# Direct Measurements: Characteristics and Challenges

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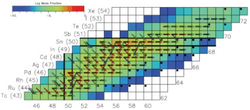
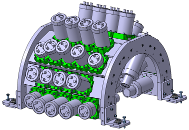
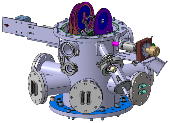
IPHC/CNRS Strasbourg

June 12, 2019



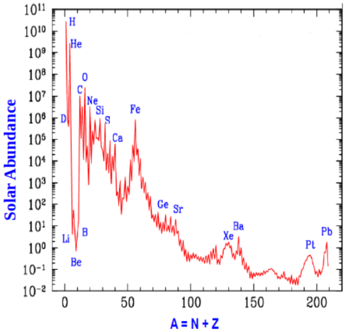




# Solar Isotopic Abundances

- solar photosphere
- most pristine meteorites




mod. E. Anders, Geochimica **53**, 197 (1998)

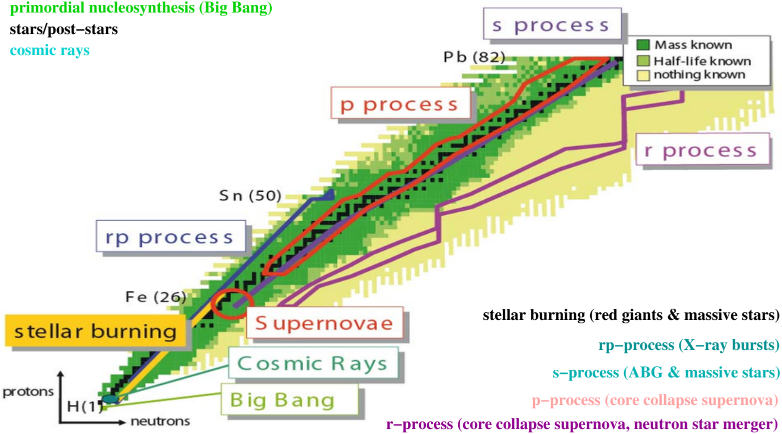
- spans from $10^{-1}$ to $10^{11}$
- exponential trend until $A = 100$
- overall flat distribution beyond

- peaks (Fe, Ba, Pb)
- gaps (Li, Be, B)

- H: ~ 75%
- He: ~ 23%
- C→ U: ~ 2%

# (Post)-Stellar Processes and Sites

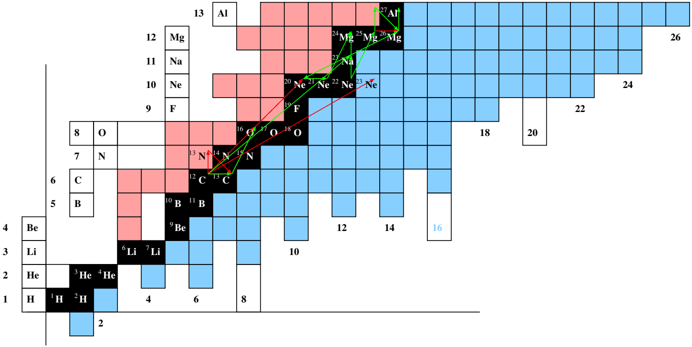
primordial nucleosynthesis (Big Bang)
stars/post–stars
cosmic rays




stellar burning (red giants & massive stars)
rp–process (X–ray bursts)
s–process (ABG & massive stars)
p–process (core collapse supernova)
r–process (core collapse supernova, neutron star merger)

mod. K. Blaum, Cont. Phys. **51**, 149 (2010)

# Stellar Burning: Reaction Flow in Carbon Burning

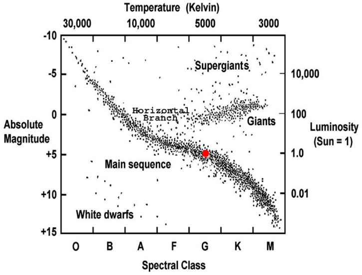



A. Chieffi *et al.*, APJ **502**, 737 (1998)

$$^{12}\mathrm{C} + {}^{12}\mathrm{C} \rightarrow {}^{24}\mathrm{Mg}^* \rightarrow {}^{24}\mathrm{Mg} + \gamma / {}^{23}\mathrm{Mg} + \mathrm{n}$$

$$\rightarrow {}^{23}\mathrm{Na}^* + \mathrm{p} / {}^{20}\mathrm{Ne}^* + \alpha$$

