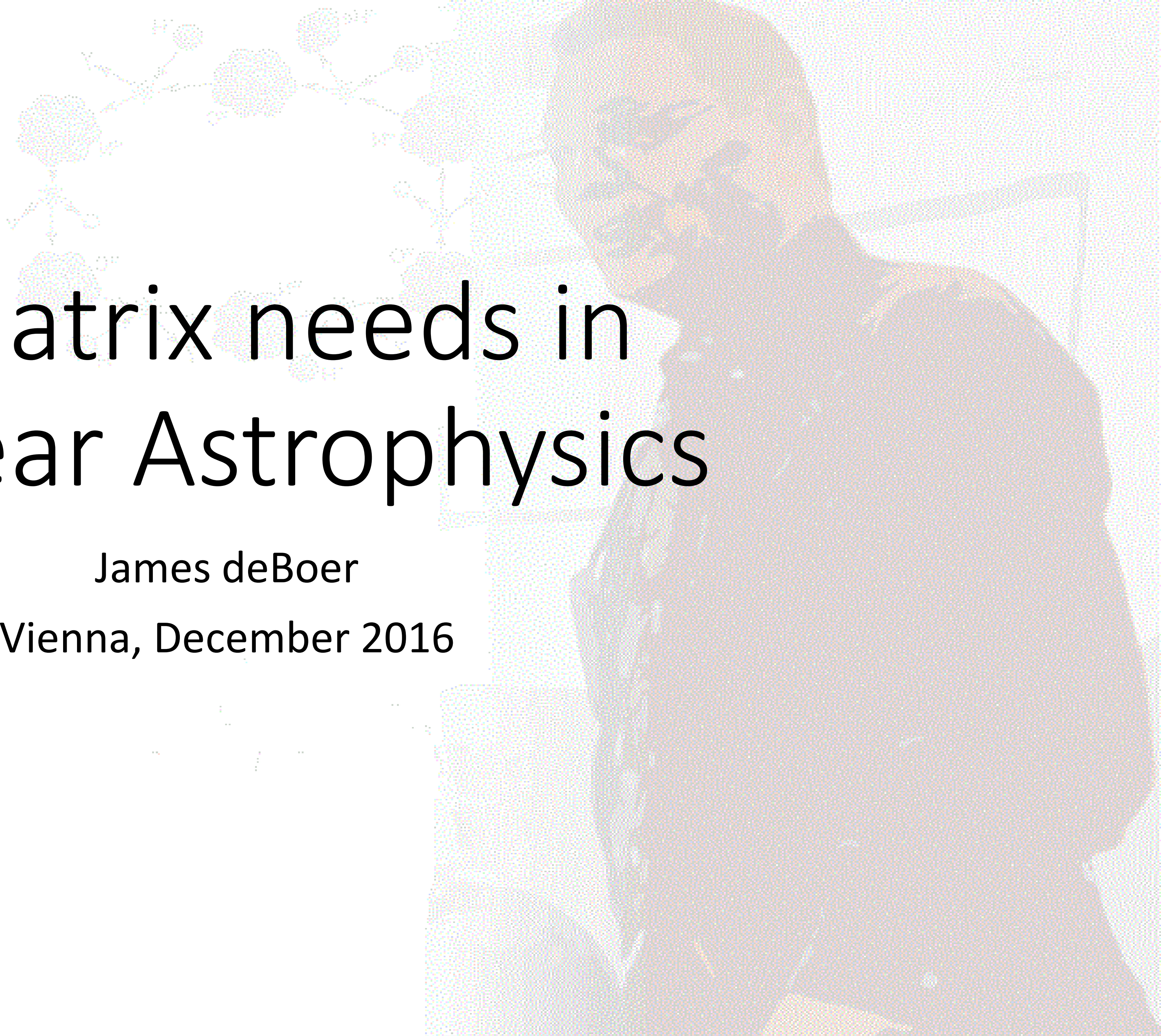
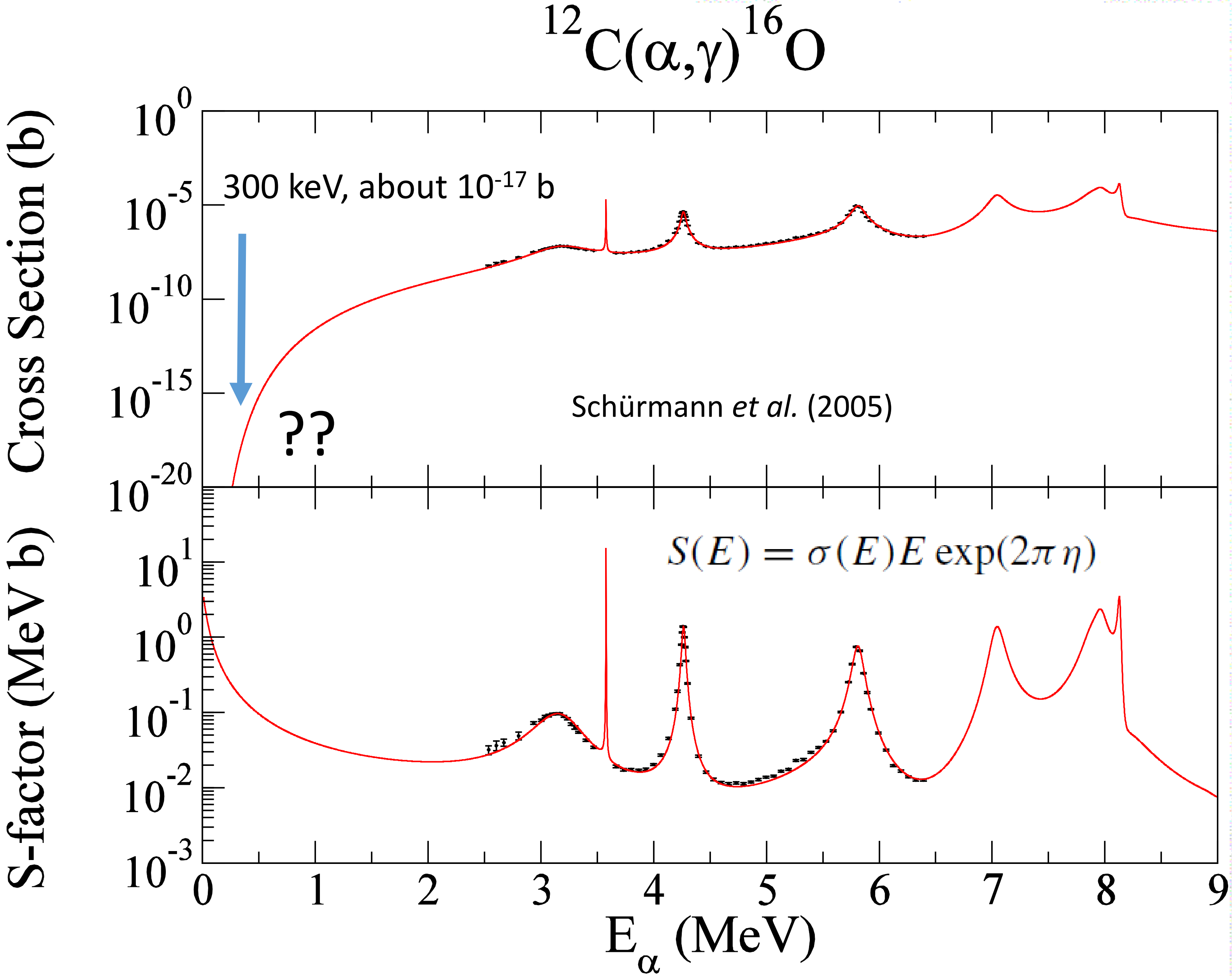


