Relativistic Winds

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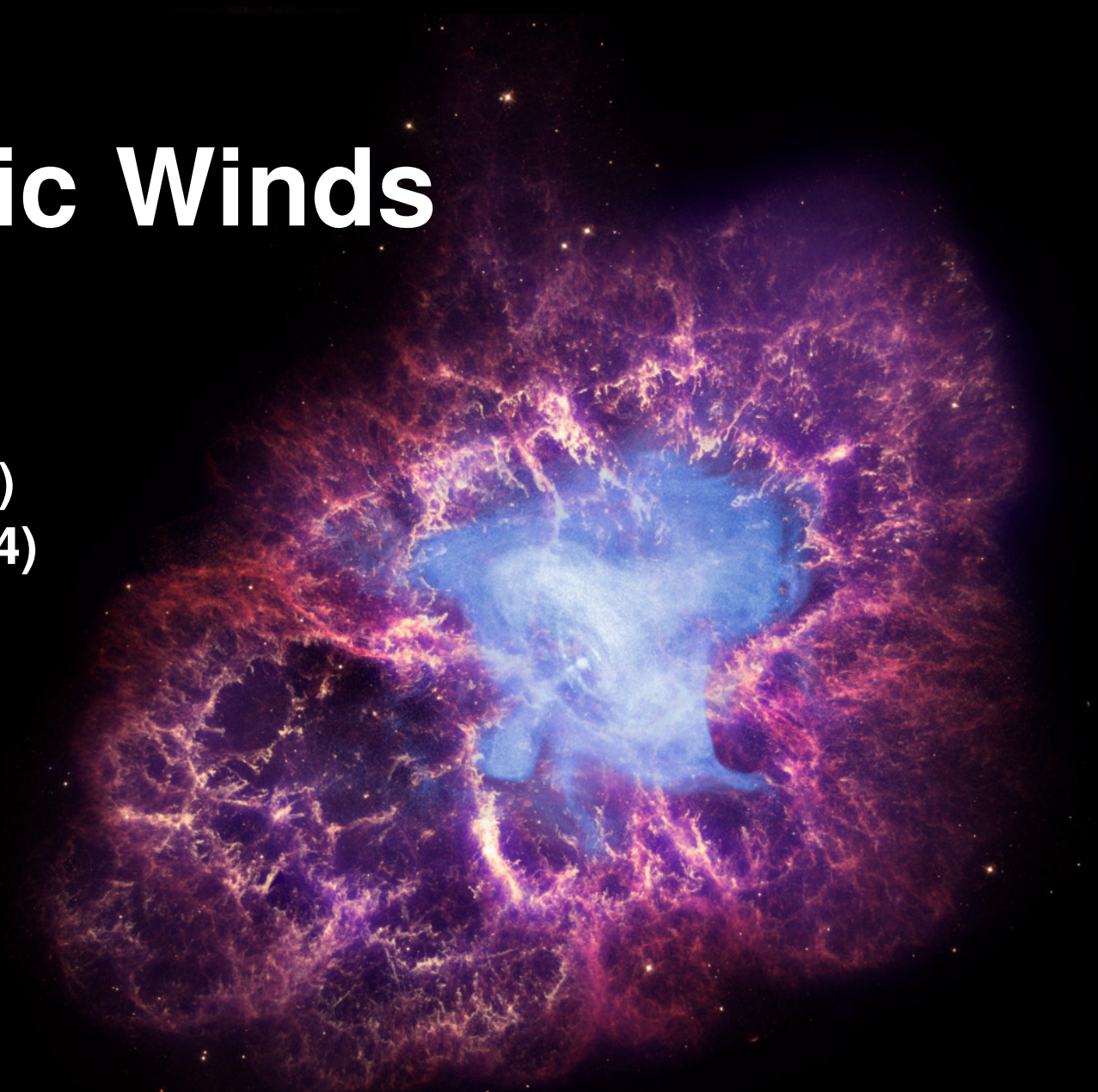
(IHEP, Tianfu CRRC)
November 27th (2024)



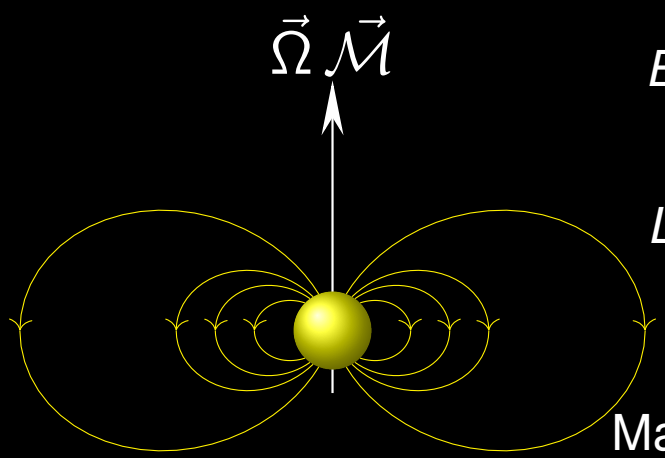
HONEST^3
“The High End of Pulsar Spectrum”

Pulsars

Fundamental relations:

$$M_{\rm psr} \approx 1.4 M_\odot$$

$$R_{\rm psr} \approx 10{\rm km}$$



Progenitor
Angular momentum:

$$R_{\rm psr}^2 \Omega = R_*^2 \Omega_*$$

Magnetic flux:

$$R_{\rm psr}^2 B = R_*^2 B_*$$

yield

$$P = \frac{2\pi}{\Omega} \sim 0.1{\rm s} \quad \text{and} \quad B \sim 10^{12}{\rm G}$$

Energy:

$$E_{\rm rot} = \frac{I\Omega^2}{2} \approx 10^{49}{\rm erg}$$

$$E_{\rm mag} = \frac{R_{\rm psr}^3 B^2}{6} \approx 10^{42}{\rm erg}$$

$$L = I\Omega\dot{\Omega} \sim \frac{1}{6}\frac{B^2\Omega^4 R^6}{c^3}$$

Magnetosphere electric field

$$E_\parallel \approx \frac{\Omega R_{\rm psr}}{c} B \sim 10^9 {\rm V\,cm^{-1}}$$

and

$$w_{B\gamma} \propto \exp\left[-\frac{8}{3}\frac{B_c}{B\sin\theta}\frac{mc^2}{\omega_\gamma}\right]$$

imply "screened" case

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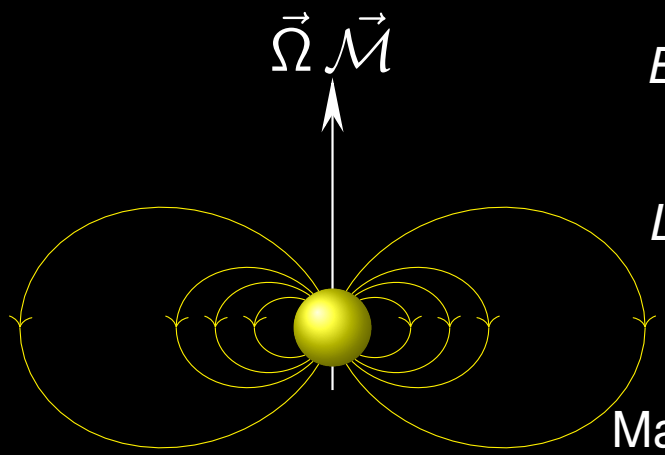

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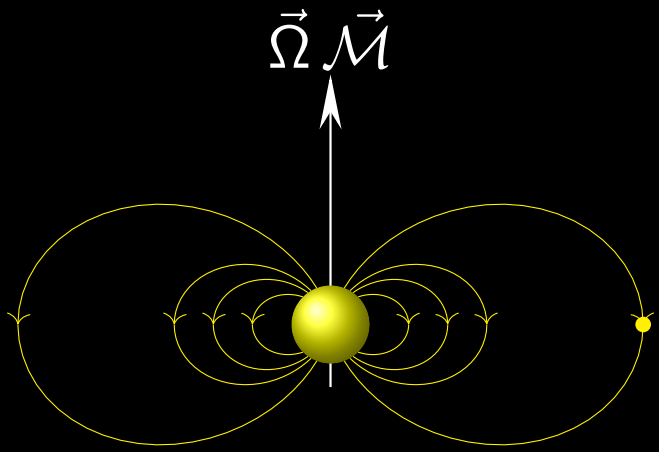
Magnetosphere with pairs

Pulsar Magnetosphere

Two important length scales:

$$R_{\rm lc} = \frac{c}{\Omega} \approx 10^3 {\rm km}$$



$$R_{\rm lc} = \frac{c}{\Omega} = 1.5 \times 10^3 \frac{P}{30{\rm ms}} {\rm km}$$

Pulsar Magnetosphere

Two important length scales:

