Anisotropic inverse Compton scattering from the circumstellar disc in PSR B1259-63

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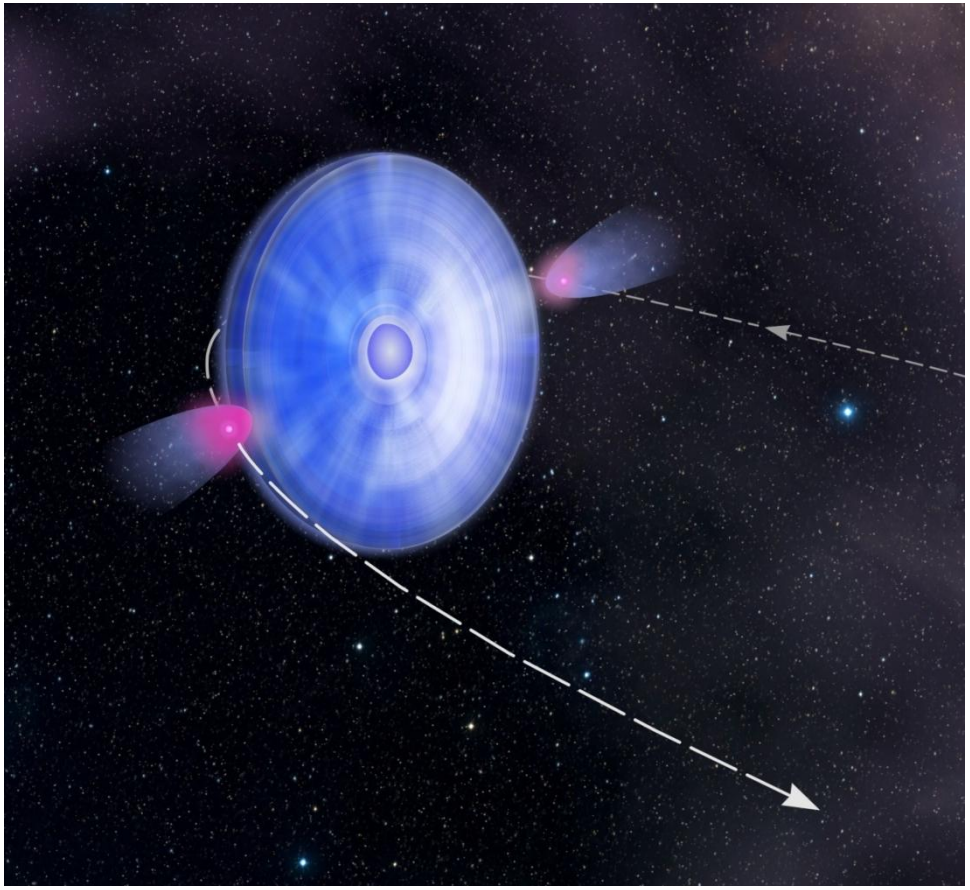
PSR B1259-63

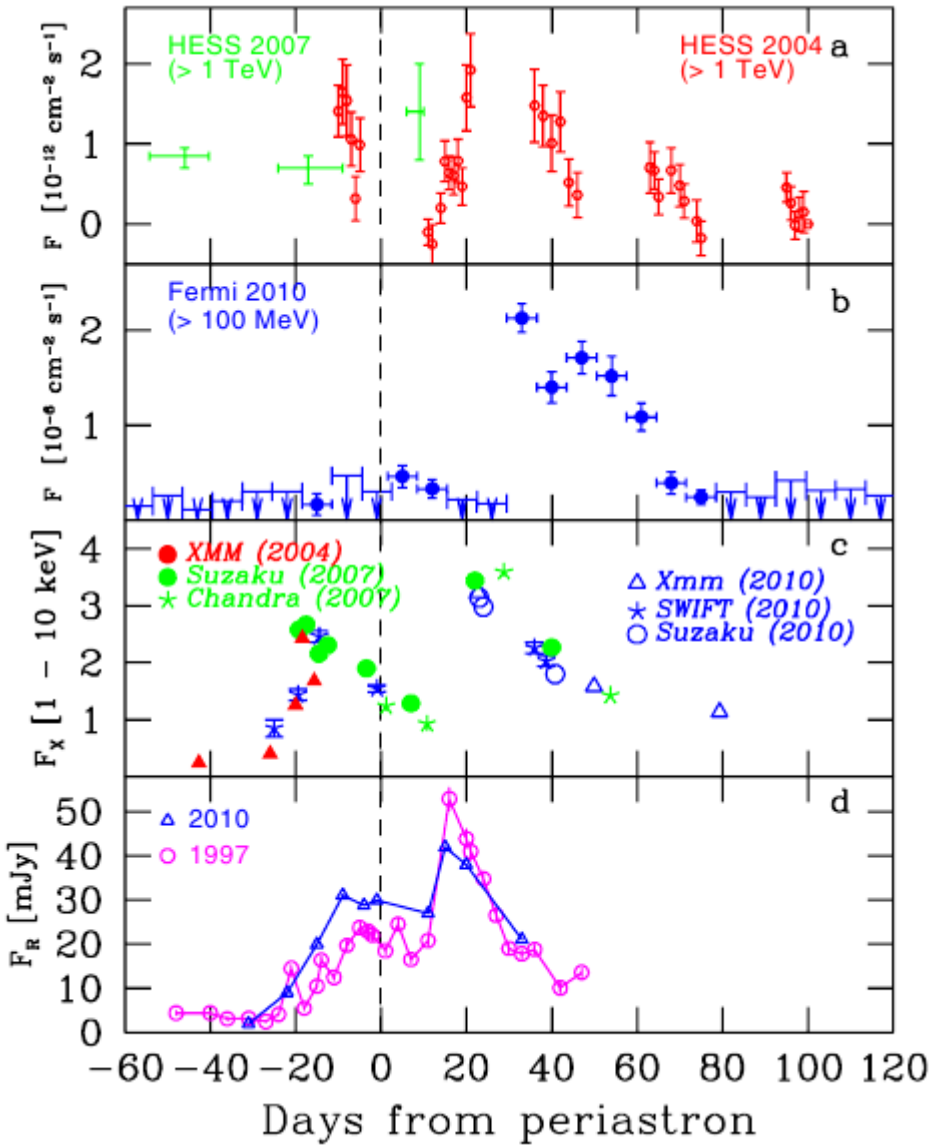
- Binary system consisting of a Be star and a 48 ms pulsar in a 3.4 year orbital period
- Spin-down luminosity of $\dot{E} = 8.25 \times 10^{35} \mathrm{erg\ s^{-1}}$
- Detected at Very High Energy (>100 GeV) with HESS (Aharonian et al. 2005) and at High Energy with Fermi (Abdo et al. 2011)
- The star is a Be type star, indicating the presence of an extended circumstellar disc.
  - Extended density region
  - IR excess associated with the disc
- Close to periastron (every 3.4 years) the pulsar appears to pass behind or through the circumstellar disc,
  - evidenced by the eclipse of the radio pulsar emission.
- It is near periastron that the majority of the non-thermal emission occurs.



NASA/Goddard Space Flight Center/Francis Reddy

PSR B1259-63

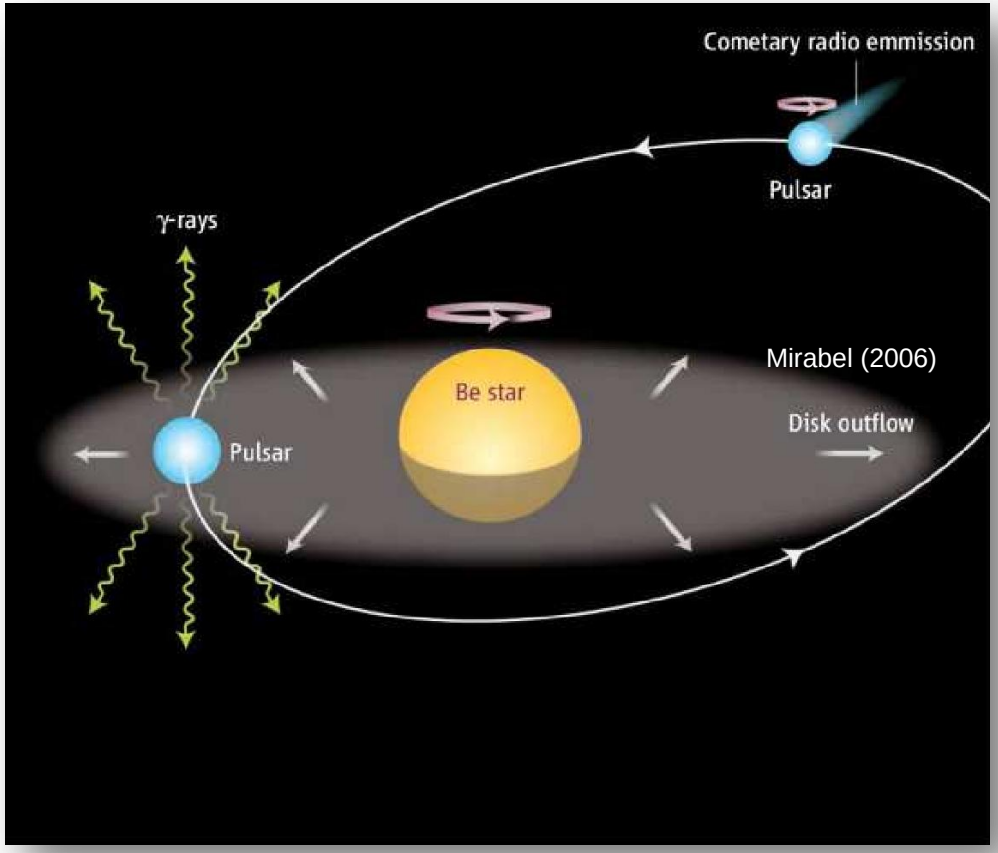
- The radio, X-ray and VHE emission is fairly consistent.
- The Fermi detection was completely unexpected
  - Faint before periastron
  - Bright after periastron
  - A implied luminosity of near 100% of the spin-down power
- The flare occurred approximately 30 days after periastron
  - This is after the presumed disc position
  - Not in-line with the radio eclipse, or the unpulsed radio, X-ray or TeV emission



Abdo et al. (2011)

Pulsars/PWNe

- Since we are dealing with a Be stars, the circumstellar disc provides an additional source of photons.
- We have considered the effects of the IR excess on the IC scattering rate, taking into account the geometry of the circumstellar disc.
- Taking into account a modified version of the Curve of growth method proposed by Waters (1984).

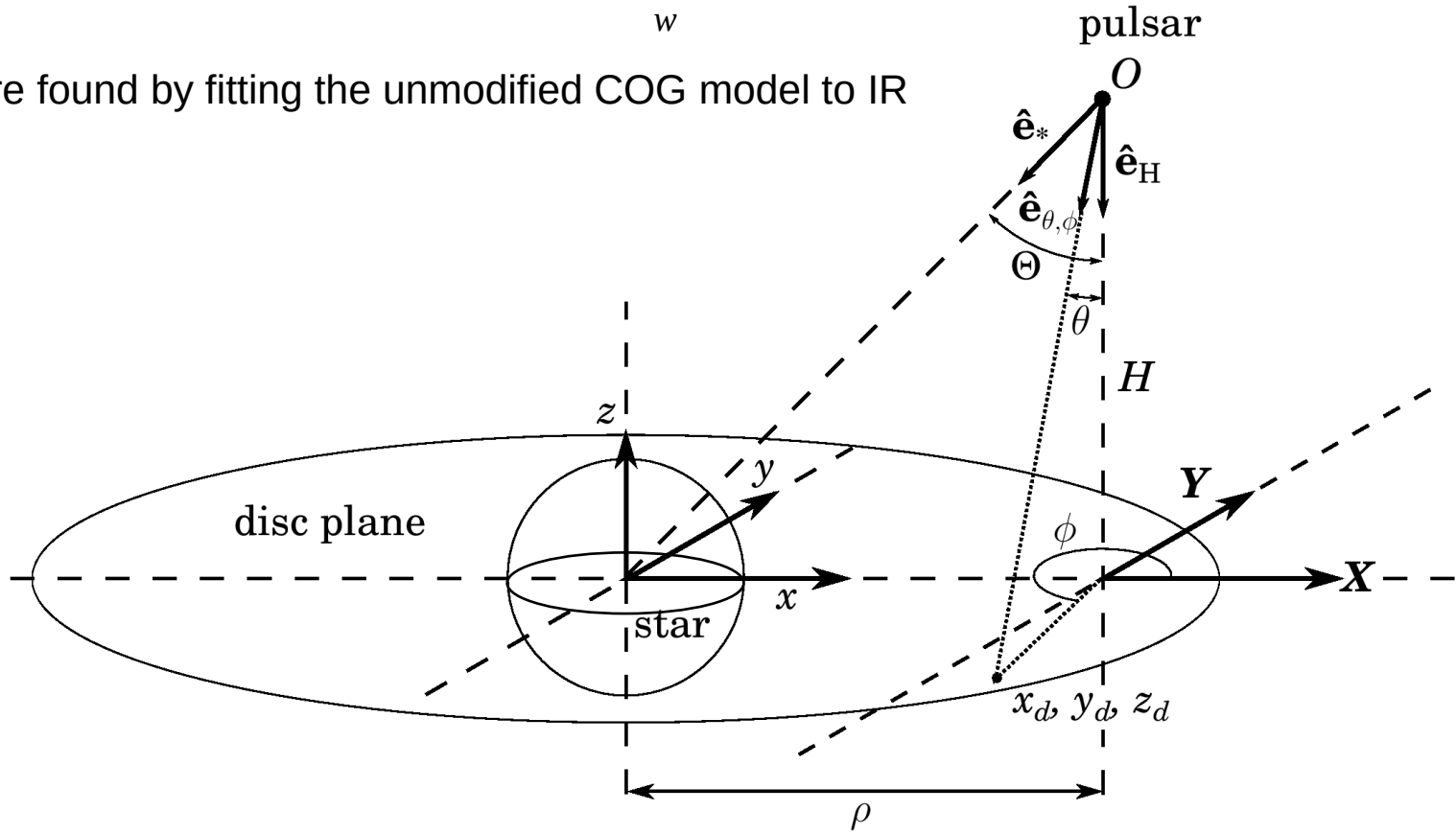


Be stars – modified COG method

- When determining the anisotropic IC scattering, calculated using the Dubus (2008) kernel, the disc photon contribution is calculated by numerically integrating over the circumstellar disc.
- For each direction the intensity along the line-of-sight is determined by calculating the optical depth from the modified geometry.

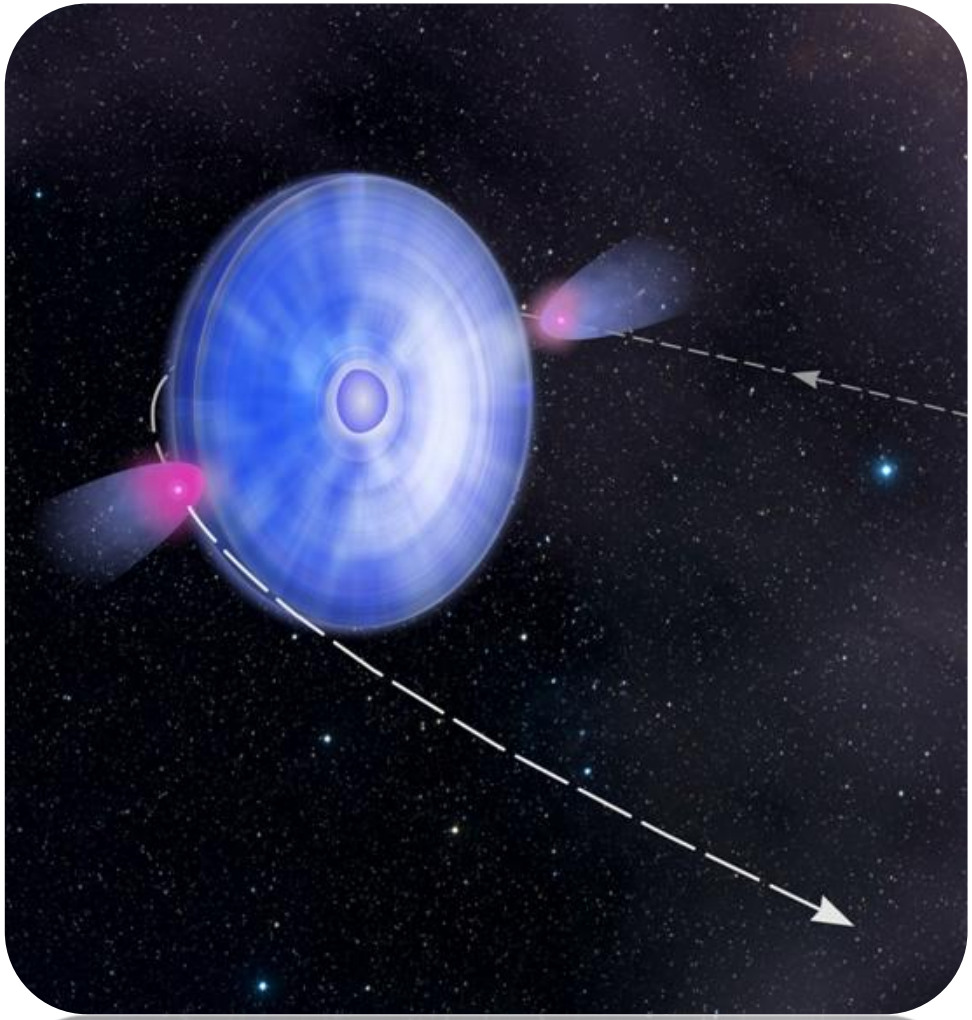
$$I_\nu = B_\nu(T)\left(1 - e^{-\tau_{\max}}\right) \qquad \tau_\nu = E_{\nu,d}\, q^{-2n+1} \int_w \cos^{2n-2} w \, \mathrm{d}w$$

- The model parameter are found by fitting the unmodified COG model to IR and optical data.



Application to PSR B1259-63

- The application of the AIC scattering to PSR B1259-63 is complicated for two main reasons:
  - The IR excess associated with the star
    - Curve of growth method applied to archive and VLT data
  - The extended geometry of the circumstellar disc
    - Stars and disc treated separately
    - Change in the IR excess during the orbital period



PSR B1259-63 – COG method

- Archive data

Optical

	W&G89	K&N77	S83	D91
V	10.01	10.04	10.05	10.07
B-V	0.754	0.74	0.72	0.73
U-B	-0.506	-0.44	-0.47	-0.47
$(U\text{-}B)_0$	-1.261			
A_ν	3.25			
$M_\nu(U\text{-}B)_0$	-4.6			

IR

Band	Wavelength μm	Magnitude	Flux Jy
J	1.235	8.026 ± 0.027	
H	1.662	7.699 ± 0.055	
Ks	2.159	7.248 ± 0.020	
A	8.28		0.2675 ± 0.0136
C	12.13		1.087 ± 0.5859

Appears to be an erroneous detection.

