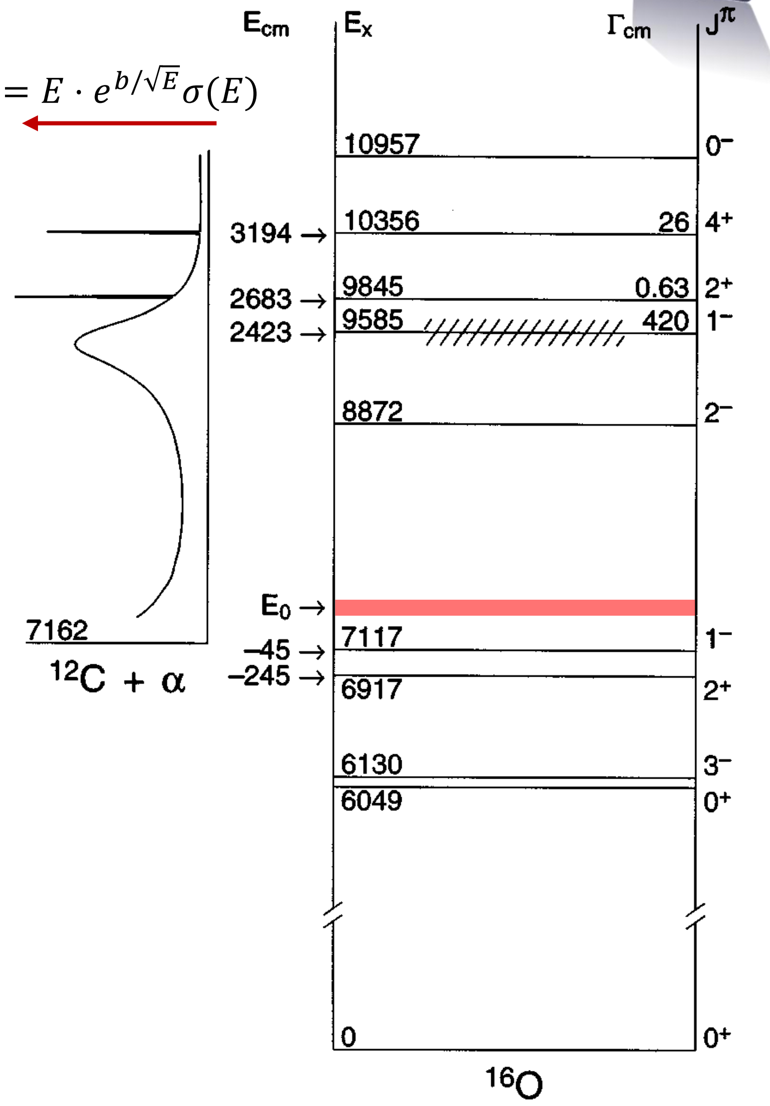
- **S-Factor $\boldsymbol{S(E)}$**
  - Deviation factor from trivial model
  - Represents any effect of nuclear structure
- Close to the Gamow-Peak the cross section is dominated by subthreshold resonances

  $\boldsymbol{\sigma_{l=1}}$ and $\boldsymbol{\sigma_{l=2}}$

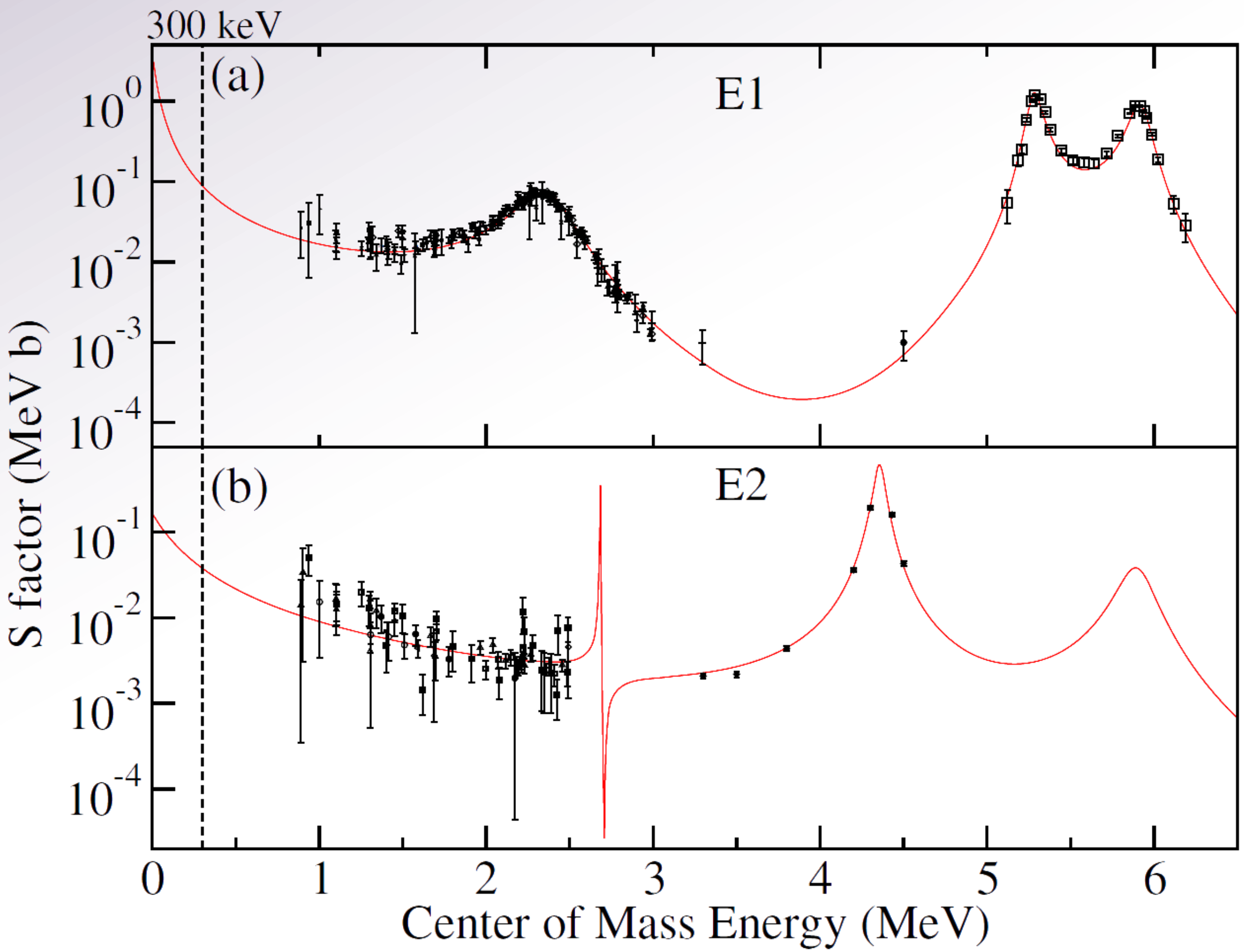
Gamow-Peak

- $E_0 = \left(\frac{1}{2} b \cdot k \cdot T\right)^{\frac{2}{3}} \approx 300$ keV@ $T \approx 2 \cdot 10^8$ K