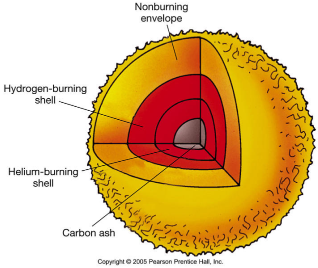
# Carbon Burning in Post Asymptotic Giant Branch Stars




$$M = (15 \ldots 60)\ M_\odot$$
$$T = (0.5 \ldots 1)\ \mathrm{GK}$$
$$\rho = (10^4 \ldots 10^5)\ \mathrm{g/cm^3}$$

hydrostatic equilibrium:

$$\frac{1}{\rho}\frac{\mathrm{d}p}{\mathrm{d}r} = -\frac{GM}{r^2};\ p(T,\rho)$$



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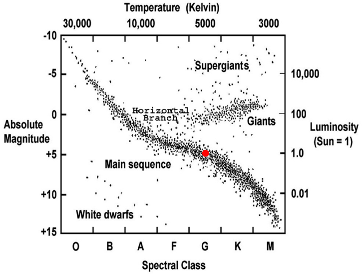


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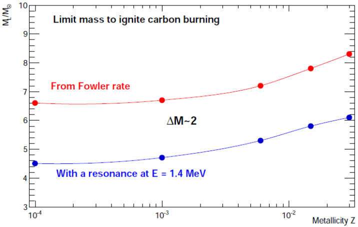
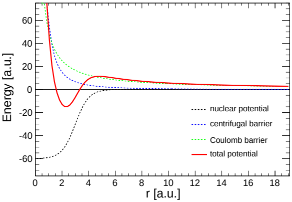


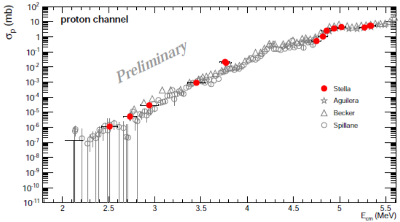

P. Staniero *et al.*, J.Phys. Conf.Ser. **665** (2016)

# Relevant Energies

Nuclear physics: cross-sections, resonances, masses, half-lives...

$$\underbrace{\sqrt{\frac{8}{\pi\mu(k_{\mathrm{B}}T)^3}}\int \sigma(E)E\exp^{-E/k_{\mathrm{B}}T}}_{\langle\sigma v\rangle} \Leftarrow \sigma(E) \Rightarrow \underbrace{\sigma(E)E\exp^{2\pi\eta+gE}}_{S^*(E)}$$



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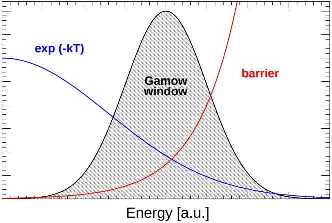
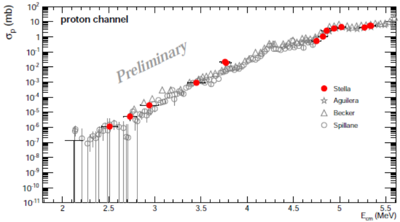
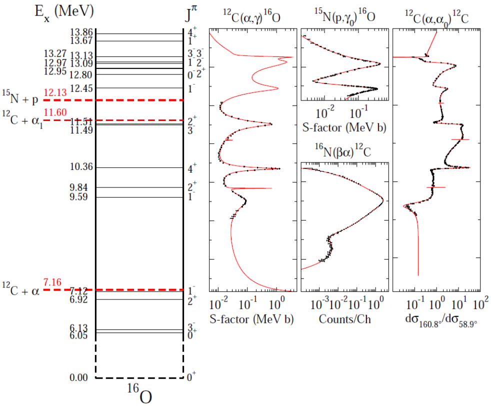


