The unreasonable effectiveness of experiments in constraining nova nucleosynthesis

Anuj Parikh

Universitat Politècnica de Catalunya
Institut d'Estudis Espacials de Catalunya

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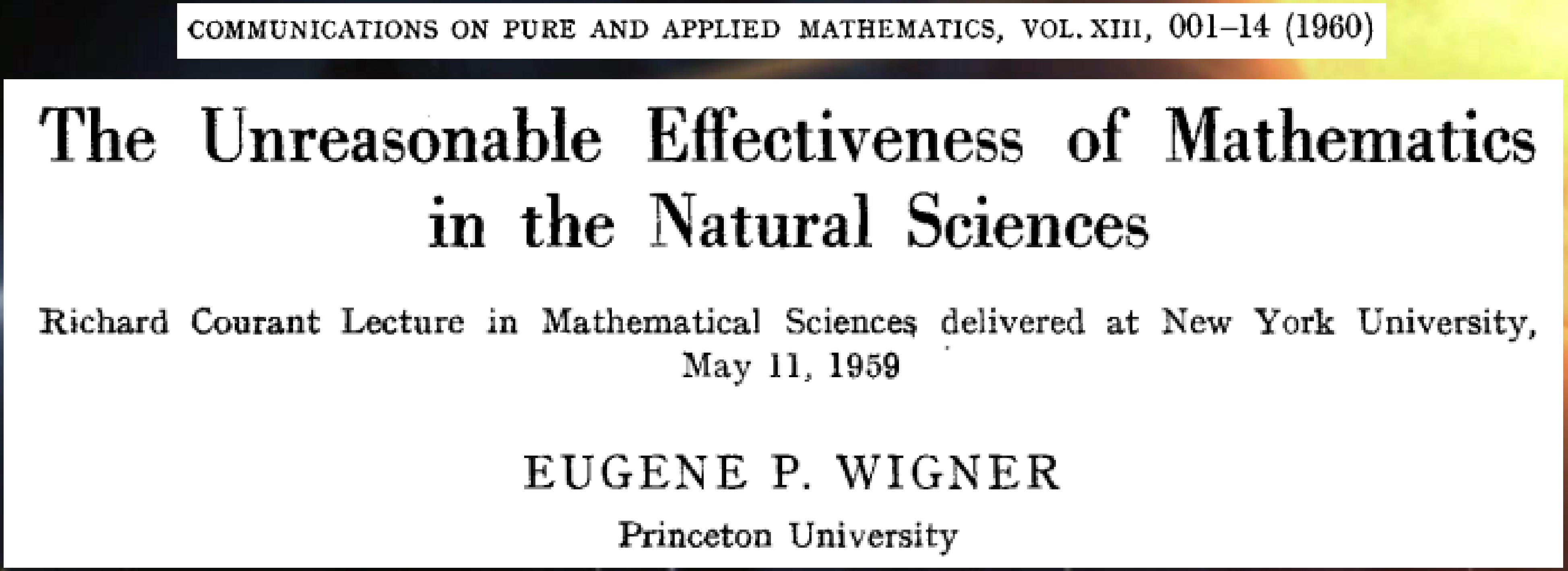


COMMUNICATIONS ON PURE AND APPLIED MATHEMATICS, VOL. XIII, 001–14 (1960)

The Unreasonable Effectiveness of Mathematics in the Natural Sciences

Richard Courant Lecture in Mathematical Sciences delivered at New York University, May 11, 1959

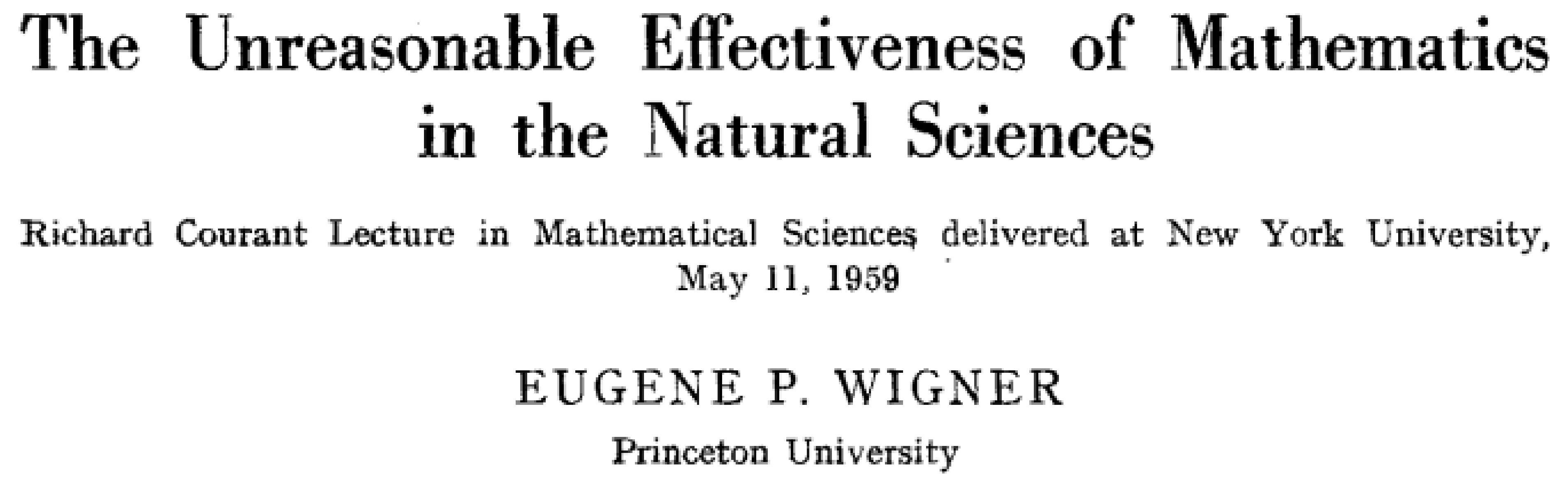
EUGENE P. WIGNER

Princeton University

The ~~unreasonable~~ effectiveness of experiments in constraining nova nucleosynthesis

due to the hard work of many people

COMMUNICATIONS ON PURE AND APPLIED MATHEMATICS, VOL. XIII, 001–14 (1960)



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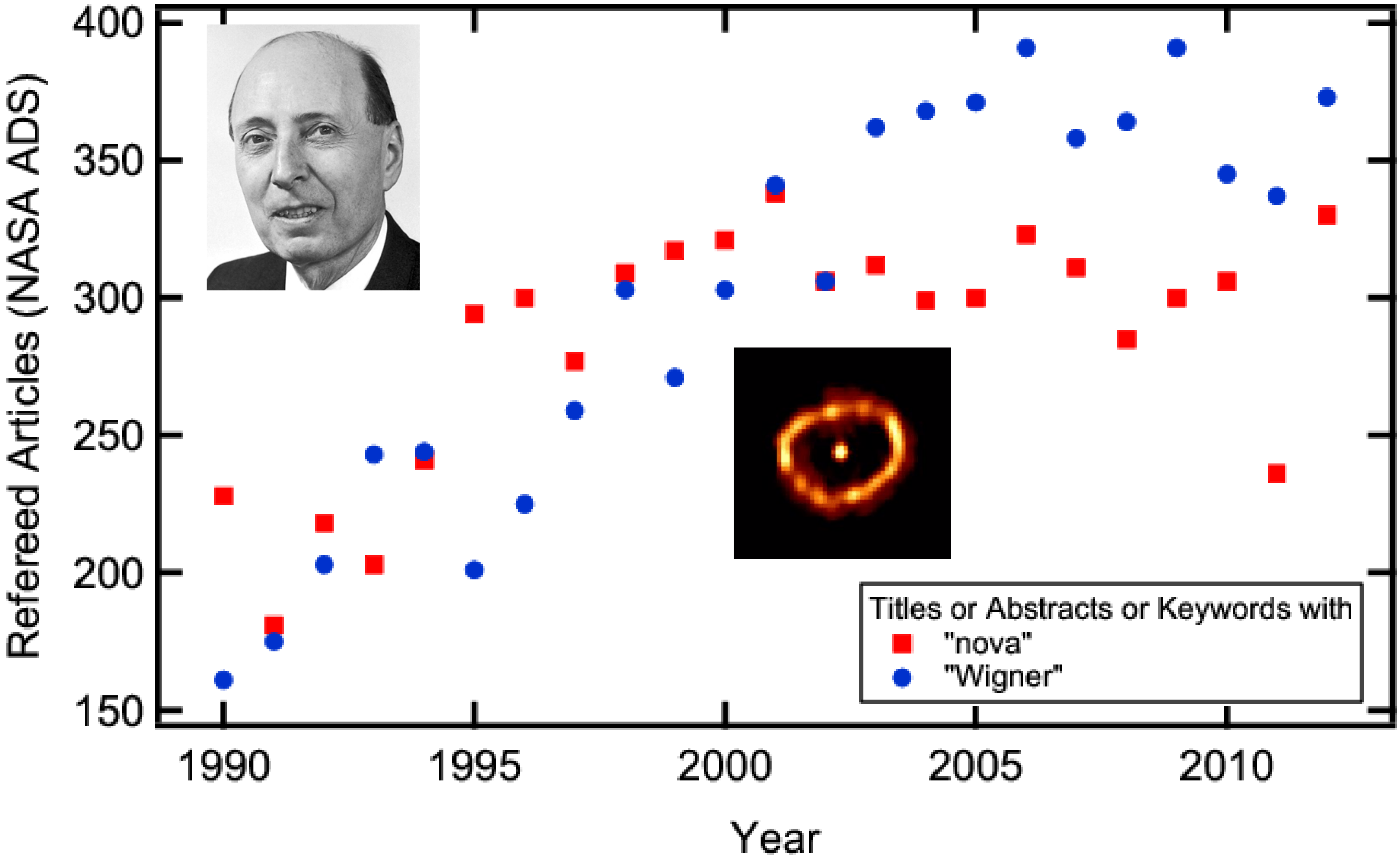
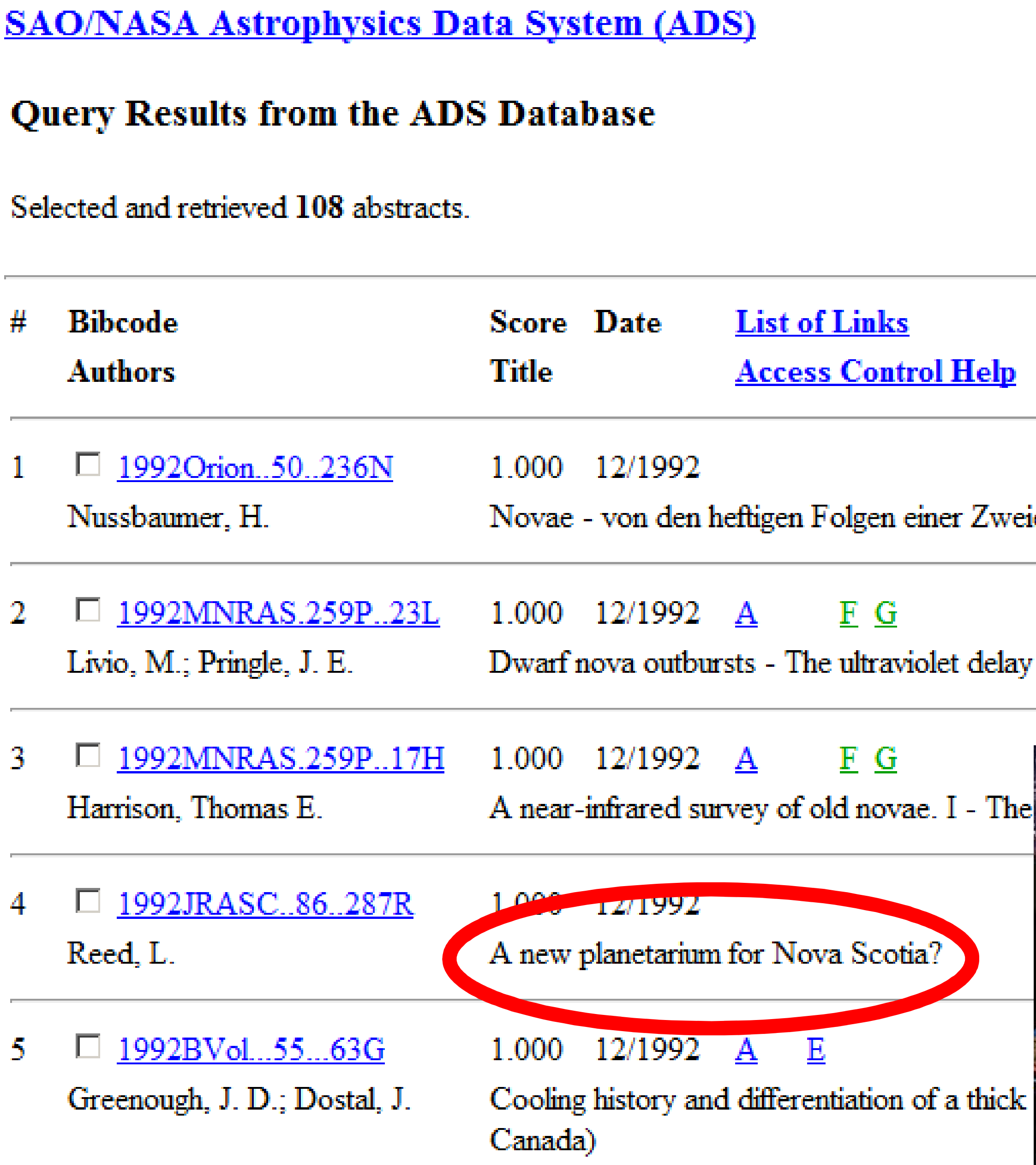
WIGNER VS A NOVA



WIGNER VS A NOVA



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3	☐ 1992MNRAS.259P..17H Harrison, Thomas E.	1.000 A near-infrared survey of old novae. I - The	12/1992	A F G
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5	☐ 1992BVol...55...63G Greenough, J. D.; Dostal, J.	1.000 Cooling history and differentiation of a thick Canada)	12/1992	A E

Classical nova explosions

REVIEWS: **"Classical Novae", eds: Bode, Evans (2008)**
José and Hernanz (2007) ...