$$S(E) = E \cdot e^{b/\sqrt{E}} \sigma(E)$$



Measurement of S-Factor

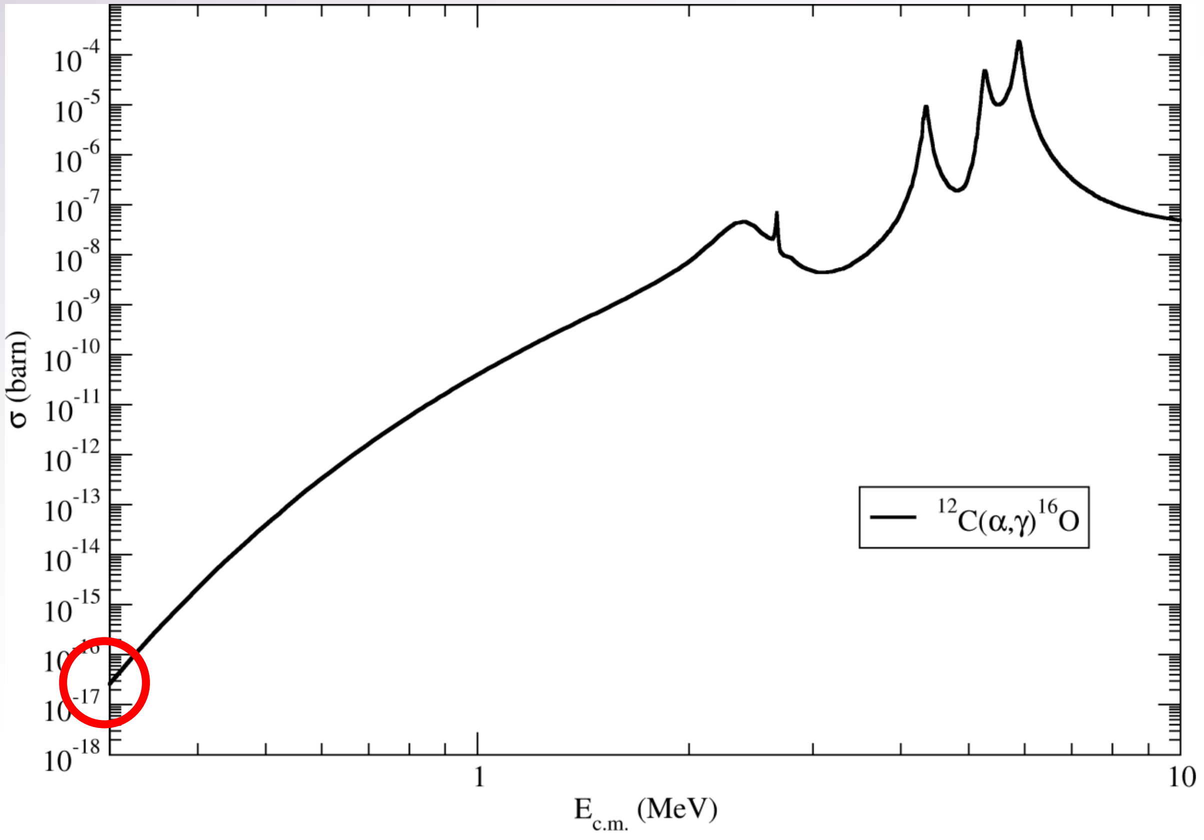


Extrapolate $S(300\ \text{keV})$

- Kunz et al. (2001)
  $165 \pm 50\ \text{keV} \cdot \text{b}$
- Hammer (2005)
  $162 \pm 39\ \text{keV} \cdot \text{b}$
- Schürmann (2012)
  $161 \pm 19_{\text{stat}}\ {}^{+8}_{-2}{}_{\text{sys}}\ \text{keV} \cdot \text{b}$

Cp. deBoer: The $^{12}C(\alpha;\gamma)^{16}O$ reaction and its implications for stellar helium burning

Cross Section



Measurement

- Cross section drops rapidly for $E < 1$ MeV
- $\sigma(E_0) \sim 10^{-17}$ barn
  -> High luminosity necessary
- Precise low-energy measurements required

Motivation

- Direct measurements never done @$E_{\text{cm}} < 0.9$ MeV

Cp. Simulation of Ugalde 2013

Feasibility Studies

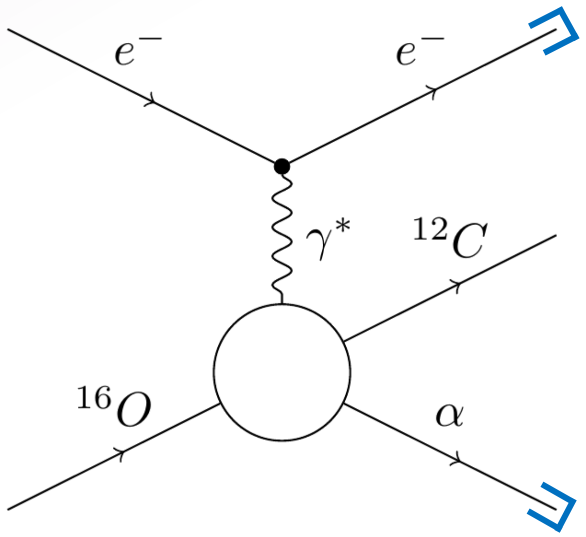
Feasibility Studies at MAGIX@MESA

Experimental Setup

- Inelastic e^- scattering on oxygen gas with low $|q|^2$ (quasi real photons)

Measurement of Coincidence (e^-, α)

- Suppress background
- Determine α-particle angular distribution



Feasibility Studies at MAGIX@MESA

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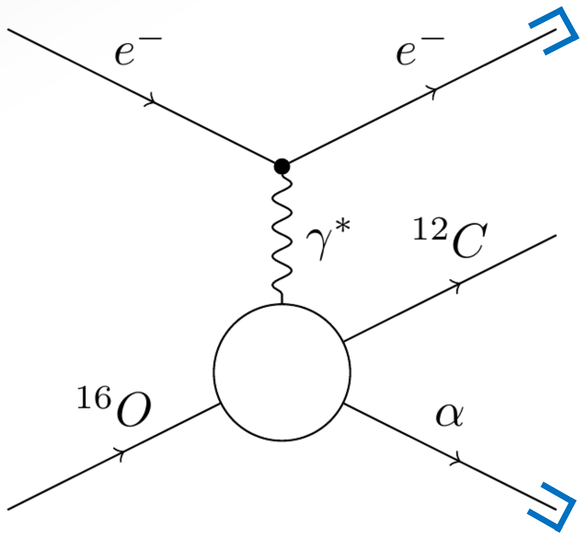


Inelastic scattering cross section

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{4\alpha^2 E'^2}{q^4}\left[W_2(q^2,\nu)\cdot\cos^2\left(\frac{\theta}{2}\right) + 2W_1(q^2,\nu)\cdot\sin^2\left(\frac{\theta}{2}\right)\right]$$

Relation beween structural functions and the transversal / longitudinal part of the virtual photon cross section σ_T, σ_L

$$W_1 = \frac{\kappa}{4\pi^2\alpha}\sigma_T \qquad W_2 = \frac{\kappa}{4\pi^2\alpha}\left(1-\frac{\nu^2}{q^2}\right)^{-1}(\sigma_L + \sigma_T)$$

with $\kappa = \frac{W^2 - M^2}{2M}$

For $|q^2| \to 0$: σ_L vanishes and $\sigma_T \to \sigma^{tot}(\gamma + {}^{16}O \to X)$

$$\frac{d^5\sigma}{d\Omega_e dE' d\Omega^*} = \Gamma \frac{d\sigma_v}{d\Omega^*}$$

