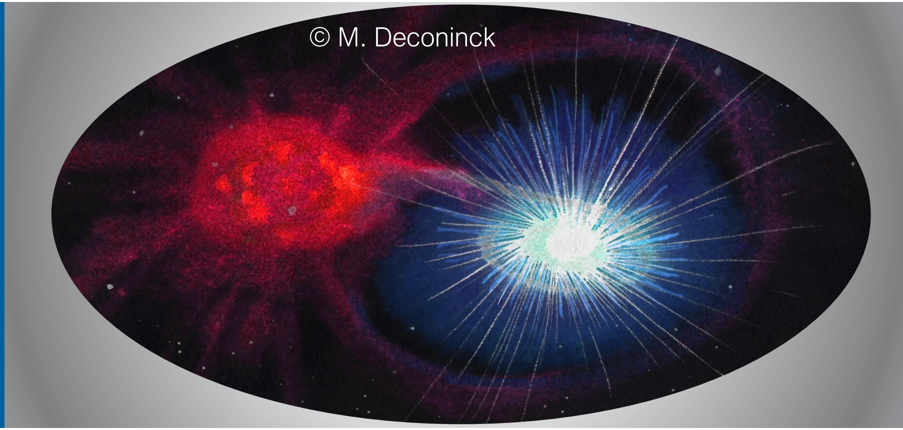
Understanding ^{22}Na cosmic abundance by measuring femtosecond lifetime in ^{23}Mg



C. Fougères[1,2], F. de Oliveira Santos[1] *et al.*

[1]GANIL CEA/DRF-CNRS/IN2P3, Caen (France)

[2]Argonne National Laboratory, Lemont (USA)

Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.

Nuclei in the Cosmos XVII
Institute for Basic Science, Daejeon, Korea 2023)

ASTROPHYSICAL MOTIVATIONS

Stellar objects of interest: novæ

Bright light in sky

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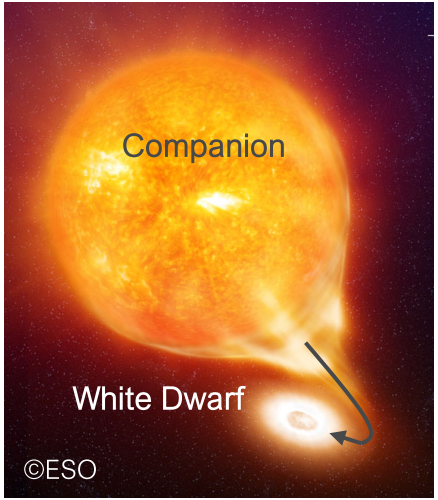
Matter accretion → explosive hydrogen burning



Impact
- Abundances of nuclei
- Isotopic composition of presolar grains
- Number of supernovae Ia → dark energy
- Test of novae models

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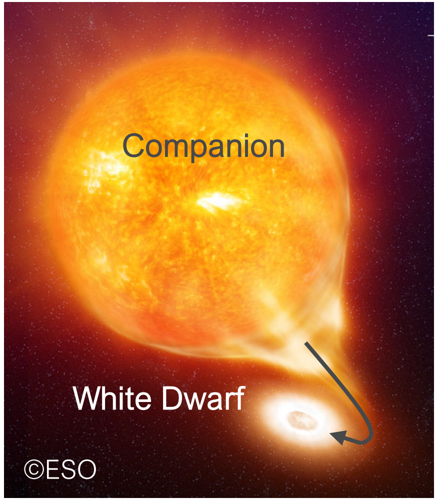

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Uncertainties

Accretion dynamics

Initial T_{WD}, M_{WD}

…

NIC XVII (IBS, Korea 2023)

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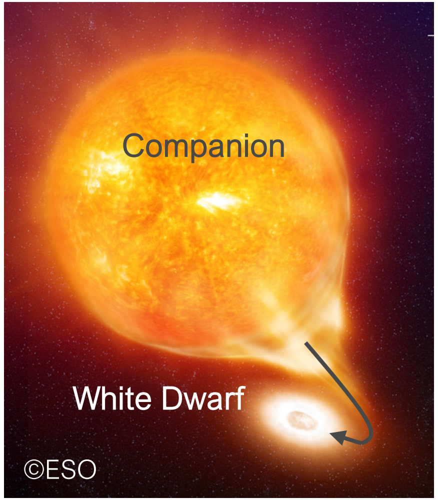

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Need of astronomical observables

Uncertainties

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Observable candidate for novæ: ^{22}Na

A compass for ONe novae

Uncertainties

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A compass for ONe novae

^{20}Ne

Uncertainties

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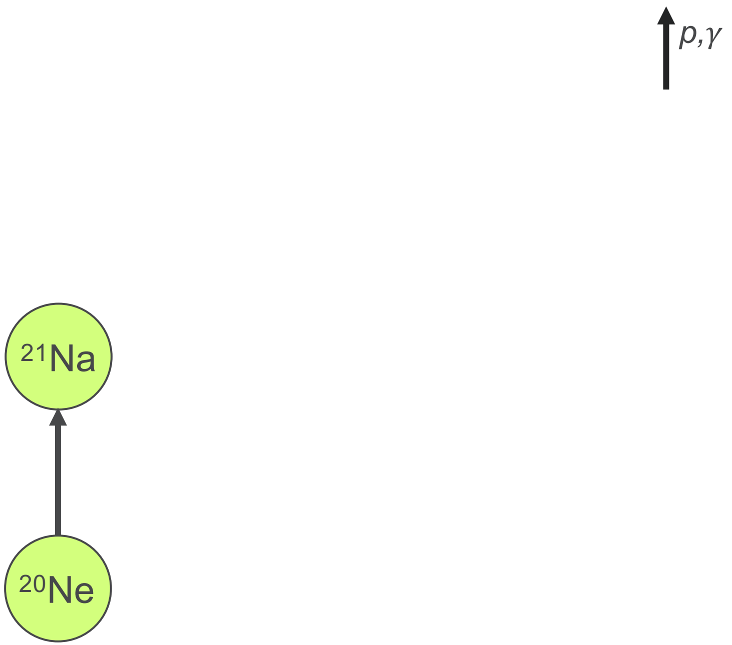

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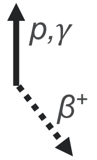

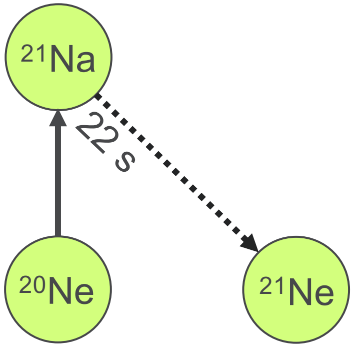

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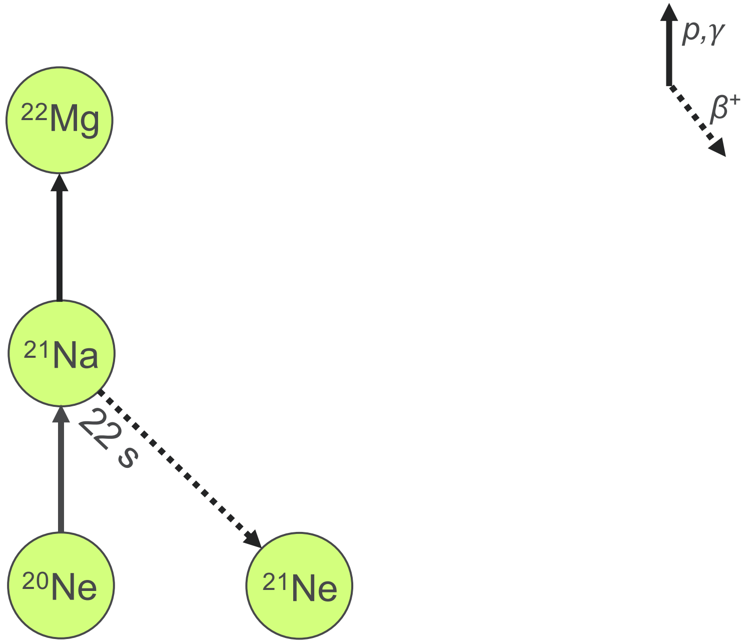

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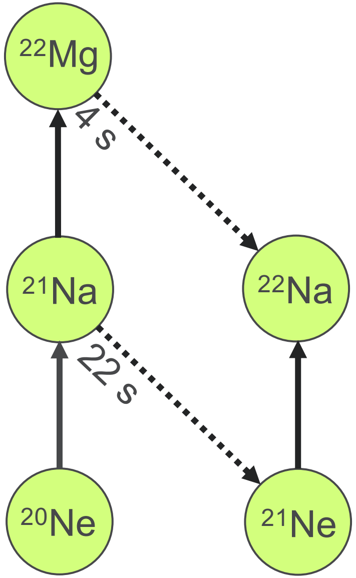

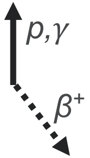

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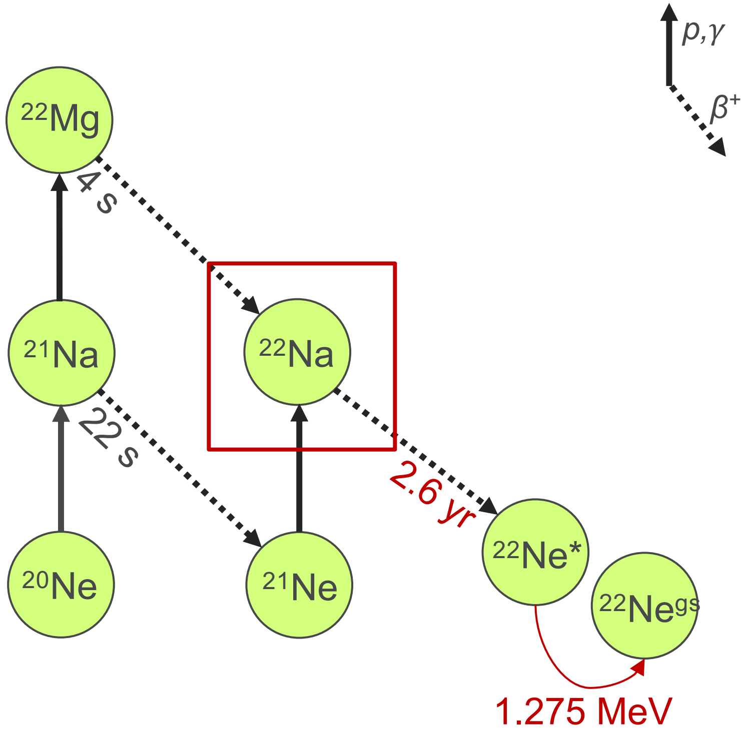
Radioactive tracer
^{22}Na
τ = 2.6 yr, E_γ = 1.275 MeV



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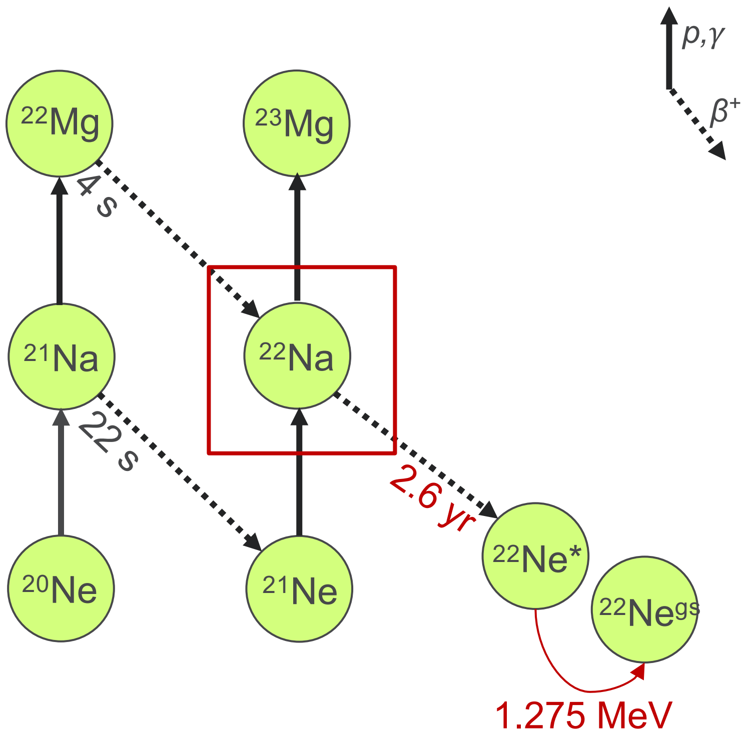