# Extrapolations: $^{12}C(\alpha,\gamma)^{16}O$




R.J. Boer *et al.*, Rev. Mod. Phys. **89**, 035007 (2017)

Resonance parameters (energy, spin, partial decay widths) of the states of interest from indirect techniques

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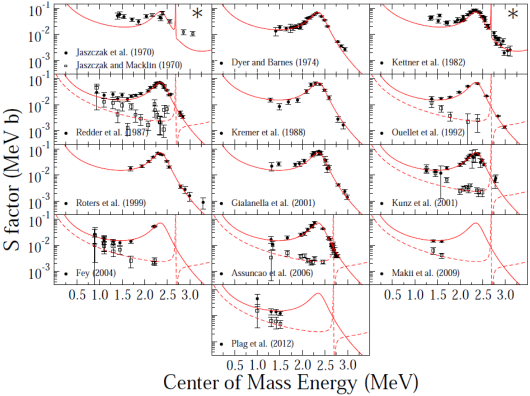



R.J. Boer *et al.*, Rev. Mod. Phys. **89**, 035007 (2017)

Resonance parameters (energy, spin, partial decay widths) of the states of interest from indirect techniques

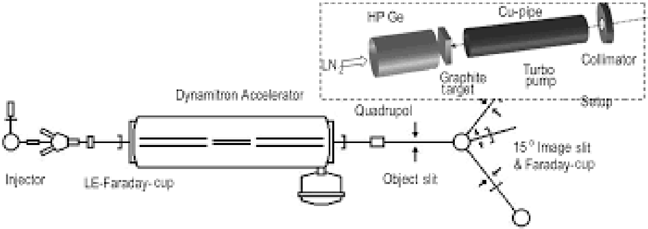
# Implications with Sub-Nanobarn Cross Sections

- Maximized target yield: 'thick' target measurements
- Amplified beam intensity
- Maximized detection efficiency
- Long data taking periods: stability of selected energy/timing gates
- Sensitivity to background contributions
- Statistical data analysis: signal to background ratio unity
- Experimental conditions as compared to astrophysics site: $e^-$ screening

# $^{12}C + ^{12}C$ with the 4 MV Dynamitron tandem in Bochum

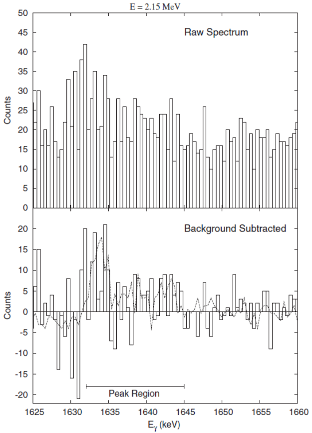
- 1 mm $^{12}C$ ultra pure (99.8%) targets on steal (Faraday cup)
- 40 p$\mu$A $^{12}C$ beam
- Ge detector faces target at 2 cm distance

+ active and passive shielding

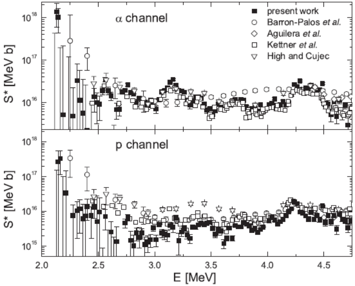



Bochum dynamitron tandem

# Analysis Strategy and Limitations




T. Spillane *et al.*, PRL **98**, 122501 (2007)




T. Spillane *et al.*, PRL **98**, 122501 (2007)

- subtraction of spectra
- modeling of background

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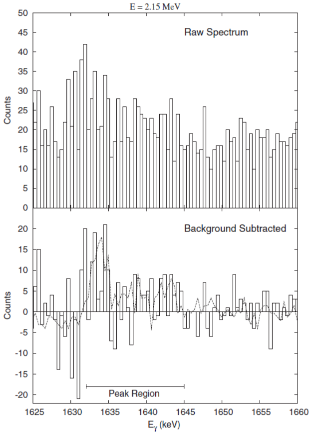
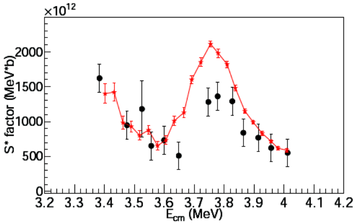


