Gamma-ray emission from nova outbursts

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Two types of gamma-ray emission from novae

- **Radioactivity** in the ejecta:
  - traces nucleosynthesis directly
  - photons with E ~ MeV expected
  - not detected yet (CGRO/Comptel, INTEGRAL/SPI)
- **Particle acceleration** in strong shocks between ejecta and circumstellar material:
  - red giant wind in symbiotic recurrent nova
  - *"dense circumstellar matter"*
  - IC or π^0 decay → photons with E>100 MeV
  - detected by Fermi/LAT

Very High Energy (VHE) Gamma-rays :
E > 100 MeV
“Fermi novae – GeV novae”

First Nova detected in (VHE) gamma-rays
Fermi/LAT - E>100 MeV

Gamma-Ray Emission Concurrent with the Nova in the Symbiotic Binary V407 Cygni

The Fermi-LAT Collaboration*†

Novae are thermonuclear explosions on a white dwarf surface fueled by mass accreted from a companion star. Current physical models posit that shocked expanding gas from the nova shell can produce x-ray emission, but emission at higher energies has not been widely expected. Here, we report the Fermi Large Area Telescope detection of variable γ-ray emission (0.1 to 10 billion electron volts) from the recently detected optical nova of the symbiotic star V407 Cygni. We propose that the material of the nova shell interacts with the dense ambient medium of the red giant primary and that particles can be accelerated effectively to produce π^0 decay γ-rays from proton-proton interactions. Emission involving inverse Compton scattering of the red giant radiation is also considered and is not ruled out.

SCIENCE VOL 329 13 AUGUST 2010

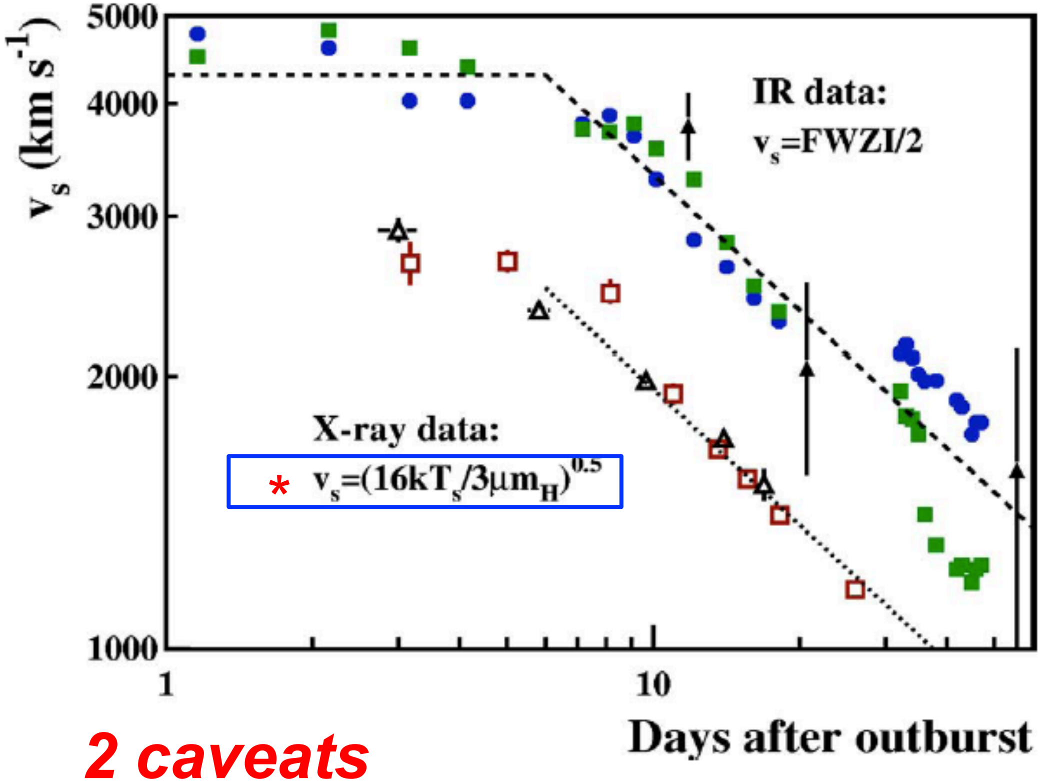
Novae detected by Fermi/LAT at E>100 MeV

- V407 Cyg: symbiotic binary WD+RG (shocks between ejecta and red giant wind)
- Nova Mon 2012: clearly not a symbiotic
- Nova Sco 2012?
- RS Oph (recurrent nova in symbiotic binary: WD + RG, 2006 eruption): would have been detected by Fermi/LAT → Tatischeff & Hernanz (2007), ApJL

RS Oph (2006 eruption): blast wave evolution

• IR (Das et al 2006, Evans et al. 2007)

• X-rays: RXTE & Swift (Sokoloski et al. 2006, Bode et al. 2006)



2 caveats

• Why shock cooling started at 6 days, when T_s was 10^8K and radiative cooling was not important? Particle acceleration - CRs
• Why v_{shock} (X-rays) < v (IR): expression* (for test particle strong shock) underestimates v_{shock} when particle accel. is efficient, because T_s is lower (particle ecape)

RS Oph (2006 eruption): evidence of particle acceleration

Non-linear diffusive shock acceleration: model of Berezhko & Ellison (1999)

- ➢ accelerated proton spectrum and post shock temperatures as a funtion of η_{inj} - the fraction of shocked protons injected into the acceleration process

Tatischeff & Hernanz, ApJL 2007

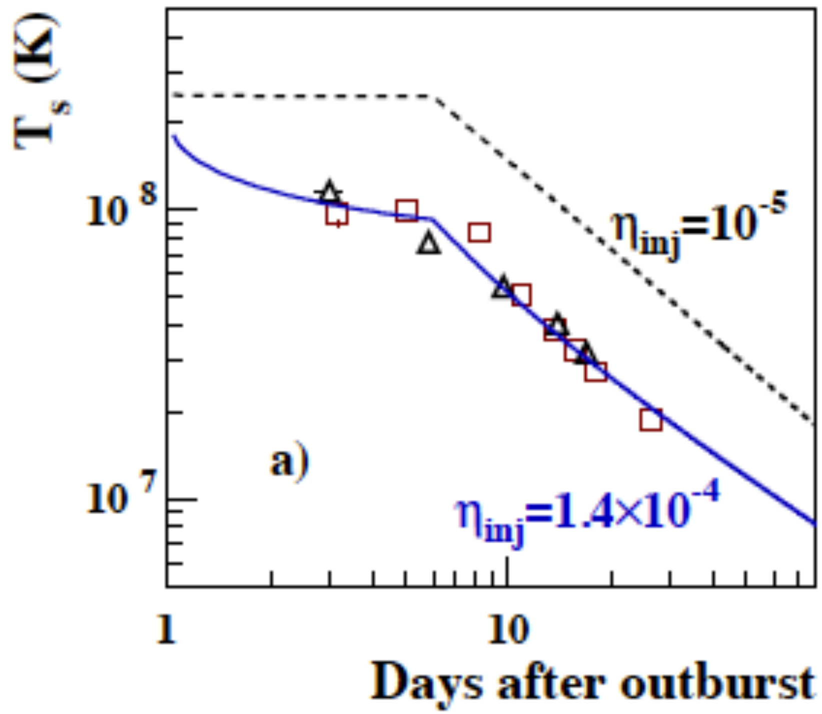
RS Oph (2006): cosmic-ray modified shock

- Good agreement with X-ray measurements of T_{shock} for moderate CR accel. efficiency η_{inj}~10^{-4}

- Energy loss rate due to particle escape

$$2\times10^{38}\left(\frac{\varepsilon_{esc}}{0.15}\right)\left(\frac{t}{6\ \text{days}}\right)^{-1.5}\ \text{erg s}^{-1}$$

~100 times larger than L_{bol} of postshock plasma ➔ *energy loss via accelerated particle escape much more efficient than radiative losses to cool the shock*



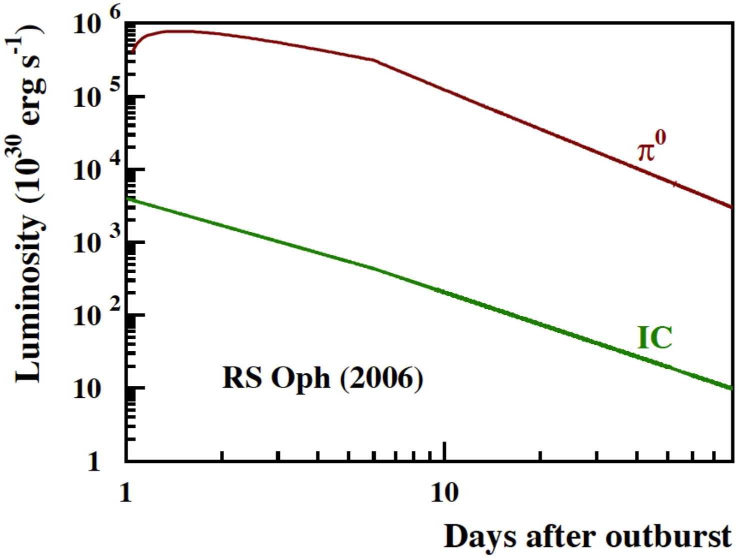
Tatischeff & Hernanz, ApJL 2007

RS Oph (2006): predicted gamma-ray emission

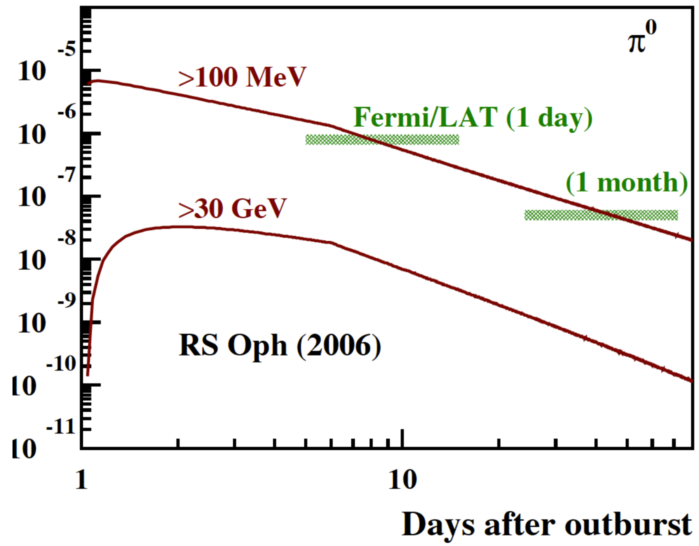
- π^0 production: from ε_{CR} and $(dM/dt)_{RG}$
- IC contribution: from non thermal synchrotron L (Kantharia et al.07, radio 1.4 GHz), L_{syn}~$5x10^{33}\ t_d^{-1.3}$ erg/s, and ejecta L, L_{ej}~L_{Edd} = $2x10^{38}$ erg/s: $L_{IC} = L_{syn} x\ U_{rad}/(B^2/8\pi)$ ~ L_{syn}

➔ π^0 production dominates

RS Oph would have been detected by Fermi!