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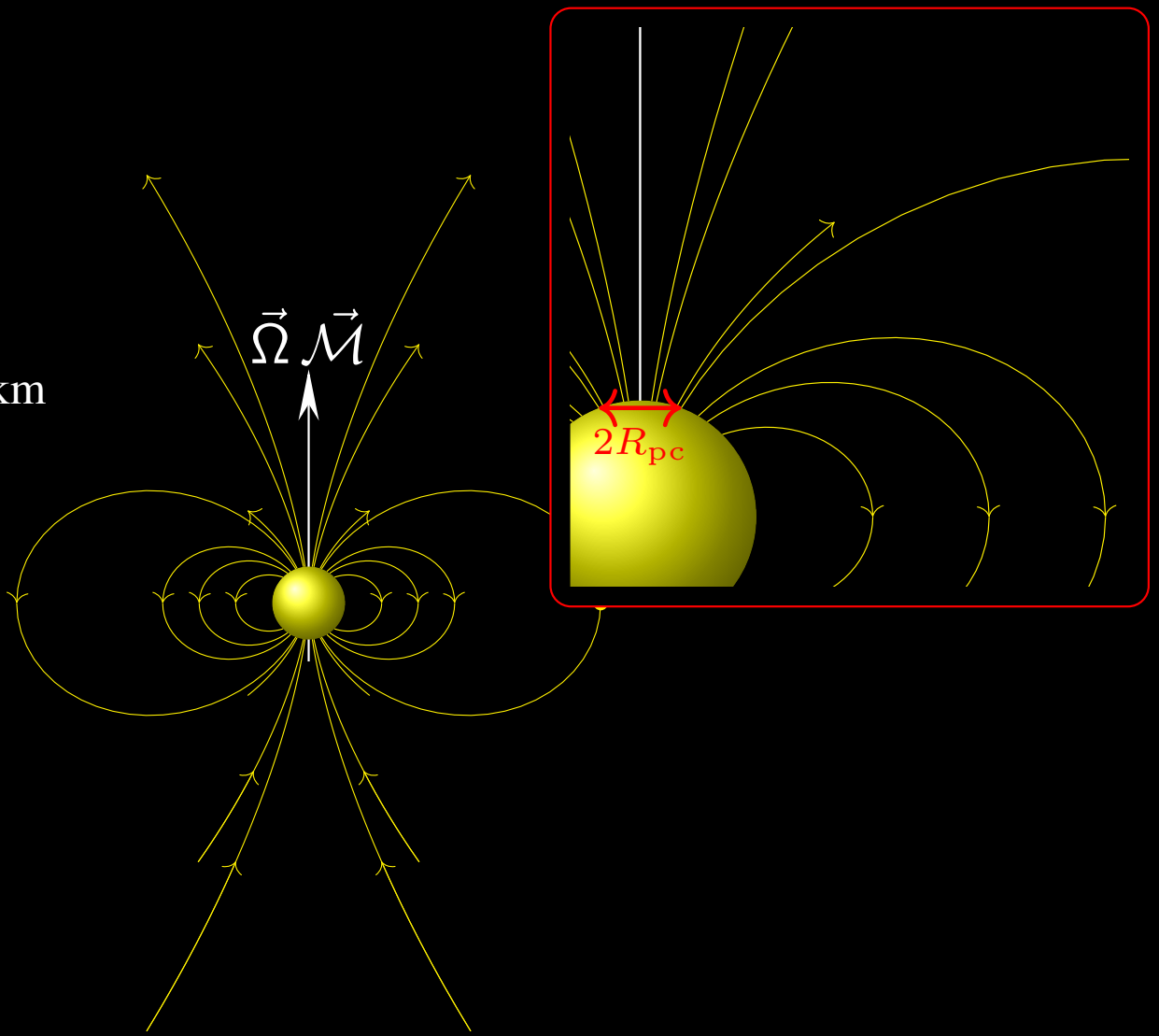
$$R_{\rm pc} = R_{\rm psr}\sqrt{\frac{\Omega R_{\rm psr}}{c}} \approx 0.1 {\rm km}$$



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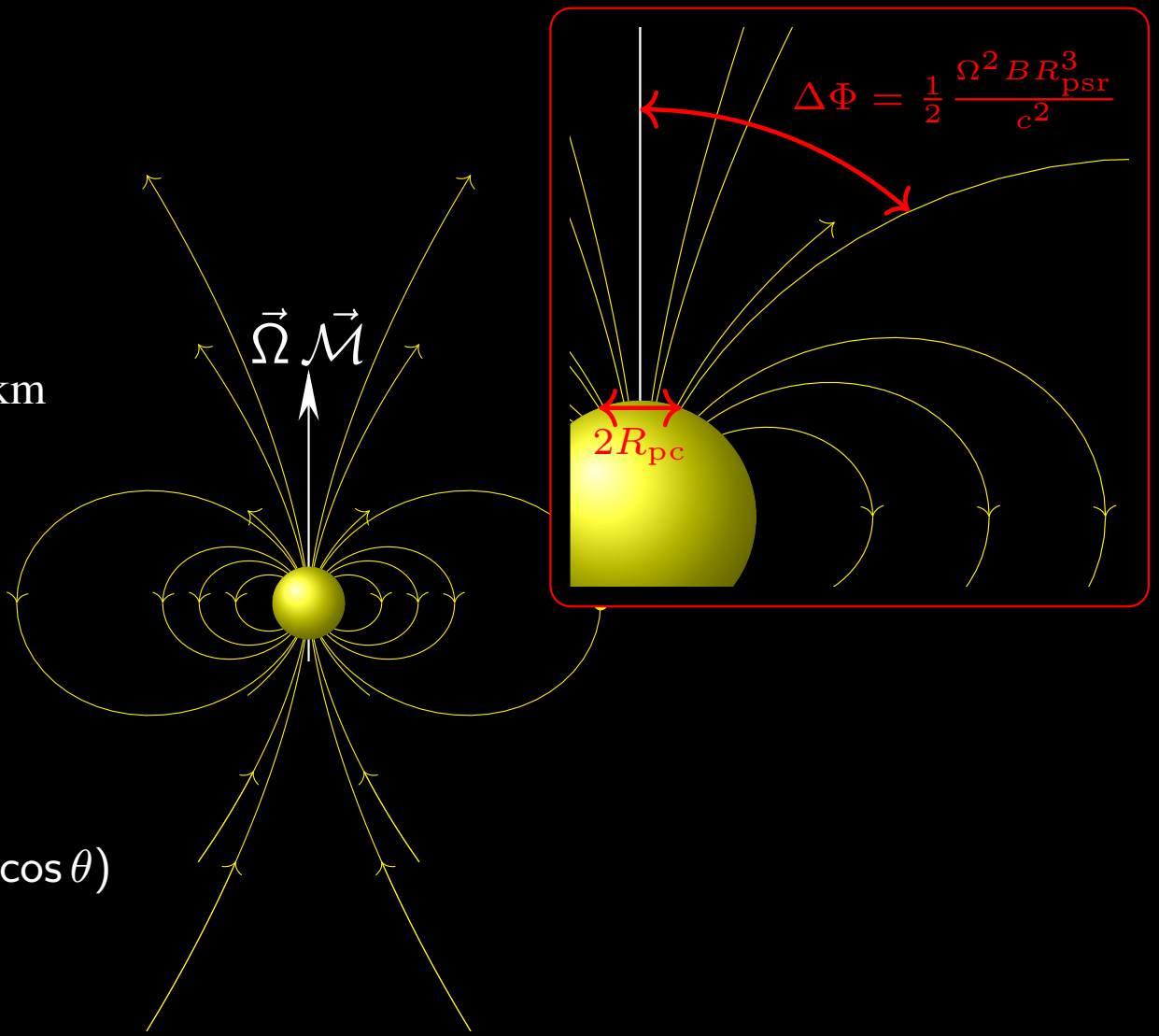

Electric potential (vacuum):

$$\Phi(r,\theta) = \frac{1}{3}\frac{\Omega B R^5}{c} r^{-3}\mathcal{P}_2(\cos\theta)$$

Plasma charge density:

$$\rho_{\rm GJ} = \frac{\Omega B}{2\pi c}$$

(Goldreich-Julian density)

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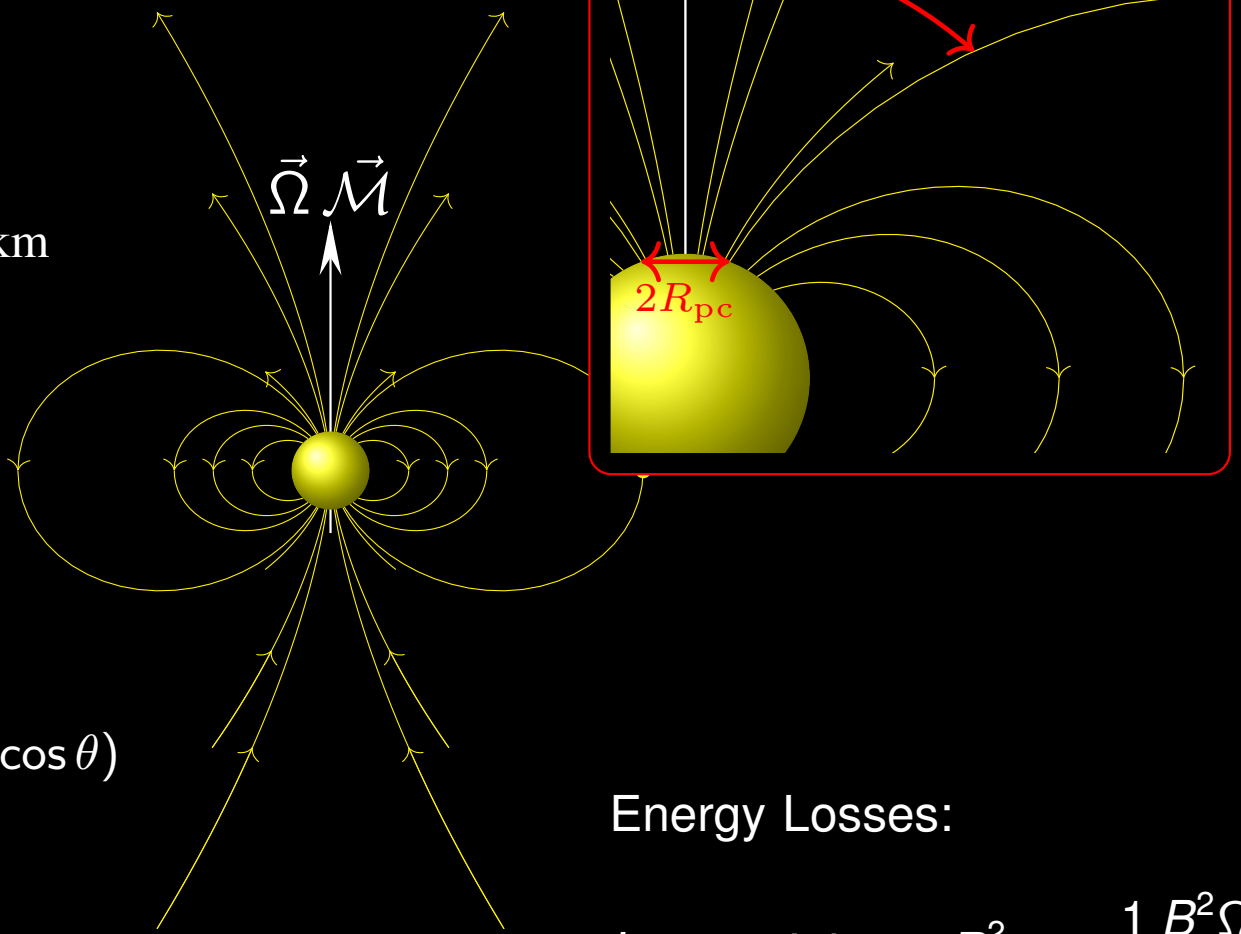

