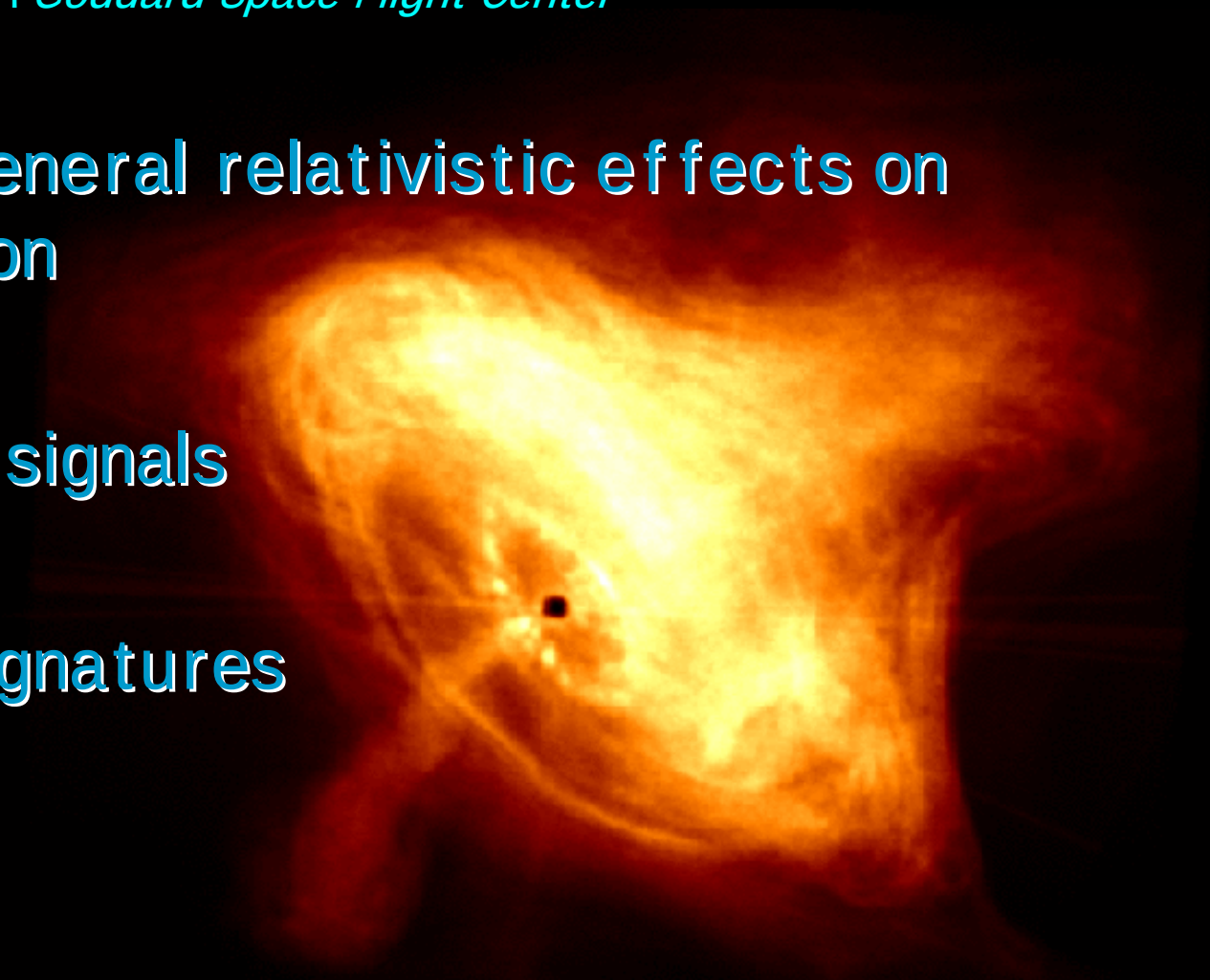
Pulsar Emission: Is It All Relative?

Alice Harding

NASA Goddard Space Flight Center

- Special and general relativistic effects on pulsed emission
- Decoding the signals
- Detectable signatures



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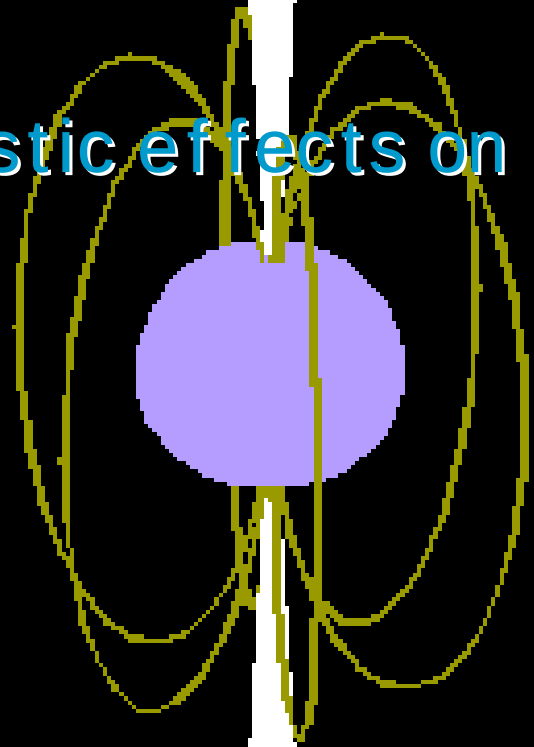
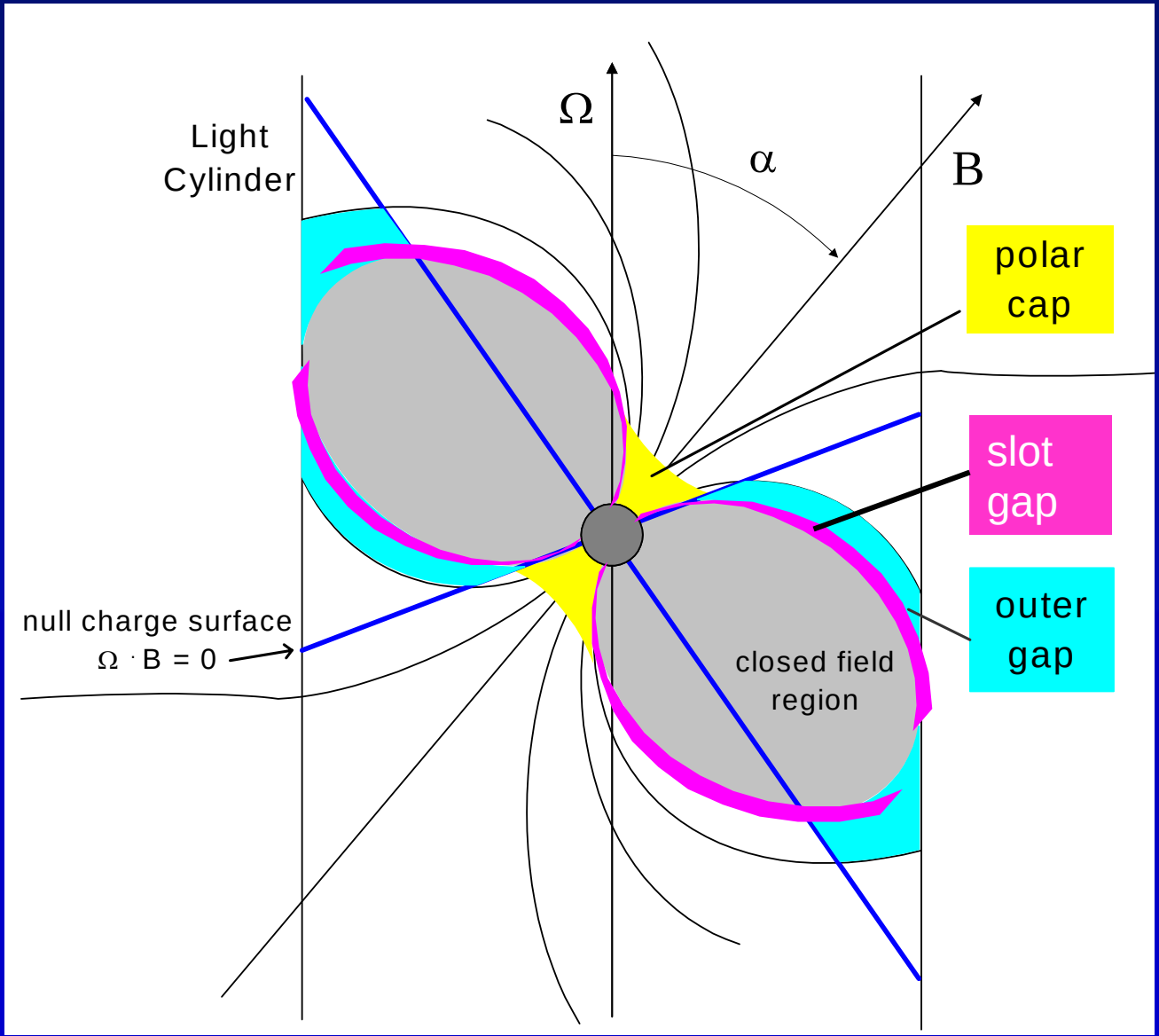


Pulsar high-energy emission models

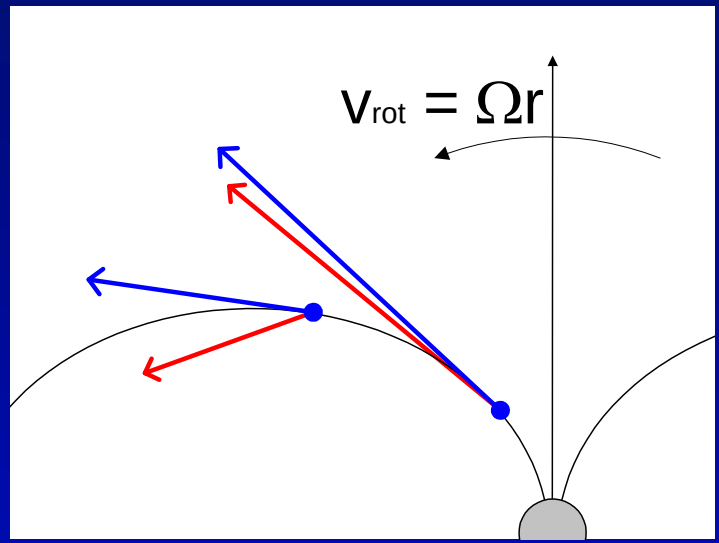


Studying the effects…

Special Relativistic Effects

- Aberration

$$\Delta\phi_{ab} \approx -\frac{r_{em}}{R_{LC}}$$

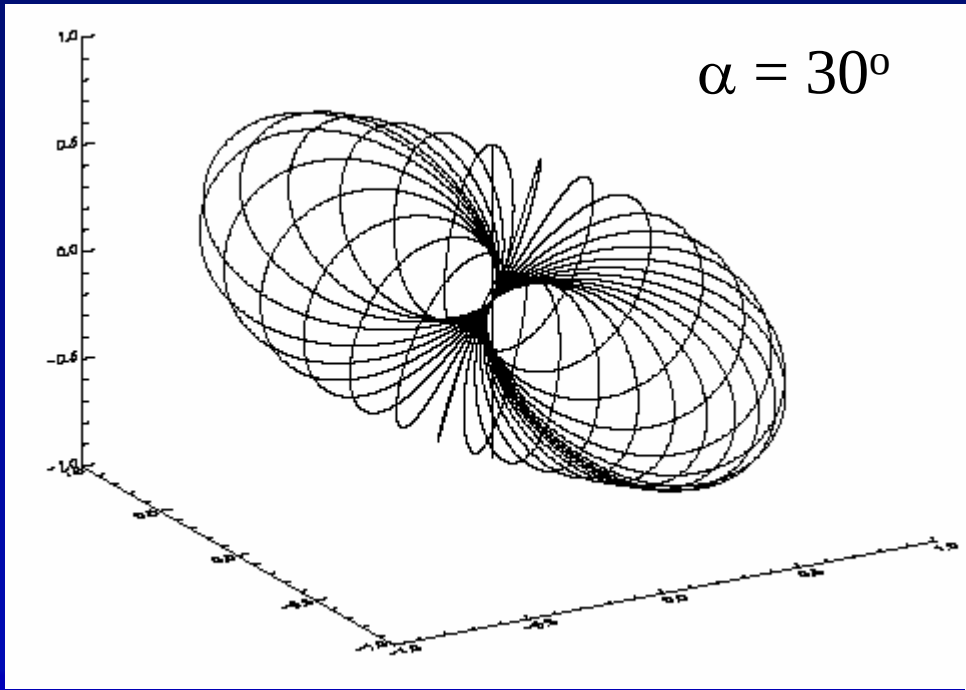


- Time-of-flight delays

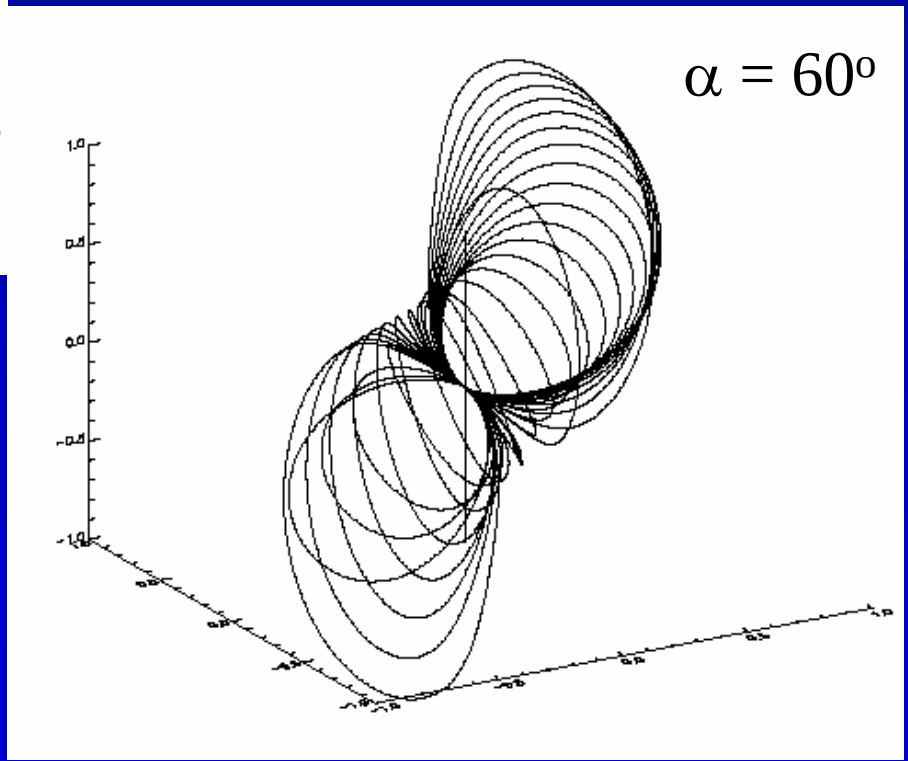
$$\Delta\phi_{ret} \approx -\frac{r_{em}}{R_{LC}}$$

