PARTICLE ACCELERATION IN PULSARS AND PULSAR WIND NEBULAE

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SUMMARY

Pulsar -> pulsar wind -> pulsar wind nebulae

- PULSARS AND THEIR MAGNETOSPHERES
  - THE GOLDREICH AND JULIAN MAGNETOSPHERE
  - GAPS, PLASMA SUPPLY, MULTIPLICITY
  - THE PULSAR WIND

- PULSAR WIND NEBULAE
  - DYNAMICS
  - PARTICLE ACCELERATION
  - RECENTS FROM GAMMA-RAYS
  - PARTICLE ESCAPE

IN GRAVITATIONAL COLLAPSE

CONSERVATION OF ANGULAR MOMENTUM $M_f R_f^2 \, \Omega_f = M_i R_i^2 \Omega_i$

CONSERVATION OF MAGNETIC FLUX $B_i R_i^2 = B_f R_f^2$

$R_i \approx 10^{11}\text{cm}$

$R_f \approx 10^{6}\text{cm}$

$\Rightarrow \left(\frac{R_i}{R_f}\right)^2 = 10^{10} \Rightarrow$

$P_i \sim 10^5\text{s} \Rightarrow P_f < 0.1\text{ms}$

$B_i \sim 100\text{G} \Rightarrow B_f \sim 10^{12}\text{G}$

EXTREME ENVIRONMENT

QED EFFECTS

MAGNETARS....

$$\hbar\omega_{\rm cy} = m_e c^2 \Rightarrow B_{\rm QED} = \frac{m_e^2 c^3}{\hbar e} \approx 5 \times 10^{13}\ {\rm G} \Rightarrow \frac{B_{\rm NS}}{B_{\rm QED}} = 0.01 - 1$$

RELATIVISTIC EFFECTS

$$v_{\rm rot} = \omega R_{\rm NS} \simeq 0.2c \left(\frac{P}{10^{-3}{\rm s}}\right)^{-1} \left(\frac{R_{\rm NS}}{10\,{\rm km}}\right)$$

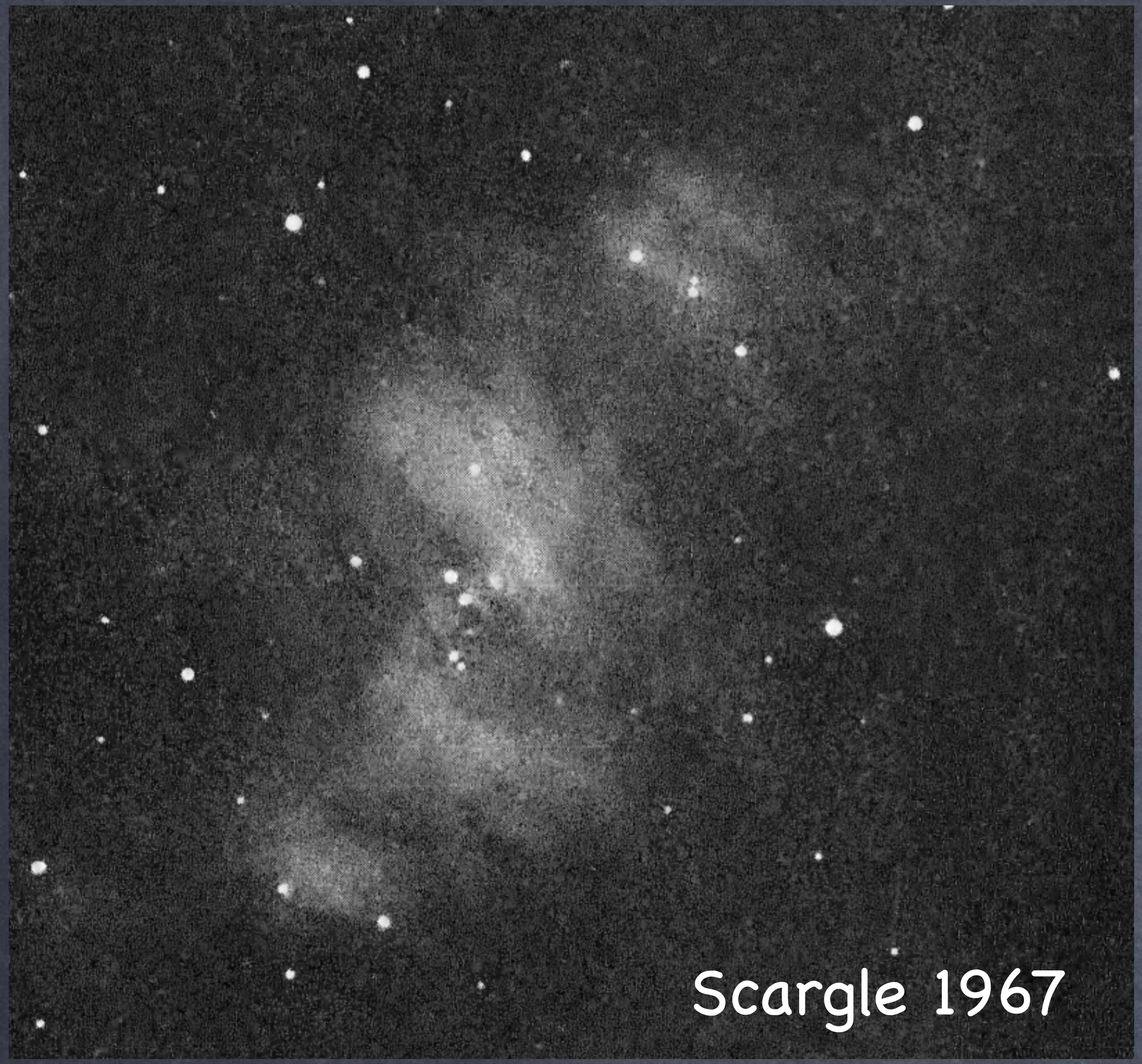
GR EFFECTS

$$R_{\rm GR} = \frac{2GM}{c^2} \Rightarrow \frac{R_{\rm NS}}{R_{\rm GR}} \simeq 3 \left(\frac{M_{\rm NS}}{1.4 M_\odot}\right)^{-1} \left(\frac{R_{\rm NS}}{10{\rm km}}\right)$$

NEUTRON STARS

- 1933: DISCOVERY OF THE NEUTRON (Chadwick 1933)
- 1934: NEUTRON STARS PROPOSED (Baade & Zwicky 1934) AS EXPLANATION FOR SUPERNOVA ENERGY RELEASE
- 1939: FIRST MEANINGFUL NEUTRON STAR EQUATION OF STATE (Tolman, Oppenheimer & Volkoff 1939): MAXIMUM MASS SMALLER THAN FOR WHITE DWARFS
- 1939-1959: NO HOPE OF OBSERVATION -> FORGOTTEN PROBLEM
- 1959: REVISED MASS ESTIMATE (Cameron 1959)
- 1967: A BRILLIANT IDEA...

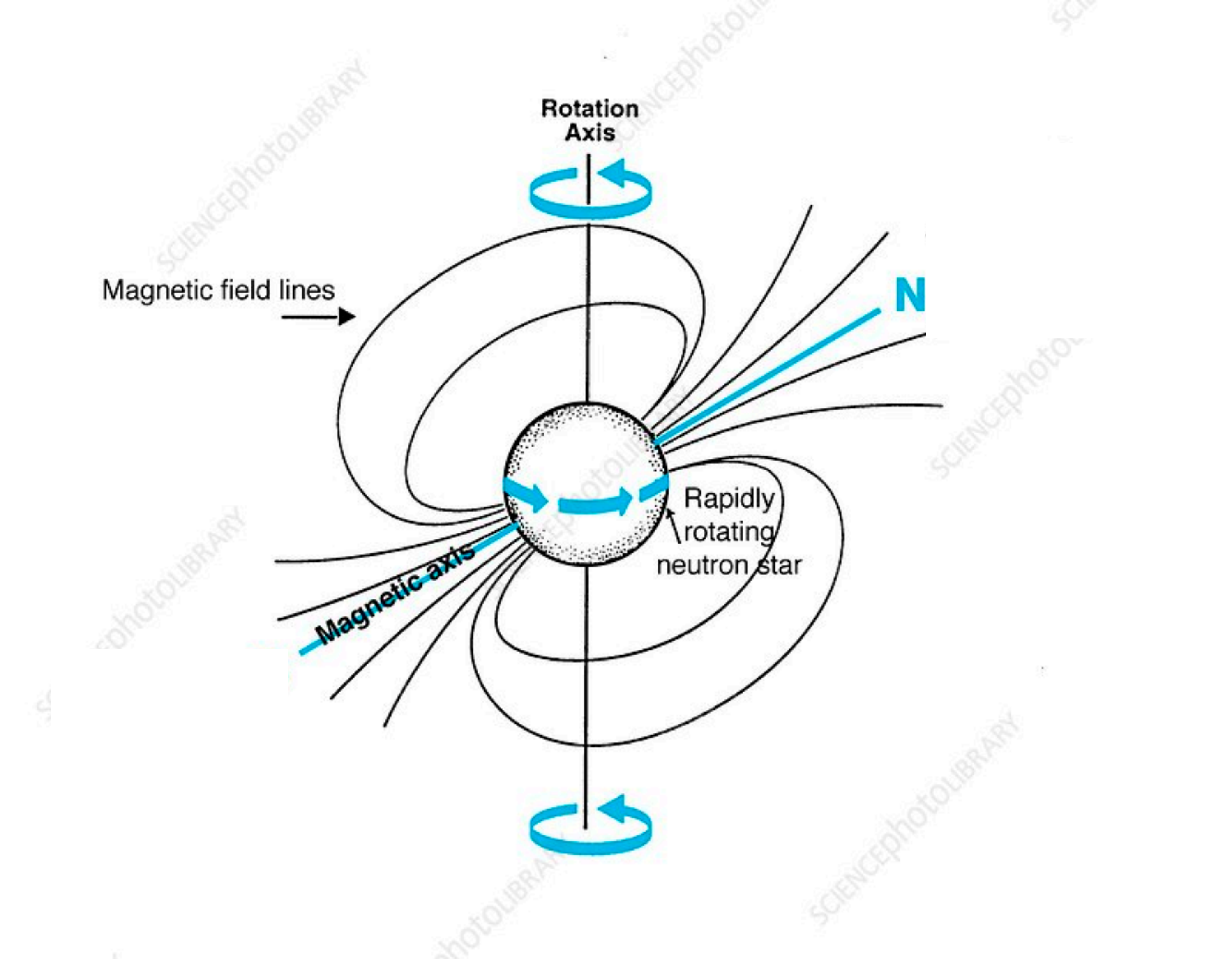
"ENERGY EMISSION FROM A NEUTRON STAR"

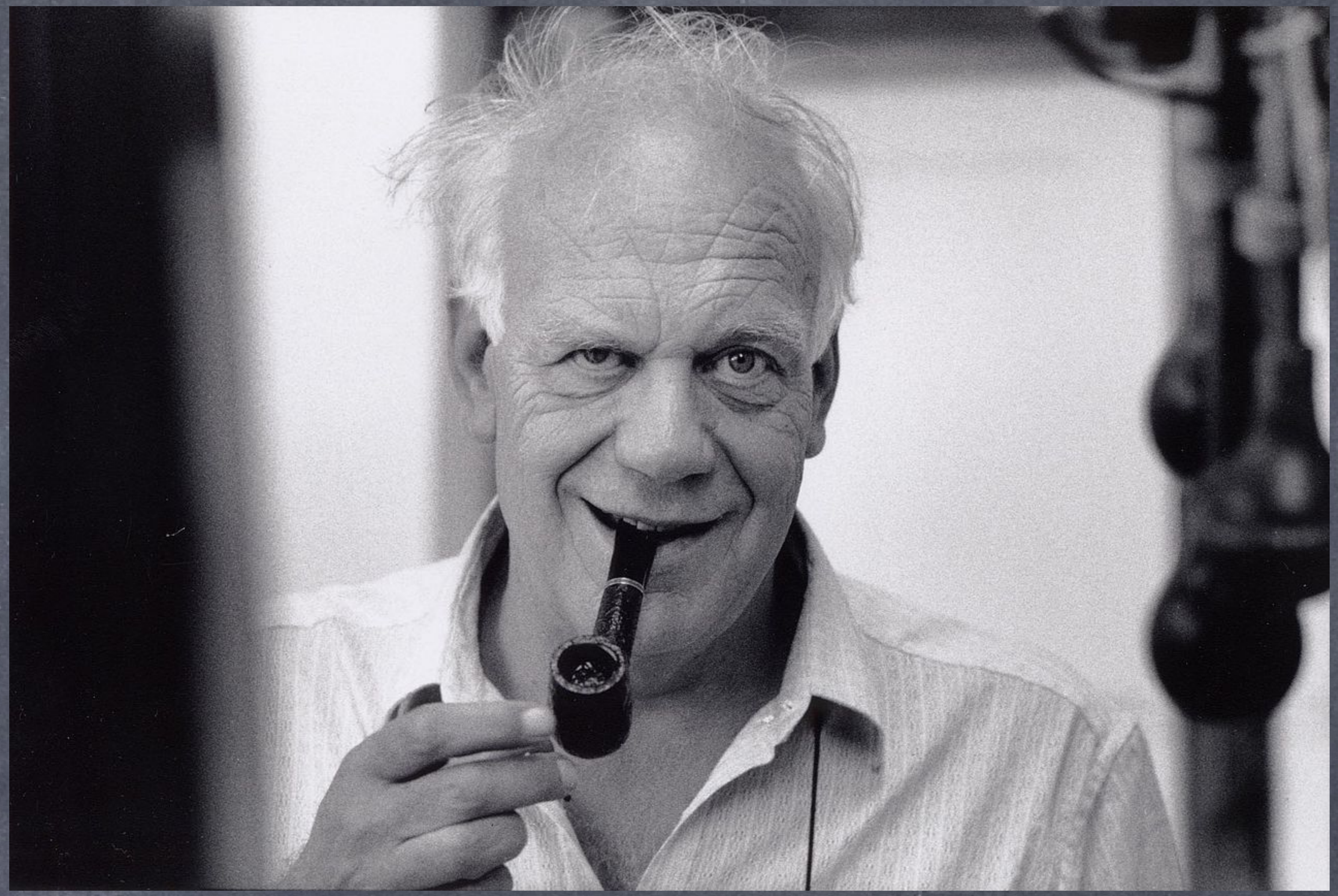


Scargle 1967

Pacini 1967

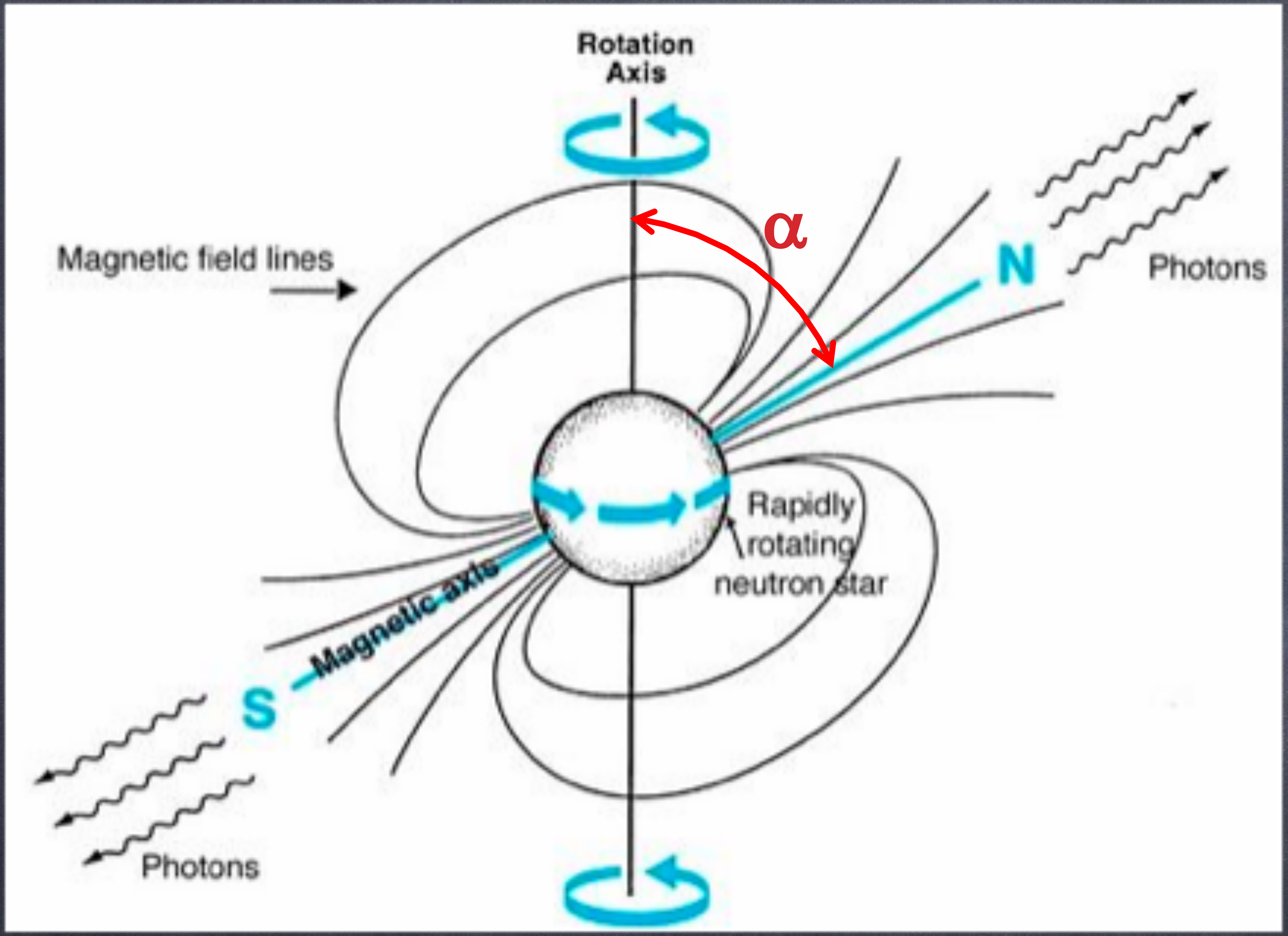
$$\dot{E} = \frac{B_\star^2\ R_\star^6 \Omega^4 \sin^2 \chi}{6c^3}$$





Franco Pacini [1939-2012]

OBLIQUE ROTATING DIPOLE



MAGNETIC MOMENT

$$\vec{\mu} = \mu_0 \left[\sin\alpha \left(\cos\Omega t \ \underline{\mathbf{e}}_1 + \sin\Omega t \ \underline{\mathbf{e}}_2 \right) + \cos\alpha \ \underline{\mathbf{e}}_3 \right]$$

MAGNETIC DIPOLE FIELD

$$\vec{B} = \frac{3\underline{\mathbf{e}}_{\mathbf{R}} \left(\vec{\mu} \cdot \underline{\mathbf{e}}_{\mathbf{R}} \right) - \vec{\mu}}{R^3} \qquad \mu_0 = \frac{B_\star R_\star^3}{2}$$

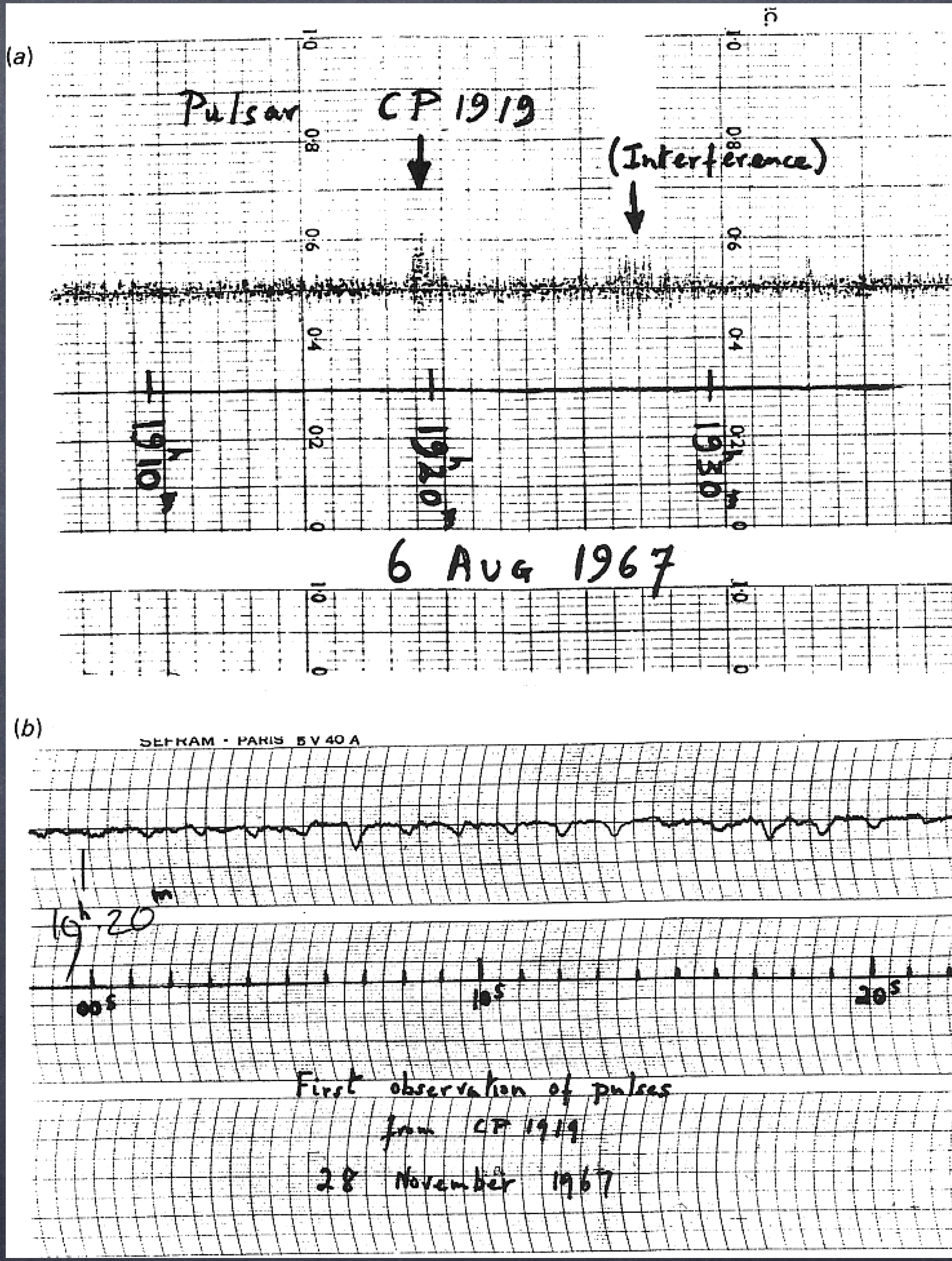
LARMOR FORMULA $$\frac{dE}{dt} = -\frac{2}{3c^3}\ddot{\mu}^2$$