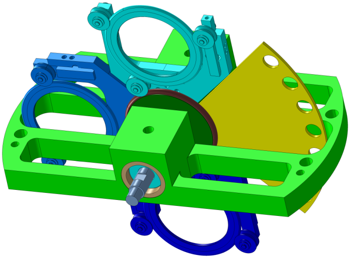

T. Spillane *et al.*, PRL **98**, 122501 (2007)



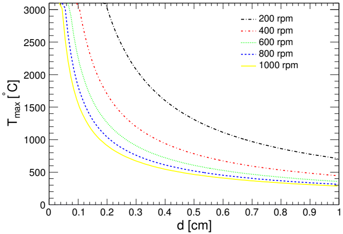

X.D. Tang *et al.*, arXiv:1905.02054 (2019)

- subtraction of spectra
- modeling of background

# Rotating Targets of Hundreds of Nanometer



- 2 p$\mu$A $^{12}$C beam
- Carbon foils of tens $\mu$g/cm$^2$
- Magnetic feed through into vacuum
- ✓ 23*24 h @ 100. . . 200 rpm




1. 7 fixed target slots
2. 3 rotating targets

   $\oslash = 4.6$ cm

   $\sim$15 cm beam track

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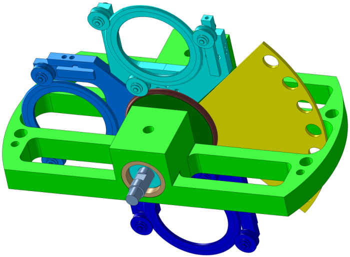

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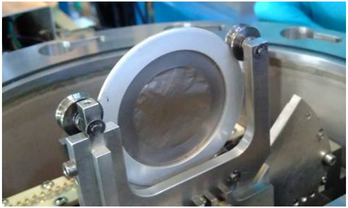

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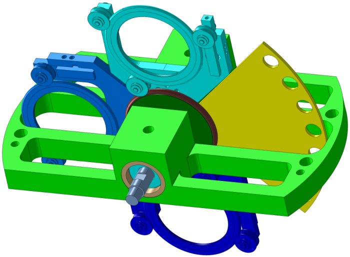

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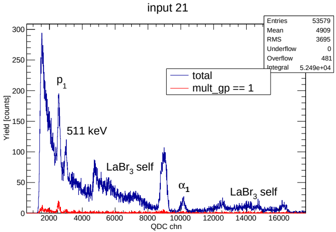
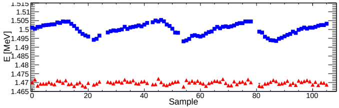
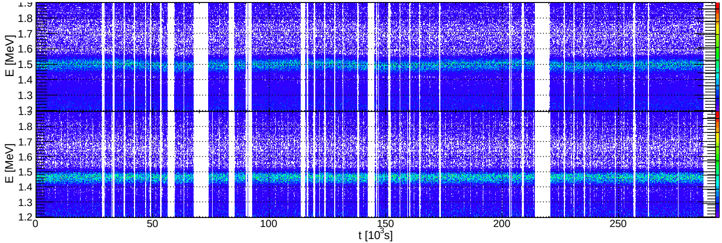
# Temperature Drift with $LaBr_3$ Detectors



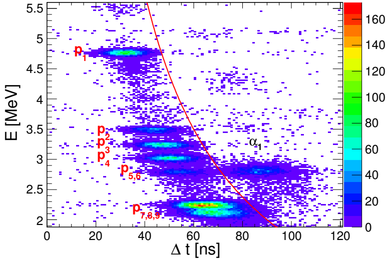

- 3 days of data; 45 min blocks
- Drift of 1.47 MeV line: 15 keV
- Since calibration: 30 keV

