Collisions of two white dwarfs and the associated nucleosynthesis

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The Beginning and Ends of Double White Dwarfs
Geological Museum, Copenhaguen (Denmark)
July 1st- 5th, 2019

WD-WD collisions are rare events !?
Only in dense ambients like the core of GC
Neglected as nucleosynthesis agents

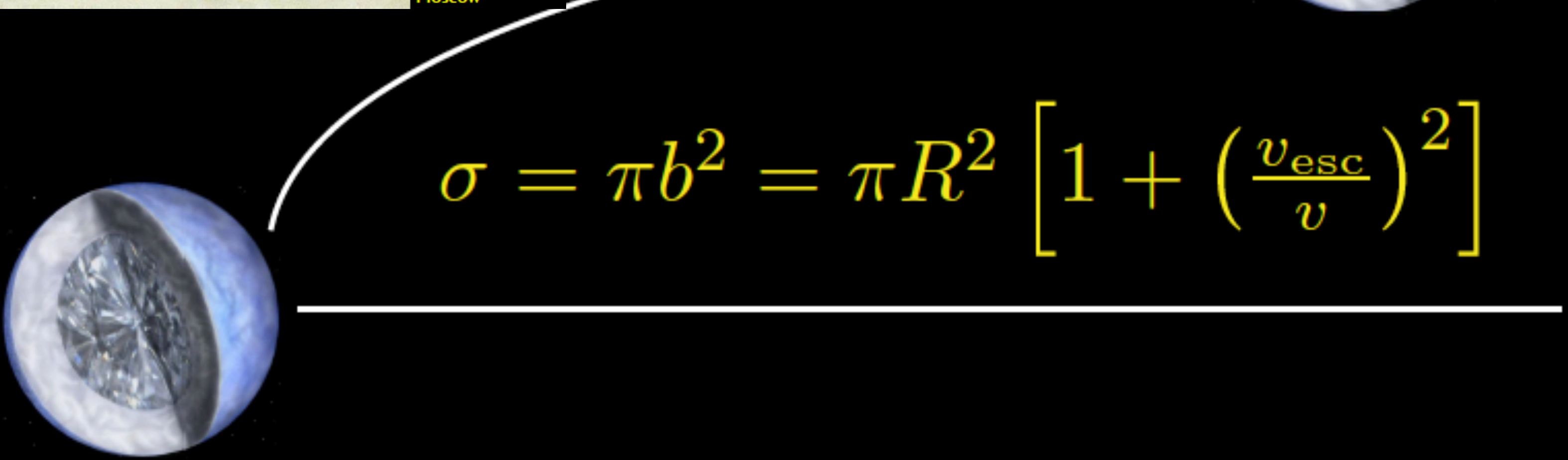
Duel Between Onegin and Lenski

Ilya Repin (1899)

Pen, brush, ink, watercolor.

Pushkin Museum, Moscow

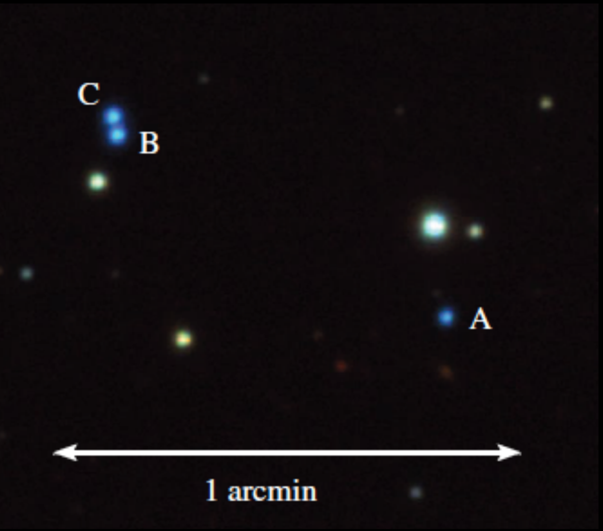
Like a duel this mechanism is single shot



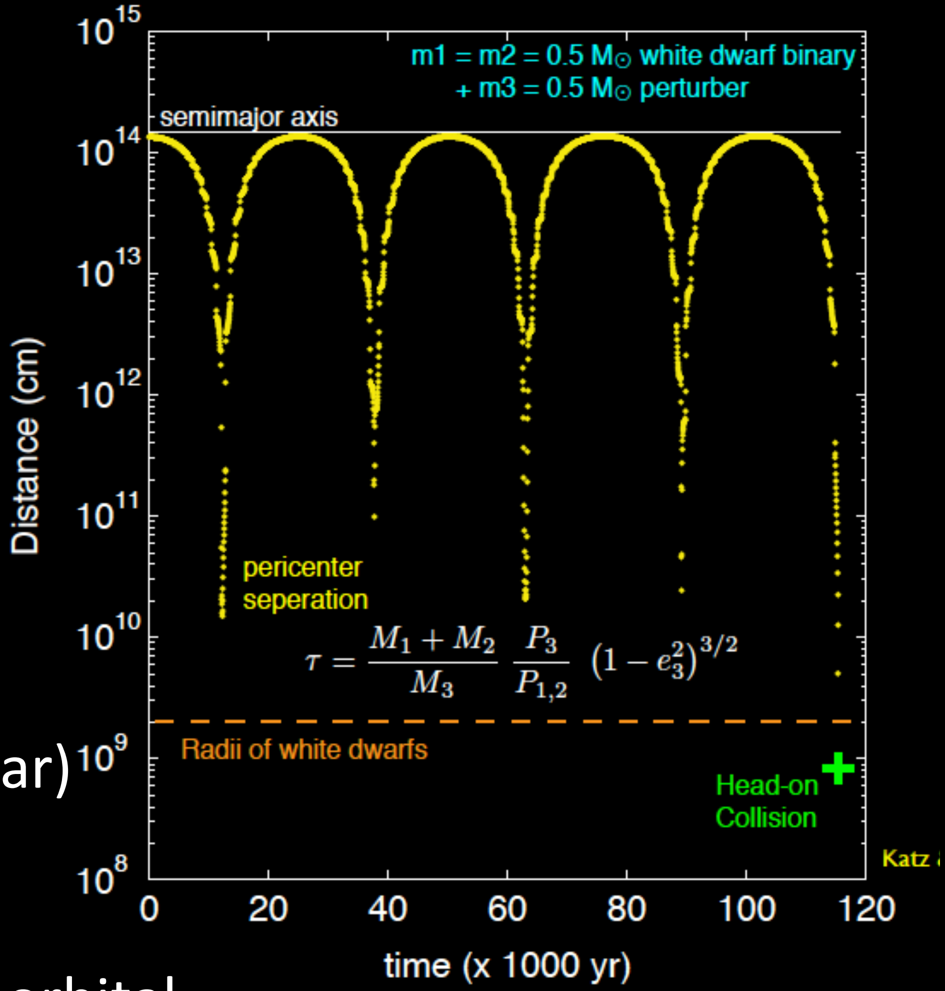
$$\sigma = \pi b^2 = \pi R^2 \left[1 + \left(\frac{v_{\rm esc}}{v}\right)^2\right]$$

From F. Timmes COCOCUBE presentation

Hierarchical stellar systems



Triple WD
J1943-1019
Perpinyà-Vallés+’19



Many field stars are in double, triple or multiple systems

Hierachical triples (binary+ a3d star) are stable but

Eccentricity of the binary and the inclination of the inner and outer orbital planes can change periodically (Kodai-Lidov cycles) leading to collisions or strong encounters

Evolution of stars in such conditions not well understood (Toonen+’16)

How frequent are these collisons? A matter of debate

Katz & Dong’12 suggest that WD-WD clean collisions in such systems could account alone the SNIa frequency (a substantial part)

Toonen+’18: Triple star evolution synthess -> $f_{ts} << f_{SNIa}$

Hallakoun & Maoz’19: From Gaia2 $N_{obs}(WDWD_T) < 10^n N_{req}(SNIa)$ $n \leq -1$

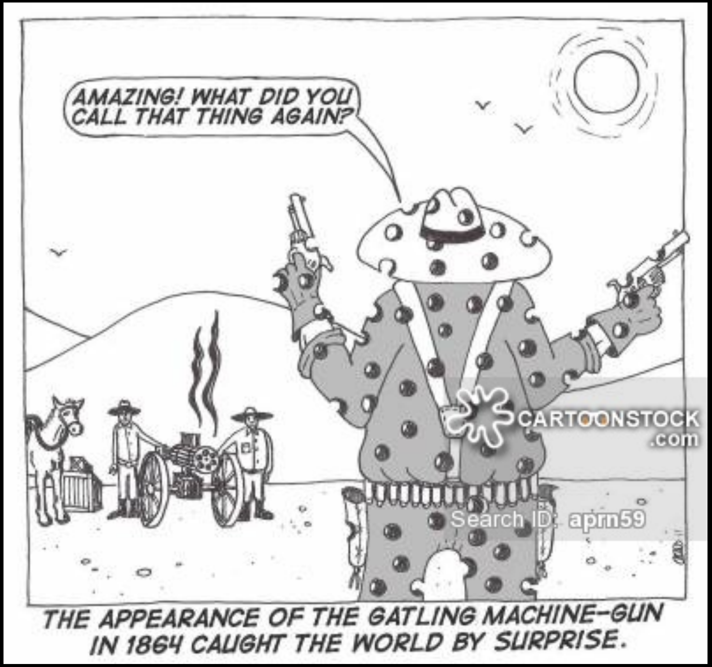
Fang Quadruple systems are more efficient

