Nucleosynthesis in nova explosions: prospects for its detection with focusing telescopes

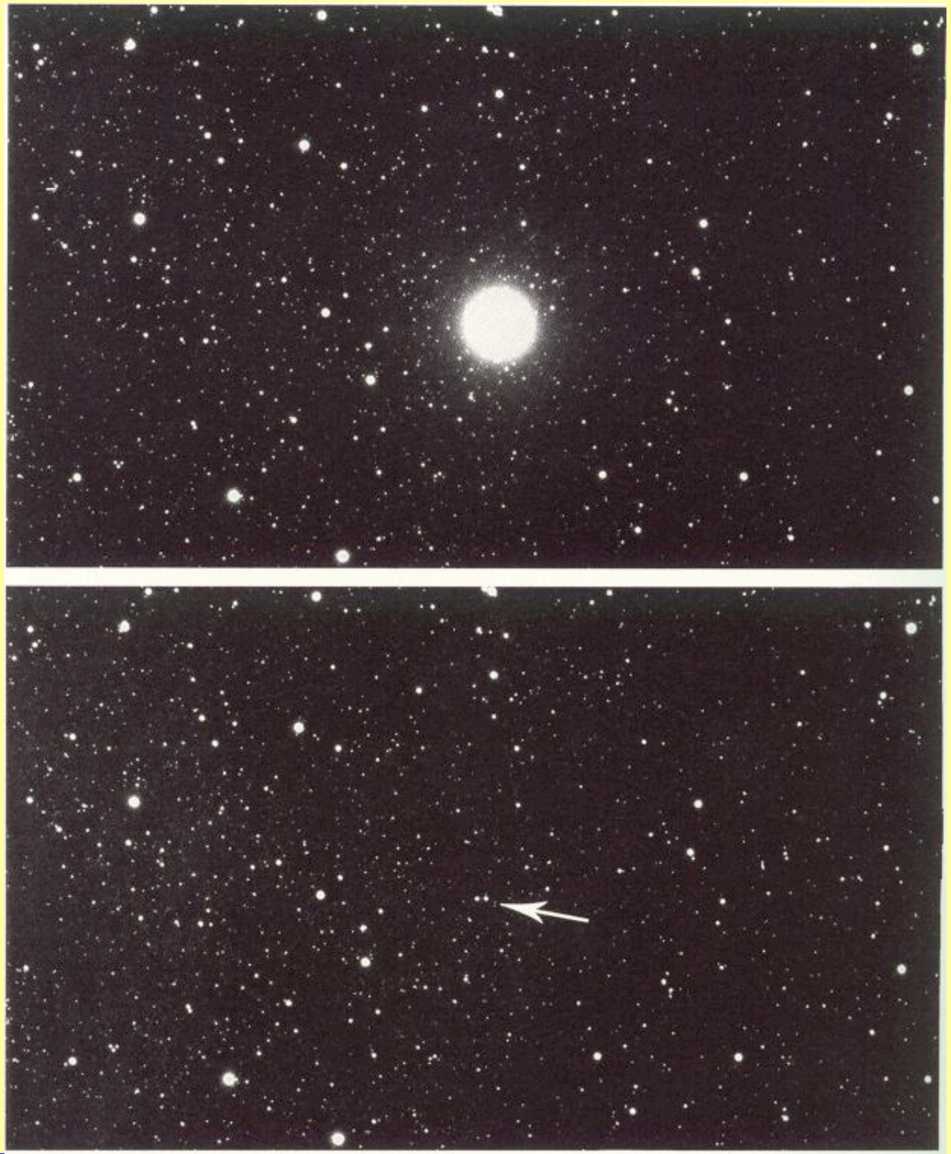
Margarita Hernanz

Institut d'Estudis Espacials de Catalunya, IEEC-CSIC
Barcelona (Spain)

- Introduction: what's a nova? General oberved properties.
- Relevance of nucleosynthesis in classical novae:
  - ¬ elemental abundances observed in particular novae
  - ¬ chemical evolution of the Galaxy
  - ¬ presolar meteoritic grains
  - ¬ **gamma-ray emission**
- **Detectability of novae with focusing gamma-ray telescopes**

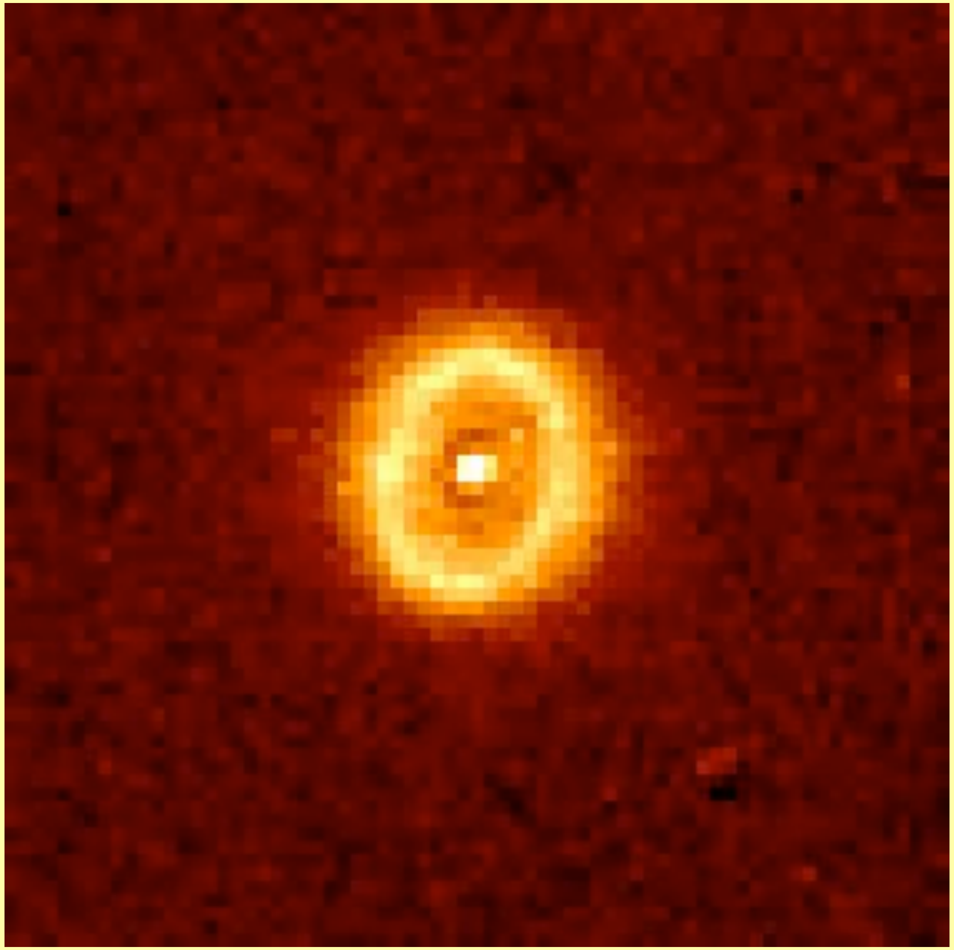
Novae discovery

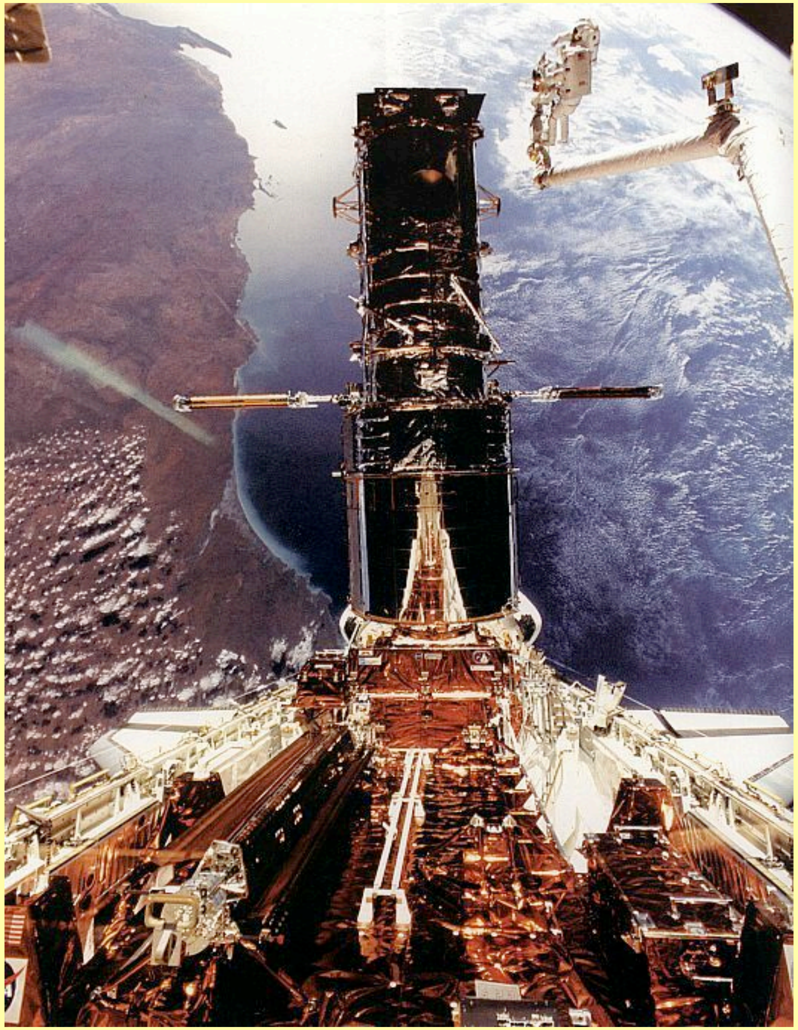
Nova Cygni 1975



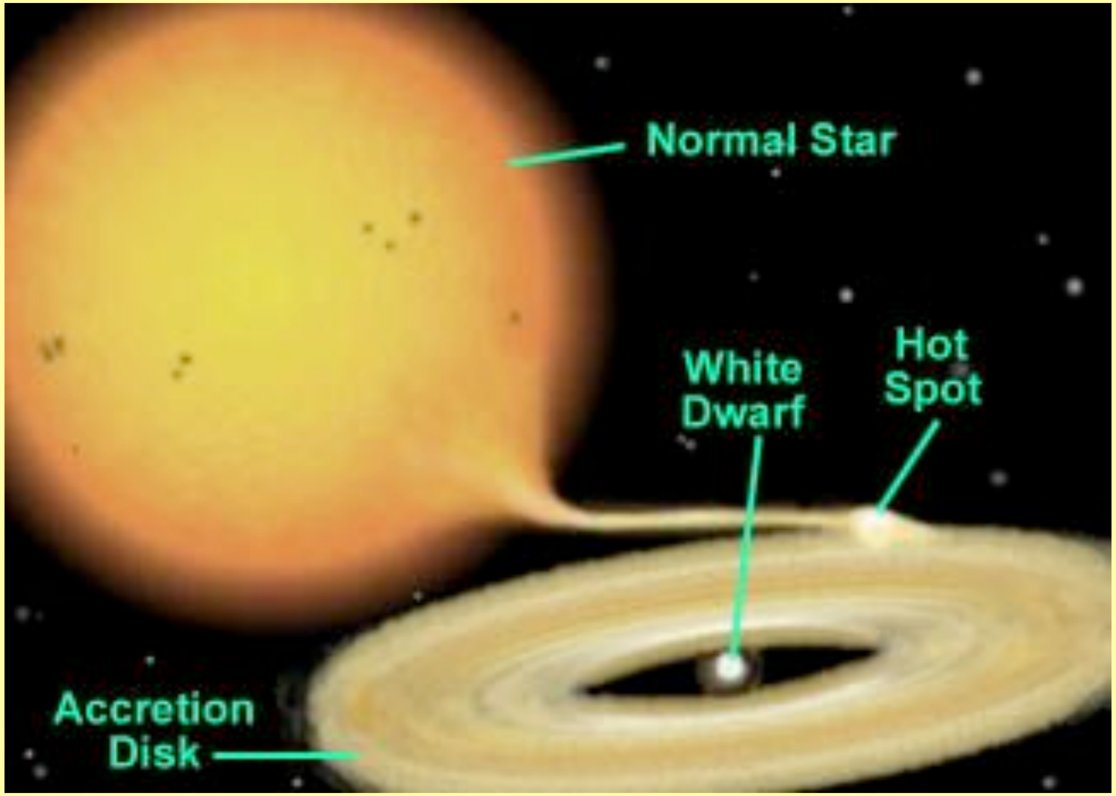
Observations with the Hubble Space Telescope (HST)

Nova Cygni 1992





What's a nova?