ENERGY LOSSES: $$\dot{E} = \frac{2}{3c^3}\frac{B_\star^2 R_\star^6}{4}\Omega^4 \sin^2\alpha \qquad \dot{E} = 10^{40}\,\frac{B_{12}^2}{P_{-3}^4}\ \mathrm{erg/s}$$

THE FIRST PULSAR

Hewish & Bell 1968

P=1.33s AND KEEPING SIDEREAL TIME



IF A ROTATING OBJECT:

$$v_{\rm rot} < v_{\rm esc} \rightarrow \Omega R < \sqrt{\frac{2G\,M}{R^2}} \quad \Rightarrow \quad P > \sqrt{\frac{2\pi^2 R^3}{GM}}$$

FOR A WHITE DWARF: P>10 S

PULSAR SPIN DOWN

$$\dot{E} = \frac{B_\star^2 \, R_\star^6 \Omega^4 \sin^2\chi}{6c^3}$$ ⟷ ROTATIONAL ENERGY LOSS ⟷ $$\dot{E} = I_\star \, \Omega \, \dot{\Omega}$$

DIPOLE

$$\frac{B_\star^2 \, R_\star^6 \Omega^4 \sin^2\chi}{6c^3} = I_\star \Omega \dot{\Omega}$$

GENERIC MULTIPOLE

$$\dot{\Omega} = -K_{sd}\Omega^n$$

$$\Omega(t) = \frac{\Omega_0}{(1 + t/\tau)^{1/(n-1)}} \qquad \dot{E} = \frac{\dot{E}_0}{(1 + t/\tau)^{\frac{n+1}{n-1}}}$$

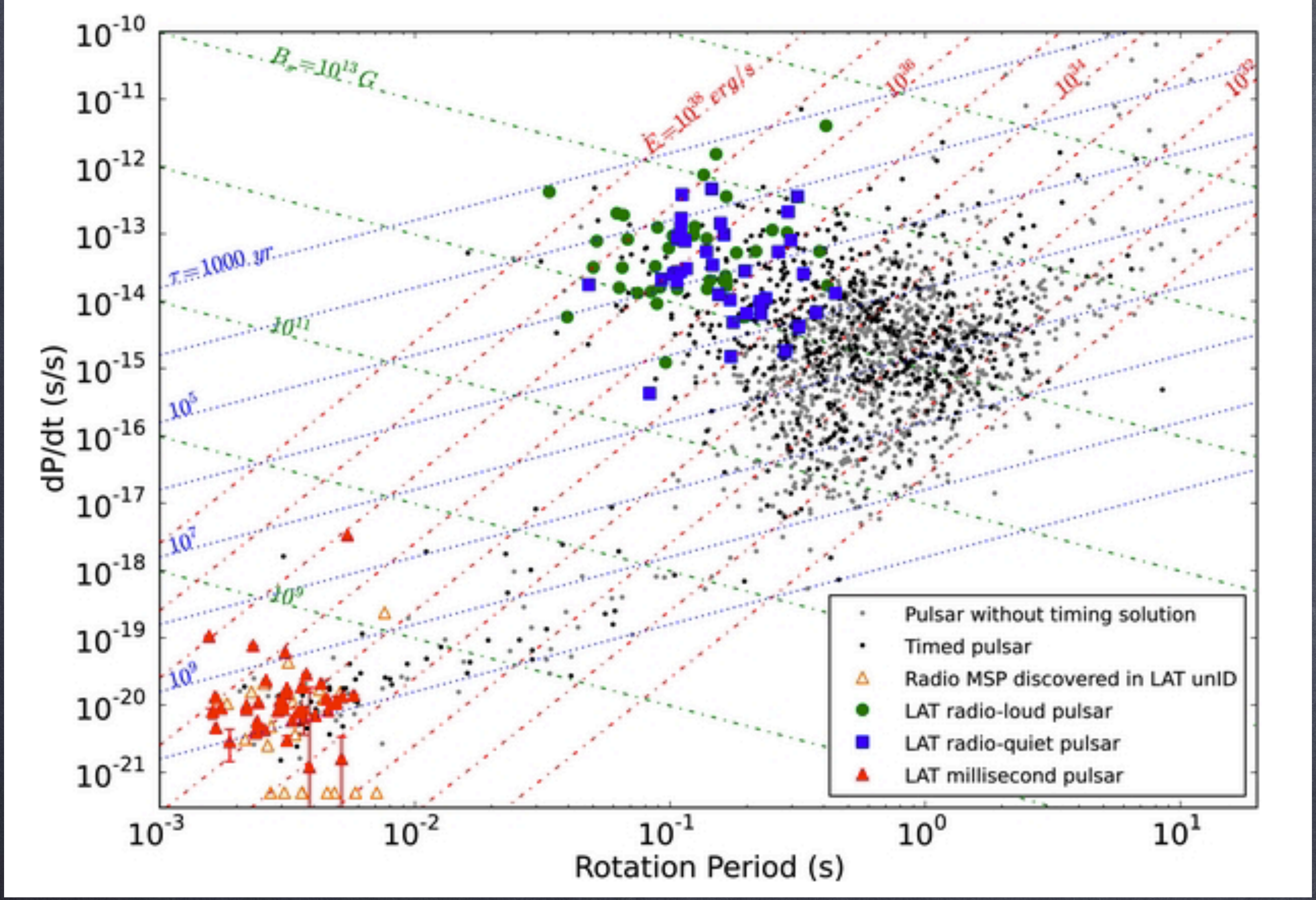
$$\tau = \frac{P_0}{(n-1)\dot{P}_0} \qquad n = \frac{\ddot{\Omega}\Omega}{\dot{\Omega}^2}$$

NOTE

$$K_{sd} = \frac{6 \, I_\star \, c^3}{B_\star^2 \, R_\star^6 \, \sin^2\chi}$$

$$n = 3 + \frac{\Omega}{\dot{\Omega}}\left(2\frac{\dot{B}_\star}{B_\star} + 2\dot{\chi}CoTg\chi + 6\frac{\dot{R}_{el}}{R_{el}} - \frac{\dot{I}}{I}\right)$$

P-PDOT DIAGRAM



Abdo+ 2013

FOR $n = 3$
(dipole)

$$\dot{E} = 4\pi^2 \, I_\star \, \dot{P} \, P^{-3}$$

$$\dot{E} \approx 5 \times 10^{31} \mathrm{erg/s} \; P^{-3} \; \dot{P}_{-15}$$

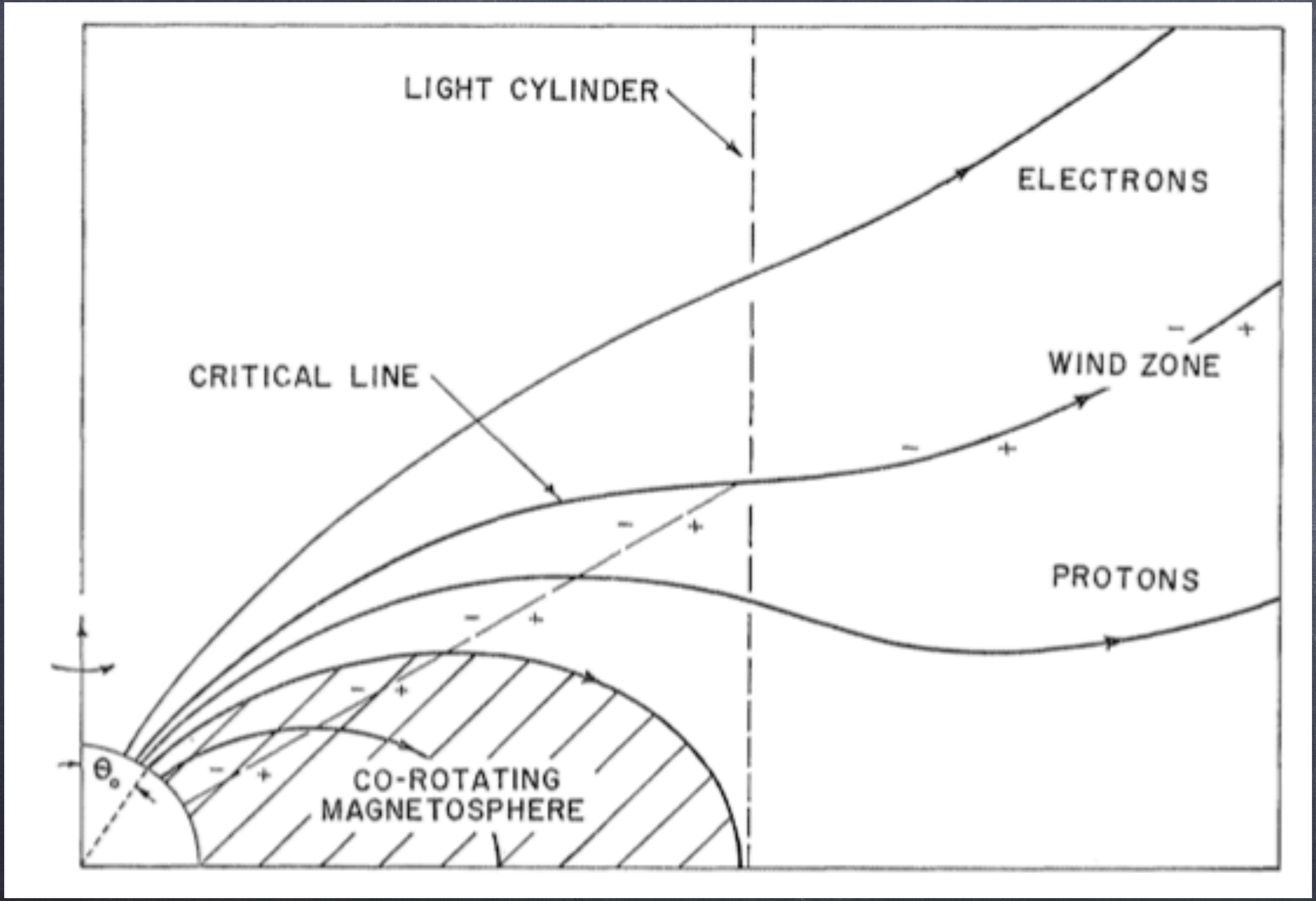
$$B_\star = \frac{(6 I_\star c^3)^{1/2}}{2\pi \, R_\star^3} \sqrt{P \, \dot{P}}$$

$$B_\star \approx 10^{12} G \sqrt{P \, \dot{P}_{-15}}$$

$$\tau = \frac{P}{2\dot{P}} \approx 3 \times 10^7 \mathrm{yr} \; P \; \dot{P}_{-15}^{-1}$$

PULSARS AS UNIPOLAR INDUCTORS

NO VACUUM PHYSICS



EVEN AN ALIGNED DIPOLE SPINS DOWN

$$\dot{E} = \frac{\mu^2\Omega^4}{c^3}\left(1 + \sin^2\chi\right)$$

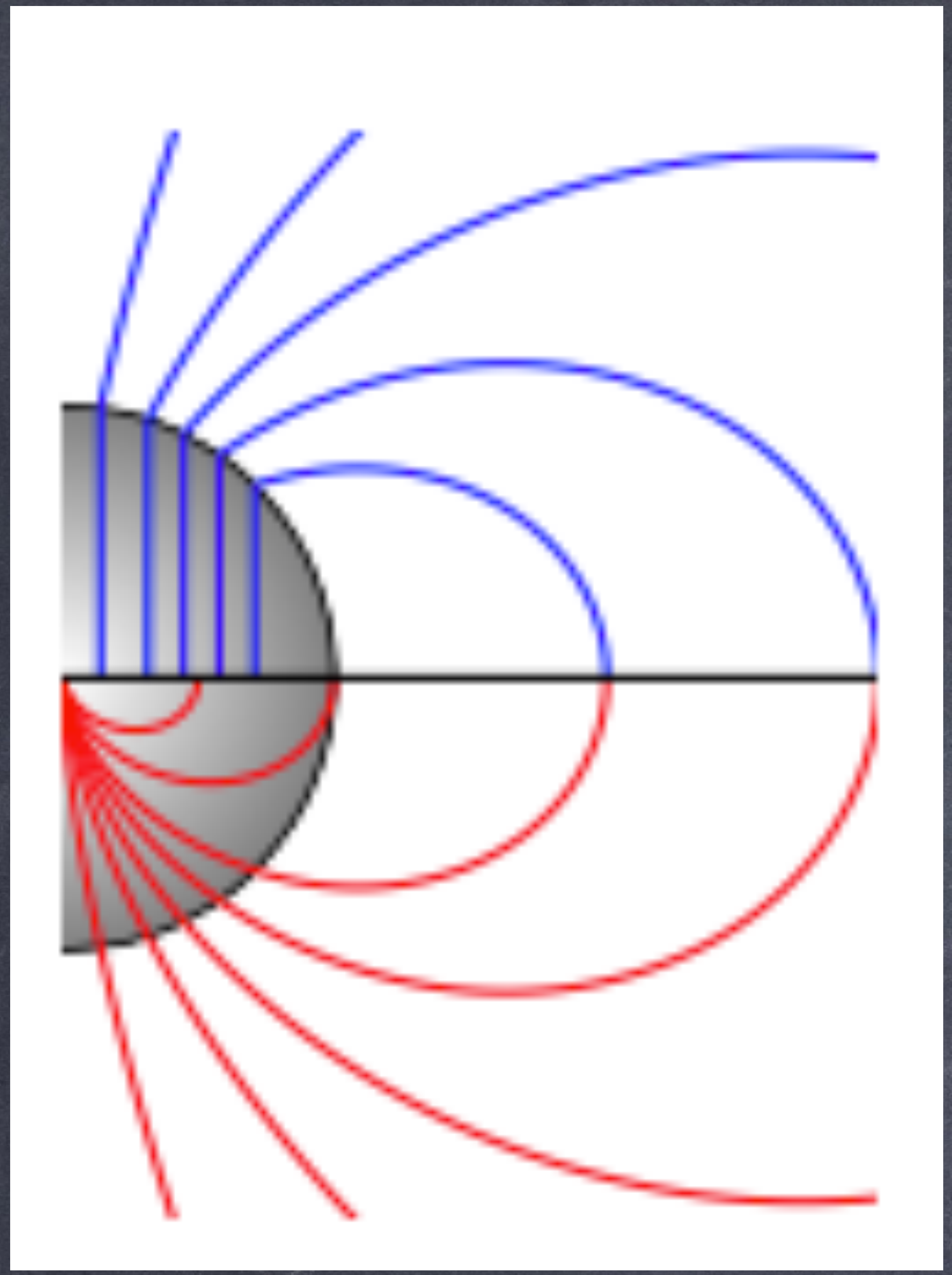
firstly obtained by means of numerical simulations

[Spitkovski 2006]

while aligned rotator in vacuum:

$$\left(\dot{E}_{\rm vac} = \frac{2}{3}\frac{\mu^2\Omega^4}{c^3}\sin^2\chi\right)$$

PULSAR: VACUUM SOLUTION of ALIGNED ROTATOR



$\vec{\Omega} = \Omega \, \underline{\mathbf{e}}_z$ $\vec{\mu} = \mu \underline{\mathbf{e}}_z$ $\mu = \dfrac{B_\star R_\star^3}{2}$

FREE CHARGES IN THE STAR ROTATE WITH $\vec{v} = \Omega \, R \, \underline{\mathbf{e}}_\phi$

$$\vec{E} + \frac{\vec{v}}{c} \wedge \vec{B} = 0 \quad \Rightarrow \quad \vec{E}^{in} = -\left(\frac{\vec{\Omega} \wedge \vec{R}}{c}\right) \wedge \vec{B}$$

IF VACUUM OUTSIDE

$\nabla^2 \Phi = 0$ $\vec{E}^{out} = -\vec{\nabla}\Phi$

BOUNDARY CONDITION AT STAR SURFACE

$E_\theta^{in}(R_\star) = E_\theta^{out}(R_\star)$

$\Phi \rightarrow \vec{E}^{out}$ $\left(E_r^{out} - E_r^{in}\right)_{R_\star} = 4\pi\sigma_e \neq 0$

FINITE CHARGE SURFACE DENSITY AT STAR SURFACE

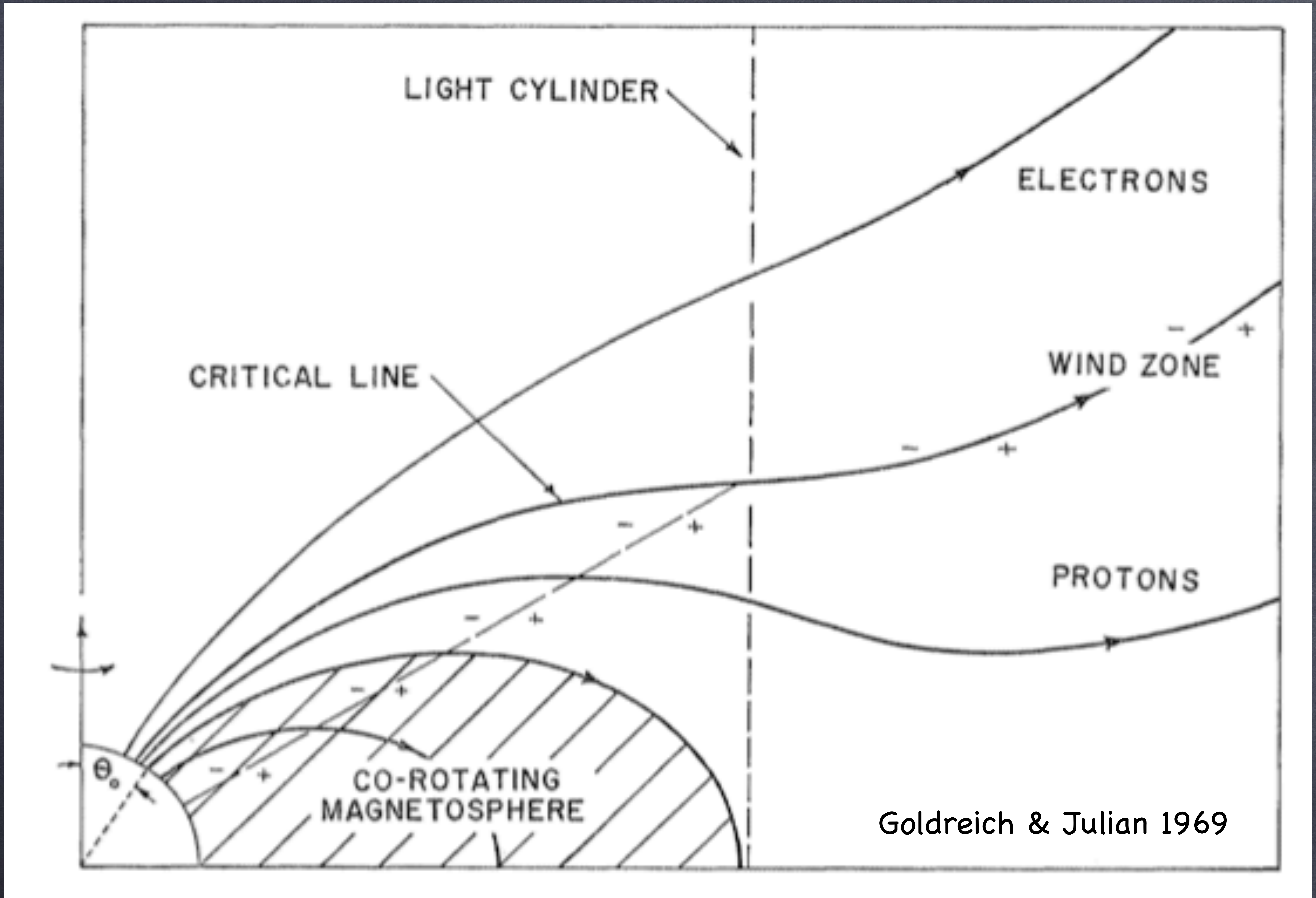
$\left(\vec{E} \cdot \vec{B}\right)_{R_\star} \neq 0$

$$eE_\parallel = e\frac{B_\star \Omega R_\star}{c}\cos^2\theta \approx \frac{0.2}{P}\,\mathrm{erg/cm}$$

$$\Rightarrow \quad \frac{eE_\parallel}{GM_\star m_e / R_\star^2} \approx 8 \times 10^{12} \frac{B_{12}}{P_{100}}$$

AND A LARGE ENOUGH FIELD TO EXTRACT IT!