PSR B1259-63 – COG method

- VLT observations 5 January 2011

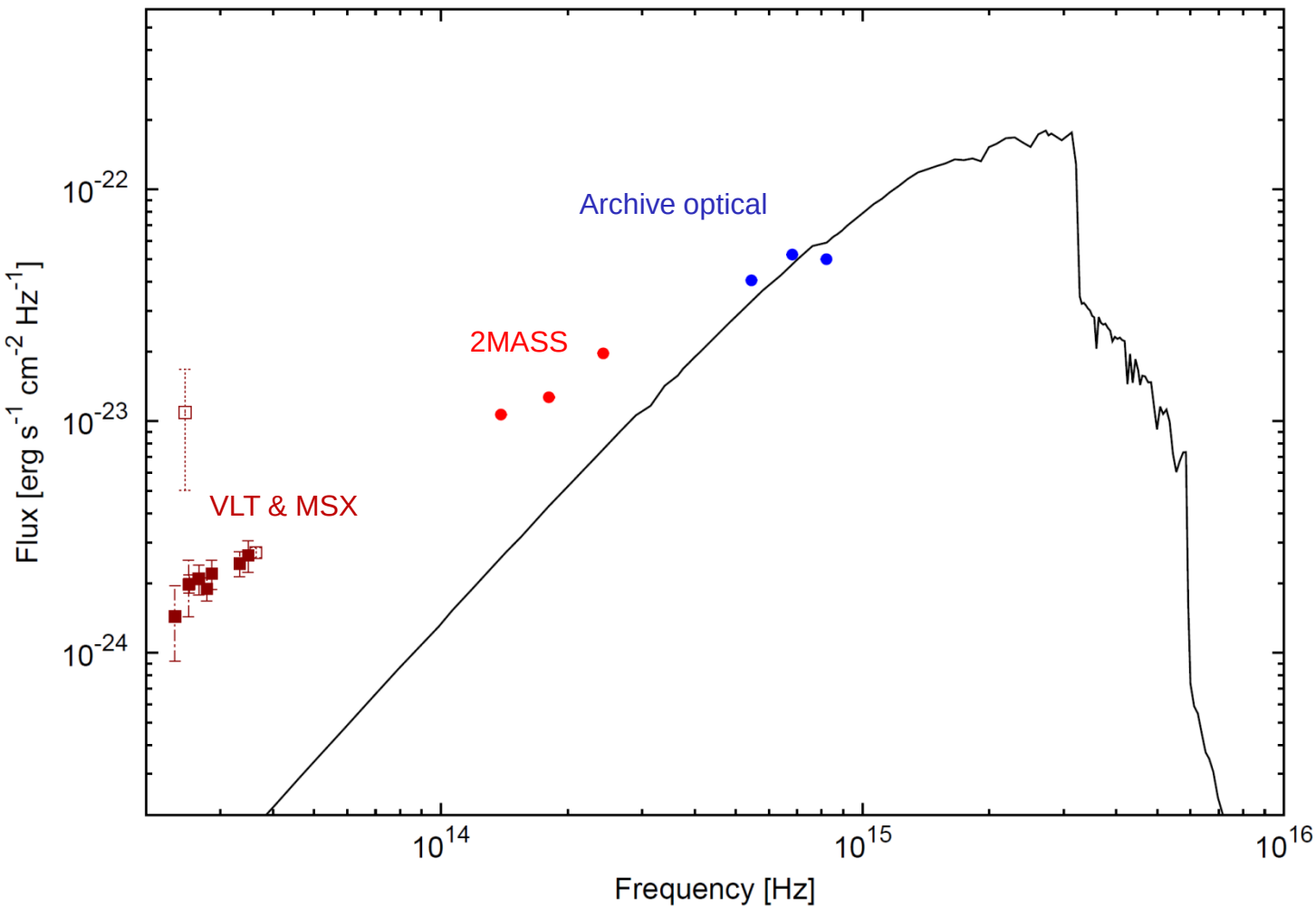
Filter	central wavelength μm	half-band width μm	F mJy	error mJy
PAH1	8.59	0.42	261	40
ArIII	8.99	0.14	241	30
SIV	10.49	0.16	218	32
SIV_2	10.77	0.19	188	21
PAH2	11.25	0.59	208	31
SiC	11.85	2.34	198	18
PAH2_2	11.88	0.37	196	54
NeII	12.81	0.21	143	51

PSR B1259-63 – Fermi flare

- IR photometry taken near periastron
- Observations undertaken with the IRSF telescope, Sutherland, South Africa, in December 2010
- No indication of a large change in magnitude.
- Measurements are consistent with previous 2MASS observations.

Date	J	H	Ks
19 Dec 10	7.999±0.038	7.584±0.045	7.176±0.082

PSR B1259-63 – COG method



Combined data set, de-reddened using E(B-V) = 0.85. Also shown in the fitted Kurucz stellar atmosphere with *T*=33000 K and log *g* =4.0.

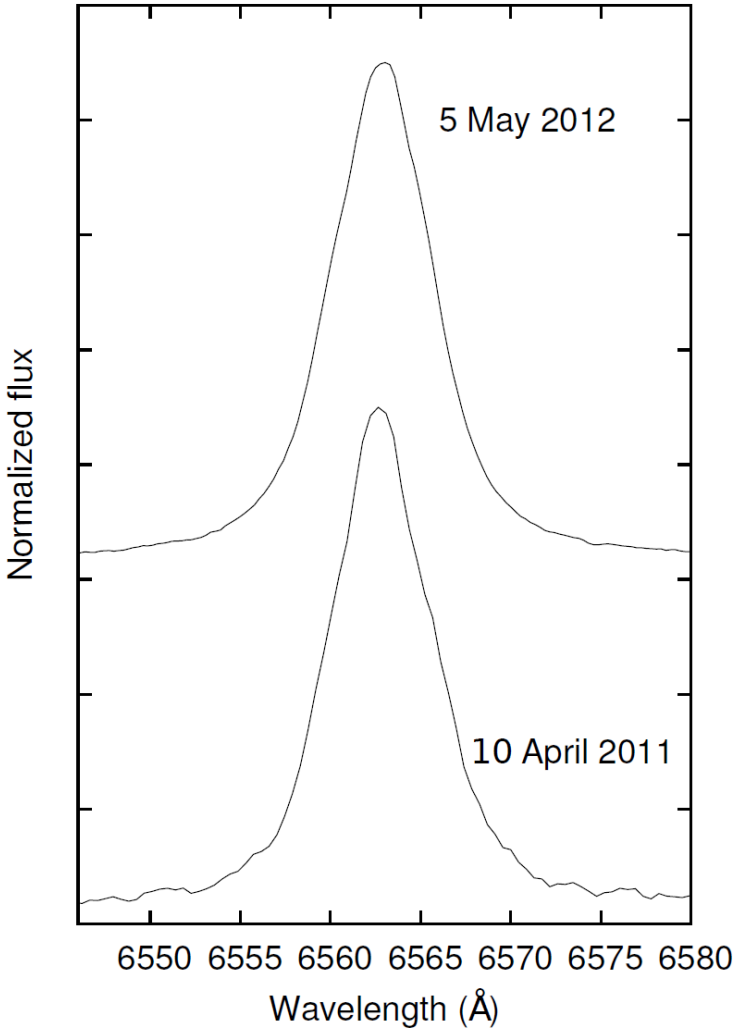
PSR B1259-63 – Fermi flare

Spectroscopic observations

- Observed with SAAO1.9 m in April 2011 and with SALT in May 2012
- We find that the Hα emission line remains dominate a few months after the disc crossing, and is still dominant in May 2012.
- Indication that the disc is not “destroyed” during the disc crossing or recovers quickly.
- Equivalent Width:

  -50 ± 5 Å in April 2011

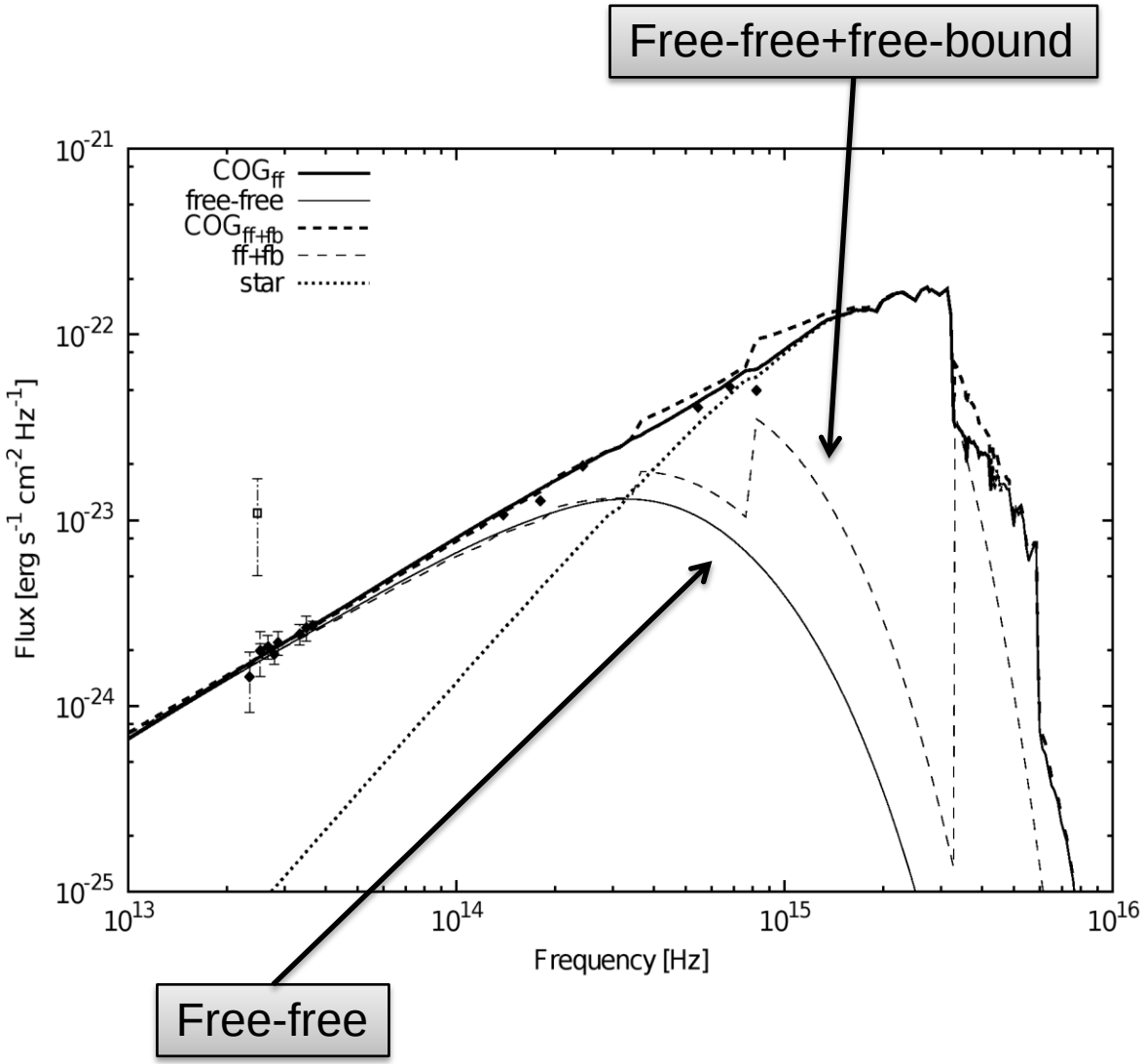
  -49 ± 2 Å in May 2012
- Most likely “normal” variability of the circumstellar disc.



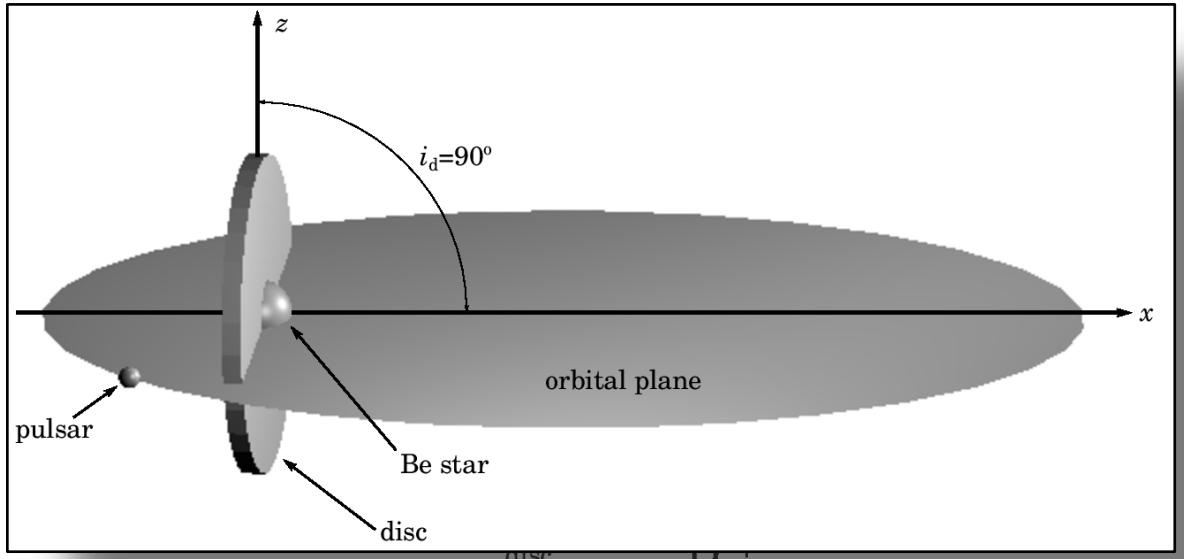
PSR B1259-63 – COG method

- Archive/VLT data:
  - Dereddening
    - E(B-V)=0.85 (Negueruela et al, 2011)
  - Star
    - $T_* = 33\,000$ K
    - log g = 4.0
  - COG fit

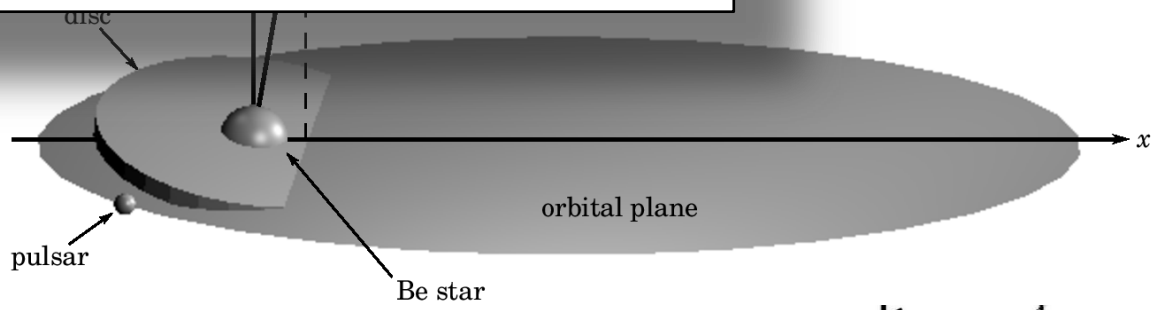
	free-free	ff+fb
n	3.0550	2.8389
$\log_{10} X_*$	10.245	9.9073
$R_{\rm disc}$	50 R_*	50 R_*
$T_{\rm disc}$	19 800 K	19 800 K
$\theta_{\rm disc}$	1°	1°