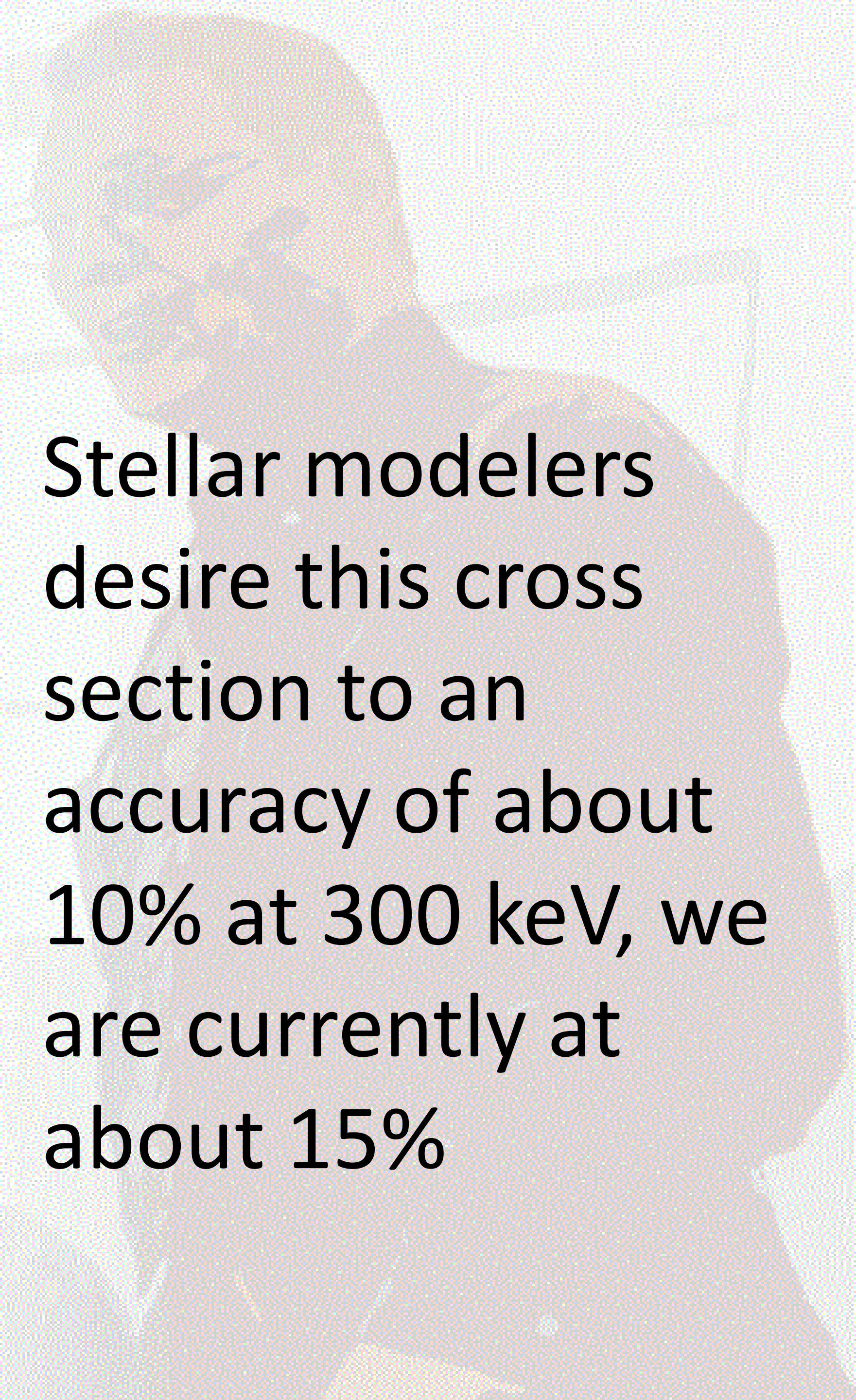
R-matrix needs in Nuclear Astrophysics

James deBoer

Vienna, December 2016

The extrapolation game

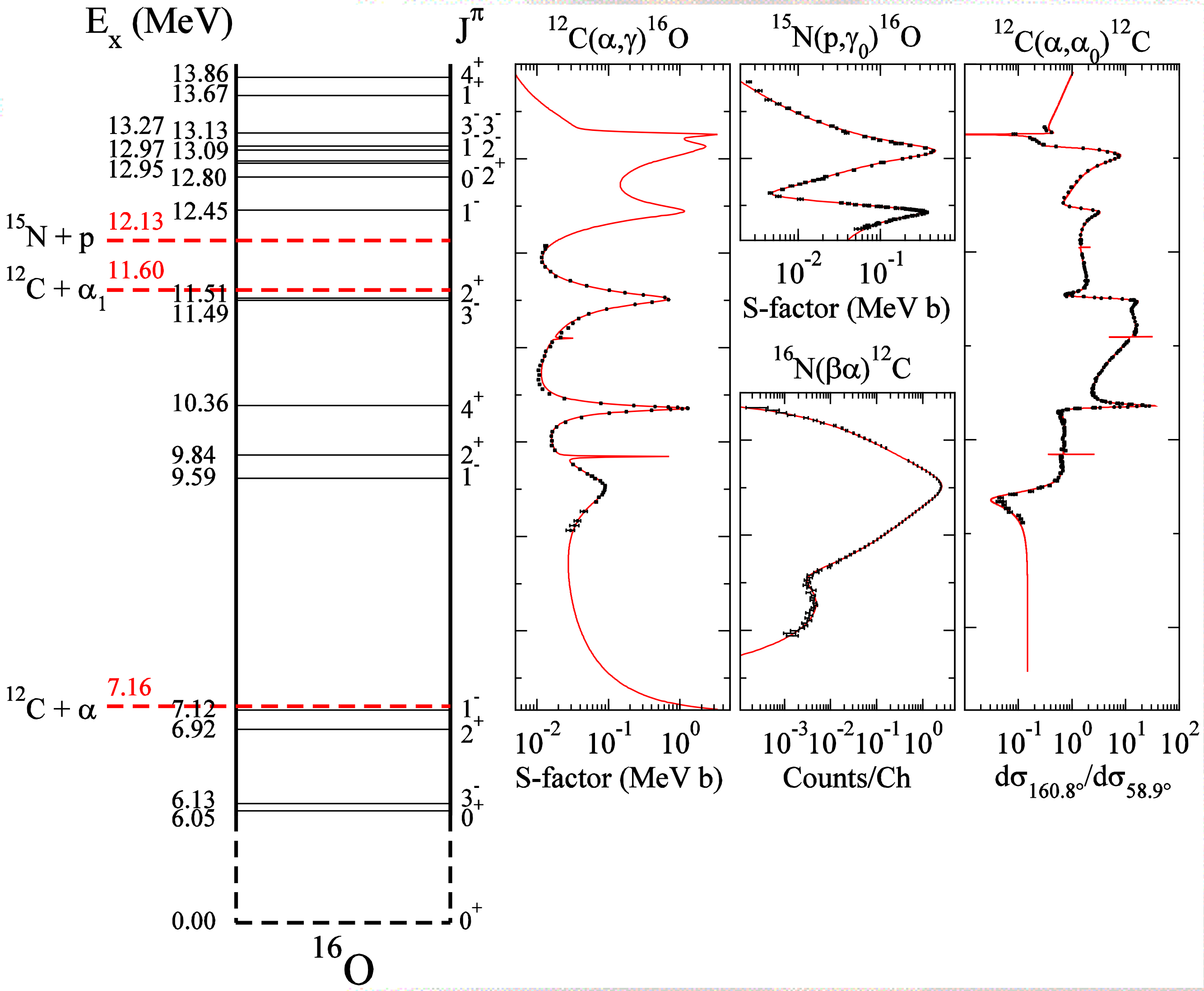


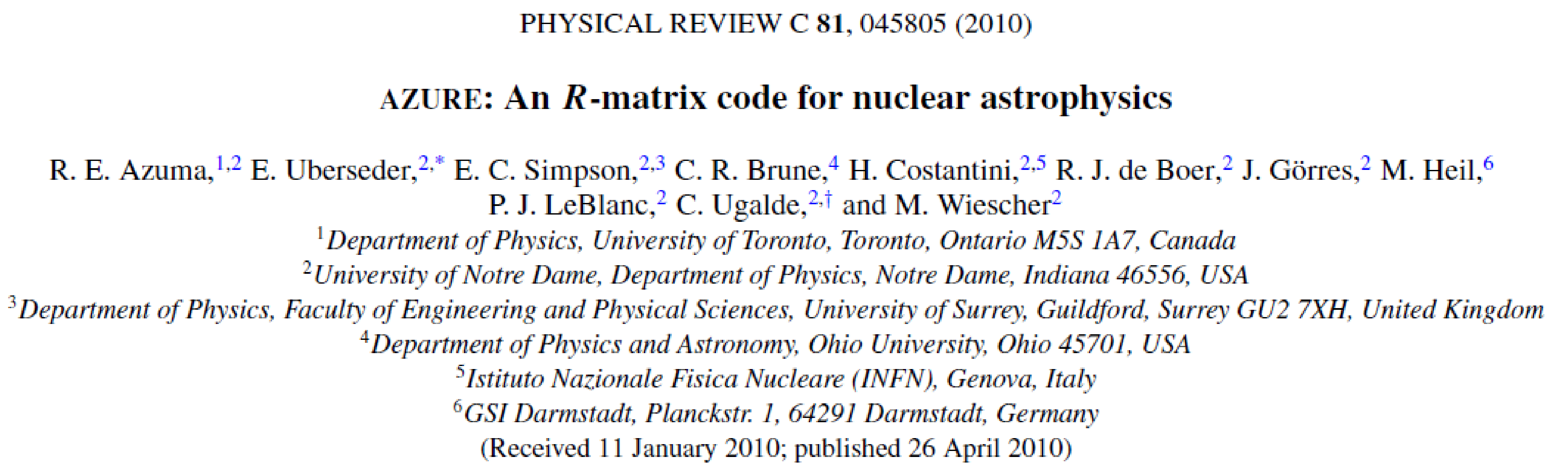


Stellar modelers desire this cross section to an accuracy of about 10% at 300 keV, we are currently at about 15%

Want a theory that can combine nuclear structure with nuclear reaction data

- Would like ab initio or other model with more nuclear information built in, but all these are no accurate enough
- Phenomenological R-matrix
  - Can combine all kinds of compound nucleus reaction data
  - Can use transfer reactions to probe properties of states inaccessible to CN reactions





PHYSICAL REVIEW C **81**, 045805 (2010)

AZURE: An *R*-matrix code for nuclear astrophysics

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(Received 11 January 2010; published 26 April 2010)

- A reliable benchmark for *R*-matrix analyses for low-mass charged particle (capture) reactions
- Open source (azure.nd.edu)

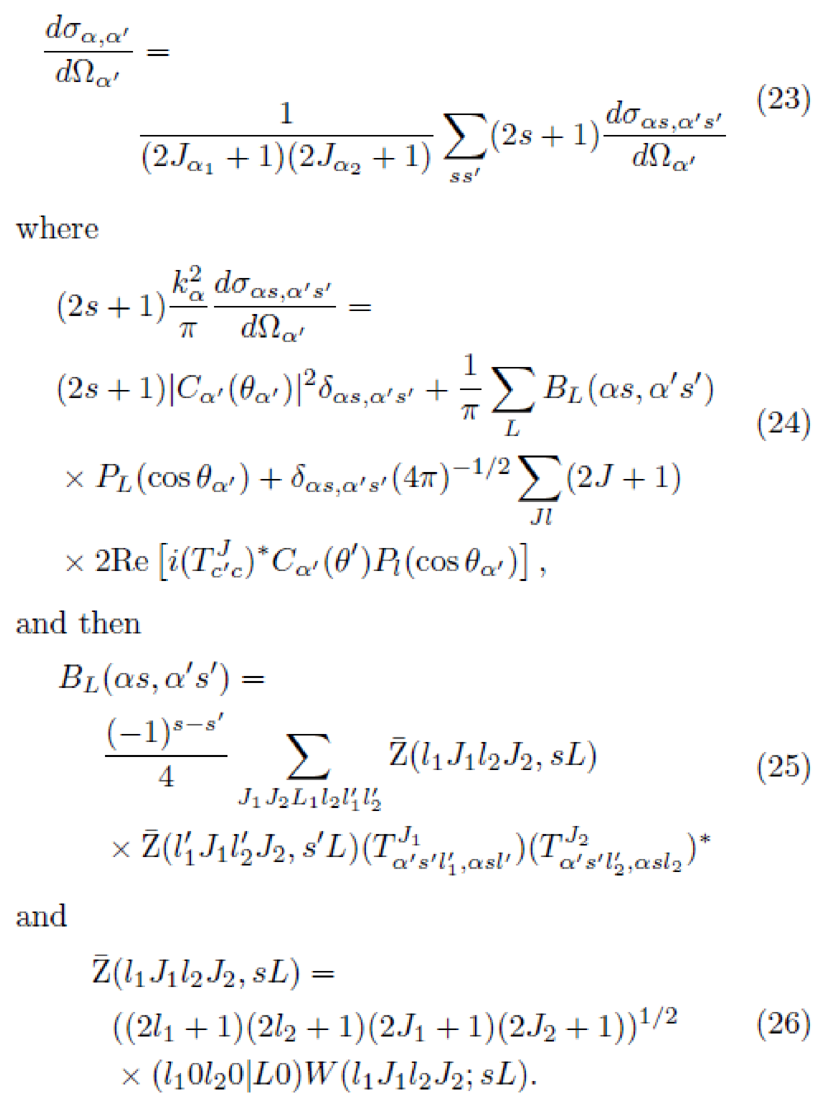
JINA–CEE

NSF

What AZURE2 can calculate

- Charged particle and neutron partitions
- Capture reaction (x, gamma)
- Multi-level multi-channel
  - To a large number (???)

