Novae: gamma-rays from radioactivities and from particle acceleration

Nova explosions in the MeV and GeVgamma-ray domain of e-ASTROGAM

Margarita Hernanz

Institute of Space Sciences (CSIC-IEEC)

Bellaterra (Barcelona), Spain

Stellar explosions: white dwarfs in close binary systems

Cataclysmic variable:

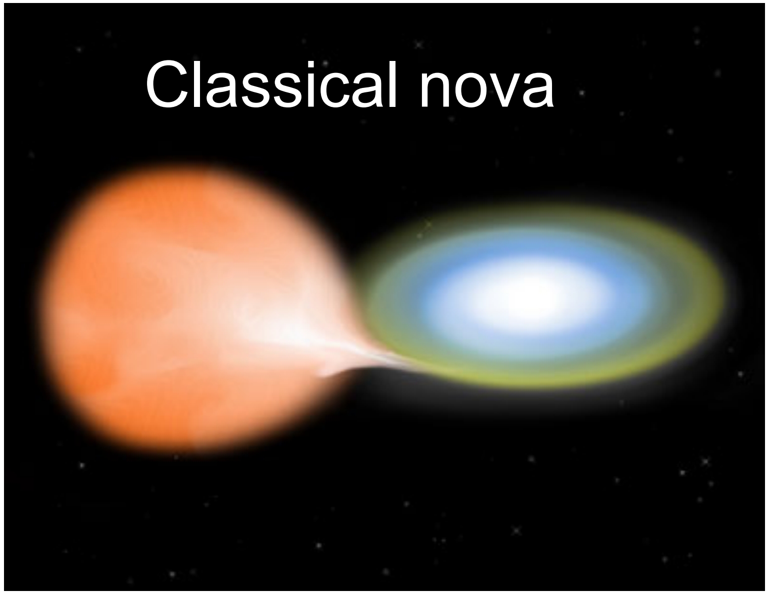
WD + Main Sequence

Roche lobe overflow

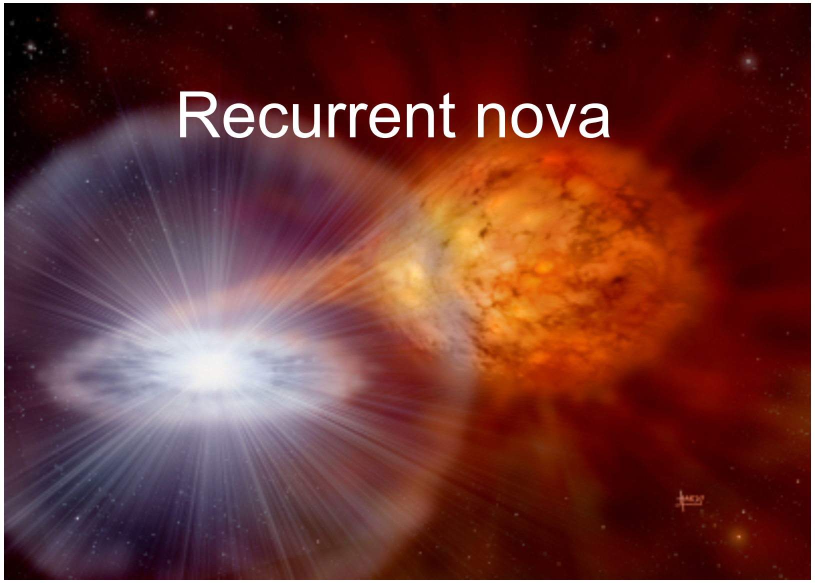
Symbiotic binary:

WD + Red Giant

accretion from a red giant wind



Hydrogen burning in degenerate conditions on top of the white dwarf



P_{rec}~10^4-10^5 yr

- **P_{rec}<100 yrs**
- **Massive WDs & M_{wd} can increase → possible SNIa scenarios**

Two types of gamma-ray emission from novae

- **Radioactivity** in the ejecta:
  - ➢ traces nucleosynthesis
  - ➢ photons with E ~ MeV
  - ➢ not detected yet: CGRO/Comptel, INTEGRAL/SPI

Two types of gamma-ray emission from novae

- **Radioactivity** in the ejecta:
  - traces nucleosynthesis
  - photons with E ~ MeV
  - not detected yet: CGRO/Comptel, INTEGRAL/SPI
- **Particle acceleration** in strong shocks
  - external shocks between ejecta and dense red giant wind in symbiotic recurrent novae
  - internal shocks within the nova ejecta in classical novae
  - IC (leptonic) or π^0 decay (hadronic) ➔ photons with E>100 MeV
  - detected with Fermi/LAT in 6 (+3) novae

High Energy (HE) Gamma-rays : E > 100 MeV

"Fermi/LAT novae"

First evidence of particle acceleration - p & e - to TeV energies in nova *predicted before Fermi launch*

EVIDENCE FOR NONLINEAR DIFFUSIVE SHOCK ACCELERATION OF COSMIC RAYS IN THE 2006 OUTBURST OF THE RECURRENT NOVA RS OPHIUCHI

V. TATISCHEFF[1] AND M. HERNANZ

THE ASTROPHYSICAL JOURNAL, 663: L101–L104, 2007 July 10

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V. TATISCHEFF[1] AND M. HERNANZ

- RS Oph: symbiotic recurrent nova (WD + RG companion)
- Two last nova eruptions: 1985 & 2006 (P_{rec} = 21 yrs) - P_{orb}=456 days – d =1.6 kpc
- Expanding shock wave sweeps red giant wind
- **Acceleration of particles (p and e) to TeV energies in a nova - RS Oph (2006) - demonstrated for the first time**

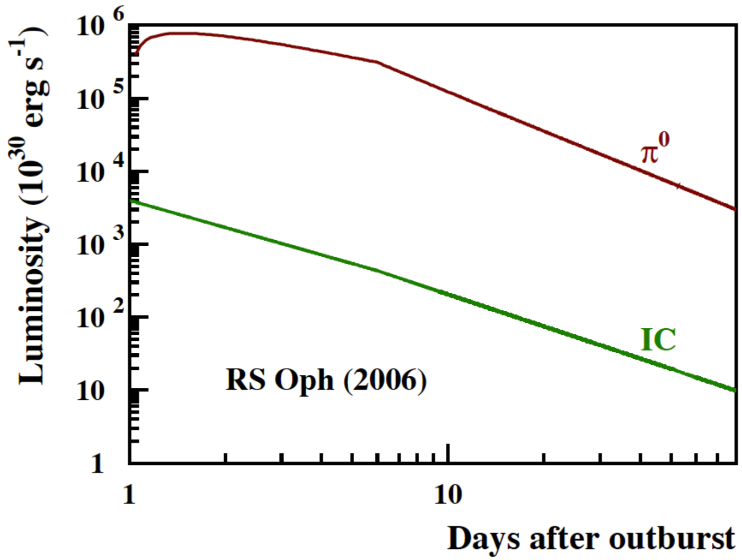
- *"Miniature SN remnant"- much dimmer & evolving much faster → study of time dependence of cosmic ray acceleration in a blast wave is possible*
- ***HE gamma-rays***

RS Oph (2006): predicted HE gamma-ray emission

- π^0 production: (p-p coll.; hadronic)
- IC contribution: (e^- -photons; leptonic) derived from non thermal synchrotron (radio) and ejecta L_{ej}~L_{Edd}

➔ π^0 production dominates

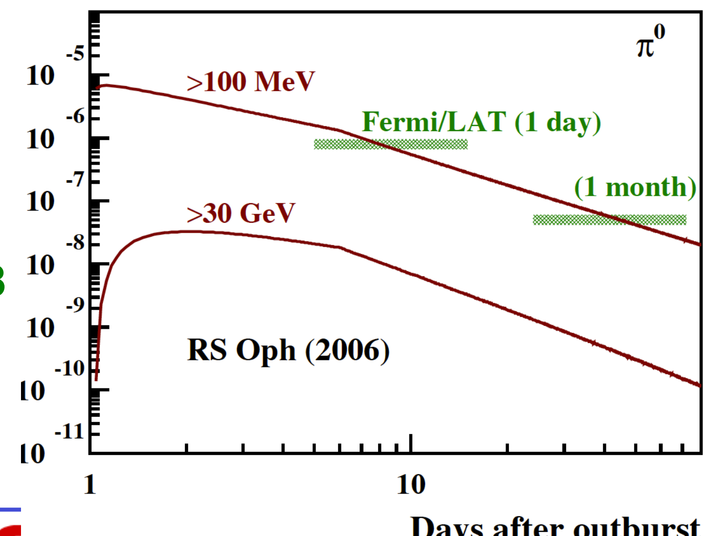
RS Oph would have been detected by Fermi!



Tatischeff, MH, ApJL 2007

TH, Cospar Symposium 2008

MH,Tatischeff, Balt. Astr. 2011 (arXiv:1111.4129)



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

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

SCIENCE VOL 329 13 AUGUST 2010

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.