- Retardation of magnetic field

Retarded vacuum dipole magnetic field

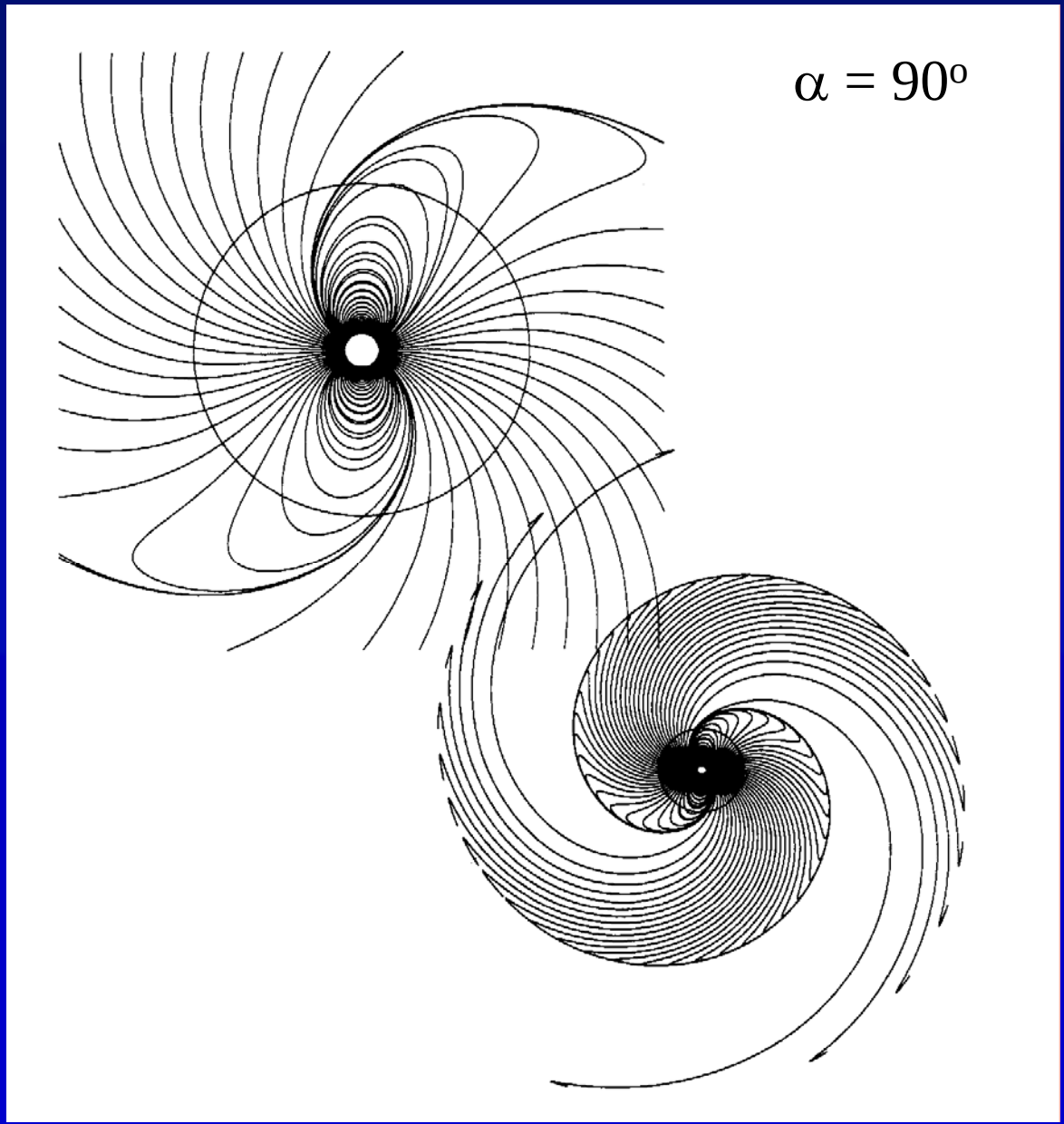


$$t_r = t - r/c$$



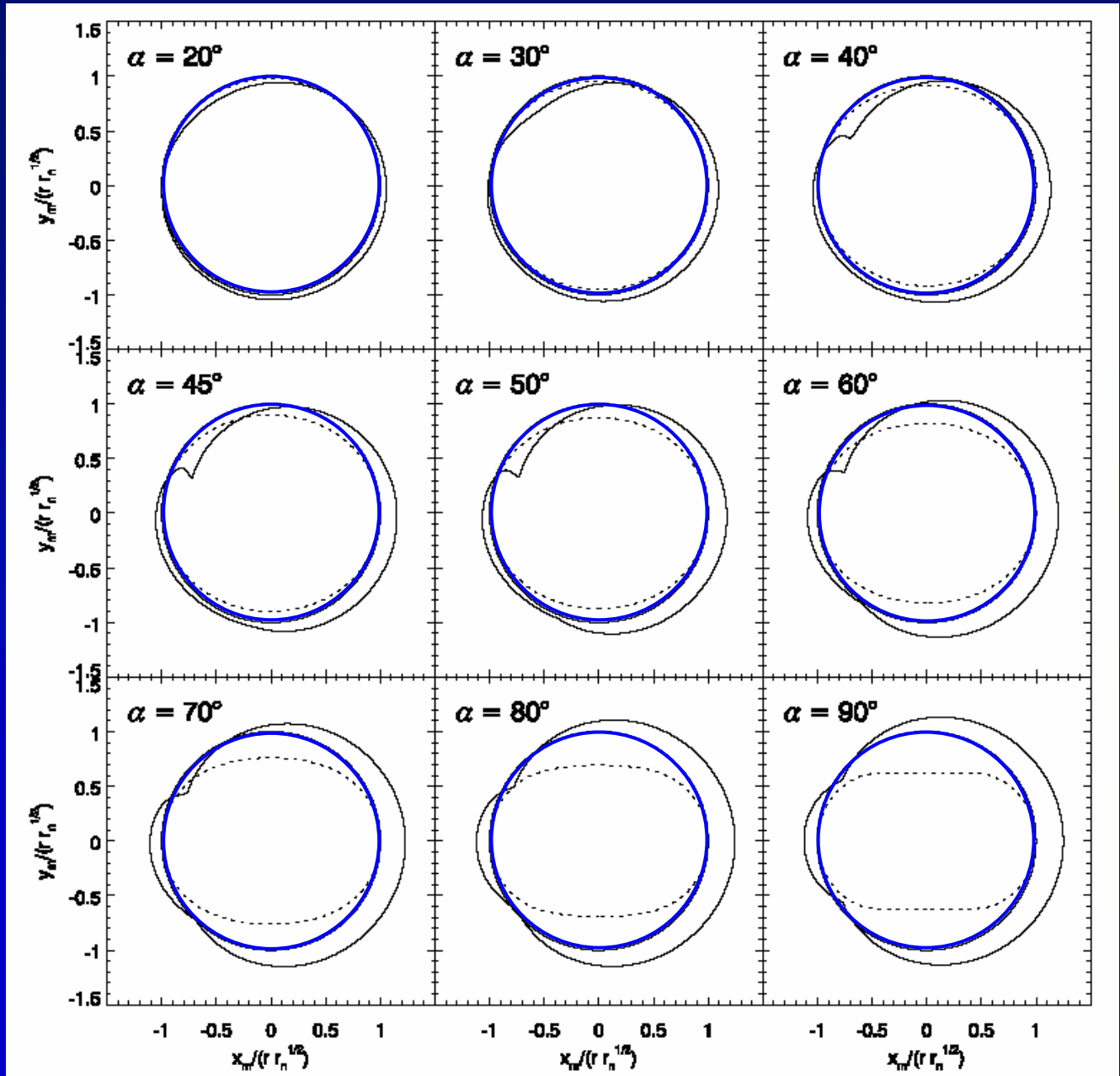
Arendt & Eilek 1998

Sweepback of magnetic field



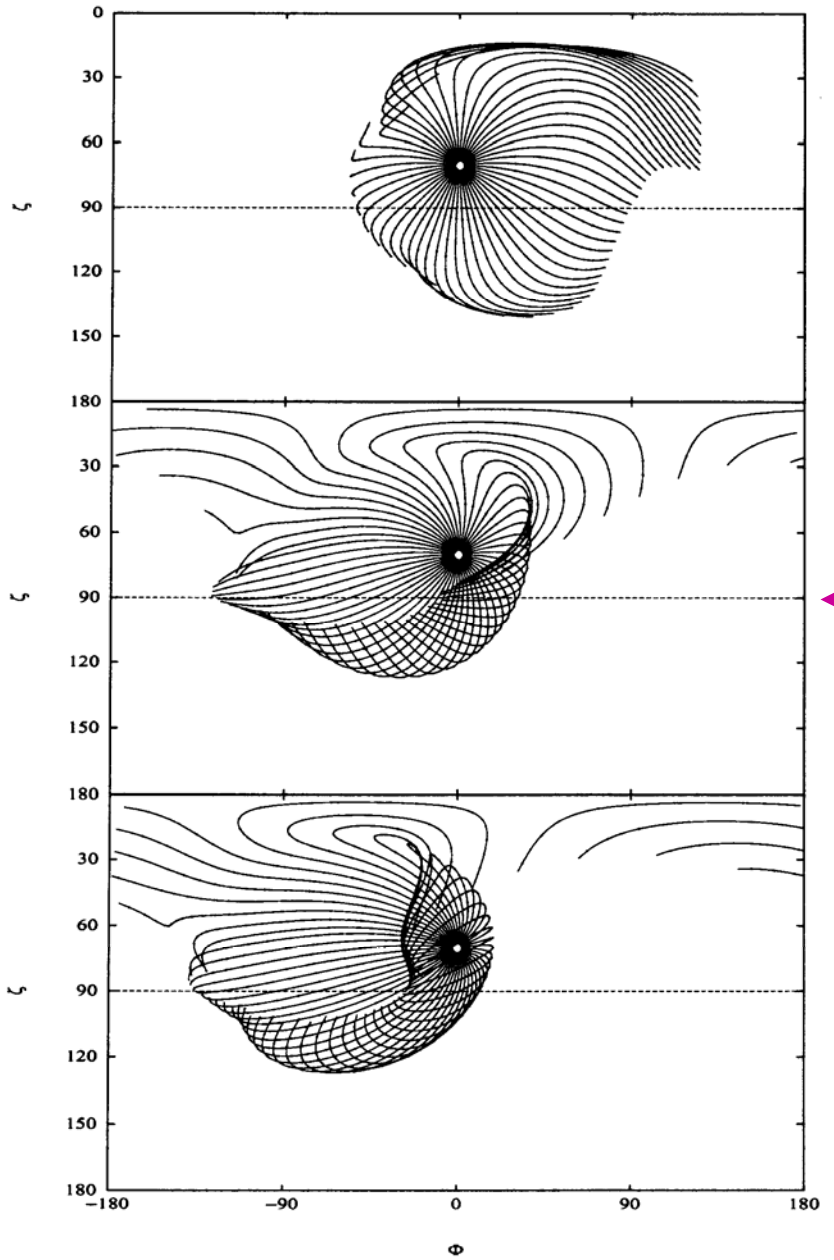
Yadigaroglu 1997

Magnetic field retardation: distortion of polar cap



Dyks & Harding 2004

Projected field lines from single pole



Sweepback only ...

plus aberration ...

... and travel time delay

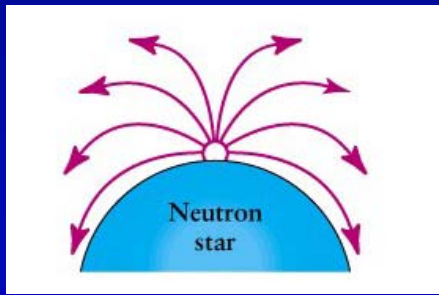
Yadigaroglu 1997

General Relativistic Effects

- Photon red shift

$$\varepsilon = \varepsilon' \left(1 - \frac{2GM}{Rc^2} \right)^{1/2}$$

- Bending of light



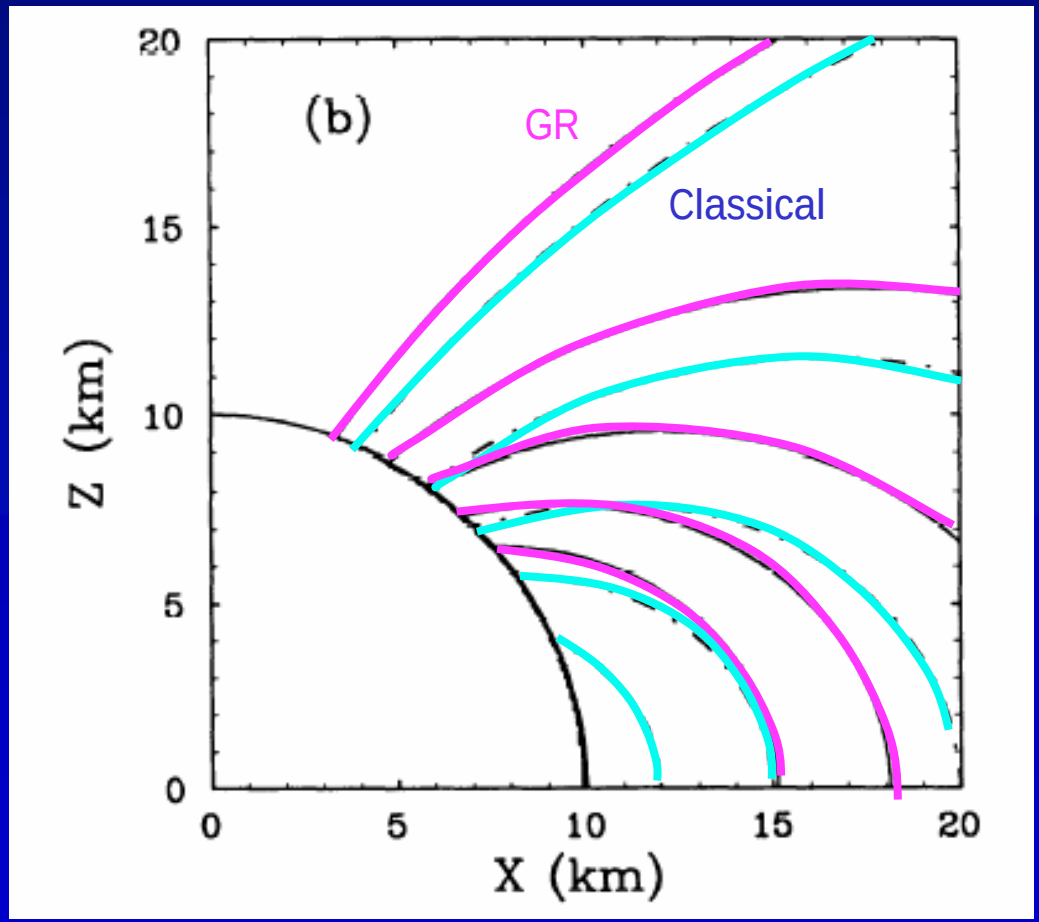
- Dipole field in curved space-time

- Inertial frame-dragging

General Relativistic Effects

- Dipole field in curved space-time

Wasserman & Shapiro (1983)



- Increase in surface field strength

$$B_0^{GR} \approx (1+\frac{r_g}{R})\ B_0^{Cl}$$

- Smaller polar cap angle

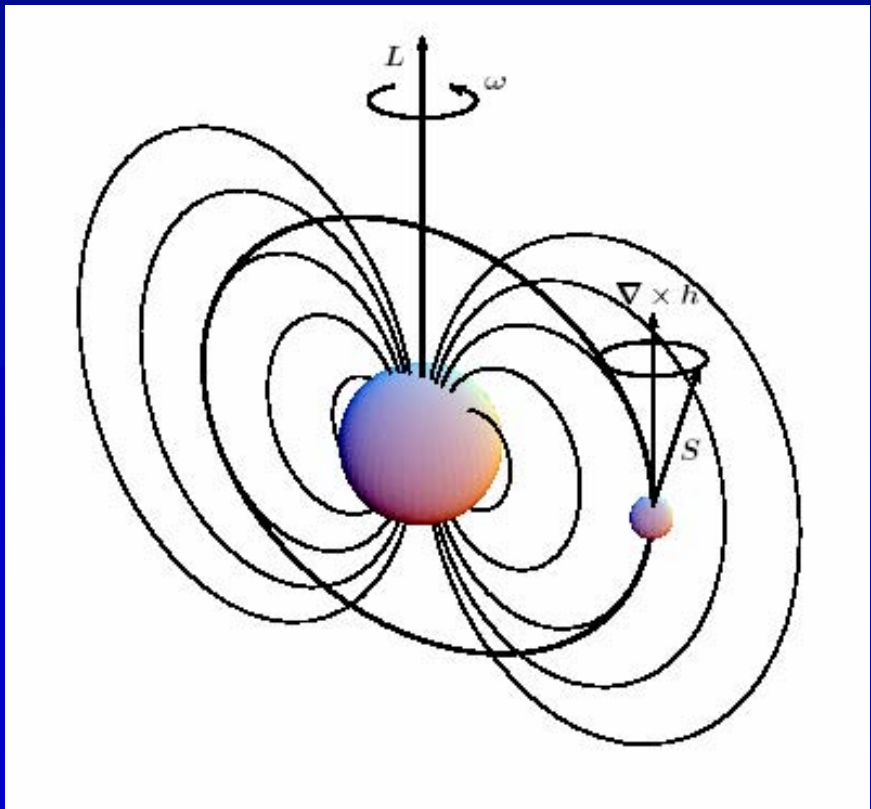
$$\theta_{GR} \approx \frac{\theta_{Cl}}{\sqrt{1+r_g/R}}$$

$$r_g / R \approx 0.25 - 0.5$$

- *Inertial-frame dragging*

  Lense-Thirring effect

$$\omega = \frac{2GL}{c^2 r^3}$$



Frame dragging electric field

$$\nabla \cdot E_{\parallel} = 4\pi(\rho - \rho_{GJ})$$

$$\rho_{GJ} \approx -\frac{1}{4\pi c}\nabla \cdot \left[\frac{1}{\alpha}(\mathrm{w\text{-}v}) \times B\right]$$

$$E_{\parallel} \propto \frac{\theta_0}{2}\left(\frac{r}{R}\right)^{-1/2} \sin\alpha\cos\phi + \kappa\left(\frac{r}{R}\right)^{-4} \cos\alpha$$