SOME HISTORY

For ≈ 2000 y, *stellae novae* = nova + supernova

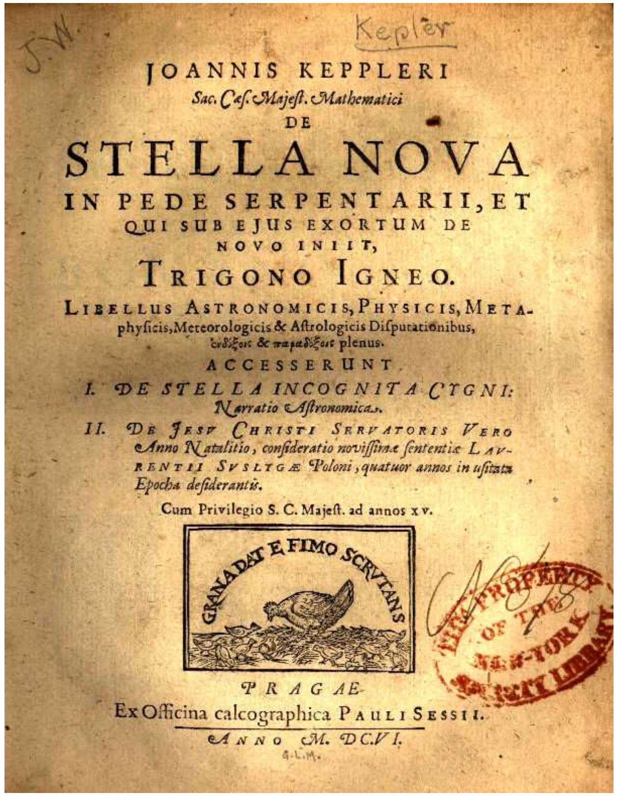
1885: Observation of a *stella nova* in the *spiral nebula* M31 (S Andromedae, Hartwig)

1920: The "Great Debate"...**distance** of the *spiral nebulae* (Curtis, Shapley)

1920s: a ≈dozen other *stellae novae* discovered in M31, **all far fainter** than that of 1885

1920s: Hubble's distance scale...*spiral nebulae* are **galaxies**!

1934: **two classes** of *stella nova*, "super-nova" for the most luminous ones (Zwicky, Baade, Lundmark)

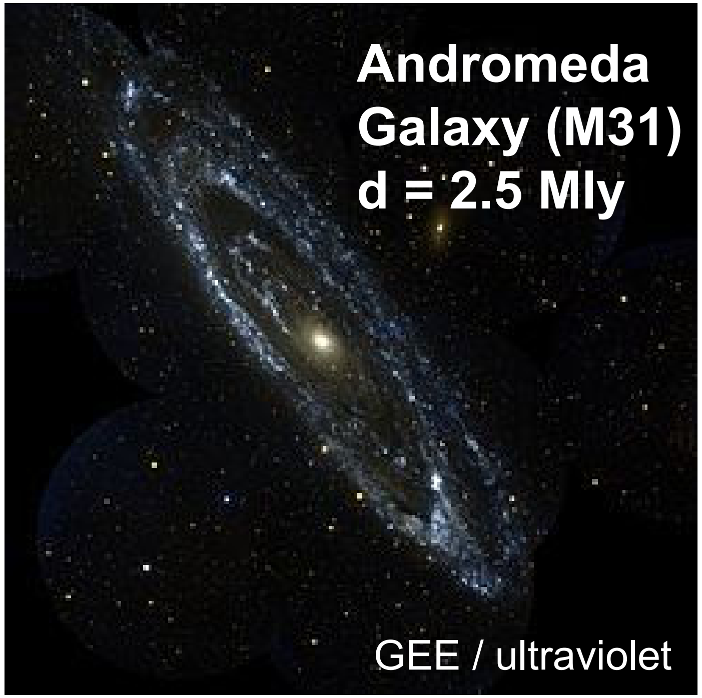


J.W.

Kepler

JOANNIS KEPPLERI
Sac. Cæſ. Majeſt. Mathematici
DE
STELLA NOVA
IN PEDE SERPENTARII, ET
QUI SUB EJUS EXORTUM DE
NOVO INIIT,
TRIGONO IGNEO.
LIBELLUS ASTRONOMICIS, PHYSICIS, META-
phyſicis, Meteorologicis & Aſtrologicis Diſputationibus,
ἐνδόξοις & παραδόξοις plenus.
ACCESSERUNT
I. *DE STELLA INCOGNITA CYGNI:*
Narratio Aſtronomica.
II. *DE JESV CHRISTI SERVATORIS VERO*
Anno Natalitio, conſideratio noviſſimæ ſententiæ LAVRENTII SVSLYGÆ Poloni, quatuor annos in uſitata Epocha deſiderantis.
Cum Privilegio S. C. Majeſt. ad annos XV.

PRAGAE
Ex Officina calcographica PAULI SESSII.
ANNO M. DCVI.
G.L.M.