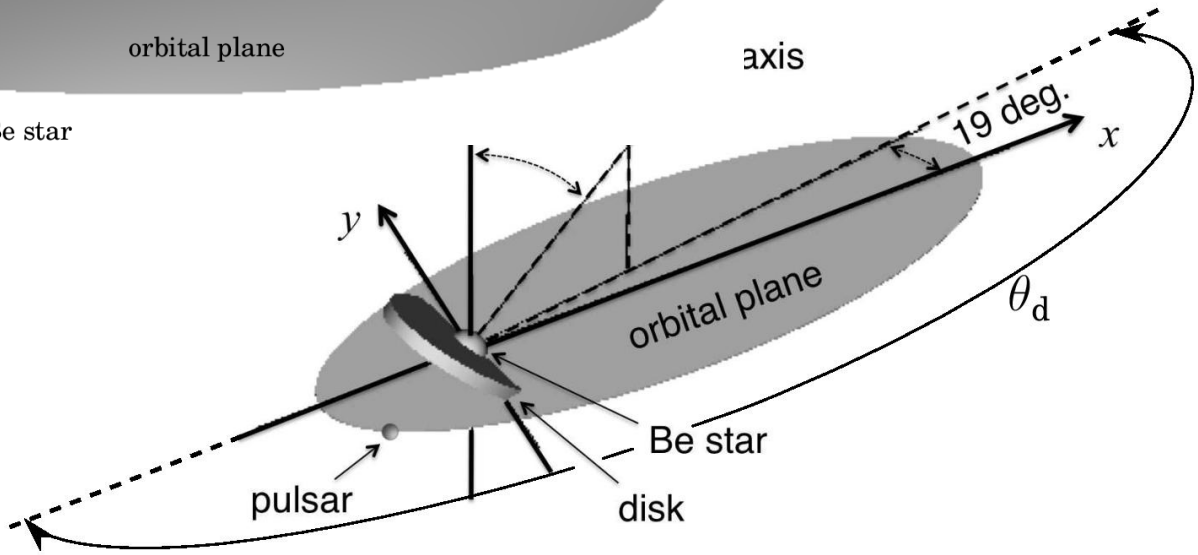
PSR B1259-63 – anisotropic scattering



90° disc



axis



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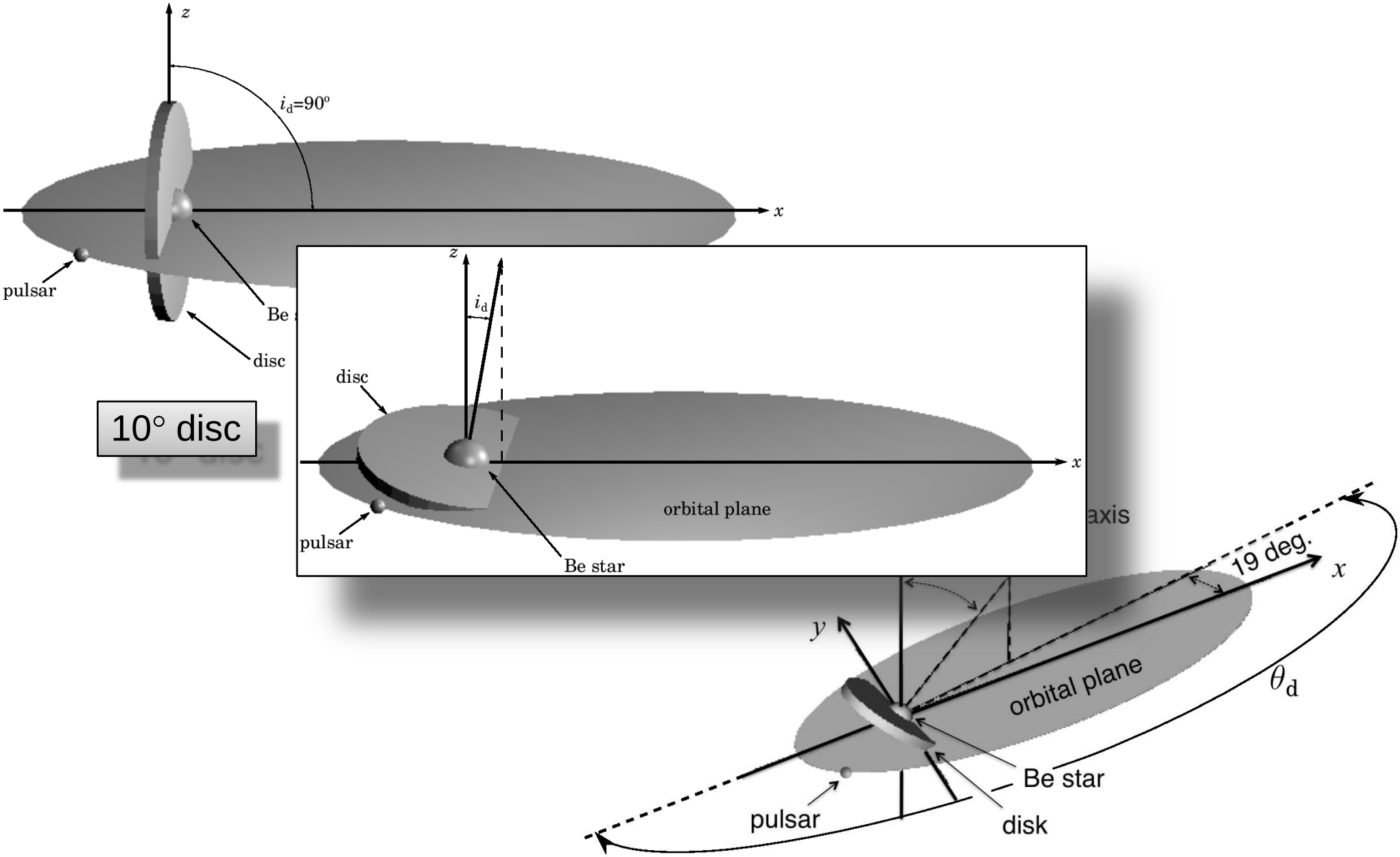
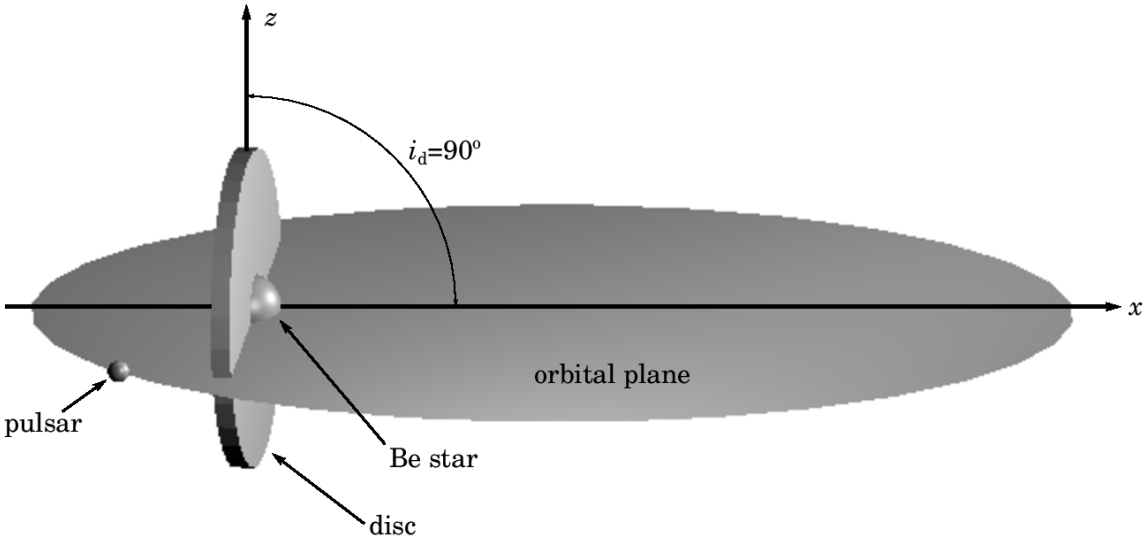
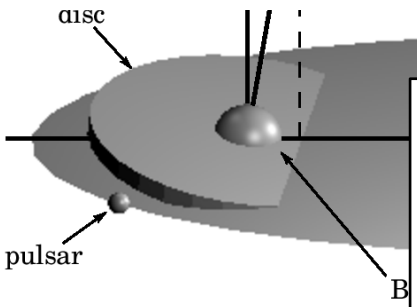
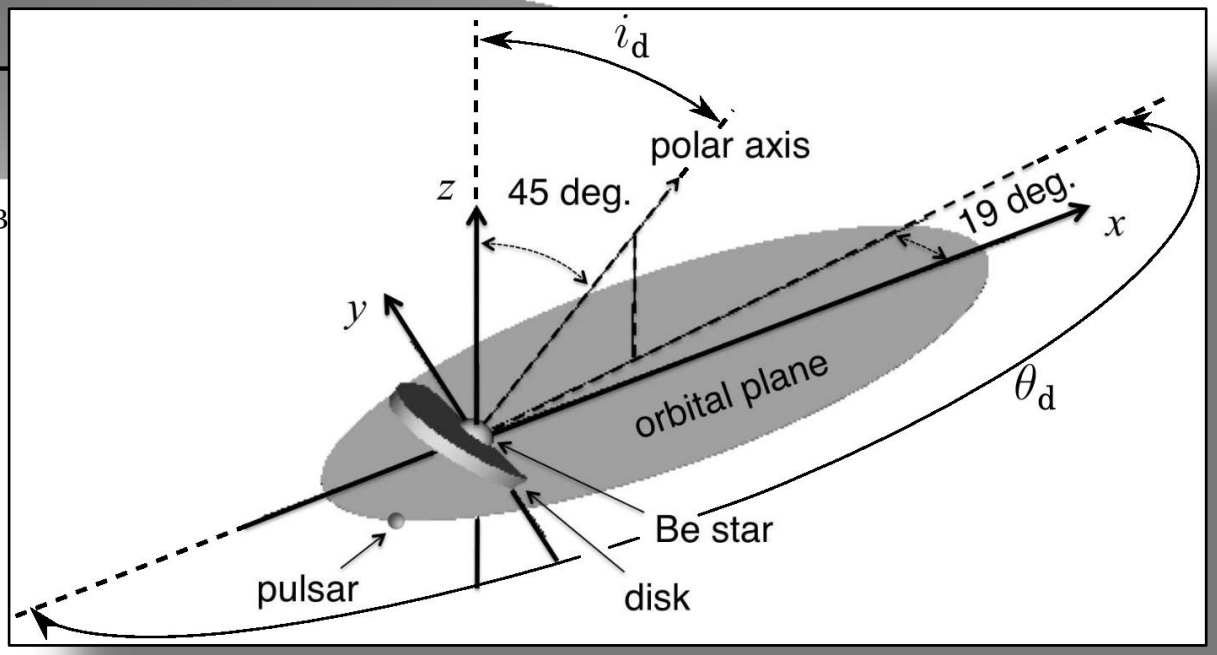


PSR B1259-63 – anisotropic scattering





45° disc

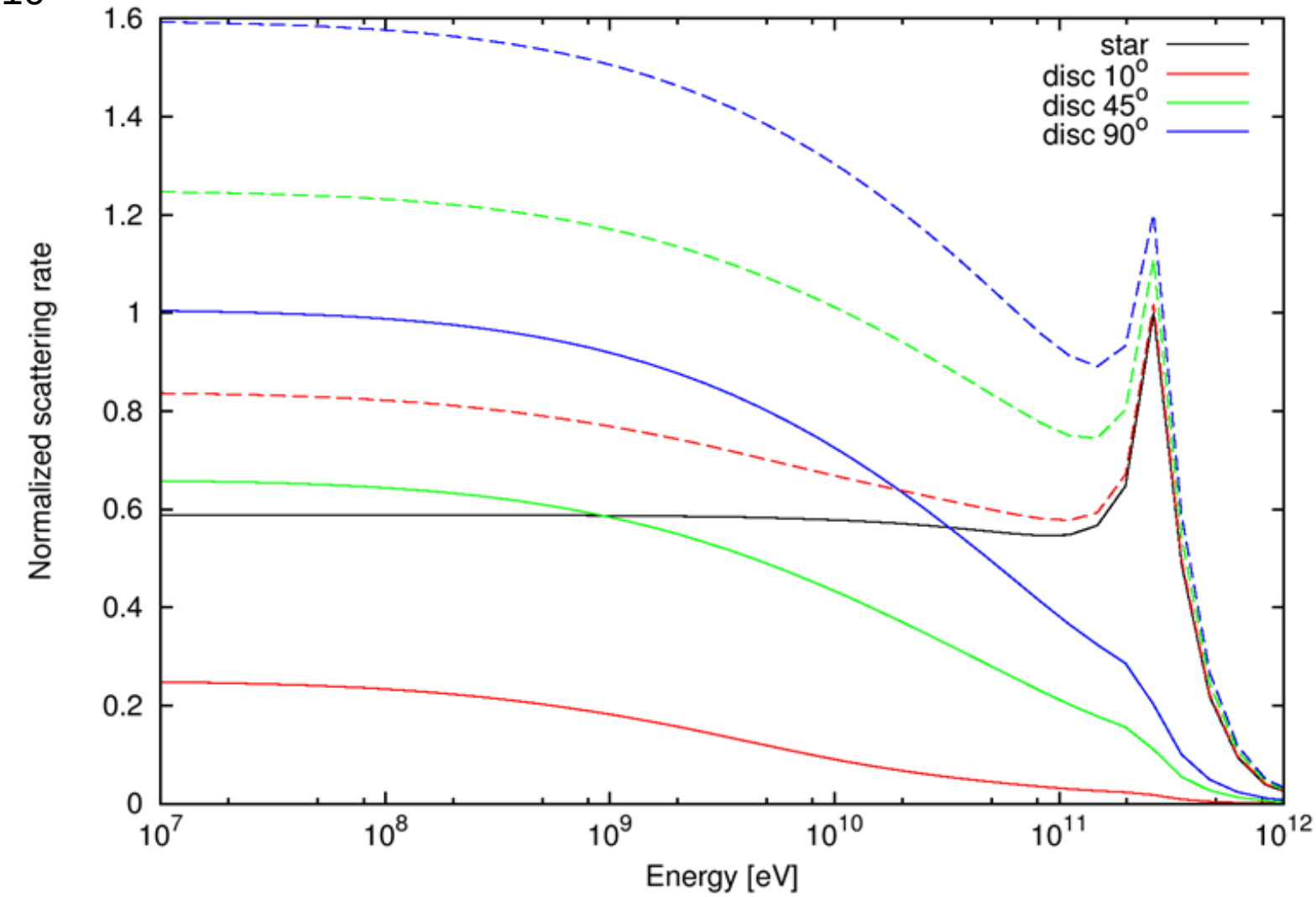


PSR B1269-63

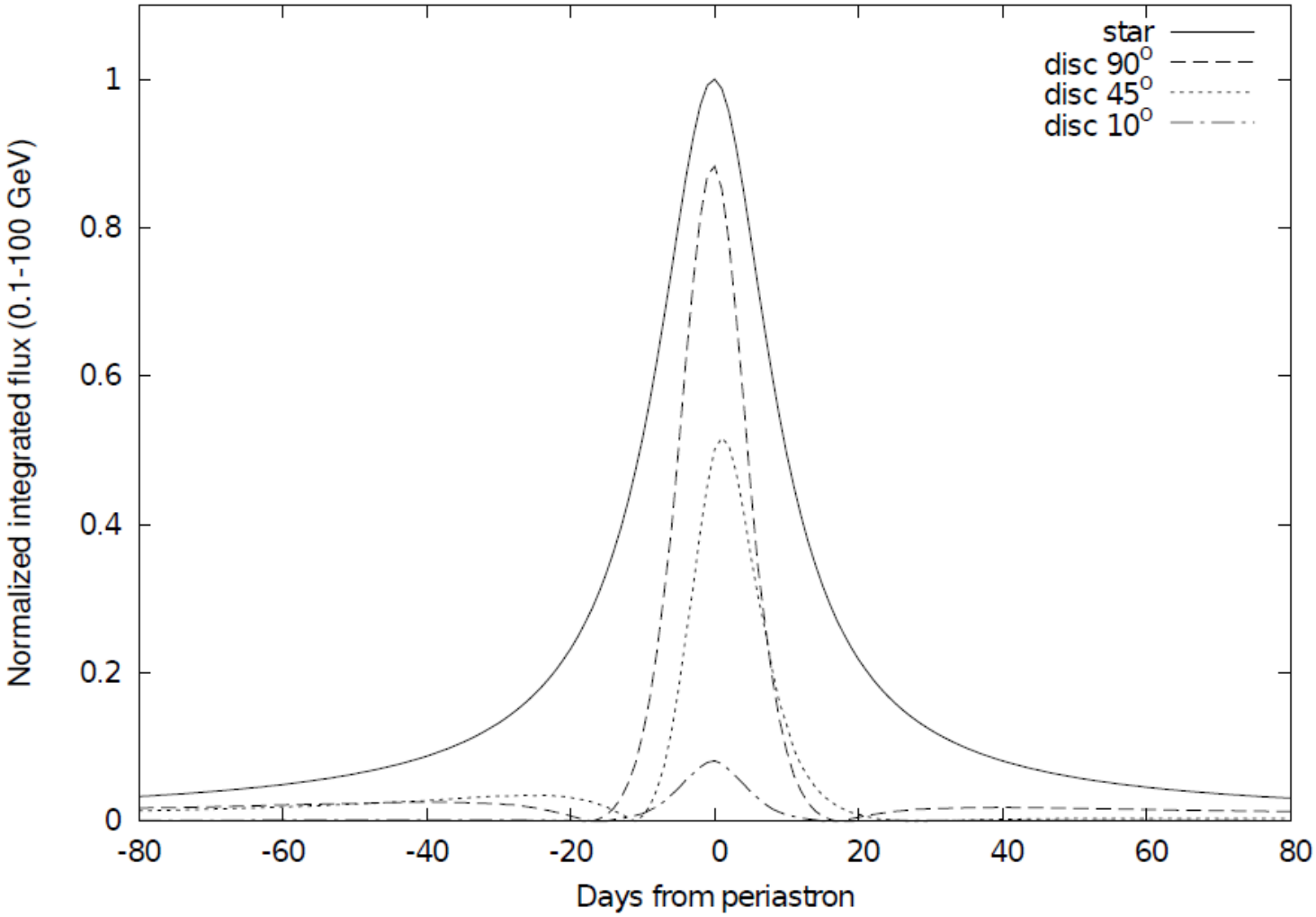
Post-shock adiabatic cooling

$\gamma = 5.4 \times 10^5 - 5.4 \times 10^7$

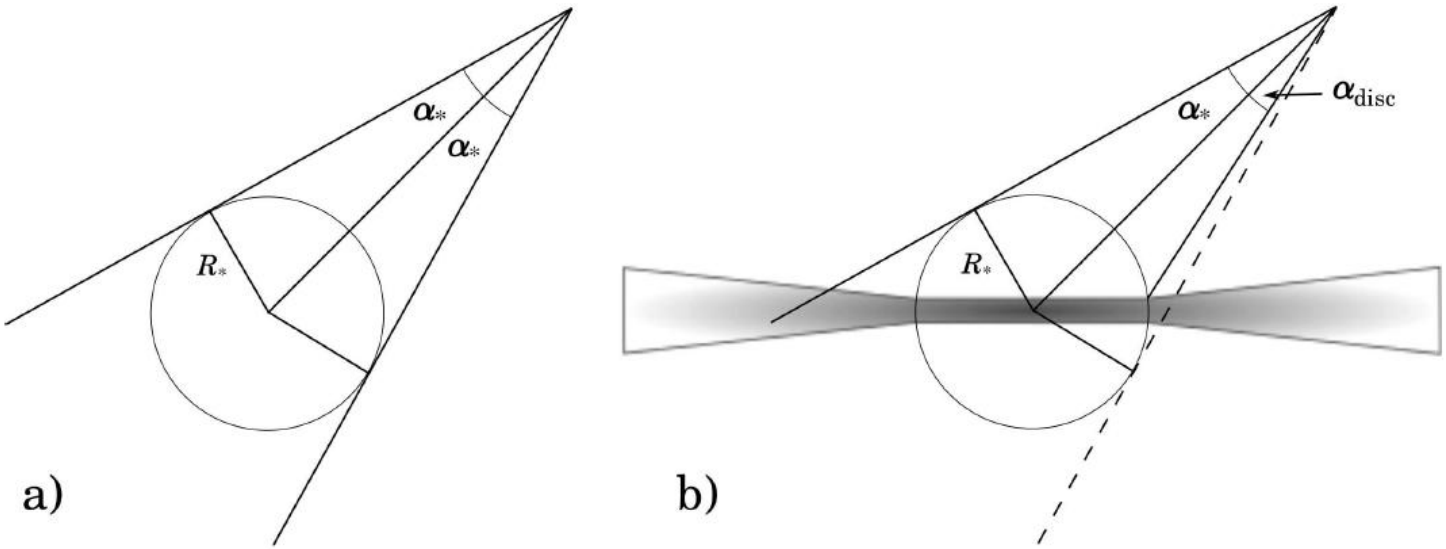
$p = 2.4$



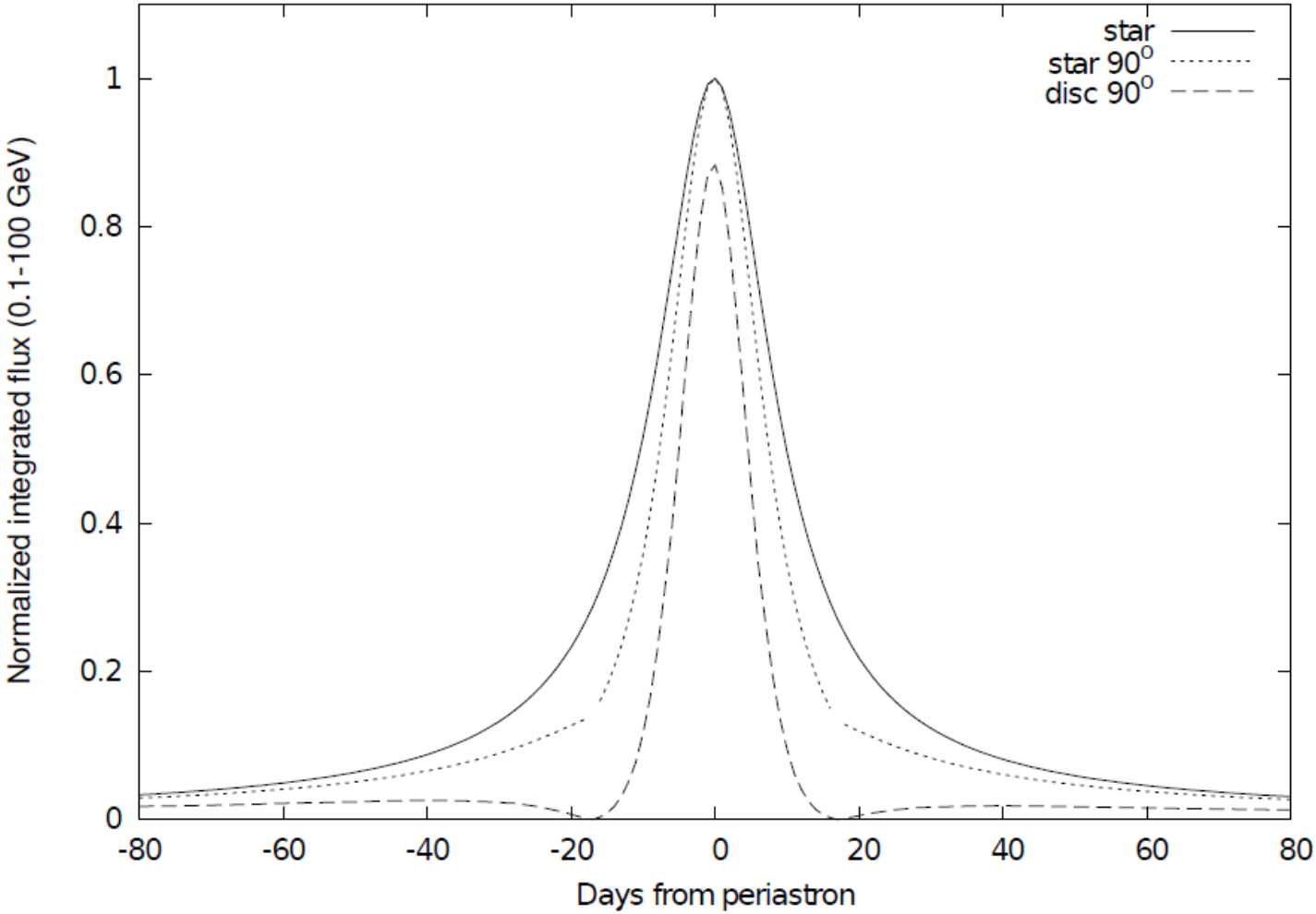
PSR B1259-63


star
disc 90°
disc 45°
disc 10°
Normalized integrated flux (0.1-100 GeV)
Days from periastron
1
0.8
0.6
0.4
0.2
0
-80
-60
-40
-20
0
20
40
60
80