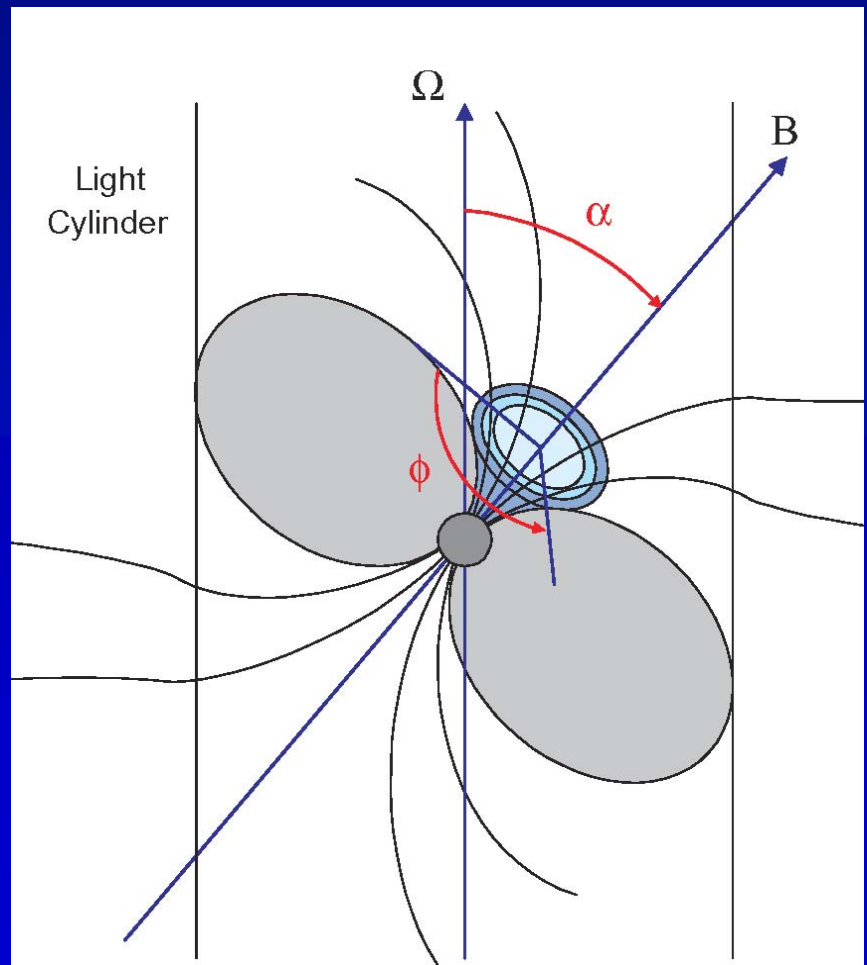
$$\kappa \propto \frac{I}{R^3} \approx 0.15$$

Mestel & Shibata 1994

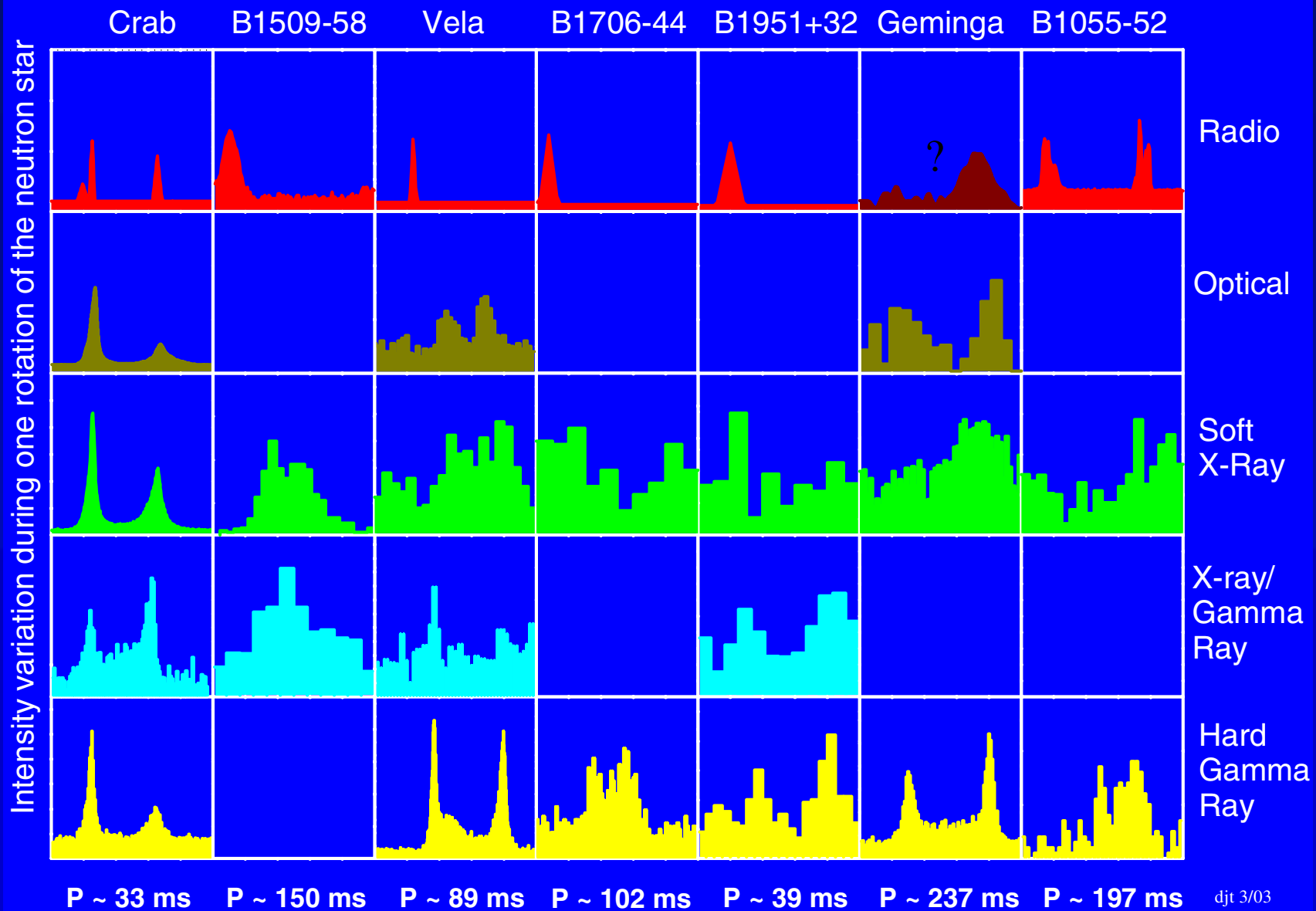
Muslimov & Tsygan 1992

Frame-dragging dominates!

$$\frac{E_{\parallel}^{GR}}{E_{\parallel}^{Cl}} \approx 42\ P$$



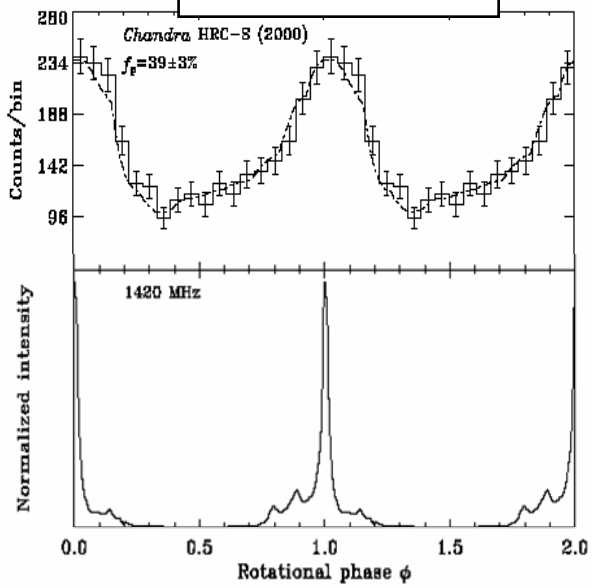
Decoding the signals…


Crab
B1509-58
Vela
B1706-44
B1951+32
Geminga
B1055-52
Intensity variation during one rotation of the neutron star
Radio
?
Optical
Soft
X-Ray
X-ray/
Gamma
Ray
Hard
Gamma
Ray
P ~ 33 ms
P ~ 150 ms
P ~ 89 ms
P ~ 102 ms
P ~ 39 ms
P ~ 237 ms
P ~ 197 ms
djt 3/03

Profiles of millisecond pulsars

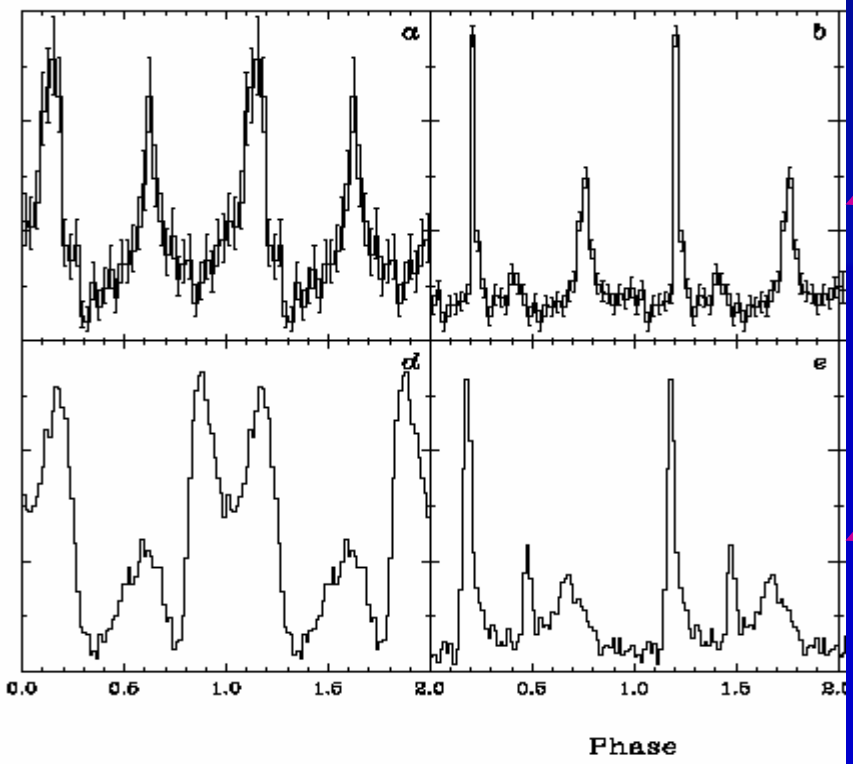
X-ray peaks (mostly) in phase with radio peaks

