X-rays and γ-rays from classical novae: constraints on models from the observations

Margarita Hernanz

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

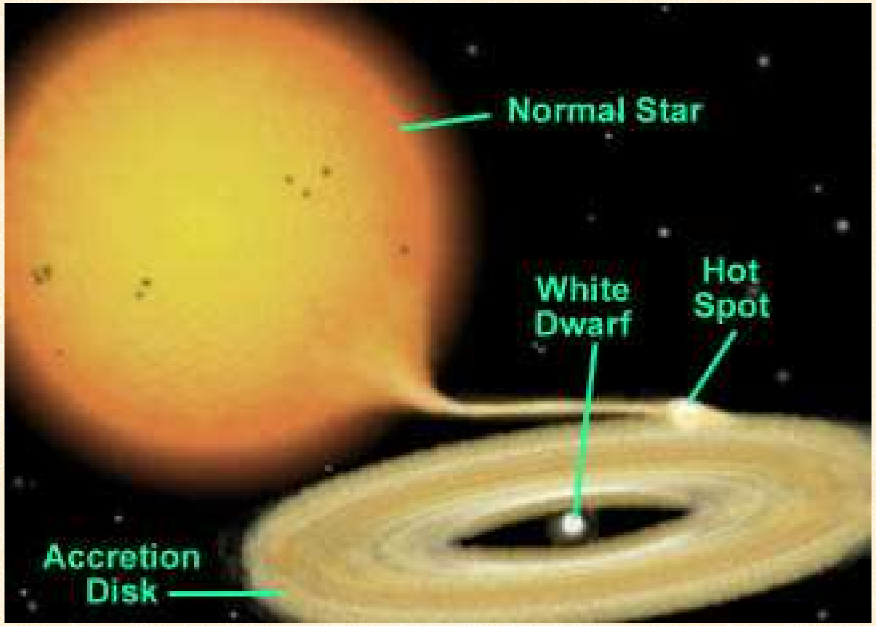
- ☐ Basic scenario of classical novae
- ☐ γ-rays: theory, observations,challenges for instrumentation
- ☐ X-rays: lessons from XMM-Newton observations and from ROSAT (Nova Cyg 1992)

X-rays and γ-rays from classical novae: constraints on models from the observations

PART I

- ☐ Basic scenario of classical novae
- ☐ γ-rays: theory, observations,challenges for instrumentation
- ☐ X-rays: lessons from XMM-Newton observations and from ROSAT (Nova Cyg 1992)

BASIC SCENARIO



Mass transfer from the companion star onto the white dwarf (cataclysmic variable)

↓

Hydrogen burning in degenerate conditions on top of the white dwarf

↓

Thermonuclear runaway

↓

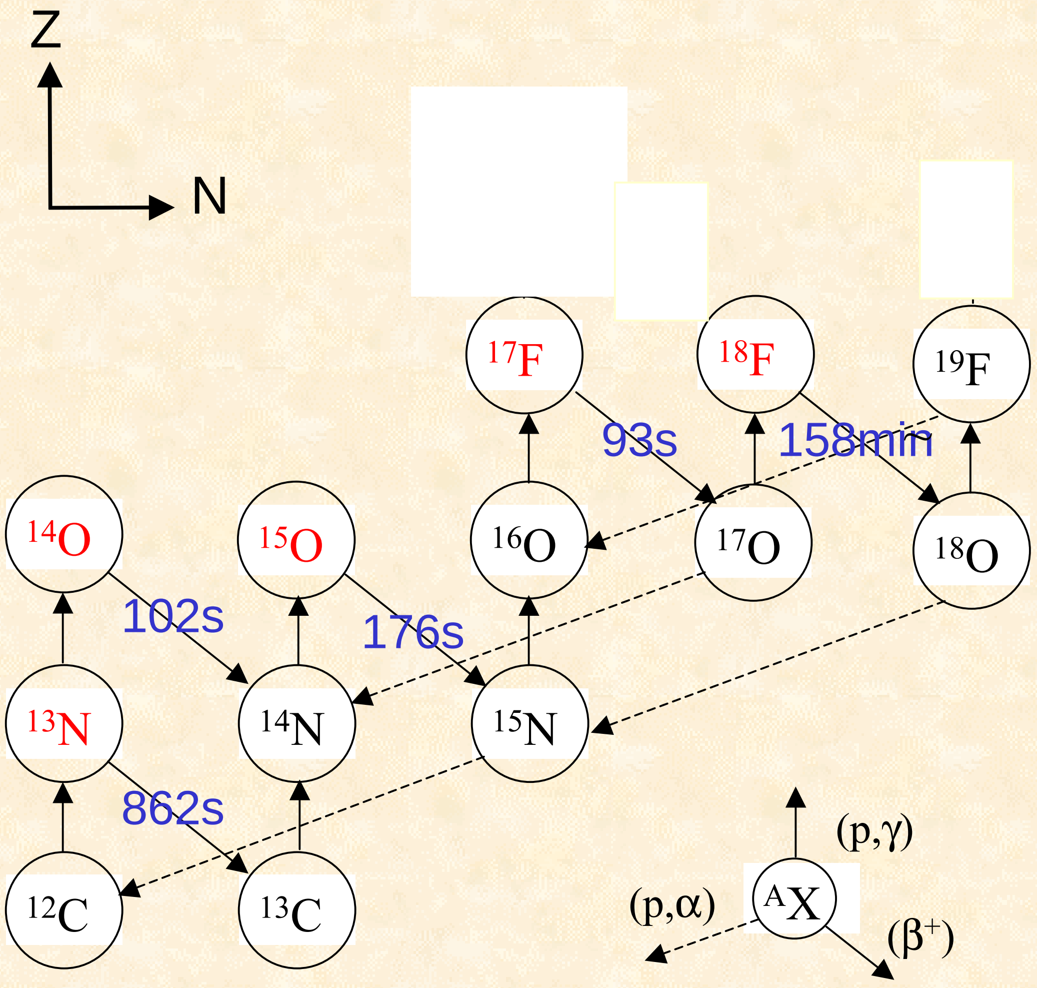
Explosive H-burning ↗

Decay of short-lived radioactive nuclei in the outer envelope (transported by convection)

↓

Envelope expansion, L increase and mass ejection

Nova Models: Thermonuclear Burning of Hydrogen. CNO cycle



- Start: $\tau_{\beta+} < \tau(p,\gamma)$

↓

CNO cycle operates in equ.

- T ~10^8 K: $\tau_{\beta+} > \tau(p,\gamma)$

↓

CNO cycle β^+-limited

(bottle neck)

- Convection:

➢fresh fuel brought to the burning shell

➢$\tau_{conv} < \tau_{\beta+}$: β^+-unstable nuclei to external cooler regions where they are preserved from destruction

Later decay on the surface leads to expansion and luminosity increase

Why novae emit γ-rays?

Explosive H-burning: synthesis of *β^+-unstable nuclei*

	^{13}N	^{14}O	^{15}O	^{17}F	^{18}F
τ	862s	102s	176s	93s	158min.

crucial for envelope expansion

crucial for γ-ray emission
(through e^--e^+ annihilation)

Other radioactive nuclei synthesized

	^{7}Be	^{22}Na	^{26}Al
τ	77days	3.75yrs	10^6yrs
line	478keV	1275keV	1809keV

e-capture

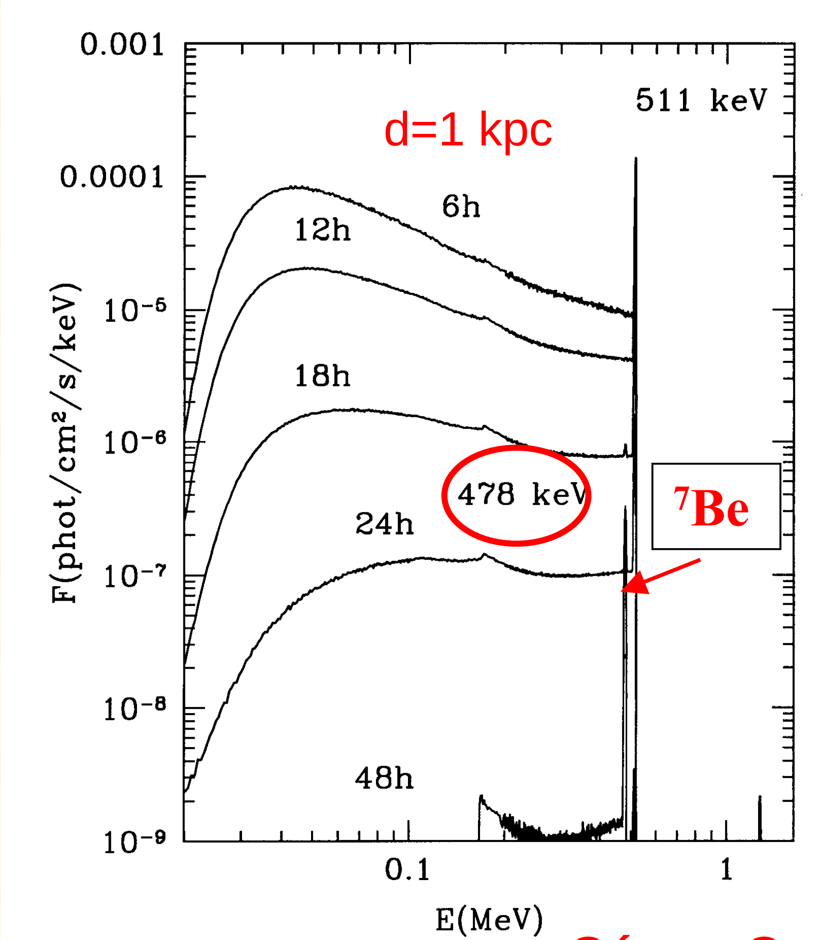
e^+-emission

Radioactive isotopes synthesized in classical novae relevant for their γ-ray emission