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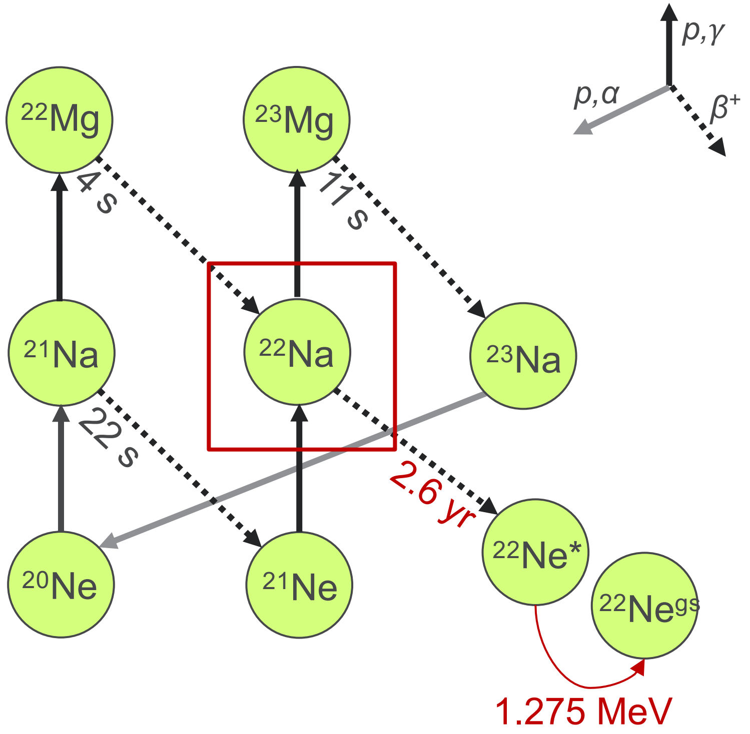

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Search for ^{22}Na

γ-ray observation campaigns (INTEGRAL, COMPTEL…)

Sensitivity improved by x30

De Angelis, J. High Energy Astrophys. ***19*** *(2018)*

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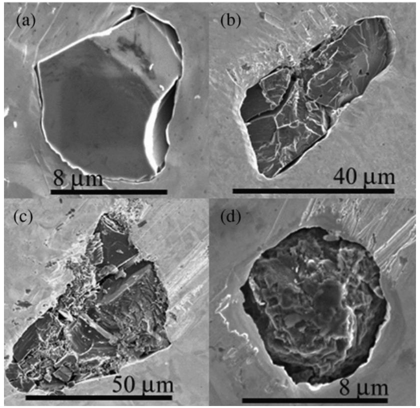

Black, Geochim. Cosmochim. Acta ***36*** *(1972)*

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GANIL spiral2 laboratoire commun CEA/DRF CNRS/IN2P3 Argonne NATIONAL LABORATORY

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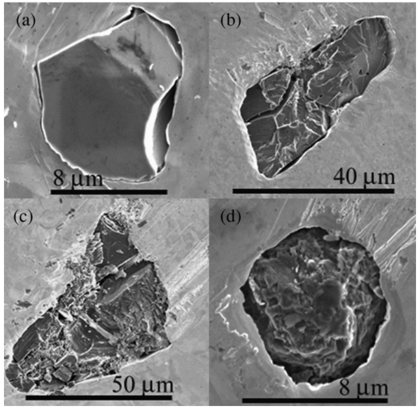

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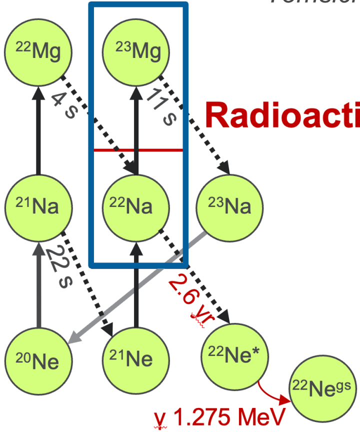

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^{22}Na$(p,\gamma)^{23}$Mg rate

Destruction $^{22}Na(p,\gamma)^{23}Mg$

Resonant reaction (Breit Wigner cross section)

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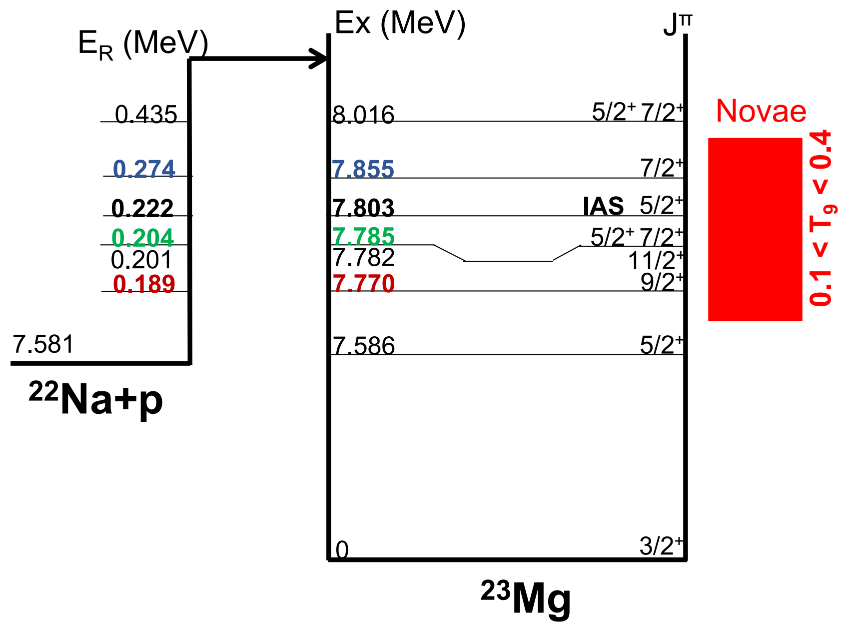
Resonant reaction (Breit Wigner cross section)

$$< \sigma v >_{\mathrm{tot}} = \Sigma_{\mathrm{R}} \left(\frac{2\pi}{\mu_{(^{22}\mathrm{Na},\ \mathrm{p})} \mathrm{k_B T}} \right)^{\frac{3}{2}} \times \hbar^2 \times \omega\gamma \times \exp\left(-\frac{\mathrm{E_R}}{\mathrm{k_B T}}\right)$$



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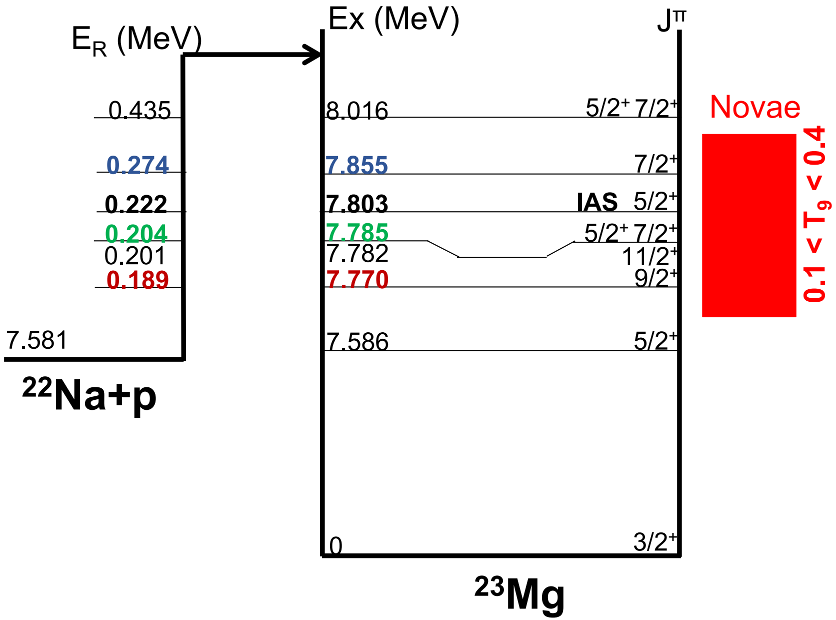
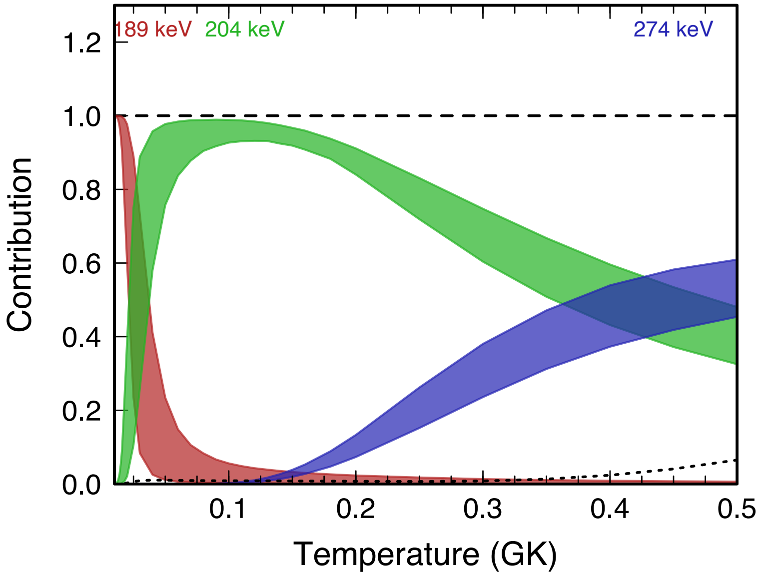


Direct measurements of $\omega\gamma$ *Sallaska, Phys. Rev. L* ***105*** *(2010)*



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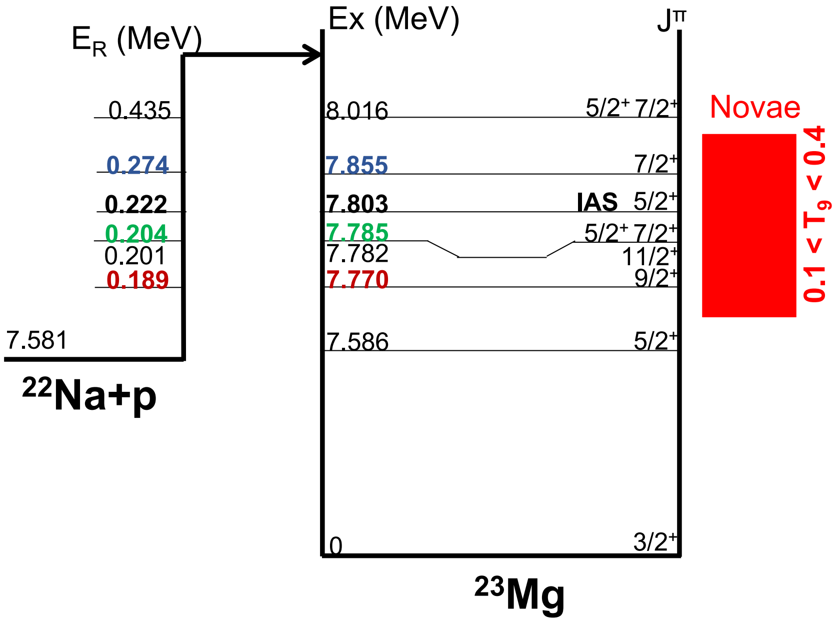

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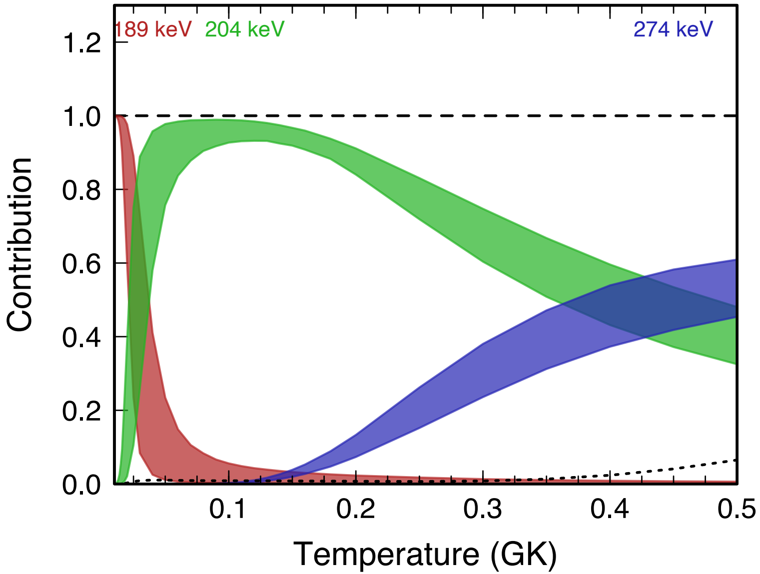
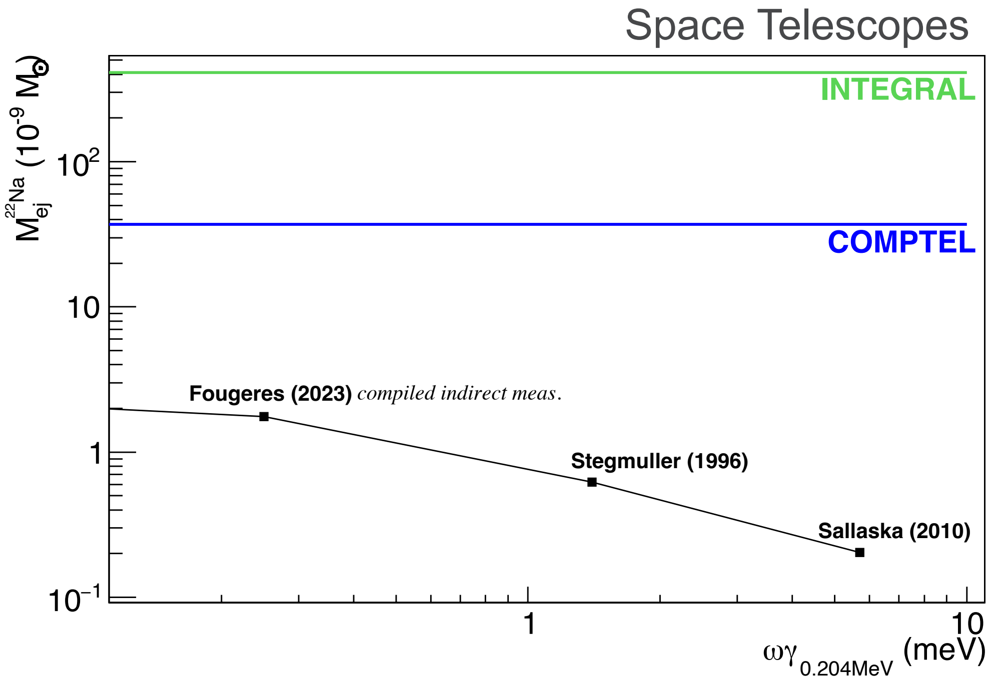