PSR J0437-4715



PSR J0218+4232

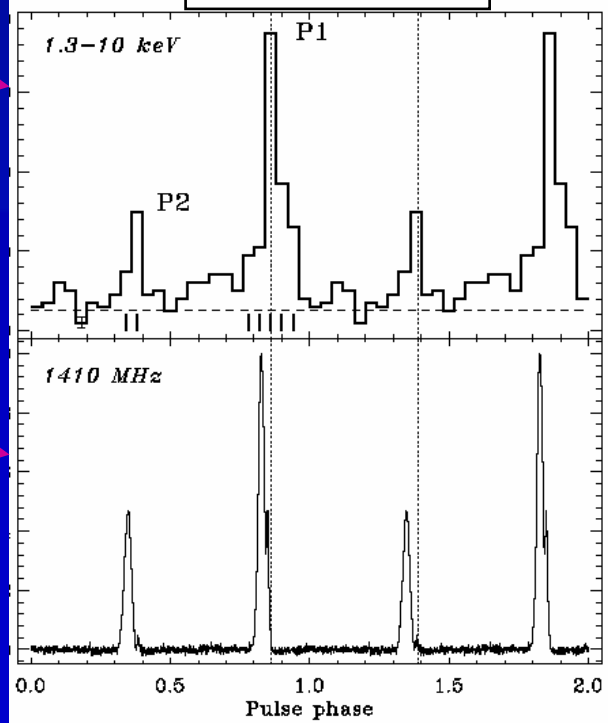
PSR B1821-24



X-Ray

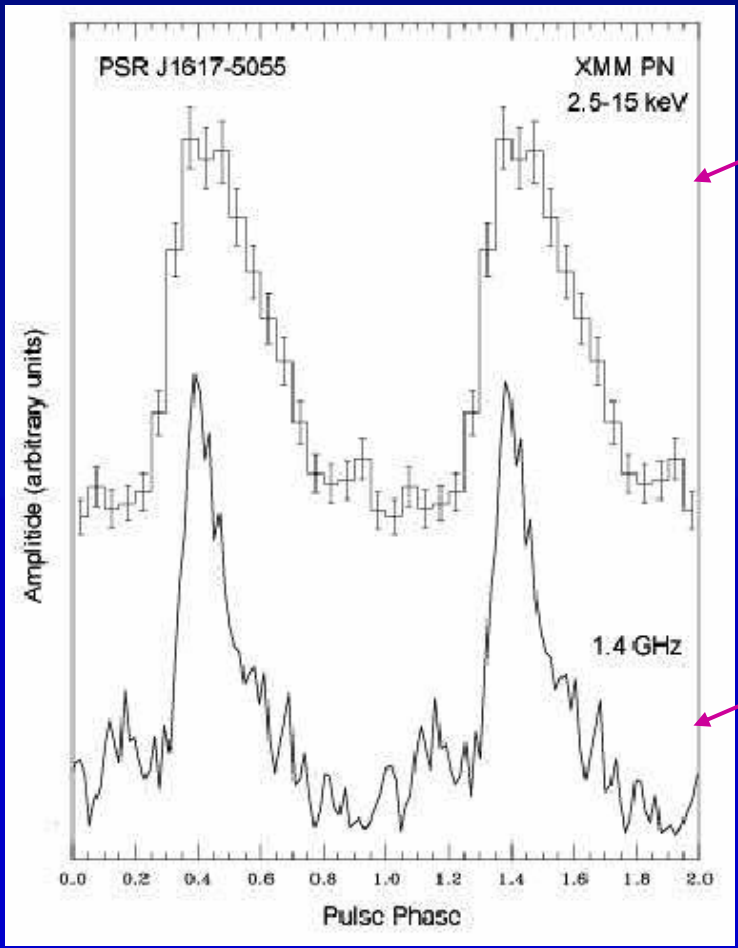
Radio

PSR B1937+21



Profiles of Short Period Pulsars

PSR J1617-5055
69 ms pulsar in RCW103

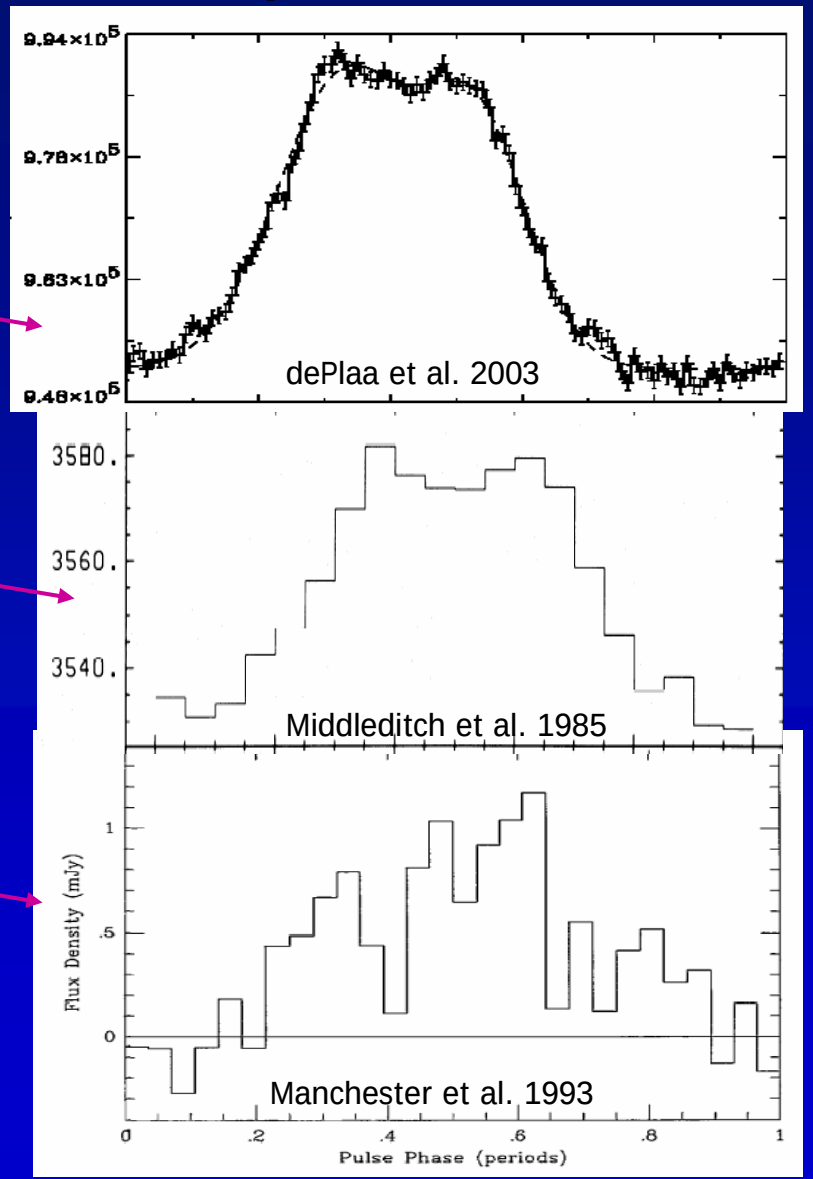


X-Ray

Optical

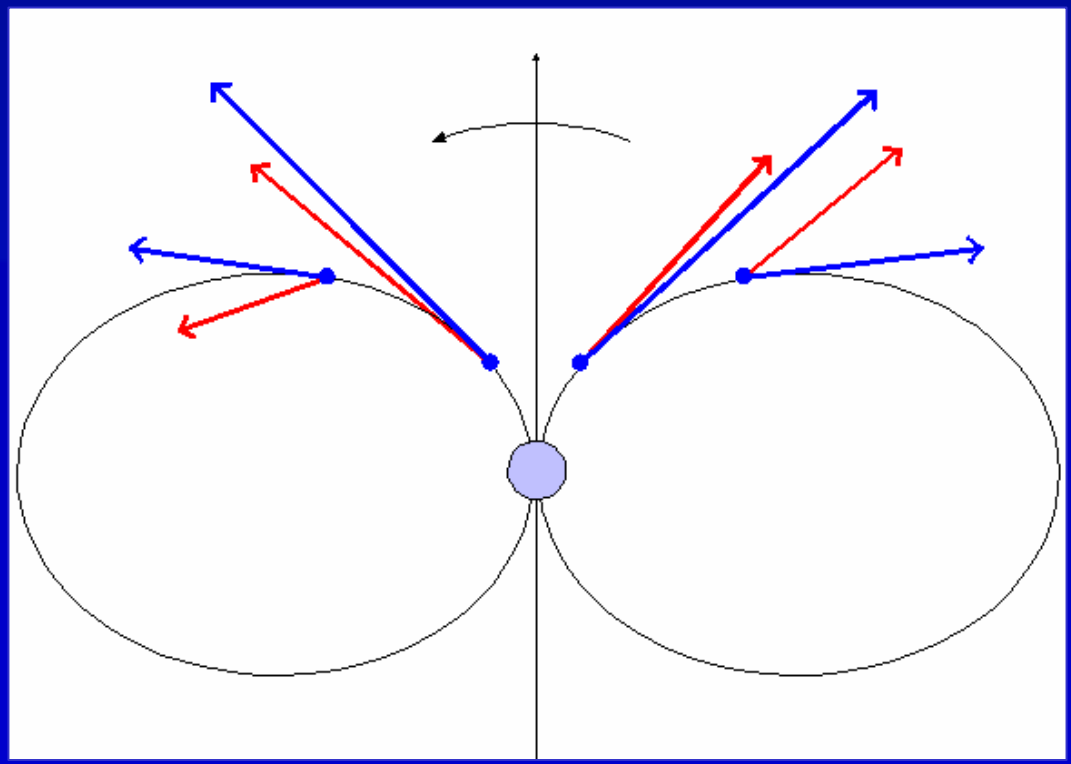
Radio

PSR B0540-69
50 ms pulsar in LMC

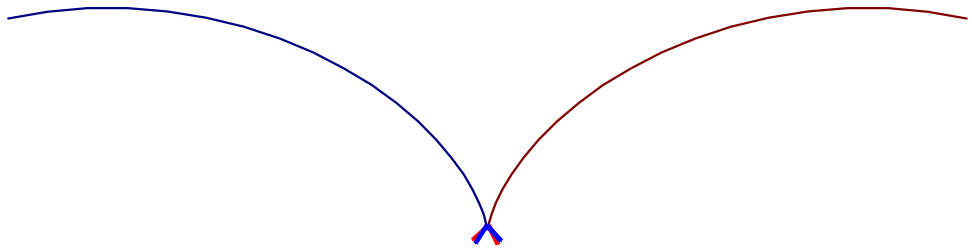


Caustic emission *Morini 1983*

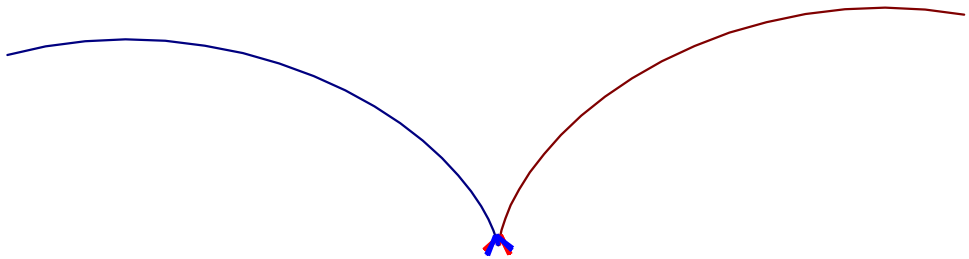
- Particles radiate along last open field line from polar cap to light cylinder
- Time-of-flight, aberration and phase delay cancel on trailing edge ⟶ emission from many altitudes arrive in phase ⟶ caustic peaks in light curve



