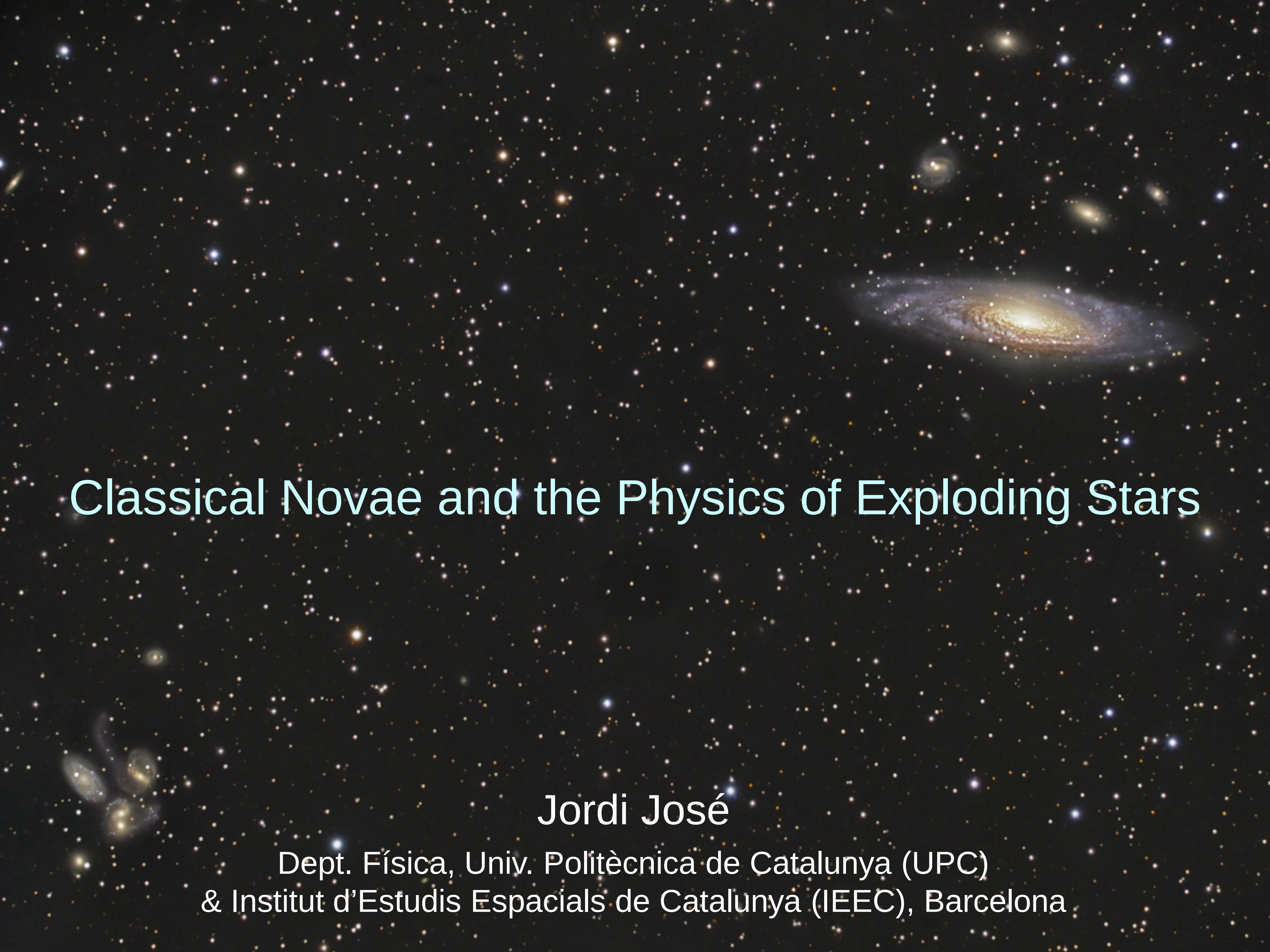


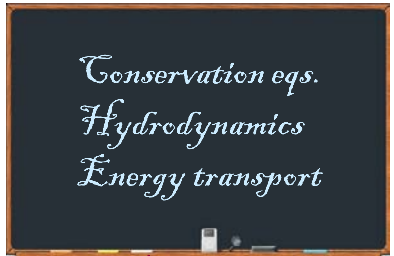
Classical Novae and the Physics of Exploding Stars

Jordi José

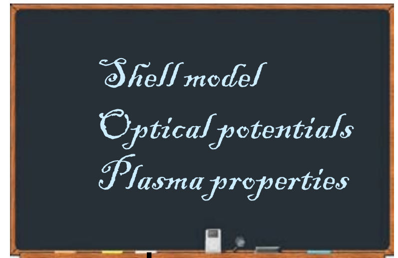
Dept. Física, Univ. Politècnica de Catalunya (UPC)
& Institut d’Estudis Espacials de Catalunya (IEEC), Barcelona

Observational Astronomy

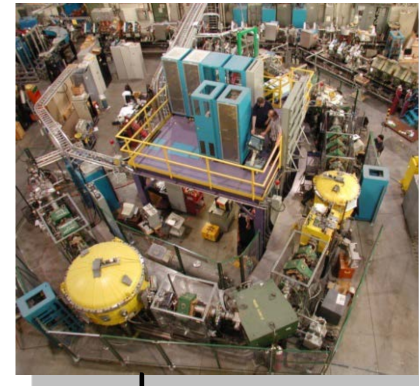
Theoretical Astrophysics



Nuclear & Atomic Theory



Nuclear Experiments



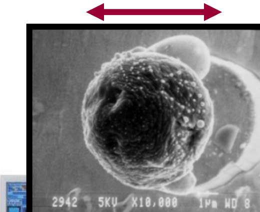
~10 m

Reaction rates, EOS, opacities...

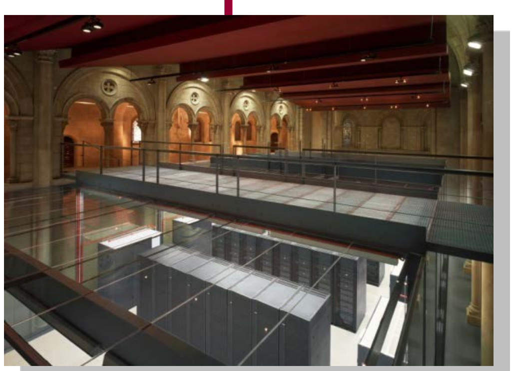
Astrophysical Models

Observables: light curves, spectra, abundances...

