HIGH-ENERGY LIGHT CURVES IN AN OFFSET POLAR CAP B-FIELD GEOMETRY

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OVERVIEW

Aim: Investigate the effect of different magnetospheric structures on pulsar light curves and additionally what the effect will be when incorporating an *E*−field to modulate the emissivity

B-field structures:

- Static dipole
- Vacuum retarded dipole
- Offset−PC dipole (Harding & Muslimov 2011)

Geometric models:

- Two−pole caustic (TPC)
- Outer gap (OG)
- Slot gap (SG)

Implement an offset-PC solution:

- Transformation
- PC rim
- SG *E*−field
- Matching parameter
- Transport equation (test curvature radiation reaction − CRR)

Our studies was done on Vela!!!

OFFSET-PC FIELD

B-field expression:

- Heuristic model of a non–dipolar magnetic structure where the PCs are offset from the magnetic–axis
- Symmetric offset PCs, i.e., offset of both magnetic PCs in the same direction

$$\mathbf{B}'_{\rm offset,s}(r',\theta',\phi') \approx \frac{\mu}{r'^3}\left[\cos\theta'\hat{\mathbf{r}}' + \frac{1}{2}(1+a)\sin\theta'\hat{\boldsymbol{\theta}}' - \epsilon\sin\theta'\cos\theta'\sin(\phi'-\phi'_0)\hat{\boldsymbol{\phi}}'\right]$$

$$a = \epsilon\cos(\phi' - \phi'_0)$$

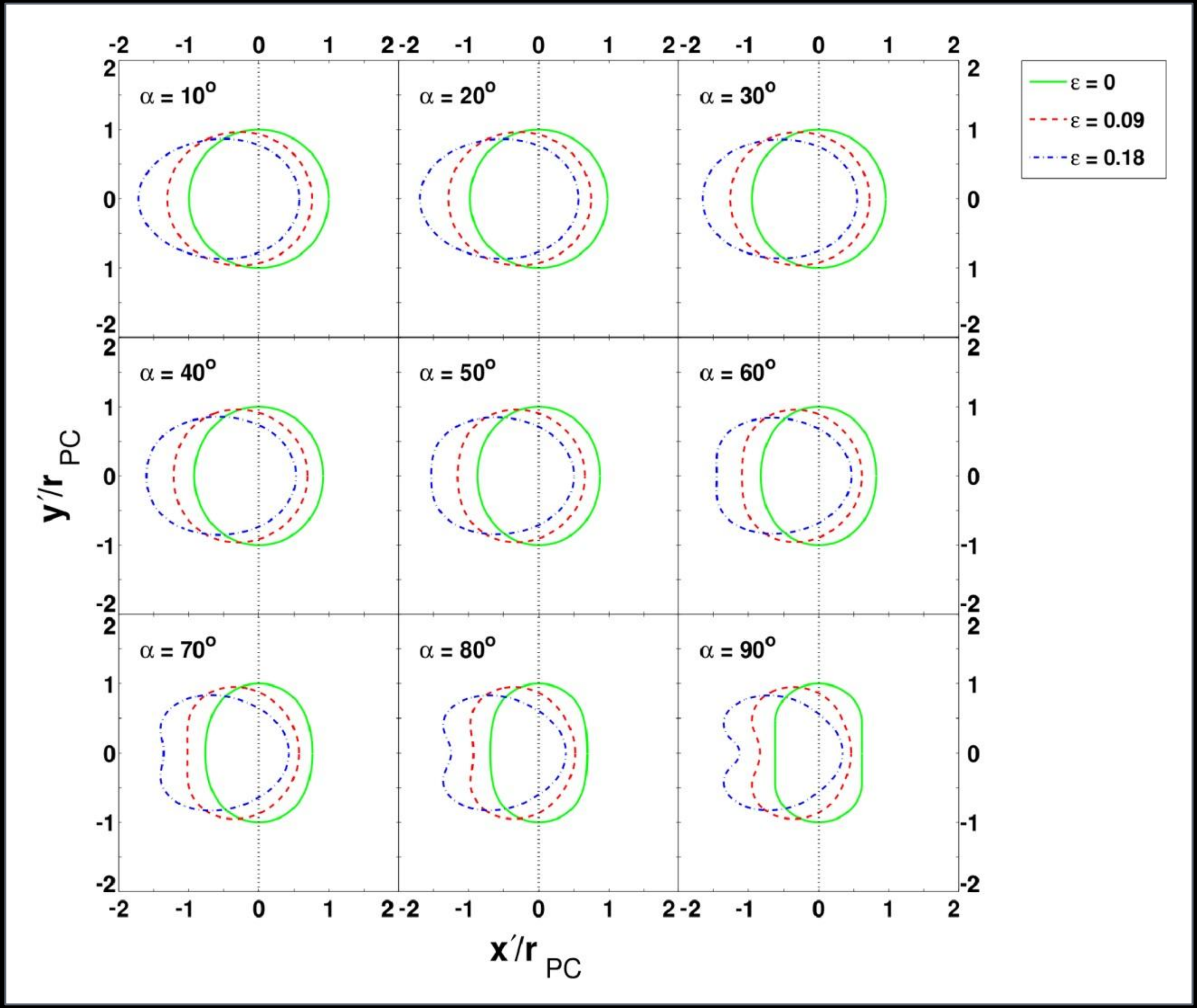
Distortions due to retardation and asymmetric currents.

Transformation:

B–field specified in the magnetic frame, but transformed the field to the co–rotating frame to determine the PC of the neutron star for this specific B–field solution

PC rim:

Need to determine rim for new B–field



SG E-field: Corrected for GR effects (Muslimov & Harding 2003, 2004)

Low–altitude and high–altitude solutions available for offset–PC dipole

$$E_{\|,\rm low} \approx -3\mathcal{E}_0 \nu_{\rm SG} x^a \Big\{ \frac{\kappa}{\eta^4} e_{1\rm A} \cos\alpha + \frac{1}{4} \frac{\theta_{\rm PC}^{1+a}}{\eta} \big[e_{2\rm A} \cos\phi_{\rm PC} + \frac{1}{4} \epsilon \kappa e_{3\rm A} (2\cos\phi_0' - \cos(2\phi_{\rm PC} - \phi_0')) \big] \sin\alpha \Big\} (1 - \xi_*^2)$$

= 0 "favourably curved" field lines

$$E_{\|,\rm high} \approx -\frac{3}{8} \Big(\frac{\Omega R}{c}\Big)^3 \frac{B_0}{f(1)} \nu_{\rm SG} x^a \Big\{ \Big[1 + \frac{1}{3}\kappa \Big(5 - \frac{8}{\eta_{\rm c}^3}\Big) + 2\frac{\eta}{\eta_{\rm LC}} \Big] \cos\alpha + \frac{3}{2} \theta_{\rm PC} H(1) \sin\alpha \cos\phi_{\rm PC} \Big\} (1 - \xi_*^2),$$