- Angle integrated cross sections
- Differential cross sections
  - Phase shifts



$$\frac{d\sigma_{\alpha,\alpha'}}{d\Omega_{\alpha'}} = \frac{1}{(2J_{\alpha_1}+1)(2J_{\alpha_2}+1)} \sum_{ss'} (2s+1) \frac{d\sigma_{\alpha s,\alpha' s'}}{d\Omega_{\alpha'}} \tag{23}$$

where

$$\begin{aligned} &(2s+1)\frac{k_\alpha^2}{\pi}\frac{d\sigma_{\alpha s,\alpha' s'}}{d\Omega_{\alpha'}} = \\ &(2s+1)|C_{\alpha'}(\theta_{\alpha'})|^2 \delta_{\alpha s,\alpha' s'} + \frac{1}{\pi}\sum_L B_L(\alpha s,\alpha' s') \\ &\times P_L(\cos\theta_{\alpha'}) + \delta_{\alpha s,\alpha' s'}(4\pi)^{-1/2}\sum_{Jl}(2J+1) \\ &\times 2\mathrm{Re}\left[i(T^J_{c'c})^* C_{\alpha'}(\theta')P_l(\cos\theta_{\alpha'})\right], \end{aligned} \tag{24}$$

and then

$$\begin{aligned} &B_L(\alpha s,\alpha' s') = \\ &\frac{(-1)^{s-s'}}{4}\sum_{J_1 J_2 L_1 l_2 l_1' l_2'} \bar{\mathrm{Z}}(l_1 J_1 l_2 J_2, sL) \\ &\times \bar{\mathrm{Z}}(l_1' J_1 l_2' J_2, s'L)(T^{J_1}_{\alpha' s' l_1',\alpha s l'})(T^{J_2}_{\alpha' s' l_2',\alpha s l_2})^* \end{aligned} \tag{25}$$

and

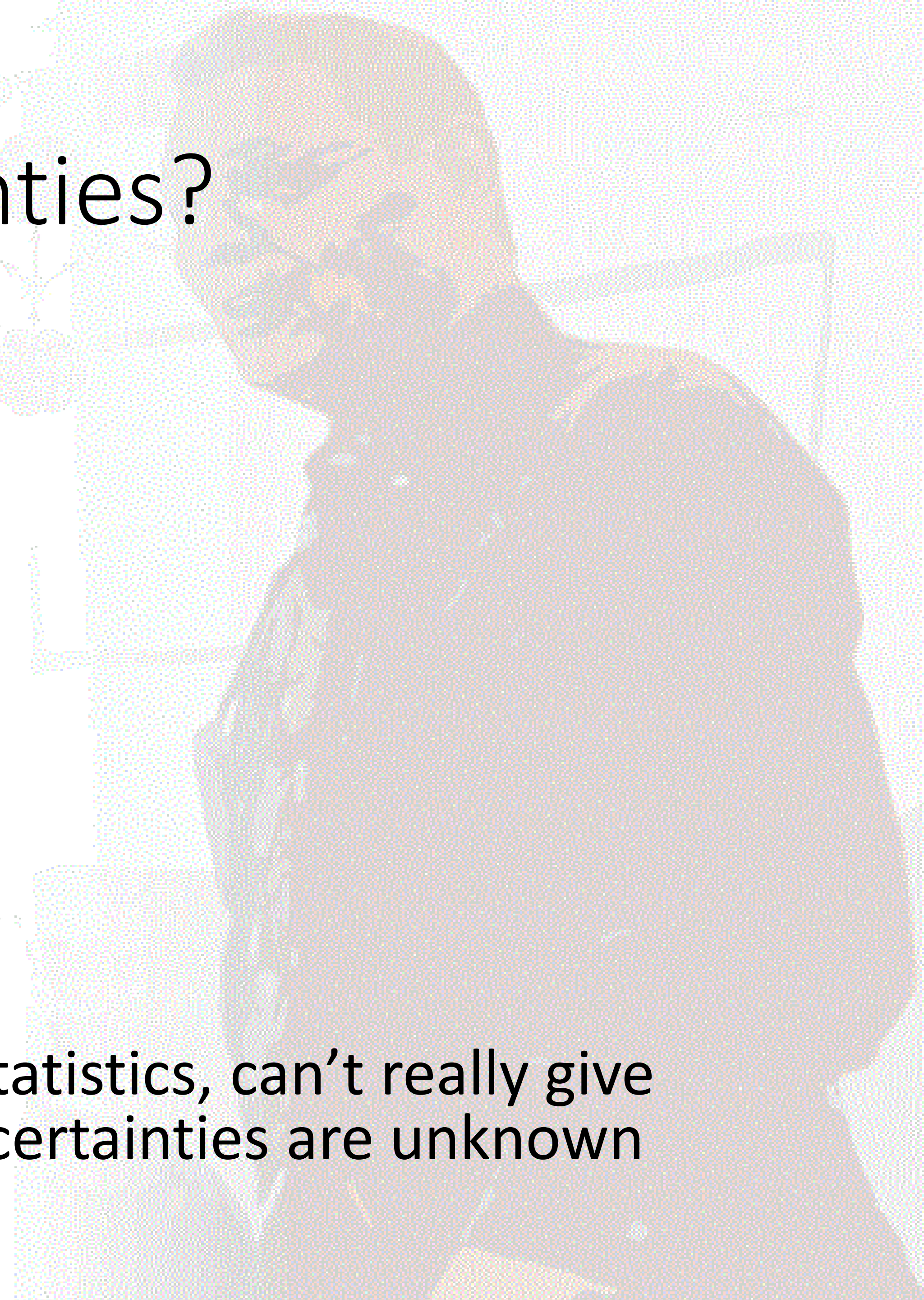
$$\begin{aligned} &\bar{\mathrm{Z}}(l_1 J_1 l_2 J_2, sL) = \\ &((2l_1+1)(2l_2+1)(2J_1+1)(2J_2+1))^{1/2} \\ &\times (l_1 0 l_2 0|L0)W(l_1 J_1 l_2 J_2; sL). \end{aligned} \tag{26}$$

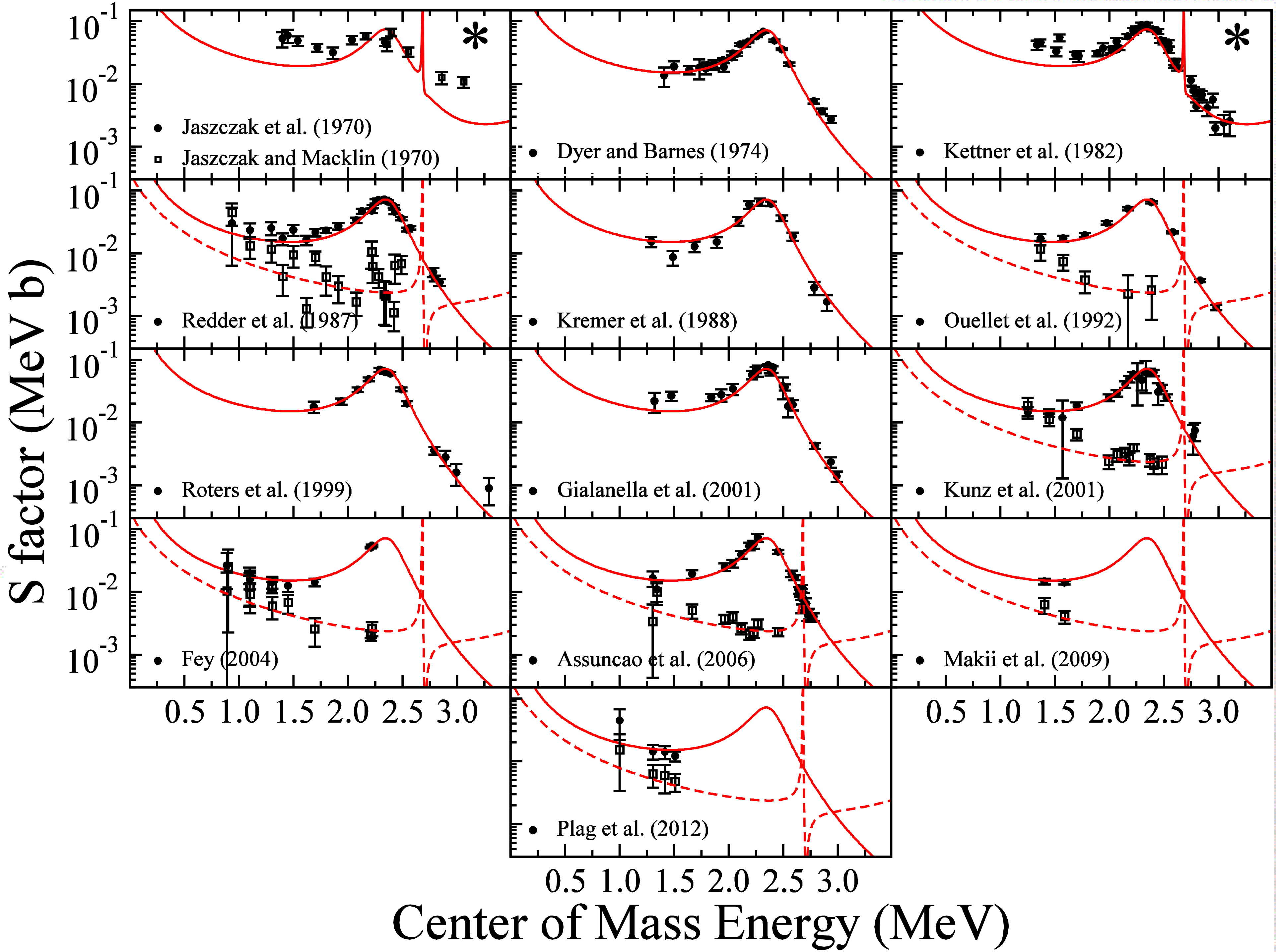
What are the main uncertainties?