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

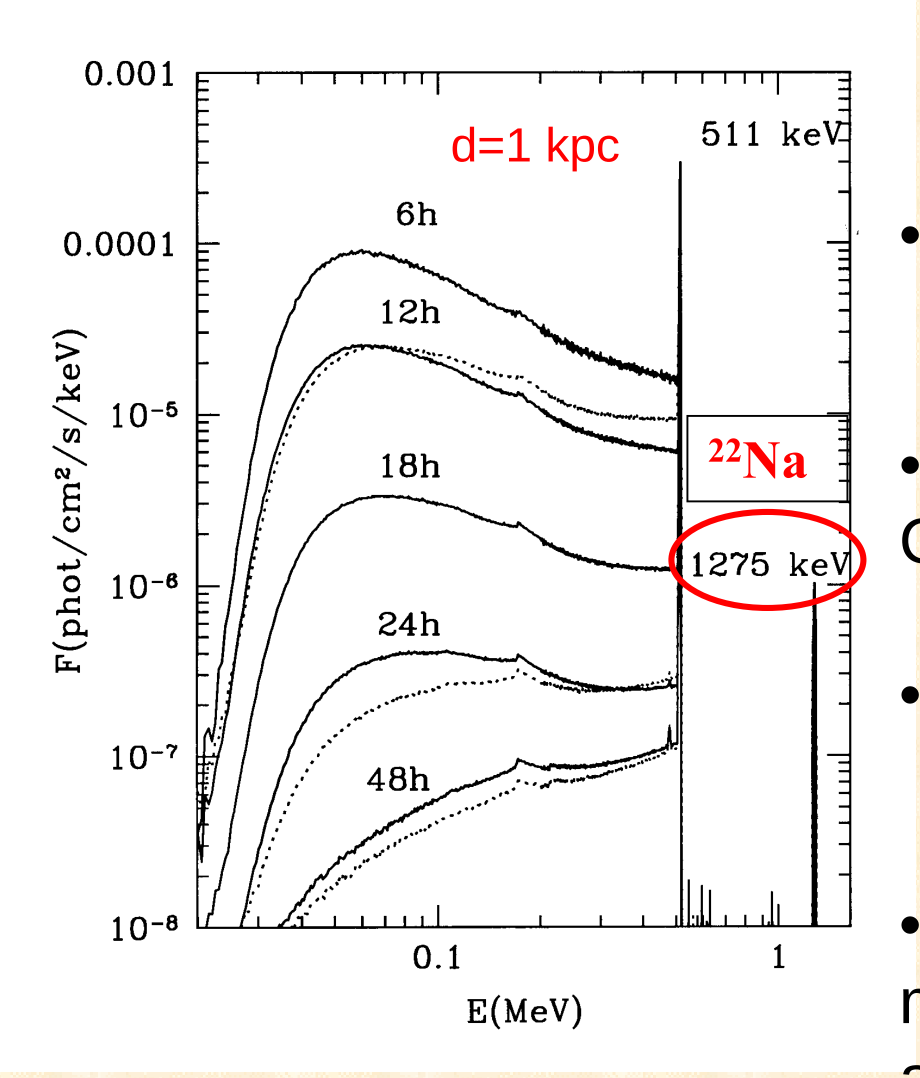
$M_{WD} = 1.15\ M_\odot$



- e^--e^+ annihilation and Comptonization: continuum and 511 keV line; e^+ from ^{13}N and ^{18}F
  → Leising & Clayton 1987
- photoelectric absorption
  → cutoff at 20 keV
- 478 keV line from ^{7}Be decay
  → Clayton 1981
- transparent at 48 h

Gómez-Gomar, Hernanz, José, Isern,1998, MNRAS
Hernanz et al 1999, ApJL, 2002...NewAR

Spectra of ONe novae



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

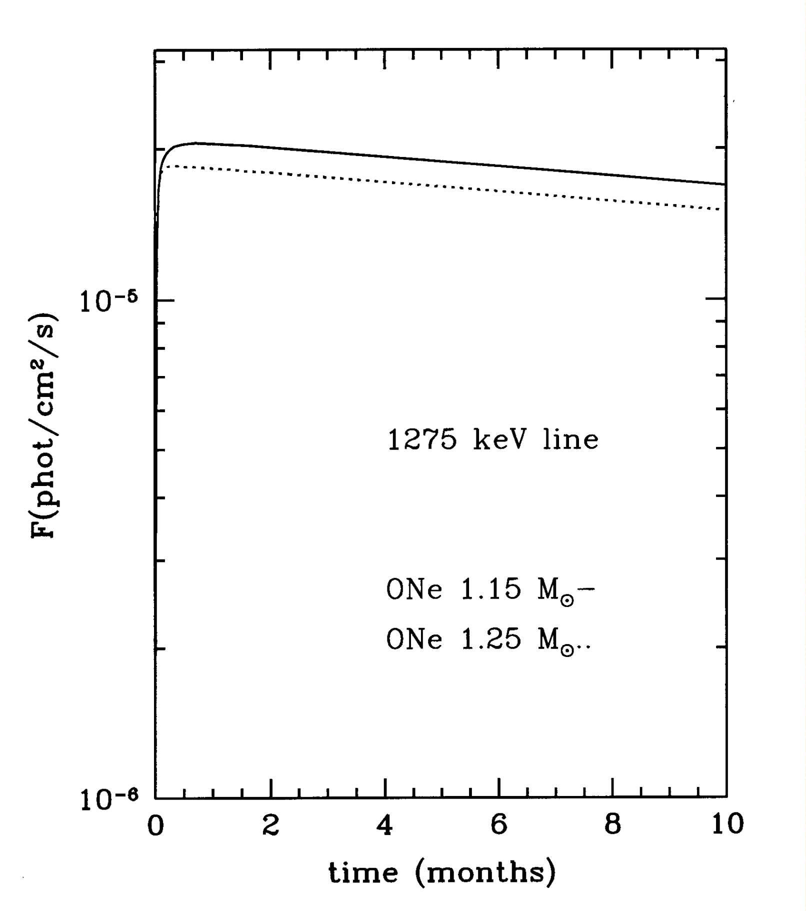
- photoelectric absorption
  → cutoff at 30 keV

- continuum and 511 keV as in CO novae

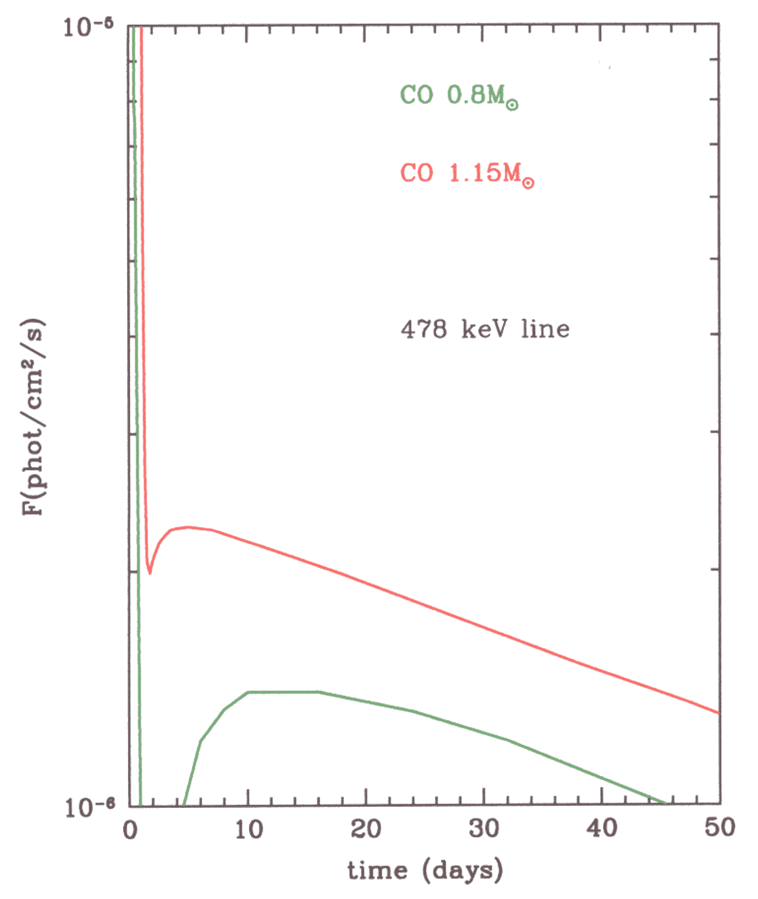
- 1275 keV line from ^{22}Na decay
  → Clayton & Hoyle, 1974