~1 – 10 μm



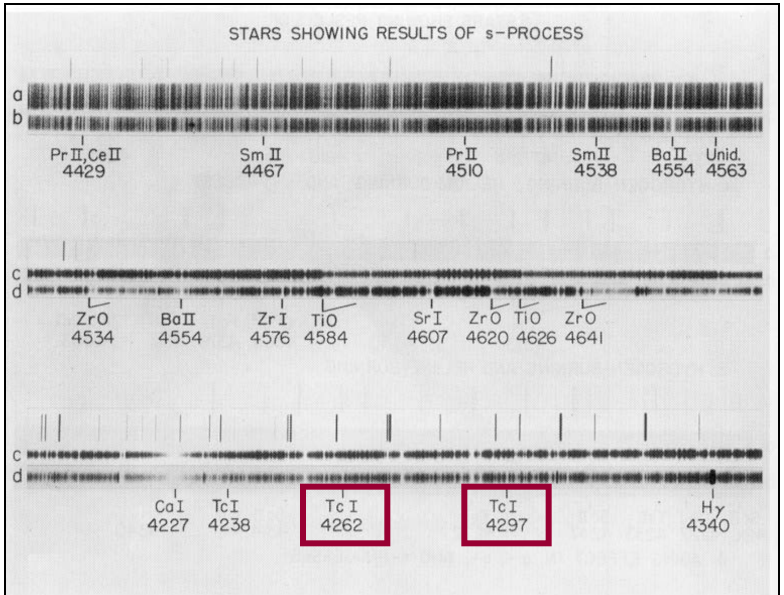
Cosmochemistry

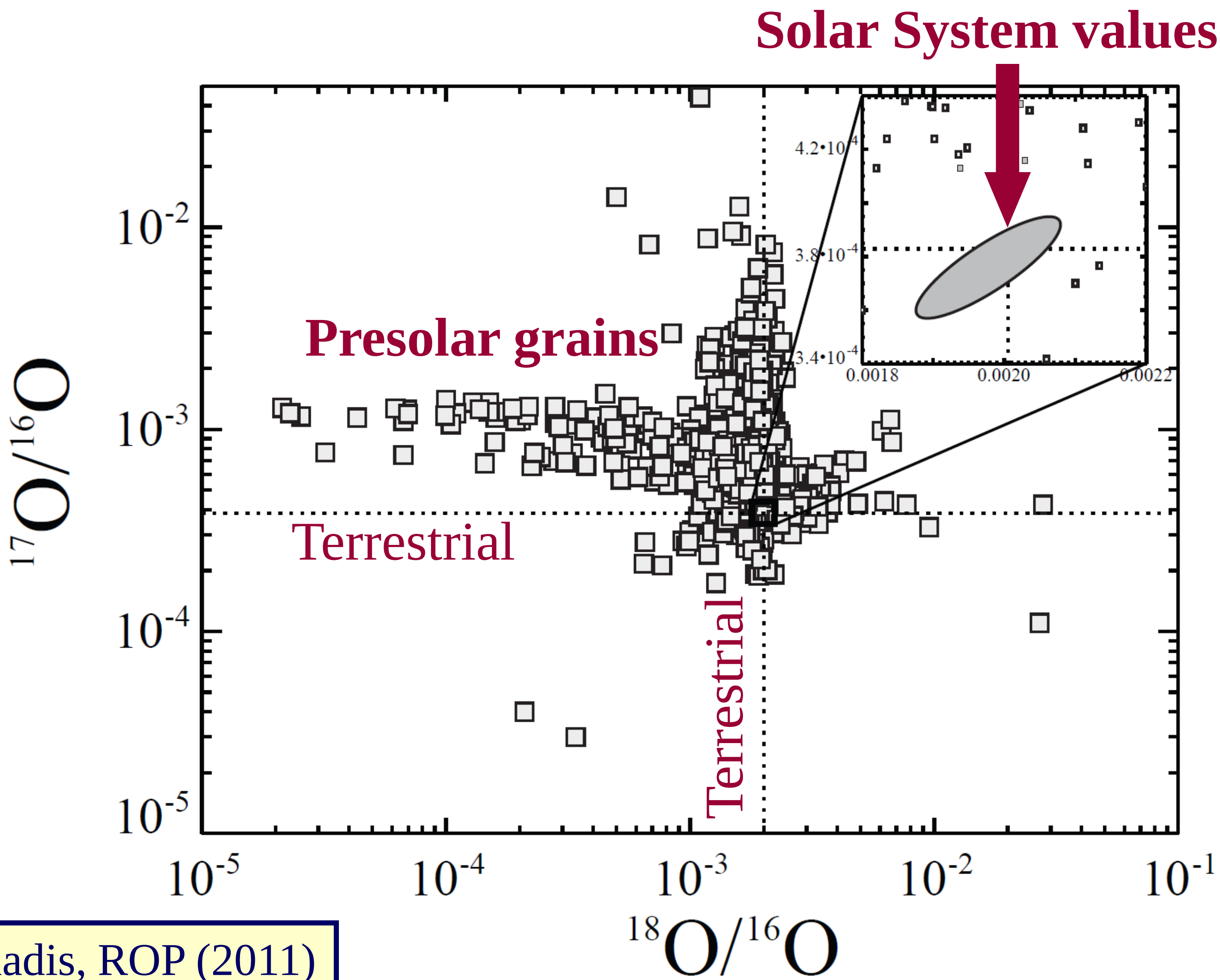


I. Stars as Nuclear Factories

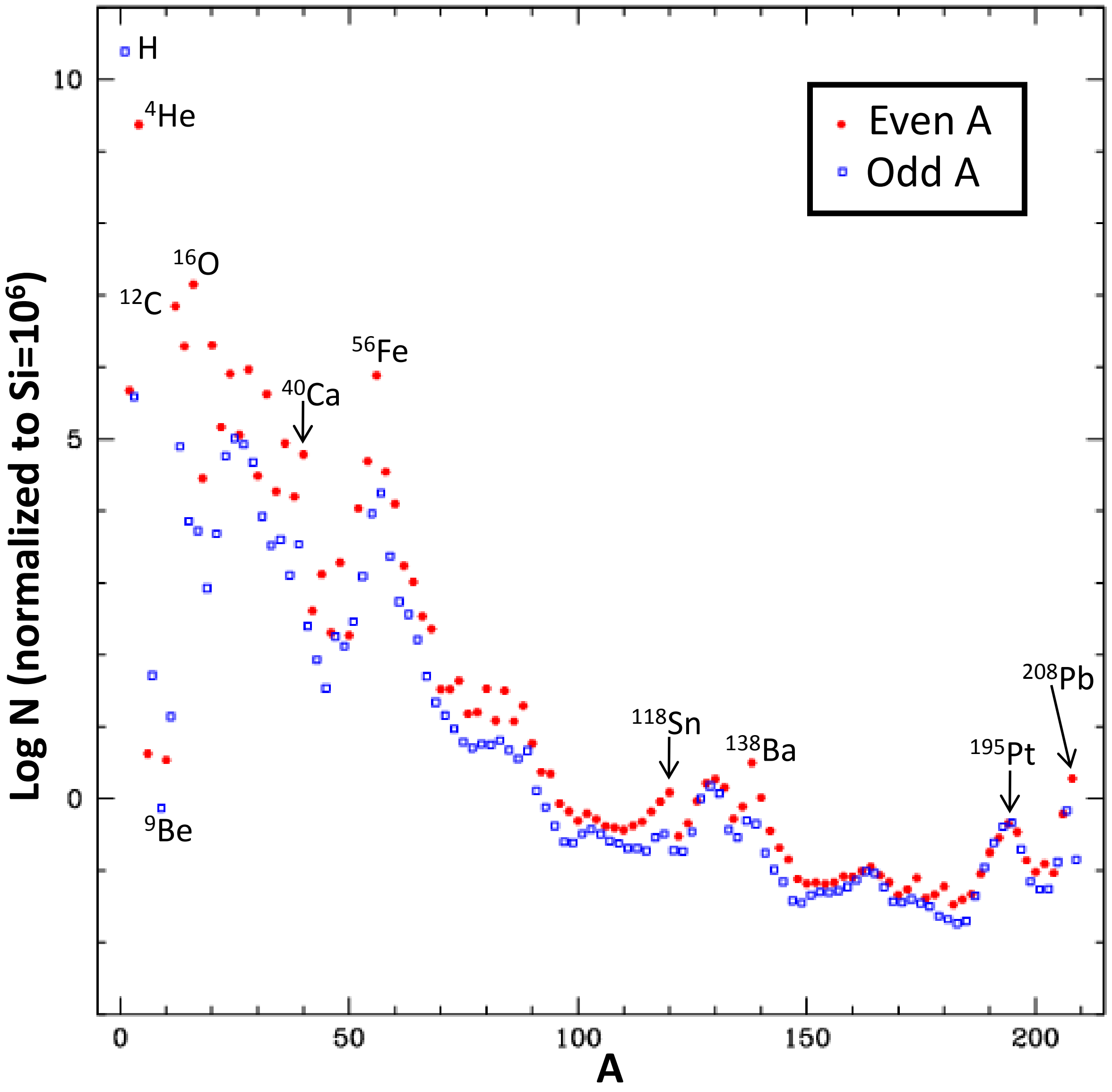
The idea that **elements** could be **synthesized in stellar environments** was developed in the mid 1940s by **F. Hoyle** (following early work on 1920/30s by Bethe, Gamow, von Weizsäcker, and others…)

P.W. Merrill detected ***technecium*** (1952) in several S stars → **Tc** has no stable isotopes (longest lived: τ ~ 4 Myr): **Stellar nucleosynthesis**

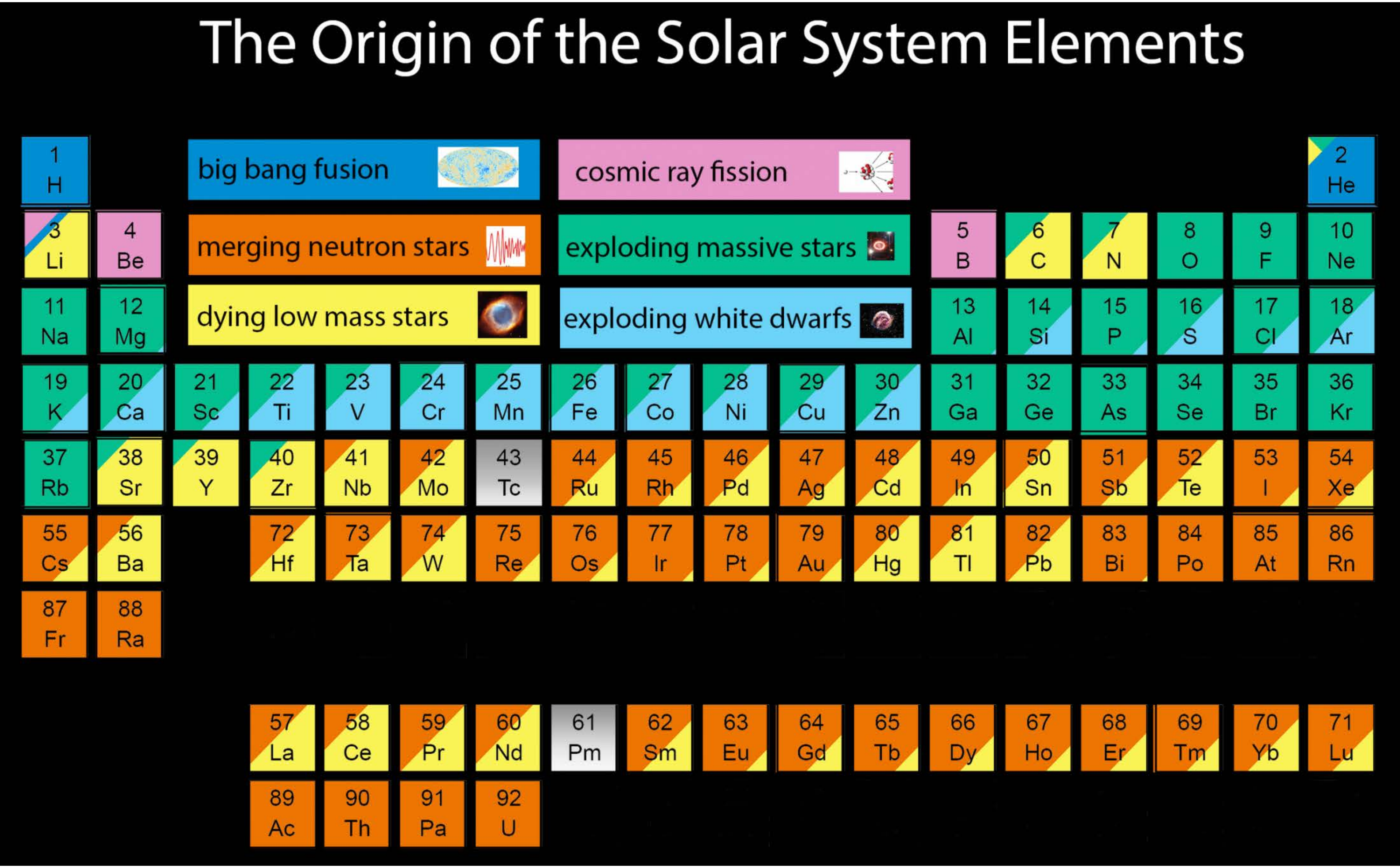


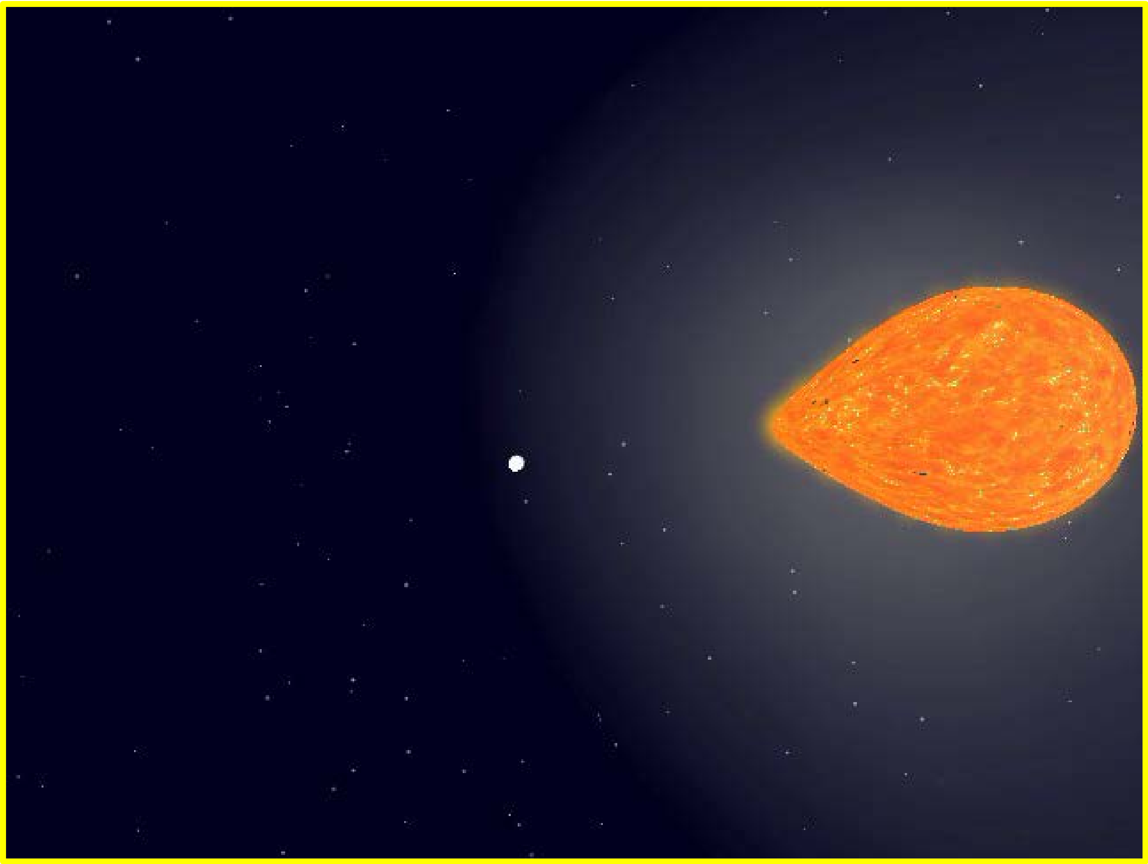


JJ & Iliadis, ROP (2011)



JJ & Iliadis (2011), ROP

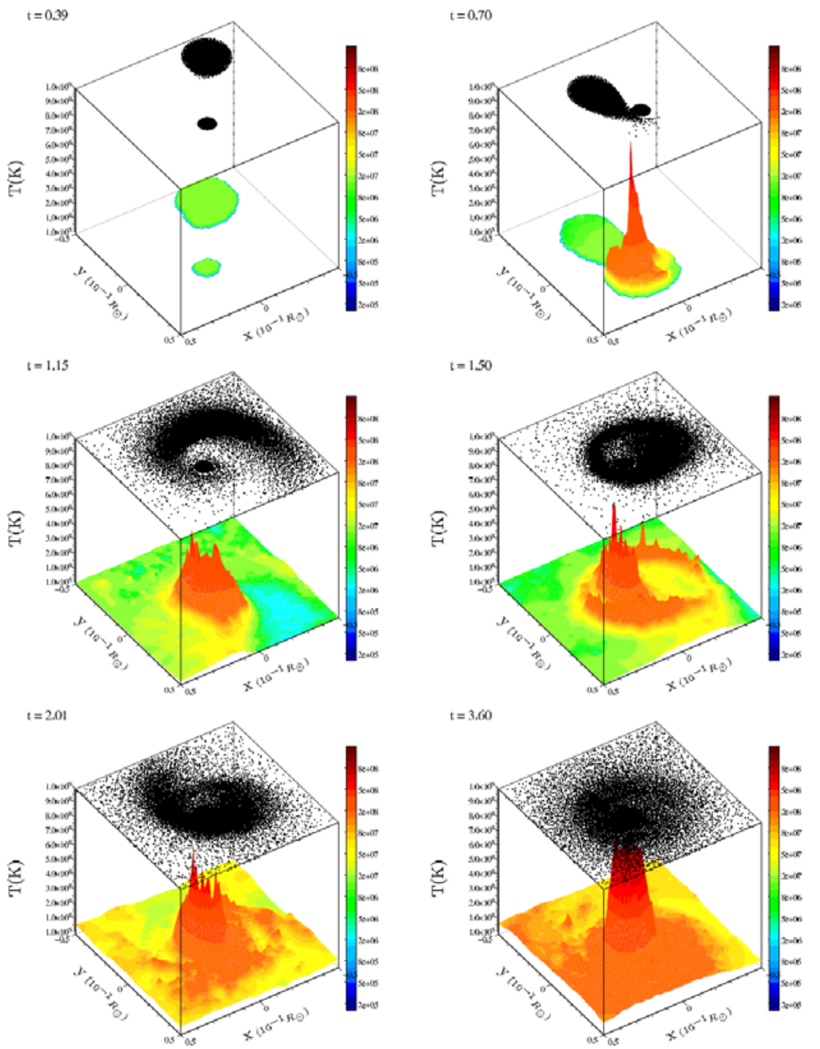

The Origin of the Solar System Elements
big bang fusion
cosmic ray fission
merging neutron stars
exploding massive stars
dying low mass stars
exploding white dwarfs
1 H
2 He
3 Li
4 Be
5 B
6 C
7 N
8 O
9 F
10 Ne
11 Na
12 Mg
13 Al
14 Si
15 P
16 S
17 Cl
18 Ar
19 K
20 Ca
21 Sc
22 Ti
23 V
24 Cr
25 Mn
26 Fe
27 Co
28 Ni
29 Cu
30 Zn
31 Ga
32 Ge
33 As
34 Se
35 Br
36 Kr
37 Rb
38 Sr
39 Y
40 Zr
41 Nb
42 Mo
43 Tc
44 Ru
45 Rh
46 Pd
47 Ag
48 Cd
49 In
50 Sn
51 Sb
52 Te
53 I
54 Xe
55 Cs
56 Ba
72 Hf
73 Ta
74 W
75 Re
76 Os
77 Ir
78 Pt
79 Au
80 Hg
81 Tl
82 Pb
83 Bi
84 Po
85 At
86 Rn
87 Fr
88 Ra
57 La
58 Ce
59 Pr
60 Nd
61 Pm
62 Sm
63 Eu
64 Gd
65 Tb
66 Dy
67 Ho
68 Er
69 Tm
70 Yb
71 Lu
89 Ac
90 Th
91 Pa
92 U