- Nuclear data
  - **Poorly defined uncertainties**
  - Conflicting data
  - Not enough documentation

- Model uncertainties
  - Channel radius
  - **Background poles**
  - Interference pattern

- Uncertainty is usually NOT dominated by statistics, can't really give confidence intervals since PDF of other uncertainties are unknown




S factor (MeV b)
10^{-1}
10^{-2}
10^{-3}
*
● Jaszczak et al. (1970)
□ Jaszczak and Macklin (1970)
● Dyer and Barnes (1974)
● Kettner et al. (1982)
● Redder et al. (1987)
● Kremer et al. (1988)
● Ouellet et al. (1992)
● Roters et al. (1999)
● Gialanella et al. (2001)
● Kunz et al. (2001)
● Fey (2004)
● Assuncao et al. (2006)
● Makii et al. (2009)
● Plag et al. (2012)
0.5 1.0 1.5 2.0 2.5 3.0
Center of Mass Energy (MeV)

Diverse sets of experiments

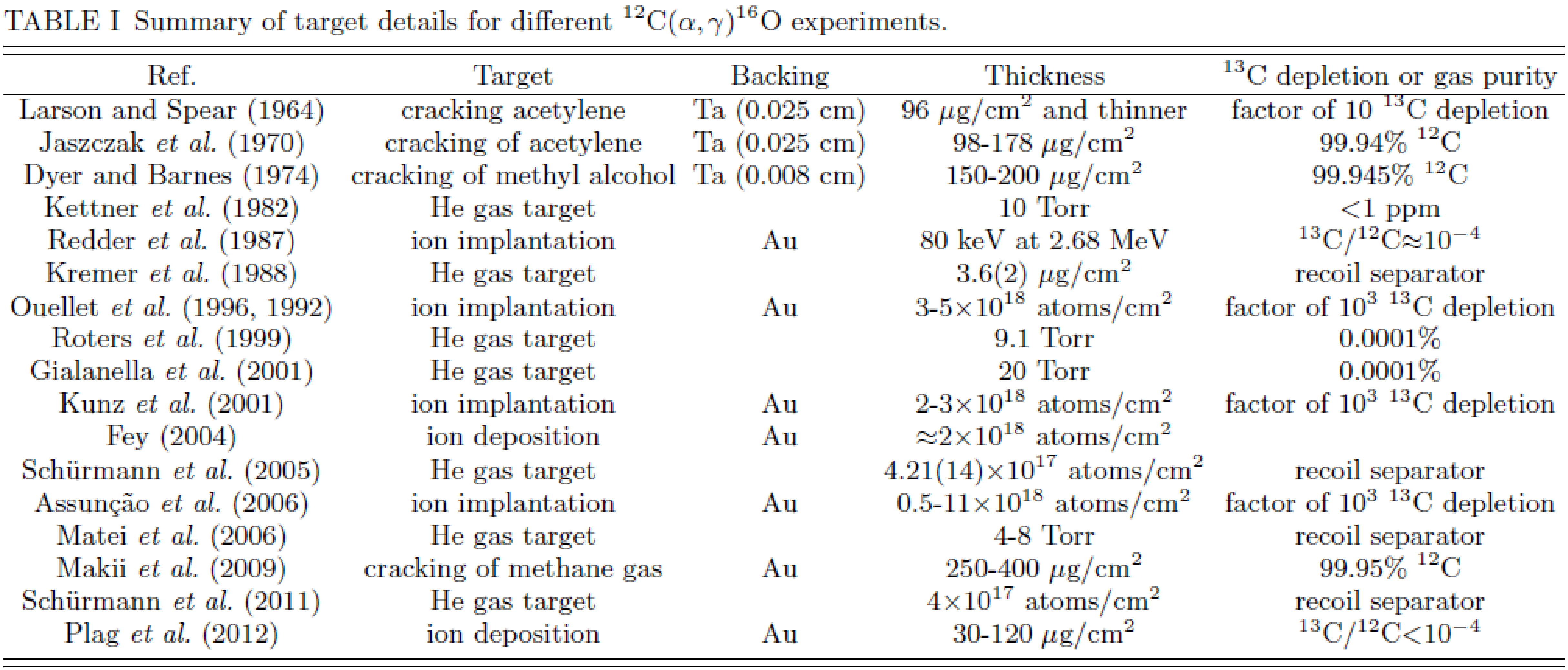
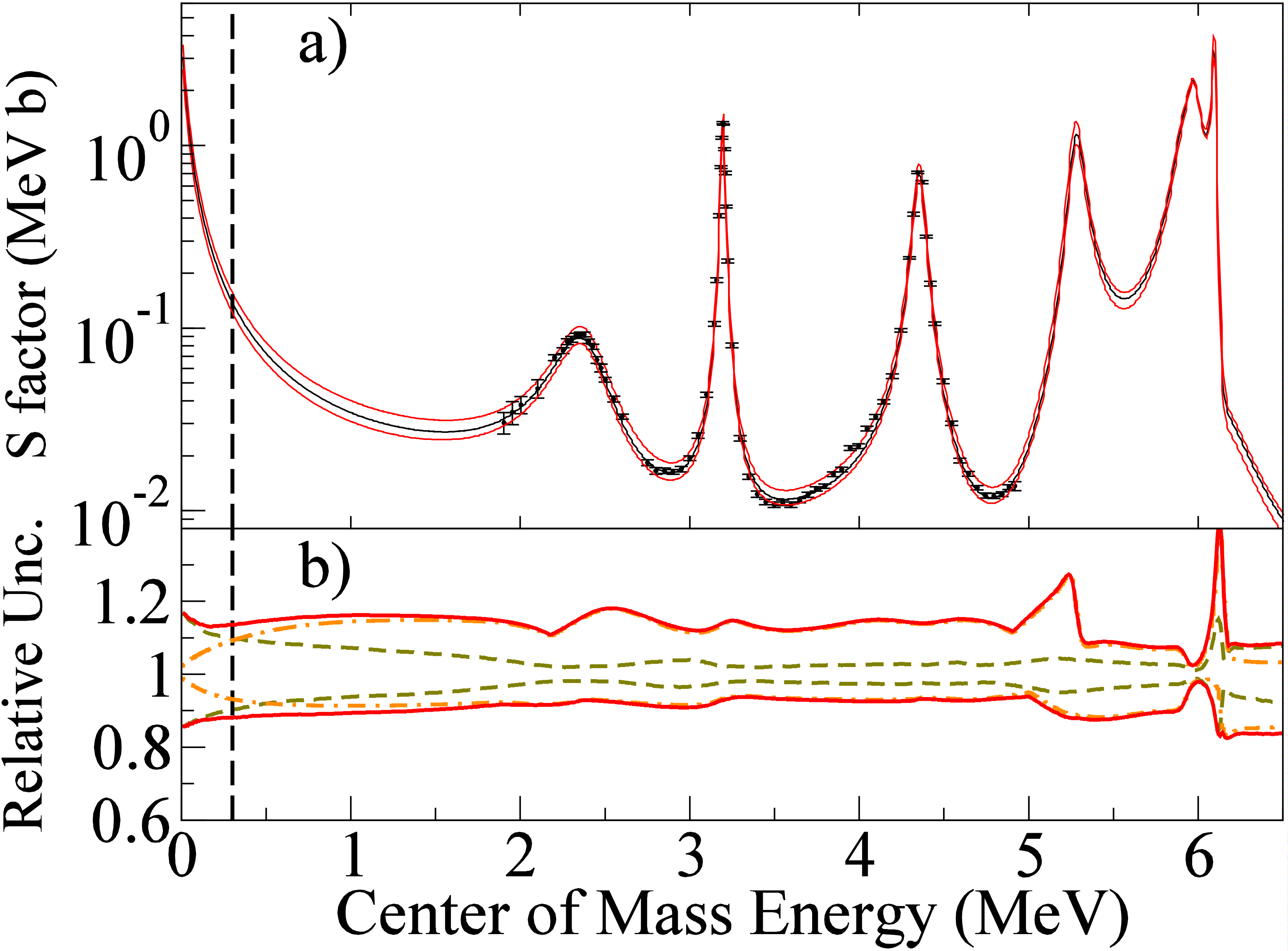


TABLE I Summary of target details for different $^{12}C(\alpha,\gamma)^{16}O$ experiments.

Ref.	Target	Backing	Thickness	^{13}C depletion or gas purity
Larson and Spear (1964)	cracking acetylene	Ta (0.025 cm)	96 $\mu g/cm^2$ and thinner	factor of 10 ^{13}C depletion
Jaszczak *et al.* (1970)	cracking of acetylene	Ta (0.025 cm)	98-178 $\mu g/cm^2$	99.94% ^{12}C
Dyer and Barnes (1974)	cracking of methyl alcohol	Ta (0.008 cm)	150-200 $\mu g/cm^2$	99.945% ^{12}C
Kettner *et al.* (1982)	He gas target		10 Torr	<1 ppm
Redder *et al.* (1987)	ion implantation	Au	80 keV at 2.68 MeV	$^{13}C/^{12}C \approx 10^{-4}$
Kremer *et al.* (1988)	He gas target		3.6(2) $\mu g/cm^2$	recoil separator
Ouellet *et al.* (1996, 1992)	ion implantation	Au	3-5$\times 10^{18}$ atoms/cm^2	factor of 10^3 ^{13}C depletion
Roters *et al.* (1999)	He gas target		9.1 Torr	0.0001%
Gialanella *et al.* (2001)	He gas target		20 Torr	0.0001%
Kunz *et al.* (2001)	ion implantation	Au	2-3$\times 10^{18}$ atoms/cm^2	factor of 10^3 ^{13}C depletion
Fey (2004)	ion deposition	Au	$\approx 2\times 10^{18}$ atoms/cm^2	
Schürmann *et al.* (2005)	He gas target		4.21(14)$\times 10^{17}$ atoms/cm^2	recoil separator
Assunção *et al.* (2006)	ion implantation	Au	0.5-11$\times 10^{18}$ atoms/cm^2	factor of 10^3 ^{13}C depletion
Matei *et al.* (2006)	He gas target		4-8 Torr	recoil separator
Makii *et al.* (2009)	cracking of methane gas	Au	250-400 $\mu g/cm^2$	99.95% ^{12}C
Schürmann *et al.* (2011)	He gas target		4$\times 10^{17}$ atoms/cm^2	recoil separator
Plag *et al.* (2012)	ion deposition	Au	30-120 $\mu g/cm^2$	$^{13}C/^{12}C<10^{-4}$

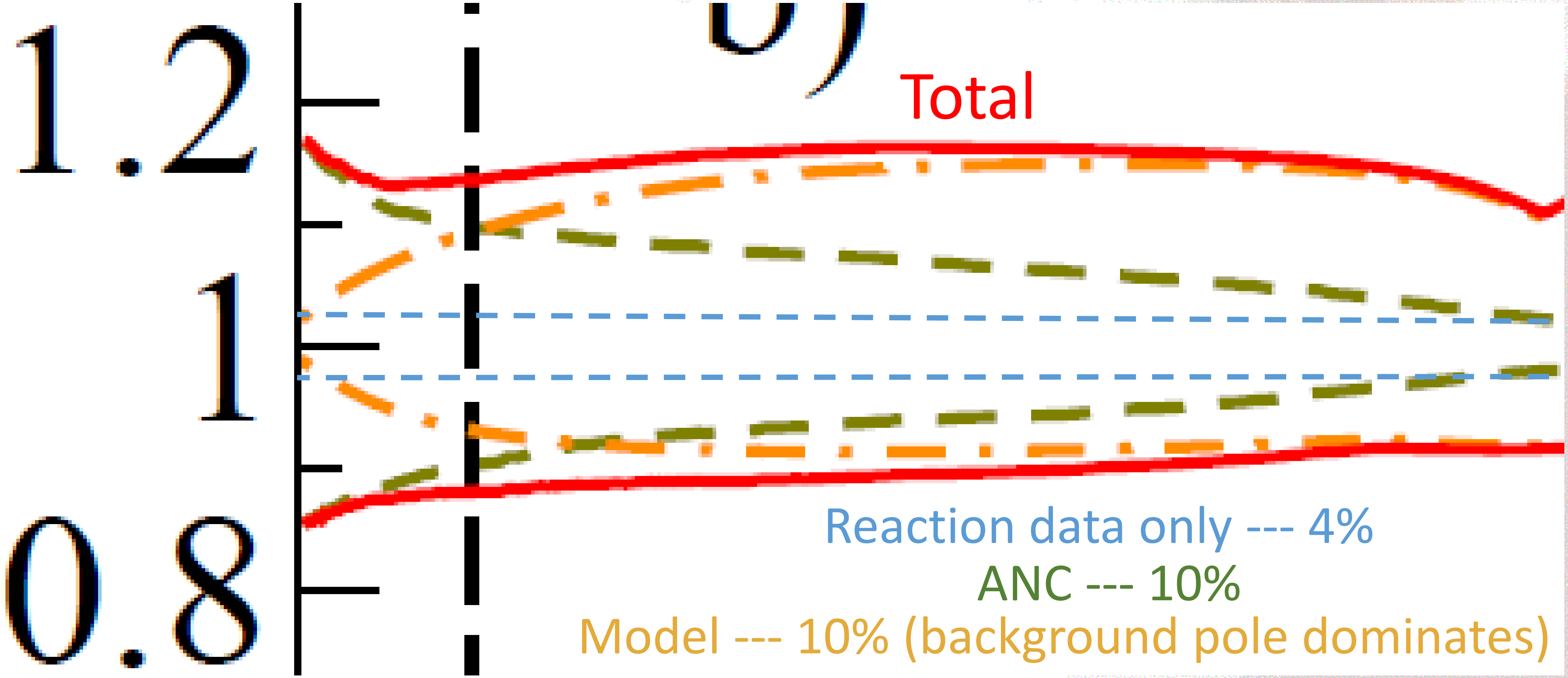
Uncertainty results: $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$