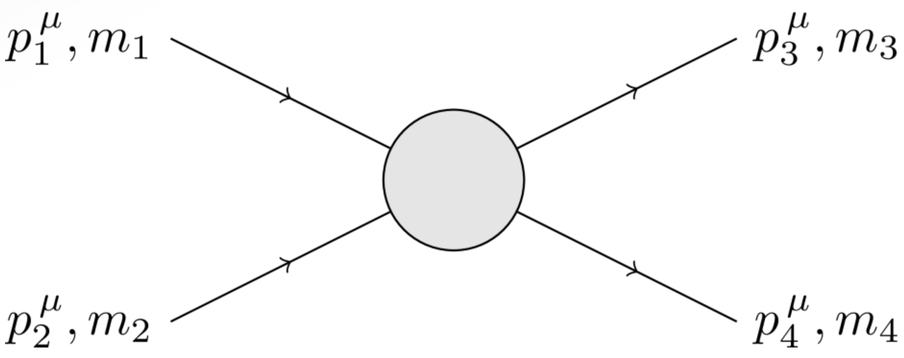
with

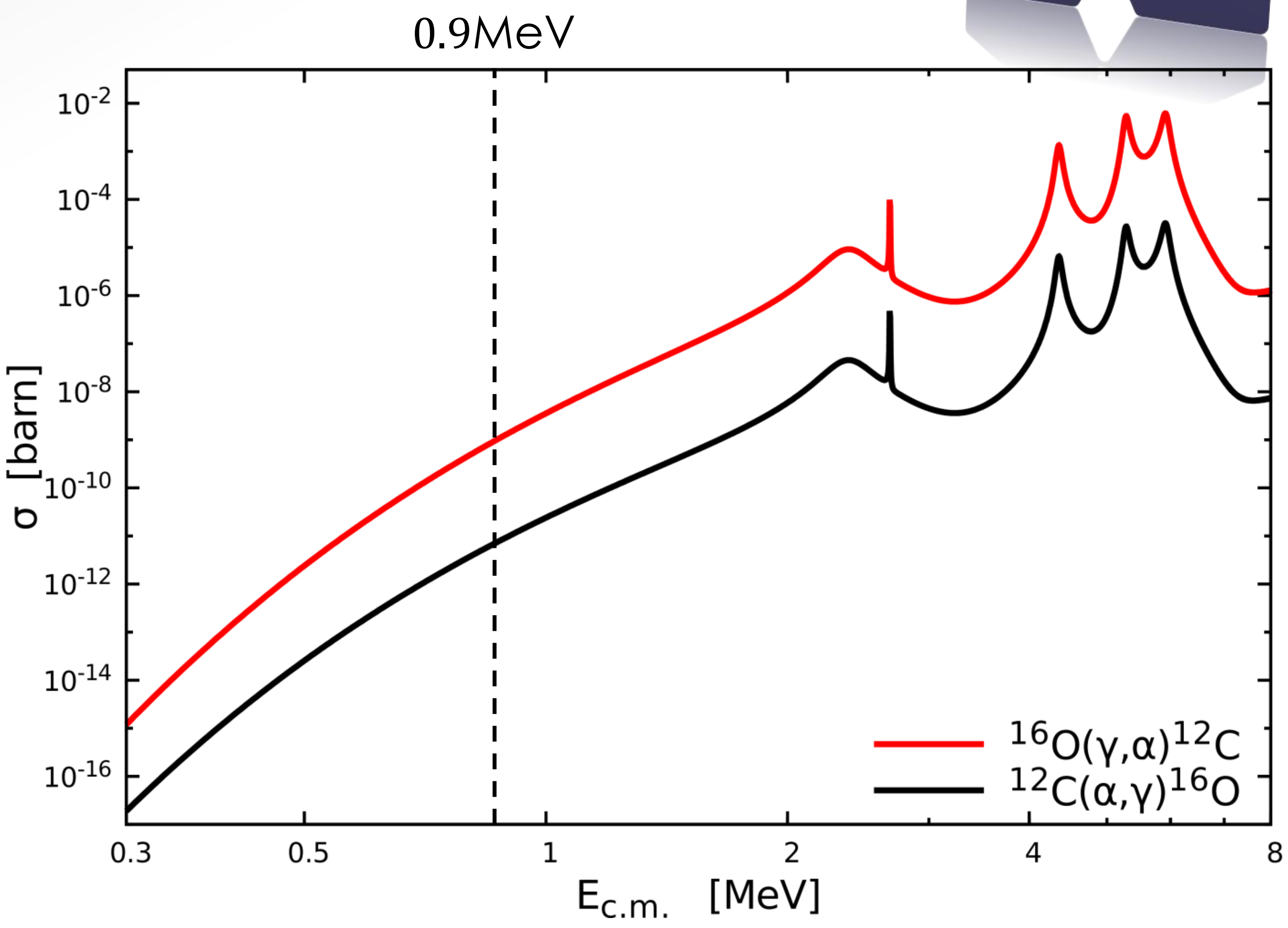
$$\Gamma = \frac{\alpha\kappa}{2\pi^2|q^2|}\cdot\frac{E'}{E}\cdot\frac{1}{1-\varepsilon} \qquad \varepsilon = \left(1 - 2\frac{\nu^2 - q^2}{q^2}\tan^2\left(\frac{\theta}{2}\right)\right)^{-1}$$

Time Reversal Factor

Time Revearsed Reaction

- Phase space examination under T-symmetry invariance
$$\frac{\sigma_{i\to f}}{\sigma_{f\to i}} = \frac{(2I_3+1)(2I_4+1)}{(2I_1+1)(2I_2+1)}\cdot\frac{|\vec{p}|_f^2}{|\vec{p}|_i^2}$$
- Cross section gains a factor of $\times 50$





Cp. Mayer-Kuckuk Kernphysik: Chapter 7.3

Simulation – General Setup

Spectrometer

- Minimum angular $\theta \sim 13°$

α –Detector

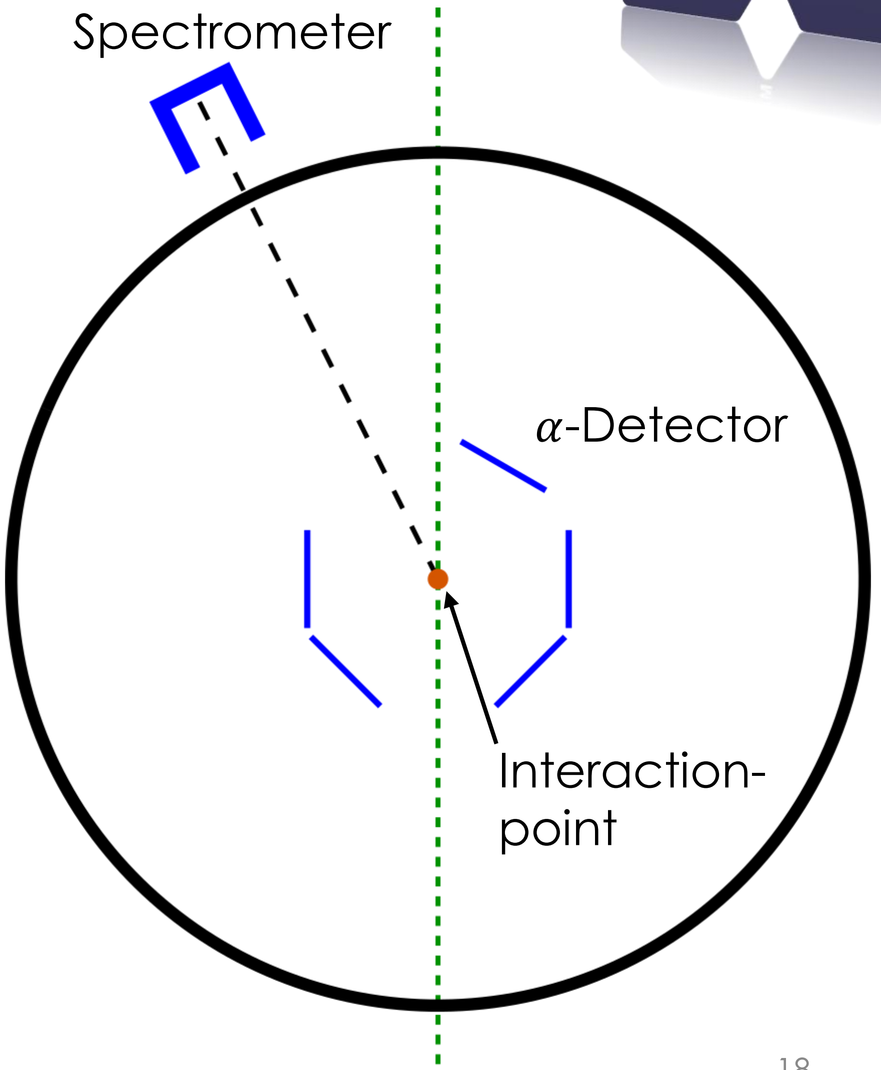
- Segmented Silicon-Detector
- 50×50 mm²
- 5 Detectors with $d = 10\text{cm}$
- Different angular $\theta = 30°, \pm 90°, \pm 120°$

Oxygen Gas-Jet

- $2 \cdot 10^{18}$ at/cm²
- Diameter = 3 mm

Parameters

- Luminosity $L \sim 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$
- Time $\text{T} = 4$ weeks
- S-Factor from AZURE2 (JINA)



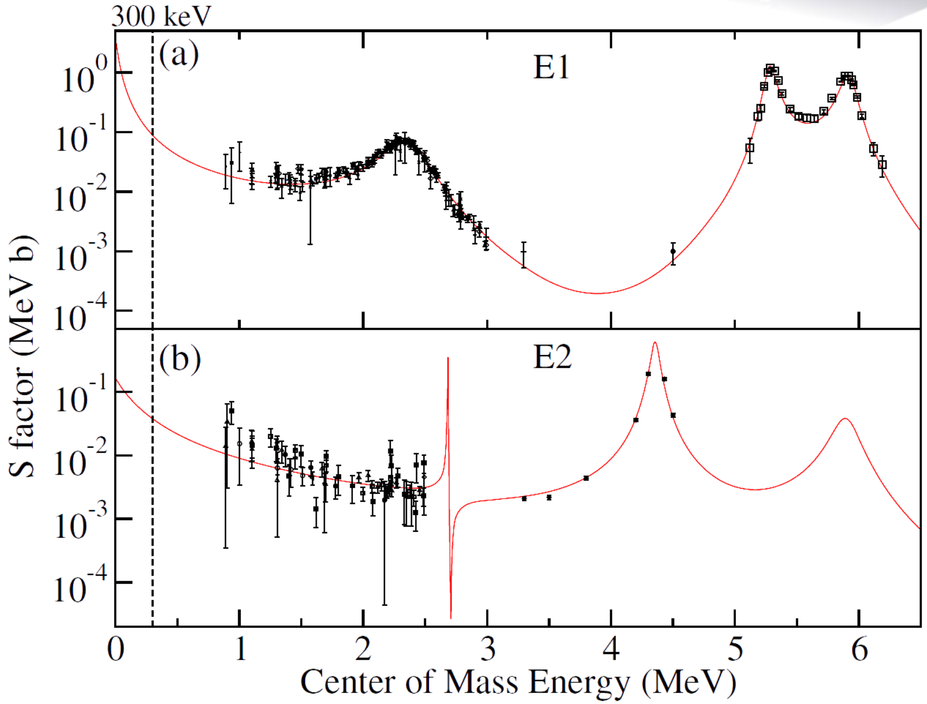
Phase 1 – MAGIX@MAMI

MAGIX@MAMI

- MAMI (Mainzer Microtron) is a running accelerator in Mainz
- $E = 195\text{MeV}@100\mu\text{A}$
- First experiment expected in **2020**
- **Talks: Philipp Eckert and Edoardo Mornacchi**