#Quick when WD are born

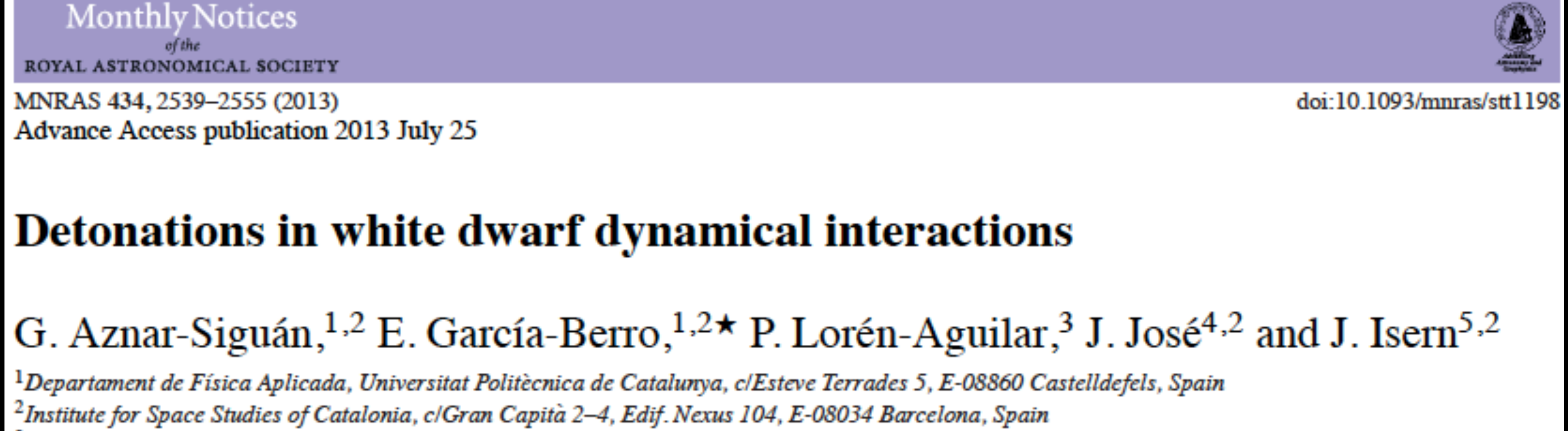
Collisions occur any where in the Galaxy with a non completely negligible frequency

We have moved from a duel with a single shot pistol to a duel with a machine gun

What happens with the ‘failed’ collisions?



THE APPEARANCE OF THE GATLING MACHINE-GUN IN 1864 CAUGHT THE WORLD BY SURPRISE.



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Advance Access publication 2013 July 25

Detonations in white dwarf dynamical interactions

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ya, c/Comte d'Urgell 187, E-08036 Barcelona, Spain
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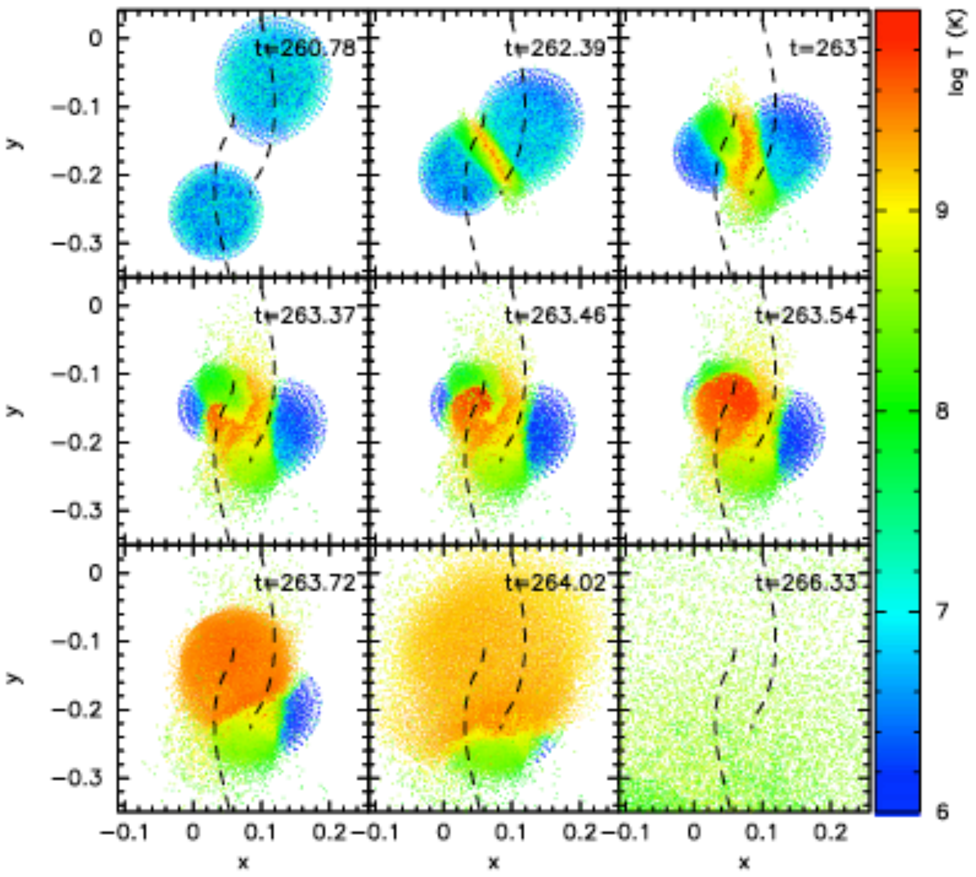
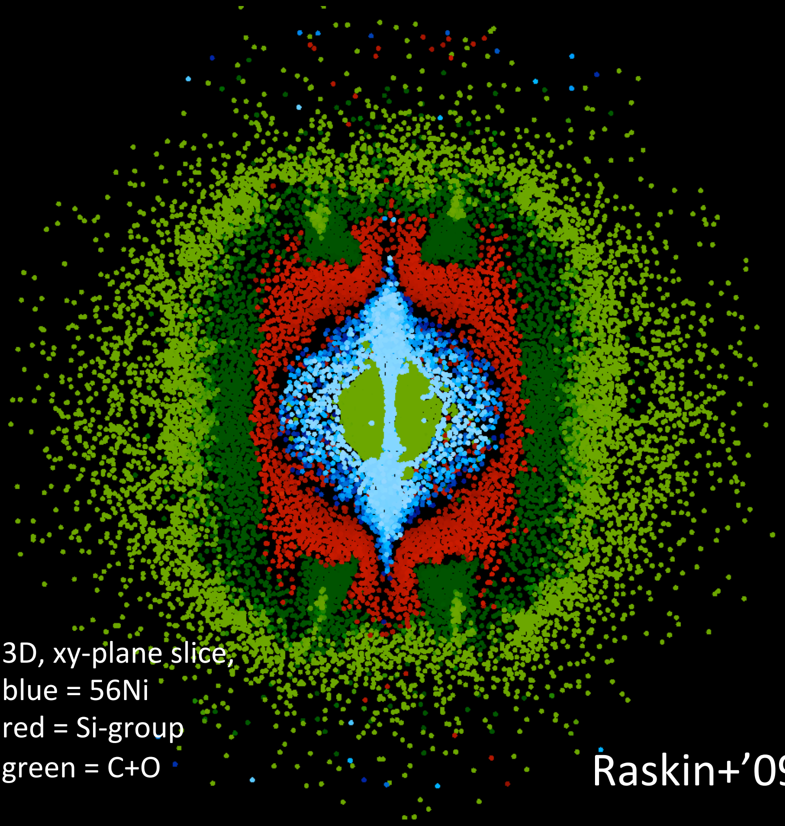
1.0+0.8 Mo



0.8 CO+ #

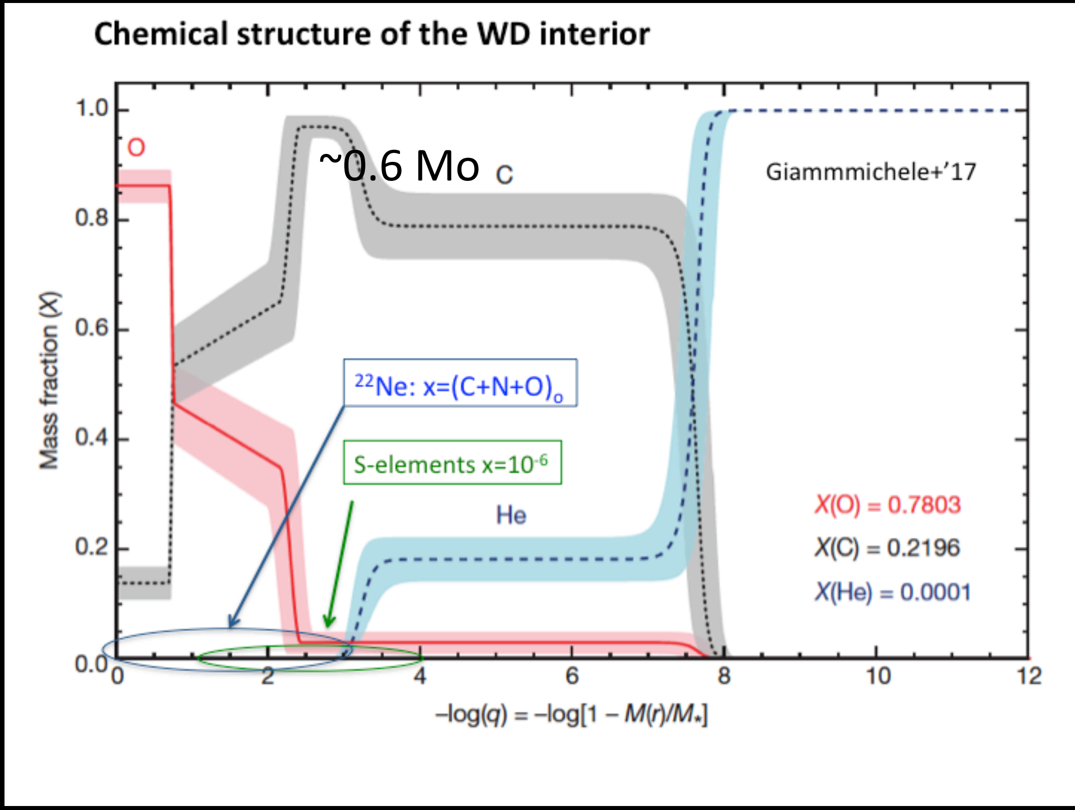
Depending on geometry, mass & chemical composition

- Detonations (^{56}Ni...)
- Partial burning (IME: Si,...)
- Ejection of WD mass



3D, xy-plane slice,
blue = 56Ni
red = Si-group
green = C+O

Raskin+’09



Chemical structure of the WD interior

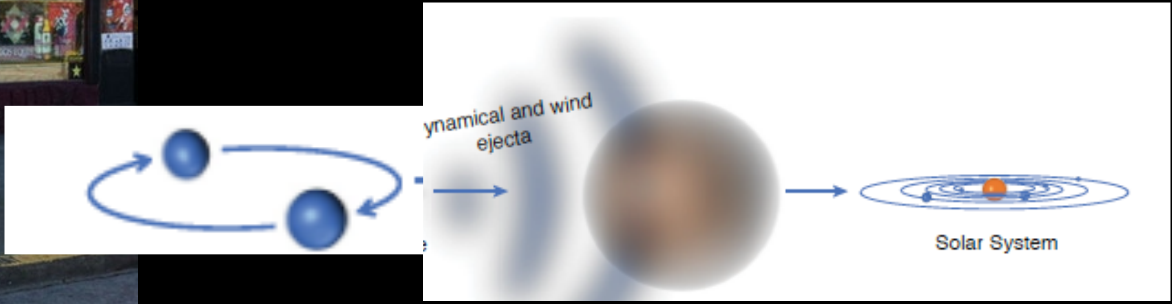
Benz+’89
Rosswood+’09
Raskin+’09,10
Hawley+’12
García-Senz+’13
Aznar-Siguan+’13,14,17

→ M_{Ni} ~0.01-1 M_o

What about this non processed material?