- 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) ~ 2×10^{-5} ph/cm^2/s

$M_{ejected}$(^{22}Na) ~ $(6\text{-}7)\times10^{-9} M_\odot$

Line width ~ 20 keV

Flux ~ $(1\text{-}2)\times10^{-6}$ ph/cm^2/s

$M_{ejected}$(^{7}Be) ~ $(0.7\text{-}1.1)\times10^{-10} M_\odot$

Line width: 3-7 keV

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

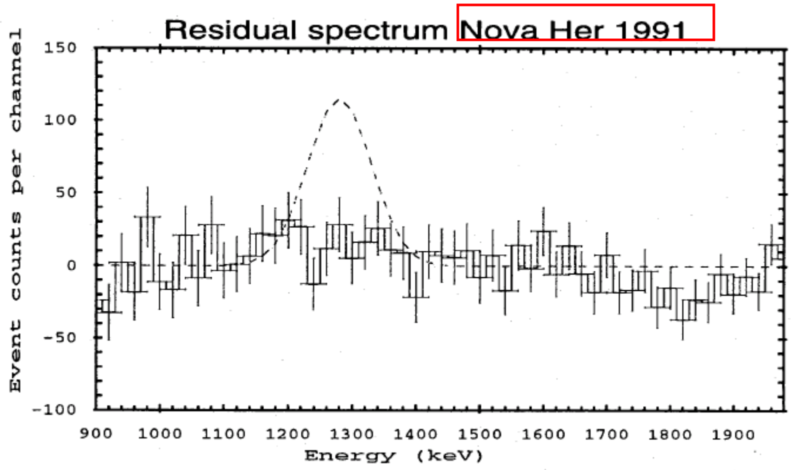


Fig. 1. Sum of residual spectra of Nova Her 1991 for the viewing periods 7.5, 13.0, 20 and 231. Statistical 1 σ error bars are shown. The dashed line represents the expected ^{22}Na line appearance according to the ejecta mass derived by Woodward et al. 1992, with a ^{22}Na mass fraction of model 3 of Starrfield et al. 1992. This signal would have been seen by COMPTEL at the significance level of $\sim 8\ \sigma$

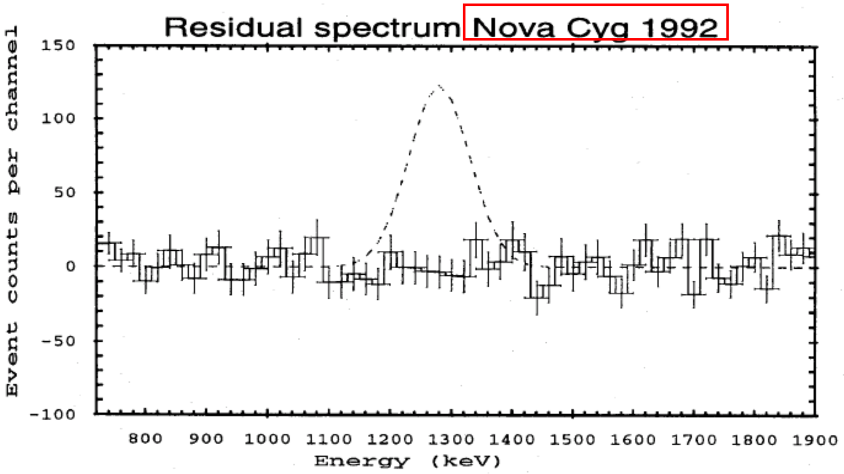


Fig. 2. Sum of the background-subtracted spectra of Nova Cyg 1992 for the viewing periods 34, 203 and 212. Statistical error bars are shown. The dashed line represents the expected ^{22}Na line appearance according to the predictions of Starrfield et al. 1992. This signal would have been seen by COMPTEL at the significance level of $\sim 17\ \sigma$

CGRO/COMPTEL: no detection; upper limits

Iyudin et al. 1995, A&A

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

CGRO/COMPTEL upper limits: Iyudin et al. 1995, A&A

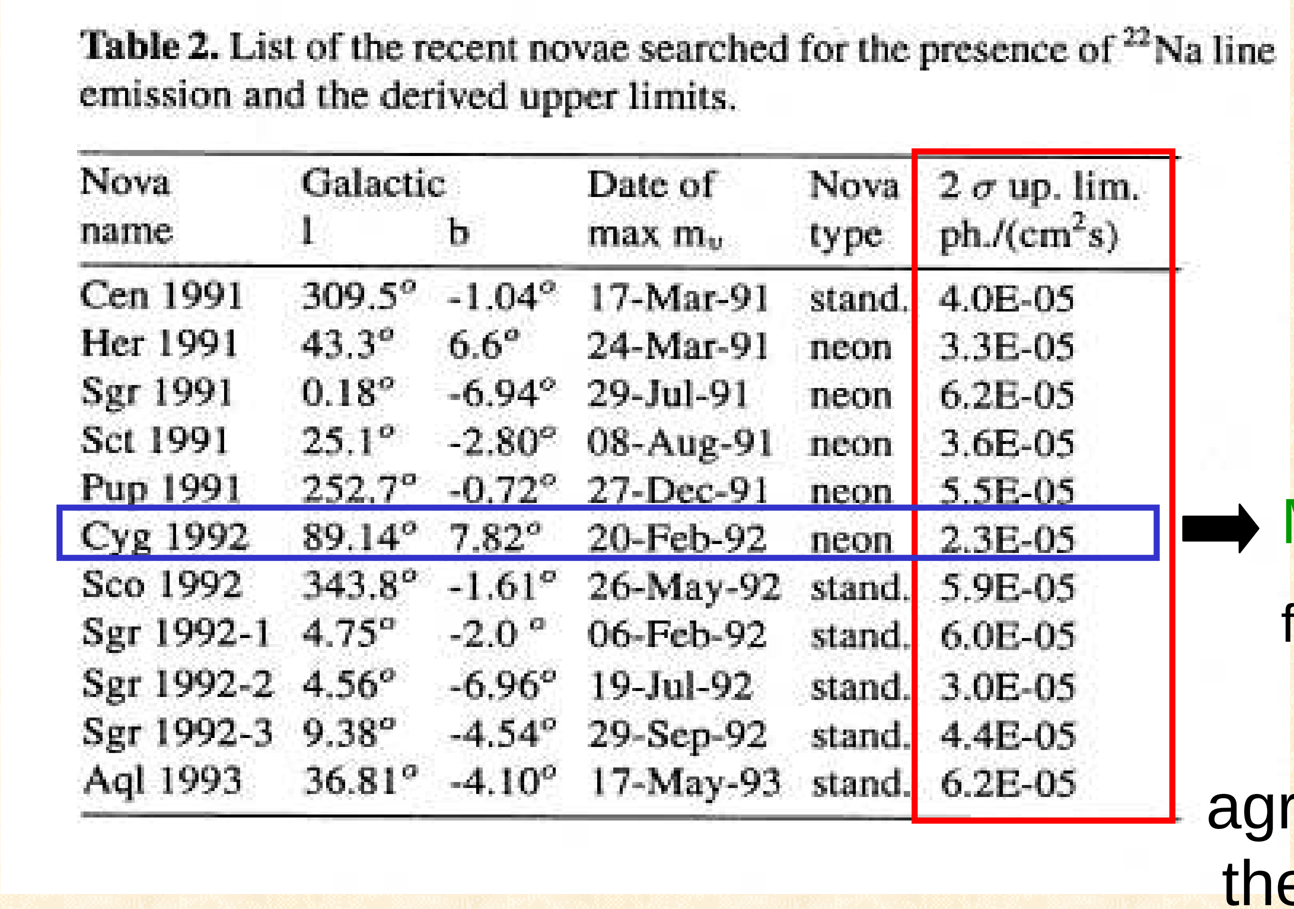


Table 2. List of the recent novae searched for the presence of ^{22}Na line emission and the derived upper limits.