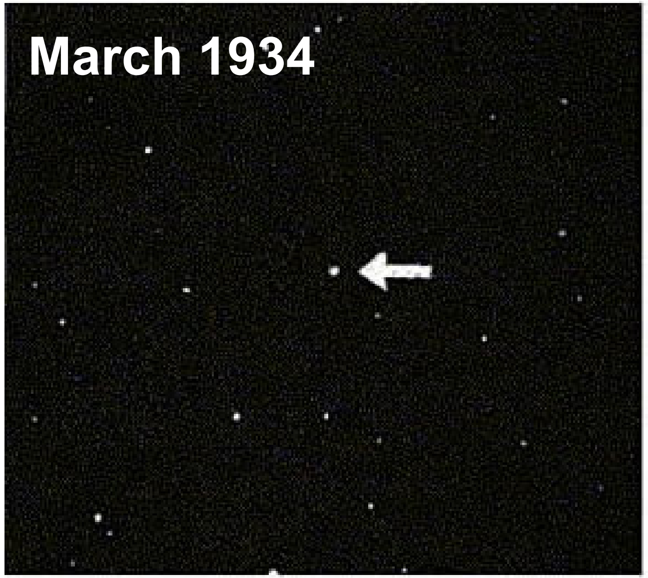


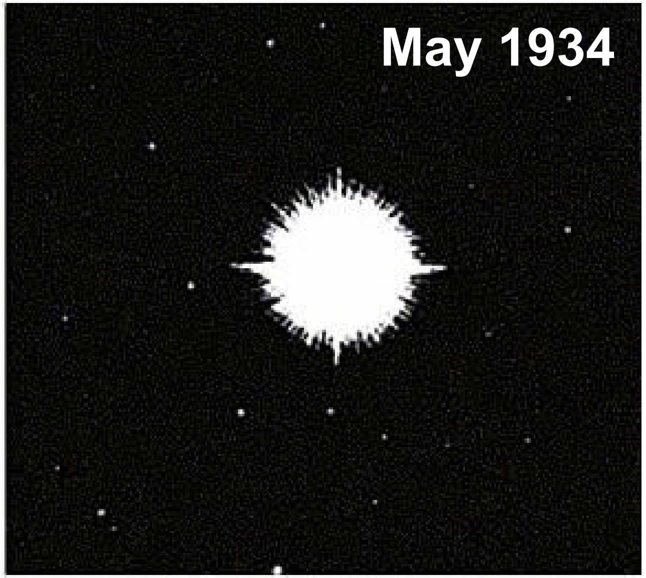
Andromeda Galaxy (M31) d = 2.5 Mly

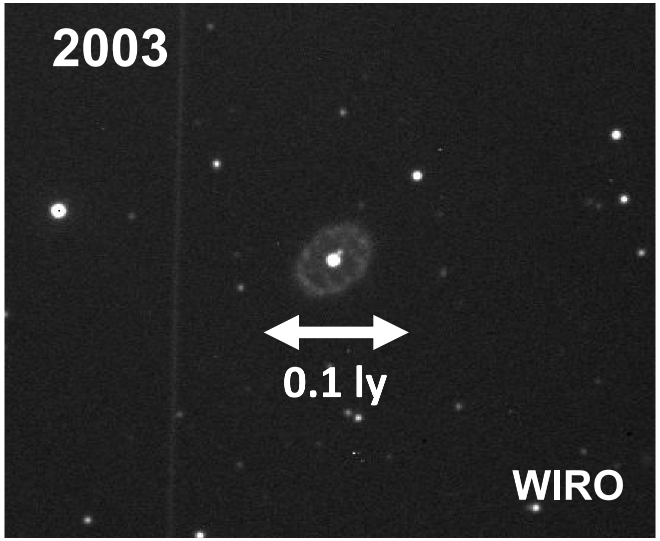
GEE / ultraviolet

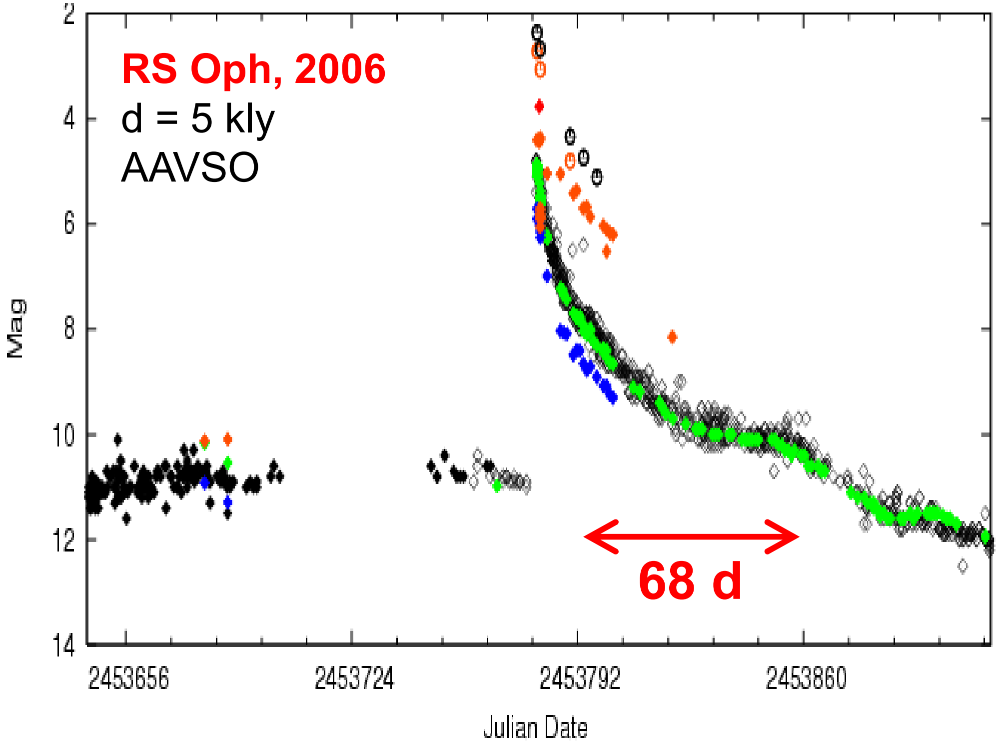
OBSERVATIONS

Nova Her 1934 (optical), d ~ 500 ly



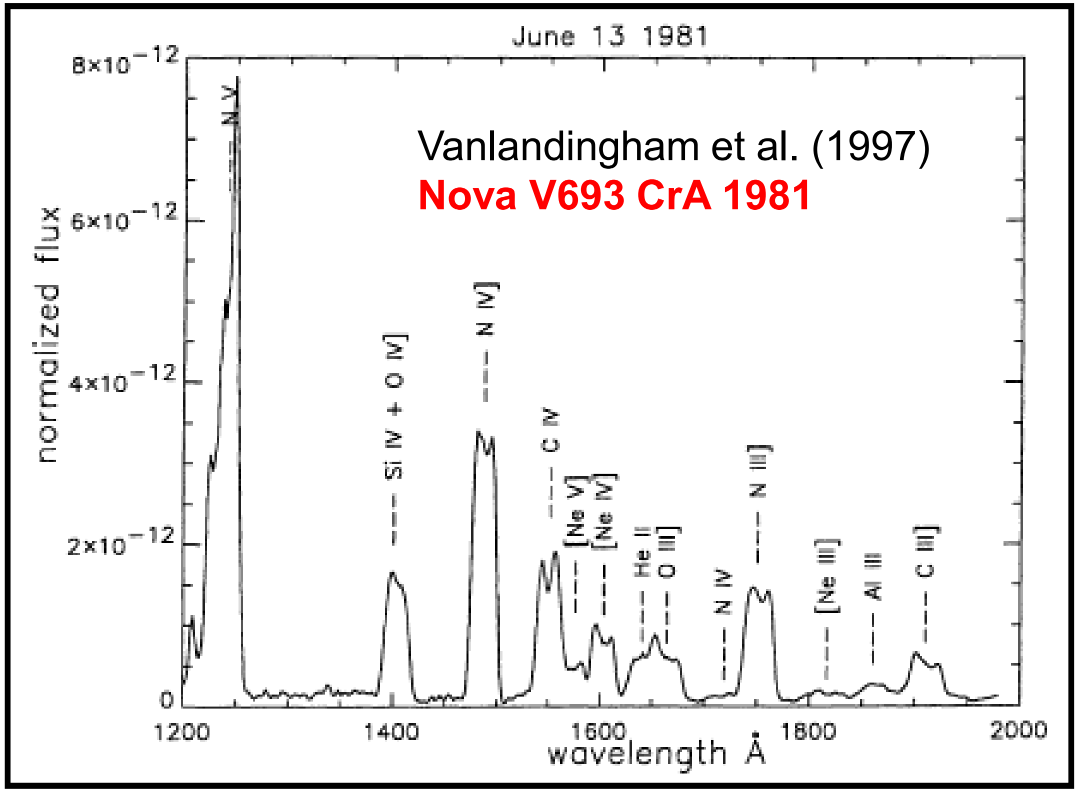






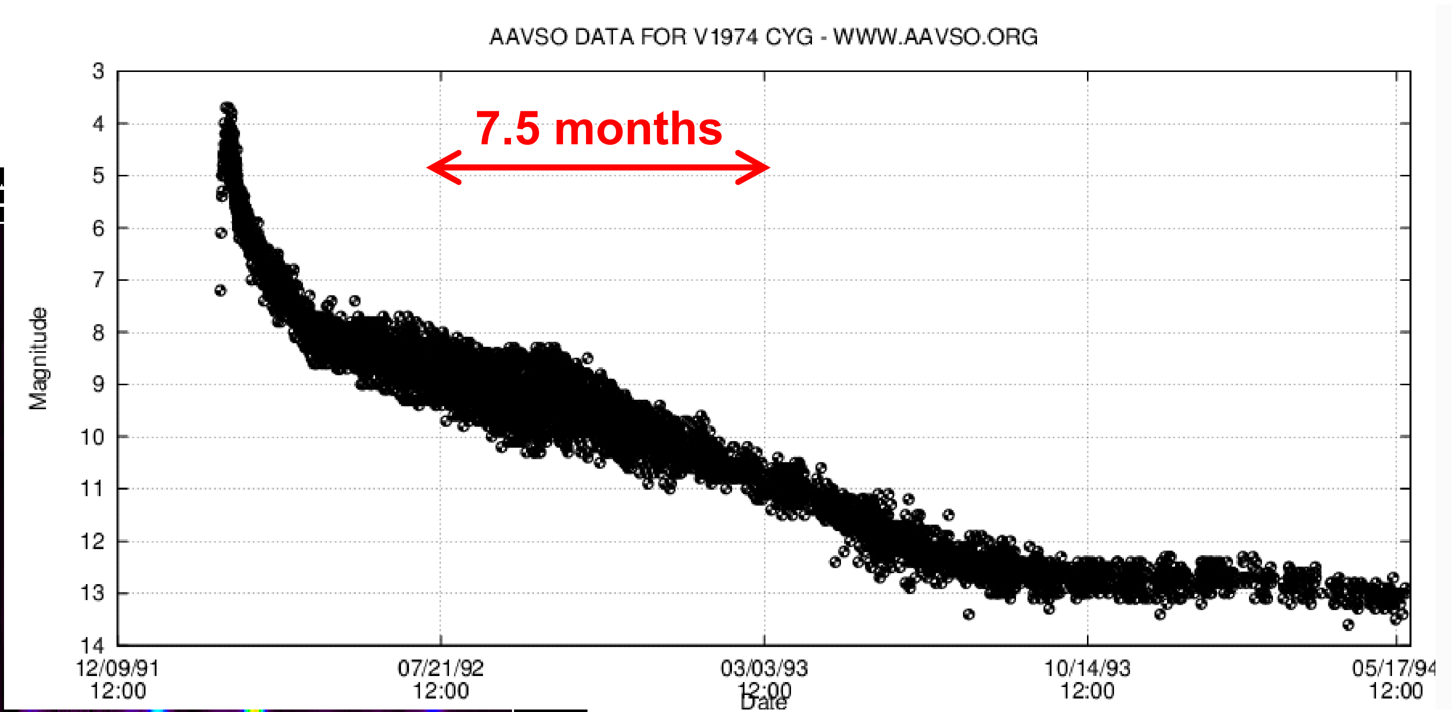
RS Oph, 2006
d = 5 kly
AAVSO

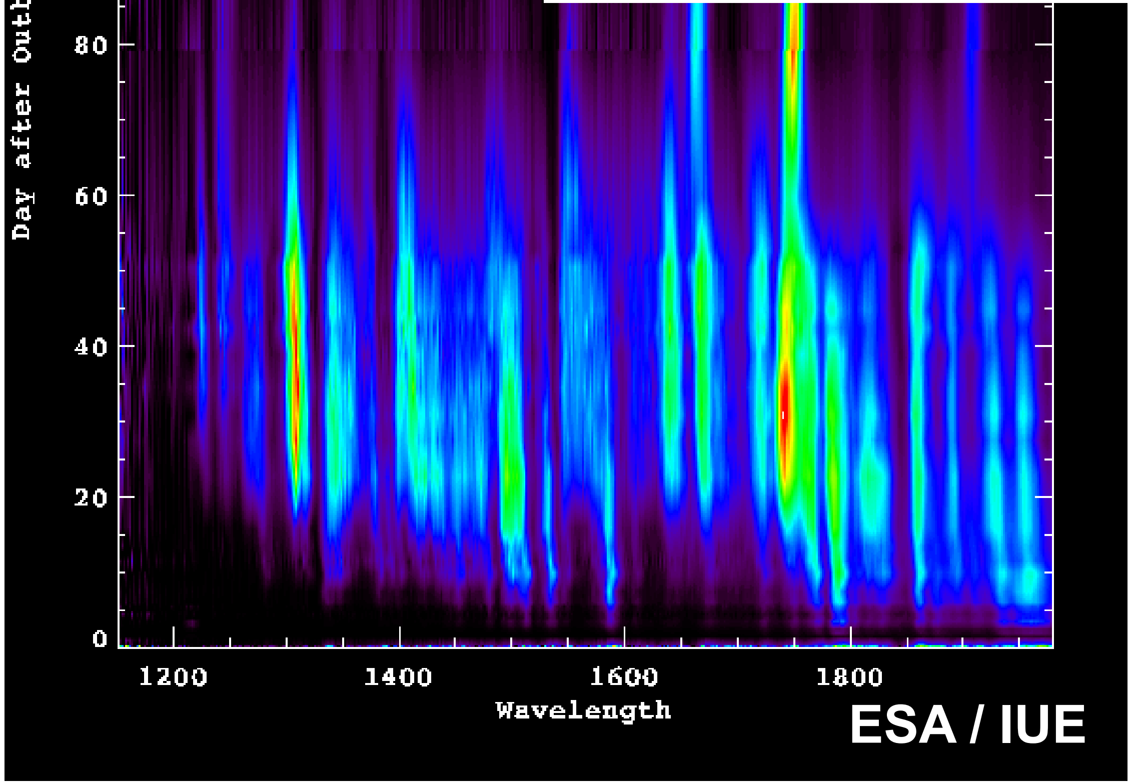
68 d



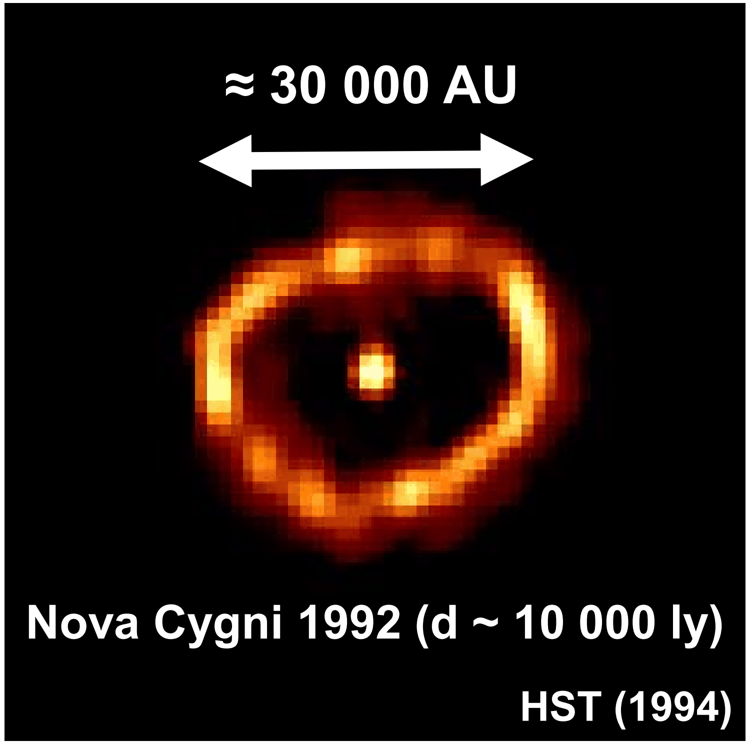
Vanlandingham et al. (1997)
Nova V693 CrA 1981

OBSERVATIONS
NOVA CYGNI 1992





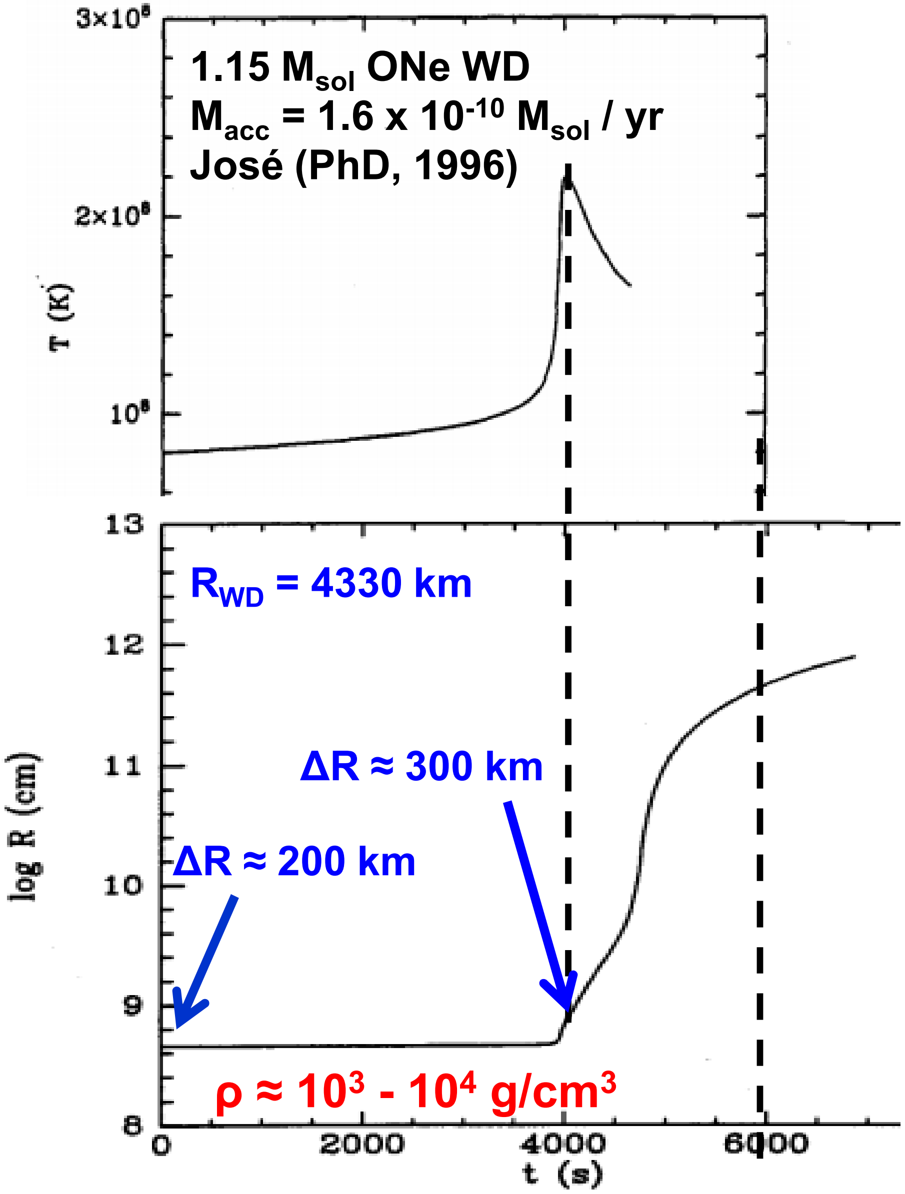
ESA / IUE



Nova Cygni 1992 (d ~ 10 000 ly)