TH, ApJL 2007; HT, Balt. Astr. 2011 (arXiv: 1111.4129)



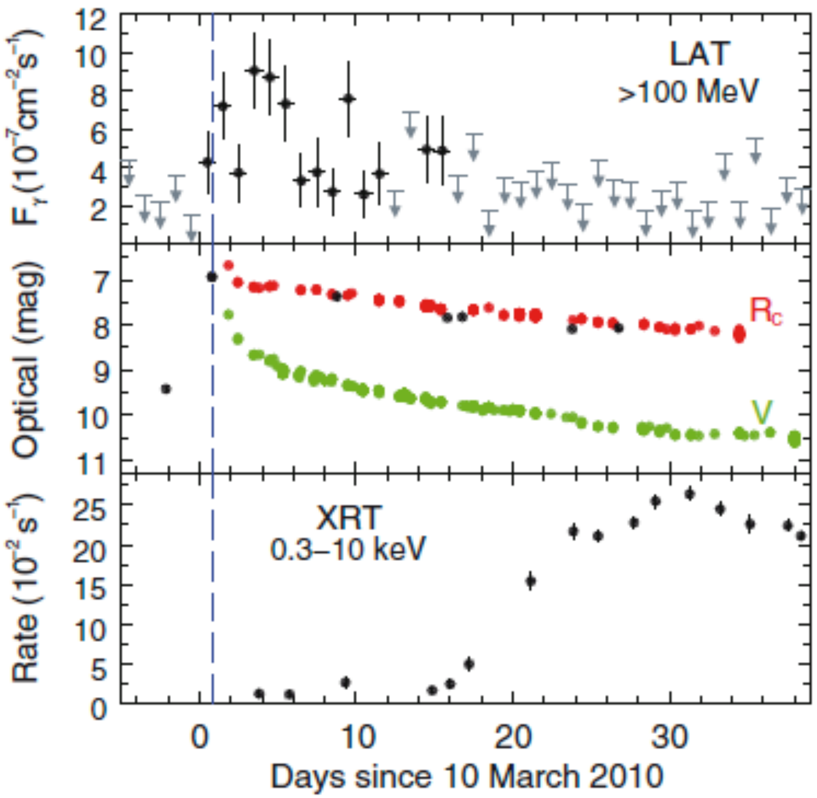
V407 Cyg : detected by Fermi/LAT

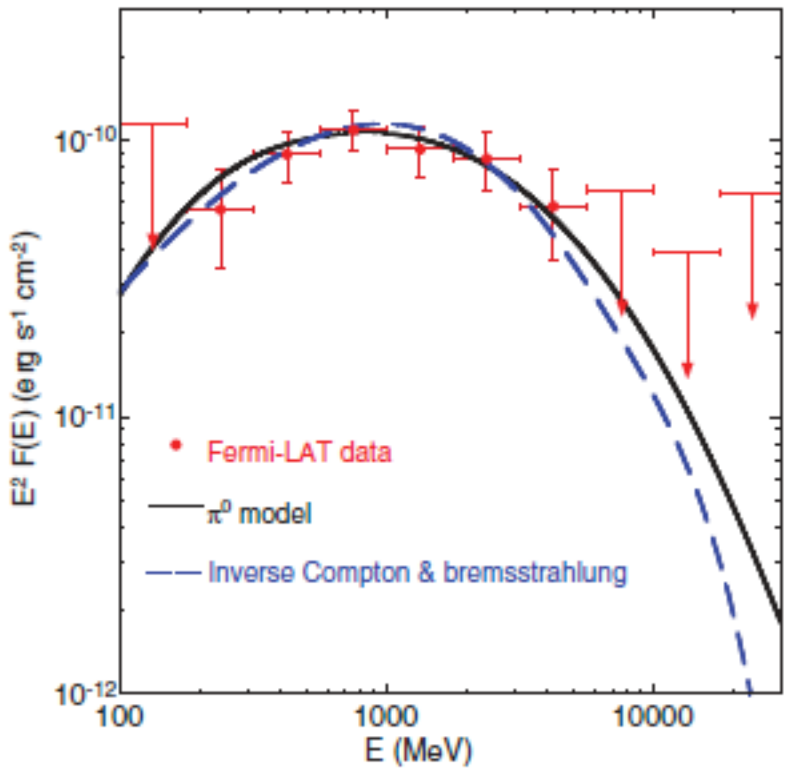
Main differences wrt RS Oph

- Not a standard recurrent nova: no regular eruptions before 2010 (Munari 2010)
- P_{orb} ~ 43 yr (456d in RS Oph) → a ~ 15 AU (10 times larger than for RS Oph) → shock wave needs ~7 days to reach d~a, so it propagates through the RG wind perturbed by the orbital motion in V407 Cyg (RS Oph, free exp. unperturbed wind at 1d)
- Non detection of early non thermal radio emission as in RS Oph. L_{syn} needed to compute IC not available from early radio observations

TH, ApJL 2007; HT, Balt. Astr. 2011 (arXiv:1111.4129)

V407 Cyg detected by Fermi/LAT

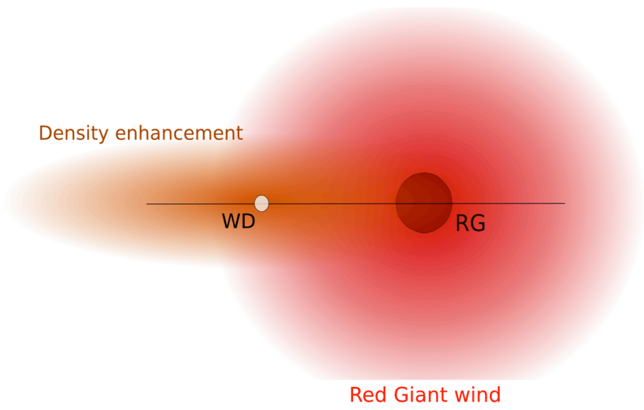




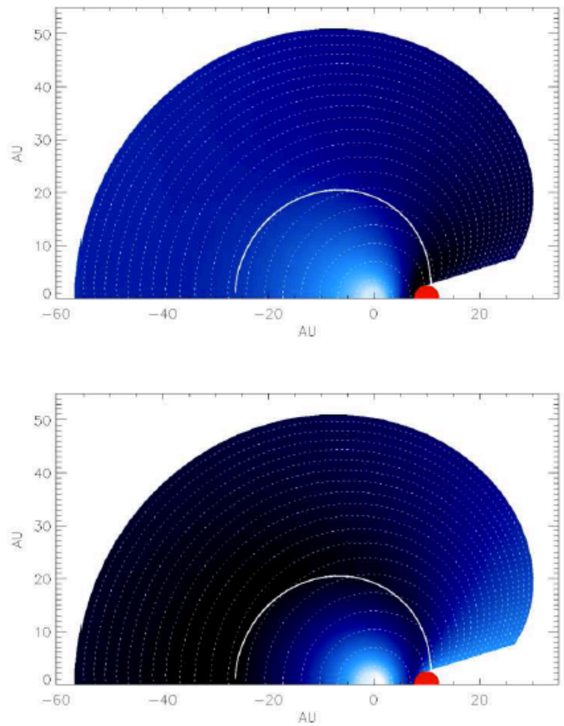
Abdo et al. 2010, Science

See next talks for (hard) X-ray and radio follow-up of V 407 Cyg

V407 Cyg: a nova detected by Fermi/LAT



Aspherical shock expansion (hydro sims. Orlando & Drake 2012)

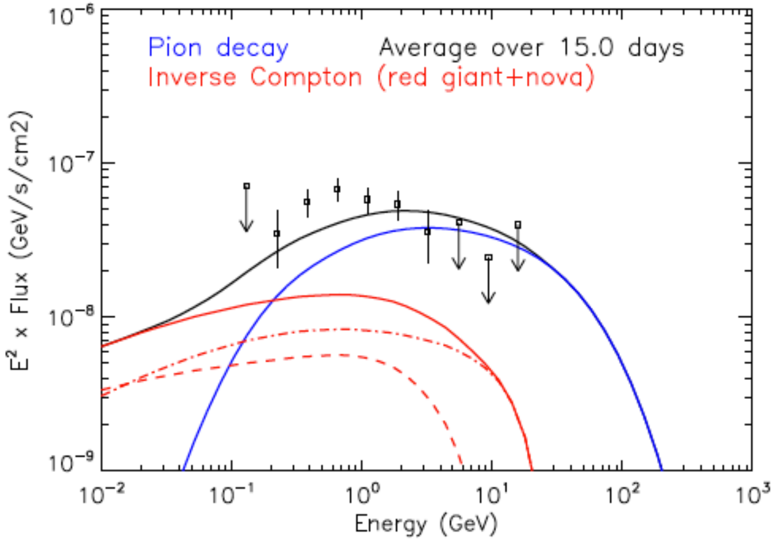


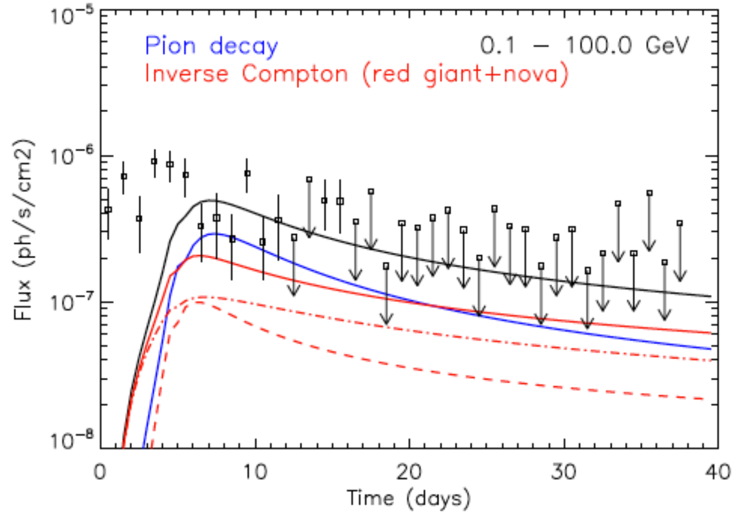
Spatial distribut. of non thermal p and e vs time
E_{max}: p(300GeV), e(20GeV)

P. Martin & G. Dubus, 2013, A&A accepted

V407 Cyg: a nova detected by Fermi/LAT

- Orbital separation:
  ~10-15 AU
- Mass-loss rate:
  5×10^{-8}-$10^{-7}M_\odot$/yr
- M_{ej}~(1-2)$\times10^{-6}M_\odot$
- Density enhancement
- p and e injec. frac:
  2×10^{-2} - 2×10^{-4}





Leptonic scenario: inverse Compton on nova light dominates

P. Martin & G. Dubus, 2013, A&A accepted

CONCLUSIONS: "Fermi novae"

- Recurrent novae in symbiotic binaries are expected to accelerate particles and emit VHE gamma-rays detectable with Fermi, because of the shock wave propagation in the dense red giant wind

- RS Oph would have been detected by Fermi

- V407 Cyg, detected by Fermi, did not behave as RS Oph, regarding X-ray and radio emission. So computing IC contribution is more "speculative"

- New detections of non symbiotic recurrent novae (N Sco 2012 and Nova Mon 2012) pose new challenges:

➔N Mon 2013 shocks with "dense" circumstellar matter (in agreement with late discovery in the optical and also late appearence of super soft X-ray emission). Radio (& hard X-rays detections but no RXTE) crucial (see next talks)

