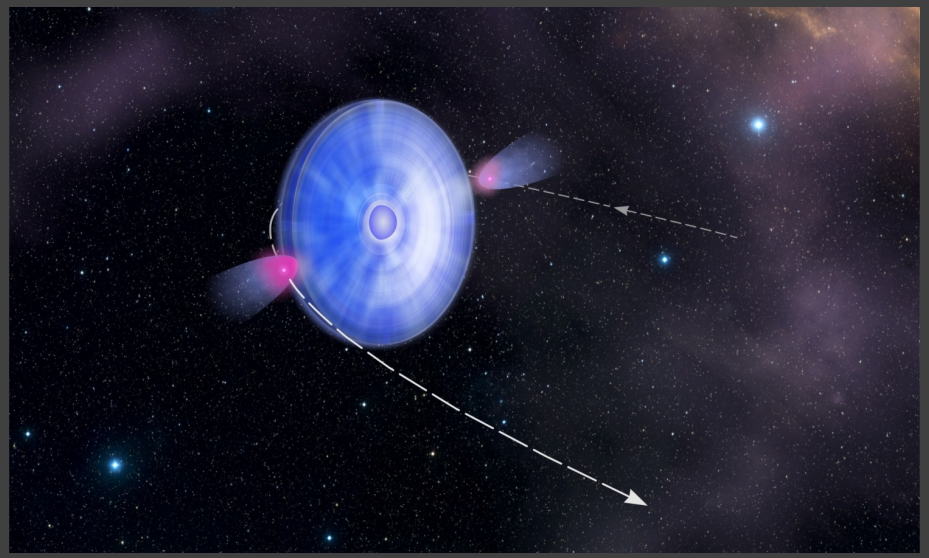


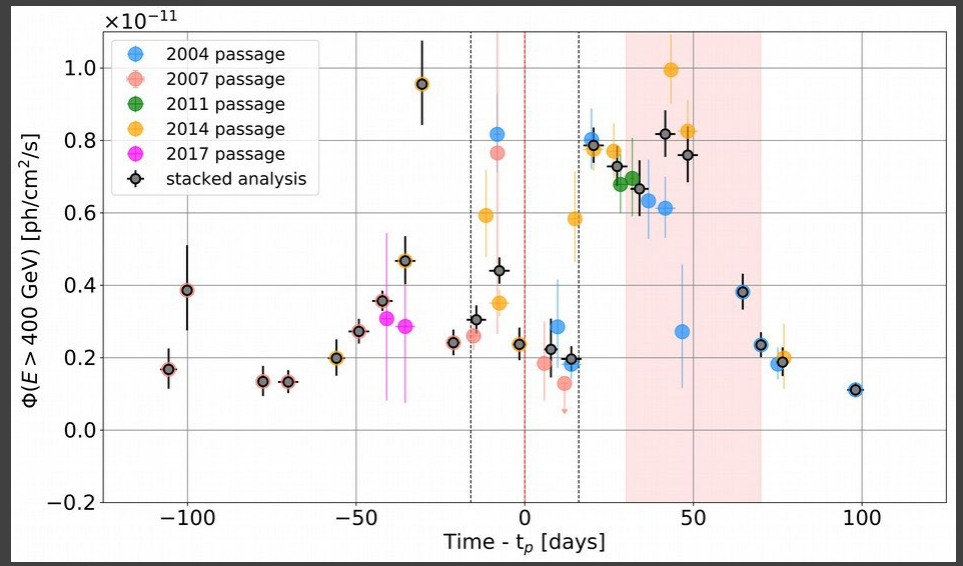
Probing orbital parameters of gamma-ray binaries with TeV light curves

IURII SUSHCH – NWU (SOUTH AFRICA)/DESY ZEUTHEN (GERMANY)

BRIAN VAN SOELEN – UFS (SOUTH AFRICA)

TeV light curves

- Variability related to the orbital period
- Often double-peak structure

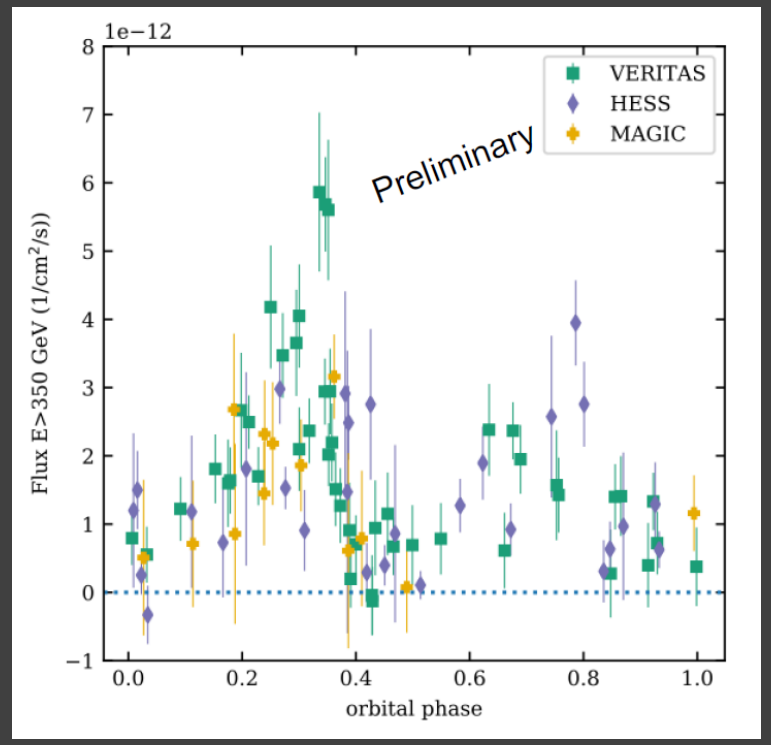


PSR B1259-63/LS 2883

Prokoph et al., ICRC 2019

HESS J0632+057

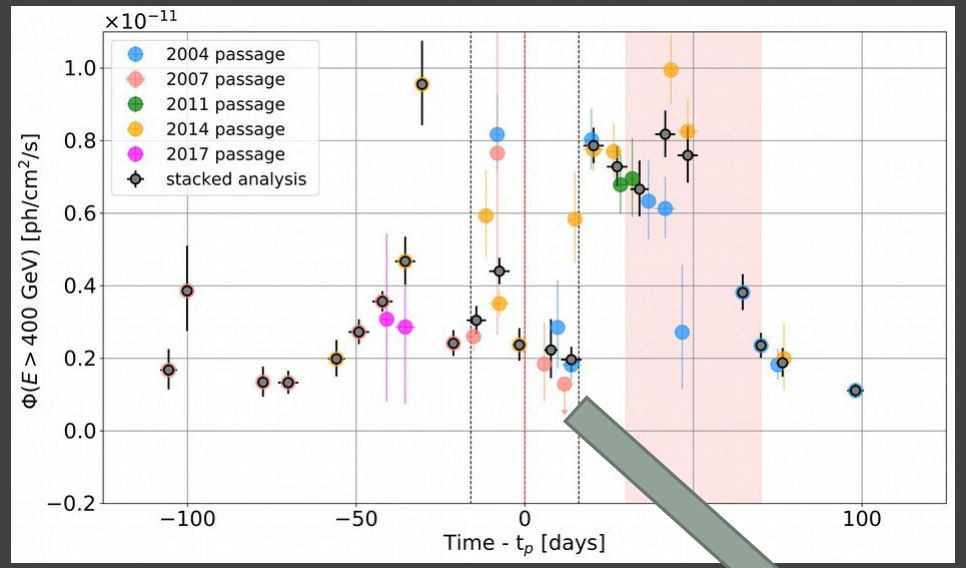
Maier et al., ICRC 2019

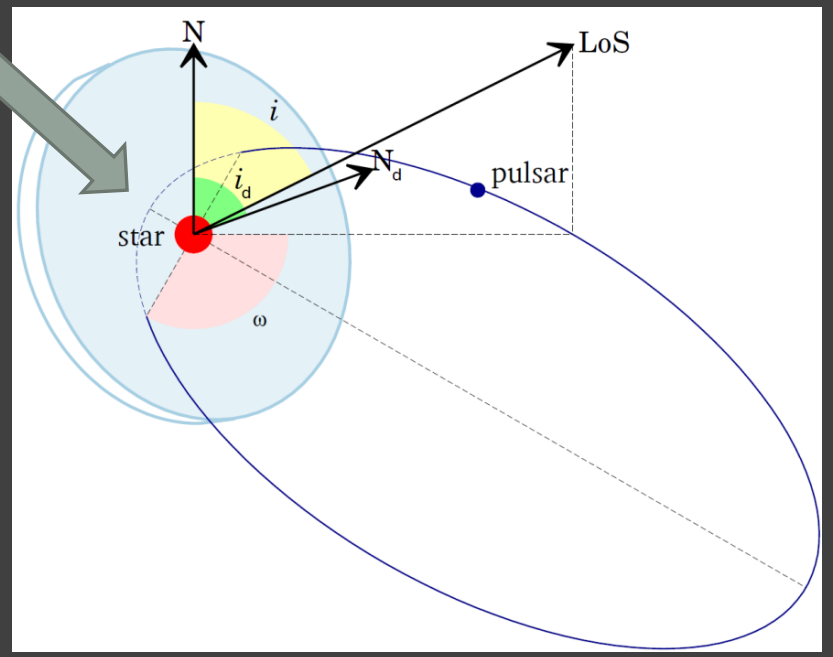


What causes the dip?