THE GOLDREICH AND JULIAN MAGNETOSPHERE



PARTICLES FLOWING ALONG OPEN FIELD LINES MAY REACH INFINITY

STAR DEVELOPS COROTATING MAGNETOSPHERE

$$\vec{E} = -\frac{\Omega\, R \sin\theta}{c} \underline{\mathbf{e}}_\phi \wedge \vec{B}$$

THROUGHOUT COROTATION REGION

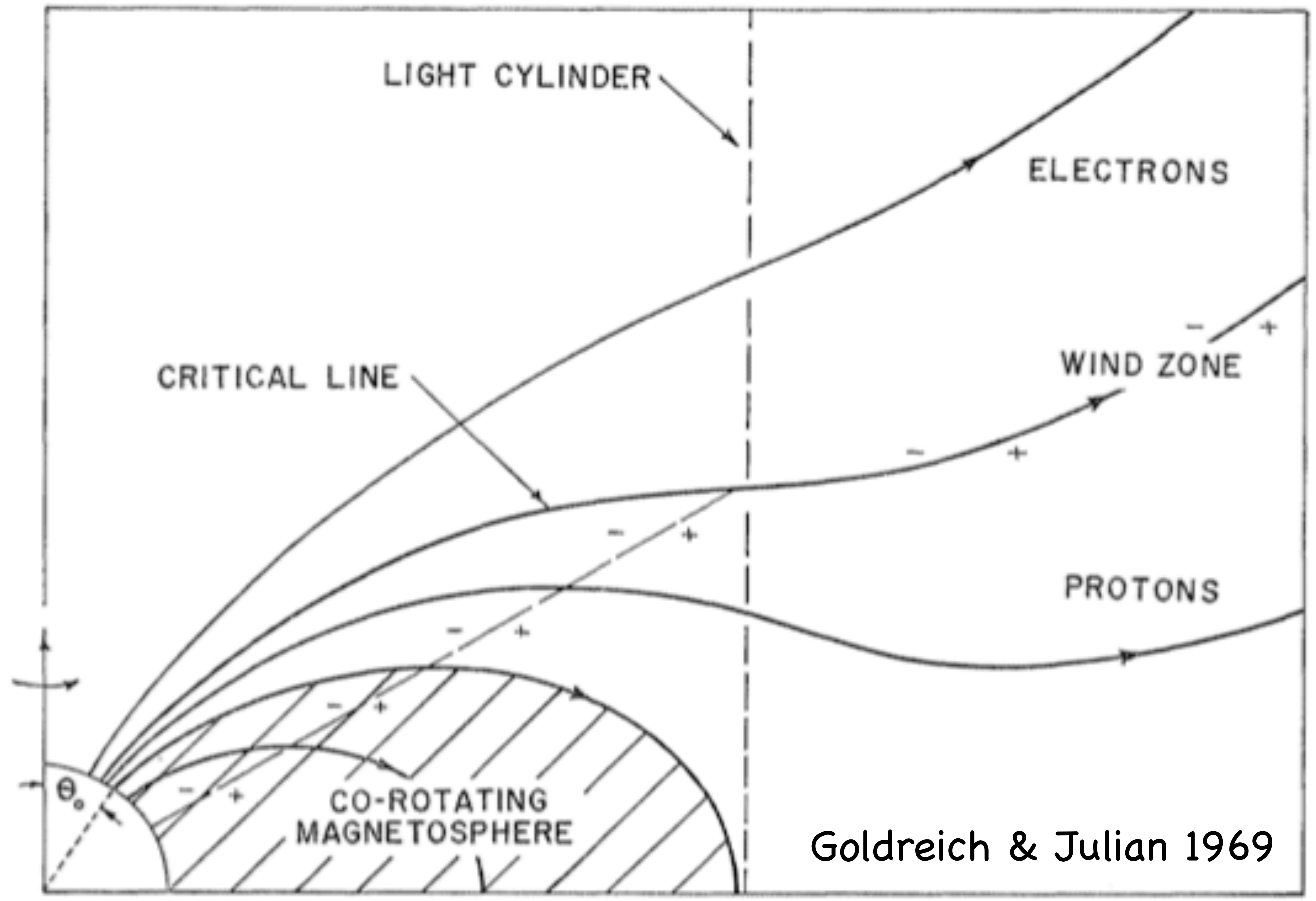
COROTATION ONLY POSSIBLE UNTIL $v < c$

LIGHT CYLINDER

$$R_L = \frac{c}{\Omega} = 5 \times 10^8 P_{100} \text{ cm}$$

THE STRUCTURE OF THE MAGNETOSPHERE

$$B_\star = \frac{2\mu_0}{R_\star^3} \qquad \vec{B} = B_\star \left(\frac{R_\star}{R}\right)^3 \left[\cos\theta \underline{\mathbf{e}}_\mathbf{R} - \frac{\sin\theta}{2}\underline{\mathbf{e}}_\theta\right]$$



Goldreich & Julian 1969

FOR DIPOLE TANGENT LINE: $\sin^2\theta/R = \text{const}$

LAST CLOSED FIELD LINE DEFINES **POLAR CAP** $\quad \sin\theta_{pc} = \sqrt{\frac{R_\star}{R_L}}$

$$\vec{E} = -\frac{\Omega\, R\sin\theta}{c}\underline{\mathbf{e}}_\phi \wedge \vec{B}$$

CHARGE DENSITY $\quad \rho_{GJ} = -\frac{\vec{\Omega}\cdot\vec{B}}{2\pi c}\frac{1}{\left[1-\left(\frac{R}{R_L}\right)^2\sin^2\theta\right]}$

CRITICAL LINE: WHERE $\vec{\Omega}\cdot\vec{B}$ CHANGES SIGN $\quad \theta_c = \arccos\sqrt{\frac{1}{3}}$

THE PULSAR POTENTIAL DROP

- Φ_{pc} IS THE ACTUAL POTENTIAL AVAILABLE
- Φ_{pc} IS A "MEASURED" QUANTITY, ONCE YOU MEASURE $\dot{E}$
- PULSARS CAN EASILY REACH THE KNEE:
  - FOR CRAB PERIOD OF 33ms $E_{max} \approx 60\ PeV$
- NEW BORN (FAST SPINNING) MAGNETARS CAN BE ZEVATRONS IN PRINCIPLE
- POTENTIAL DROPS LARGER THAN Φ_{pc} AND UP TO SOME FRACTION OF Φ_{tot} CAN BE ACHIEVED IN THE MAGNETOSPHERE IF FOR SOME REASONS MORE FIELD LINES ARE OPEN

POTENTIAL DROP ACROSS PC

$$\Delta\Phi_{pc} = -\frac{B_\star \Omega R_\star^2}{2c}\sin^2\theta_{pc}$$

NOTICE:

$$\Delta\Phi_{pc} = -\frac{B_\star \Omega R_\star^2}{2c}\frac{R_\star}{R_L} \approx -\sqrt{\dot{E}/c}$$

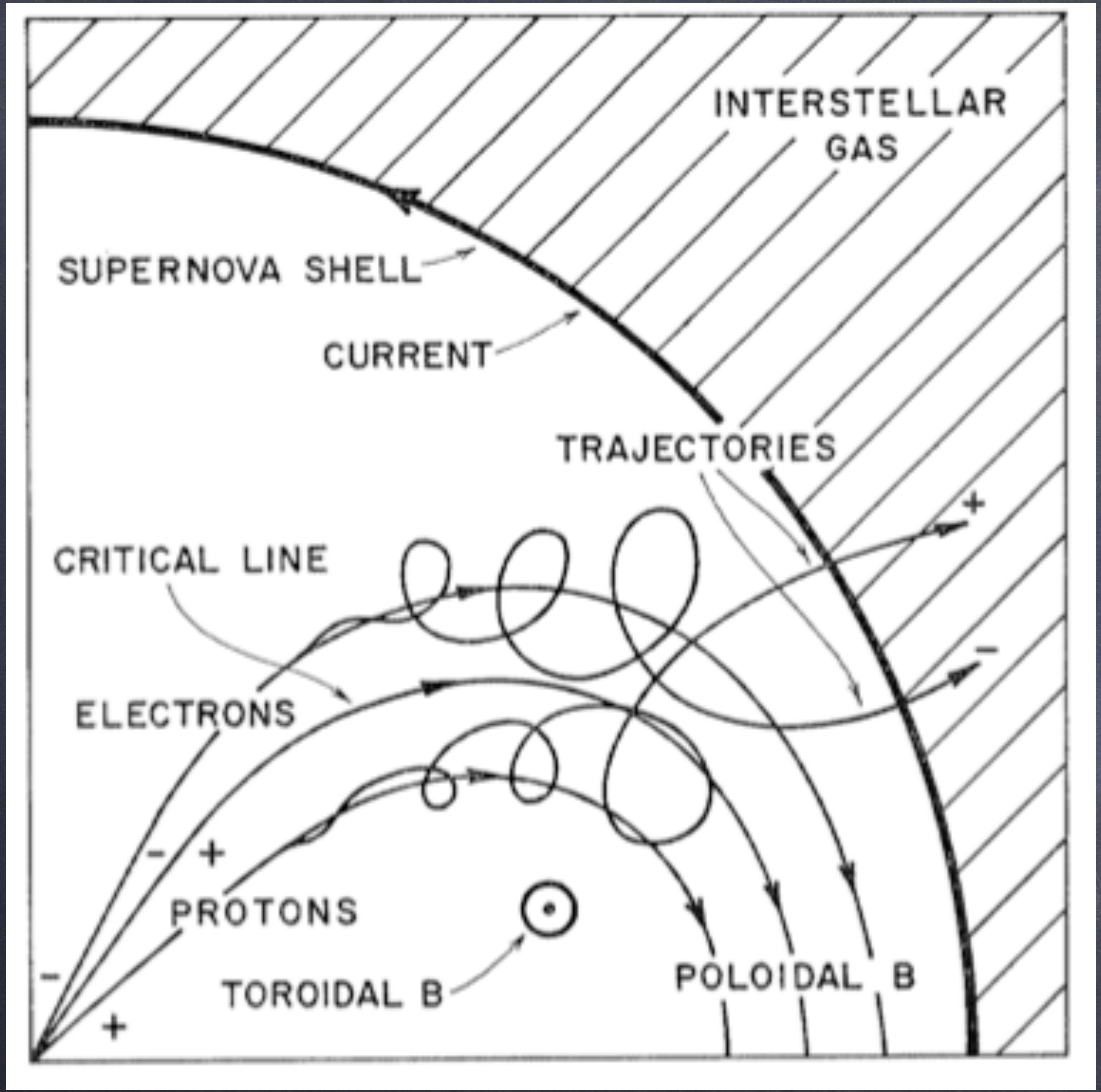
$$E_{max} = e\Phi = 6.5 \times 10^{14}\frac{B_{12}}{P_{100}^2}\ \mathrm{eV}$$

POTENTIAL DROP BETWEEN POLE AND INFINITY

$$\Delta\Phi_{tot} = -\frac{B_\star \Omega R_\star^2}{3c} = \frac{R_L}{R_\star}\Delta\Phi_{pc}$$

$$E_{max} = e\Phi = 2 \times 10^{17}\frac{B_{12}}{P_{100}^2}\ \mathrm{eV}$$

FLAWS OF THE GJ MODEL



Goldreich & Julian 1969

- VACUUM FIELD NOT SELF-CONSISTENT:
  - NEGLECT OF DISPLACEMENT CURRENT (Deutsch 1955)
  - NEGLECT PARTICLE INERTIA
  - NEGLECT OF MONOPOLE TERM (Michel 1969)
- CHARGE SUPPLY UNCLEAR
- CHARGE SEPARATED FLOW OR QUASI NEUTRAL PLASMA?

$$\left(\frac{G\ M_\star m_e}{R_\star k_B} \approx 10^9\ \mathrm{K} \right)$$

WHY DOES AN ALIGNED ROTATOR SPIN DOWN?

VACUUM SOLUTION:

$$\dot{E}_{\rm vac} = \frac{2}{3}\frac{\mu^2\Omega^4}{c^3}\sin^2\chi$$

FORCE-FREE SOLUTION:
accounting for particles in the magnetosphere

$$\dot{E} = \frac{\mu^2\Omega^4}{c^3}\left(1+\sin^2\chi\right)$$

ENERGY LOSS BY A GJ FLUX OF PARTICLES LEAVING THE STAR POLAR CAP AT PULSAR DROP

$$\dot{E}_{\rm part} = \dot{N}_{GJ}E_{drop}$$

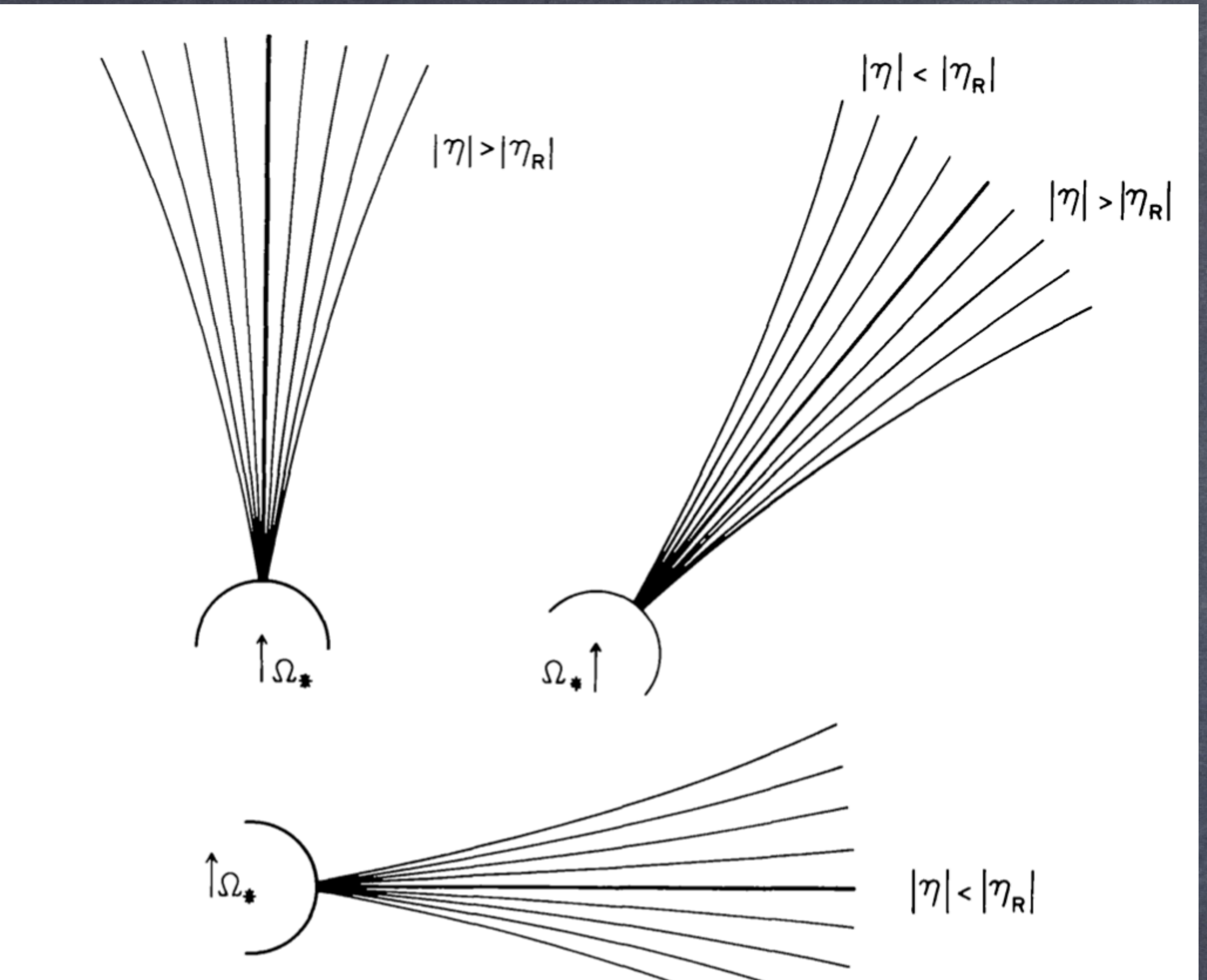
$$\dot{N}_{GJ} = \frac{\Omega B}{2\pi c e}\left(\pi\, R_\star^2\frac{R_\star}{R_L}\right)c \approx \frac{\sqrt{c\,\dot{E}}}{e}$$

$$E_{drop} = e\Delta\Phi_{pc} = e\sqrt{\dot{E}/c}$$

$$\dot{E}_{\rm part} = \dot{E}$$

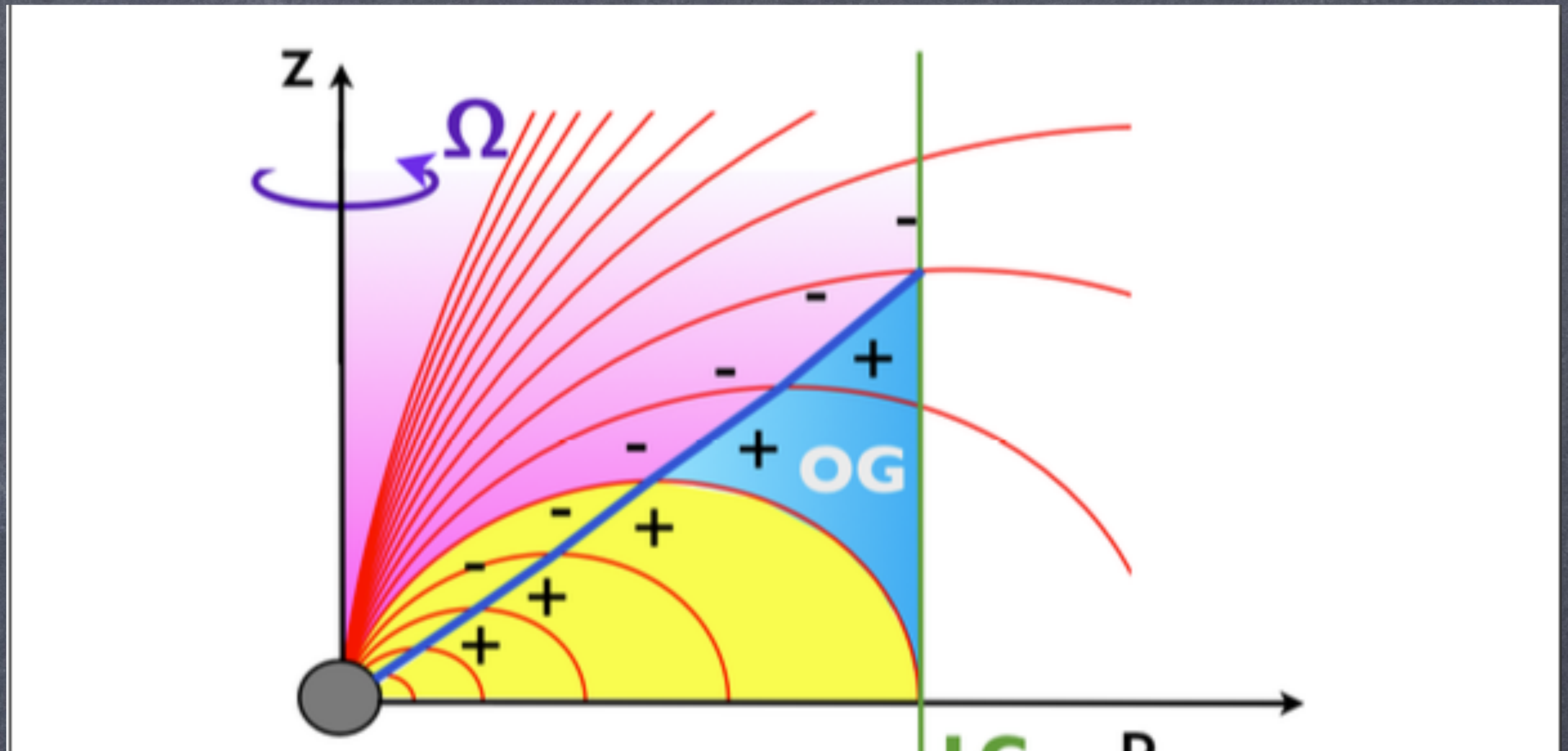
SPACE CHARGE LIMITED FLOW

POLAR CAPS



Arons 1979

OUTER GAPS

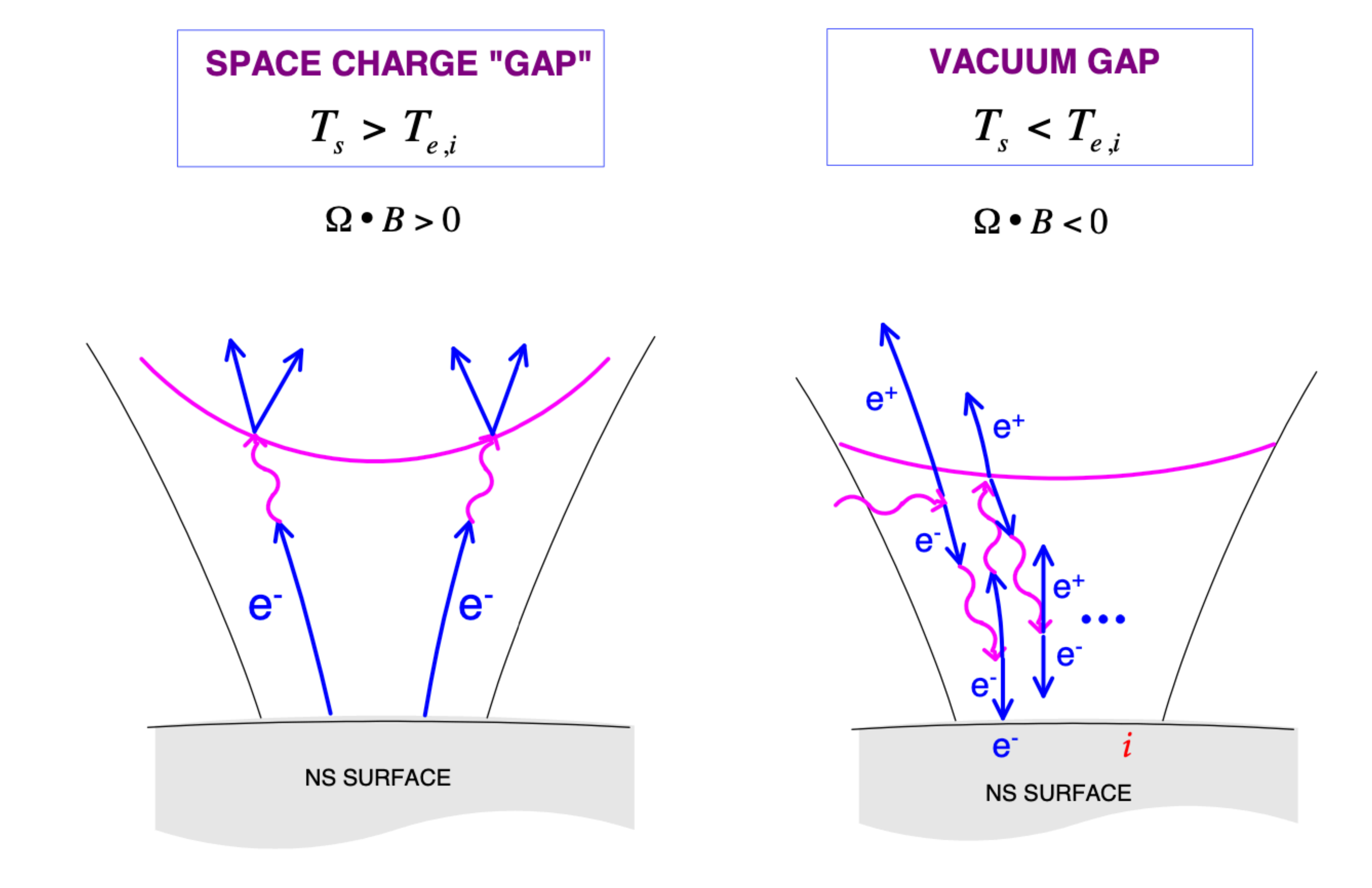


Cheng & Ruderman 1977

$\rho^{\star}_{\mathrm{GJ}} = J_{\star}/c \qquad J = J_{\star}\dfrac{B}{B_{\star}} \qquad J_{GJ} = c\rho_{GJ} \propto B_z$