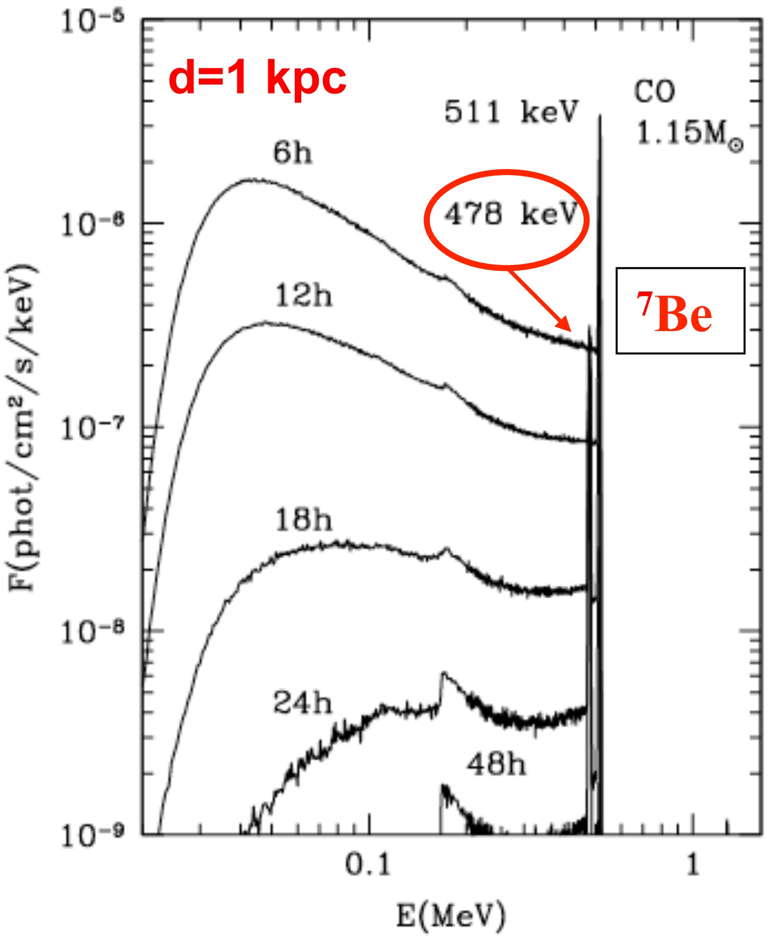
Gamma-rays from radioactivities:
E ~ 1 MeV

Why do novae emit gamma-rays with E~1 MeV? Main radioactive isotopes synthesized in novae

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

➡ photoelectric absorption
  ➡ cutoff at 20 keV

➡ transparent at 24-48 h

- 478 keV line from ^{7}Be decay

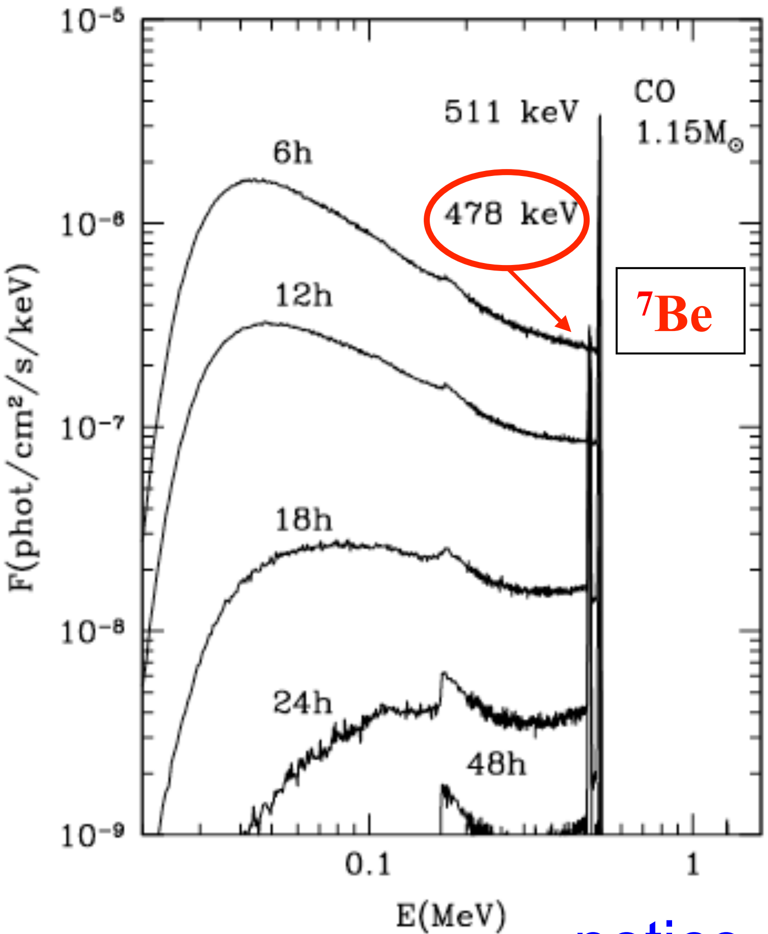
Hydrodynamic & nucleosynthesis:SHIVA JH98
MC code for gamma-ray spectra: Gómez-Gomar et al.1998, MNRAS; Hernanz et al 1999, ApJL
New nucleosynthesis from José with Iliadis et al. nucl. reactions (2010-2011): less ^{18}F

Spectra of CO novae

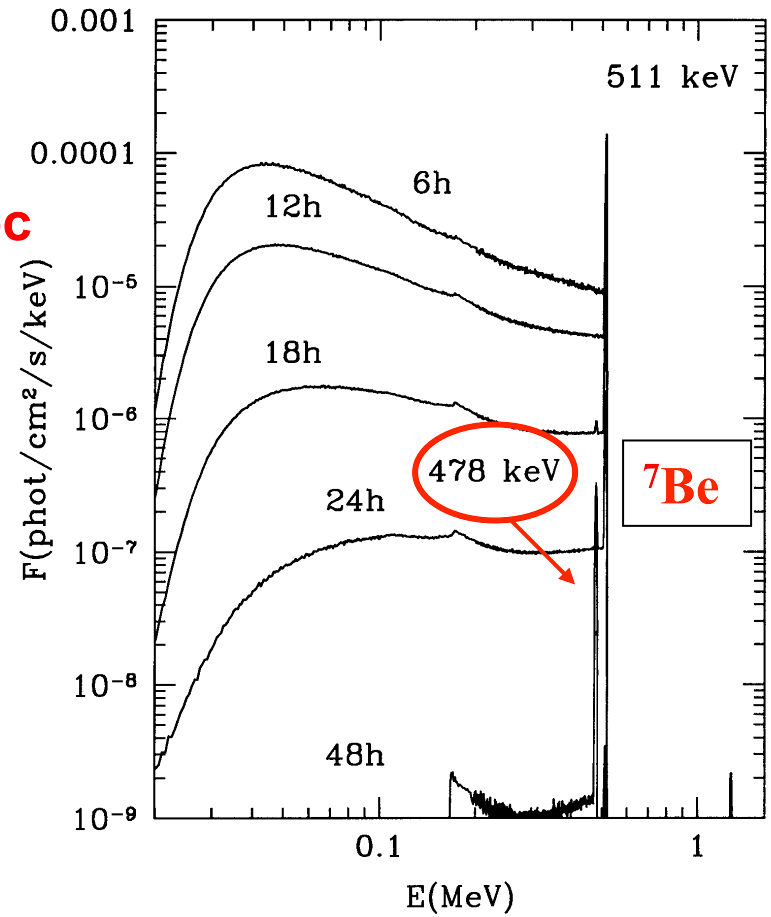
NEW: less ^{18}F

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

OLD

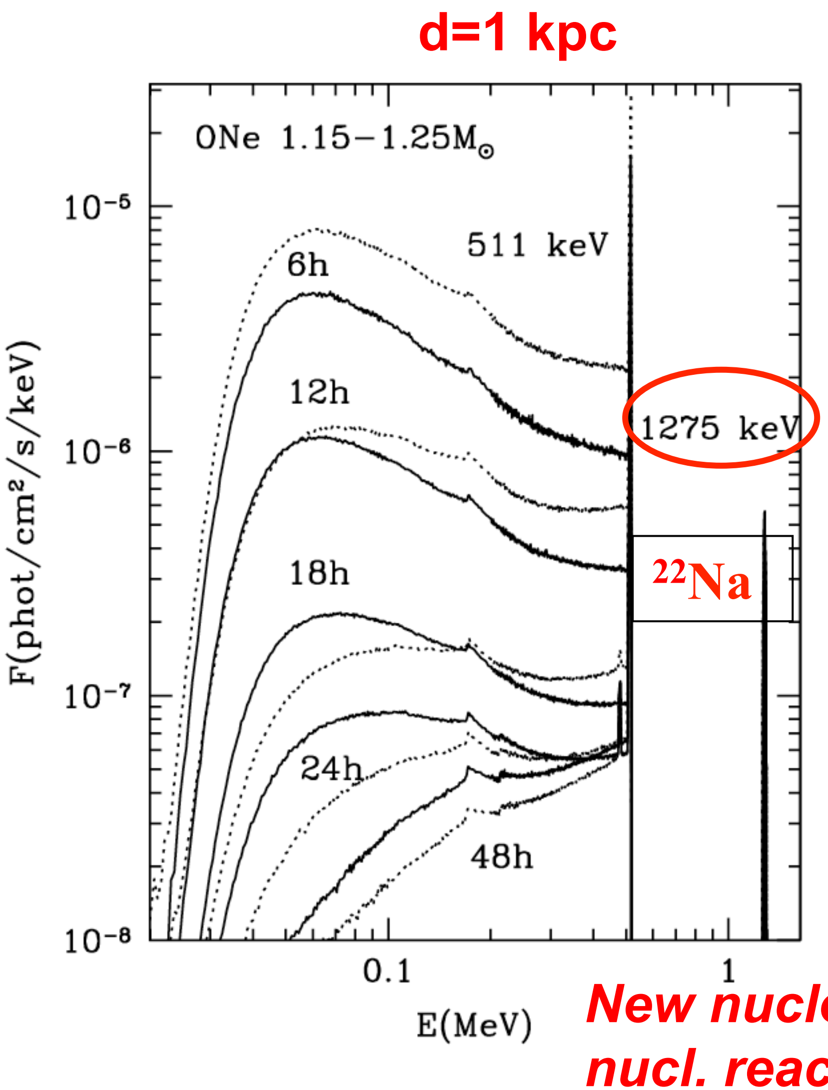


d=1 kpc



notice different y scales

Spectra of ONe novae



M_{WD} = 1.15-1.25 $M_\odot$

- continuum and 511 keV line
  ➡ as in CO novae but photoelectric absorption
  ➡ cutoff at 30 keV