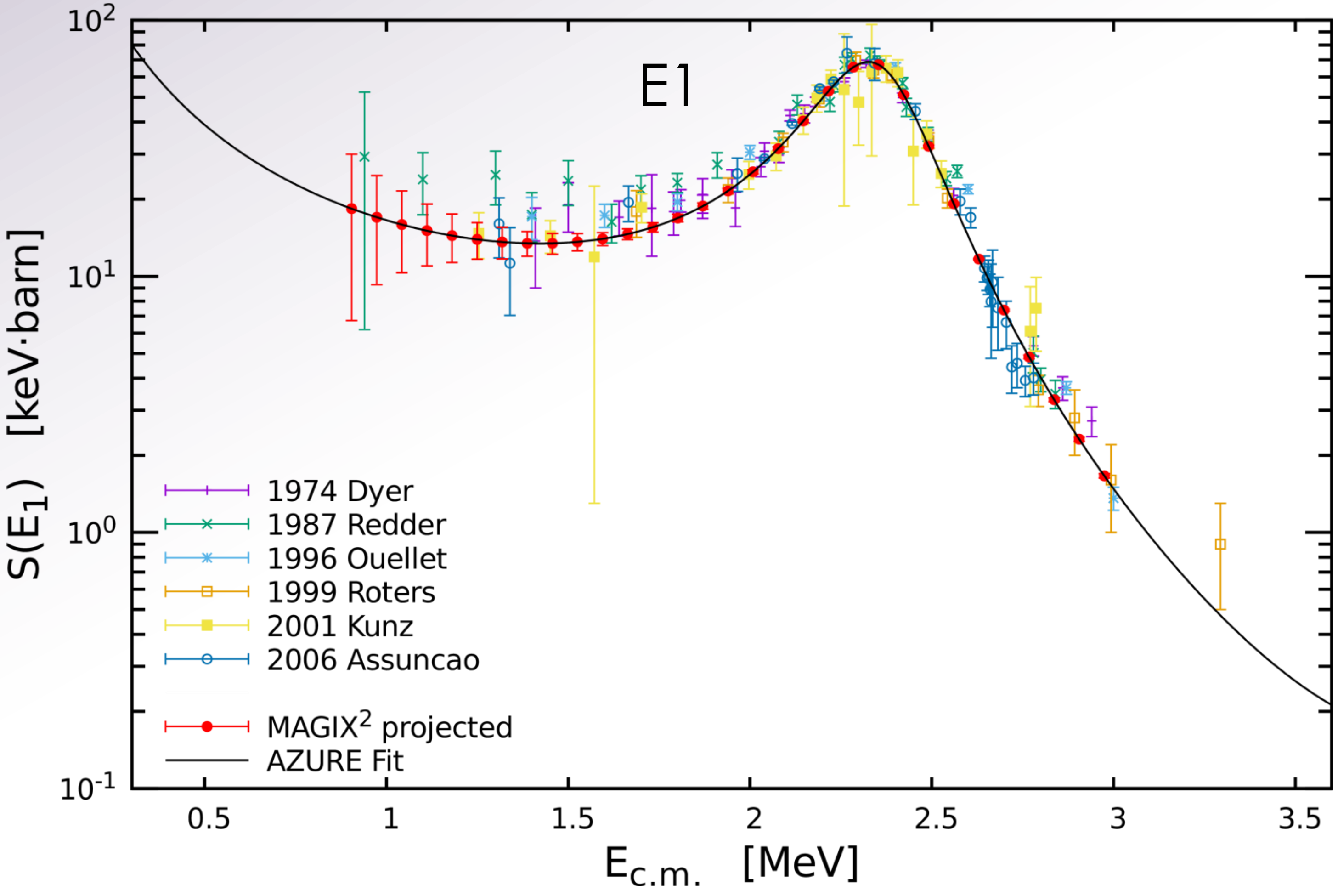
The goal

- Test Silicon-Strip Detectors for the $\alpha -$ particles detection
- Measurement of the cross section in the well known area of $E_{cm} > 1.8\ MeV$
- Compare results with existing data
- Determine the unknown longitudinal parameter



Cp. R. deBoer et al. „The $^{12}C(\alpha;\gamma)^{16}O$ reaction and its implications for stellar helium burning"

Phase 2 – MAGIX@MESA Simulation



Setup

- MAGIX@MESA (expected in **2023**)
- $E = 105$ MeV@1 mA
- Spectrometer $\theta \sim 13°$

Result

- We can measure the S-Factor for $E_{\text{c.m.}} > 0.9$ MeV
- Compatible precision to existing measurements
- Expected statistical errors increase significantly for $E_{\text{c.m.}} < 0.9$ MeV

How to improve this result

Increase cross section

- $$\sigma \propto \frac{E'}{E|q^2|} = \frac{1}{E^2 \sin^2\frac{\theta}{2}}$$

Modify Parameters

- Decrease energy:

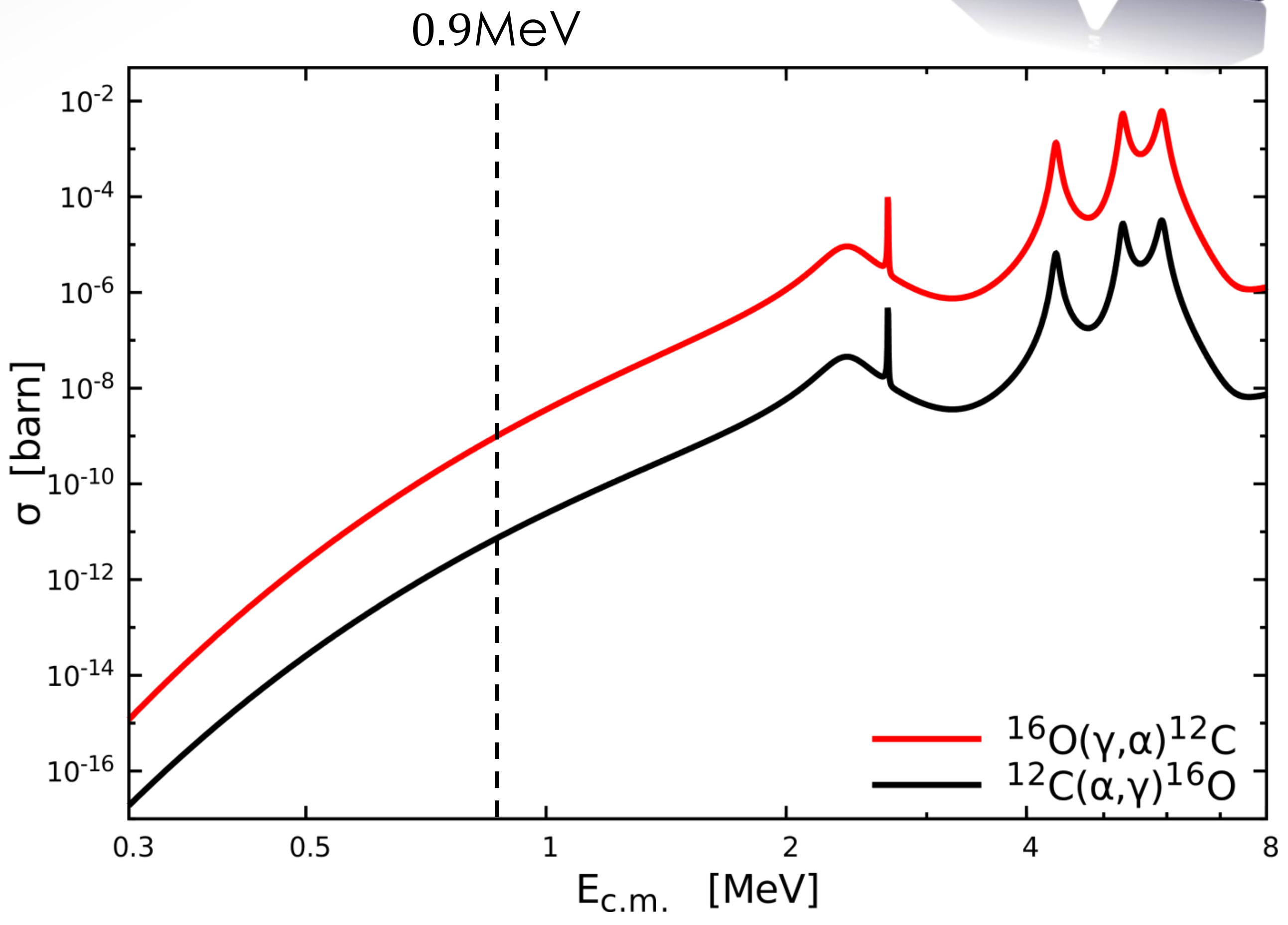
  $E = 105\ MeV$ to $10\ MeV \quad \Rightarrow \quad \sigma \times 100$