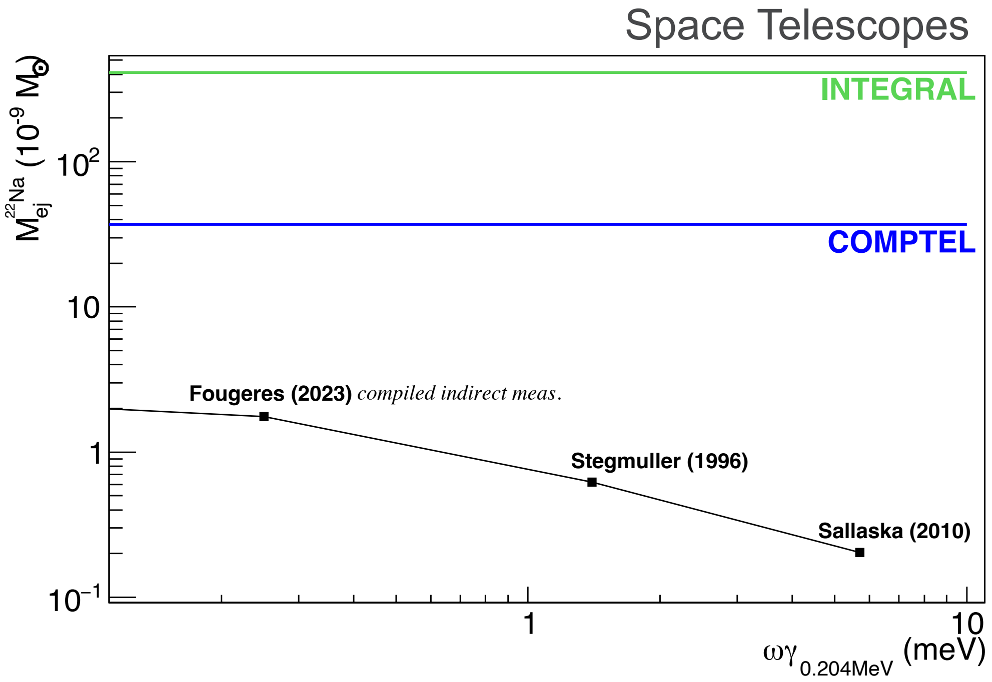
Dominant resonance in $^{23}Mg^*$
(E_x = 7.785 MeV, E_R = 0.204 MeV)

Impact of $\omega\gamma_{0.204MeV}$ on ejected ^{22}Na



Fougères, EPJ Web Conf. ***279*** *(2023)*

Impact of $\omega\gamma_{0.204\mathrm{MeV}}$ on ejected ^{22}Na



Fougères, EPJ Web Conf. ***279*** *(2023)*

Disagreement in $\omega\gamma$ ➔ **predicted ^{22}Na ~ x10**

Indirect determination of $\omega\gamma$ at $E_R = 0.204$ MeV

$$\omega\gamma = \frac{2J_{^{23}\mathrm{Mg}} + 1}{(2J_{^{22}\mathrm{Na}} + 1)(2J_{\mathrm{p}} + 1)} \times \frac{\hbar}{\tau} \times \mathrm{BR_p}(1 - \mathrm{BR_p})$$

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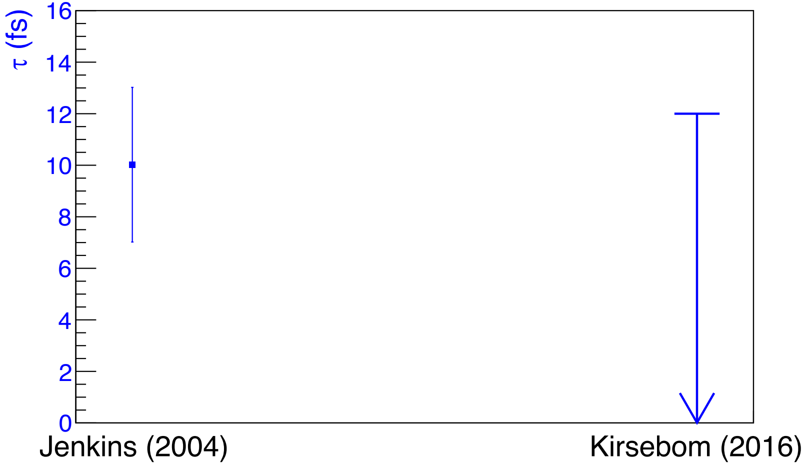

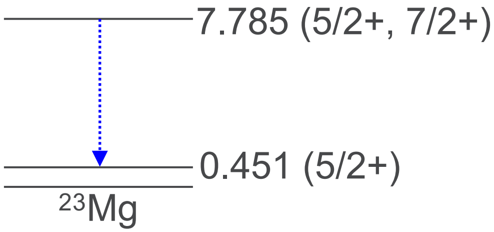

Shell model ~1 fs

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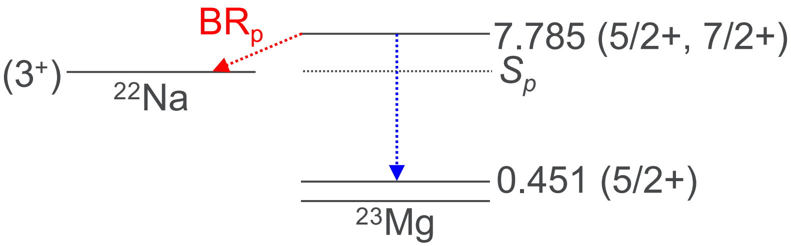
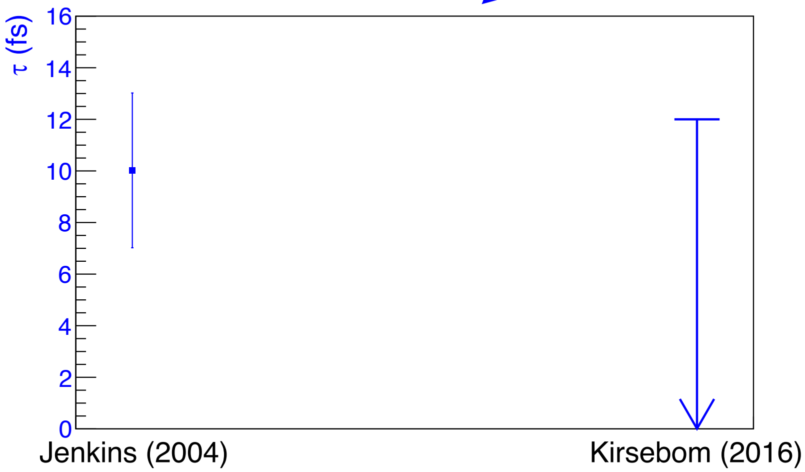




Shell model ~1 fs

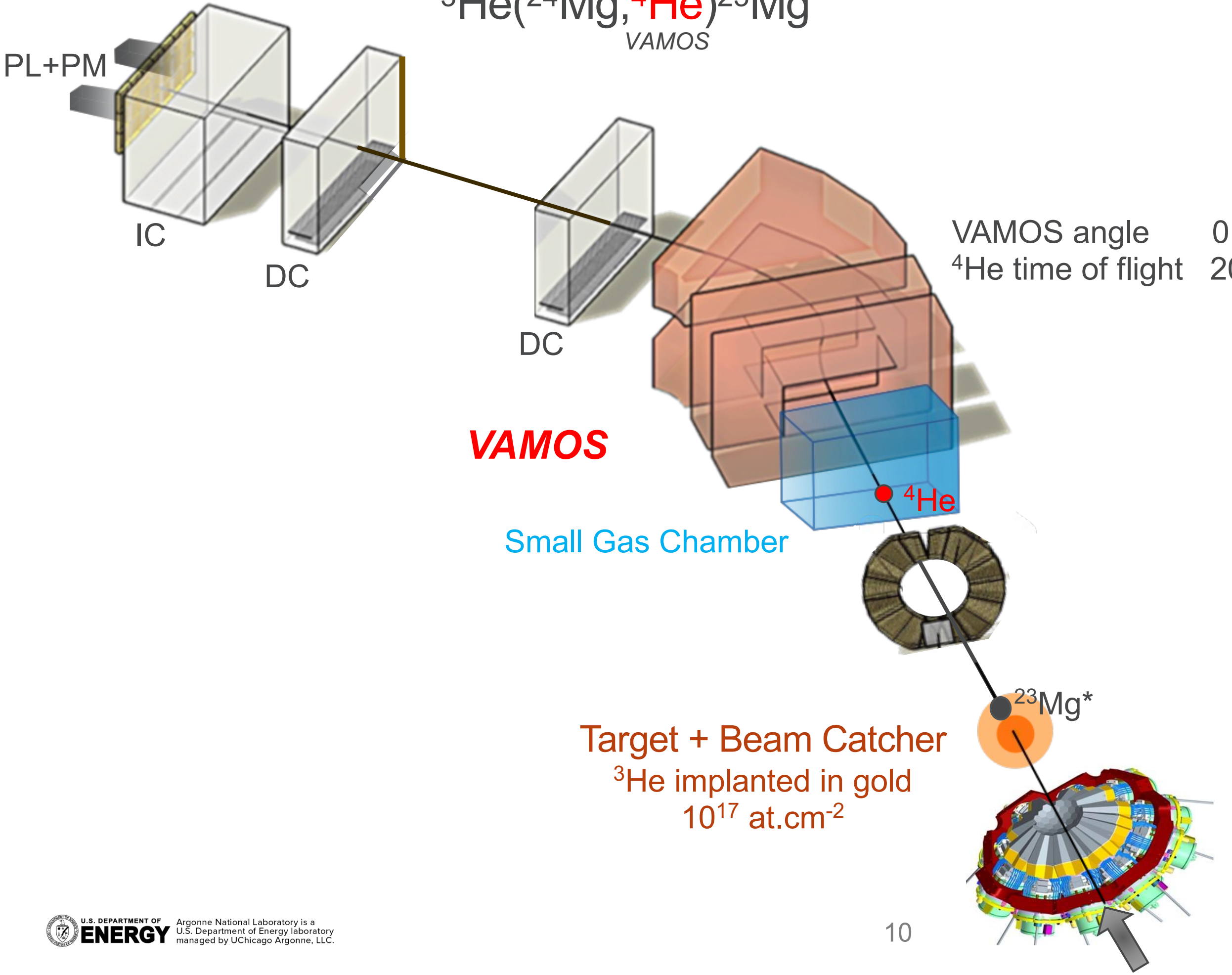
EXPERIMENTAL APPROACH AND RESULTS

Set-up

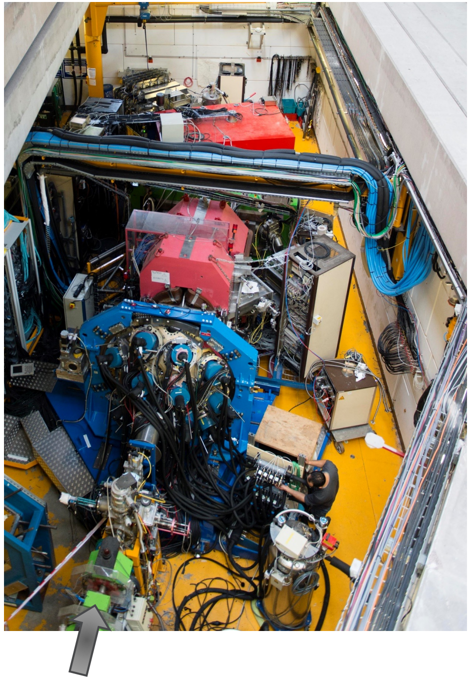
Michelagnoli, PI (GANIL 2016)