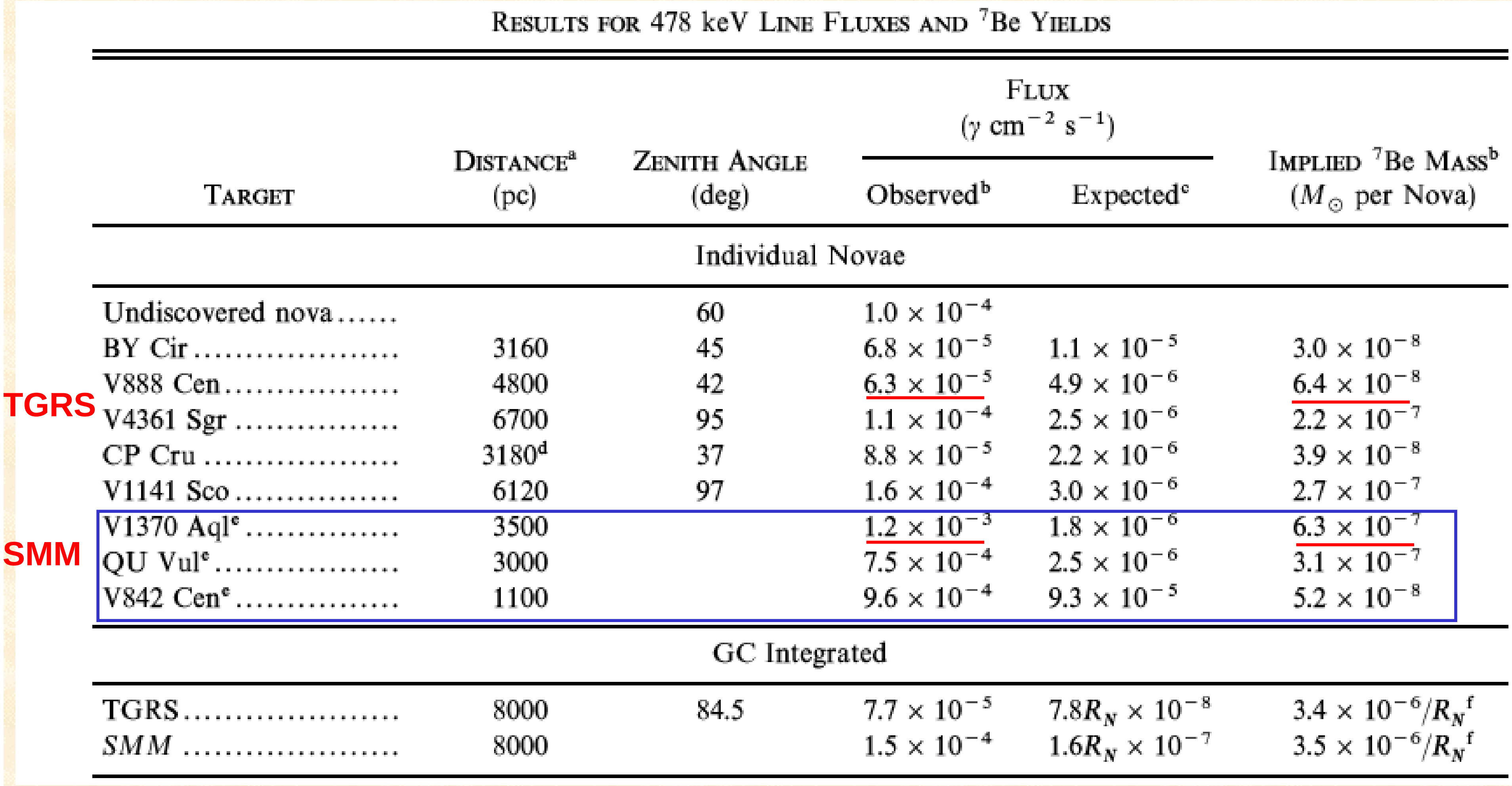
Nova name	Galactic l	b	Date of max m_v	Nova type	2 σ up. lim. ph./(cm^{2}s)
Cen 1991	309.5°	-1.04°	17-Mar-91	stand.	4.0E-05
Her 1991	43.3°	6.6°	24-Mar-91	neon	3.3E-05
Sgr 1991	0.18°	-6.94°	29-Jul-91	neon	6.2E-05
Sct 1991	25.1°	-2.80°	08-Aug-91	neon	3.6E-05
Pup 1991	252.7°	-0.72°	27-Dec-91	neon	5.5E-05
Cyg 1992	89.14°	7.82°	20-Feb-92	neon	2.3E-05
Sco 1992	343.8°	-1.61°	26-May-92	stand.	5.9E-05
Sgr 1992-1	4.75°	-2.0 °	06-Feb-92	stand.	6.0E-05
Sgr 1992-2	4.56°	-6.96°	19-Jul-92	stand.	3.0E-05
Sgr 1992-3	9.38°	-4.54°	29-Sep-92	stand.	4.4E-05
Aql 1993	36.81°	-4.10°	17-May-93	stand.	6.2E-05

➡ $M_{ej}(^{22}Na)<3 \times 10^{-8} M_{\odot}$

for d=1.7 kpc

Upper limits in agreement with current theoretical predictions

Observations: 478 keV line (^{7}Be)



Results for 478 keV Line Fluxes and ^{7}Be Yields

Target	Distance[a] (pc)	Zenith Angle (deg)	Flux (γ cm^{-2} s^{-1}) Observed[b]	Flux (γ cm^{-2} s^{-1}) Expected[c]	Implied ^{7}Be Mass[b] ($M_\odot$ per Nova)
			Individual Novae		
Undiscovered nova		60	1.0×10^{-4}		
BY Cir	3160	45	6.8×10^{-5}	1.1×10^{-5}	3.0×10^{-8}
V888 Cen	4800	42	6.3×10^{-5}	4.9×10^{-6}	6.4×10^{-8}
V4361 Sgr	6700	95	1.1×10^{-4}	2.5×10^{-6}	2.2×10^{-7}
CP Cru	3180[d]	37	8.8×10^{-5}	2.2×10^{-6}	3.9×10^{-8}
V1141 Sco	6120	97	1.6×10^{-4}	3.0×10^{-6}	2.7×10^{-7}
V1370 Aql[e]	3500		1.2×10^{-3}	1.8×10^{-6}	6.3×10^{-7}
QU Vul[e]	3000		7.5×10^{-4}	2.5×10^{-6}	3.1×10^{-7}
V842 Cen[e]	1100		9.6×10^{-4}	9.3×10^{-5}	5.2×10^{-8}
			GC Integrated		
TGRS	8000	84.5	7.7×10^{-5}	$7.8R_N \times 10^{-8}$	$3.4 \times 10^{-6}/R_N$[f]
SMM	8000		1.5×10^{-4}	$1.6R_N \times 10^{-7}$	$3.5 \times 10^{-6}/R_N$[f]

TGRS

SMM

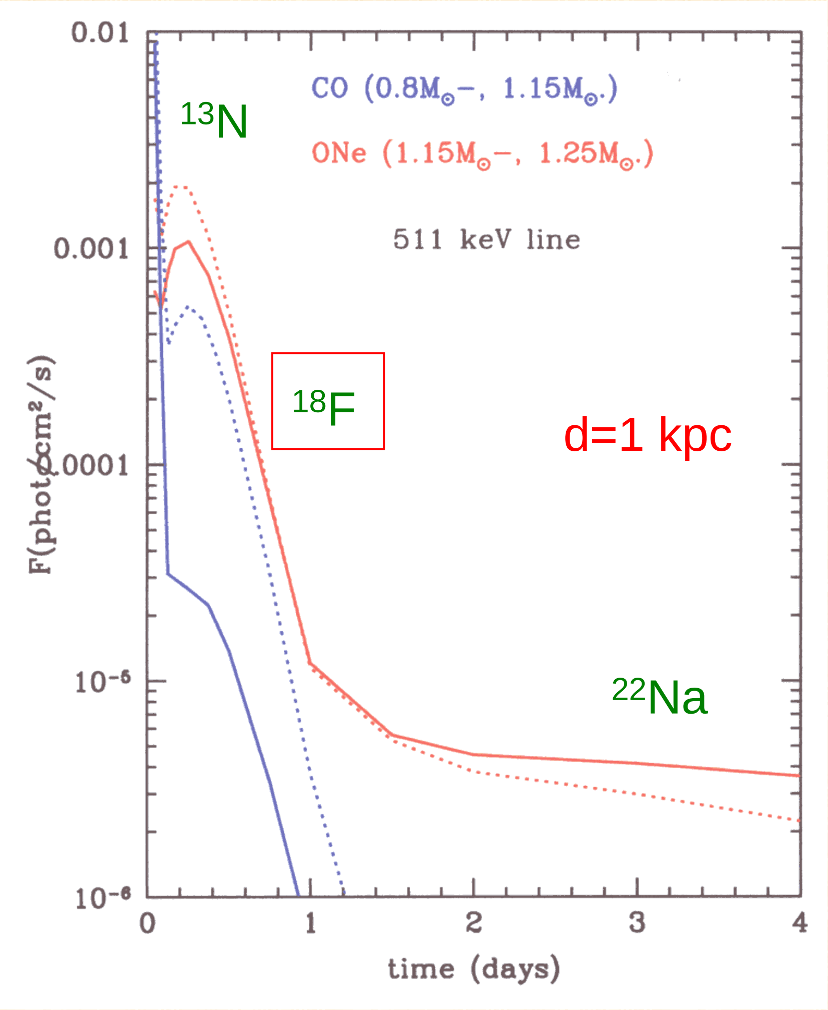
Theory: $F<2.5\text{x}10^{-6}/d_{kpc}^{2}$