ANCs + data unc

Model

Uncertainty results



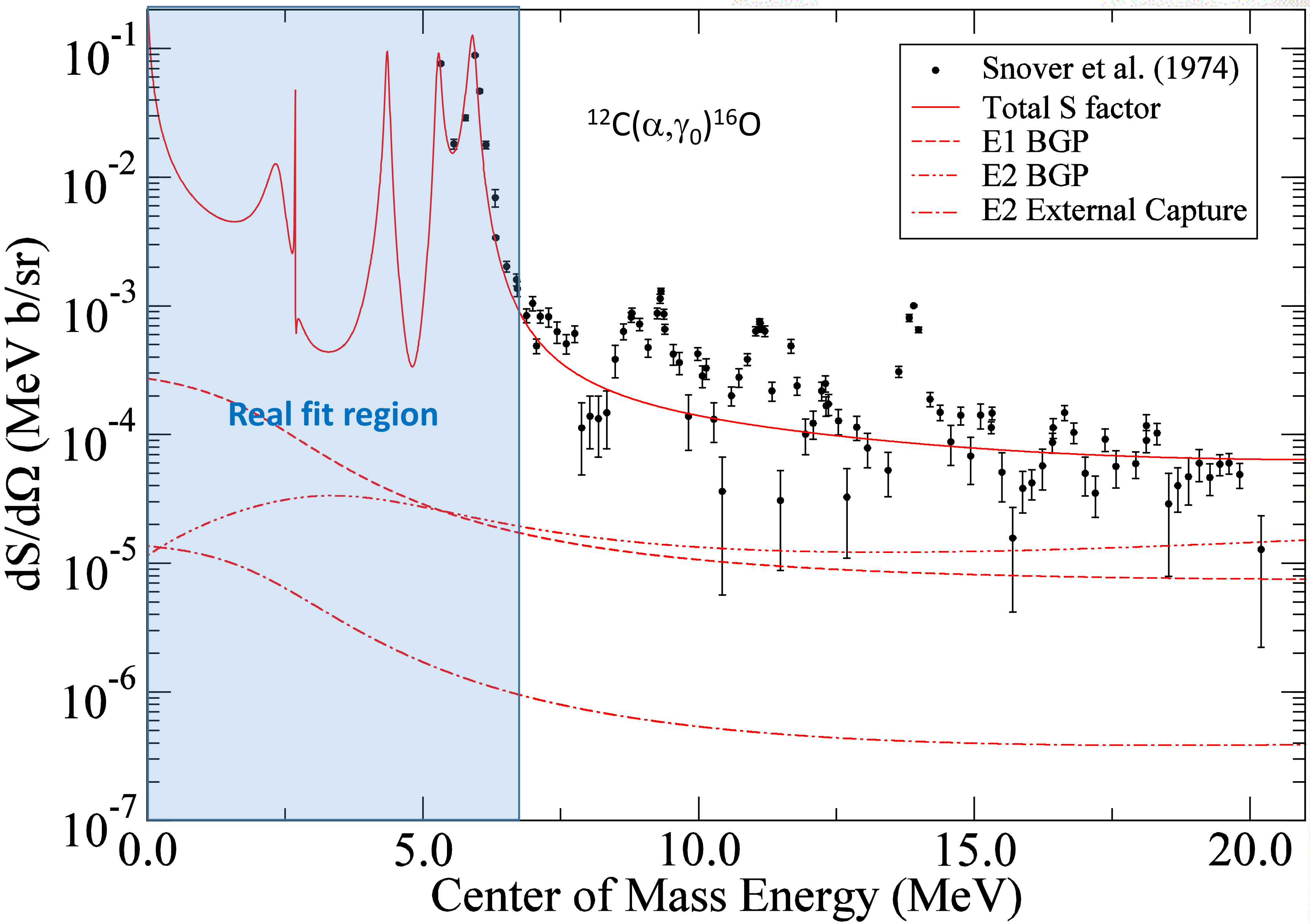
Total

Reaction data only --- 4%

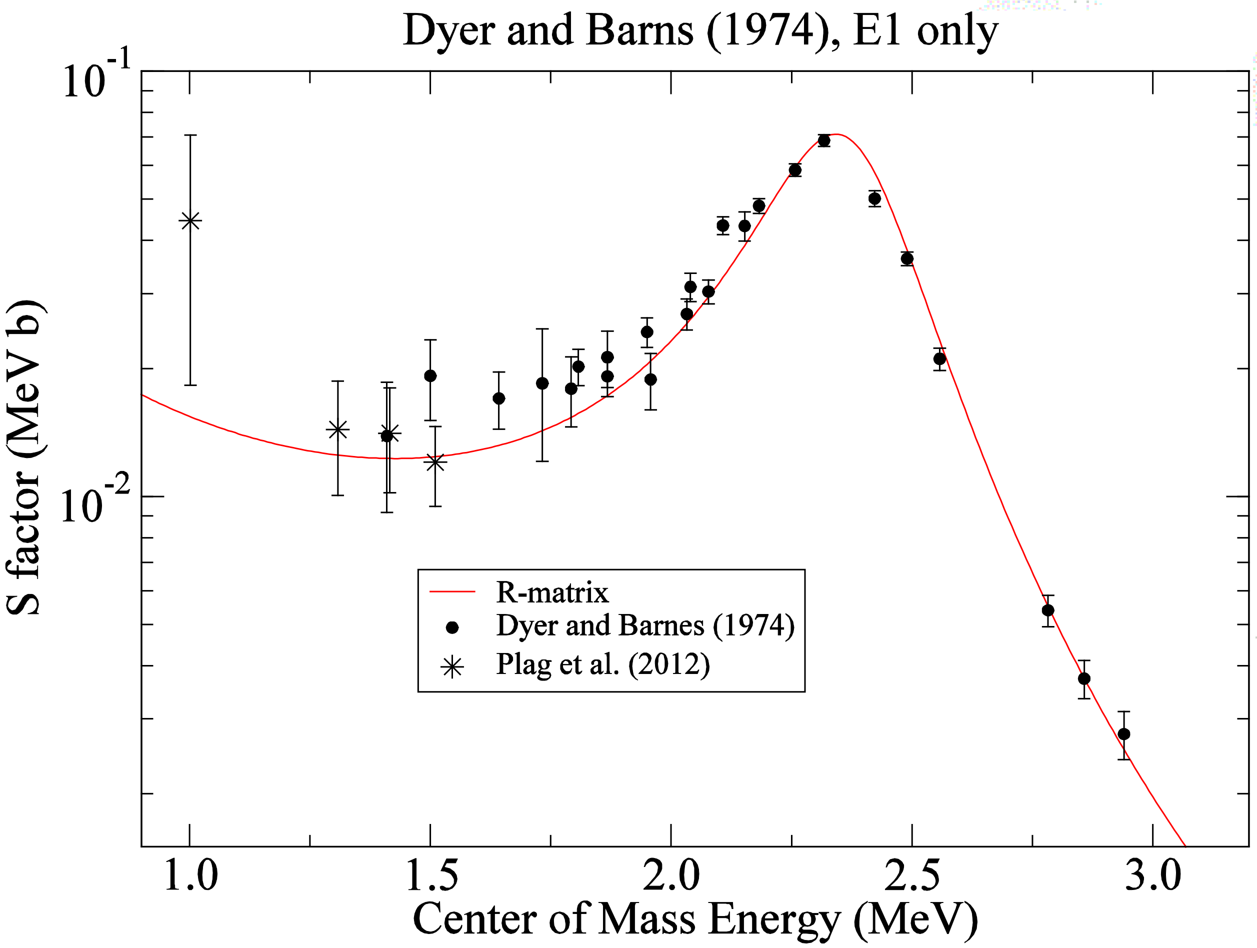
ANC --- 10%

Model --- 10% (background pole dominates)