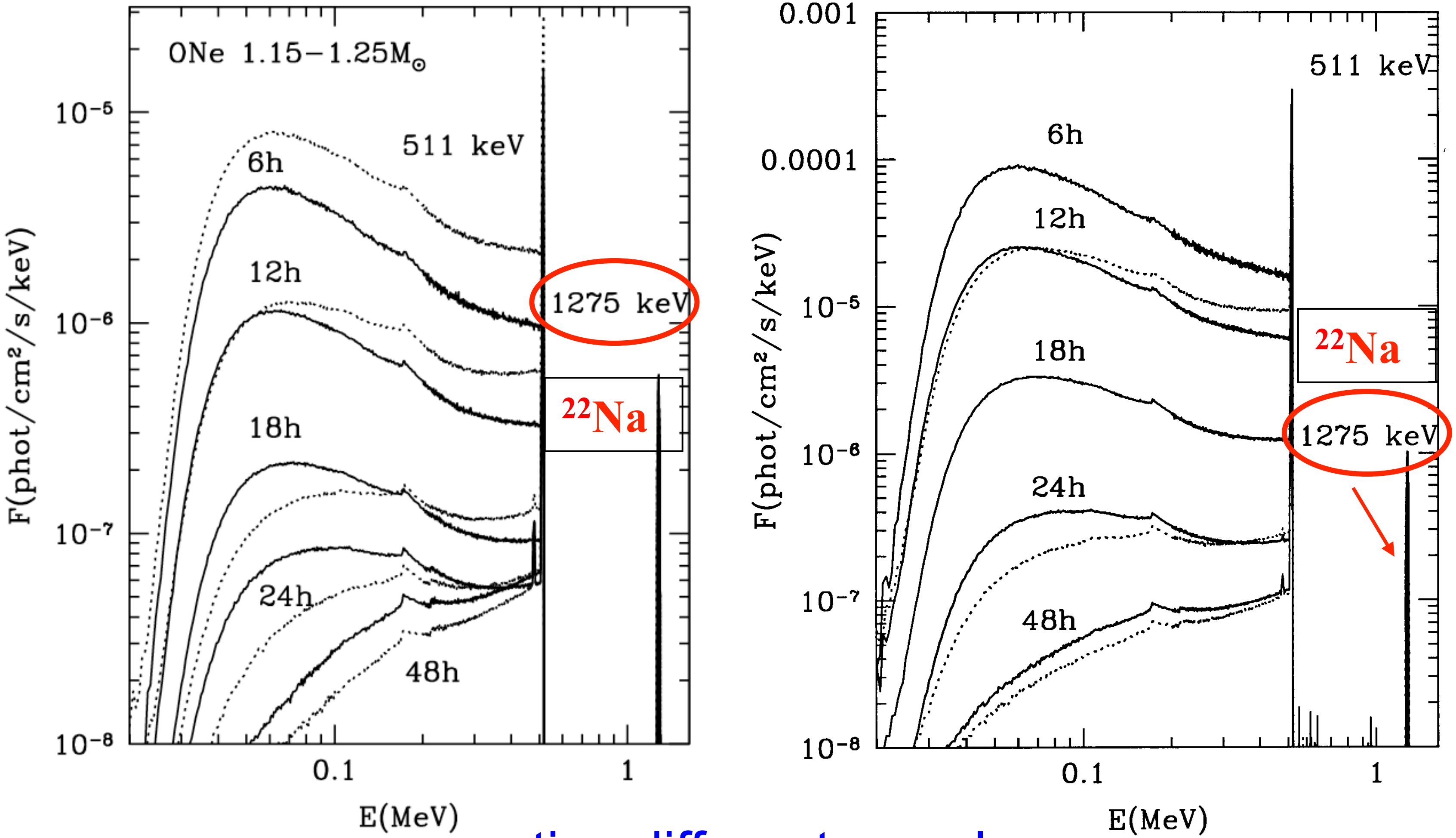
- 1275 keV line from ^{22}Na decay

- 1.15 & 1.25 $M_\odot$: 1.25 more transparent ➔ larger emission early and smaller later

New nucleosynthesis from José, with Iliadis et al. nucl. reactions (2010-2011): less ^{18}F

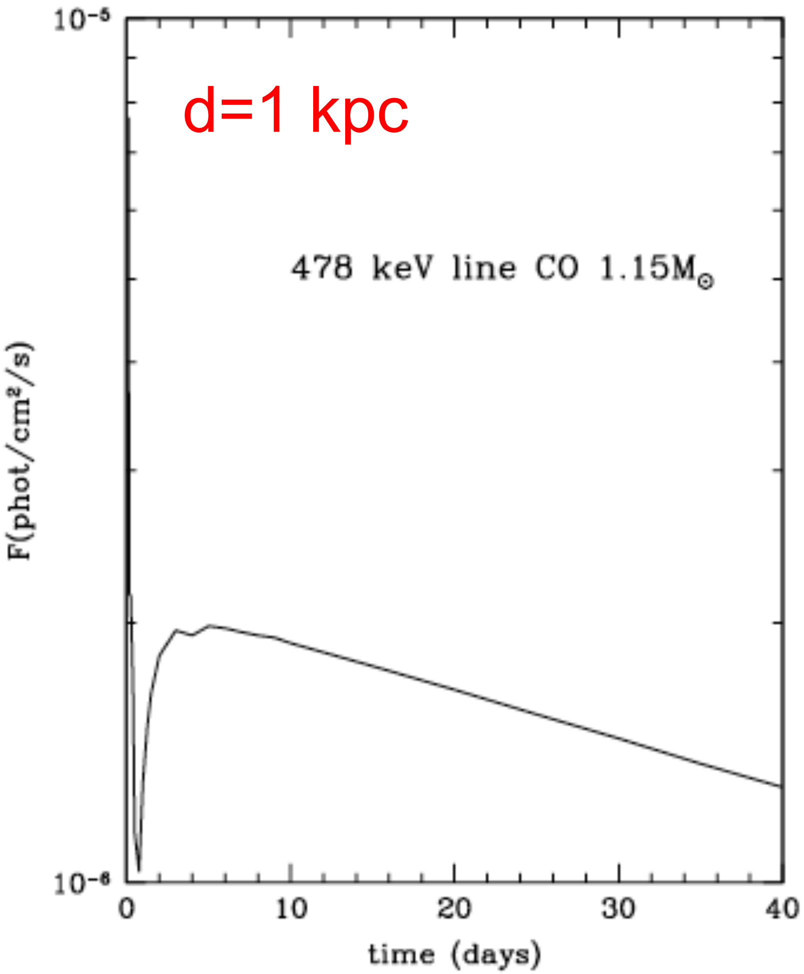
Spectra of ONe novae

NEW: less ^{18}F **d=1 kpc** OLD



notice different y scales

Light curves: 478 keV (^{7}Be) line



Mainly in CO novae

t_{max}: 5 days (1.15 $M_\odot$)

duration: some weeks

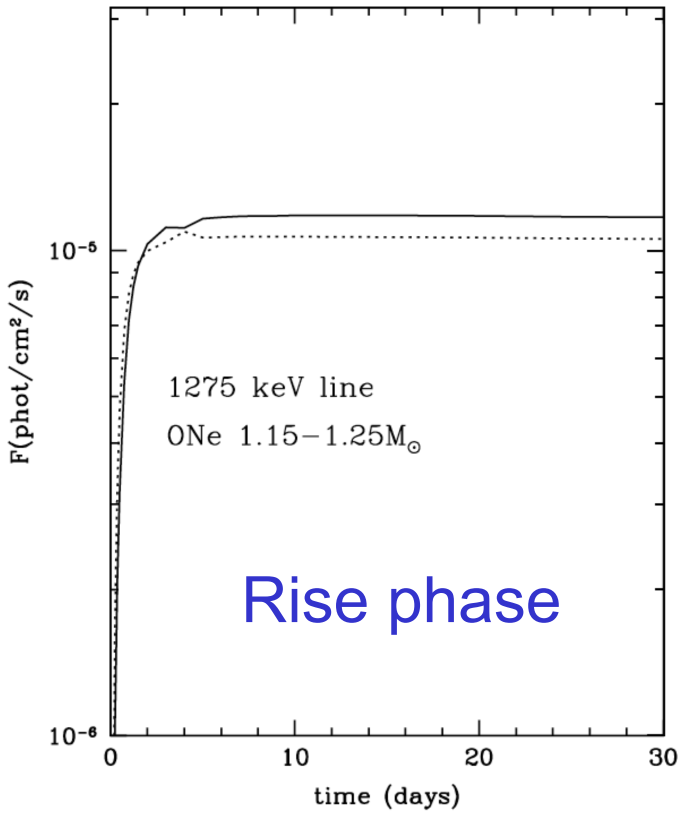
Flux : (1-2)x10^{-6} ph/cm^2/s

Line width: 3-7 keV

→ ^{7}Be decays into ^{7}Li

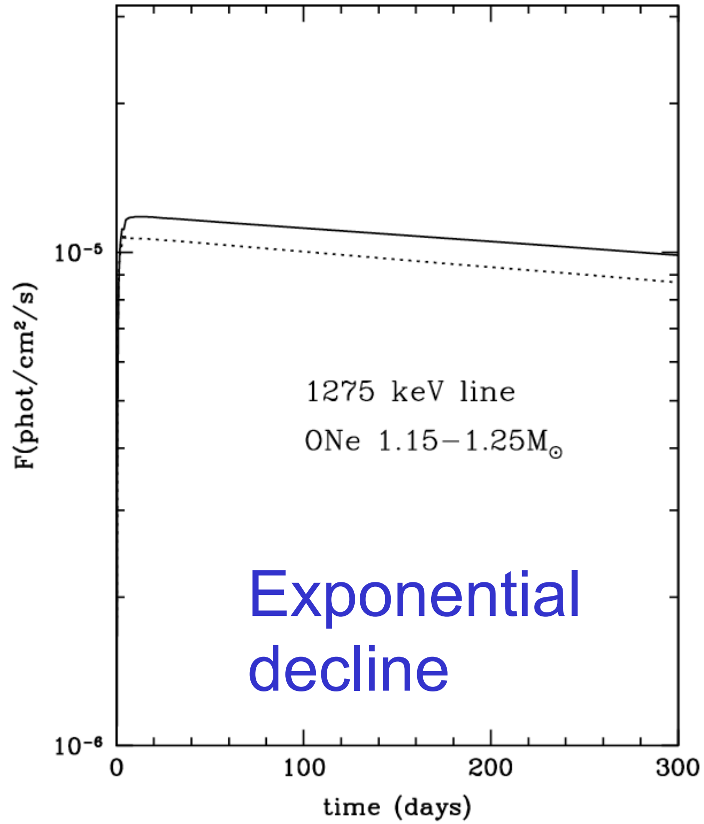
New models from José. Nucl. reactions from Iliadis et al. (2010-2011)

Light curves: 1275 keV (^{22}Na) line



Only in ONe novae

d=1 kpc



t_{max}: 15 days (1.15M$_\odot$), 4-8 days (1.25 M$_\odot$) – duration: months

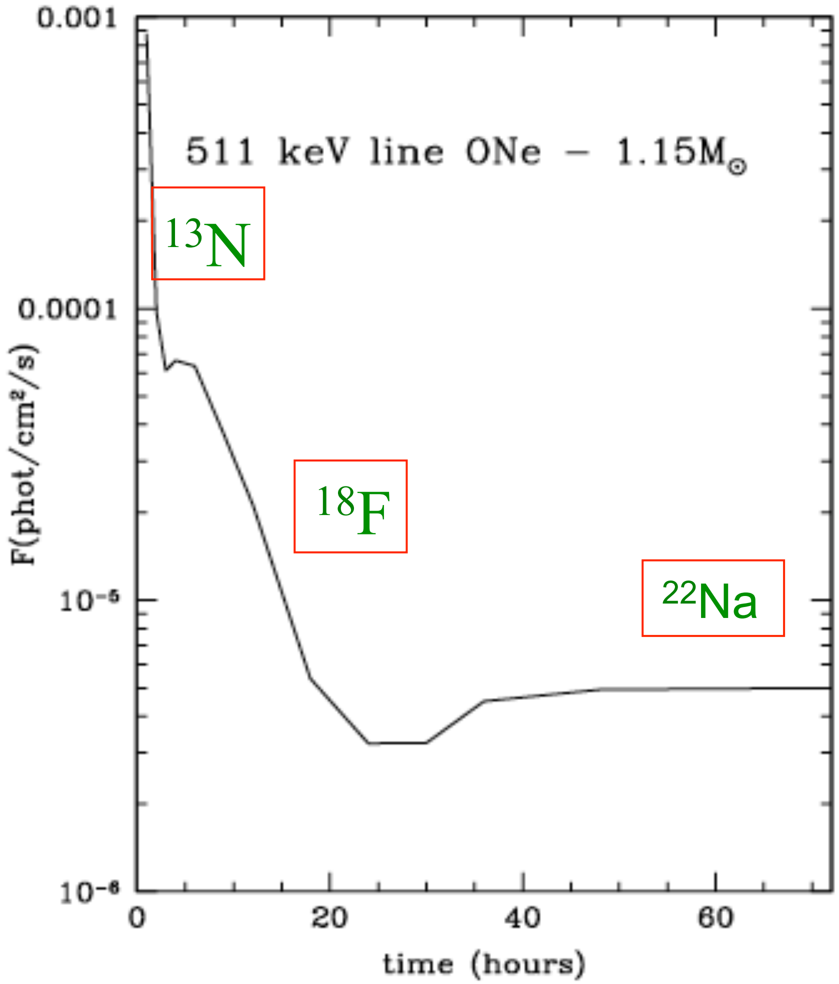
Flux: (1.1-1.2)x10^{-5} ph/cm^2/s - Line width : 20 keV