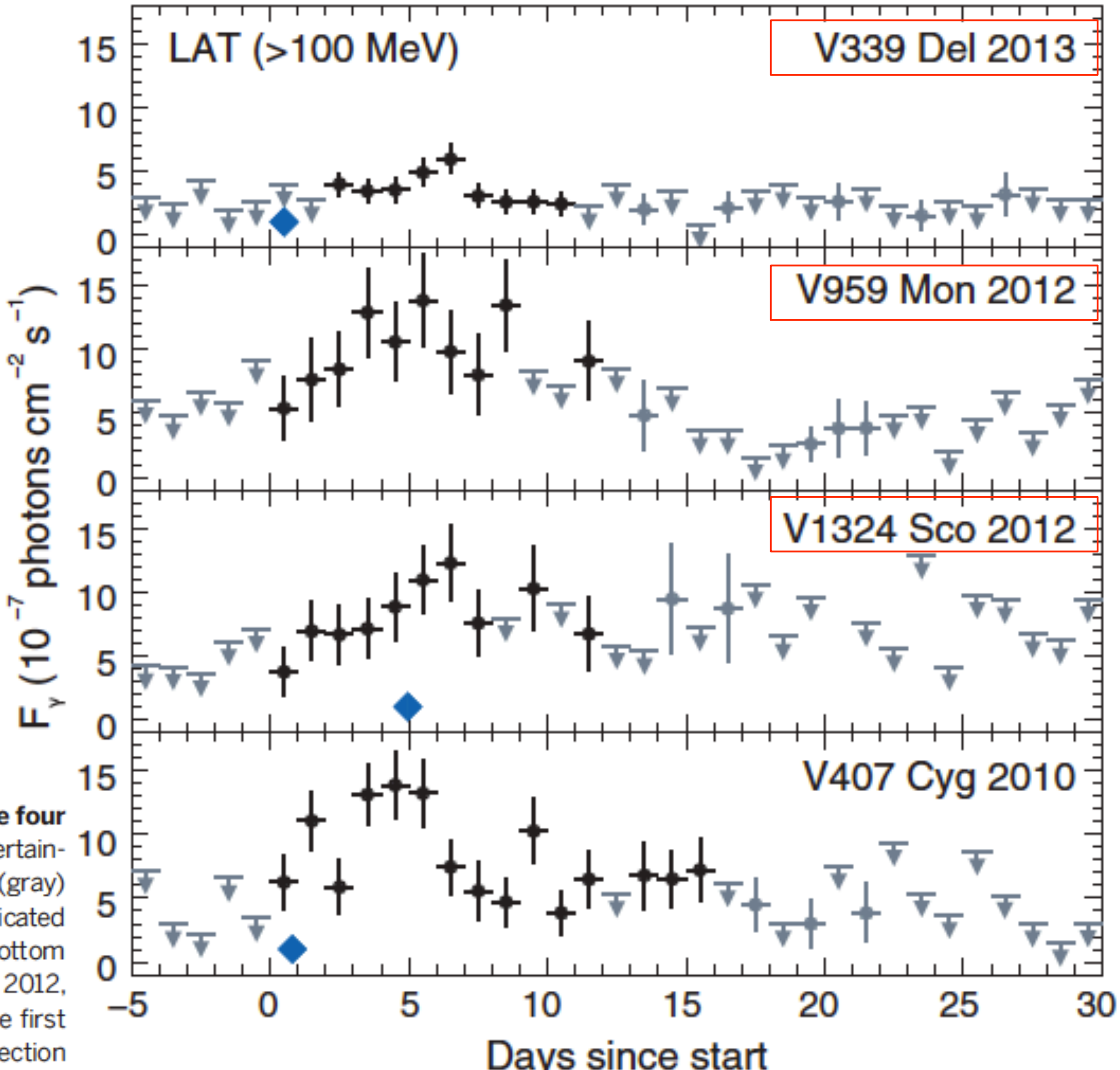
Fermi establishes classical novae as a distinct class of gamma-ray sources

The Fermi-LAT Collaboration*†

Science **345**, 554 (2014)

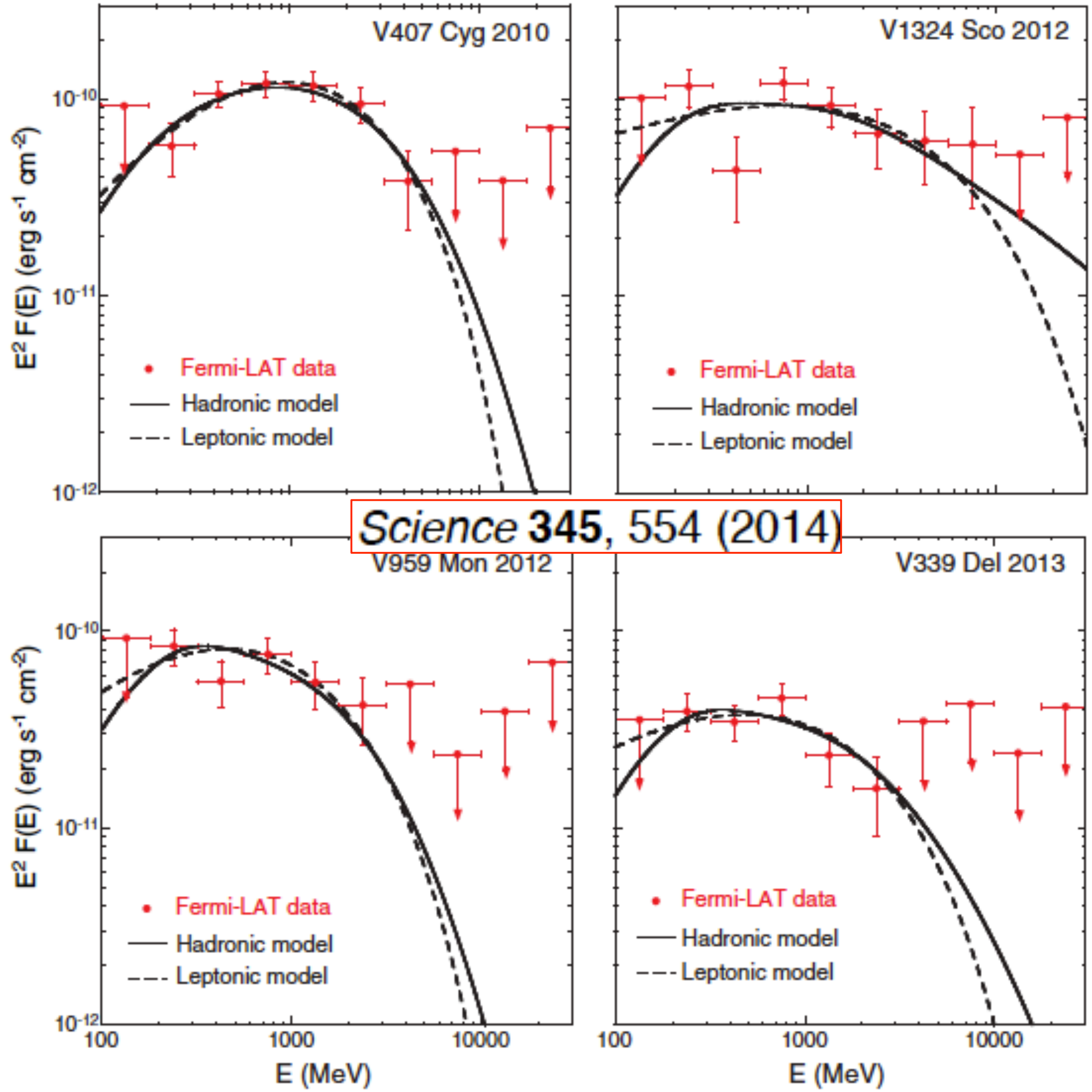
A classical nova results from runaway thermonuclear explosions on the surface of a white dwarf that accretes matter from a low-mass main-sequence stellar companion. In 2012 and 2013, three novae were detected in γ rays and stood in contrast to the first γ-ray–detected nova V407 Cygni 2010, which belongs to a rare class of symbiotic binary systems. Despite likely differences in the compositions and masses of their white dwarf progenitors, the three classical novae are similarly characterized as soft-spectrum transient γ-ray sources detected over 2- to 3-week durations. The γ-ray detections point to unexpected high-energy particle acceleration processes linked to the mass ejection from thermonuclear explosions in an unanticipated class of Galactic γ-ray sources.

- ***V407 Cyg: WD + red giant (wind) system (symbiotic nova)***
- ***CNe: WD + MS also detected by Fermi at E>100 MeV***



Science **345**, 554 (2014)

Fig. 2. Fermi-LAT 1-day binned light curves of the four γ-ray detected novae. Vertical bars indicate 1 σ uncertainties for data points with >3 σ (black) and 2 to 3 σ (gray) significances; otherwise, 2 σ upper limits are indicated with gray arrows. Start times t_s (from top to bottom panels) of 16 August 2013, 19 June 2012, 15 June 2012, and 10 March 2010 were defined as the day of the first γ-ray detection. In V339 Del, there was a 2.4 σ detection in 0.5-day binned data beginning 16.5 August (*13*), the epoch of the optical peak (blue diamond in each panel).