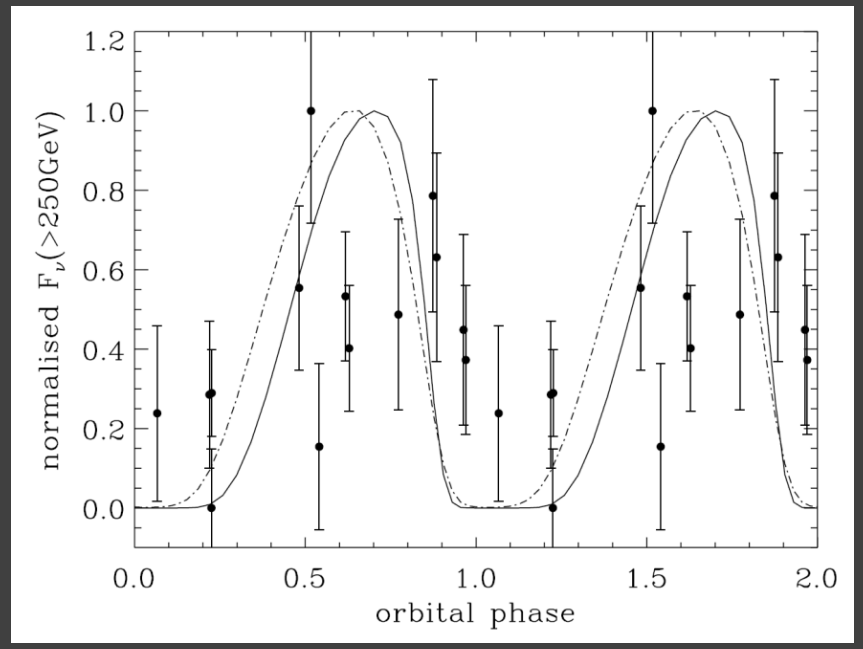
- Naively one would expect highest flux at periastron due to the highest energy density of stellar photons
- But that's where we see the dip!

PSR B1259-63/LS 2883





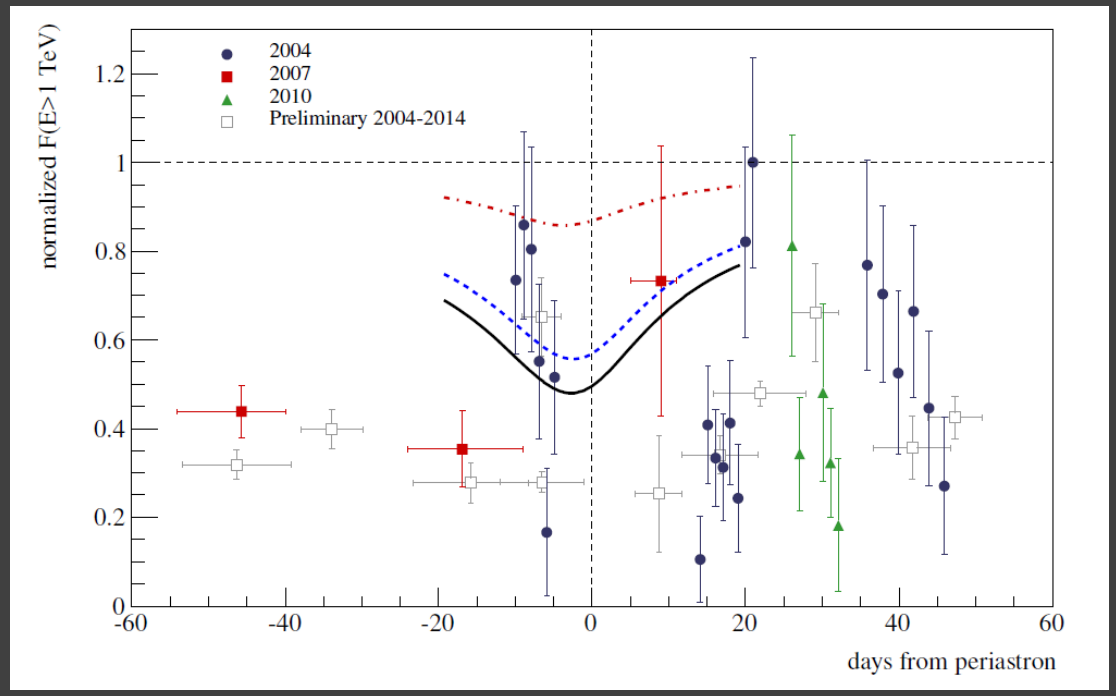
Gamma-gamma absorption



Dubus, 2006

LS 5039: Both location and depth of the minimum can be roughly explained by absorption

PSR B1259-63: Location of the minimum can be explained by absorption but not the depth



Sushch & van Soelen, 2017

Gamma-gamma absorption

$$\tau_{\gamma\gamma} = \int_0^l dl \int_0^{4\pi} (1-\mu)\, d\Omega \int_{\frac{2}{\epsilon_\gamma(1-\mu)}}^{\infty} n_{ph}(\epsilon,\Omega)\sigma_{\gamma\gamma}(\epsilon,\epsilon_\gamma,\mu)d\epsilon\,; \quad \mu = \cos\theta$$

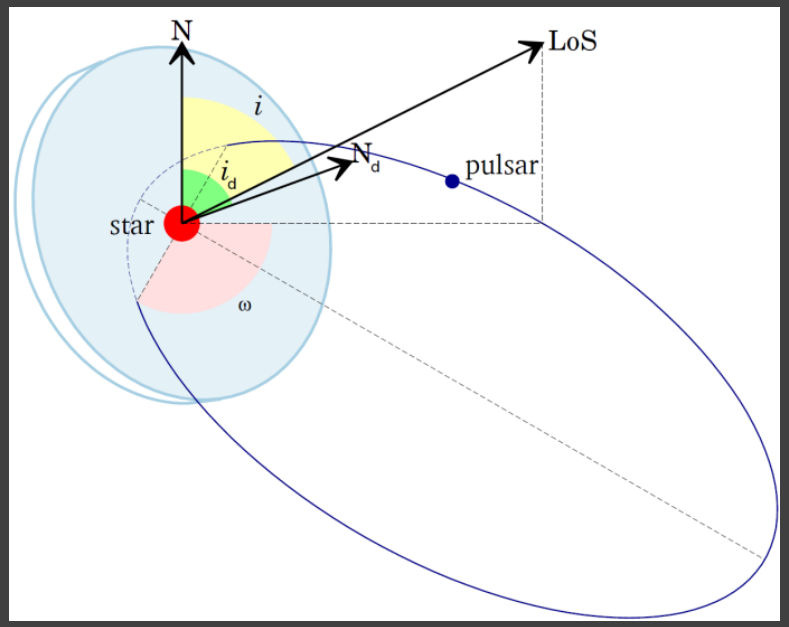
depends on the distance to the star

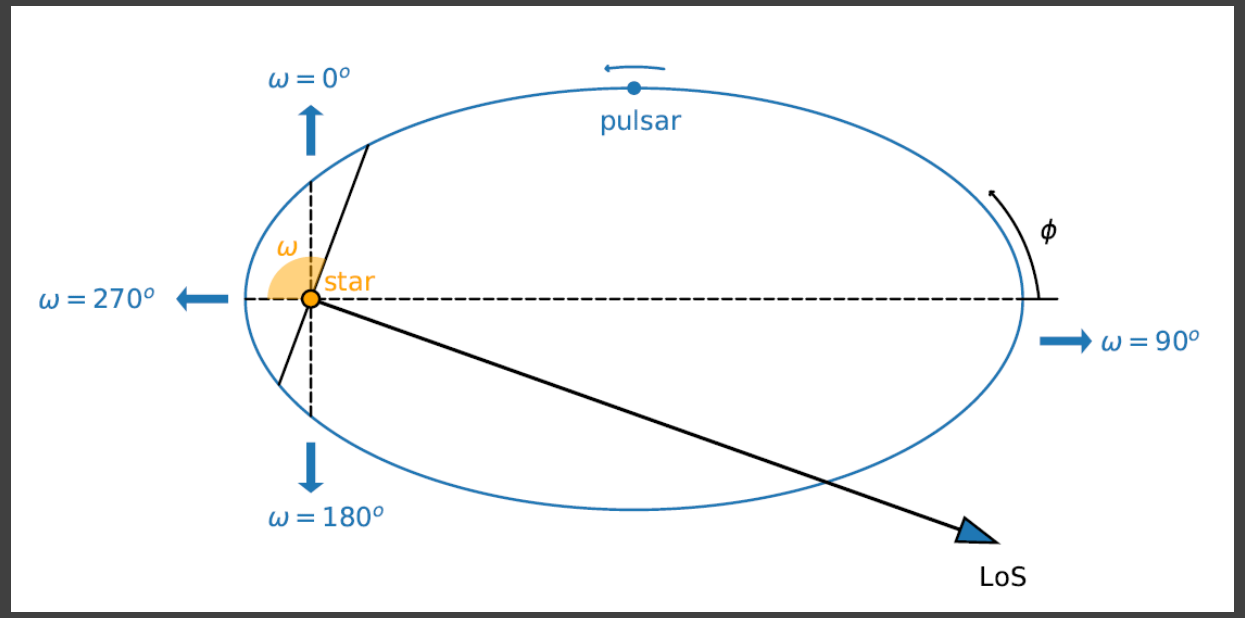
(e, i, ω, φ)

e – eccentricity
i – inclination angle
ω – longitude of periastron
φ – orbital phase