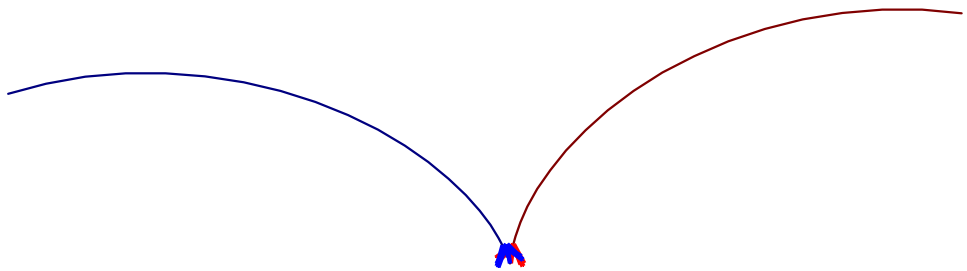
Formation of caustics



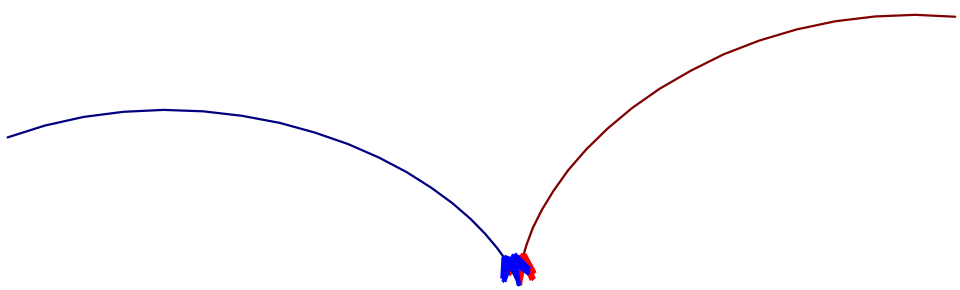
Formation of caustics



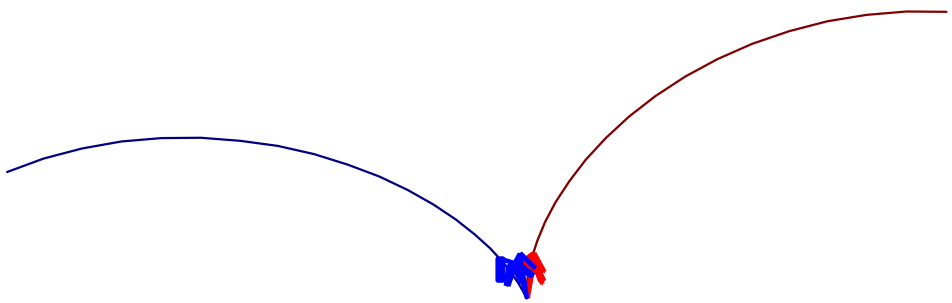
Formation of caustics



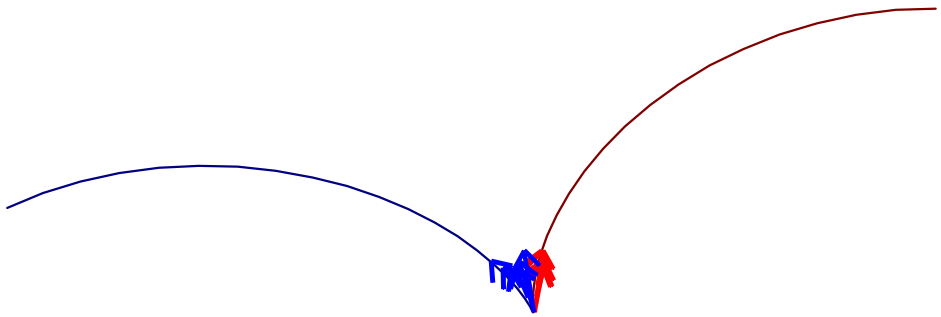
Formation of caustics



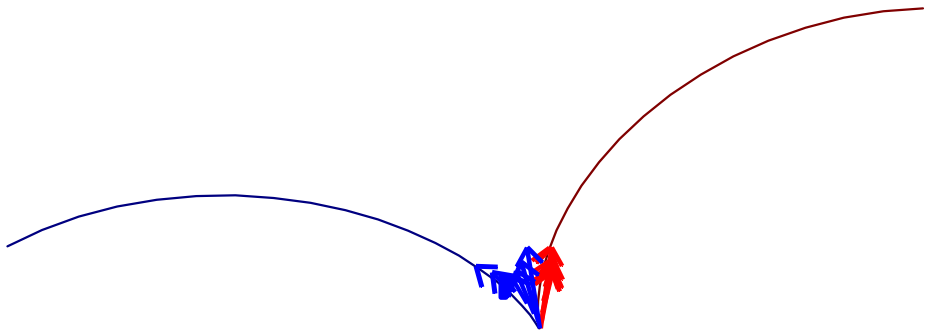
Formation of caustics



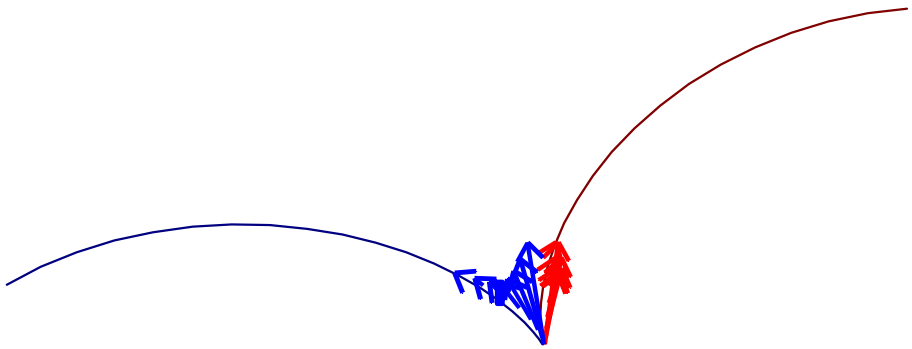
Formation of caustics



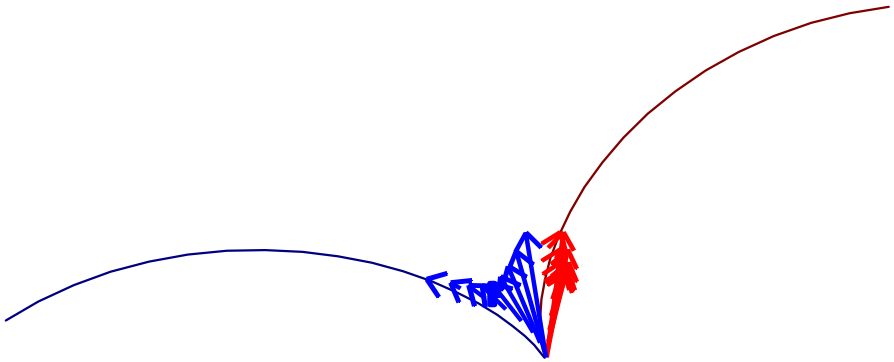
Formation of caustics



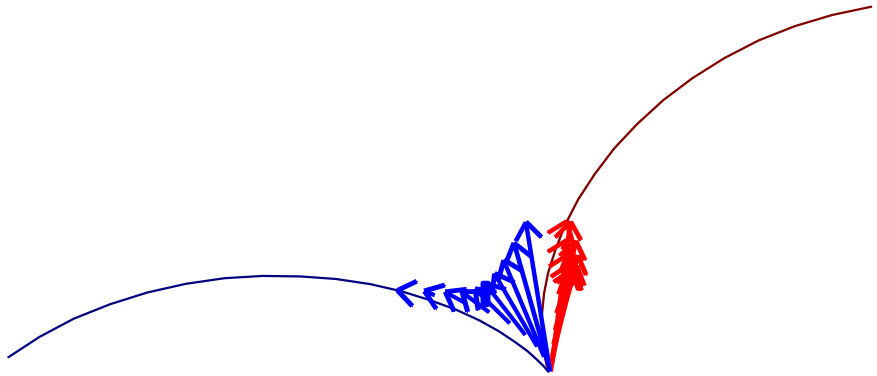
Formation of caustics



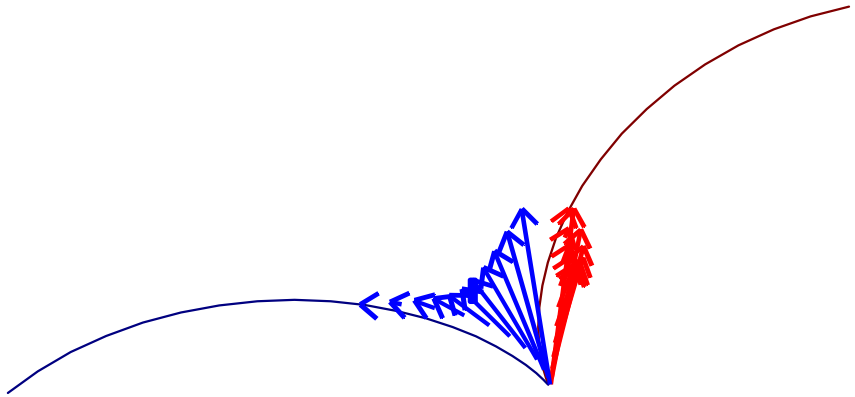
Formation of caustics



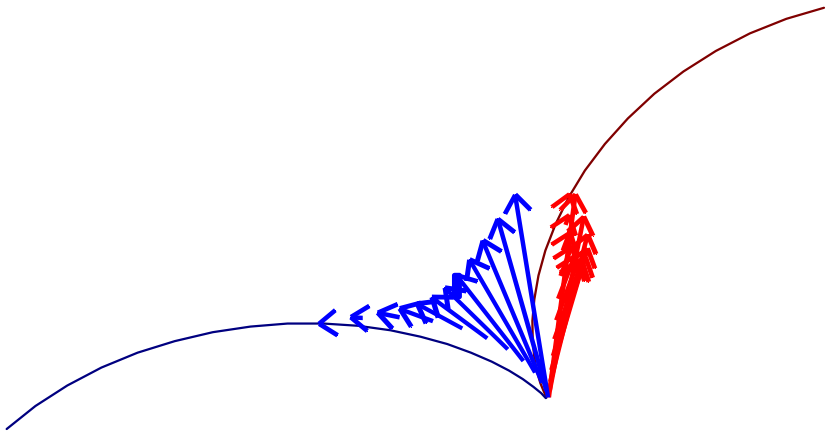
Formation of caustics



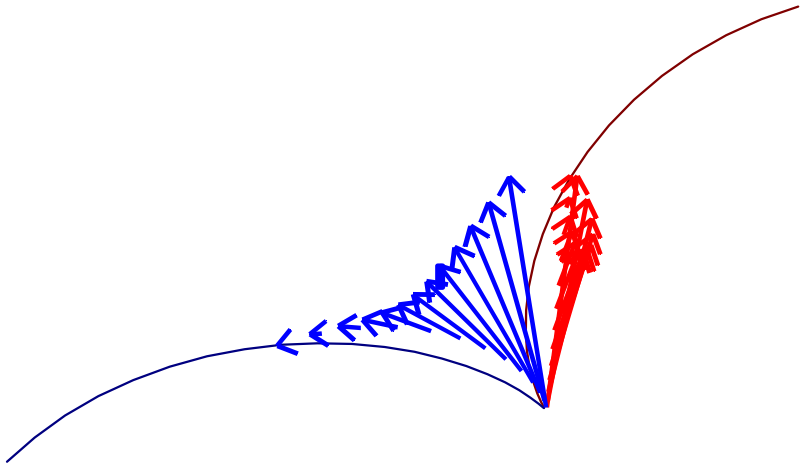
Formation of caustics



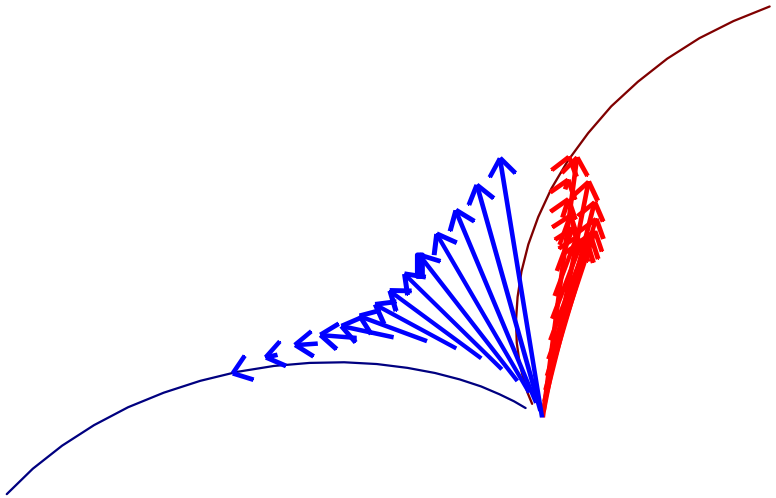
Formation of caustics



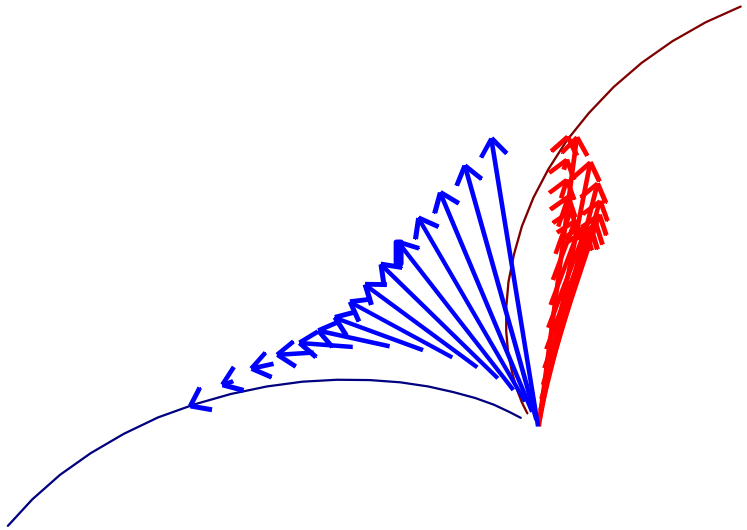
Formation of caustics



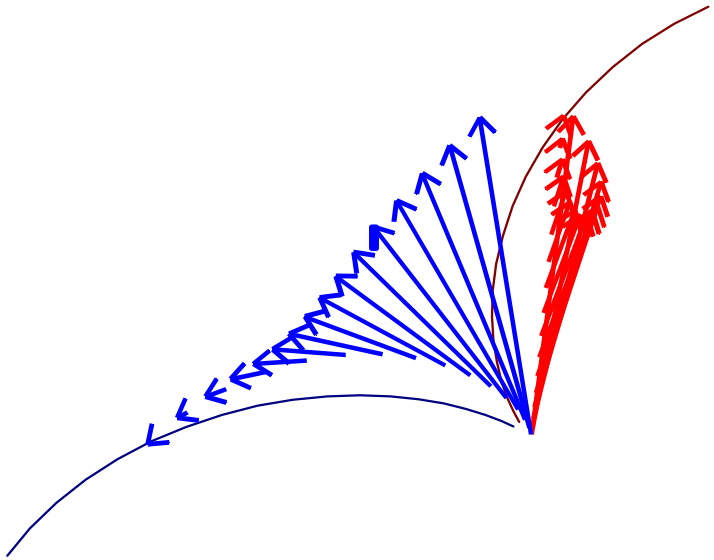
Formation of caustics



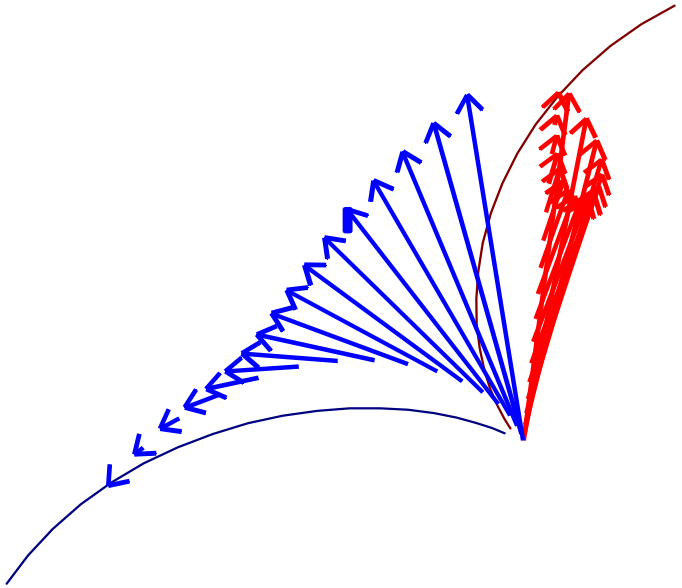
Formation of caustics



Formation of caustics



Formation of caustics



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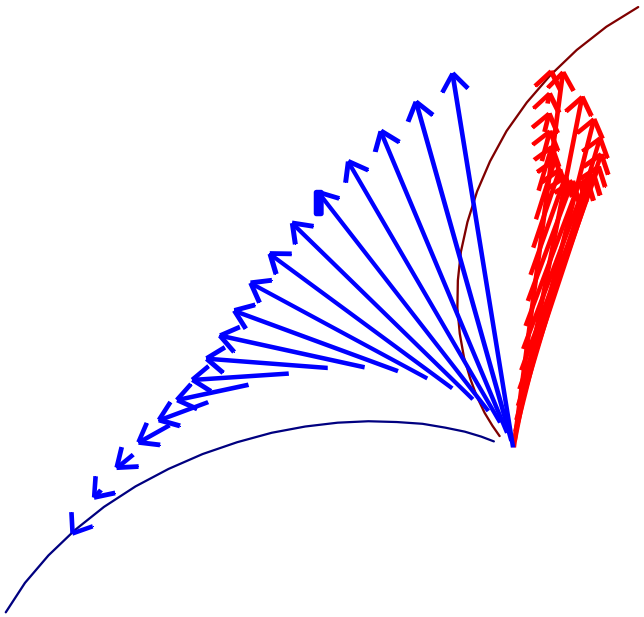
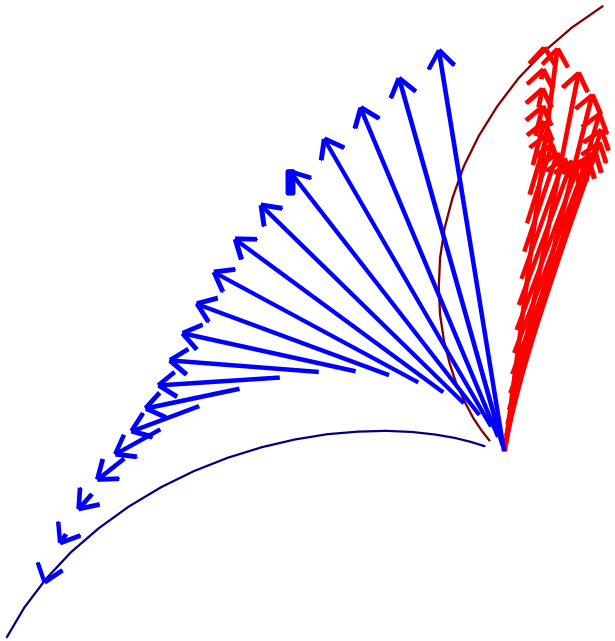
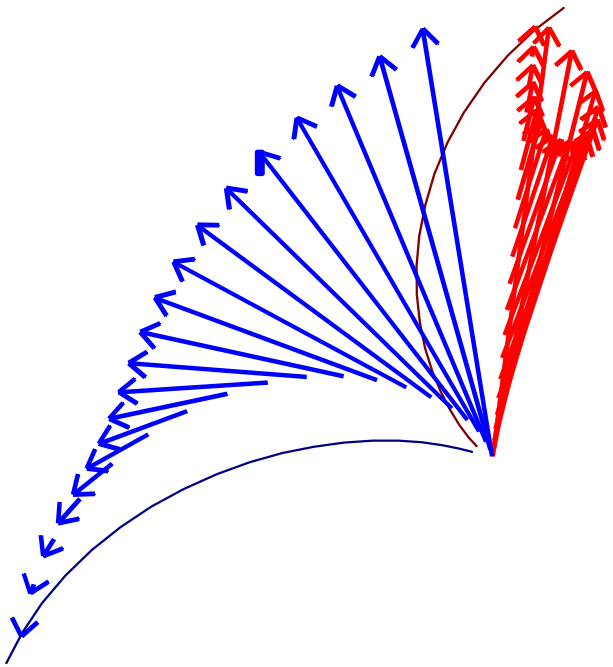


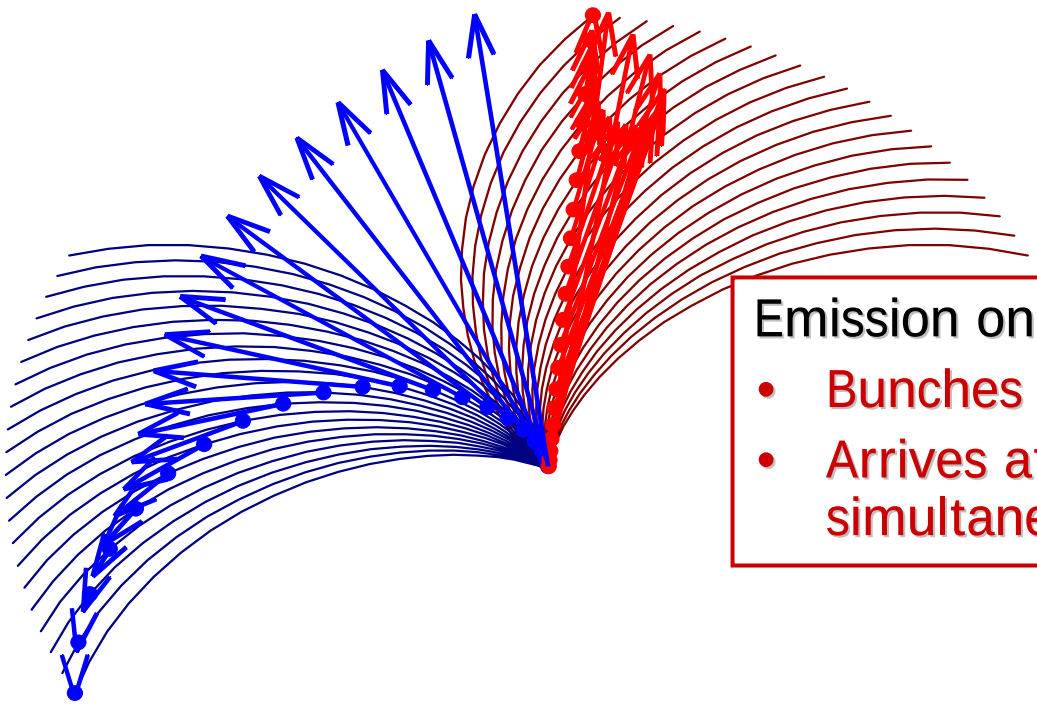
Formation of caustics



Formation of caustics



Formation of caustics



Emission on trailing field lines

- Bunches in phase
- Arrives at inertial observer simultaneously

Emission on leading field lines

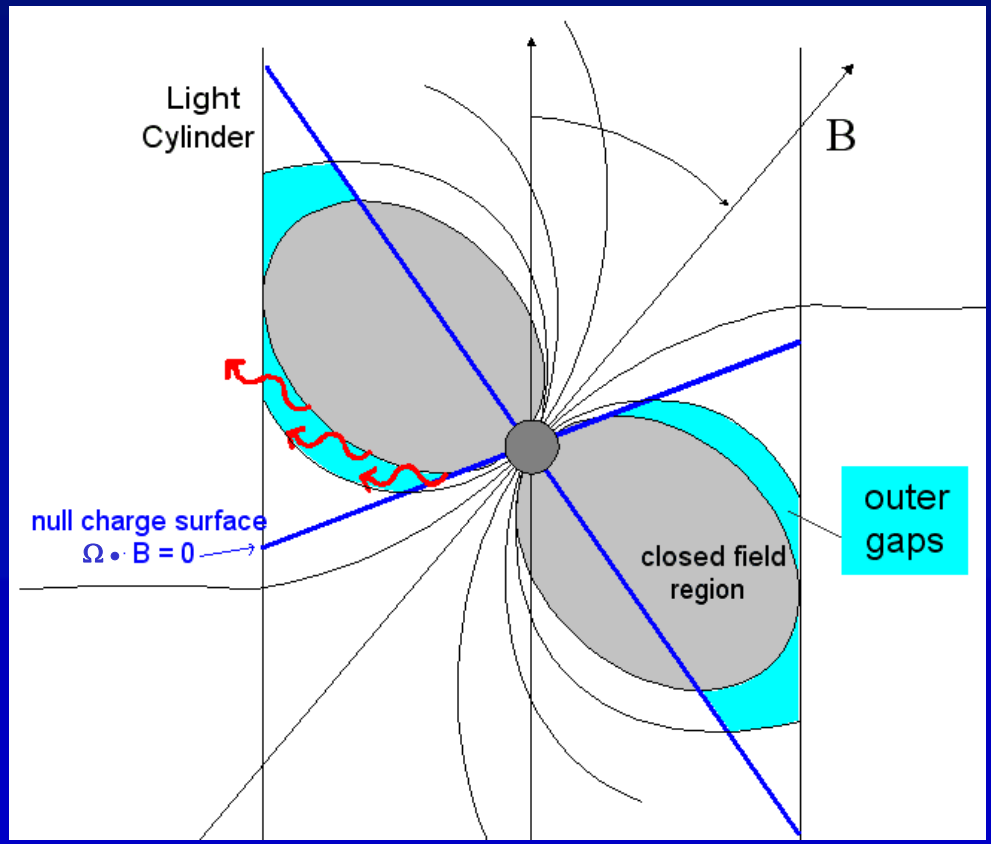
- Spreads out in phase
- Arrives at inertial observer at different times