Fitting to higher energy

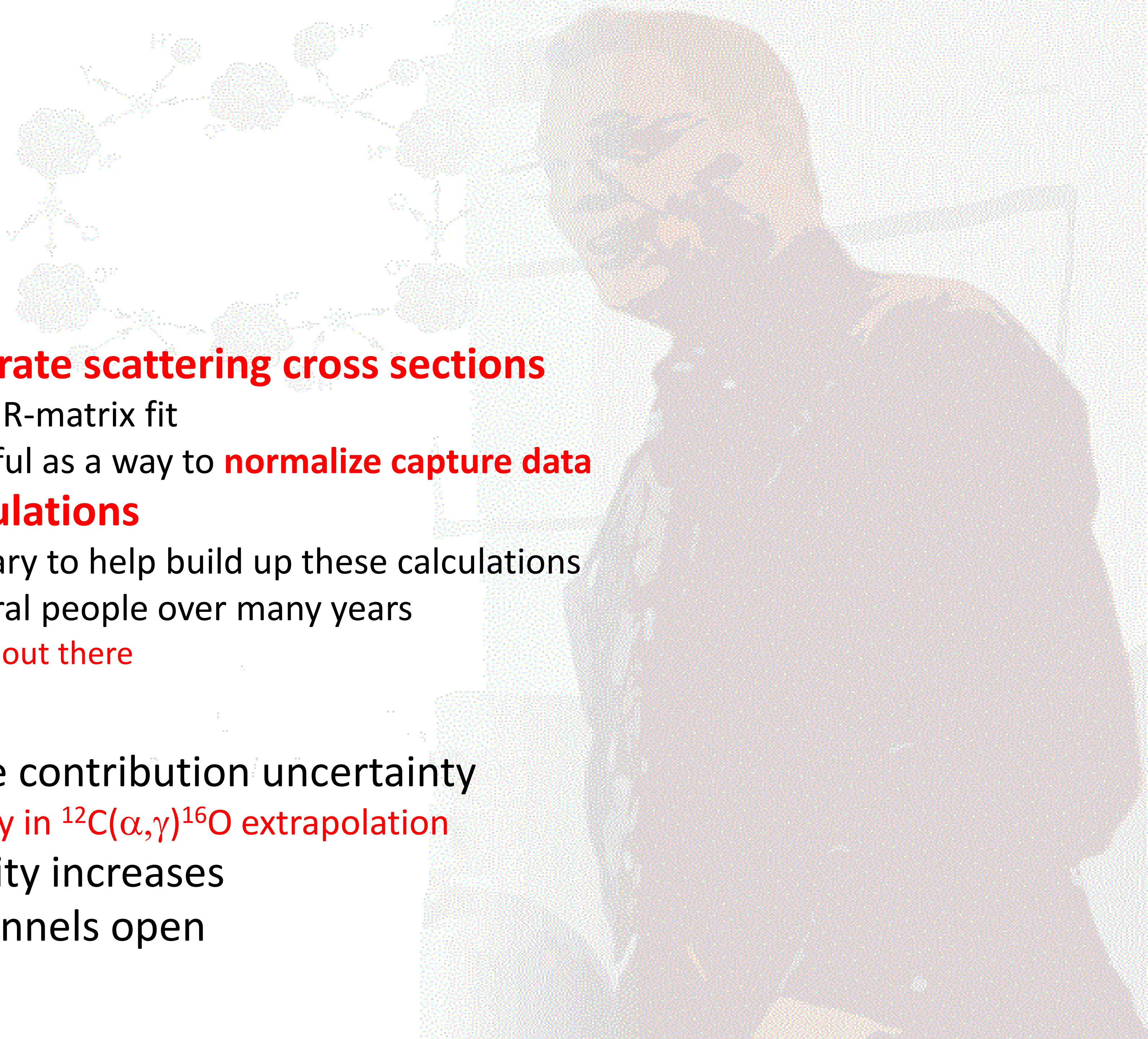


The way forward?



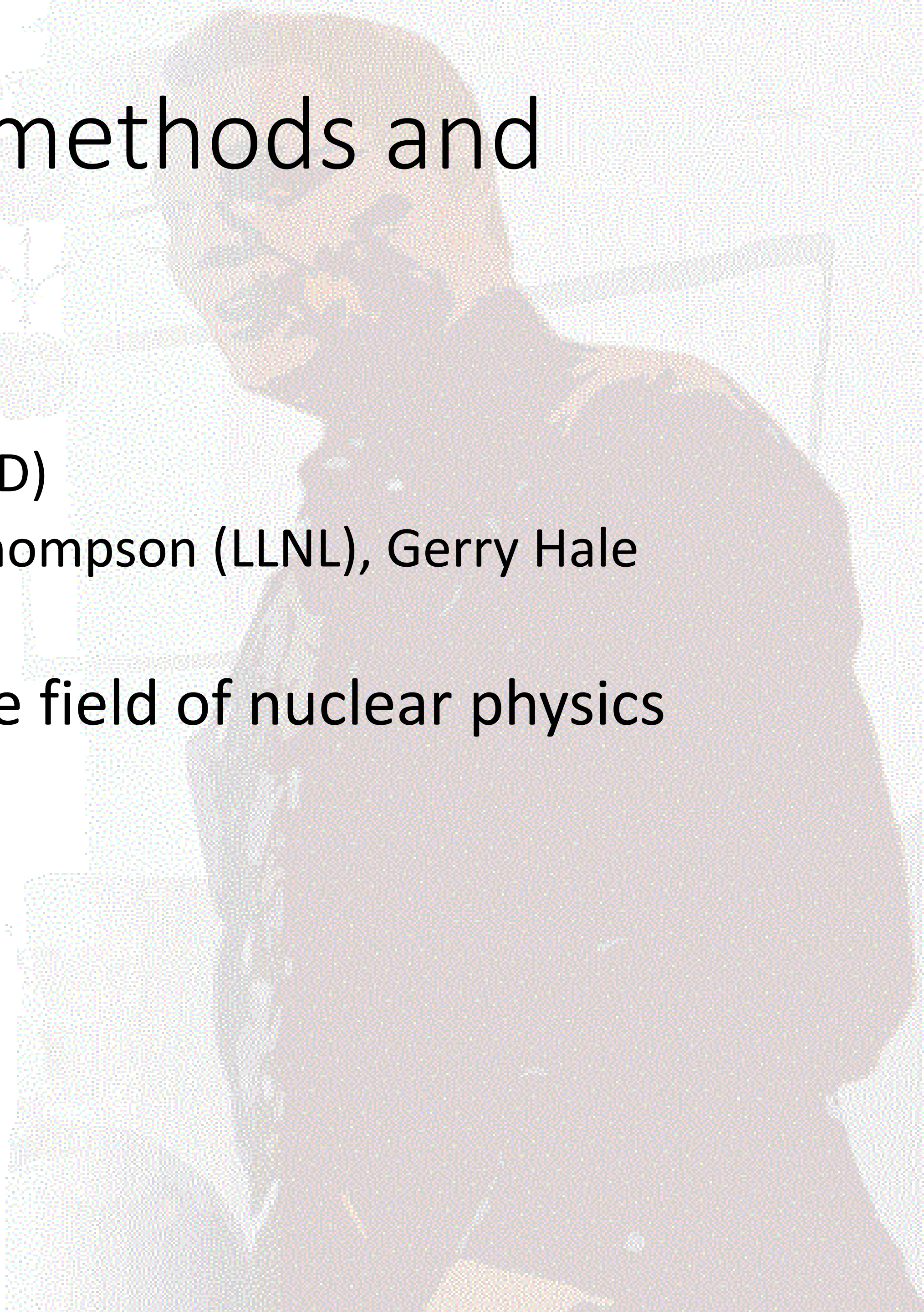
- Direct measurements are becoming more and more difficult
  - Underground
  - Heavy shielding
  - Large target and geometry corrections
- Indirect measurements are at a limit with their own model uncertainties
  - (^{6}Li,d) sub-Coulomb transfer

common goals



- Improve quality of data
  - **High precision and accurate scattering cross sections**
    - Useful for multi-channel R-matrix fit
    - Arguably even more useful as a way to **normalize capture data**
  - **Library of R-matrix calculations**
    - Large data bases necessary to help build up these calculations
    - Contributions from several people over many years
      - Not many Gerry Hales out there
- Fitting to higher energy
  - Reduce background pole contribution uncertainty
    - Largest single uncertainty in $^{12}C(\alpha,\gamma)^{16}O$ extrapolation
  - Hard to do as level density increases
  - Three body reaction channels open

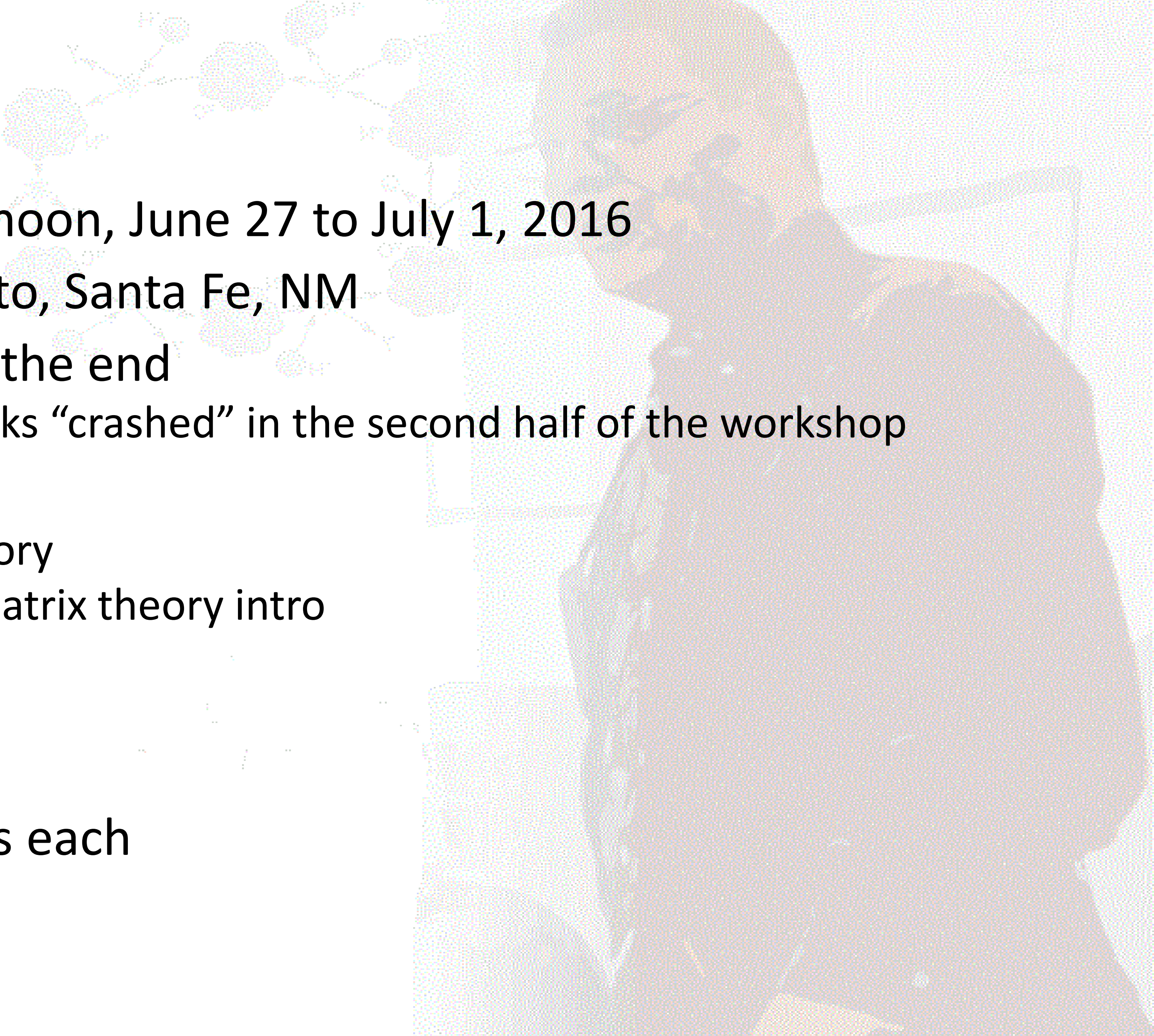
2016 R-matrix workshop on methods and applications