- CHARGE DENSITY LOCALLY NEEDED CAN BE SUPPLIED FROM THE STAR ONLY FOR FIELD LINES WITH DECREASING $B_{\|}/B$ A FRACTION OF THE TOTAL FOR OBLIQUE ROTATORS
- UNSCREENED ELECTRIC FIELD IS LEFT IN ALL CASES IF PARTICLES FROM STAR SURFACE ONLY

SPACE CHARGE GAPS AND VACUUM GAPS



Usov & Melrose 1995
Harding 2007

Charged particles are bounded to the star due to lattice structure in strong magnetic field

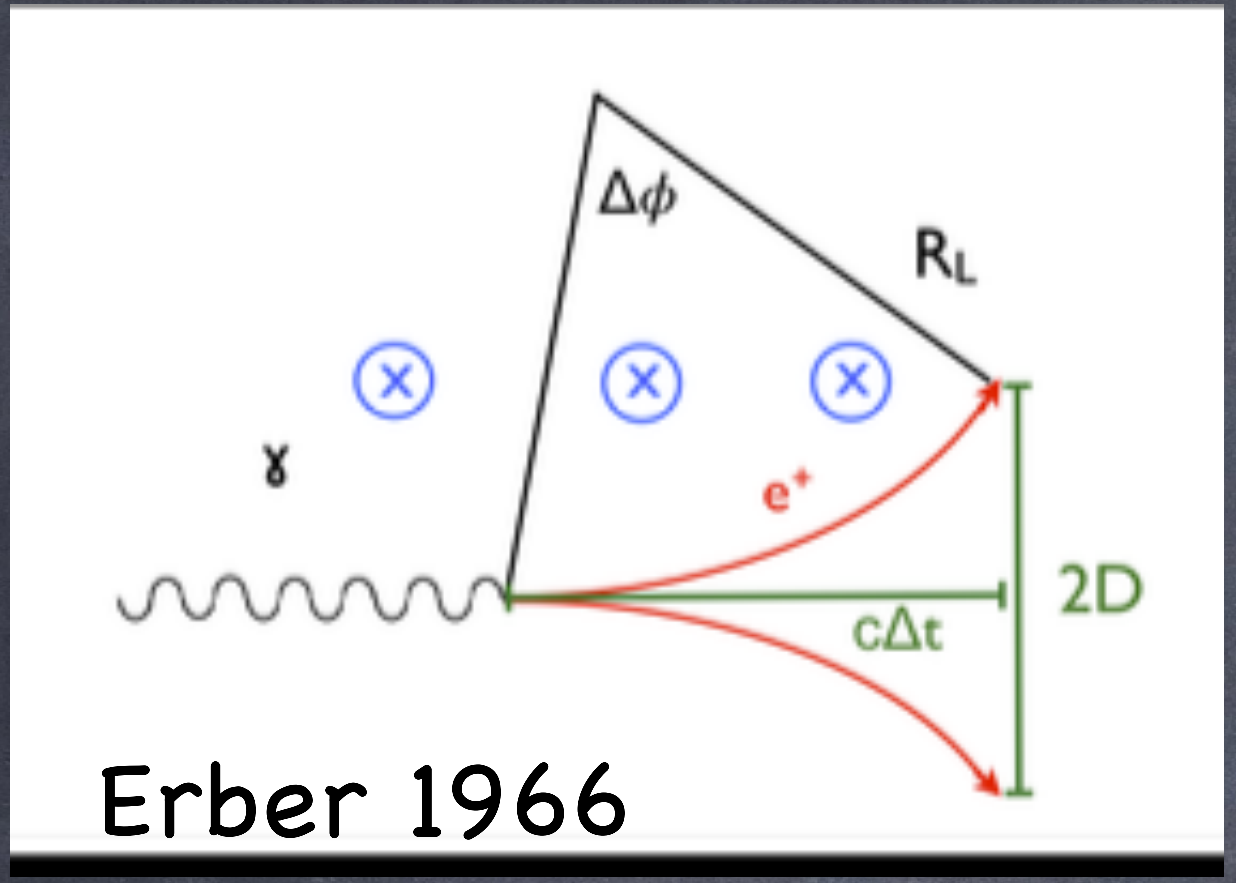
Thermoionic emission temperatures:

$$T_e \approx 3.6 \times 10^5 \text{ K} \left(\frac{Z}{26}\right)^{0.8} \left(\frac{B_\star}{10^{12}\text{G}}\right)^{0.4}$$

$$T_i \approx 3.5 \times 10^5 \text{ K} \left(\frac{B_\star}{10^{12}\text{G}}\right)^{0.73}$$

Particles below those temperature are bounded to the star

MAGNETIC PAIR PRODUCTION



$h\nu > 2m_ec^2 \Rightarrow$ PHOTON CAN CREATE PAIR $\begin{cases} h\nu \to 2m_ec^2\gamma \\ h\nu/c \to 2m_ec^2\gamma\beta \end{cases} \Rightarrow \Delta E \sim \frac{2\,(m_e\,c^2)^2}{h\nu}$

IN VACUUM PAIR LIVES ONLY $\Delta t \sim \hbar/\Delta E$

IF B-FIELD $\Delta\phi = \frac{c\Delta t}{r_L} \Rightarrow D \sim c\ \Delta t\ \Delta\Phi$

PAIR BECOMES REAL IF $D > \lambda_C = \frac{h}{m_ec}$

$$D \approx \frac{\lambda_C}{4\pi}\left(\frac{h\nu}{m_ec^2}\right)\left(\frac{B}{B_{QED}}\right) = \chi\frac{\lambda_C}{4\pi}$$

$$\chi = \frac{\epsilon_\gamma}{m_ec^2}\frac{B}{B_{\rm QED}} = 0.4\left(\frac{\epsilon_\gamma}{10\rm MeV}\right)\left(\frac{B}{10^{12}\rm G}\right)$$

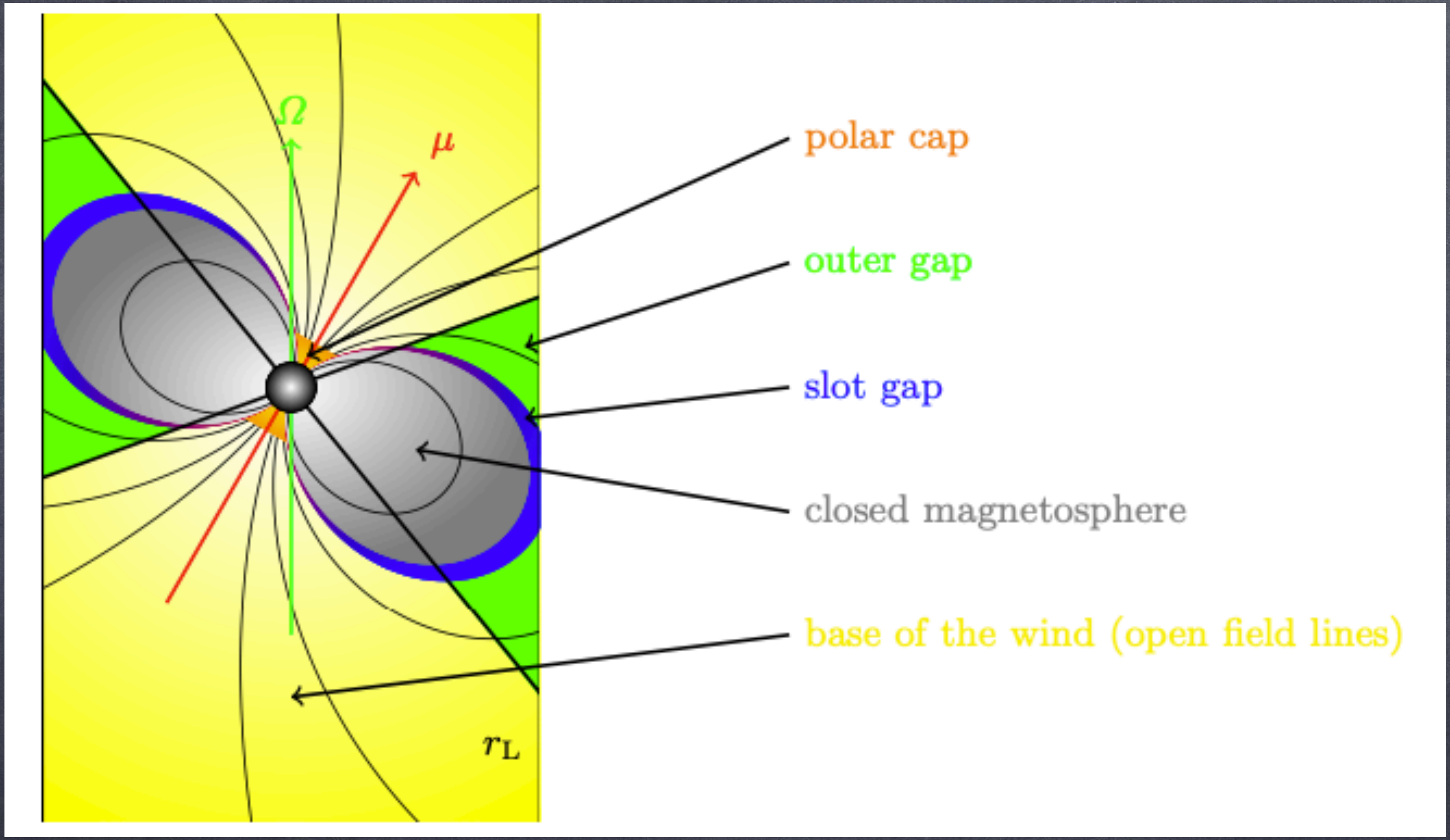
$\chi \gg 1 \Rightarrow$ EXTREMELY EFFECTIVE PAIR CREATION

$\chi < 1 \Rightarrow$ PAIR CREATION SUPPRESSED AS $\exp(-4/3\chi)$

PAIR CREATION LENGTH: $l_p = \frac{4.4}{\alpha_{fs}}\lambda_c\frac{B_{\rm QED}}{B}\exp\left(\frac{4}{3\chi}\right)$

RAPIDLY CHANGING QUANTITY IN THE MAGNETOSPHERE

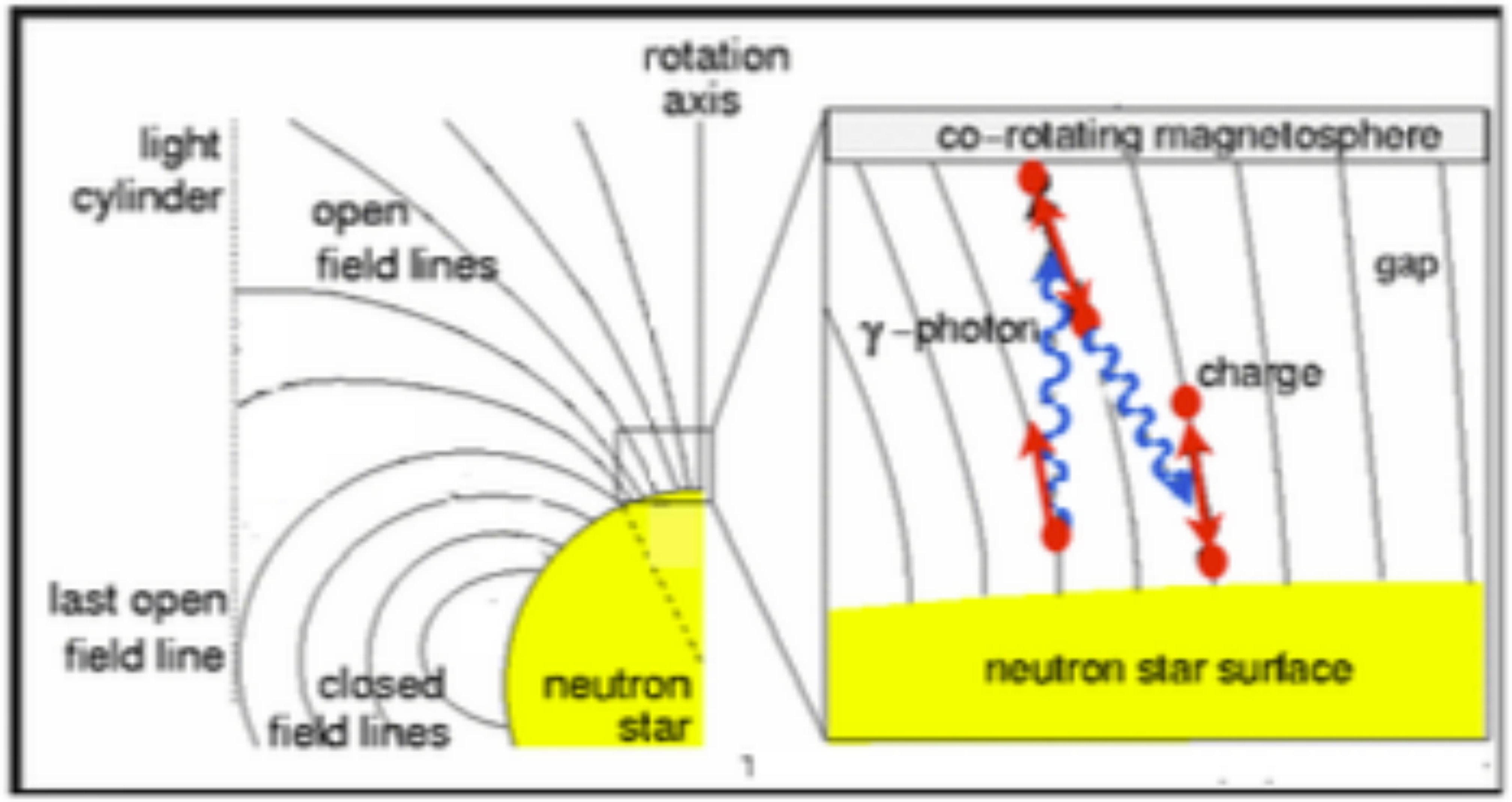
ALL GAPS

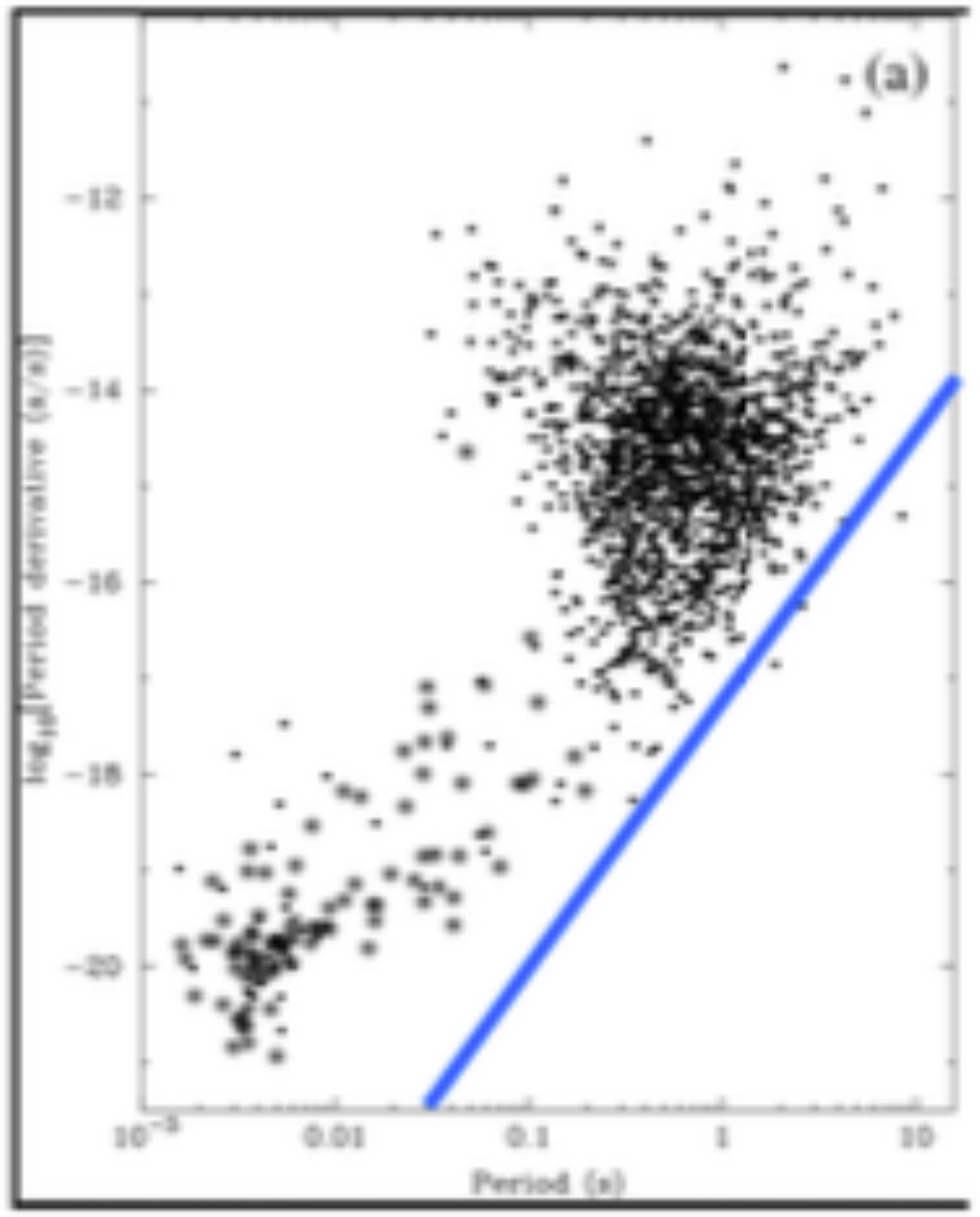


Petri 2017

DIAGNOSTICS OF THE CASCADE

DEATHLINE GAMMA-RAYS MULTIPLICITY





e^- ⟹ Curvature or ICS on star X-rays ⟹ γ (E_γ>50 MeV) ⟹ $\gamma + B \rightarrow e^+ + e^-$