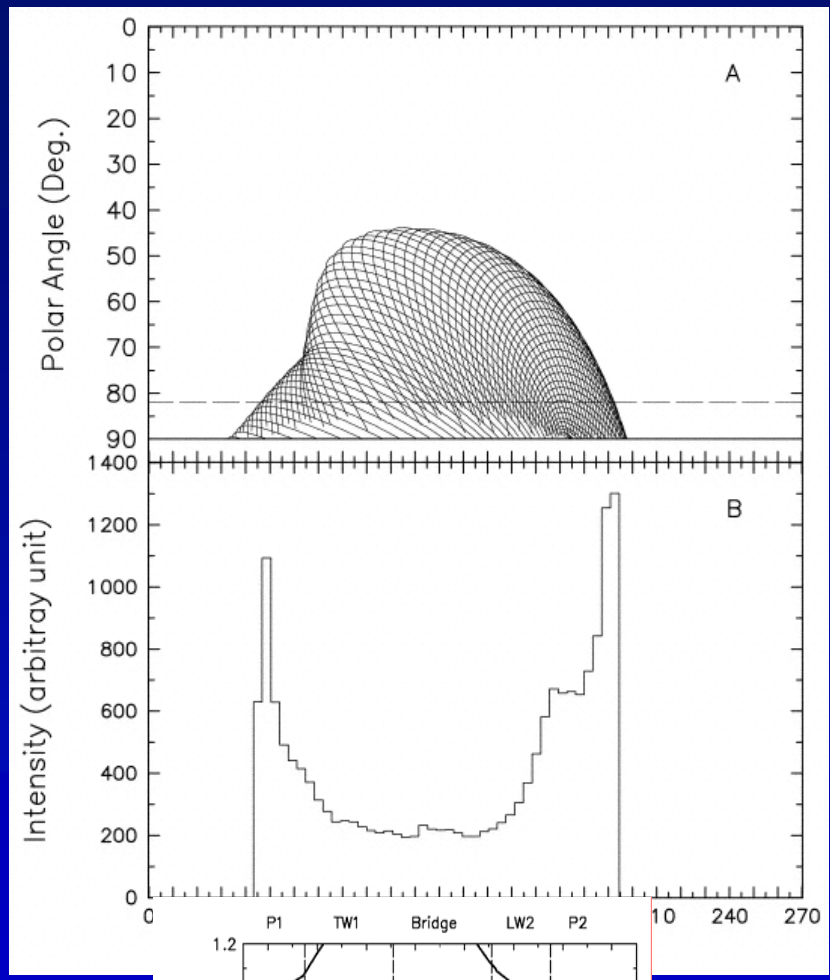
Caustic emission

- Dipole magnetic field
- Outer edge of open volume

Outer Gap Model

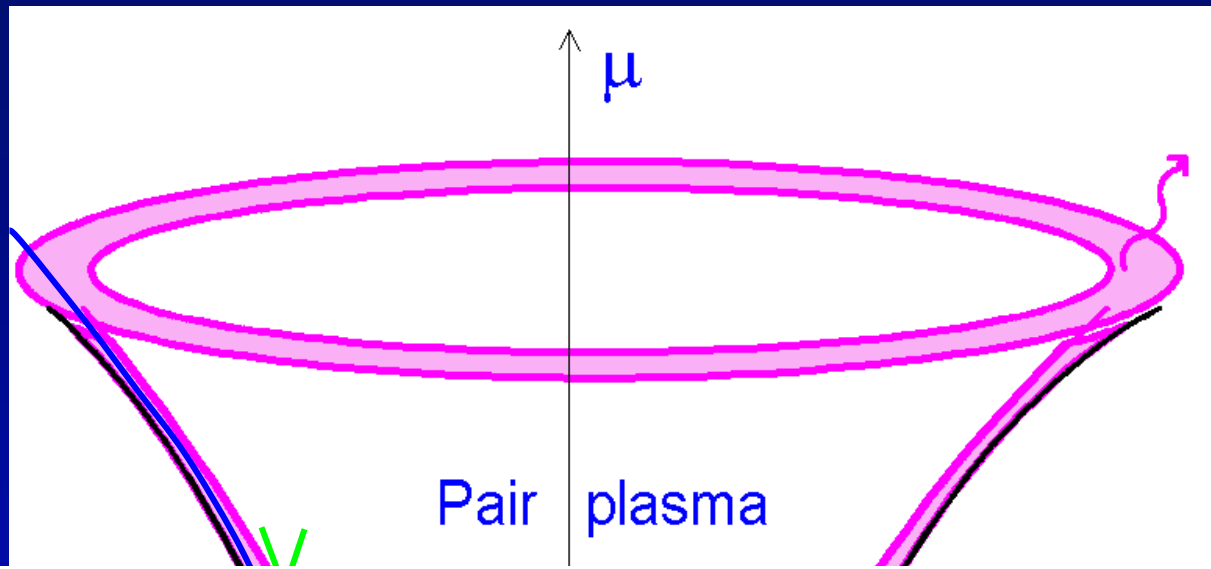
Romani & Yadigaroglu 1995
Cheng, Ruderman & Zhang 2000

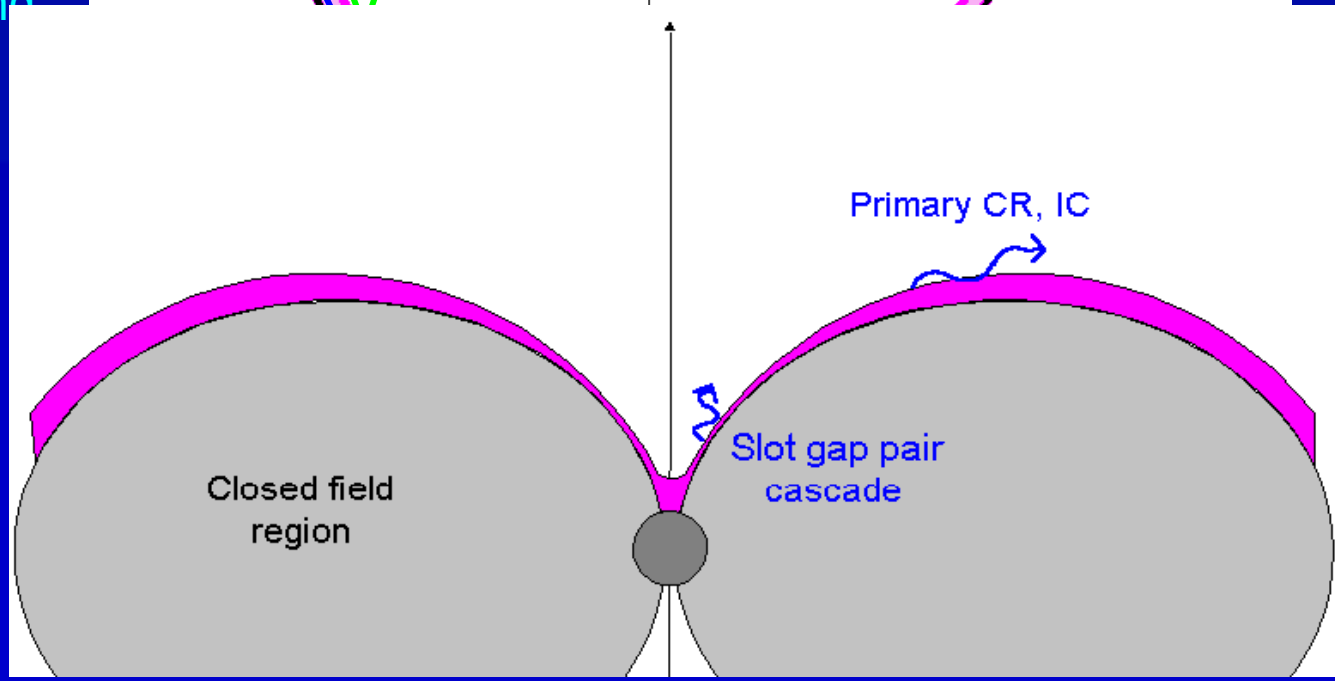




Slot gap model

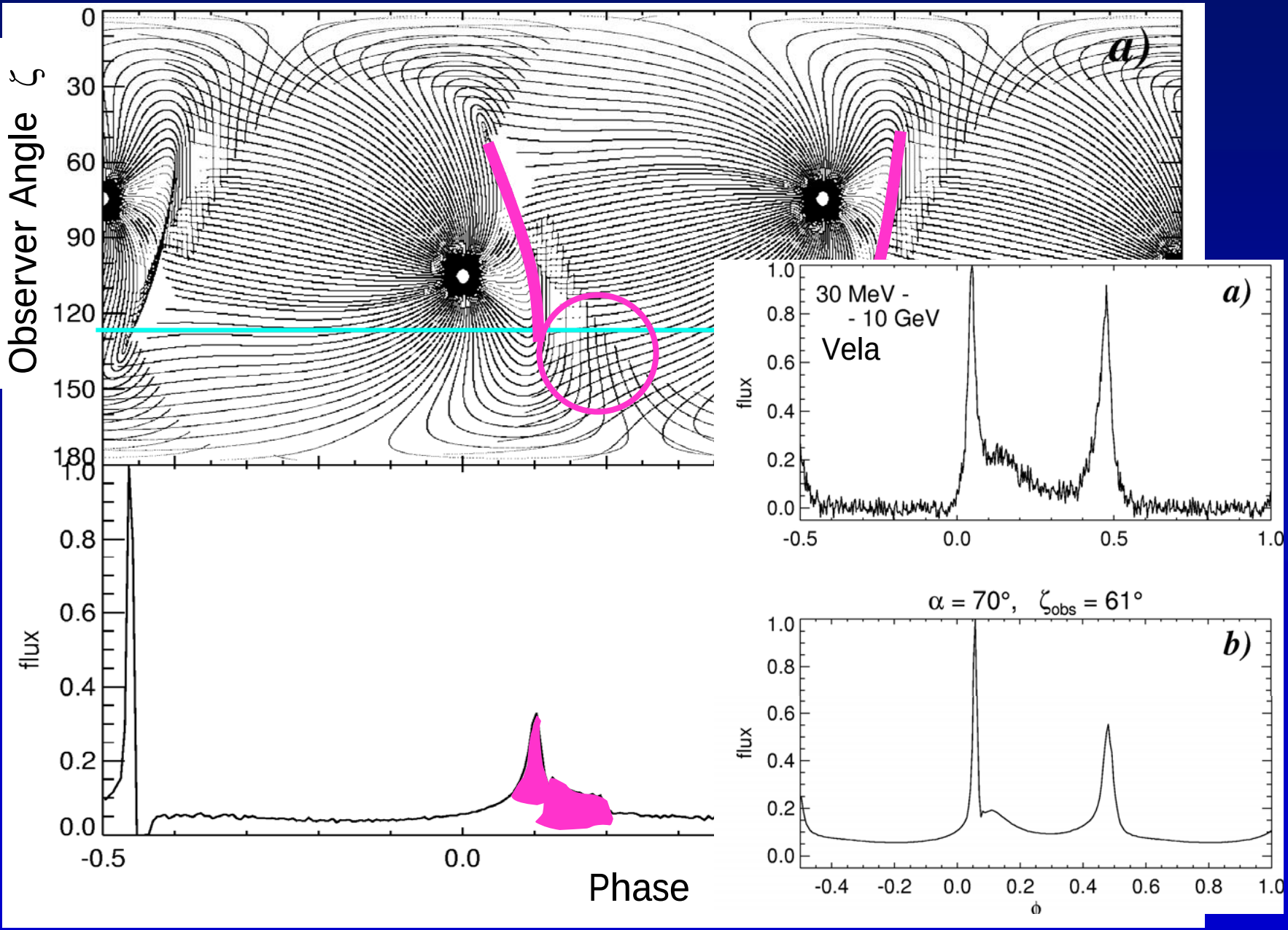
- **Pair-free zone near last open field-line**
  (Arons 1983, Muslimov & Harding 2003, 2004)
  - ➡ Slower acceleration
  - ➡ Pair formation front at higher altitude
  - ➡ Slot gap forms between conducting walls
- **$E_{||}$ acceleration is not screened**