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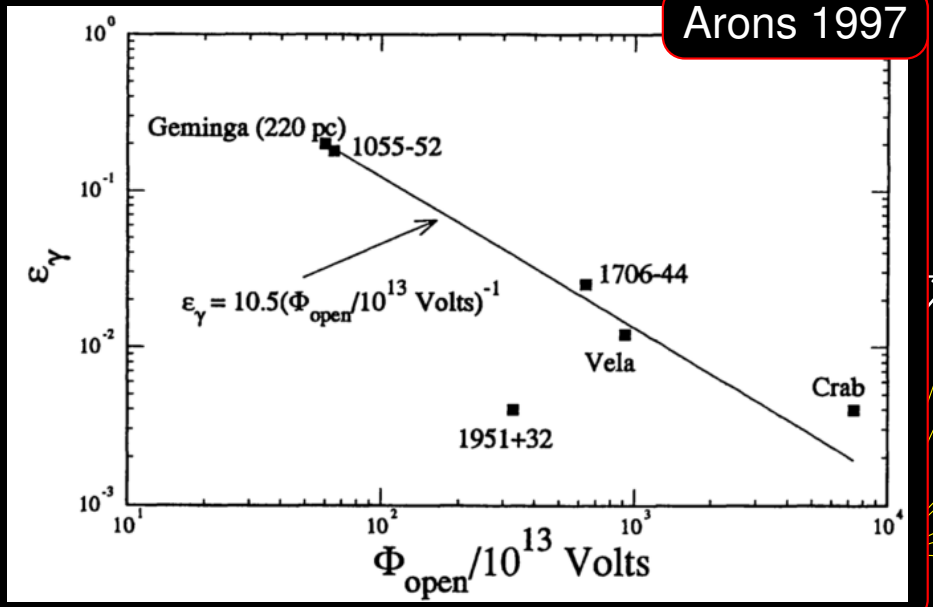
Pulsars are very efficient plasma "machines"

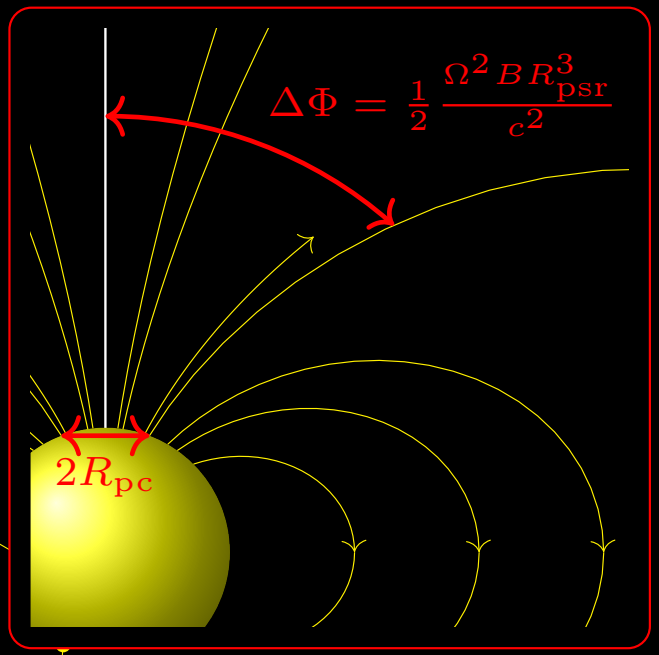
Energy Losses:

$$L_{\rm wind} \approx \Delta\Phi \rho_{\rm GJ} \pi R_{\rm pc}^2 c \sim \frac{1}{4}\frac{B^2\Omega^4 R^6}{c^3}$$

$$L_{\rm sd} = I\Omega\dot{\Omega} \sim \frac{1}{6}\frac{B^2\Omega^4 R^6}{c^3}$$

Pulsar Magnetosphere





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Pulsars Eject Relativistic Winds