$^{3}He(^{24}Mg,{}^{4}He)^{23}Mg^{*}$

VAMOS



VAMOS angle 0 deg
^{4}He time of flight 200 ns



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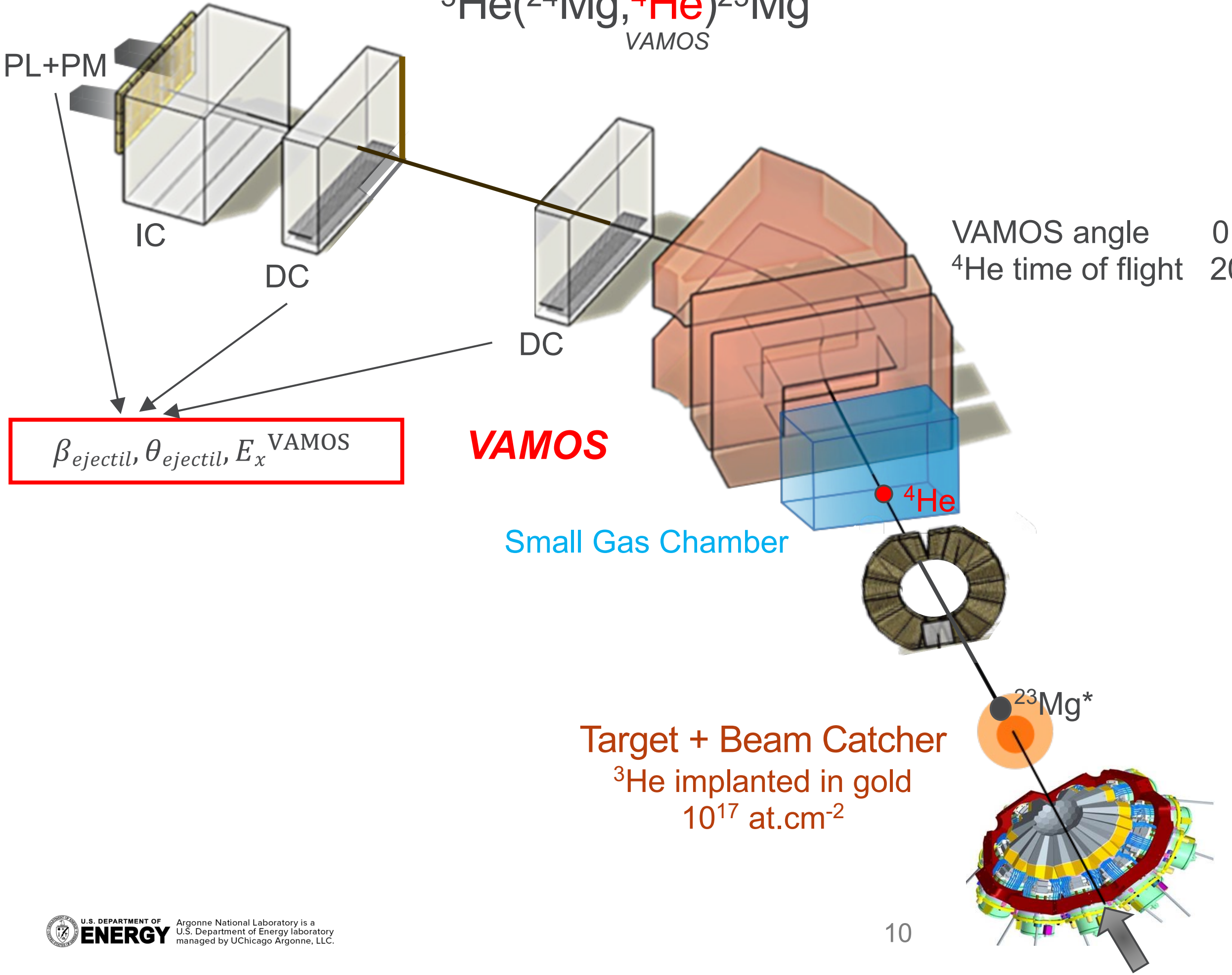

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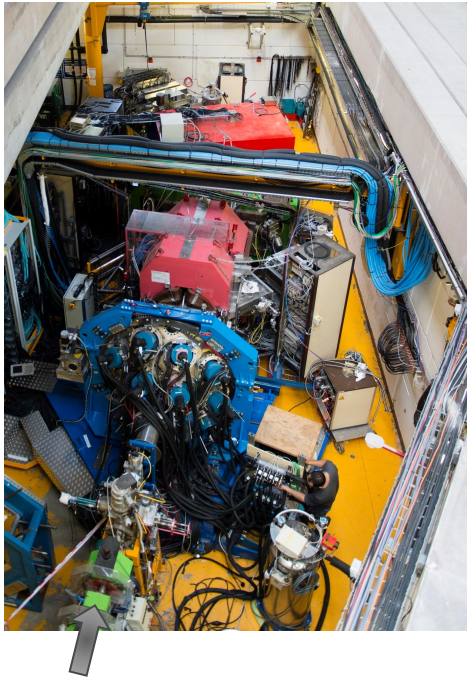

^{24}Mg at 4.6 MeV/u

Set-up

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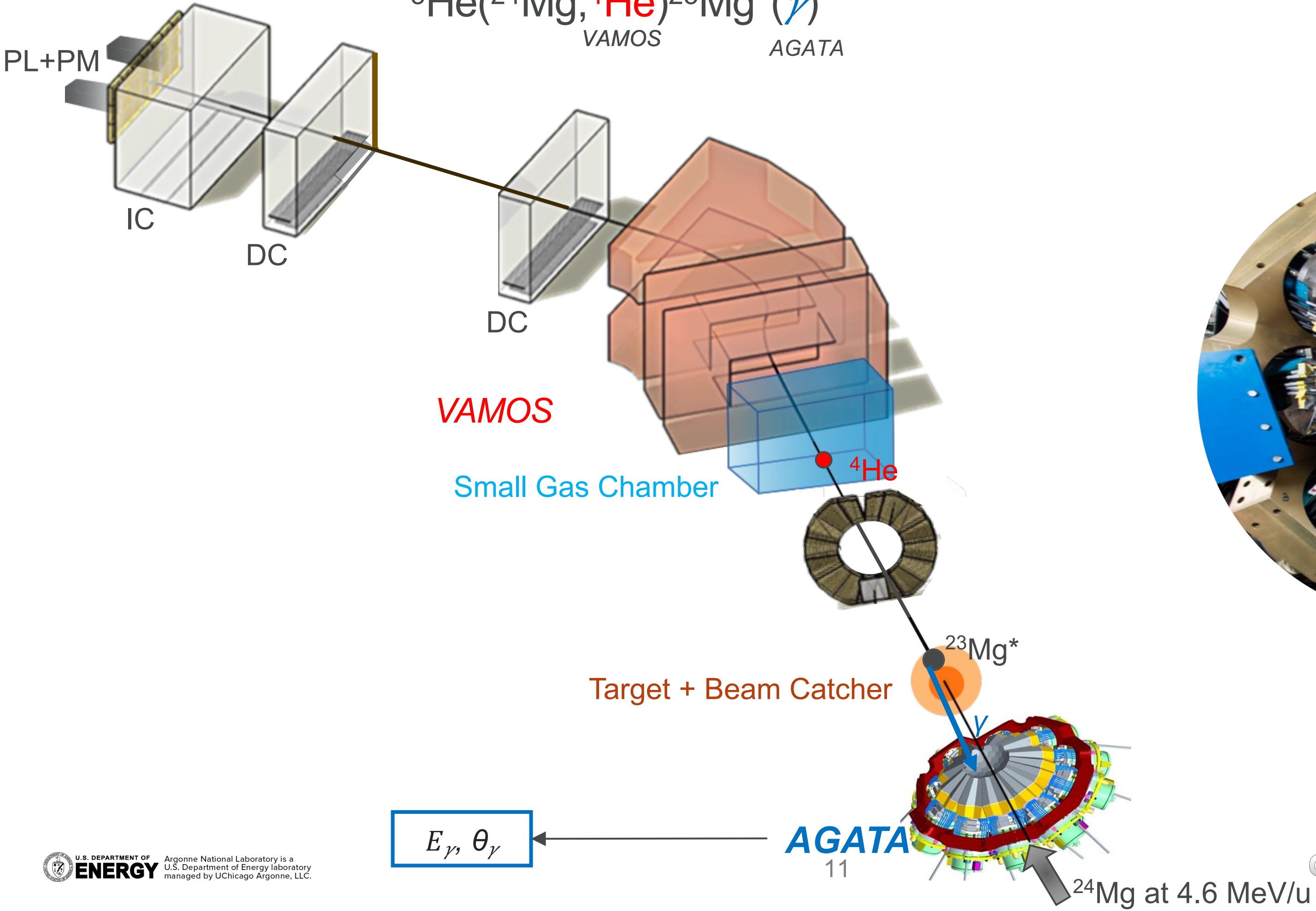
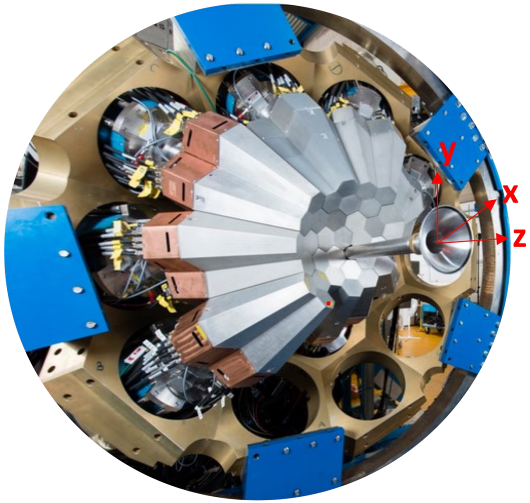
$^{3}\mathrm{He}(^{24}\mathrm{Mg},{}^{4}\mathrm{He})^{23}\mathrm{Mg}^{*}(\gamma)$

VAMOS *AGATA*

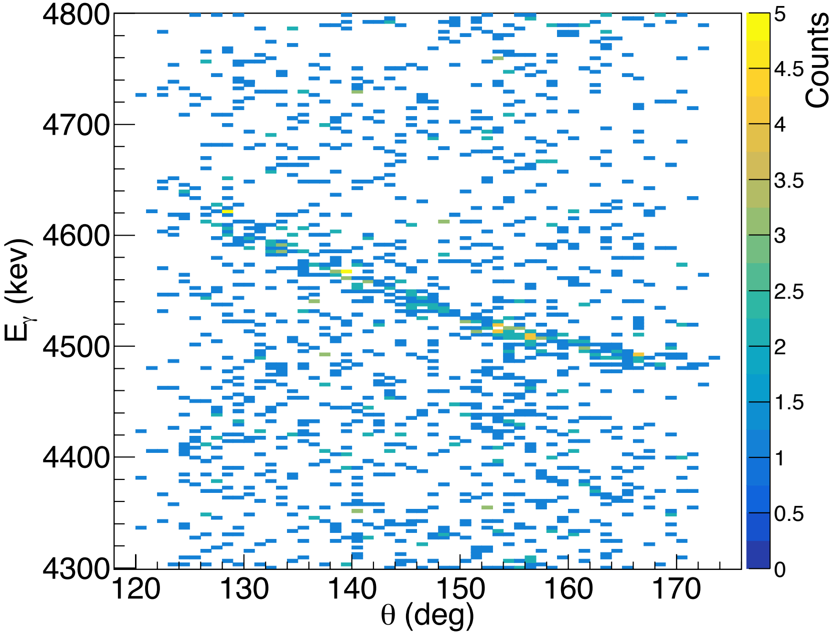




Accessing to γ–ray transitions

$^{3}He(^{24}Mg,^{4}He)^{23}Mg^{*}(\gamma)$

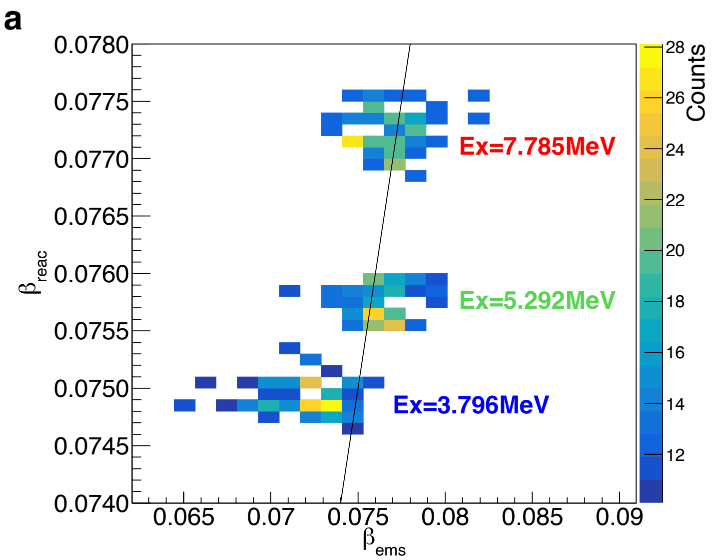
E_x**=5.29(16) MeV**



New method to femtosecond nuclear lifetimes

(a) Particle-particle correlations

- β_{reac} from $(\beta_{beam}, \beta_{ejectil}, \theta_{ejectil})$



Fougères, Nat. Commun. ***14*** *(2023)*

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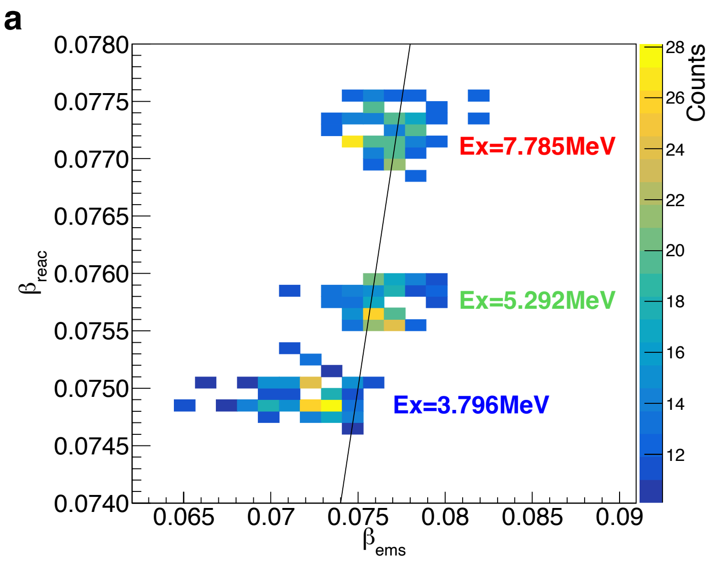
- β_{ems} from (E_{γ}, θ) $\longrightarrow$ $$\beta_{\text{ems}} = \frac{R^2\cos(\theta) + \sqrt{1 + R^2\cos^2(\theta) - R^2}}{R^2\cos^2(\theta) + 1}$$

$$R = \frac{E_\gamma}{E_{\gamma,0}}$$



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New method to femtosecond nuclear lifetimes