New models from José, with nucl. react. from Iliadis et al. (2010-2011)

No detection up to now

ToO proposals for INTEGRAL/SPI - since its launch in 2002 - not triggered yet

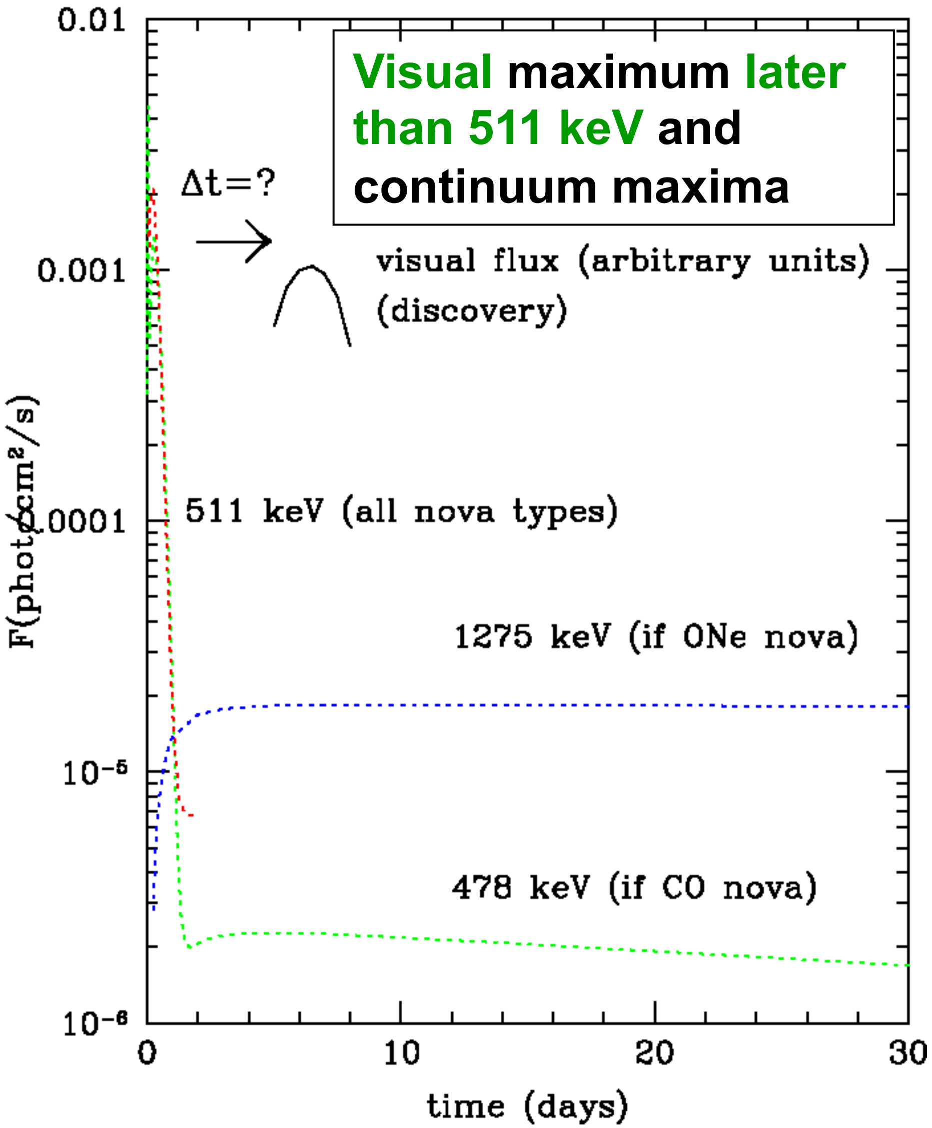
Light curves: 511 keV line: CO and ONe novae



- Intense (but short duration)
- Very early appearence, before visual max. (before discovery)

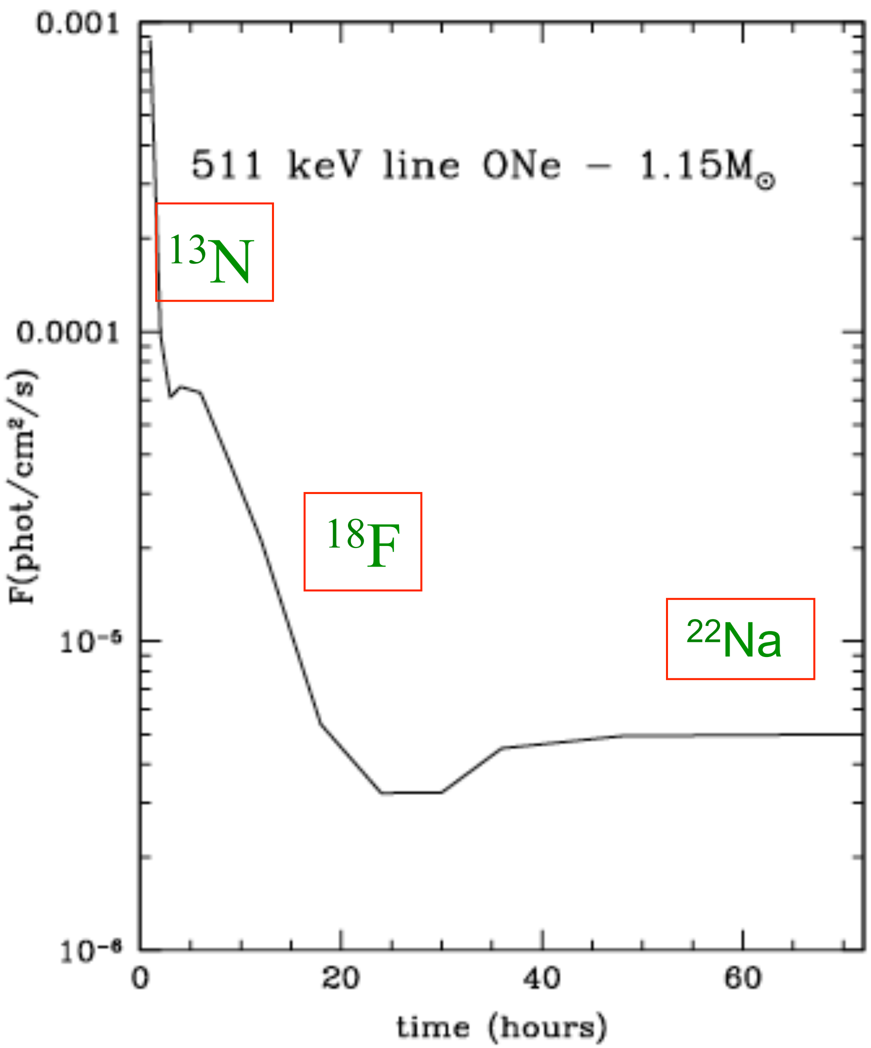
New models from José. Nucl. reactions from Iliadis et al. (2010-2011): less ^{18}F

Gamma-ray and visual light curves



➡ Detection requires "a posteriori" analyses with wide FOV instruments (see later)

Light curves: 511 keV line: CO and ONe novae



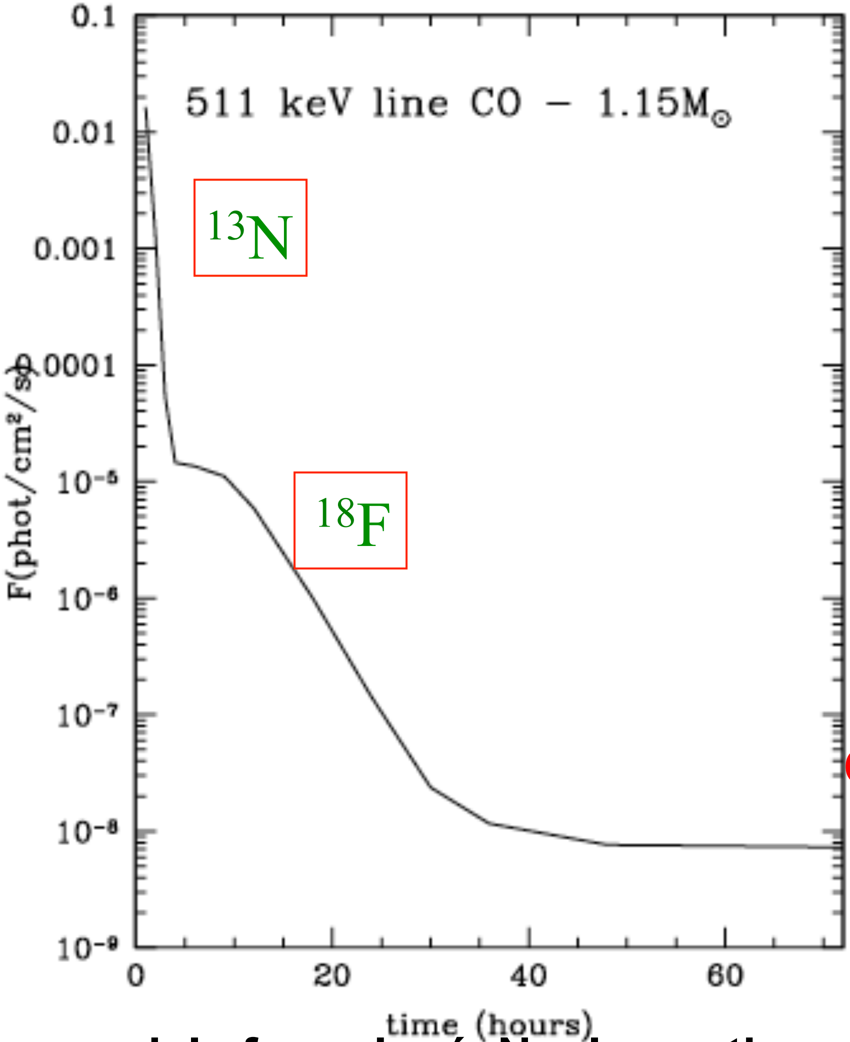
- Intense (but short duration)
- Very early appearence, before visual max. (before discovery)
- ^{18}F longer duration emission: radically reduced
- ^{13}N very short peak remains (but model dependent: ***convection***)
- ^{22}Na low flux tail remains:

~ *10 days* duration, with a flat flux ~ *5×10^{-6} ph/cm^2/s*

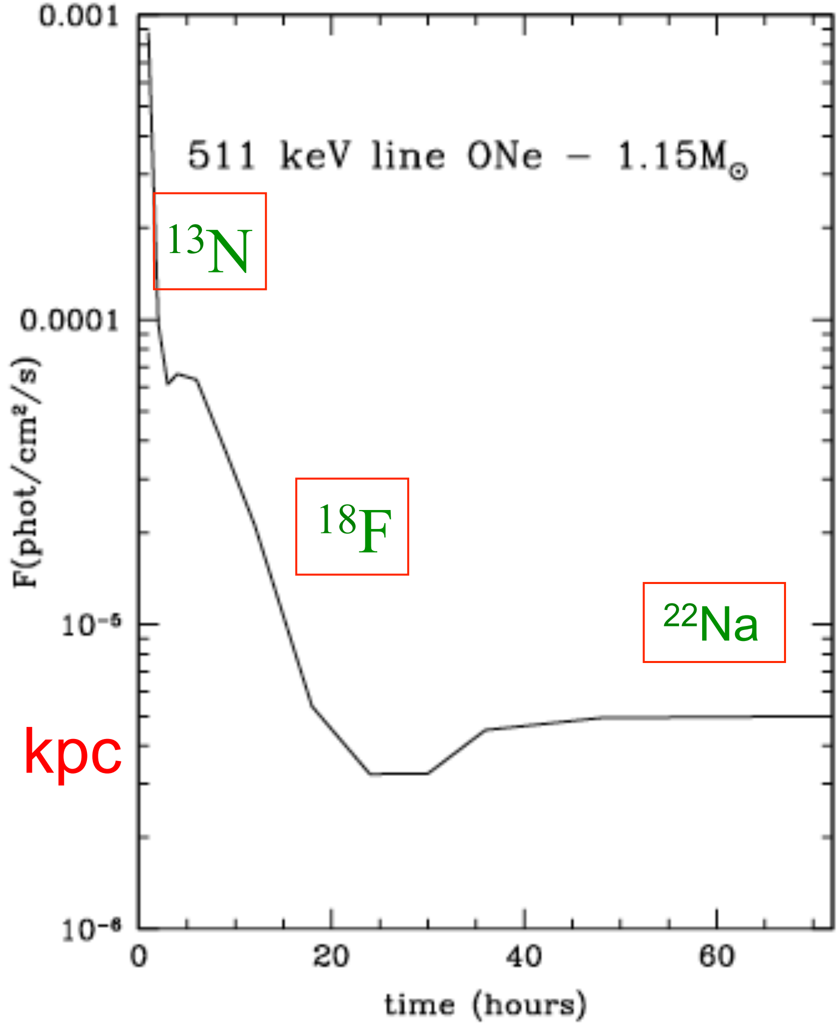
➢ *unique diagnostic of envelope properties **(chem. comp. & transpar.)***

New models from José. Nucl. reactions from Iliadis et al. (2010-2011): less ^{18}F

Light curves: 511 keV line: CO and ONe novae



d=1 kpc



New models from José. Nucl. reactions from Iliadis et al. (2010-2011): much less ^{18}F