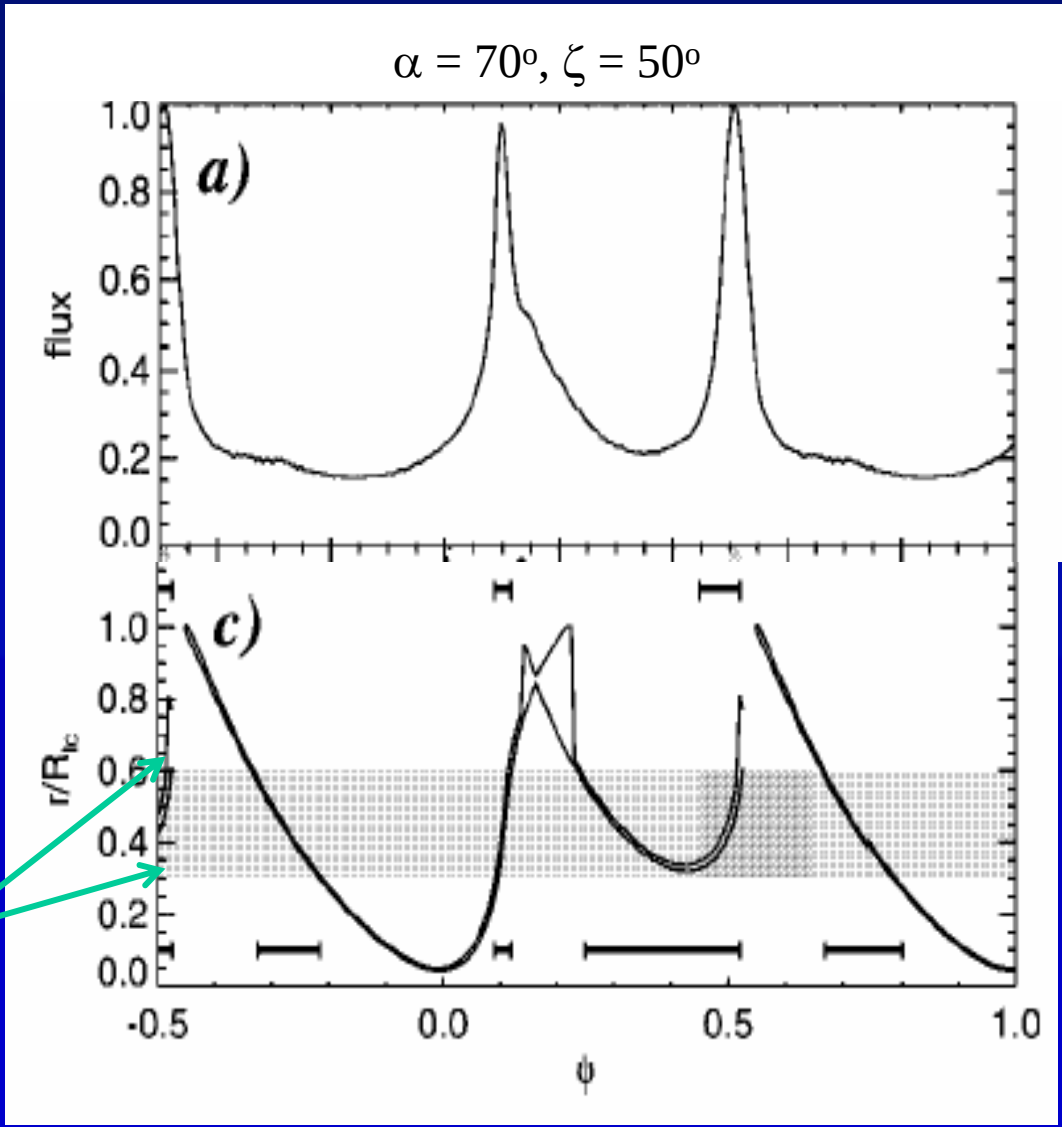


Slot gap/Caustic Model

Dyks & Rudak 2003
Dyks, Harding & Rudak 2004

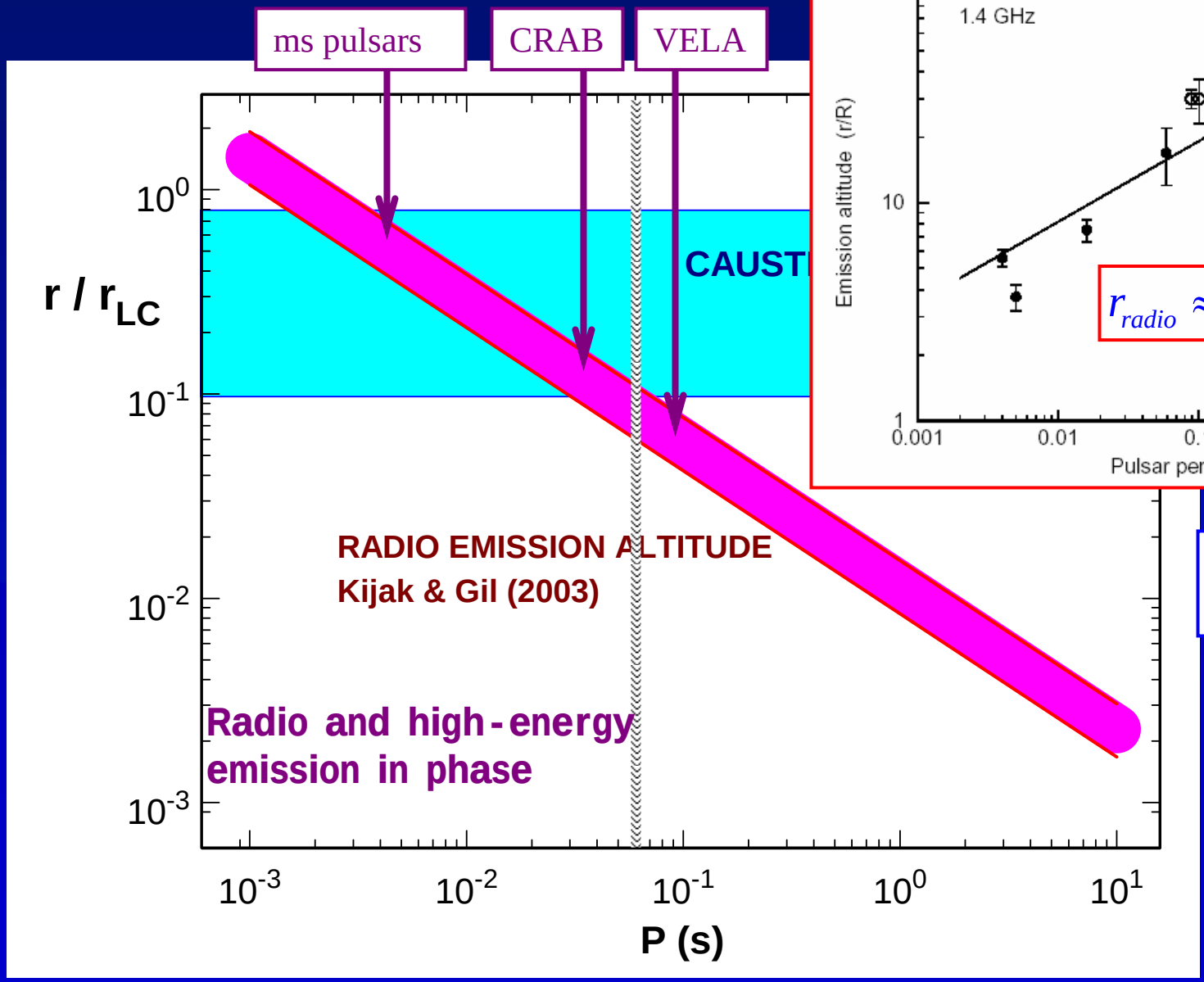


Slot gap/caustic model: emission altitudes



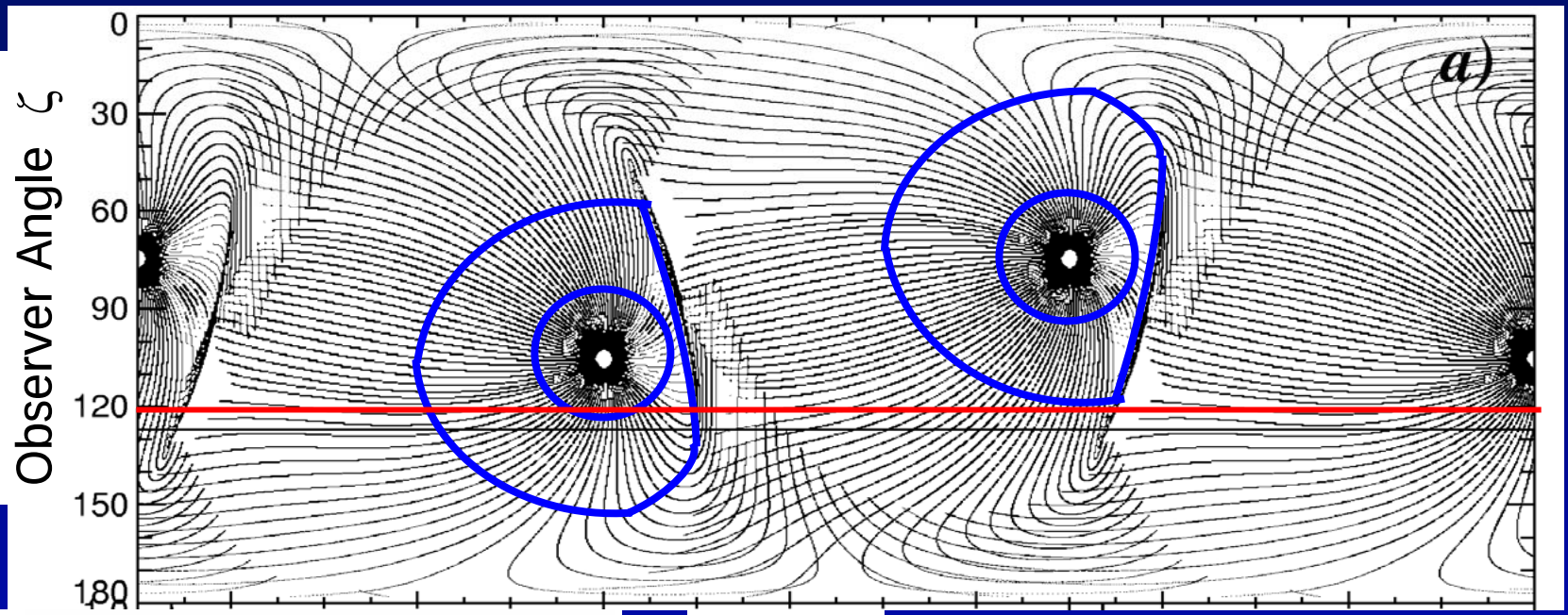
Caustic emission occurs at altitudes ~ 0.1 – 0.6 R_{lc}

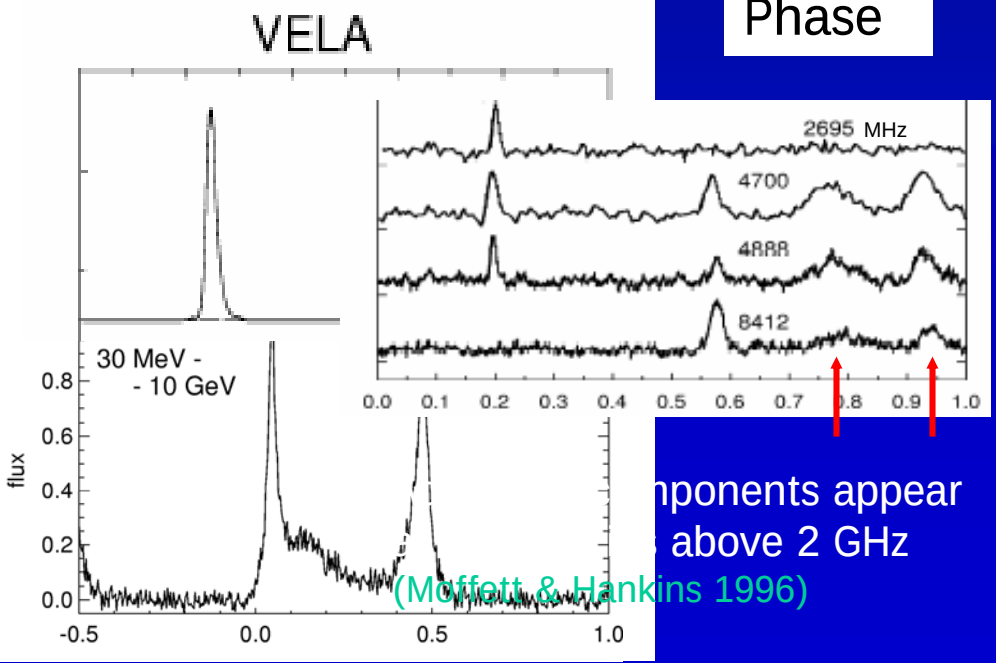
Radio emission in caustic peaks?



$$r_{LC} = \frac{c}{\Omega} = 4800R\,P$$

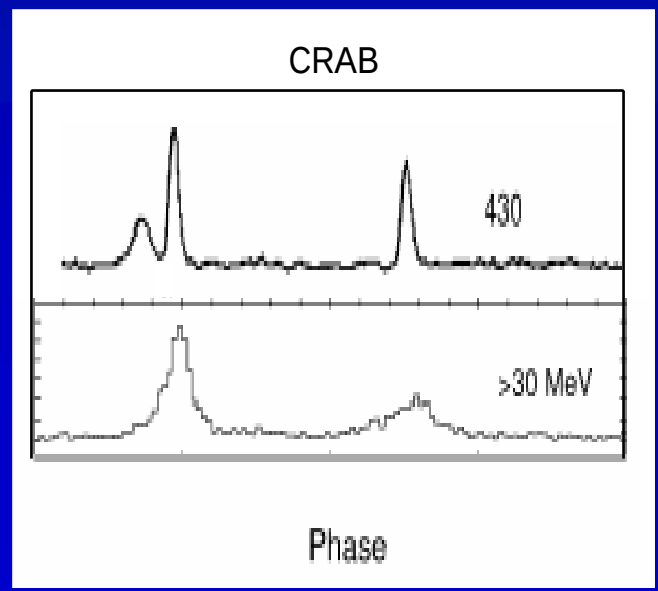
Gamma-ray and radio caustic peaks





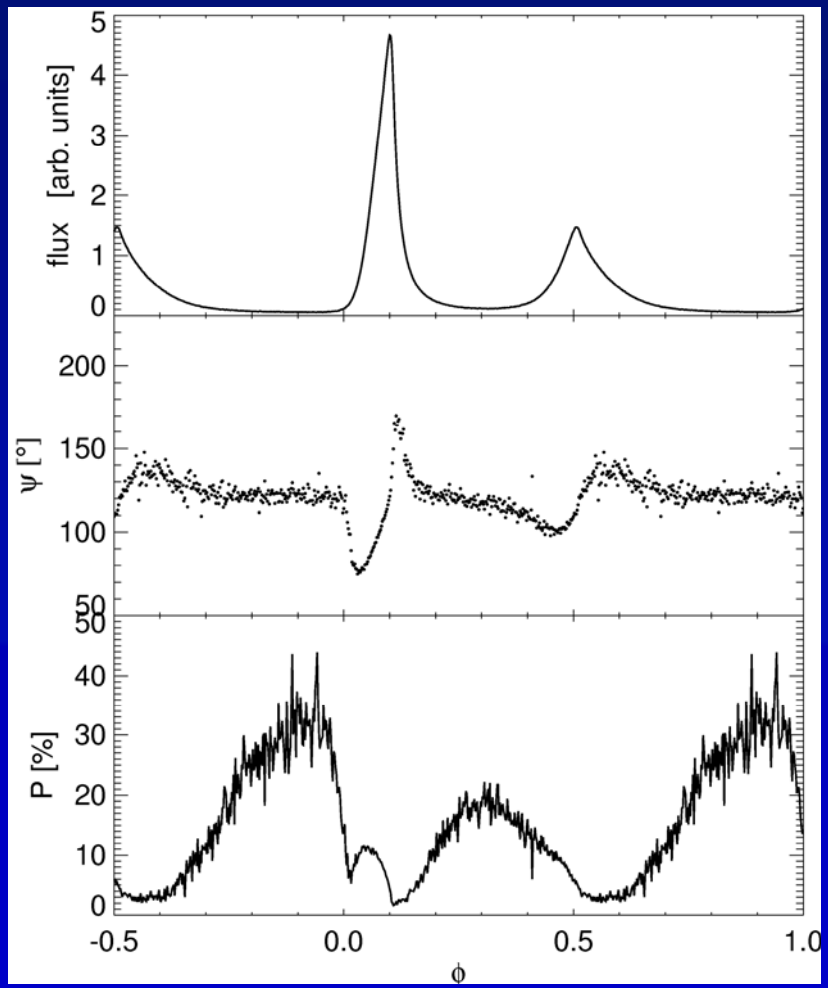
nponents appear
above 2 GHz

(Moffett & Hankins 1996)

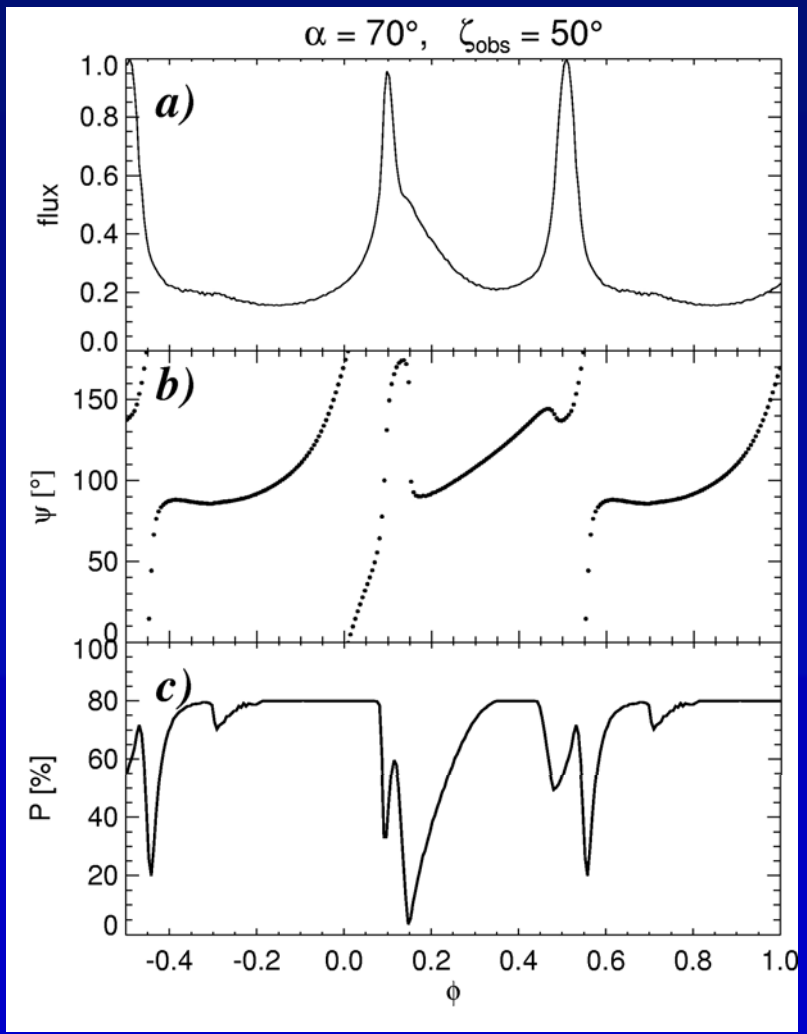


Detecting the signatures...

Polarization of Crab Pulsar – signature of caustics?