Harris et al. 1991 and 2001

e^{-} - e^{+} annihilation emission

Light curves: 511 keV line

In CO and ONe novae



Model	t_{max}^{*} (h)	F_{max} (ph/cm^2/s)**
CO, 0.8 M$_\odot$	- - -	2.6 x 10^{-5}
CO, 1.15 M$_\odot$	6.5	5.3 x 10^{-4}
ONe, 1.15 M$_\odot$	6	1.0 x 10^{-3}
ONe, 1.25 M$_\odot$	5	1.9 x 10^{-3}

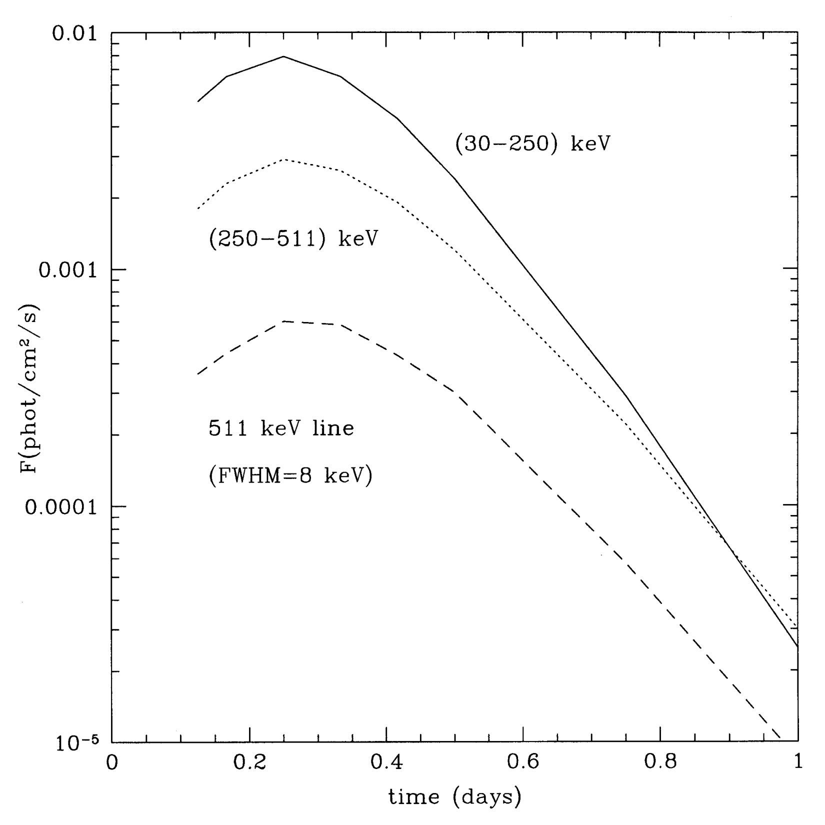
- 511 keV line in ONe novae remains after 2 days until ~ 1 week because of e$^+$ from ^{22}Na
- Intense (but short duration)
- Very early appearence, before visual maximum (i.e, before discovery)

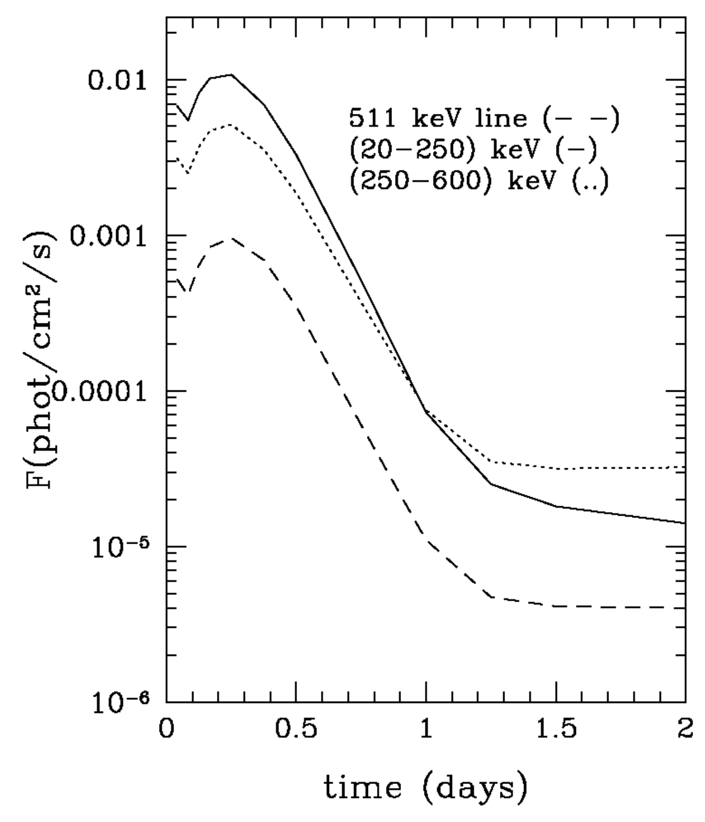
➢ WARNING: nuclear reaction rates affecting ^{18}F still uncertain (^{17}O+p ^{18}F+p)