Geometry

- Inclination i – the angle between the normal to the orbital plane and direction towards the observer
- Longitude of periastron ω – the angle between the ascending node and periastron
- Orbital phase φ – measured from apastron in the direction of movement

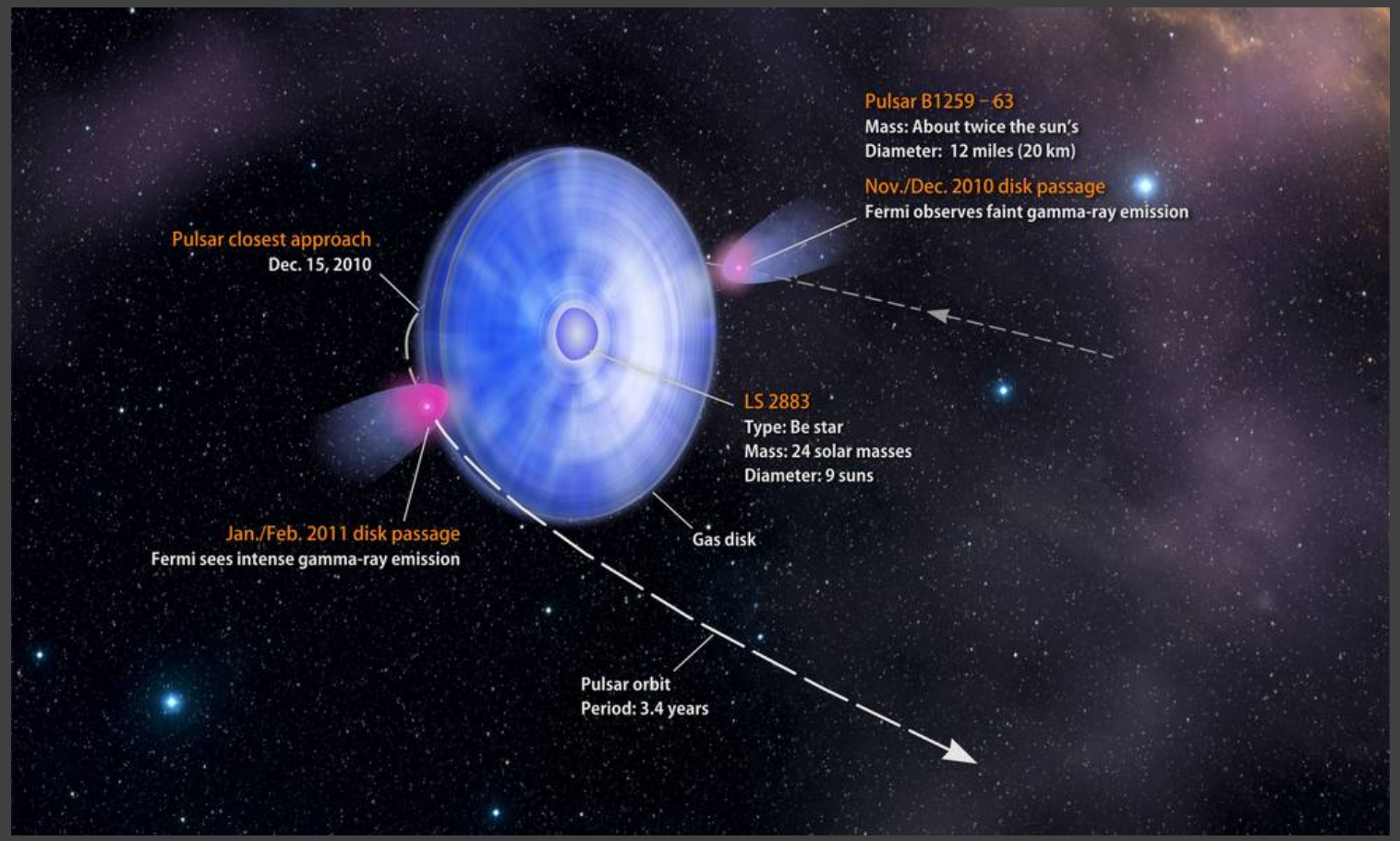




Test case: PSR B1259-63

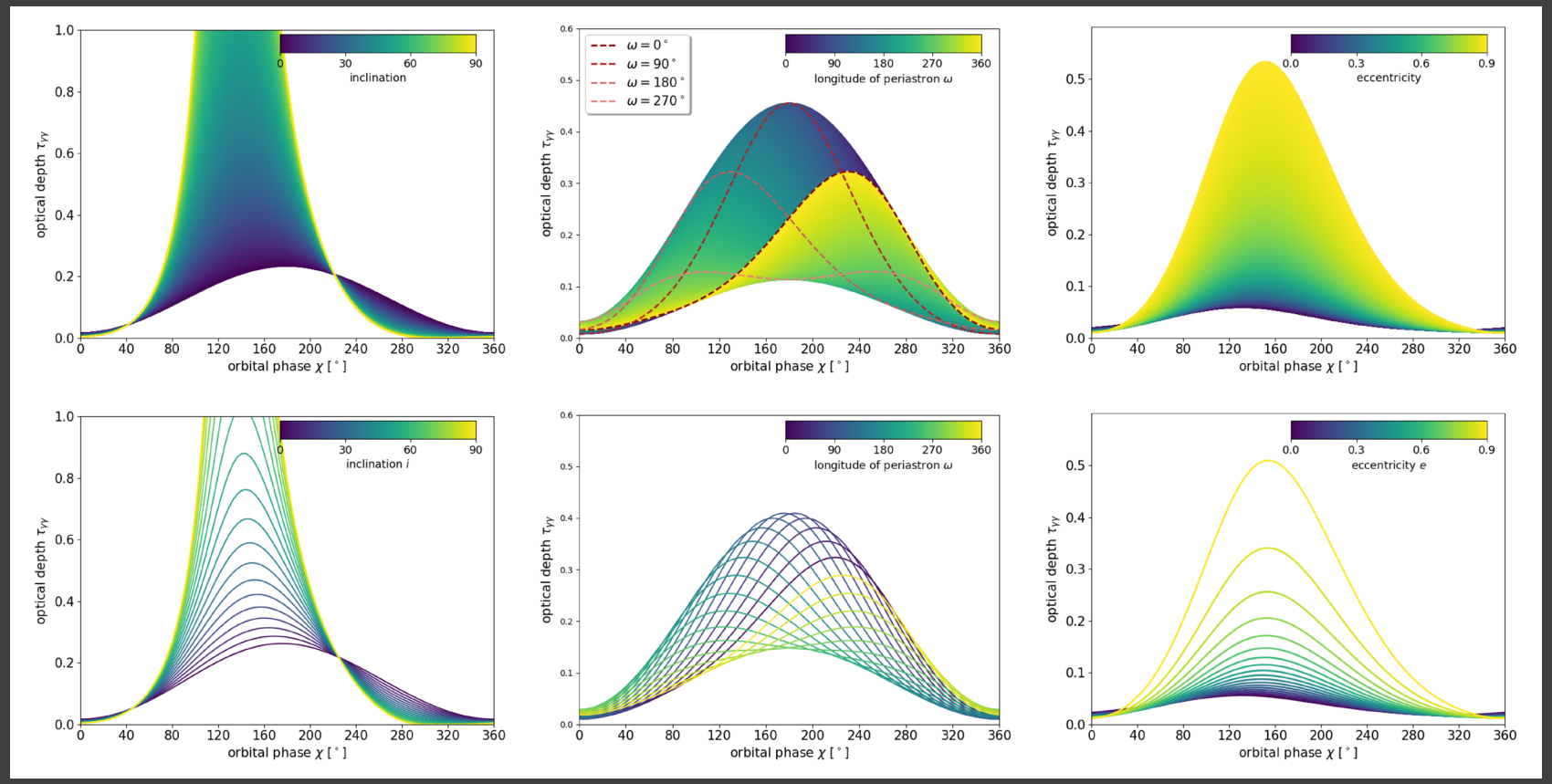
Orbit:	P_{orb} = 3.4 years
	Eccentricity = 0.87
	Inclination = 22.2 deg
	Longitude of periastron = 138.7 deg
	Pulsar:
	P = 48 ms
	$L_{SD} = 8 \times 10^{35}$ erg/s
	$t_c = 3.3 \times 10^5$ years
Star:	Be star
	$L_{star} = 2.3 \times 10^{38}$ erg/s
	T = 27500 – 30000 K
	M = 31 M_{sun}
	R = 8.1 – 9.7 R_{sun}
	D = 2.3 kpc

Orbital parameters are well determined from observations!