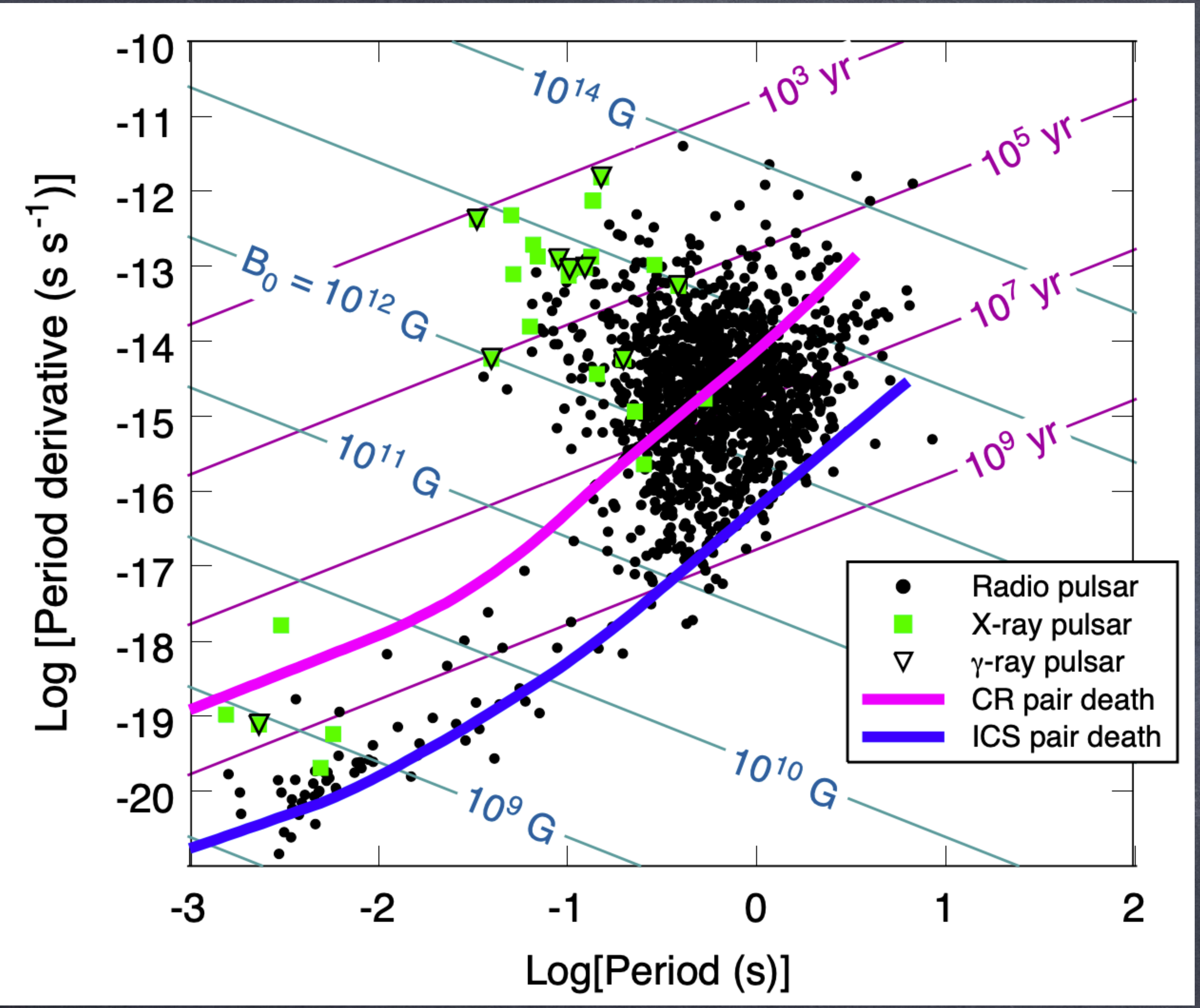
$\gamma_{primary} \sim 10^7$ $\gamma_{secondary} \sim 10^{2-3}$

γ-**RAYS**

$$L_{\text{radio}} \leq 10^{-10} \dot{E}$$

$$L_\gamma \sim 10^{-2} \dot{E}$$

DEATHLINE AND MULTIPLICITY



Harding 2007

Peak of curvature radiation photon energy

$$\epsilon_{\gamma,\mathrm{CR}} = 3\lambda_C \gamma^3/(2\rho_c)$$

Photon energy of Inverse Compton in Klein-Nishina limit:

$$\epsilon_{\gamma,\mathrm{IC}} \sim \gamma$$

$$\Rightarrow \epsilon_{\gamma,\mathrm{CR}} \ll \epsilon_{\gamma,\mathrm{IC}}$$

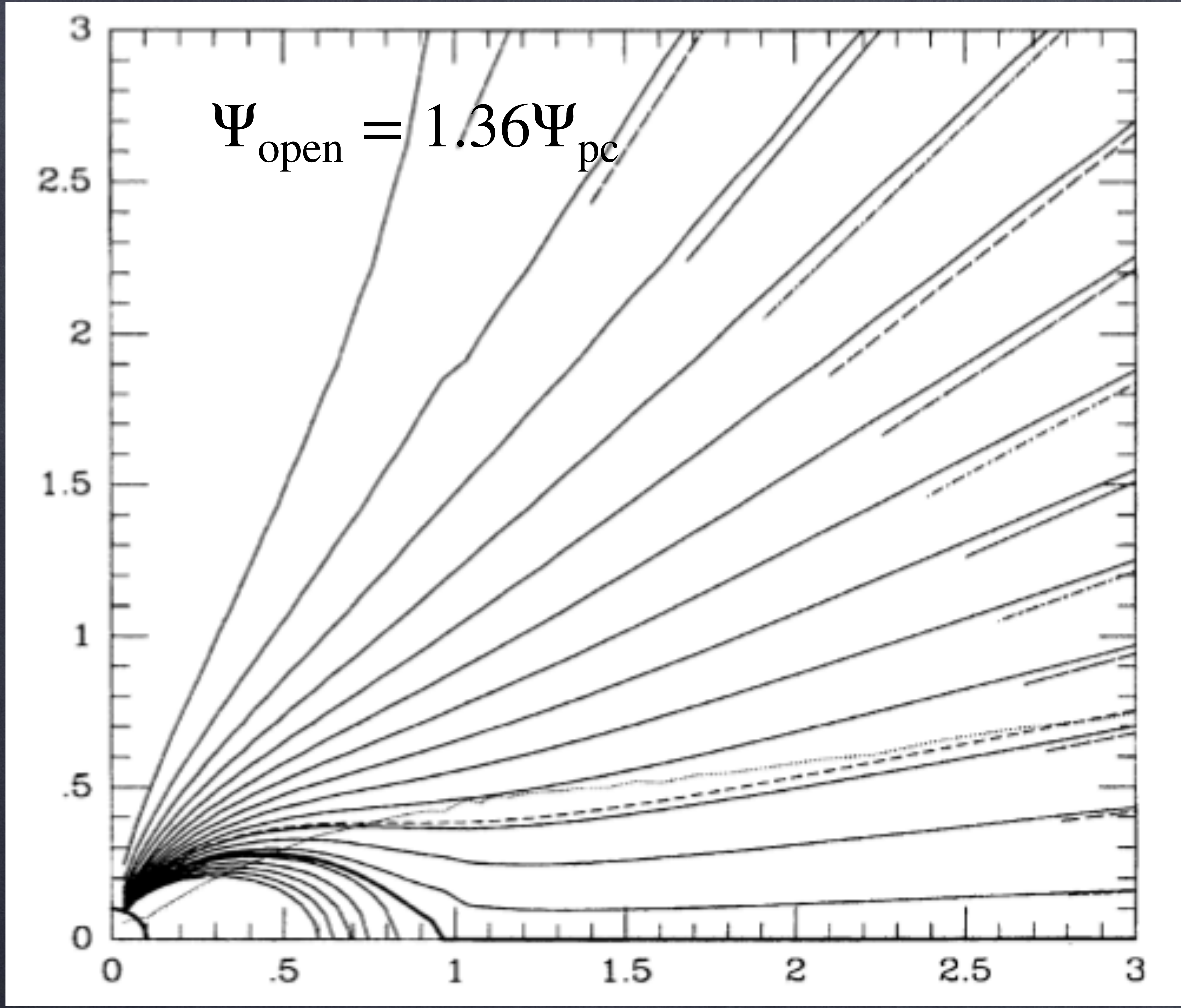
Pair production of CR photons require larger Lorents factors than IC

HIGHEST MULTIPLICITY FOR SYNCHROTRON/ CURVATURE POWERED GAPS: K< few x 10^5

BUT.... PWNe

THE PULSAR WIND

THE ALIGNED ROTATOR



Contopoulos, Kazanas, Fendt 2001

$$F(R,\theta) \propto \frac{\sin^2\theta}{R^2}$$

ALIGNED ROTATING DIPOLE
VERY SIMILAR TO SPLIT MONOPOLE

$$\vec{B} = B_L \left[\left(\frac{R_L}{R}\right)^2 \underline{\mathbf{e}}_{\mathbf{R}} - \left(\frac{R_L}{R}\right) \sin\theta \, \underline{\mathbf{e}}_\phi \right]$$

$$\vec{E} = -B_L \left(\frac{R_L}{R}\right) \sin\theta \, \underline{\mathbf{e}}_\theta$$

YET ANOTHER WAY TO LOOK AT THE STAR SPIN-DOWN: POYNTING FLUX THROUGH THE LIGHT CYLINDER SURFACE:

$$\dot{E} = \pi S_L R_L^2 \qquad S_L = \frac{B_L^2}{4\pi} c\pi R_L^2 \qquad B_L = B_\star \left(\frac{R_\star}{R_L}\right)^3$$

$$\dot{E} \approx \frac{B_\star^2 \Omega^4 R_\star^6}{c^3}$$

ENERGY BUDGET

ENERGY FLUX THAT LEAVES THE PSR

$$\dot{E} = \kappa \dot{N}_{GJ} m_e \Gamma c^2 \left(1 + \frac{m_i}{\kappa m_e} + \sigma \right)$$

$$\sigma = \frac{B^2}{4\pi\ n_{\pm}\ m_e\ c^2\ \Gamma^2}$$

$\kappa =$ multiplicity due to pair creation

ELECTRON-POSITRON PAIRS

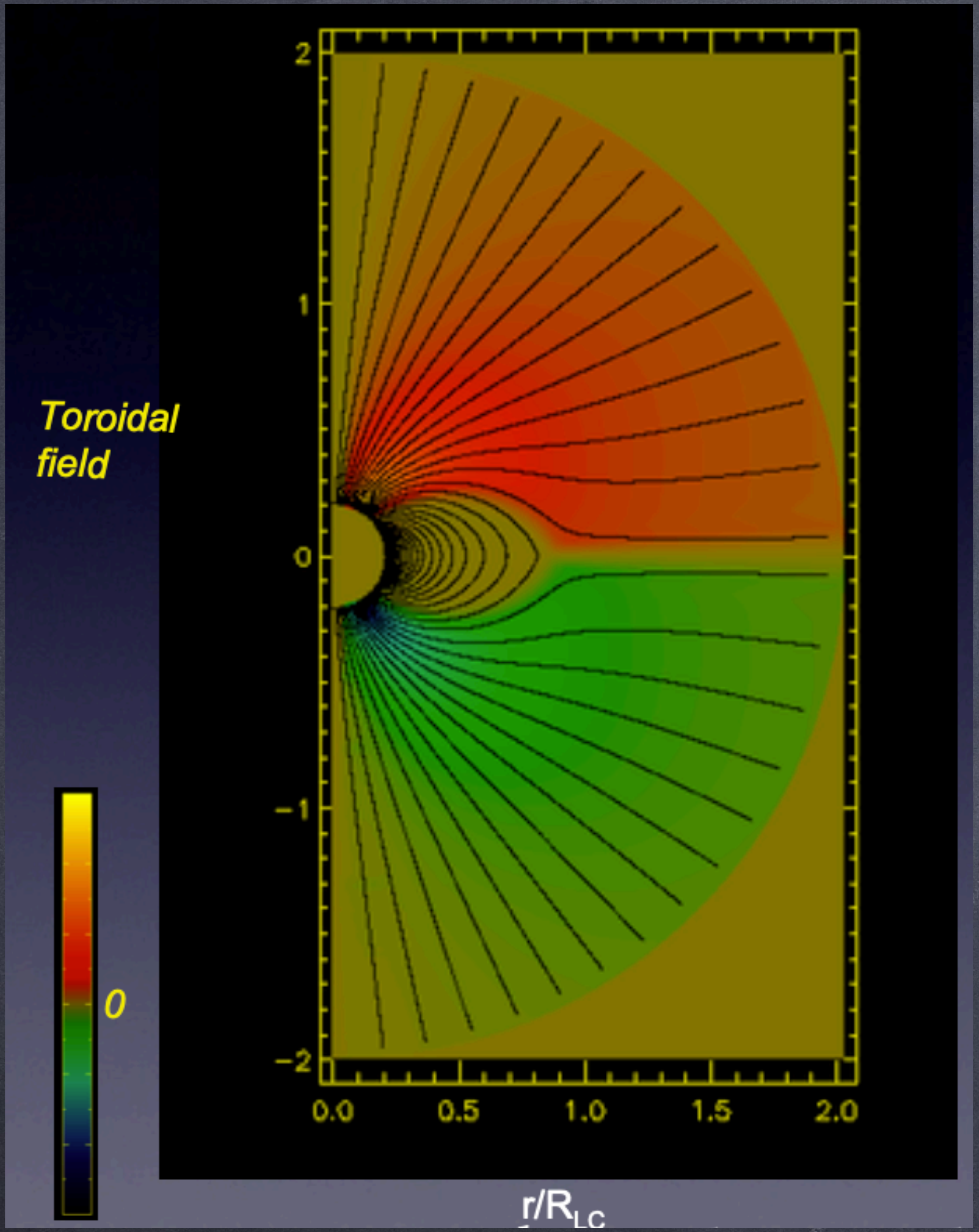
IONS

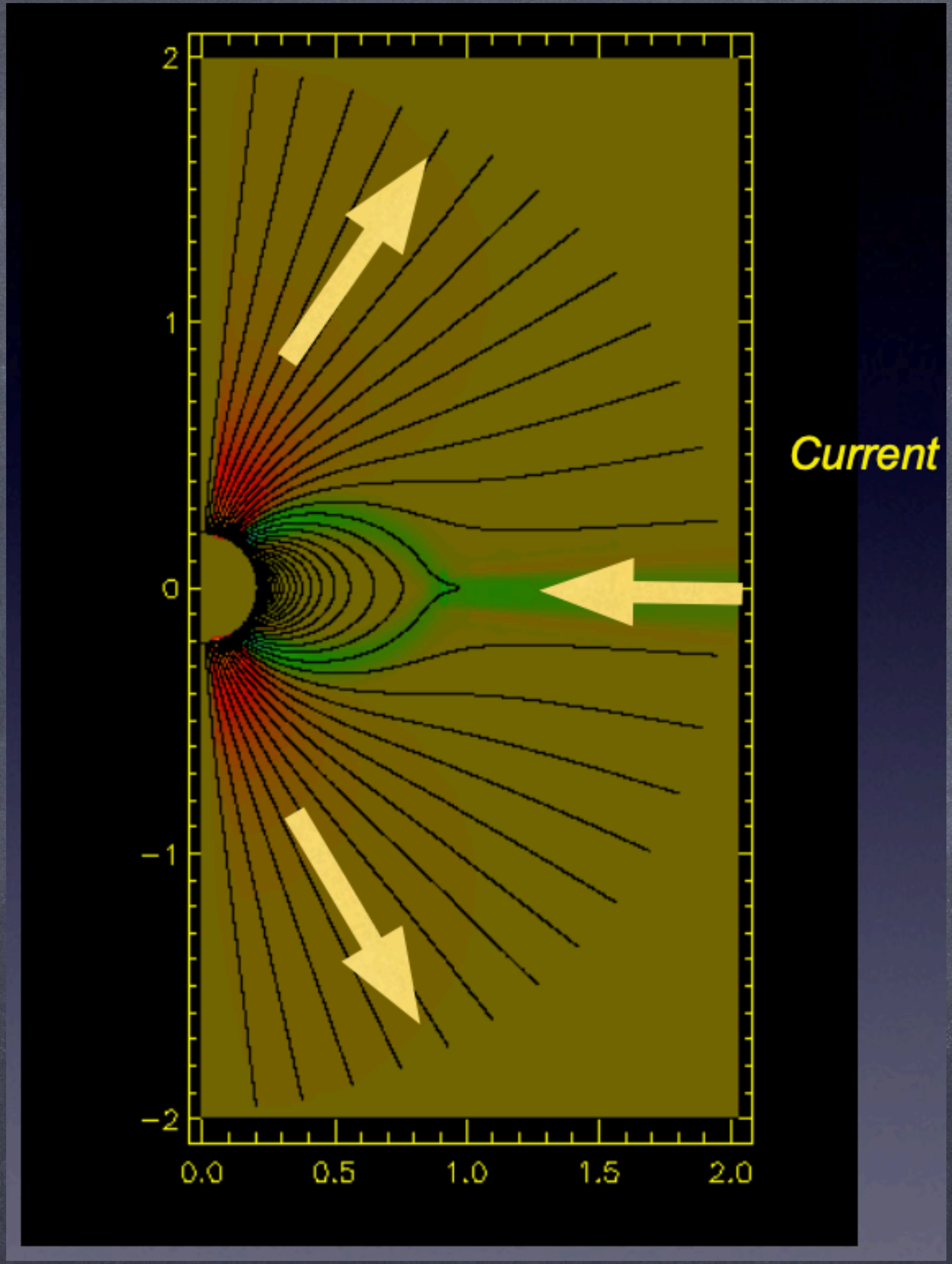
MAGNETIC FIELD

CAN WE CONSTRAIN κ AND σ ?

WHAT ABOUT IONS ?

TIME-DEPENDENT FORCE-FREE SOLUTION

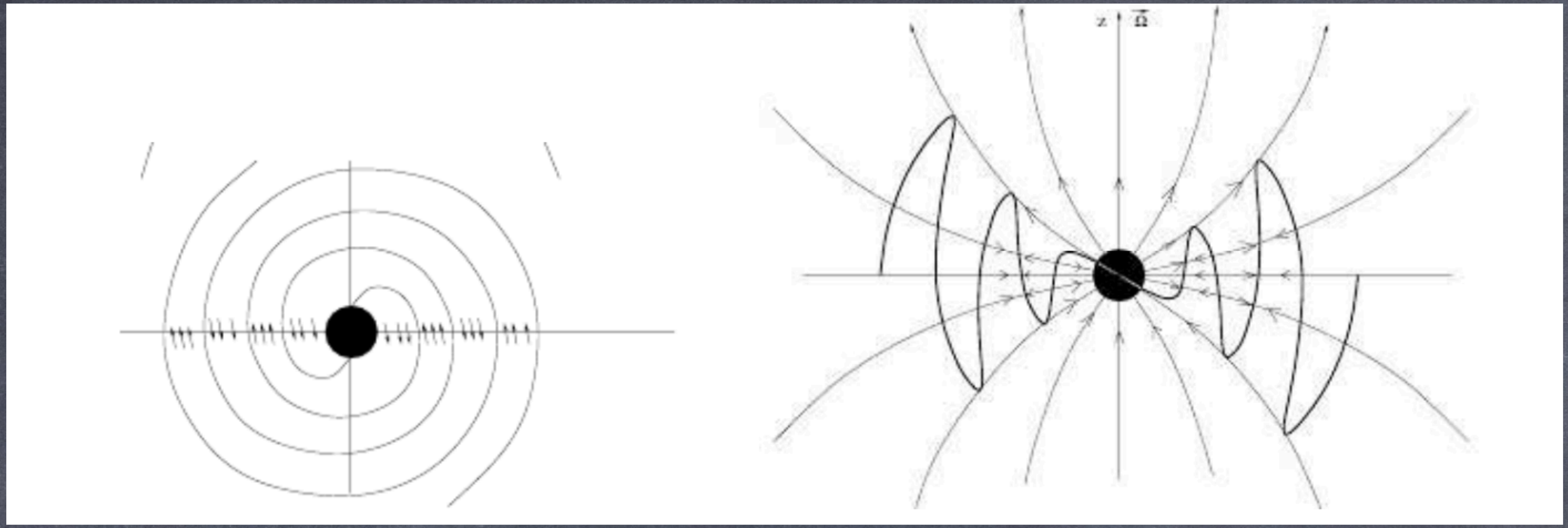




Spitkovsky 2006

$$F(R,\theta) \propto \frac{\sin^2\theta}{R^2}$$

THE CURRENT SHEET



$$\underline{\mathbf{e}}_{\mathbf{R}} = \sin\theta\cos\phi\ \underline{\mathbf{e}}_{\mathbf{1}} + \sin\theta\sin\phi\ \underline{\mathbf{e}}_{\mathbf{2}} + \cos\theta\ \underline{\mathbf{e}}_{\mathbf{3}}$$

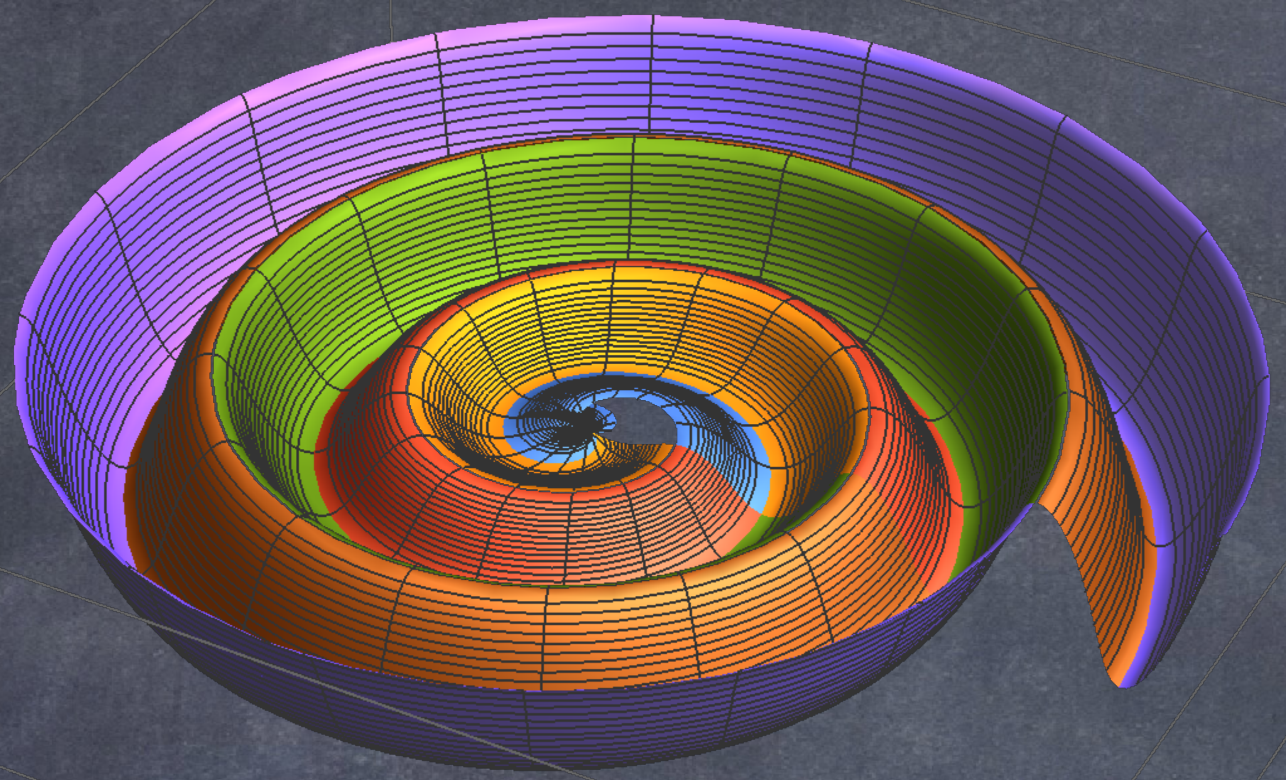
$$\overrightarrow{\mu} = \mu\left[\sin\chi\cos\Omega t\ \underline{\mathbf{e}}_{\mathbf{1}} + \sin\chi\sin\Omega t\ \underline{\mathbf{e}}_{\mathbf{2}} + \cos\chi\ \underline{\mathbf{e}}_{\mathbf{3}}\right]$$

$$\overrightarrow{\mu}\cdot\underline{\mathbf{e}}_{\mathbf{R}} = \mu\left\{\sin\theta\sin\chi\cos\phi\cos\Omega t + \sin\theta\sin\chi\sin\phi\sin\Omega t + \cos\theta\cos\chi\right\}$$