- Organizers
  - Co-chairs --- Mark Paris (LANL) and myself (UND)
  - Goran Arbanas (ORNL), Carl Brune (OU), Ian Thompson (LLNL), Gerry Hale (LANL), and Morgan White (LANL)
- Goal: Bring together people from across the field of nuclear physics who utilize *R*-matrix in order to share ideas
  - Nuclear astrophysics
  - Nuclear structure
  - Nuclear application

Stats

- Monday 9 AM to Friday noon, June 27 to July 1, 2016
- The Inn and Spa at Loretto, Santa Fe, NM
- About 50 participants in the end
  - Some additional LANL folks “crashed” in the second half of the workshop
- Overview Talks
  - Gerry Hale, R-matrix history
  - Ian Thompson, Basic R-matrix theory intro
  - Goran Arbanas, SAMMY
  - Mark Paris, EDA
  - Myself, AZURE2 demo
- 33 talks total, 30 minutes each

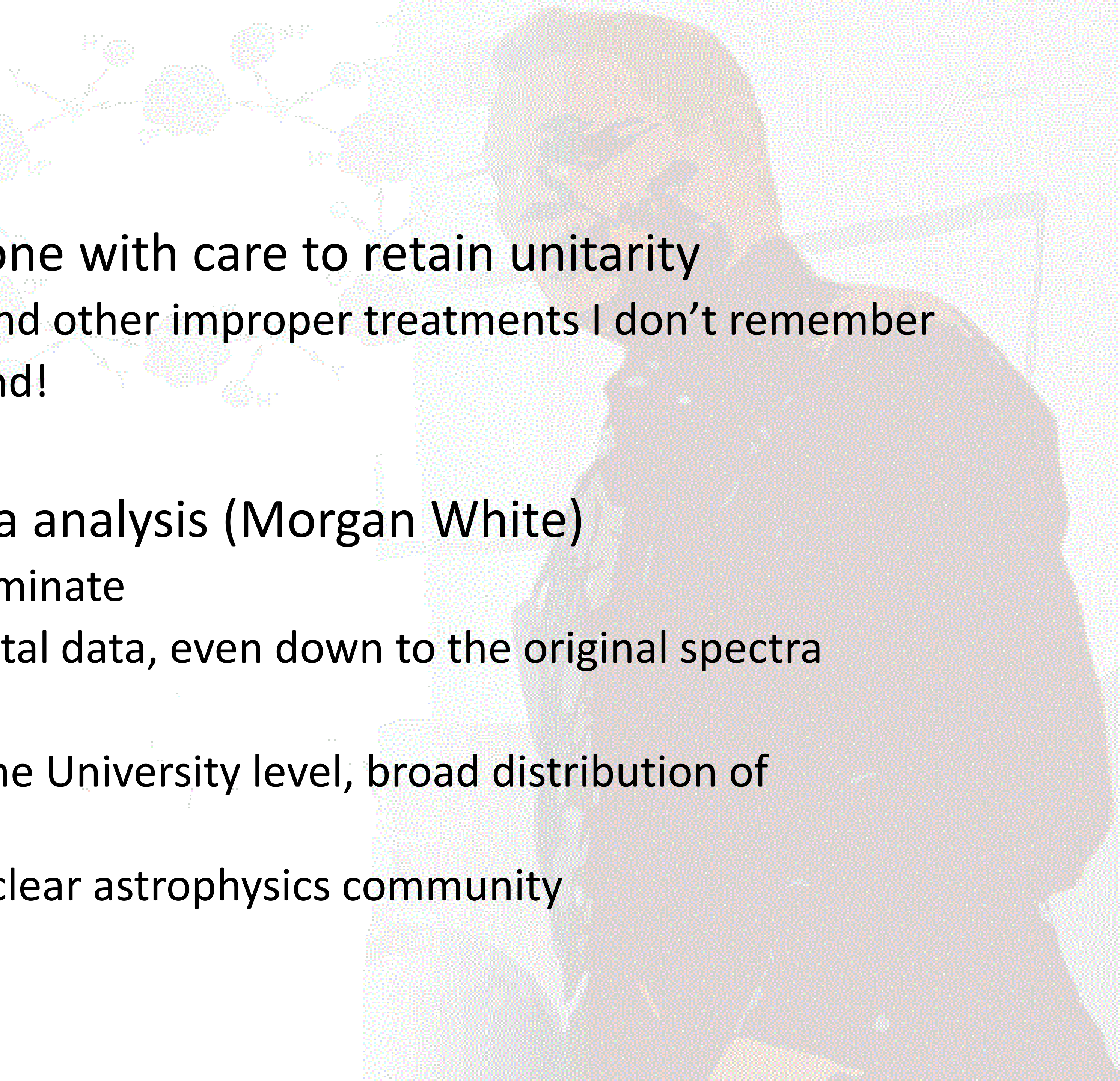


Thank you
Satoshi!

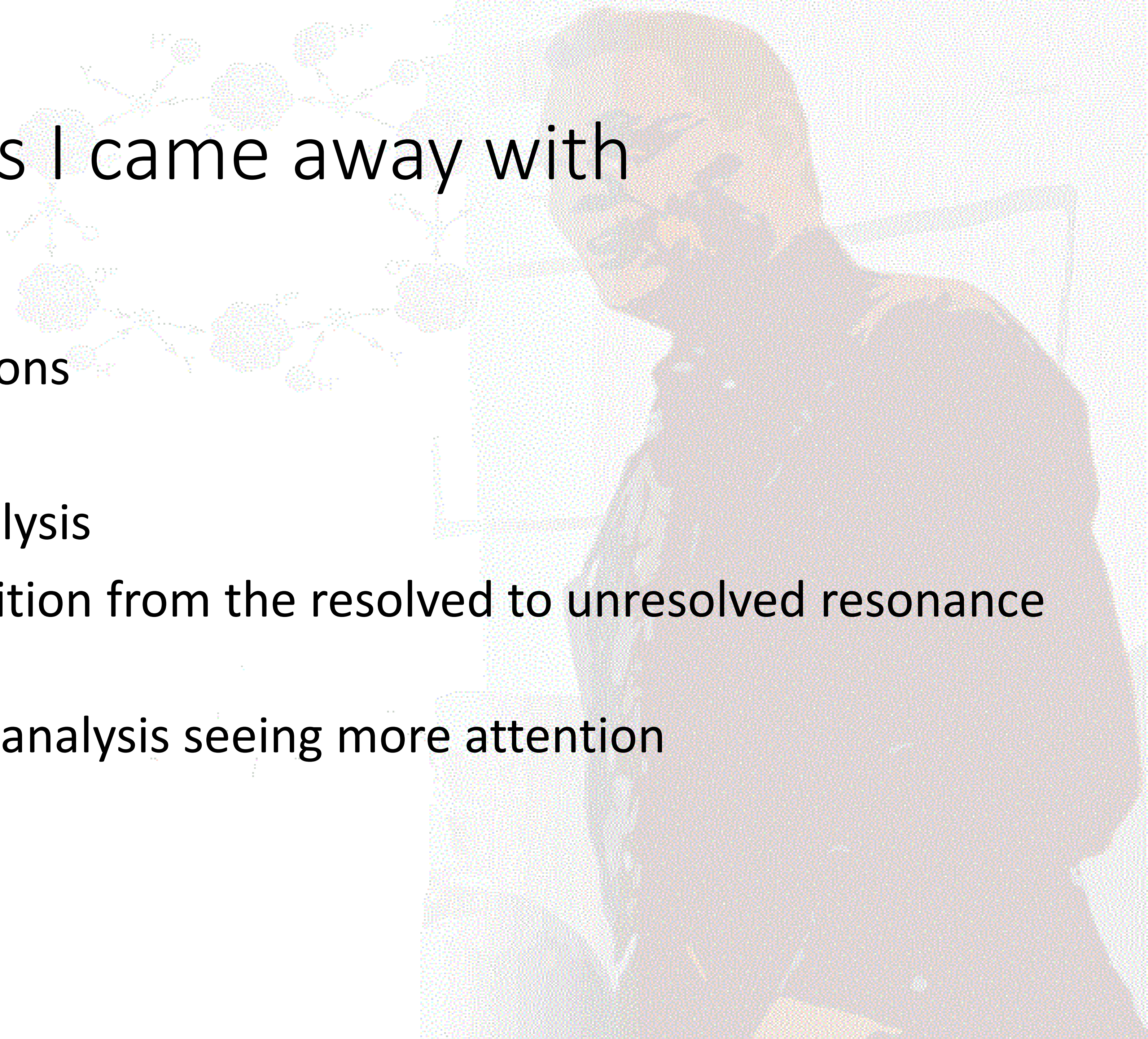
Some points made

- Hybrid R-matrix must be done with care to retain unitarity
  - Imaginary potential terms and other improper treatments I don’t remember
  - Just adding in flat background!

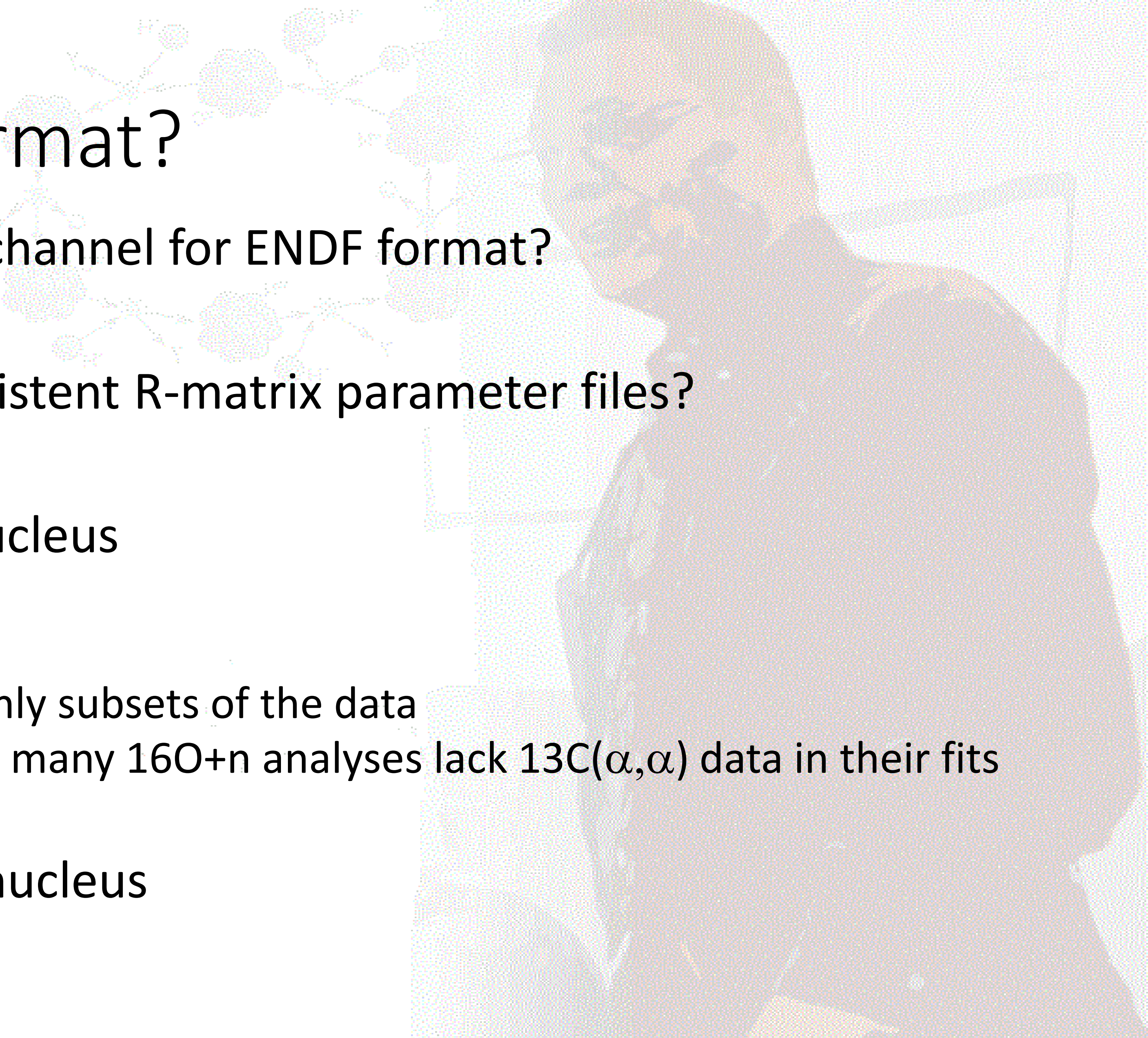
- Desire for standardized data analysis (Morgan White)
  - Systematic uncertainties dominate
  - Better records of experimental data, even down to the original spectra
  - More standardized codes?
  - I think this is a big issue at the University level, broad distribution of experience level
  - Varies greatly within the nuclear astrophysics community