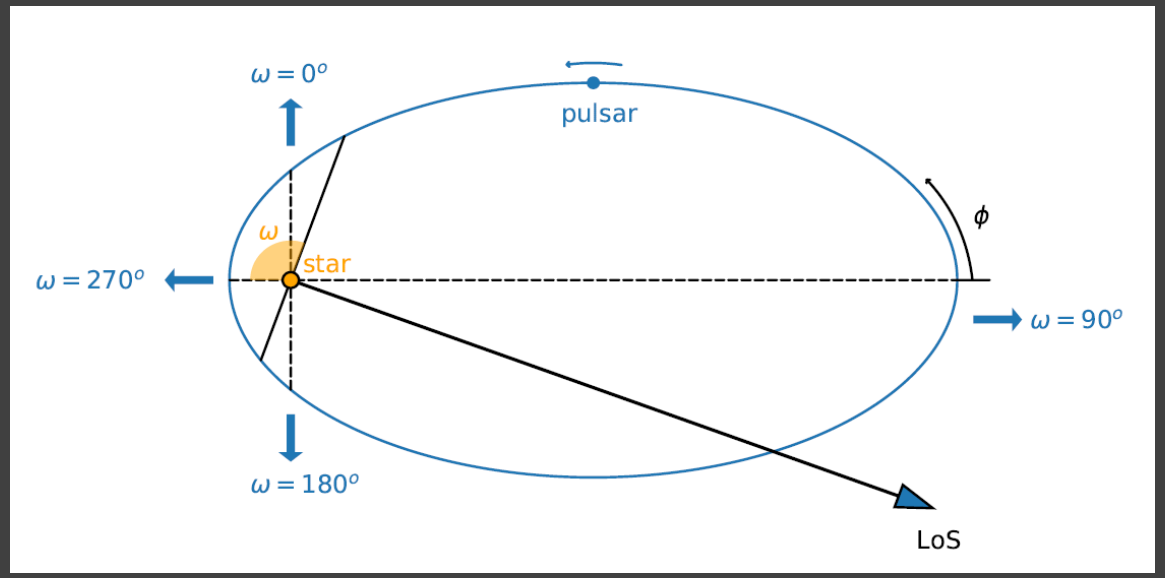
Credits: NASA's Goddard Space Flight Center/Francis Reddy

Dependence of opacity on parameters



Simplified analytic solution
(look for it in proceedings/forthcoming paper)

Exact numeric solution

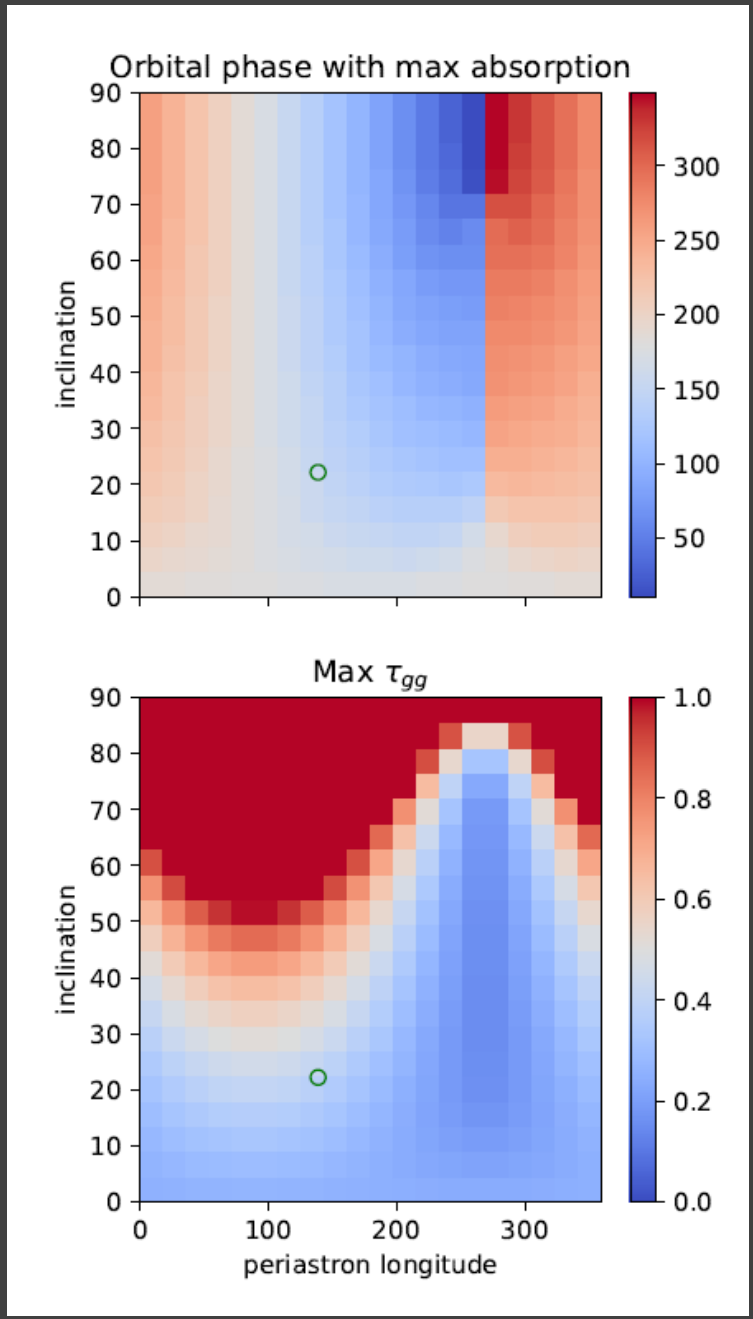


Method

- Main assumption: the minimum in the TeV light curve is defined by the highest gamma-gamma absorption
- For a fixed eccentricity we vary inclination (0°, 90°) and longitude of periastron (0°, 360°) and for each combination of (i, ω) we calculate the orbital phase at which absorption for a 1 TeV photon would be the highest
- Gamma-gamma absorption is calculated taking into account only stellar photons (without circumstellar disk) and assuming that gamma-ray emission is produced at the pulsar position

Test:
PSR B1259-63

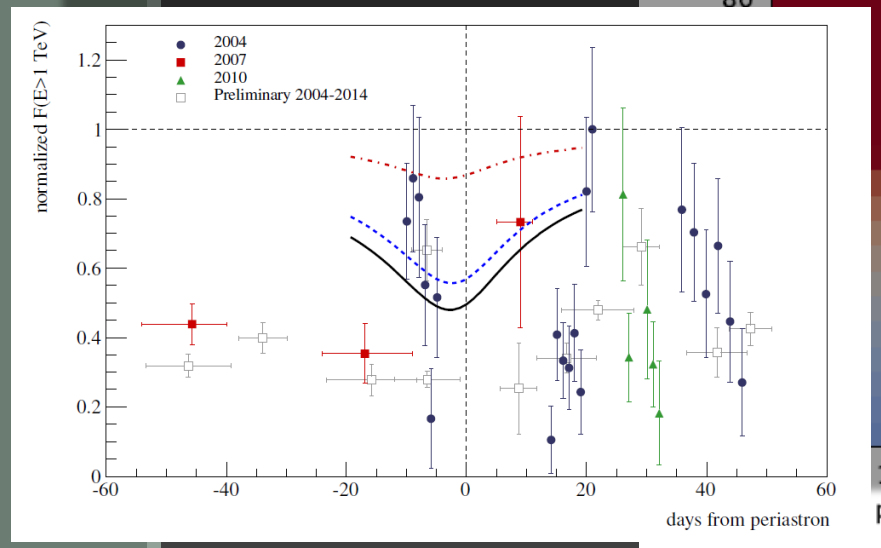
- orbital parameters are well determined from observations