The Stardust Market

If this ejecta can form dust and survives the ISM shocks



Adapted from José'16

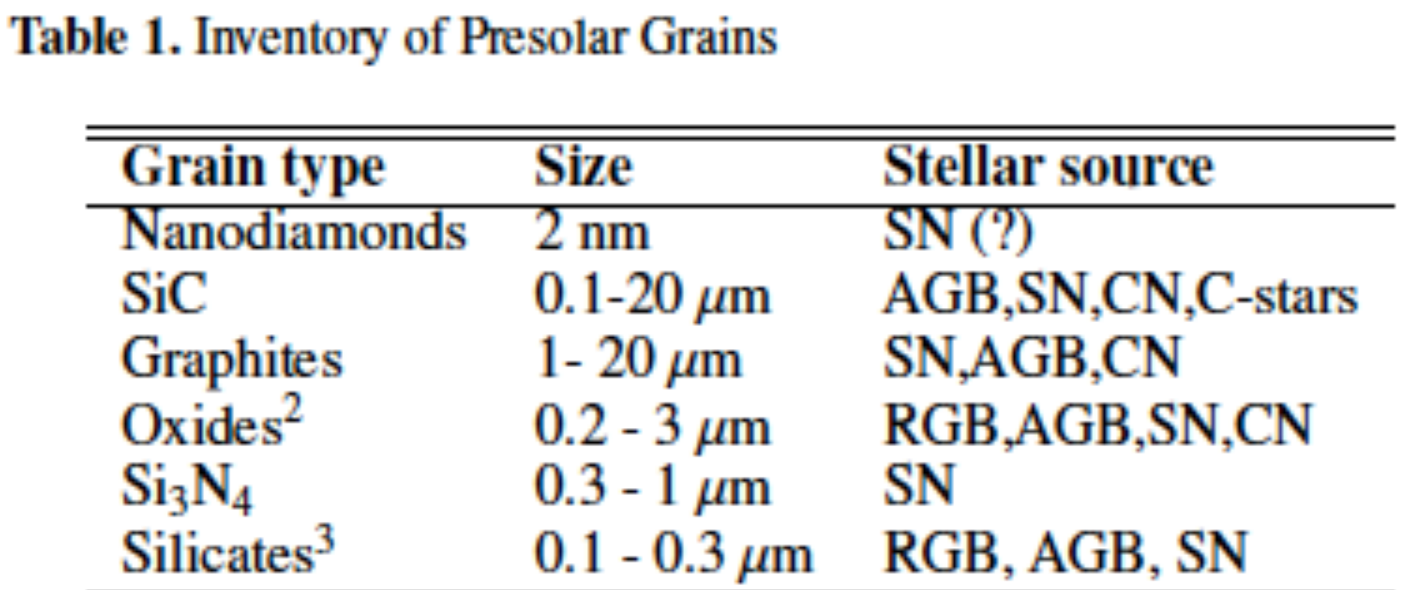


Table 1. Inventory of Presolar Grains

Grain type	Size	Stellar source
Nanodiamonds	2 nm	SN (?)
SiC	0.1-20 μm	AGB,SN,CN,C-stars
Graphites	1- 20 μm	SN,AGB,CN
Oxides[2]	0.2 - 3 μm	RGB,AGB,SN,CN
Si_3N_4	0.3 - 1 μm	SN
Silicates[3]	0.1 - 0.3 μm	RGB, AGB, SN

Murchison meteorite

Ne-E: Grains containing important amounts of ^{22}Ne (Black & Pepin'69) in Orgueil Meteorite

$(^{20}Ne/^{22}Ne)_E \sim 3.4$ $(^{20}Ne/^{22}Ne)_{solar} \sim 13.6$

Series of new measurements in Orgueil & Murchisson lowered this value

Two types of Ne-E
*Ne-E(H): released at high T (1100-1500 °C) & high density (2.5-3.1 g/cc)
*Ne-E(L): " low T(500-800 °C) & low density (2.4-2.5 g/cc)

Carrier Ne-E(H): SiC grains Probably formed in AGB stars
Carrier Ne-E(L): graphite: Probably in CCSN

Formation of graphite implies absence of oxygen

Murchison meteorite

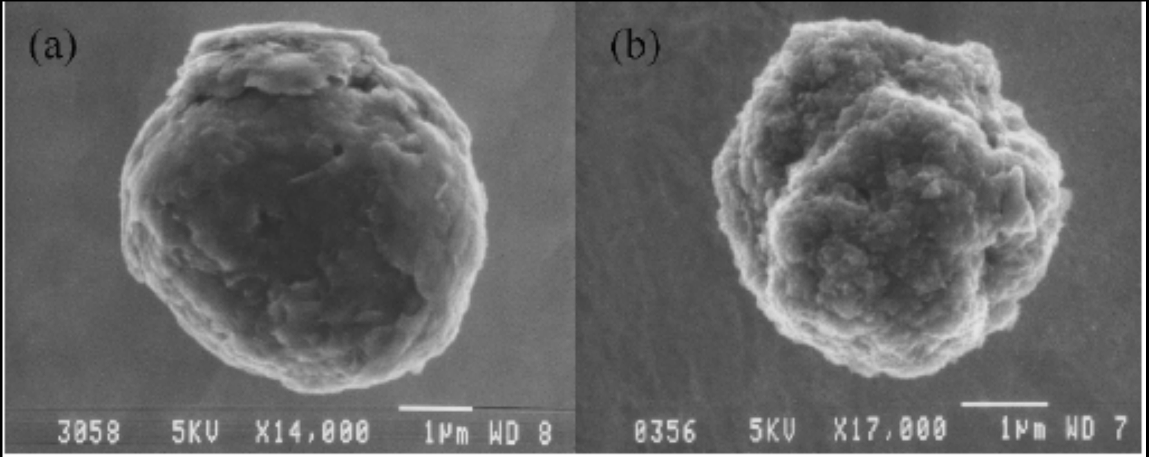
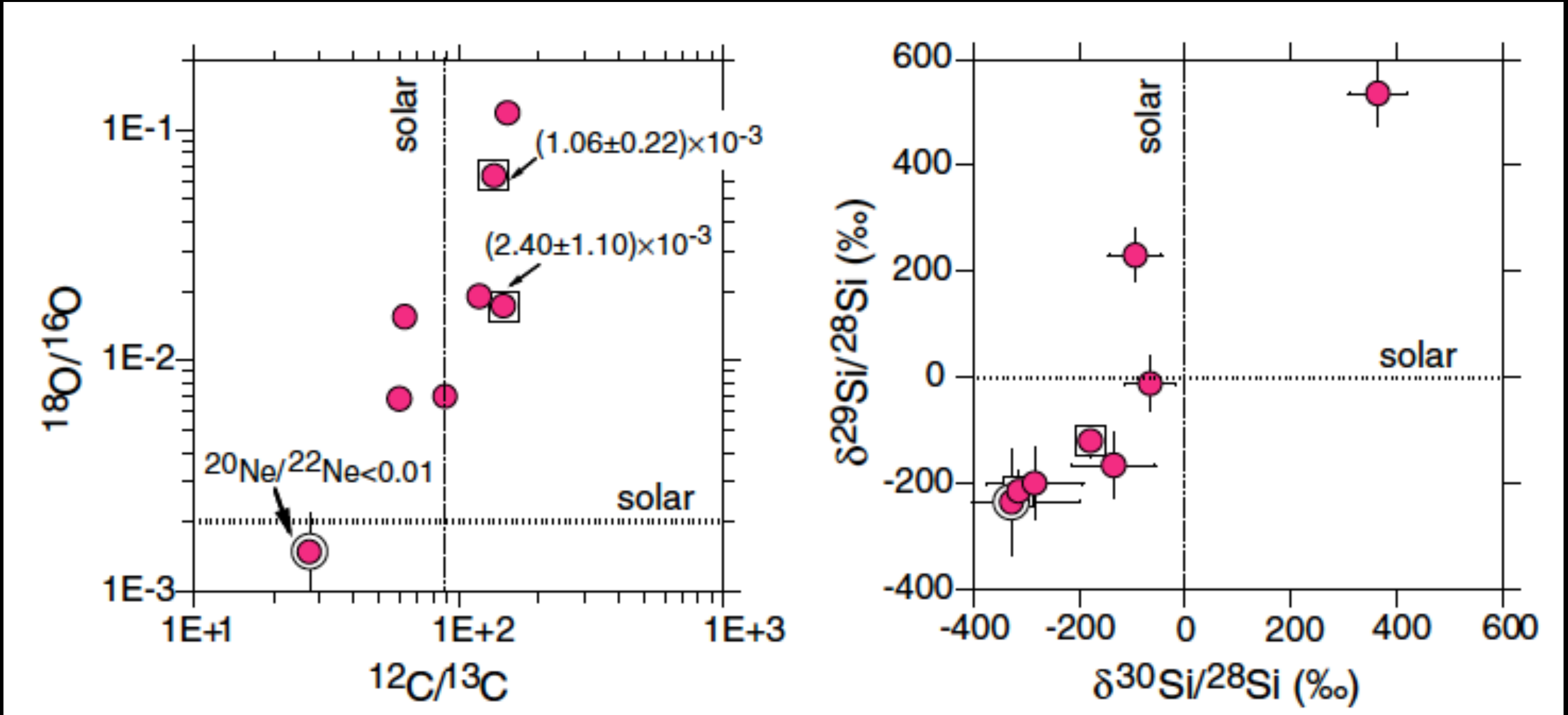


Fig. 10. Presolar graphite grains show two morphologies. (a) A graphite grain of the "onion" type, with a layered surface structure. (b) A graphite grain of the "cauliflower" type, which appears as aggregates of small grains.