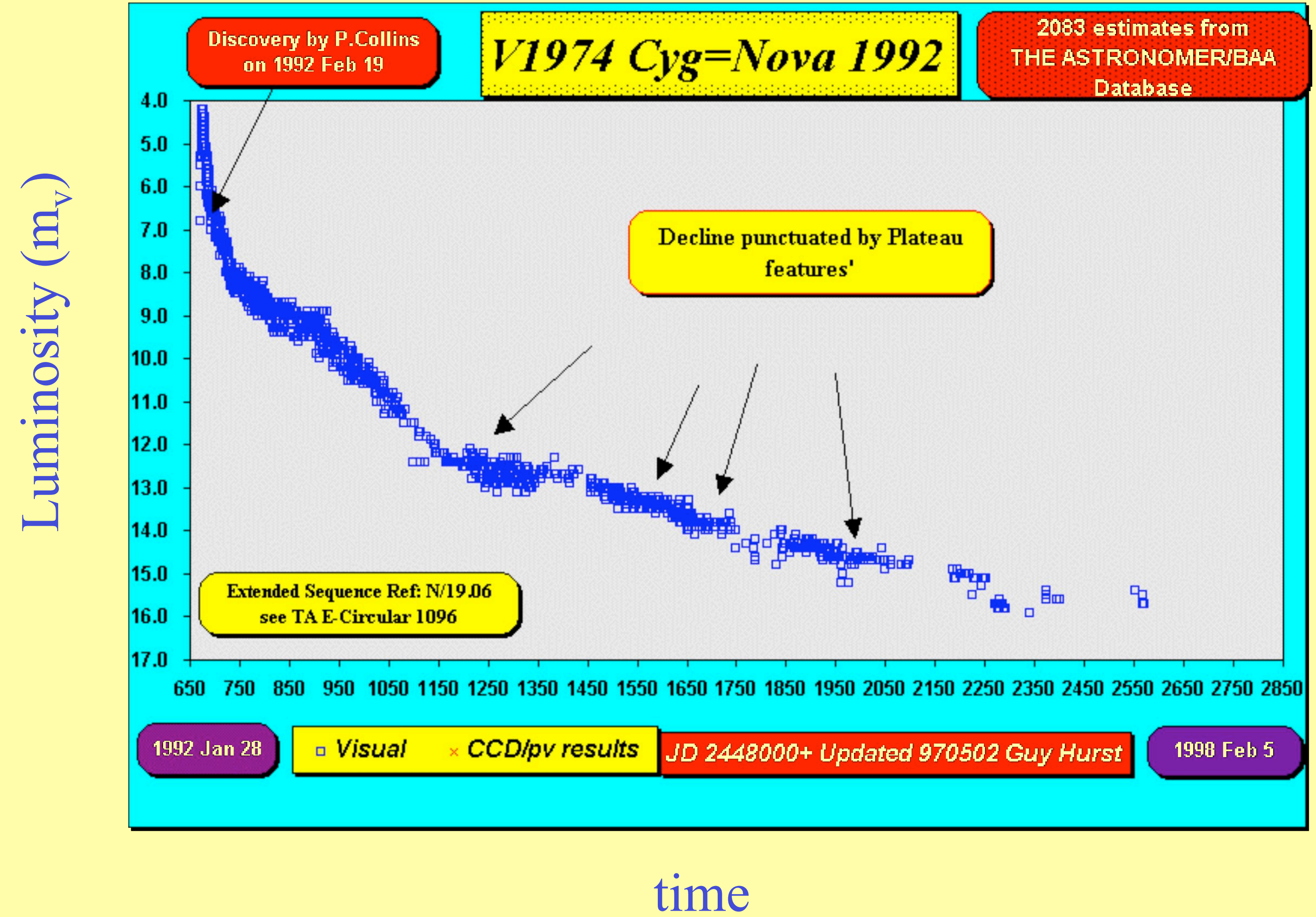


Hydrogen explosive burning on top of a white dwarf in a close binary system (companion star: low-mass main sequence ~ Sun)

Novae observations: some properties

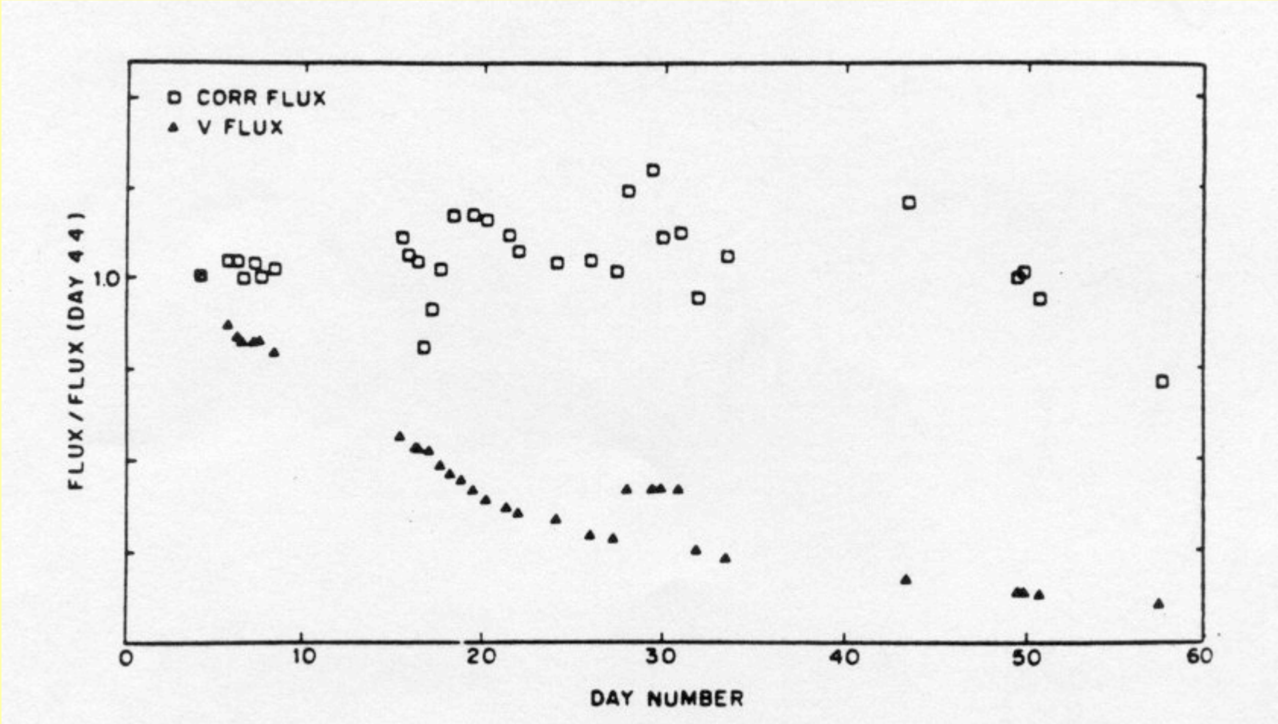
- Occur on carbon-oxygen (CO, $M<1.1\ M_\odot$) or oxygen-neon (ONe, $M>1.1\ M_\odot$) white dwarfs
- Ejected masses: 10^{-5}-$10^{-4}\ M_\odot$ - No disruption of the star in contrast with supernovae; recurrent phenomena ~10^4-10^5 yr
- Expansion velocities of the ejecta ~ 10^2-10^3 km/s
- Energetics and luminosity: 10^{45} erg; $10^5 L_\odot$ (~10^{38} erg/s)
- Ejecta enhanced in C, N, O, Ne w.r.t. solar
- Nova rate in the Milky Way: ~35 per yr (but <5 observed)

Nova observations: optical light curve



Novae observations: light curves

UV satellites: $L_{bol}(L_V+L_{UV})$=constant in novae



FH Ser 1970 – Gallagher & Code 1974

Abundances in novae ejecta from optical and UV spectra

Object	Year	Reference	H	He	C	N	O	Ne	Na-Fe	Z	$(Z/Z_\odot)$	$(Ne/Ne_\odot)$	CNO/Ne-Fe
Solar	...	1	0.71	0.27	0.0031	0.001	0.0097	0.0018	0.0034	0.019	1.0	1.0	2.7
T Aur	1891	2	0.47	0.40	...	0.079	0.051	...	...	0.13	6.8	...	...
RR Pic ...	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2.9
DQ Her ...	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	..
DQ Her	1934	5	0.27	0.16	0.058	0.29	0.22	...	...	0.57	30.	...	...
HR Del	1967	6	0.45	0.48	...	0.027	0.047	0.0030	...	0.077	4.1	1.7	25.
V1500 Cyg	1975	7	0.49	0.21	0.070	0.075	0.13	0.023	...	0.30	16.	13.	12.
V1500 Cyg	1975	8	0.57	0.27	0.058	0.041	0.050	0.0099	...	0.16	8.4	5.6	15.
V1668 Cyg	1978	9	0.45	0.23	0.047	0.14	0.13	0.0068	...	0.32	17.	3.9	47.
V1668 Cyg	1978	10	0.45	0.22	0.070	0.14	0.12	...	...	0.33	17.	...	...
V693 CrA	1981	11	0.40	0.21	0.004	0.069	0.067	0.023	...	0.39	21.	128.	...
V693 CrA	1981	12	0.29	0.32	0.046	0.080	0.12	0.17	0.016	0.39	21.	97.	1.3
V693 CrA	1981	10	0.16	0.18	0.0078	0.14	0.21	0.26	0.030	0.66	35.	148.	1.2
V1370 Aql	1982	13	0.053	0.088	0.035	0.14	0.051	0.52	0.11	0.86	45.	296.	0.36
V1370 Aql	1982	10	0.044	0.10	0.050	0.19	0.037	0.56	0.017	0.86	45.	296.	0.48
GQ Mus	1983	14	0.37	0.39	0.0081	0.13	0.095	0.0023	0.0039	0.2 4	13.	1.2	38.
PW Vul	1984	15	0.69	0.25	0.0033	0.049	0.014	0.00066	...	0.067	3.5	0.38	100.
PW Vul	1984	10	0.47	0.23	0.073	0.14	0.083	0.0040	0.0048	0.30	16.	2.3	34.
PW Vul	1984	16	0.617	0.247	0.018	0.069	0.0443	0.001	0.0027	0.14	7.7	1.	31.
QU Vul	1984	17	0.30	0.60	0.0013	0.018	0.039	0.040	0.0049	0.10	5.3	23.	1.3
QU Vul	1984	10	0.33	0.26	0.0095	0.074	0.17	0.086	0.063	0.40	21.	49.	1.7
QU Vul	1984	18	0.36	0.19	...	0.071	0.19	0.18	0.0014	0.44	23.	100.	1.4
V842 Cen	1986	10	0.41	0.23	0.12	0.21	0.030	0.00090	0.0038	0.36	19.	0.51	77.
V827 Her	1987	10	0.36	0.29	0.087	0.24	0.016	0.00066	0.0021	0.35	18.	0.38	124.
QV Vul	1987	10	0.68	0.27	...	0.010	0.041	0.00099	0.00096	0.053	2.8	0.56	26.
V2214 Oph	1988	10	0.34	0.26	...	0.31	0.060	0.017	0.015	0.40	21.	9.7	12.
V977 Sco	1989	10	0.51	0.30	[illegible]	0.042	0.030	0.026	0.0027	0.10	5.3	15.	2.5
V433 Sct	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	33.
V351 Pup	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2.4
V1974 Cyg	1992	18	0.19	0.32	...	0.085	0.29	0.11	0.0051	0.49	27.	68.	3.2
V1974 Cyg	1992	20	0.30	0.52	0.015	0.023	0.10	0.037	0.075	0.18	9.7	21.	3.1
V838 Her	1991	11	0.60	0.31	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.11	31.	...