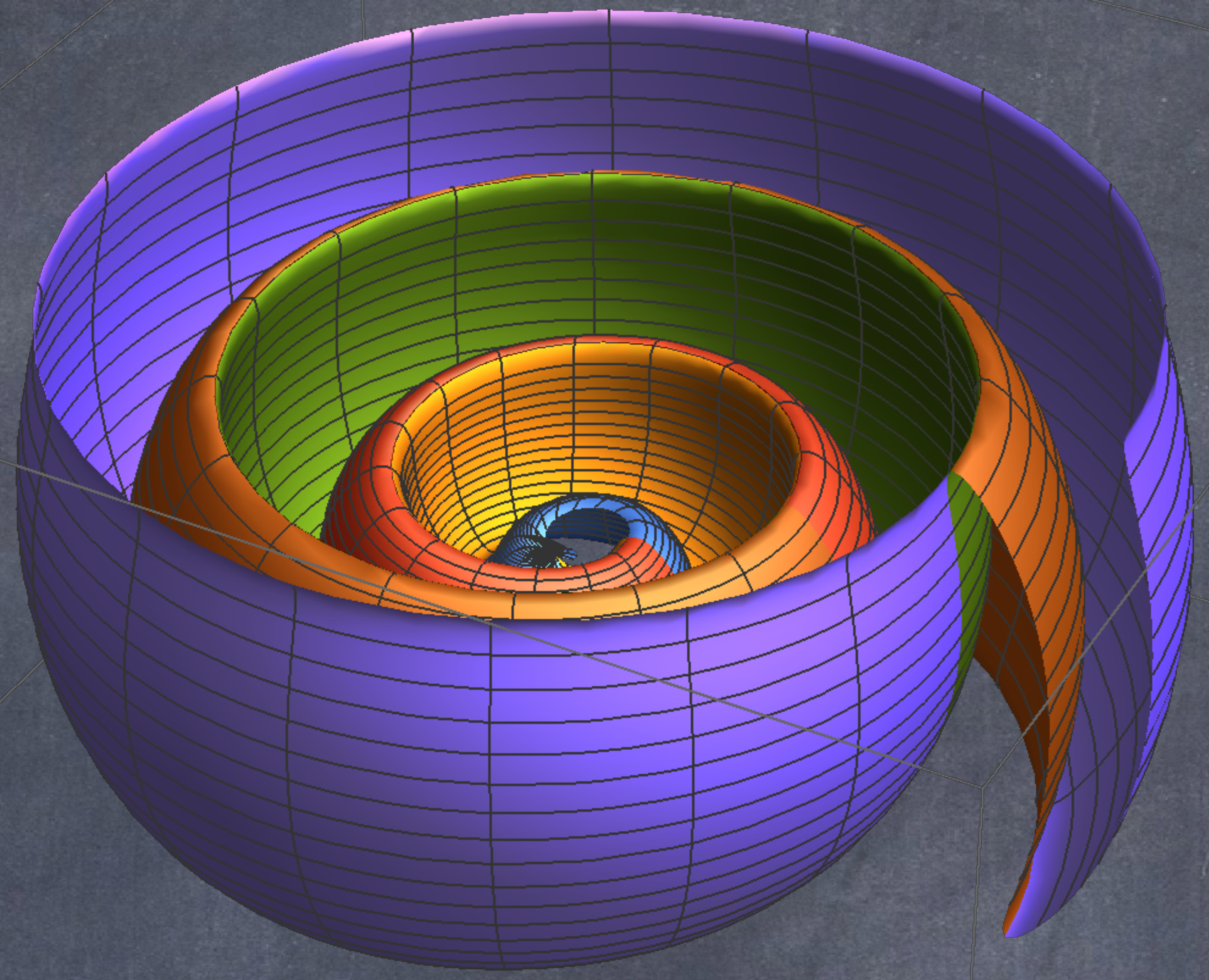
$$\overrightarrow{\mu}\cdot\underline{\mathbf{e}}_{\mathbf{R}} = 0 \quad \Longleftrightarrow \quad \Psi(t,\theta,\phi) = \sin\theta\sin\chi\cos(\phi-\Omega t) + \cos\theta\ \cos\chi = 0$$

PATTERN PROPAGATES AT SPEED V

The Current Sheet



$\chi = 10^\circ$



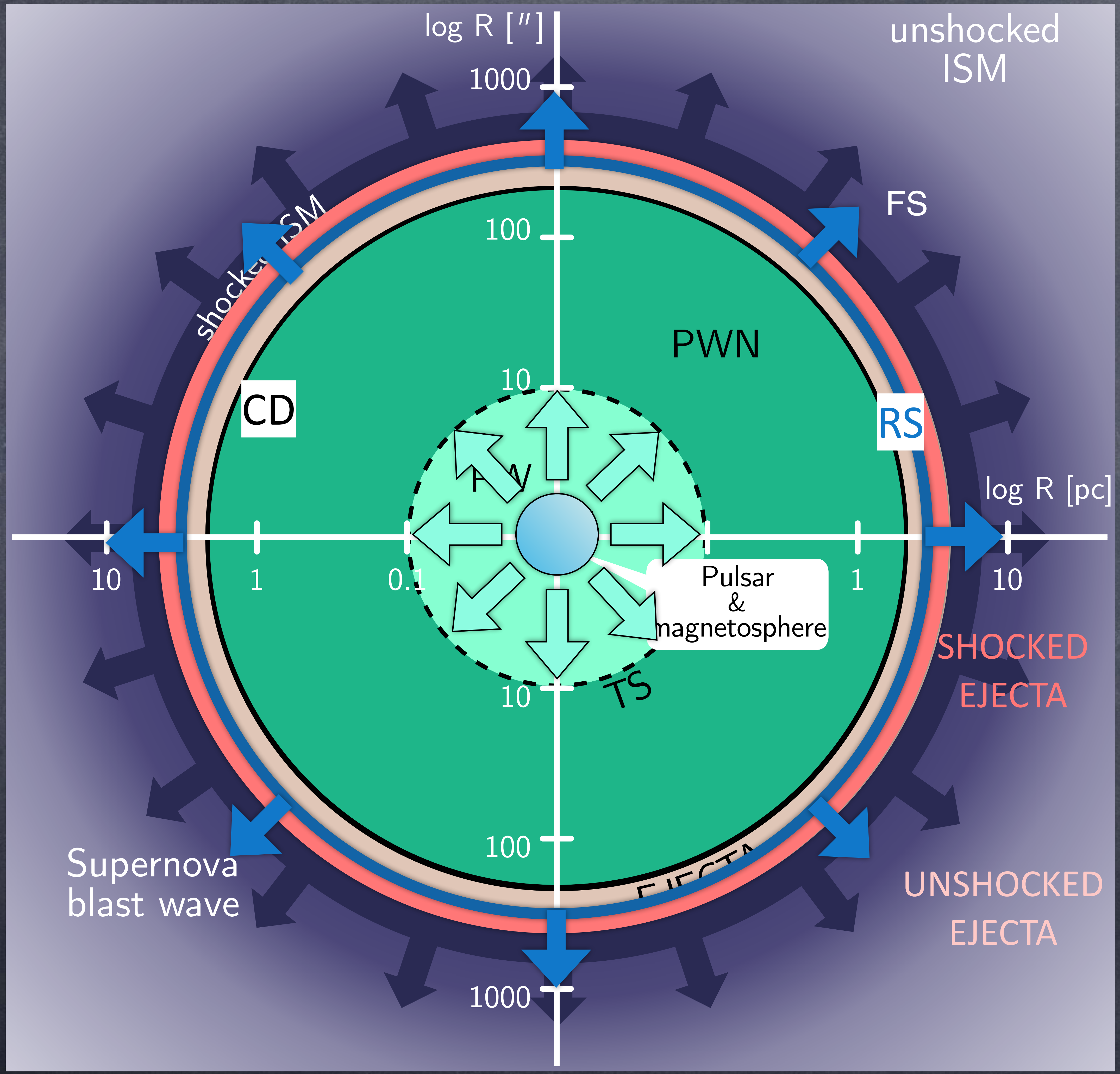
$\chi = 30^\circ$

$$\Psi(t, R, \theta, \phi) = \sin\theta \sin\chi \cos\left[\phi - \Omega\left(t - \frac{R}{V}\right)\right] + \cos\theta \ \cos\chi = 0$$

$$r_s(\theta, \phi, t) = \frac{v}{\Omega}\left\{\Omega t - \phi + 2\pi\, l \pm \arccos\left[-\frac{\cos\chi}{\sin\chi}\frac{\cos\theta}{\sin\theta}\right]\right\}$$

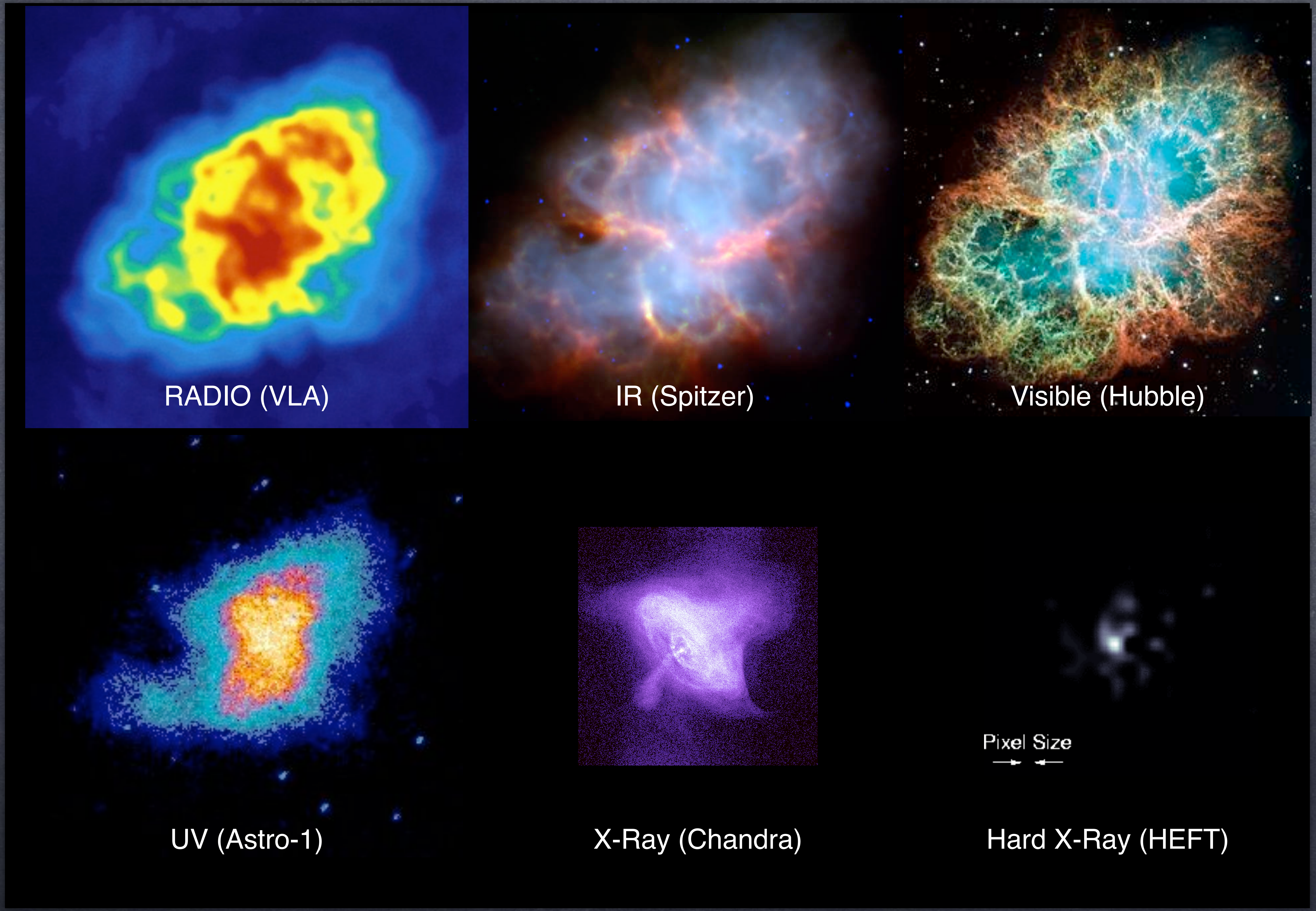
PULSAR WIND NEBULAE

BASIC PICTURE FOR YOUNG SYSTEMS



Adapted from Kennel & Coroniti 1984

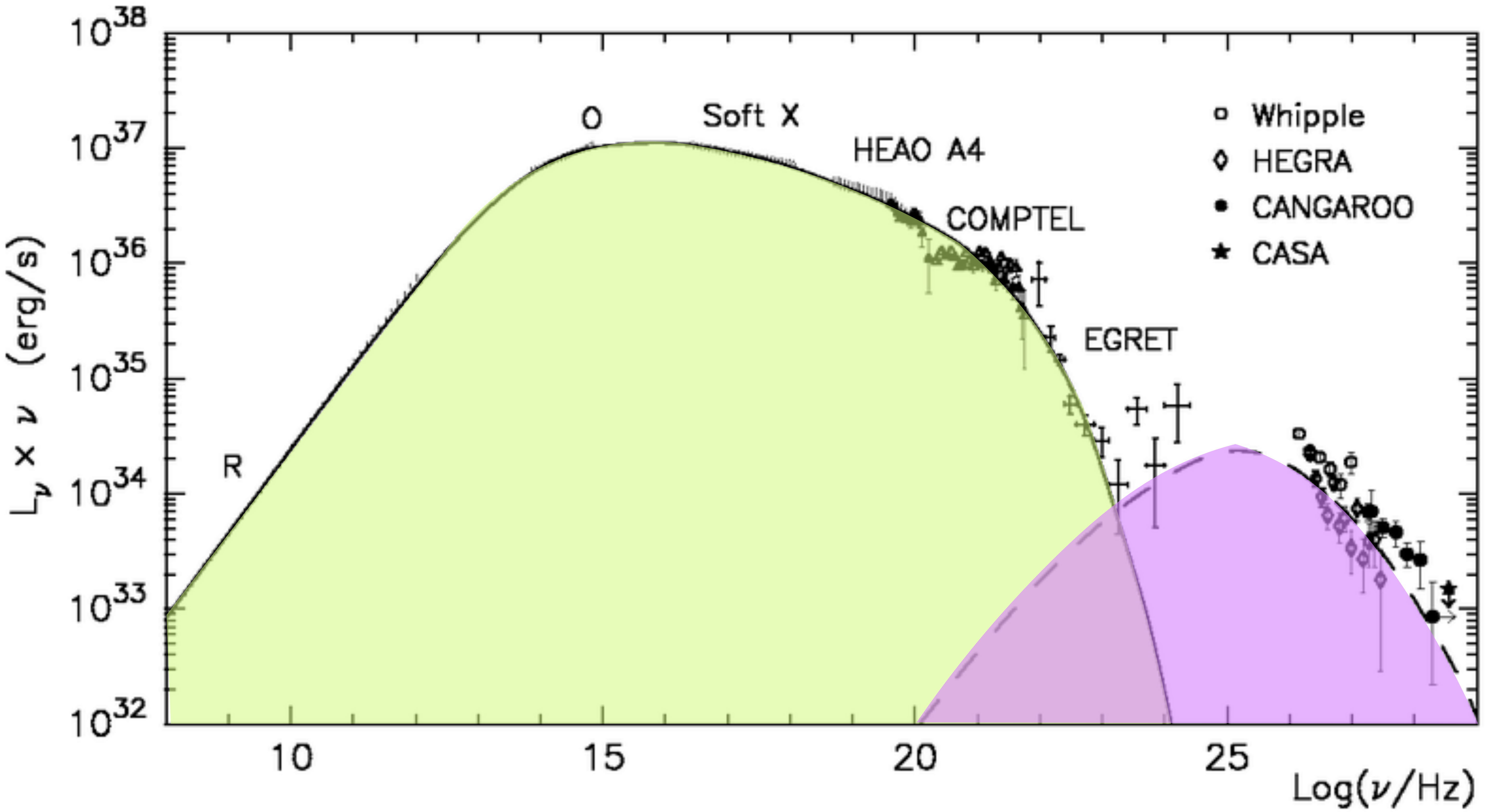
"THE CRAB NEBULA AT DIFFERENT FREQUENCIES



THE CRAB NEBULA SPECTRUM

BROAD BAND NON-THERMAL SPECTRUM

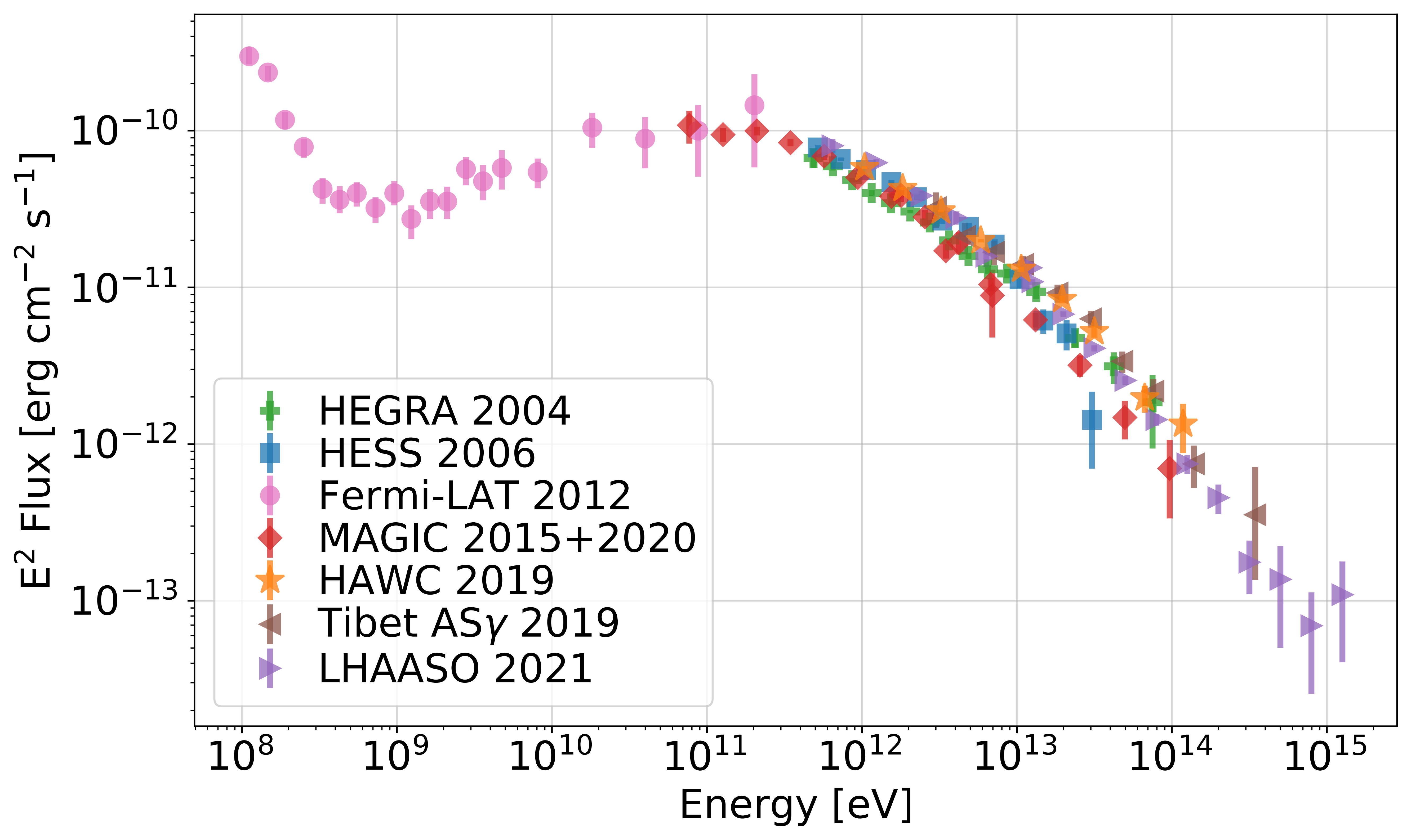
CRAB NEBULA spectrum [adapted from Atoyan & Aharonian 1996]



synchrotron radiation by relativistic particles in the nebular B field

Inverse Compton scattering with local photon field

THE CRAB NEBULA IN GAMMA-RAYS



Amato & Olmi 2021

THE ONLY ESTABLISHED GALACTIC PEVATRON!!!