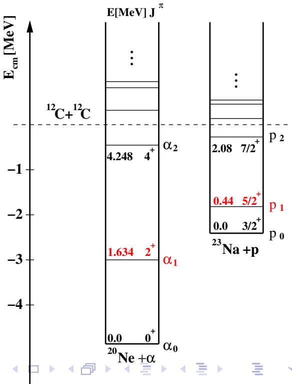


# Fast Timing for Exclusive Fusion Cross Sections

- Synchronization of 1 GHz gamma DAQ and 125 MHz particle DAQ
- Timing insufficient to resolve ToF gap between alphas and protons
- Differing energy deposition dynamics in detector substrate



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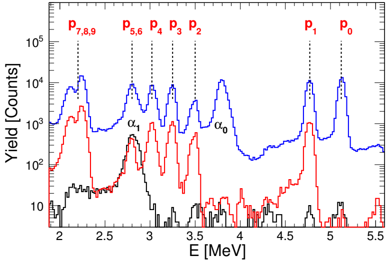


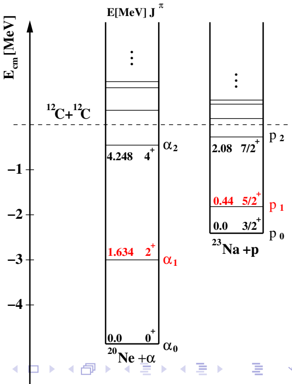

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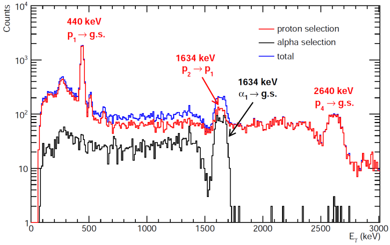
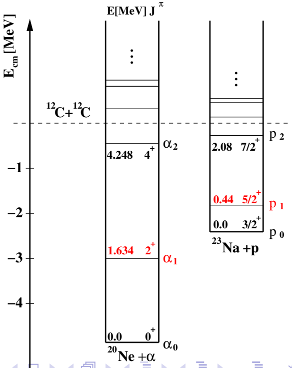
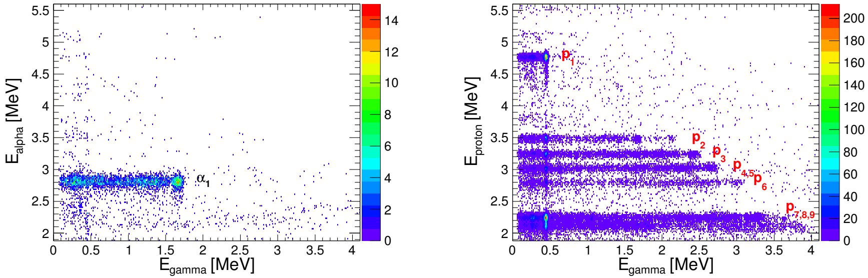


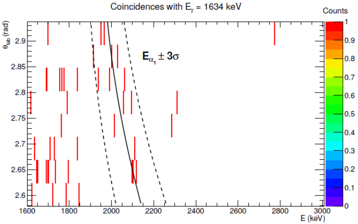
# Gamma-Particle Matrices for Fusion around the Barrier

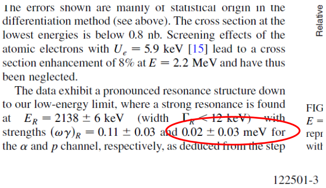



- Meaningful physics spectra
- Background subtraction based on non-coincident events

  Deep sub-barrier energy regime
- Reliable gates
- Statistical analysis of counts

# Redefinition of the Confidence Interval





The errors shown are mainly of statistical origin in the differentiation method (see above). The cross section at the lowest energies is below 0.8 nb. Screening effects of the atomic electrons with $U_e = 5.9$ keV [15] lead to a cross section enhancement of 8% at $E = 2.2$ MeV and have thus been neglected.