(a) Particle-particle correlations

(b) Angle-integrated velocity-difference profile

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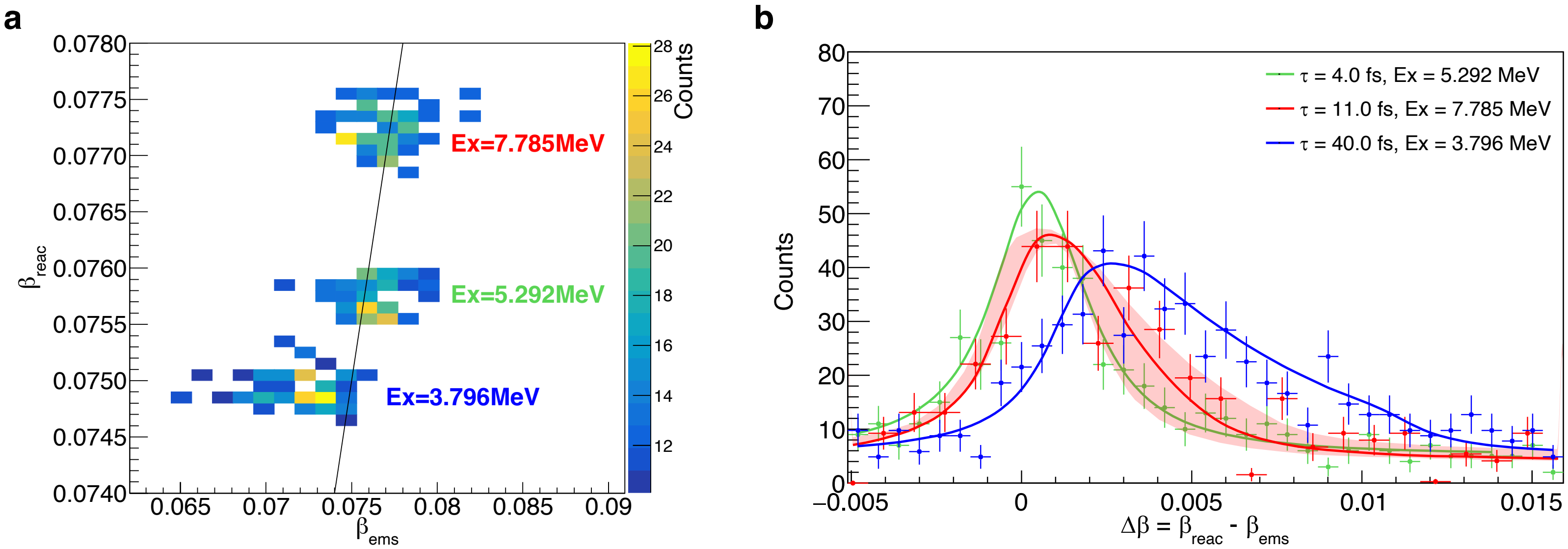

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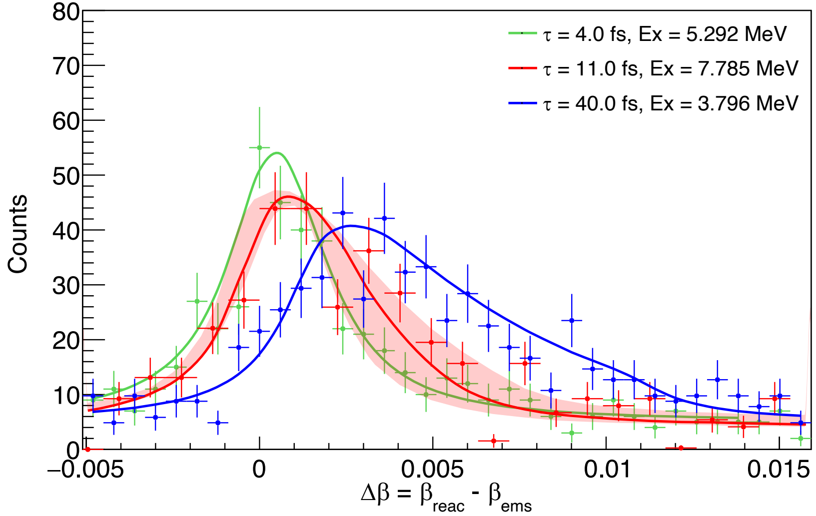
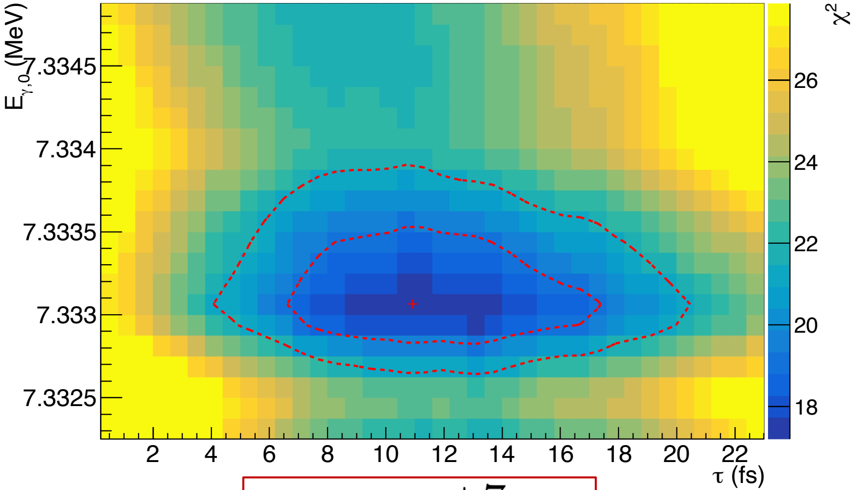


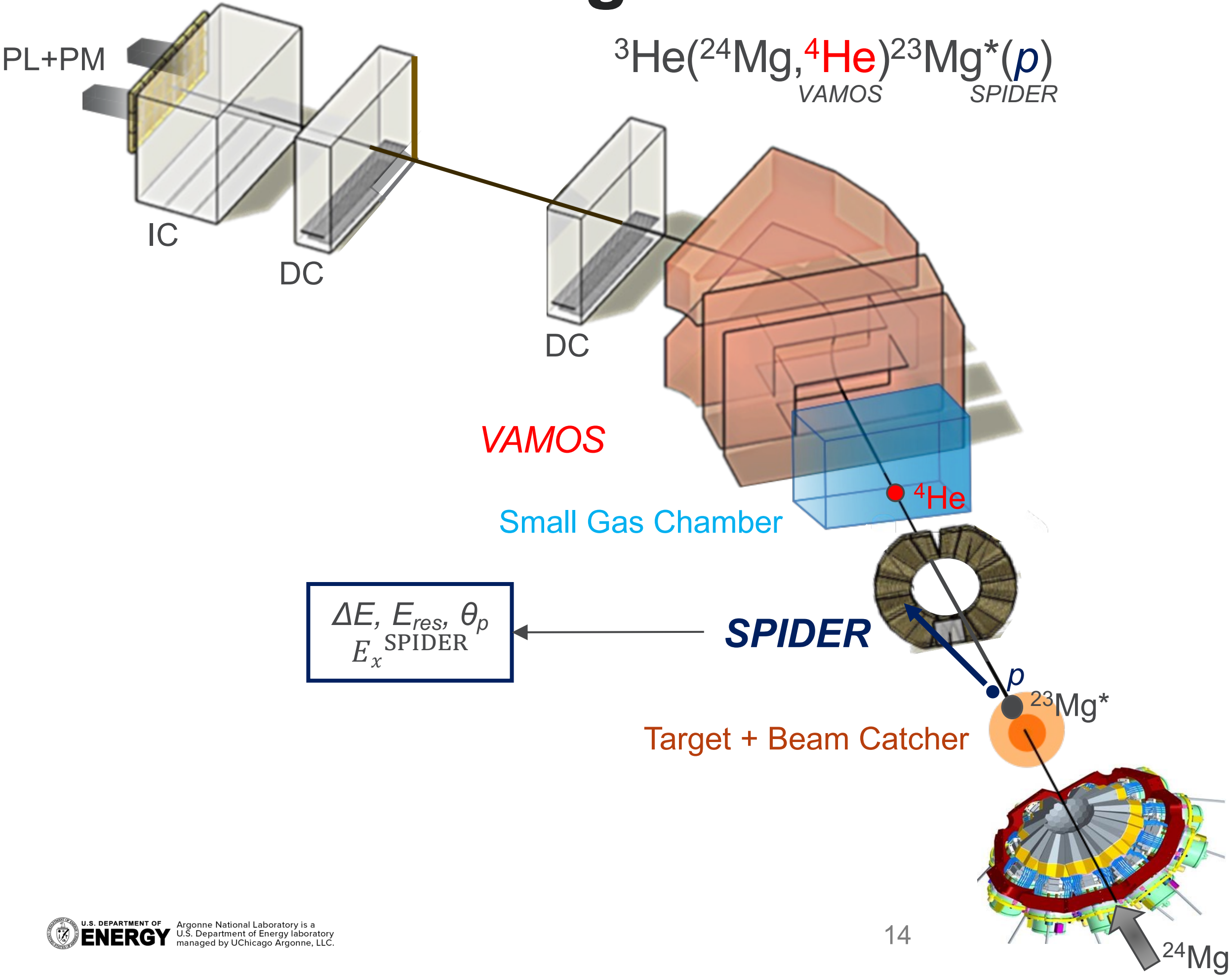


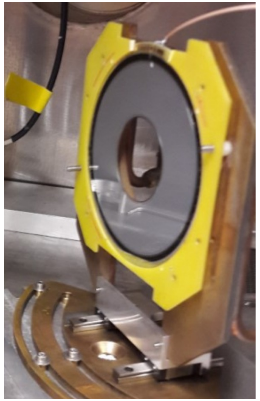
$$\boxed{\tau = 11^{+7}_{-5}\ \text{fs}}$$

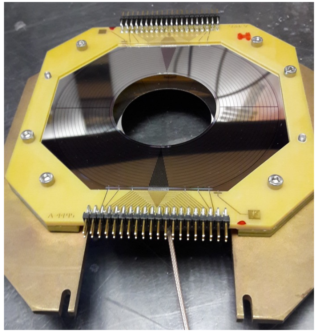
Fougères, Nat. Commun. ***14*** *(2023)*

Proton branching ratio

^{3}He(^{24}Mg,^{4}He)^{23}Mg*(p)







Proton branching ratio

Michelagnoli, PI (GANIL 2016)