  (maximum factor)

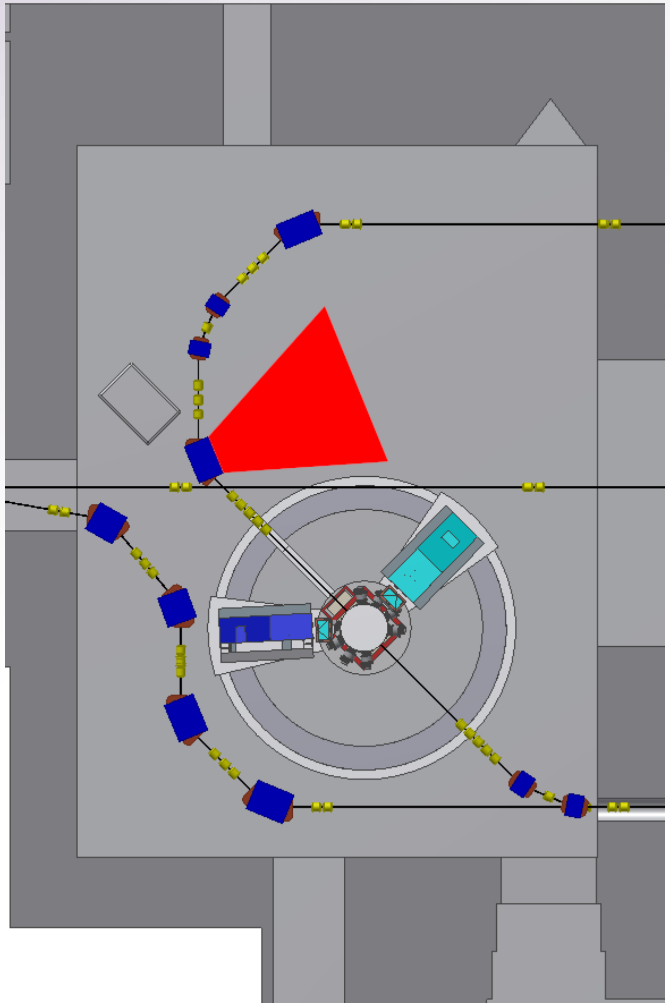
- Decrease angle:

  $\theta = 10°$ to $1° \quad \Rightarrow \quad \sigma \times 100$

  $\theta = 10°$ to $0.1° \quad \Rightarrow \quad \sigma \times 1000$



Phase 3 – Zero Degree Tagger



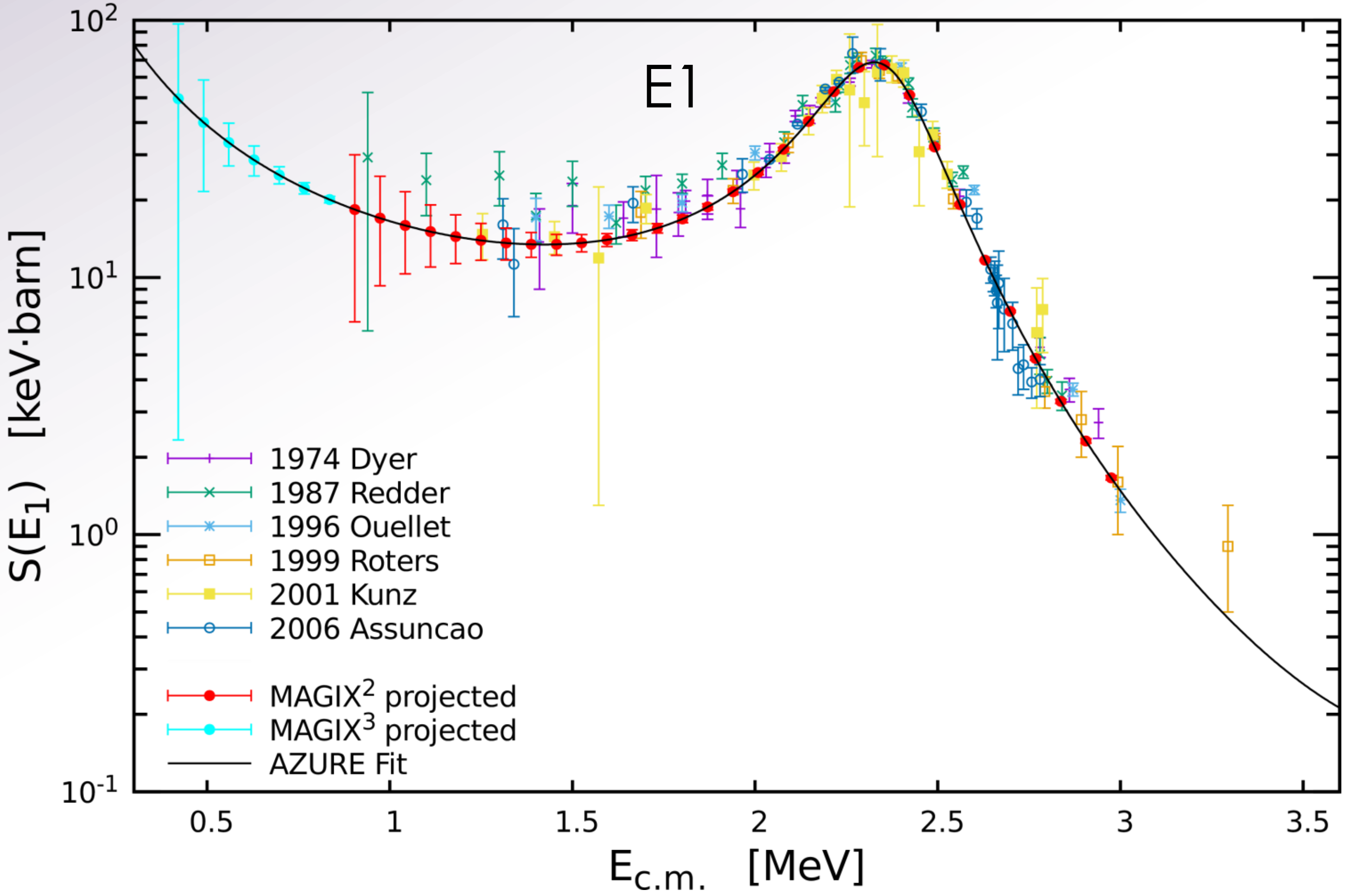
ERL Mode Integrated Tagger

- Use first deflection magnet to seperate scattered electrons from beam
- Minimum Energy loss
- Theta-Acceptance $\theta_e = 0 - 0.5°$

Tagger Design

- Under progress
- Special design for deflection magnet
- Deflection angle 45°
- Distance ~ 1m
- Width ~ 80cm

Phase 3 – Simulation of Zero Degree Tagger



Setup

- MAGIX@MESA
- $E = 105$ MeV@1 mA

Zero-Degree Tagger

- Simulation uses Ideal detector
- Theta-Range $\theta_e = 0 - 0.5\,°$

Result

- Statistical errors much smaller for

$$E_{c.m.} > 0.5\ MeV$$

Summary/Outlook

Summary / Outlook

S-Factor of $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$

- Inelastic electron scattering on oxygen gas
- Detection of the scattered electron and the α – particle in coincidence