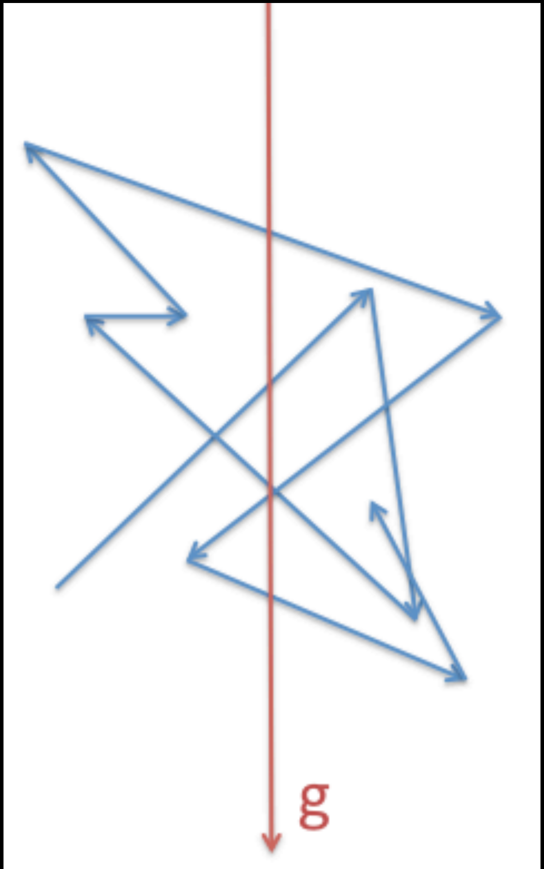
$(^{20}Ne/^{22}Ne)_{solar} \sim 13.6$

Amari'09

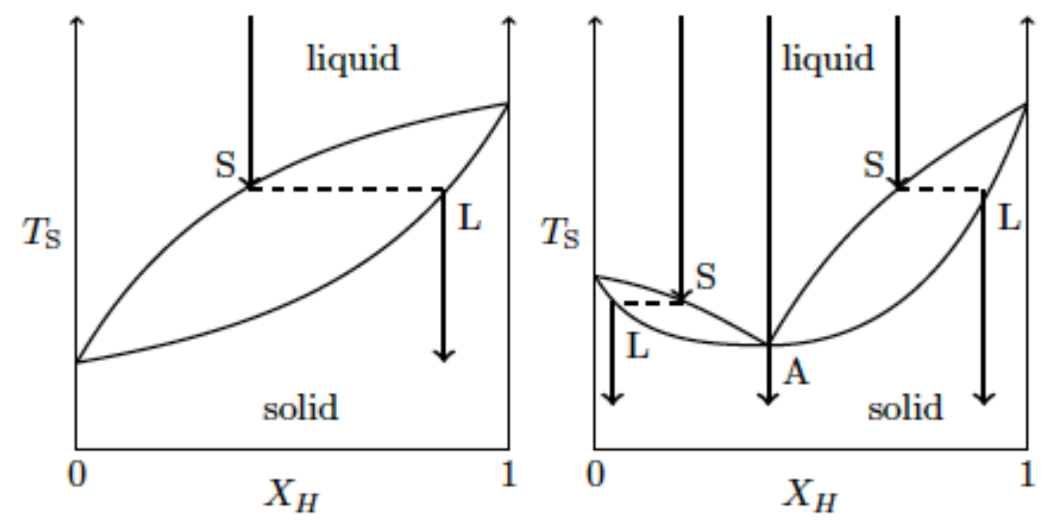


How the chemical composition of white dwarf interiors evolves?

Diffusion



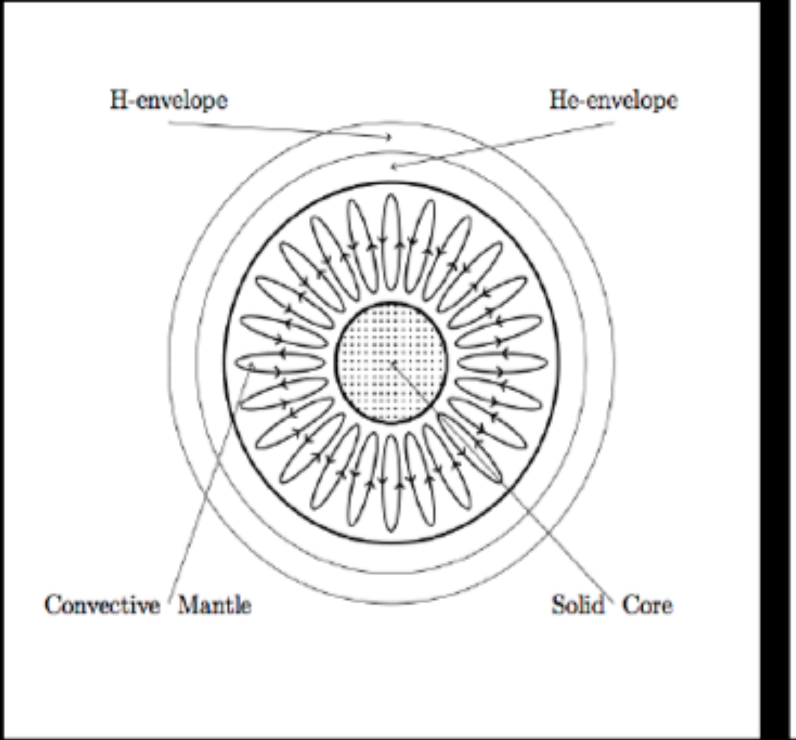
Crystallization of Coulomb plasmas



$$\Gamma = \frac{(Ze)^2}{ak_BT} = 170 - 180$$

Hernanz+'94
Segretain+'94
Isern+'91
Isern+'97
Isern+'00

Structure of the white dwarf upon crystallization



THE ASTROPHYSICAL JOURNAL LETTERS, 836:L28 (5pp), 2017 February 20

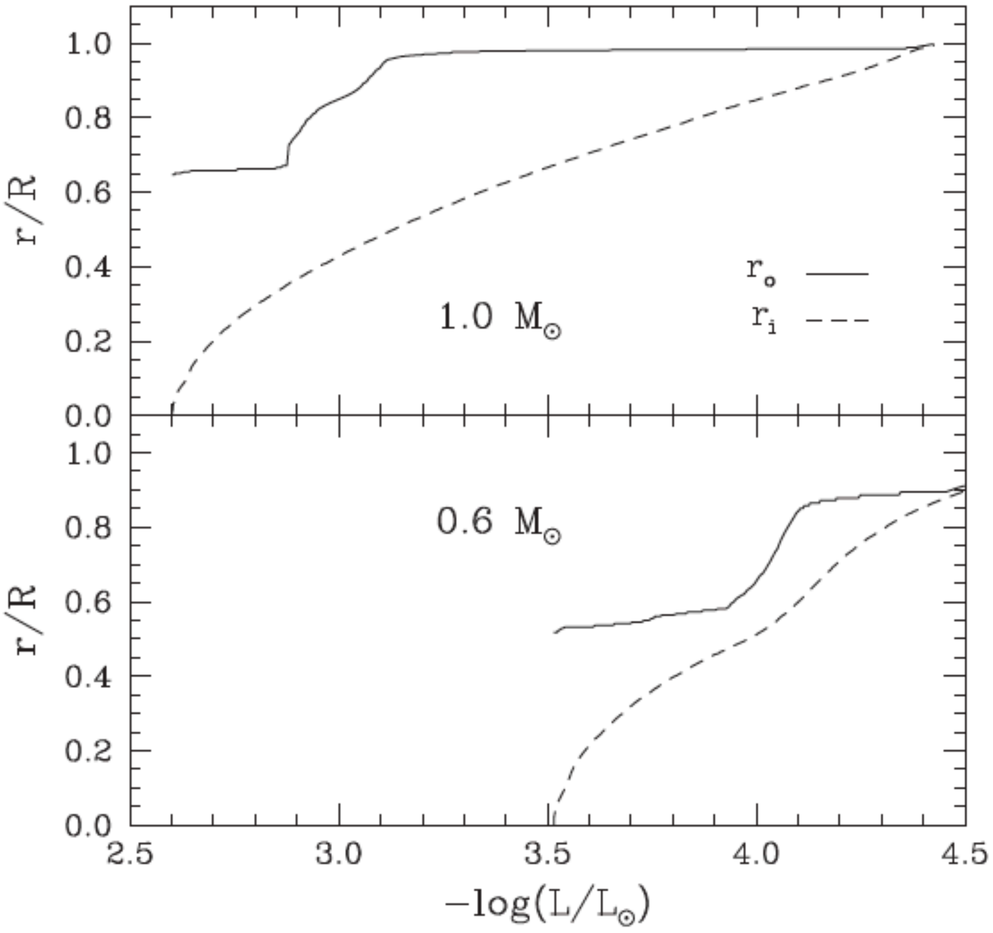
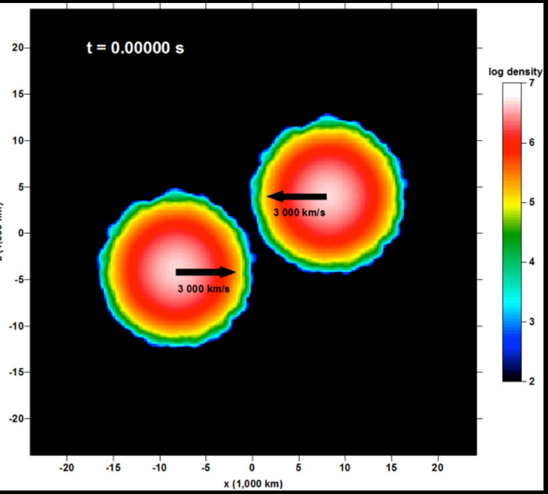
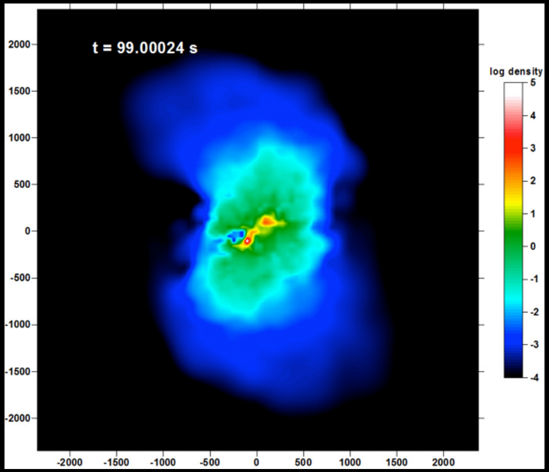