X-ray/TeV nebula

termination shock

r

$R_{ts} \approx 10^9 R_{lc}$

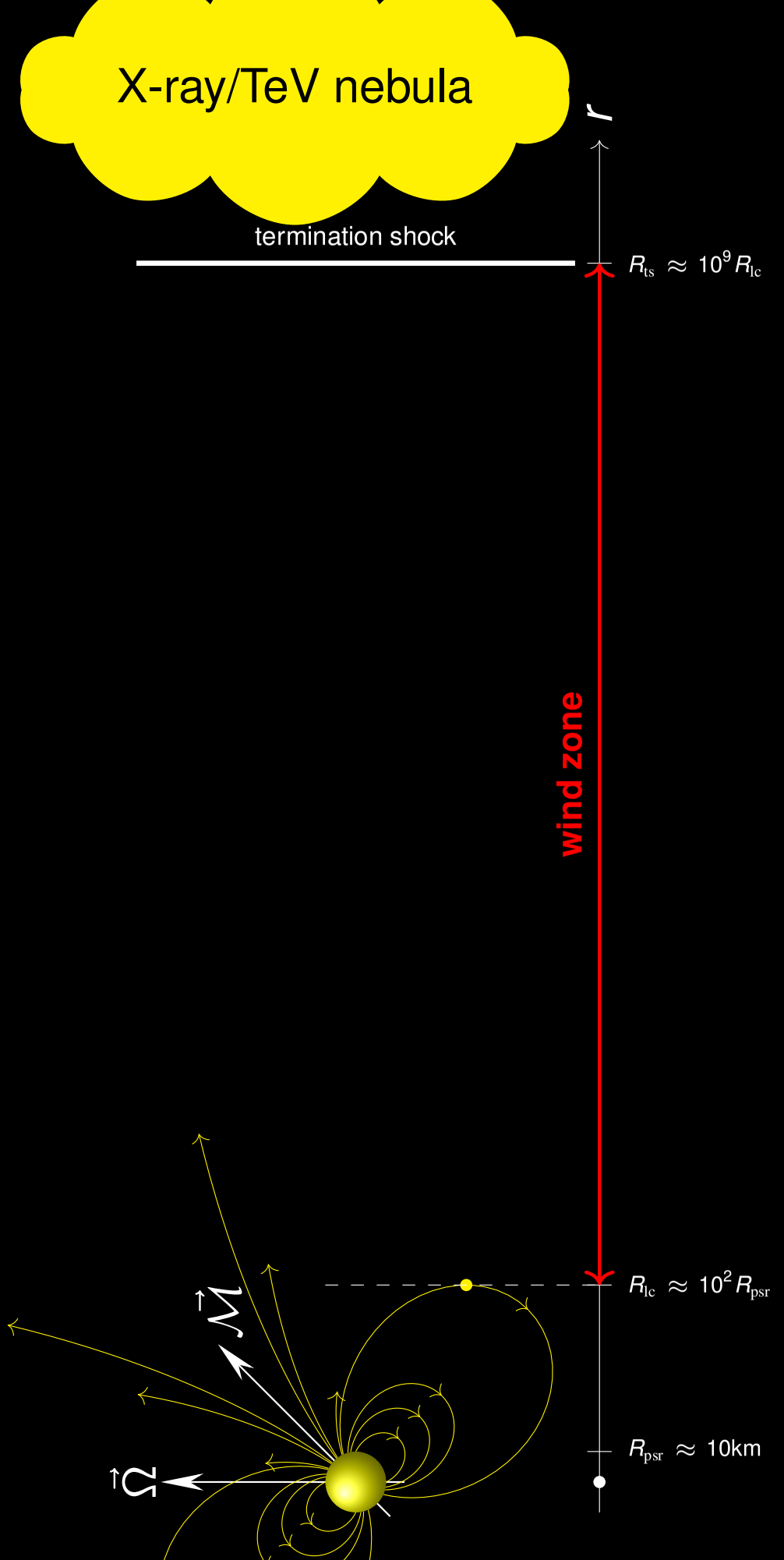
$R_{lc} \approx 10^2 R_{psr}$

$\vec{M}$

$\vec{\Omega}$

$R_{psr} \approx 10\text{km}$

Pulsars Eject Relativistic Winds



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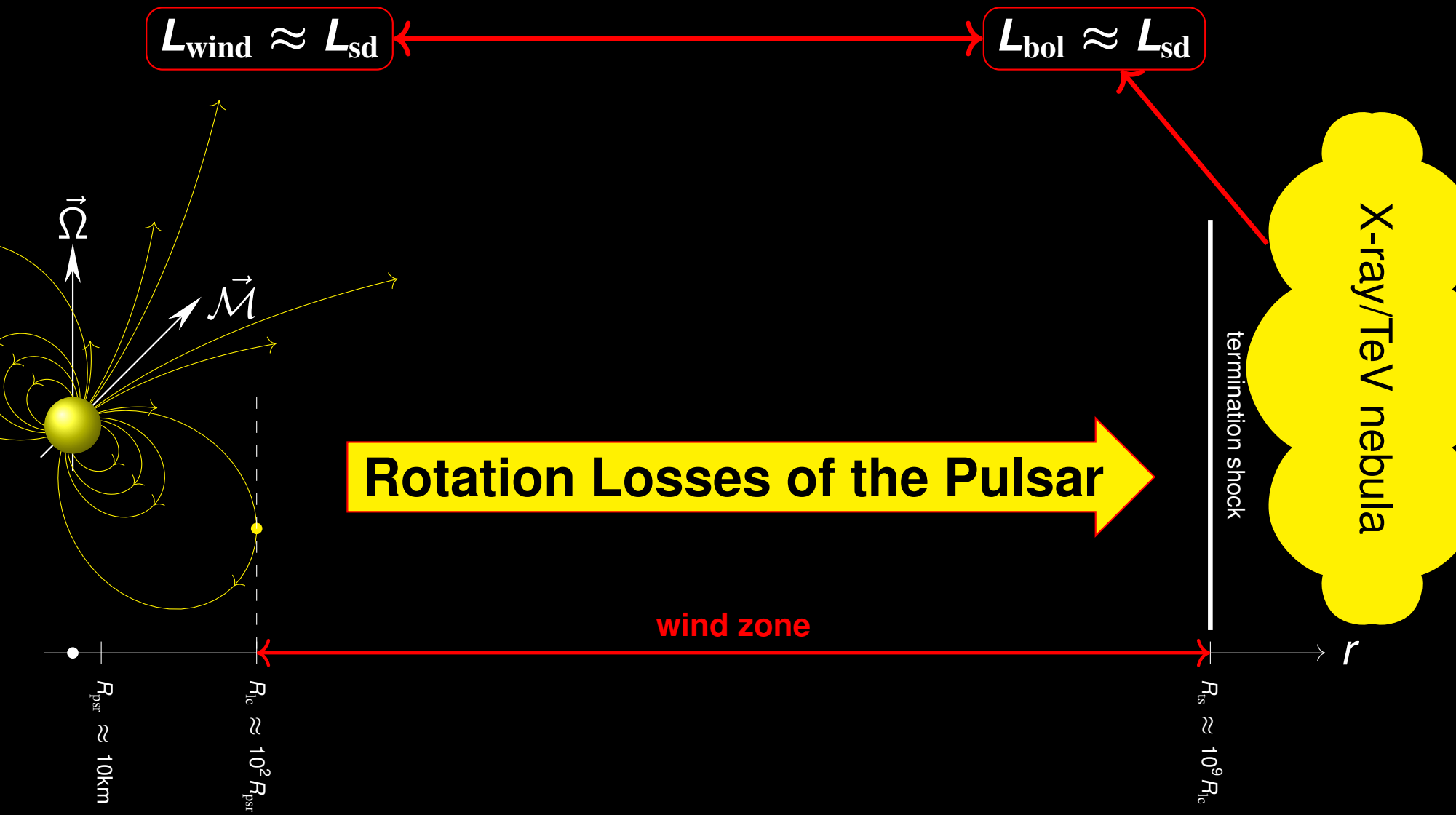

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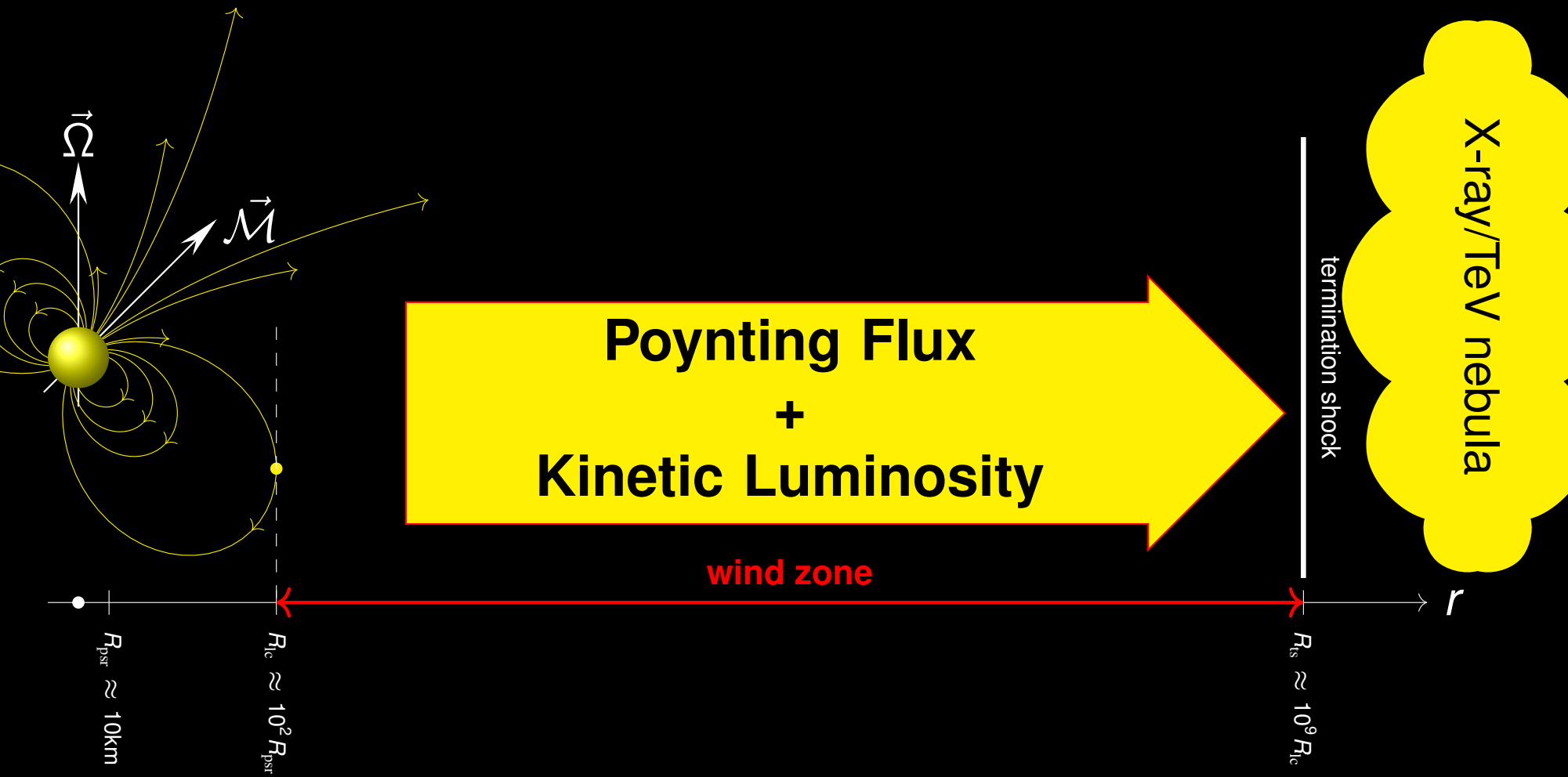

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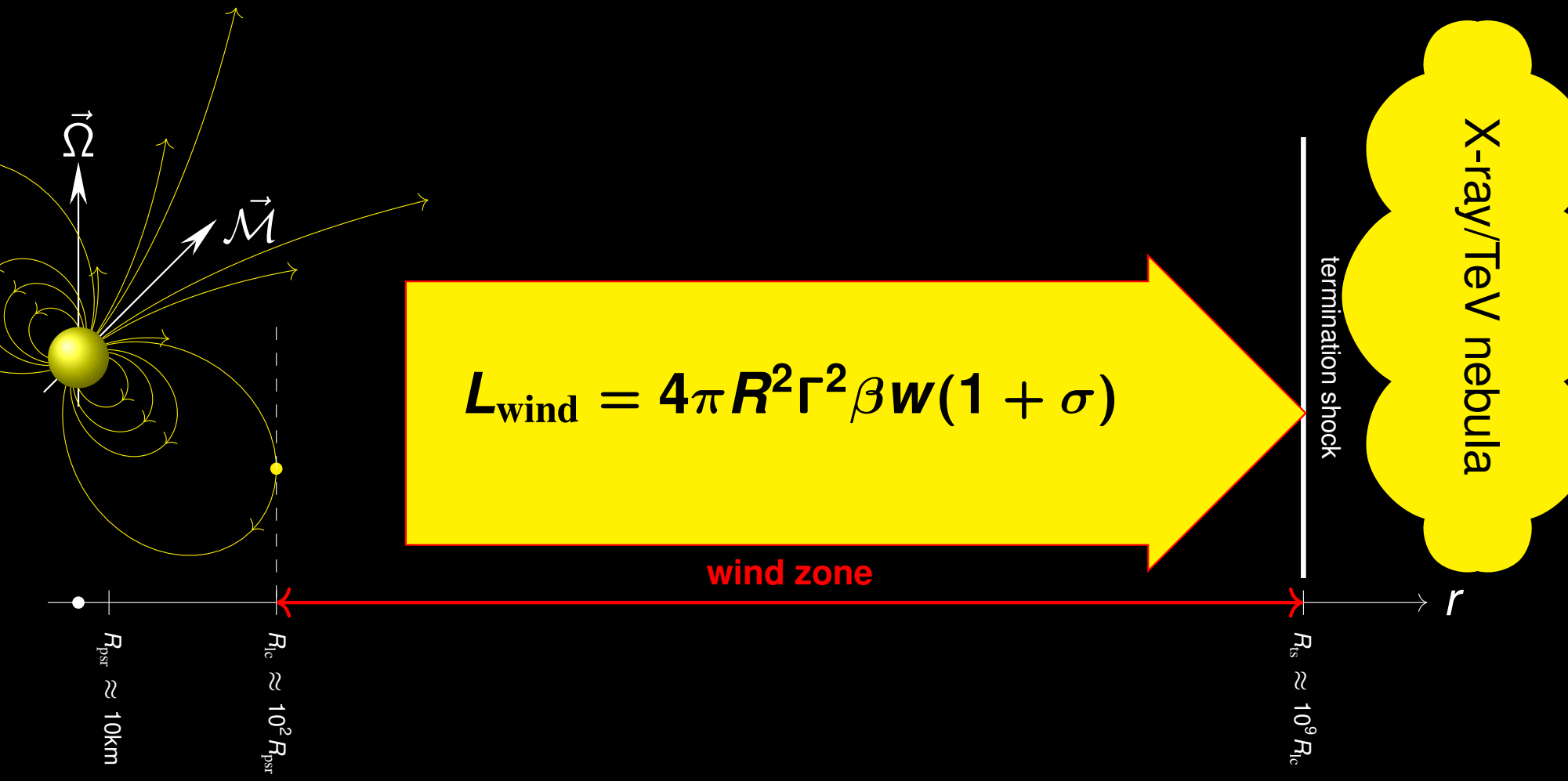