V1370 Aql 1982 $Z=0.86=45\ Z_\odot$; $Ne=0.56=296\ Ne_\odot$

QU Vul 1984 $Z=0.44=23\ Z_\odot$; $Ne=0.18=100\ Ne_\odot$

Gehrz et al 1998, PASP

Nova nucleosynthesis and chemical evolution of the Galaxy

M_{ejec}(theor.) ~ $2 \times 10^{-5}\ M_{\odot}$/nova

R(novae) ~ 35 novae/yr

Age of the Galaxy ~ 10^{10} yrs

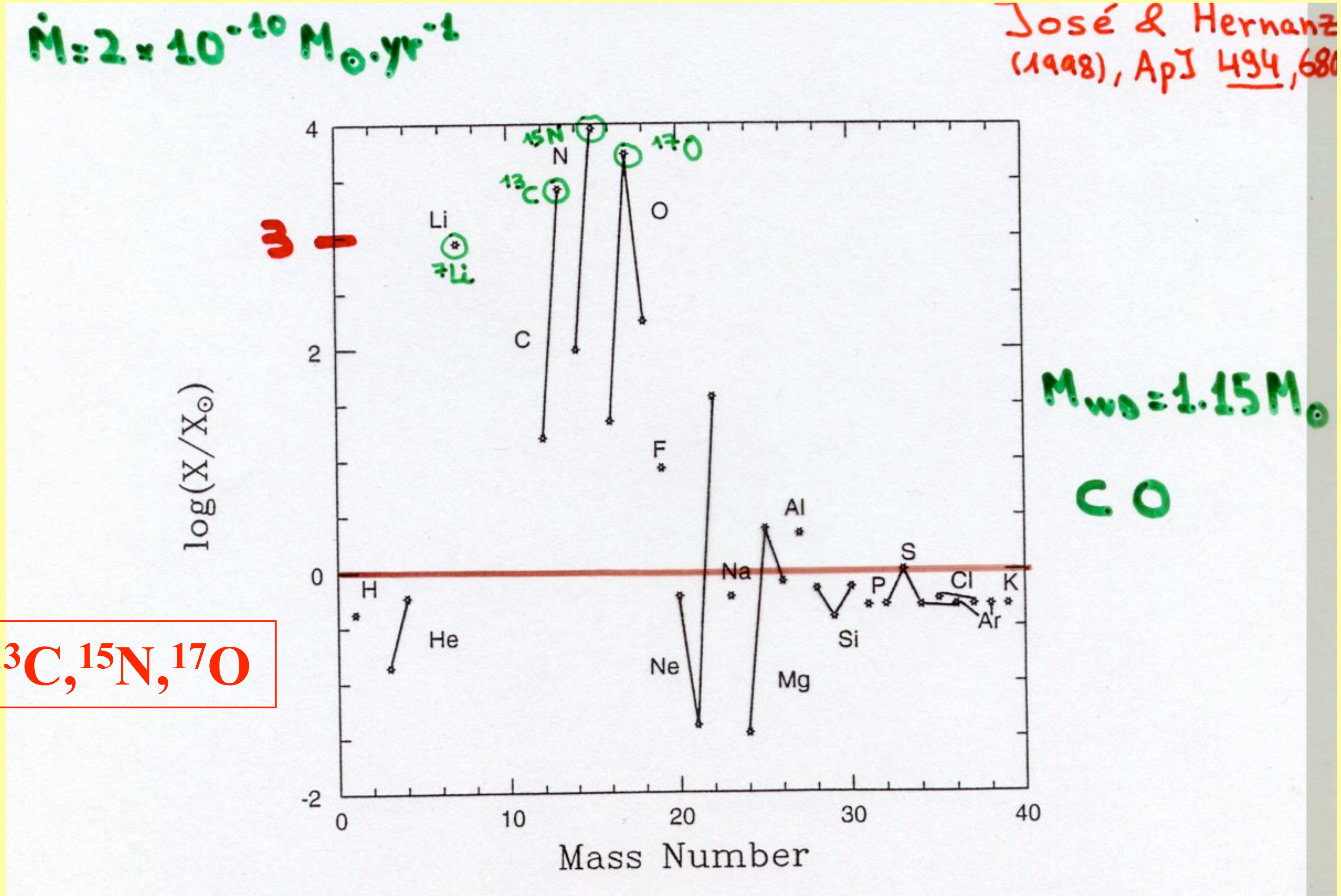
↓

$M_{ejec,total}$(novae) ~ $7 \times 10^{6}\ M_{\odot} = (7 \times 10^{-4}\ M_{\odot}/yr) \approx 1/3000\ M_{gal}$(gas+dust)

↓

Novae can account for the galactic abundances of the isotopes they overproduce (w.r.t. sun) by factors ***≥ 3000***

Nova nucleosynthesis: overproductions w.r.t. solar



^{7}Li, ^{13}C, ^{15}N, ^{17}O

Astron. Astrophys. 352, 117–128 (1999)

The galactic lithium evolution revisited*

D. Romano[1,2], F. Matteucci[3,1], P. Molaro[2], and P. Bonifacio[2]

[1] SISSA/ISAS, Via Beirut 2–4, 34014 Trieste, Italy
[2] Osservatorio Astronomico di Trieste, Via G.B. Tiepolo 11, 34131 Trieste, Italy
[3] Dipartimento di Astronomia, Università di Trieste, Via G.B. Tiepolo 11, 34131 Trieste, Italy

Received 26 April 1999 / Accepted 5 October 1999

In order to reproduce the upper envelope of the A(Li) vs [Fe/H] diagram we need to take into account several stellar Li sources: AGB stars, Type II SNe and novae. In particular, novae are required to reproduce the steep rise of A(Li) between the formation of the Solar System and the present time, as is evident from the data we sampled. On the other hand, ^{7}Li yields for SNeII should be lowered by at least a factor of two in order to reproduce the extension of the Spite plateau.

Nova nucleosynthesis and Galactic evolution of the CNO isotopes

MNRAS, 2004

Donatella Romano[1,2] and Francesca Matteucci[3]
[1] International School for Advanced Studies, SISSA/ISAS, Via Beirut 2-4, I-34014 Trieste, Italy
[2] INAF, Osservatorio Astronomico di Bologna, Via Ranzani 1, I-40127 Bologna, Italy; romano@bo.astro.it
[3] Dipartimento di Astronomia, Università di Trieste, Via G.B. Tiepolo 11, I-34131 Trieste, Italy; matteucci@ts.astro.it

In this paper, we adopt detailed nucleosynthesis in the ejecta of classical novae as published by José & Hernanz (1998) for a grid of hydrodynamical nova models spanning a wide range of CO and ONe WD masses ($0.8-1.35\ M_{\odot}$) and mixing levels between the accreted envelope and the outermost shells of the underlying WD core (25% – 75%). We find that, when included in a detailed model for the chemical evolution of the Milky Way, they produce $^{12}C/^{13}C$, $^{14}N/^{15}N$ and $^{16}O/^{17}O$ ratios decreasing with increasing metallicity, i.e., decreasing with time at the solar radius and increasing with Galactocentric distance at the present time, in agreement with the trends inferred from observations. However, if novae are

^{7}Li

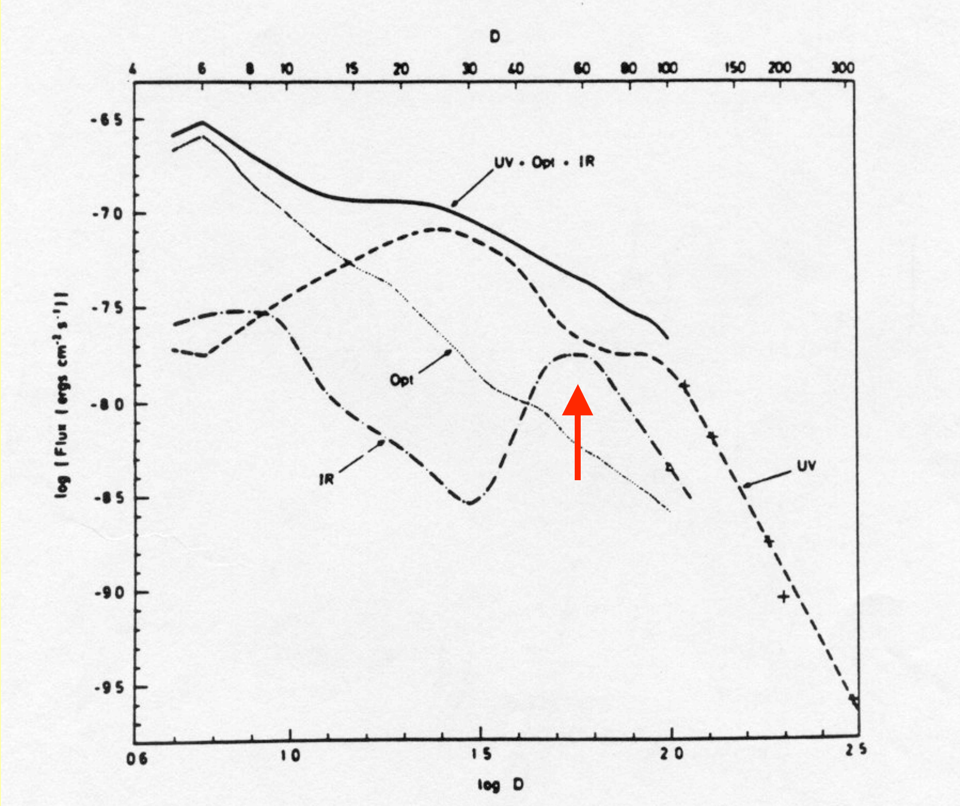
CNO: ^{13}C, ^{15}N, ^{17}O

See as well Alibés, Labay & Canal, 2001, A&A

Dust in novae

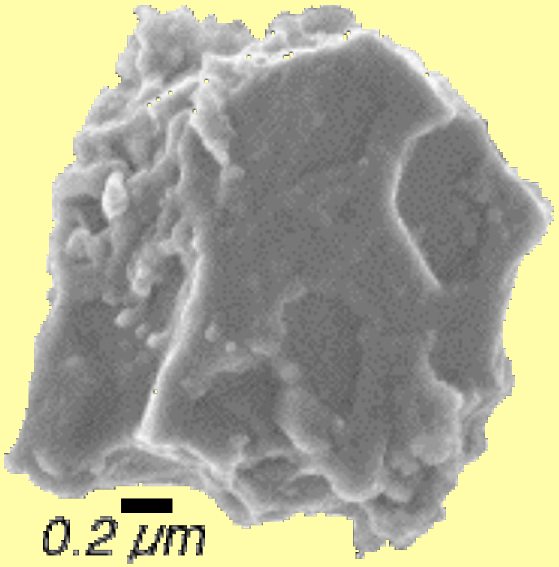
IR observations indicate that dust grains are formed in many novae

Nova Cyg 1978



Novae and presolar meteoritic grains

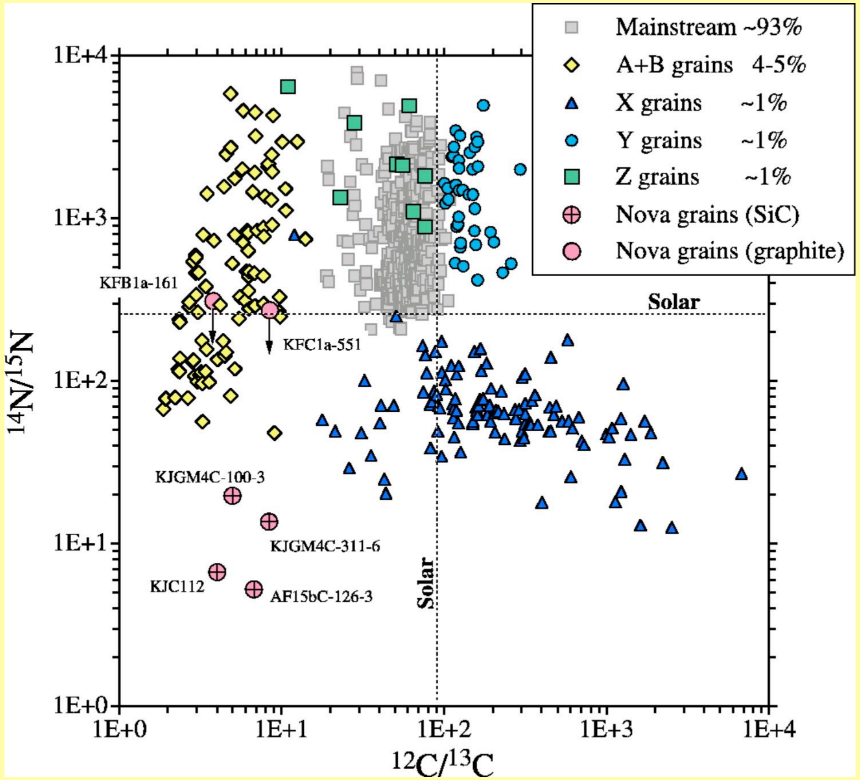
Primitive meteorites contain presolar grains, which condensed in stellar atmospheres or in supernova or nova ejecta, and survived their "interstellar trip" and solar system formation