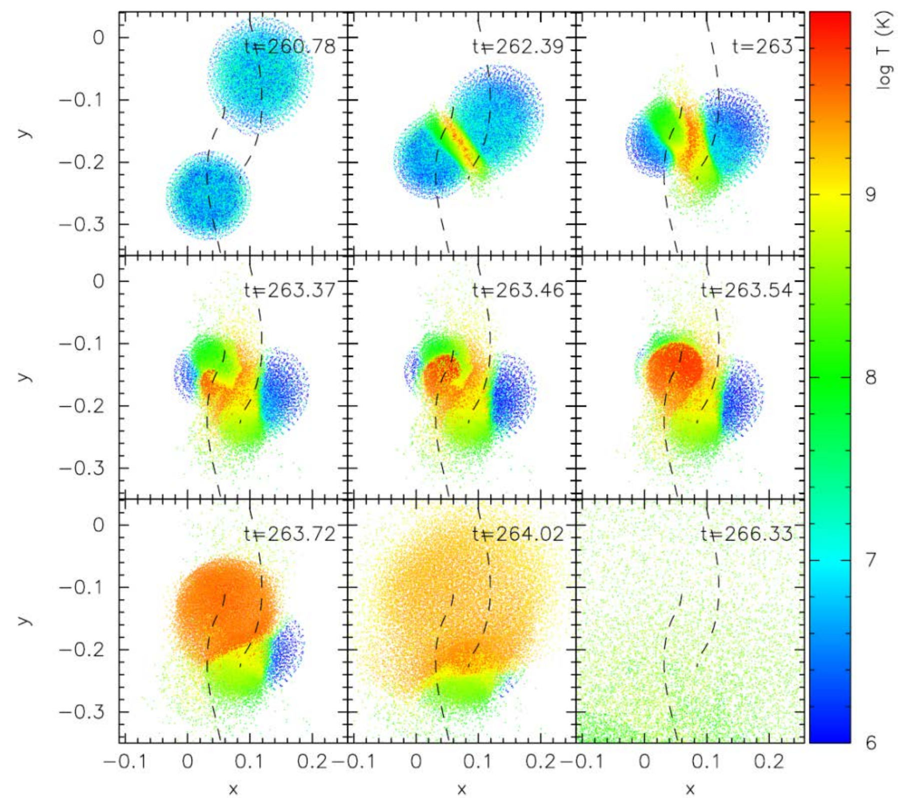
Type Ia (or thermonuclear) **Supernovae** [SN Ia]
Classical Nova Outbursts [CN]
} WD

X-Ray Bursts [XRBs]: NS

Stellar Mergers and Collisions



Guerrero, García-Berro & Isern, A&A (2004)



Detonations in WD dynamic interactions

Aznar-Siguán, García-Berro, Lorén-Aguilar, JJ & Isern, MNRAS (2013)

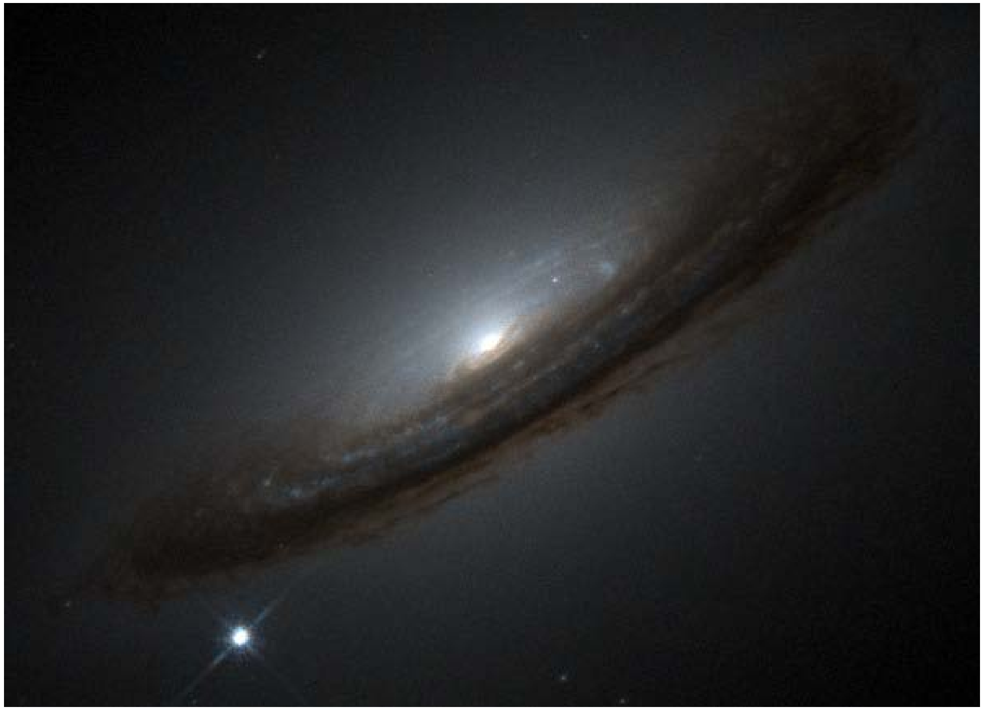
II. Type Ia Supernovae

Thermonuclear (Type Ia) Supernovae

$v \sim 10^4$ km/s, $L_{Peak} \sim 10^{10}\ L_\odot$, $E \sim 10^{51}$ erg, $M_{ej} = 1.4\ M_\odot$

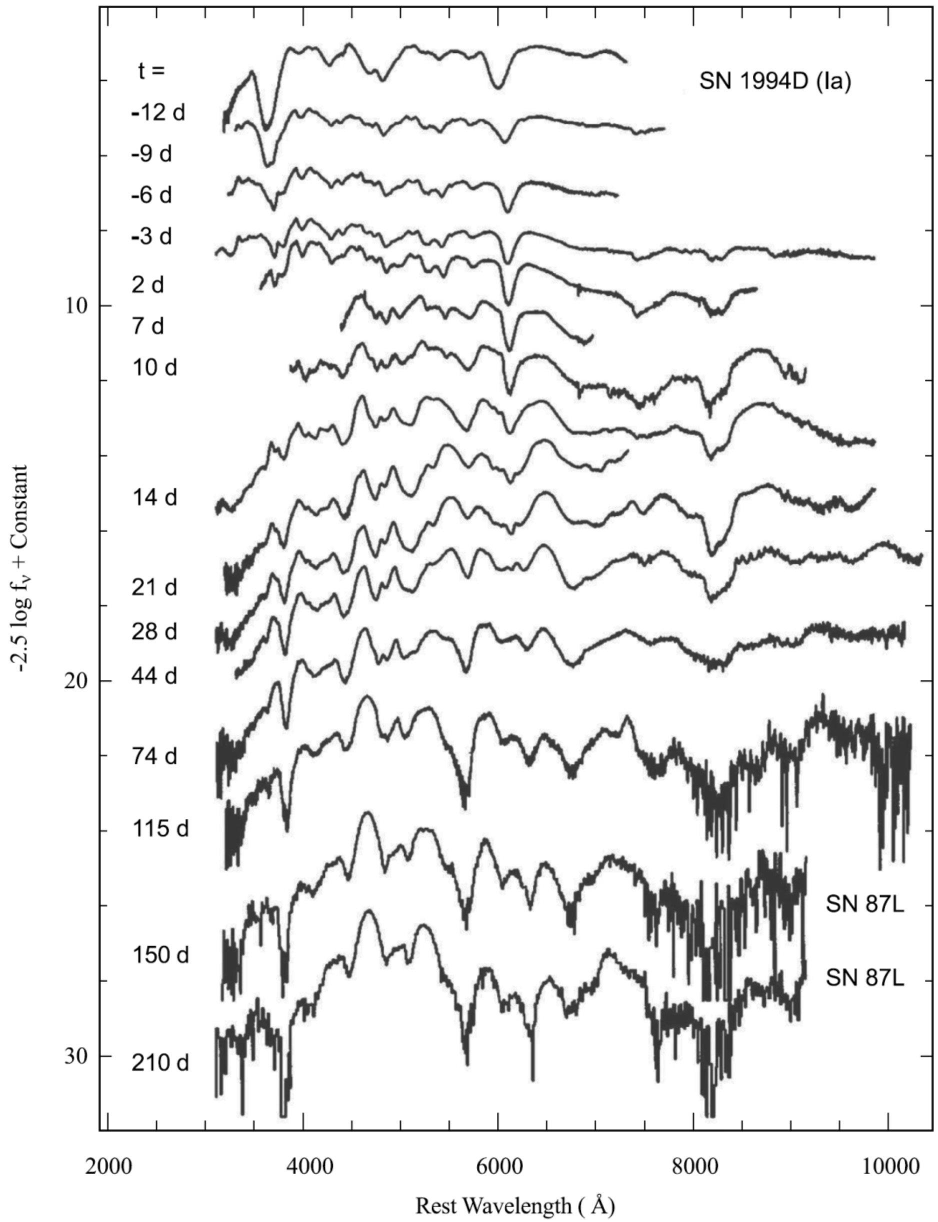
no remnant left

* **homogeneity:** ~70% of all **SN Ia** have similar spectra, light curves and peak absolute magnitudes (Li et al. 2011): **diversity of SNIa progenitors??**

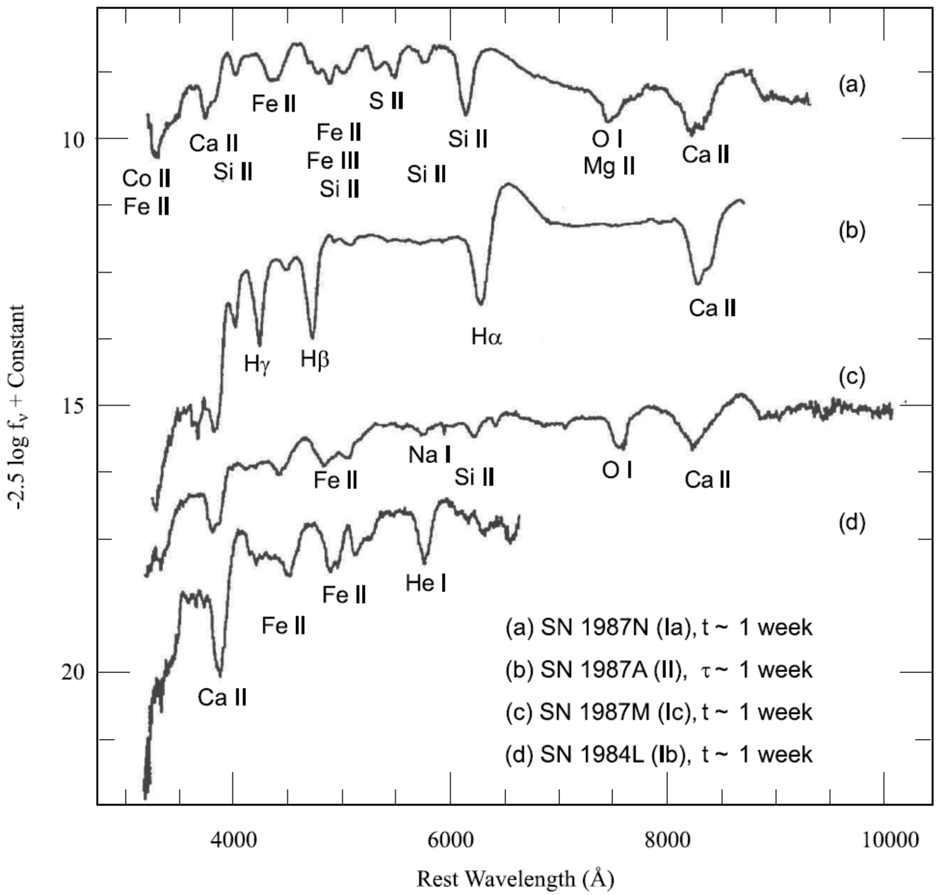


* Scenario: not fully understood
- Single degenerate scenario:
  WD + ‘Normal’ companion
- Double degenerate scenario:
  WD + WD