MAGIX²

- Spectrometer at minimum angular $\theta \sim 13°$
- We can measure the S-Factor for $E_{\mathrm{c.m.}} > 0.9\ \mathrm{MeV}$
- Compatible precision to existing measurements

MAGIX³

- Zero Degree Tagger will improve the results
- Simulation predicts: We can measure the S-Factor for $E_{\mathrm{c.m.}} > 0.5\ \mathrm{MeV}$

THANK YOU FOR YOUR ATTENTION!

http://magix.kph.uni-mainz.de

SFB 1044

ACCELENCE

PRISMA

Massachusetts Institute of Technology

University of Ljubljana

Westfälische Wilhelms-Universität Münster

Johannes Gutenberg Universität Mainz

BACKUP

MAGIX - Spectrometers

Spectrometer

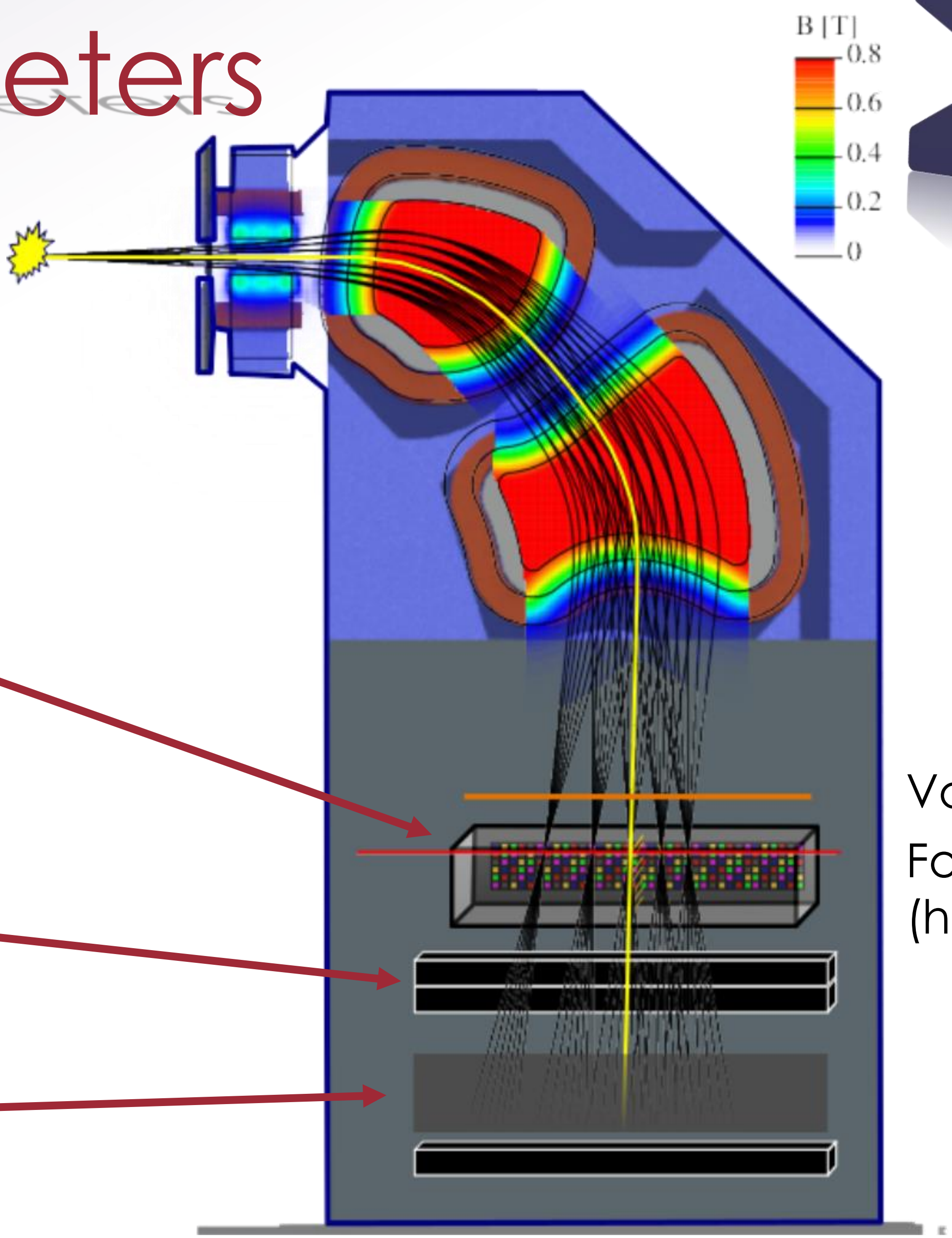
- High momentum resolution $\frac{\Delta p}{p} < 10^{-4}$
- Angular resolution $\Delta\theta < 0.05°$

Time Projection Chamber

- Minimal radiation thickness
- Tracking multiple trace points
  -> 5(multiplicities) x 20(rows)

Trigger-System

- Trigger, Timing and PID purposes
- 4 active segmented scintillator layers
- Lead shield in between



Vacuum foil

Focal plane (horizontal)

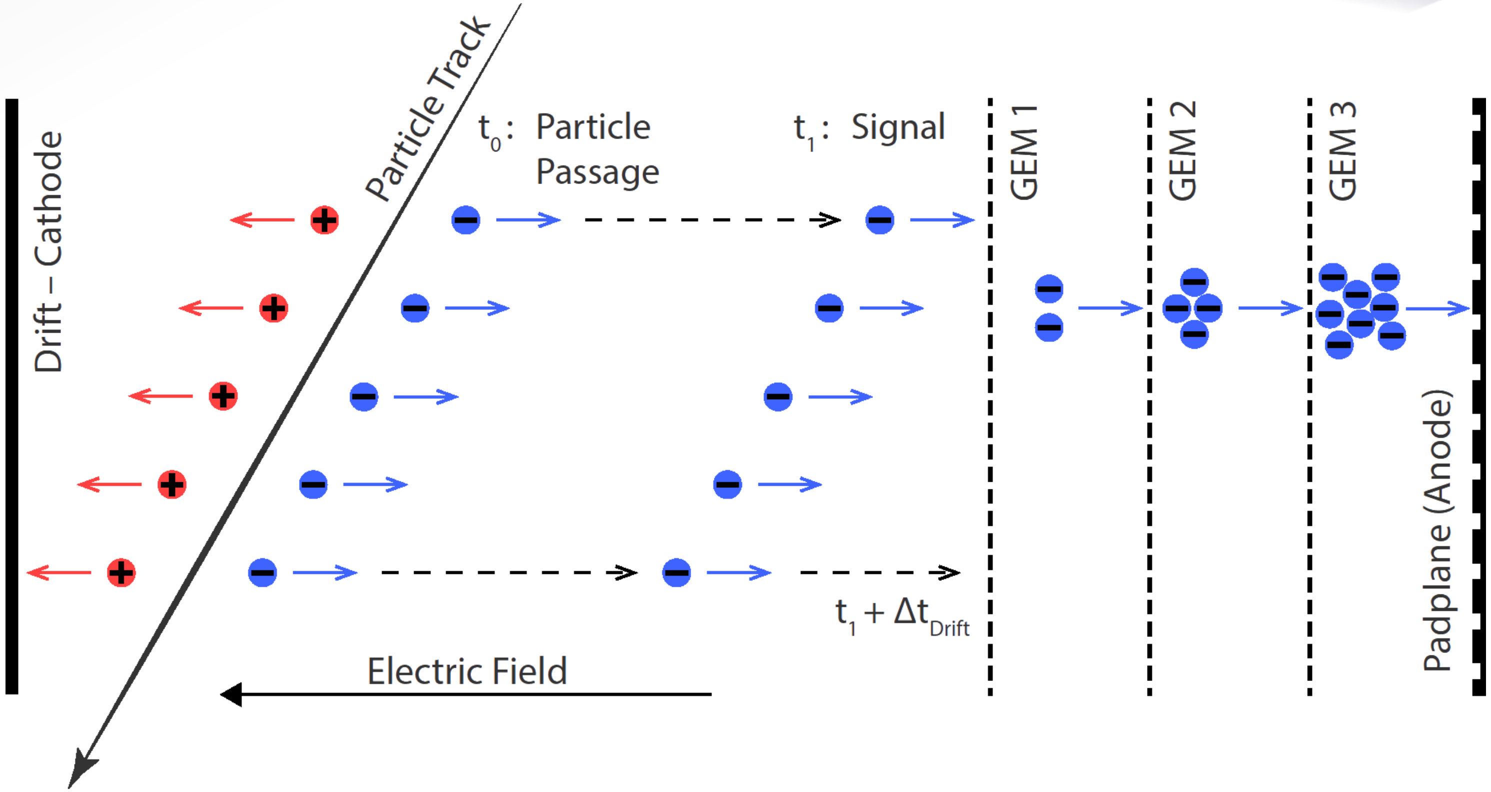
Time Projection Chamber

Working principle

- Particle transits active volume
- Ionisation
- Electrons drift along the E-field to readout
- GEMs amplify the electrons