Science **345**, 554 (2014)

Fig. 3. Fermi-LAT >100-MeV average γ-ray spectra of the four novae over the full 17- to 27-day durations. Vertical bars indicate 1 σ uncertainties for data points with significances >2 σ otherwise, arrows indicate 2 σ limits. The best-fit hadronic and leptonic model curves are overlaid.

Discrimination between hadronic and leptonic emission models requires a sensitivity of

$\sim 10^{-11}$ erg cm^{-2} s^{-1} at 30 MeV in ~10 days

(P. Jean priv. comm.)

Should be possible with ASTROGAM

Mechanism of particle acceleration in classical novae: not well understood yet

Binary orbits as the driver of γ-ray emission and mass ejection in classical novae

Laura Chomiuk[1], Justin D. Linford[1], Jun Yang[2,3,4], T. J. O'Brien[5], Zsolt Paragi[3], Amy J. Mioduszewski[6], R. J. Beswick[5], C. C. Cheung[7], Koji Mukai[8,9], Thomas Nelson[10], Valério A. R. M. Ribeiro[11], Michael P. Rupen[6,12], J. L. Sokoloski[13], Jennifer Weston[13], Yong Zheng[13], Michael F. Bode[14], Stewart Eyres[15], Nirupam Roy[16] & Gregory B. Taylor[17]

Nature, 2014

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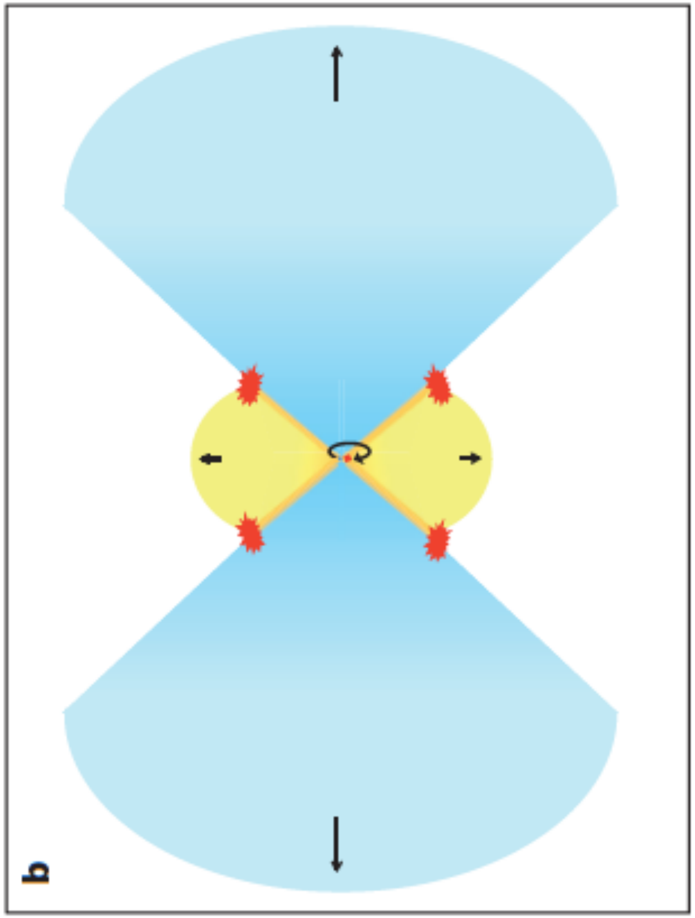

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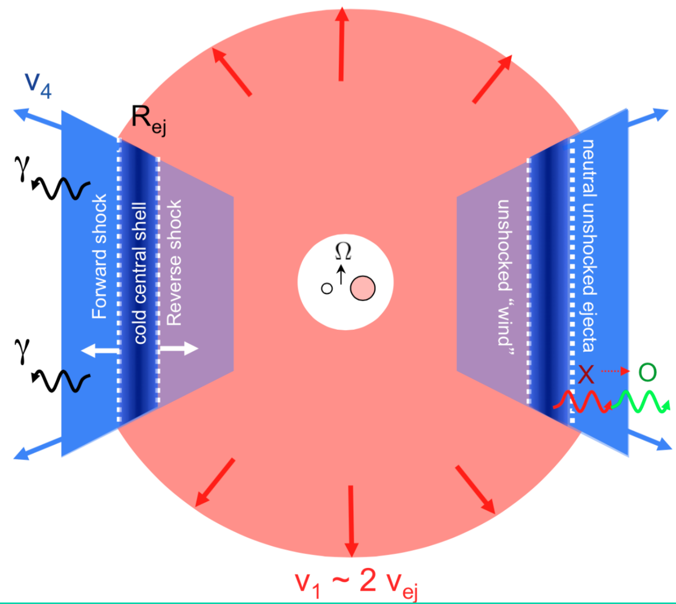


Metzger et al., 2015, MNRAS

- Slow shell ejected first (equatorial "belt" shaped by binary orbit)
- Fast wind sweeps that shell: shocks, revealed by radio

FERMI-LAT GAMMA-RAY DETECTIONS OF CLASSICAL NOVAE V1369 CENTAURI 2013 AND V5668 SAGITTARII 2015

Cheung et al., ApJ (2016)

Other detections of CNe

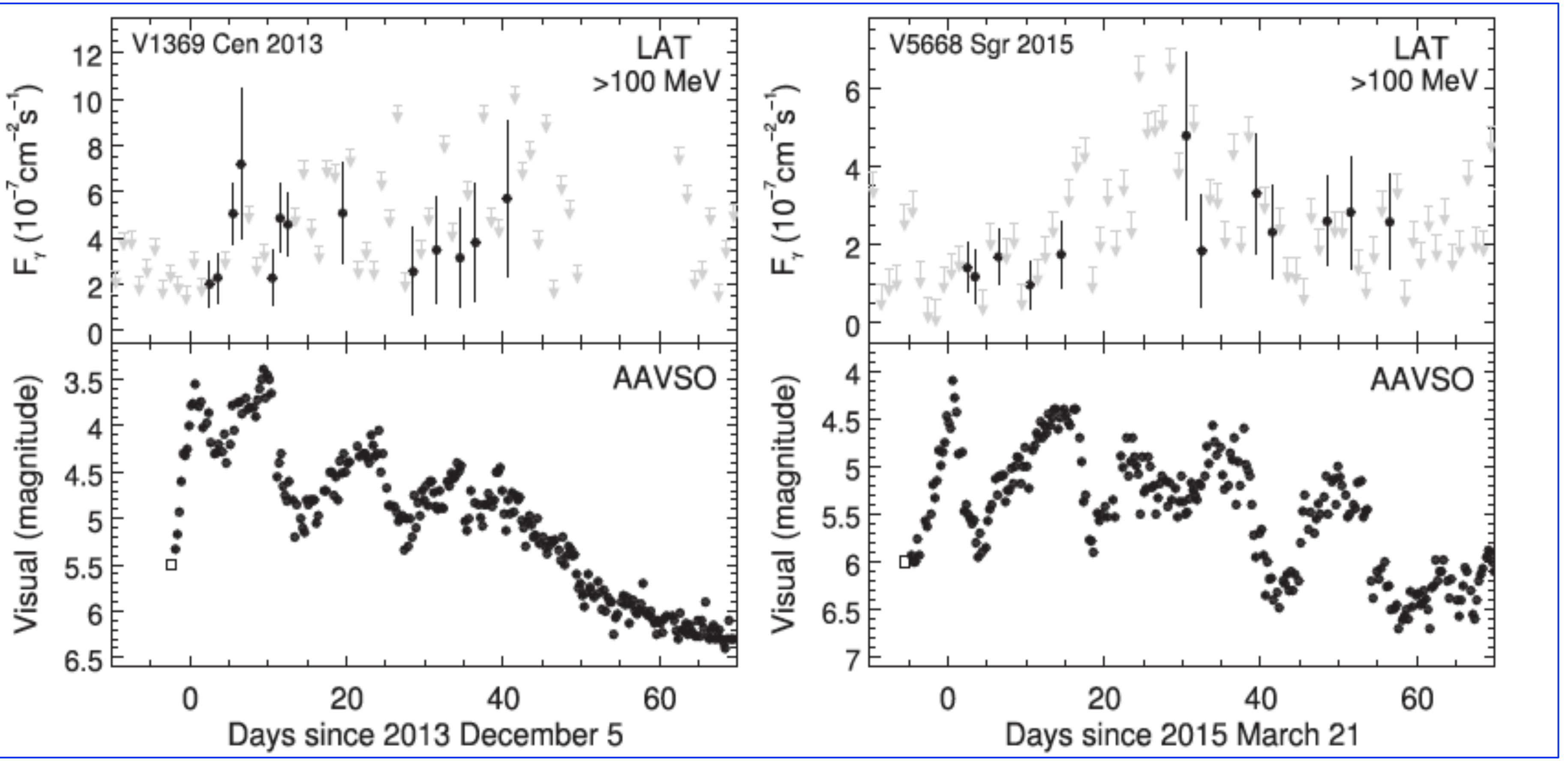


Figure 1. *Fermi*-LAT 1-day bin >100 MeV γ-ray (top panels) and optical (bottom panels) light curves for V1369 Cen (left) and V5668 Sgr (right). For the LAT data, vertical lines indicate 1σ uncertainties when TS $\geqslant$ 4.0 and gray arrows indicate 2σ upper limits when TS < 4.0 (see Appendix A for tabulated fluxes, TS values, and corresponding exposures). The optical discovery measurements (open squares) are shown separately from the subsequent 0.25-day bin averaged data extracted from the AAVSO database (filled circles).

