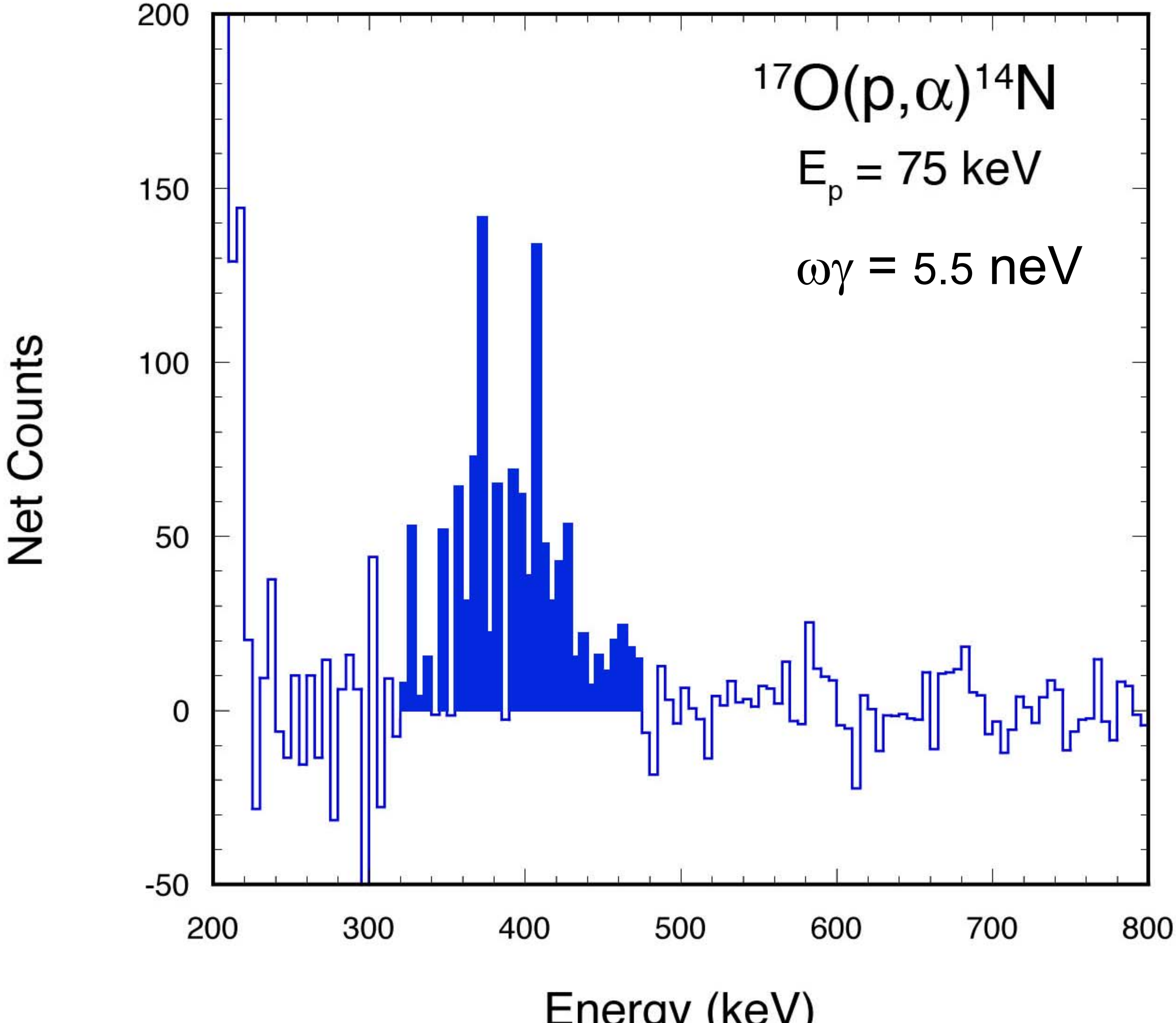

The Red Sox will win
the world series

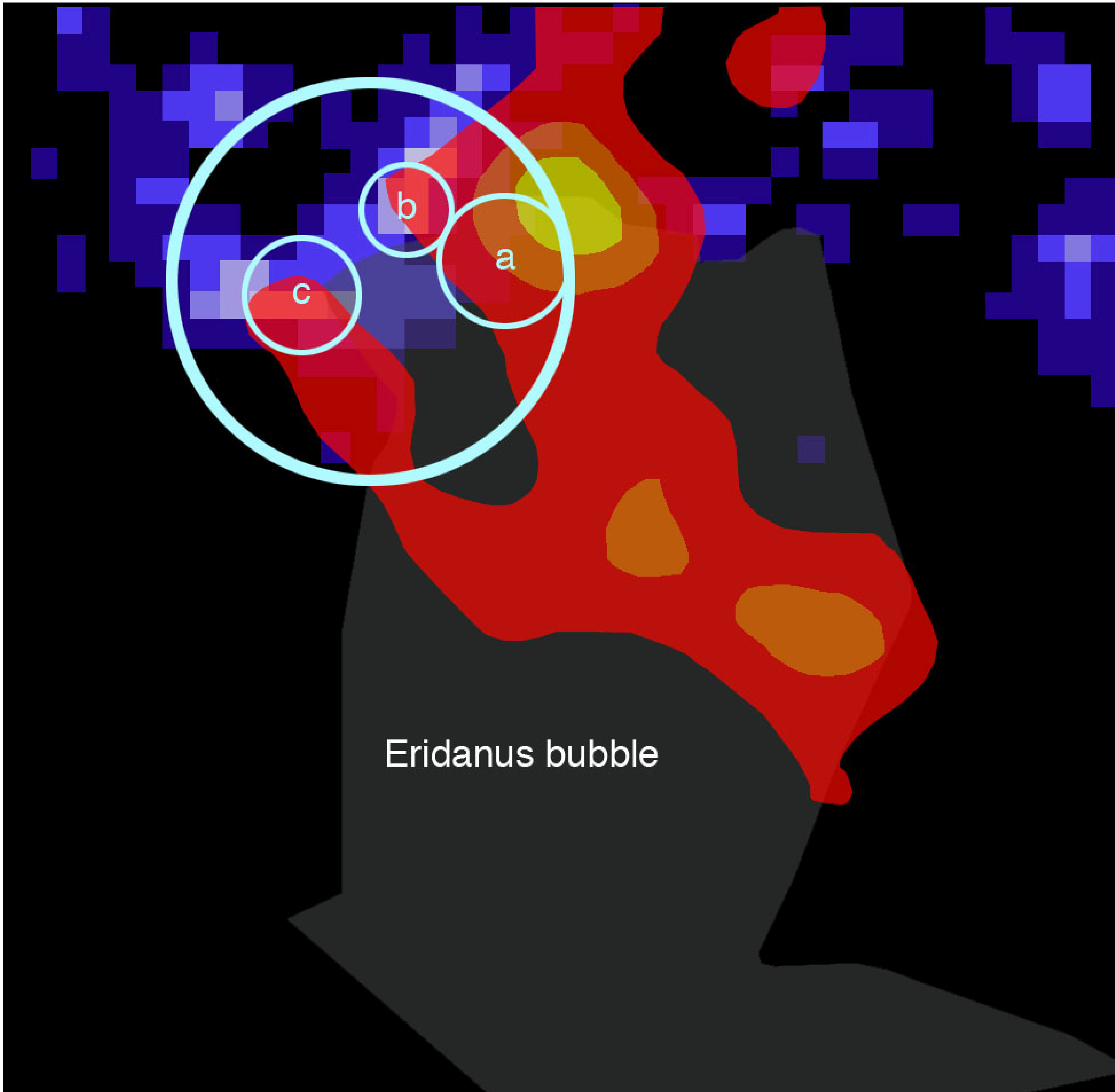
First Results from LENA

Why build a dedicated, low-energy accelerator facility for nuclear astrophysics?



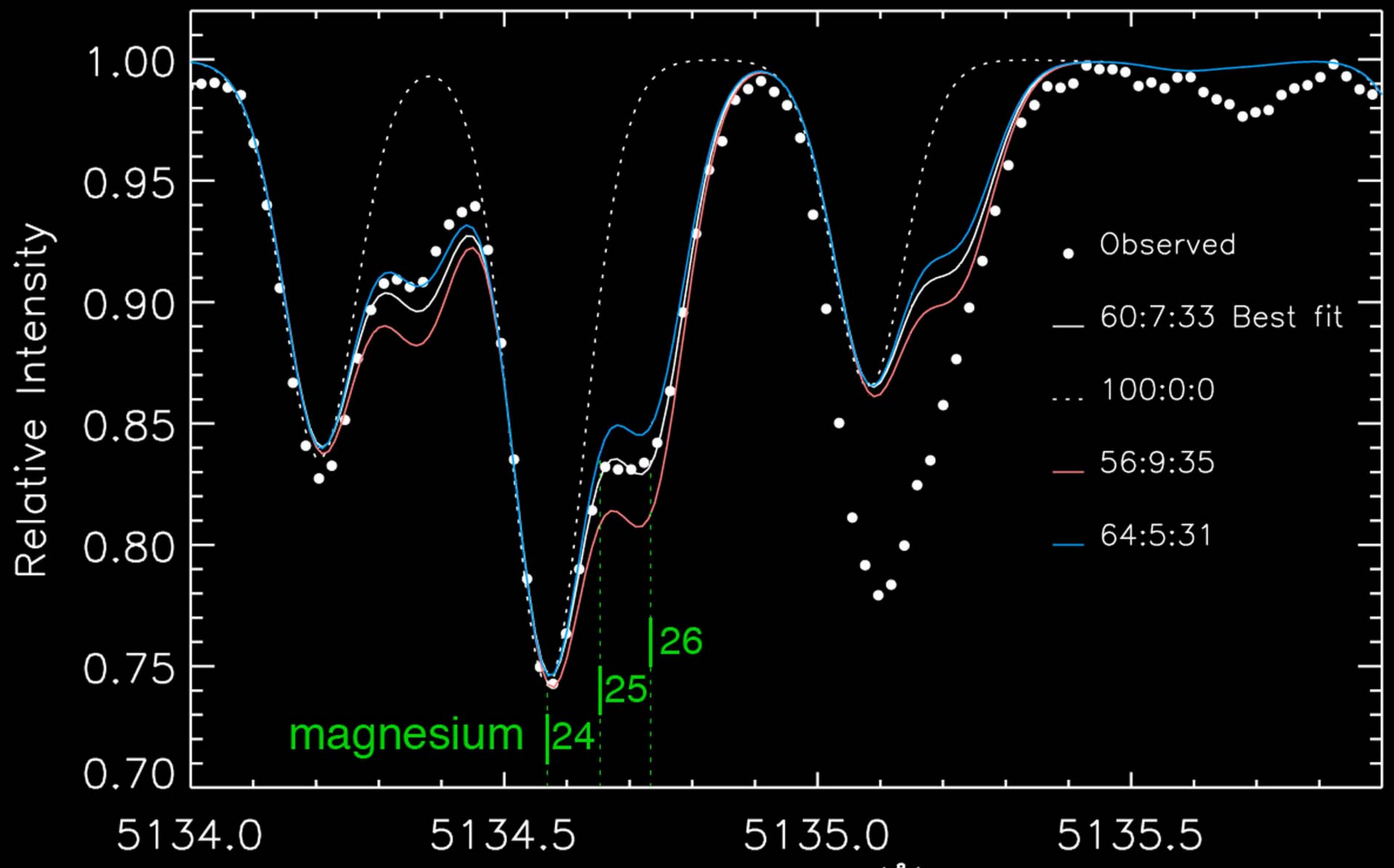
J.C. Blackmon et al. Phys. Rev. Lett. ***74****, 2642 (1995)*

*R. Diehl et al. New Astro. Rev. **48**, 81 (2004)*

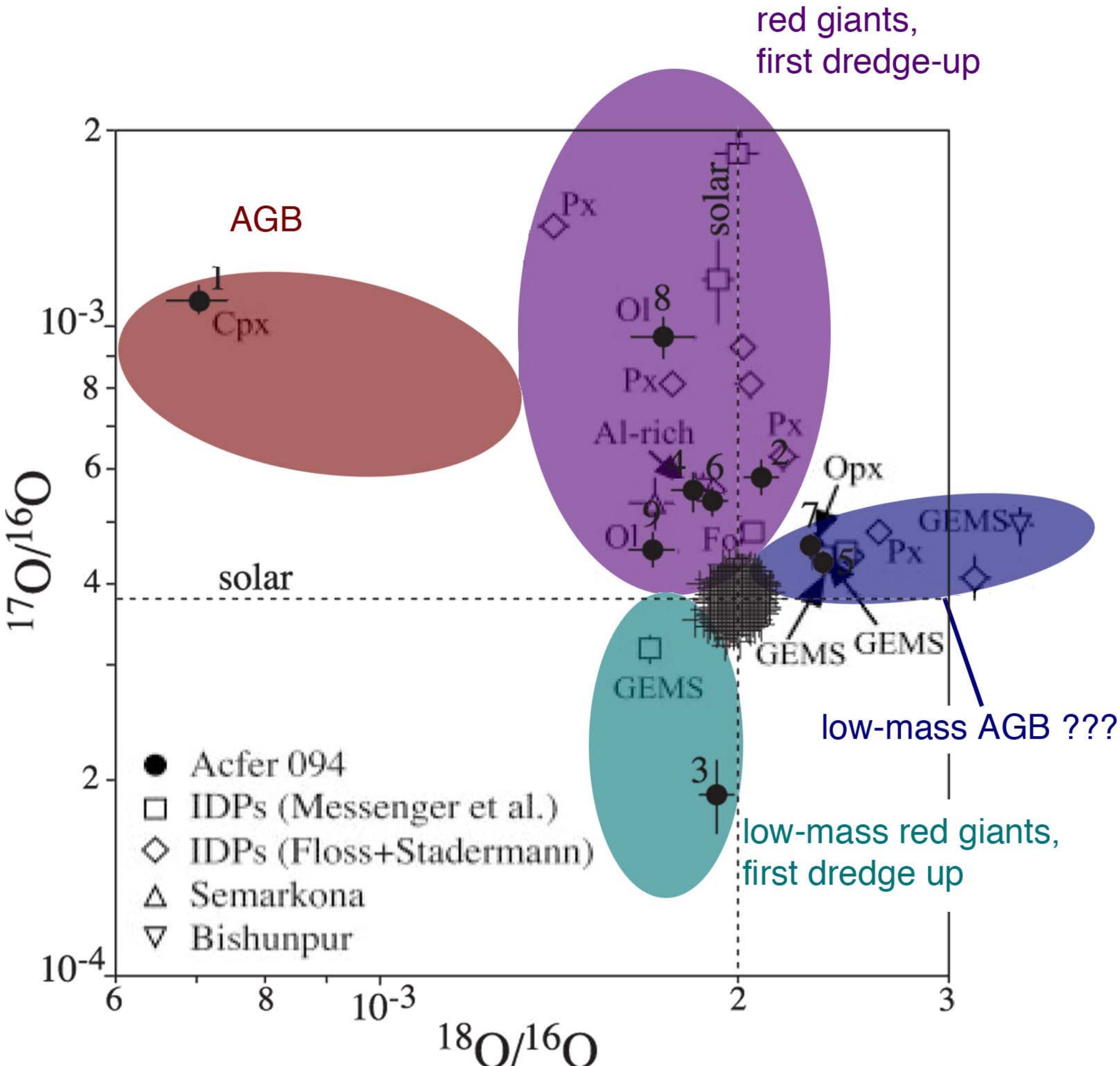


Abundances in NGC 6752

*D. Yong et al. A&A **402**, 985 (2003)*



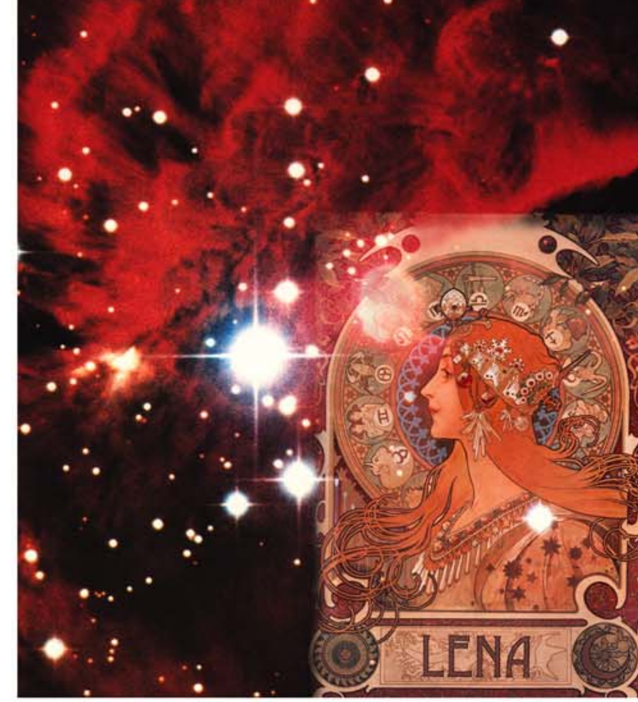
*A.N. Nguyen and E. Zinner, Science **303**, 1496 (2004)*

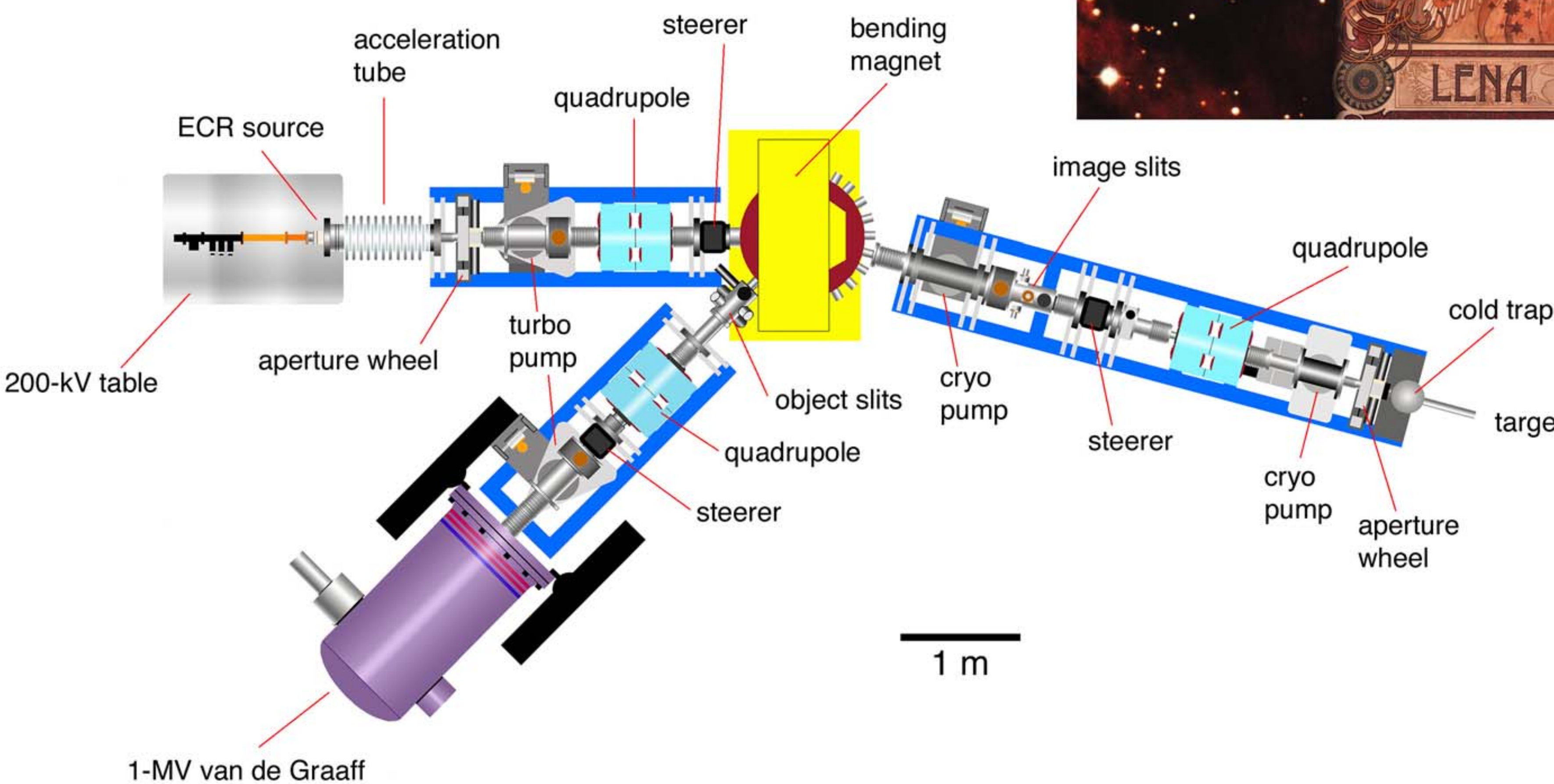


Design considerations:

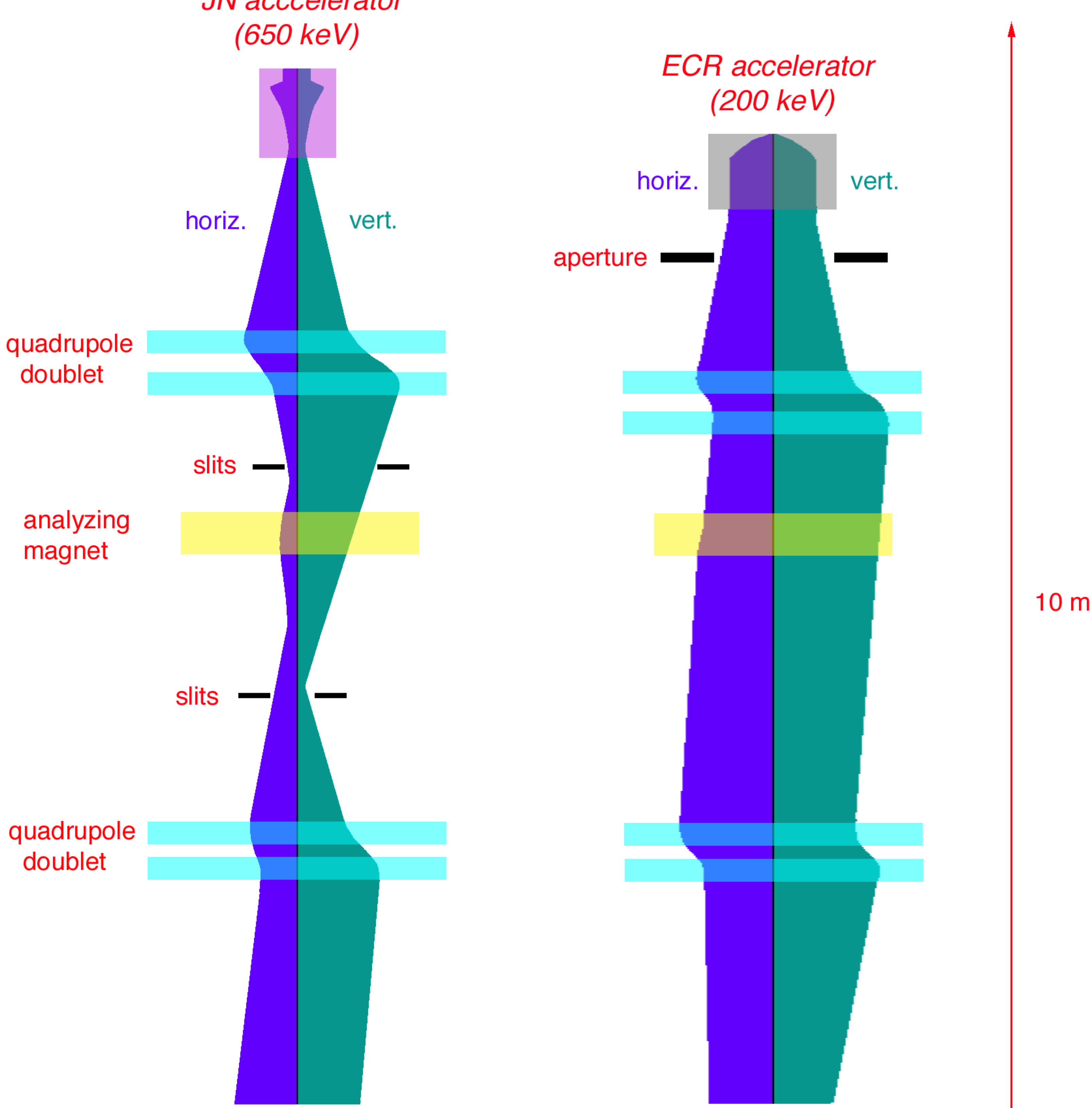
- Must be cheap
- Want $E \approx 0$ - 500 keV, $\Delta E \leq 1$ keV
  $I \sim 1$ mA for $E \leq 100$ keV
  $I \sim 0.2$ mA for $E > 100$ keV
- Beam quality should be “reasonable”
- Must run for extended periods with minimal effort
- Must be cheap