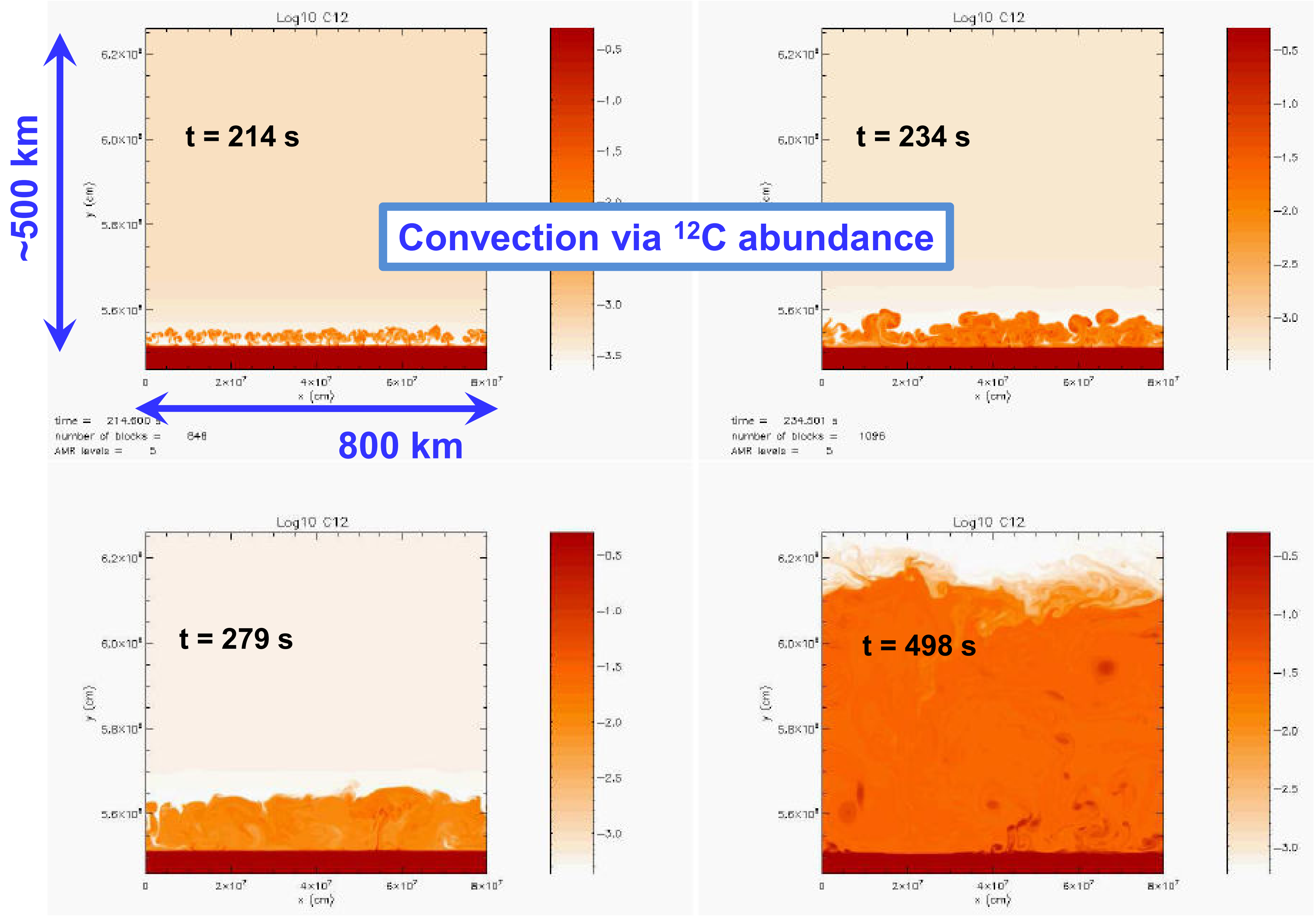
HST (1994)

MECHANISM: Unstable thermonuclear burning of accreted matter **on the surface of a white dwarf star**



- **close binary systems (1 − 12 h)**
- **accretion for ≈ 10^5 years***
- **envelope is *degenerate***
- **from few x 10^7 K to T_{peak} ≈ 10 − 100 days**
- **outburst is confined to the envelope**

MECHANISM: Unstable thermonuclear burning of accreted matter **on the surface of a white dwarf star**



Casanova et al. (2010, 2011)

MECHANISM: Unstable thermonuclear burning of accreted matter **on the surface of a white dwarf star**

FIRST MODELS:

Schatzmann 1950, 1951; Cameron 1959; Rose 1968; Starrfield 1971 (**the need for CNO enhancement**); ...

LATER:

Parameterized/one-zone models: Hillebrandt and Thielemann 1982; Wiescher et al. 1986; Weiss and Truran 1990; ...

1-D hydrodynamic models: Prialnik and Kovetz 1995; Starrfield et al. 1998; Jose and Hernanz 1998; Paxton et al. 2011 ...

Multidimensional models (limited): Shara 1982, Fryxell and Woosley 1982, Shankar et al. 1992, Glasner and Livne 1995, Kercek et al. 1998, Kercek et al. 1999 (3D), Glasner et al. 2005, Glasner et al. 2007, Casanova et al. 2010, Casanova et al. 2011 (3D)

KEY variables: M_{WD}, M_{acc}, Z_{acc}, $L_{initial}$, mixing

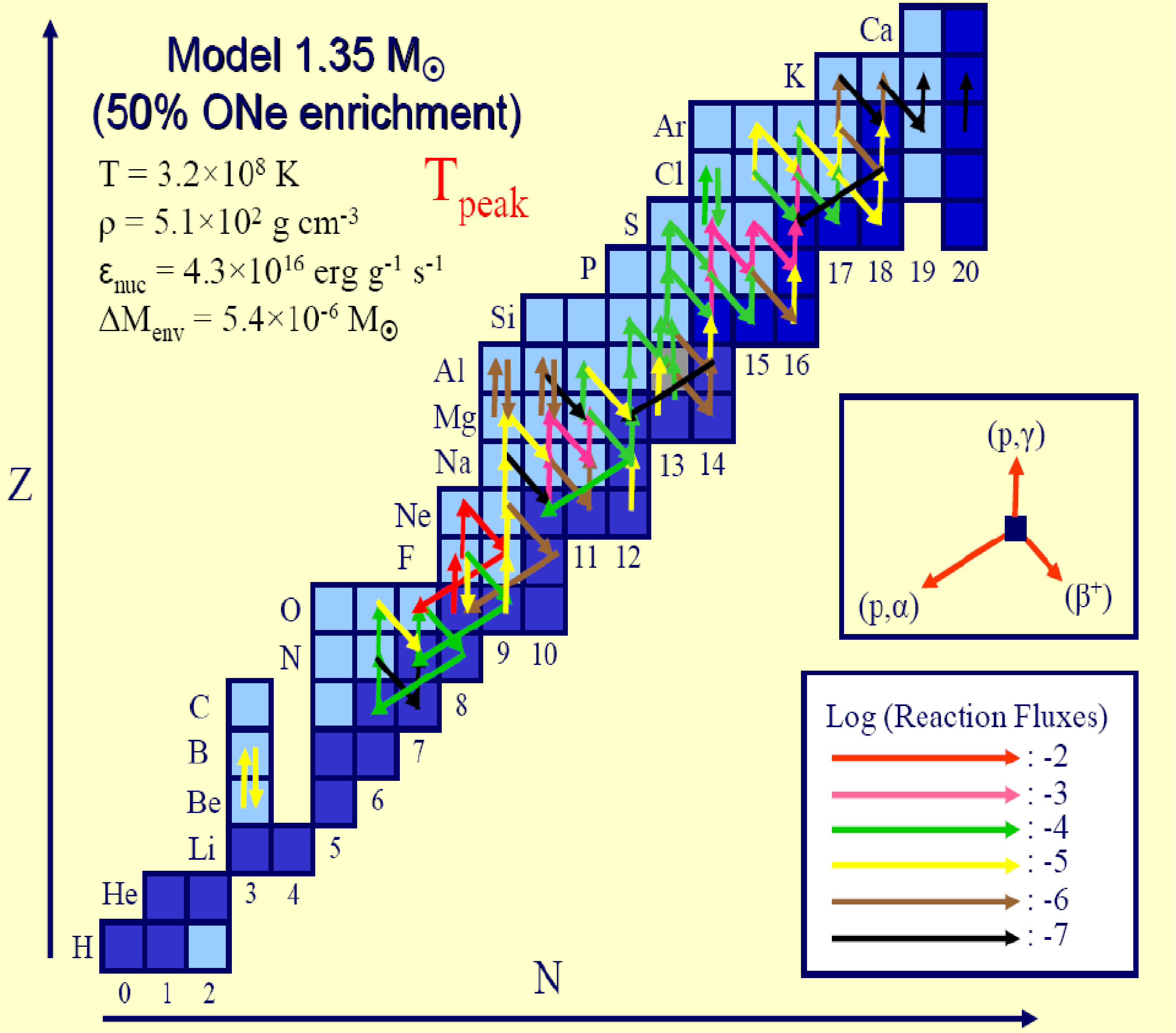
NUCLEOSYNTHESIS:

MultiD models: limited in scope, networks ≤ 15 isotopes

Still need to rely on 1D hydro models for detailed nucleosynthesis calculations

MODELS → *for nucleosynthesis* – *1D hydrodynamic*

→ **reaction networks: ≈ 100 species, H – Ca**



José, Casanova, Moreno, García-Berro, AP, and Iliadis (2010)

MODELS

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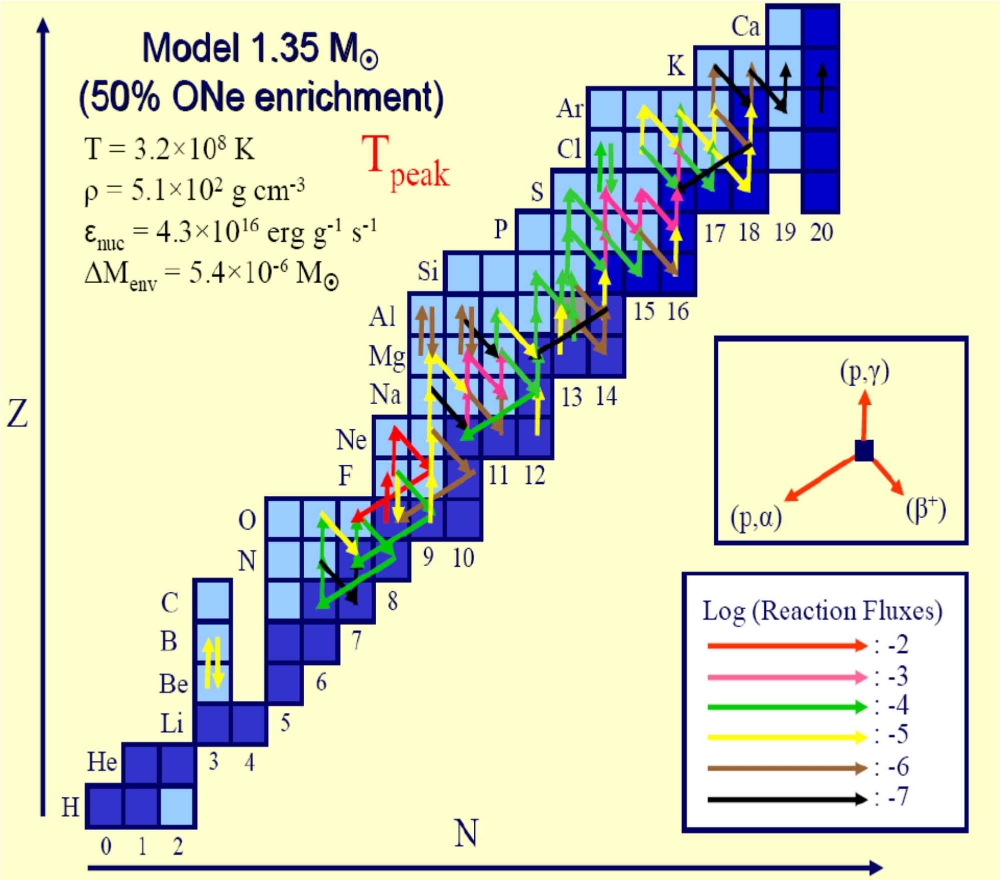