Light curves: 511 keV line and continuum

CO Nova, 1.15 $M_\odot$

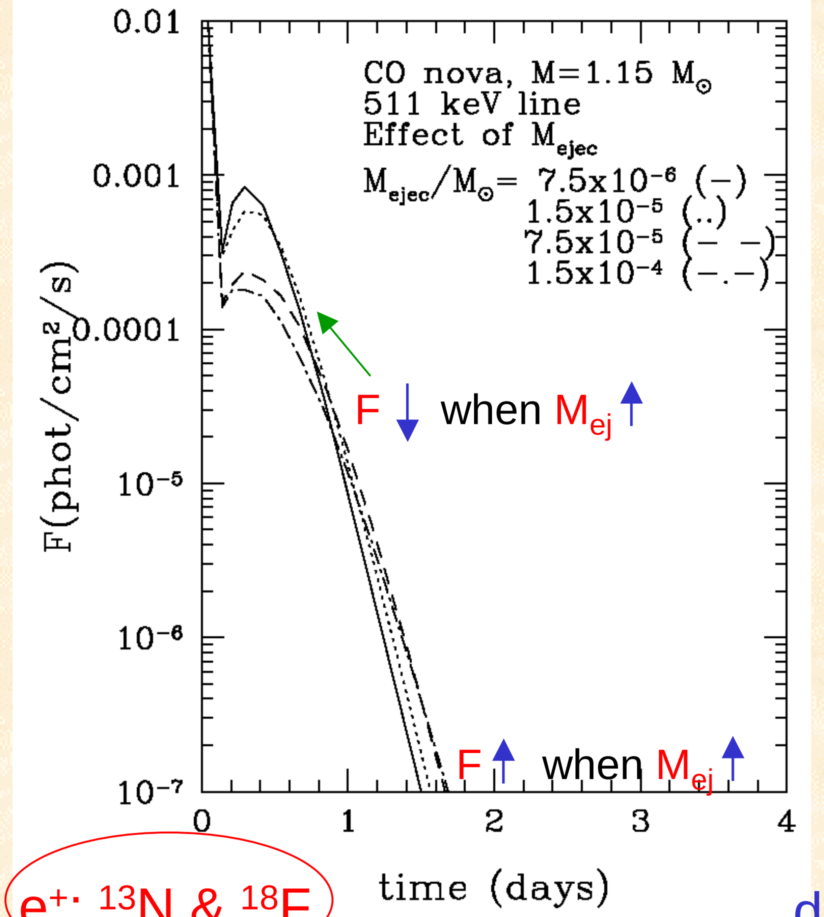
ONe Nova, 1.15 $M_\odot$





d=1 kpc

Light curves: 511 keV line. Influence of $M_{ejected}$

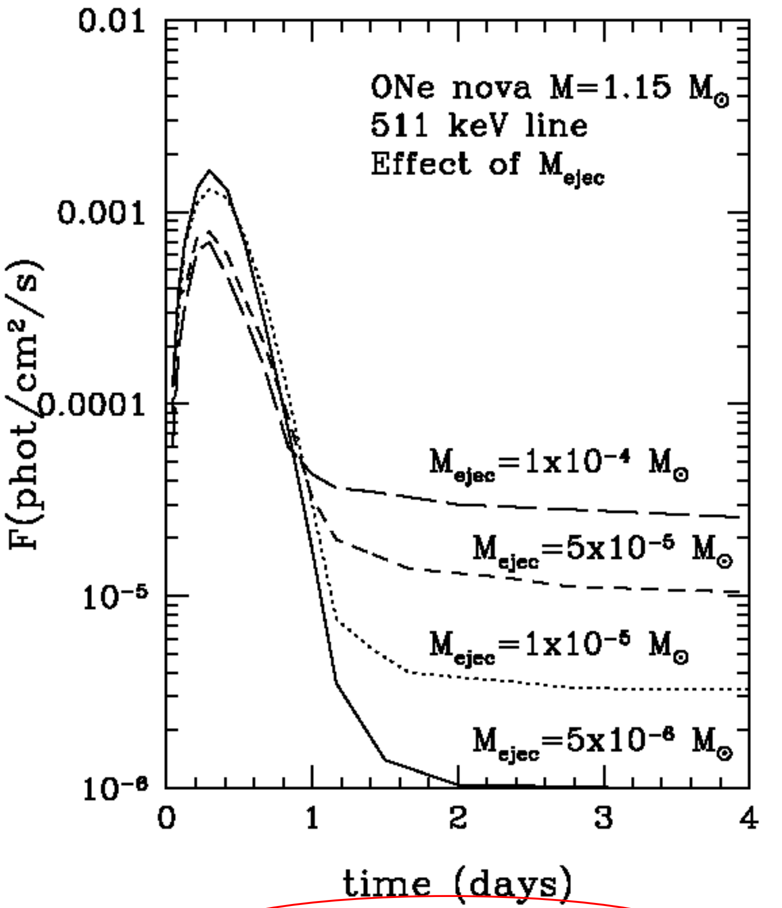


F ↓ when M_{ej} ↑

F ↑ when M_{ej} ↑

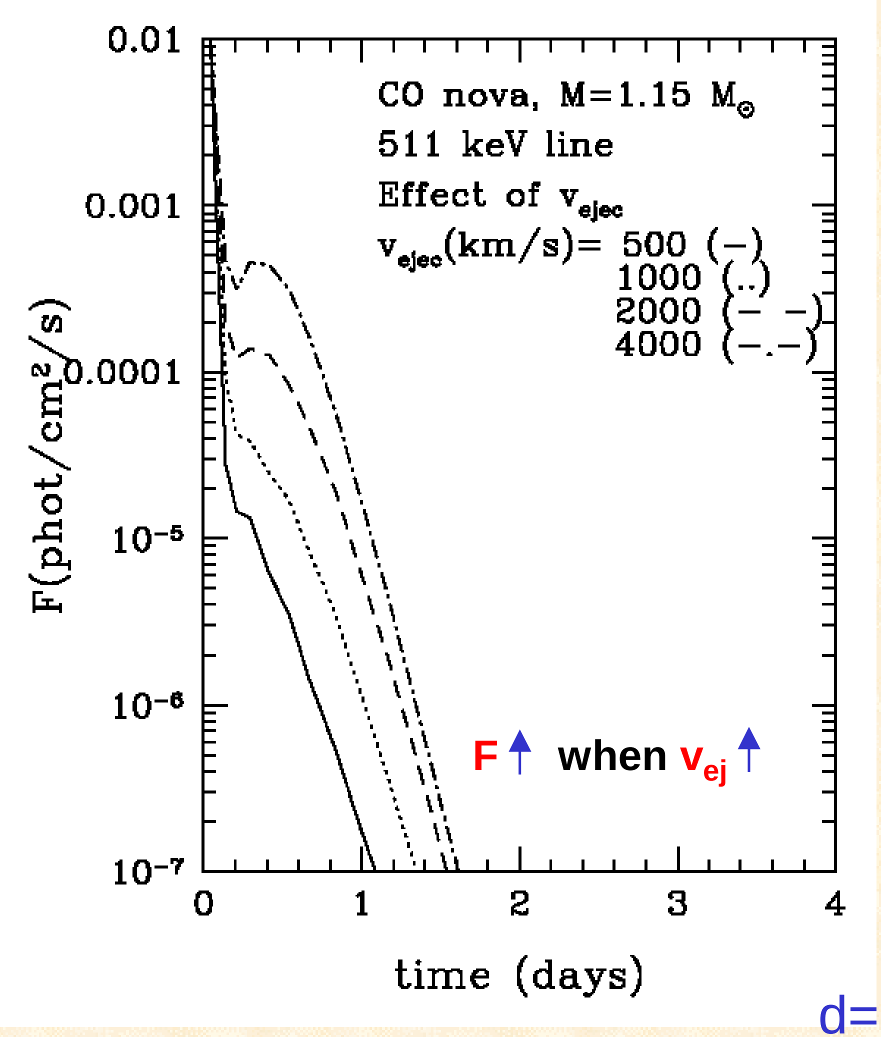
e^+: ^{13}N & ^{18}F

d=1 kpc

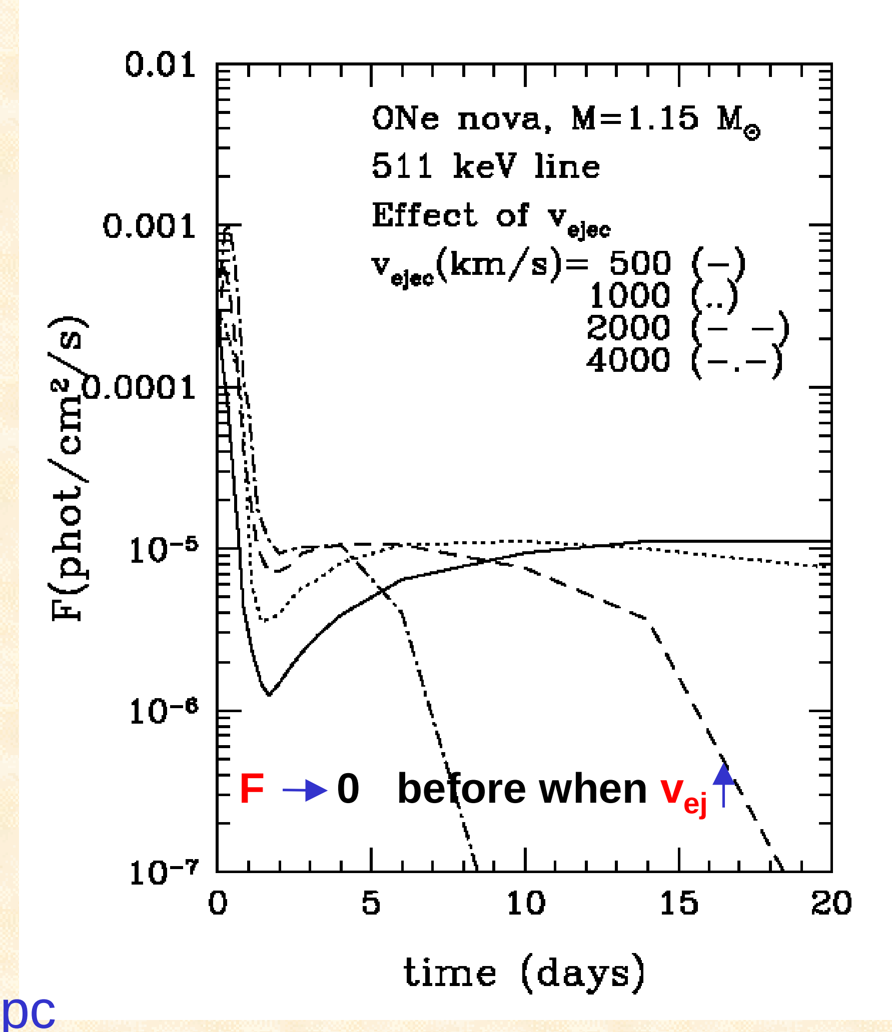


e^+: ^{13}N, ^{18}F & ^{22}Na

Light curves: 511 keV line. Influence of $v_{ejec.}$



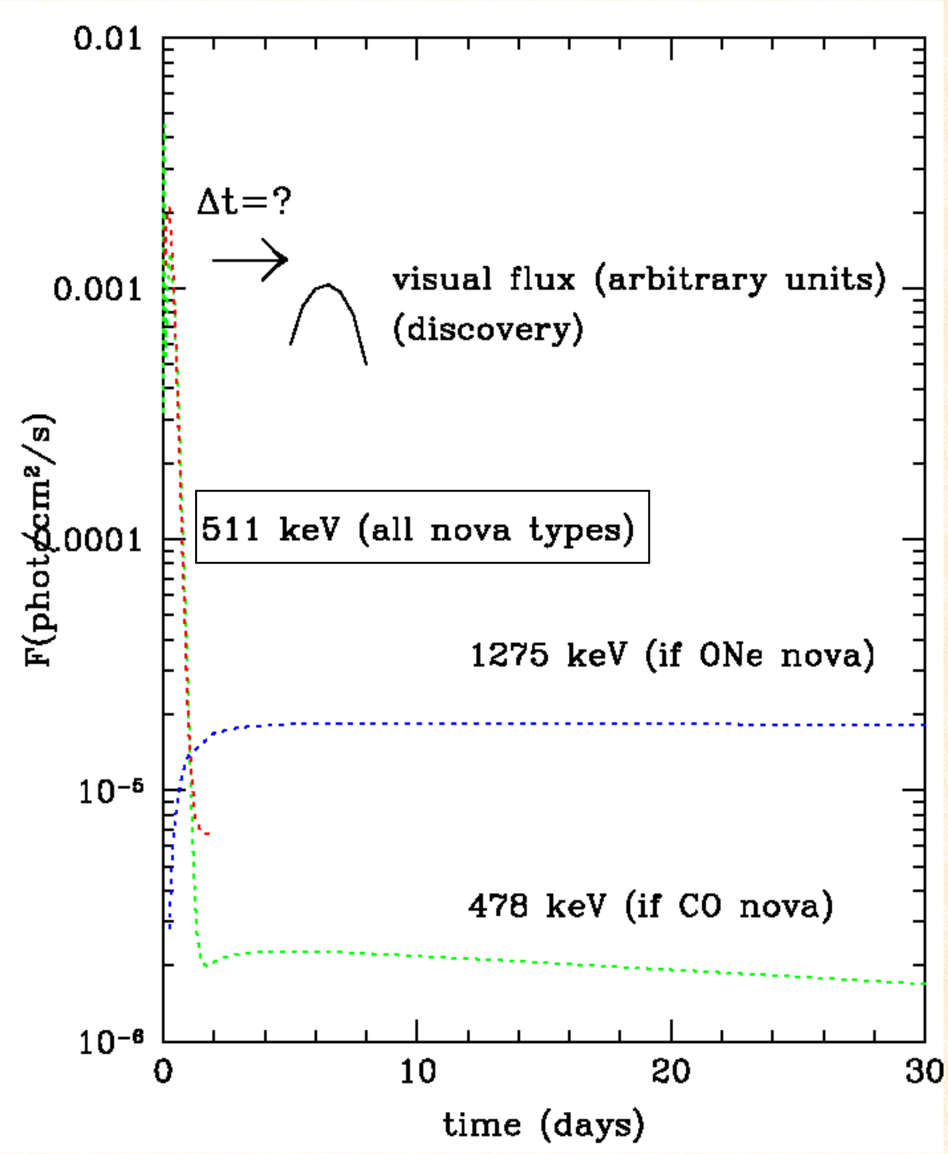
F ↑ when v_{ej} ↑



F → 0 before when v_{ej} ↑

d=1 kpc

Gamma-ray and visual light curves

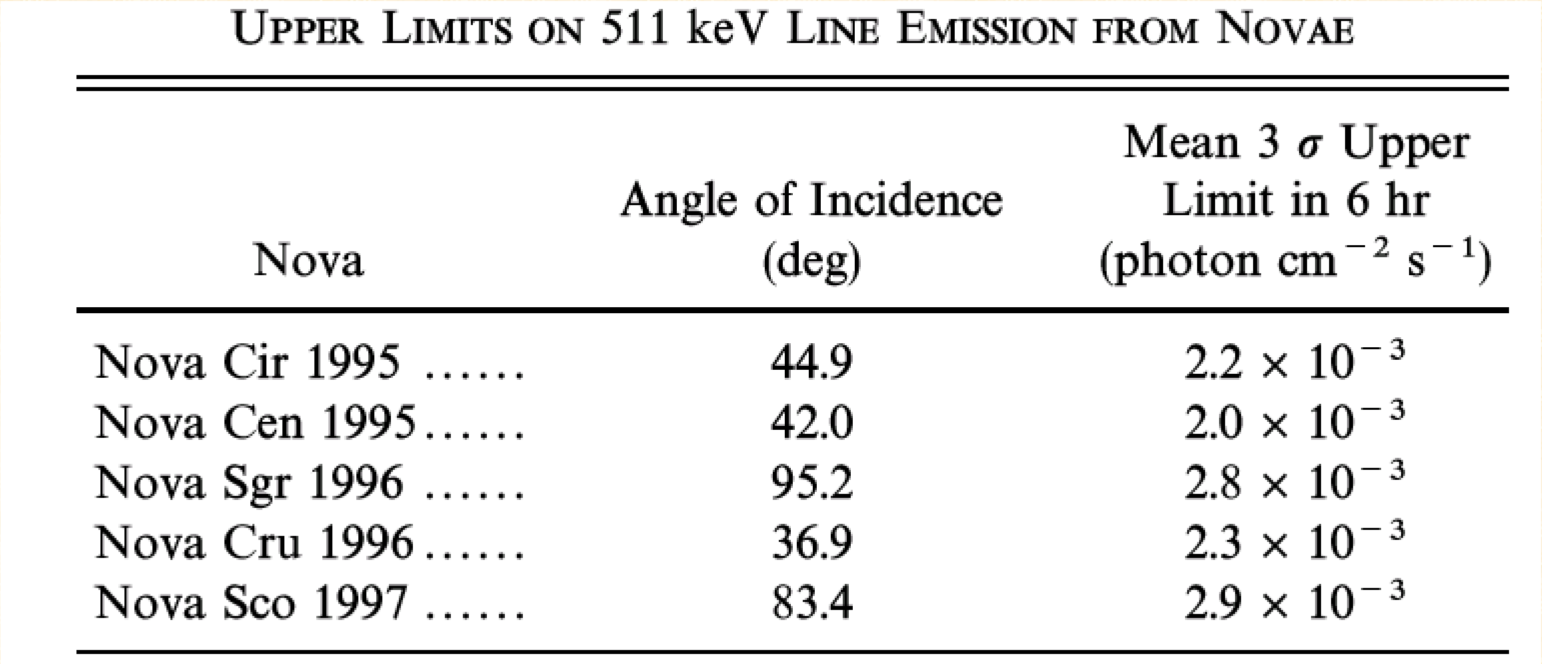


Continuum & 511 keV line, (e^--e^+ annihilation), are intense, but very short and before visual discovery

- detection requires "a posteriori" analyses with wide FOV instruments CGRO/BATSE WIND/TGRS, RHESSI, SWIFT/BAT
- future hard X/soft γ-ray surveys like EXIST can provide unique information about the Galactic nova distribution

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