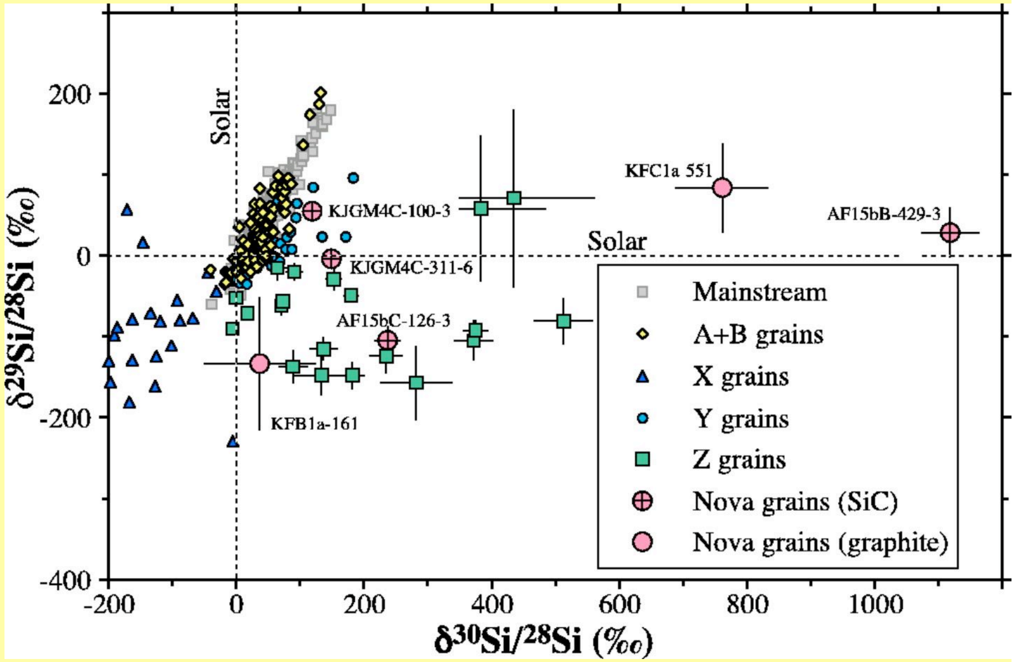


Isotopic abundances measurements in lab their origin permit to deduce where they formed

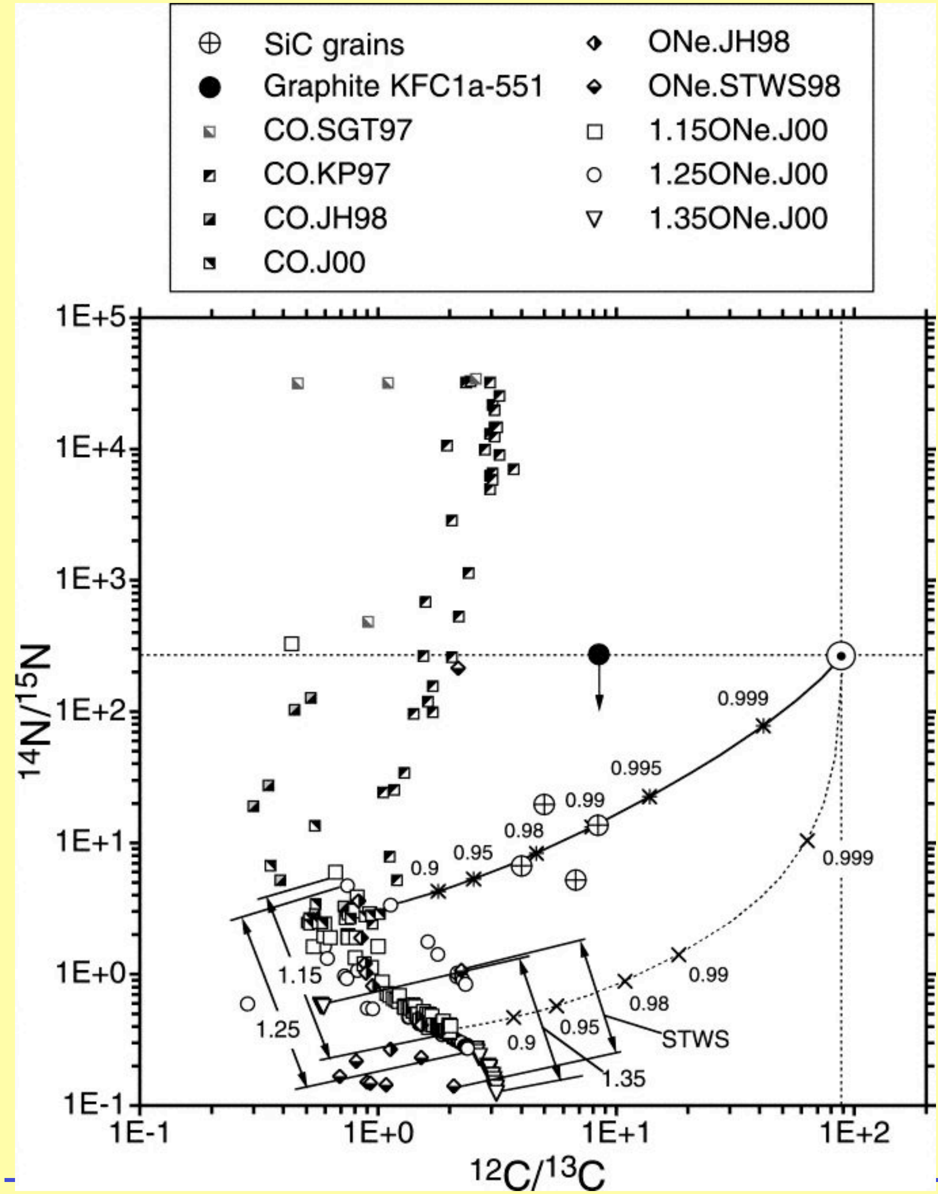
Novae and presolar meteoritic grains

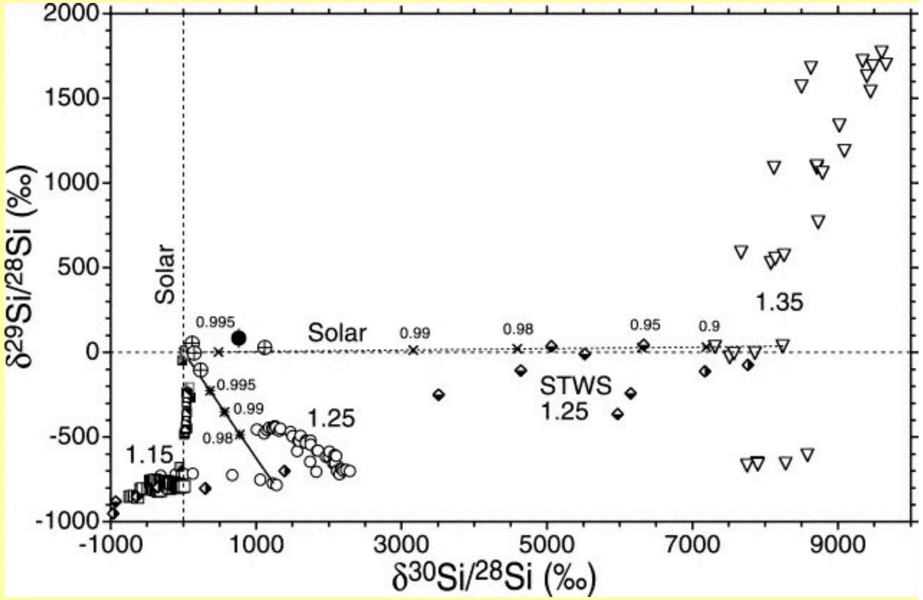
Five SiC and two graphite grains from the Murchison and Acfer 094 meteorites show isotopic compositions indicating a nova origin: Amari, Gao, Nittler, Zinner, José, Hernanz & Lewis (2001); José, Hernanz, Amari, Lodders & Zinner (2004)





Novae and presolar meteoritic grains





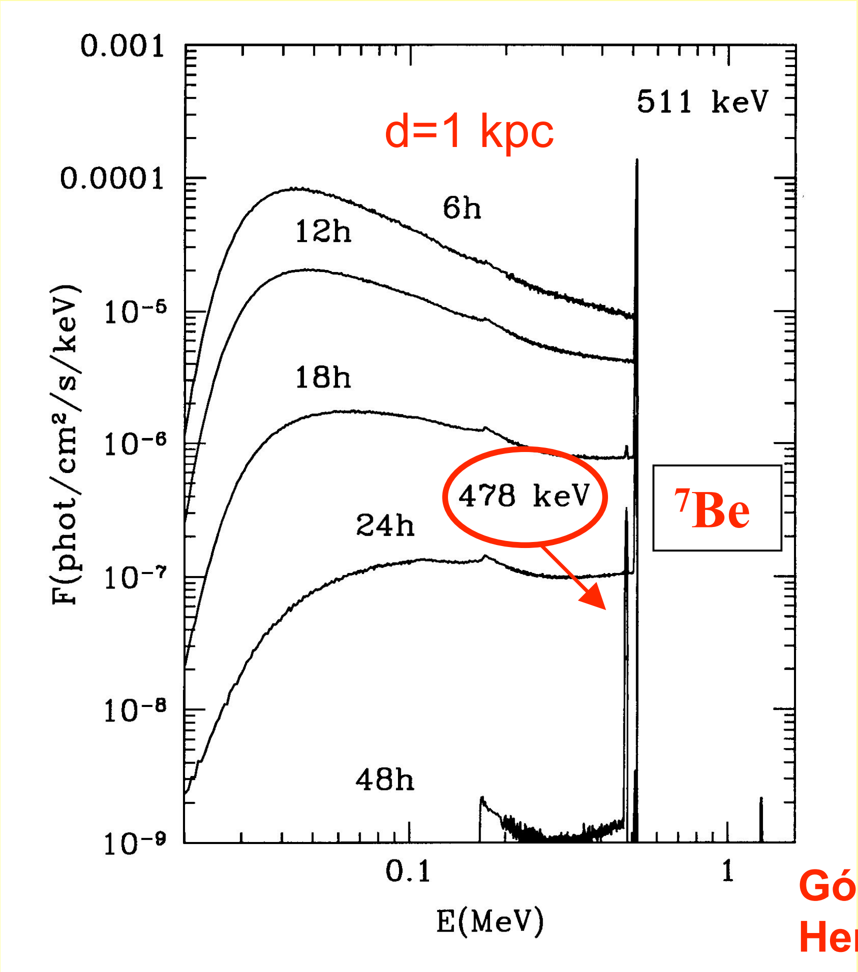
Amari et al. 2001

Why novae emit gamma-rays? Main radioactive isotopes synthesized in classical novae

Nucleus	τ	Type of emission	Nova type
^{13}N (β^+)	862 s	511 keV line continuum (E<511 keV)	CO and ONe
^{18}F (β^+)	158 min	511 keV line continuum (E<511 keV)	CO and ONe
^{7}Be (ec)	77 days	478 keV line	CO mainly
^{22}Na (β^+)	3.75 yr	1275 keV line	ONe
^{26}Al (β^+)	1.0×10^6 yr	1809 keV line	ONe