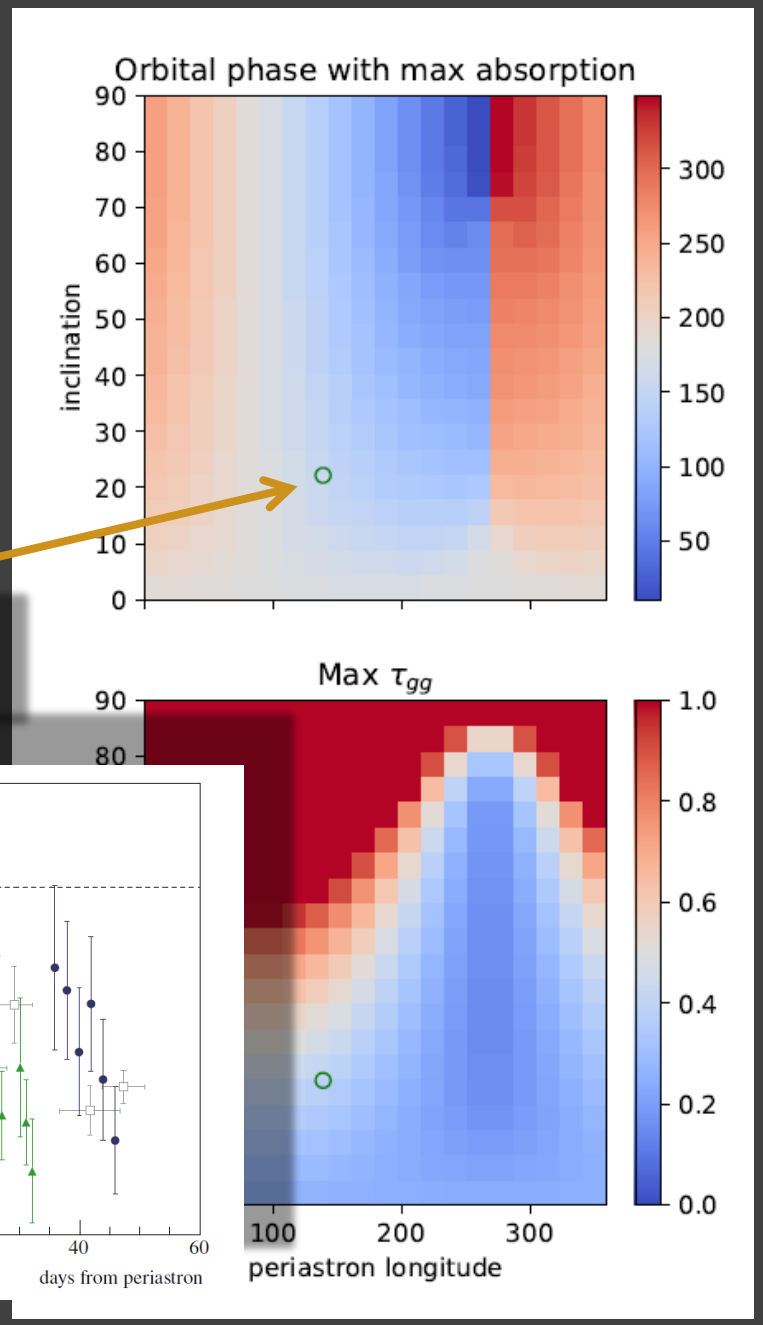


Test:
PSR B1259-63

- orbital parameters are well determined from observations

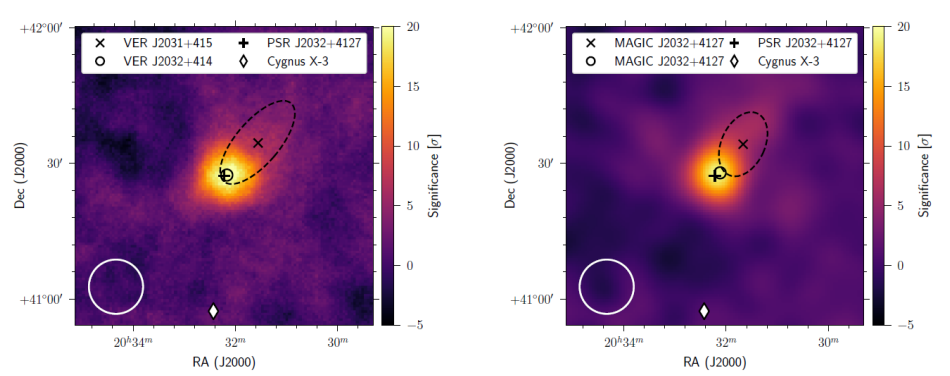
Orbital phase: 154 deg
Time: 2 days before periastron



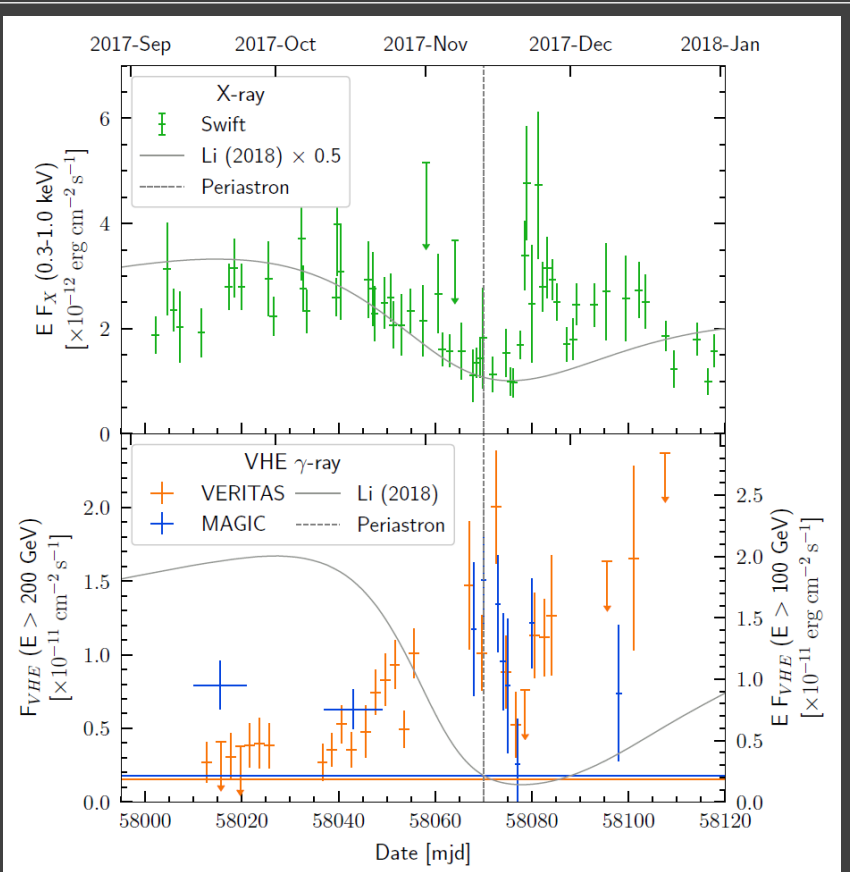


PSR J2032+4127/ MT91 213

- New member of the class
- Detected in 2017
- Coincident with TeV J2032+413
- Orbital period of 45-50 years
- X-ray dip is not coincident with the gamma-ray dip
- TeV light curve has its minimum about 10-20 days after periastron