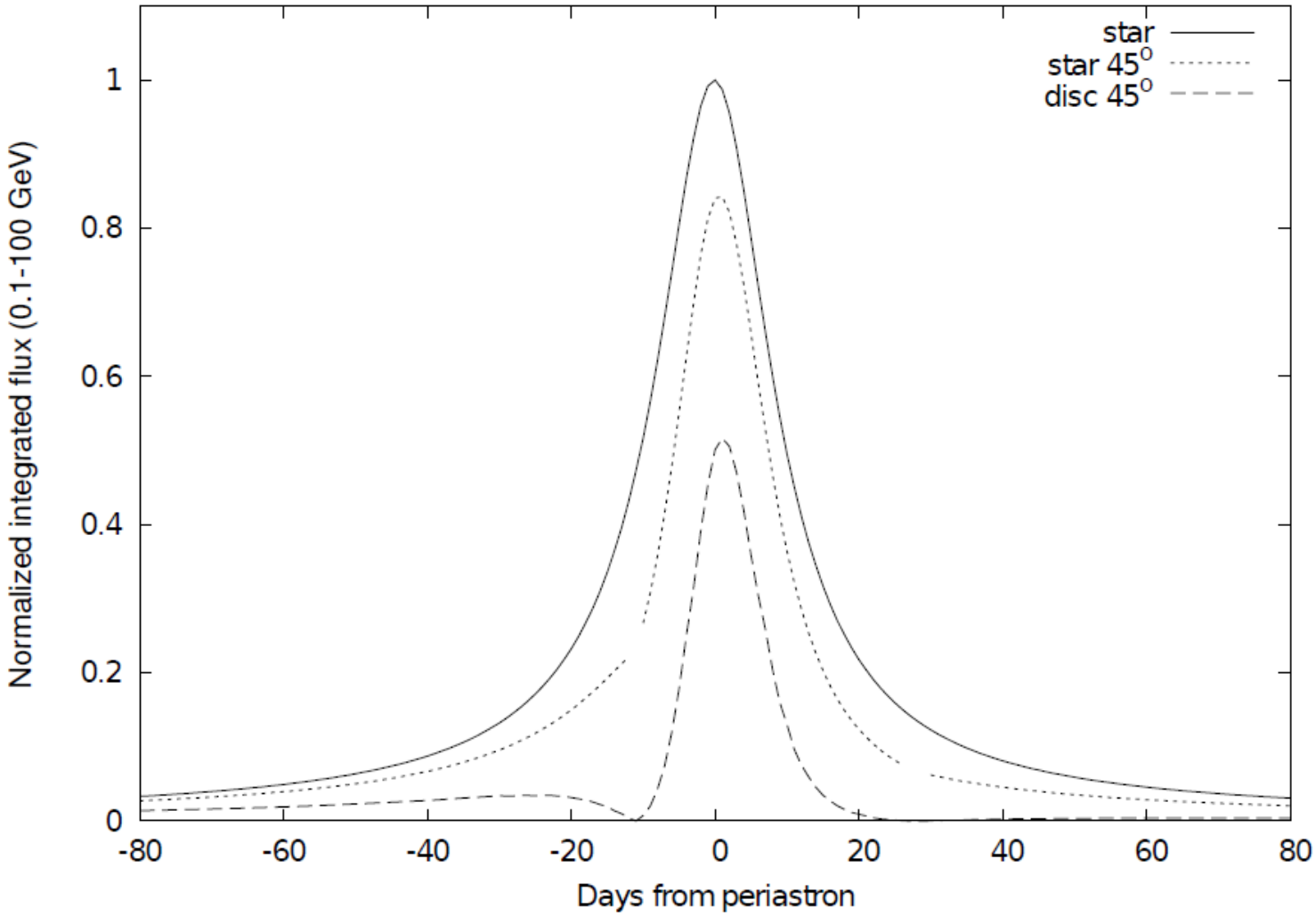
PSR B1259-63 – anisotropic scattering



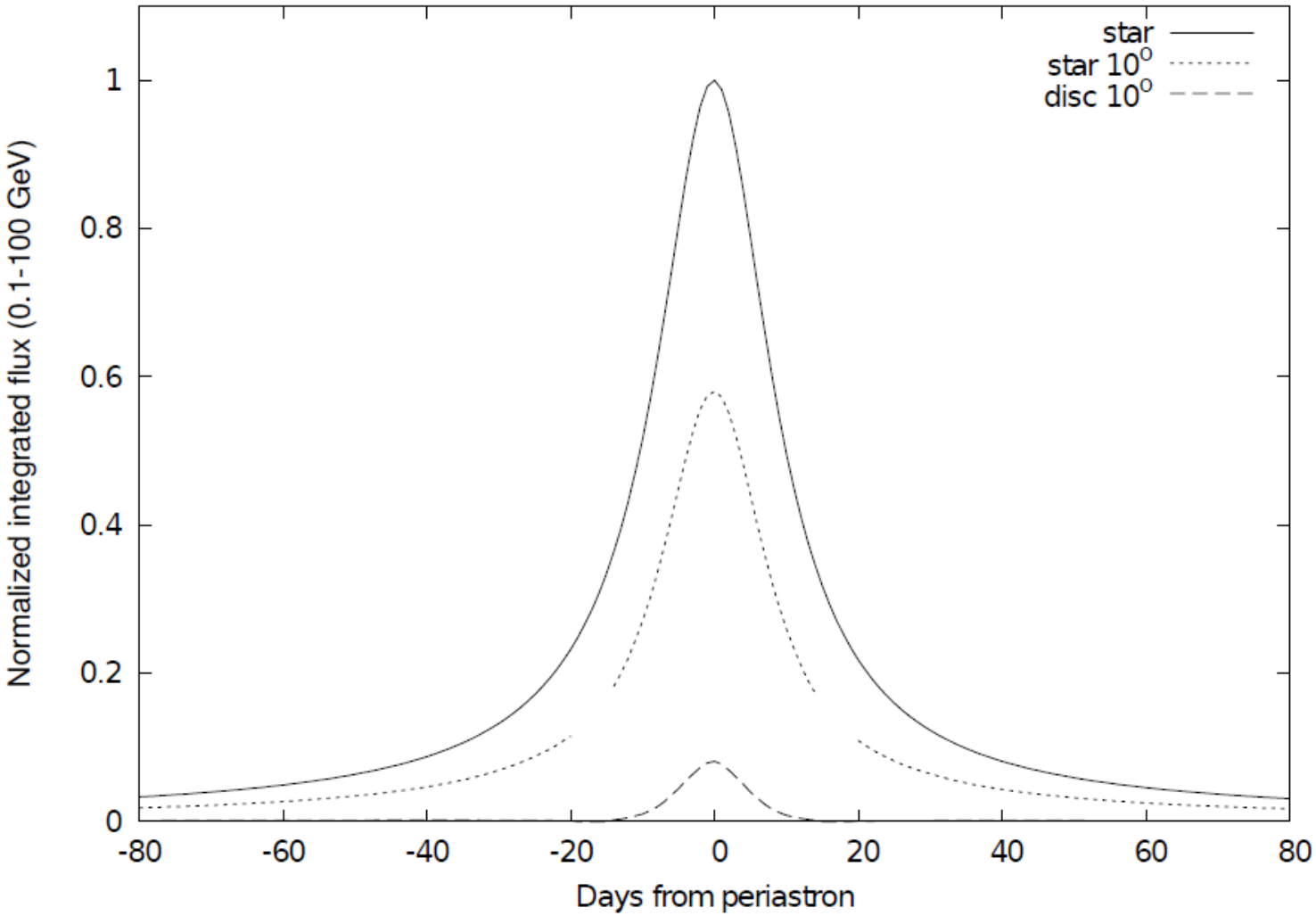
PSR B1259-63


star
star 90°
disc 90°
Normalized integrated flux (0.1-100 GeV)
Days from periastron
1
0.8
0.6
0.4
0.2
0
-80
-60
-40
-20
0
20
40
60
80

PSR B1259-63

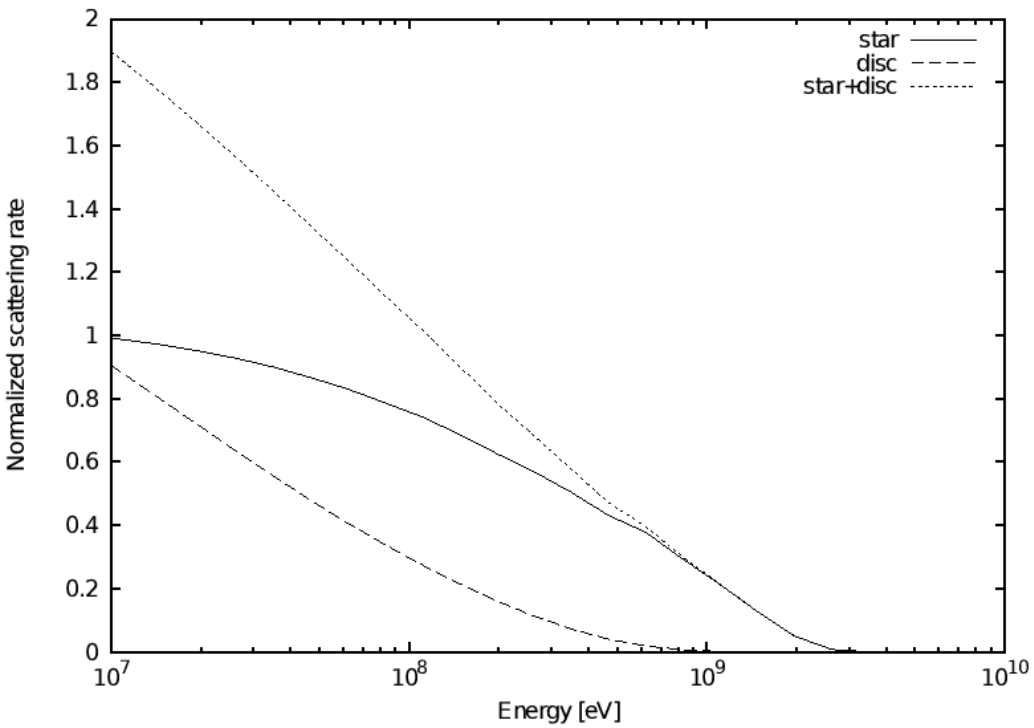

star
star 45°
disc 45°
Normalized integrated flux (0.1-100 GeV)
1
0.8
0.6
0.4
0.2
0
-80
-60
-40
-20
0
20
40
60
80
Days from periastron

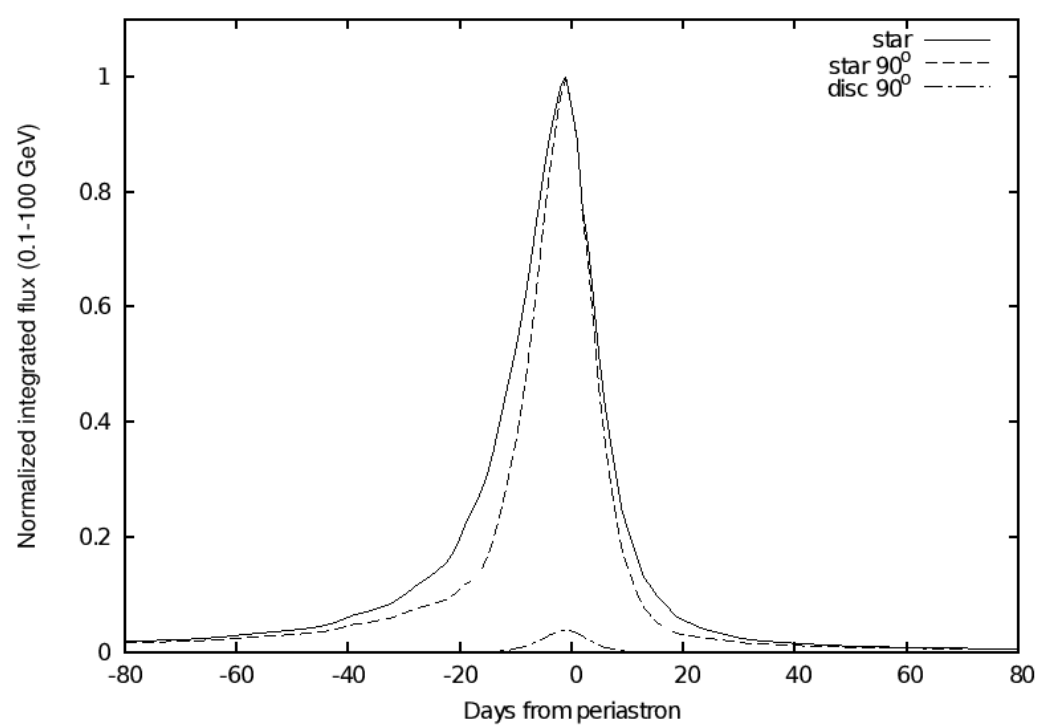
PSR B1259-63


star
star 10°
disc 10°
Normalized integrated flux (0.1-100 GeV)
Days from periastron
0
0.2
0.4
0.6
0.8
1
-80
-60
-40
-20
0
20
40
60
80

PSR B1259-63

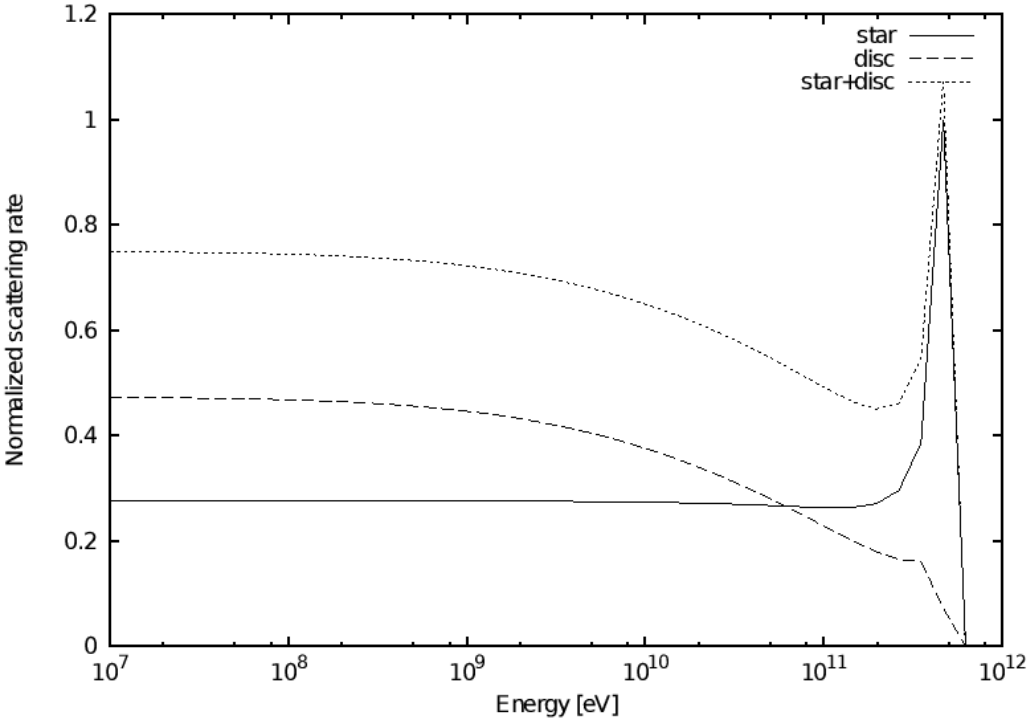
- Pre-shock electron distribution
  - $\gamma = 10^4$

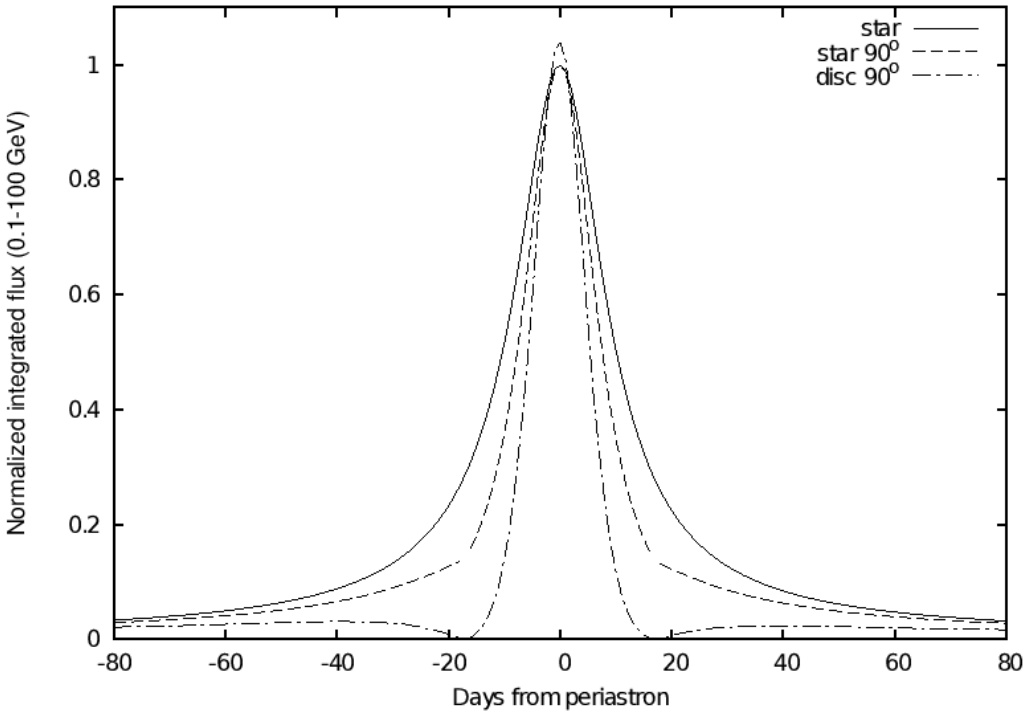




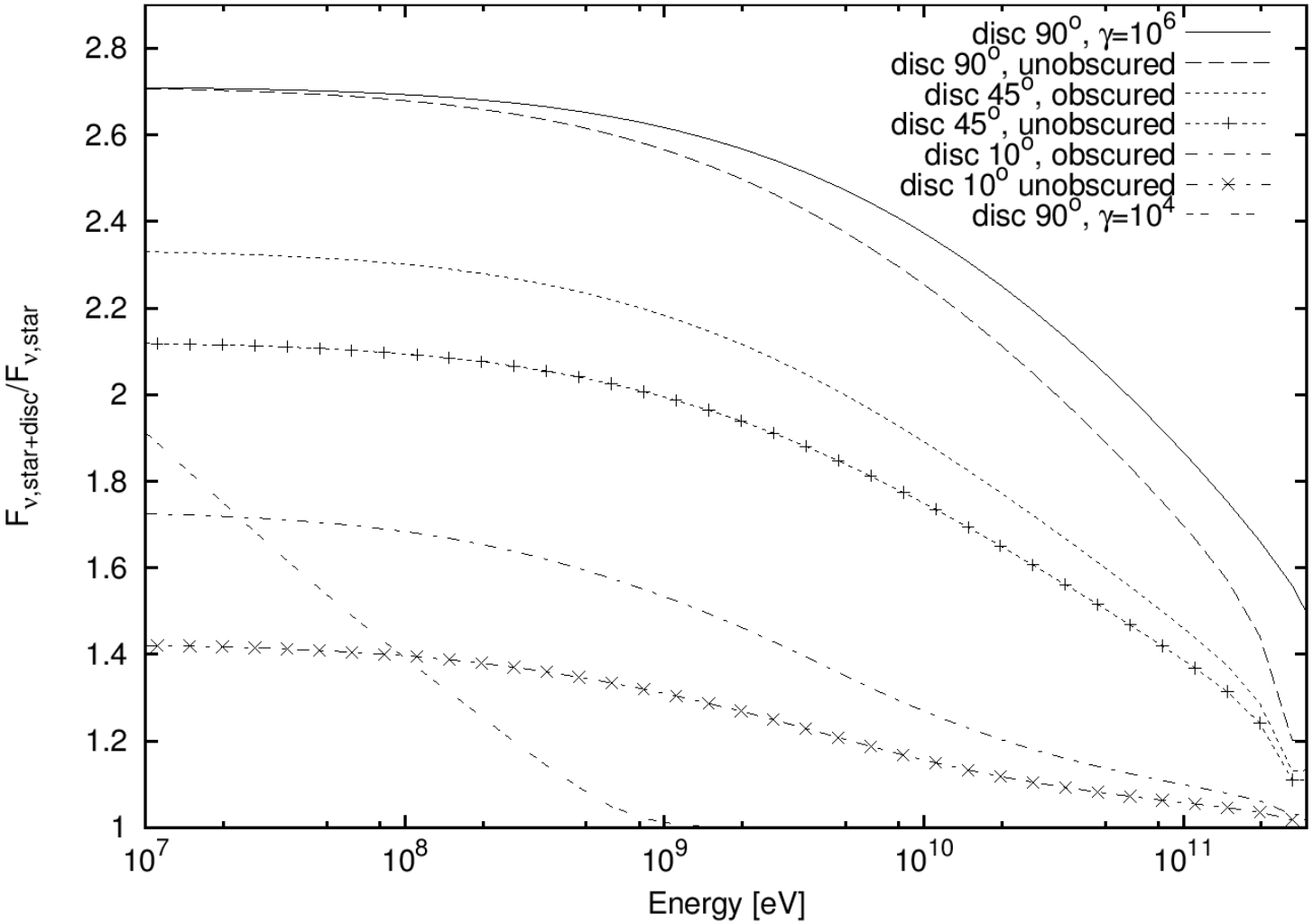
PSR B1259-63

- Pre-shock electron distribution
  - $\gamma = 10^6$



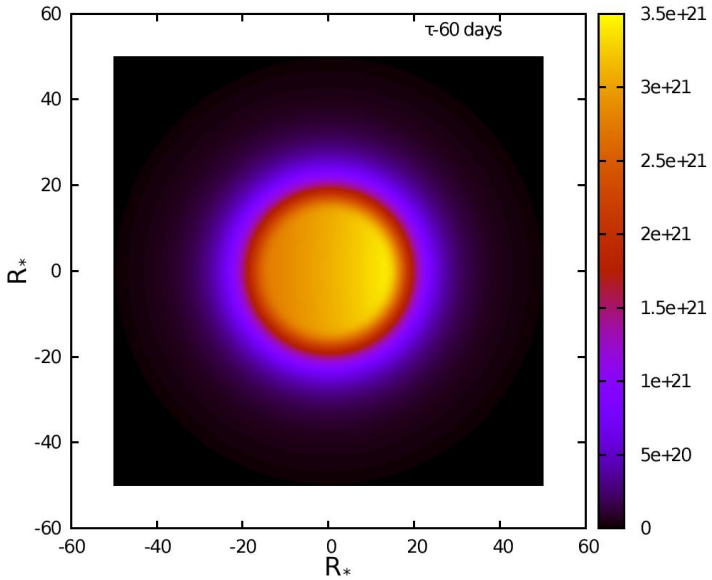


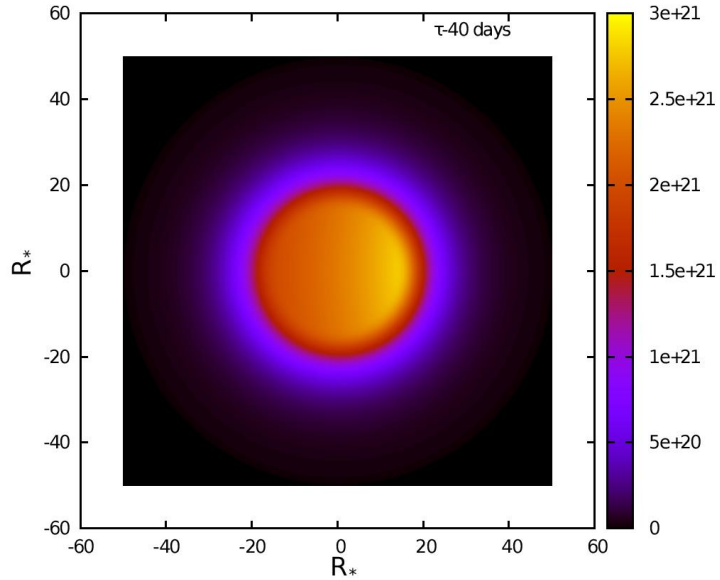
PSR B1259-63


disc 90°, γ=10^6
disc 90°, unobscured
disc 45°, obscured
disc 45°, unobscured
disc 10°, obscured
disc 10° unobscured
disc 90°, γ=10^4
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
10^7
10^8
10^9
10^10
10^11
Energy [eV]
F_ν,star+disc/F_ν,star