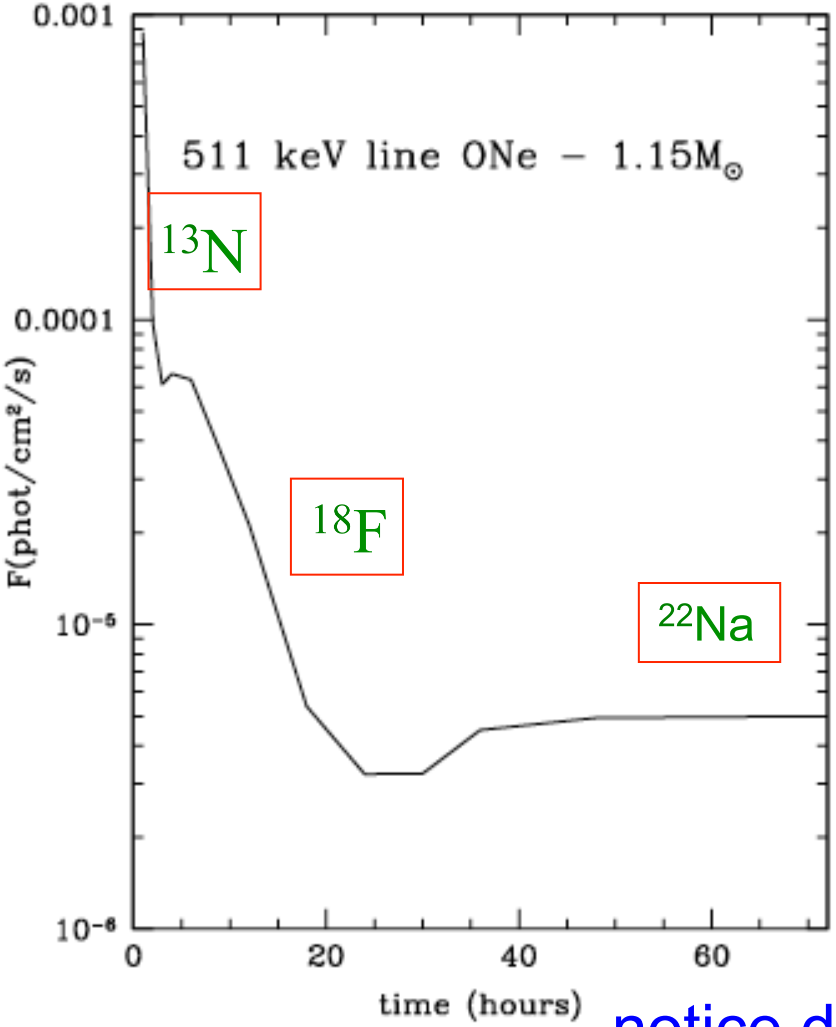
notice different y scales

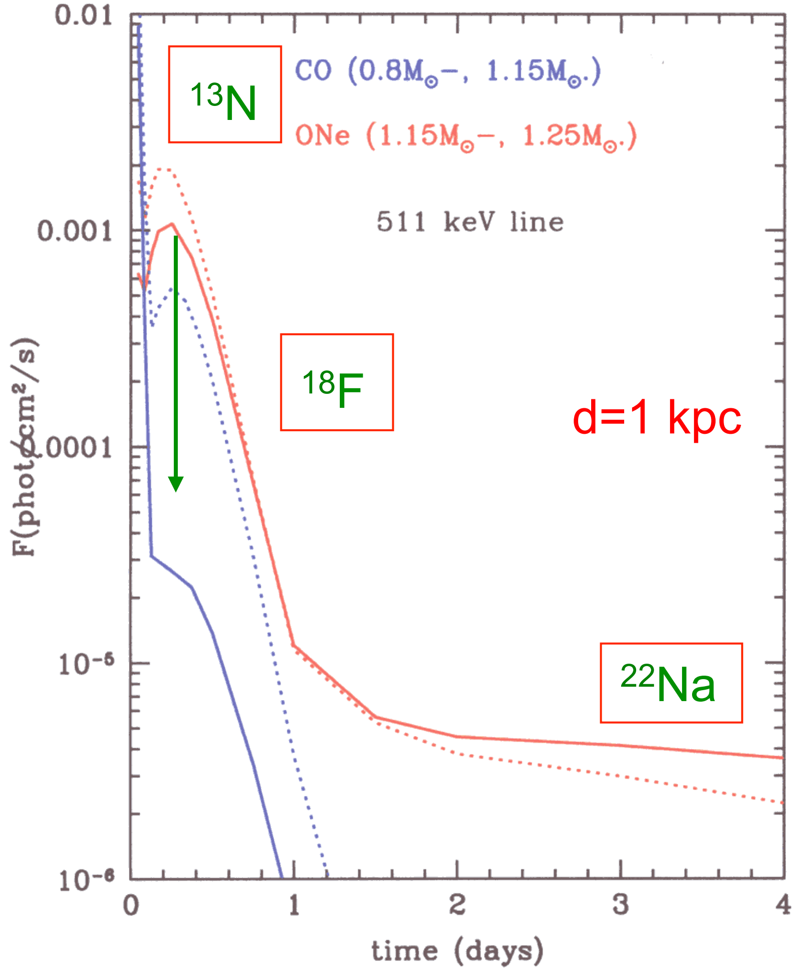
Light curves: 511 keV line

ONe new

d=1 kpc

OLD

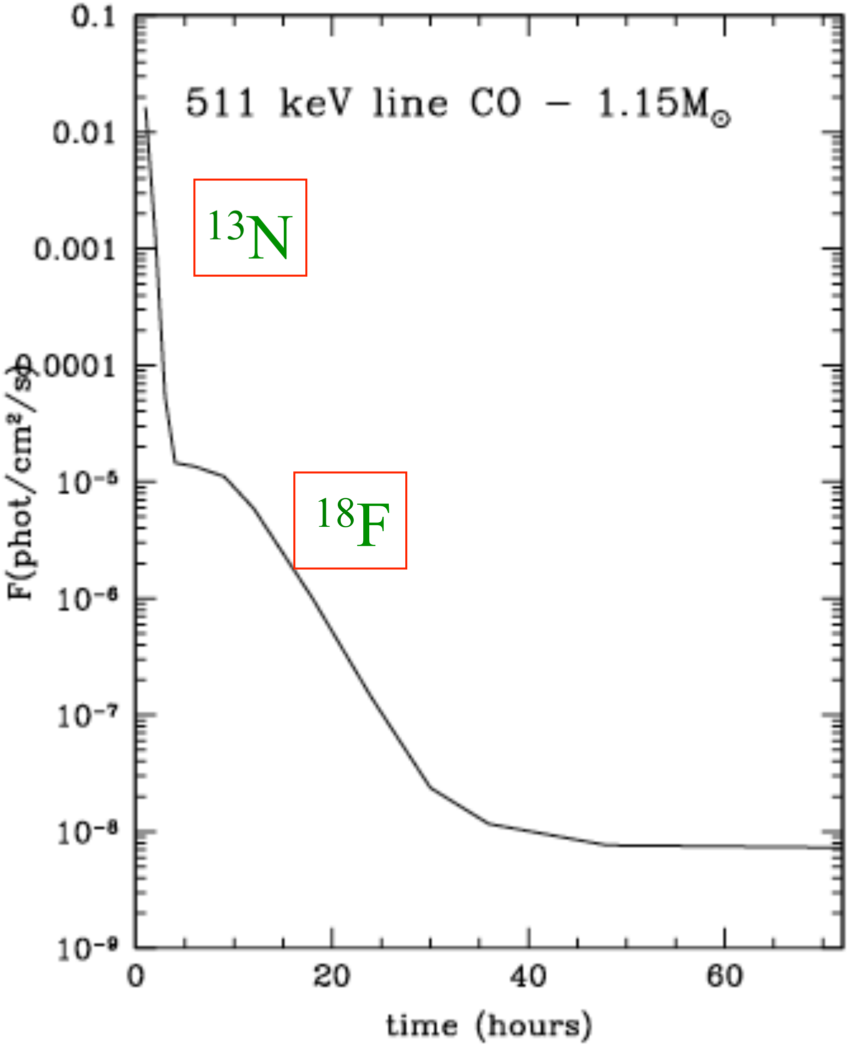




notice different y scales

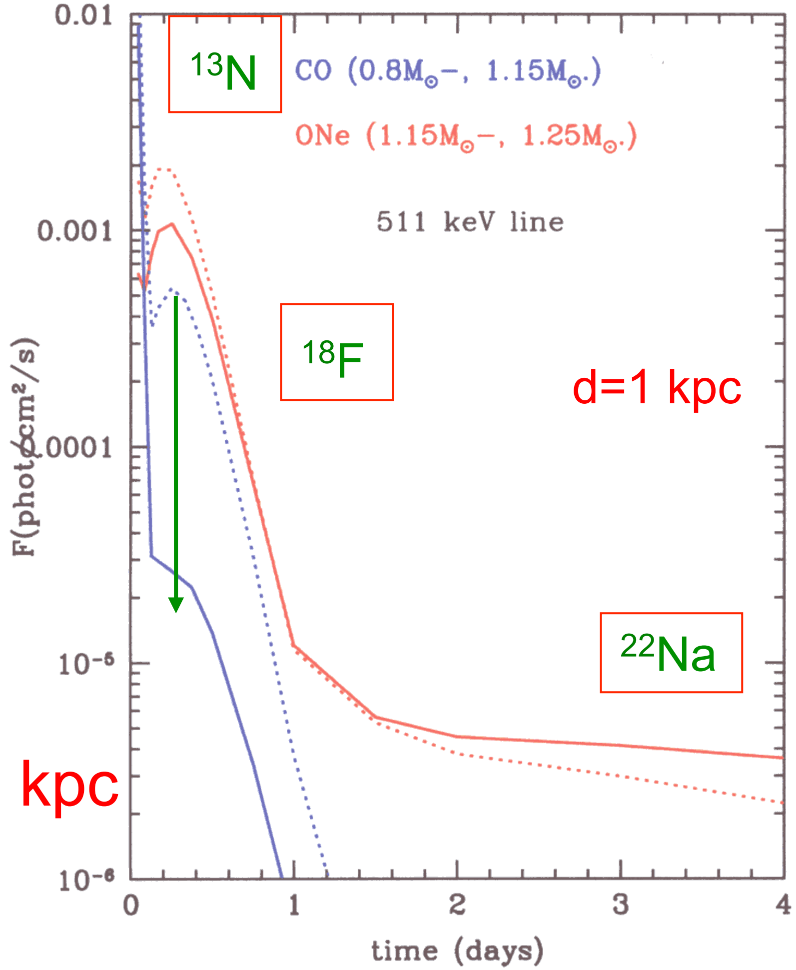
Light curves: 511 keV line

CO new

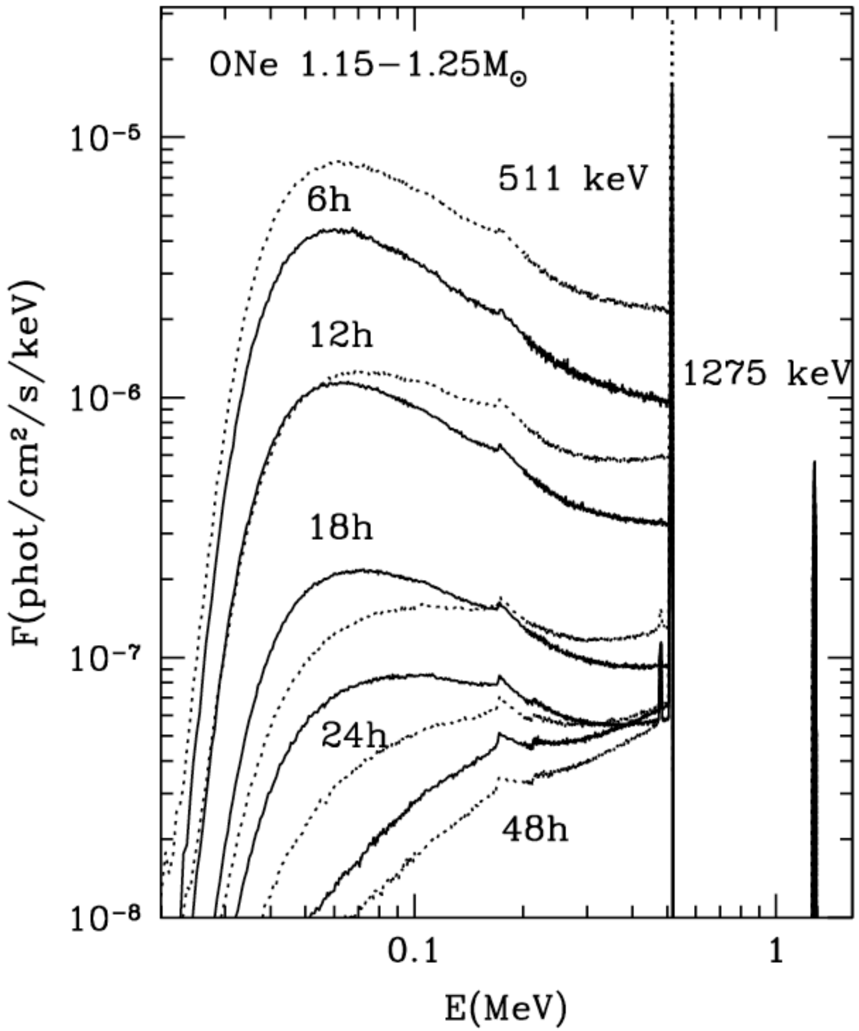


d=1 kpc

OLD



Spectra of ONe novae: Comptonization and hard X-rays



Compton degradation of gamma-rays from classical novae ***CAN NOT*** be responsible of their ***early hard X-ray emission, e.g., SWIFT/BAT det. of RS Oph; Suzaku det. of V2491 Cyg (2008)***:

- Cut-off at 20 keV (photoelectric abs.)
- Fast disappearence: 2days (w.r.t T_{max}, i.e., before visual outburst)

Spectra of ONe novae: caution with Comptonization calculation

THE ASTROPHYSICAL JOURNAL LETTERS, 723:L84–L88, 2010 November 1 doi:10.1088/2041-8205/723/1/L84

COMPTON DEGRADATION OF GAMMA-RAY LINE EMISSION FROM RADIOACTIVE ISOTOPES IN THE CLASSICAL NOVA V2491 CYGNI

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Received 2010 July 26; accepted 2010 September 17; published 2010 October 13

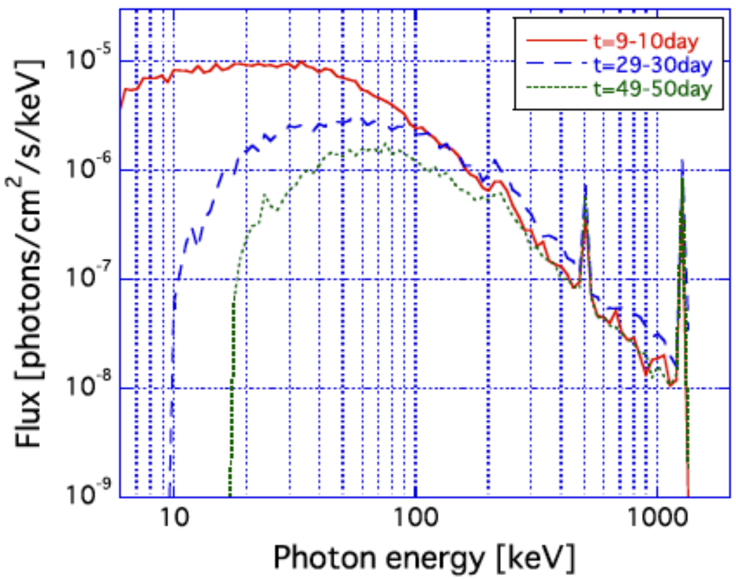
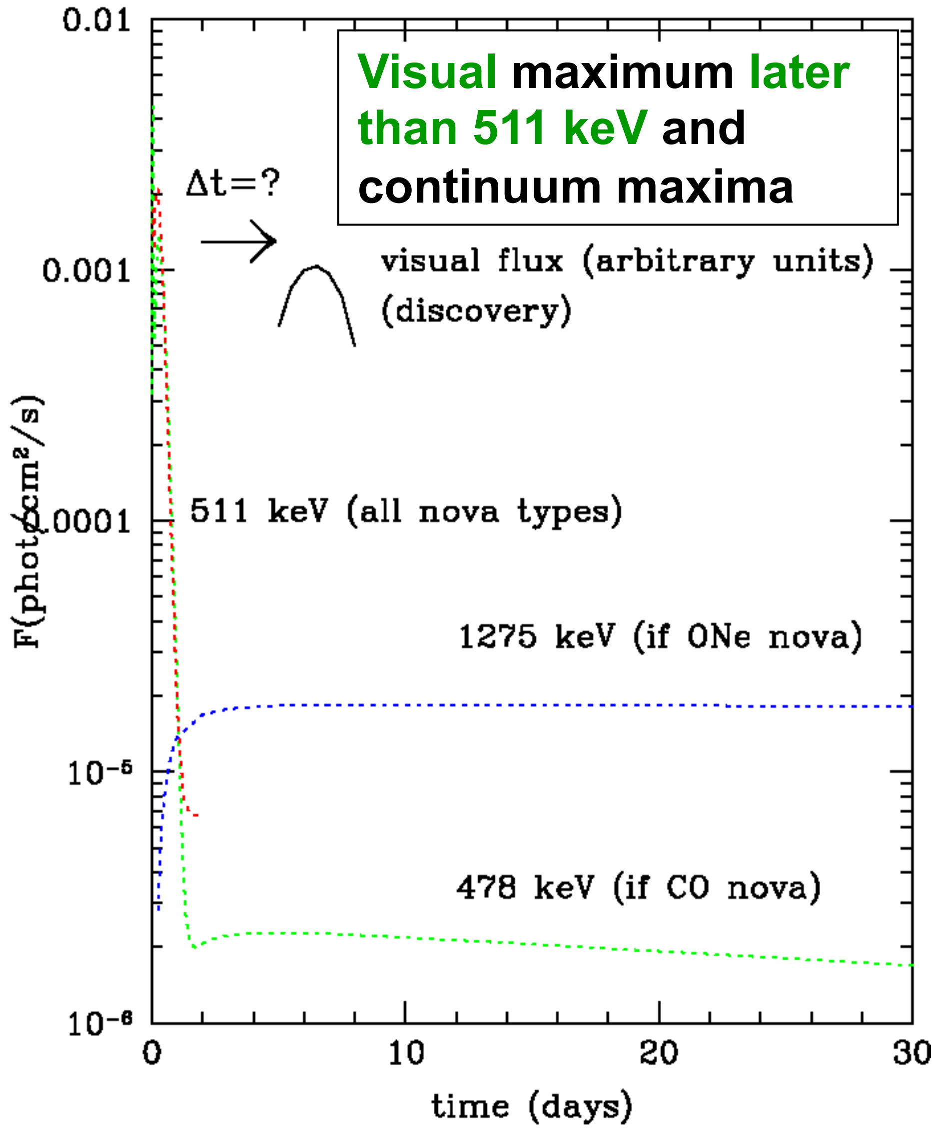


Figure 1. Resultant energy spectra of photons escaping from the ejecta. The seed photons are injected from $t = 9$ day to $t = 10$ day (solid line), from $t = 29$ day to $t = 30$ day (dashed line), and from $t = 49$ day to $t = 50$ day (dotted line). The free parameters characterizing the ejecta are $v_{ej} = 4000$ km s^{-1}, $M_{ej} = 10^{-3}\ M_\odot$, and $R_{in} = 3 \times 10^{12}$ cm. Photoelectric absorption is neglected ($Z = 0$).