* main **Fe factories**

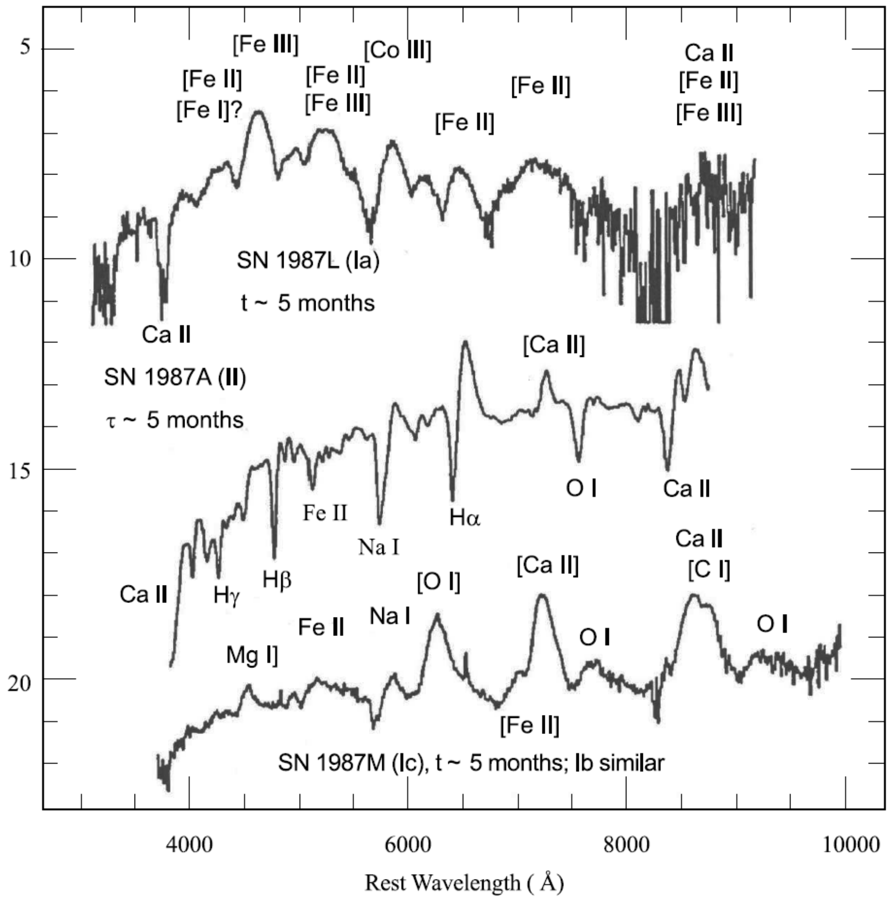

t =
-12 d
-9 d
-6 d
-3 d
2 d
7 d
10 d
14 d
21 d
28 d
44 d
74 d
115 d
150 d
210 d
SN 1994D (Ia)
SN 87L
SN 87L
10
20
30
-2.5 log f_ν + Constant
2000
4000
6000
8000
10000
Rest Wavelength (Å)

Intermediate-mass elements



Early spectra

Fe-peak elements



Late spectra

Thermonuclear Supernovae: Ignition mechanism

Central C-ignition in Chandrasekhar-mass WDs

$M_{CO} \sim 1.4\ M_{\odot}$

Detonation: supersonic flame

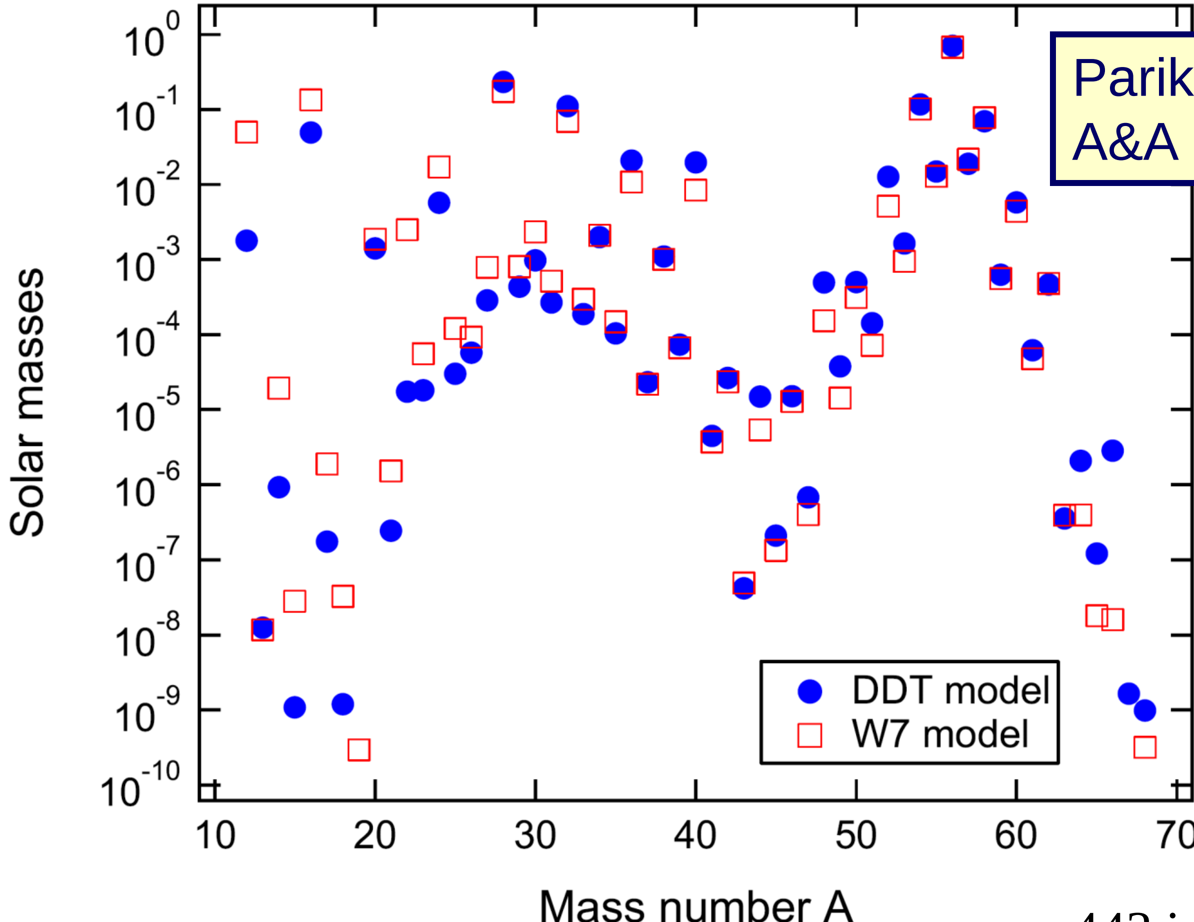
C,O $\not\rightarrow$ Ni

Deflagration: subsonic velocity

Deflagration ⟷ detonation:
Delayed detonation

Thermonuclear Supernovae: Nucleosynthesis

Supernovae are crucial for life... But never get too close!

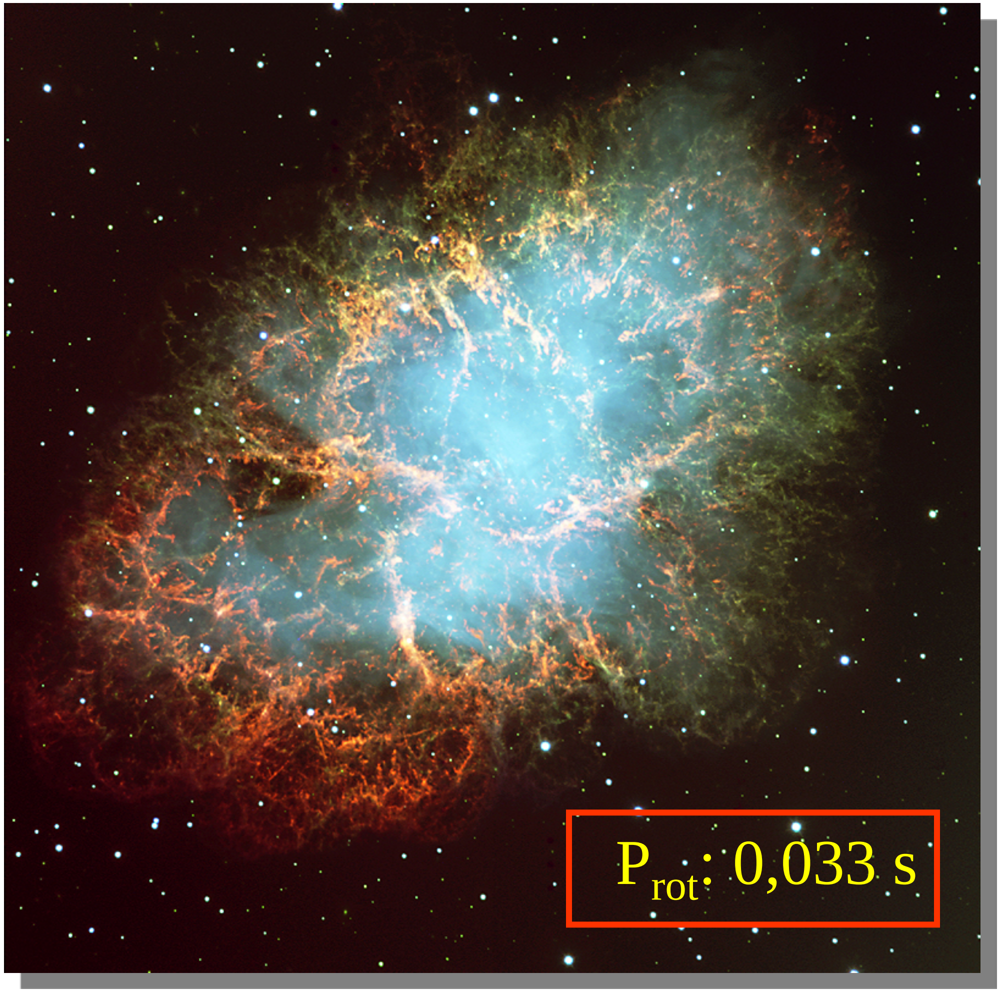


Parikh, JJ, Seitenzahl & Röpke, A&A (2013)

443 isotopes (H − Kr); 5267 links

Historical Supernovae:

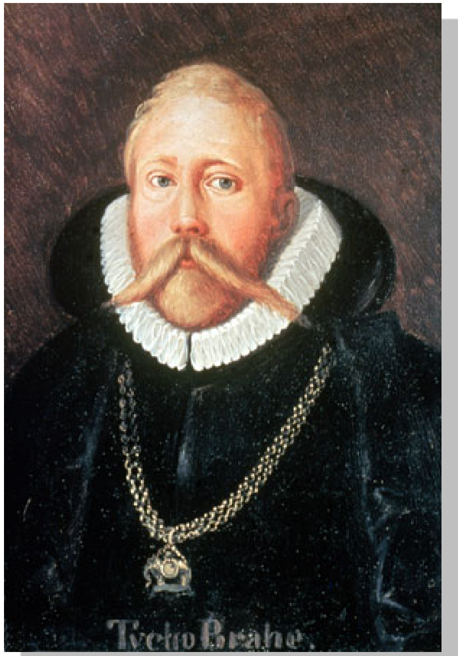
185 aC, 386, 393, 1006, 1054, 1181, 1572, 1604

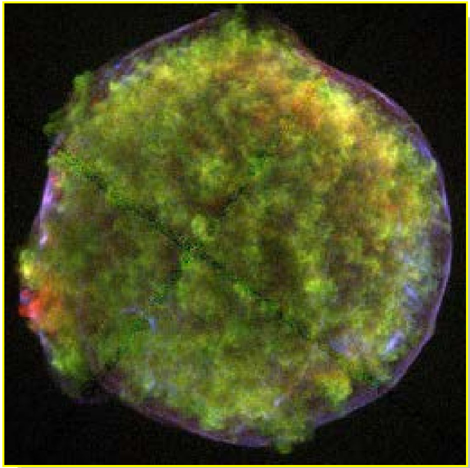


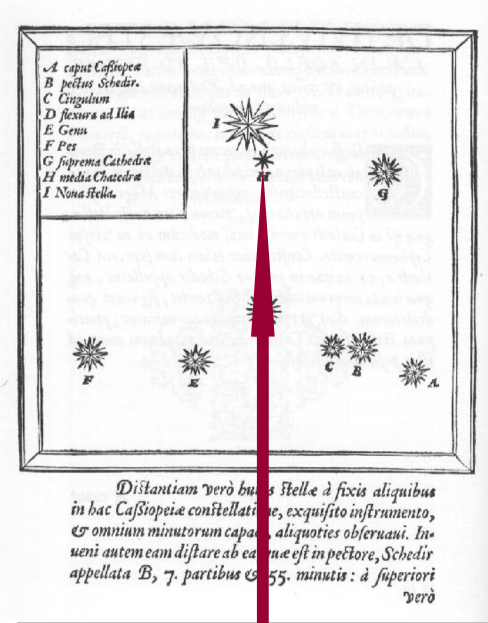
Frequency: ~1 supernova every ~30 years per Galaxy

"On the 11th day of November in the evening after sunset... I noticed that a **new and unusual star**, surpassing the other stars in brilliancy, was shining... and since I had, from boyhood, known all the stars of the heavens perfectly, it was quite evident to me that **there had never been any star in that place of the sky** [...] I was so astonished of this sight [...] a miracle indeed, one that has never been previously seen before our time, in any age since the beginning of the world."