PSR B1259-63

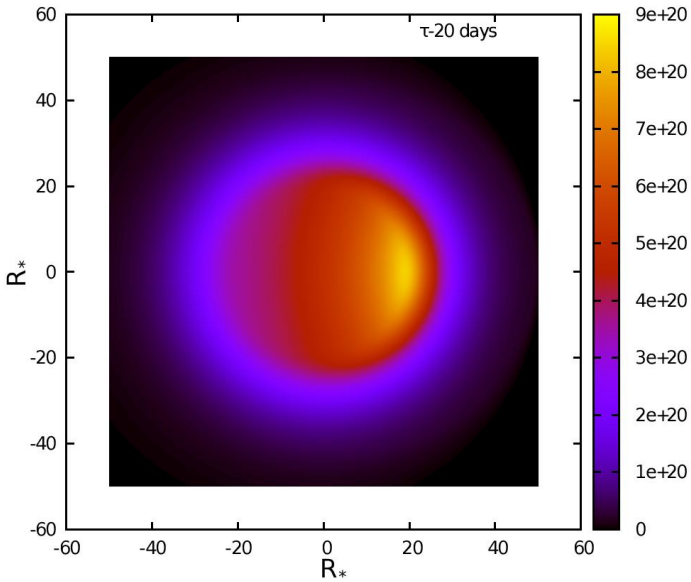
$\tau + 60\,\text{days}$

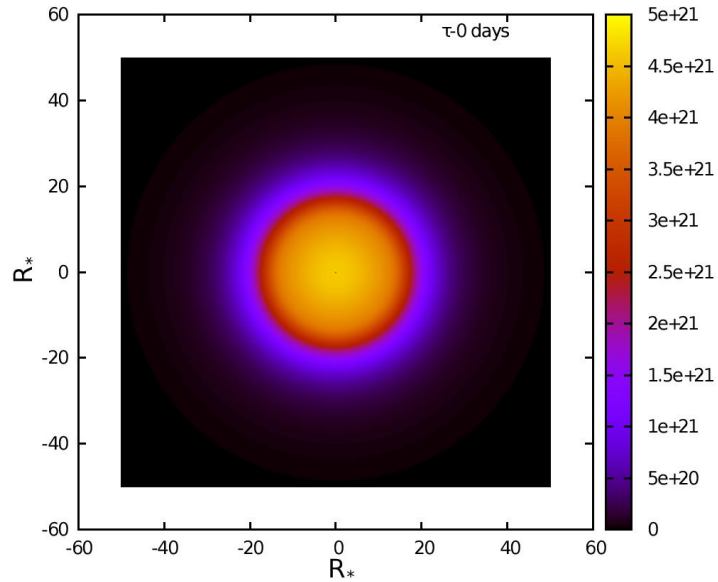




$\tau + 40\,\text{days}$

$\tau + 20\,\text{days}$





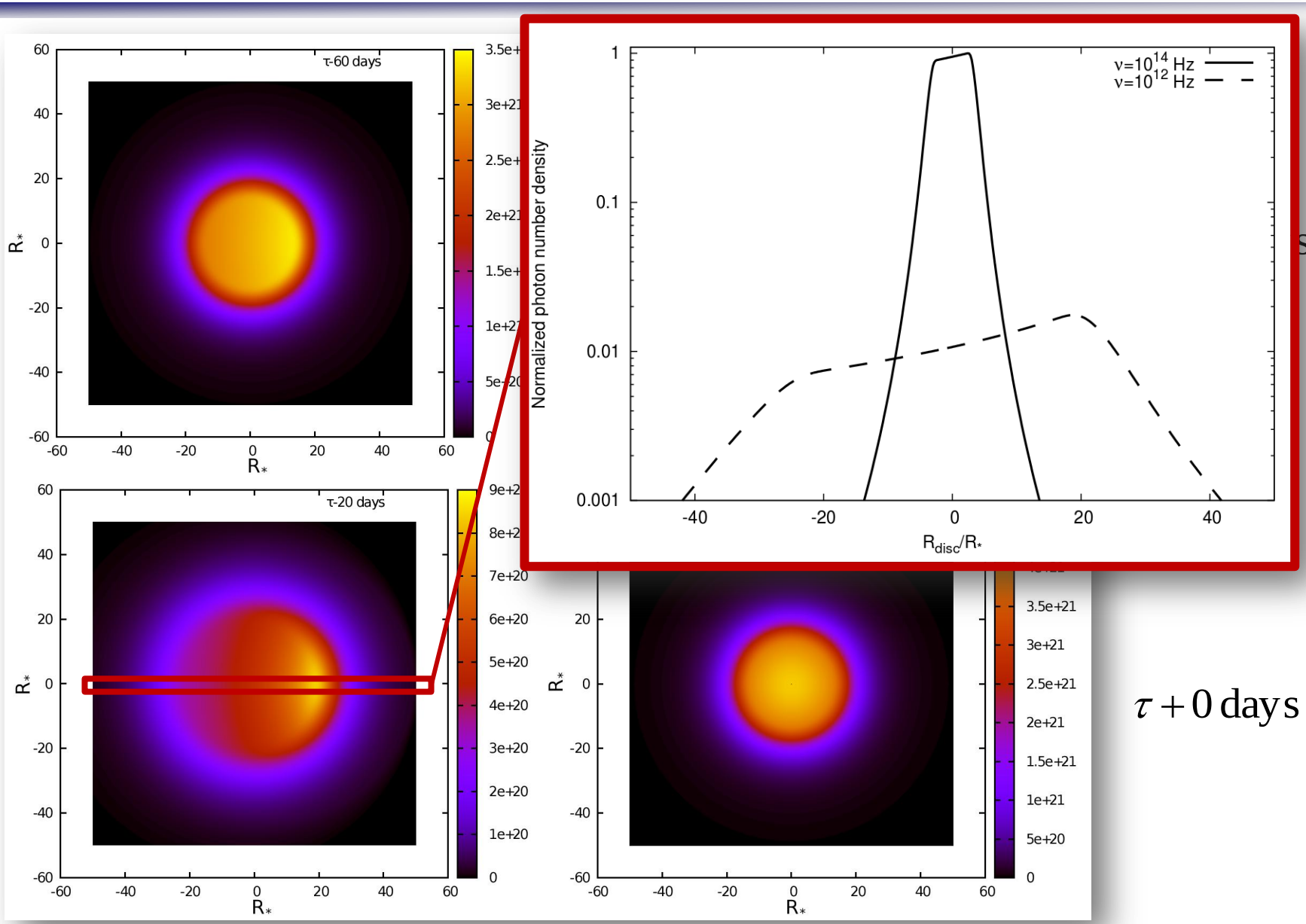
$\tau + 0\,\text{days}$

PSR B1259-63

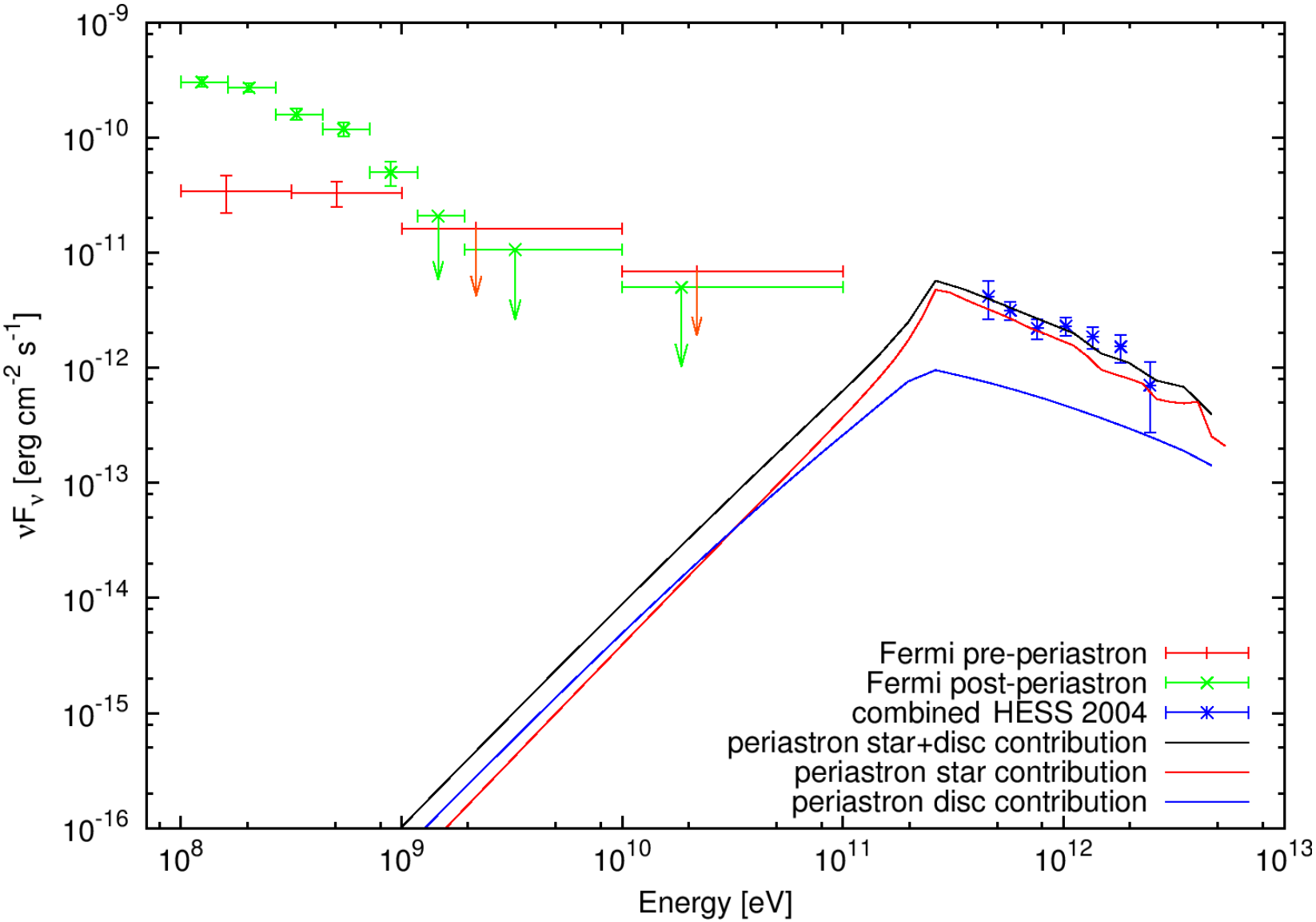
$\tau + 60$ days

$\tau + 20$ days

$\tau + 0$ days

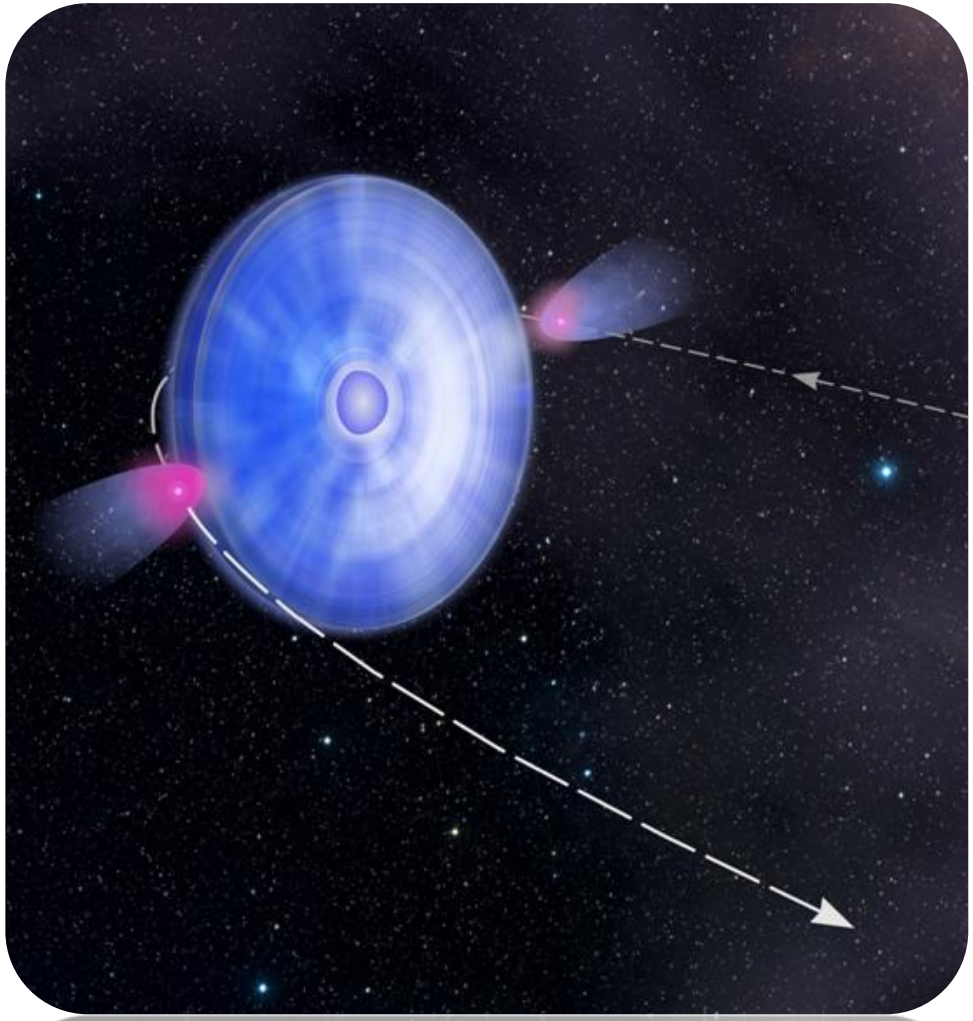


PSR B1259-63


10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
νF_ν [erg cm^{-2} s^{-1}]
10^{8}
10^{9}
10^{10}
10^{11}
10^{12}
10^{13}
Energy [eV]
Fermi pre-periastron
Fermi post-periastron
combined HESS 2004
periastron star+disc contribution
periastron star contribution
periastron disc contribution

Conclusion

- Observations of PSR B1259-63 show a large bright circumstellar disc around the star
- This flux from the disc has been modelled using the COG method
- This COG method as been modified to account for the IR emission as seen from the pulsar
- Anisotropic and isotropic IC scattering models show that the IR excess could increase the flux by a factor >2 at GeV energies,
- However the maximum contribution occurs at periastron and not near the disc crossing phase.
- The degree of shock heating is not clear, and additional observations near the disc crossing epochs is required.



Thank you

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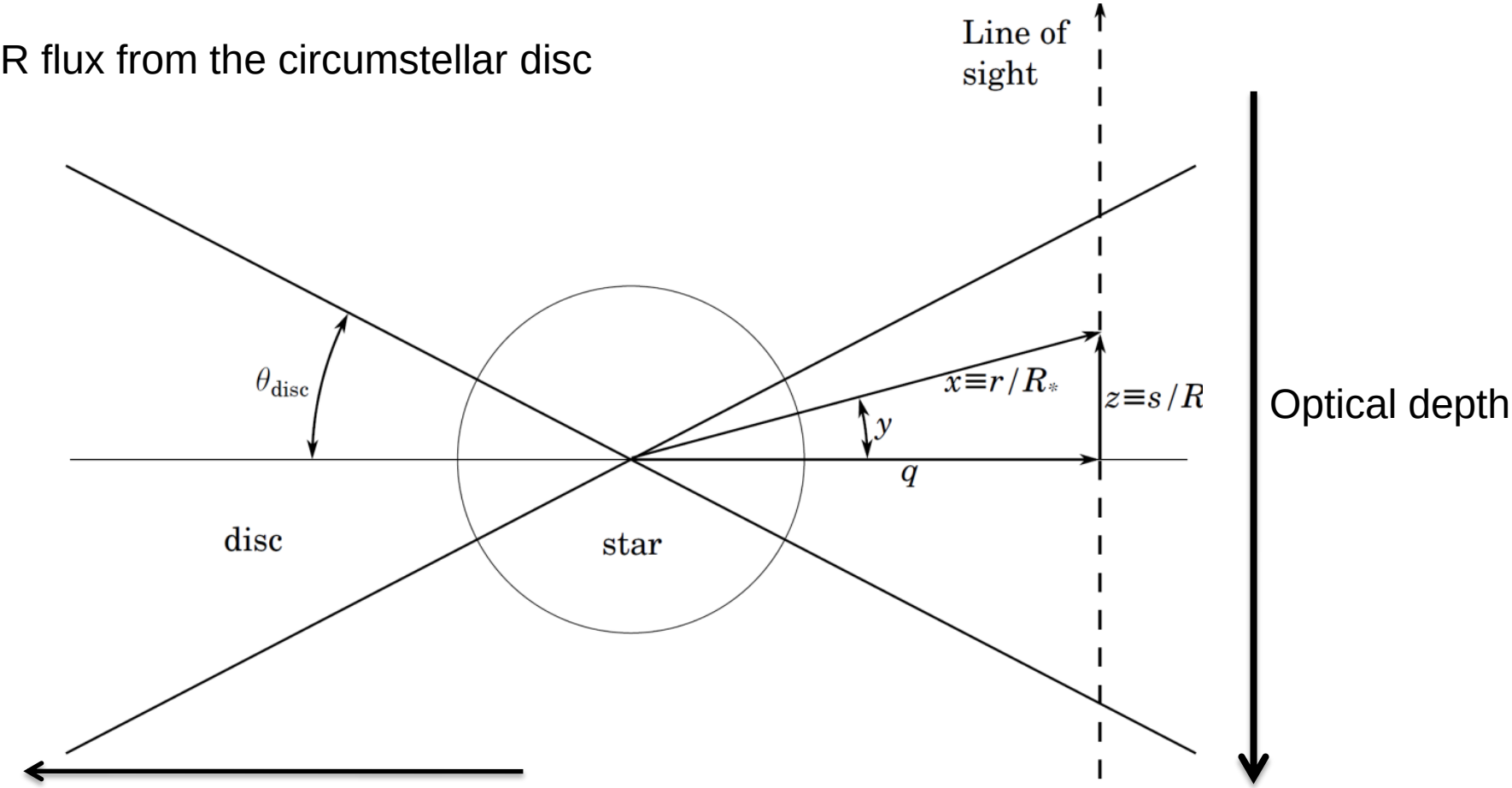
Additional slides