Note: magnetic azimuthal angle in E–field is π out of phase with that of B–field

Match these to obtain general SG E–field over all altitudes on each B–field line

$\eta_{\rm c}(P, \dot{P}, \alpha, \epsilon, \xi, \phi_{\rm PC})$

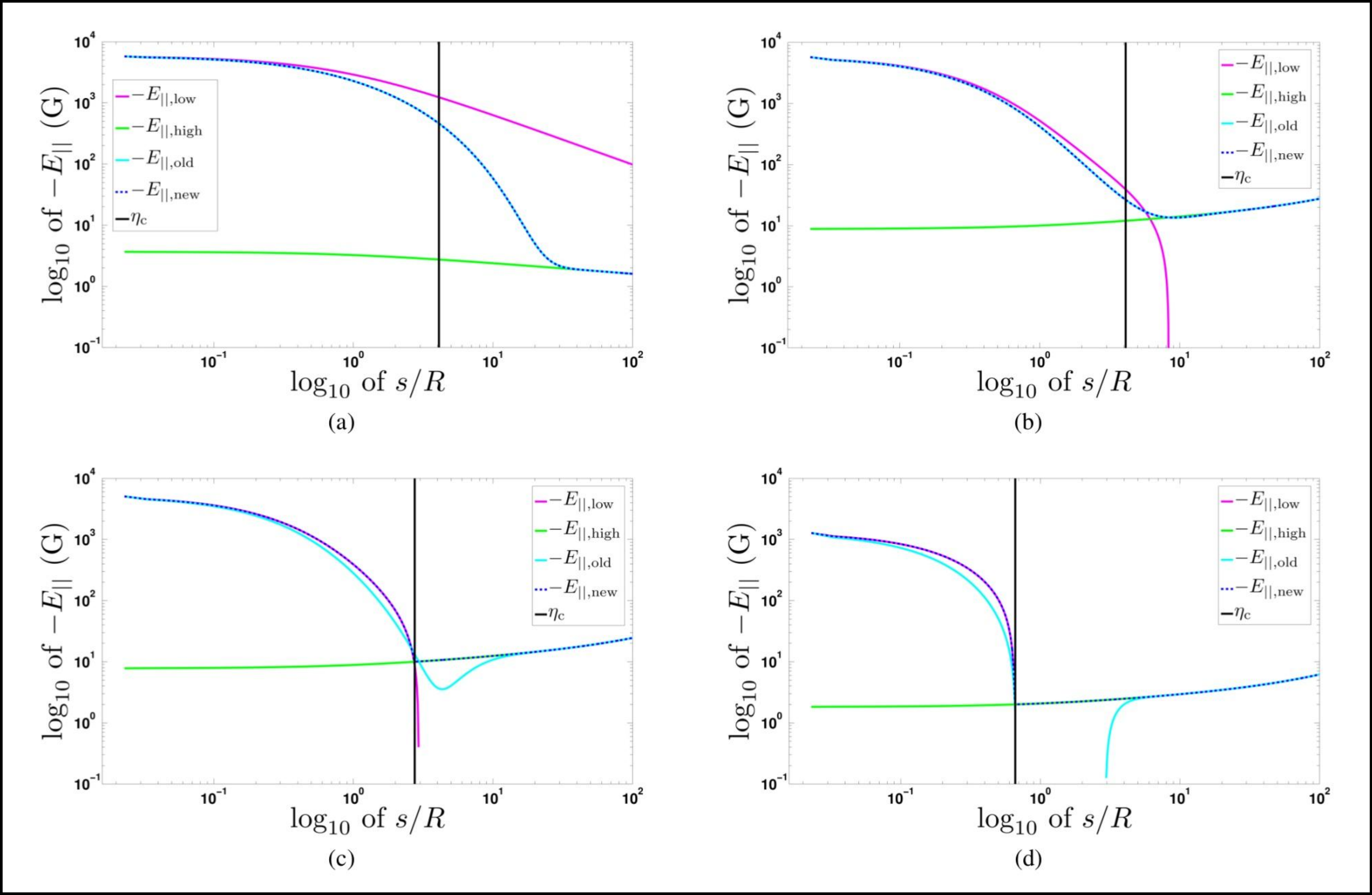
MATCHING PARAMETER (Barnard et al. 2016, submitted)

$$E_{\|,\rm SG} \simeq E_{\|,\rm low} \exp\left(\frac{-(\eta - 1)}{(\eta_{\rm c} - 1)} \right) + E_{\|,\rm high}$$

SG E-field:

Problems encountered when matching

$$E_{\|,\mathrm{SG}} \simeq E_{\|,\mathrm{low}} \exp\left(\frac{-(\eta-1)}{(\eta_{\mathrm{c}}-1)}\right) + E_{\|,\mathrm{high}}$$

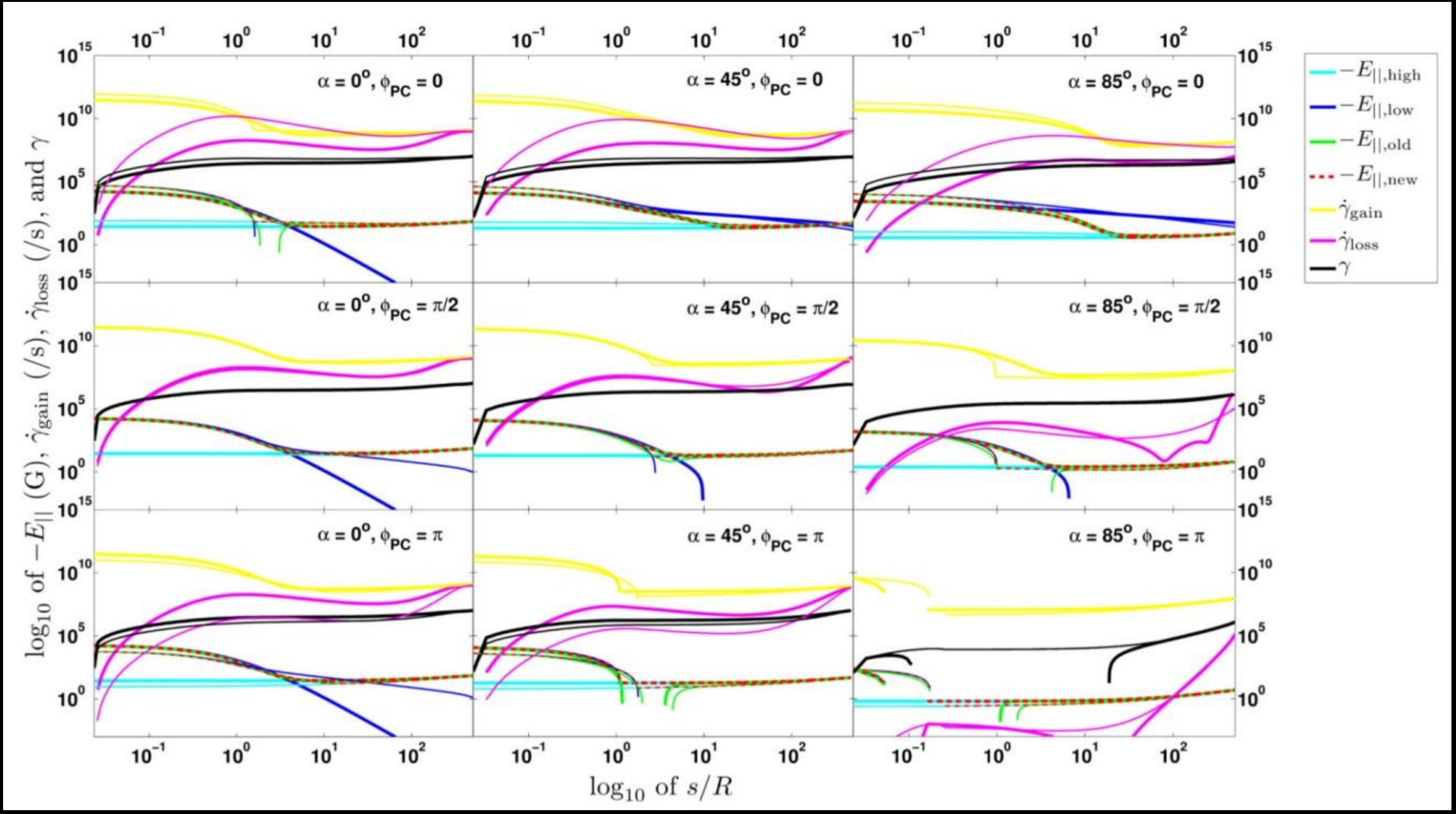


Transport Equation :

$$\dot{\gamma} = \dot{\gamma}_{\rm gain} + \dot{\gamma}_{\rm loss} = \frac{eE_{\|,\rm total}}{mc} - \frac{2e^2\gamma_e^4}{3\rho_{\rm curv}^2 mc}$$