The data exhibit a pronounced resonance structure down to our low-energy limit, where a strong resonance is found at $E_R = 2138 \pm 6$ keV (width $\Gamma_R < 12$ keV) with strengths $(\omega\gamma)_R = 0.11 \pm 0.03$ and $0.02 \pm 0.03$ meV for the $\alpha$ and $p$ channel, respectively, as deduced from the step

122501-3

T. Spillane *et al.*, PRL, **98** 122501 (2007)

$$n = 15 \text{ (observed)}$$

$$b = R_\gamma \cdot R_\alpha \cdot t_{\text{coinc}} \cdot t_{exp}$$

$$= 12 \text{ (bkgr.)}$$

$$\mu = n - b = 3 \text{ (signal)}$$

$$\frac{\Delta\mu}{\mu} = \sqrt{\left(\frac{\Delta n}{n}\right)^2 + \left(\frac{\Delta b}{b}\right)^2} \approx \frac{\Delta n}{n}$$

$$\rightarrow \mu = 3 \pm \sqrt{15} \text{ unphysical}$$

$$\Rightarrow \mu \in [0, 6.32]$$

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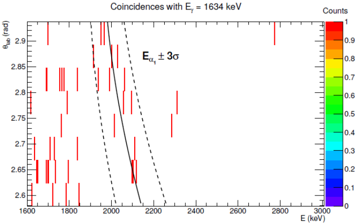


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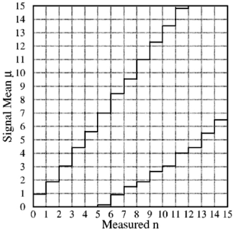


G.Feldman, R.Cousin, PRD **57** 7 (1998), b=3

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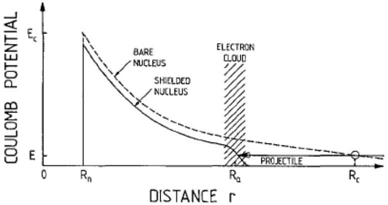
# Laboratory: Cross-Section Enhancement

shielding potential between target atoms and (part.) ionised beam




H.J. Assenbaum *et al.*, Z. Phys. A **327**, 461 (1987)

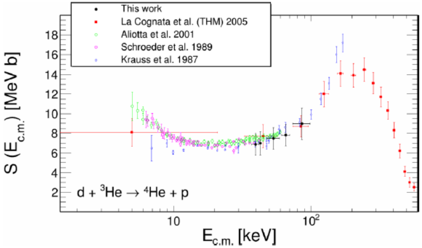
$$U_e = Z_1 Z_2 e^2 / R_a$$
$$E_{eff} = E_{beam} + U_e$$
$$\hookrightarrow E_{eff} / E_{beam}$$

- effect more pronounced for heavier systems ($\alpha$+$^{12}$C, $^{12}$C+$^{12}$C)
- experimental relative energies lower in light systems ($d + d$, $d$+$^{3}$He)
- discussion about interpretation of data with light systems:

G. Fiorentini *et al.*, Z. Phys A **350**, 289 (1995)
F.C. Barker, Nuc. Phys. A **707**, 277 (2002)

# Laser Plasma Induced $^{3}He(d,p)^{4}He$

- mixture of $^{3}$He and d heated by laser pulses
- d+$^{3}$He undergo 'Coulomb explosion' in hot plasma




D. Lattuada *et al.*, PRC **93**, 045808 (2016)

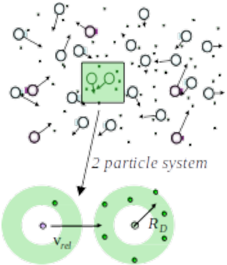
- non biased measurement by electron screening
- improve error bars:
  1. more precise measurement of the ion energy distribution
  2. higher accuracy with particle yields

# Astrophysical Site: Cross-Section Enhancement

shielding potential between partners from electron gas

- Debye-Hückel theory
- depends strongly on astrophysics site
- $^{12}C+^{12}C$:

  several predictions




N. Itoh *et al.*, Astrophy. Jour. **234**, 1079 (1979)
P. Quarati *et al.*, Astrophy. Jour. **666**, 1303 (2007)

Thank you very much for your attention!