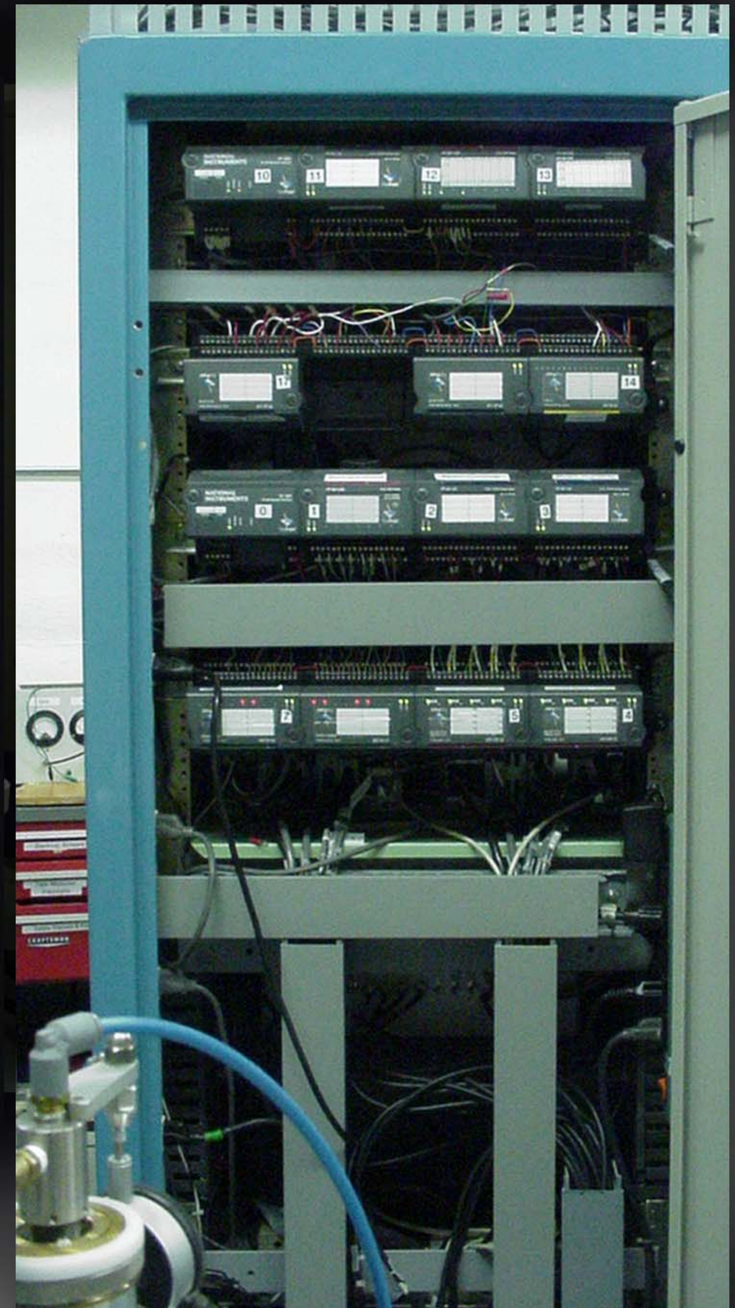
LENA





the Laboratory for Experimental Nuclear Astrophysics

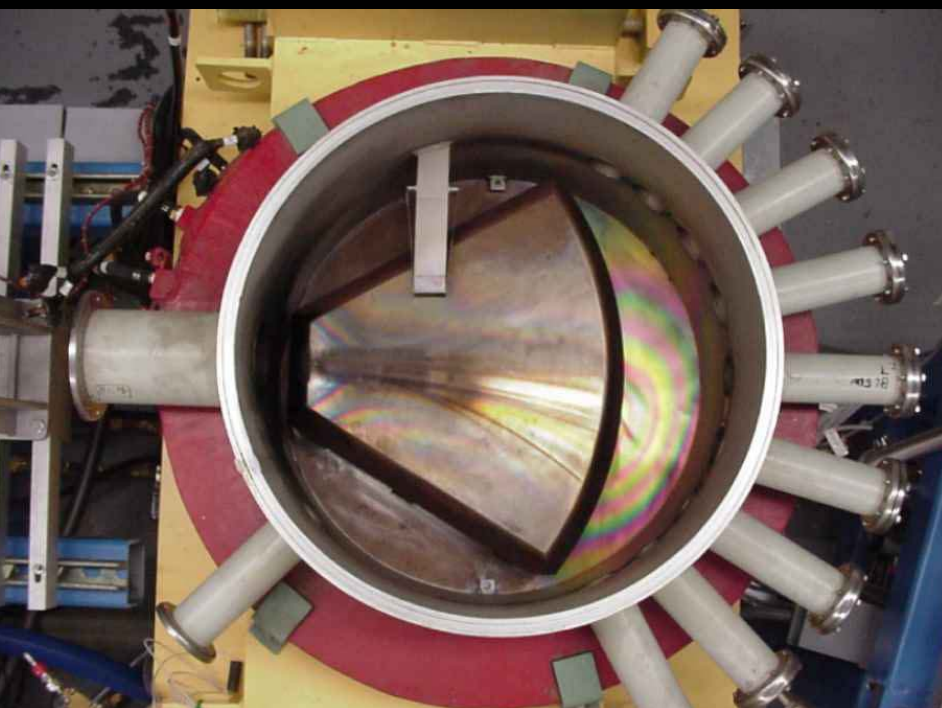

JN accelerator
(650 keV)
ECR accelerator
(200 keV)
horiz.
vert.
horiz.
vert.
aperture
quadrupole
doublet
slits
analyzing
magnet
slits
quadrupole
doublet
10 m



control via LabView with FieldPoint

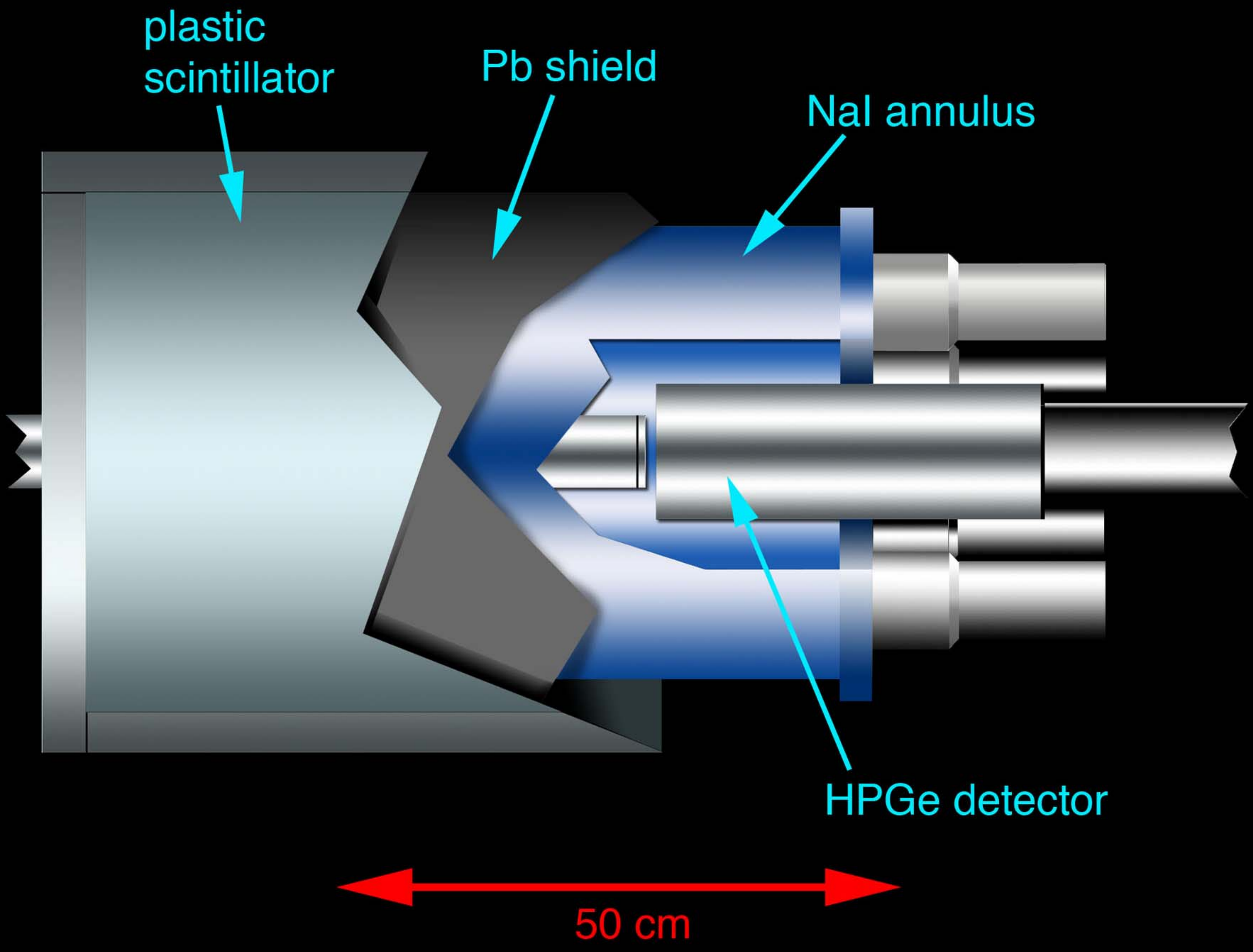
9/99

1/03





beam
target
HPGe


plastic
scintillator
Pb shield
NaI annulus
HPGe detector
50 cm

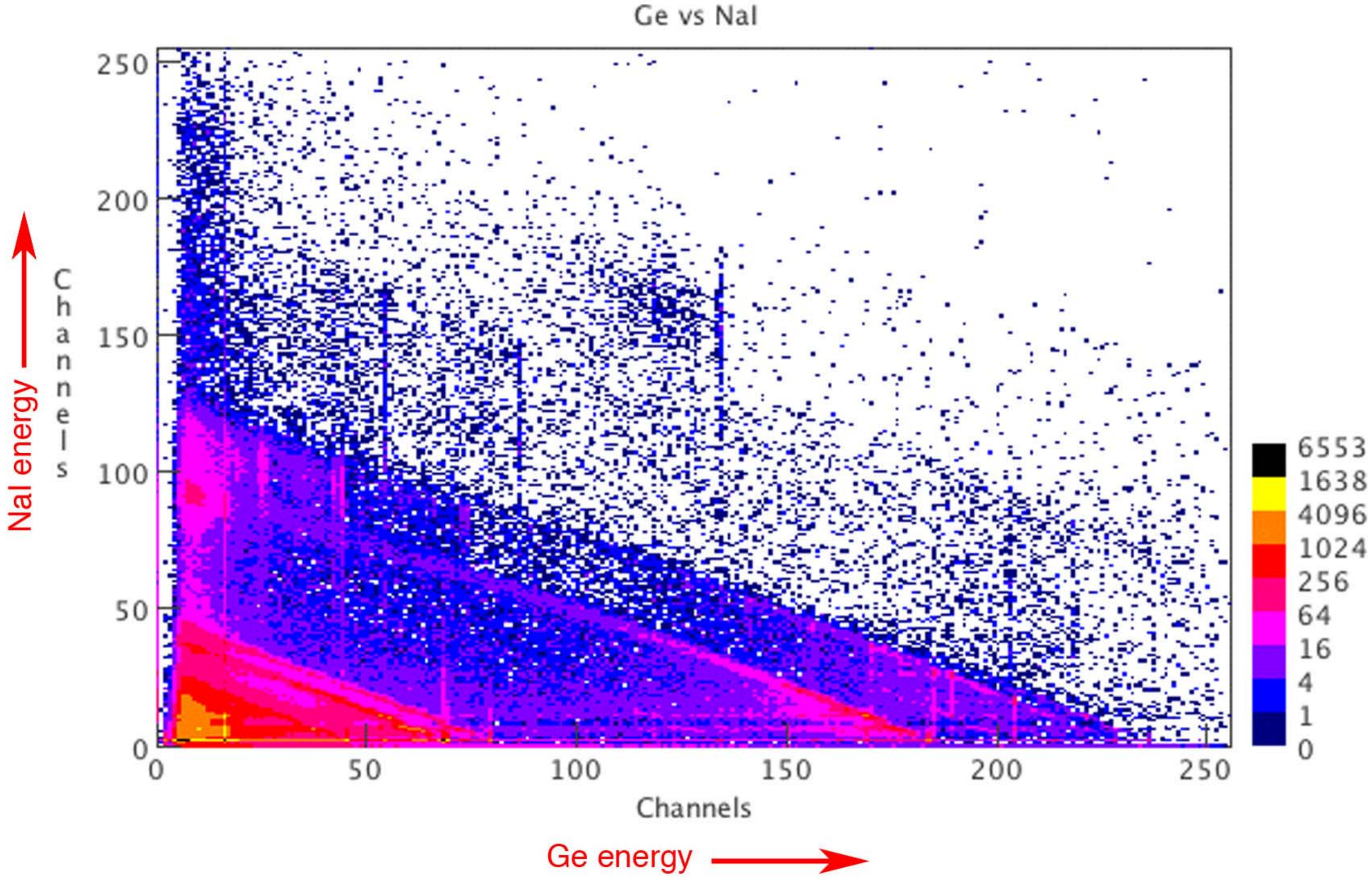
Event trigger:

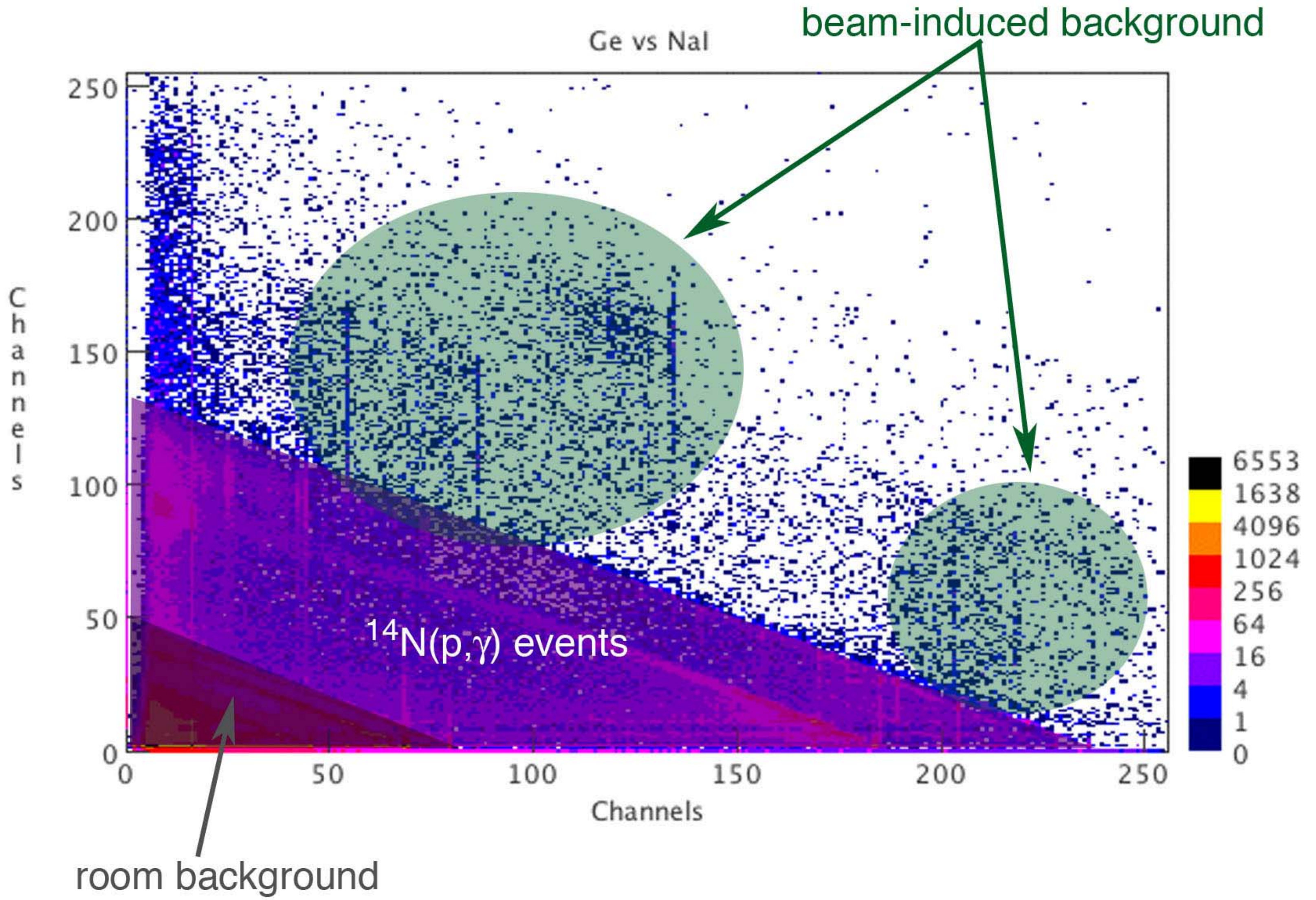
1. Ge - veto anticoincidence
2. beam pulse
   (infinite future)

Cuts:

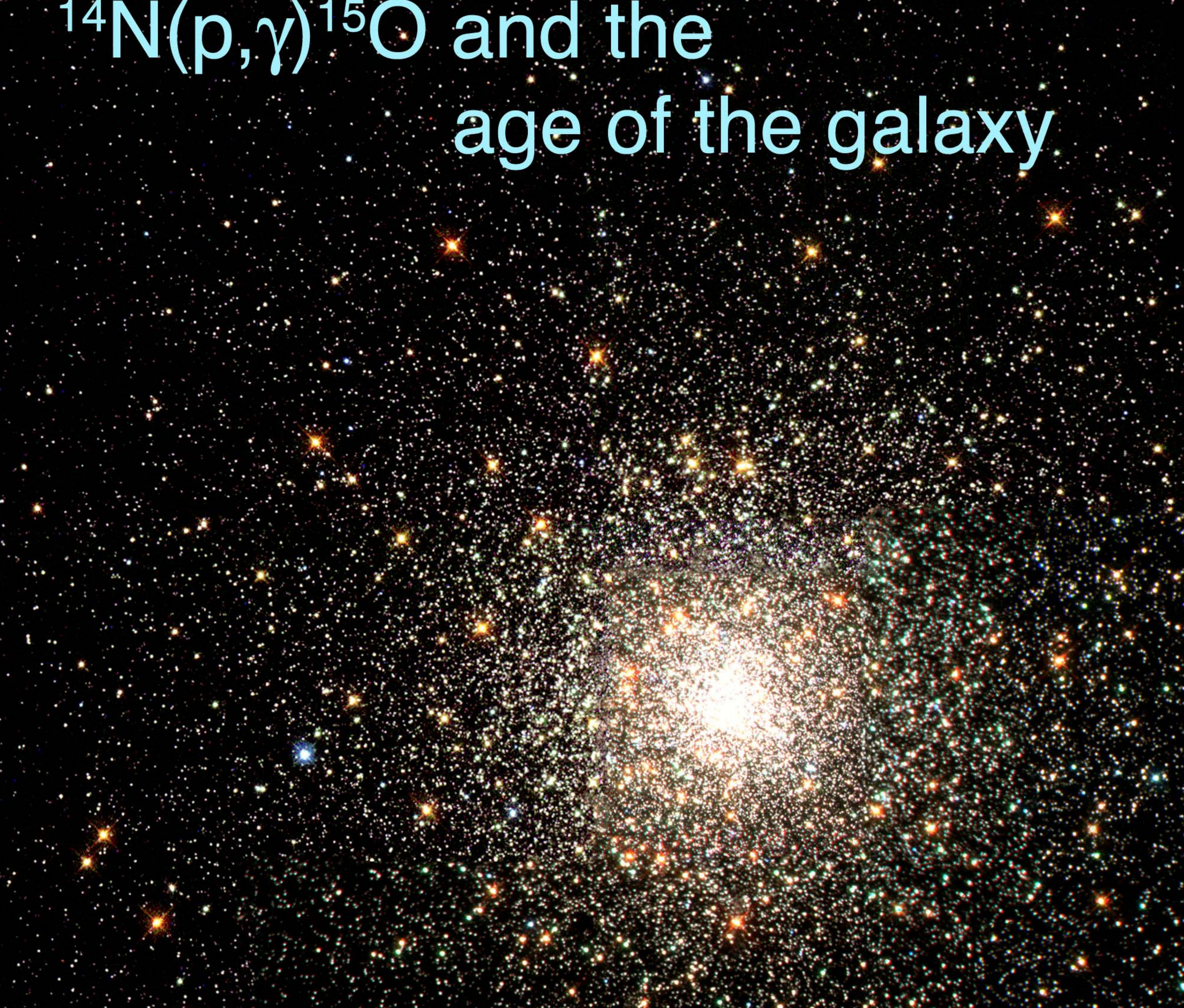
1. time
2. E(Ge) vs. E(NaI)
3. multiplicity
4. inner NaI vs. outer NaI
   (future)
5. Ge pulse shape (soon?)

$^{14}N(p,\gamma)^{15}O$




beam-induced background
Ge vs NaI
Channels
Channels
$^{14}N(p,\gamma)$ events
room background
6553
1638
4096
1024
256
64
16
4
1
0

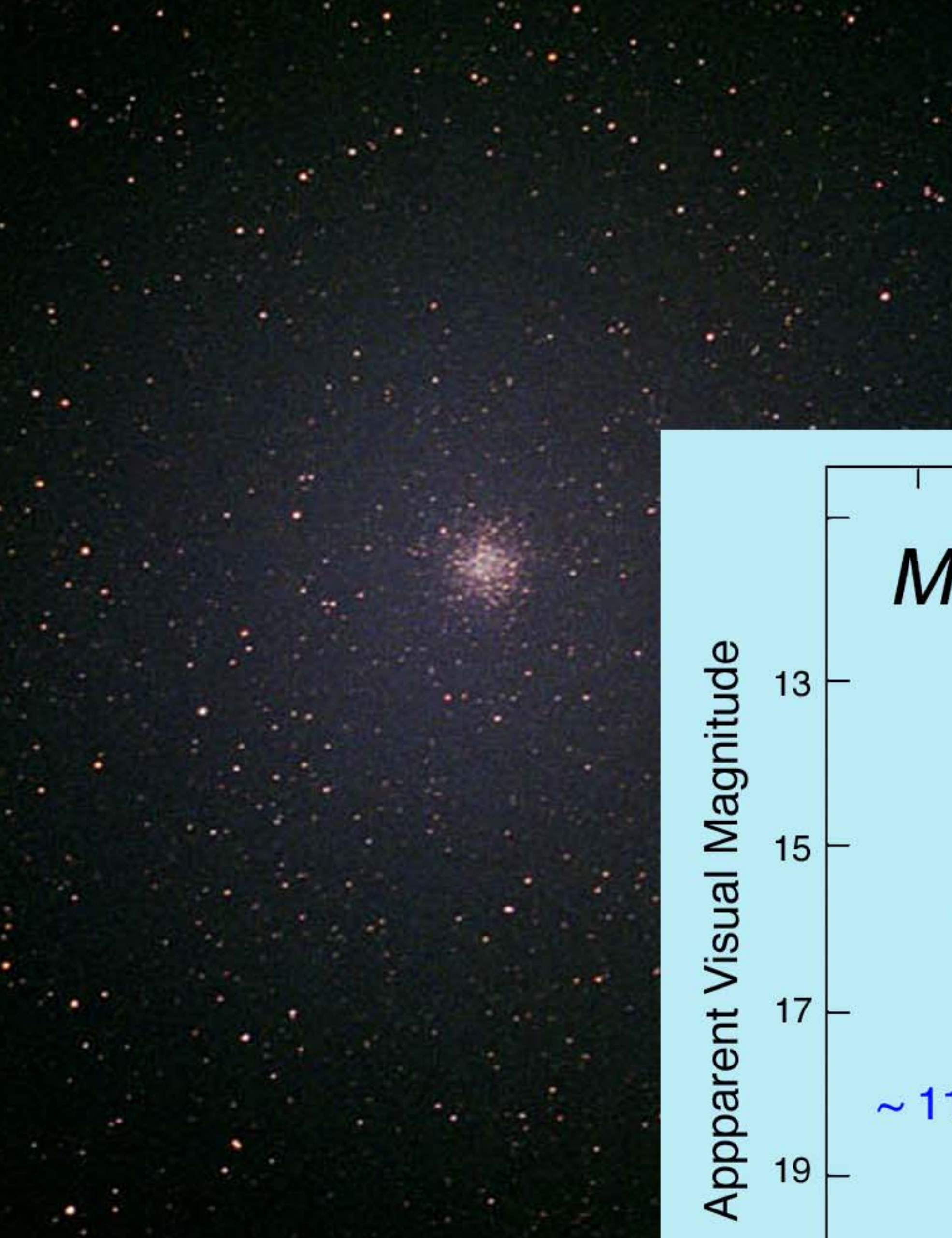
$^{14}N(p,\gamma)^{15}O$ and the age of the galaxy