SN 1572 (Tycho)



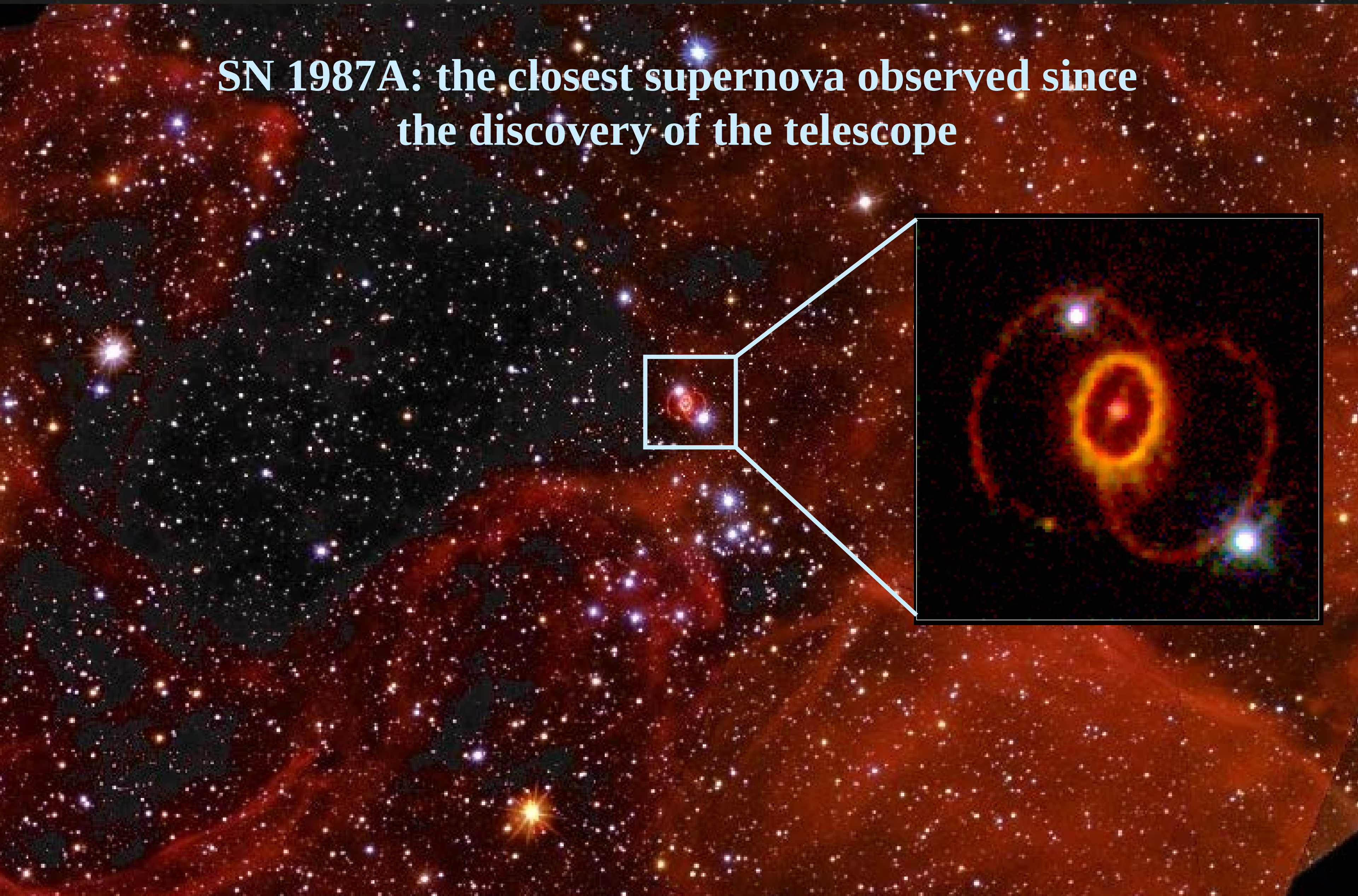




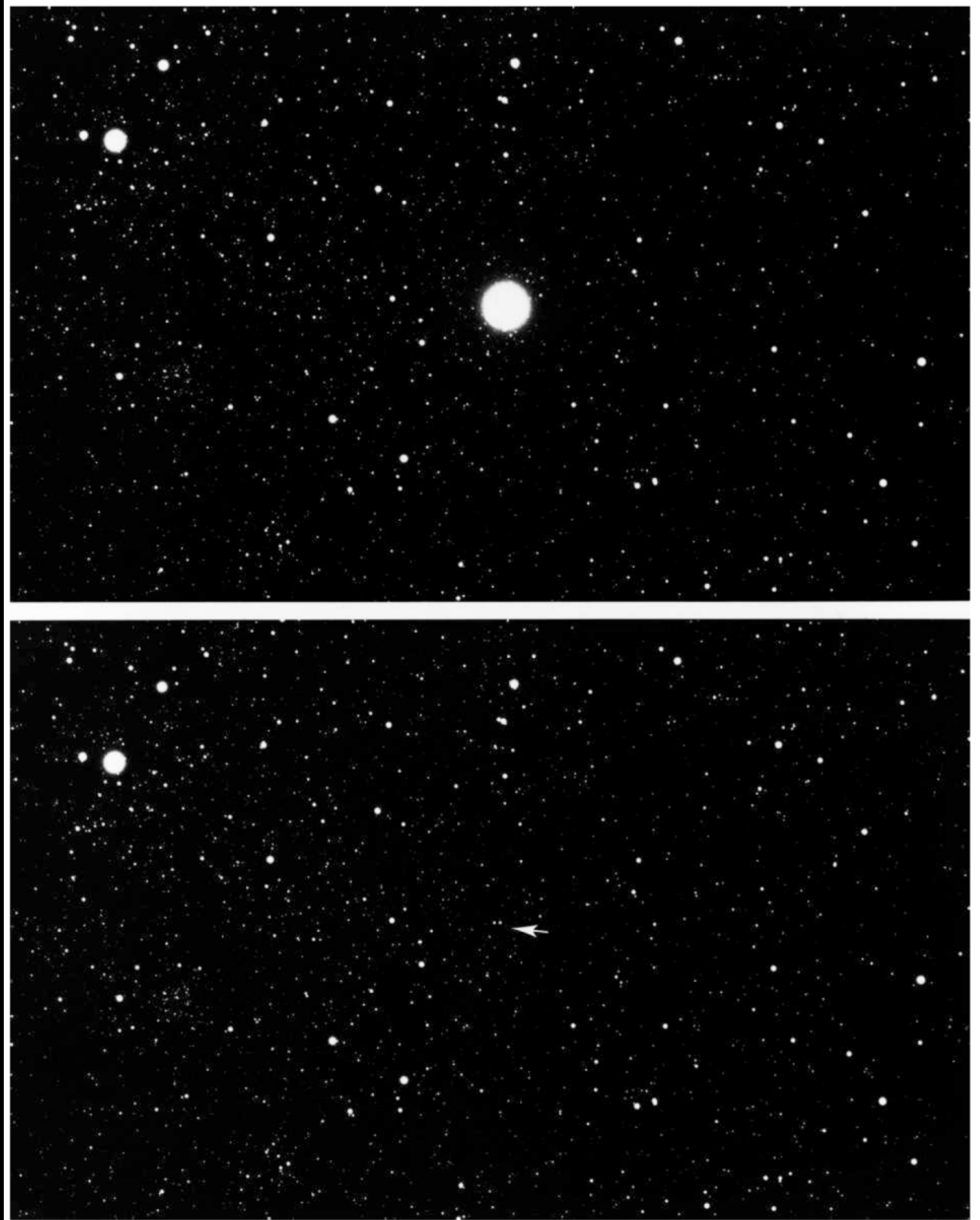
Diſtantiam verò hu s ſtellæ à fixis aliquibus in hac Caßiopeiæ conſtellati e, exquiſito inſtrumento, & omnium minutorum capa , aliquoties obſeruaui. Inueni autem eam diſtare ab ea uæ eſt in pectore, Schedir appellata B, 7. partibus & 55. minutis: à ſuperiori verò

A "new star" (*nova stella*)
Nov. 11, 1572
Tycho Brahe

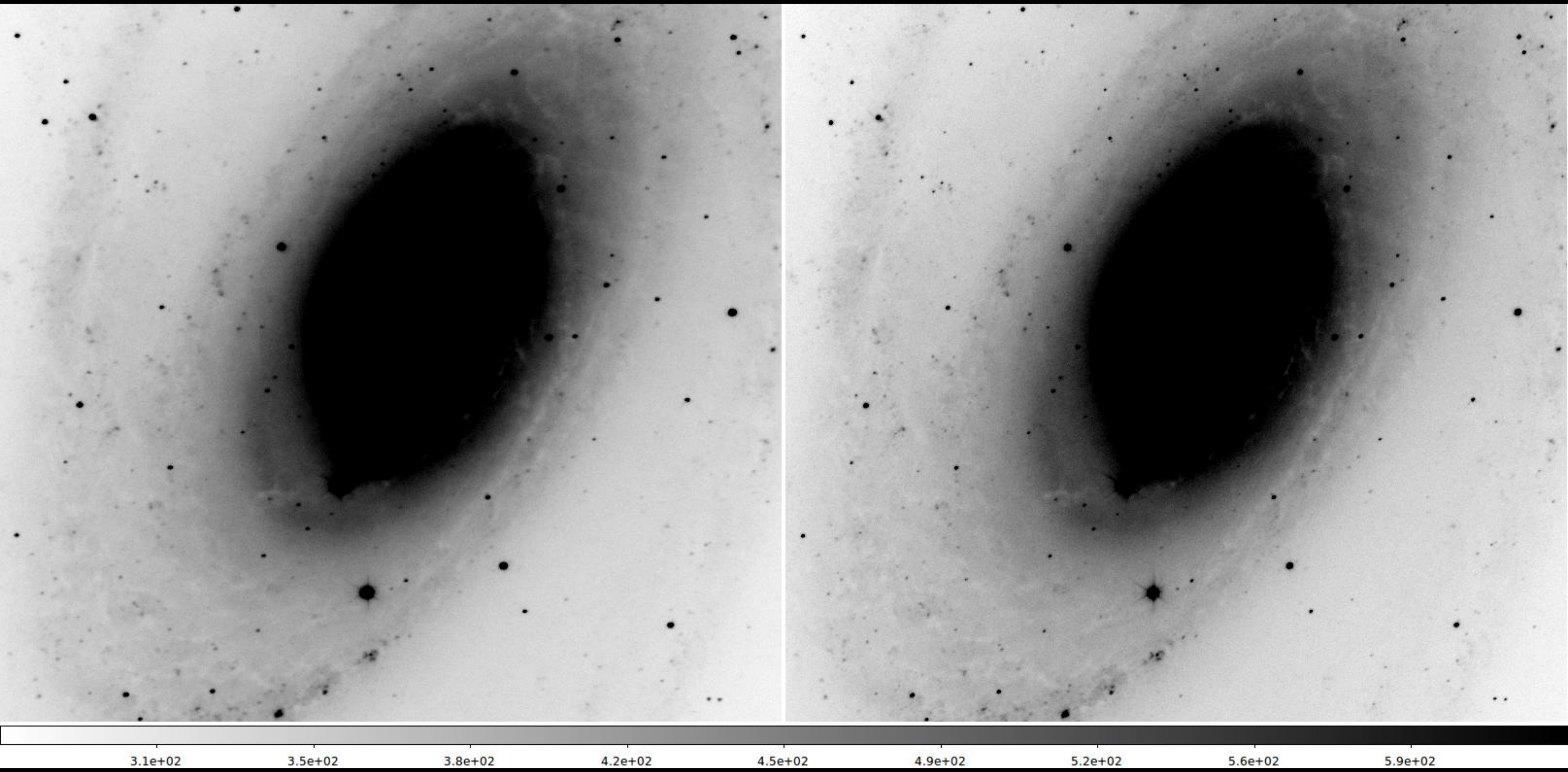
SN 1987A: the closest supernova observed since the discovery of the telescope



III. Classical Novae



Nova Cygni 1975



M81 Galaxy, observed with the 80 cm Joan Oró robotic telescope, Montsec Observatory (near Barcelona)
April 2016

SPOILER Alert!!