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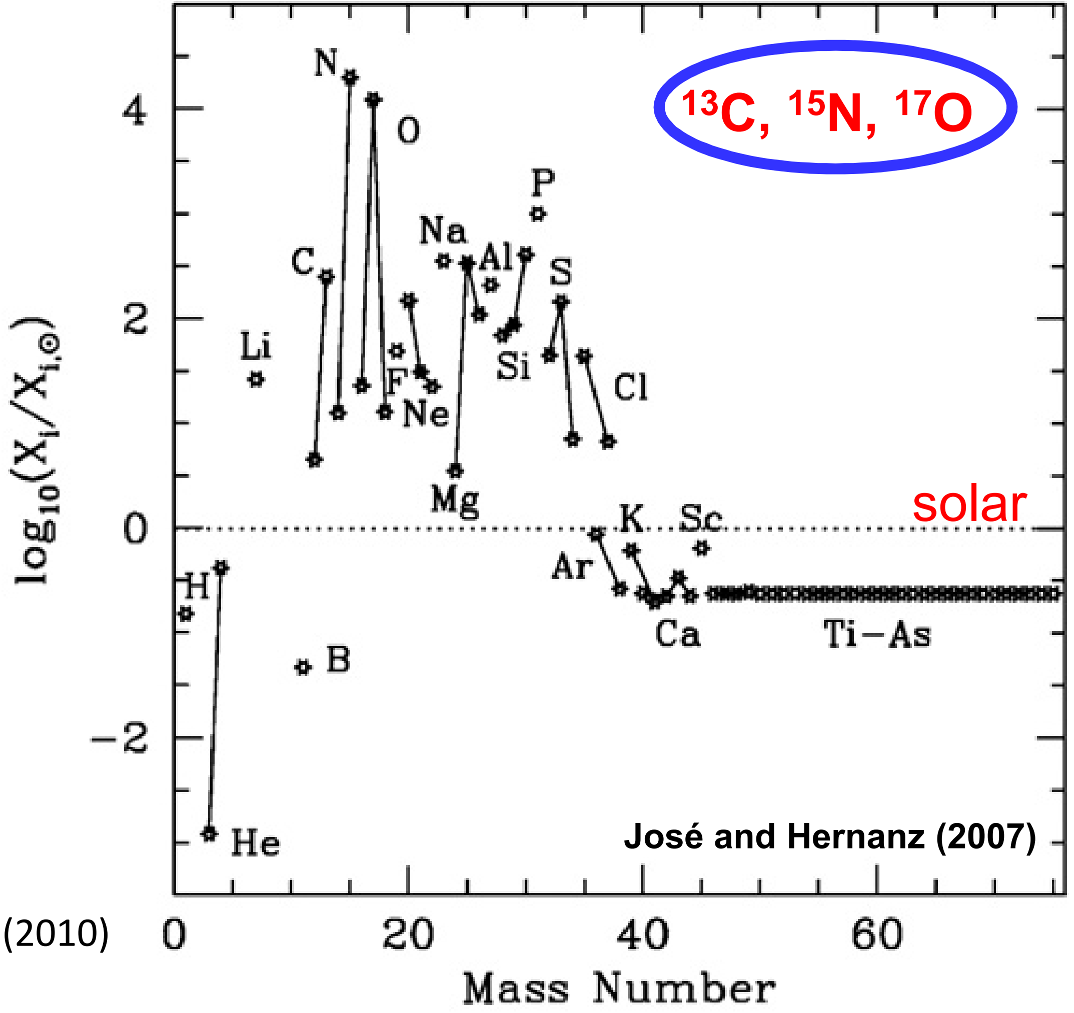


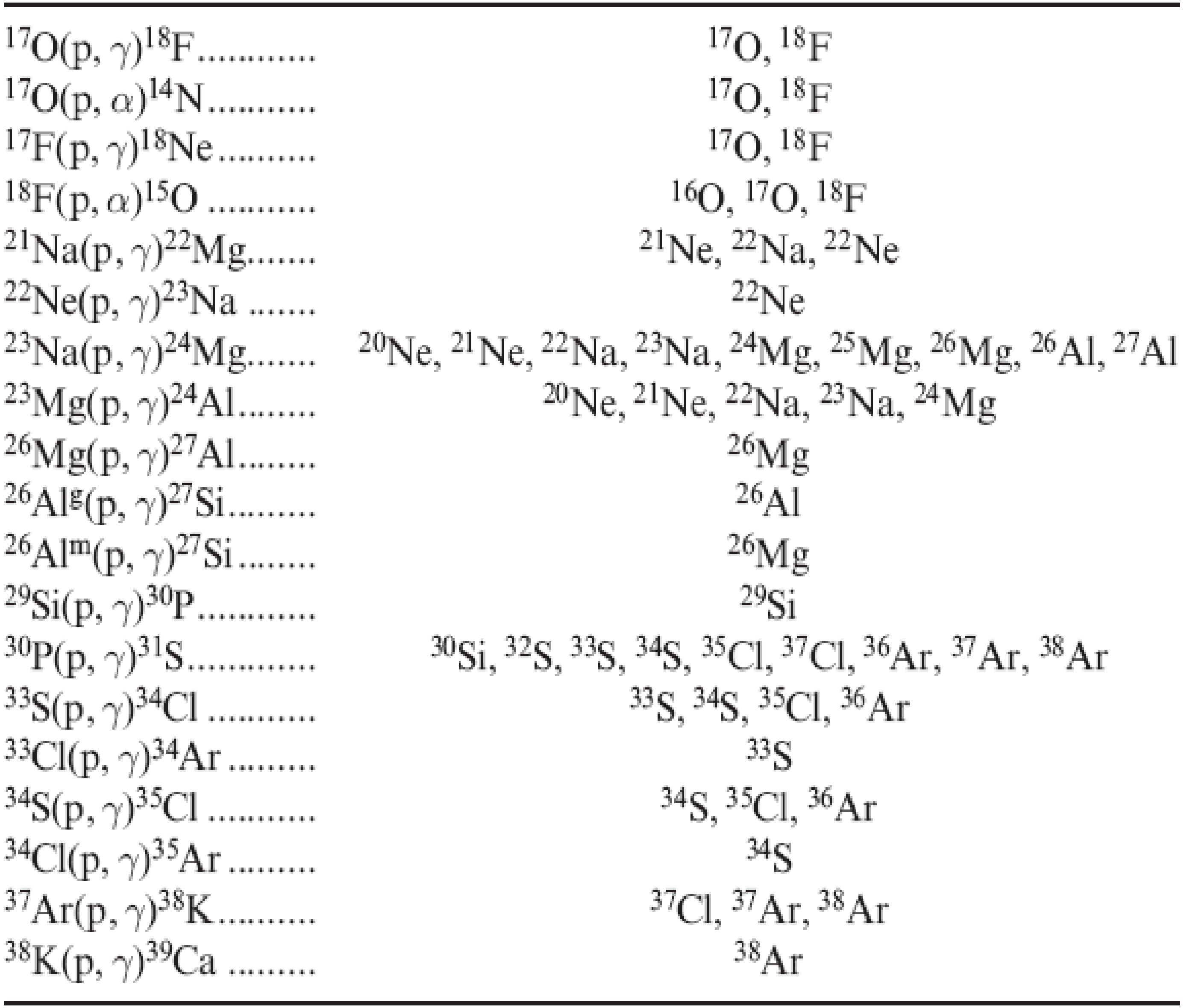
José and Hernanz (2007)

How reliable are these nucleosynthesis predictions?

NUCLEAR PHYSICS

Nova sensitivity study (Iliadis et al. (2002)) :

- input from **5 different** hydrodynamic nova simulations
- Variation of **each** of 175 reaction rates within errors



^{17}O(p, γ)^{18}F............	^{17}O, ^{18}F
^{17}O(p, α)^{14}N...........	^{17}O, ^{18}F
^{17}F(p, γ)^{18}Ne..........	^{17}O, ^{18}F
^{18}F(p, α)^{15}O	^{16}O, ^{17}O, ^{18}F
^{21}Na(p, γ)^{22}Mg.......	^{21}Ne, ^{22}Na, ^{22}Ne
^{22}Ne(p, γ)^{23}Na	^{22}Ne
^{23}Na(p, γ)^{24}Mg.......	^{20}Ne, ^{21}Ne, ^{22}Na, ^{23}Na, ^{24}Mg, ^{25}Mg, ^{26}Mg, ^{26}Al, ^{27}Al
^{23}Mg(p, γ)^{24}Al........	^{20}Ne, ^{21}Ne, ^{22}Na, ^{23}Na, ^{24}Mg
^{26}Mg(p, γ)^{27}Al........	^{26}Mg
^{26}Al^{g}(p, γ)^{27}Si.........	^{26}Al
^{26}Al^{m}(p, γ)^{27}Si	^{26}Mg
^{29}Si(p, γ)^{30}P............	^{29}Si
^{30}P(p, γ)^{31}S.............	^{30}Si, ^{32}S, ^{33}S, ^{34}S, ^{35}Cl, ^{37}Cl, ^{36}Ar, ^{37}Ar, ^{38}Ar
^{33}S(p, γ)^{34}Cl	^{33}S, ^{34}S, ^{35}Cl, ^{36}Ar
^{33}Cl(p, γ)^{34}Ar	^{33}S
^{34}S(p, γ)^{35}Cl	^{34}S, ^{35}Cl, ^{36}Ar
^{34}Cl(p, γ)^{35}Ar	^{34}S
^{37}Ar(p, γ)^{38}K..........	^{37}Cl, ^{37}Ar, ^{38}Ar
^{38}K(p, γ)^{39}Ca	^{38}Ar

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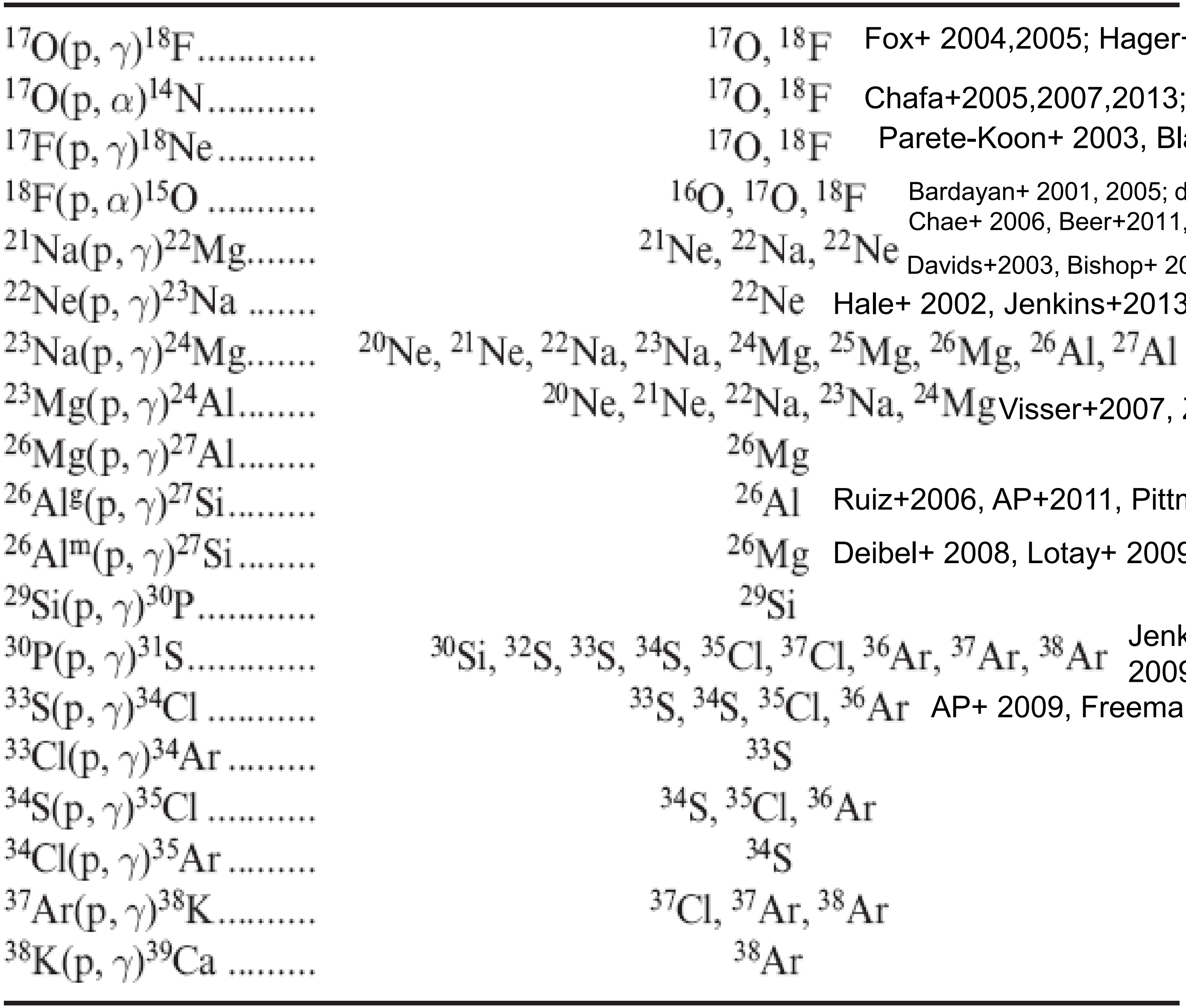


$^{17}O(p,\gamma)^{18}F$...........	^{17}O, ^{18}F	Fox+ 2004,2005; Hager+2012, Kontos+2012, LUNA
$^{17}O(p,\alpha)^{14}N$...........	^{17}O, ^{18}F	Chafa+2005,2007,2013; Sergi+2013, LUNA
$^{17}F(p,\gamma)^{18}Ne$..........	^{17}O, ^{18}F	Parete-Koon+ 2003, Blacknom+2003, Dufour+2004
$^{18}F(p,\alpha)^{15}O$	^{16}O, ^{17}O, ^{18}F	Bardayan+ 2001, 2005; de Sereville+ 2003, 2005, 2007; Kozub+ 2005, Chae+ 2006, Beer+2011, Adekola+2011, Mountford+2012, Laird+2013
$^{21}Na(p,\gamma)^{22}Mg$.......	^{21}Ne, ^{22}Na, ^{22}Ne	Davids+2003, Bishop+ 2003, D'Auria+ 2004, Seweryniak+2005, Liu+2007
$^{22}Ne(p,\gamma)^{23}Na$	^{22}Ne	Hale+ 2002, Jenkins+2013
$^{23}Na(p,\gamma)^{24}Mg$.......	^{20}Ne, ^{21}Ne, ^{22}Na, ^{23}Na, ^{24}Mg, ^{25}Mg, ^{26}Mg, ^{26}Al, ^{27}Al	Rowland+2004, Hale+2004
$^{23}Mg(p,\gamma)^{24}Al$........	^{20}Ne, ^{21}Ne, ^{22}Na, ^{23}Na, ^{24}Mg	Visser+2007, Zegers+ 2008, Lotay+ 2008
$^{26}Mg(p,\gamma)^{27}Al$........	^{26}Mg	
$^{26}Al^{g}(p,\gamma)^{27}Si$.........	^{26}Al	Ruiz+2006, AP+2011, Pittman+2012
$^{26}Al^{m}(p,\gamma)^{27}Si$........	^{26}Mg	Deibel+ 2008, Lotay+ 2009, 2011
$^{29}Si(p,\gamma)^{30}P$............	^{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	Jenkins+2006, Ma+2007, Wrede+2007, 2009. AP+2011, Dohery+2012, Irvine+2013
$^{33}S(p,\gamma)^{34}Cl$	^{33}S, ^{34}S, ^{35}Cl, ^{36}Ar	AP+ 2009, Freeman+ 2011, Fallis+2013
$^{33}Cl(p,\gamma)^{34}Ar$	^{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	