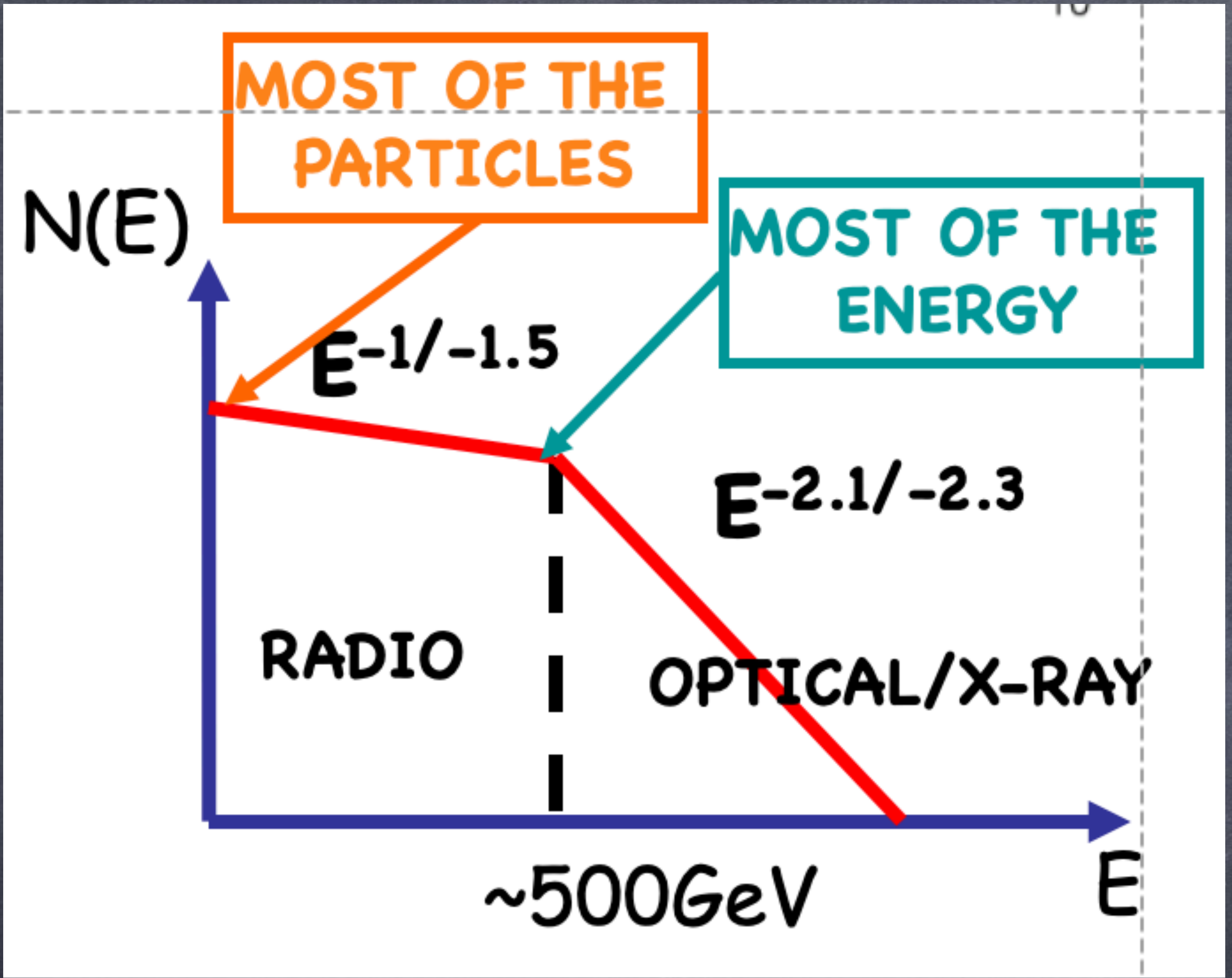
FOR ICS ON CMB

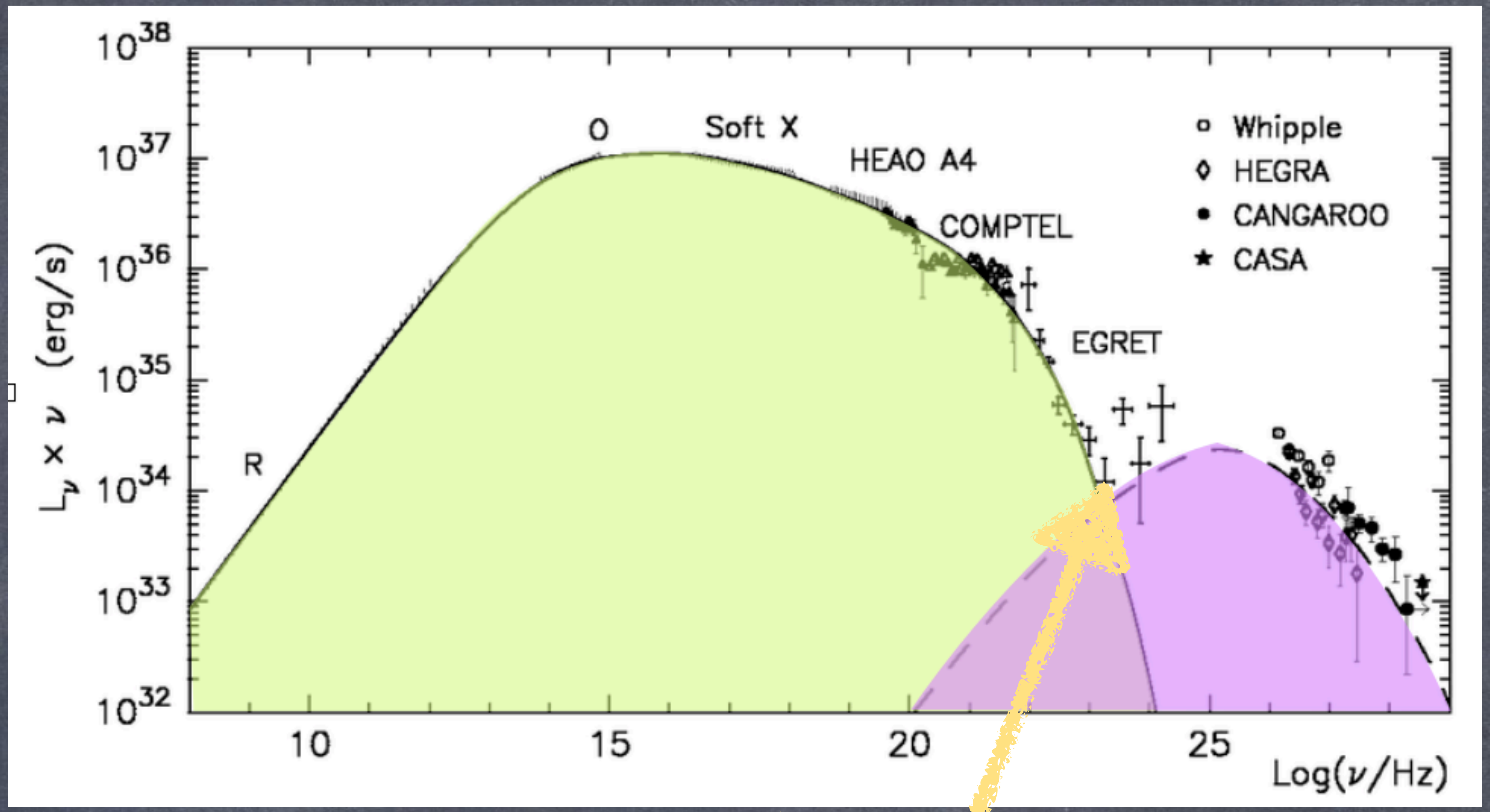
$$\epsilon_\gamma \approx 0.37\ (E_e/\mathrm{PeV})^{1.3}\ \mathrm{PeV}$$

HIGHEST ENERGY LHAASO DATA POINT

$$E_e \approx 2.4\ \mathrm{PeV}$$

EMITTING PARTICLES





PeV ELECTRONS

$B_{NEB} \approx 100\ \mu G$

$L_{NEB} > 20\,\%\,\dot{E}$

ONE ZONE MODELS
(Pacini & Salvati 1973, EA+ 2000, Bucciantini+ 2011….)

EXTRAORDINARY ACCELERATOR!

BUT….

BIG OPEN QUESTION

WHAT WE KNOW:

- MOST EFFICIENT ACCELERATORS IN NATURE

  $\epsilon_{\rm acc} \lesssim 30\,\%$

- ENERGY FLUX THAT LEAVES THE PSR

$$\dot{E} = \kappa \dot{N}_{GJ} m_e \Gamma c^2 \left(1 + \frac{m_i}{\kappa m_e} + \sigma \right)$$

$$\sigma = \frac{B^2}{4\pi\ n_\pm\ m_e\ c^2\ \Gamma^2}$$

WE DO NOT KNOW:

- WHAT THE ACCELERATION MECHANISM(S) IS (ARE)

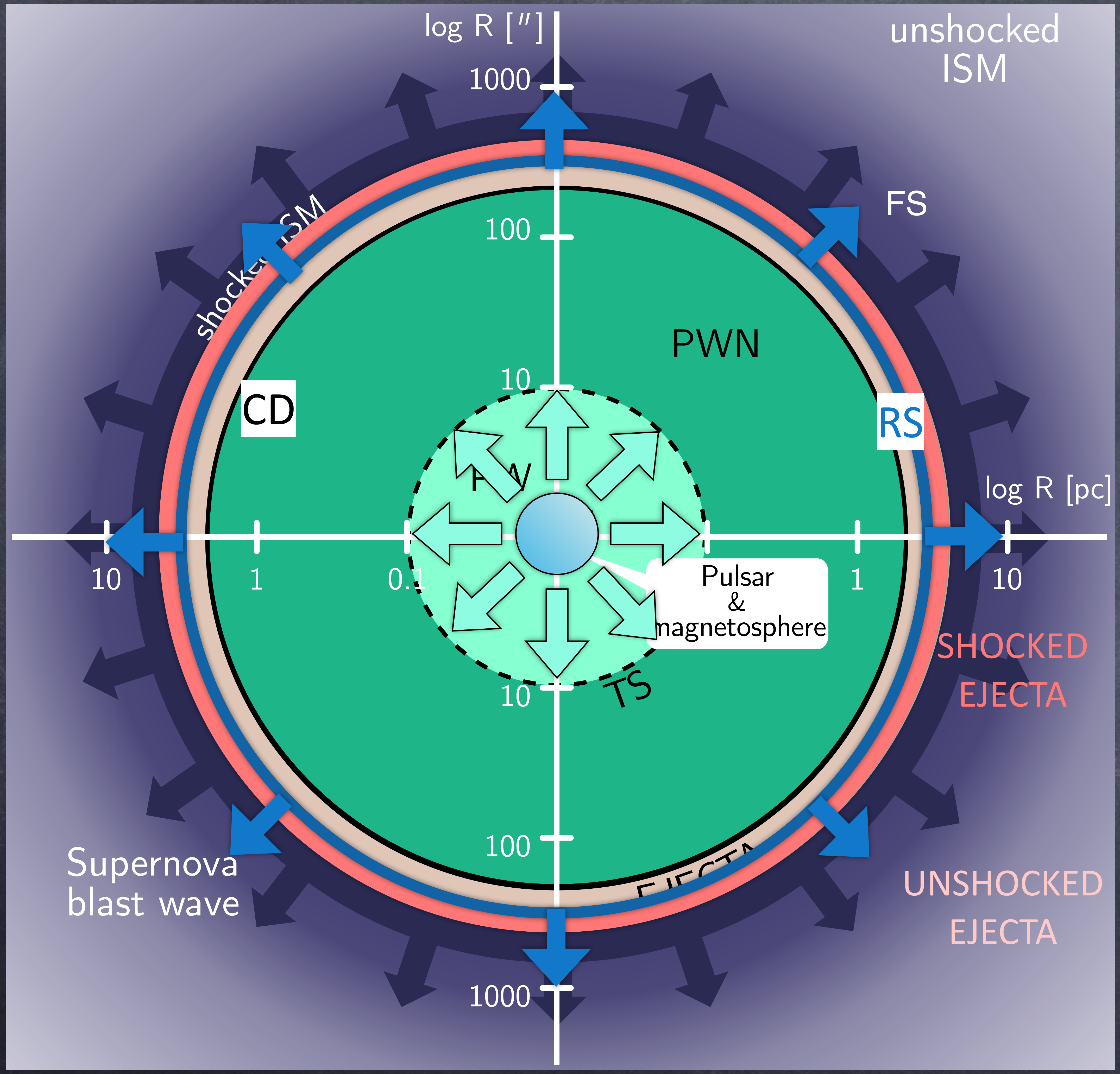
POSSIBILITIES DEPEND ON

WIND COMPOSITION (IONS? κ?)

WIND MAGNETIZATION (σ?)

← IN PRINCIPLE BOTH DEPEND ON LOCATION

BASIC PICTURE OF A PWN



Adapted from Kennel & Coroniti 1984

[Del Zanna & Olmi 2017]

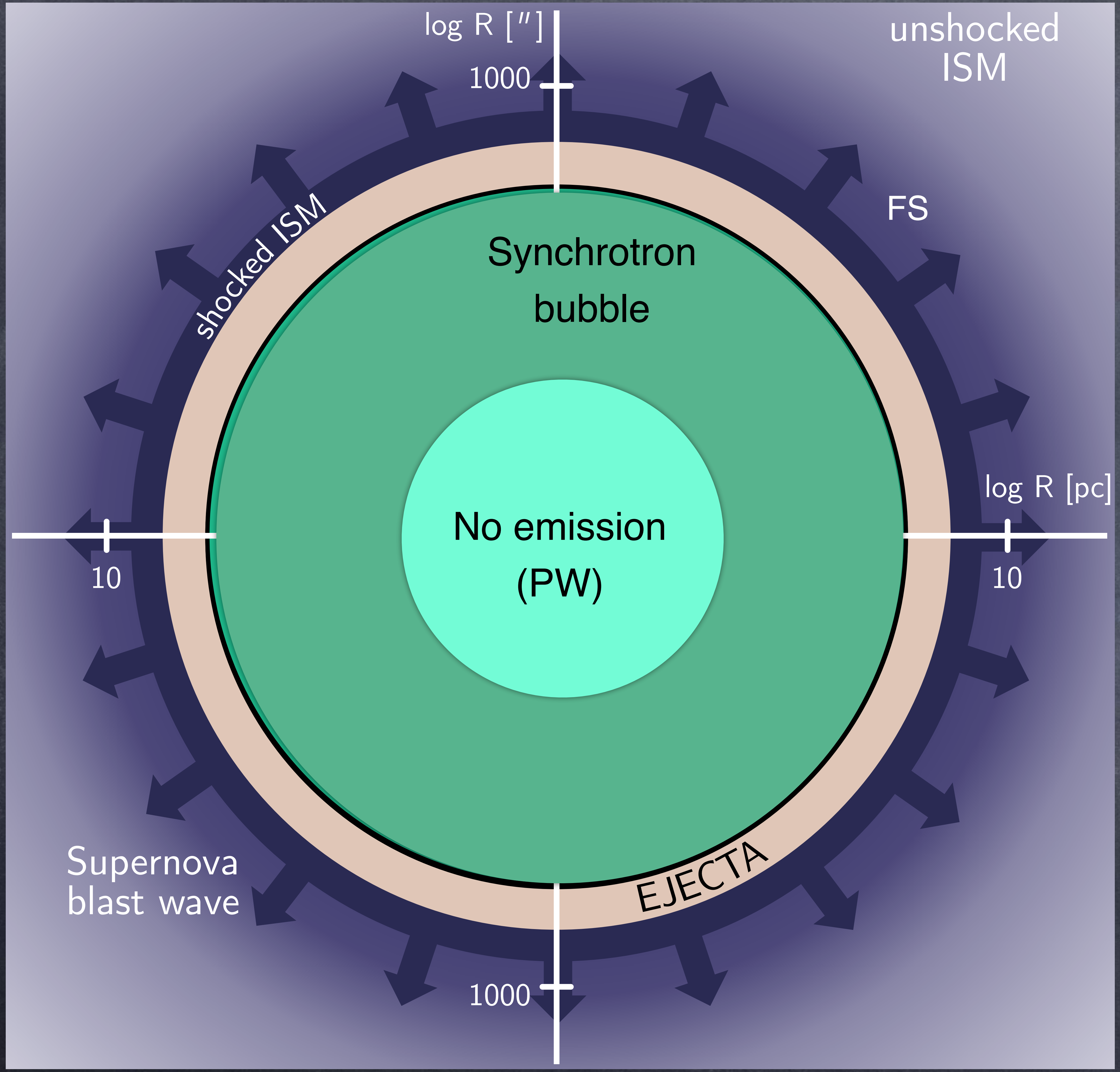
R_{TS} = termination shock radius

R_N = nebula radius

$$\frac{\dot{E}}{4\pi c R_{TS}^2} = P_{PWN} = \frac{\dot{E}\ t}{4\pi R_N^3}$$

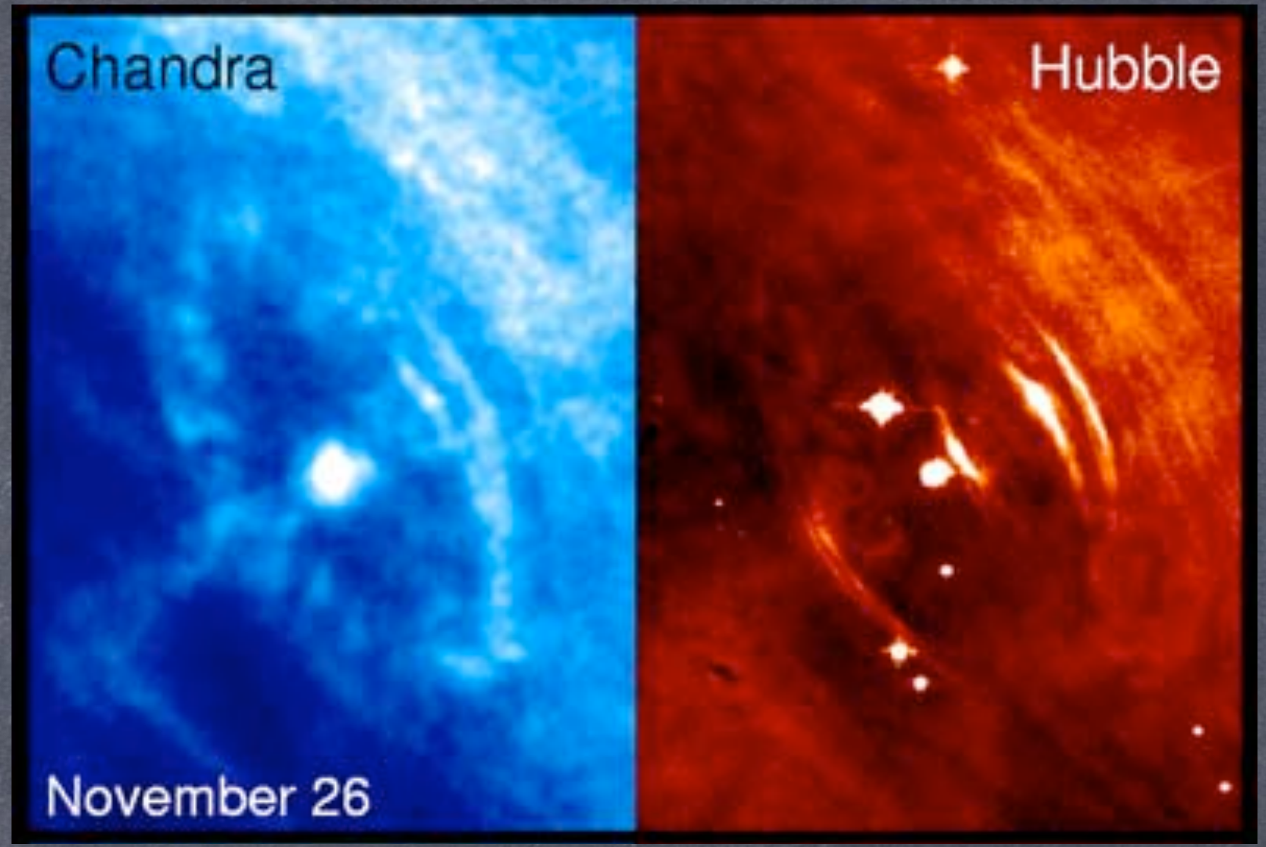
$$R_{TS} = \left(\frac{v_N}{c}\right)^{1/2} R_N$$

THE TERMINATION SHOCK



Adapted from Kennel & Coroniti 1984

[Del Zanna & Olmi 2017]