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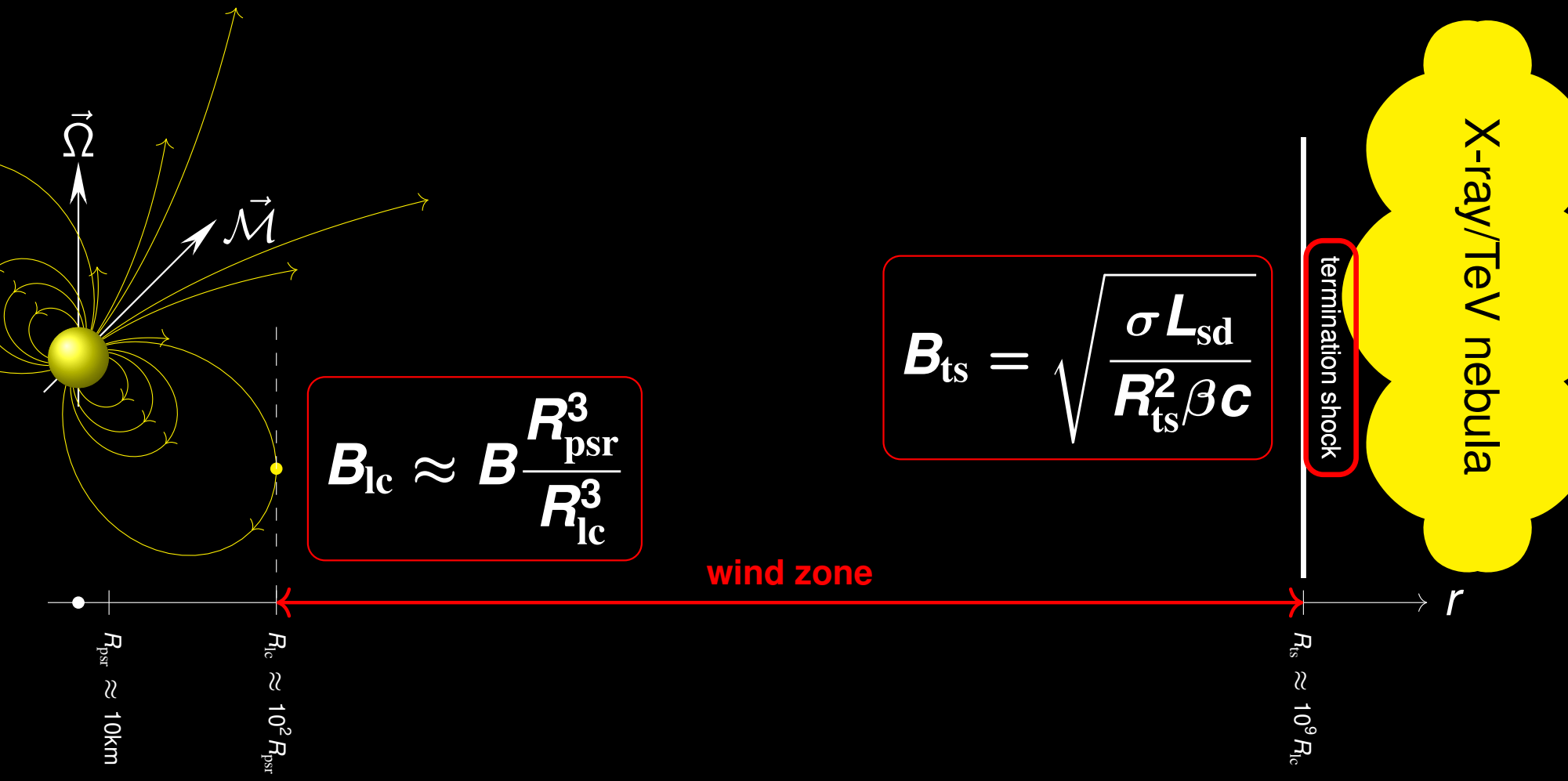
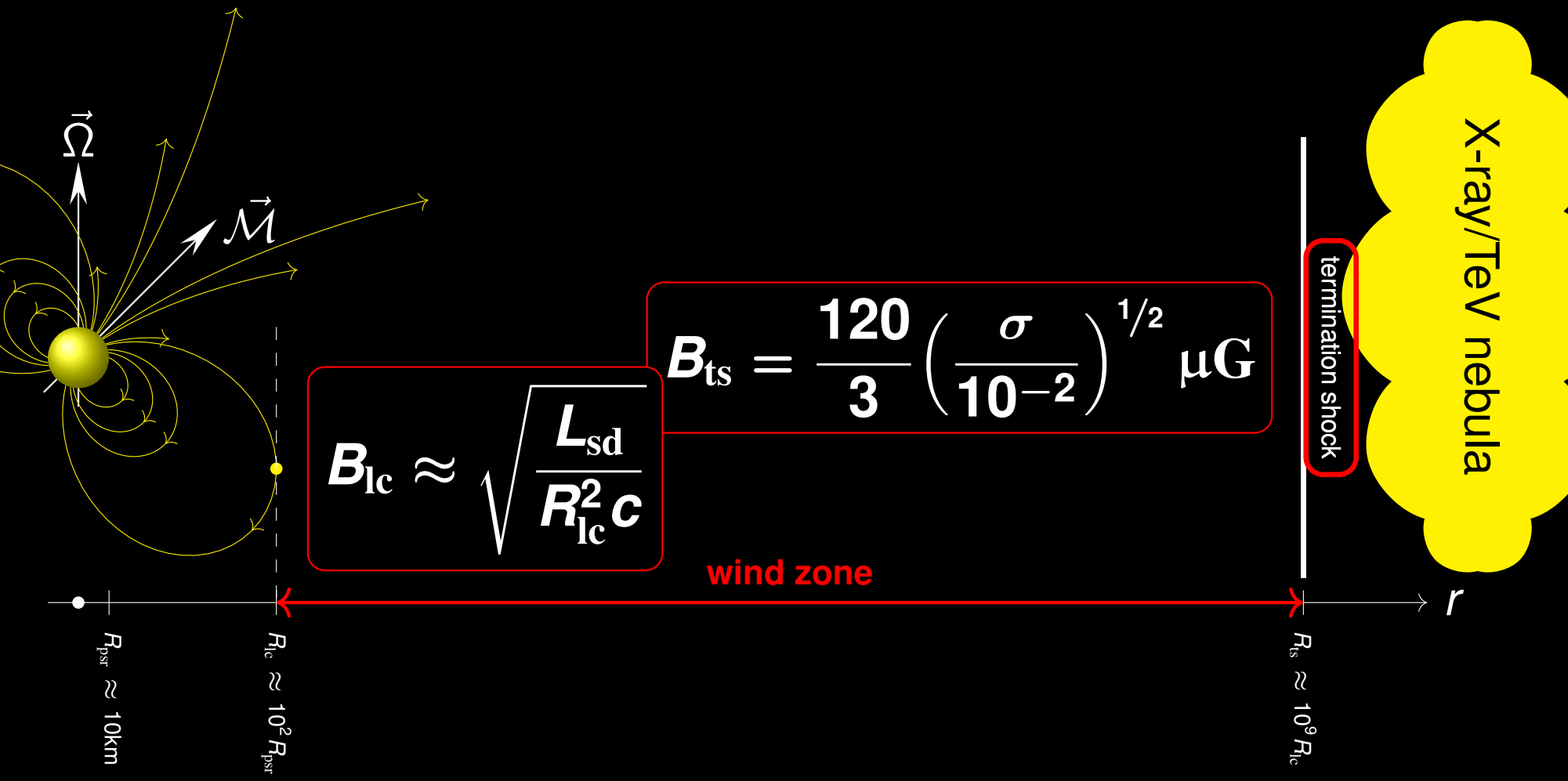
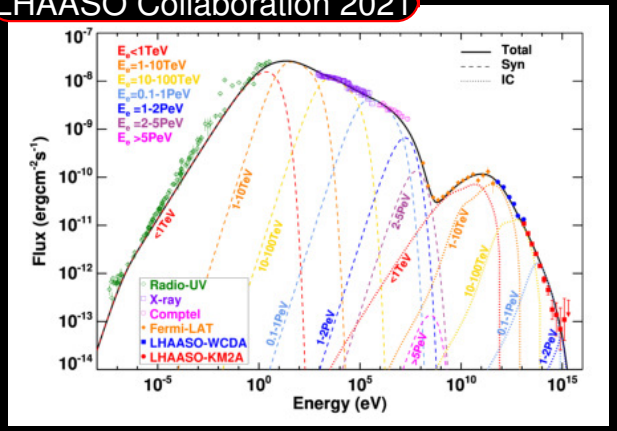