Spectra of CO novae

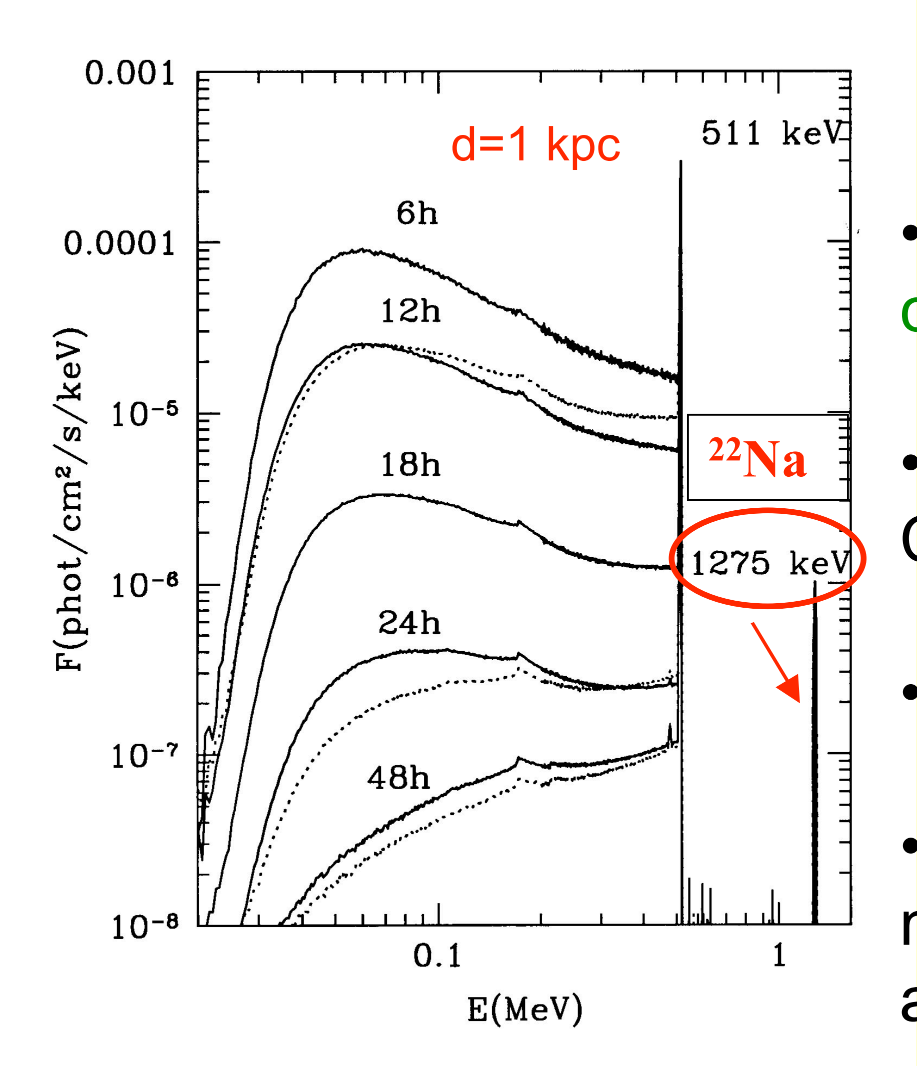
$M_{WD} = 1.15\ M_{\odot}$



- e^--e^+ annihilation and Comptonization ➡ continuum and 511 keV line; e^+ from ^{13}N and ^{18}F
  ➡ predicted theoretically by Clayton & Hoyle 1974; Leising & Clayton 1987
- photoelectric absorption
  ➡ cutoff at 20 keV
- 478 keV line from ^{7}Be decay
- transparent at 48 h

Gómez-Gomar, Hernanz, José, Isern,1998, MNRAS
Hernanz et al 1999, ApJL

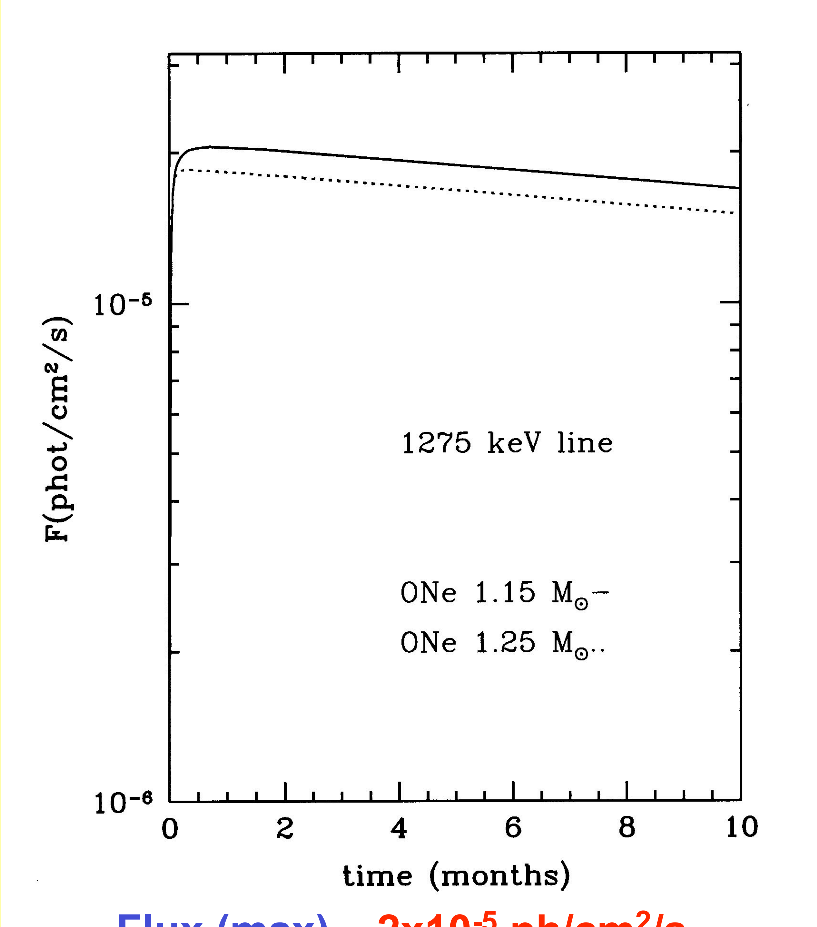
Spectra of ONe novae



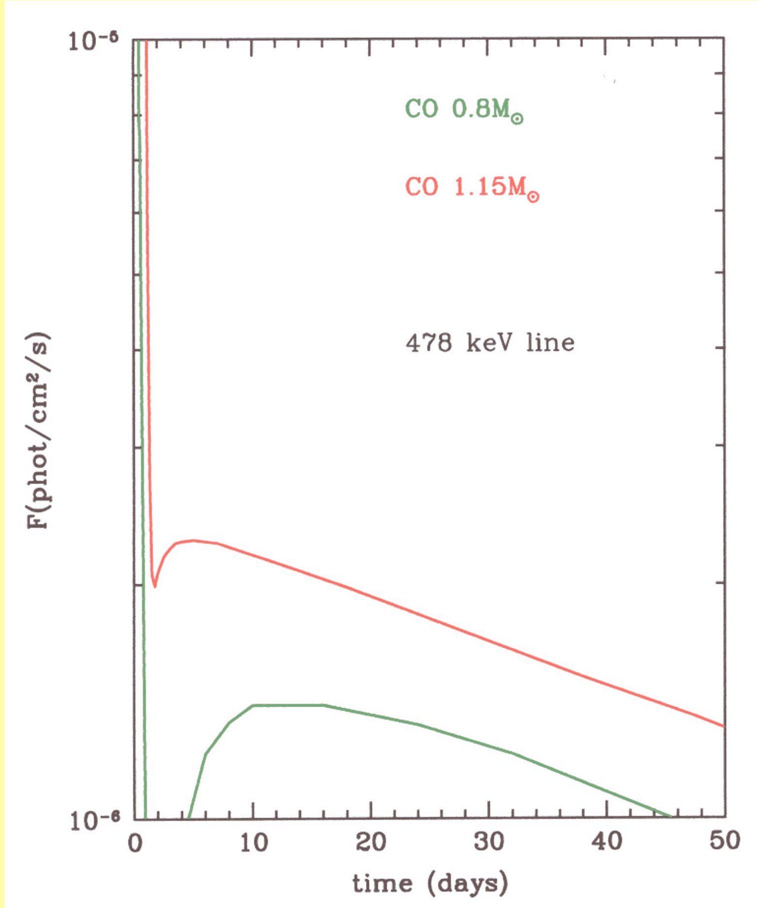
M_{WD} = 1.15 $M_\odot$ (solid)
1.25 $M_\odot$ (dotted)

- photoelectric absorption → cutoff at 30 keV
- continuum and 511 keV as in CO novae
- 1275 keV line from ^{22}Na decay
- similar behaviour for the 2 models, because of similar KE and yields

Light curves: 1275 keV (^{22}Na) & 478 (^{7}Be) lines



d=1 kpc



Flux (max) ~ 2x10^{-5} ph/cm^2/s

$M_{ejected}$(^{22}Na) ~ (6-7)x10^{-9}$M_\odot$

Line width ~ 20 keV

Flux ~ (1-2)x10^{-6} ph/cm^2/s

$M_{ejected}$(^{7}Be) ~ (0.7-1.1)x10^{-10}$M_\odot$

Line width: 3-7 keV

Observations : 1275 keV line (^{22}Na)

CGRO/COMPTEL searched for 1275 keV emission in many novae: no detection, upper limits

CGRO/COMPTEL most constraining upper limit (Nova Cyg 1992, d=2.3 kpc) in agreement with current theoretical predictions:

$F < 2.3 \times 10^{-5}$ phot/cm^2/s ➔ $M_{ej}(^{22}Na) < 3.0 \times 10^{-8} M_{\odot}$

Iyudin et al. 1995, A&A

Observations: 478 keV line (^7Be)

WIND/TGRS and SMM/GRS: no detection; upper limits (Harris et al. 1991 and 2001), in agreement with current theoretical predictions

- WIND/TGRS: $F<6.3x10^{-5}$ phot/cm^2/s
- SMM/GRS: $F<7.5x10^{-4}$ phot/cm^2/s

Prospects for detectability with INTEGRAL/SPI

*Table 1. SPI 3σ detectability of ^{7}Be (478 keV) and ^{22}Na (1275 keV) lines from classical novae**

Line (E Δ E,keV)	t_{obs}(ks)	F_{min} ($ph/cm^2/s$)	d(kpc)
478 (8)	10^3	7.98×10^{-5}	0.16
478 (8)	1.2×10^3	7.28×10^{-5}	0.17
478 (8)	2.4×10^3	5.15×10^{-5}	0.20
1275 (20)	10^3	7.28×10^{-5}	0.52
1275 (20)	1.2×10^3	6.64×10^{-5}	0.55
1275 (20)	2.4×10^3	4.70×10^{-5}	0.65

* F_{min} are the fluxes which would give a 3σ detection of the lines, with the quoted observation times, which have been computed with the Observation Time Estimator for INTEGRAL *OTE*. The detectability distances have been computed adopting as model fluxes for the 478 keV and 1275 keV lines, at 1 kpc, 2×10^{-6} and 2×10^{-5} $ph/cm^2/s$, for a typical CO and ONe nova, respectively (see Gómez-Gomar et al. (1998); Hernanz et al. (1999)).

Width of the lines fully taken into account
Future missions needed!
MAX (γ-ray lens), ACT (Advanced Compton Telescope)

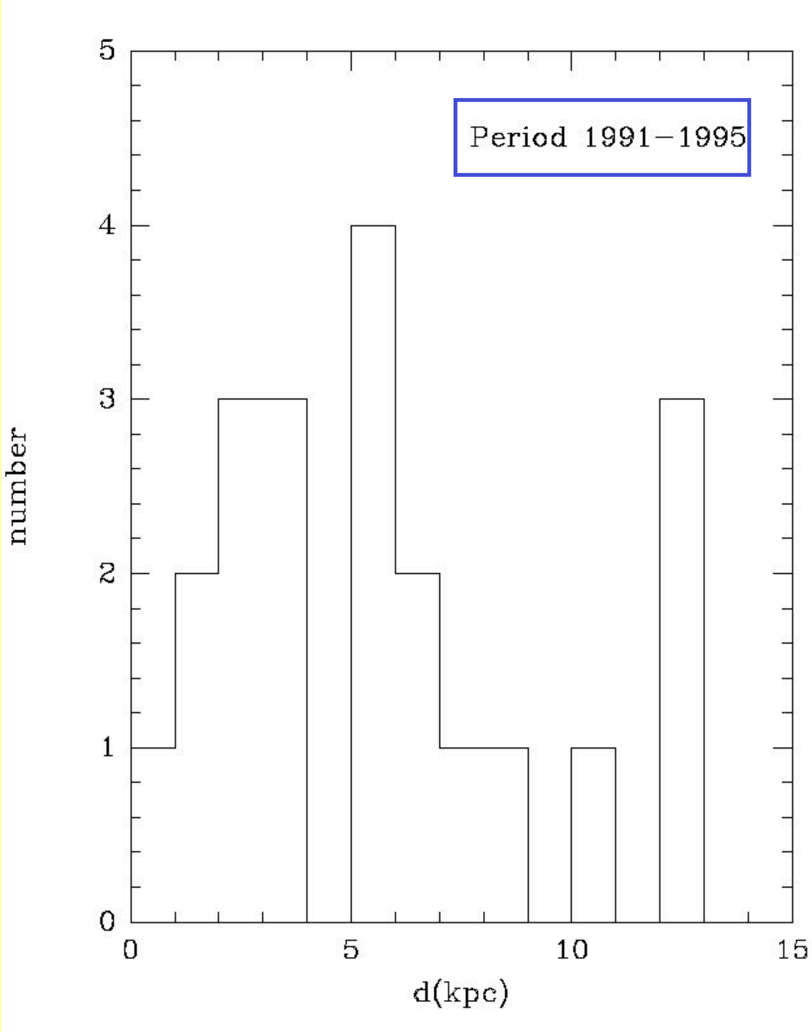
Novae distances (observed)