Observations: 511 keV line

WIND/TGRS: “constraining” the Galactic nova rate from a survey of the Southern Sky during 1995-1997

From the non detection, an upper limit of the Galactic nova rate was extracted:

➡ $< 123\ \mathrm{yr}^{-1}$ (CO novae; $r_{\mathrm{detect.}}$: 0.9 kpc)

$< 238\ \mathrm{yr}^{-1}$ (ONe novae; $r_{\mathrm{detect.}}$: 0.7 kpc)

Promising for future wide FOV instruments sensitive in the soft γ-ray range (20-511) keV

Harris et al. 2000, ApJ

Observations: 511 keV line

CGRO/BATSE

List of nearby novae (d < 3-4 kpc) since CGRO launch

	Pup91	Sgr92#1	**Cyg92**	**Sco92**	Cas93	Aql95	Cir95	**Vel99**
Date of discovery	Dec 27	Feb 13	**Feb 19**	**May 26**	Dec 8	Feb 7	Jan 27	**May 22**
m_v (max.)	6.4	7.3	**4.2**	**7.3**	5.3	8.1	7.2	**2.8**
t_2 (d)	15	4-14	**16**	**73**	33	11	20	**6**
d (kpc)	2.9	3.6	**1.7**	**0.8**	2.8	1.9	4	**2**

- Only upper limits, 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

Hernanz, Smith, Fishman, et al., 2000, Proc. 5th CGRO Symp.