(c) VERITAS Fall 2017 sky map (d) MAGIC Fall 2017 sky map



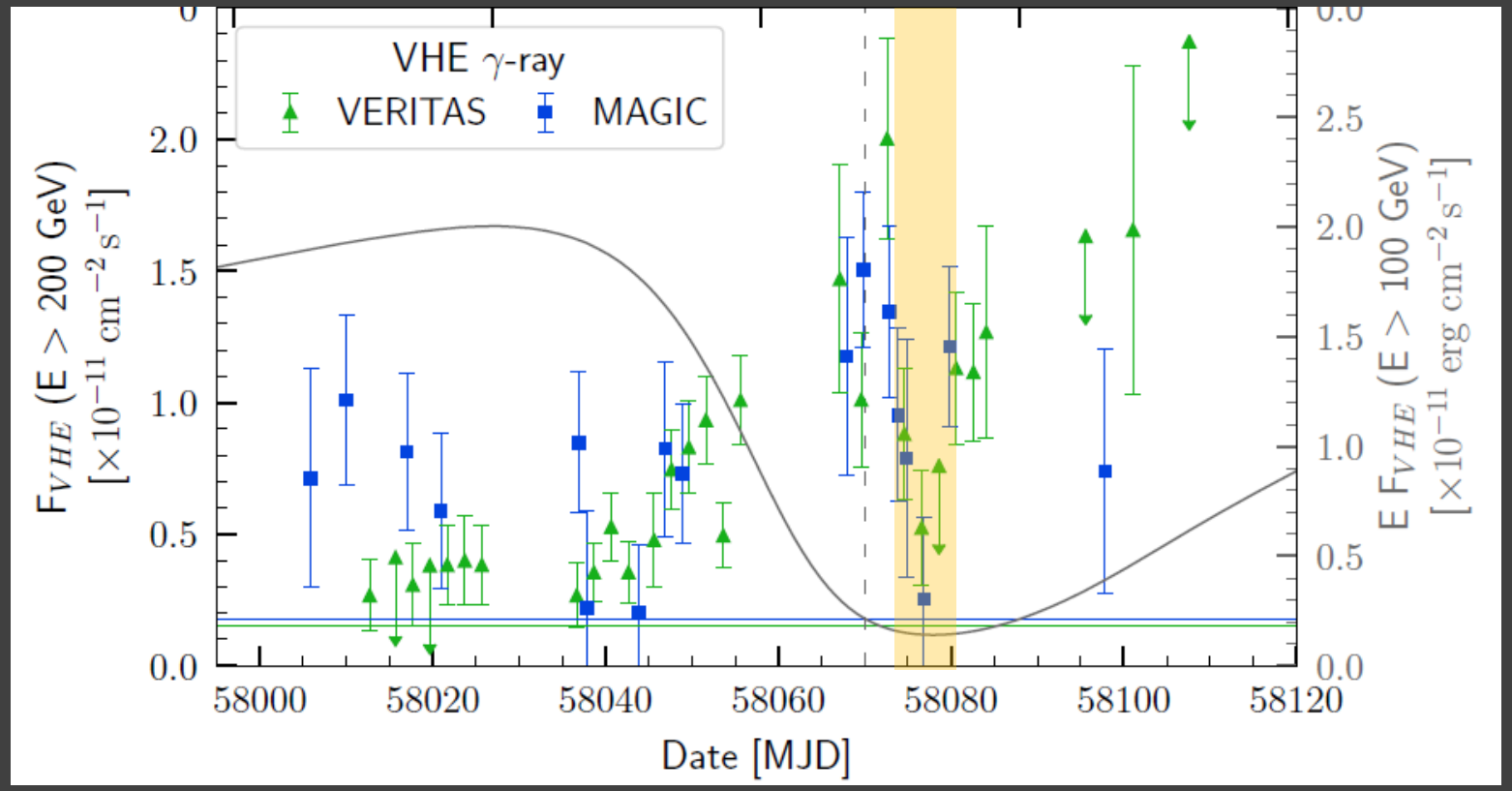
(b) Periastron

VERITAS & MAGIC, 2018

Orbital solutions

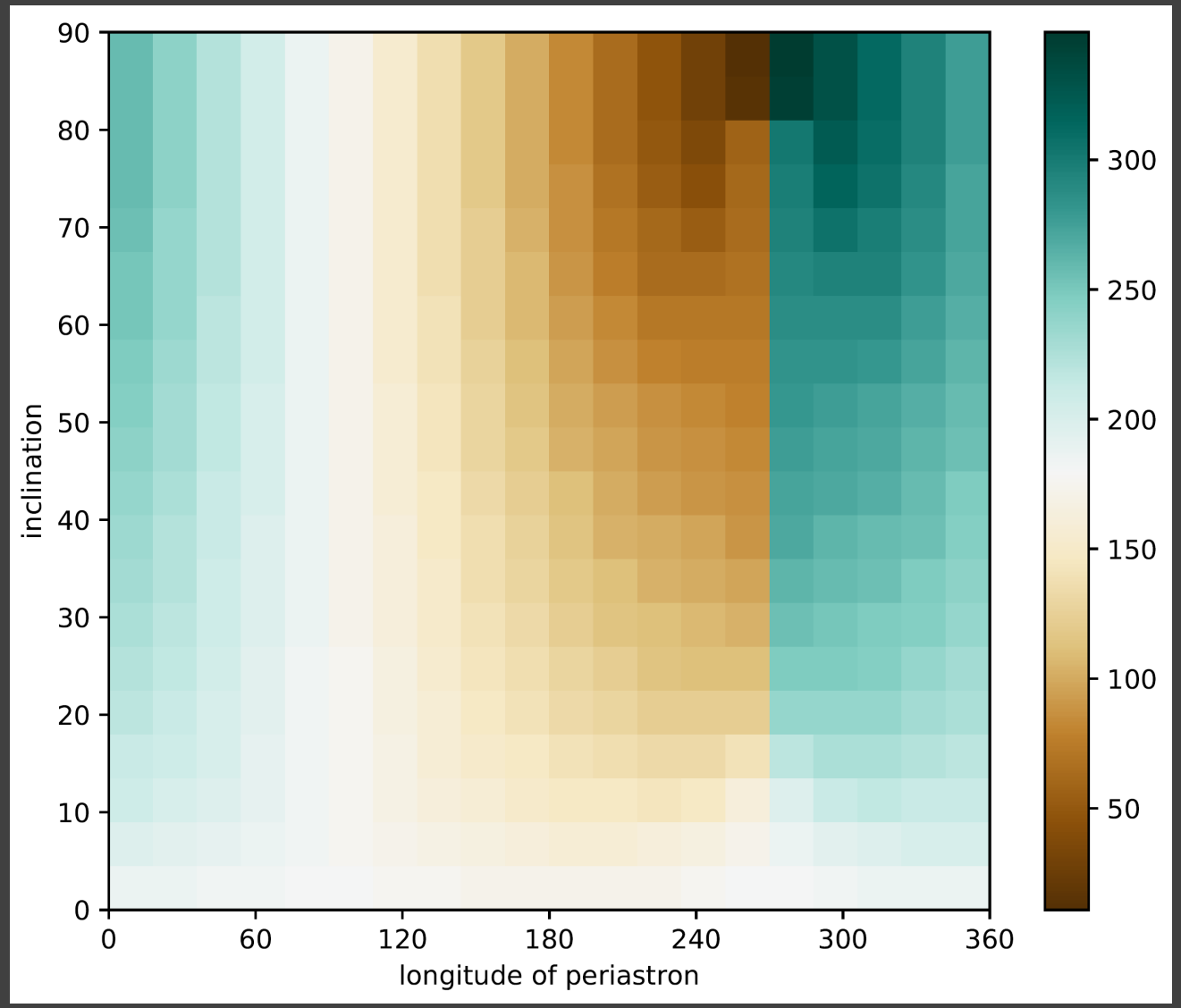
Parameter	Model 1	Model 2	Model 3
Right ascension, α (J2000.0)	$20^h32^m13^s.119(2)$	$20^h32^m13^s.119(2)$	$20^h32^m13^s.119(2)$
Declination, δ (J2000.0)	$41°27'24''.38(2)$	$41°27'24''.35(2)$	$41°27'24''.34(2)$
Epoch of frequency, t_0 (MJD)	55700.0	55700.0	55700.0
Frequency, ν_0 (Hz)	6.980 979(5)	6.980 975(6)	6.980 973(7)
Frequency time derivative, $\dot{\nu}_0$ ($10^{-12}s^{-2}$)	−0.5396(5)	−0.5538(4)	−0.5617(5)
Orbital period, P_b (d)	16 000	17 000	17 670
Epoch of periastron, T_0 (MJD)	58053(1)	58069(1)	58068(2)
Projected semimajor axis, x (light-second)	7138(48)	9022(216)	16335(3737)
Eccentricity, ϵ	0.936(1)	0.961(2)	0.989(5)
Longitude of periastron, ω (deg)	52(1)	40(1)	21(5)
Mass function, f_m ($M_\odot$)	1.5	2.7	15.0
Glitch epoch, T_g (MJD)	55 810.77	55 810.77	55 810.77
Frequency, $\Delta\nu_g$ (10^{-6} Hz)	1.9064(1)	1.9073(1)	1.9076(1)
Frequency time derivative, $\Delta\dot{\nu}_g$ ($10^{-15}s^{-2}$)	−0.501(8)	−0.545(7)	−0.564(6)
DM (pc cm^{-3})	114.68(3)	114.67(2)	114.66(2)
DM time derivative, DM1 (pc $cm^{-3}yr^{-1}$)	−0.02(1)	−0.01(1)	−0.01(1)
rms timing residual, σ_t (ms)	0.53	0.44	0.42

PSR J2032+4127: TeV light curve



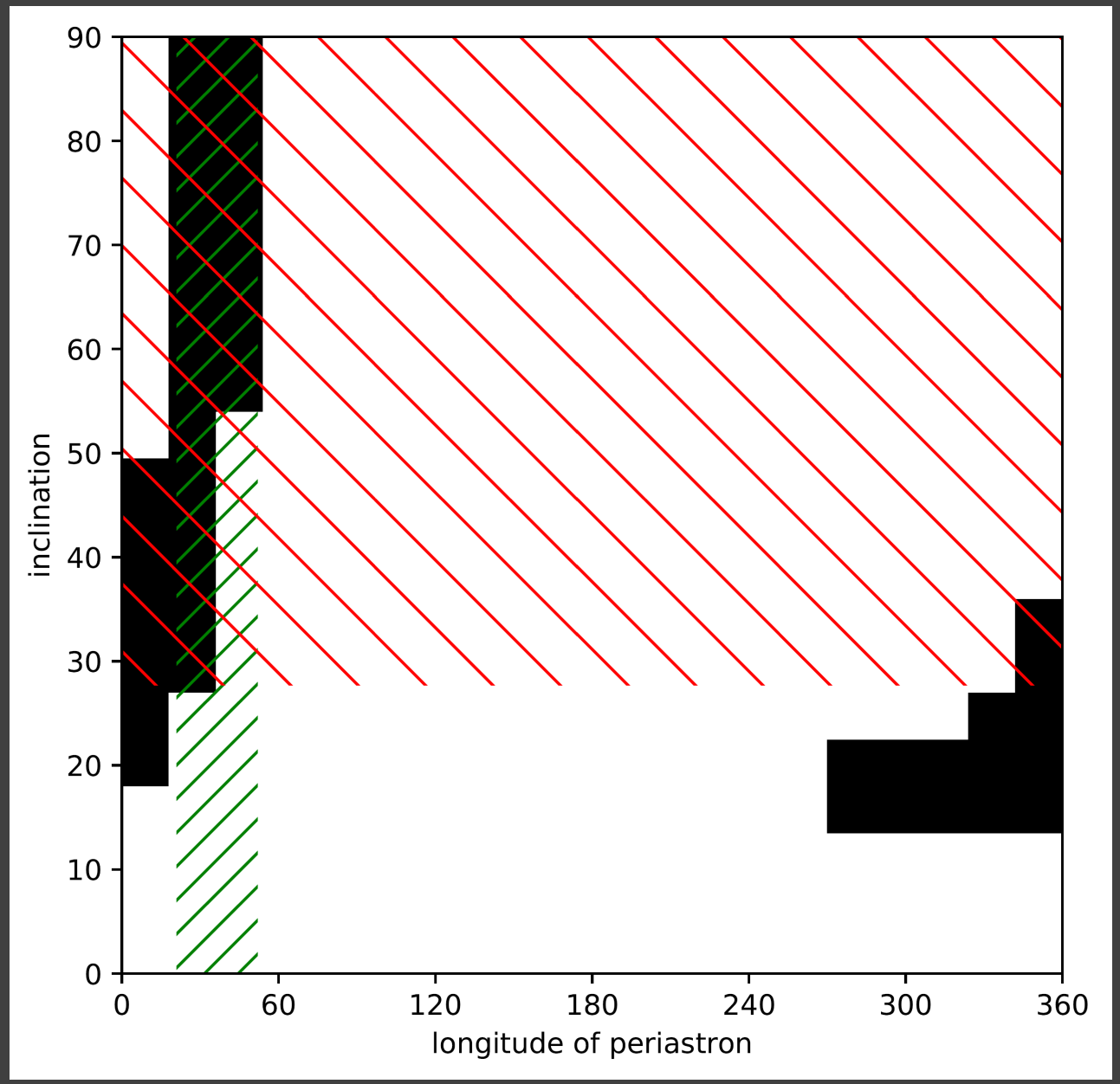
VERITAS & MAGIC, 2018

- Minimum occurs 10-20 days after periastron
- Corresponds to the orbital phase of 216-242 deg for P = 17000 days