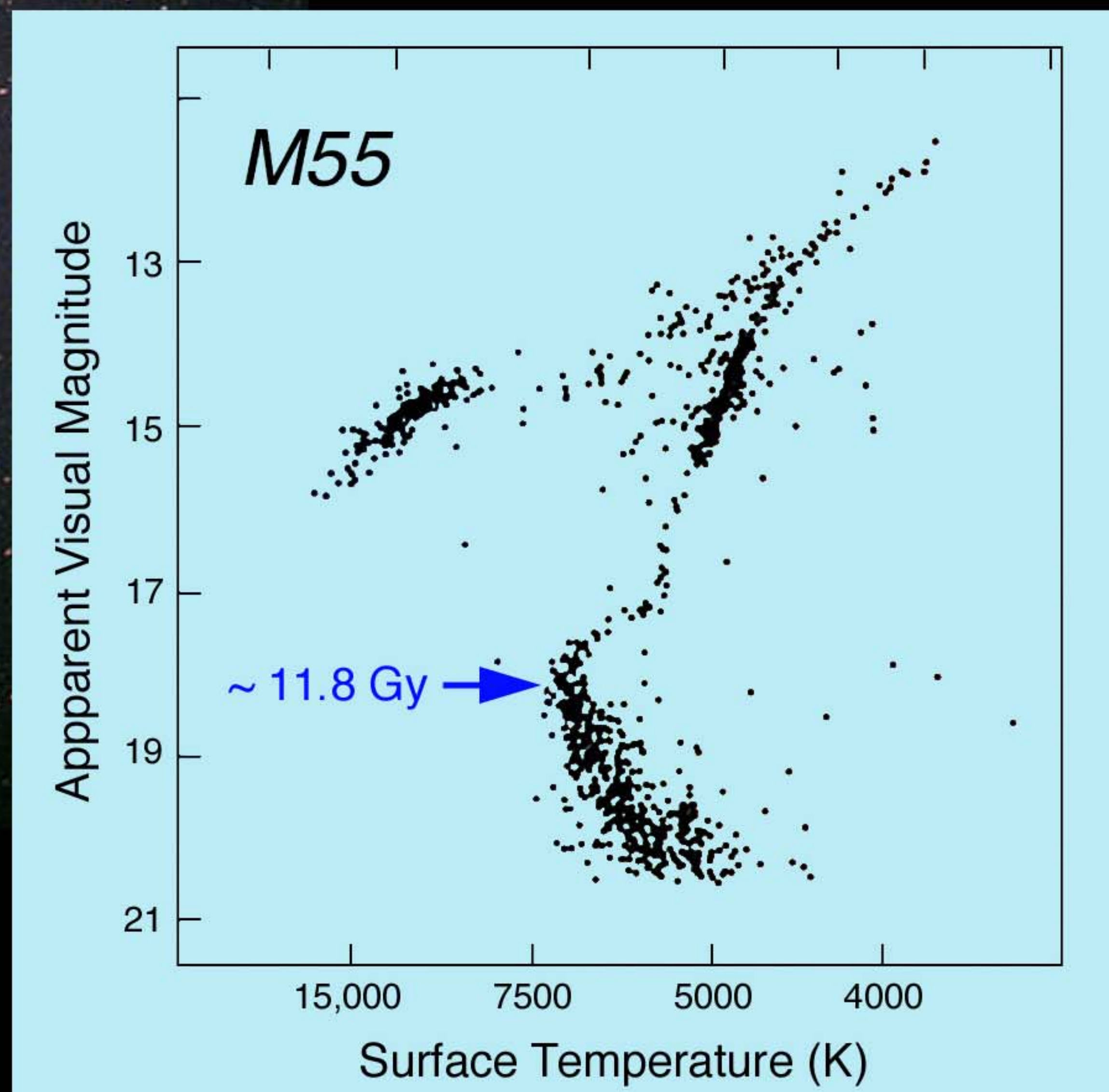


Globular clusters are coeval, chemically homogeneous groups of 10^3 - 10^6 stars

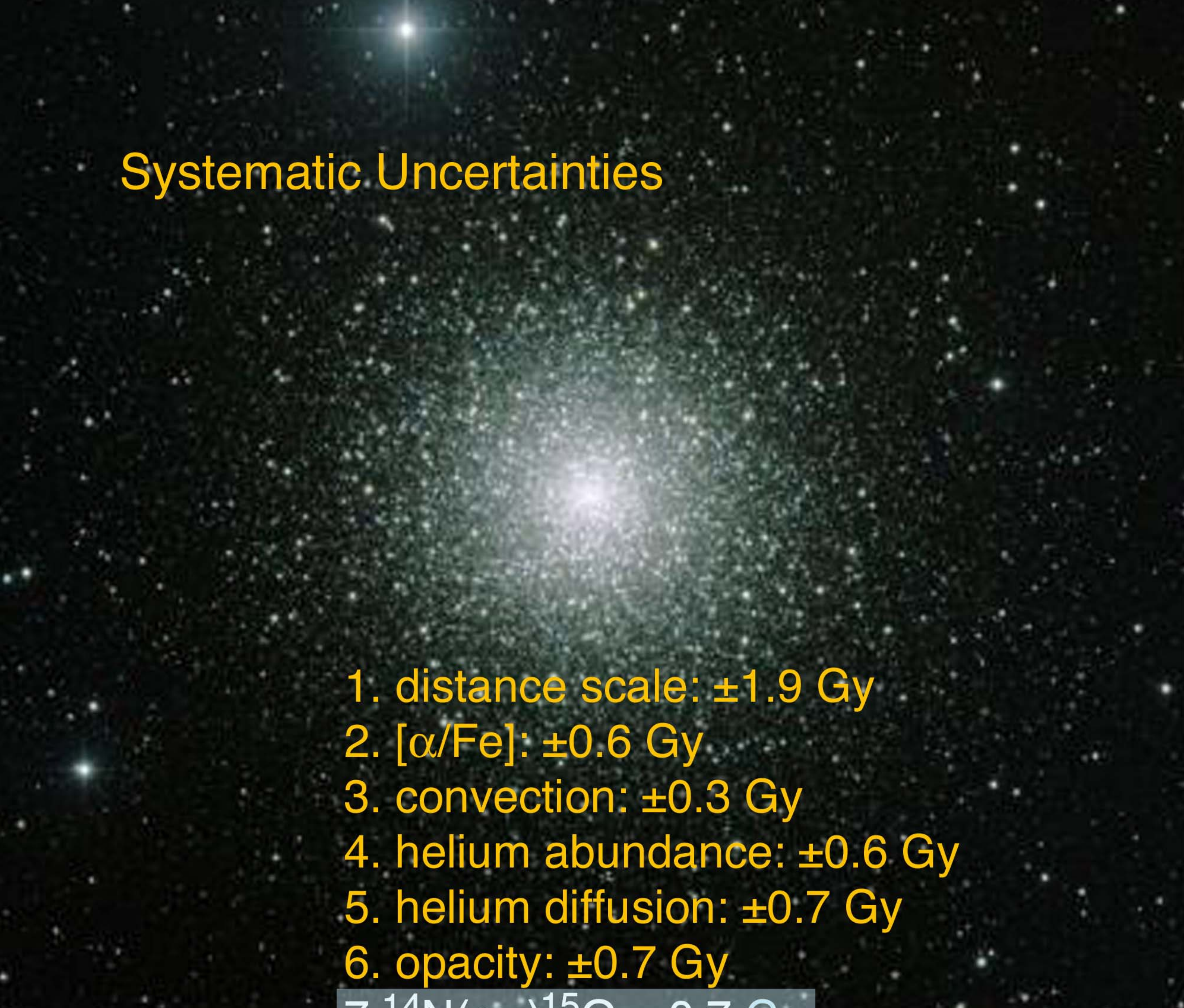
They provide an integrated sequence of stellar evolution

Kinematics and ages trace out the evolution of structure



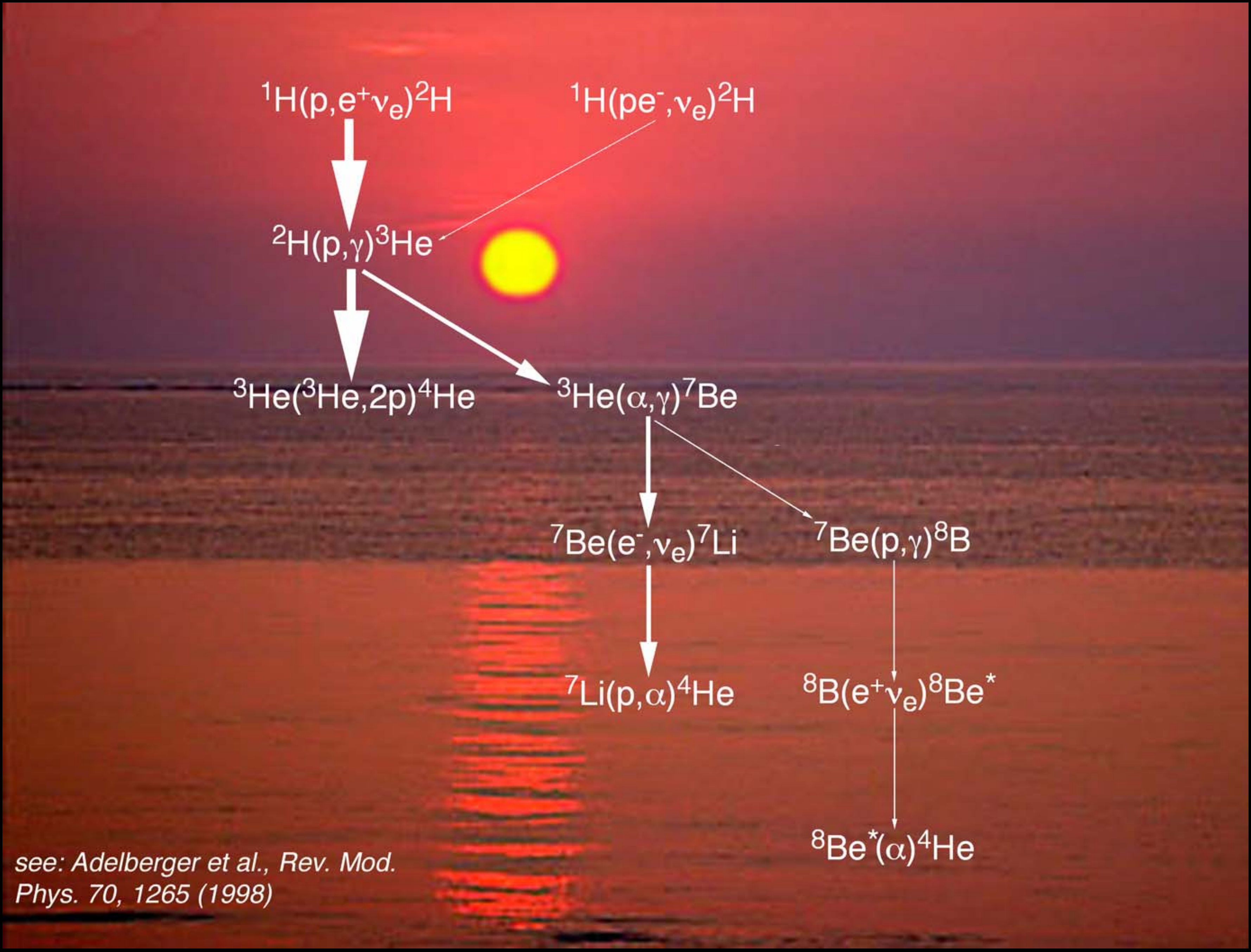


M55
Appparent Visual Magnitude
13
15
17
19
21
~ 11.8 Gy
15,000
7500
5000
4000
Surface Temperature (K)

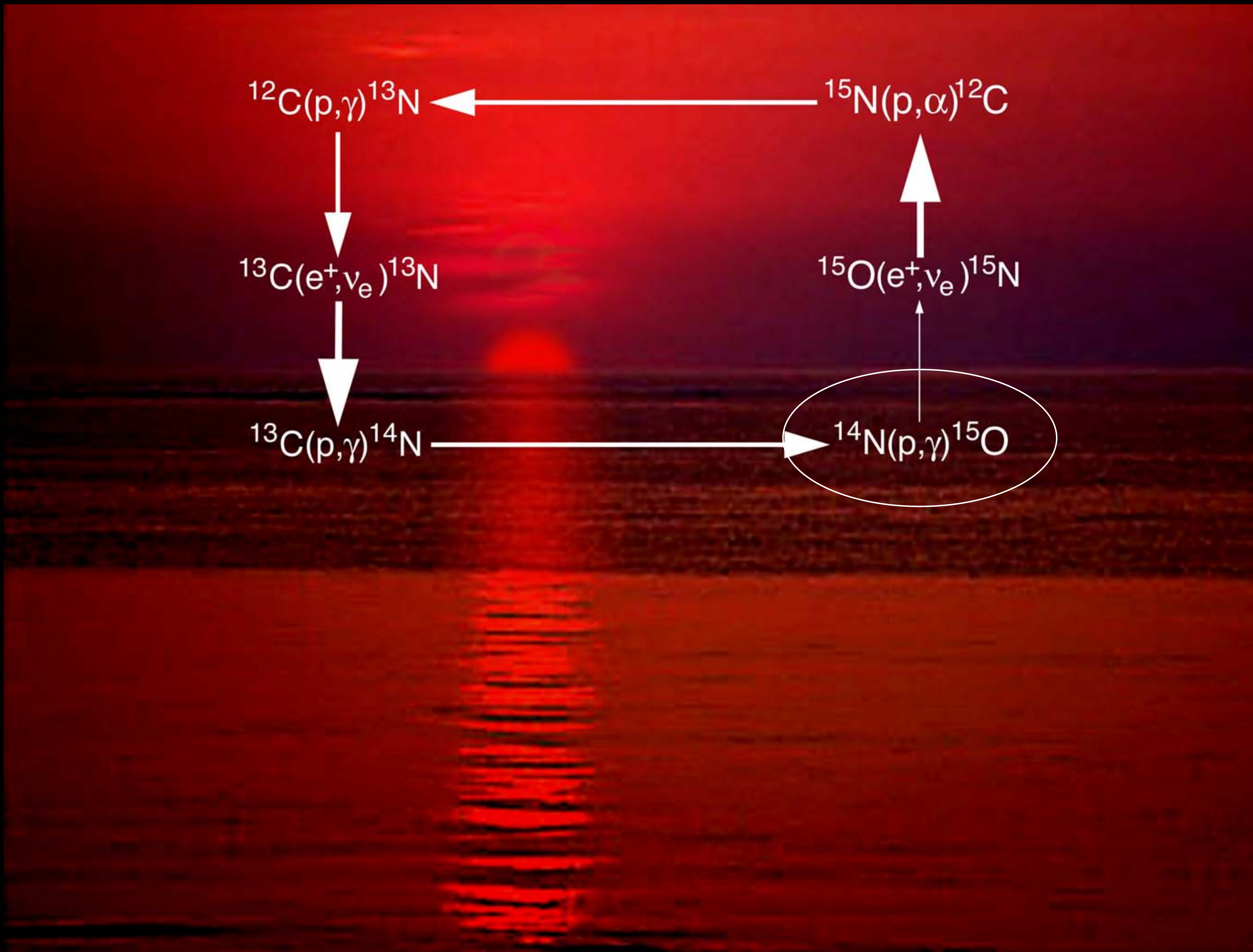


Systematic Uncertainties

1. distance scale: ±1.9 Gy
2. [α/Fe]: ±0.6 Gy
3. convection: ±0.3 Gy
4. helium abundance: ±0.6 Gy
5. helium diffusion: ±0.7 Gy
6. opacity: ±0.7 Gy

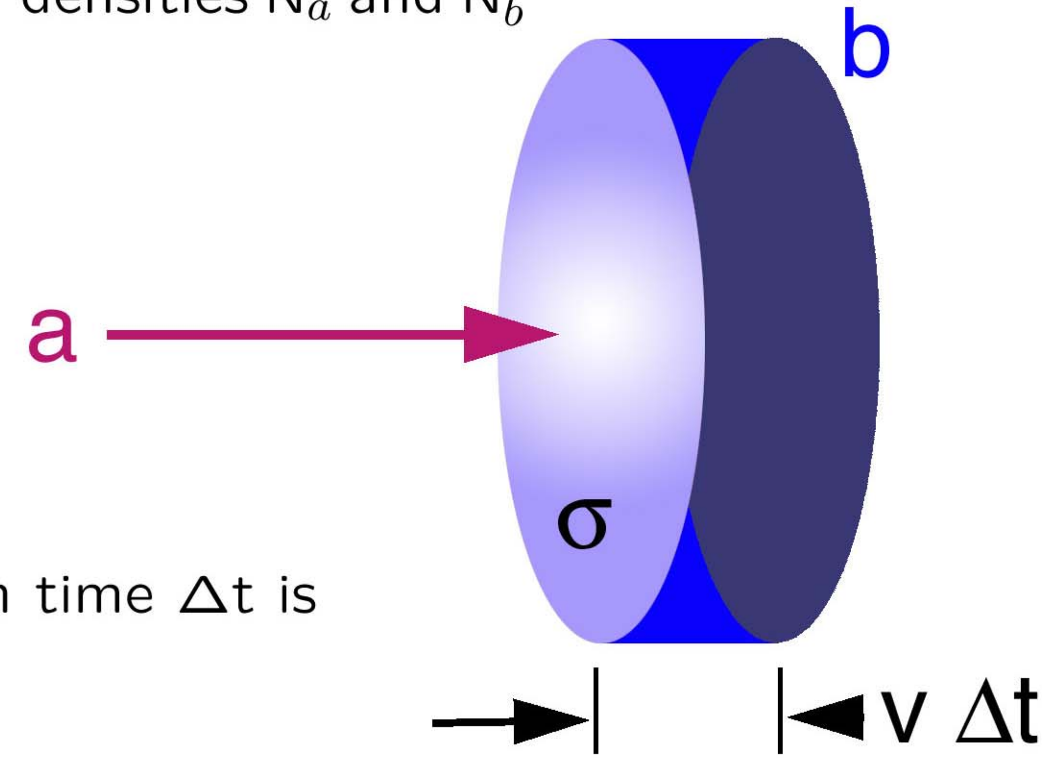


$^1H(p,e^+\nu_e)^2H$
$^1H(pe^-,\nu_e)^2H$
$^2H(p,\gamma)^3He$
$^3He(^3He,2p)^4He$
$^3He(\alpha,\gamma)^7Be$
$^7Be(e^-,\nu_e)^7Li$
$^7Be(p,\gamma)^8B$
$^7Li(p,\alpha)^4He$
$^8B(e^+\nu_e)^8Be^*$
$^8Be^*(\alpha)^4He$
see: Adelberger et al., Rev. Mod. Phys. 70, 1265 (1998)


$^{12}C(p,\gamma)^{13}N$
$^{15}N(p,\alpha)^{12}C$
$^{13}C(e^+,\nu_e)^{13}N$
$^{15}O(e^+,\nu_e)^{15}N$
$^{13}C(p,\gamma)^{14}N$
$^{14}N(p,\gamma)^{15}O$

Thermonuclear reaction rate

reaction a + b with number densities N_a and N_b



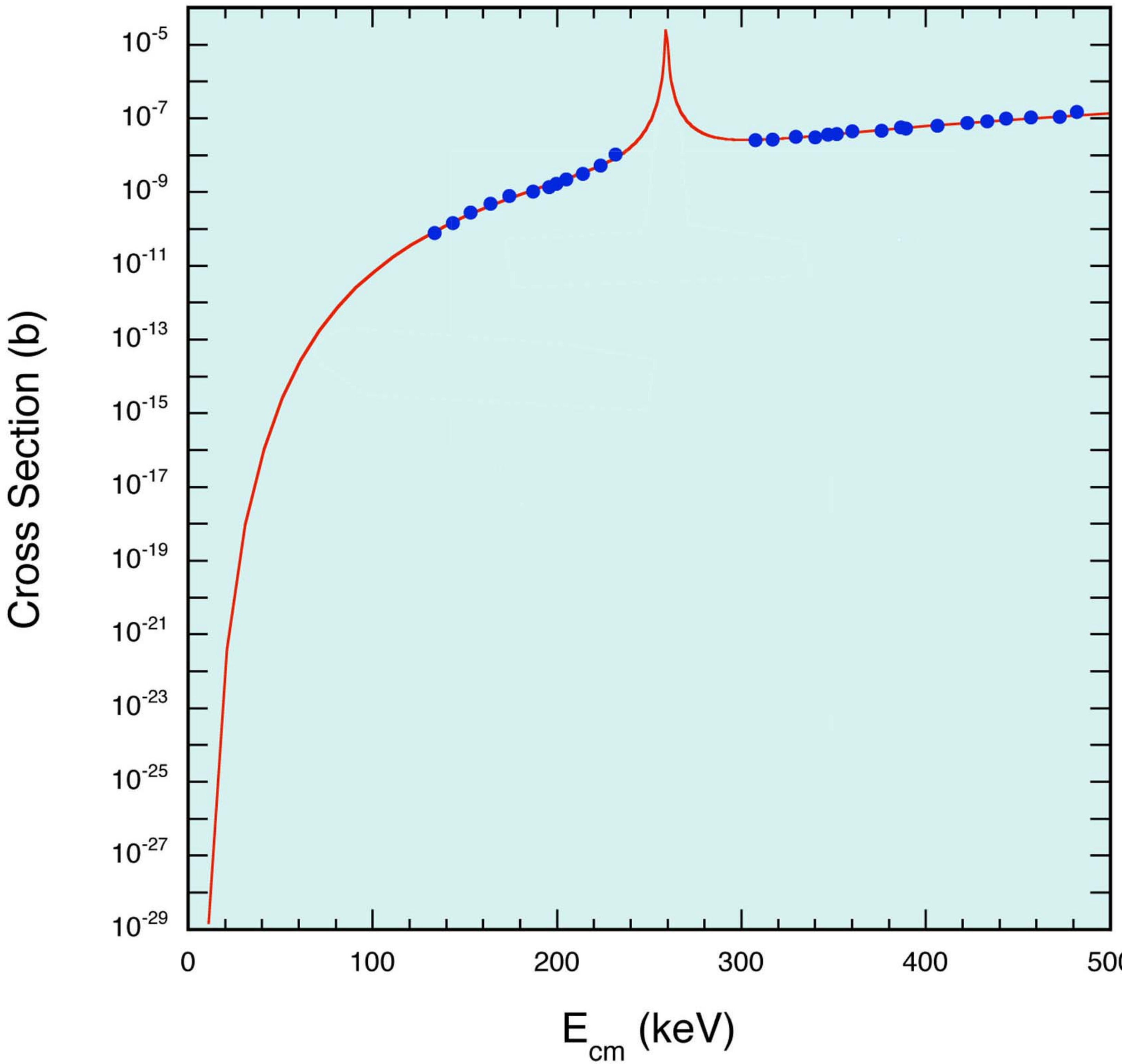
number of nuclei reacting in time Δt is

$$N_b \times \sigma v \times \Delta t$$

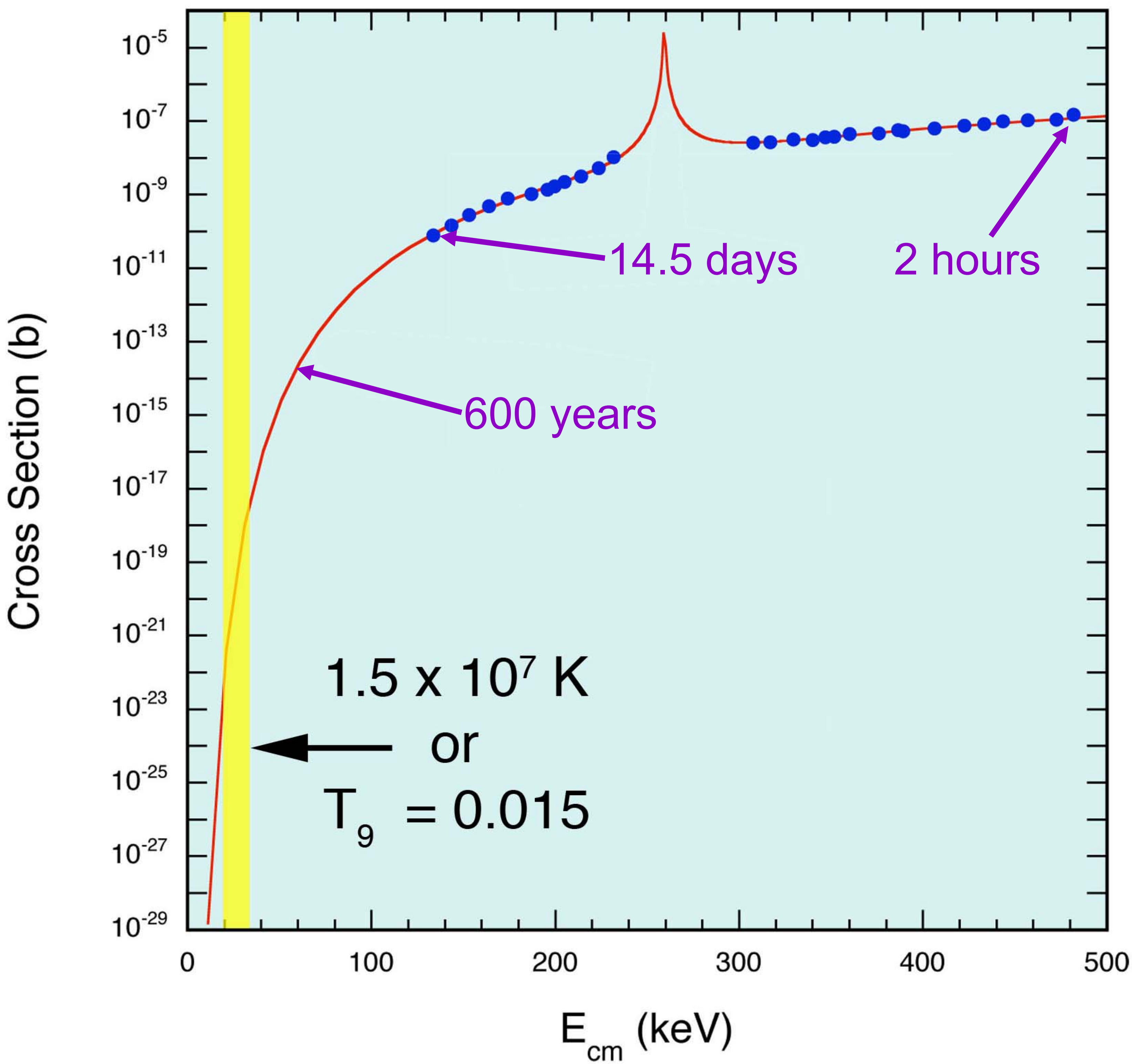
$$\text{Rate} = N_b \times \sigma v$$

$$\frac{\text{Rate}}{\text{unit volume of gas}} = \frac{N_a N_b \cdot \sigma v}{1+\delta_{ab}}$$

$$\langle \sigma v \rangle = \sqrt{\frac{8}{\mu\pi(kT)^3}} \int_0^\infty \sigma(E) E e^{-E/kT} dE$$