FERMI-LAT GAMMA-RAY DETECTIONS OF CLASSICAL NOVAE V1369 CENTAURI 2013 AND V5668 SAGITTARII 2015

Cheung et al., ApJ (2016)

V1389 Cen 2013 & V5669 Sgr 2015: dimmer and with longer duration – multiple peaks in optical light curve

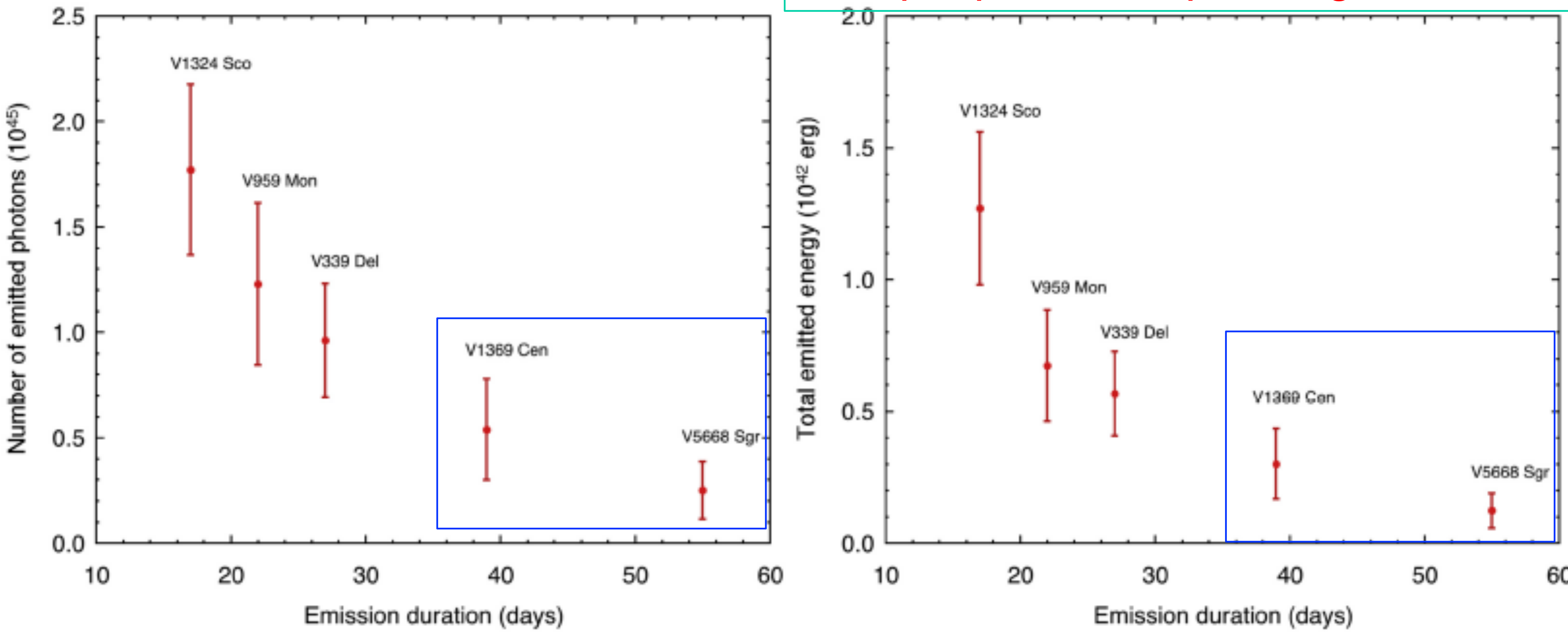


Figure 5. For the five classical novae with reported *Fermi*-LAT detections (thus excluding the symbiotic-like recurrent nova V407 Cyg), the total number of >100 MeV γ-ray photons emitted (left panel) and total emitted energies (right panel) are plotted vs. the LAT-measured γ-ray durations.

FERMI-LAT GAMMA-RAY DETECTIONS OF CLASSICAL NOVAE V1369 CENTAURI 2013 AND V5668 SAGITTARII 2015

Cheung et al., ApJ (2016)

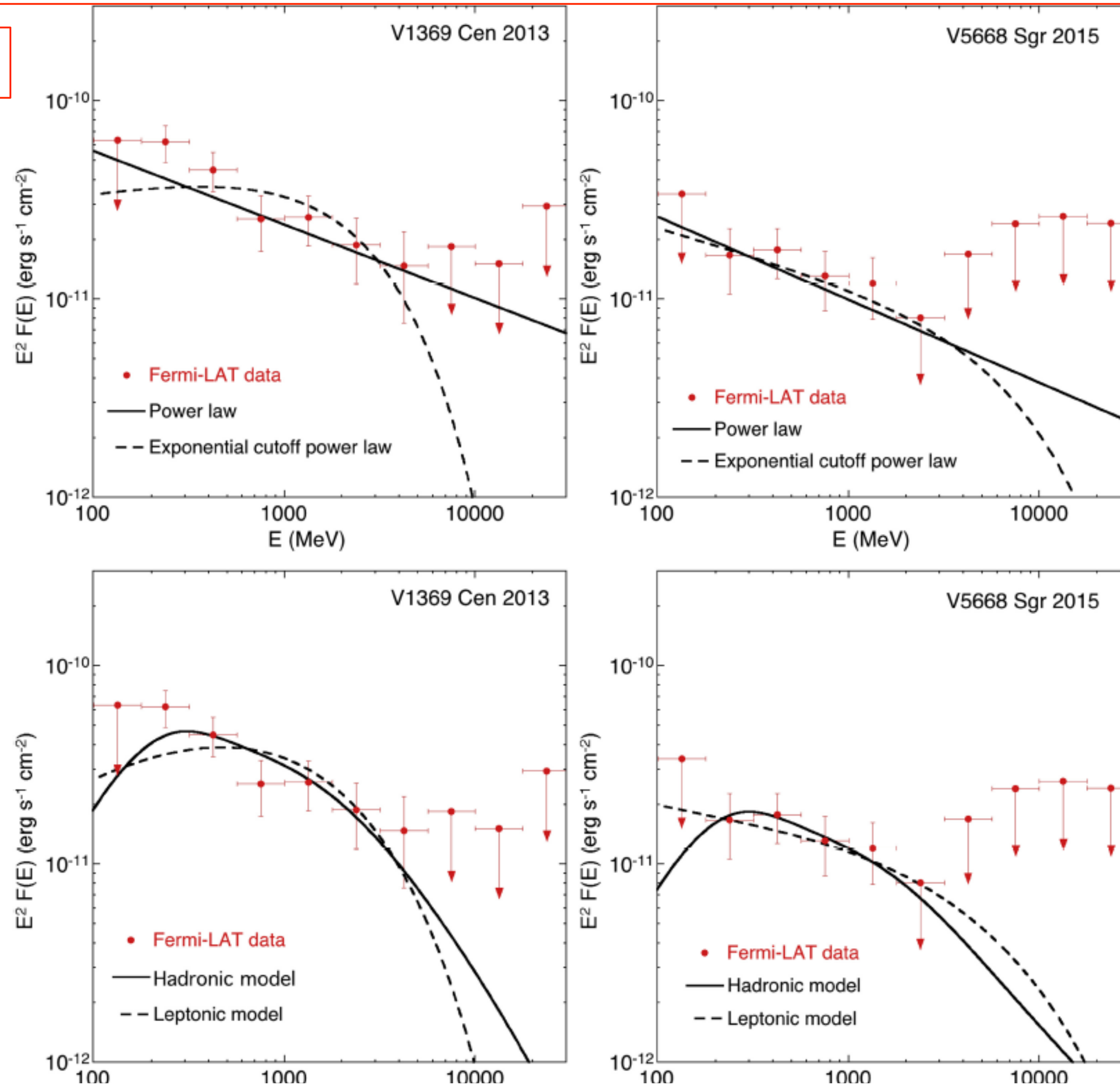


Figure 2. *Fermi*-LAT >100 MeV average spectra of V1369 Cen (left panels) and V5668 Sgr (right panels) with vertical bars indicating 1σ uncertainties for data points with TS $\geqslant$ 4; otherwise, 2σ upper limits are plotted. Overlaid are the PL and ECPL fits (top panels) and hadronic and leptonic model fits (bottom panels).