PSR J2032+4127:

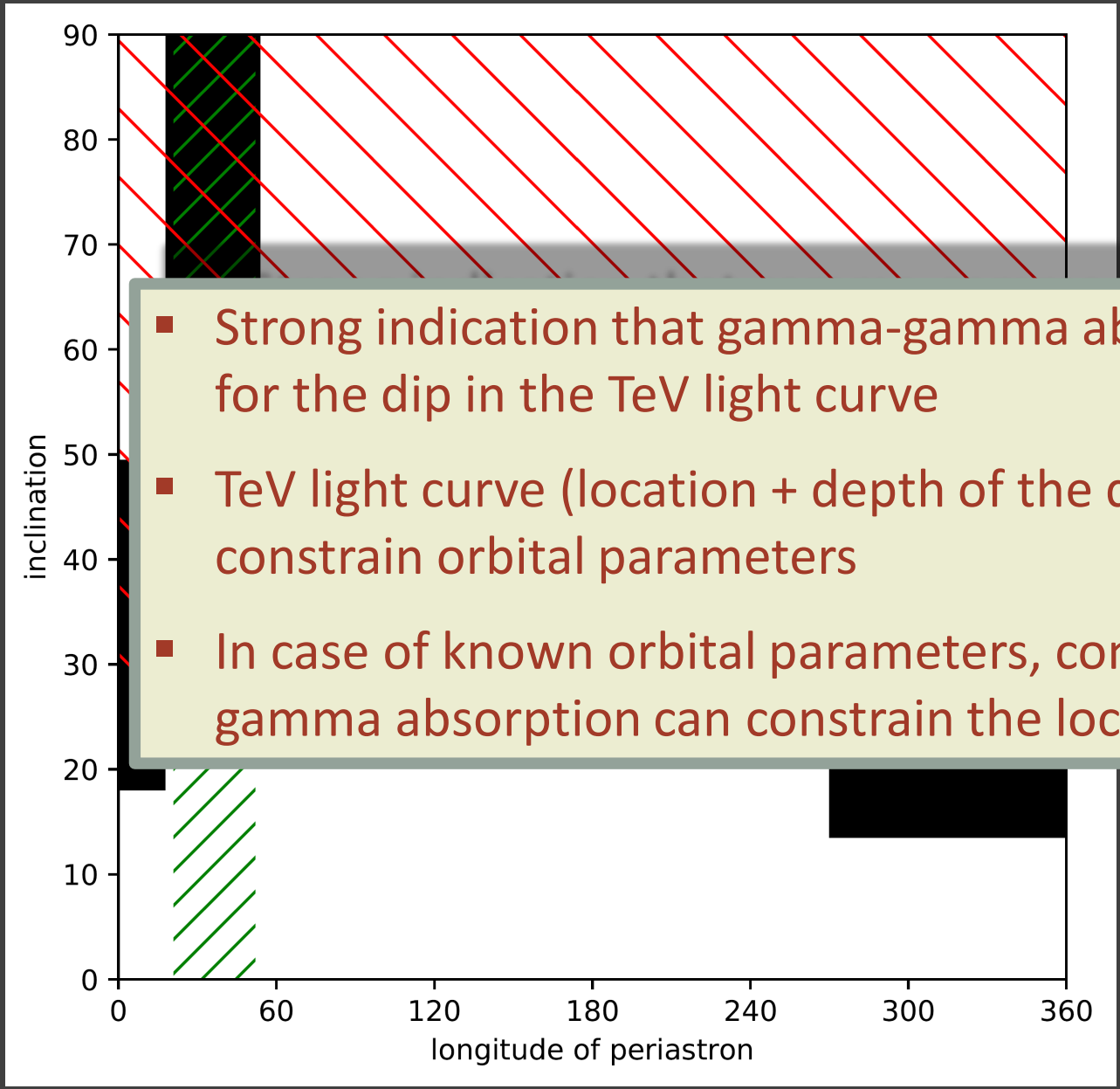
e = 0.961 (0.936-0.989)



PSR J2032+4127:

allowed solutions

- Green and read dashed areas correspond to constraints set by optical observations (Ho et al. 2017)



PSR J2032+4127:

- Strong indication that gamma-gamma absorption is indeed responsible for the dip in the TeV light curve
- TeV light curve (location + depth of the dip) can be successfully used to constrain orbital parameters
- In case of known orbital parameters, connection of the dip to the gamma-gamma absorption can constrain the location of the emitting region