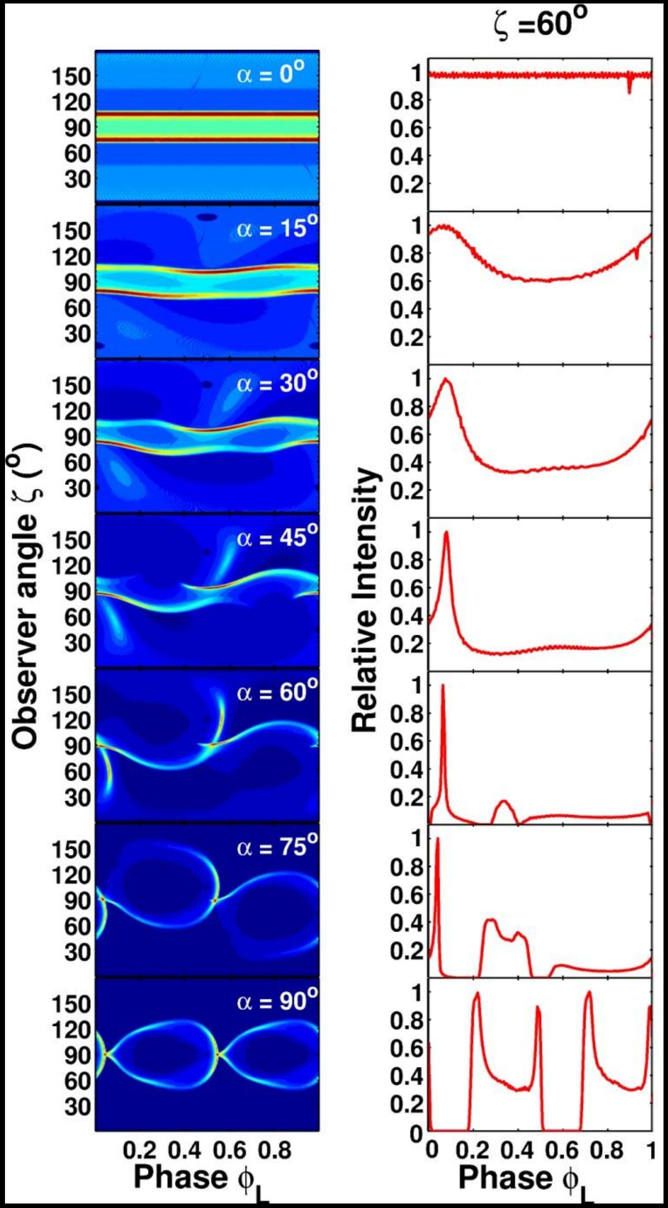
Solve transport equation using general SG E−field, on each B−field line.

$\varepsilon = 0$ (thick lines), $\varepsilon = 0.18$ (thin lines)

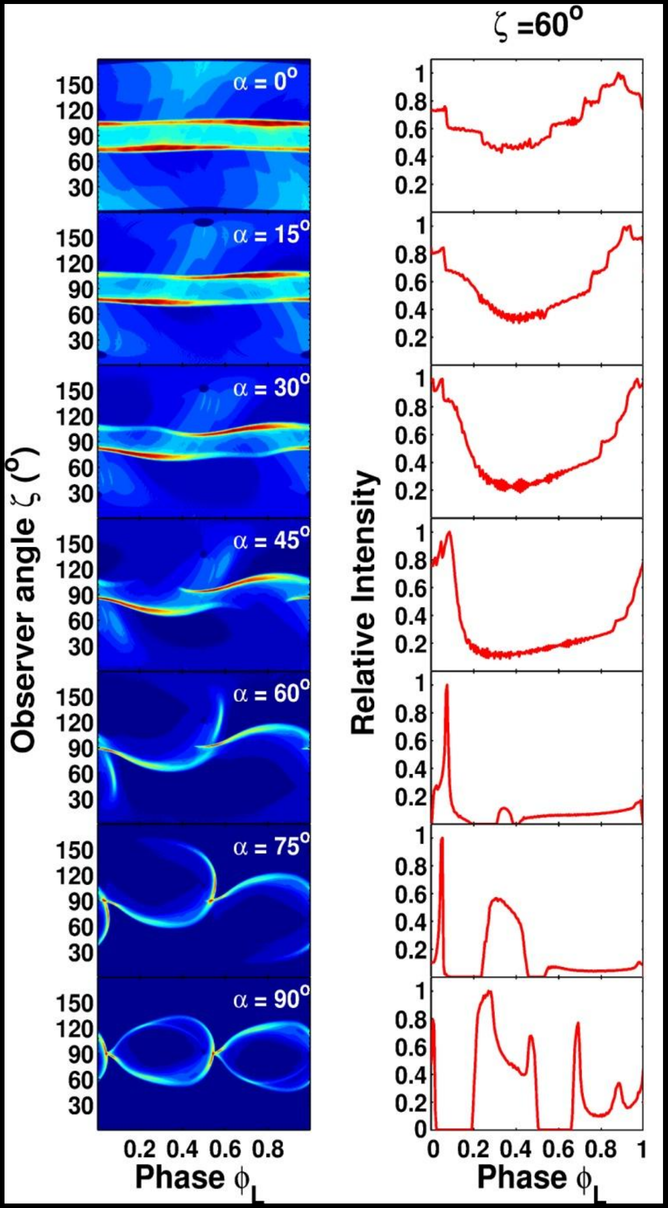


RESULTS: Uniform emissivity (TPC model)