3D track reconstruction

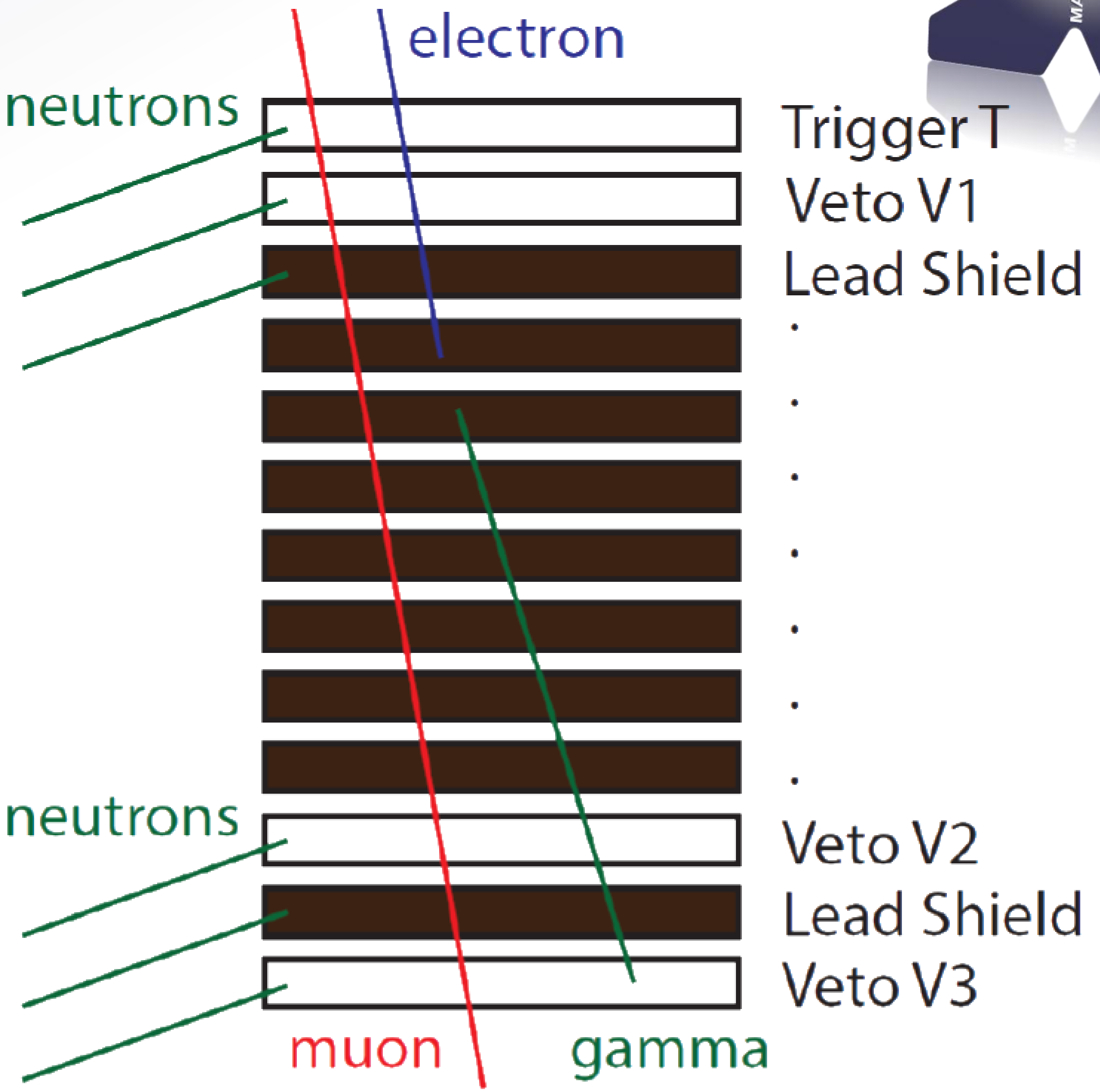
- X and Y component in readout plane
- Z component with drift time



Trigger-System

Trigger and Veto-System

- Electrons and muons point in the same direction
- Beam induced neutrons
- Different particles have different detector signatures



MAMI and MESA at KPH Mainz

MAMI

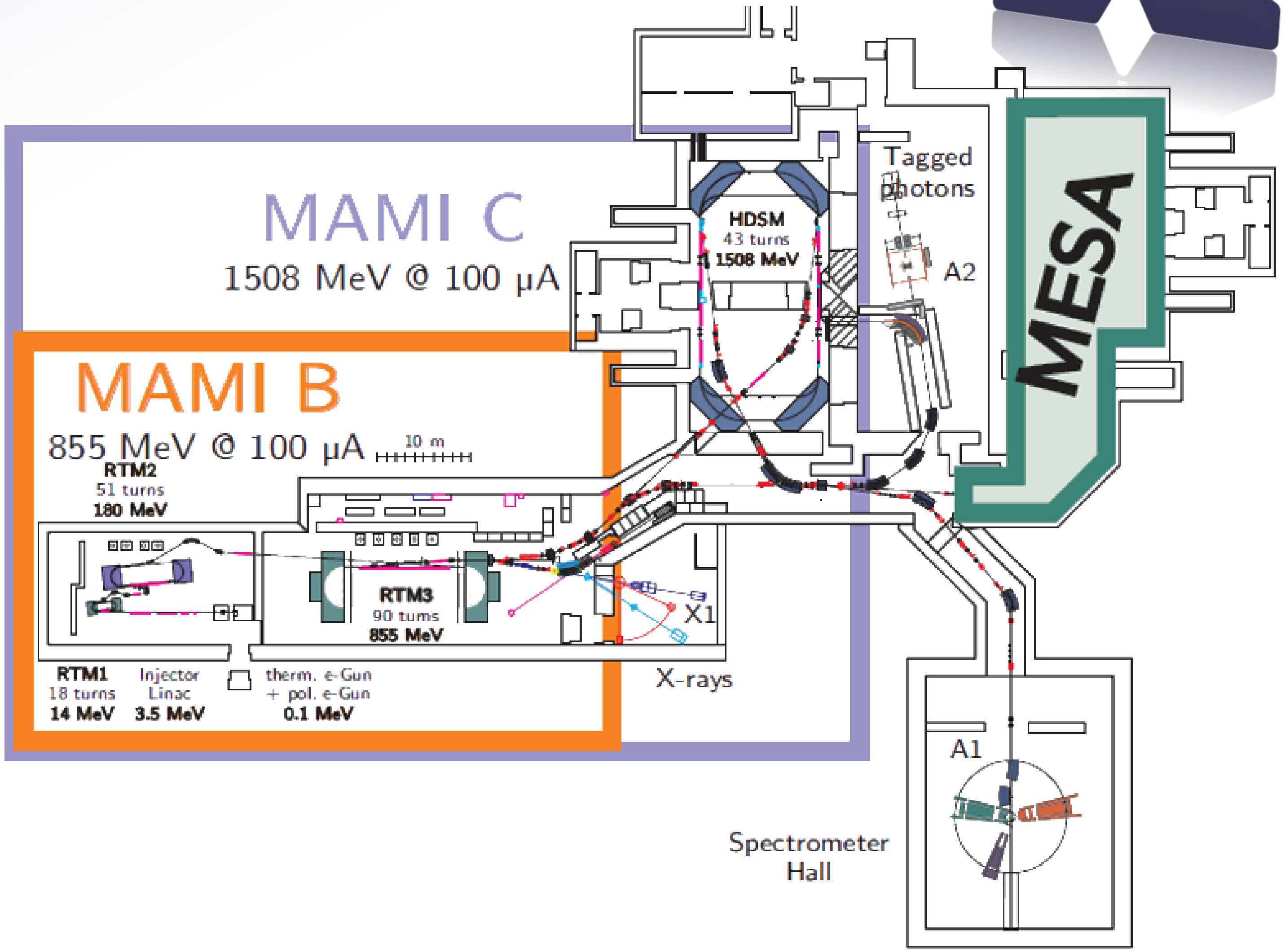
- Electron Accelerator
- Operating since >25 years
- Up to 1508 MeV@100 µA

Physics

- Electron scattering
- Real photos
- X-Ray radiation

MESA

- Build in the existing facility + Extension for MESA halls



Timeline for MESA

Construction

- Construction of the extended MESA hall will delay the construction start of the accelerator and experiments to at least **2021**.