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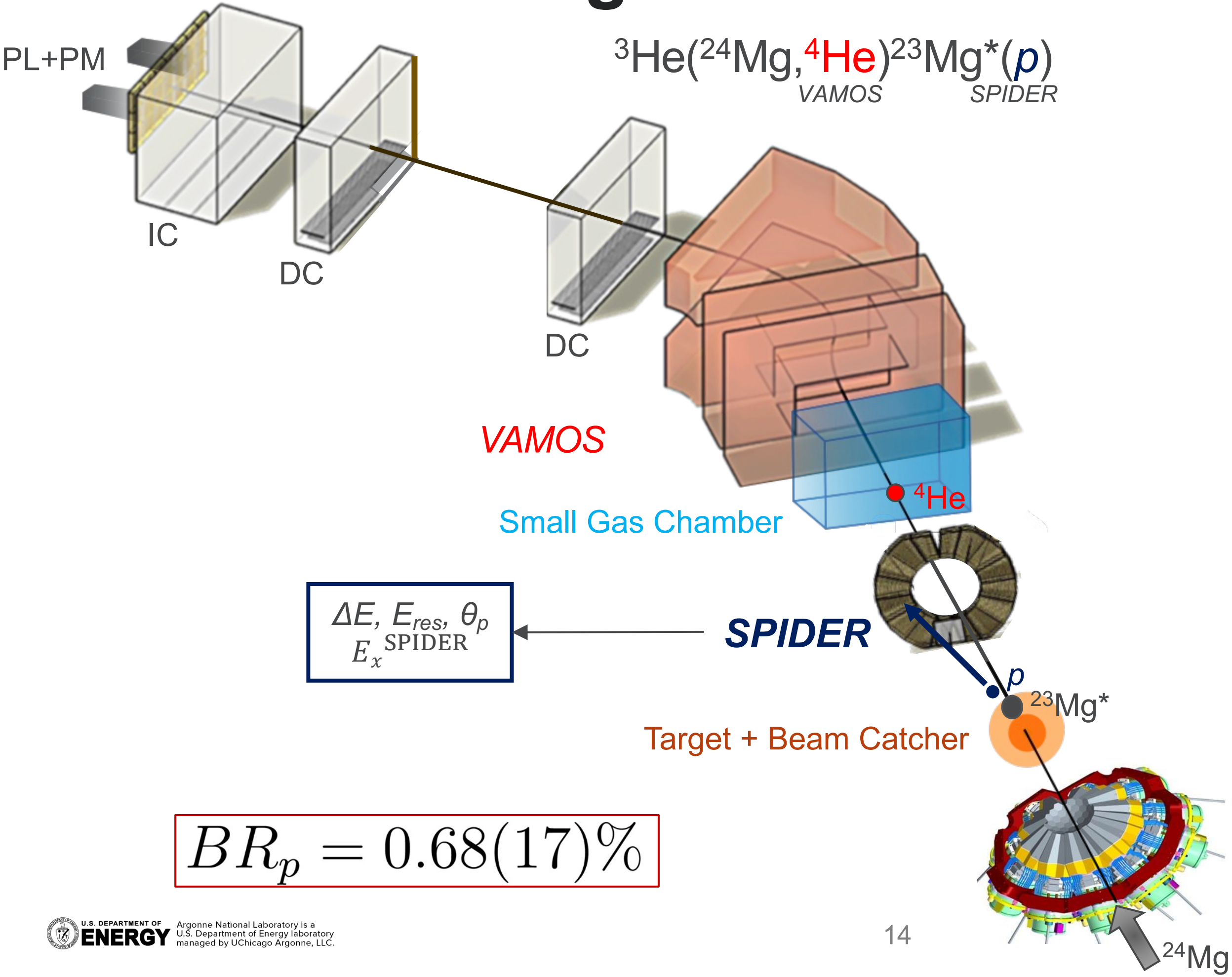
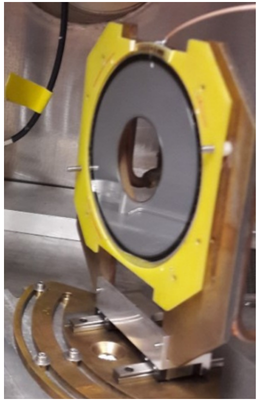
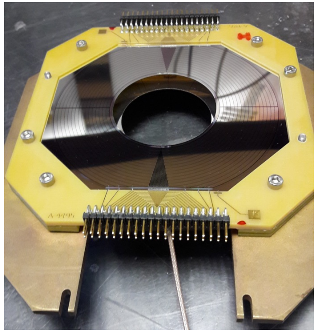
VAMOS SPIDER



$$\boxed{BR_p = 0.68(17)\%}$$





ASTROPHYSICAL IMPACT

Reevaluation of the $^{22}Na(p,\gamma)^{23}Mg$ rate

Monte-Carlo calculations, with $\boxed{\omega\gamma = 0.24^{+0.11}_{-0.04}\ \mathrm{meV}}$ at E_R=0.204 MeV

Longland, Nuc. Phys. A ***240*** *(2010)*

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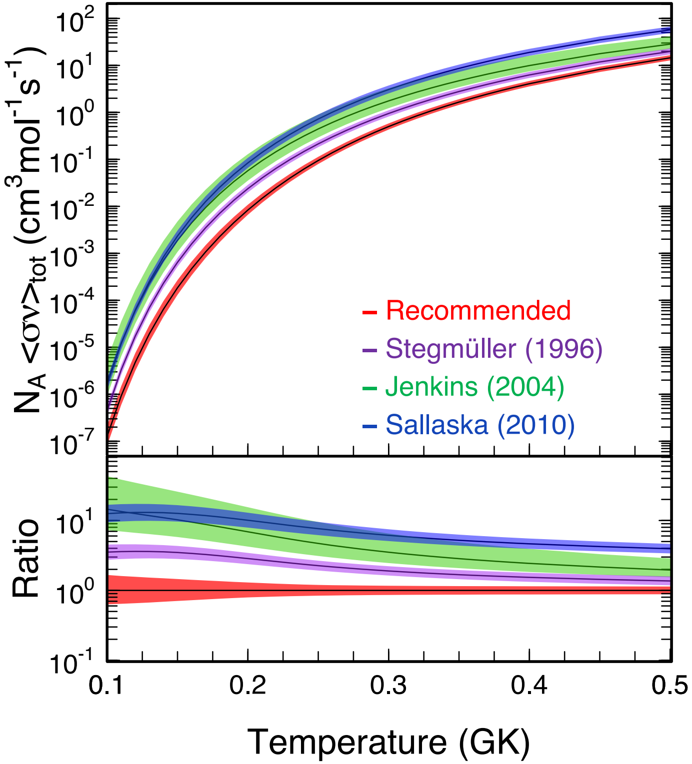

Fougères, Nat. Commun. ***14*** *(2023)*

Reevaluation of the $^{22}Na(p,\gamma)^{23}Mg$ rate

Monte-Carlo calculations, with $\boxed{\omega\gamma = 0.24^{+0.11}_{-0.04}\ \mathrm{meV}}$ at E_R=0.204 MeV

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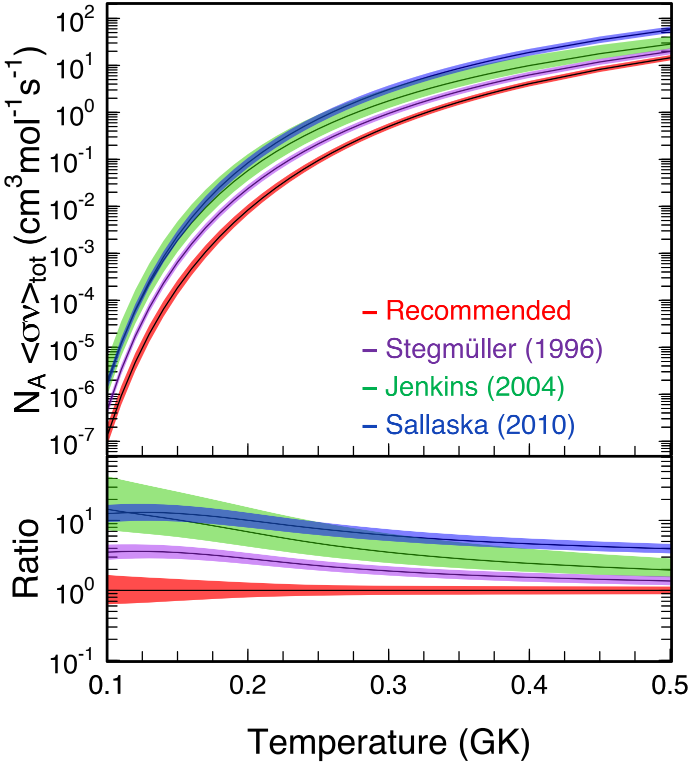

Impact on ejected ^{22}Na from novae?

*Fougères, Nat. Commun. **14** (2023)*

Constrains on ONe novae

Accretion dynamics
Initial T_{WD}, M_{WD}

^{22}Na abundance in novae

Simulations of novae

MESA
*Paxton, Astrophys. J. Suppl. Ser. **208** (2013)*

SHIVA
José, CRC Press (2016)

Model	115a	115b	125	135
HD code	*MESA*	*SHIVA*	*SHIVA*	*SHIVA*
M_{WD} ($M_{\odot}$)	1.15	1.15	1.25	1.35
R_{WD} (km)	4428	4334	3797	2258
T_{peak} (10^8 K)	2.12	2.27	2.48	3.13
M_{ejec} (10^{-5} $M_{\odot}$)	4.63	2.46	1.90	0.46
X(^{22}Na)	$\mathbf{3.1 \times 10^{-4}}$	$\mathbf{3.2 \times 10^{-4}}$	$\mathbf{3.7 \times 10^{-4}}$	$\mathbf{9.1 \times 10^{-4}}$

*Fougères, Nat. Commun. **14** (2023)*

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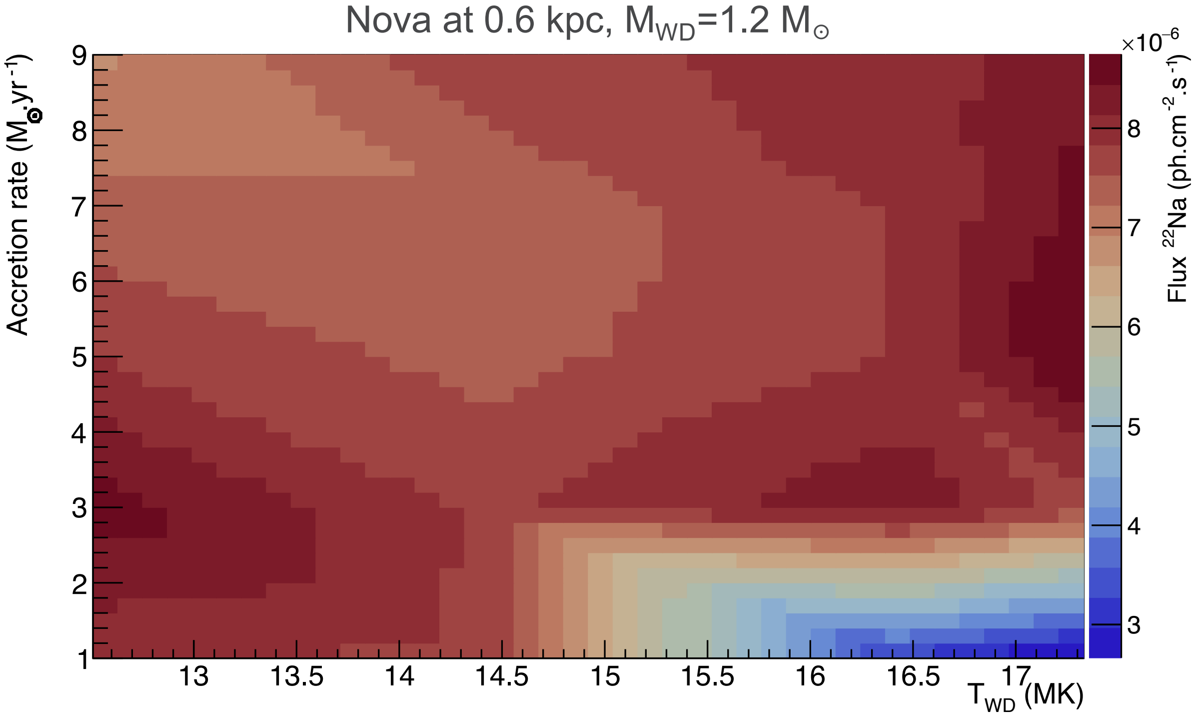

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Constrains on ONe novae

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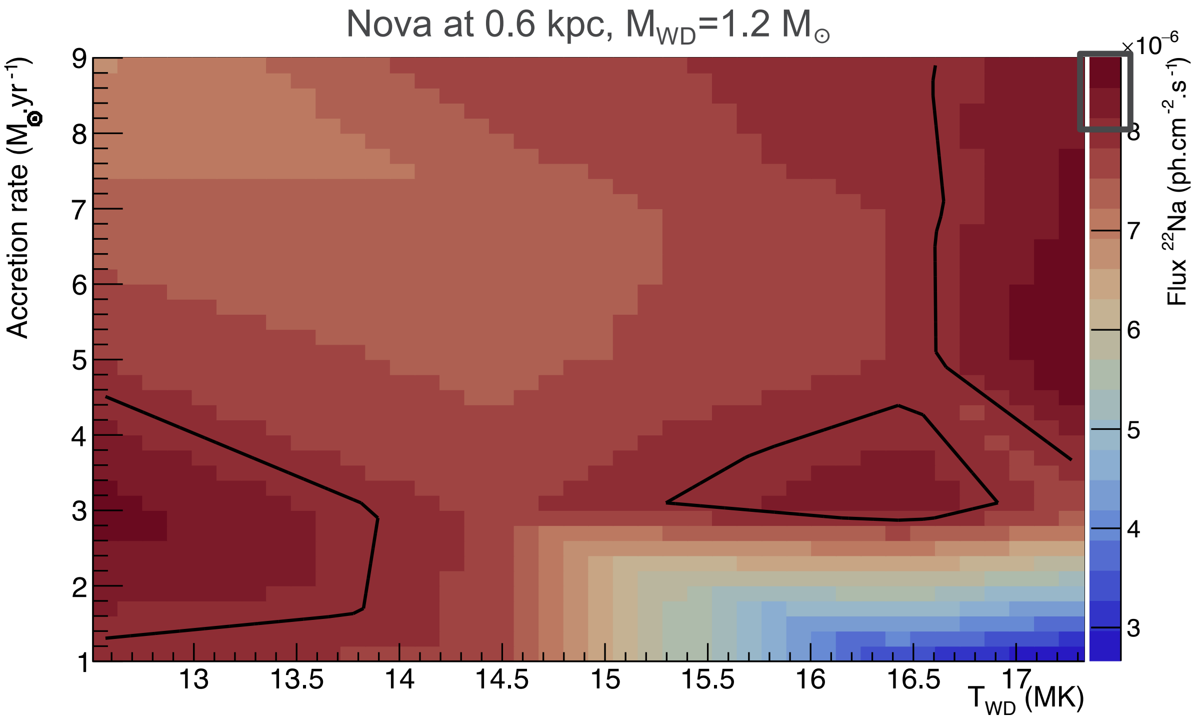