$\varepsilon = 0$

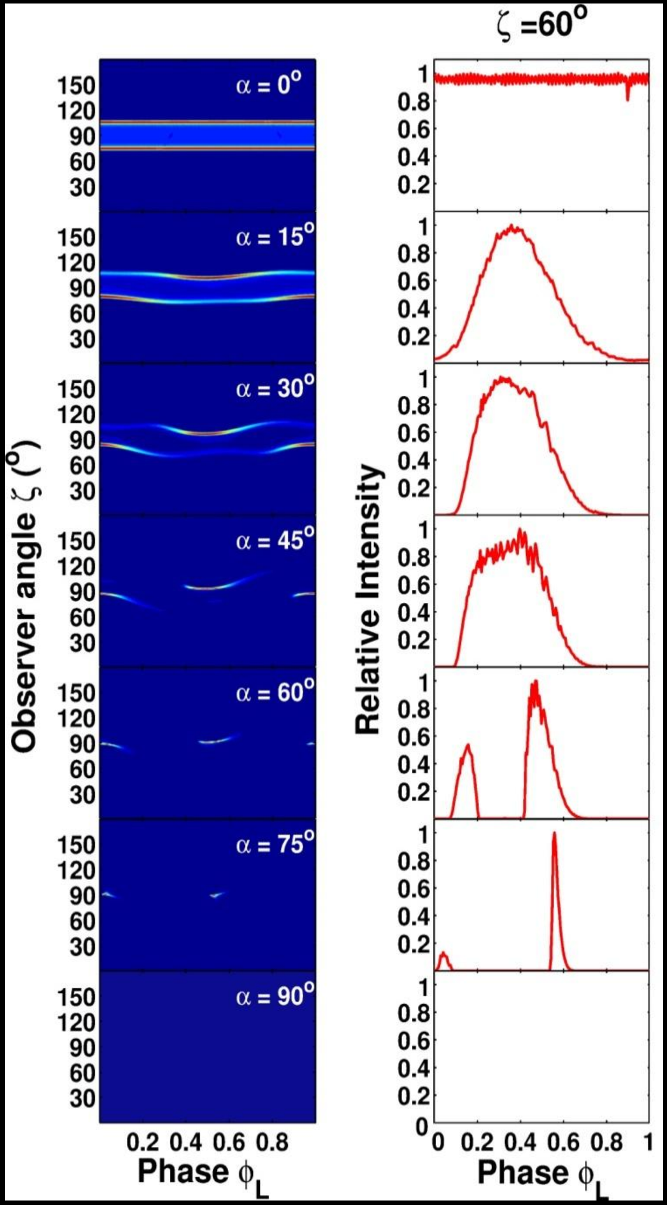


$\varepsilon = 0.18$

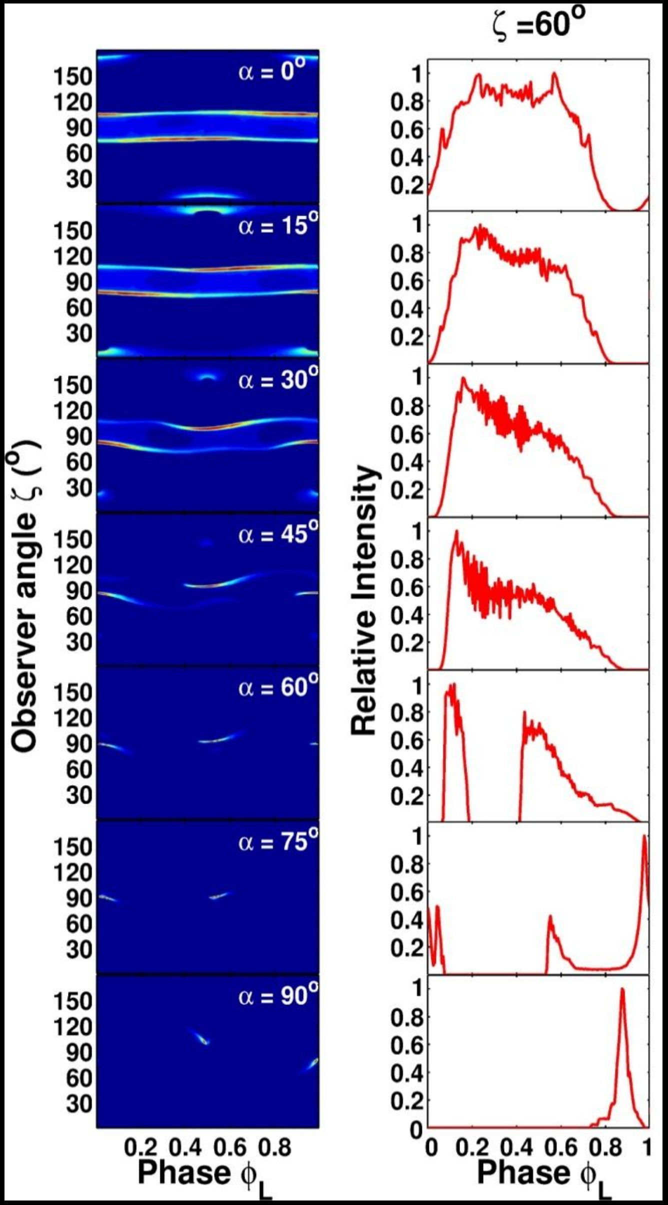


RESULTS: Variable emissivity (SG model)

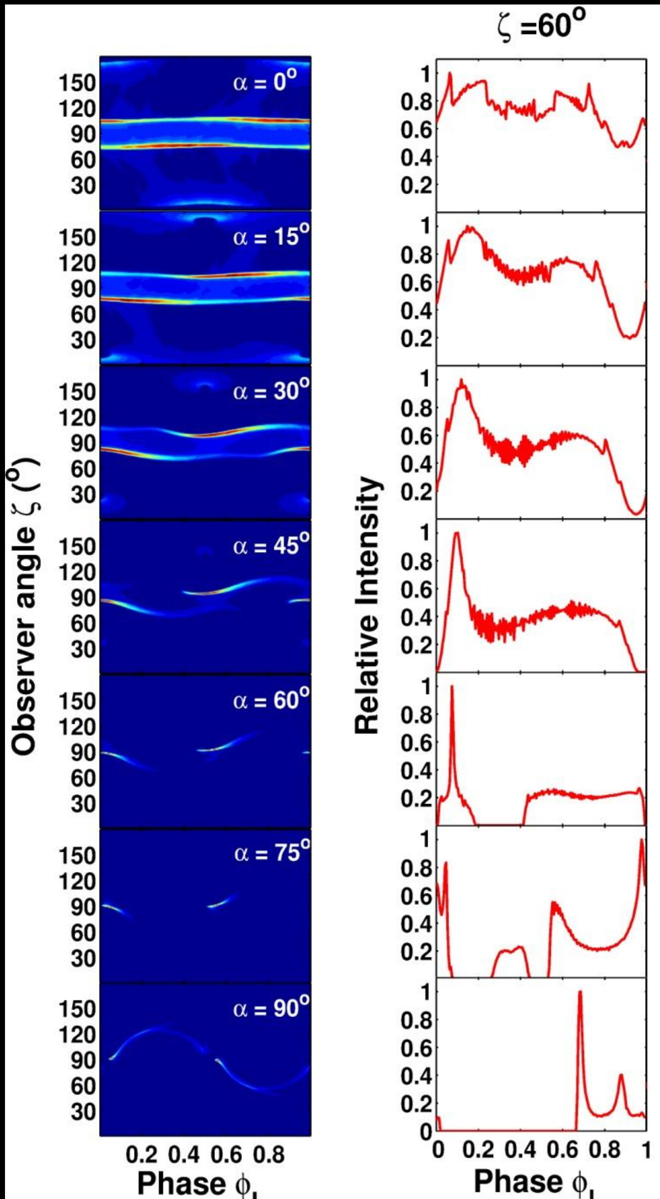
$\varepsilon = 0$



$\varepsilon = 0.18$



RESULTS: Variable emissivity (vary the magnitude of the SG E-field)