M81 Galaxy

Novae have been observed in all wavelengths (but detected in γ-rays only at E > 100 MeV)

The Classical Nova ID Card

Moderate rise times (<1 – 2 days):

8 – 18 magnitude increase in brigthness

$L_{Peak} \sim 10^4 - 10^5 L_\odot$

Stellar binary systems: WD + MS (often, K-M dwarfs)

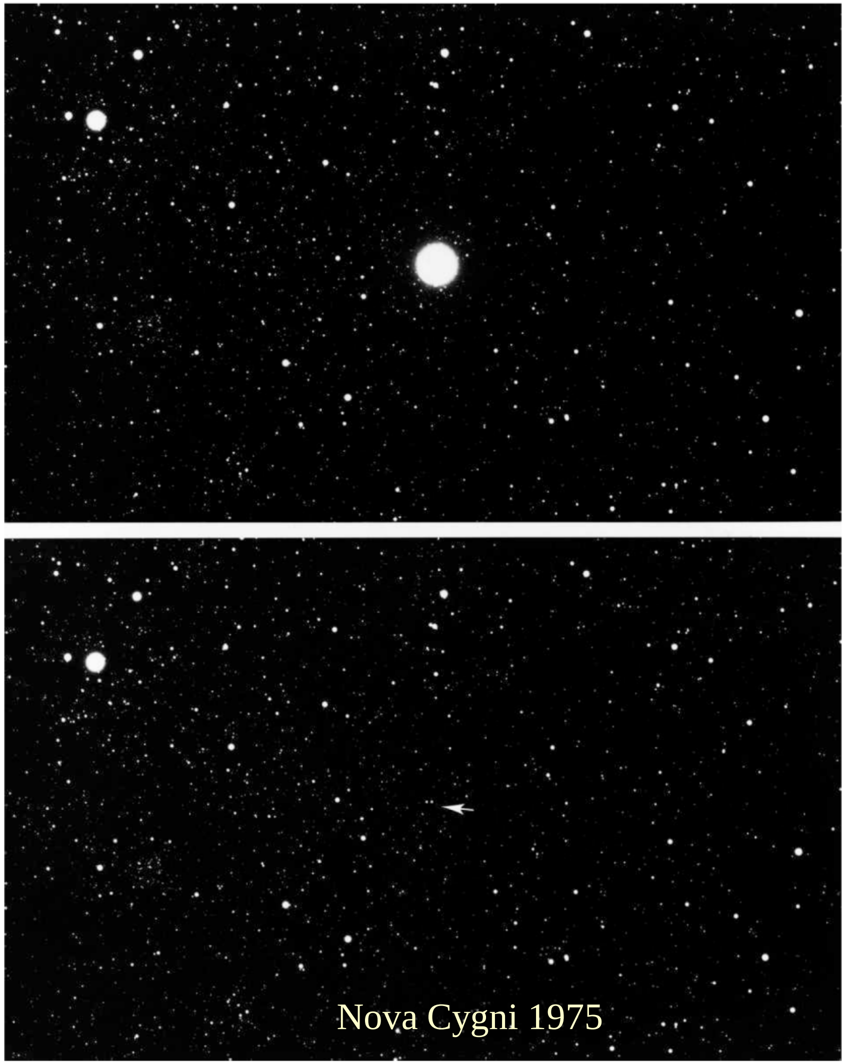
Recurrence time: ~ 1 - 10 yr (RNe) – 10^5 yr (CNe)

Frequency: 30 ± 10 yr^{-1}

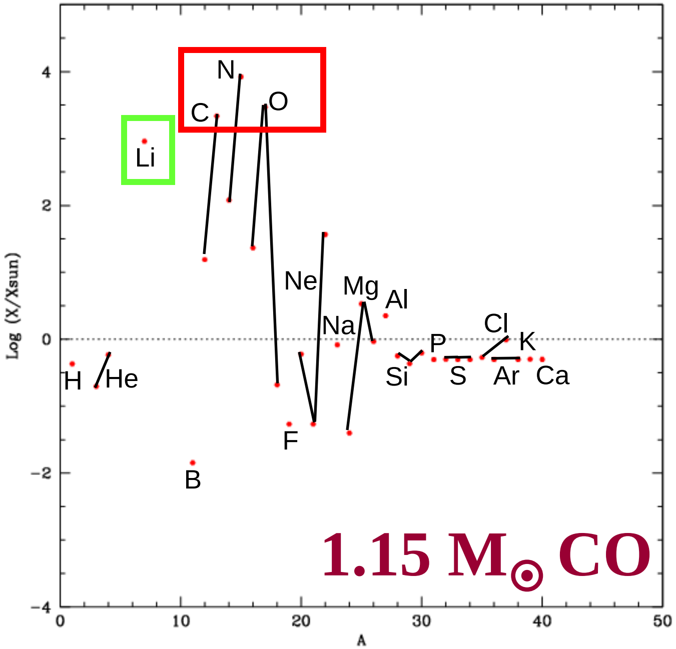
Observed frequency: ~ 10 yr^{-1}

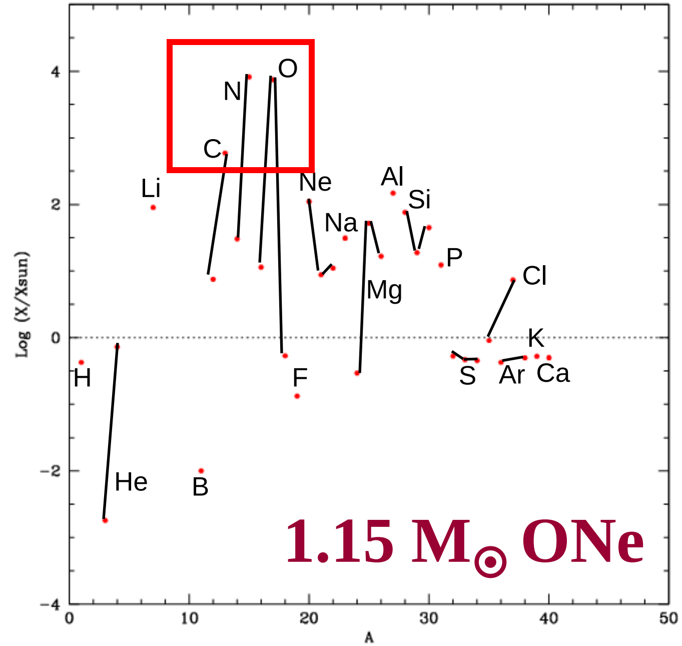
E ~ 10^{45} ergs

Mass ejected: $10^{-3} - 10^{-7} M_\odot$ (~10^3 km s^{-1})



Nova Cygni 1975


1.15 M⊙ CO
Log (X/Xsun)
A
H
He
Li
B
C
N
O
F
Ne
Na
Mg
Al
Si
P
S
Cl
Ar
K
Ca


1.15 M⊙ ONe
Log (X/Xsun)
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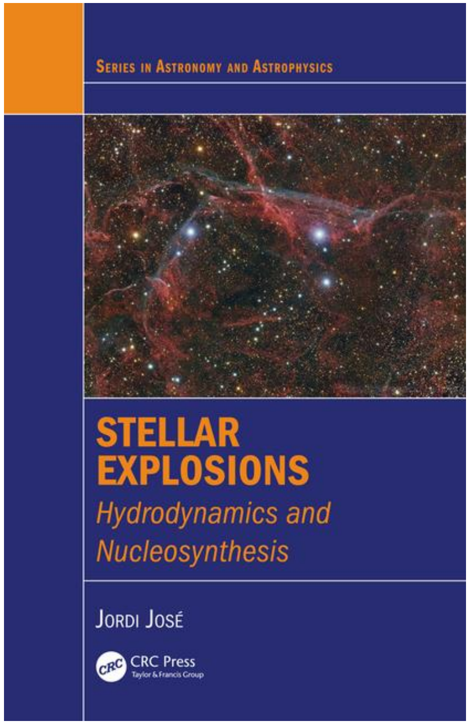
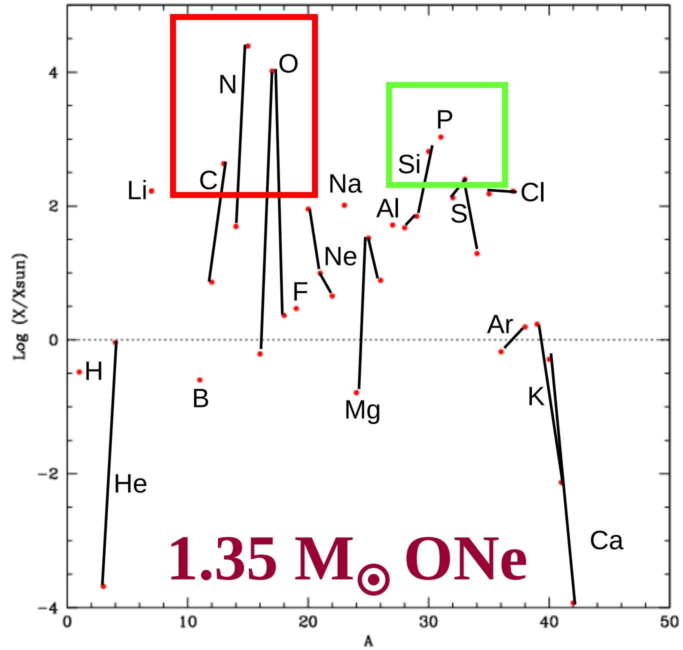
S
Cl
Ar
K
Ca


Series in Astronomy and Astrophysics
STELLAR EXPLOSIONS
Hydrodynamics and Nucleosynthesis
Jordi José
CRC Press
Taylor & Francis Group


1.35 M⊙ ONe
Log (X/Xsun)
A
H
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Li
B
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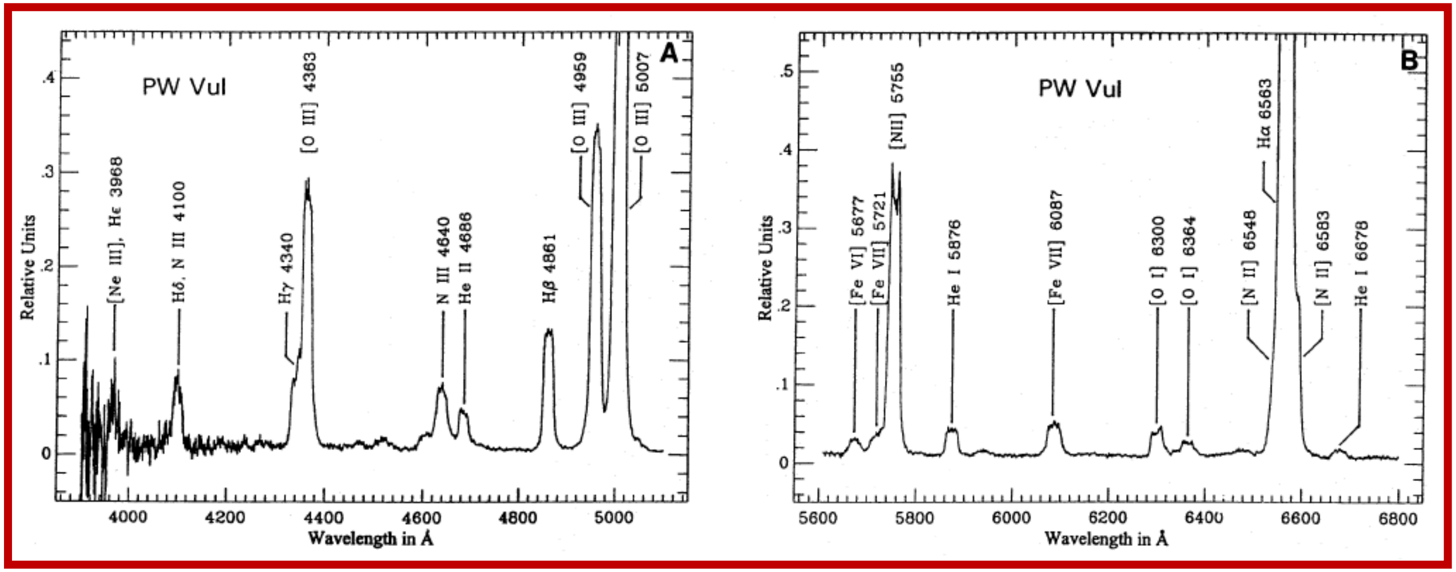