Distances from Shafter 1997, ApJ

These data will be used to estimate the probabilities to have novae at given distances

~35 novae/yr in our Galaxy, but only **3-5/yr** are discovered

1275 keV: d<0.5kpc → 1/5 yr



Detectabilities with MAX

MAX - 3σ narrow line sensitivity

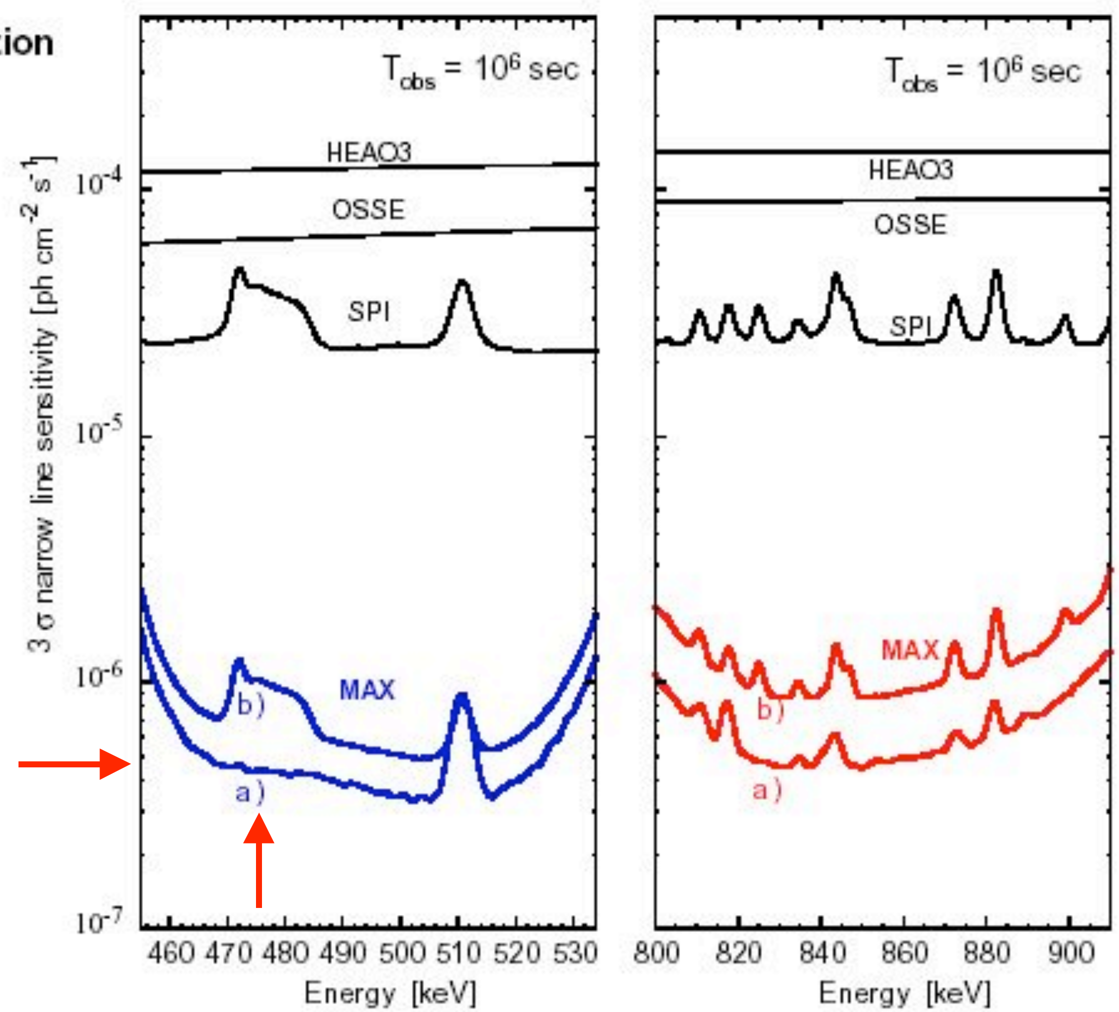
simultaneous observation in two broad energy bands

- **E/dE ~ 500**
- **ang. res. ~ 1'**
- **timing**
- **polarisation**

options

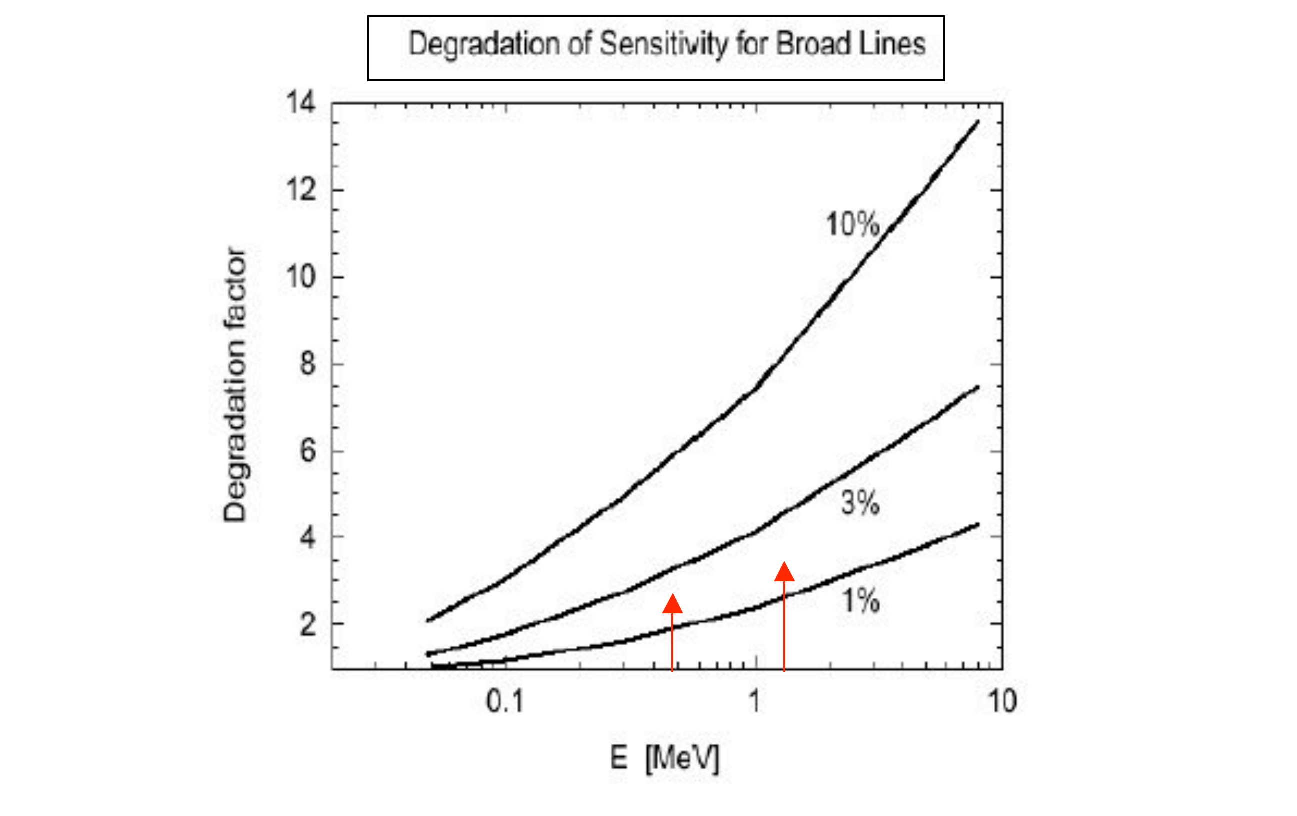
a) baseline detector
Ge Compton stack

b) single detector
SPI type GeD



from Peter vB

INTEGRAL/SPI Observer's Manual (AO3, 2004)



Degradation factor for the 478 and 1275 keV lines:

478 keV: ΔE/E: <1.5% => f ~ **2** => **$2^{1/2}$ = 1.4** worse for d

1275 keV: ΔE/E: 1.6% => f ~ **3** => **$3^{1/2}$ = 1.7** worse for d

Detectability with MAX of the 478 keV (^7Be) line from novae

- If MAX sensitivity at 478 keV were ~$5x10^{-7}$ ph/cm^2/s, it could detect the ^7Be line from novae up to 2 kpc (ideal case of a narrow line)

  - BUT the line is not narrow: width 3-7 keV → ΔE/E~0.6-1.5%, then degradation factor ~2 in sensitivity ($2^{1/2}$=1.4 in detect. distance)

  - Number of novae per year at d≤1.4 kpc: <3 every 5 years. Better: ~half of them, since only CO novae produce ^7Be: *around 0.3 nova per year* (small number statistics ⇒ large fluctuations)

Detectability with “MAX” of the 1275 keV (^{22}Na) line from novae

➢ If MAX sensitivity at 1275 keV were ~5×10^{-7} ph/cm^2/s for a narrow line (~ for the 847 keV line) it could detect the ^{22}Na line from novae up to 6 kpc

➢BUT the line is not narrow: width around 20 keV - $\Delta E/E$~1.6%, then degradation factor~3 in sensitivity ($3^{1/2}$=1.7 in detect. distance)

¬ Novae ^{22}Na line at 1275 keV detectable up to ~4 kpc

➢Number of novae per year at $d \leq 4$ kpc: **9 every 5 years.** Better: ~half of them, since only ONe emit produce ^{22}Na: *around 1 nova per year*

Detectability with "MAX" of the 1275 keV (^{22}Na) line from novae

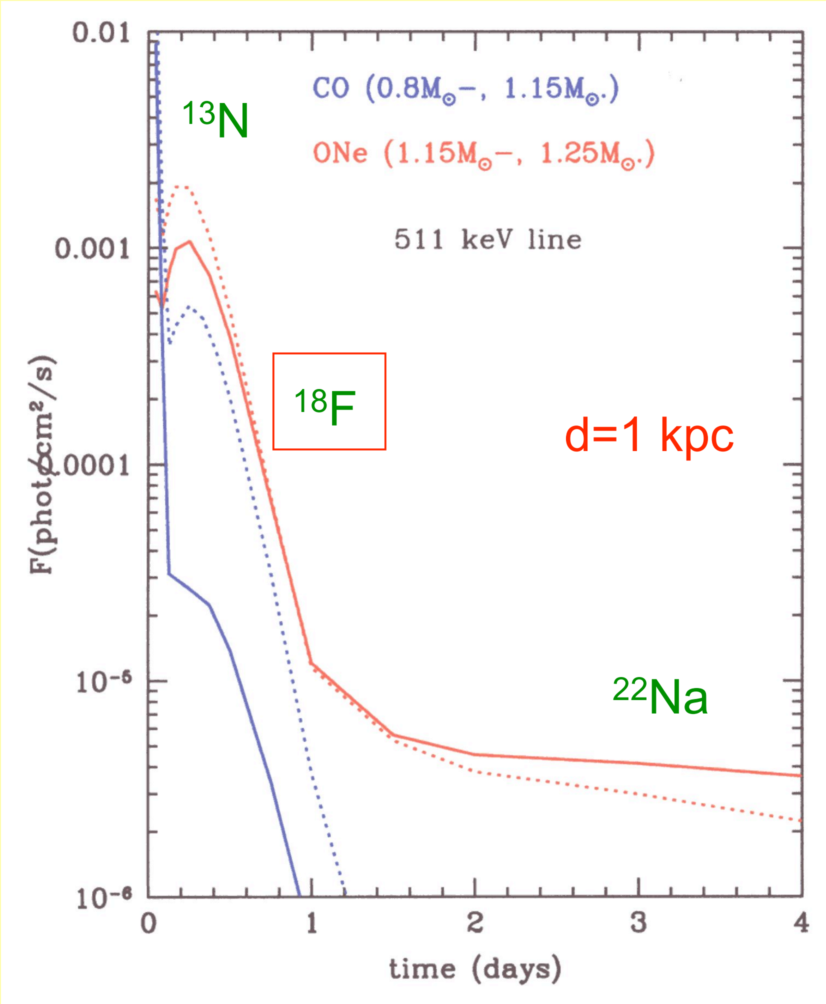
- To detect virtually ***all novae*** **(**d≤8 kpc), sensitivity for a broad line with ΔE/E~1.5% at 1275 keV should be **3x10^{-7} ph/cm^2/s** (**16 every 5 years** or ~half of them, since only ONe emit produce ^{22}Na → ~**2 novae/yr**).