Pulsars Eject Relativistic Winds



Pulsars Eject Relativistic Winds

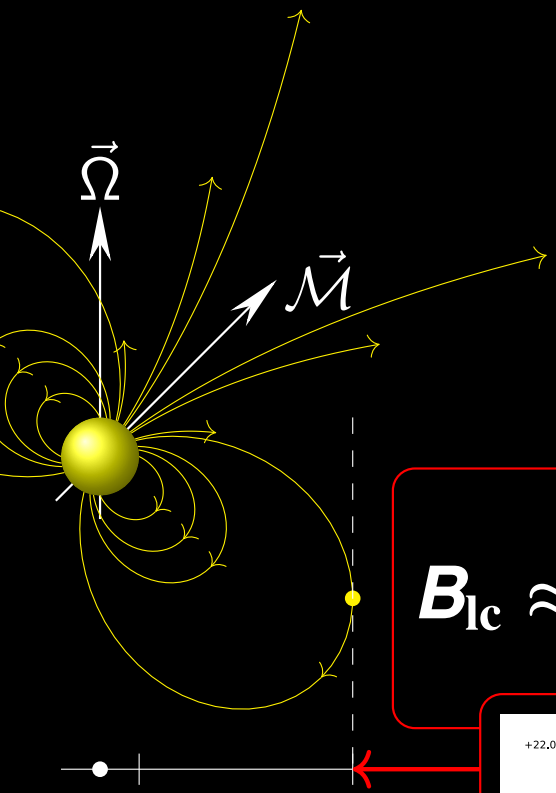
LHAASO Collaboration 2021



$$B_{\rm ts} = \frac{120}{3}\left(\frac{\sigma}{10^{-2}}\right)^{1/2}\ \mu{\rm G}$$

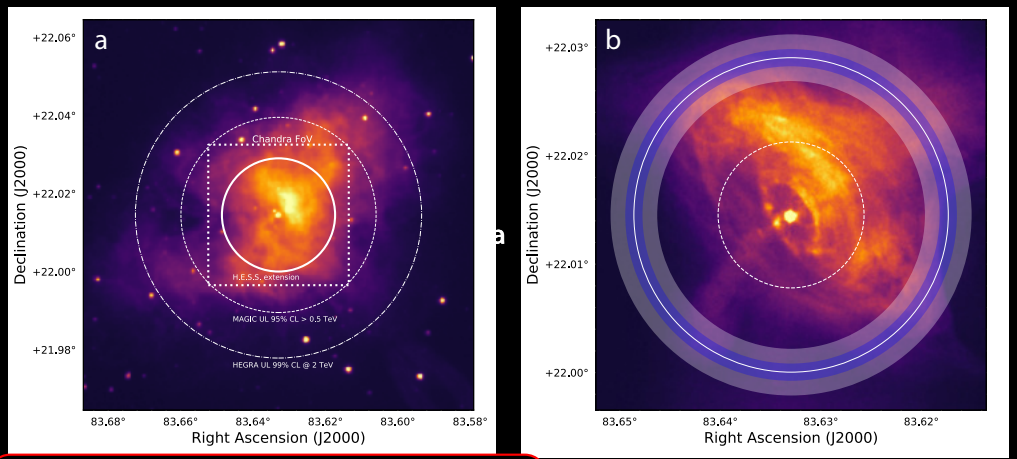
$$B_{\rm lc} \approx \sqrt{\frac{L_{\rm sd}}{R_{\rm lc}^2 c}}$$

σ is low: Kennel&Coroniti(1984), Aharonian&Atoyan(1995)



termination shock

X-ray/TeV nebula

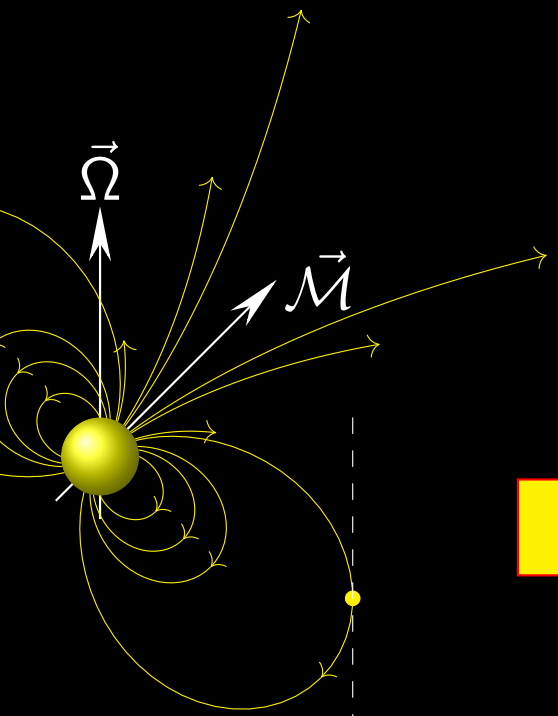


H.E.S.S. Collaboration 2019

r

$R_{\rm ts} \approx 10^9 R_{\rm lc}$

Pulsars Eject Relativistic Winds



$\sigma \approx 1$ for $r \approx R_{\rm lc}$

wind bulk acceleration

$\sigma \ll 1$ for $r \approx R_{\rm ts}$

wind zone

termination shock

X-ray/TeV nebula

r

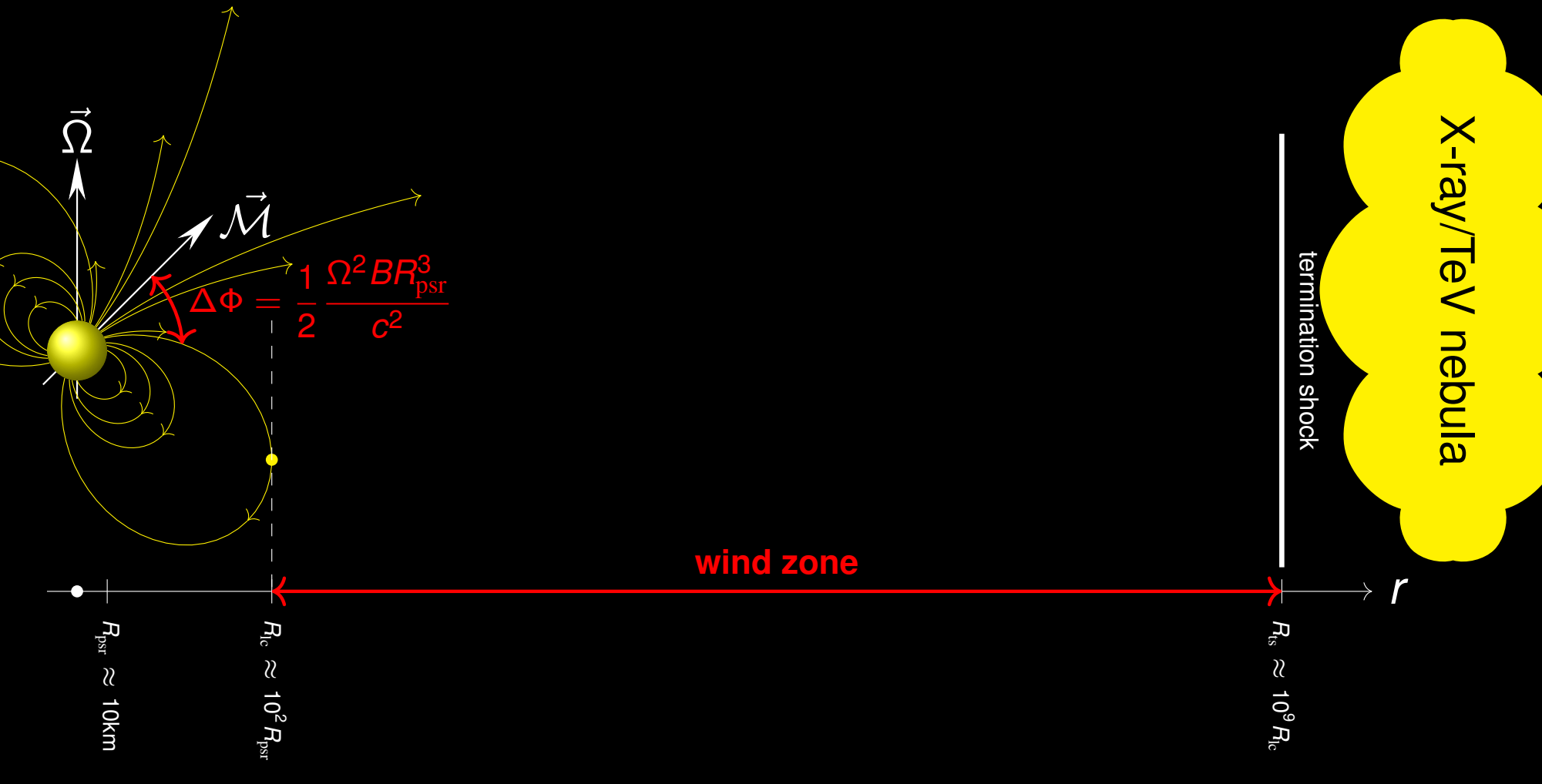
$R_{\rm psr} \approx 10{\rm km}$

$R_{\rm lc} \approx 10^2 R_{\rm psr}$

$R_{\rm ts} \approx 10^9 R_{\rm lc}$

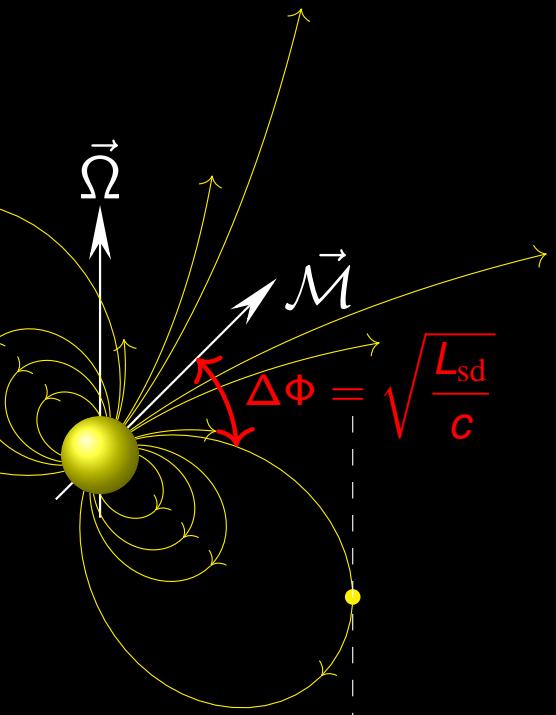
...aka "σ problem"...