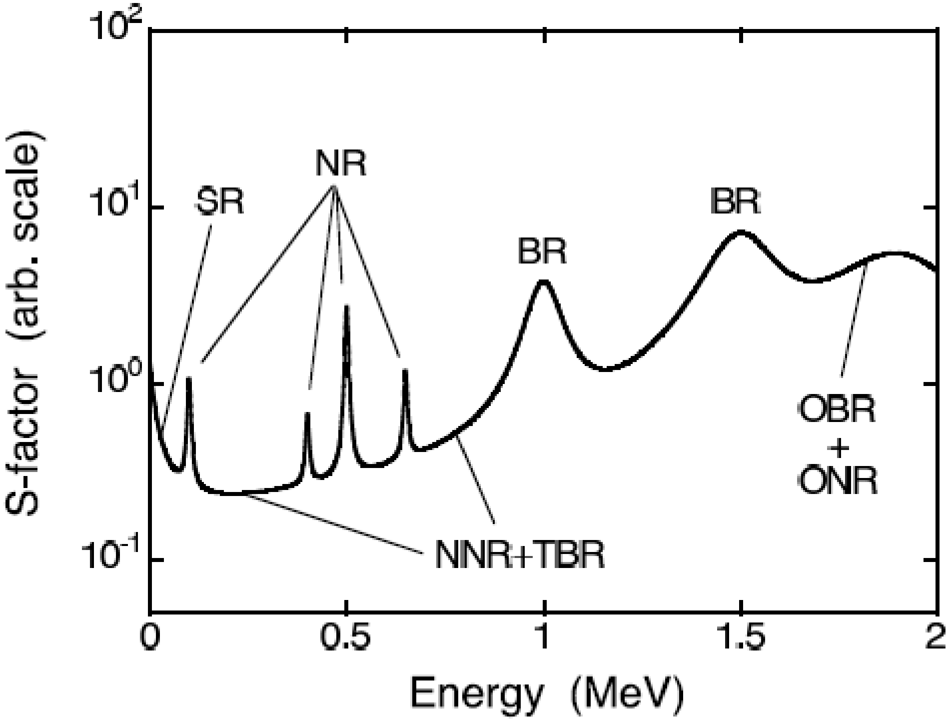
How are these thermonuclear rates determined?

Reaction rate per particle pair at some temperature T

$$N_A\langle\sigma v\rangle = \left(\frac{8}{\pi m_{01}}\right)^{1/2}\frac{N_A}{(kT)^{3/2}}\int_0^\infty E\,\sigma(E)\,e^{-E/kT}\,dE$$

So...."just" measure σ(E) (or estimate it from theory) and solve!

For reactions involved in novae, the cross-section is often dominated by a few contributions from narrow resonances



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$$\sigma_{\mathrm{BW}}(E) = \frac{\lambda^2}{4\pi}\frac{(2J+1)(1+\delta_{01})}{(2j_0+1)(2j_1+1)}\frac{\Gamma_a\Gamma_b}{(E_r-E)^2+\Gamma^2/4}$$

An isolated resonance can be described by the Breit-Wigner formula

How are these thermonuclear rates determined?

Reaction rate per particle pair at some temperature T

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$$N_A\langle\sigma v\rangle = N_A\left(\frac{2\pi}{m_{01}kT}\right)^{3/2}\hbar^2 e^{-E_r/kT}\omega\gamma$$

An isolated resonance can be described by the Breit-Wigner formula

$$\omega\gamma = \frac{2J+1}{(2J_t+1)(2J_p+1)}\frac{\Gamma_p\Gamma_\gamma}{\Gamma}.$$

How are these thermonuclear rates determined?

For these cases, the problem may be reduced to determining the parameters of resonances

$$<\sigma\upsilon>=\left(\frac{2\pi}{\mu kT}\right)^{3/2}\hbar^2\sum_i(\omega\gamma)_i\exp\left(\frac{-(E_{R,i}^{CM})}{kT}\right)$$

$$\omega\gamma=\frac{\boxed{2J+}1}{(2J_t+1)(2J_p+1)}\boxed{\frac{\Gamma_p\Gamma_\gamma}{\Gamma}}.$$

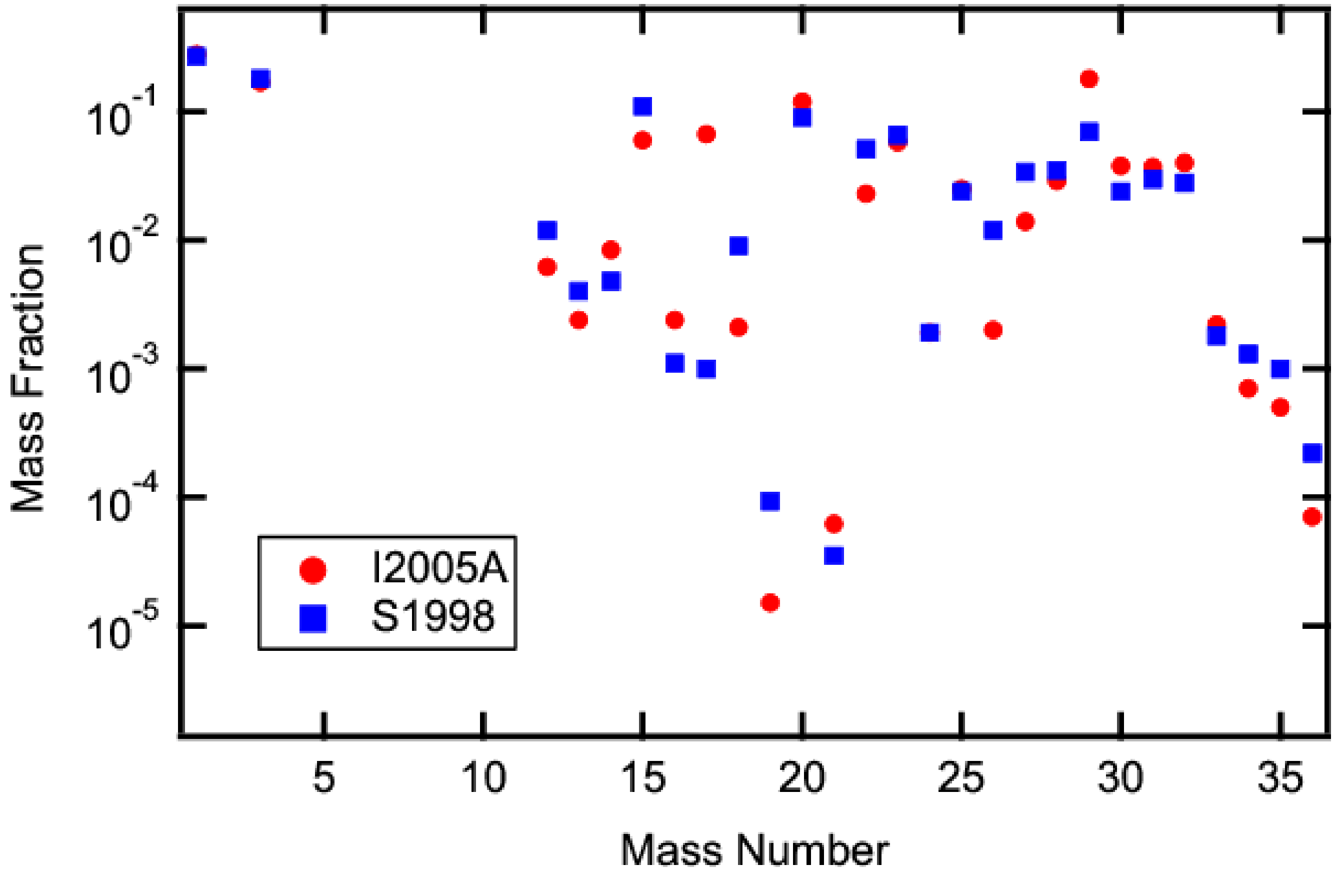
$$\Gamma_p=\frac{2\hbar^2}{\mu a^2}P_l\boxed{C^2S}\theta^2_{s.p.}$$

These may be determined through indirect measurements (stable beams/targets, high cross-sections)

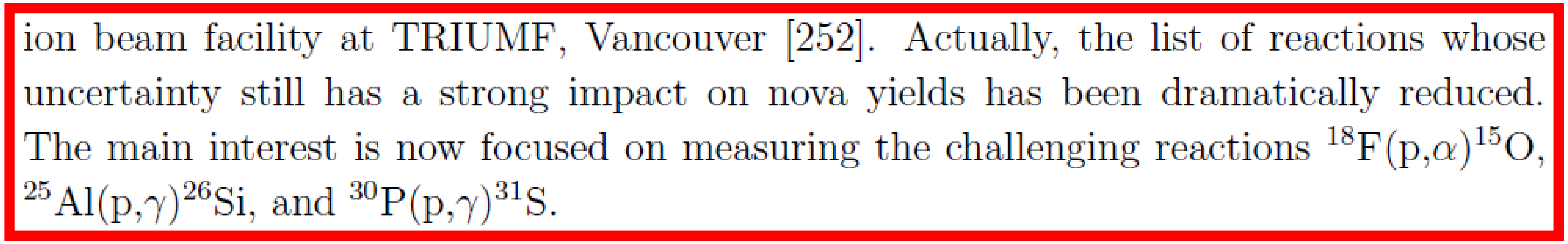
NUCLEAR PHYSICS

MOST nuclear reaction rates involved in standard models of classical nova explosions are sufficiently well-constrained.

Effect of an updated reaction network on nucleosynthesis predictions



With data from Starfield+ (2009) 1D hydro models



ion beam facility at TRIUMF, Vancouver [252]. Actually, the list of reactions whose uncertainty still has a strong impact on nova yields has been dramatically reduced. The main interest is now focused on measuring the challenging reactions $^{18}F(p,\alpha)^{15}O$, $^{25}Al(p,\gamma)^{26}Si$, and $^{30}P(p,\gamma)^{31}S$.

José and Iliadis (2011)

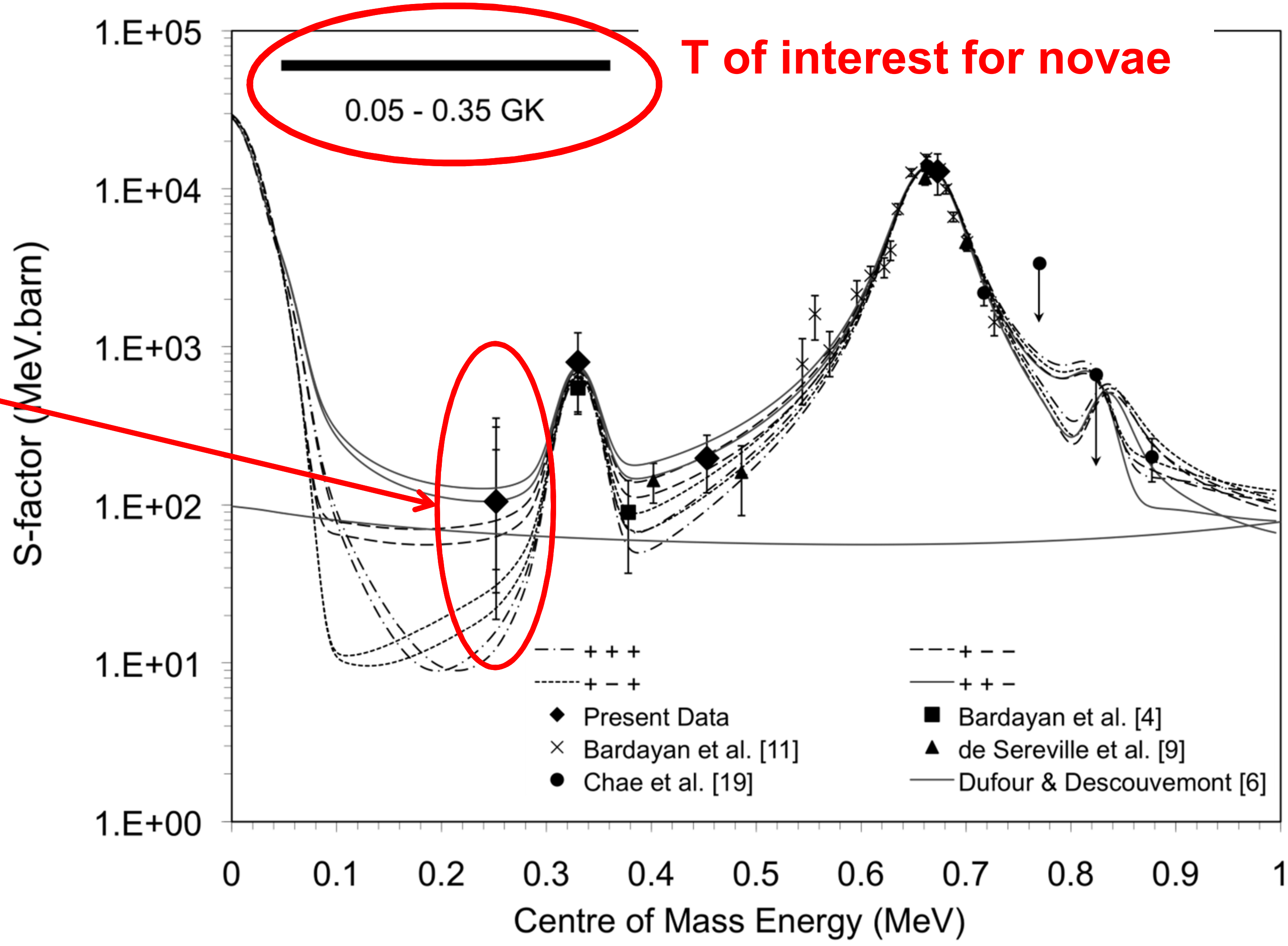
$^{18}F(p,\alpha)^{15}O$

Direct (recent): Chae+ 2006, de Sereville+ 2009, Murphy+ 2009, Beer+ 2011
Indirect (recent): Dalouzy+ 2009, Adekola+ 2011a, 2011b, 2012, Laird+ 2013