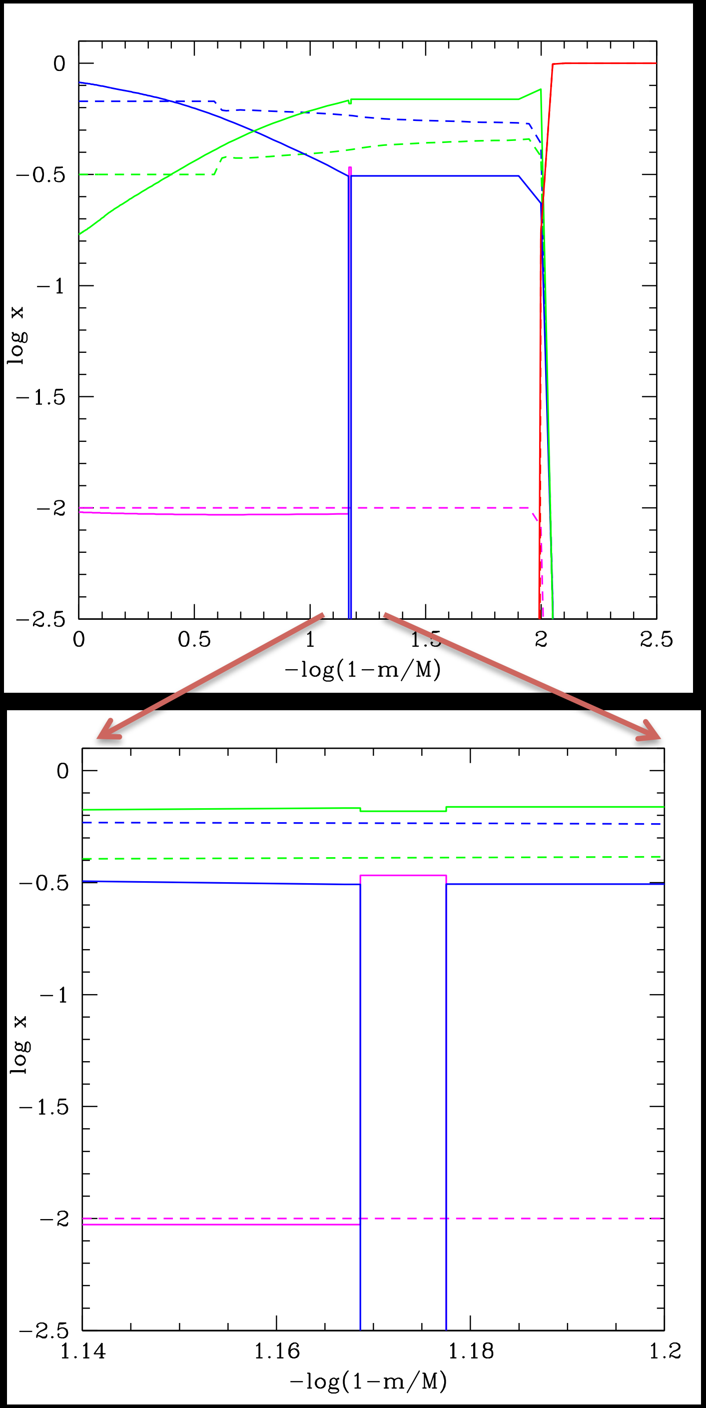
Figure 1. Evolution of the inner and outer radii of the convective mantle of a carbon–oxygen white dwarf as a function of the luminosity. The upper and lower panels correspond to white dwarfs with masses 1.0 and 0.6 $M_\odot$, respectively. Their respective total radii are $R = 4.7 \times 10^8$ and 7.5×10^8 cm.