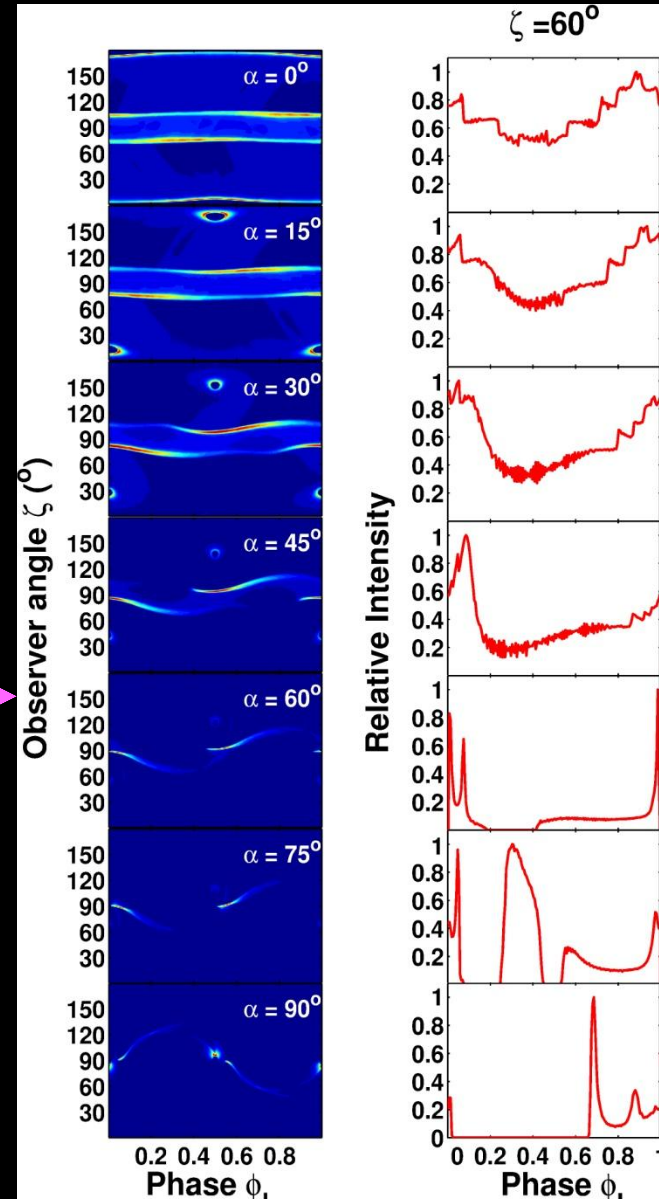


Case 1: $\varepsilon = 0.18$

- Lowered minimum energy to 1 MeV
- Hard X-ray band

Case 2: $\varepsilon = 0.18$

- Increased E-field by a factor 100
- Gamma-ray band



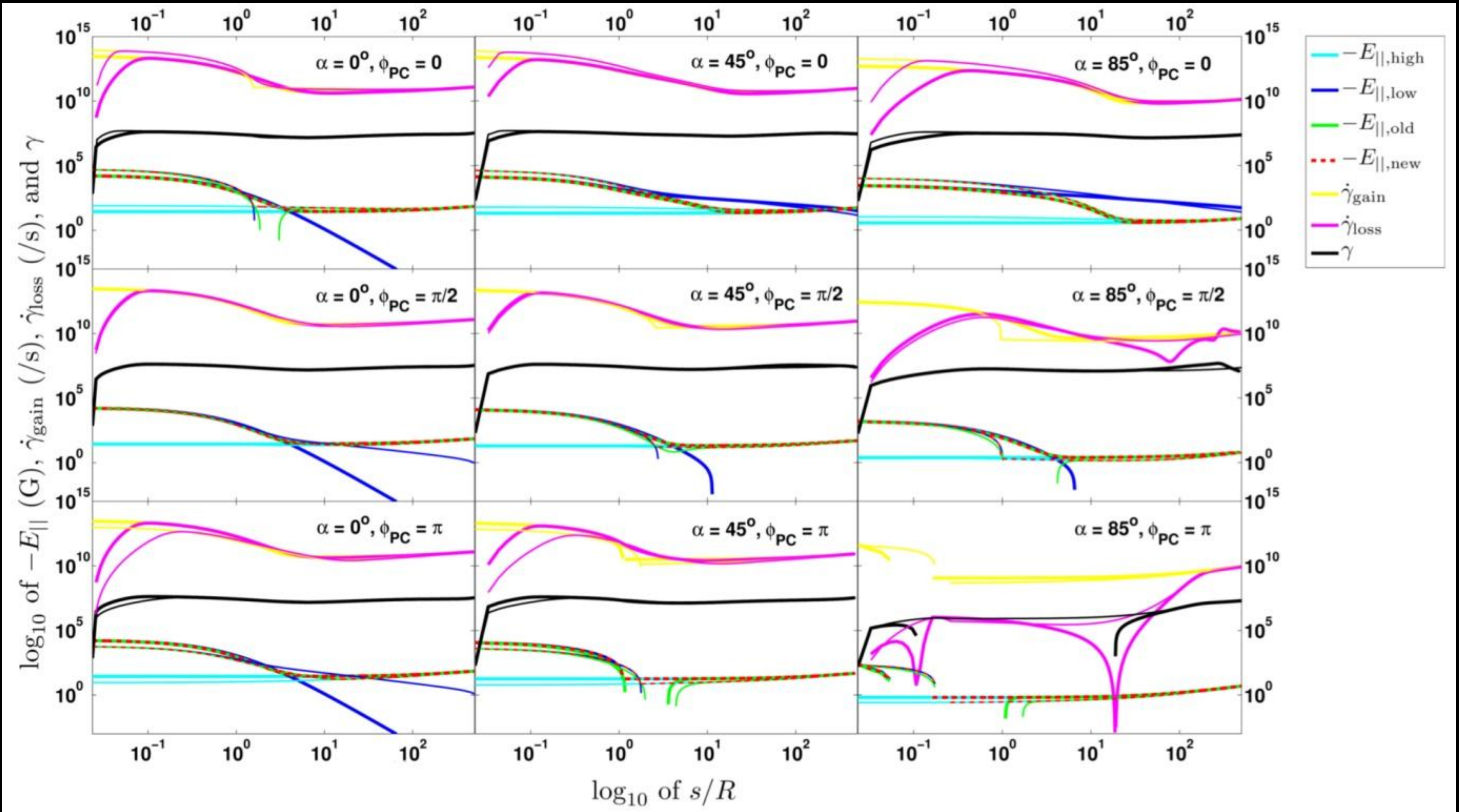
Transport Equation :

$$\dot{\gamma} = \dot{\gamma}_{\text{gain}} + \dot{\gamma}_{\text{loss}} = \frac{eE_{\|,\text{total}}}{mc} - \frac{2e^2\gamma_e^4}{3\rho_{\text{curv}}^2 mc}$$

Solve transport equation using general SG

E−field increased by a factor 100.