DIRECT:

Beer+ (2011)
TRIUMF
$5x10^6$ pps

2 counts in 5 days

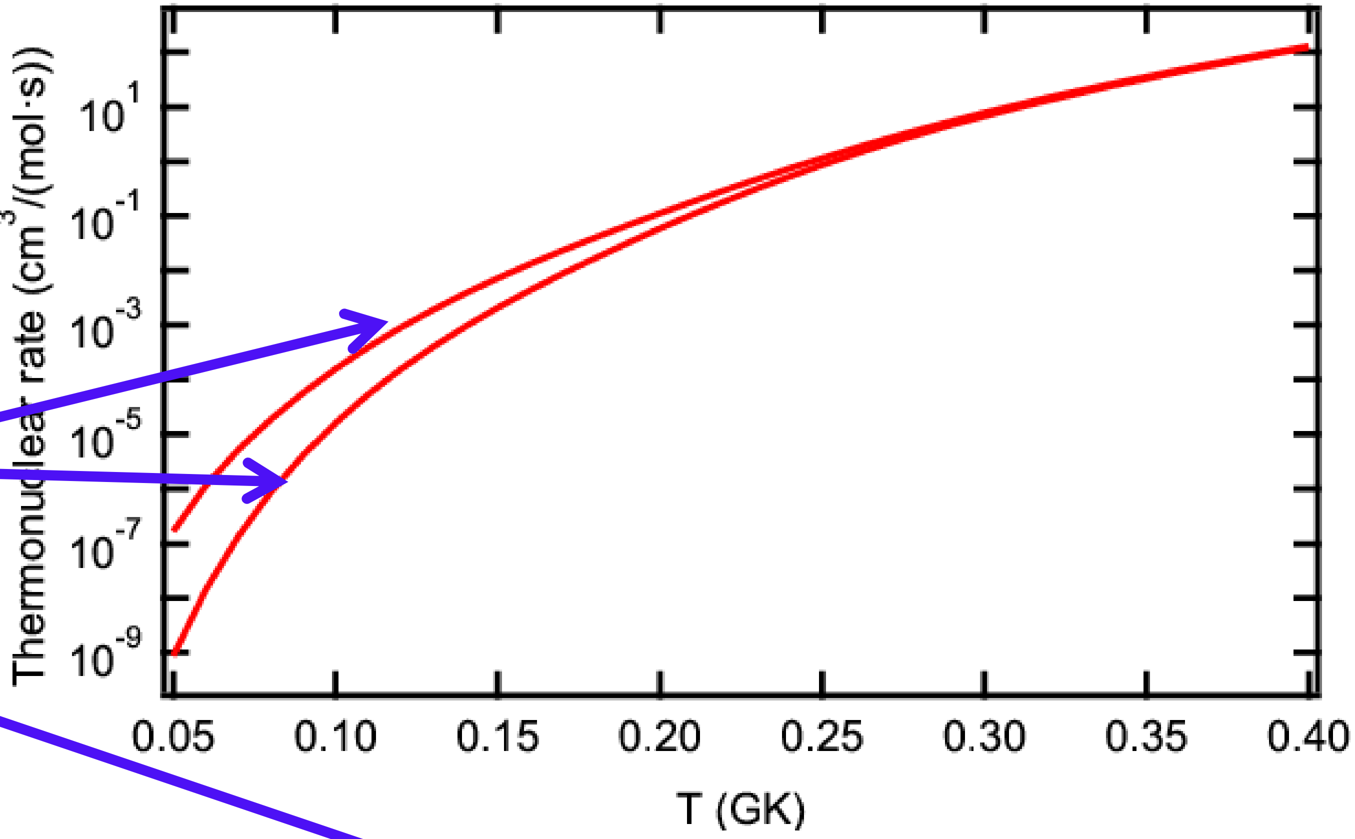


T of interest for novae

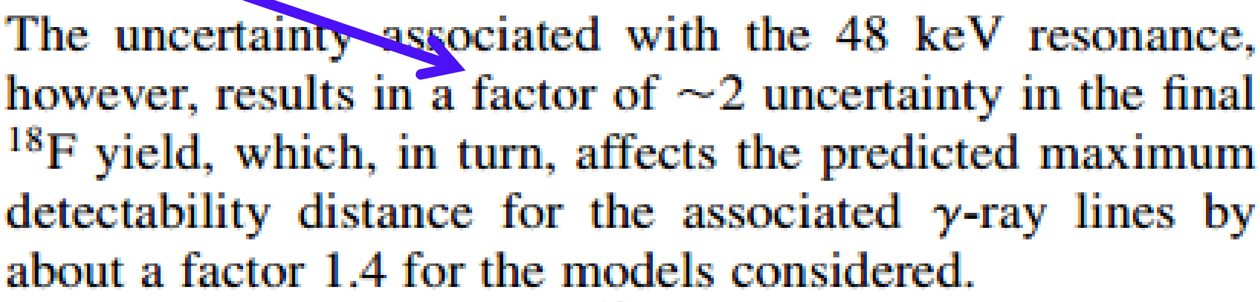
$^{18}F(p,\alpha)^{15}O$

Direct (recent): Chae+ 2006, de Sereville+ 2009, Murphy+ 2009, Beer+ 2011
Indirect (recent): Dalouzy+ 2009, Adekola+ 2011a, 2011b, 2012, Laird+ 2013

Laird, AP++ (2013)
experimental rate
varied within
uncertainties



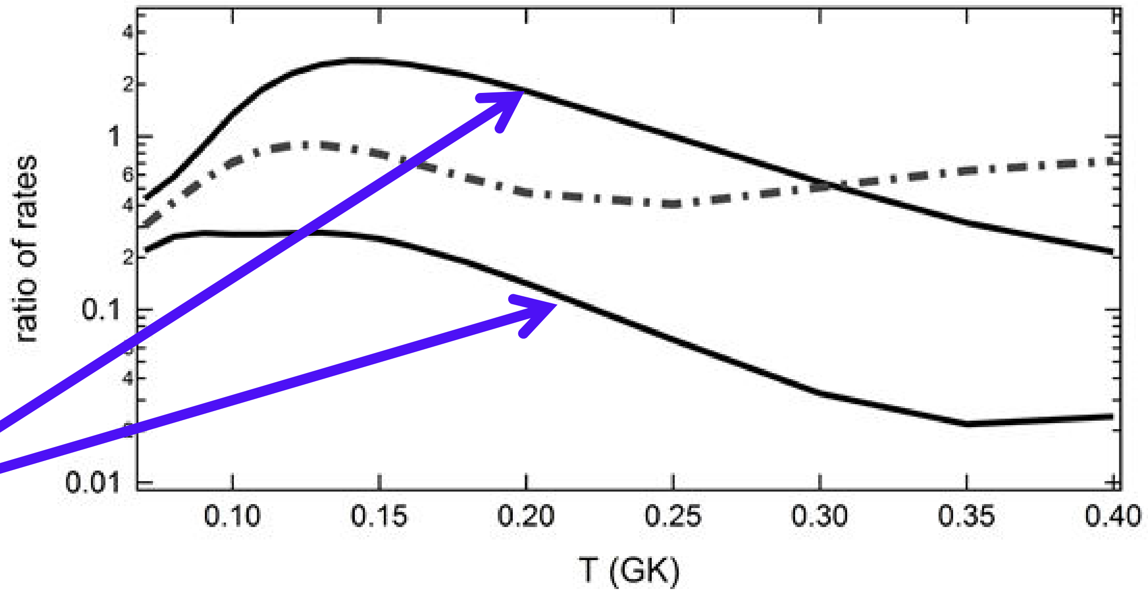
1D hydro nova model


The uncertainty associated with the 48 keV resonance, however, results in a factor of ~2 uncertainty in the final ^{18}F yield, which, in turn, affects the predicted maximum detectability distance for the associated γ-ray lines by about a factor 1.4 for the models considered.

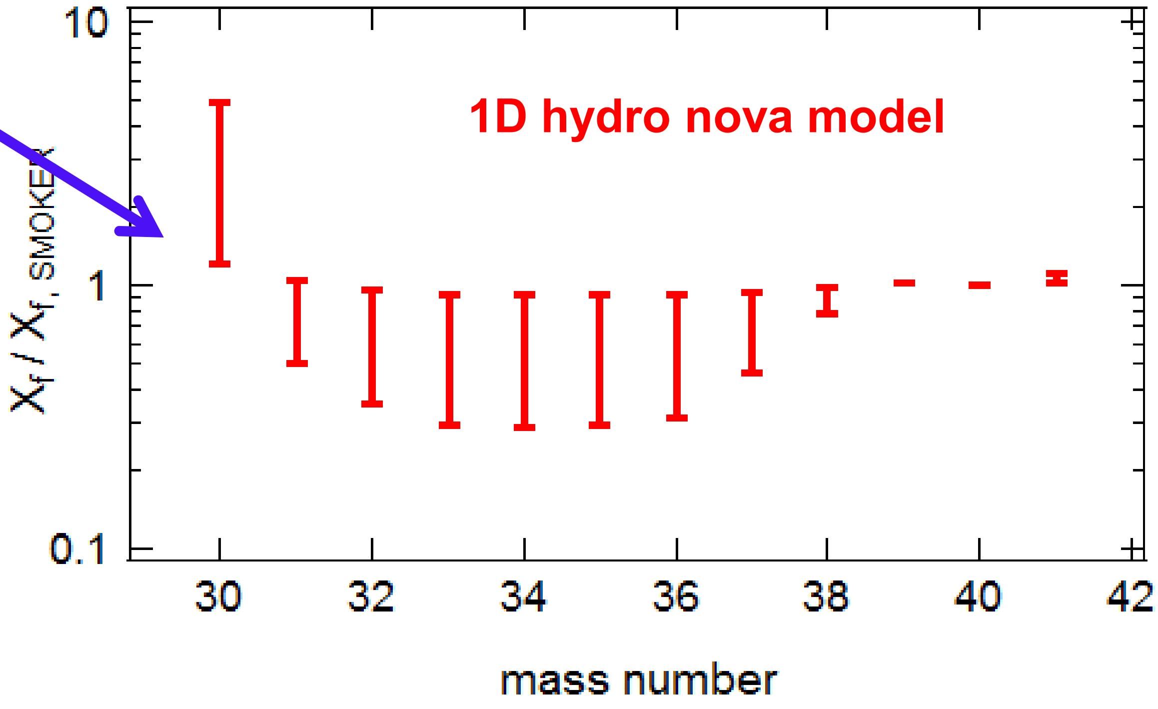
γ-ray emission from novae may initially be dominated by contributions from e+-e- following $^{18}F(\beta+)$ ($t_{1/2}$ = 110 m)