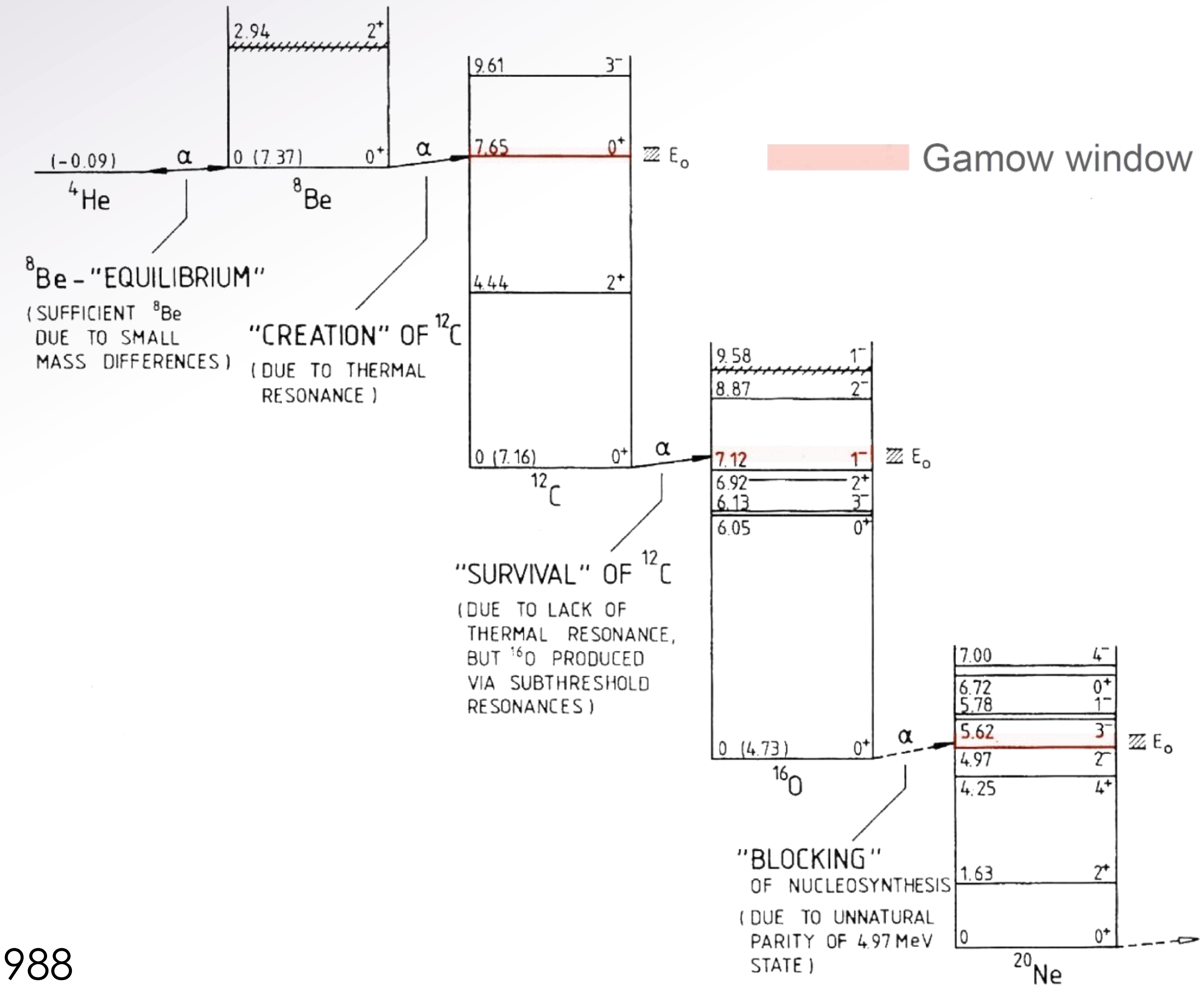
Commissioning

- Commissioning of the accelerator is planned to start in **2022**

First beam

- First beam to experiments can be expected **in 2023**

Helium Burning in Red Giants



Rolfs and Rodney, 1988

Differential cross section

$$4\pi \left(\frac{d\sigma}{d\Omega}\right)_{(\gamma,\alpha)} (E,\theta)$$

$$= \sigma_{E1}(E)[1 - P_2(\cos\theta)]$$

$$+\sigma_{E2}(E)\left[1 + \frac{5}{7}P_2(\cos\theta) - \frac{12}{7}P_4(\cos\theta)\right]$$

$$+6\cos\Phi_{12}(E)\sqrt{\frac{\sigma_{E1}(E)\sigma_{E2}(E)}{5}}[P_1(\cos\theta) - P_3(\cos\theta)]$$

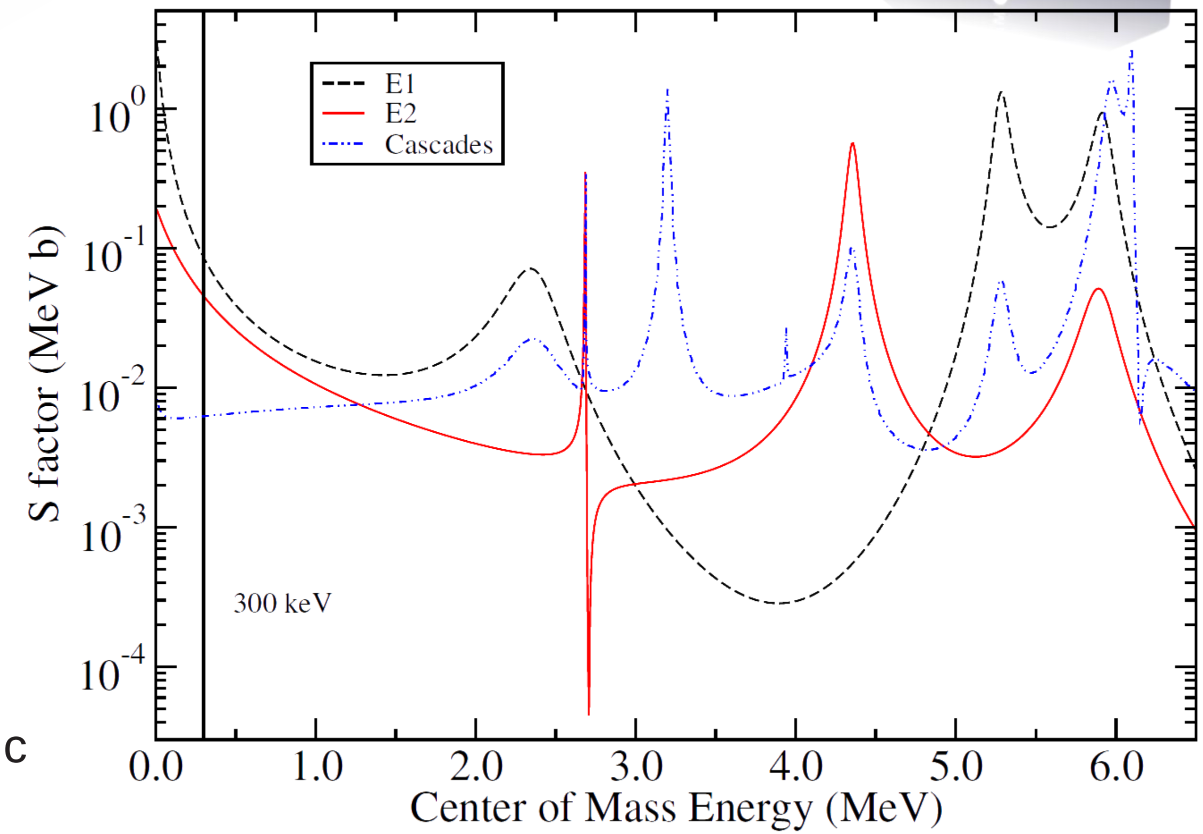
With the phase between E1 and E2

$$\Phi_{12} = \delta_d - \delta_p - \arctan\frac{\eta}{2}$$

where $\delta_{p,d}$ are the p- and d-wave phase shifts from elastic α-scattering on carbon

And the Sommerfeld parameter $\eta = \frac{Z_\alpha Z_{^{12}C} \cdot \alpha c}{v}$

Cp. deBoer



Cp. I. Friščić et al. A New Approach to Determine Radiative Capture Reaction Rates at Astrophzsical Energies