Summary of novae detected (predicted to be) by Fermi/LAT

Newest detections

Table 1: Summary of the novae detected by *Fermi*

System year	RS Oph (2006)	V407 Cyg 2010	V1324 Sco 2012	V959 Mon 2012	V339 Del 2013	V1369 Cen 2013	V745 Sco 2014	V5668 Sgr 2015	ASASSN −16kt 2016	J18102829 −2729590 2016	ASASSN −16ma 2016
Distance (kpc)	1.6	2.7	4.5	3.6	4.2	2.5	8	2	?	?	?
Nova class	RN	RN	CN	CN	CN	CN	RN	CN	CN	CN	CN
γ-ray emission											
Fermi/LAT detection	X	√	√	√	√	√	upper limits	√	√	√	√
Days after optical maximum	-	0	-4	?	0	1.5	1	1.5	1	0	1
γ-ray duration (days)	-	22	17	22	27	40	1	60	3	4	9
γ-ray flux $\times 10^{-7}$ph cm^{-2}s^{-1}	predicted	14	13	14	4	5.7	3	1.4	1.8	2.6	9.7

Nova Lup 2016	V5855 Sgr 2016

Symbiotic recurrent novae

Classical Novae

Laura Delgado PhD

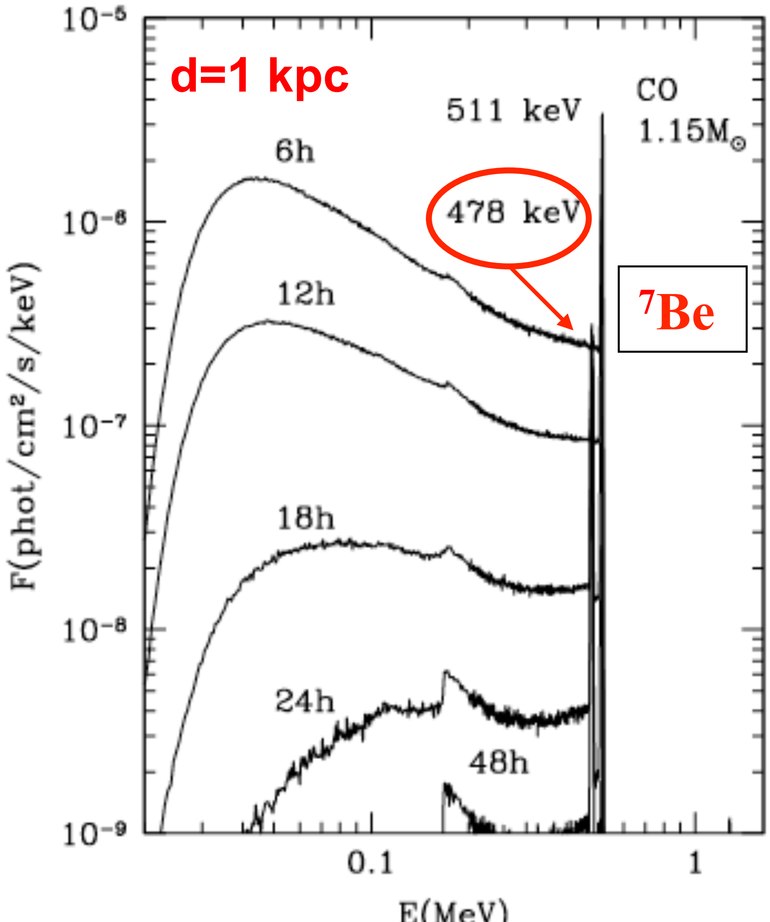
Gamma-rays from radioactivities: E ~ 1 MeV

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

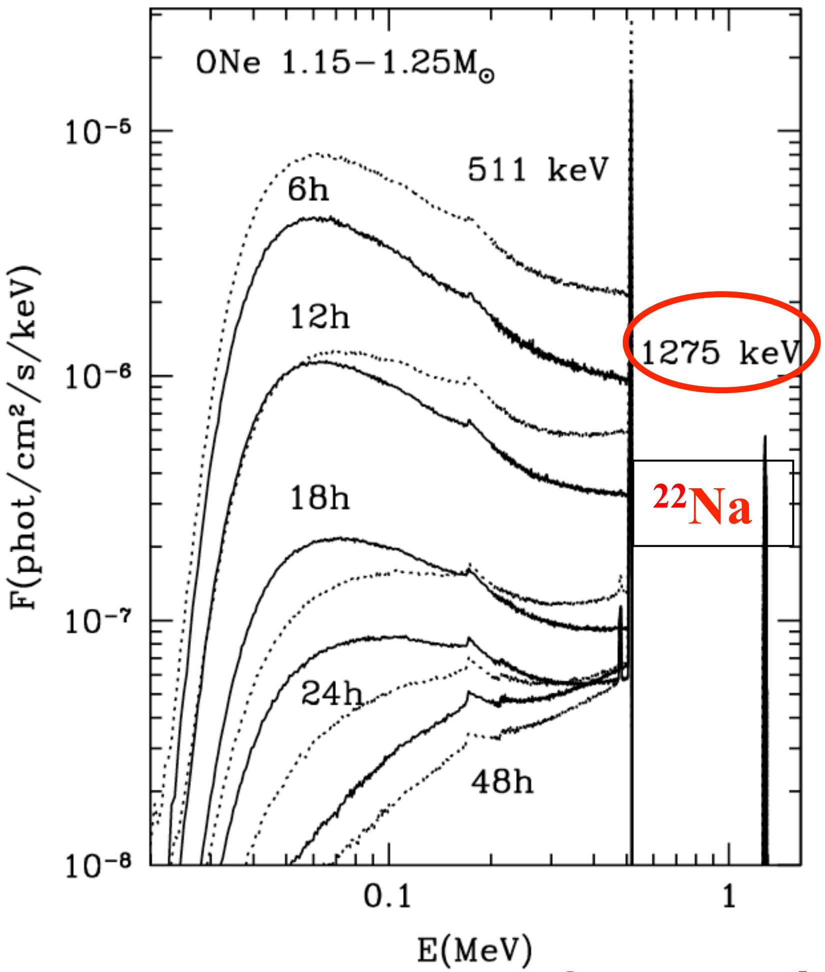
- 478 keV line from ^{7}Be decay

Hydrodynamics & 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. react. 2010-2011:
***less ^{18}F* – Chaffa et al., DeSéréville et al., …**

Spectra of ONe novae

d=1 kpc

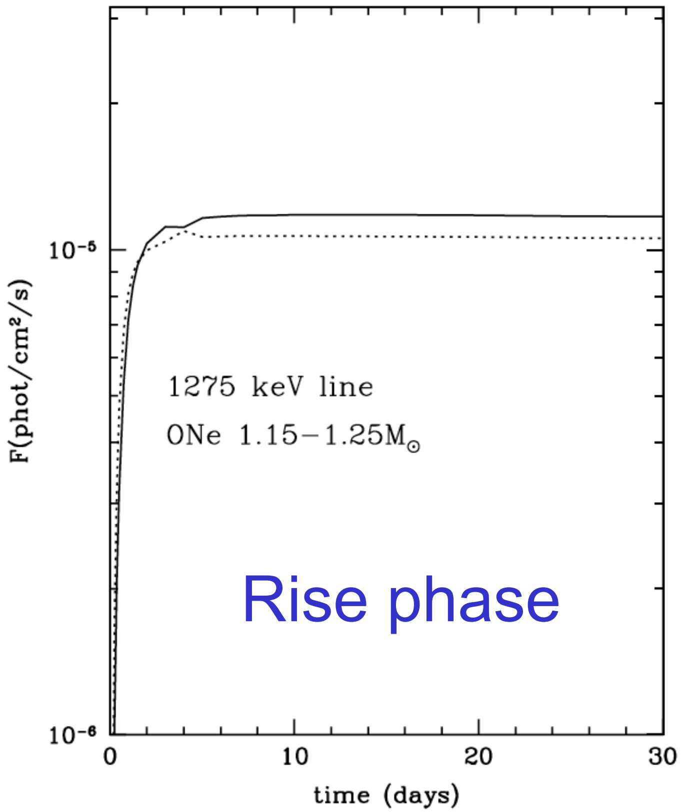


M_{WD} = 1.15-1.25 $M_{\odot}$

- 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

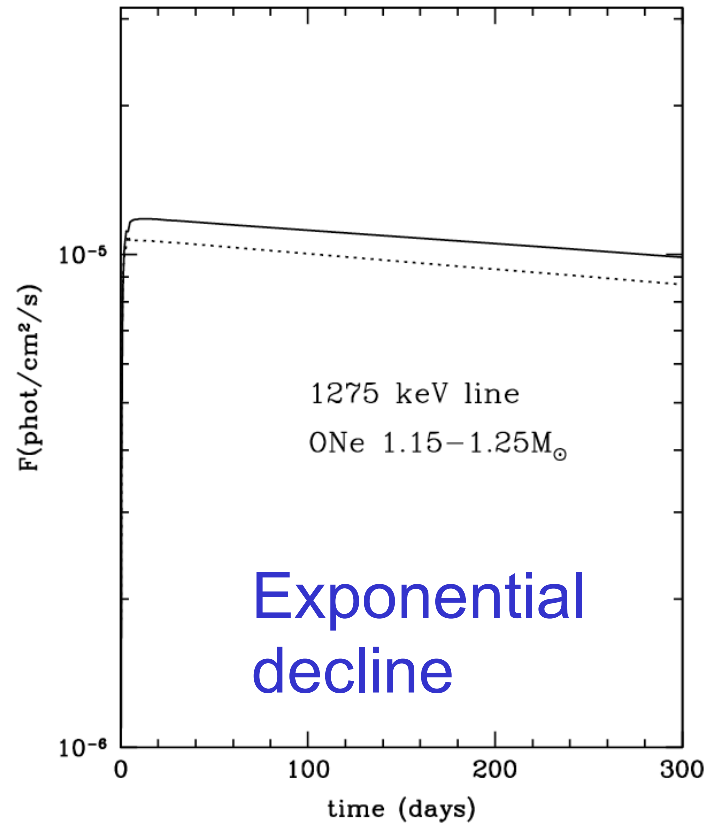
New nucleosynthesis from José, with Iliadis et al. nucl. react. 2010-2011:
***less ^{18}F –* Chaffa et al., DeSéréville et al., …**