Cross Section (b)
10-5
10-7
10-9
10-11
10-13
10-15
10-17
10-19
10-21
10-23
10-25
10-27
10-29
0
100
200
300
400
500
E cm (keV)



14.5 days
2 hours
600 years
1.5 x 10^7 K
or
T_9 = 0.015
Cross Section (b)
E_cm (keV)
10^-5
10^-7
10^-9
10^-11
10^-13
10^-15
10^-17
10^-19
10^-21
10^-23
10^-25
10^-27
10^-29
0
100
200
300
400
500

"Direct capture"

$\sigma = \pi\lambda\!\!\!^{-2}$ x (tunneling probability) x (matrix element)

$$= \frac{1}{E} \times e^{-b/E^{1/2}} \times S(E)$$

[S(E) is the "astrophysical S-factor"]

"Resonance capture"

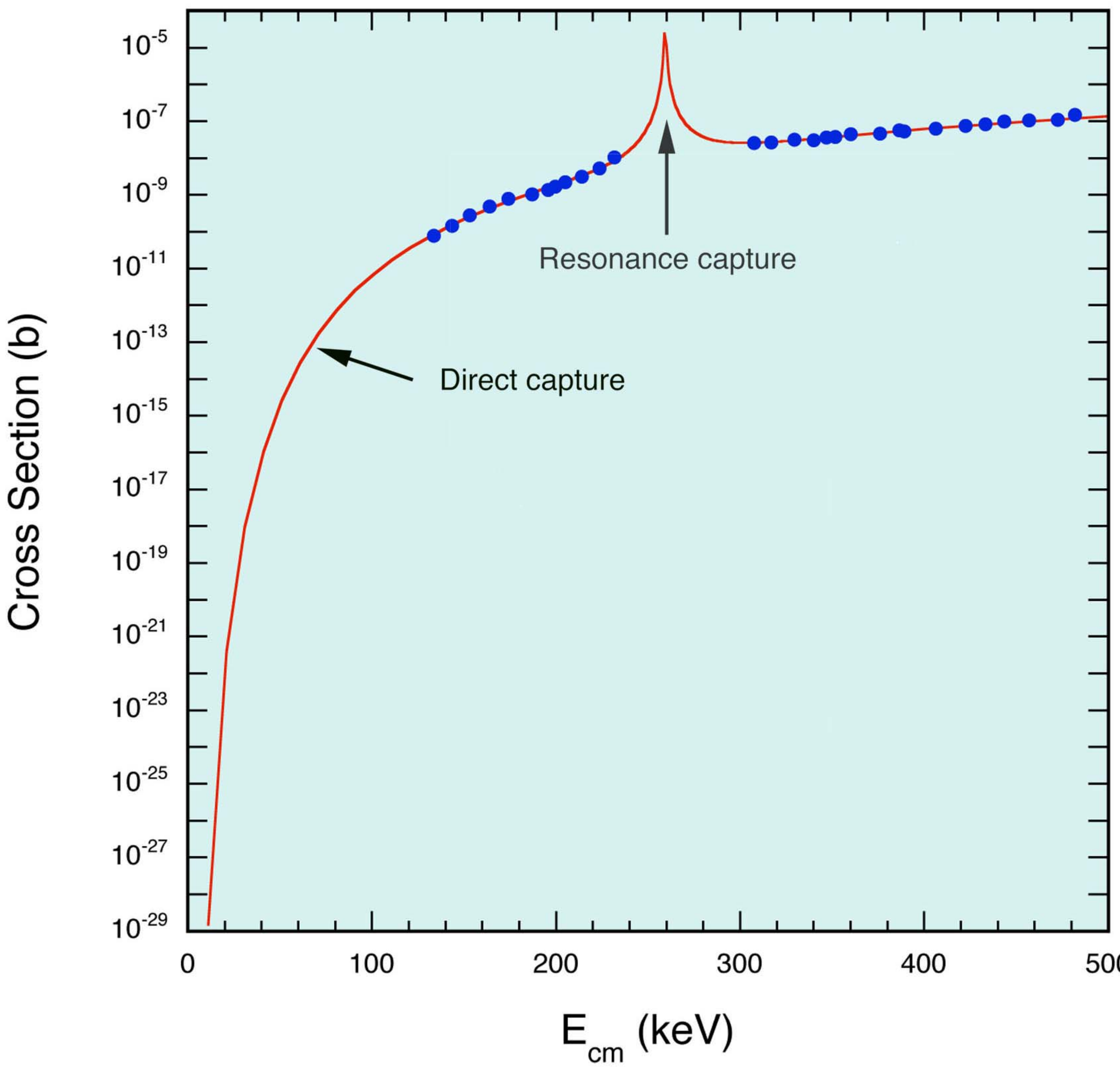
for a (p,γ) reaction:

$$\sigma = \pi \lambda\!\!\!^{-2}\, \omega \, \frac{\Gamma_p \, \Gamma_\gamma}{(E - E_r)^2 + \Gamma^2/4}$$

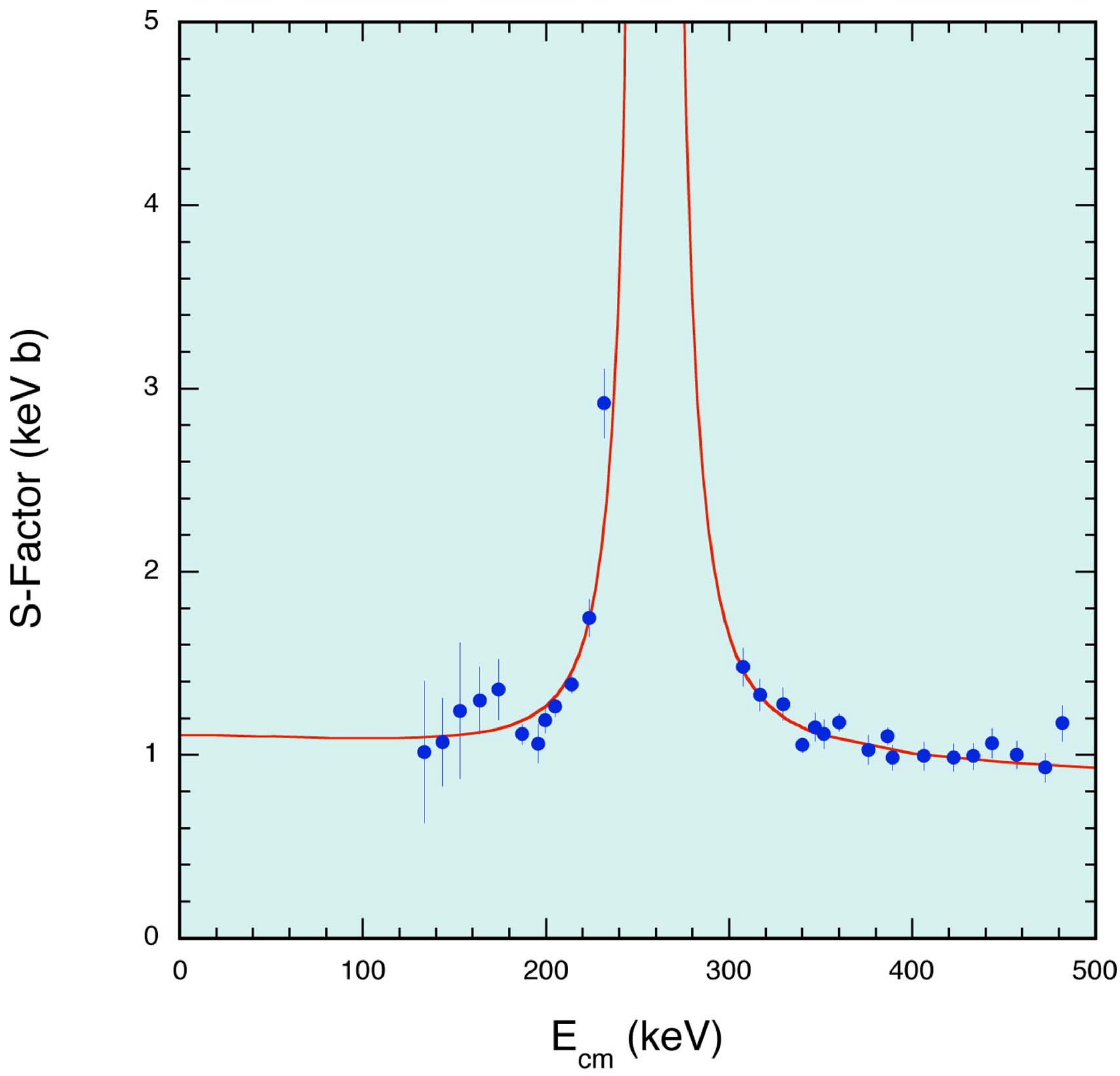
$$\Gamma = \Gamma_p + \Gamma_\alpha + \Gamma_\gamma \ldots \qquad \tau = \hbar / \Gamma$$

if the resonance is "narrow":

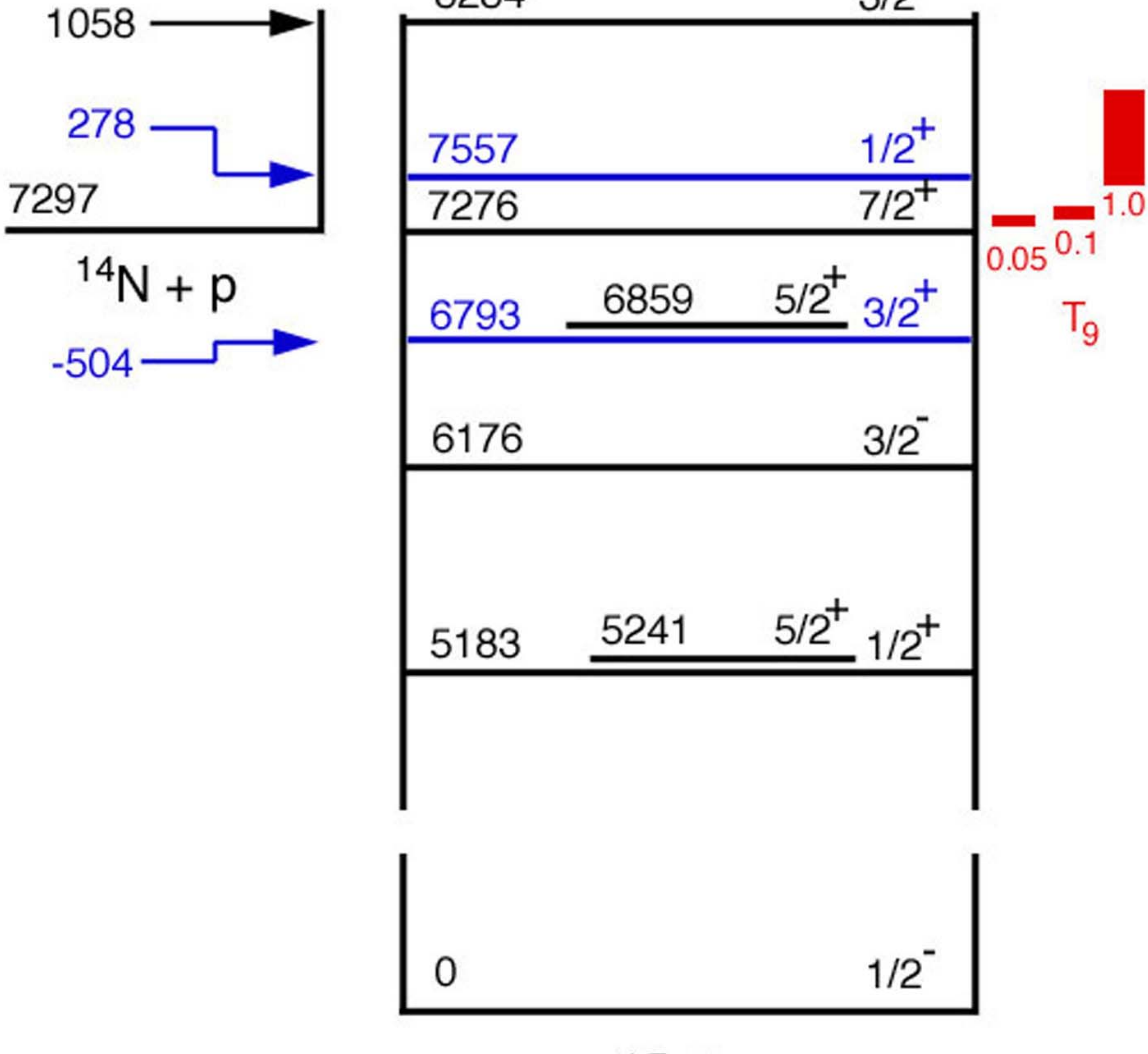
$$\langle \sigma v \rangle \propto \underbrace{\omega\gamma}_{\omega \frac{\Gamma_p \Gamma_\gamma}{\Gamma}} \cdot e^{-E_r/kT}$$

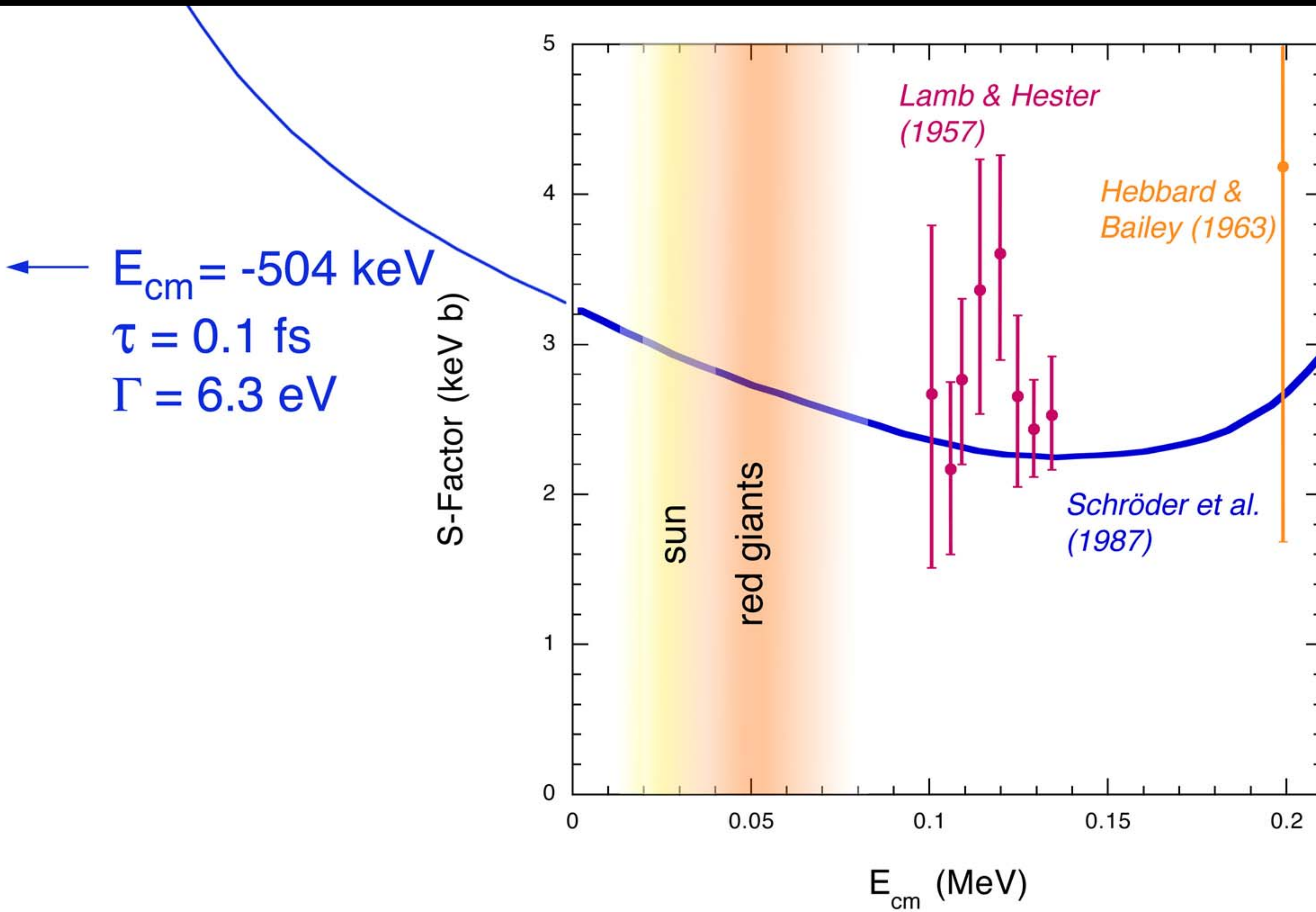


Cross Section (b)
10-5
10-7
10-9
10-11
10-13
10-15
10-17
10-19
10-21
10-23
10-25
10-27
10-29
Resonance capture
Direct capture
0
100
200
300
400
500
E cm (keV)



5
4
3
2
1
0
S-Factor (keV b)
0
100
200
300
400
500
E$_{cm}$ (keV)


1058
278
7297
$^{14}N + p$
-504
7557 1/2+
7276 7/2+
6859 5/2+
6793 3/2+
6176 3/2-
5241 5/2+
5183 1/2+
0 1/2-
0.05
0.1
1.0
T_9

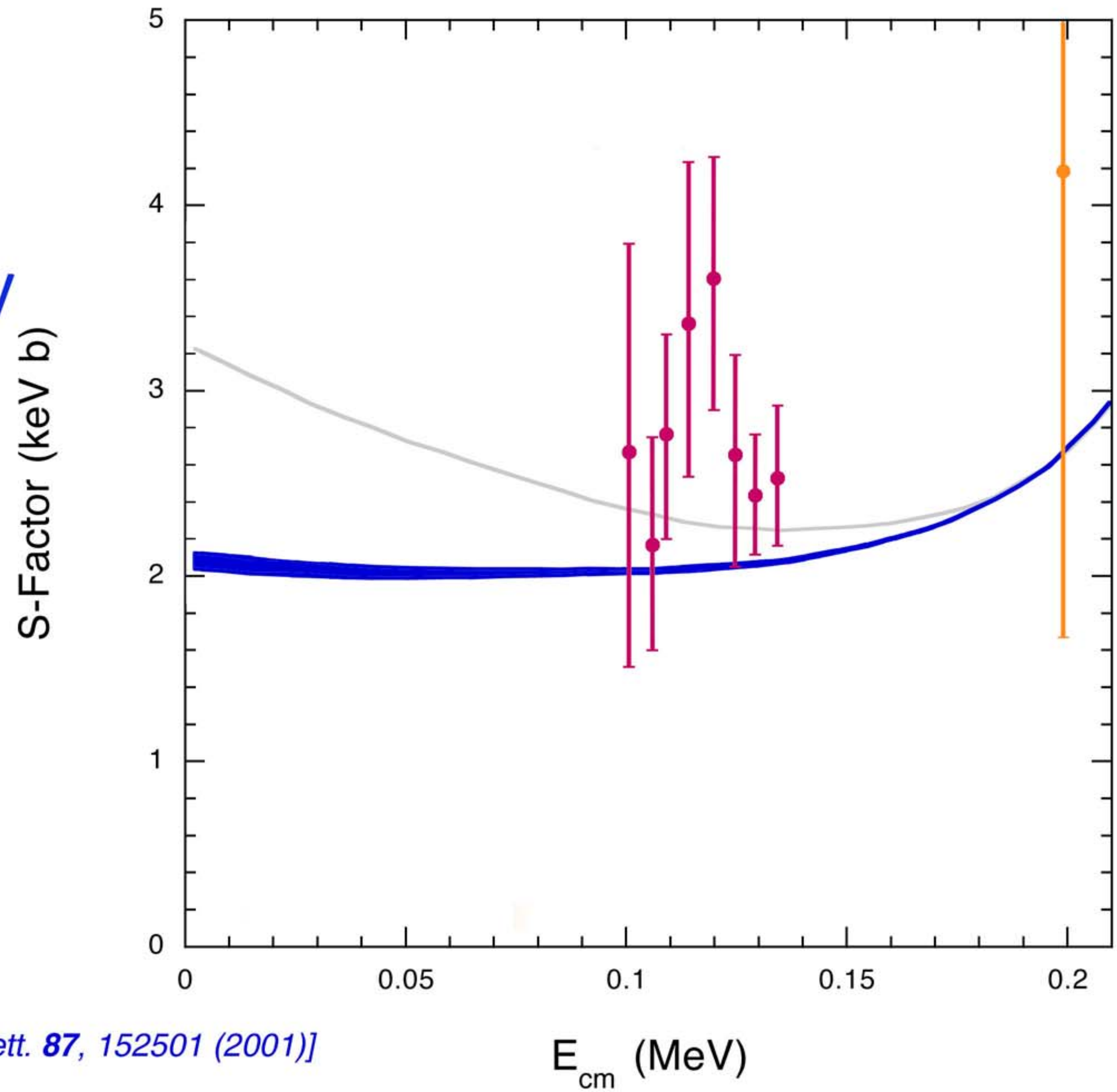


E_{cm} = -504 keV
τ = 0.1 fs
Γ = 6.3 eV
S-Factor (keV b)
5
4
3
2
1
0
0
0.05
0.1
0.15
0.2
E_{cm} (MeV)
sun
red giants
Lamb & Hester (1957)
Hebbard & Bailey (1963)
Schröder et al. (1987)

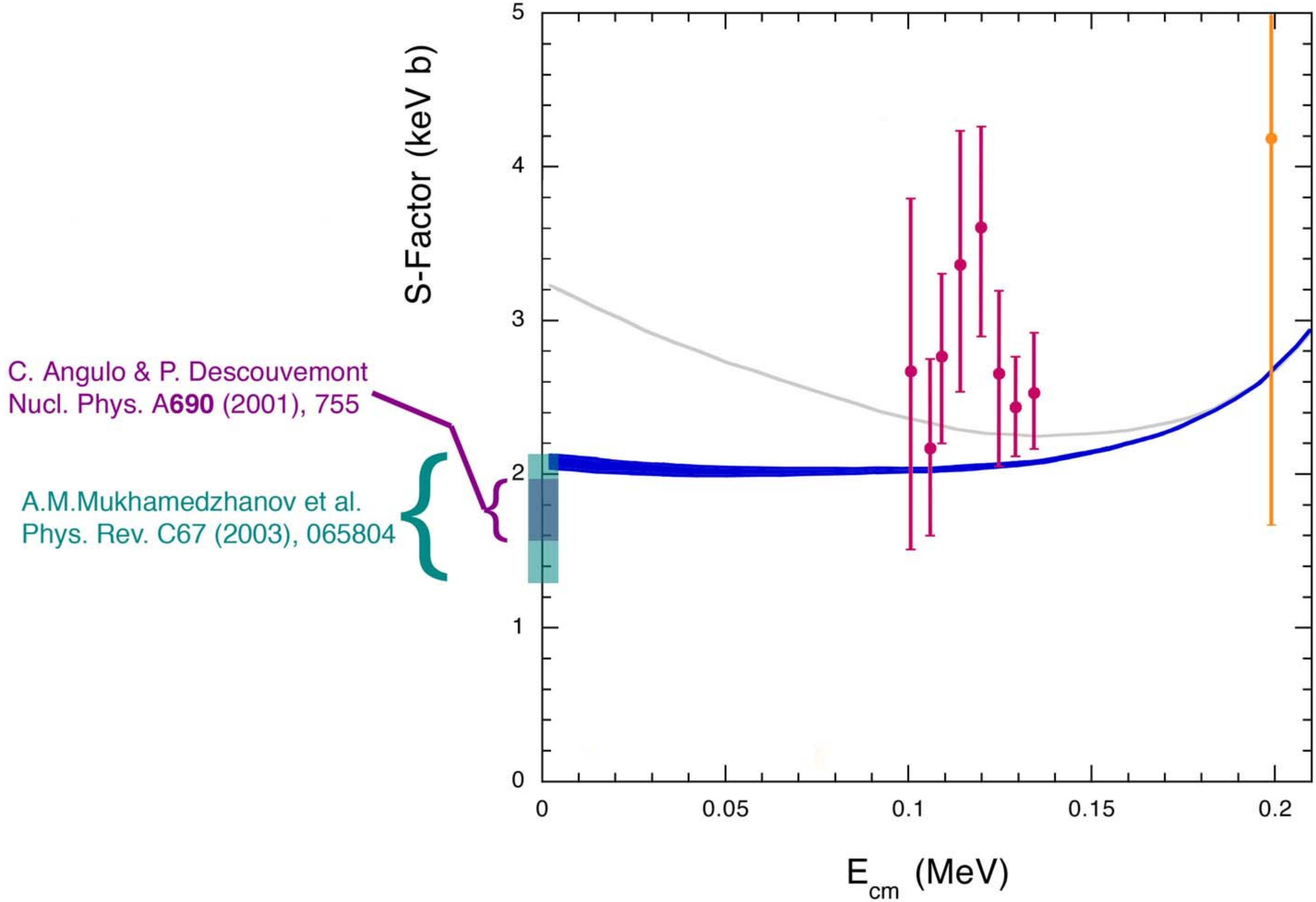
← E_{cm} = -504 keV

$\tau = 1.60^{+0.75}_{-0.72}$ fs (90% CL)