$^{30}P(p,\gamma)^{31}S$

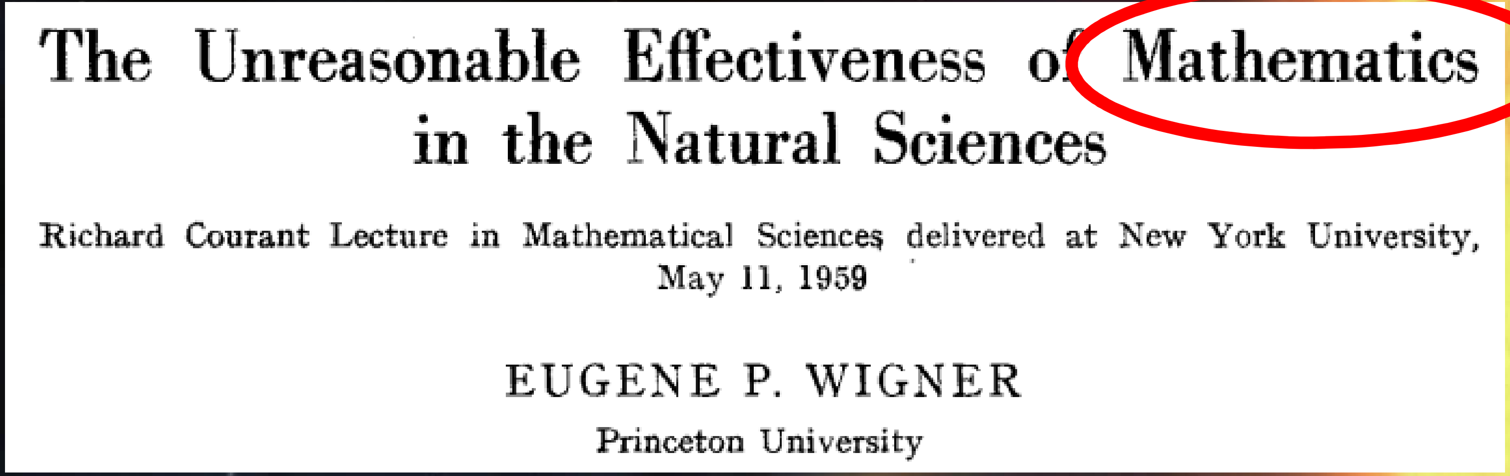
Indirect (recent): Jenkins+ 2006, Ma+ 2007, Wrede+ 2007, 2009, AP+ 2011, Doherty+ 2012, Irvine+ 2013



AP++ (2011)
experimental rate
varied within
uncertainties


1D hydro nova model

The unreasonable effectiveness of experiments in constraining nova nucleosynthesis



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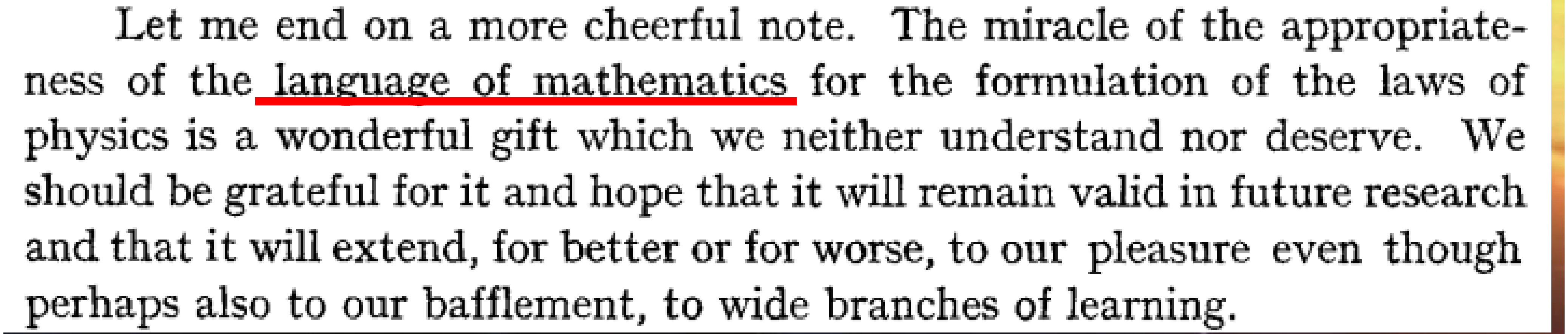
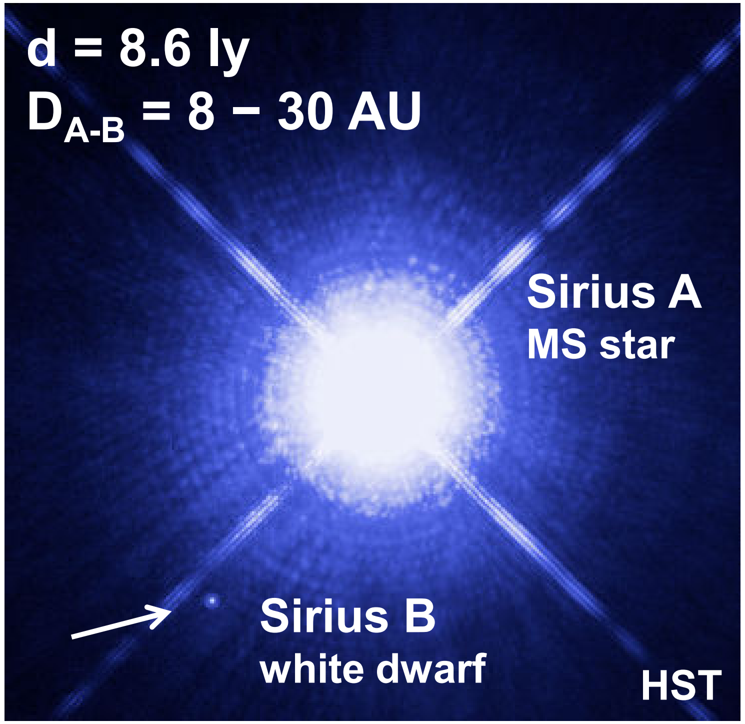


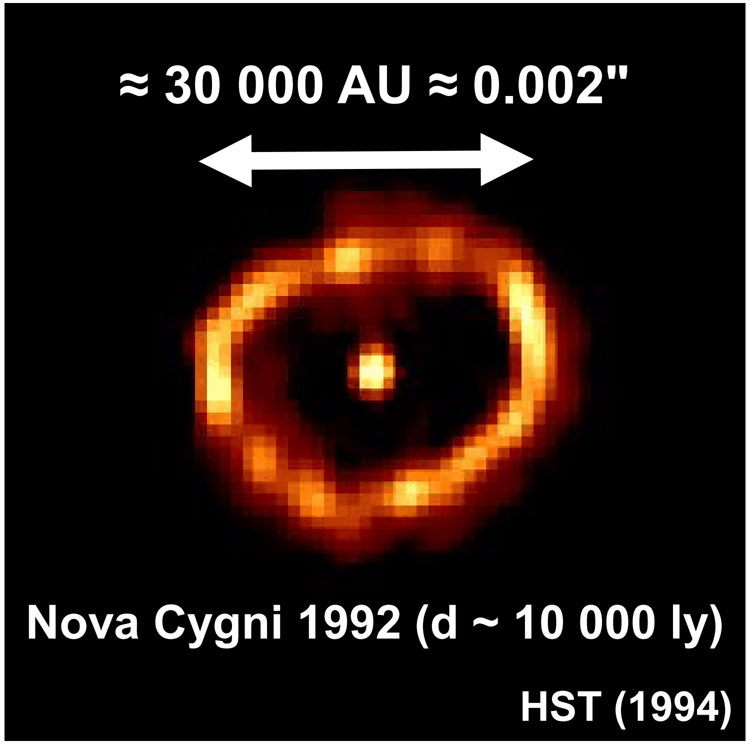
Let me end on a more cheerful note. The miracle of the appropriateness of the language of mathematics for the formulation of the laws of physics is a wonderful gift which we neither understand nor deserve. We should be grateful for it and hope that it will remain valid in future research and that it will extend, for better or for worse, to our pleasure even though perhaps also to our bafflement, to wide branches of learning.

Classical nova explosions

Compact object:	white dwarf (CO / ONe)
L_{max}:	~ $10^4 – 10^5$ L_{sol}
$\Delta t_{lightcurve}$:	~ days – months
$T_{orbital}$:	~ 1 – 16 h
t_{rec}:	~ $10^4 – 10^5$ yr
T_{peak}:	~ 0.1 – 0.4 GK
ρ_{peak}:	~ $10^3 – 10^4$ g / cm^3
envelope:	~ 100 km
$\#_{Galaxy}$:	~ 30 / yr
Ejecta:	~ $10^{-4} – 10^{-5}$ M_{sol} / nova
nucleosynthesis:	H – Ca

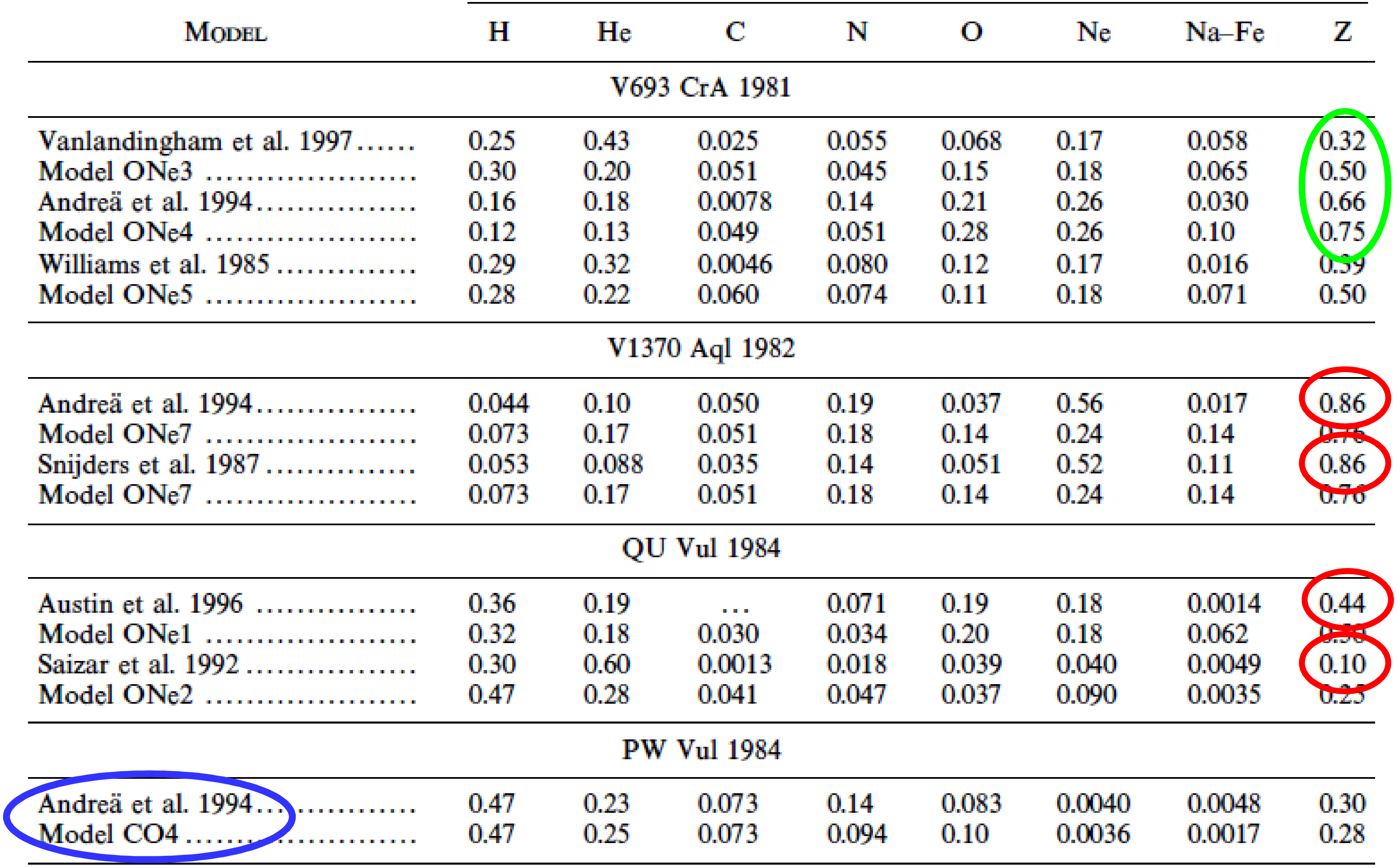
Most of the thermonuclear reaction rates involved are constrained by experiments





OBSERVATIONS

mass fraction in ejecta



MODEL	H	He	C	N	O	Ne	Na–Fe	Z
V693 CrA 1981								
Vanlandingham et al. 1997	0.25	0.43	0.025	0.055	0.068	0.17	0.058	0.32
Model ONe3	0.30	0.20	0.051	0.045	0.15	0.18	0.065	0.50
Andreä et al. 1994	0.16	0.18	0.0078	0.14	0.21	0.26	0.030	0.66
Model ONe4	0.12	0.13	0.049	0.051	0.28	0.26	0.10	0.75
Williams et al. 1985	0.29	0.32	0.0046	0.080	0.12	0.17	0.016	0.39
Model ONe5	0.28	0.22	0.060	0.074	0.11	0.18	0.071	0.50
V1370 Aql 1982								
Andreä et al. 1994	0.044	0.10	0.050	0.19	0.037	0.56	0.017	0.86
Model ONe7	0.073	0.17	0.051	0.18	0.14	0.24	0.14	0.76
Snijders et al. 1987	0.053	0.088	0.035	0.14	0.051	0.52	0.11	0.86
Model ONe7	0.073	0.17	0.051	0.18	0.14	0.24	0.14	0.76
QU Vul 1984								
Austin et al. 1996	0.36	0.19	…	0.071	0.19	0.18	0.0014	0.44
Model ONe1	0.32	0.18	0.030	0.034	0.20	0.18	0.062	0.50
Saizar et al. 1992	0.30	0.60	0.0013	0.018	0.039	0.040	0.0049	0.10
Model ONe2	0.47	0.28	0.041	0.047	0.037	0.090	0.0035	0.23
PW Vul 1984								
Andreä et al. 1994	0.47	0.23	0.073	0.14	0.083	0.0040	0.0048	0.30
Model CO4	0.47	0.25	0.073	0.094	0.10	0.0036	0.0017	0.28

José and Hernanz (1998)