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



Only in
ONe
novae

d=1 kpc

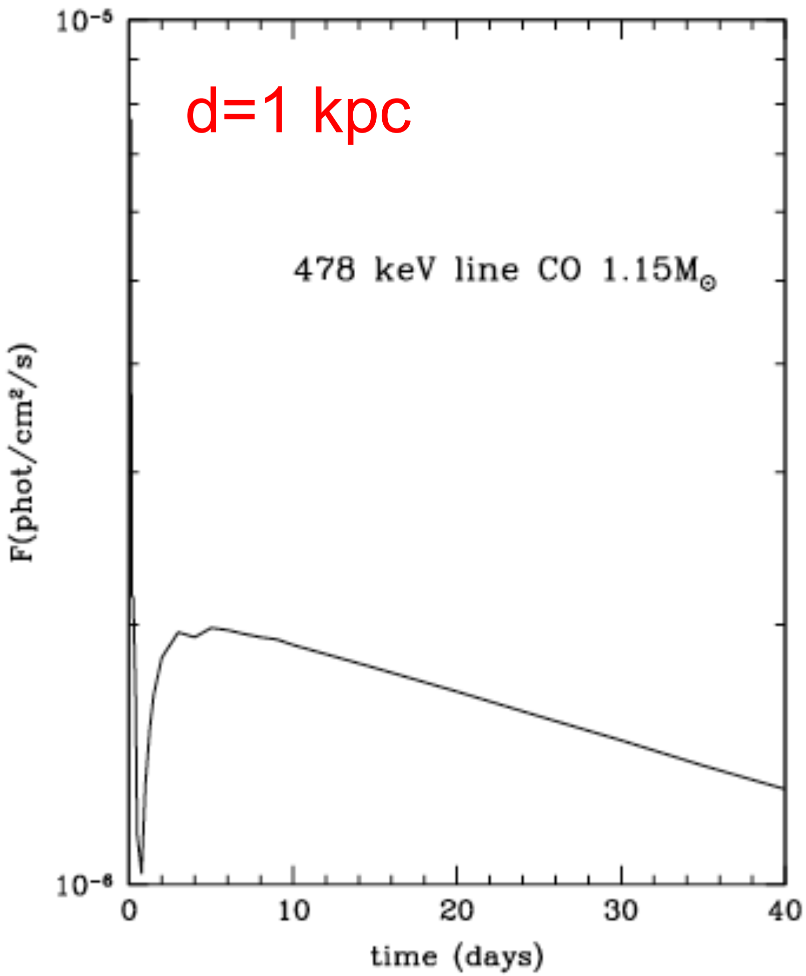


t_{max}: 15 days (1.15M$_\odot$), 4-8 days (1.25 M$_\odot$) – duration: months

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)

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



Mainly in CO novae

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

duration: some weeks

Flux : $(1\text{-}2)\times10^{-6}$ 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)

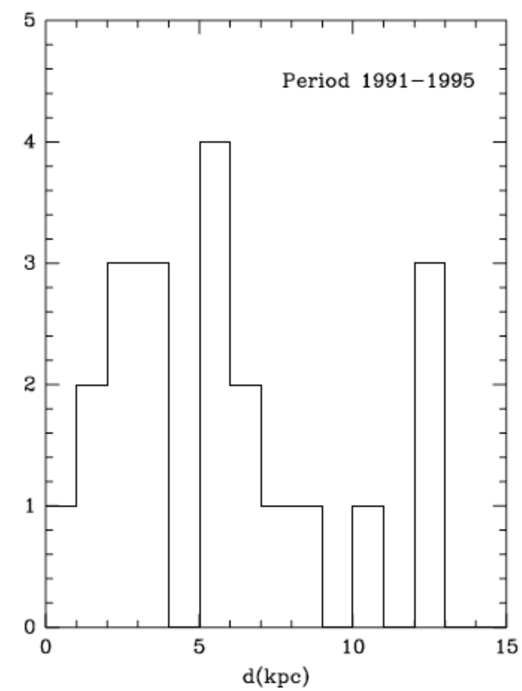
^{7}Be (478keV) and ^{22}Na (1275 keV) not detected yet (e.g., with CGRO/COMPTEL)

Detectability with INTEGRAL/SPI

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

Line (E and ΔE in keV)	t_{obs}(ks)	$F_{min,hexagonal}$ (ph/cm^2/s)	d(kpc)
478 (8)	4×10^3	5.1×10^{-5}	0.2
1275 (20)	4×10^3	4.7×10^{-5}	0.5

F_{min} are the fluxes which would give a 3σ detection of the lines with the quoted observation time



ToO proposals for INTEGRAL/SPI (PI: MH)

- since its launch in 2002

not triggered yet

ASTROGAM: 25 x better → d: 5 x larger

19 FEBRUARY 2015 | VOL 518 | NATURE | 381

LETTER

doi:10.1038/nature14161

Explosive lithium production in the classical nova V339 Del (Nova Delphini 2013)

Akito Tajitsu[1], Kozo Sadakane[2], Hiroyuki Naito[3,4], Akira Arai[5,6] & Wako Aoki[7]

found. Here we report the detection of highly blue-shifted resonance lines of the singly ionized radioactive isotope of beryllium, ^{7}Be, in the near-ultraviolet spectra of the classical nova V339 Del (Nova Delphini 2013) 38 to 48 days after the explosion. ^{7}Be decays to form ^{7}Li within a short time (half-life of 53.22 days[4]). The ^{7}Be was created during the

ASTROPHYSICS

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News & Views

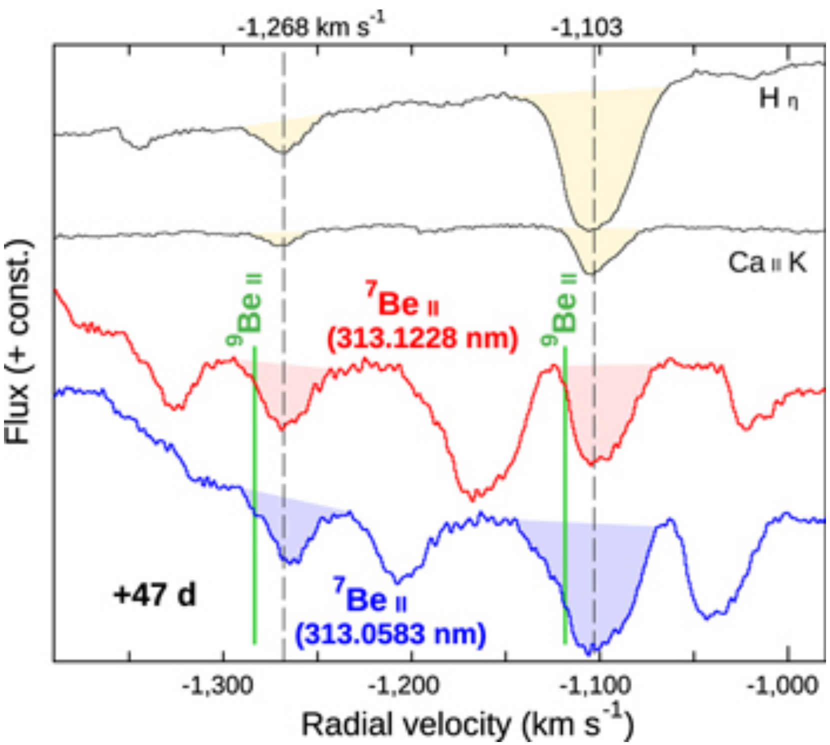
A lithium-rich stellar explosion

The contribution of explosions known as novae to the lithium content of the Milky Way is uncertain. Radioactive beryllium, which transforms into lithium, has been detected for the first time in one such explosion. SEE LETTER P.381

MARGARITA HERNANZ

during supernova explosions and their dimmer

First detection of ^{7}Be (^{7}Li) in a nova: Nova Del 2013, CO nova



- Subaru Telescope: 8.2-m diameter. Mauna Kea (Hawaï)
- High Dispersion Spectrograph (HDS): spectral resolution 60 000 - 90 000 (0.0052 nm @ 312-313 nm)
- Able to distinguish ^{9}Be II doublet at 313.0422 nm & 313.1067 nm from the ^{7}Be II doublet at 313.0583 nm & 313.1228 nm
- Blueshifted lines with 1103 & 1168 km/s (also H and Ca)