Be stars – COG method

Curve of Growth method (Waters 1986)

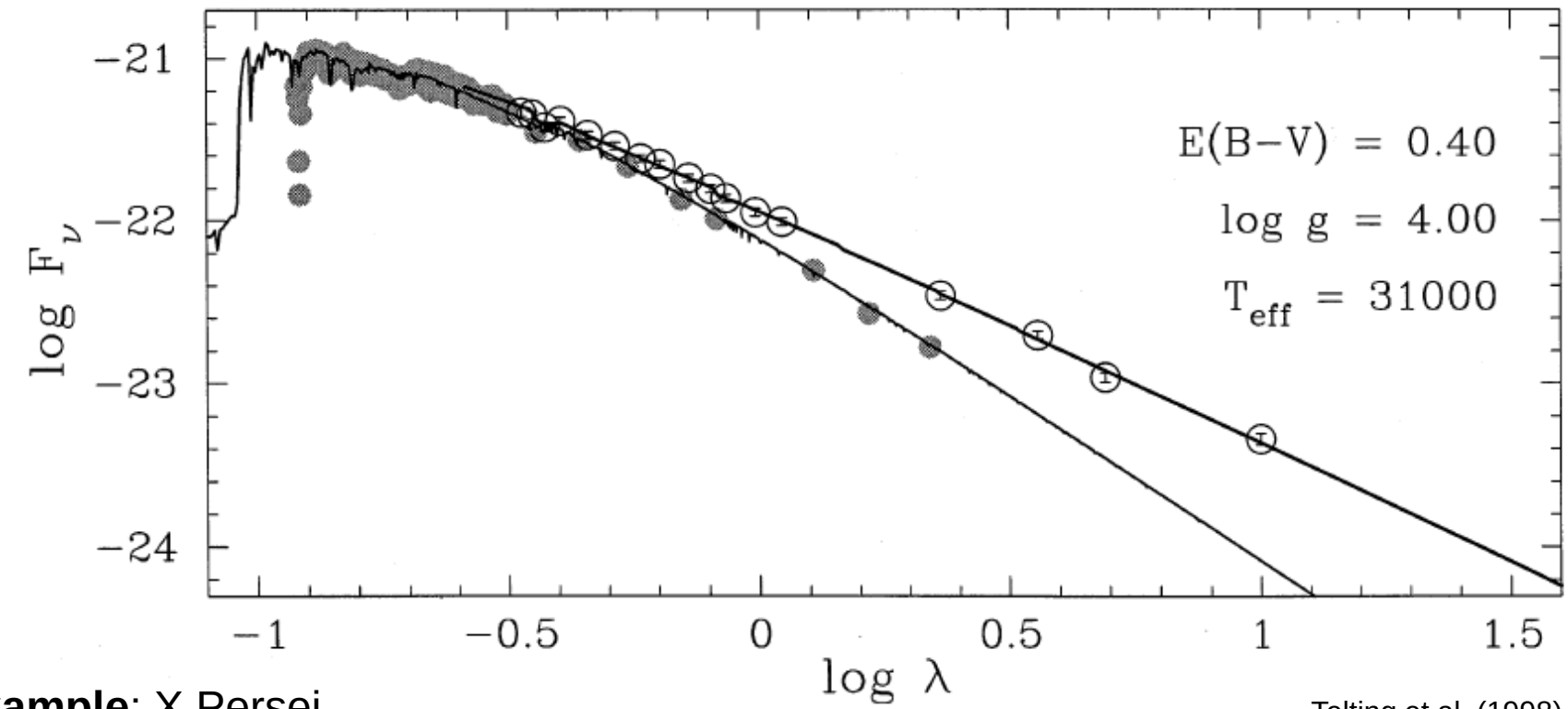
•Model the IR flux from the circumstellar disc



$$\rho = \rho_0 \left(\frac{r}{R_*}\right)^{-n}$$

Isothermal disc

Be stars – COG method



Telting et al. (1998)

Example: X Persei

- n = 4.73
- log X_* = 8.99

Fit with Levenberg-Marquardt method

- R_{disc} = 5.00
- θ_{disc} = 5°
- T_{eff} = 31000 K

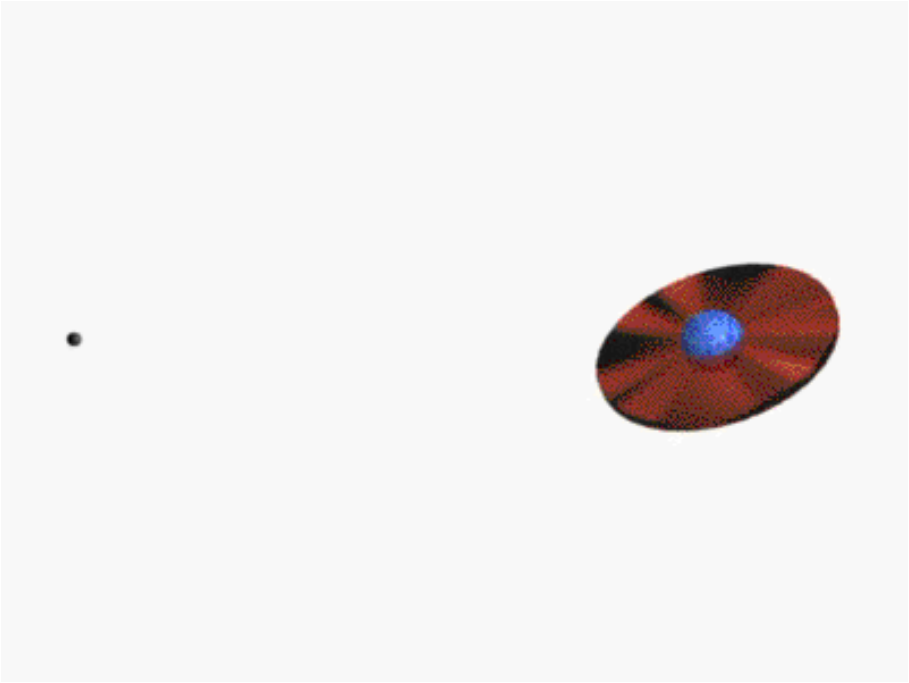
Held constant

Be stars – COG method

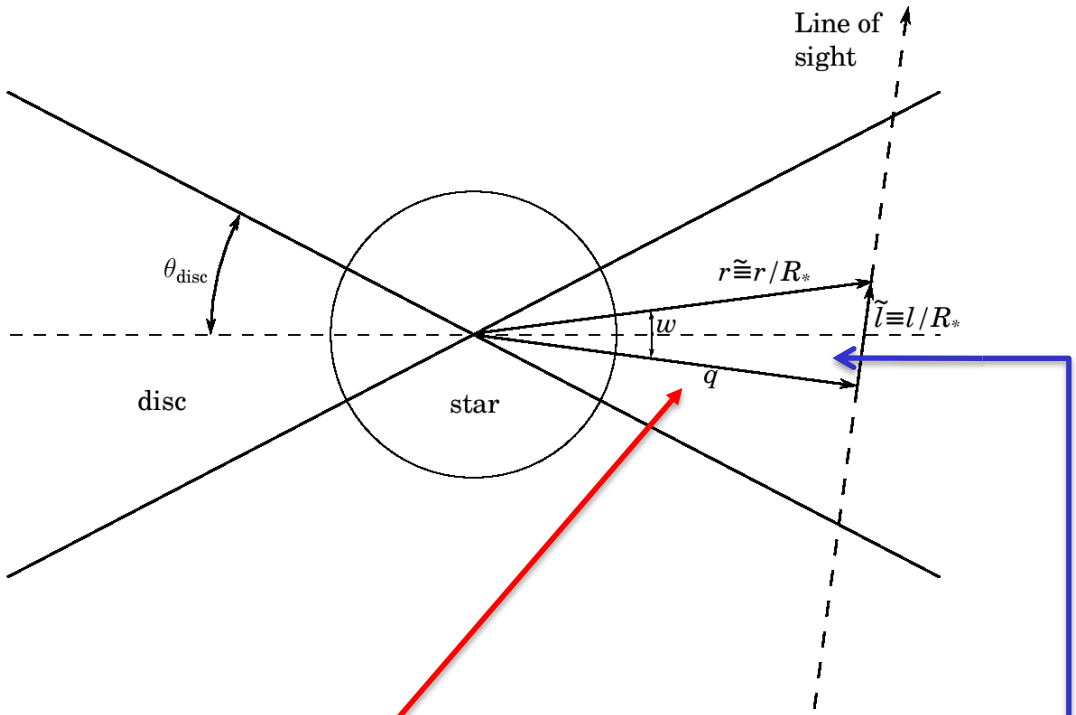
- Waters (1986) showed that the observed flux does not change dramatically with inclination, particularly for low inclinations

- However, from the pulsars point-of-view, the size and orientation will change dramatically around periastron

- A modified COG method must be implemented determined the IR excess as observed from the pulsar.



Be stars – modified COG method



$$\tau_\nu = E_{\nu,\mathrm{d}} q^{-2n+1} \int_w \cos^{2n-2} w \, dw,$$

$$I_\nu(q) = B_\nu(T) \left(1 - \mathrm{e}^{-\tau_{\max}}\right)$$

Inverse Compton scattering

The total scattering rate is

$$\frac{dN_{\gamma,\epsilon_0}}{dt\,d\epsilon_1} = K_0 \frac{\pi r_e^2 c(1-\beta\cos\theta_0)}{\gamma(1-\beta x_0)} \left[1+\mu_0^2+\left(\frac{\gamma\epsilon_1}{m_\mathrm{e}c^2}\right)^2 \frac{(1-\beta x_0)^2(1-\mu_0)^2}{1-\frac{\gamma\epsilon_1}{m_\mathrm{e}c^2}(1-\beta x_0)(1-\mu_0)}\right]$$

where

$$\mu_0 = \left(\frac{x_0-\beta}{1-\beta x_0}\right) C_{\theta_0} \qquad C_{\theta_0} = \frac{\cos\theta_0-\beta}{1-\beta\cos\theta_0}$$

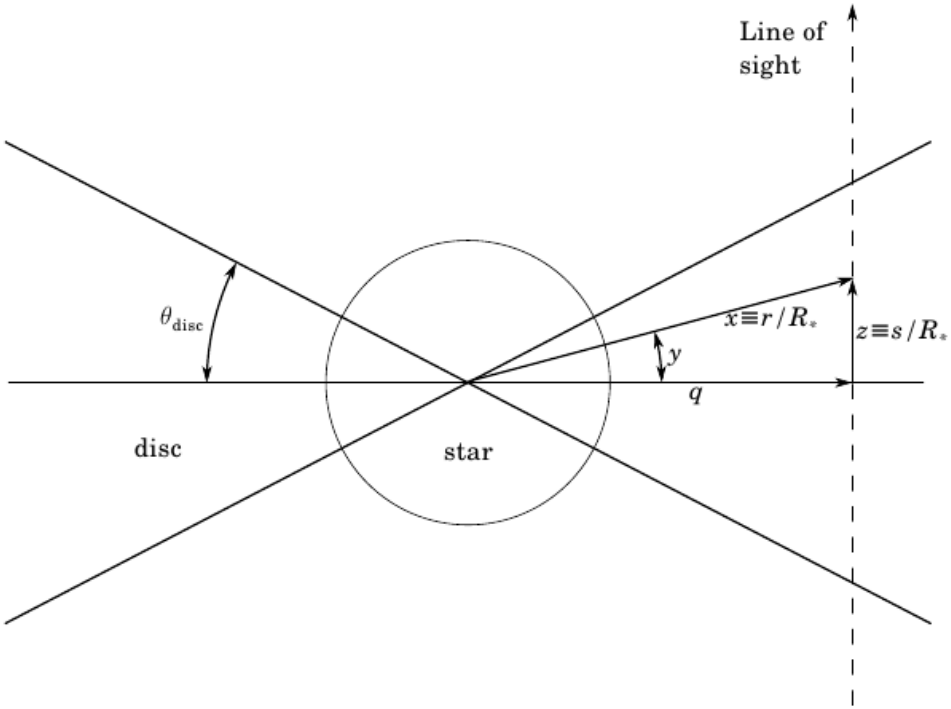
$$x_0 = \frac{1-\frac{\epsilon_0}{\epsilon_1}(1-\beta\cos\theta_0)+\frac{\gamma\epsilon_0}{m_\mathrm{e}c^2}(1-\beta\cos\theta_0)(1+\beta C_{\theta_0})}{\beta+\frac{\gamma\epsilon_0}{m_\mathrm{e}c^2}(1-\beta\cos\theta_0)(\beta+C_{\theta_0})}$$

$$K_0 = \frac{\left(1-\frac{\gamma\epsilon_1}{m_\mathrm{e}c^2}\left[1+\beta C_{\theta_0}-(\beta+C_{\theta_0})\,x_0\right]\right)^2}{\left|\beta\gamma\epsilon_1+\frac{\epsilon_1^2}{m_\mathrm{e}c^2}C_{\theta_0}\right|}$$

Be stars – COG method

- Waters (1986):
- The intensity along any line-of-sight is then

$$
\begin{aligned}
I_\nu(q) &= \int_0^{\tau_{\max}(q)} B(\nu,T)\mathrm{e}^{-\tau_\nu}\, d\tau \\
&= B(\nu,T)\left(1-\mathrm{e}^{-\tau_{\max}(q)}\right),
\end{aligned}
$$



- The optical depth through the disc is given by

$$\tau_\nu = E_{\nu,d}\, q^{-2n+1} \int_y \cos^{2n-2} y\, dy$$

where $E_{\nu,d} = X_* X_\lambda$

$$X_\lambda = \lambda^2 \left\{ \left(1-\mathrm{e}^{-h\nu/kT}\right) / \left(h\nu/kT\right) \right\} \left\{ g(\nu,T) + b(\nu,T) \right\},$$

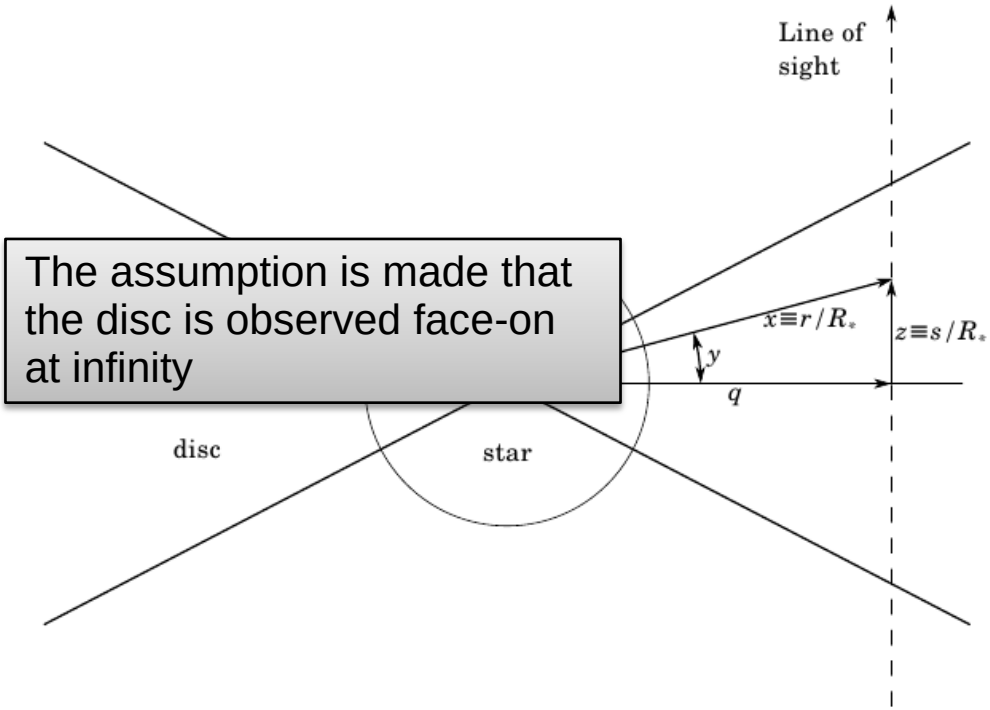
$$
\begin{aligned}
X_{*,d} &= \left[3.692\times 10^8 \frac{h}{c^2 k} m_{\mathrm{p}}^{-2} R_\odot\right] \bar{z}^2 T^{-3/2} \mu^{-2} \varpi \rho_0^2 \frac{R_*}{R_\odot} \\
&= 4.923\times 10^{35} \bar{z}^2 T^{-3/2} \mu^{-2} \varpi \rho_0^2 \frac{R_*}{R_\odot},
\end{aligned}
$$

Be stars – COG method

- The observed flux from a Be star is then given by

$$
\begin{aligned}
F &= \int I_\nu(q)\cos\theta\, d\Omega \\
&= \int_0^{2\pi}\int_\theta I_\nu(q)\cos\theta\sin\theta\, d\theta d\phi \\
&= 2\pi\int_q I_\nu(q)(1)\left(\frac{qR_*}{D}\right)\left(\frac{R_*}{D}\right)\, dq \\
&= \left(\frac{R_*}{D}\right)^2\int_0^{R_{\rm disc}/R_*} 2\pi q\, I_\nu(q)\, dq,
\end{aligned}
$$

The assumption is made that the disc is observed face-on at infinity



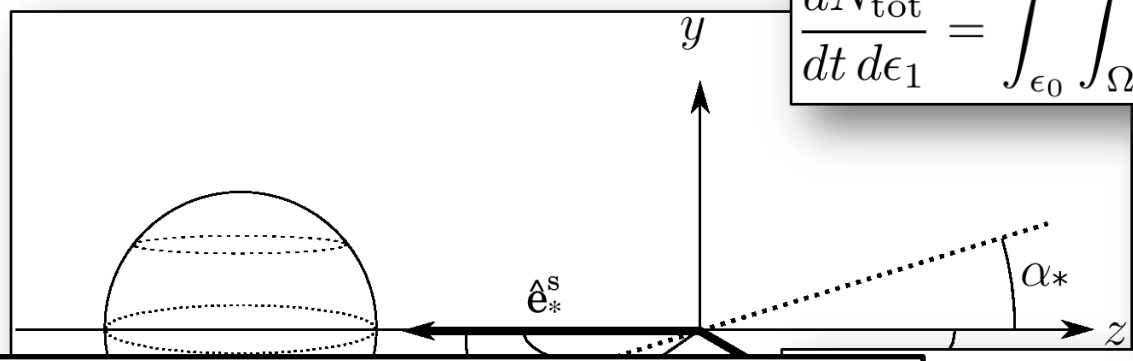
The model is fitted to the observed flux by fitting the five parameters