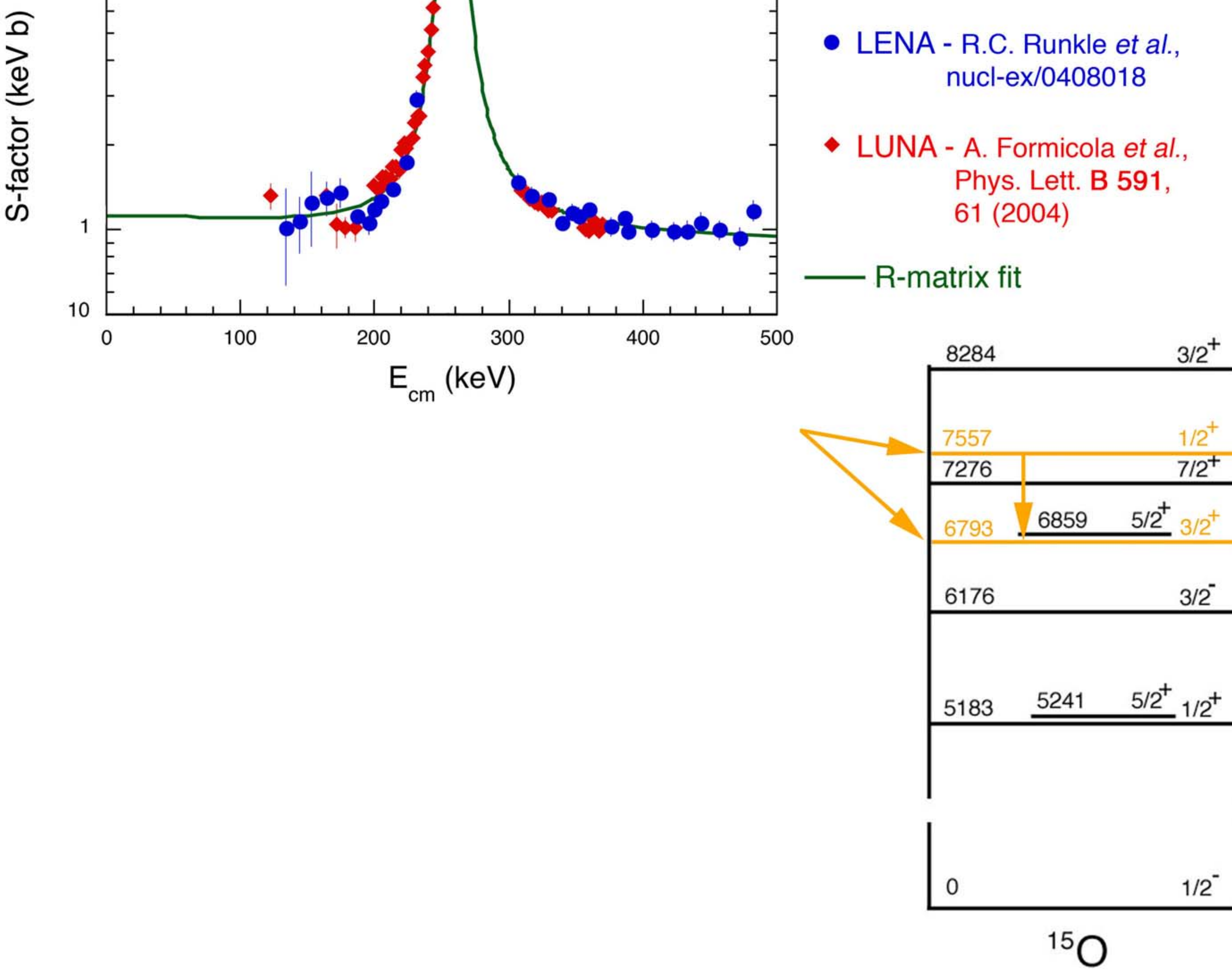
$\Gamma = 0.41^{+0.34}_{-0.13}$ eV

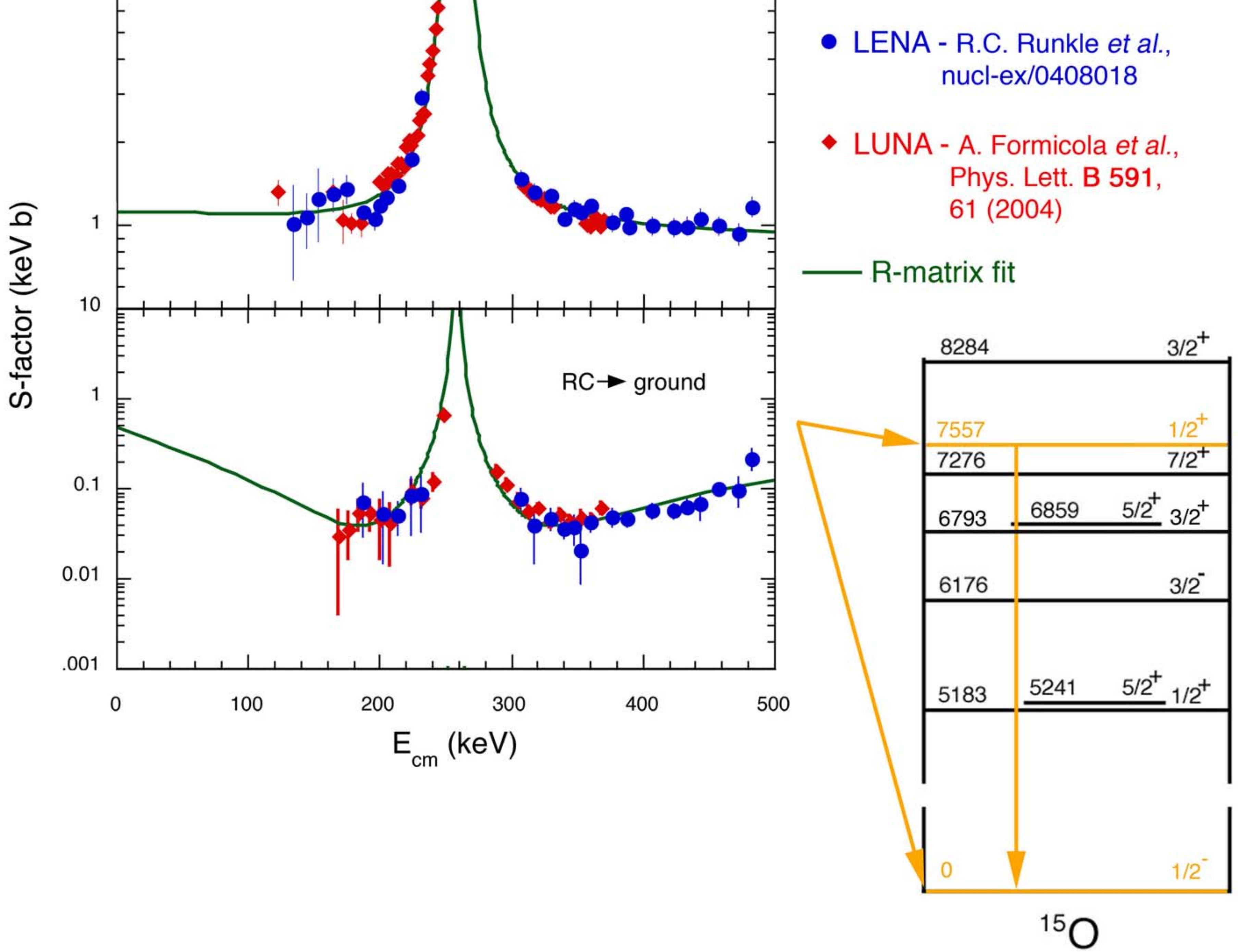


[P.F. Bertone et al., Phys. Rev. Lett. ***87****, 152501 (2001)]*

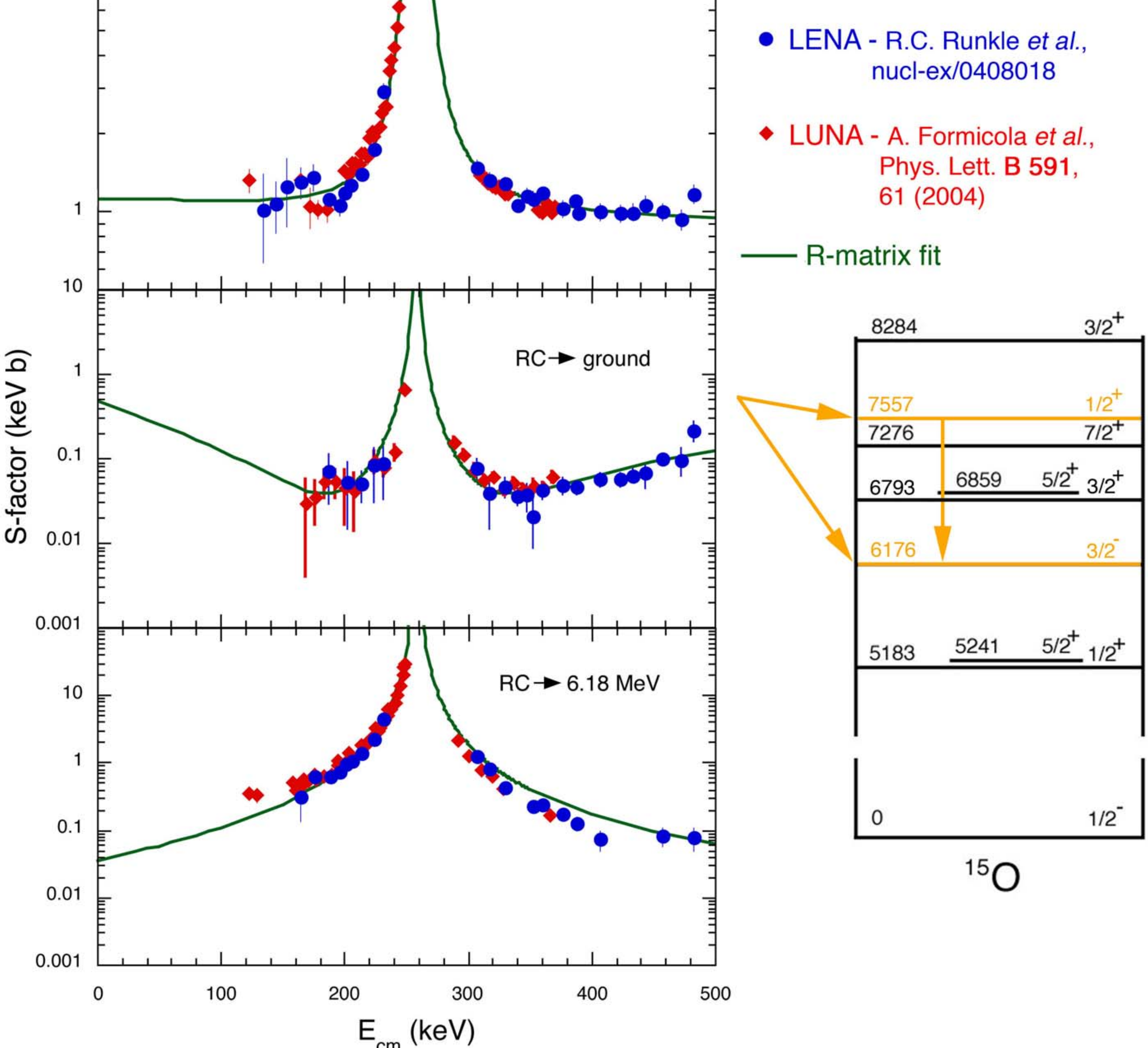


C. Angulo & P. Descouvemont
Nucl. Phys. A690 (2001), 755
A.M.Mukhamedzhanov et al.
Phys. Rev. C67 (2003), 065804
S-Factor (keV b)
0
1
2
3
4
5
0
0.05
0.1
0.15
0.2
E_cm (MeV)

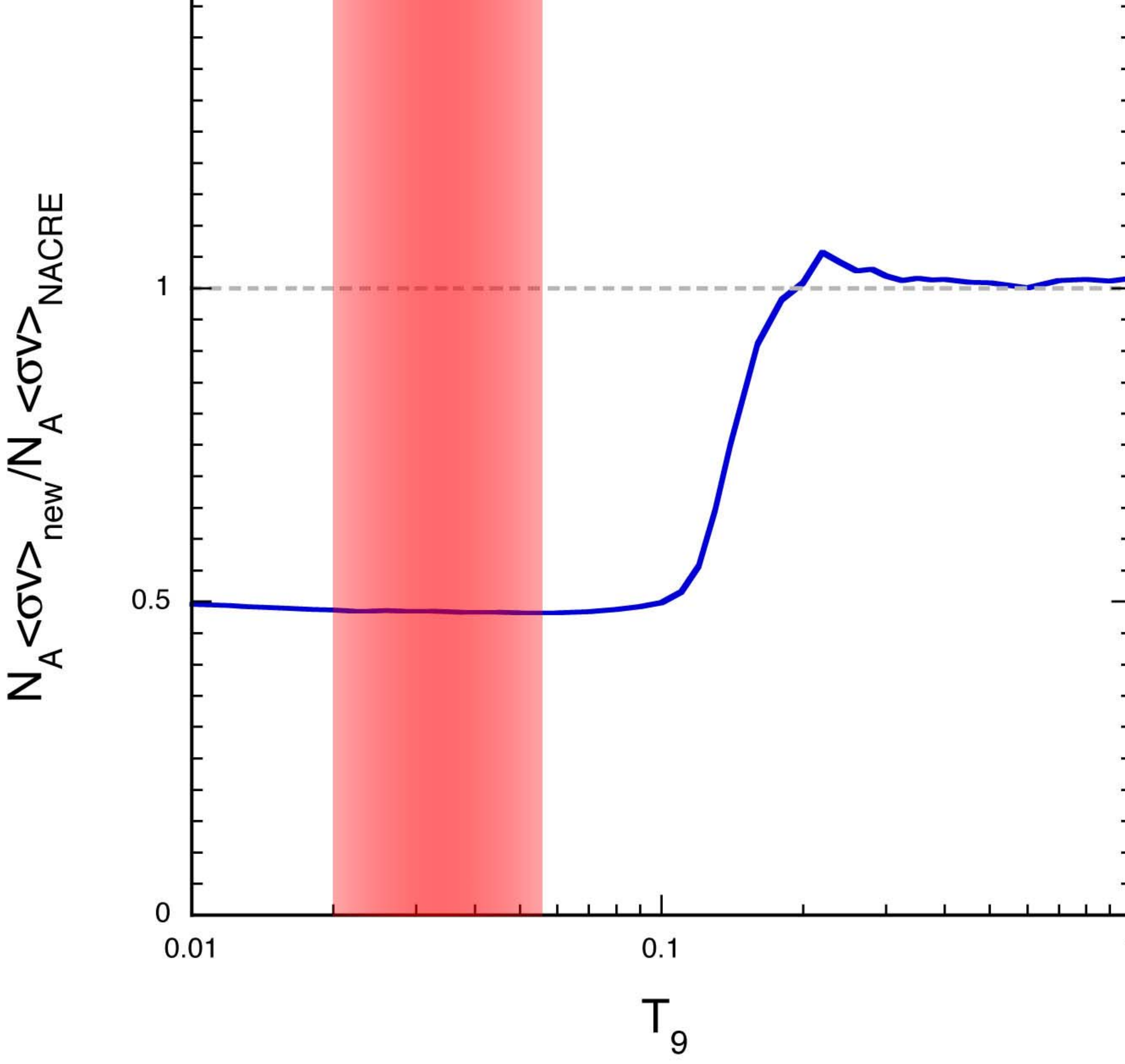

S-factor (keV b)
1
10
0
100
200
300
400
500
E_cm (keV)
LENA - R.C. Runkle et al., nucl-ex/0408018
LUNA - A. Formicola et al., Phys. Lett. B 591, 61 (2004)
R-matrix fit
8284 3/2+
7557 1/2+
7276 7/2+
6859 5/2+
6793 3/2+
6176 3/2-
5241 5/2+
5183 1/2+
0 1/2-
15O



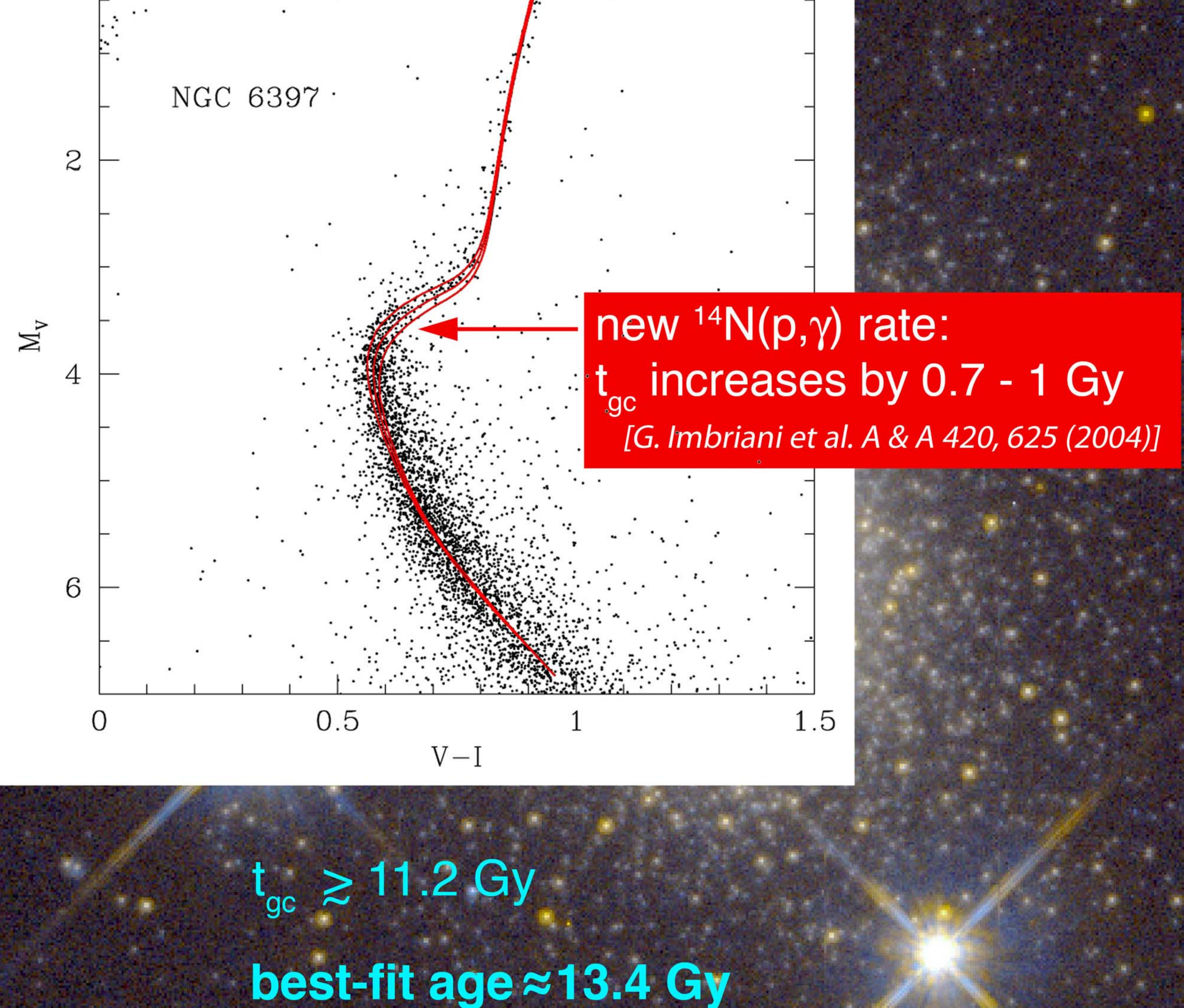
LENA - R.C. Runkle et al., nucl-ex/0408018
LUNA - A. Formicola et al., Phys. Lett. B 591, 61 (2004)
R-matrix fit
S-factor (keV b)
RC→ ground
E_{cm} (keV)
8284 3/2+
7557 1/2+
7276 7/2+
6793 6859 5/2+ 3/2+
6176 3/2-
5183 5241 5/2+ 1/2+
0 1/2-
^{15}O



LENA - R.C. Runkle et al., nucl-ex/0408018
LUNA - A. Formicola et al., Phys. Lett. B 591, 61 (2004)
R-matrix fit
RC → ground
RC → 6.18 MeV
S-factor (keV b)
E_cm (keV)
8284 3/2+
7557 1/2+
7276 7/2+
6793 6859 5/2+ 3/2+
6176 3/2-
5183 5241 5/2+ 1/2+
0 1/2-
15O

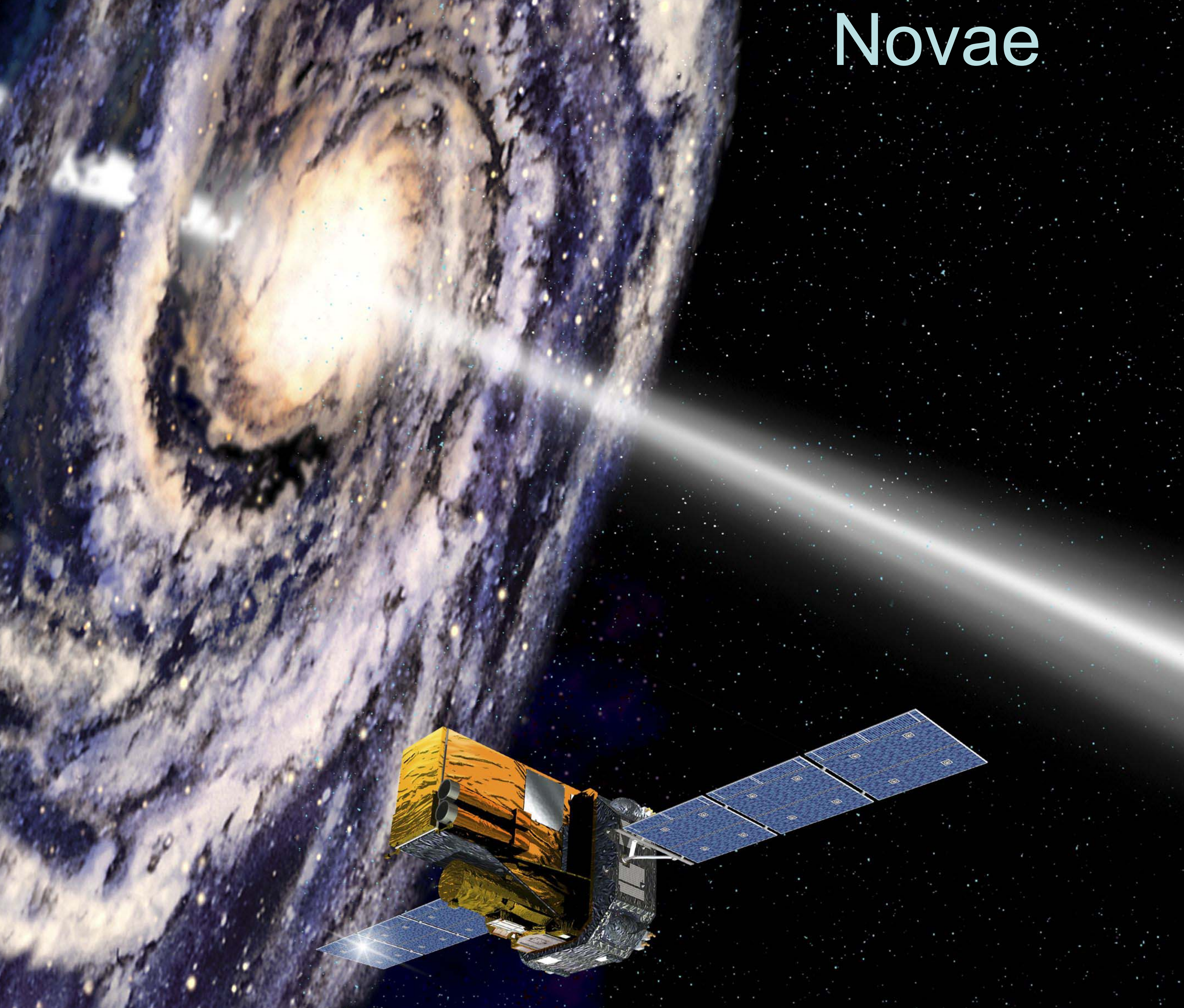


1
0.5
0
0.01
0.1
1
$N_A\langle\sigma v\rangle_{new}/N_A\langle\sigma v\rangle_{NACRE}$
T_9