$e^- - e^+$ annihilation emission

Light curves: 511 keV line

Modelt^{max*} (h)F^{max} (ph/cm^2/s)**CO, 0.8 M- - -2.6 x 1(

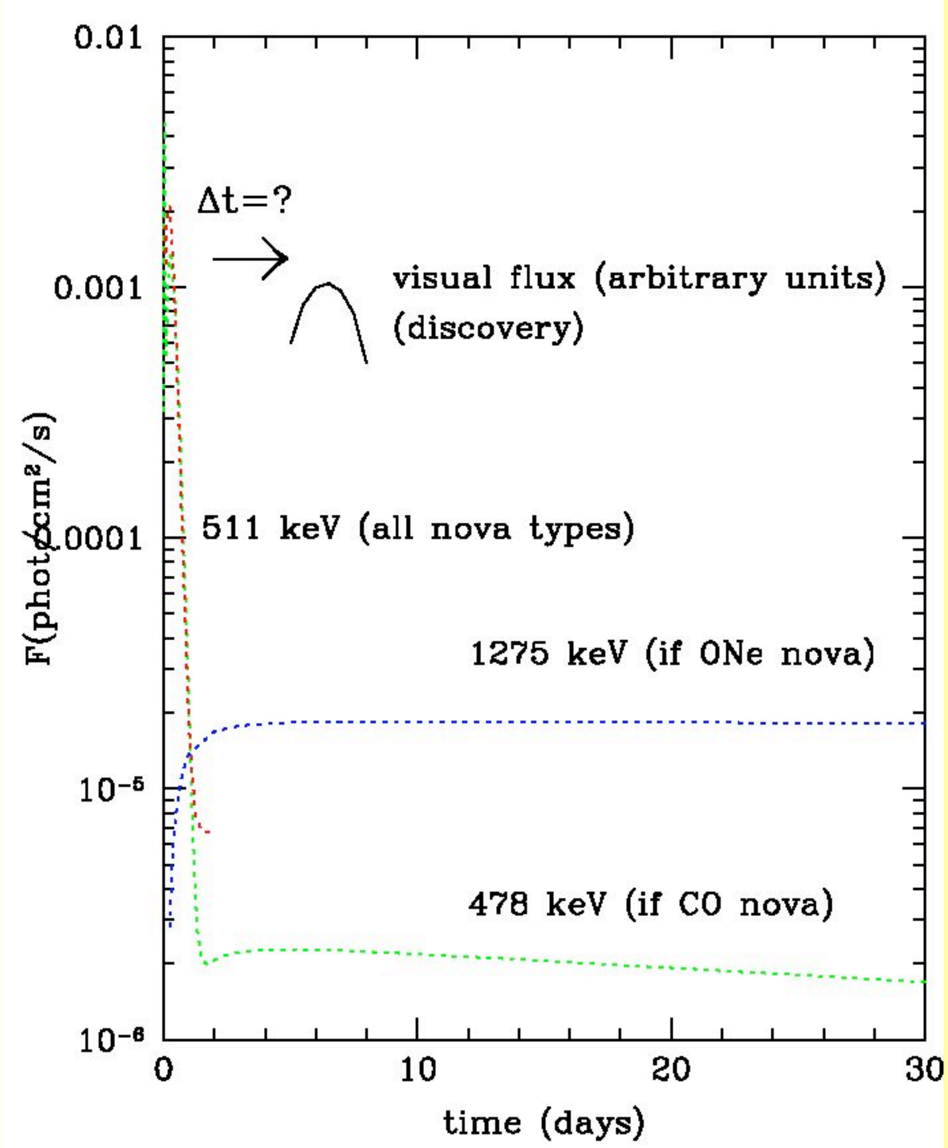
In CO and ONe novae



- 511 keV line in ONe novae remains after 2 days until ~ 1 week because of e^+ from ^{22}Na
- Intense (but short duration)
- Very early appearence, before visual maximum (i.e, before discovery)

¬ WARNING: nuclear reaction rates affecting ^{18}F still uncertain (^{17}O+p ^{18}F+p)

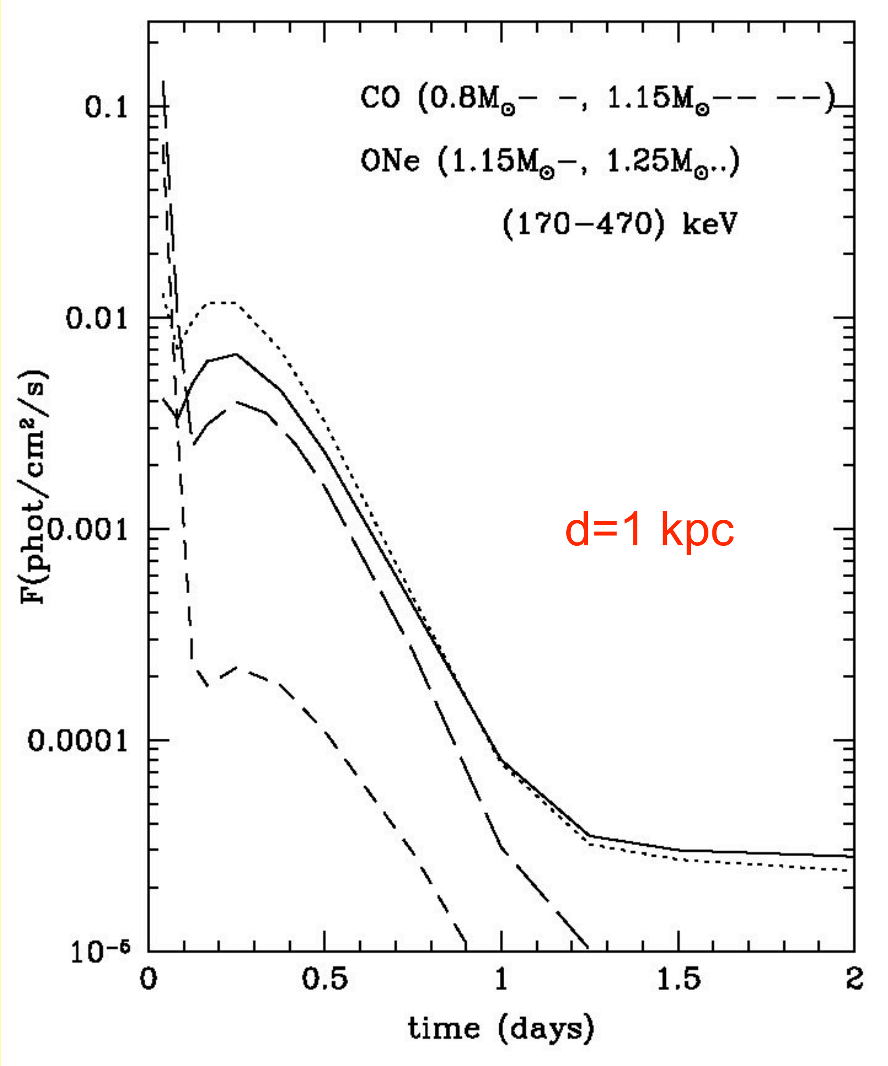
Gamma-ray and visual light curves



The continuum and the 511 keV line, e^--e^+ annihilation, are intense, but their duration is very short and they appear before visual discovery

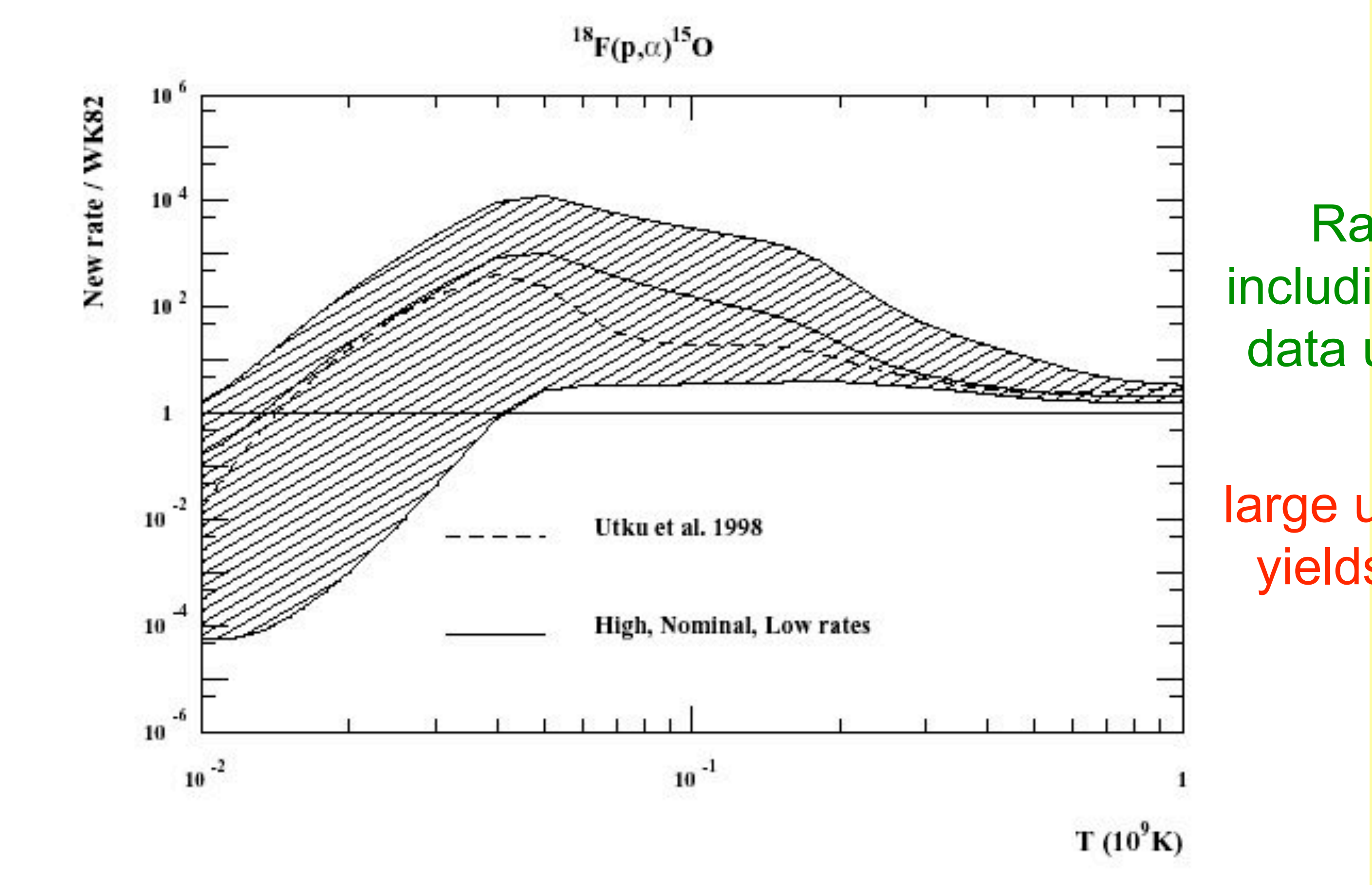
➡ detection requires "a posteriori" analyses with wide FOV instruments (BATSE, TGRS, RHESSI)

Light curves: continuum



Same WARNING as for 511 keV line applies

Nuclear uncertainties related with ^{18}F synthesis (511 keV & continuum emission)