- n
- X_*
- $R_{\rm disc}$
- $\theta_{\rm disc}$
- $T_{\rm eff}$

PSR B1259-63 – anisotropic scattering

- The anisotropic approximation takes into account the geometry of the star and the circumstellar disc

$$\frac{dN_{\rm tot}}{dt\,d\epsilon_1} = \int_{\epsilon_0}\int_{\Omega}\int_{\gamma} n_{\rm e}(\gamma)\,n_{\rm ph}(\epsilon_0)\,\frac{dN_{\gamma,\epsilon}}{dt\,d\epsilon_1}\cos\vartheta\,d\gamma\,d\epsilon_0\,d\Omega$$



$$\Omega = \int_0^{2\pi}\int_0^{\alpha_*} \sin\theta\,d\theta d\phi$$

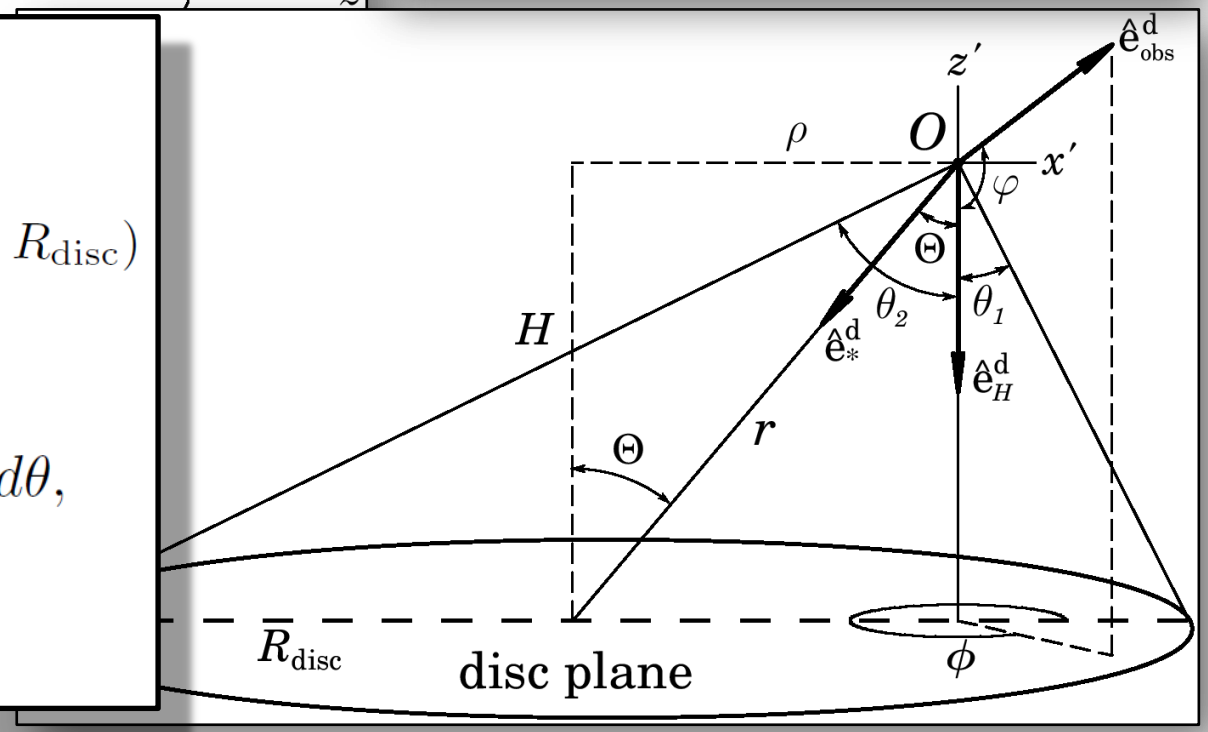
$$\Omega = \Omega_1 + \Omega_2$$

$$\Omega_1 = \int_0^{2\pi}\int_0^{\theta_1} \sin\theta\,d\theta d\phi, \quad (\rho < R_{\rm disc})$$

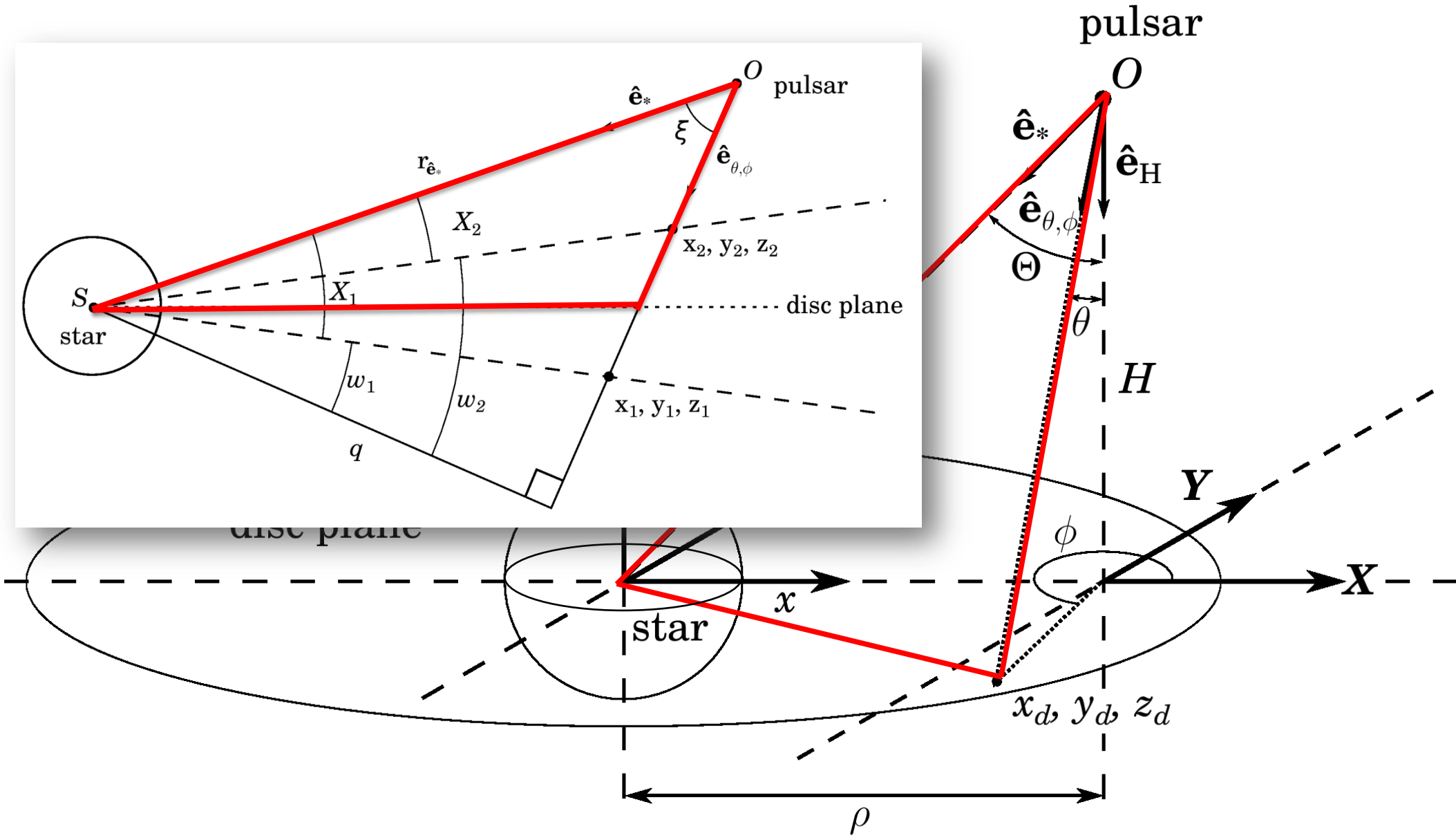
$$= 0, \quad (\rho \geq R_{\rm disc}),$$

$$\Omega_2 = \int_{\theta_1}^{\theta_2}\int_{\cos^{-1}(\tau_\phi)}^{2\pi-\cos^{-1}(\tau_\phi)} \sin\theta\,d\phi d\theta,$$

$$\tau_\phi(\theta) = \frac{R_{\rm disc}^2 - \rho^2 - H^2\tan^2\theta}{2\rho H\tan\theta}$$



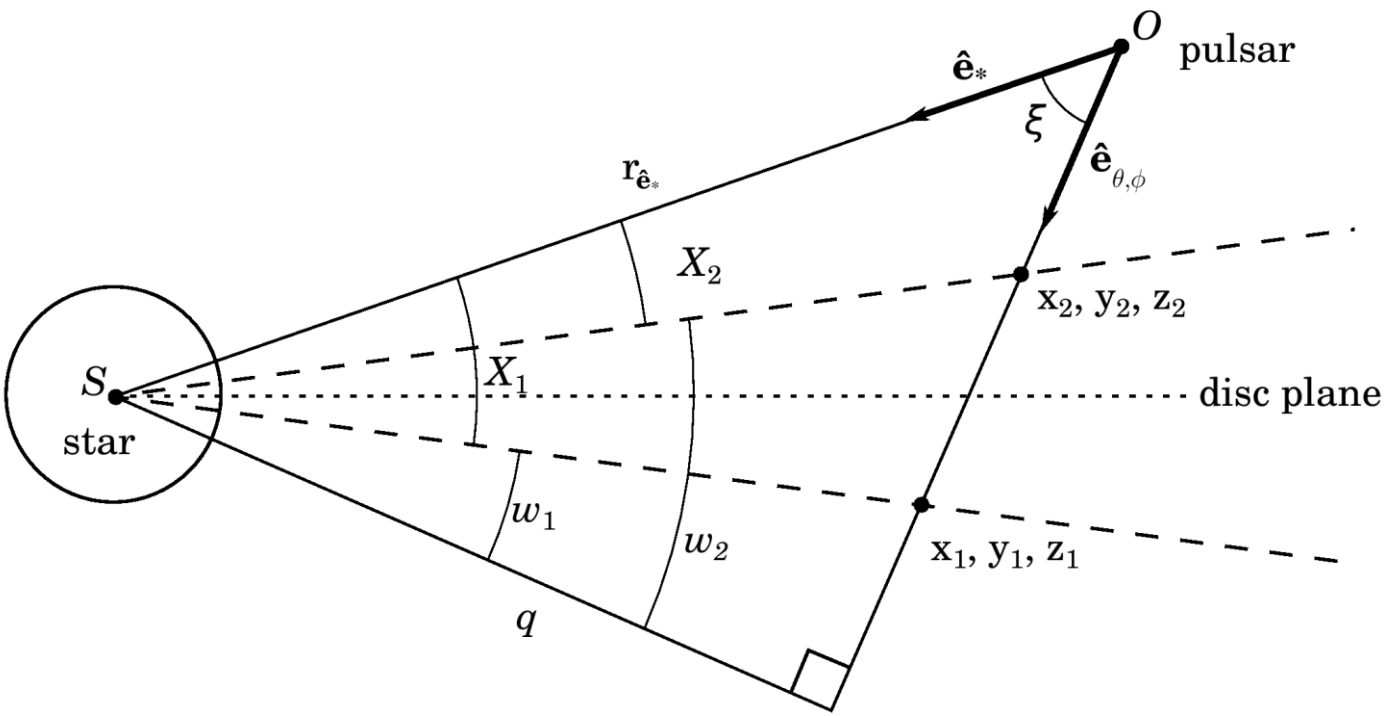
Be stars – modified COG method



Be stars – modified COG method

- The impact parameter is determined by

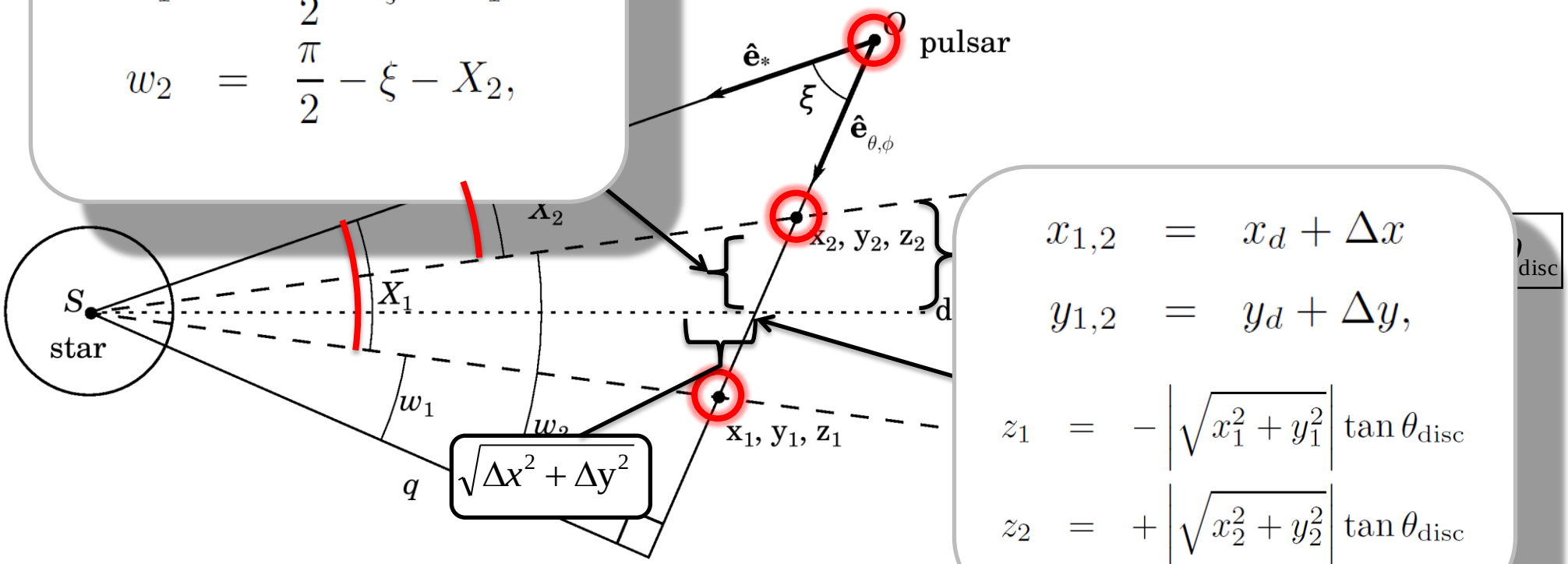
$$q = r_{\hat{\mathbf{e}}_*} \sin \xi,$$



Be stars – modified COG method

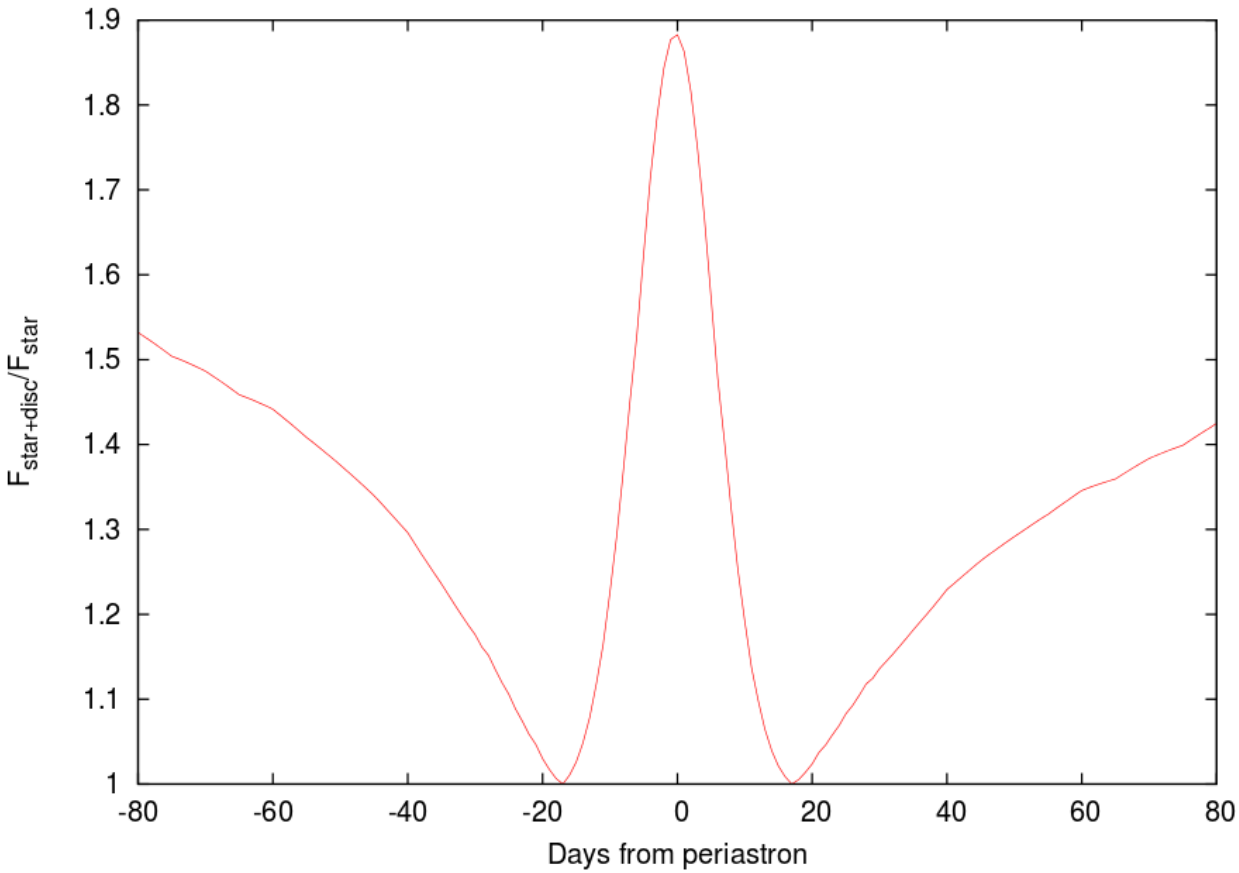
- The limits on *w* are determined by the positions x_1,y_1,z_1 & x_2,y_2,z_2
- The position of the disc intercepts are found by solving for the position where $h_d = h_l$

$$w_1 = \frac{\pi}{2} - \xi - X_1$$
$$w_2 = \frac{\pi}{2} - \xi - X_2,$$



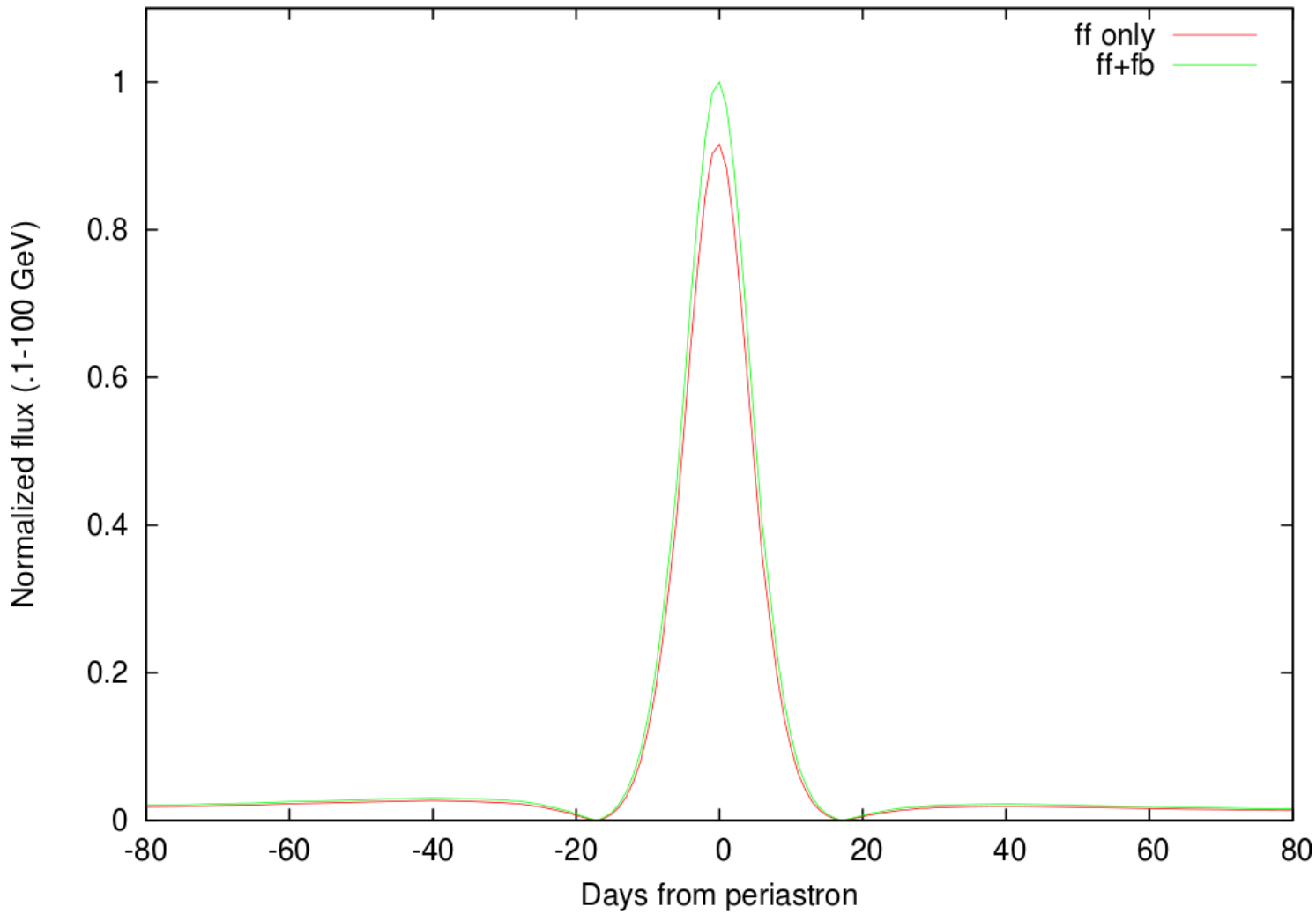
$$x_{1,2} = x_d + \Delta x$$
$$y_{1,2} = y_d + \Delta y,$$
$$z_1 = -\left|\sqrt{x_1^2 + y_1^2}\right| \tan\theta_{\rm disc}$$
$$z_2 = +\left|\sqrt{x_2^2 + y_2^2}\right| \tan\theta_{\rm disc}$$