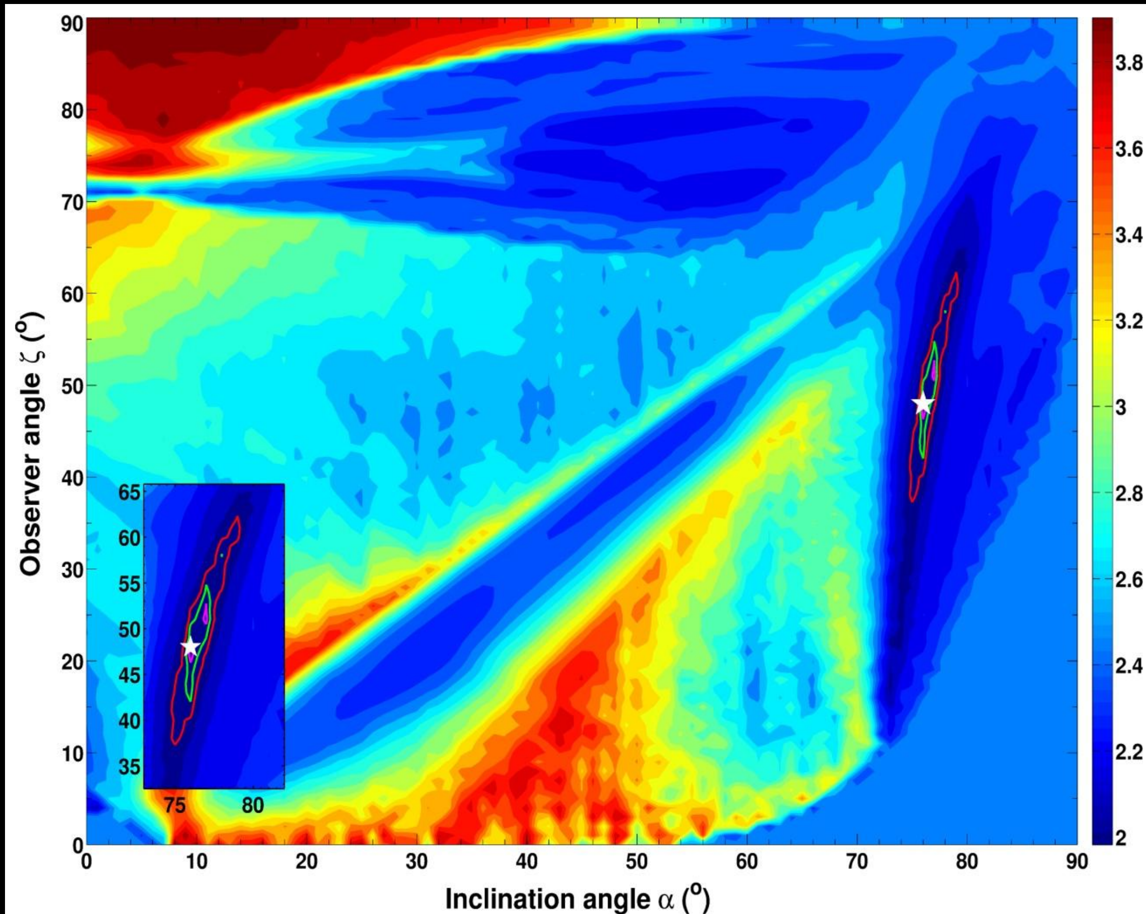
$\varepsilon = 0$ (thick lines), $\varepsilon = 0.18$ (thin lines)



RESULTS:

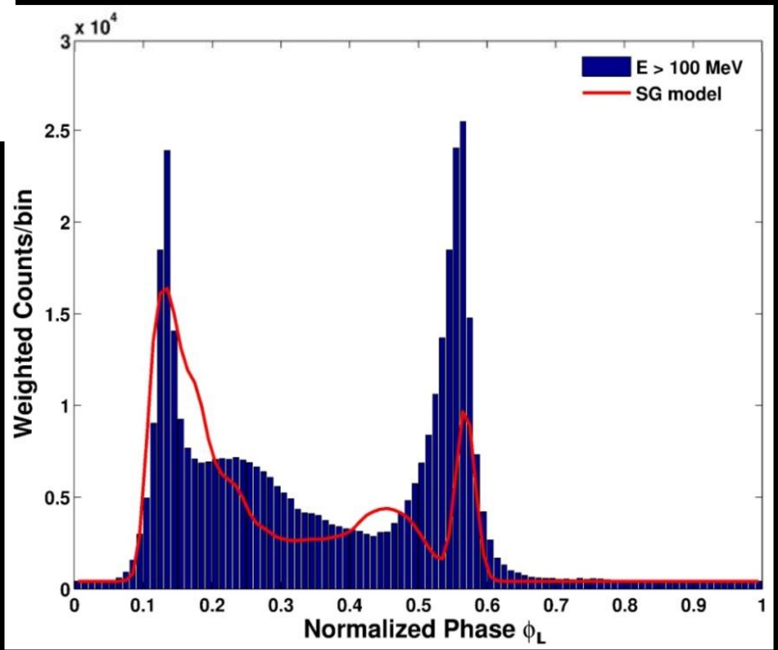
Fitting model light curves to Vela data

- Used a usual chi–squared method (Breed et al. 2014, 2015)
- search the multivariate solution space for optimal model parameters



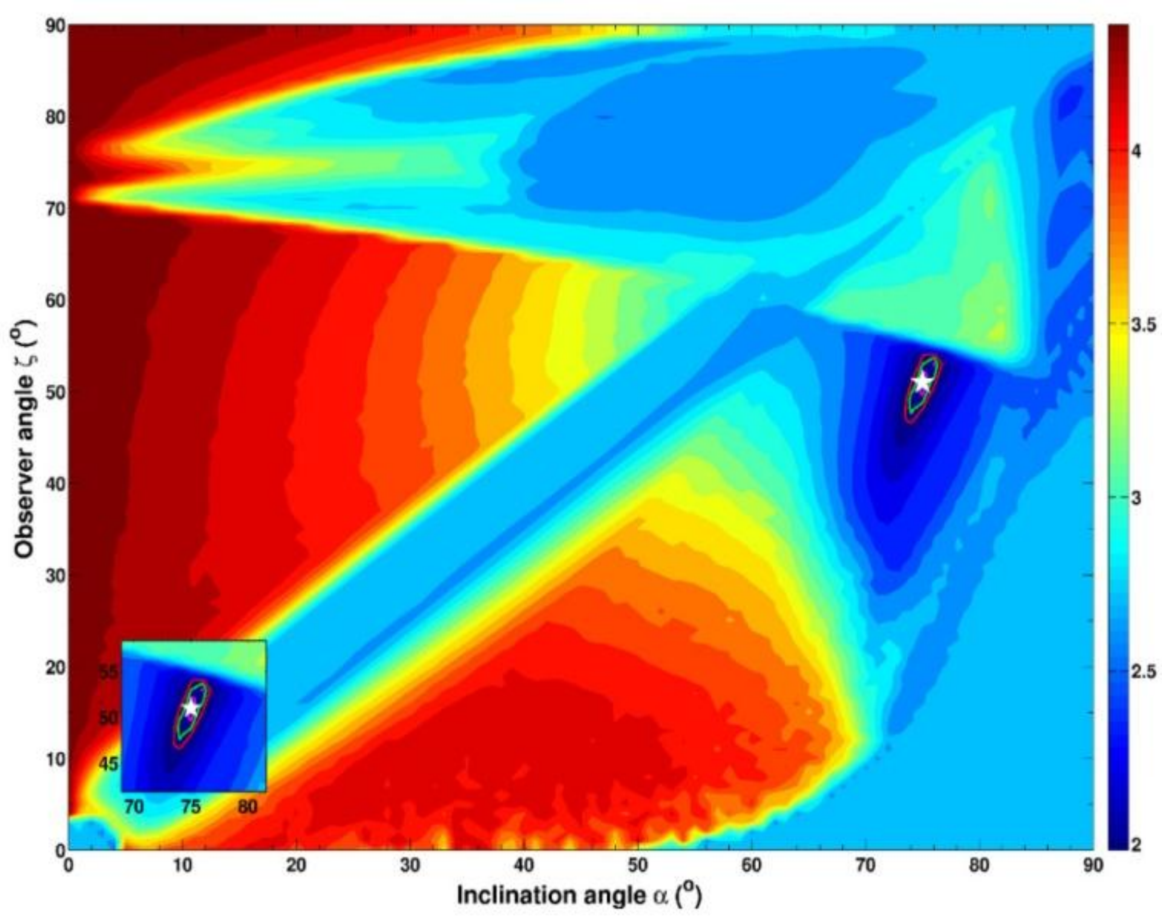
Chi-squared contour

Best-fit model light curve



Best fit to the data for offset–PC field:
SG model for $\varepsilon = 0.15$

RESULTS:

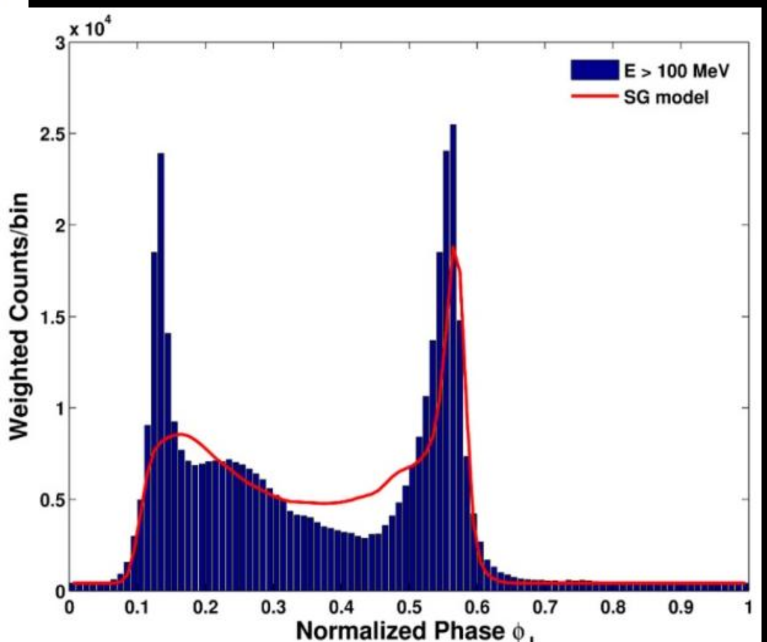


Chi-squared contour

Fitting model light curves to Vela data

Increased E–field by a factor 100

Best-fit model light curve:



Best fit to the data for offset–PC field: TPC model for $\varepsilon = 0$

RESULTS:

$$\Delta\xi^2 = \xi^2 - \xi^2_{\rm opt} = N_{\rm dof}\left(\frac{\chi^2}{\chi^2_{\rm opt}} - 1\right)$$

First:

Compared the optimal and alternative models for each B–field

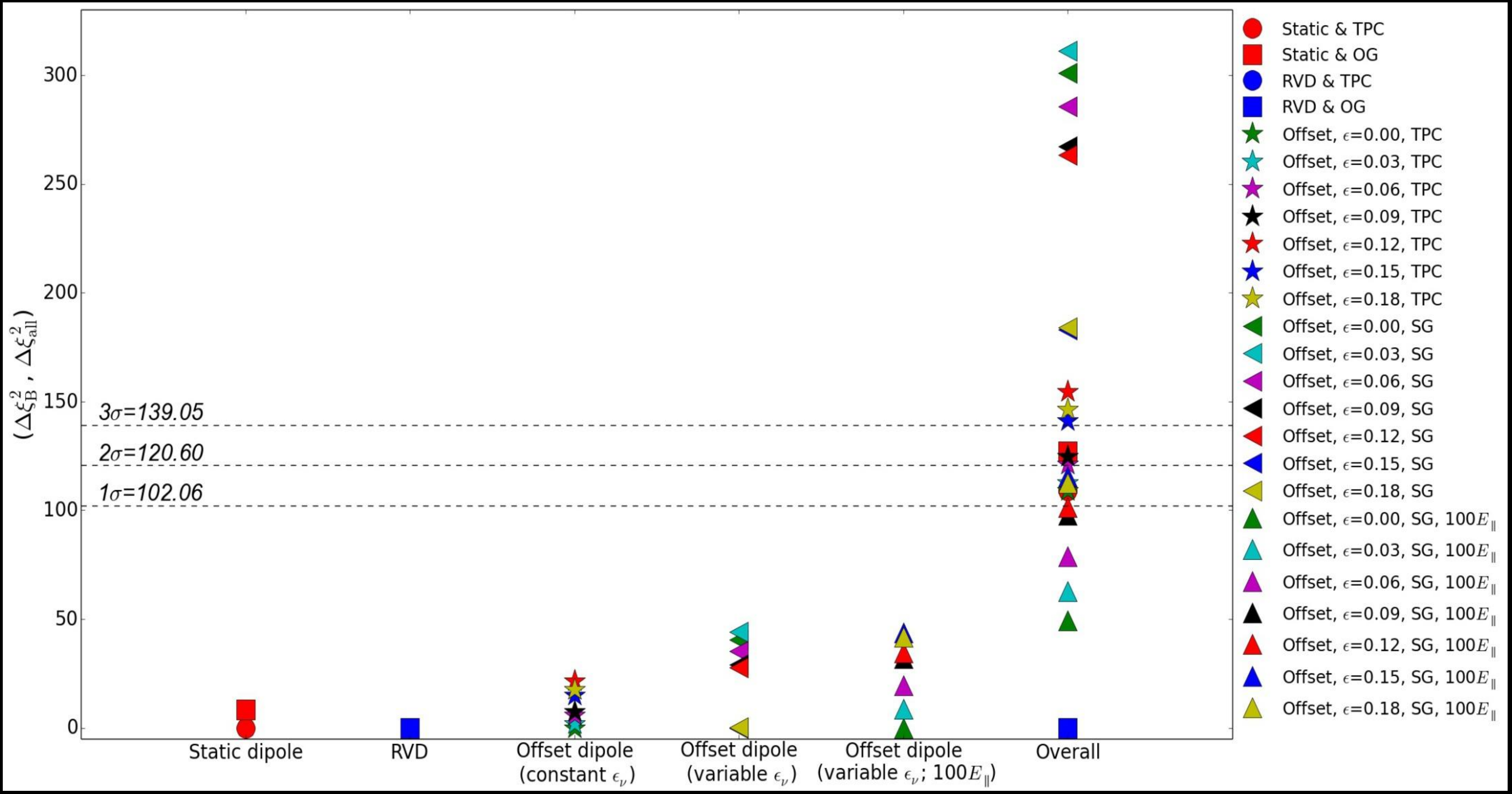
Second:

Compared all B–field and model combinations to the OVERALL optimal B–field and model combination