The structure of the WD remembers that of the Earth

0.64 Mo + 0.64 Mo (Bravo’18)
Density versus time





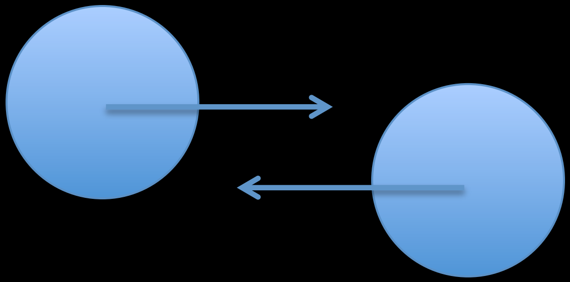


During the collision 3-8x10^{-4} M_o of C+^{22}Ne are ejected

Isern & Bravo’18 RNAAS
Isern & Bravo’18 EUWD21

Collision modelling

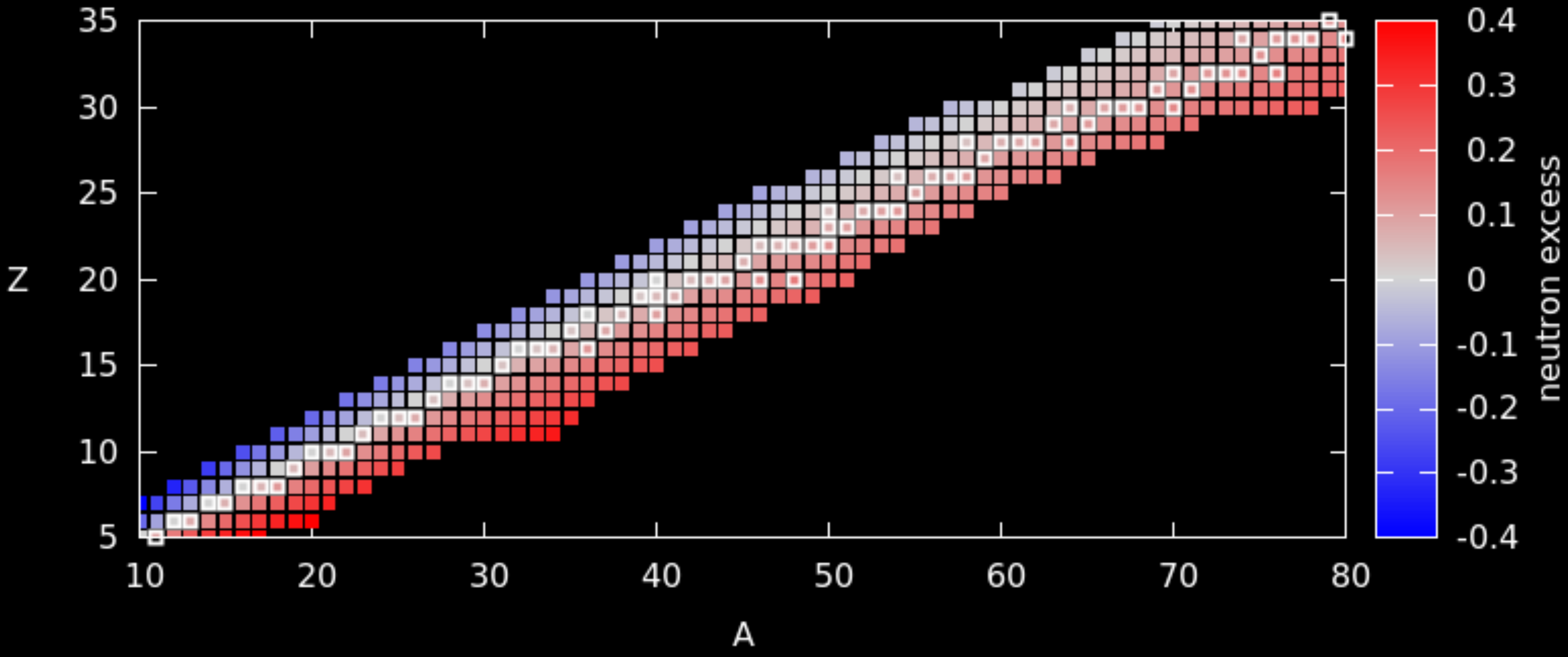
Bravo & Isern in preparation

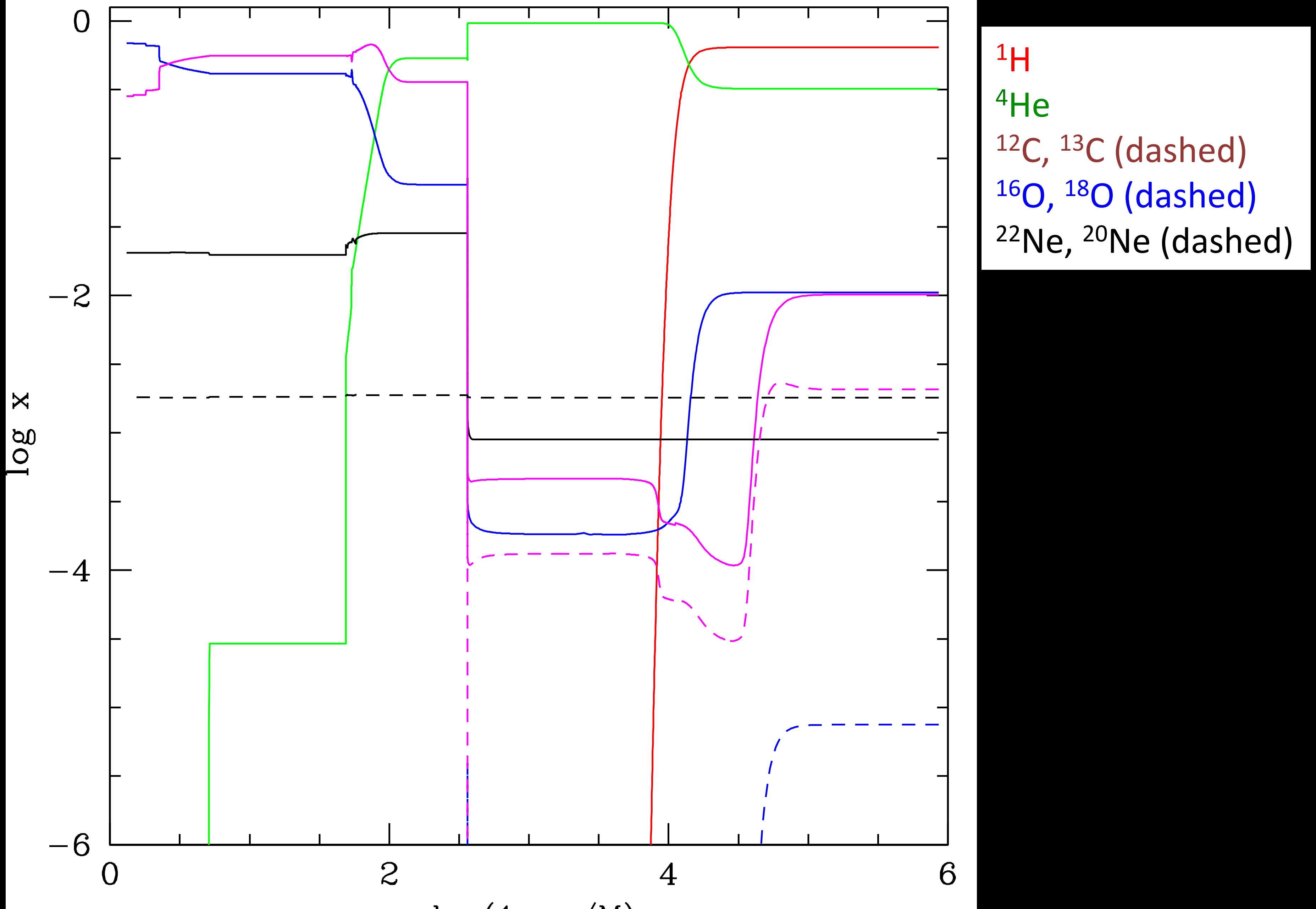


Adapted from the SPH code used in SNIa simulations:
Garcia-Senz, D., Bravo, E. & Serichol, N. (1998)
Bravo, E. et al. (2009)

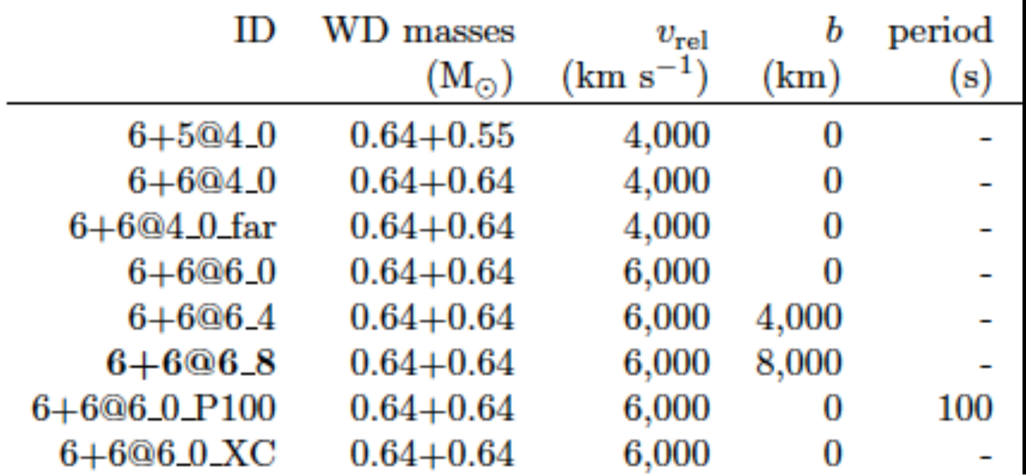
Post processing: A: 1-> 100; 720 isotopes, starting with those of H, Li,...

Grafics only 10 < A < 80





Camisassa+'16



ID	WD masses ($M_\odot$)	$v_{\rm rel}$ (km s^{-1})	b (km)	period (s)
6+5@4_0	0.64+0.55	4,000	0	-
6+6@4_0	0.64+0.64	4,000	0	-
6+6@4_0_far	0.64+0.64	4,000	0	-
6+6@6_0	0.64+0.64	6,000	0	-
6+6@6_4	0.64+0.64	6,000	4,000	-
6+6@6_8	0.64+0.64	6,000	8,000	-
6+6@6_0_P100	0.64+0.64	6,000	0	100
6+6@6_0_XC	0.64+0.64	6,000	0	-

Parallel velocities
Non rotating except **P100

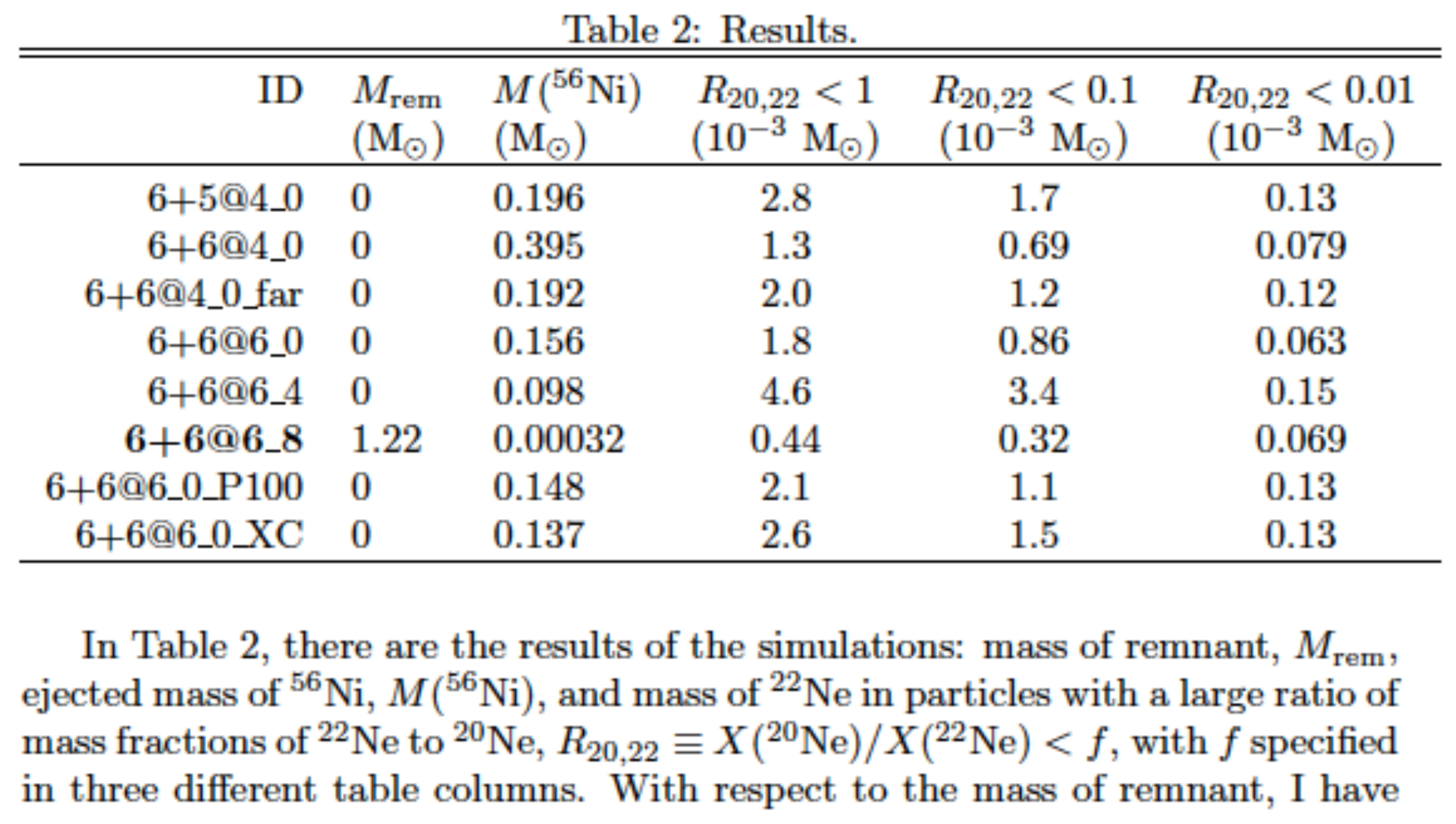
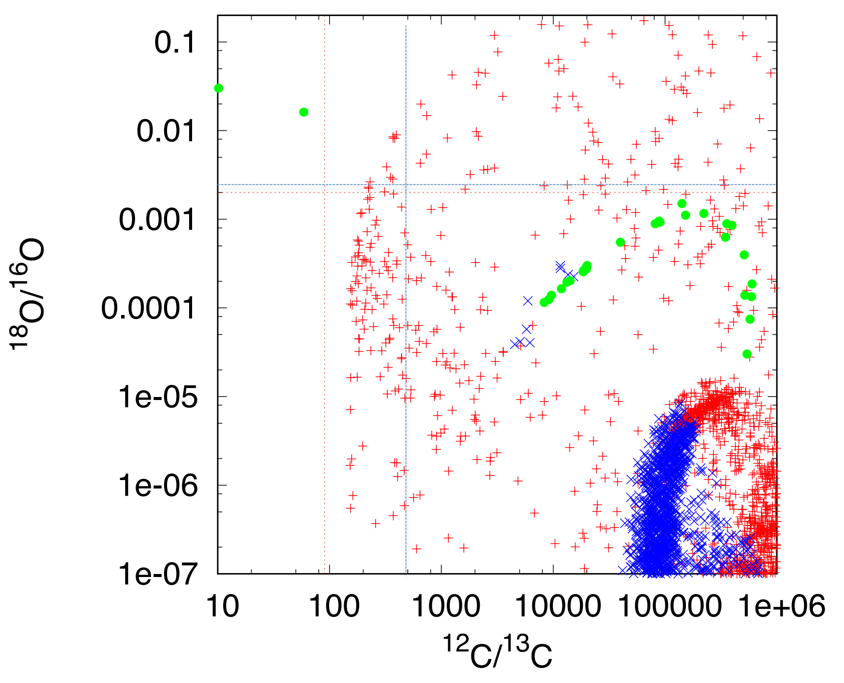
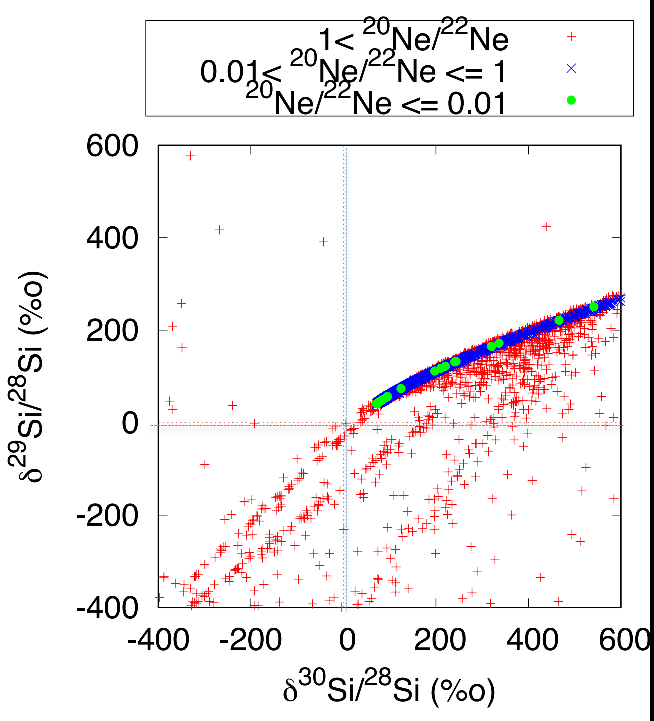