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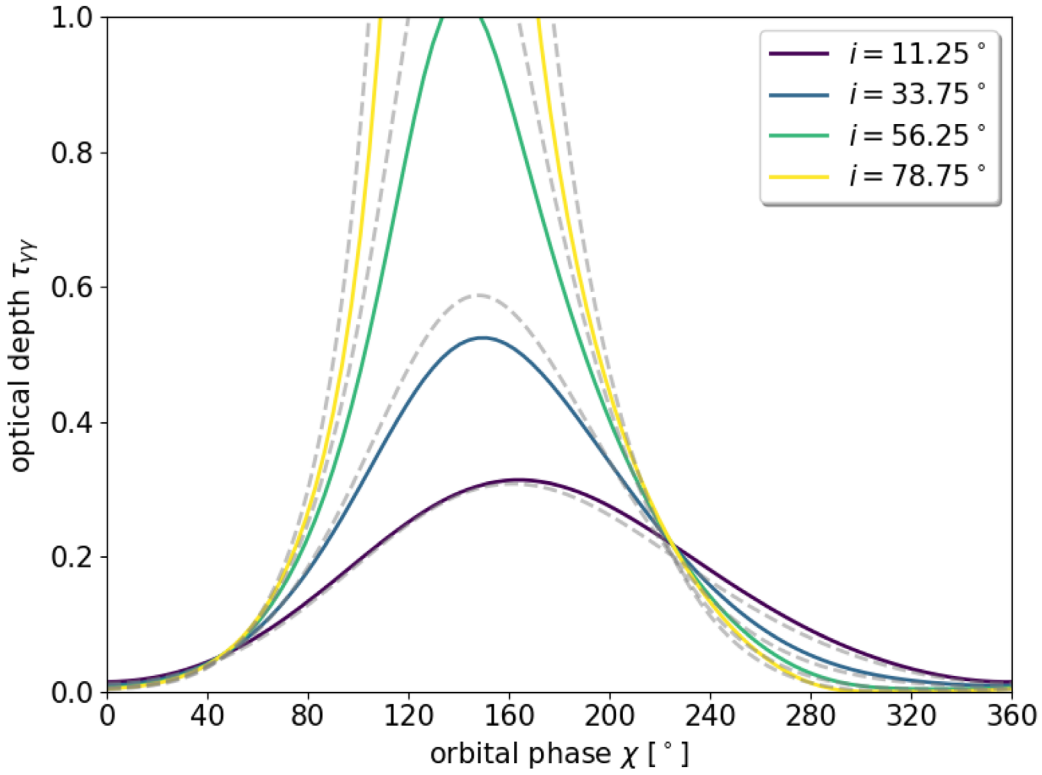
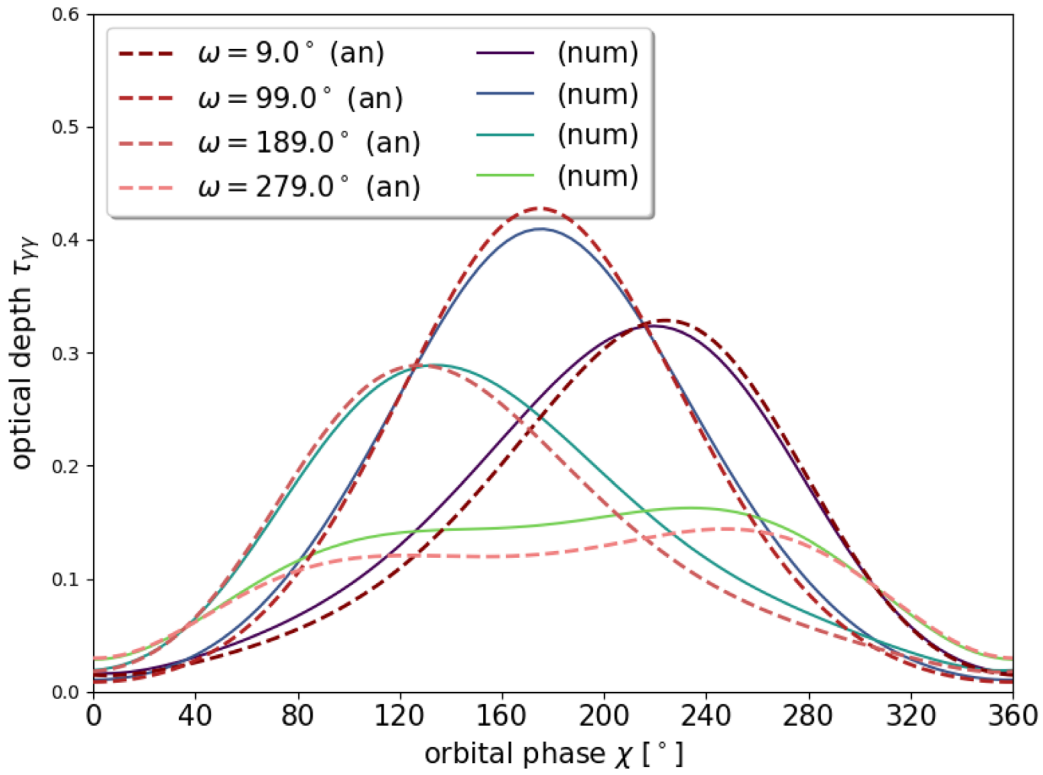
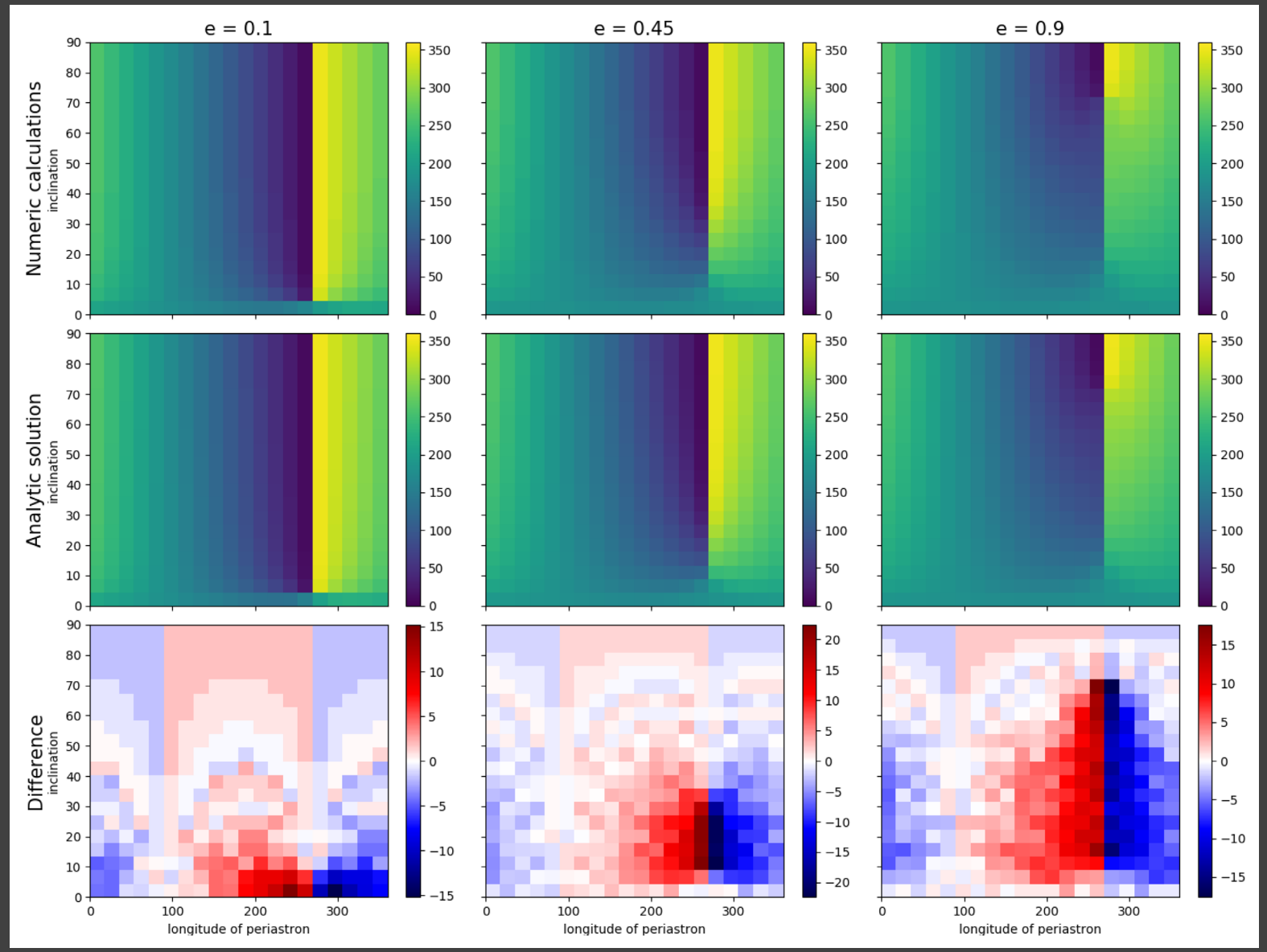
Backup slides

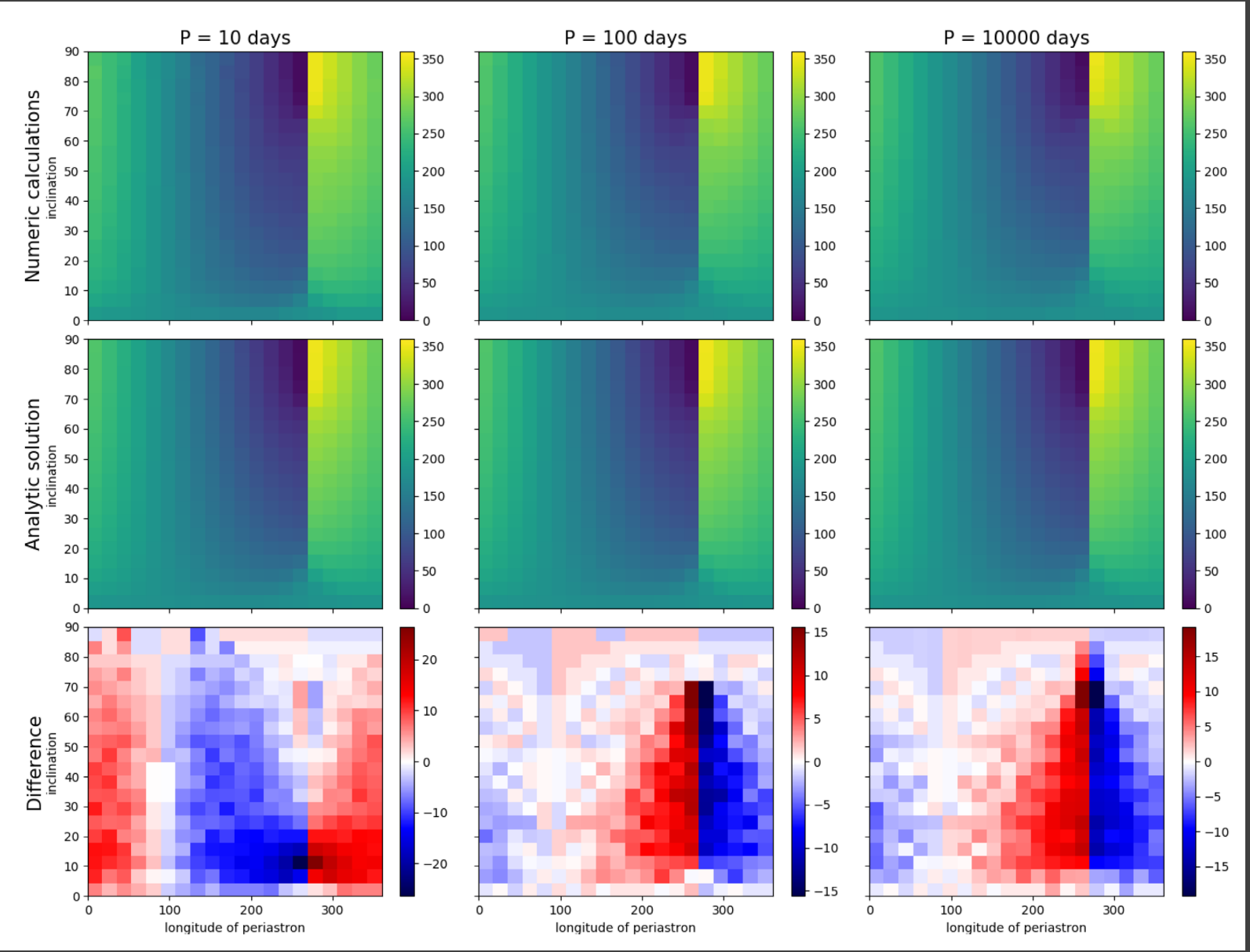
Analytic VS Numeric







Location of max absorption (for different eccentricity)



Location of max absorption (for different orbital period)