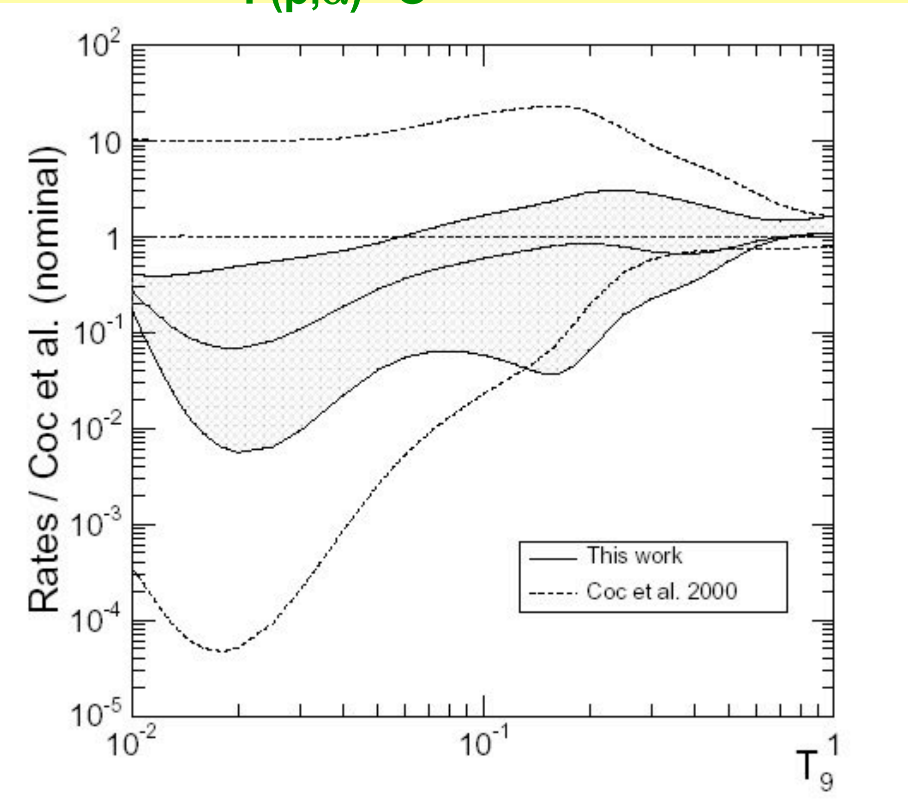
Coc, Hernanz, José, Thibaud, 2000, A&A

Rates obtained including experimental data up to the end of 1999:

large uncertainty in ^{18}F yields (factor ~ 300)

Nuclear uncertainties related with ^{18}F synthesis (511 keV & continuum emission)

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



$^{18}F(p,\alpha)^{15}O$ - $^{18}F(p,\gamma)^{19}Ne$

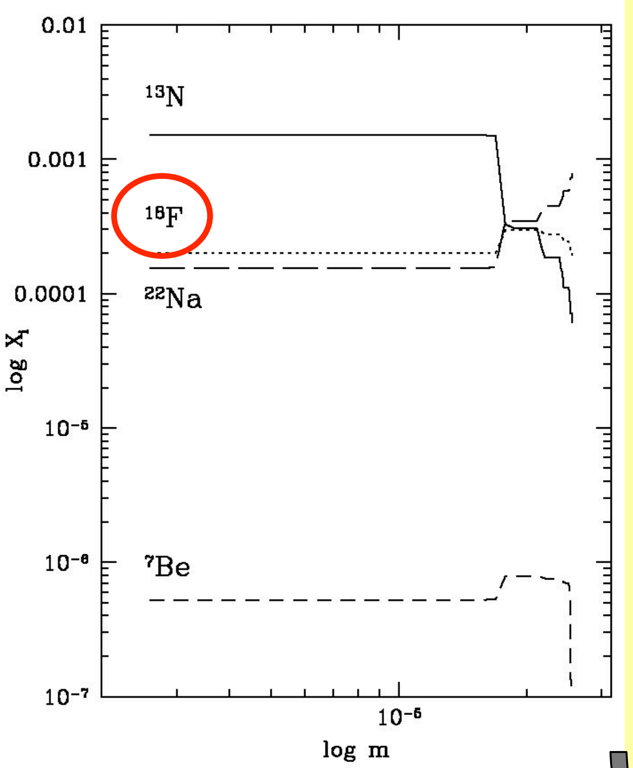
- de Séréville et al. 2003 and preprint 2005: *reduction of the uncertainty*

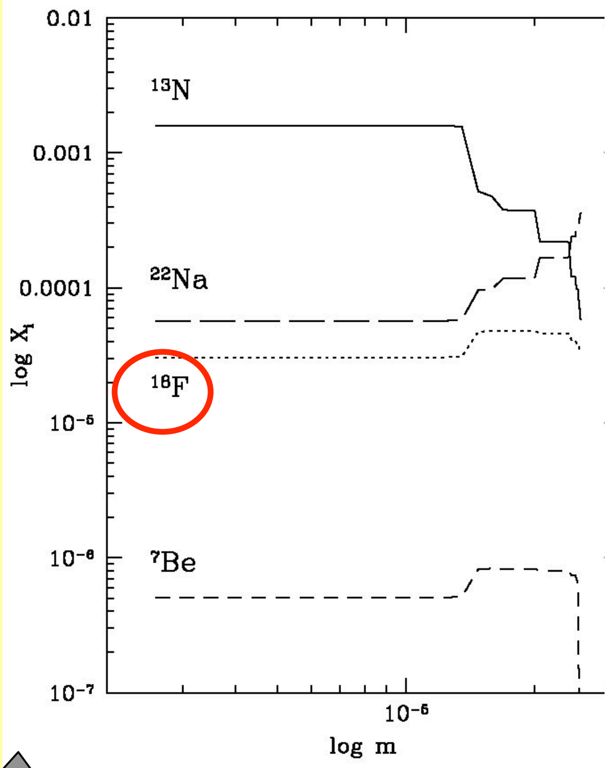
$^{17}O(p,\gamma)^{18}F$ - $^{17}O(p,\alpha)^{14}N$

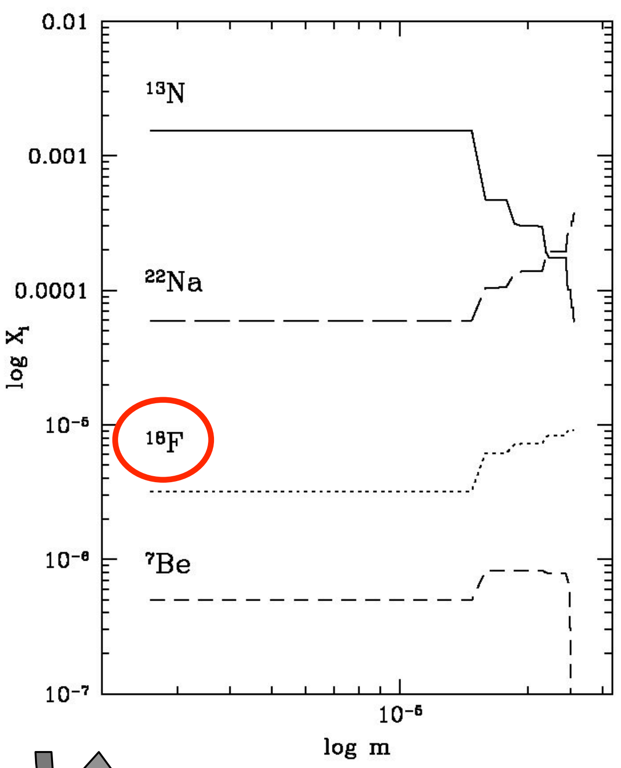
- Fox et al. 2004: uncertainties reduced
- Chafa et al. 2005: new larger ^{17}O+p rates, less ^{18}F

Uncertainties in the ^{18}F yields reduced by a factor of ~5 (^{18}F+p) and by a factor of ~3 (^{17}O+p) in the nova T range: still factor ~20 in ^{18}F yields

Nuclear uncertainties related with ^{18}F synthesis (511 keV & continuum emission)







1.15 $M_\odot$ ONe nova

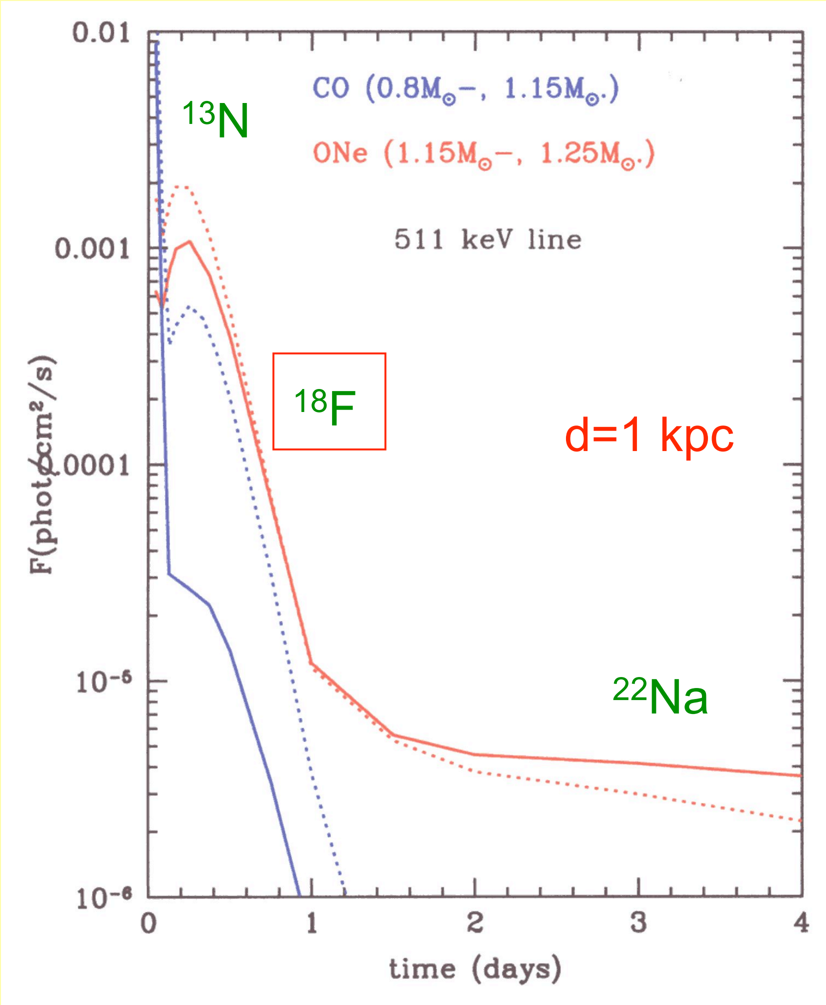
X(^{18}F) ↓ f~**6** f~**8**

Hernanz et al. 1999, ApJL **Coc et al. 2000, A&A** **Chafa et al. 2005, PRL**

f~48 (^{18}F yields) f~7 in detectability distances

$e^- - e^+$ annihilation emission

In CO and ONe novae



- ^{13}N very short peak remains (very model dependent)
- ^{22}Na low flux tail → ~ 10 days duration, at a level flux ~ 2 x 478 flux 478 keV line from ^{7}Be

Observations: 511 keV line

WIND/TGRS: no detection; upper limits

Upper Limits on 511 keV Line Emission from Novae

Nova	Angle of Incidence (deg)	Mean 3 σ Upper Limit in 6 hr (photon cm^{-2} s^{-1})
Nova Cir 1995	44.9	2.2×10^{-3}
Nova Cen 1995......	42.0	2.0×10^{-3}
Nova Sgr 1996	95.2	2.8×10^{-3}
Nova Cru 1996......	36.9	2.3×10^{-3}
Nova Sco 1997	83.4	2.9×10^{-3}

- Observation of 5 known Galactic novae in the broad TGRS FOV in the period 1995 Jan - 1997 June
- High E-resolution Ge detector: ability to detect 511 keV line blueshifted w.r.t. background line

Harris et al. 1999, ApJ

Summary of BATSE observations

- All upper limits are compatible with theory

-The 3-σ sensitivity using the 511 keV line only is similar to that of Harris et al. 1999 with Wind/TGRS. But the sensitivity of Harris et al. requires a particular line blueshift, whereas ours is independent on the blueshift.

- The 3-σ sensitivity using the 250-511 keV data with assumed Comptonization is a little more than a factor of 2 better than Harris et al. 1999.

Detection of γ-rays from novae

➔ amount of *^{7}Be or ^{22}Na*, only detectable in this way

➔ classification as CO or ONe ➔white dwarf mass

➔ ejected mass problem:

X_i (theory) x $M_{ejec,total}$ (optical+IR obs.) ⟺ $M_{i,ejected}$ (γ-ray obs)

• **Very important point** (for novae and specially for supernovae): the *sensitivities* adopted to compute detectability distances should be those for *broad lines*. For novae, typical widths are ≤8 keV for the 478 & 511 keV lines and ~20 keV for the 1275 keV line: $\Delta E/E \sim 1.5\%$