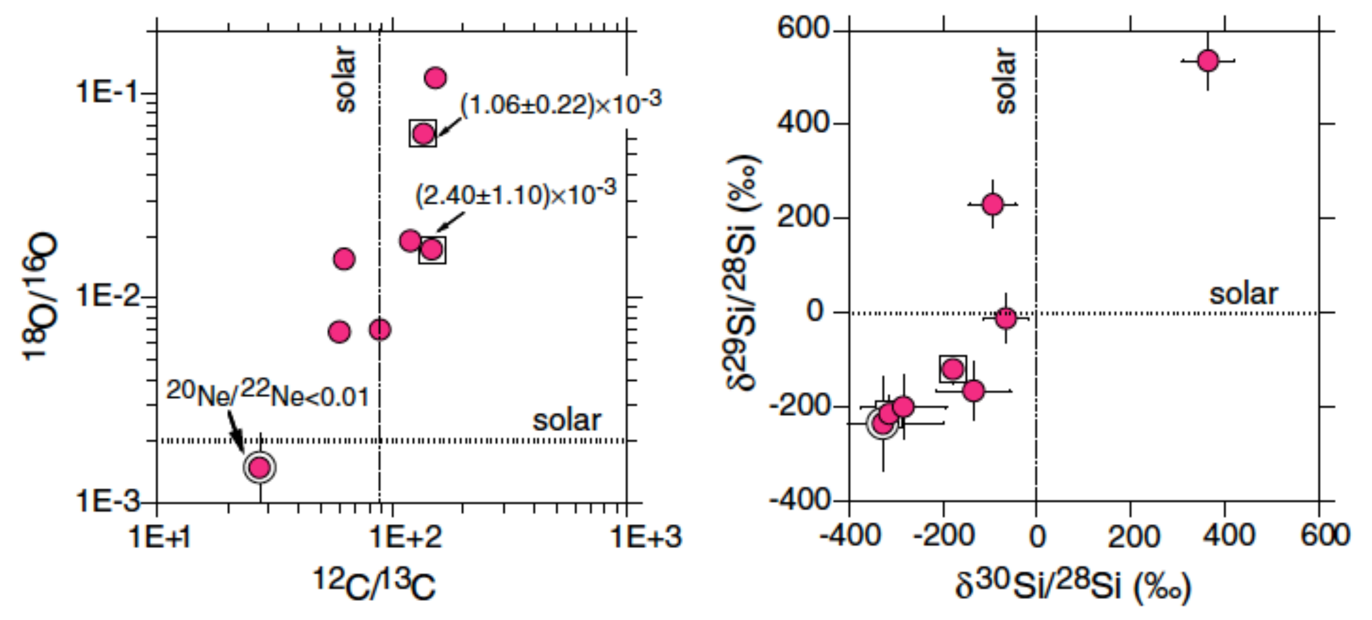
Table 2: Results.

ID	$M_{\rm rem}$ ($M_\odot$)	$M(^{56}{\rm Ni})$ ($M_\odot$)	$R_{20,22} < 1$ (10^{-3} $M_\odot$)	$R_{20,22} < 0.1$ (10^{-3} $M_\odot$)	$R_{20,22} < 0.01$ (10^{-3} $M_\odot$)
6+5@4_0	0	0.196	2.8	1.7	0.13
6+6@4_0	0	0.395	1.3	0.69	0.079
6+6@4_0_far	0	0.192	2.0	1.2	0.12
6+6@6_0	0	0.156	1.8	0.86	0.063
6+6@6_4	0	0.098	4.6	3.4	0.15
6+6@6_8	1.22	0.00032	0.44	0.32	0.069
6+6@6_0_P100	0	0.148	2.1	1.1	0.13
6+6@6_0_XC	0	0.137	2.6	1.5	0.13

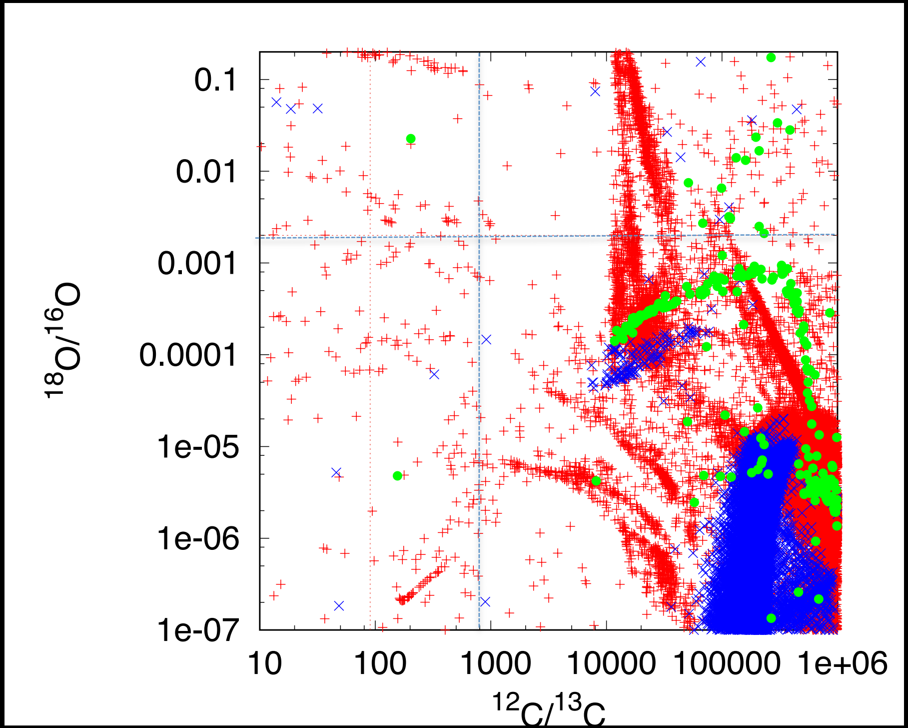
In Table 2, there are the results of the simulations: mass of remnant, $M_{\rm rem}$, ejected mass of ^{56}Ni, $M(^{56}{\rm Ni})$, and mass of ^{22}Ne in particles with a large ratio of mass fractions of ^{22}Ne to ^{20}Ne, $R_{20,22} \equiv X(^{20}{\rm Ne})/X(^{22}{\rm Ne}) < f$, with f specified in three different table columns. With respect to the mass of remnant, I have

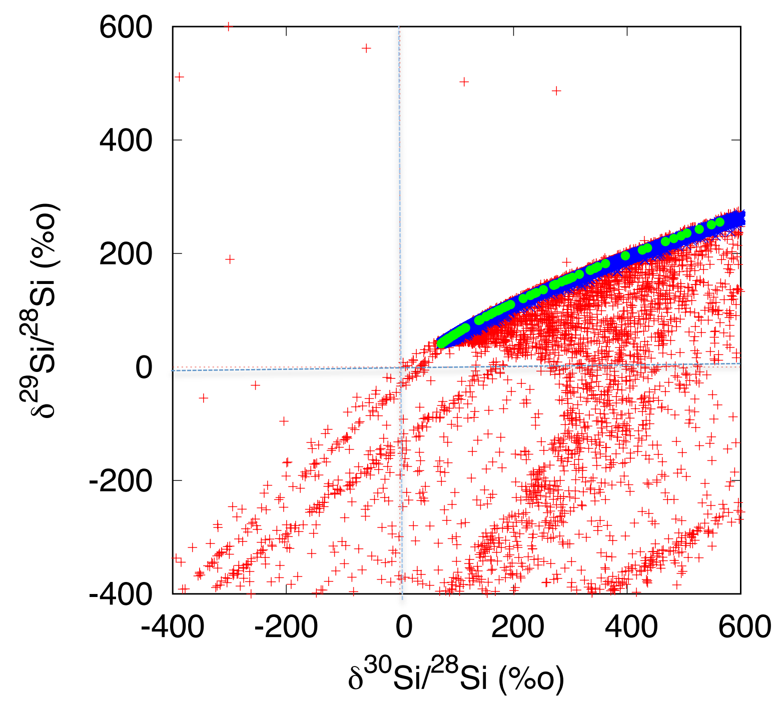

0.1
0.01
0.001
0.0001
1e-05
1e-06
1e-07
$^{18}O/^{16}O$
10
100
1000
10000
100000
1e+06
$^{12}C/^{13}C$