What are Pulsars Winds?



What are Pulsars Winds?

Hillas Criterion (for $\beta \to 1$): $R_{\rm ts} > \dfrac{E_{\rm max}}{eB_{\rm ts}}$



$\Delta\Phi = \beta B_{\rm ts} R_{\rm ts}$

termination shock

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wind zone

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$\sigma \approx 1$

$\sigma \ll 1$

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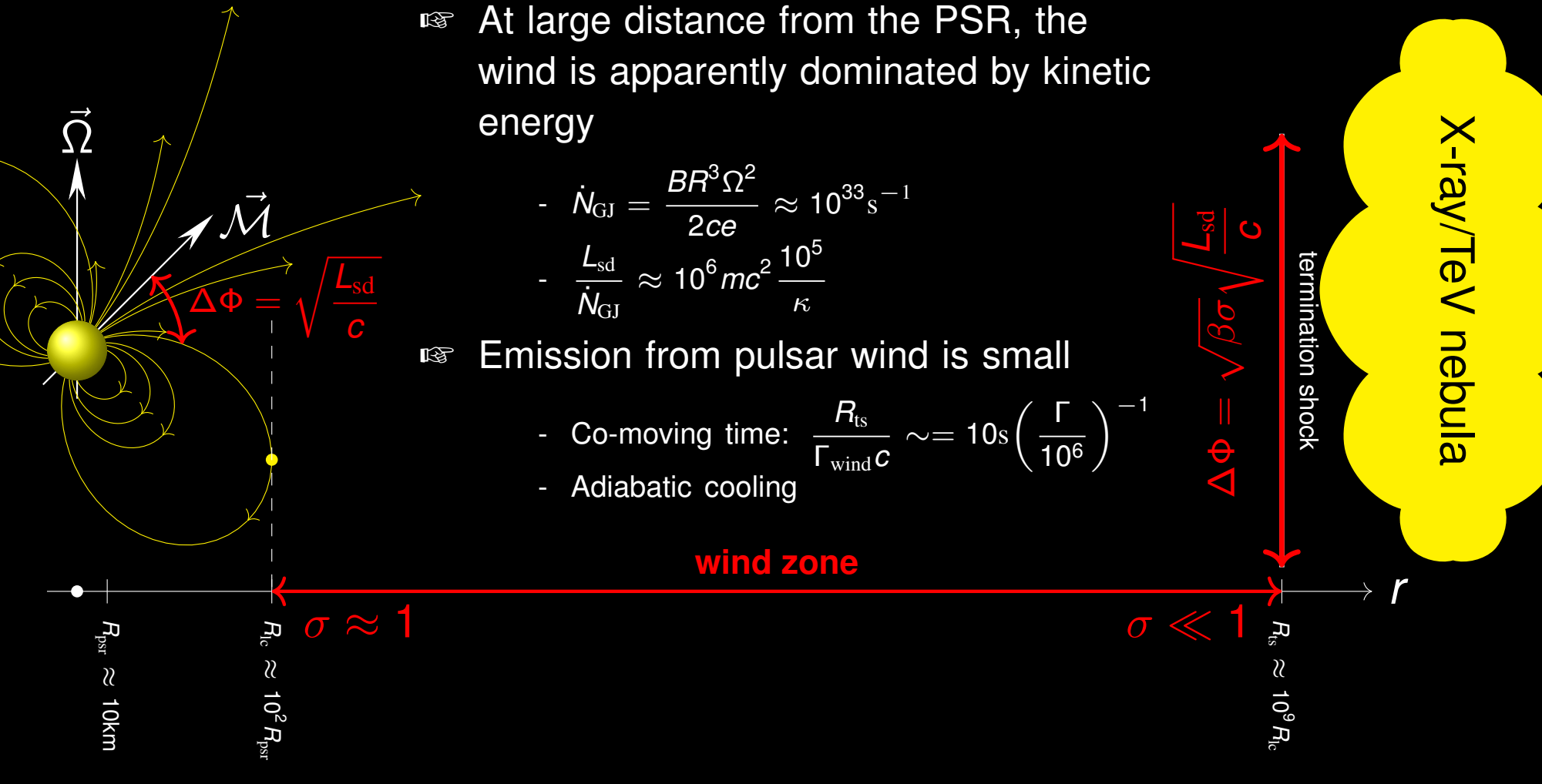
What are Pulsars Winds?

- Relativistic MHD outflow that transport pulsar spindown losses to the nebula
- Complex electromagnetic processes take place in the wind
- At large distance from the PSR, the wind is apparently dominated by kinetic energy
  - $\dot{N}_{\rm GJ} = \dfrac{BR^3\Omega^2}{2ce} \approx 10^{33}\,{\rm s}^{-1}$
  - $\dfrac{L_{\rm sd}}{\dot{N}_{\rm GJ}} \approx 10^6 mc^2 \dfrac{10^5}{\kappa}$
- Emission from pulsar wind is small
  - Co-moving time: $\dfrac{R_{\rm ts}}{\Gamma_{\rm wind} c} \sim= 10{\rm s}\left(\dfrac{\Gamma}{10^6}\right)^{-1}$
  - Adiabatic cooling

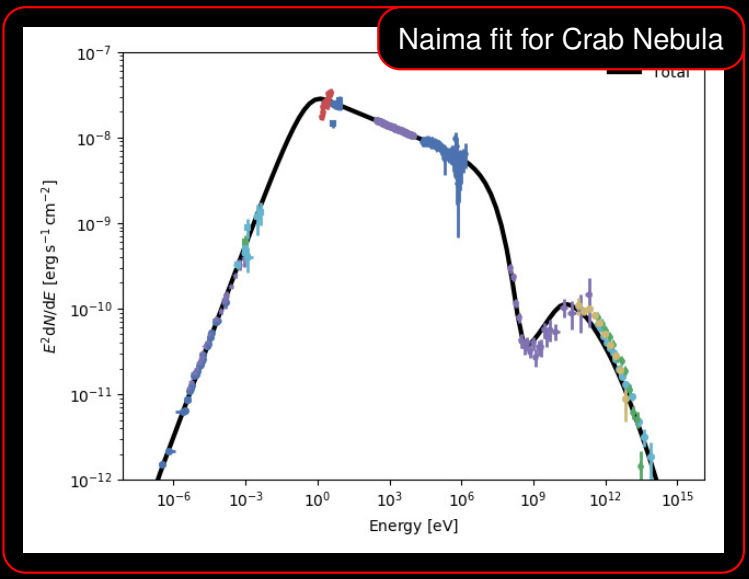


Emission from Pulsars Winds

- The radiation losses in the wind zone are much smaller that in the nebula
- Wind moves with enormous bulk Lorentz factor $\Gamma_{\rm wind} \sim 10^3 - 10^6$, but since wind solid angle is large, there is no Doppler boosting like in jets
- Wind acceleration is accompanied with adiabatic cooling, thus synchrotron emission from the wind is strongly suppressed and radiated at lower frequencies

$$\hbar\omega_{\rm syn} \propto \Gamma_{\rm wind}\left(\frac{B}{\Gamma_{\rm wind}}\right)\left(\frac{E}{\Gamma_{\rm wind}}\right)^2 \propto \Gamma_{\rm wind}^{-2}$$

- IC emission from the wind is hard to distinguish from the nebula emission, unless it features a specific time pattern...



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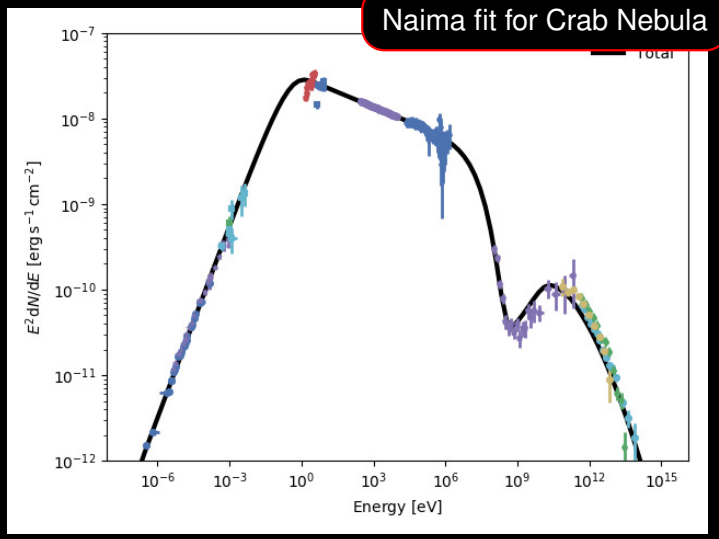
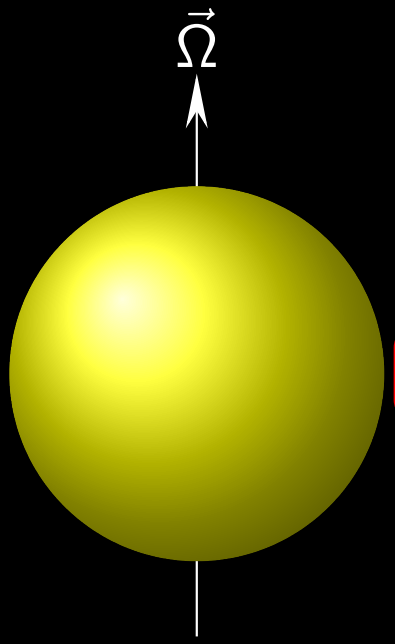




$L = I\Omega\dot{\Omega}$

Angular momentum?