AIC model comparisons



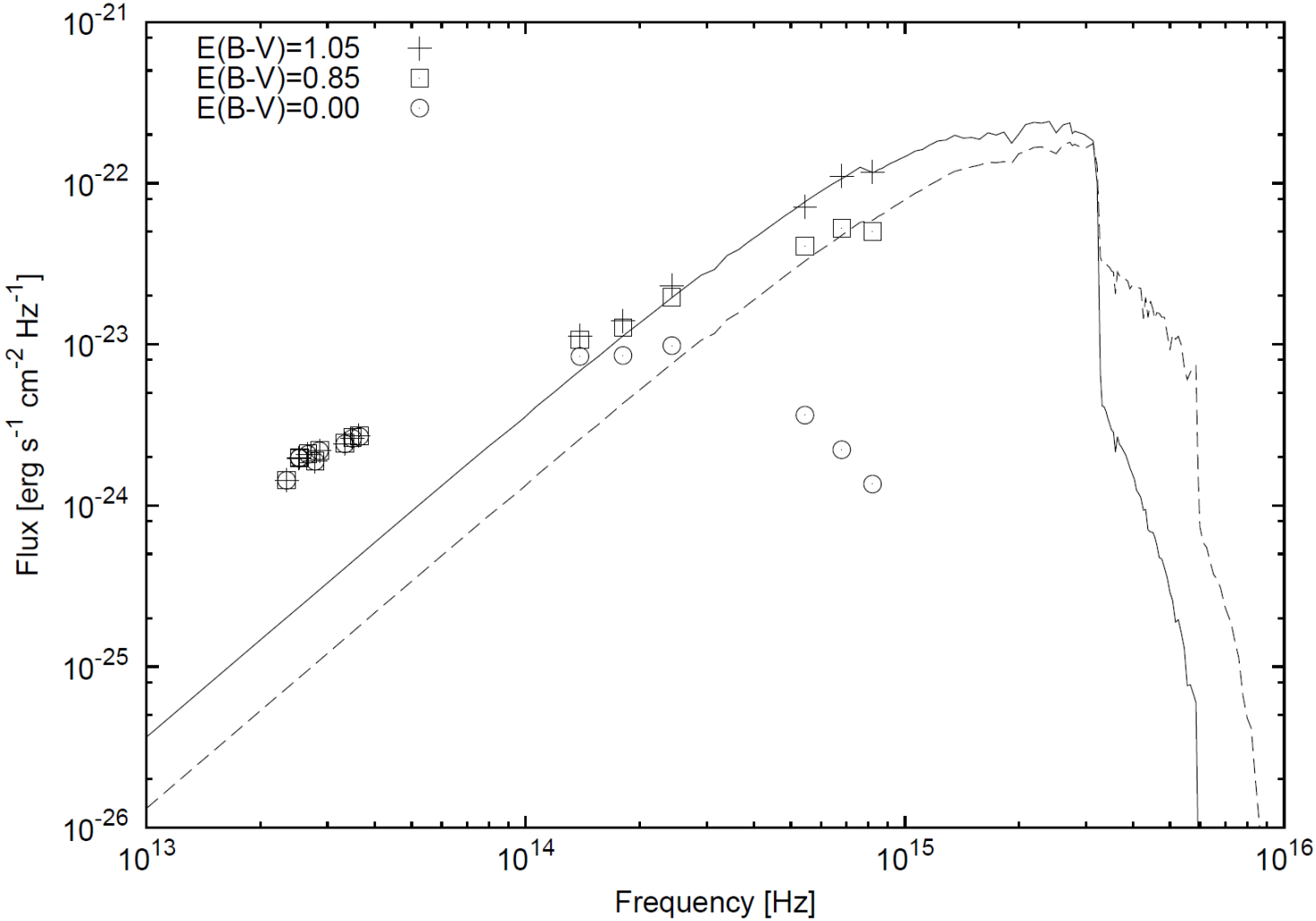
Flux ratio (F_{total}/F_{star}) for days from periastron

AIC model comparisons

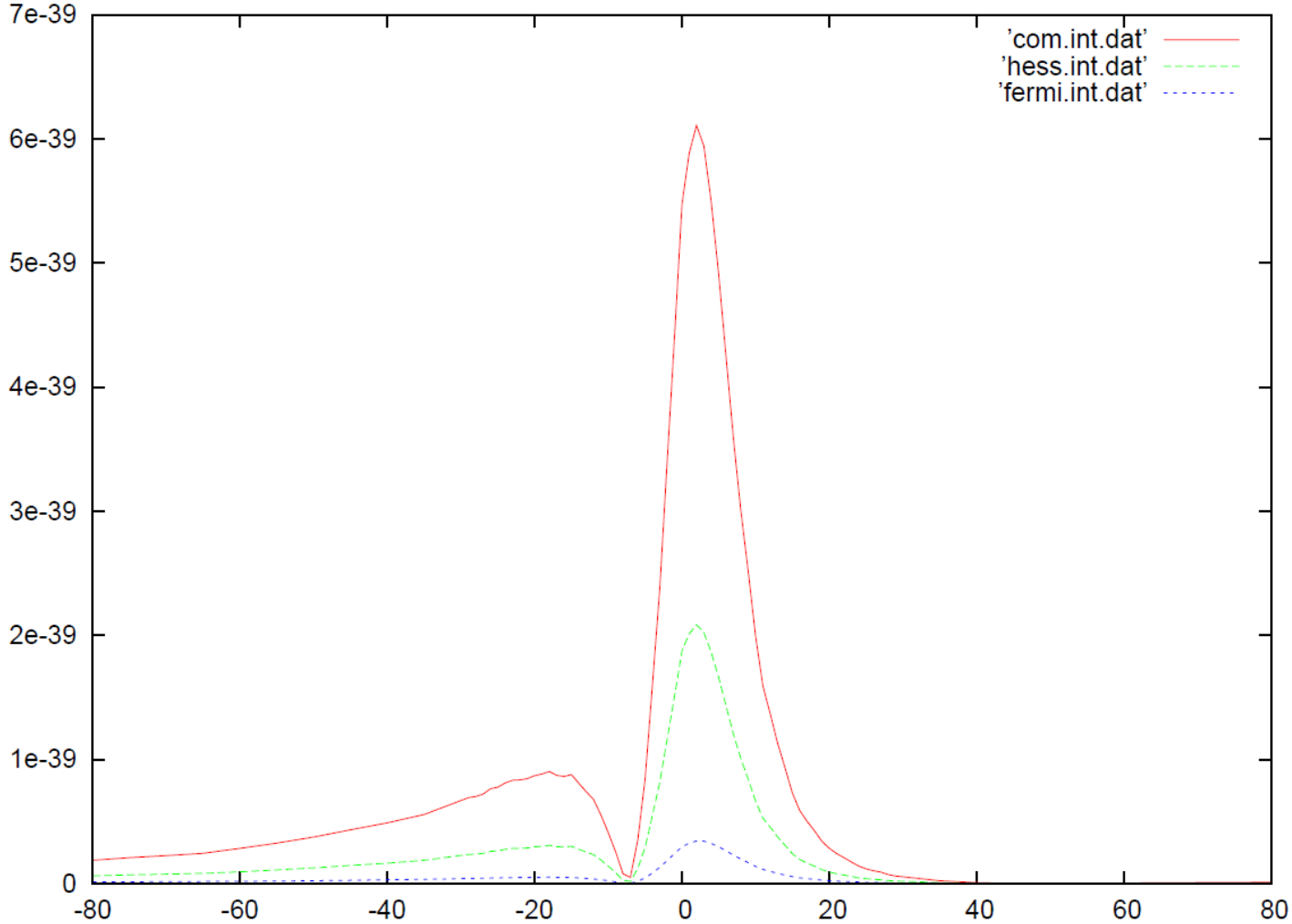


Comparison between the effect of the free-free vs free-free+free-bound fit on the AIC scattering rate

PSR B1259-63 – Comparison between the COG fits



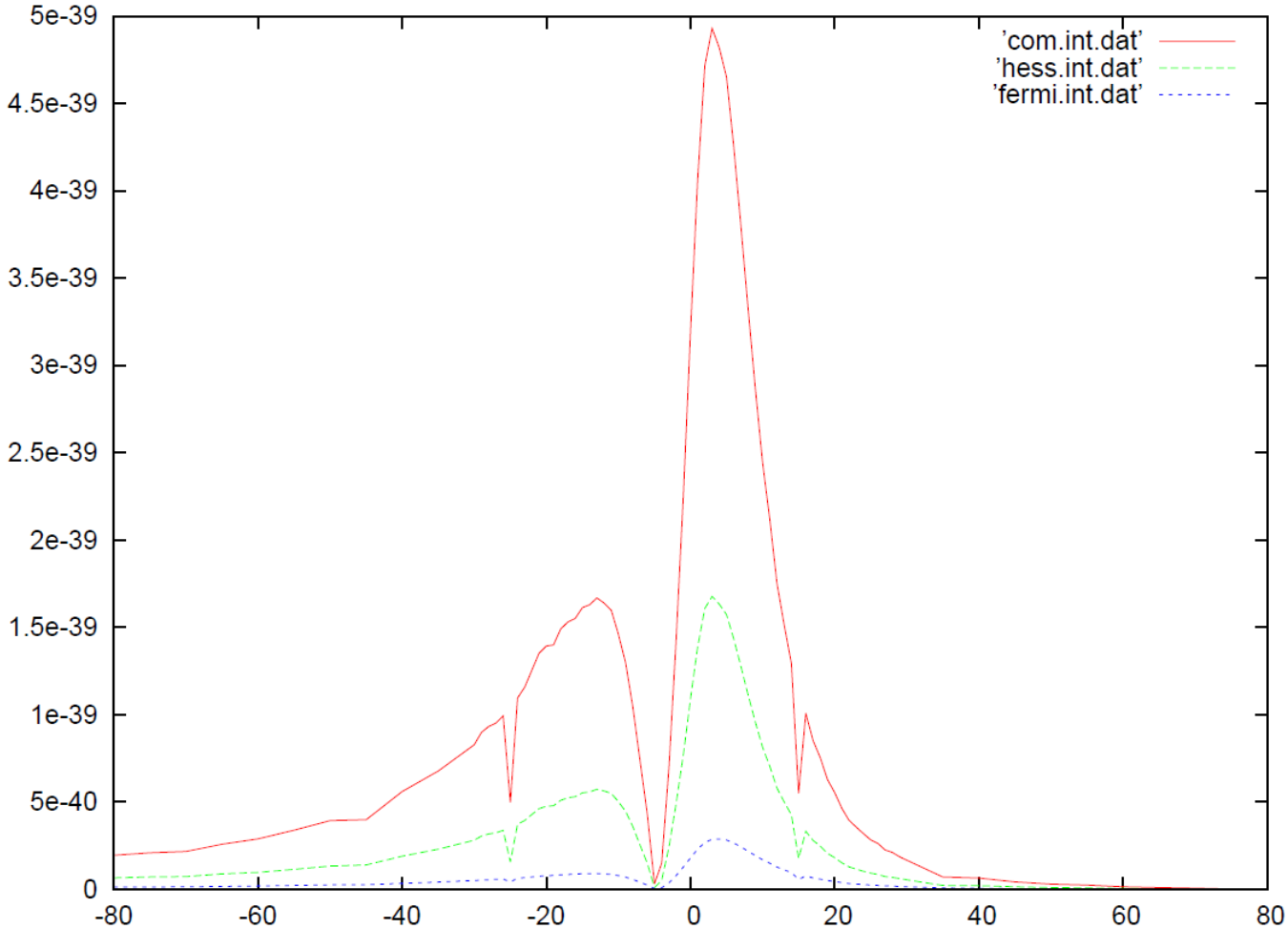
PSR B1259-63 – Other disc orientations



$$i = 90^\circ$$

$$\theta_{\mathrm{disc}} = 36^\circ$$

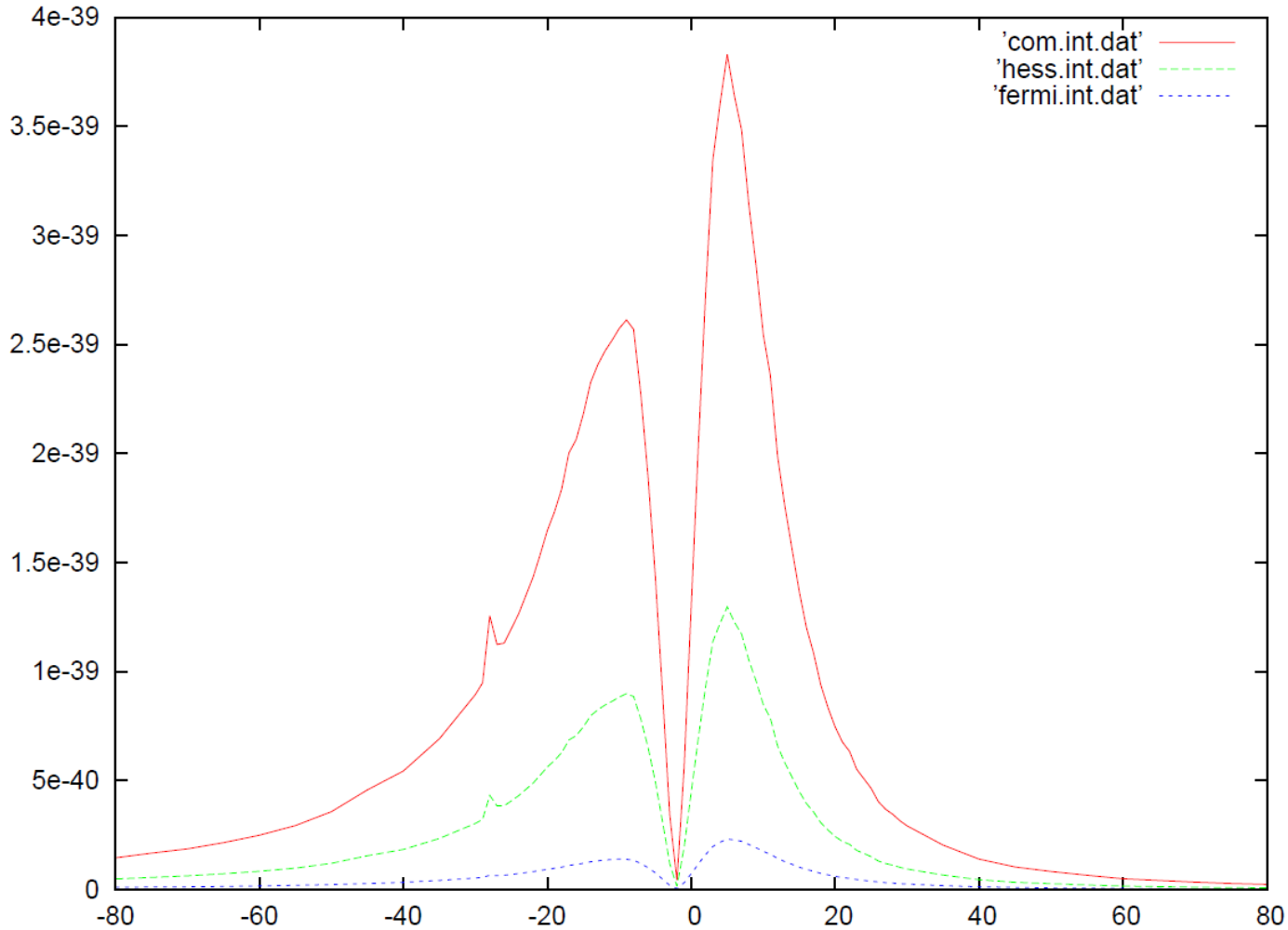
PSR B1259-63 – Other disc orientations



$$i = 90^{\circ}$$

$$\theta_{\mathrm{disc}} = 54^{\circ}$$

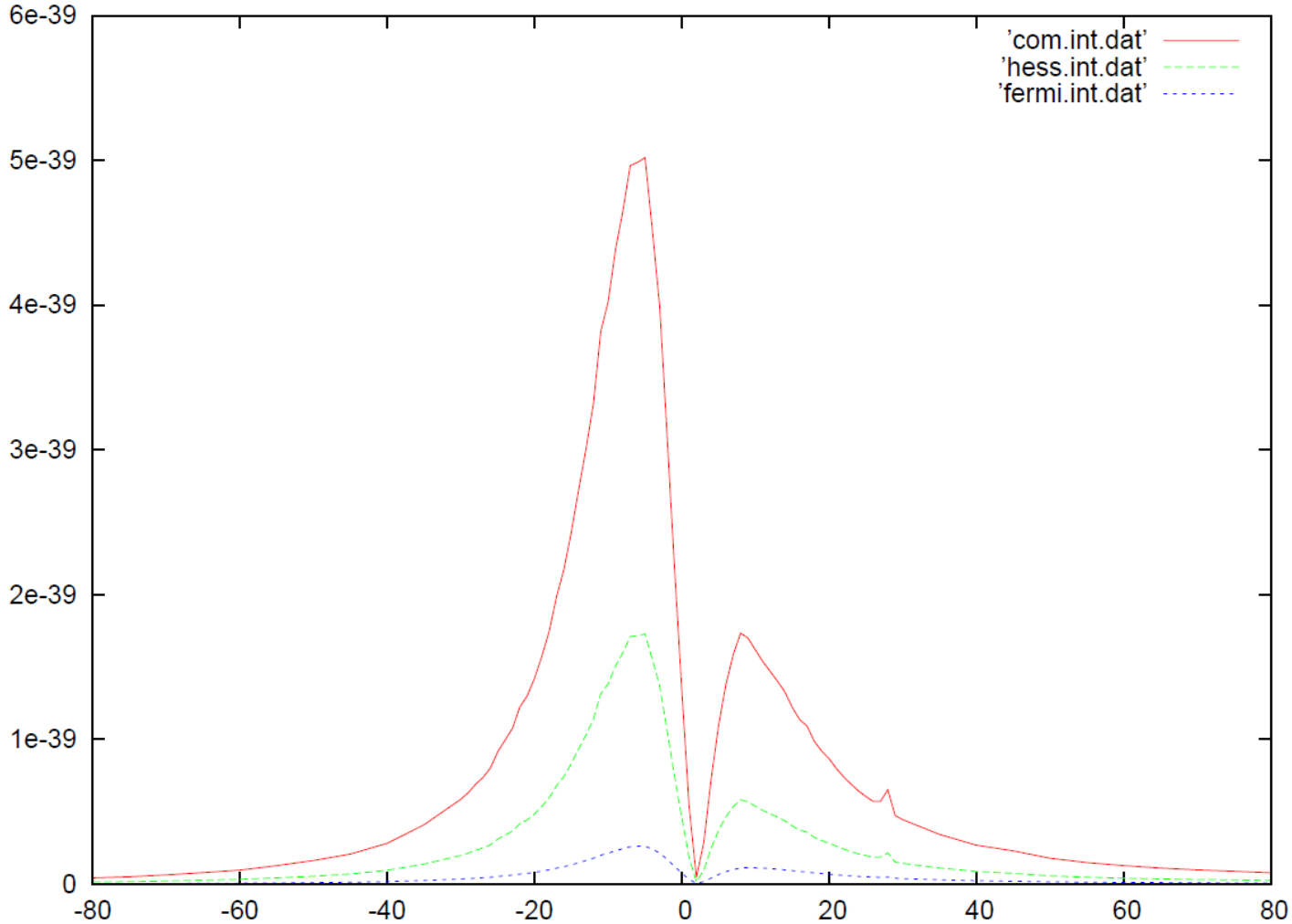
PSR B1259-63 – Other disc orientations



$$i = 90^\circ$$

$$\theta_{\mathrm{disc}} = 72^\circ$$

PSR B1259-63 – Other disc orientations



$$i = 90^\circ$$

$$\theta_{\mathrm{disc}} = 108^\circ$$