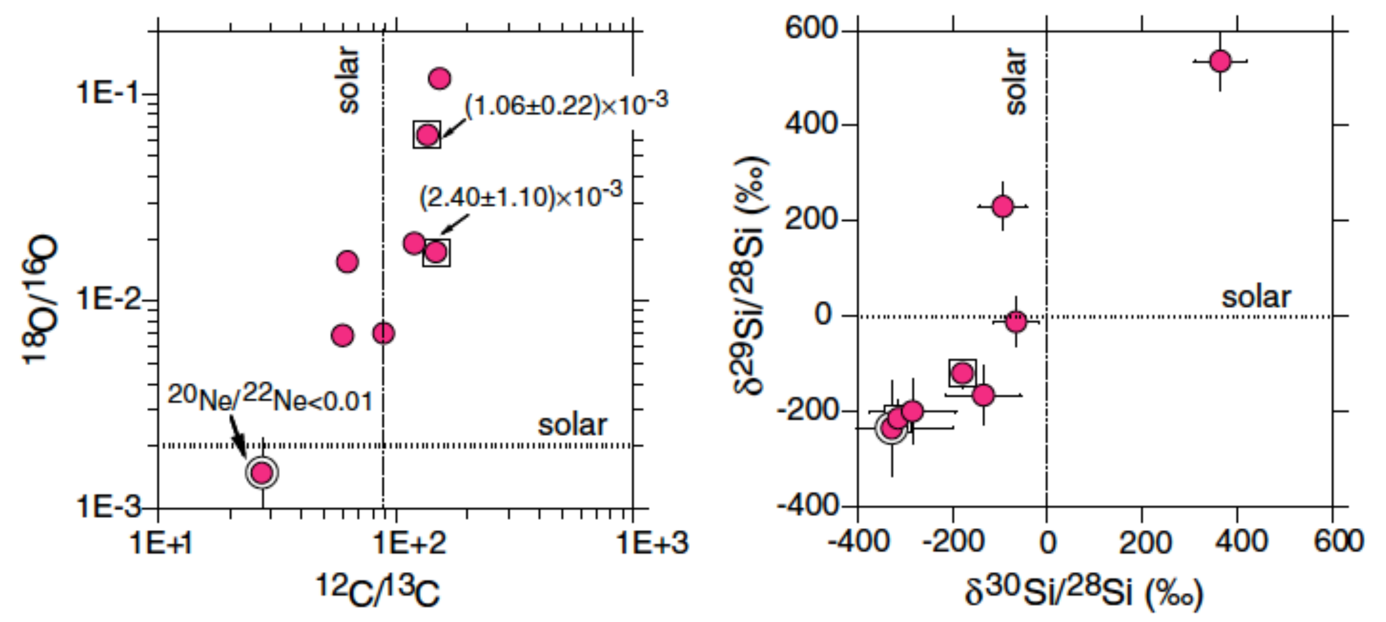

$1< {}^{20}Ne/{}^{22}Ne$ +
$0.01< {}^{20}Ne/{}^{22}Ne <= 1$ ×
$^{20}Ne/^{22}Ne <= 0.01$ ●
600
400
200
0
-200
-400
$\delta^{29}Si/^{28}Si$ (%o)
-400
-200
0
200
400
600
$\delta^{30}Si/^{28}Si$ (%o)


1E-1
1E-2
1E-3
$^{18}O/^{16}O$
solar
$(1.06\pm0.22)\times10^{-3}$
$(2.40\pm1.10)\times10^{-3}$
$^{20}Ne/^{22}Ne<0.01$
solar
1E+1
1E+2
1E+3
$^{12}C/^{13}C$
600
400
200
0
-200
-400
$\delta^{29}Si/^{28}Si$ (‰)
solar
solar
-400
-200
0
200
400
600
$\delta^{30}Si/^{28}Si$ (‰)

6+6@6.0


0.1
0.01
0.001
0.0001
1e-05
1e-06
1e-07
10
100
1000
10000
100000
1e+06
$^{18}O/^{16}O$
$^{12}C/^{13}C$


600
400
200
0
-200
-400
-400
-200
0
200
400
600
$\delta^{29}Si/^{28}Si$ (%o)
$\delta^{30}Si/^{28}Si$ (%o)


1E-1
1E-2
1E-3
1E+1
1E+2
1E+3
$^{18}O/^{16}O$
$^{12}C/^{13}C$
solar
solar
(1.06±0.22)×10^{-3}
(2.40±1.10)×10^{-3}
$^{20}Ne/^{22}Ne<0.01$
600
400
200
0
-200
-400
-400
-200
0
200
400
600
$\delta^{29}Si/^{28}Si$ (‰)
$\delta^{30}Si/^{28}Si$ (‰)
solar
solar

6+6@6.8

Diffusion

Iben & MacDonald’85

- Radiative forces can be ignored
- Particles, including electrons are Maxwellian
- Main thermal velocities are much greater than diffusion velocities
- Magnetic fields are absent
- Thermal diffusion can be ignored

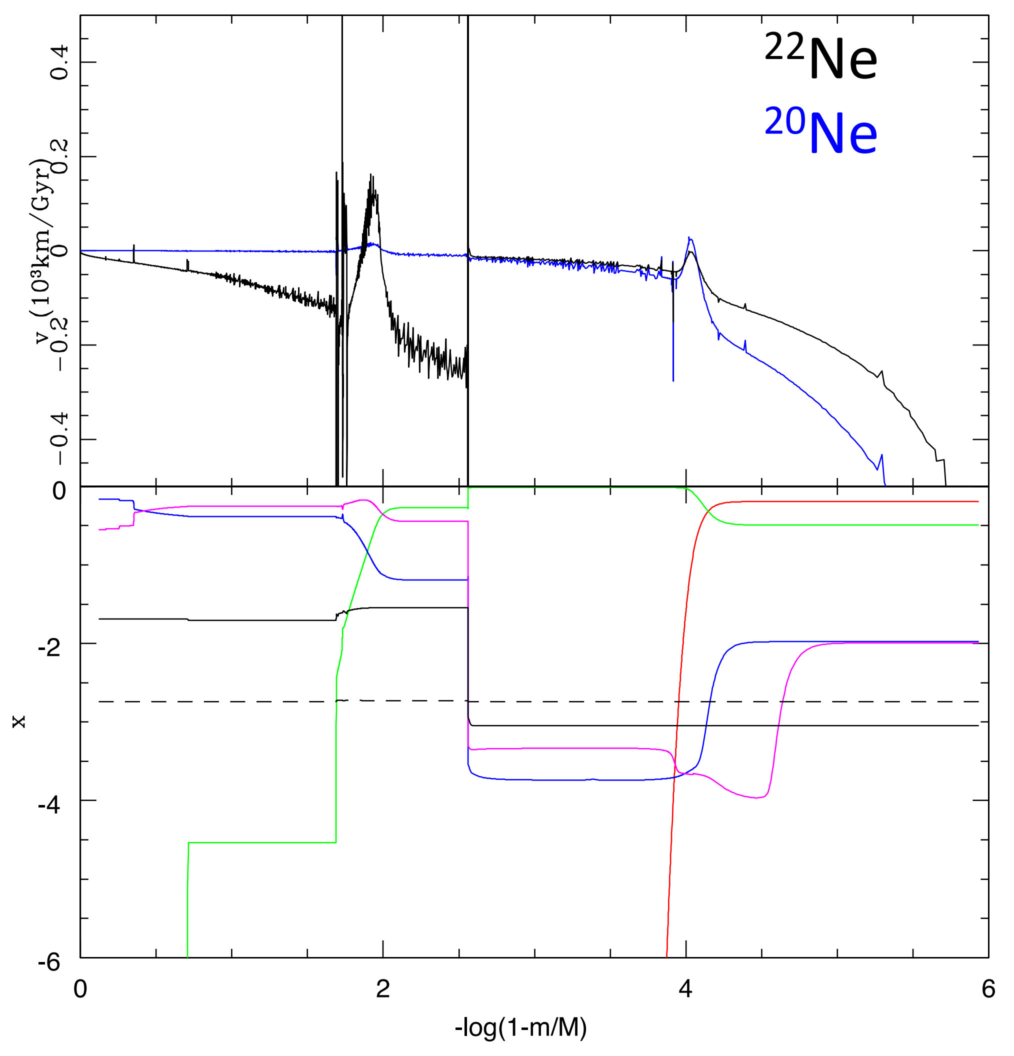
$$\frac{dP_i}{dr} - \frac{\rho_i}{\rho}\frac{dP}{dr} - n_i Z_i q_e E = \sum_{j\neq i} K_{ij}\left(w_j - w_i\right)$$

$$\sum A_i n_i w_i = 0$$

$$\sum Z_i n_i w_i = 0$$

$$\frac{1}{n_i}\sum_j K_{ij}\left(w_i - w_j\right) - Z_i e E = -A_i m_H g - kT\frac{d\ln T}{dr} - kT\frac{d\ln n_i}{dr}$$

$$J_2 = A\left(\frac{Z_2}{A_2} - \frac{Z_1}{A_1}\right)\nabla P + B\nabla n_2 + C\nabla T + \left(Z_2^{2/3} - Z_1^{2/3}\right)\nabla n_e$$



The mass of electron negligible
Trace element
EoS with Madelung term only

A promising scenario to account for some of the chemical anomalies observed in meteorites

How the other isotopes evolve?
Which is the behavior of polymixtures?
Which is the dynamics of dust formation under such conditions?
Nucleosynthesis?
Is there time enough to guarantee the formation of the azeotropic layer?
Can these anomalies constrain the rate of collisions?
Are there enough collisions to make this mechanism relevant?

Presolar grains?
Extrasolar grains?

Illustration : ESO/ M. Kornmesser

Ouamuamua: First extrasolar asteroid detected
Frequency: TBD (~1/yr within orbit of Earth)
Plans to obtain samples

Conclusions

Once formed the interior of white dwarfs continue to evolve
  * Gravitational settling
  * Crystallization
Important consequences
  * Sources of energy
  * Asteroseismological properties
  * Internal magnetic fields
  * Source of isotopic anomalies if important amounts of unprocessed material are ejected without mixing.
  * …