OPTIMA, Kanbach et al. 2003



Dyks, Harding & Rudak 2004

X-ray polarimetry

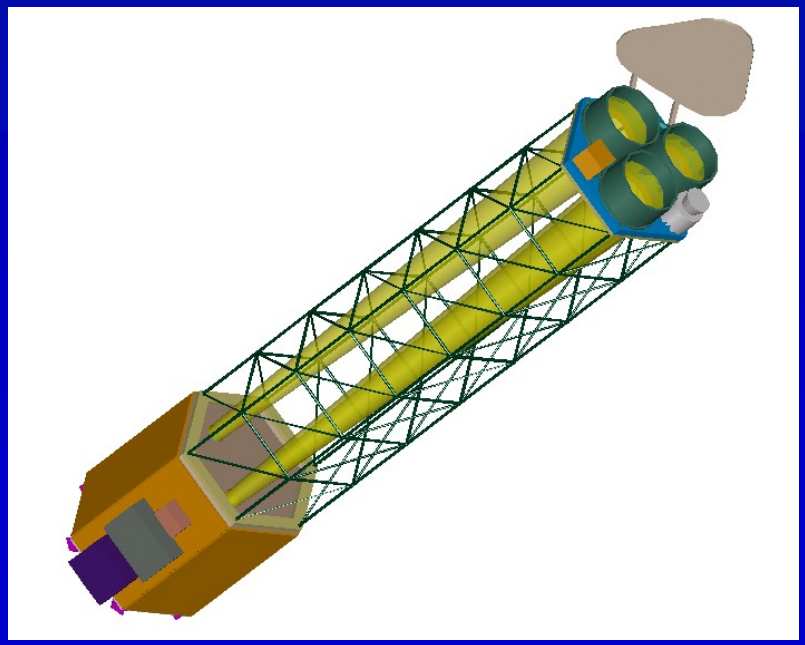
Present

INTEGRAL 100-500 keV

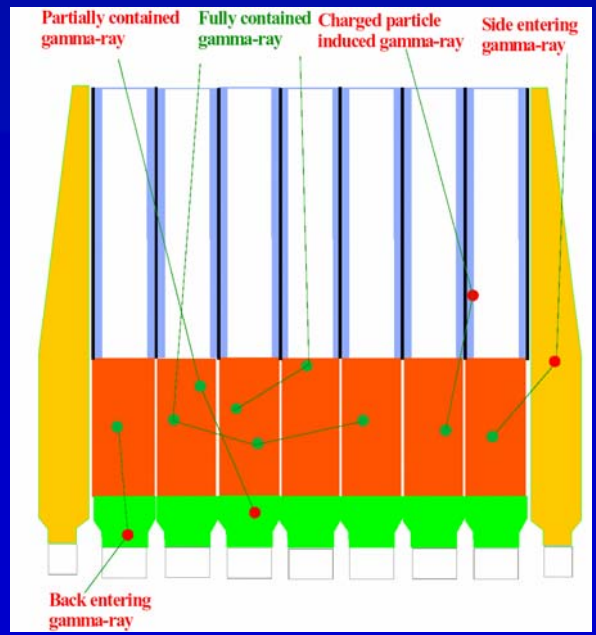
RHESSI >20 keV

Future

AXP 2-10 keV

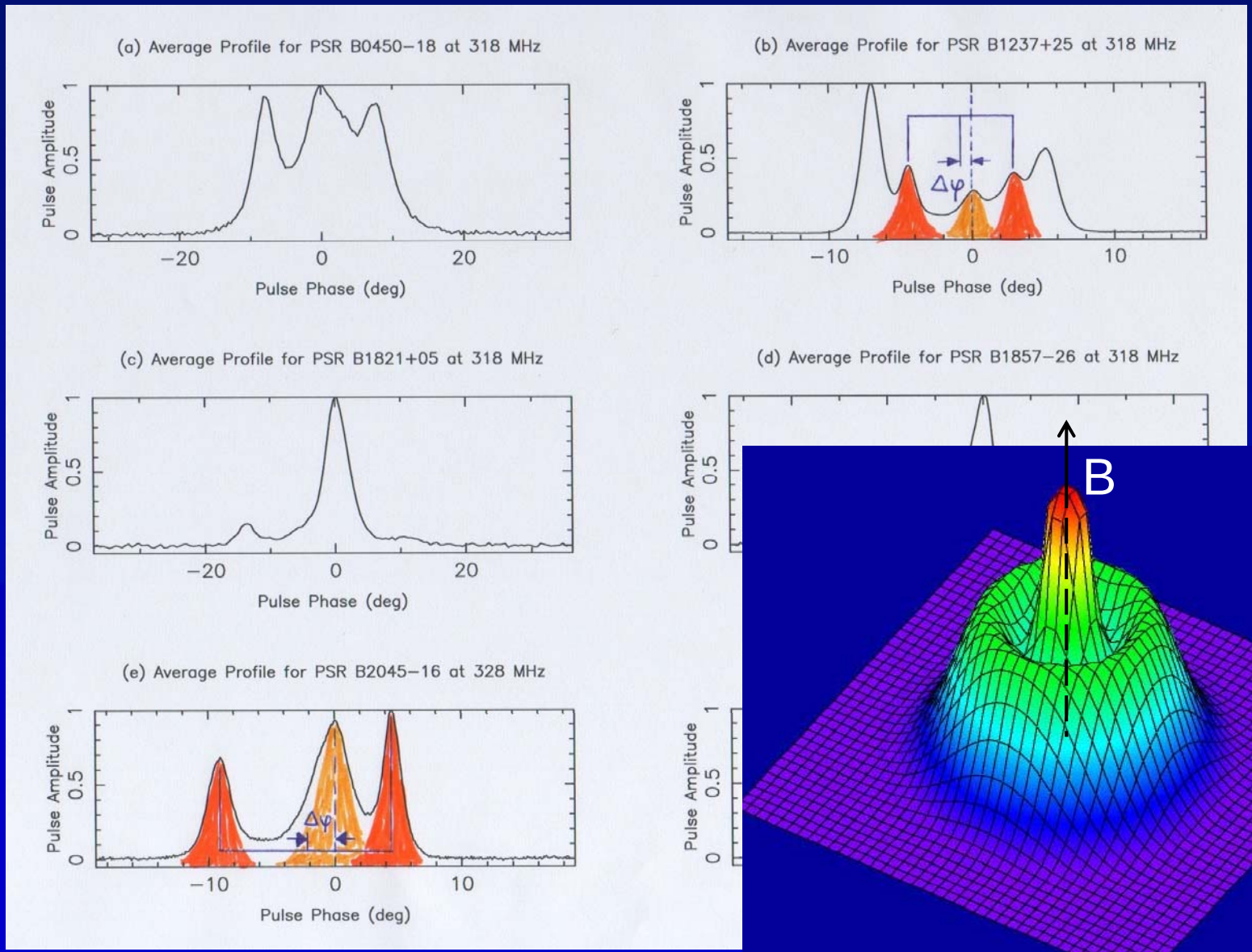


POGO 25-200 keV



Relativistic phase shifts in radio profiles

(Blaskiewicz, Cordes & Wasserman 1991, Gangadhara & Gupta 2001)



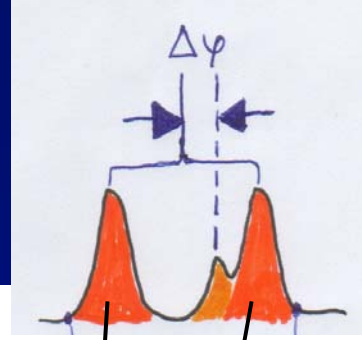
Gupta & Gangadhara (2003)

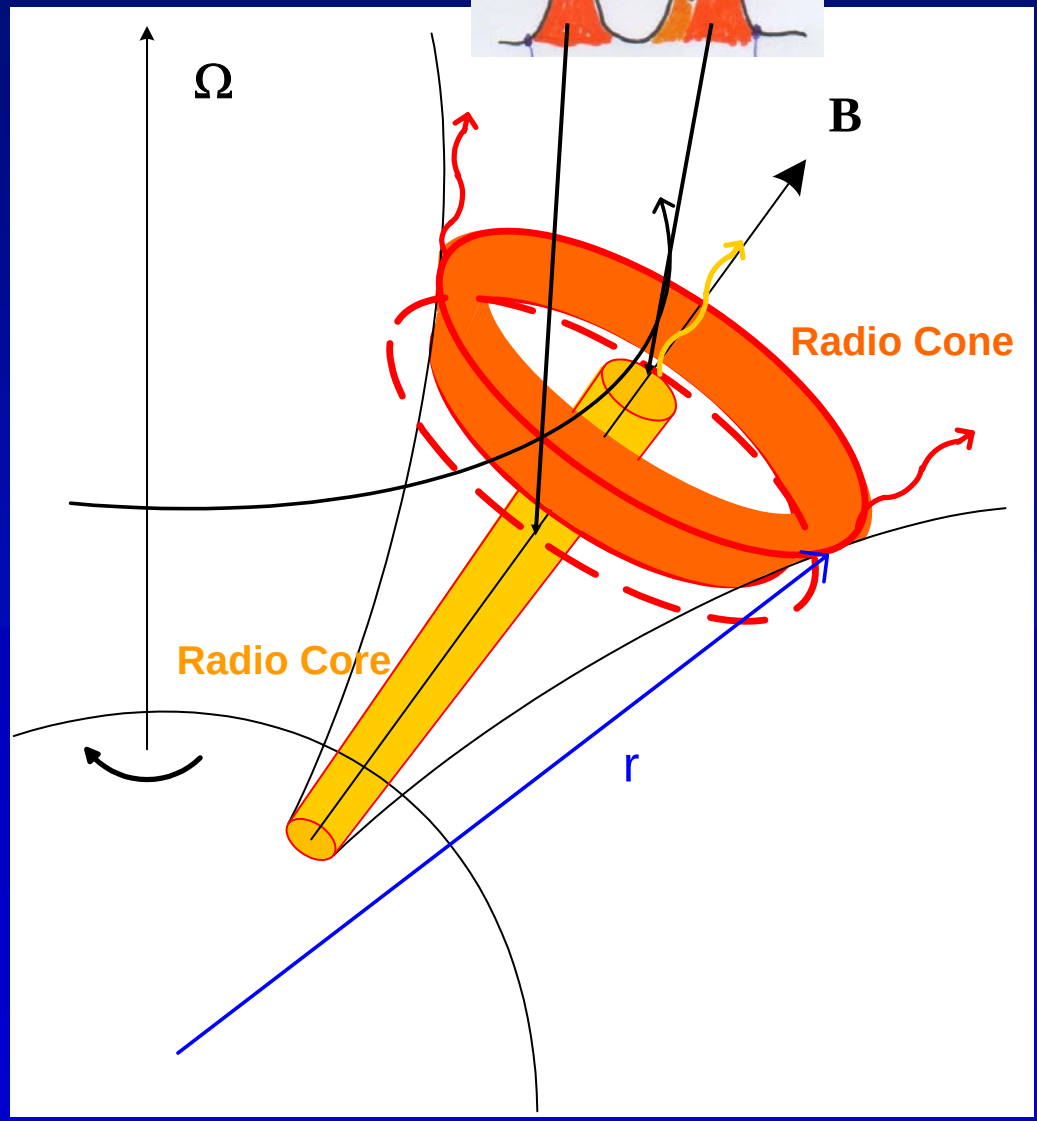
Relativistic Phase Shift

Aberration + light travel time

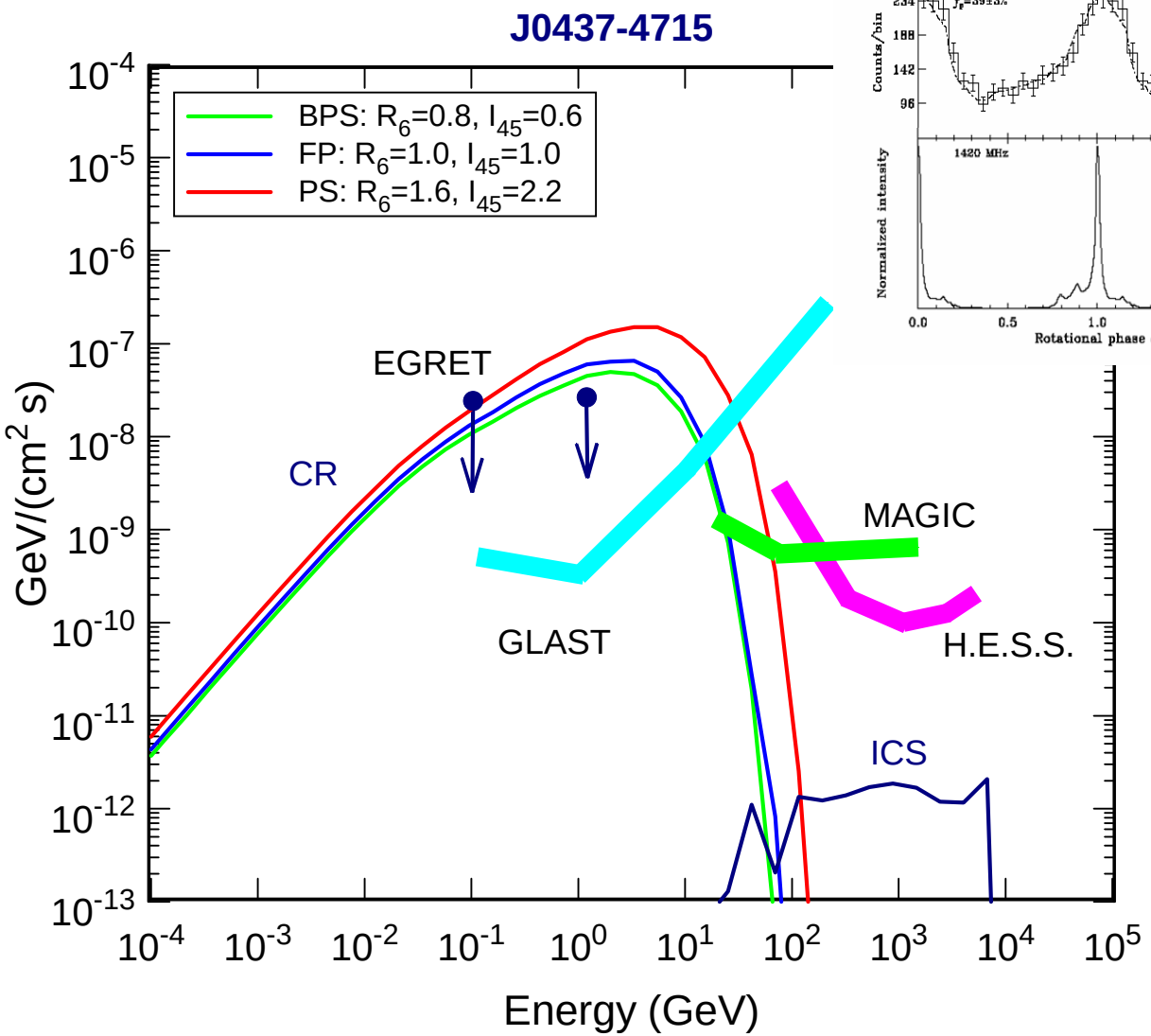
$$\Delta\phi = 2\frac{r}{R_{LC}}$$

Dyks, Rudak & Harding 2004





Curvature radiation from millisecond pulsars: constraining frame-dragging acceleration



$$\gamma_{CRR} = \left(\frac{3}{2} \frac{E_{\|} \rho_c^2}{e} \right)^{1/4}$$

$$\varepsilon_{peak}^{CR} \approx \frac{2\lambda_c}{\rho_c} \gamma_{CRR}^3$$

Bulik, Rudak & Dyks 2000

Luo, Shibata & Melrose 2000

Harding, Muslimov & Zhang 2002

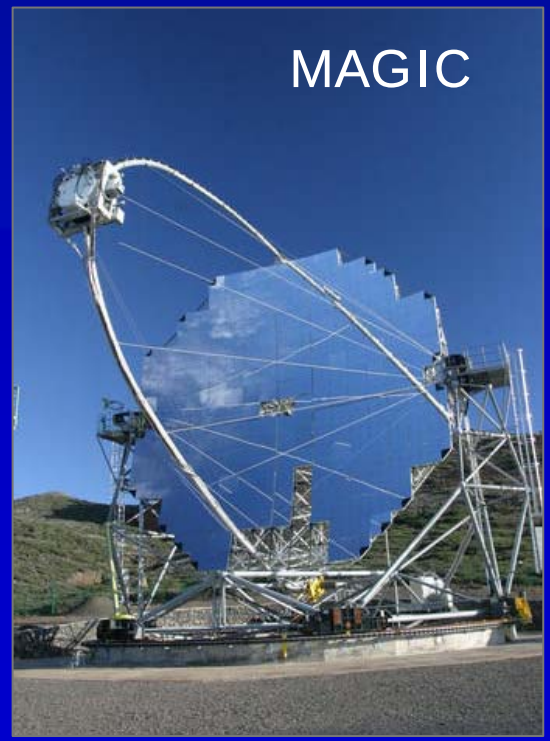
Venter & DeJager 2004

Harding, Usov & Muslimov 2004


VERITAS
(photomontage)


GLAST


H.E.S.S.


MAGIC

Conclusions

- SR effects strongly influence emission in outer magnetosphere (> 0.1 R_{LC}) – all altitudes for ms pulsars
- GR effects strong near NS surface
- Fast pulsars ➞ caustics influence light curves at both radio and high energies ➞ phase coincidence