Constrain novae parameters with observed flux

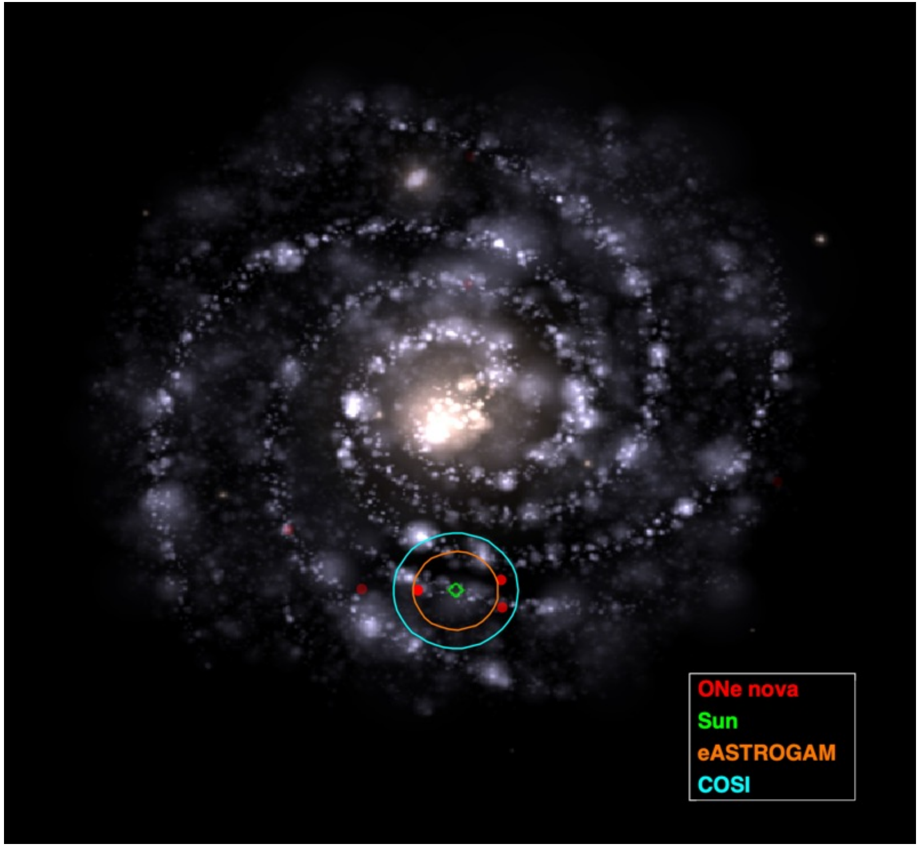
Fougères, Nat. Commun. ***14*** *(2023)*

Prospects for γ-ray astronomy

Limit in detection distance

Survey of 8 observed ONe novae (60 yr)

Hachisu, Astrophys. J. Suppl. Ser. ***242*** *(2019)*
José, CRC Press (2016)



Future MeV
γ-ray space telescopes

e-ASTROGAM *De Angelis (2018)*

2.7(5) kpc

COSI *Tomsick (2020)*

4(7) kpc

Prospects for γ-ray astronomy

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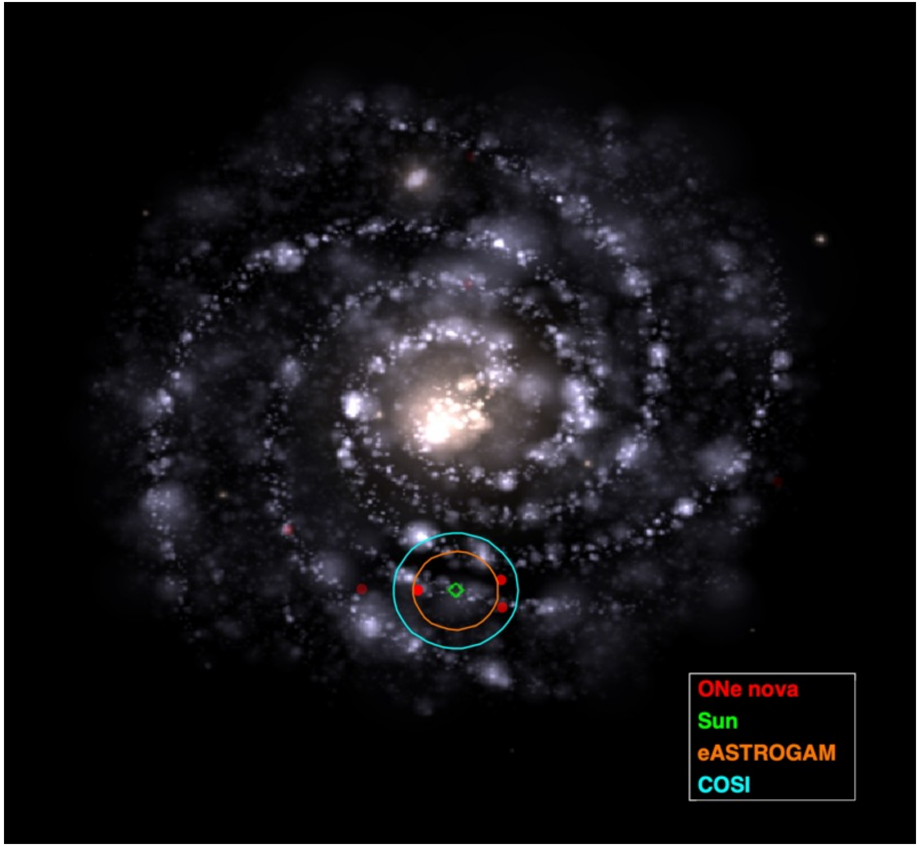

Future MeV
γ-ray space telescopes

e-ASTROGAM *De Angelis (2018)*
2.7(5) kpc

COSI *Tomsick (2020)*
4(7) kpc

Detection frequency
(^{22}Na)
≥1 event / 60 yr
≥1 event / 20 yr

THANK YOU FOR THE KIND ATTENTION

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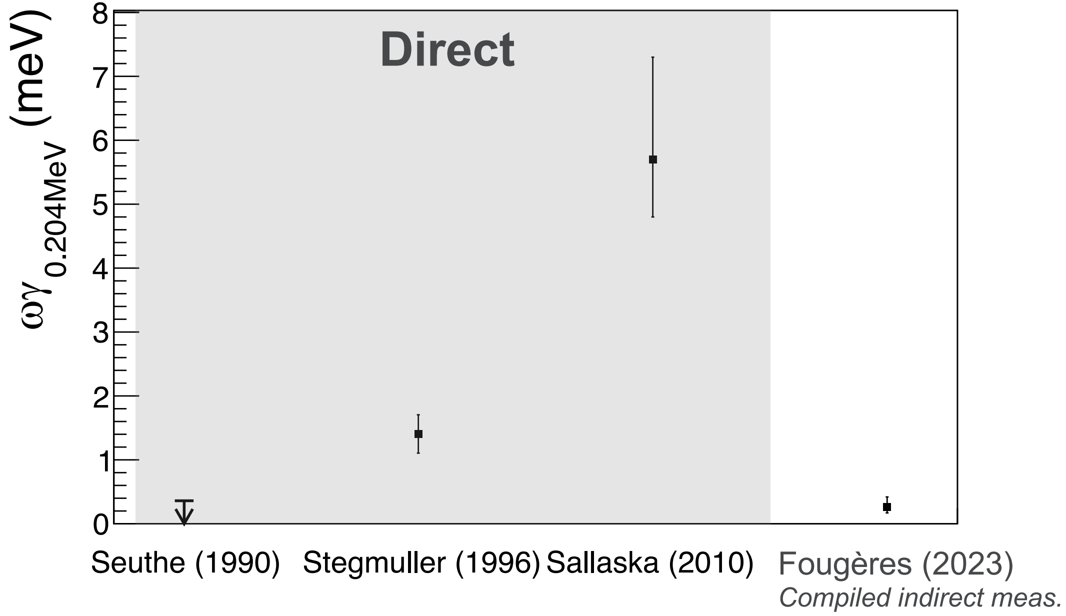
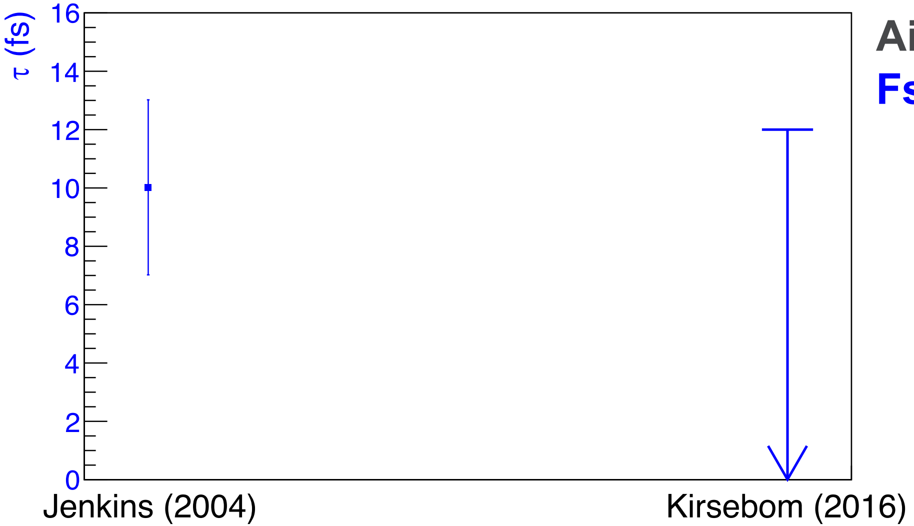
Status of ωγ at E_R=0.204 MeV



Disagreement in ωγ

Experiment choice: indirect strength determination

$$\omega\gamma = \frac{2J_{^{23}\mathrm{Mg}}+1}{(2J_{^{22}\mathrm{Na}}+1)(2J_p+1)} \times \frac{\hbar}{\tau} \times \mathrm{BR_p}(1-\mathrm{BR_p})$$