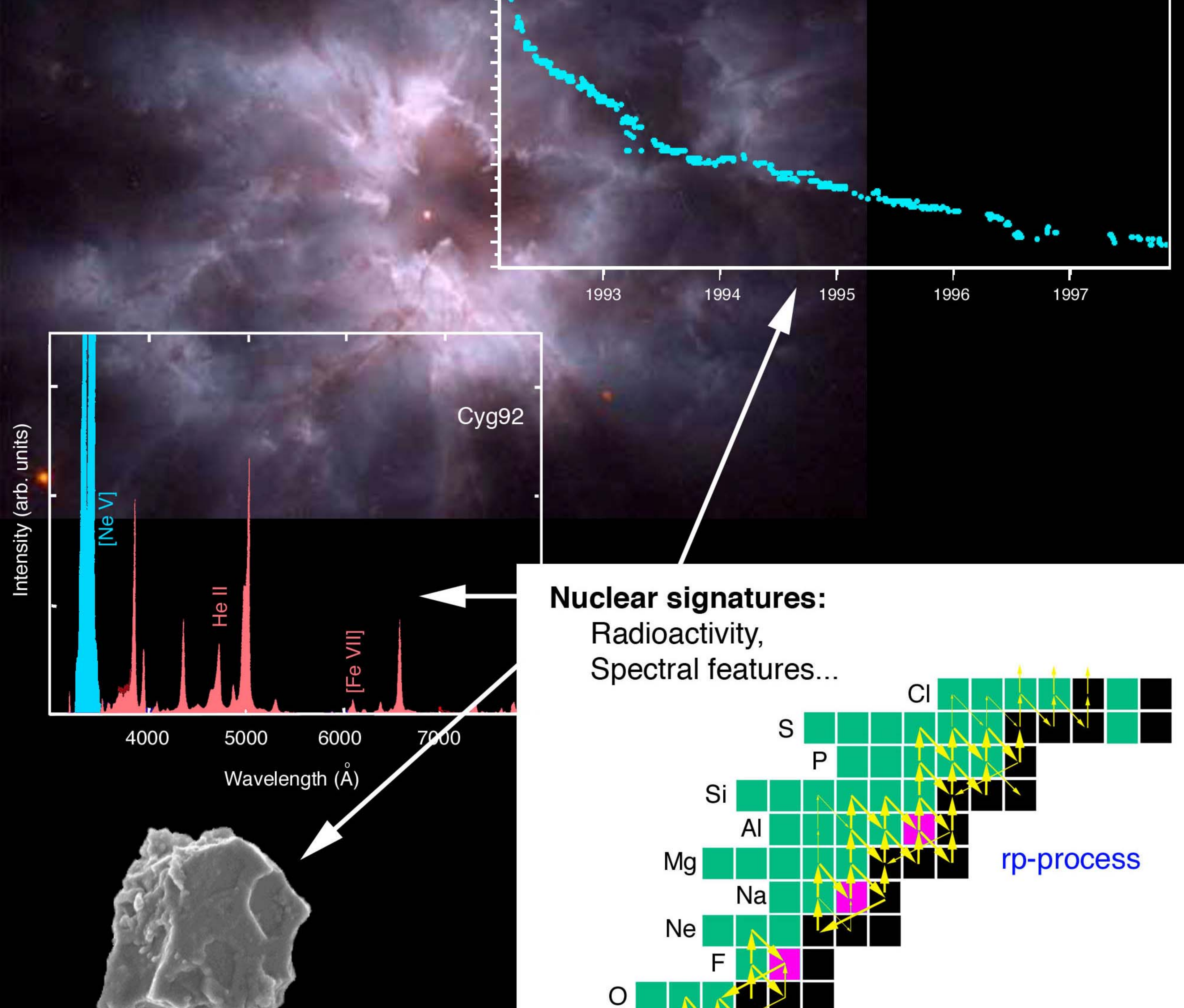


NGC 6397
M_V
2
4
6
0
0.5
1
1.5
V−I
new ¹⁴N(p,γ) rate:
t_gc increases by 0.7 - 1 Gy
[G. Imbriani et al. A & A 420, 625 (2004)]
t_gc ≳ 11.2 Gy
best-fit age ≈ 13.4 Gy

Novae



QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

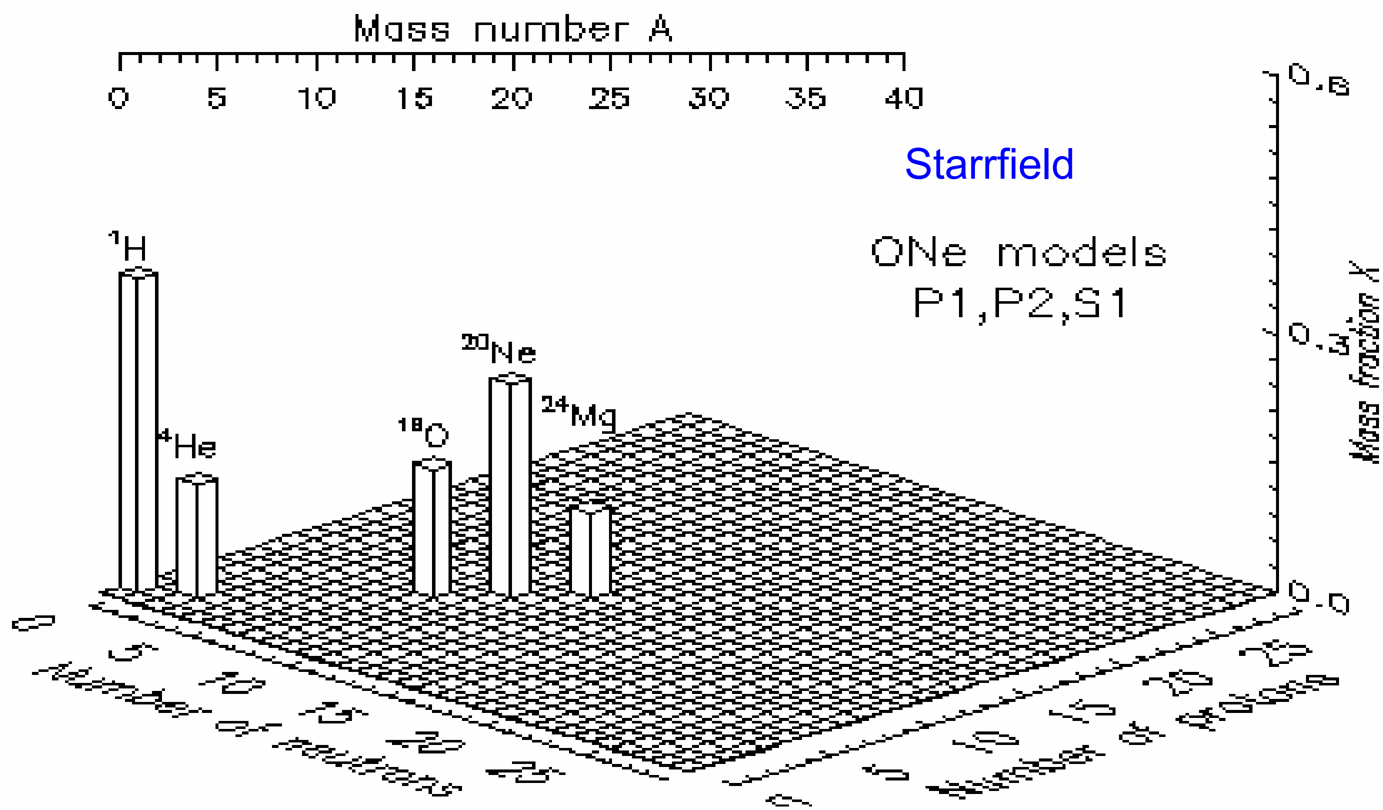

1993
1994
1995
1996
1997
Cyg92
Intensity (arb. units)
[Ne V]
He II
[Fe VII]
4000
5000
6000
7000
Wavelength (Å)
Nuclear signatures:
Radioactivity,
Spectral features...
Cl
S
P
Si
Al
Mg
Na
Ne
F
O
rp-process

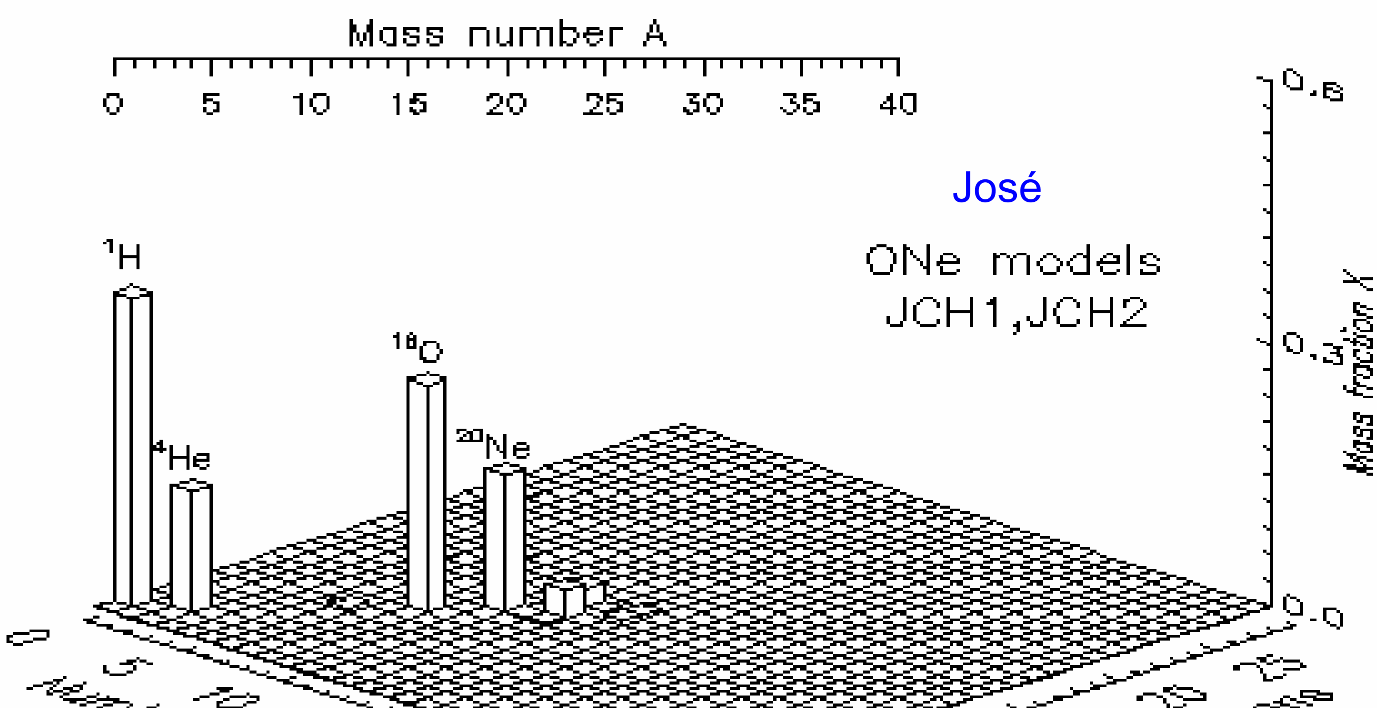
QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

Questions:

- mass of white dwarf
- initial composition
- accretion rate
- role of convection
- ejected mass
- nuclear physics

Initial composition(s)





What reactions are important?

The Astrophysical Journal Supplement Series, 142:105–137, 2002 September

THE EFFECTS OF THERMONUCLEAR REACTION-RATE VARIATIONS ON NOVA NUCLEOSYNTHESIS: A SENSITIVITY STUDY

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Received 2002 January 19; accepted 2002 April 25

Properties of Recent Evolutionary Nova Models[a]

Property	Model						
	P1	P2	S1	JCH 1	JCH 2	JH 1	JH 2
WD mass ($M_\odot$)	1.25	1.35	1.35	1.15	1.25	0.8	1.0
WD composition	ONe	ONe	ONe	ONe	ONe	CO	CO
Mixing (%)[b]	50	50	50	50	50	25	50
T_{peak} (10^6 K)	290	356	418	231	251	145	170
L_{peak} ($10^4\ L_\odot$)	4.3	16.3	39	26	46	3.5	23
M_{acc} ($10^{-5}\ M_\odot$)	3.2	1.5	3.8	3.2	2.2	9.7	3.9
$\dot{M}_{acc}$ ($10^{-10}\ M_\odot\ yr^{-1}$)	16	16	1.6	2.0	2.0	2.0	2.0
M_{ej} ($10^{-5}\ M_\odot$)	0.0	0.62	2.2	2.6	1.8	7.0	2.3

[a] Models labeled "P," "S," "JCH," and "JH" are adopted from Politano et al. 1995, S. Starrfield et al. 2002 (in preparation), José et al. 1999, and José & Hernanz 1998, respectively.

[b] This is the percentage of mixing assumed between solar accreted matter and white dwarf core material. The initial envelope composition is given in Table 2.

Reaction	Isotope i	Reaction Rate Multiplied by 100	10	2	0.5	0.1	0.01
$^{3}He(\alpha,\gamma)^{7}Be$	^{7}Be	...	...	0.43	1.3	...	...
$^{7}Be(p,\gamma)^{8}B$	^{7}Be	...	...	0.10	4.0	...	...
$^{8}B(p,\gamma)^{9}C$	^{7}Be	...	0.67	0.92	1.1	1.1	...
$^{13}N(p,\gamma)^{14}O$	^{13}C	...	...	0.87	1.1	...	...
$^{14}N(p,\gamma)^{15}O$	^{15}N	...	...	1.6	0.61	...	...
$^{15}N(p,\gamma)^{16}O$	^{16}O	...	...	1.3	0.89	...	...
$^{15}N(p,\alpha)^{12}C$	^{15}N	...	...	0.49	1.9	...	...
	^{16}O	...	...	0.89	1.3	...	...
$^{16}O(p,\gamma)^{17}F$	^{16}O	...	...	0.35	21	...	...
$^{17}O(p,\gamma)^{18}F$	^{12}C	...	1.2	1.0	0.95	0.95	...
	^{13}C	...	1.2	1.0	0.96	0.96	...
	^{15}N	...	1.5	1.1	0.90	0.88	...
	^{17}O	...	0.54	0.89	1.0	1.1	...
	^{18}F	...	5.2	1.8	0.53	0.11	...
	^{18}O	...	5.3	1.8	0.53	0.11	...
	^{19}F	...	5.3	1.8	0.53	0.11	...
$^{17}O(p,\alpha)^{14}N$	^{12}C	...	1.2	1.0	0.90	0.81	...
	^{13}C	...	1.2	1.0	0.91	0.83	...
	^{14}N	...	1.2	1.1	0.89	0.74	...
	^{17}O	...	0.029	0.57	1.4	2.0	...
	^{18}F	...	0.041	0.59	1.4	2.0	...
	^{18}O	...	0.042	0.59	1.4	2.0	...
	^{19}F	...	0.067	0.61	1.3	1.9	...
$^{17}F(p,\gamma)^{18}Ne$	^{12}C	...	1.2	1.0	0.90	0.86	...
	^{13}C	...	1.3	1.1	0.91	0.87	...
	^{16}O	...	1.4	1.1	0.95	0.89	...
	^{15}N	...	0.88	0.94	1.0	1.0	...
	^{17}O	...	0.057	0.71	1.2	1.4	...
	^{18}F	...	0.056	0.71	1.2	1.4	...
	^{18}O	...	0.059	0.71	1.2	1.4	...
	^{19}F	...	0.056	0.72	1.2	1.4	...
$^{18}O(p,\alpha)^{15}N$	^{18}O	...	...	0.53	1.7	...	...
	^{19}F	...	...	0.61	1.7	...	...
$^{18}F(p,\gamma)^{19}Ne$	^{16}O	...	2.1	1.2	0.95	0.89	...
	^{19}F	...	3.2	1.2	0.89	0.78	...
$^{18}F(p,\alpha)^{15}O$	^{15}N	1.0	0.94	0.94	1.1	1.3	3.6
	^{16}O	0.89	0.89	0.95	1.2	2.1	12
	^{18}F	0.021	0.17	0.59	1.7	6.5	41
	^{18}O	0.020	0.16	0.60	1.7	6.3	41
	^{19}F	0.013	0.12	0.54	1.8	8.3	56
$^{20}Ne(p,\gamma)^{21}Na$	^{20}Ne	...	...	0.85	1.1	...	...
	^{21}Ne	...	...	1.7	0.54	...	...
	^{22}Na	...	...	1.7	0.59	...	...
	^{22}Ne	...	...	1.6	0.57	...	...
	^{23}Na	...	...	1.7	0.55	...	...
	^{24}Mg	...	...	1.7	0.57	...	...
	^{25}Mg	...	...	1.7	0.56	...	...
	^{26}Al	...	...	1.7	0.55	...	...
	^{26}Mg	...	...	1.6	0.55	...	...
	^{27}Al	...	...	1.7	0.56	...	...
	^{28}Si	...	...	1.4	0.69	...	...
	^{29}Si	...	...	1.4	0.71	...	...
	^{30}Si	...	...	1.1	0.86	...	...
$^{21}Ne(p,\gamma)^{22}Na$	^{21}Ne	...	...	0.46	2.3	...	...
$^{21}Na(p,\gamma)^{22}Mg$	^{22}Na	0.83	0.88	1.0	1.1	1.3	1.5
	^{22}Ne	0.79	0.85	0.95	1.1	1.2	1.5
	^{23}Na	0.95	0.95	0.95	1.1	1.3	2.1
	^{24}Mg	0.96	0.96	0.98	1.1	1.4	2.2

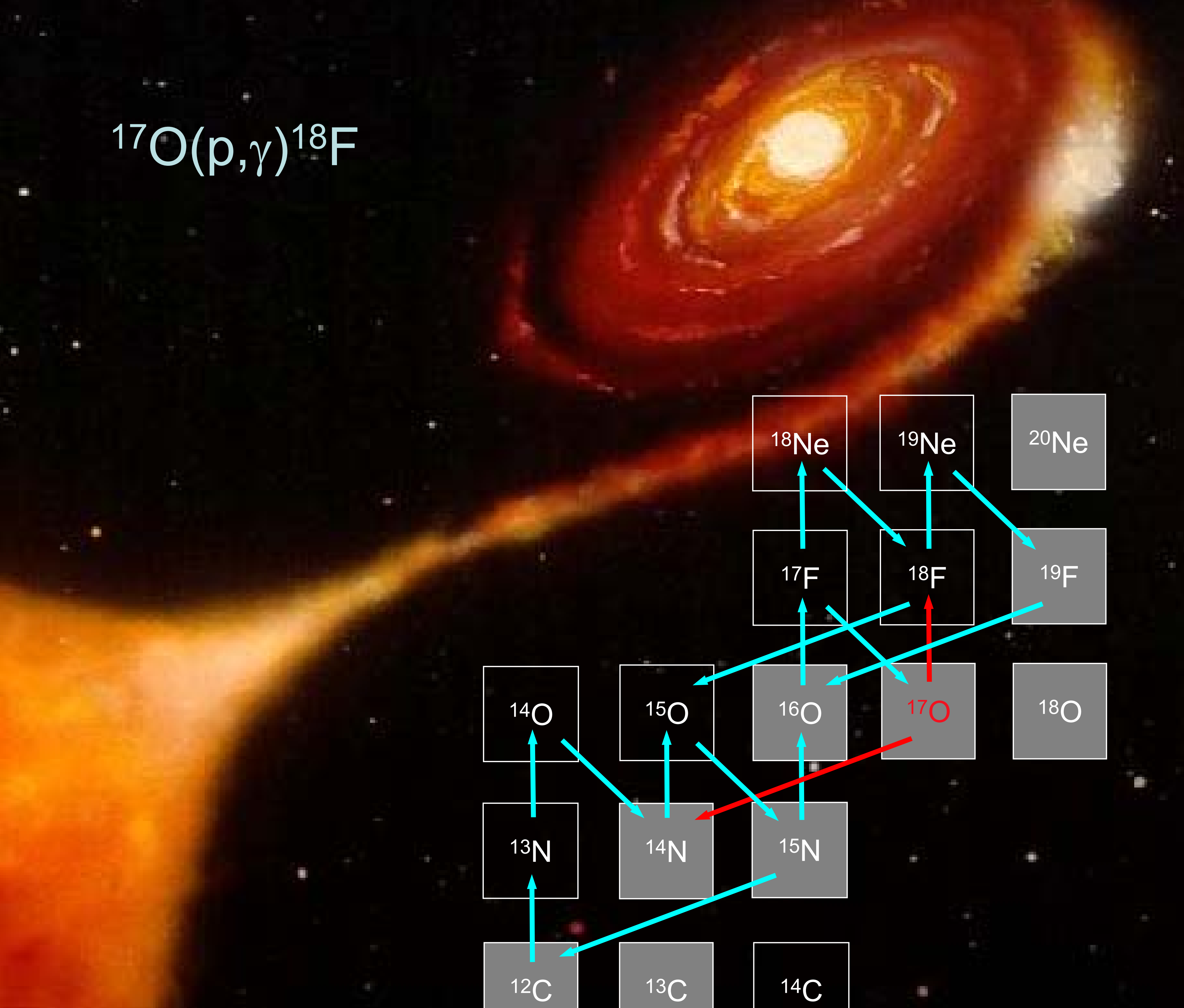
Reaction-Rate Variation[b]	Isotopic Abundance Change[c]
CO Nova Models	
$^{17}O(p, \gamma)^{18}F$...........	^{18}F
$^{17}O(p, \alpha)^{14}N$..........	^{17}O, ^{18}F
$^{18}F(p, \alpha)^{15}O$	^{18}F
$^{22}Ne(p, \gamma)^{23}Na$	^{22}Ne, ^{23}Na, ^{24}Mg, ^{25}Mg, ^{26}Al
$^{23}Na(p, \gamma)^{24}Mg$.......	^{24}Mg
$^{26}Mg(p, \gamma)^{27}Al$........	^{26}Mg
$^{26}Al^{g}(p, \gamma)^{27}Si$.........	^{26}Al
ONe Nova Models	
$^{17}O(p, \gamma)^{18}F$...........	^{17}O, ^{18}F
$^{17}O(p, \alpha)^{14}N$..........	^{17}O, ^{18}F
$^{17}F(p, \gamma)^{18}Ne$..........	^{17}O, ^{18}F
$^{18}F(p, \alpha)^{15}O$	^{16}O, ^{17}O, ^{18}F
$^{21}Na(p, \gamma)^{22}Mg$.......	^{21}Ne, ^{22}Na, ^{22}Ne
$^{22}Ne(p, \gamma)^{23}Na$	^{22}Ne
$^{23}Na(p, \gamma)^{24}Mg$.......	^{20}Ne, ^{21}Ne, ^{22}Na, ^{23}Na, ^{24}Mg, ^{25}Mg, ^{26}Mg, ^{26}Al, ^{27}Al
$^{23}Mg(p, \gamma)^{24}Al$........	^{20}Ne, ^{21}Ne, ^{22}Na, ^{23}Na, ^{24}Mg
$^{26}Mg(p, \gamma)^{27}Al$........	^{26}Mg
$^{26}Al^{g}(p, \gamma)^{27}Si$.........	^{26}Al
$^{26}Al^{m}(p, \gamma)^{27}Si$........	^{26}Mg
$^{29}Si(p, \gamma)^{30}P$...........	^{29}Si
$^{30}P(p, \gamma)^{31}S$............	^{30}Si, ^{32}S, ^{33}S, ^{34}S, ^{35}Cl, ^{37}Cl, ^{36}Ar, ^{37}Ar, ^{38}Ar
$^{33}S(p, \gamma)^{34}Cl$	^{33}S, ^{34}S, ^{35}Cl, ^{36}Ar
$^{33}Cl(p, \gamma)^{34}Ar$	^{33}S
$^{34}S(p, \gamma)^{35}Cl$	^{34}S, ^{35}Cl, ^{36}Ar
$^{34}Cl(p, \gamma)^{35}Ar$	^{34}S
$^{37}Ar(p, \gamma)^{38}K$..........	^{37}Cl, ^{37}Ar, ^{38}Ar
$^{38}K(p, \gamma)^{39}Ca$	^{38}Ar

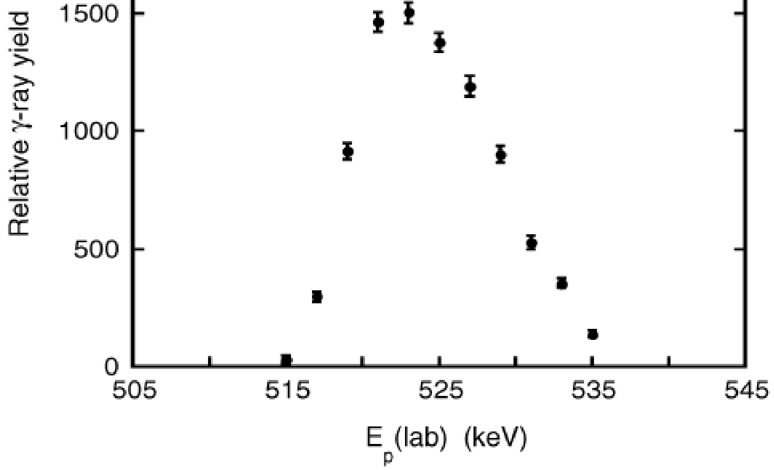
[a] The table provides only a qualitative overview for some of our results; see Tables 5–11 and § 5 for complete quantitative results.