Detection of ^{7}Be (^{7}Li) in Nova Del 2013 - Summary

- $X(7Be, th, max.) = 10^{-5.1} = 8.2 \times 10^{-6}$
- $X(7Be, obs) = 10^{-4.3+/-0.3} = 5.0 \times 10^{-5}$
  - obs. factor 6 larger than predicted

- Novae could be much larger contributors to galactic ^{7}Li than expected
- Interesting way to detect ^{7}Li through its parent nucleus radioactive ^{7}Be

Other novae with detected ^{7}Be (^{7}Li)

THE ^{7}Be II RESONANCE LINES IN TWO CLASSICAL NOVAE V5668 SGR AND V2944 OPH

AKITO TAJITSU[1], KOZO SADAKANE[2], HIROYUKI NAITO[3], AKIRA ARAI[4], HIDEYO KAWAKITA[4], AND WAKO AOKI[5]

Highly Enriched ^{7}Be in the ejecta of Nova Sagittarii 2015 No. 2 (V5668 Sgr) and the Galactic ^{7}Li origin

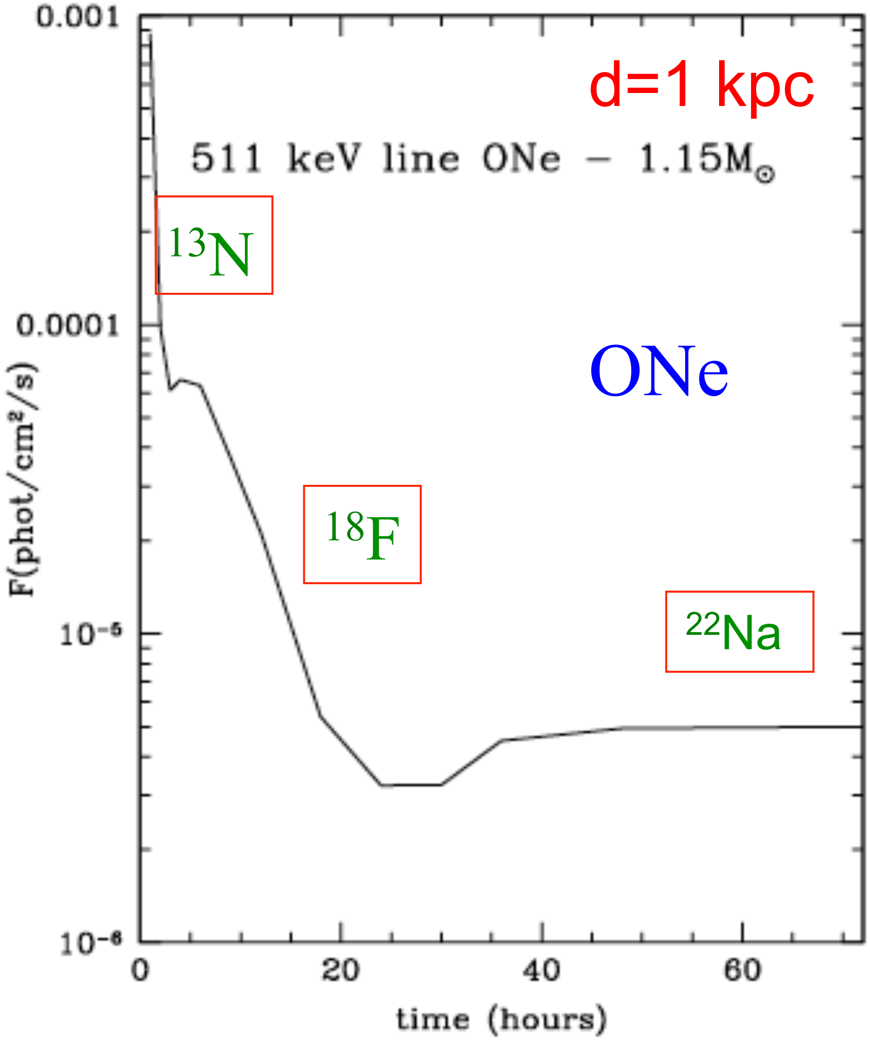
Molaro, P.[1], Izzo, L.[2], Mason, E. [1], Bonifacio, P.[3], Della Valle, M.[4,5], ⋆, †

EARLY OPTICAL SPECTRA OF NOVA V1369 CEN SHOW THE PRESENCE OF LITHIUM

LUCA IZZO[1,2], MASSIMO DELLA VALLE[2,3], ELENA MASON[4], FRANCESCA MATTEUCCI[5], DONATELLA ROMANO[6], LUCA PASQUINI[7], LEONARDO VANZI[8], ANDRES JORDAN[9], JOSÉ MIGUEL FERNANDEZ[10], PAZ BLUHM[10], RAFAEL BRAHM[10], NESTOR ESPINOZA[10], AND ROBERT WILLIAMS[11]

Detection of the 478 keV gamma-ray line would be a clear and independent proof!!

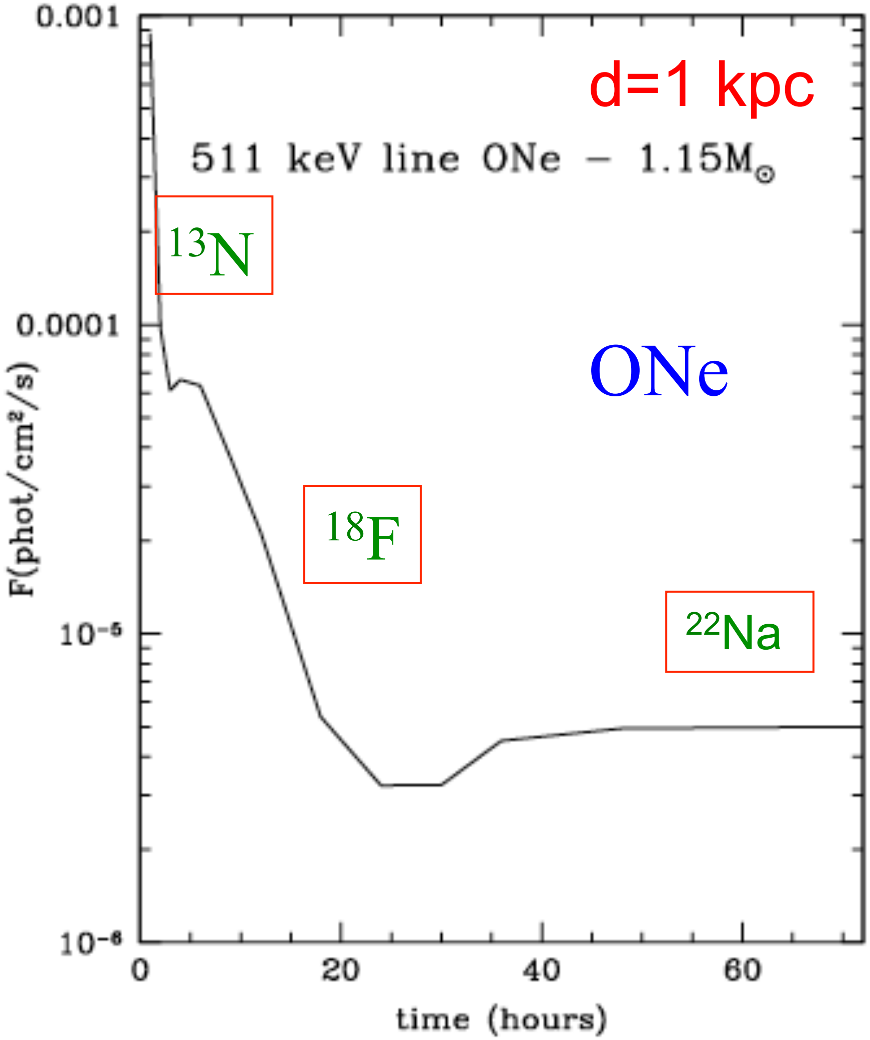
Light curves: 511 keV line: CO and ONe novae