Aim: (τ, BR$_p$) of the Ex=7.785MeV state in ^{23}Mg*

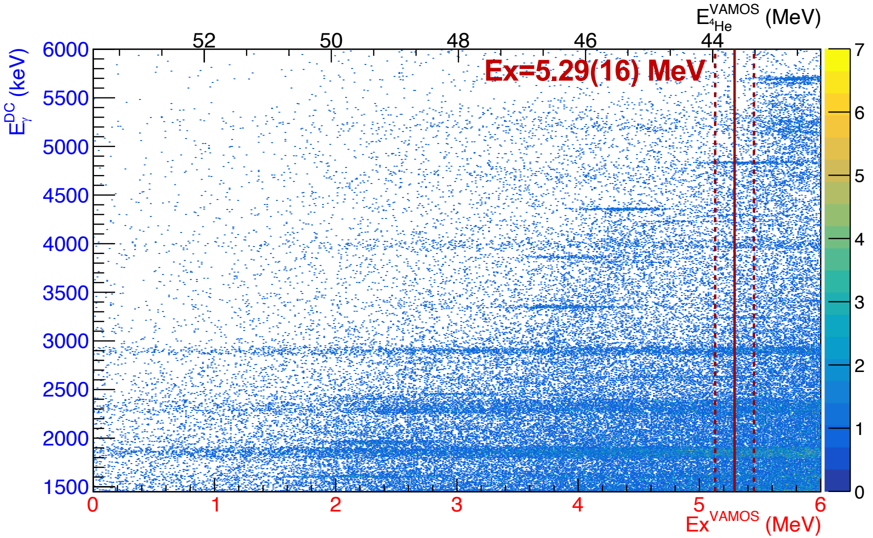
Fs resolution required

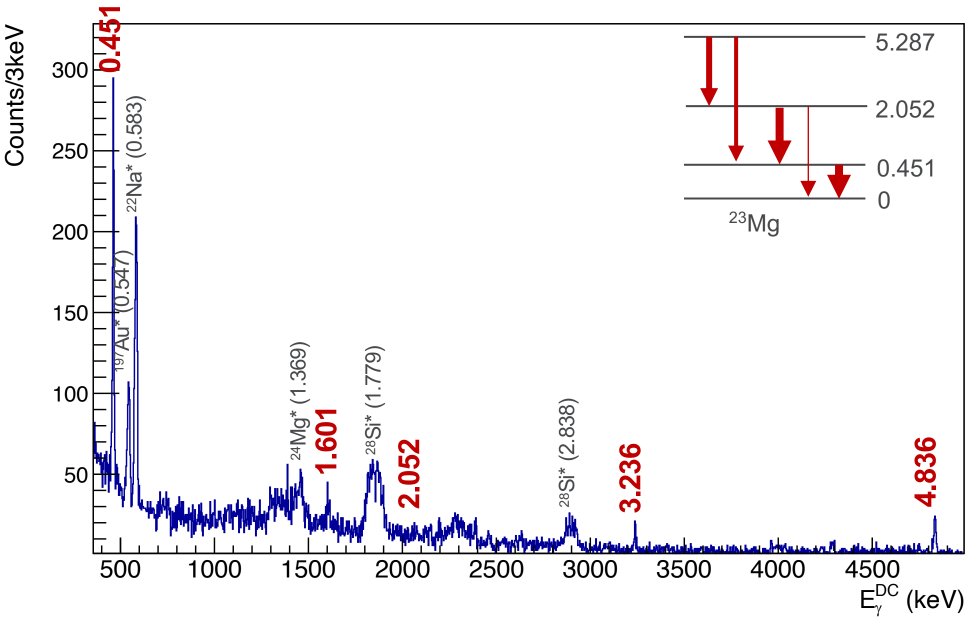
Shell model ~1 fs

Identification of populated states

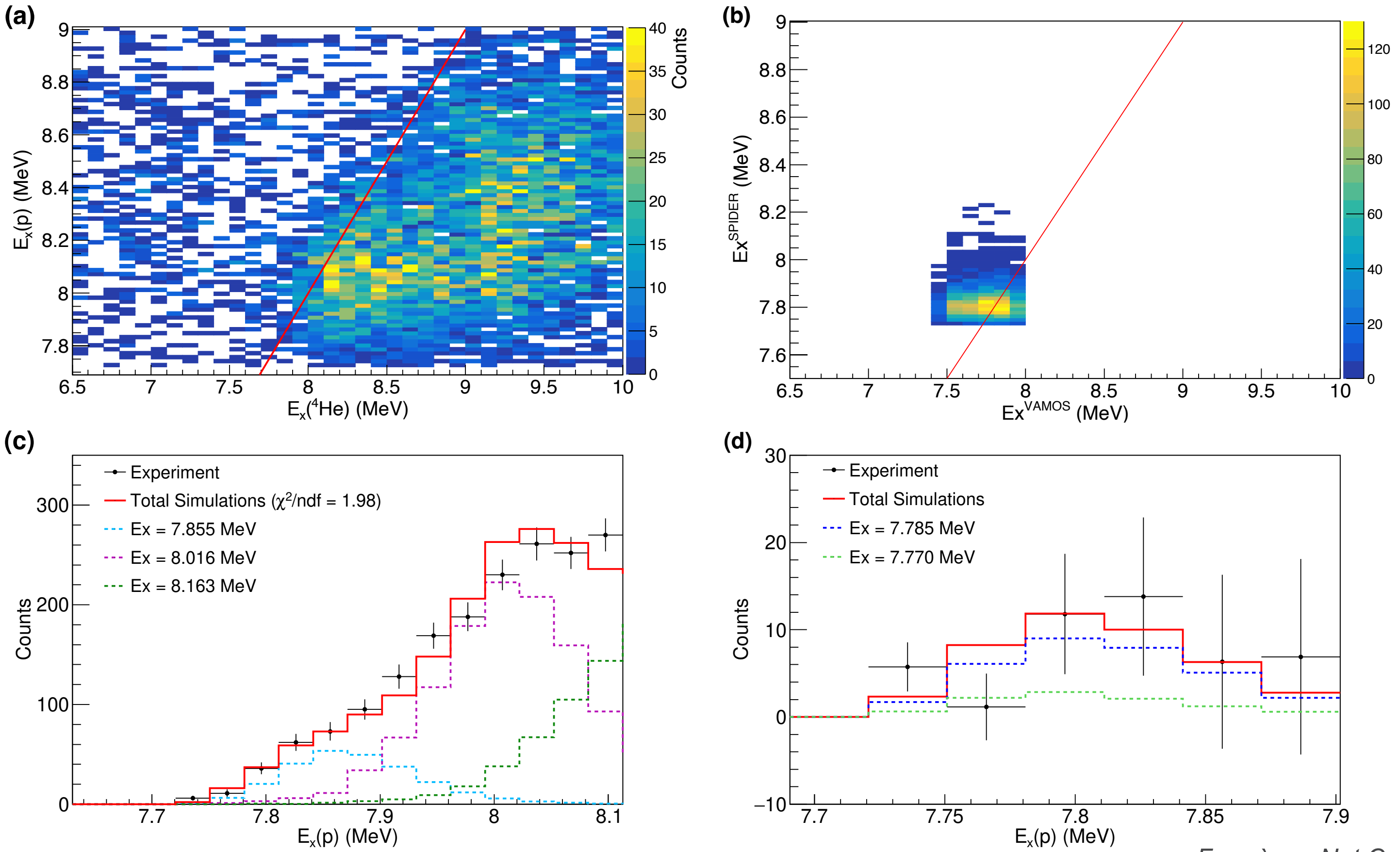
$^{3}He(^{24}Mg,^{4}He)^{23}Mg^{*}(\gamma)$

E_x^{VAMOS} E_γ^{DC}





Proton branching ratio: plots



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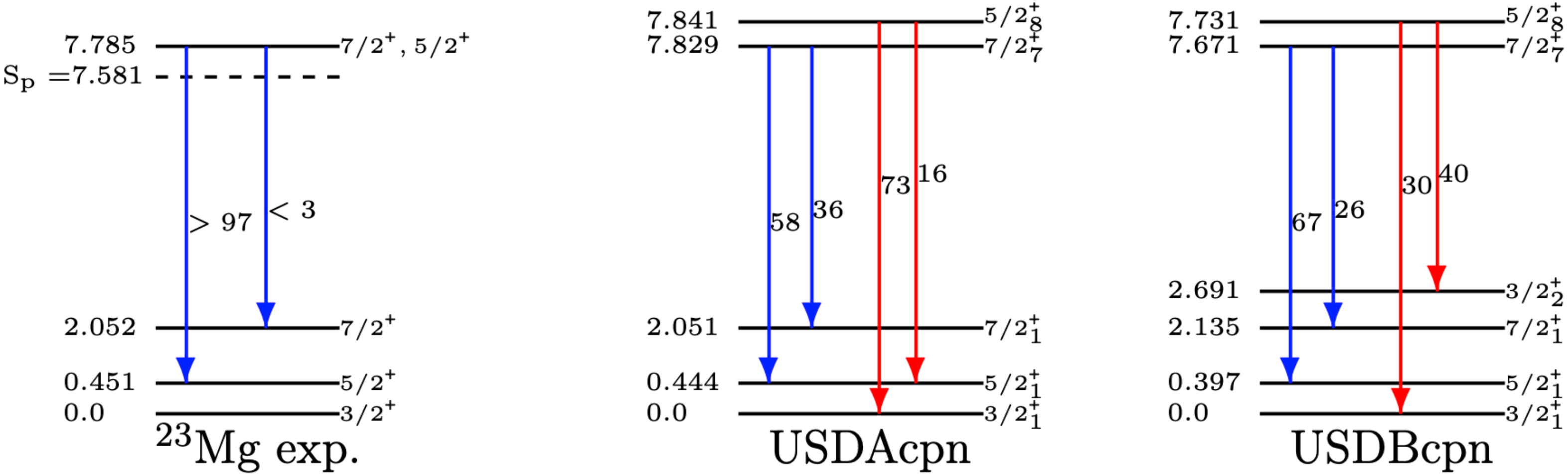
Shell model insights: spin

1. γ-ray decay path → ***7/2+***

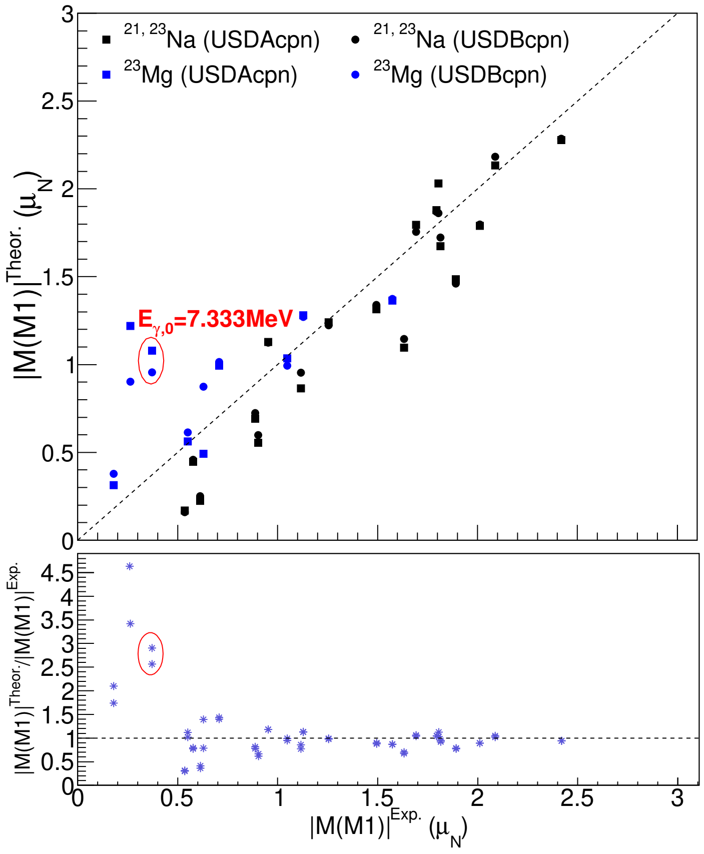


2. β-delayed probability → ***(5/2, 7/2)+***
   $\log_{10}(ft)=3.305(23)$ vs

3. No mixing with the E_x=7.801MeV IAS. → ***7/2+***

Fougères, EPJ Web Conf. ***279*** *(2023)*

Shell model insights: reduced M1 matrix element

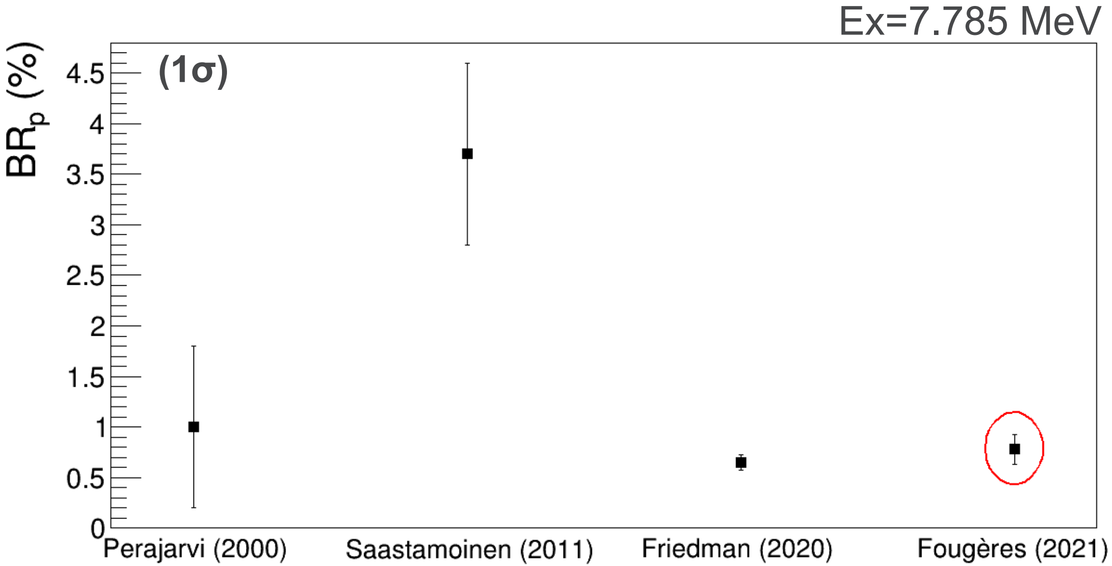


Fougères, EPJ Web Conf. **279** (2023)

Proton branching ratio measurement

$$\omega\gamma = \frac{2J_{^{23}\mathrm{Mg}}+1}{(2J_{^{22}\mathrm{Na}}+1)(2J_{\mathrm{p}}+1)} \times \frac{\hbar}{\tau} \times \mathrm{BR_p}(1-\mathrm{BR_p})$$

Present work



New status on $\omega\gamma_{0.204\ \mathrm{MeV}}$

Present work