- *No Compton scattering* included
- Photoelectric absorption neglected in some of the models
- Positrons only from ^{22}Na: huge amounts of 22Na needed (~10^5 more than predicted) , different timing, not free escape)

Gamma-ray and visual light curves - reminder

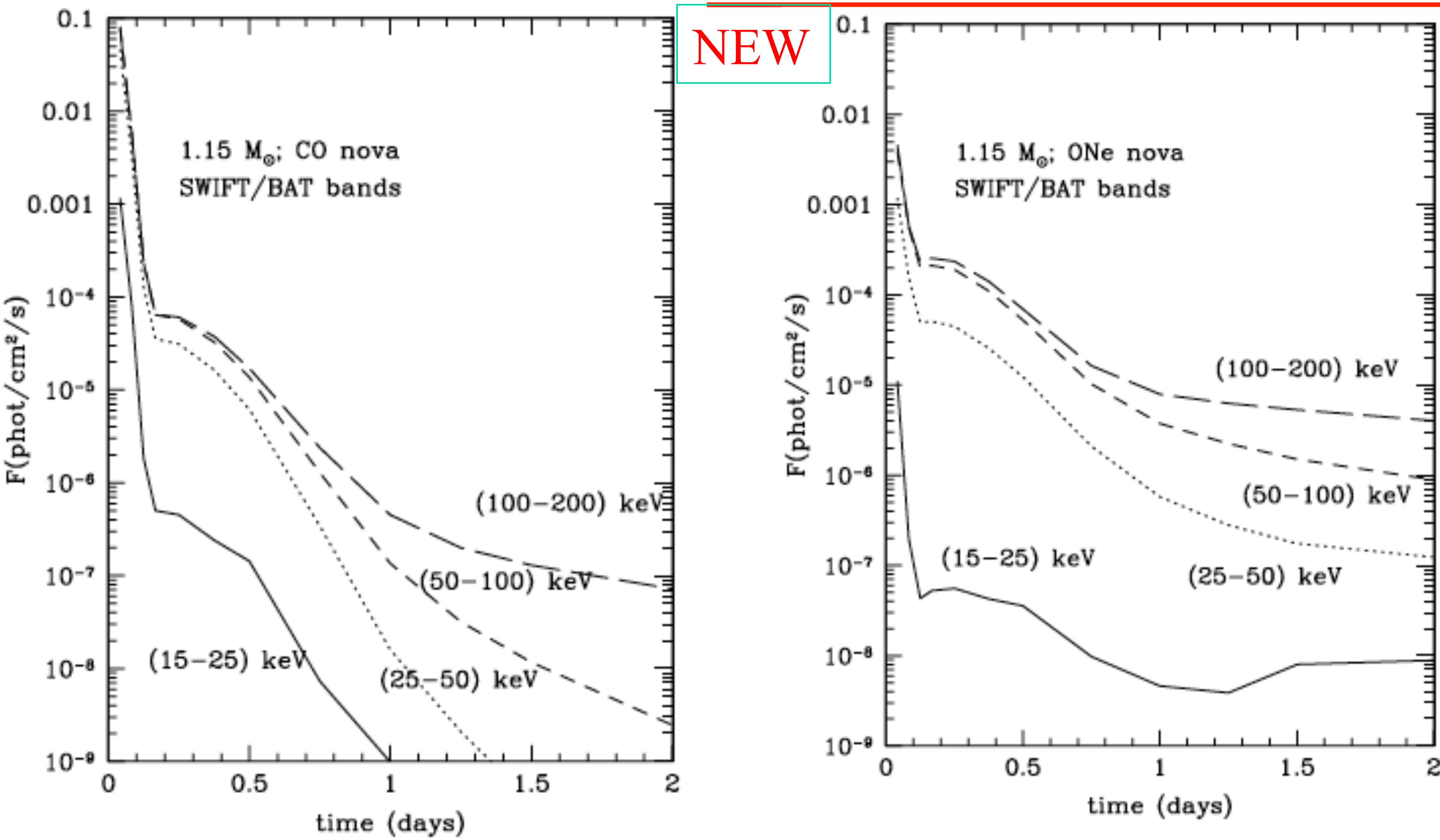


- Detection requires "a posteriori" analyses with wide FOV instruments all used; negative results

- *All-sky monitoring with Compton telescope perfectly suited:*
  CGRO/BATSE,
  WIND/TGRS
  SWIFT/BAT
  All used: negative results

e^- - e^+ annihilation emission: continuum SWIFT/BAT

NEW



Senziani, Skinner, Jean, Hernanz, A&A, 2008: search based in these continua in all novae in the FoV of SWIFT/BAT (2005-2007)

e^- - e^+ annihilation emission: continuum SWIFT/BAT

Nova	year	m_V at visual max	t_2 (days)	E(B-V)	d_{MMRD} (kpc)	Δt_{best} (10% coverage time)	Upper limit (ph cm^2 s^{-1}) (10% coverage time)	d_{max} (kpc) (10% coverage time)	Δt_{best} (50% coverage time)	Upper limit (ph cm^2 s^{-1}) (50% coverage time)	d_{max} (kpc) (50% coverage time)
V2361 Cyg	2005	10	5.5 ± 0.5	1.2	$10.80^{+2.91}_{-2.30}$	DPH	5.9×10^{-3}	3.8	DPH	1.5×10^{-2}	2.3
V382 Nor	2005	9.7	14.5 ± 2.5	1.50-1.51 (*)	$4.8^{+1.8}_{-1.2}$	DPH	2.1×10^{-2}	1.8 (0.5)	DPH	2.6×10^{-2}	0.1 (0.1)
V378 Ser	2005	11.6	52 ± 18	0.74	$18.88^{+7.71}_{-4.50}$	DPH	1.1×10^{-2}	2.7	DPH	4.7×10^{-2}	0.1
V5115 Sgr	2005	7.75	4 ± 2	0.53	$10.22^{+3.08}_{-2.38}$	DPH	6.0×10^{-3}	3.7 (0.9)	DPH	2.4×10^{-2}	0.2 (0.2)
V1663 Aql	2005	10.7	14 ± 6	2	$3.88^{+1.83}_{-1.38}$	DPH	4.5×10^{-3}	4.1 (1.0)	12h	2.7×10^{-3}	0.1 (0.2)
V5116 Sgr	2005	7.2	7 ± 4	0.34-0.57 (*)	$8.3^{+5.1}_{-3.1}$	DPH	1.2×10^{-2}	0.1 (0.1)	DPH	1.2×10^{-2}	0.1 (0.1)
V1188 Sco	2005	8.9	12 ± 5	1.09-1.49 (*)	$4.4^{+4.8}_{-1.9}$	DPH	5.2×10^{-3}	3.9 (1.0)	DPH	5.6×10^{-2}	0.6 (0.2)
V1047 Cen	2005	7.4	4.5 ± 1.5	1.28-1.38 (*)	2.8 ± 0.5	DPH	1.0×10^{-2}	2.7 (0.7)	DPH	2.6×10^{-1}	0.2 (0.2)
V476 Sct	2005	11.4	12 ± 2	2.0	$5.69^{+1.85}_{-1.43}$	1h	2.4×10^{-2}	1.8 (0.5)	DPH	2.4×10^{-1}	0.1 (0.1)
V477 Sct	2005	10.75	7.5 ± 2.5	1.3	$12.74^{+4.04}_{-3.16}$	1h	9.0×10^{-3}	2.8 (0.7)	1h	5.0×10^{-2}	0.3 (0.2)
V2575 Oph	2006	11	31 ± 2	1.5	$5.63^{+1.69}_{-1.28}$	DPH	7.8×10^{-3}	3.2	DPH	4.1×10^{-2}	1.2
V5117 Sgr	2006	9.9	59 ± 11	0.5 ± 0.15	$11.91^{+0.63}_{-0.45}$	1h	1.3×10^{-2}	2.5 (0.6)	1h	2.2×10^{-1}	0.3 (0.2)
V2362 Cyg	2006	7.75	7 ± 2.5	0.59	$8.90^{+2.81}_{-2.19}$	DPH	1.4×10^{-2}	2.3	1h	1.2×10^{-1}	0.6
V2576 Oph	2006	9.2	25.5 ± 2.5	0.62	$9.58^{+3.32}_{-2.37}$	DPH	8.9×10^{-3}	3.0	DPH	4.6×10^{-2}	1.3

No detection (24 novae in Swift/BAT FoV) – Upper limits - Detectability d < d

Senziani, Skinner, Jean, Hernanz, A&A, 2008

e^- - e^+ annihilation emission: continuum SWIFT/BAT

Nova	year	m_V at visual max	t_2 (days)	E(B-V)	d_{MMRD} (kpc)	Δt_{best}	10% coverage time Upper limit (ph cm^2 s^{-1})	d_{max} (kpc)	Δt_{best}	50% coverage time Upper limit (ph cm^2 s^{-1})	d_{max} (kpc)
V1065 Cen	2007	8.7	19.5 ± 1	0.77-0.84 (*)	$7.55^{+1.65}_{-1.15}$	1h	7.6×10^{-3}	3.2 (0.8)	1h	2.7×10^{-2}	1.6 (0.4)
V1280 Sco	2007	4	13 ± 1	0.39-0.55 (*)	2.1±0.4	1h	9.1×10^{-3}	3.0 (0.8)	DPH	2.7×10^{-2}	1.6 (0.4)
V1281 Sco	2007	8.8	8 ± 4	0.7	$12.10^{+4.28}_{-3.37}$	1h	9.1×10^{-3}	2.9 (0.7)	DPH	3.2×10^{-2}	1.7 (0.4)
V2467 Cyg	2007	7.6	8 ± 2	1.6±0.1	$1.93^{+0.26}_{-0.24}$	1h	9.3×10^{-3}	2.9 (0.7)	DPH	5.3×10^{-2}	1.1 (0.3)
V2615 Oph	2007	8.75	36.5 ± 4.5	1.0-1.3	$3.09^{+0.21}_{-0.15}$	1h	2.3×10^{-2}	1.9	DPH	9.3×10^{-2}	0.9
V5558 Sgr	2007	6.5	6 ± 1	0.8	$3.78^{+1.06}_{-0.83}$	1h	2.8×10^{-2}	1.7 (0.5)	DPH	1.1×10^{-1}	0.9 (0.2)
V598 Pup	2007	?	?	?	?	DPH	2.6×10^{-2}	1.8	DPH	1.1×10^{-1}	0.1
V390 Nor	2007	9.8	49.5 ± 5.5	1.0	$5.74^{+1.67}_{-1.26}$	1h	2.1×10^{-2}	1.9 (0.5)	1h	6.7×10^{-2}	1.0 (0.3)
V458 Vul	2007	8.1	8.5 ± 3.5	0.6	$10.01^{+3.45}_{-2.71}$	1h	2.8×10^{-2}	1.7 (0.4)	DPH	1.1×10^{-1}	0.4 (0.1)
V597 Pup	2007	?	?	0.3	?	1h	2.2×10^{-2}	1.8 (0.5)	DPH	9.8×10^{-2}	0.8 (0.2)

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Some key questions about novae that gamma-rays could help to answer

If enough sensitivity to detect novae in the MeV E range

❖ ***Mixing*** between accreted matter (solar-like) and white dwarf matter: ***CO vs. ONe novae spectra***

❖ ***Efficiency of convection: 511 keV peak (^{13}N) and continuum***

❖ Contribution of novae to ***galactic ^{7}Li and ^{26}Al content***

❖ ***Spatial distribution*** in the Galaxy and ***nova rate: no visual extinction problem***

❖ ***Ejected masses***: discrepancy between measured and predicted (some observed are larger than predicted):

e.g. ^{22}Na: X_i (theory) x $M_{ejec,total}$ (optical + IR obs.) ⟺ $M_{i,ejected}$ (γ-ray obs)

➡ ***not a good enough instrument concept yet***