Andrëa et al. (1994)

PW Vul 1984

	H	He	C	N	O	Ne	Na-Fe	Z
Observation	0.47	0.23	0.073	0.14	0.083	0.0040	0.0048	0.30
Theory	0.47	0.25	0.073	0.094	0.10	0.0036	0.0037	0.28

(JJ & Hernanz 1998)

Presolar Grains and Dust

Evidence for **dust formation** (IR) accompanying nova outbursts

Gehrz et al. (1998)

Nova	Year	V_o (km s^{-1})	Types of Dust Formed[b]
FH Ser	1970	560	C
V1229 Aql	1970	575	C
V1301 Aql	1975	...	C
V1500 Cyg[a]	1975	1180	...
NQ Vul	1976	750	C
V4021 Sgr	1977	...	C
LW Ser	1978	1250	C
V1668 Cyg	1978	1300	C
V1370 Aql[d]	1982	2800	C; SiC; SiO_2
GQ Mus	1983	600	No dust
PW Vul	1984 #1	285	C
QU Vul[a]	1984 #2	1–5000	SiO_2
OS And[a,c]	1986	900	C?
V1819 Cyg[a]	1986	1000	No dust
V842 Cen	1986	1200	C; SiC; HC
V827 Her[a]	1987	1000	C
V4135 Sgr	1987	500	...
QV Vul	1987	700	C; SiO_2; HC; SiC
LMC 1988 #1	1988 #1	800	C?
LMC 1988 #2	1988 #2	1500	...
V2214 Oph	1988	500	...
V838 Her	1991	3500	C
V1974 Cyg[a]	1992	2250	No dust
V705 Cas	1993	840	C; HC; SiO_2
Aql 1995[a]	1995	1510	C

THE ASTROPHYSICAL JOURNAL, 203:490–496, 1976 January 15

GRAINS OF ANOMALOUS ISOTOPIC COMPOSITION FROM NOVAE

DONALD D. CLAYTON AND FRED HOYLE*
Department of Space Physics and Astronomy, Rice University
Received 1975 April 28; revised 1975 June 26

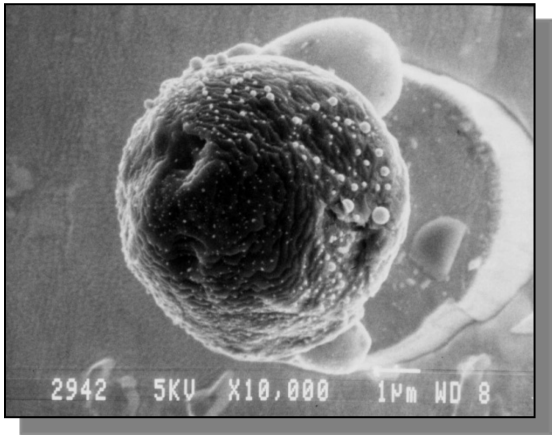
Isotopic peculiarities: ^{13}C, ^{14}C, ^{18}O, ^{22}Na, ^{26}Al, ^{30}Si

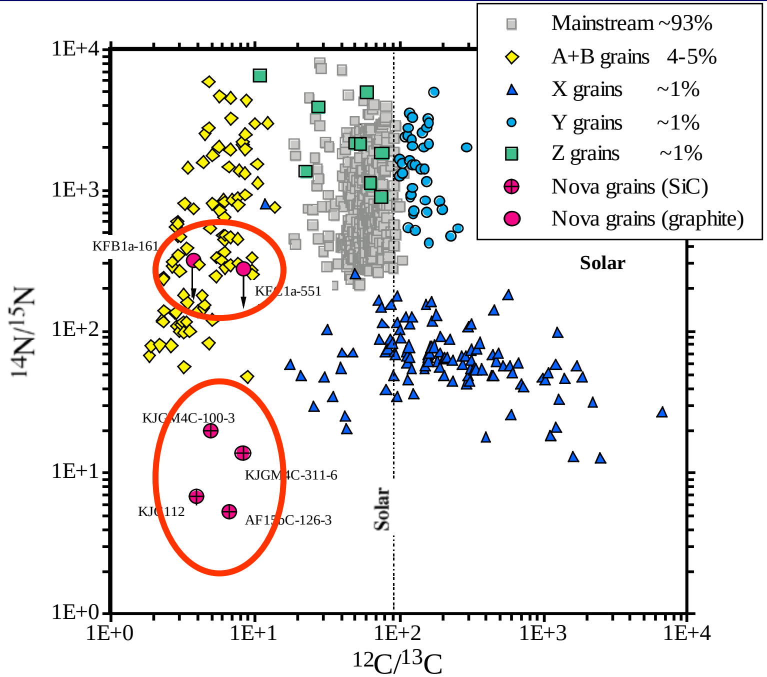
THE ASTROPHYSICAL JOURNAL, 551:1065–1072, 2001 April 20

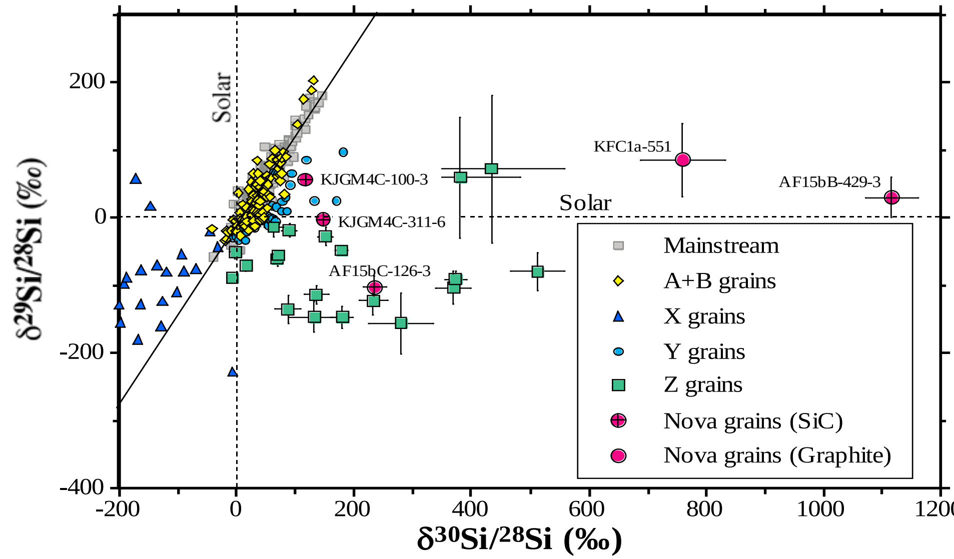
PRESOLAR GRAINS FROM NOVAE

SACHIKO AMARI, XIA GAO,[1] LARRY R. NITTLER,[2] AND ERNST ZINNER
Laboratory for Space Sciences and the Physics Department, Washington University, St. Louis, MO 63130-4899; sa@howdy.wustl.edu, ekz@howdy.wustl.edu
JORDI JOSÉ[3] AND MARGARITA HERNANZ
Institut d'Estudis Espacials de Catalunya (IEEC/CSIC), E-08034 Barcelona, Spain; jjose@ieec.fcr.es, hernanz@ieec.fcr.es
AND
ROY S. LEWIS
Enrico Fermi Institute, University of Chicago, Chicago, IL 60637-1433; r-lewis@uchicago.edu
Received 2000 September 15; accepted 2000 December 18

Presolar Grains

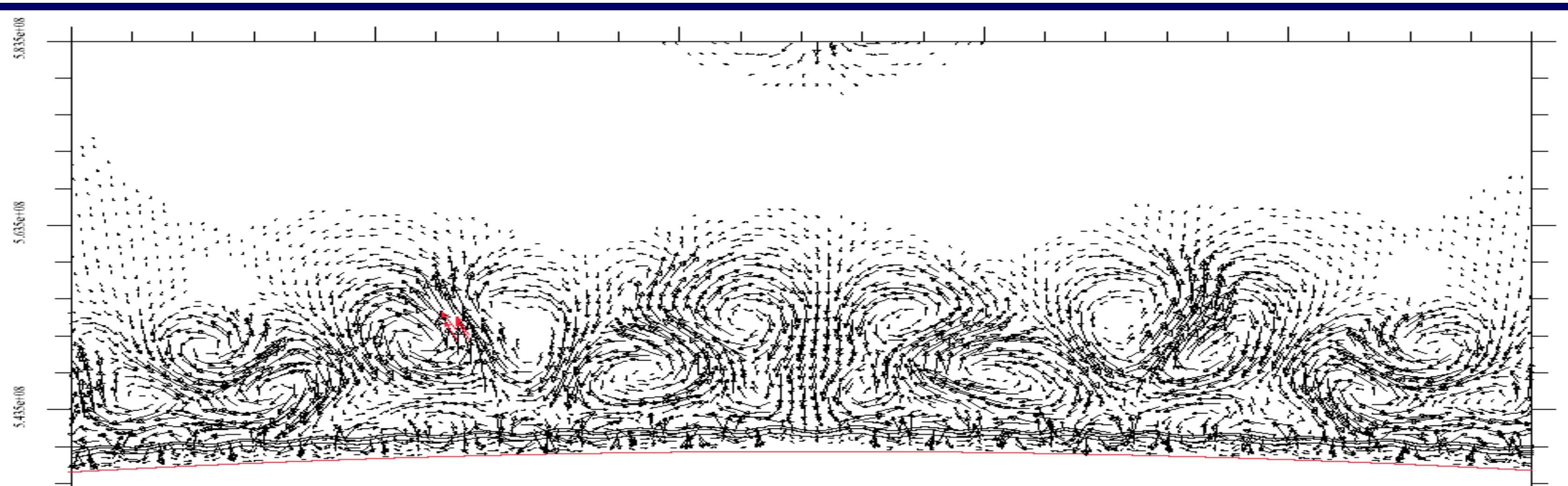






Current Challenges for Classical Novae

- The amount of **mass ejected** predicted by 1-D models is smaller than values *inferred* observationally
- The **mixing** mechanism at work at the core-envelope interface during nova outbursts is not fully understood

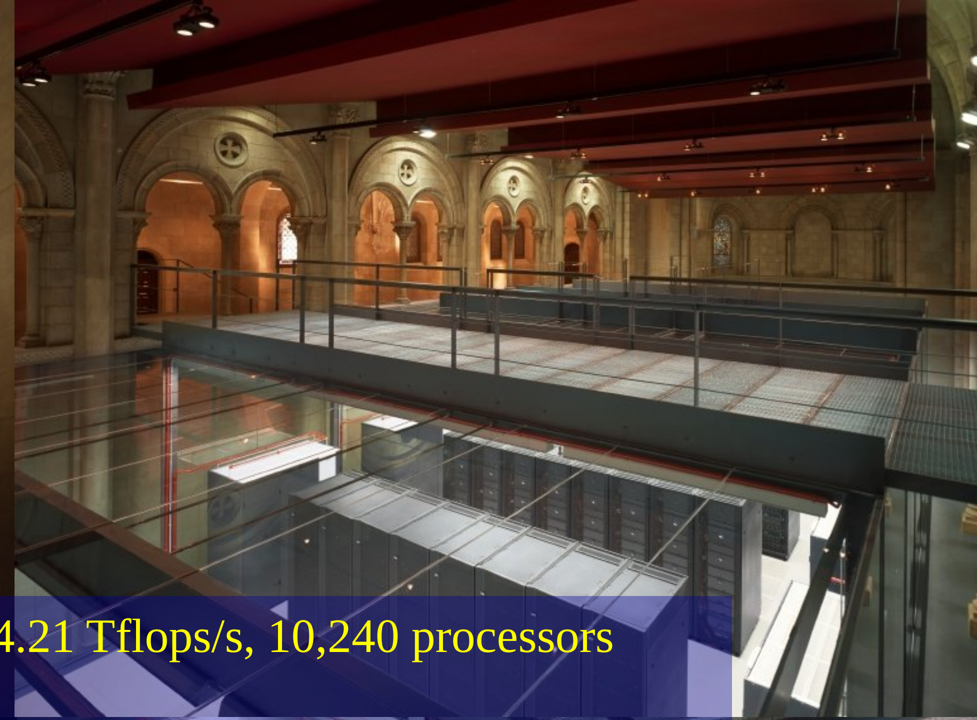


Glasner & Livne 1995; Glasner, Livne, & Truran 1997, 2005, 2007, 2012

The build-up of **convective eddies** at the envelope's base (2-D) causes **shear flow** at the core/envelope interface [**Kelvin-Helmholtz instability**]: pure "solar-like" accreted material can be **enriched** at the late stages of the TNR by some sort of ***convective overshoot*** (Woosley 1986), leading to a powerful nova event!