Pulsed IC Emission from Wind

- Energy–Angular Momentum losses of pulsar:

$$\dot{E}_{\rm sd} = \Omega \dot{M}_{\rm sd}$$

- Energy carried by an electron:

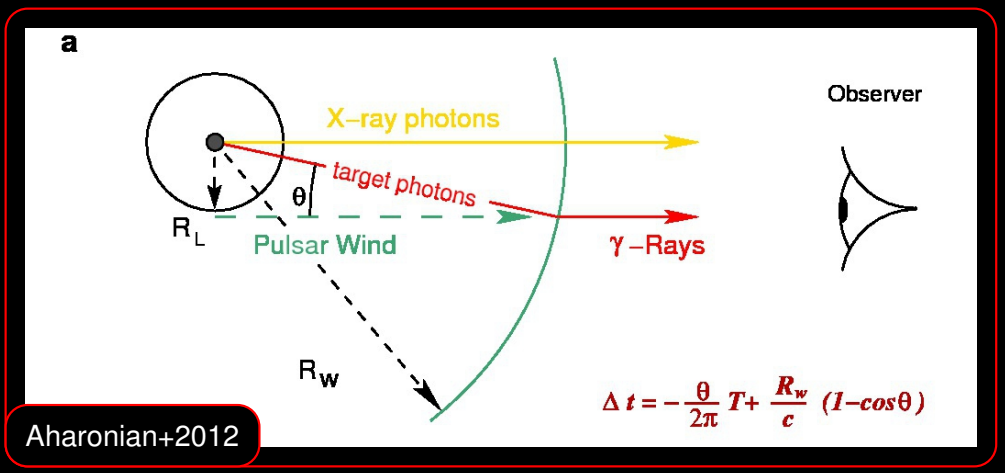
$$\Gamma_{\rm w} mc^2$$

- Angular Momentum carried by an electron:

$$\Gamma_{\rm w} m r_\perp v$$

- Pulsar wind trajectory when $\sigma \ll 1$:

$$r_\perp = \frac{c}{\Omega} = R_{\rm L}$$



Aharonian+2012

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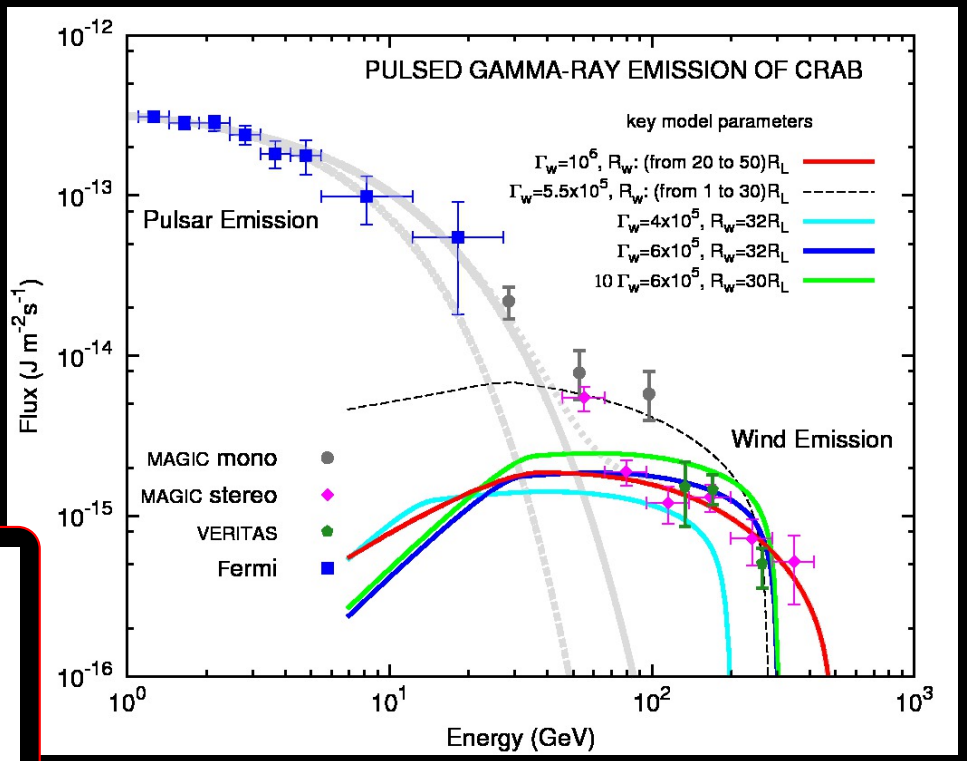

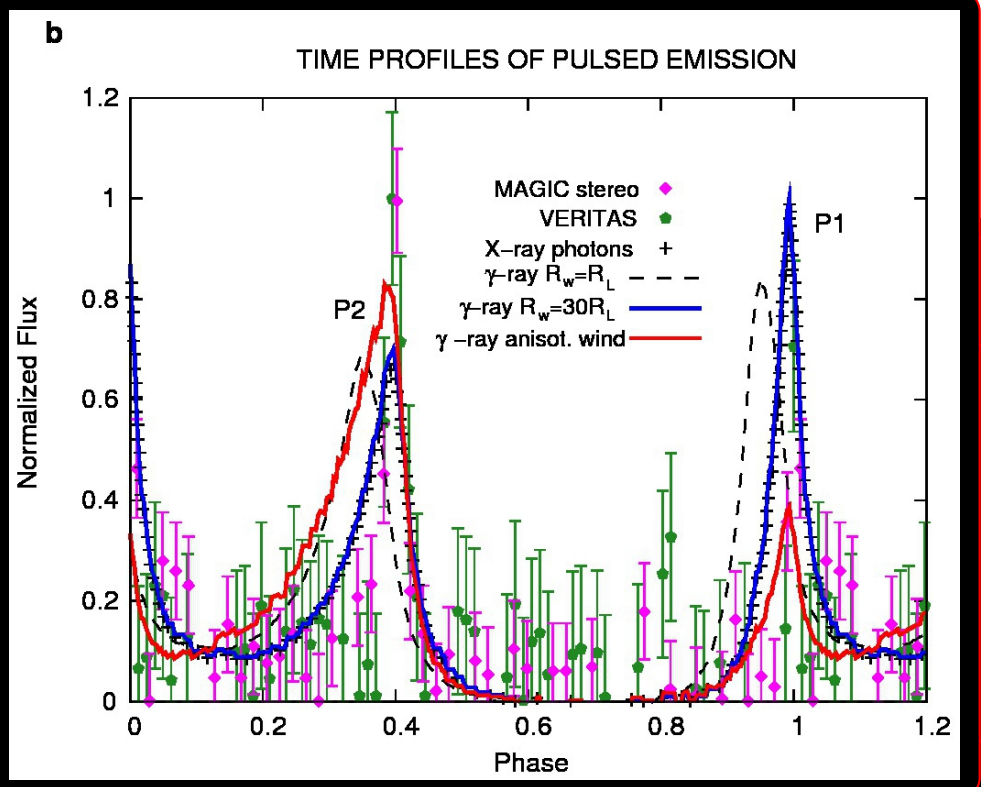

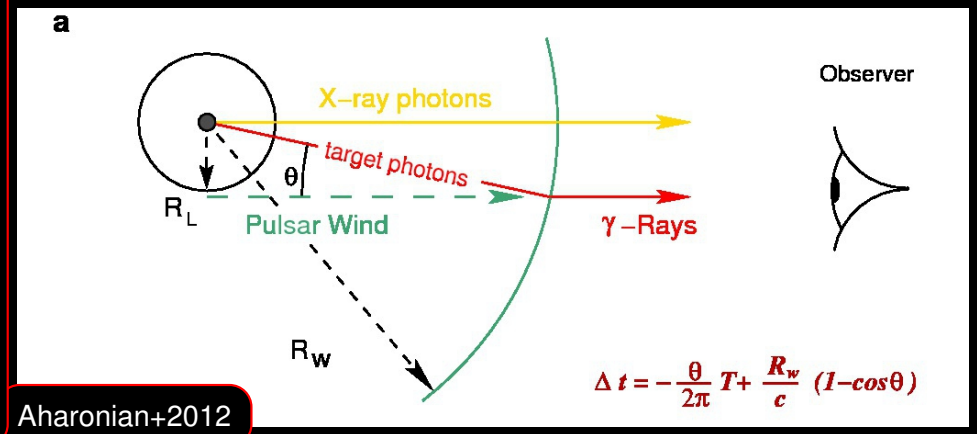

Aharonian+2012

Summary

- Pulsar winds carry almost the entire rotation energy losses of pulsars to sub-pc distances
- We expect that complicated processes occur along the way leading to an efficient dissipation of electromagnetic energy
- However winds are not efficient emitters, thus their emission can be effectively hidden by the nebula dominant contribution
- Synchrotron emission is suppressed by luminosity and peaking frequency (because of adiabatic cooling and weakening of the magnetic field)
- Conservation of angular momentum implies that pulsar wind can up-scatter photons emitted by the pulsar
- Under certain conditions (most critically early wind acceleration) the wind IC emission may appear as a pulsed signal correlated with the X-ray band