[b] Only those reactions are listed that have a significant influence on isotopic abundances in at least one of the nova models considered in the present work (Table 1).

[c] Only those isotopes are listed whose abundances change by more than

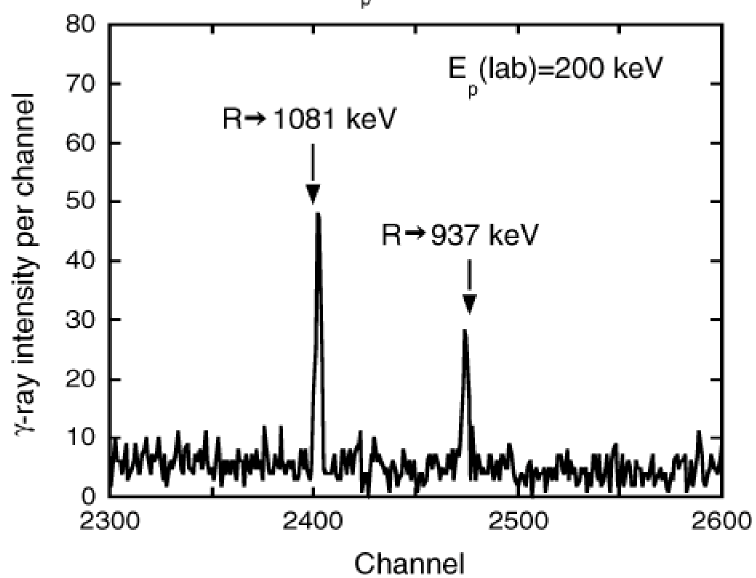
$^{17}O(p,\gamma)^{18}F$

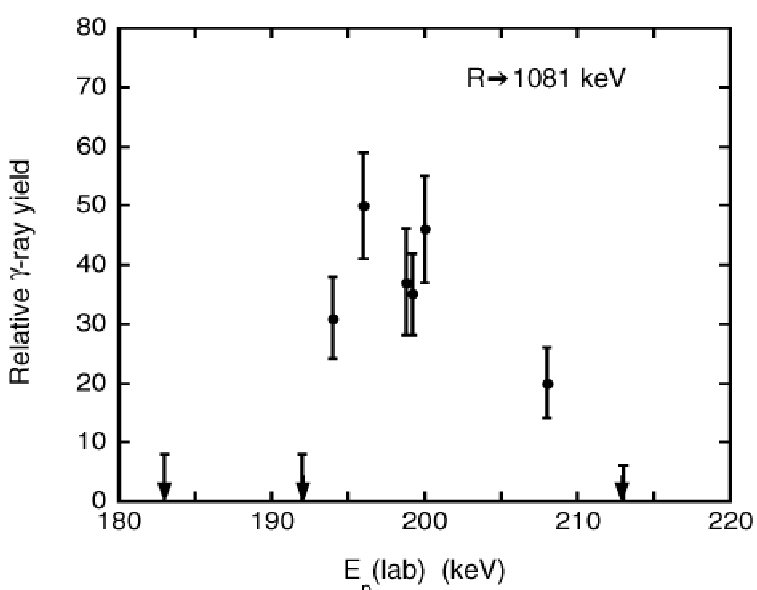




$E_{cm} = 489$ keV

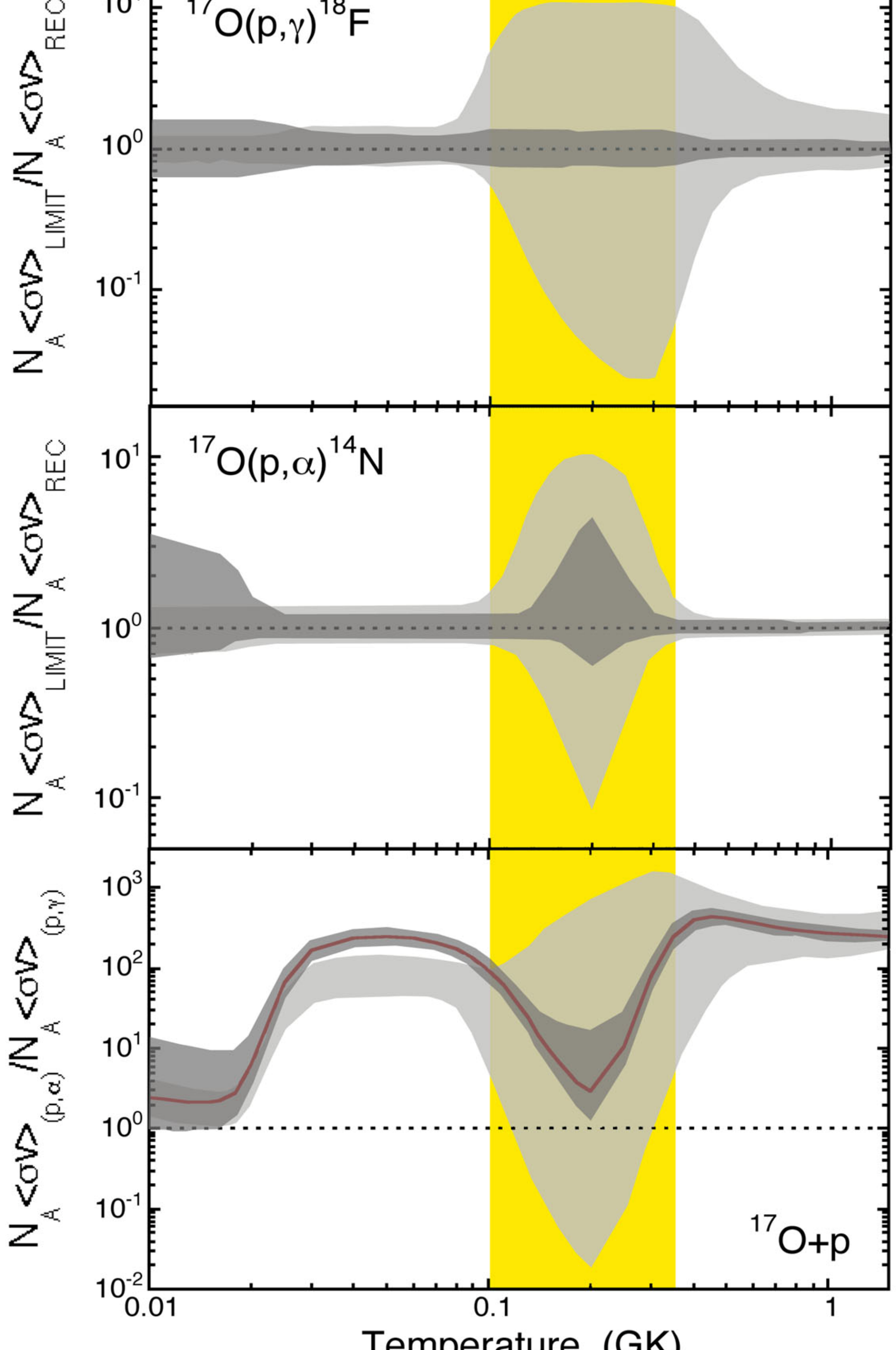
$\omega\gamma = 0.022$ eV



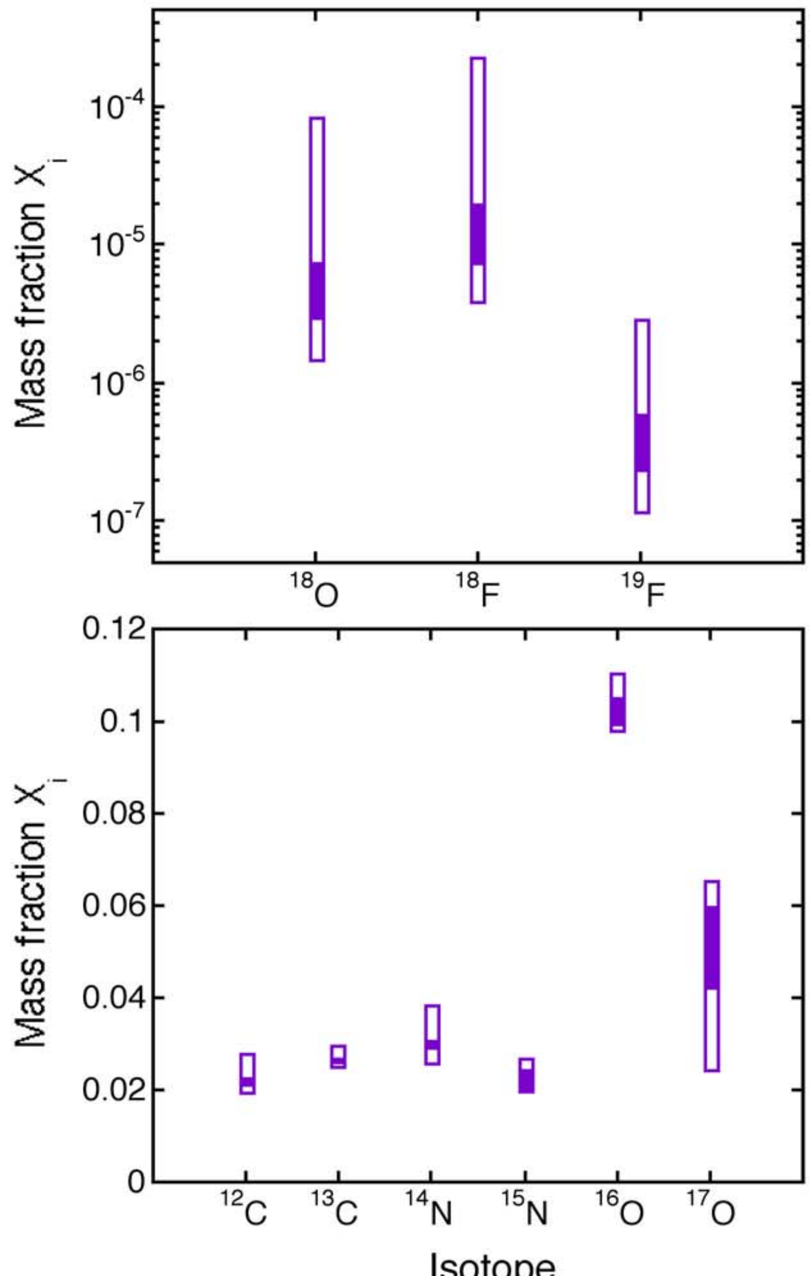


$E_{cm} = 179$ keV

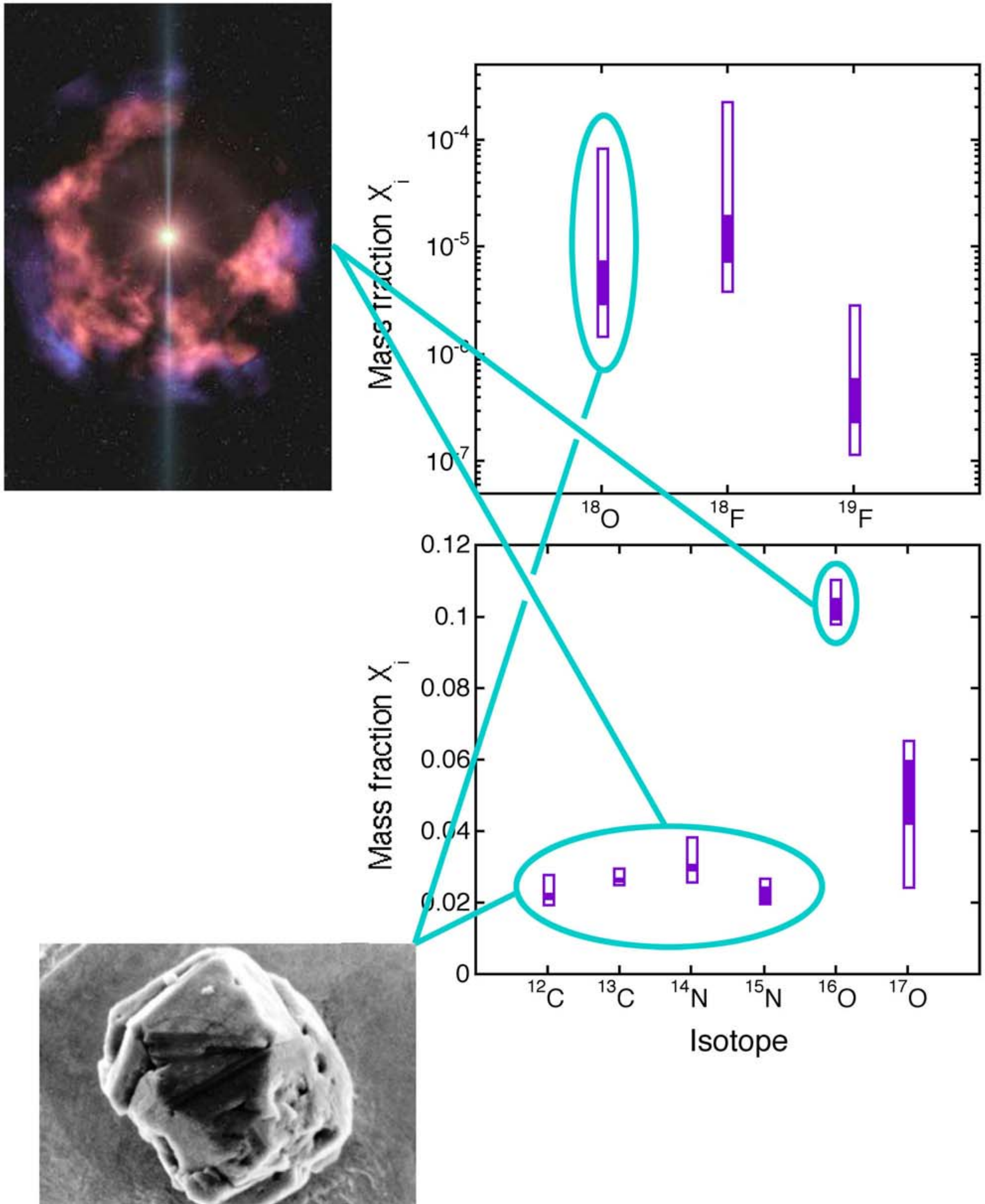
$\omega\gamma = 1.2(2)$ μeV



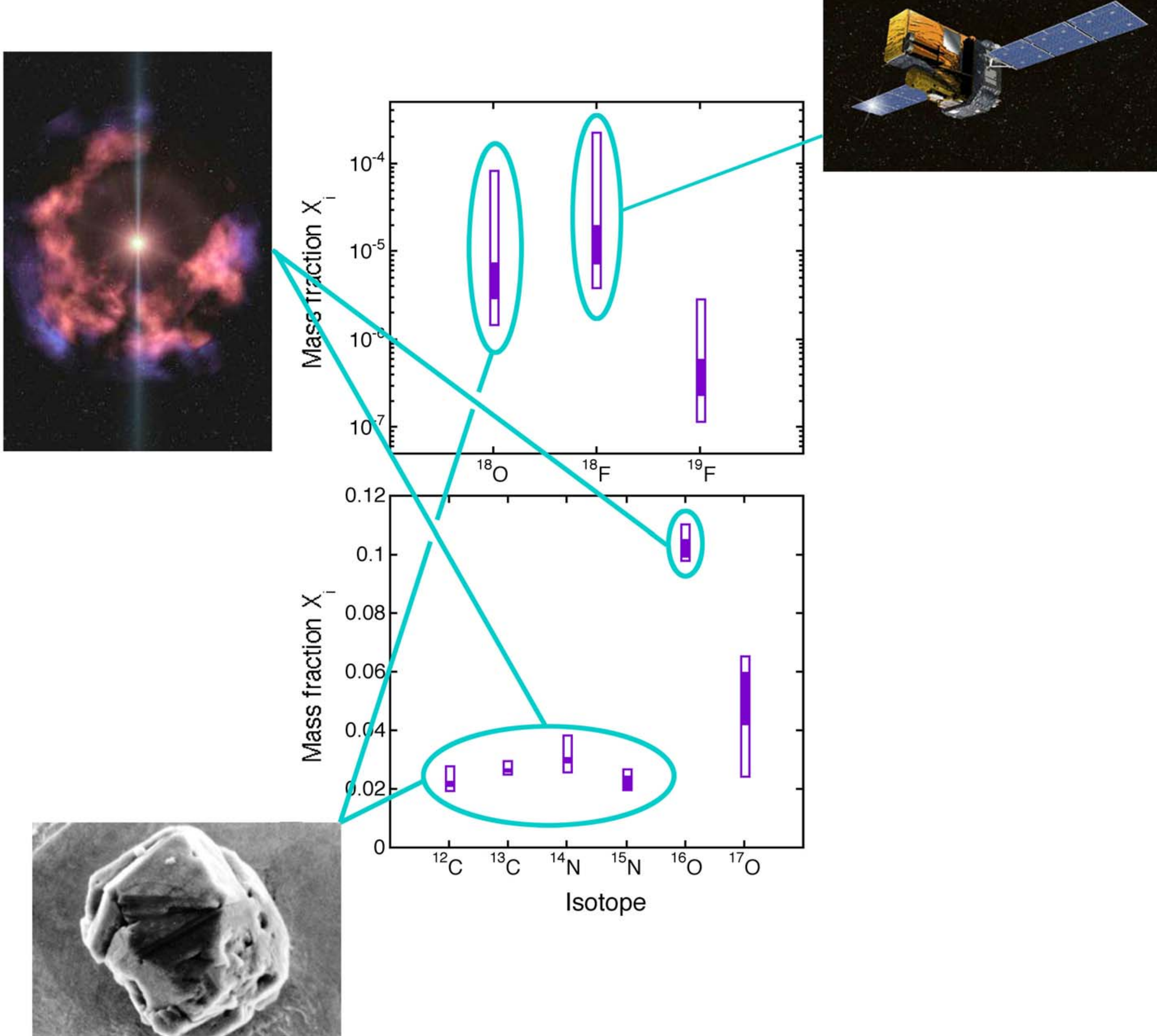
$^{17}O(p,\gamma)^{18}F$
$^{17}O(p,\alpha)^{14}N$
$^{17}O+p$
$N_A\langle\sigma v\rangle_{LIMIT}/N_A\langle\sigma v\rangle_{REC}$
$N_A\langle\sigma v\rangle_{(p,\alpha)}/N_A\langle\sigma v\rangle_{(p,\gamma)}$
Temperature (GK)
0.01
0.1
1



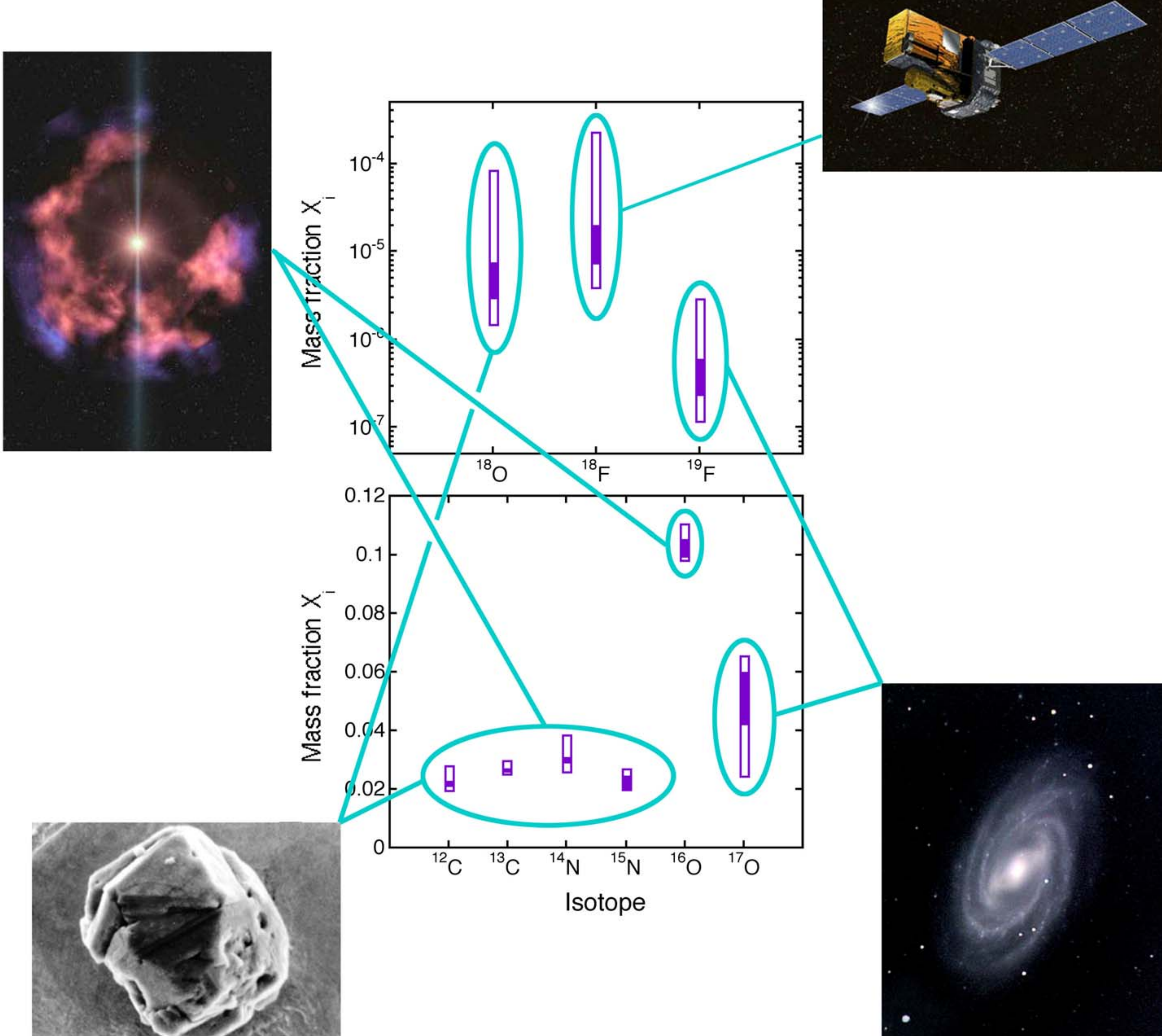
Mass fraction X_i
10^-4
10^-5
10^-6
10^-7
18O
18F
19F
0.12
0.1
0.08
0.06
0.04
0.02
0
12C
13C
14N
15N
16O
17O
Isotope



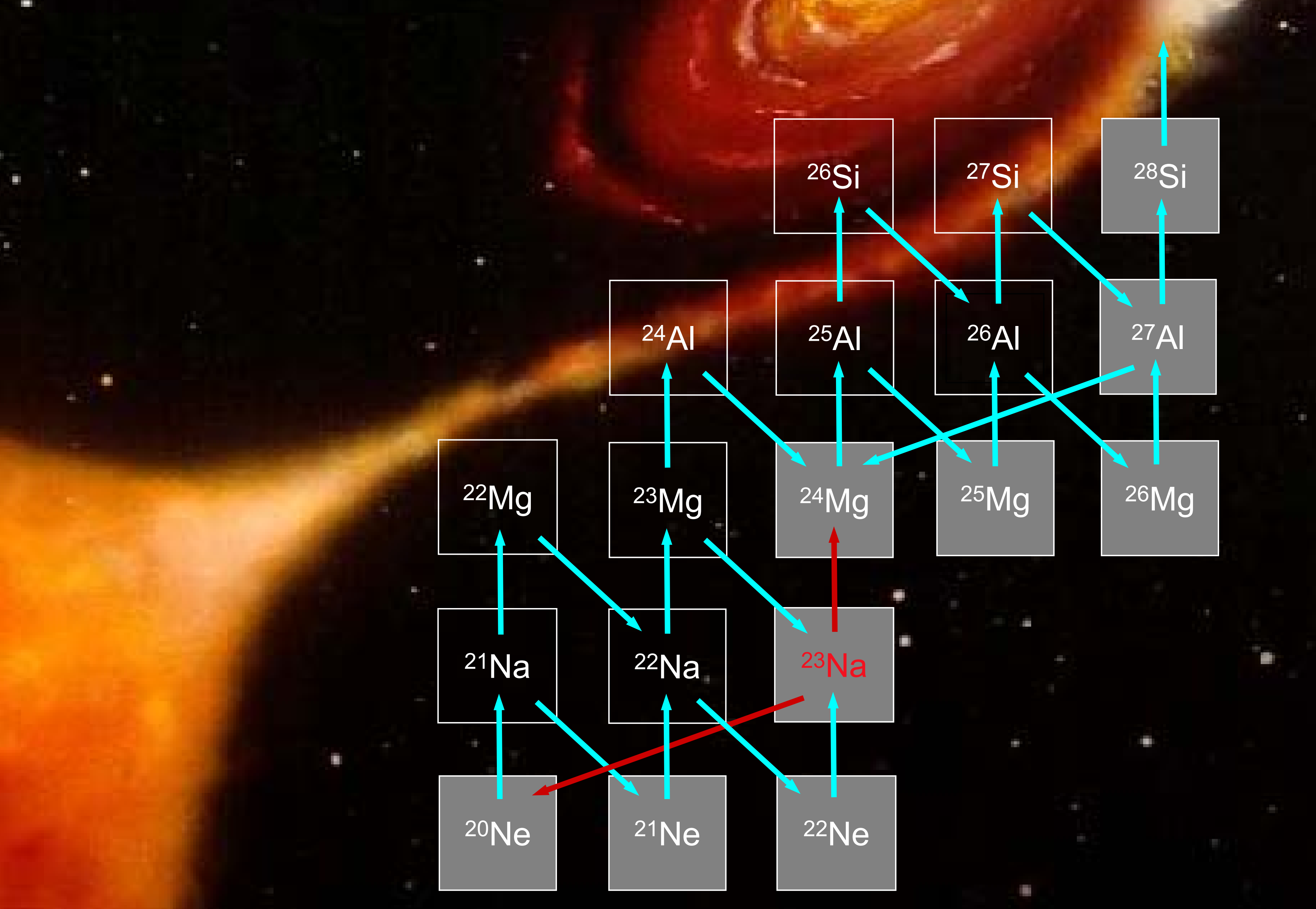
Mass fraction X_i
10^-4
10^-5
10^-6
10^-7
18O
18F
19F
0.12
0.1
0.08
0.06
0.04
0.02
0
12C
13C
14N
15N
16O
17O
Isotope