Combinations Model	ϵ	χ^2 ($\times 10^5$)	Our Best-fit Parameters α (°)	ζ (°)	A	$\Delta\phi_{\rm L}$	$\Delta\xi^2_{\rm B}$	$\Delta\xi^2_{\rm all}$	Other Multi-wavelength Fits α (°)	ζ (°)	Reference
Static dipole B-field:											
TPC	...	0.819	73^{+3}_{-2}	45^{+4}_{-4}	1.3	0.55	0.00	108.75			
OG	...	0.891	64^{+5}_{-3}	86^{+1}_{-1}	1.3	0.05	8.44	126.75			
RVD B-field:											
TPC	...	3.278	54^{+5}_{-5}	67^{+5}_{-3}	0.5	0.05	723.50	723.50			
OG	...	0.384	78^{+1}_{-1}	69^{+2}_{-1}	1.3	0.00	0.00	0.00			
Offset dipole B-field for constant ϵ_ν:											
TPC	0.00	0.819	73^{+3}_{-2}	45^{+4}_{-4}	1.3	0.55	0.00	108.75			
	0.03	0.834	73^{+2}_{-2}	43^{+4}_{-5}	1.3	0.55	1.76	112.50			
	0.06	0.867	73^{+2}_{-2}	42^{+5}_{-5}	1.3	0.55	5.63	120.75			
	0.09	0.882	73^{+1}_{-2}	41^{+3}_{-5}	1.3	0.55	7.39	124.50			
	0.12	1.000	74^{+1}_{-3}	42^{+3}_{-6}	1.4	0.55	21.22	154.00			
	0.15	0.948	73^{+1}_{-2}	39^{+3}_{-5}	1.4	0.55	15.12	141.00			
	0.18	0.969	73^{+2}_{-3}	37^{+4}_{-4}	1.3	0.55	17.58	146.25			
Offset dipole B-field for variable ϵ_ν:											
SG	0.00	1.587	21^{+3}_{-3}	71^{+1}_{-1}	0.5	0.85	40.52	300.75			
	0.03	1.627	73^{+1}_{-1}	17^{+4}_{-3}	0.7	0.55	43.96	310.75			
	0.06	1.525	72^{+2}_{-1}	14^{+5}_{-1}	0.5	0.60	35.18	285.25			
	0.09	1.452	73^{+1}_{-1}	17^{+3}_{-1}	0.6	0.55	28.90	267.00			
	0.12	1.437	74^{+1}_{-1}	27^{+1}_{-7}	0.8	0.55	27.61	263.25			
	0.15	1.116	76^{+3}_{-1}	48^{+15}_{-11}	0.7	0.55	0.00	183.00			
	0.18	1.119	75^{+2}_{-1}	40^{+6}_{-4}	0.5	0.55	0.26	183.75			
Offset dipole B-field for variable ϵ_ν ($100E_{\parallel}$):											
SG	0.00	0.581	75^{+3}_{-1}	51^{+2}_{-5}	1.1	0.55	0.00	49.27			
	0.03	0.634	75^{+2}_{-2}	49^{+5}_{-5}	1.1	0.55	8.73	62.48			
	0.06	0.698	75^{+3}_{-3}	49^{+5}_{-6}	1.1	0.55	19.39	78.61			
	0.09	0.774	75^{+3}_{-3}	50^{+5}_{-9}	1.1	0.55	31.90	97.54			
	0.12	0.789	77^{+2}_{-3}	54^{+2}_{-8}	1.1	0.55	34.42	101.36			
	0.15	0.845	77^{+2}_{-4}	55^{+1}_{-14}	0.9	0.55	43.62	115.28			
	0.18	0.834	78^{+1}_{-2}	55^{+1}_{-5}	0.8	0.55	41.80	112.51			
RVM									53	59.5	1
X-ray torus										$63.6^{+0.07}_{-0.05}$	2
RVD & TPC									62–68	64	3
RVD & OG									75	64	3
RVD & Symmetric SG									44^{+4}_{-1}	54^{+1}_{-5}	4
RVD & Asymmetric SG									65^{+1}_{-2}	65.5^{+2}_{-1}	4
RVD & OG									88^{+2}_{-3}	66.5^{+1}_{-1}	4
FF & Symmetric SG									15^{+1}_{-1}	68.5^{+1}_{-1}	4
FF & Asymmetric SG									55^{+10}_{-20}	54.5^{+4}_{-14}	4
FF & OG									80^{+1}_{-1}	53^{+1}_{-1}	4
RVD & PC									3^{+2}_{-3}	4^{+2}_{-2}	5
RVD & SG									45^{+2}_{-2}	69^{+2}_{-2}	5
RVD & OG									71^{+2}_{-2}	83^{+2}_{-2}	5
RVD & OPC									56^{+2}_{-2}	77^{+2}_{-2}	5

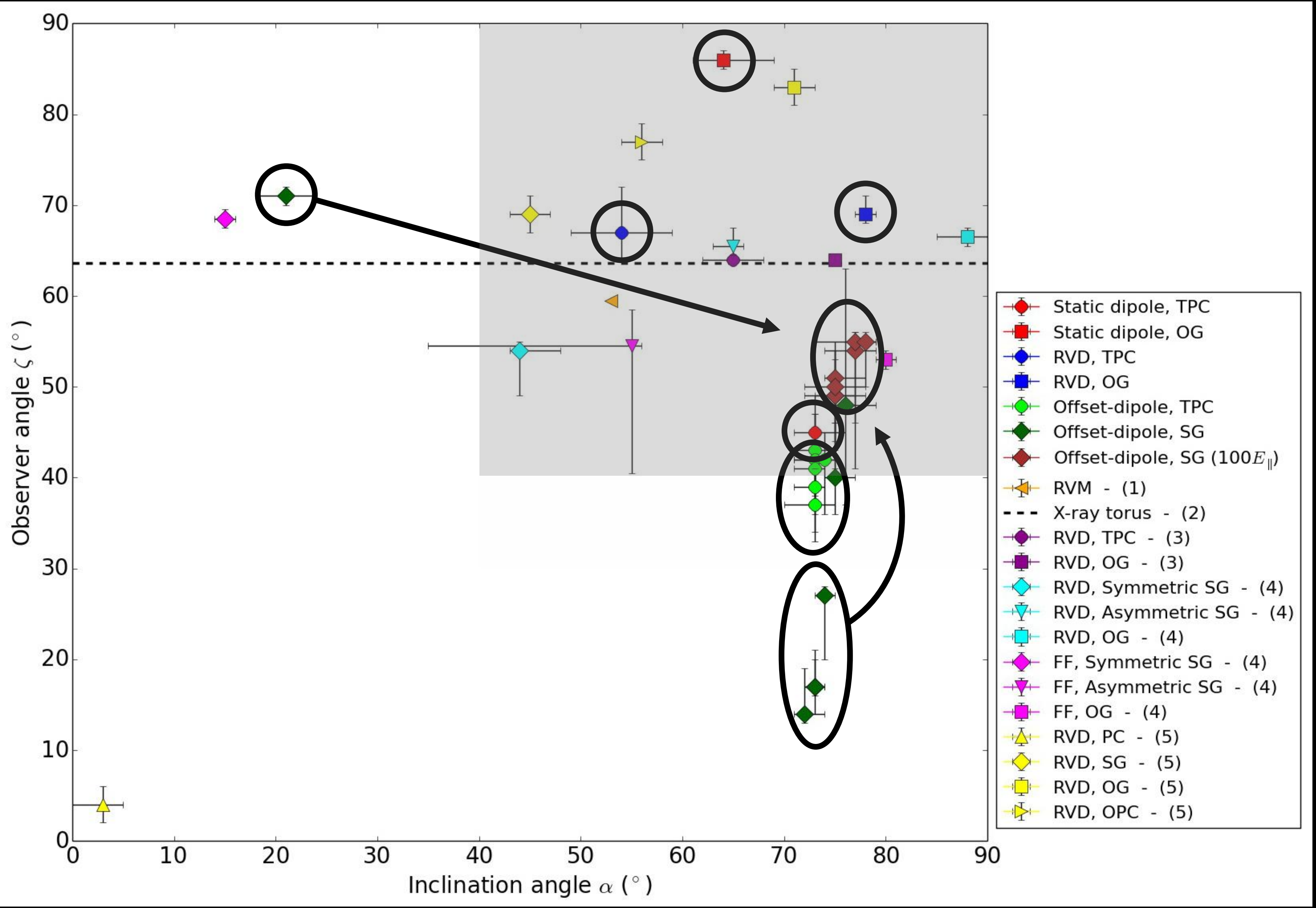
RESULTS: Comparison of the best-fit solutions

(Pierbattista et al. 2015)



RESULTS:

References. — (1) Johnston et al. 2005; (2) Ng & Romani 2008; (3) Watters et al. 2009; (4) DeCesar 2013; and (5) Pierbattista et al. 2015.



CONCLUSIONS

For an offset-PC magnetosphere:

- Therefore both the *B*–field and *E*–field have an impact on the predicted light curves.

- Solving the particle transport equation shows that the particle energy only becomes large enough to yield significant curvature radiation at large altitudes above the stellar surface, given this relatively low *E*–field. Therefore, particles do not always attain the radiation–reaction limit.

- Our overall optimal light curve t is for the retarded vacuum dipole field and outer gap model. But the offset–PC dipole delivers an second overall optimal fit.