Prospects for detectability with INTEGRAL/SPI

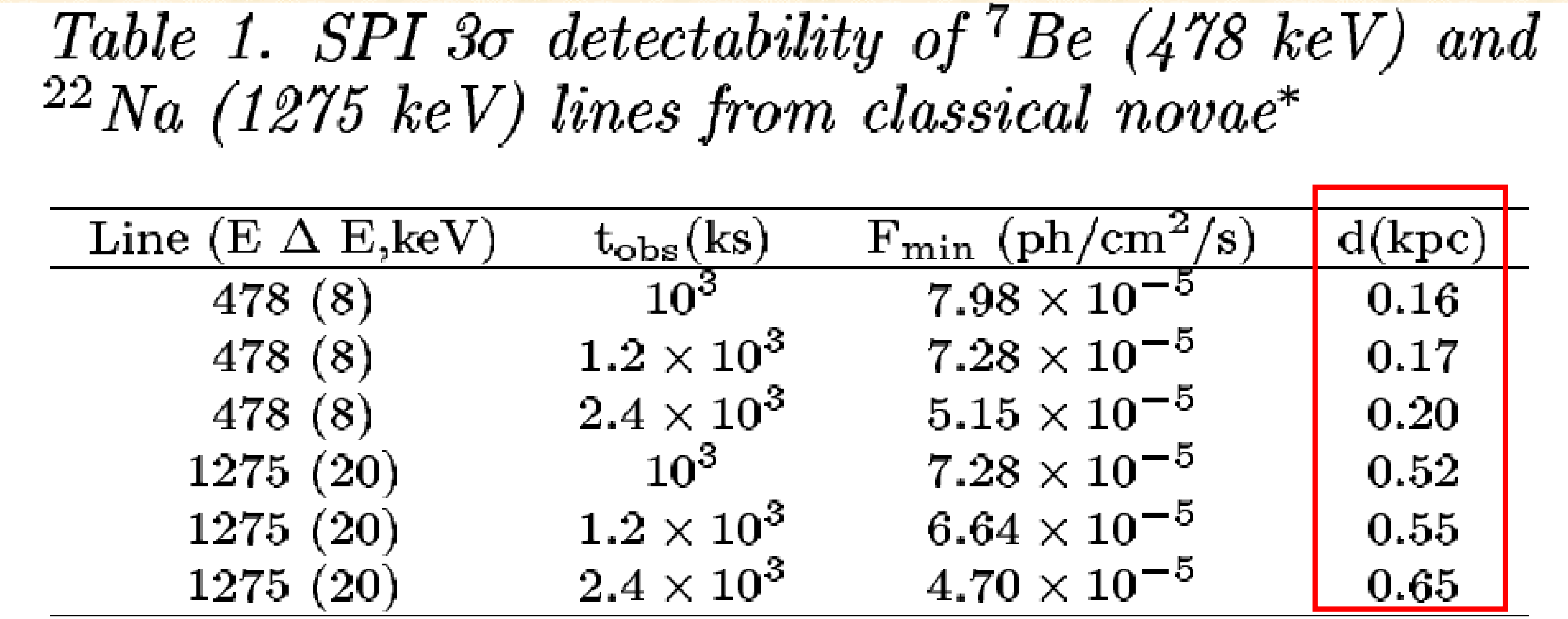
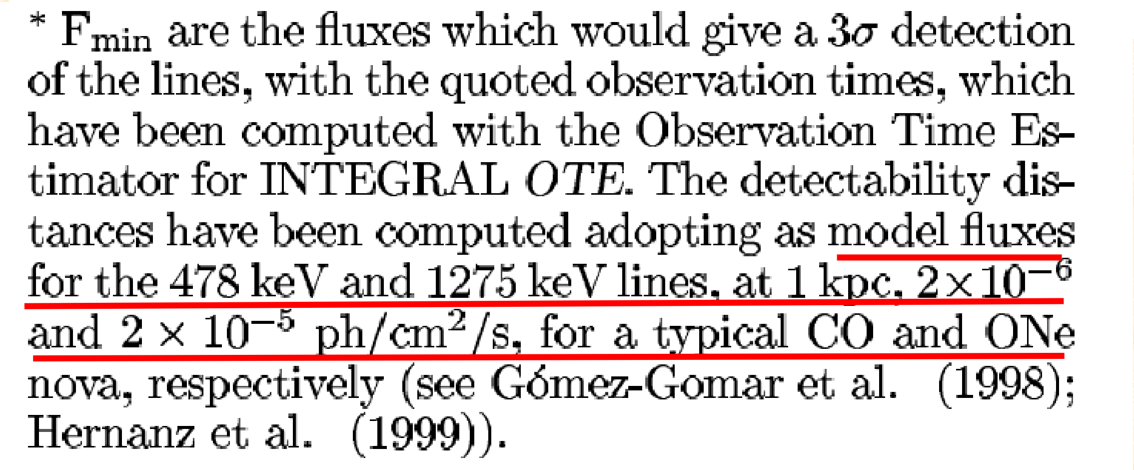


*Table 1. SPI 3σ detectability of ^{7}Be (478 keV) and ^{22}Na (1275 keV) lines from classical novae**

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: GRI (γ-ray lens), ACT (Advanced Compton Telescope)

Need of more sensitive intruments

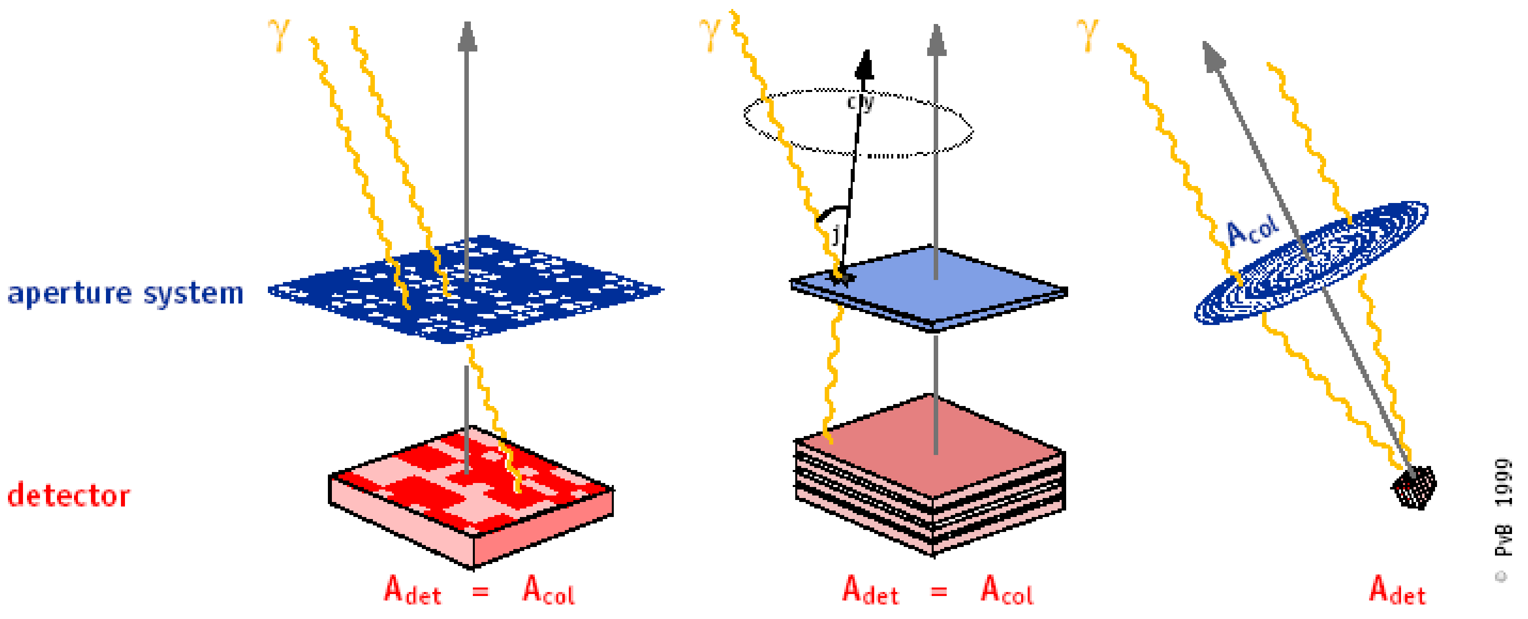
Future planned missions

- GRI (Gamma-Ray Imager based on a Laue focusing γ-ray lens) → *see talk by Wunderer*

- ACT (Advanced Compton Telescope) → *see talk by Boggs*

Why focusing γ-rays?

	modulating aperture systems	Compton telescopes	crystal lens telescopes
aperture / effect	geometric optics absorption	quantum optics incoherent scattering	wave optics coherent scattering



signal S	~	A_{col}	A_{col}	A_{col}
background B	~	$V_{det} \sim A_{det} = A_{col}$	$V_{det} \sim A_{det} = A_{col}$	$V_{det} \sim A_{det} << A_{col}$
S/B	≈	const (A)	const(A)	A_{col}/A_{det}

from Peter von Ballmoos, CESR, Toulouse

PART II: see talk on Friday 11