Interesting topics I came away with



- 3 body exit channel reactions
- Fission exit channel
- Advanced uncertainty analysis
- Hybrid theories that transition from the resolved to unresolved resonance regions
- Charged particle R-matrix analysis seeing more attention



Issue with file format?

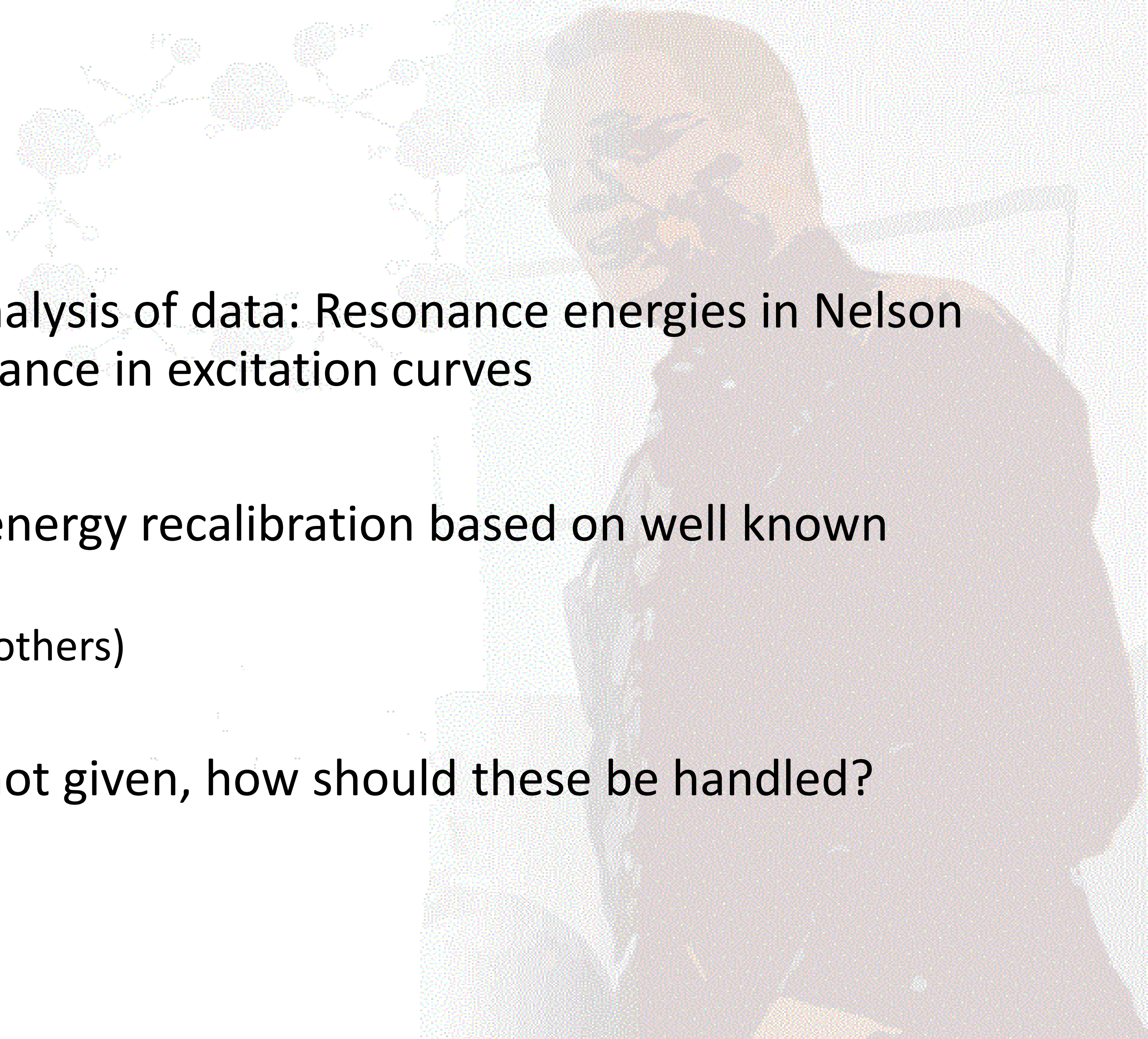
- Why only one entrance channel for ENDF format?

- Could this lead to inconsistent R-matrix parameter files?

- Ex. --- 17O compound nucleus
    - 16O+n file
    - 13C+a file
    - Sometimes people use only subsets of the data
    - Already an issue because many 16O+n analyses lack 13C(α,α) data in their fits

- One file per compound nucleus

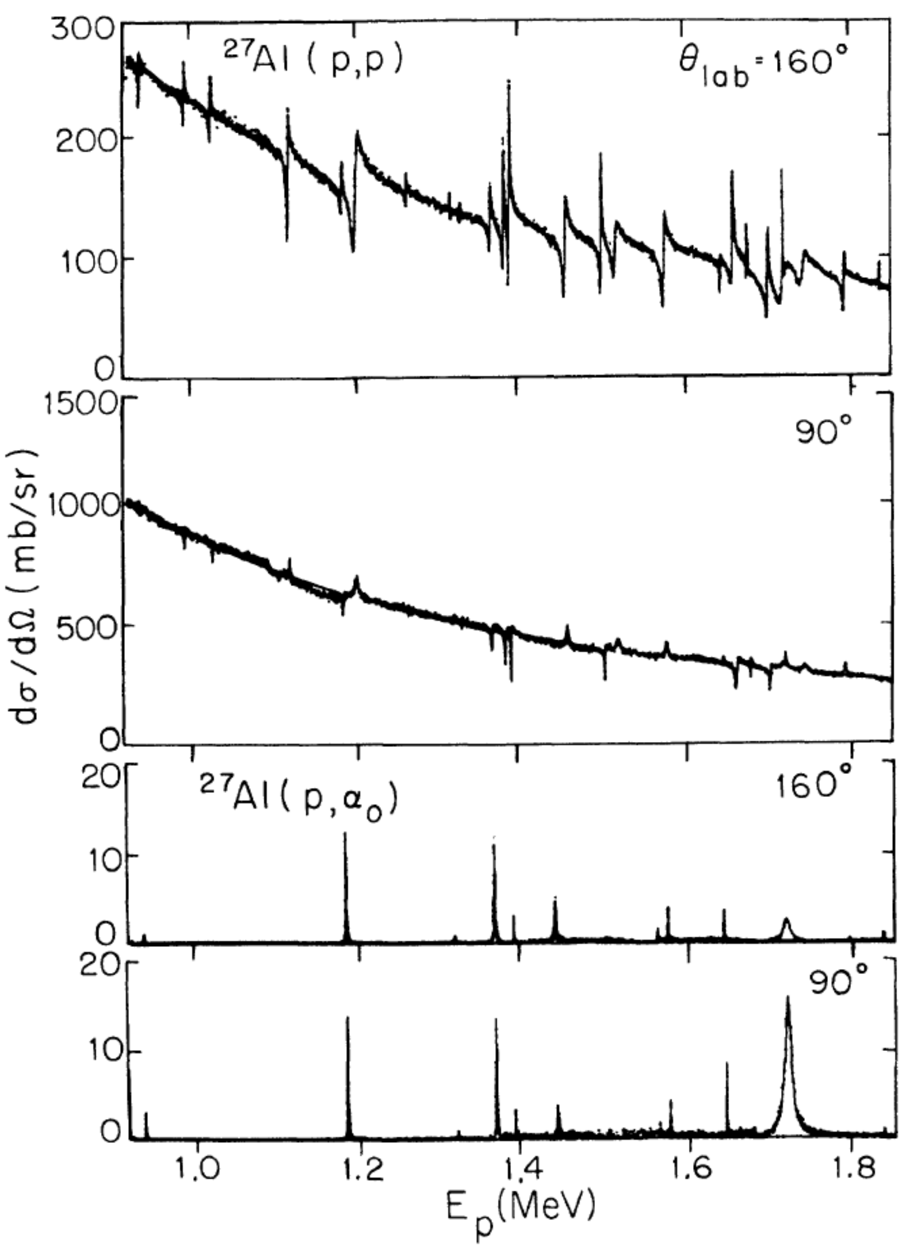
^{27}Al(p,γ)



- Problem with further analysis of data: Resonance energies in Nelson et al. don’t match resonance in excitation curves
- Fix: linear or quadratic energy recalibration based on well known resonances
  - 992 and 1800 keV (plus others)
- Also, uncertainties are not given, how should these be handled?

Uncertainty treatment

- Nelson says uncertainties on points are about 3%
  - This probably only applies to the scattering data
  - 3% → 1000 counts in scattering peak, probably more like 1 to 2% usually (1% → 10,000)
  - But this does not apply to other reaction channel data
- (p,p) data have cross sections of about 100's to a few 10's of mb/sr, (p,a0) cross sections range from always less than 20 mb/sr, usually much less



One suggestion

- If stats dominate uncertainty, scale uncertainty on other channels assuming 3% uncertainty for scattering points
    - $Y = \sigma N_t N_b \varepsilon$,
    - %unc ~ 1/sqrt(Y)
    - Measurements made simultaneously
    - $\%unc_{reac}/\%unc_{scat} \approx \mathrm{sqrt}(Y_{scat}/Y_{reac})$