- 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

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

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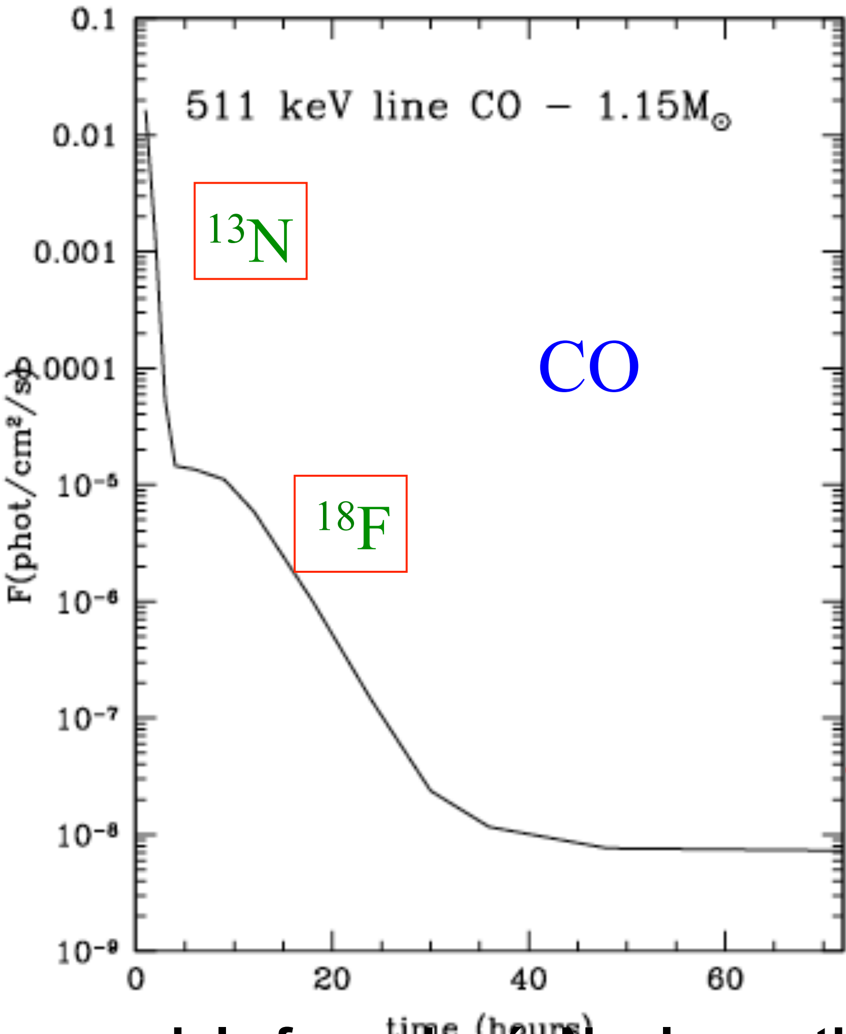
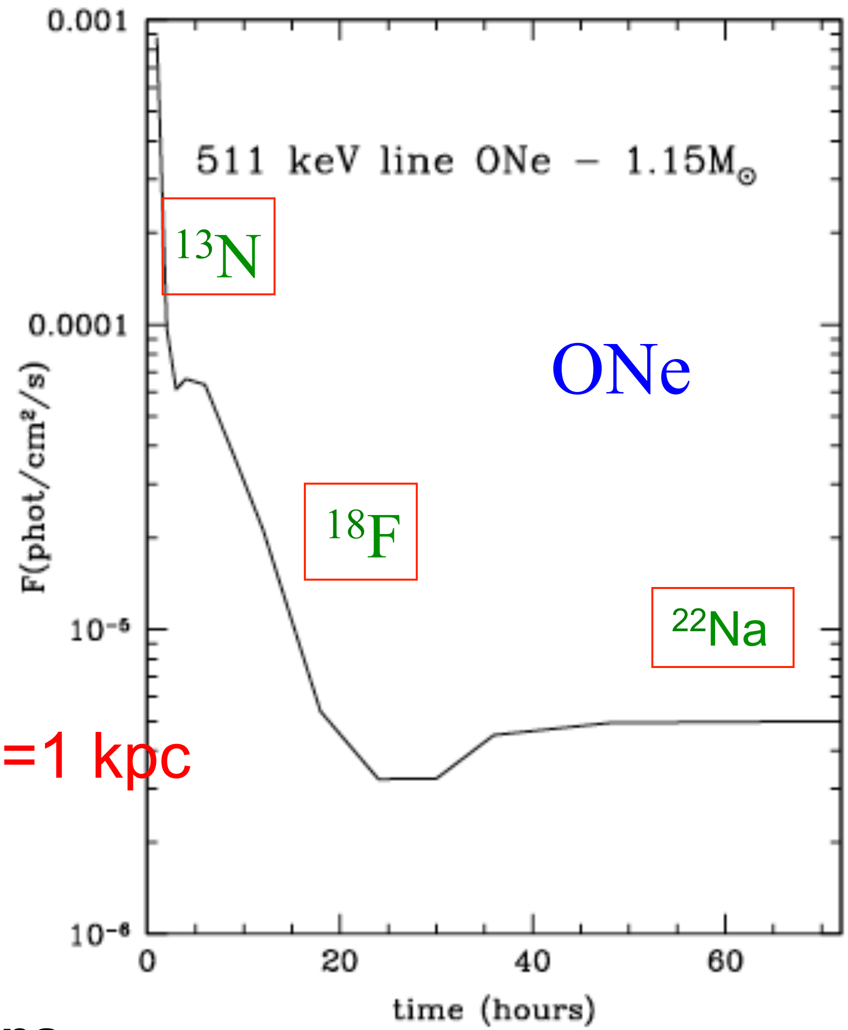


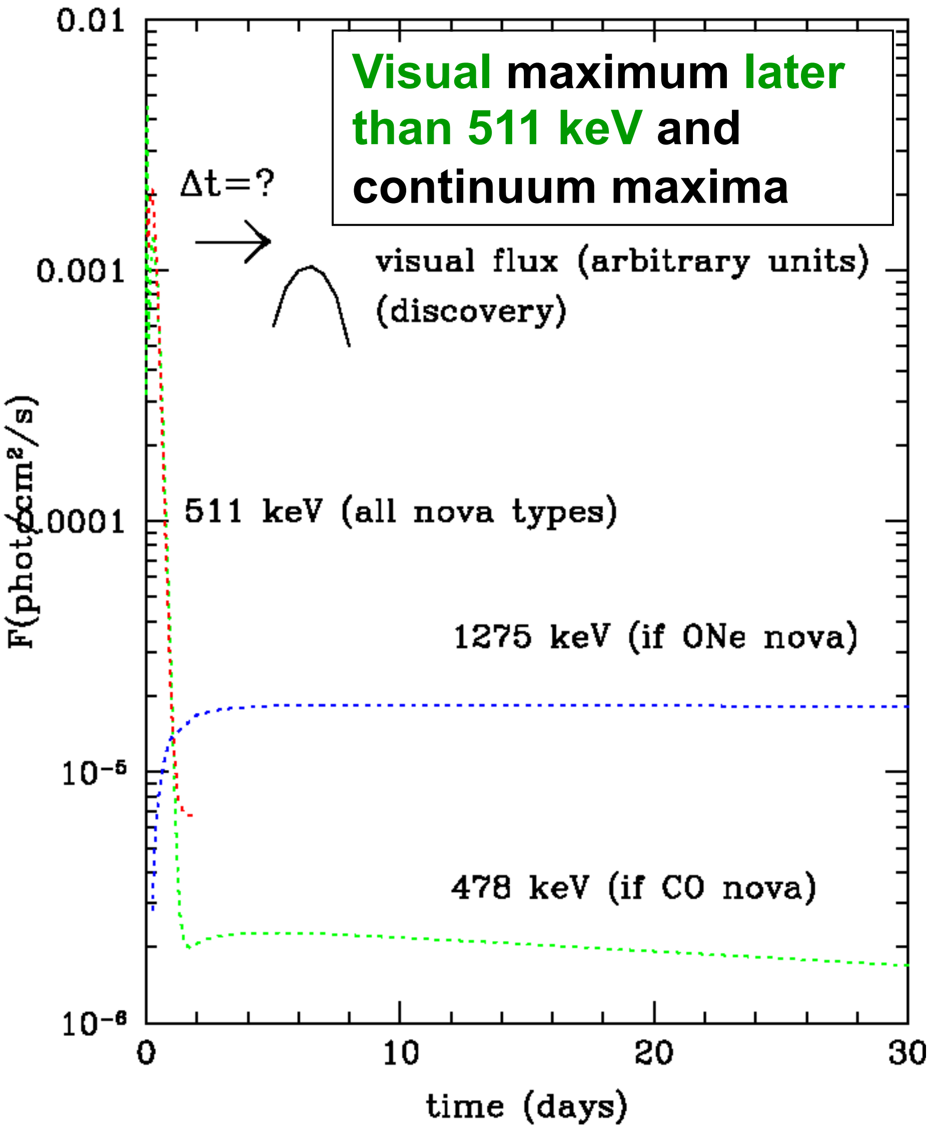
d=1 kpc



notice different y scales

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 all used; negative results

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

- **eASTROGAM**?

Summary

- **HE gamma.rays**: e-ASTROGAM would represent an important step forward for the understanding of the process of particle acceleration in novae, e.g., leptonic versus hadronic, and nova mass outflows in general (comparison to SNRs: much shorter evolutiontimescale)
  - Contemporaneous multiwavelength coverage is crucial (radio, IR, X)
- **MeV gamma-rays**: close novae could be detected - 1275 keV (22Na), 478 keV (7Be), 511 keV & continuum (e^+-e)
  - relevance for the origin of 7Li in the Galaxy
  - understanding of mixing and convection in the nova envelope
  - discovering novae hidden by interstellar dust