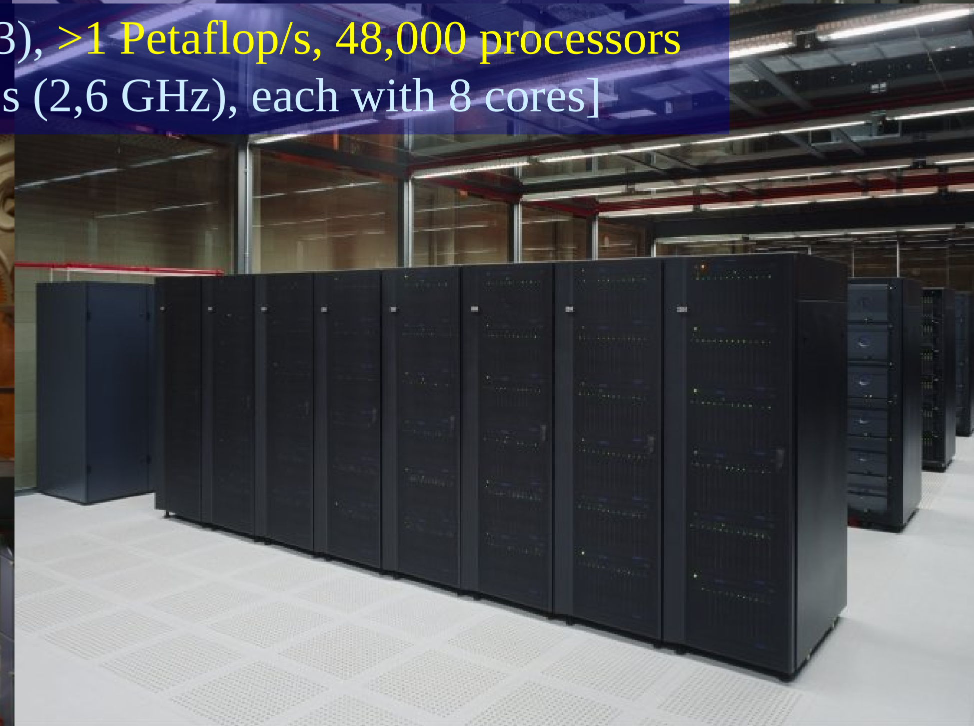
Kelvin-Helmholtz instabilities

Casanova, JJ, García-Berro,Shore & Calder, Nature, 2011

MareNostrum II (BSC, 2006), 94.21 Tflops/s, 10,240 processors

MareNostrum III (BSC, Jan. 2013), >1 Petaflop/s, 48,000 processors
[6,000 Intel SandyBridge chips (2,6 GHz), each with 8 cores]

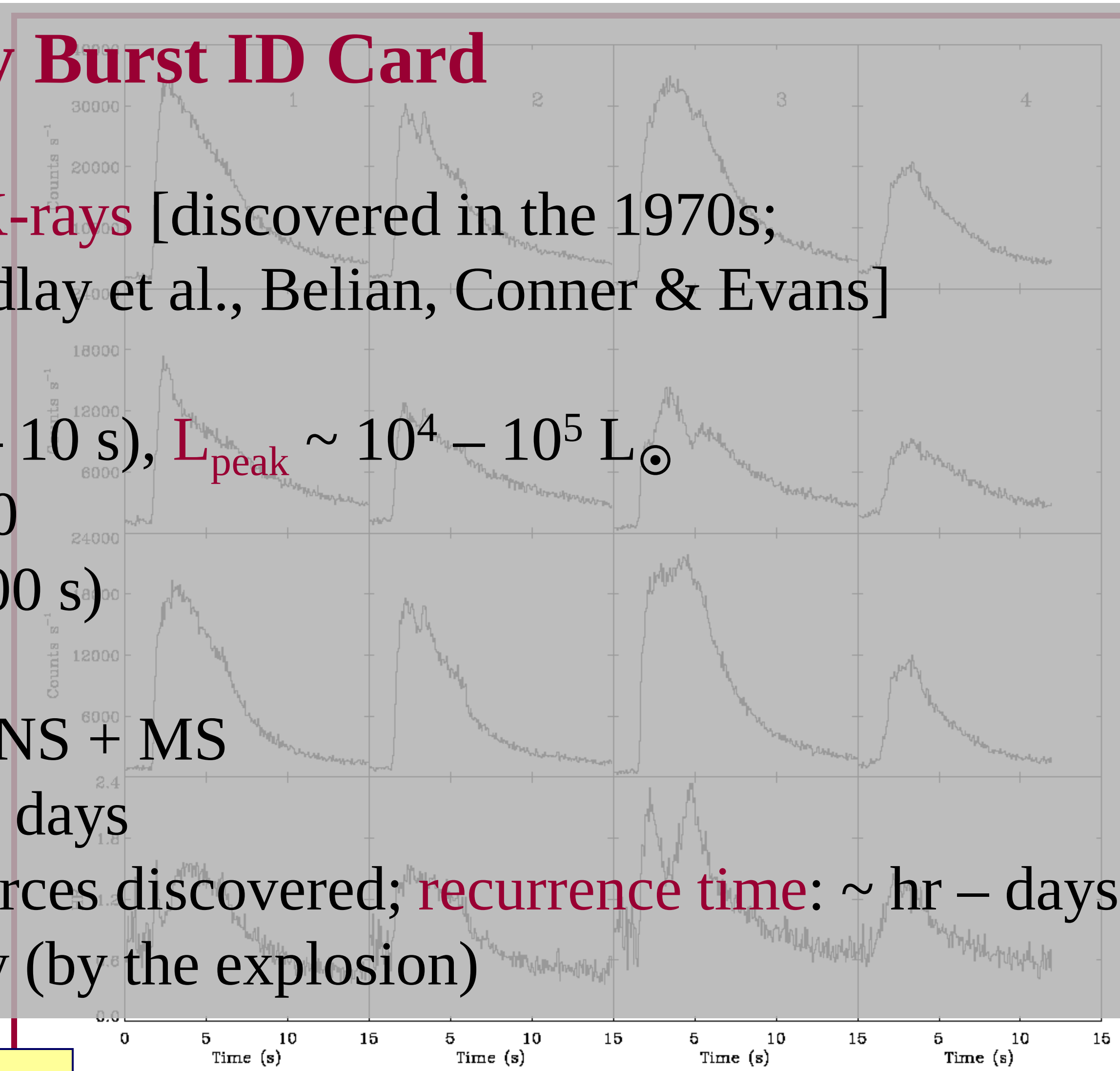
IV. Type I X-Ray Bursts

The (Type I) X-Ray Burst ID Card

Prominent emitters in X-rays [discovered in the 1970s; Babushkina et al., Grindlay et al., Belian, Conner & Evans]

Very fast rise times (1 – 10 s), $L_{peak} \sim 10^4 – 10^5\ L_\odot$
$\alpha = L_{persistent}/L_{burst} \sim 100$
$E \sim 10^{39}$ ergs (in 10 - 100 s)

Stellar binary systems: NS + MS
Recurrence time: ~ hr – days
About 100 Galactic sources discovered; recurrence time: ~ hr – days
Mass ejected? Unlikely (by the explosion)



Strohmeyer & Bildsten (2002)
4U 1728 –34, RXTE

Nucleosynthesis in Type I X-Ray Bursts

Santa Fe, NM

NS ➞ $T_{peak} > 10^9$ **K,** $\rho_{max} \sim 10^6$ **g.cm**$^{-3}$

Detailed nucleosynthesis studies require **hundreds of isotopes**, up to **SnSbTe** mass region (Schatz et al. 2001) or beyond (the flow in Koike et al. 2004 reaches ^{126}Xe), and thousands of nuclear interactions

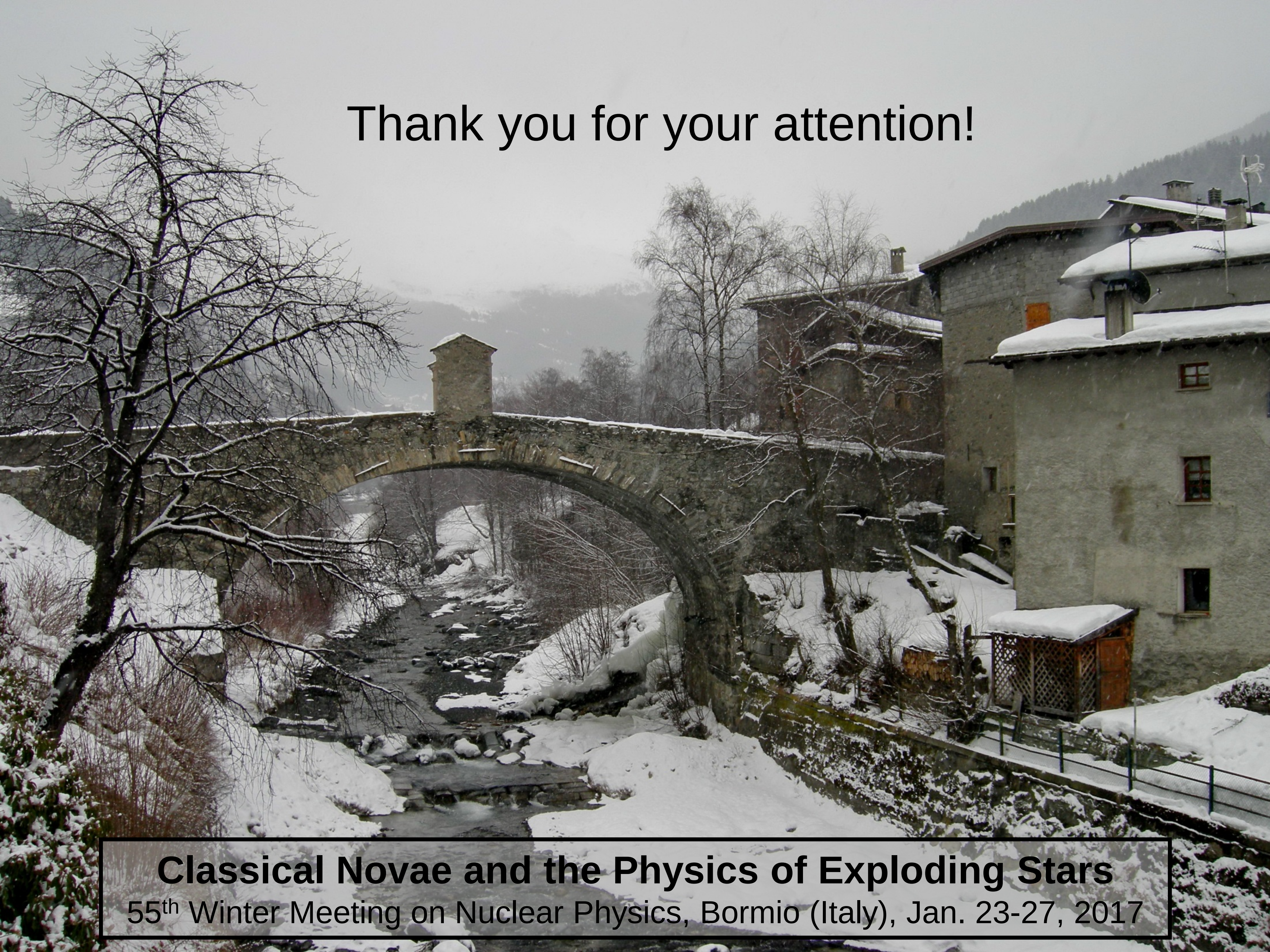
Main nuclear reaction flow driven by the *rp-process* (rapid p-captures and β^+-decays), the 3α-reaction, and the *αp-process* (a sequence of (α,p) and (p,γ) reactions), and proceeds away from the valley of stability, merging with the proton drip-line beyond **A = 38** (Schatz et al. 1999)

Degeneracy
At the very early stages of accretion, the envelope in both CNe and XRBs is mildly degenerate → A small T increase is enough **to lift degeneracy** (~ 10% Tpeak)

NS → $M_{NS} \sim 1.4\ M_{\odot}$, $R_{NS} \sim 10$ km → $v_{esc} = \sqrt{2G\ M_{NS}/R_{NS}} \sim$ **190,000 km s^{-1}**

WD → $M_{WD} \sim 1\ M_{\odot}$, $R_{WD} \sim 6000$ km → $v_{esc} \sim$ **7000 km s^{-1}**

➡ **CNe are halted by expansion** while **XRBs are halted by fuel consumption** (due to efficient CNO–breakout reactions)


Thank you for your attention!
Classical Novae and the Physics of Exploding Stars
55th Winter Meeting on Nuclear Physics, Bormio (Italy), Jan. 23-27, 2017