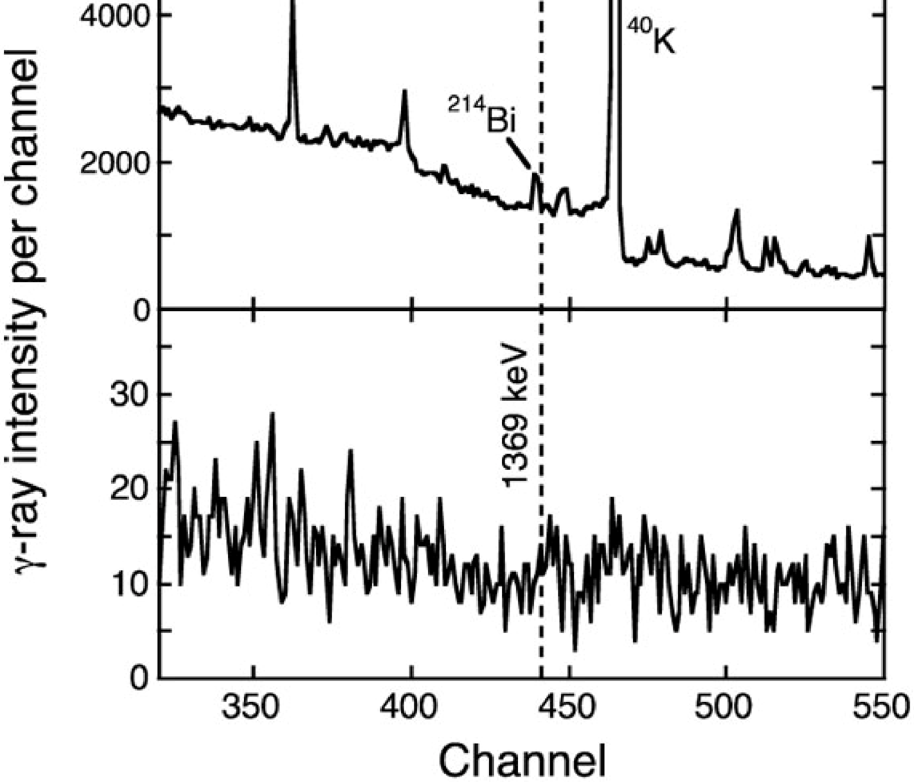


Mass fraction X_i
10^{-4}
10^{-5}
10^{-6}
10^{-7}
^{18}O
^{18}F
^{19}F
Mass fraction X_i
0.12
0.1
0.08
0.06
0.04
0.02
0
^{12}C
^{13}C
^{14}N
^{15}N
^{16}O
^{17}O
Isotope


Mass fraction X_i
10^{-4}
10^{-5}
10^{-6}
10^{-7}
^{18}O
^{18}F
^{19}F
Mass fraction X_i
0.12
0.1
0.08
0.06
0.04
0.02
0
^{12}C
^{13}C
^{14}N
^{15}N
^{16}O
^{17}O
Isotope

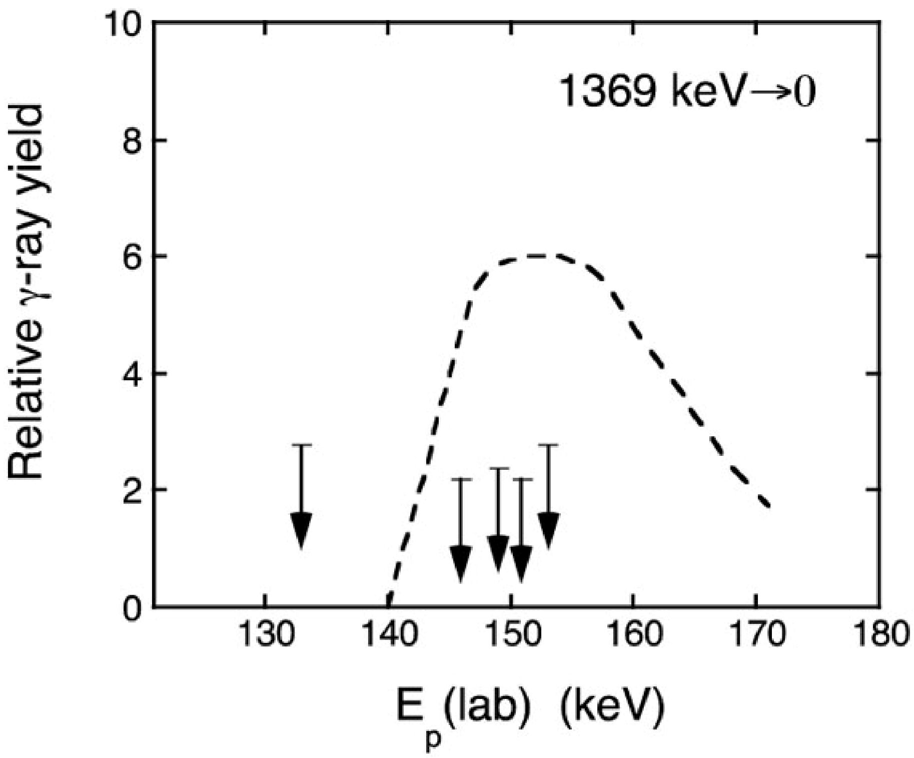
$^{23}Na(p,\gamma)^{24}Mg$





singles

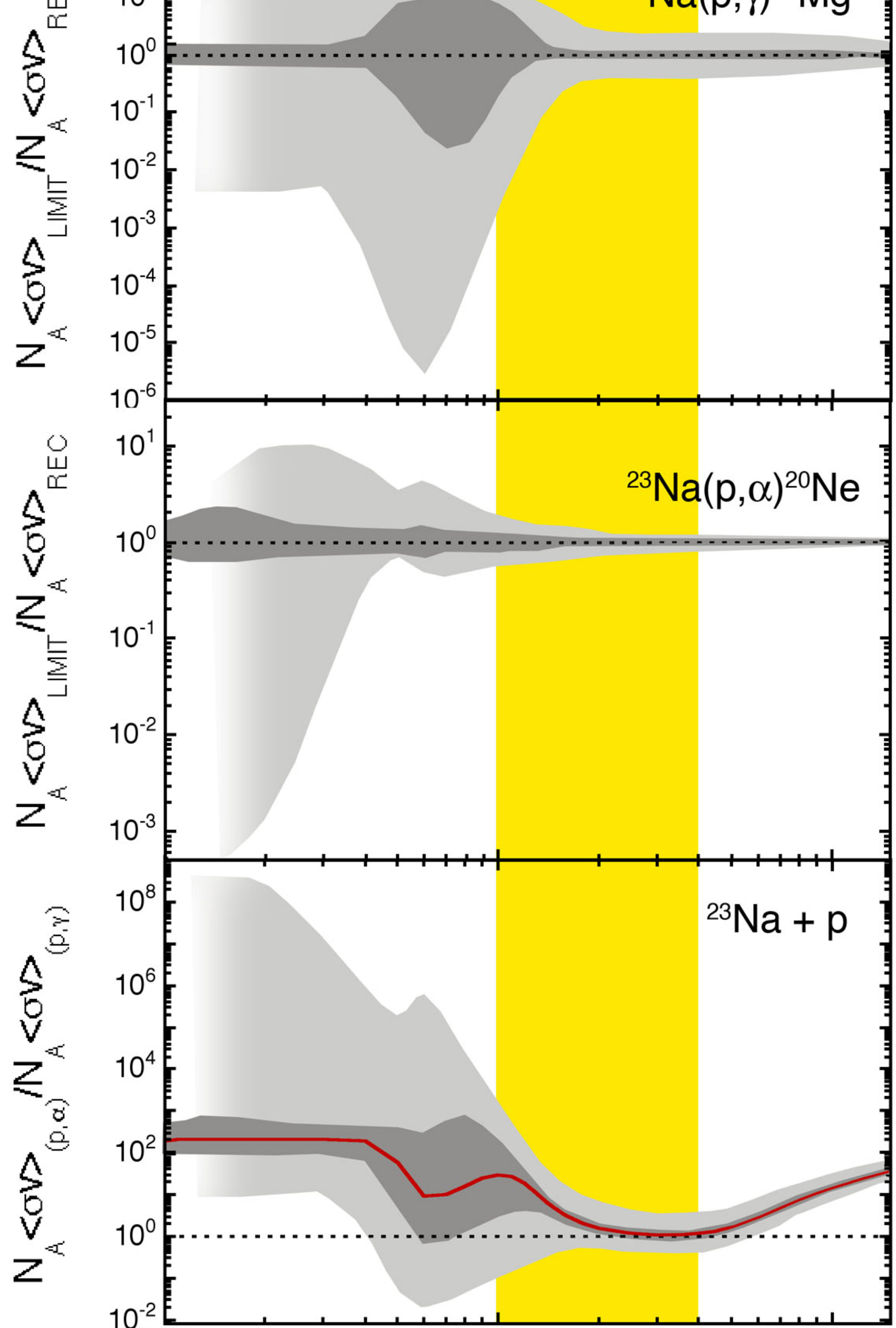
Ge-NaI coincidence



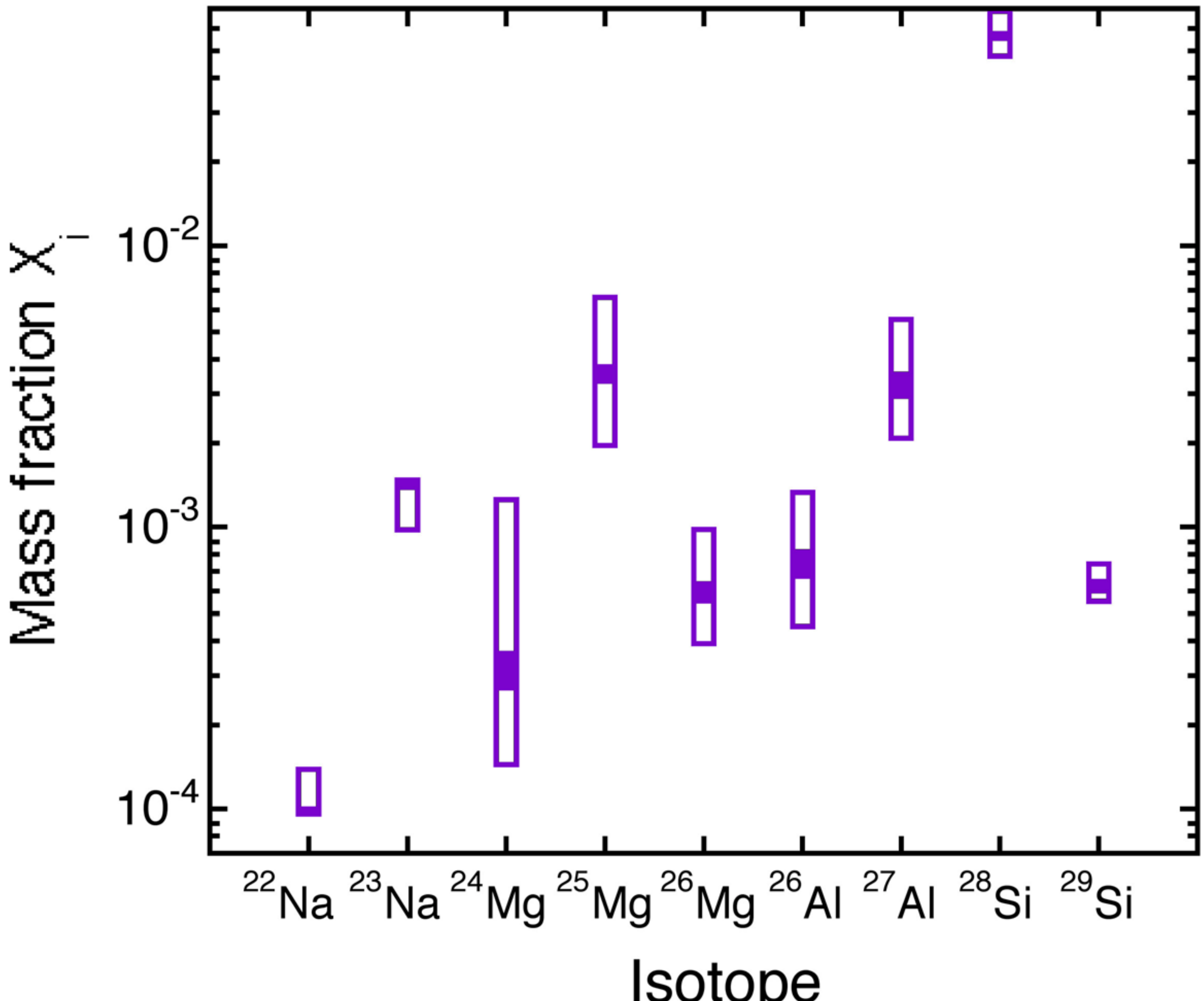
E_{cm} = 138 keV

$\omega\gamma \leq 0.15\ \mu$eV

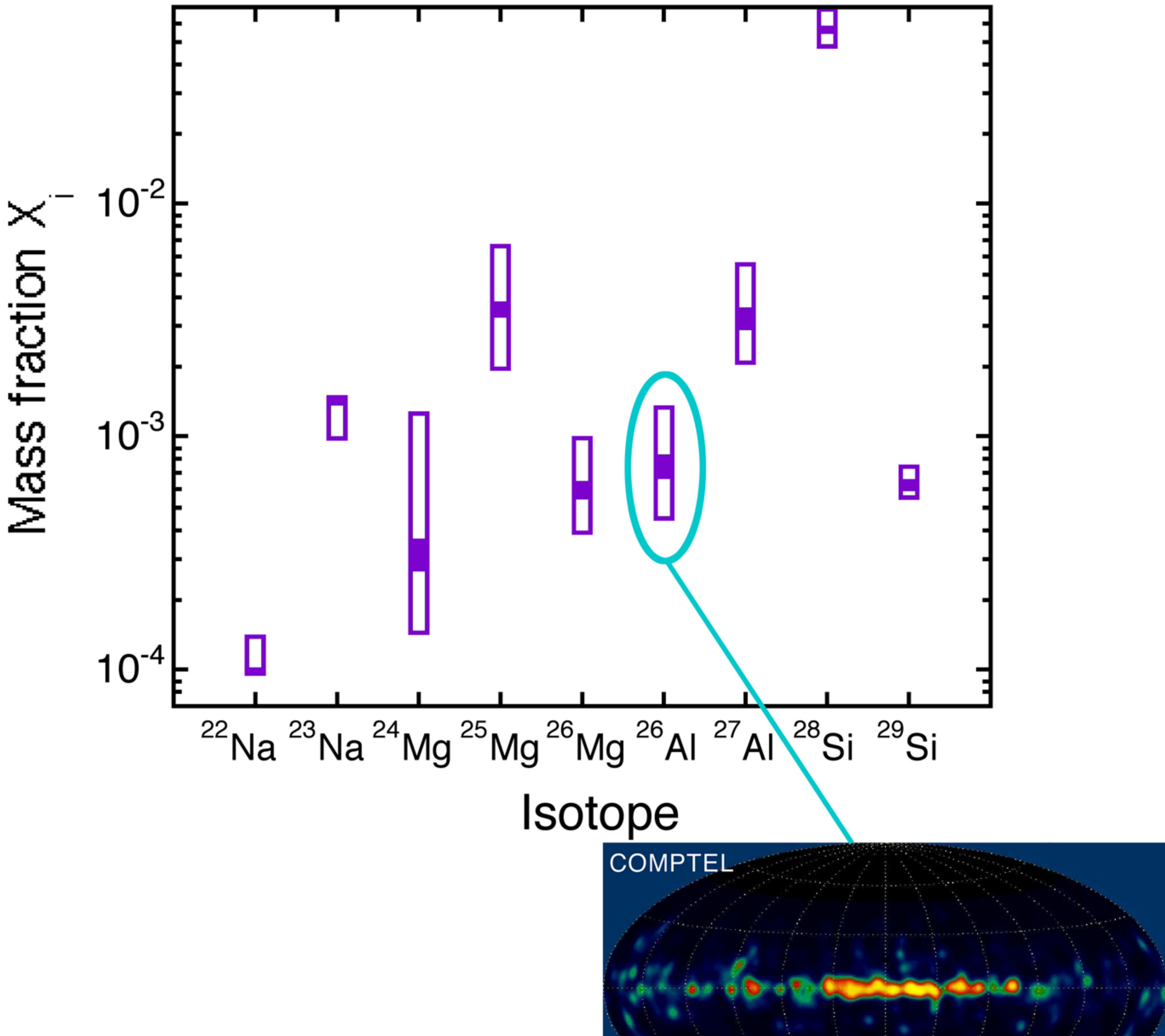
C. Rowland et al., Ap. J. Lett. (to be published)



^{23}Na(p,γ)^{24}Mg
$N_A\langle\sigma v\rangle_{LIMIT}/N_A\langle\sigma v\rangle_{REC}$
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
^{23}Na(p,α)^{20}Ne
10^1
^{23}Na + p
$N_A\langle\sigma v\rangle_{(p,\alpha)}/N_A\langle\sigma v\rangle_{(p,\gamma)}$
10^8
10^6
10^4
10^2



Mass fraction X_i
10^-2
10^-3
10^-4
22Na
23Na
24Mg
25Mg
26Mg
26Al
27Al
28Si
29Si
Isotope



Mass fraction X_i
10^-2
10^-3
10^-4
22Na
23Na
24Mg
25Mg
26Mg
26Al
27Al
28Si
29Si
Isotope
COMPTEL

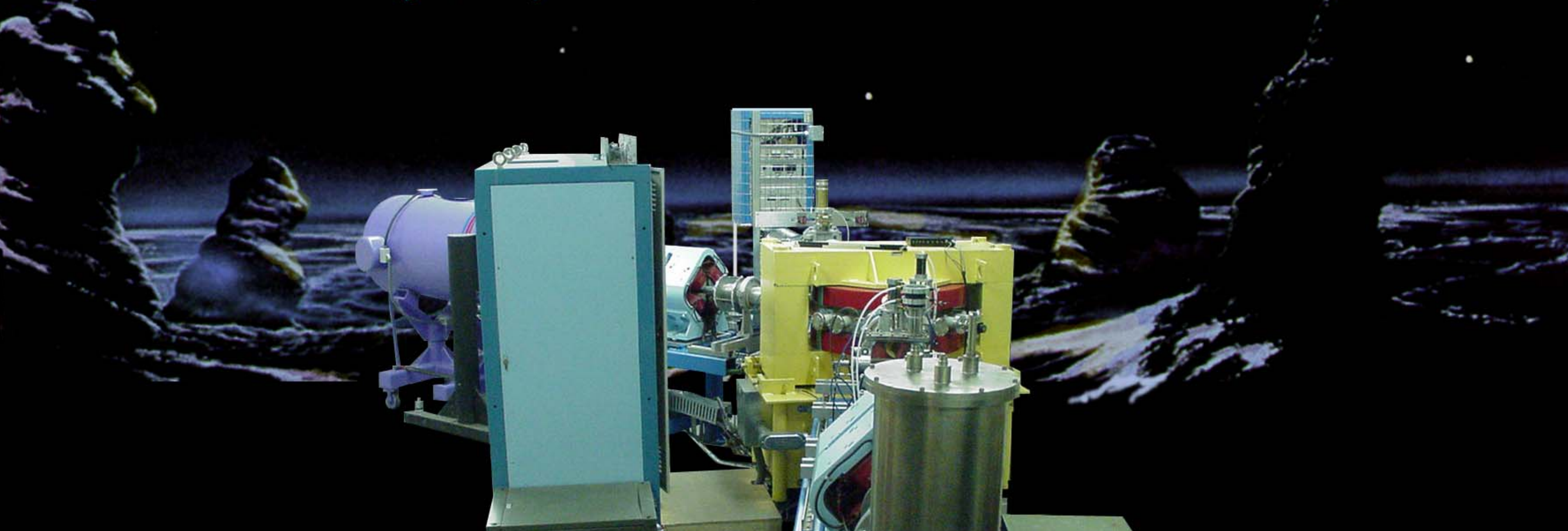
The role of a ground-level laboratory:

1. *Development of targets / detection schemes*

2. *Measurements at "higher" energies*

3. *Measurements in cases where cosmic rays are not a limiting factor*

4. *Measurements in cases where the reaction signature is sufficiently unique*



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Chris Fox
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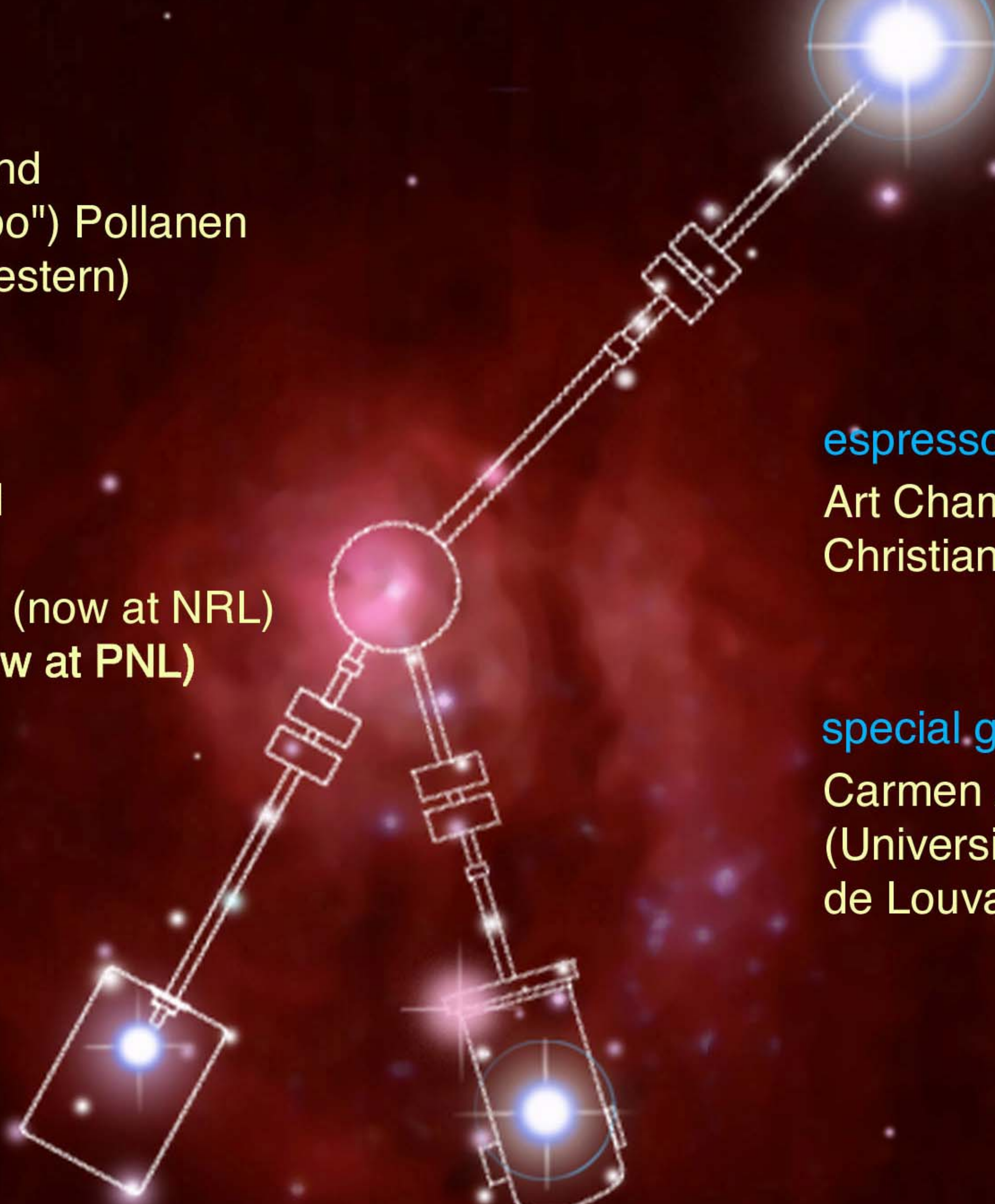

espresso connoisseurs:

Art Champagne
Christian Iliadis

special guest star:

Carmen Angulo
(Université catholique
de Louvain)

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