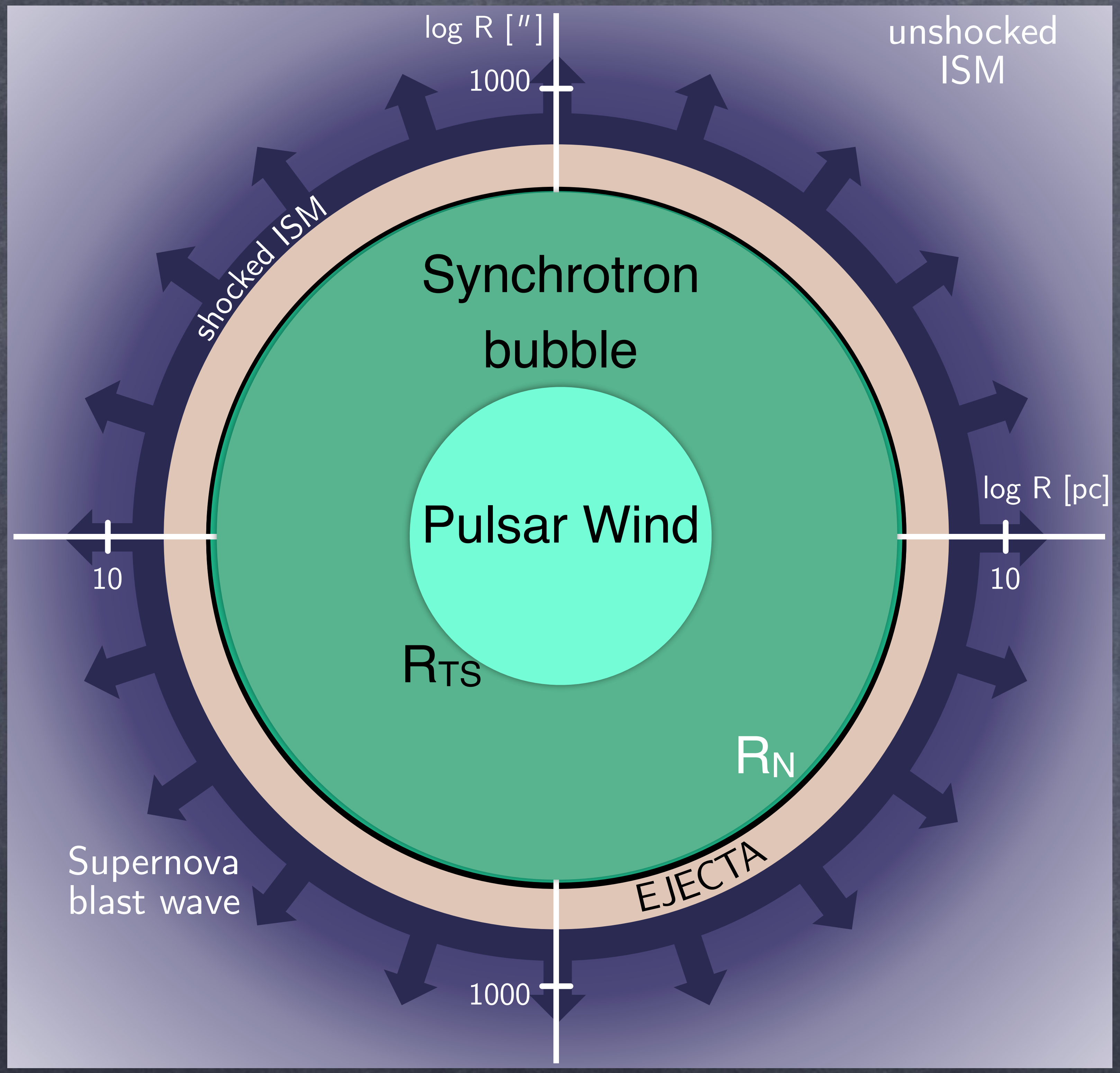


$$R_{TS} = \left(\frac{v_N}{c}\right)^{1/2} R_N$$

DISSIPATION AND PARTICLE [redacted]

1D/2D STATIC MODELS OF PWNE

[Rees & Gunn 1974, Kennel & Coroniti 1984, Emmering & Chevalier 1987, Begelman & Li 1992]

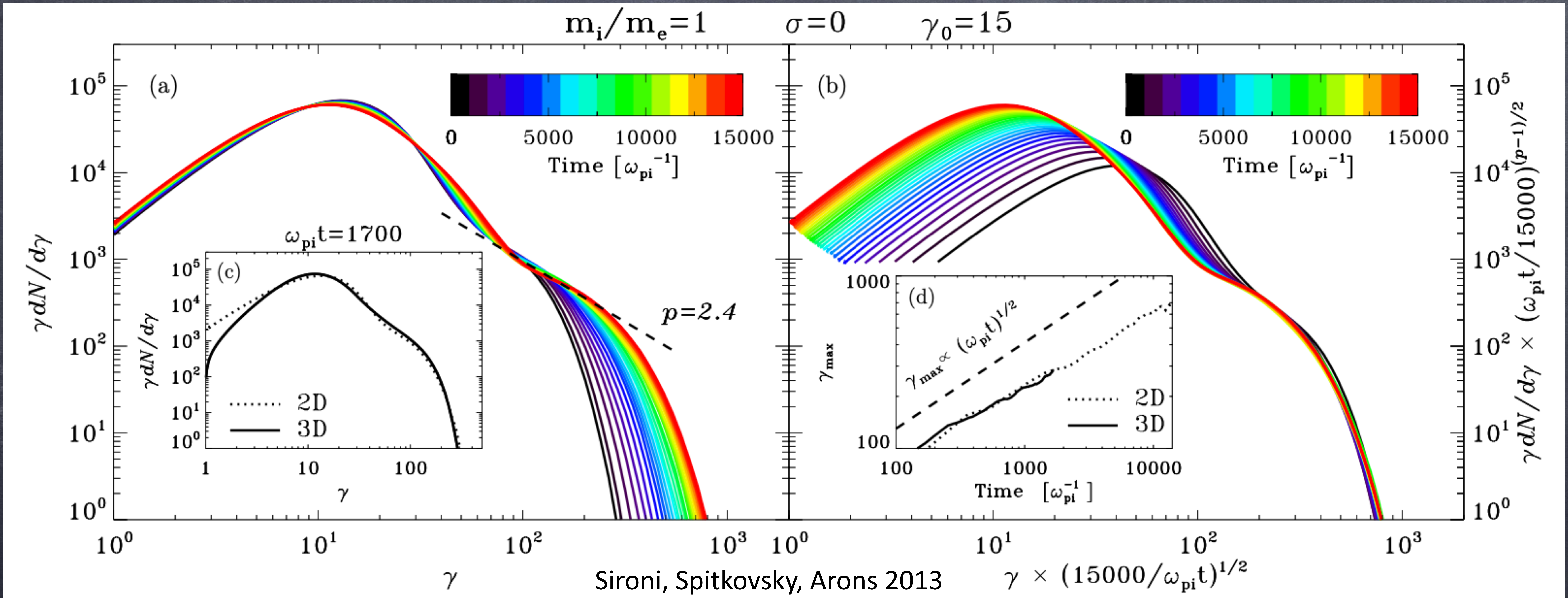


FROM DYNAMICS AND RADIATION MODELING OF OPTICAL /X-RAY EMISSION OF THE NEBULA

- particle spectral index(es) → $\gamma = 2.3$
- wind Lorentz factor → $\Gamma = 3 \times 10^6$
- wind magnetization → $\sigma = v_N/c \approx 3 \times 10^{-3}$
- particle injection rate → $\dot{N} \approx 10^{38}\ s^{-1}$

PARTICLE ACCELERATION MECHANISMS

FERMI ACCELERATION (RELATIVISTIC UNMAGNETIZED!)

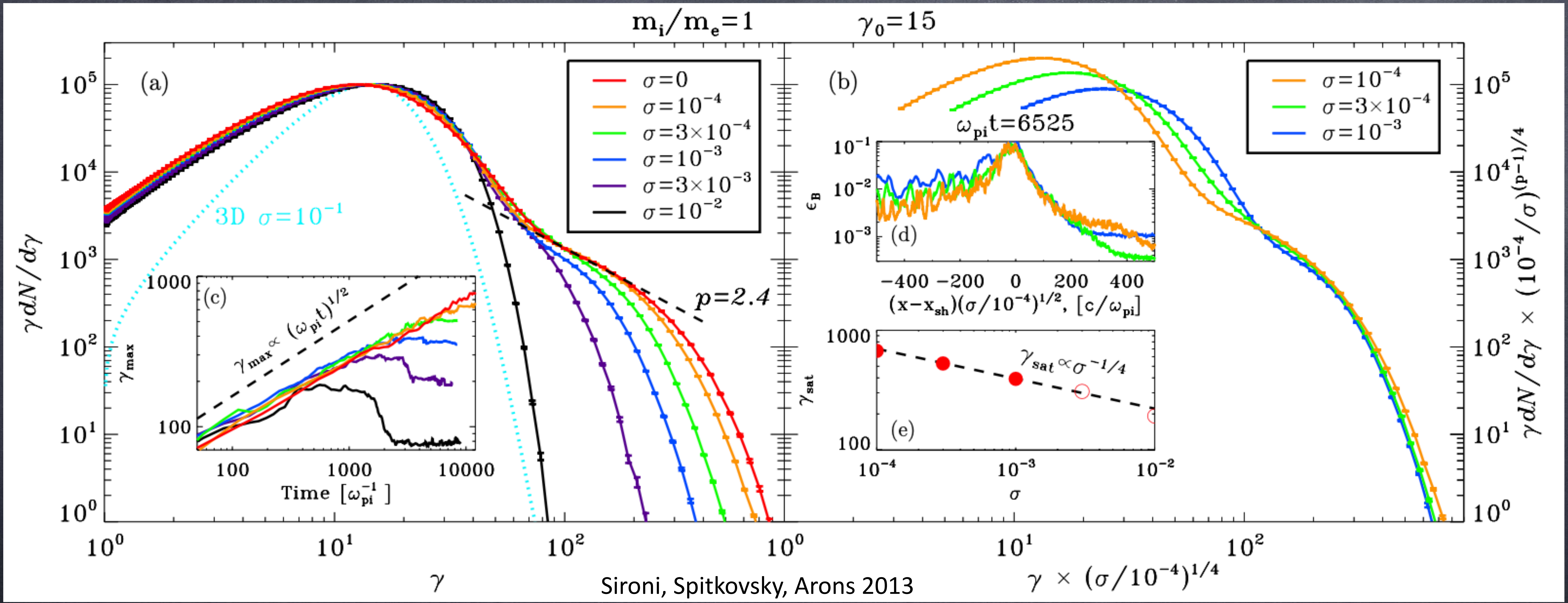


Sironi, Spitkovsky, Arons 2013

POWER-LAW DEVELOPS BUT SLOW PROCESS!

SCATTERING ON SMALL-SCALE TURBULENCE: $E_{MAX} \propto t^{1/2}$

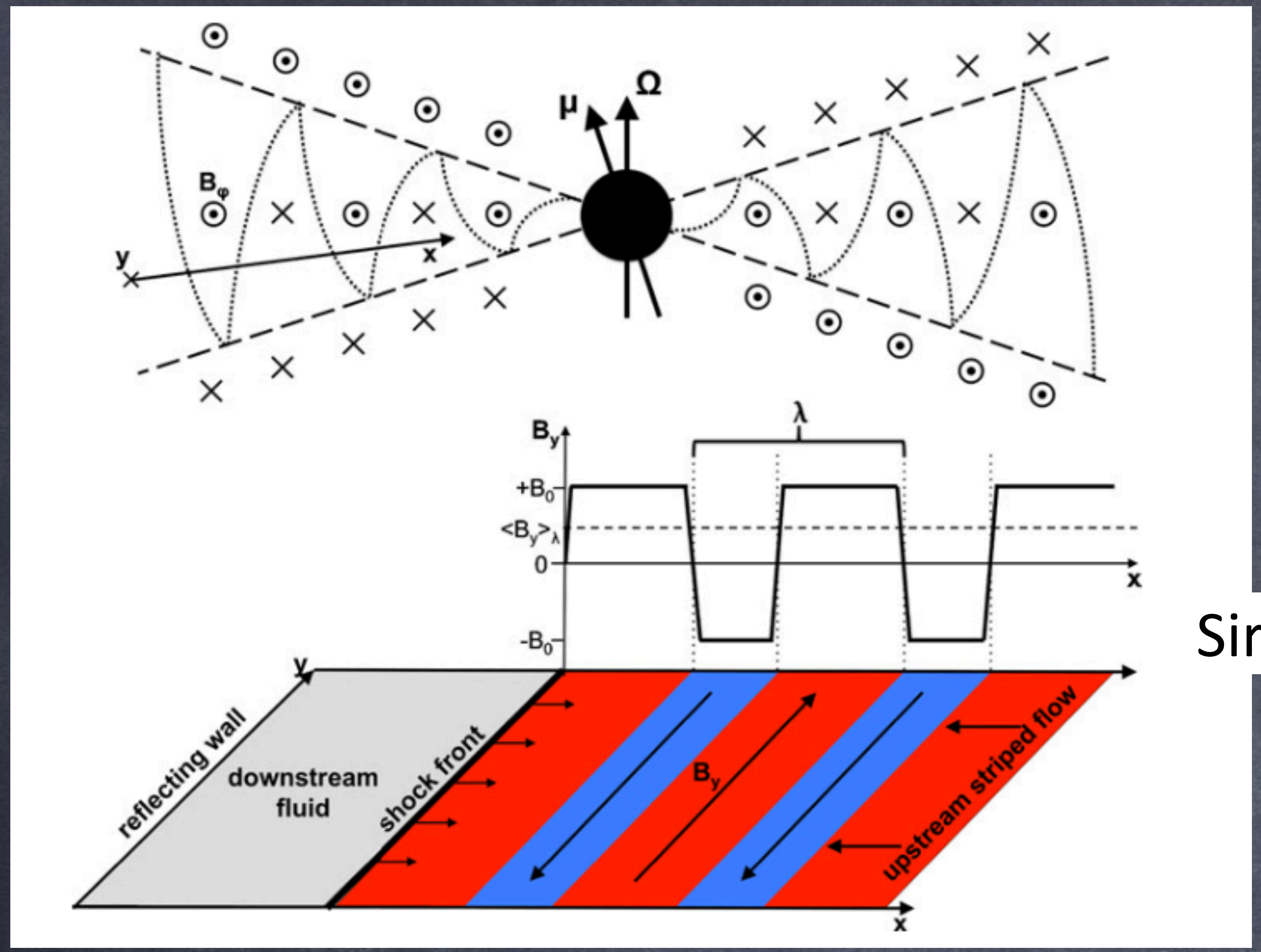
FERMI ACCELERATION (RELATIVISTIC MAGNETIZED!)



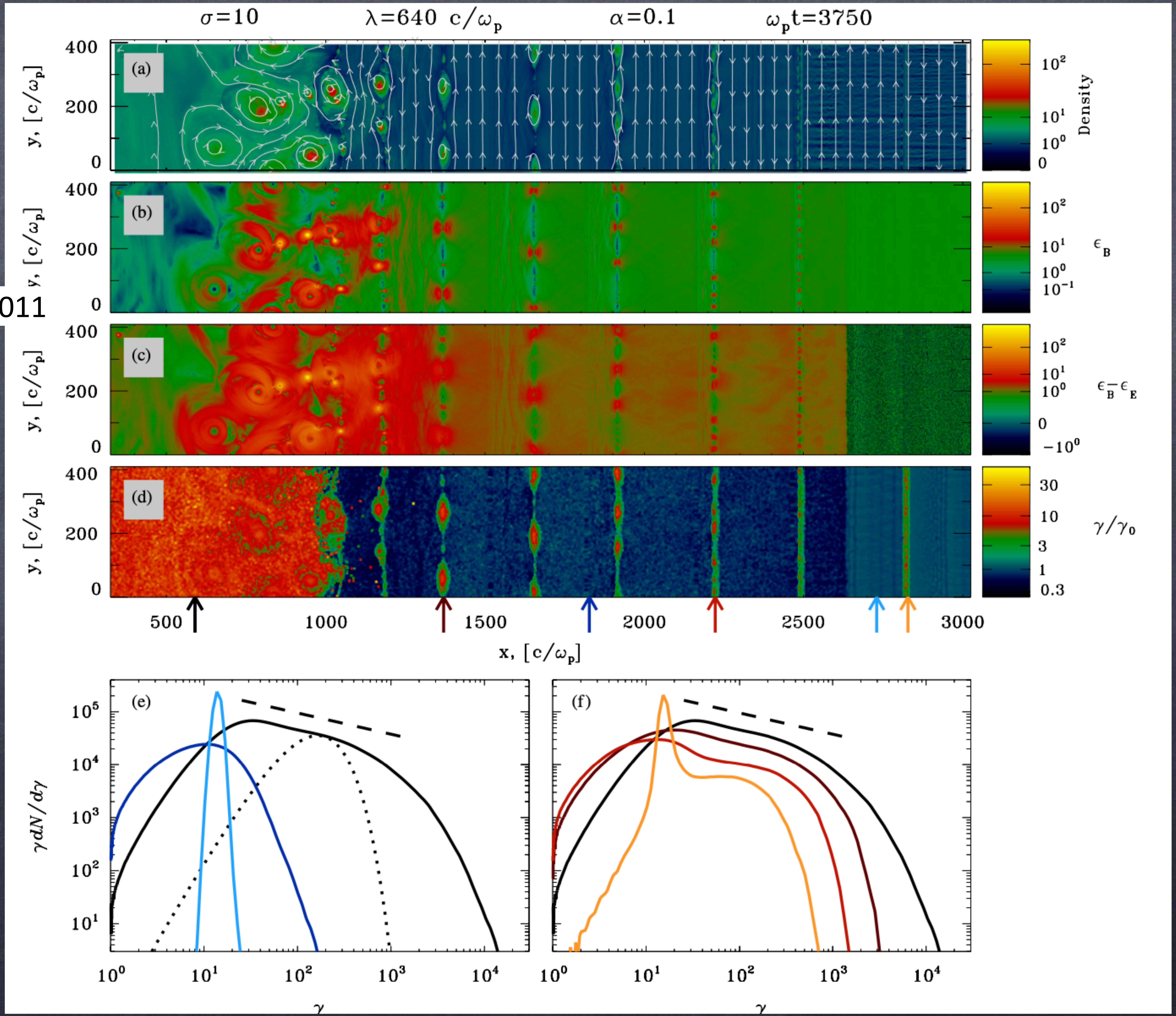
ACCELERATION COMPLETELY SUPPRESSED FOR $\sigma > 10^{-3}$

$E_{\rm MAX} \approx \sigma^{-1/4}$

FORCED MAGNETIC RECONNECTION



Sironi, Spitkovsky 2011



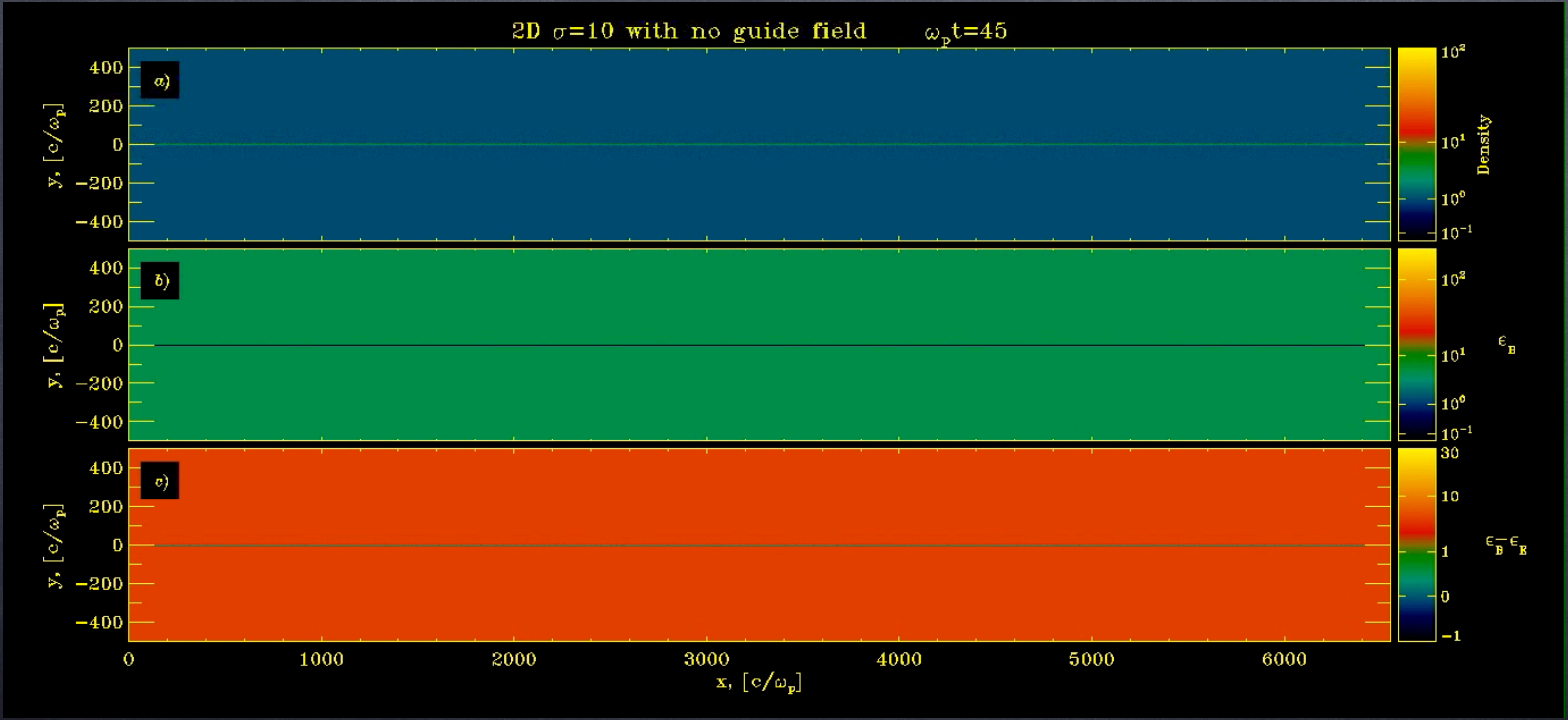
IN PRINCIPLE VERY FLAT SPECTRA AT LOW ENERGY

FERMI ACCELERATION IN UNMAGNETIZED PLASMA AFTERWARDS

RESULTS DEPEND ON

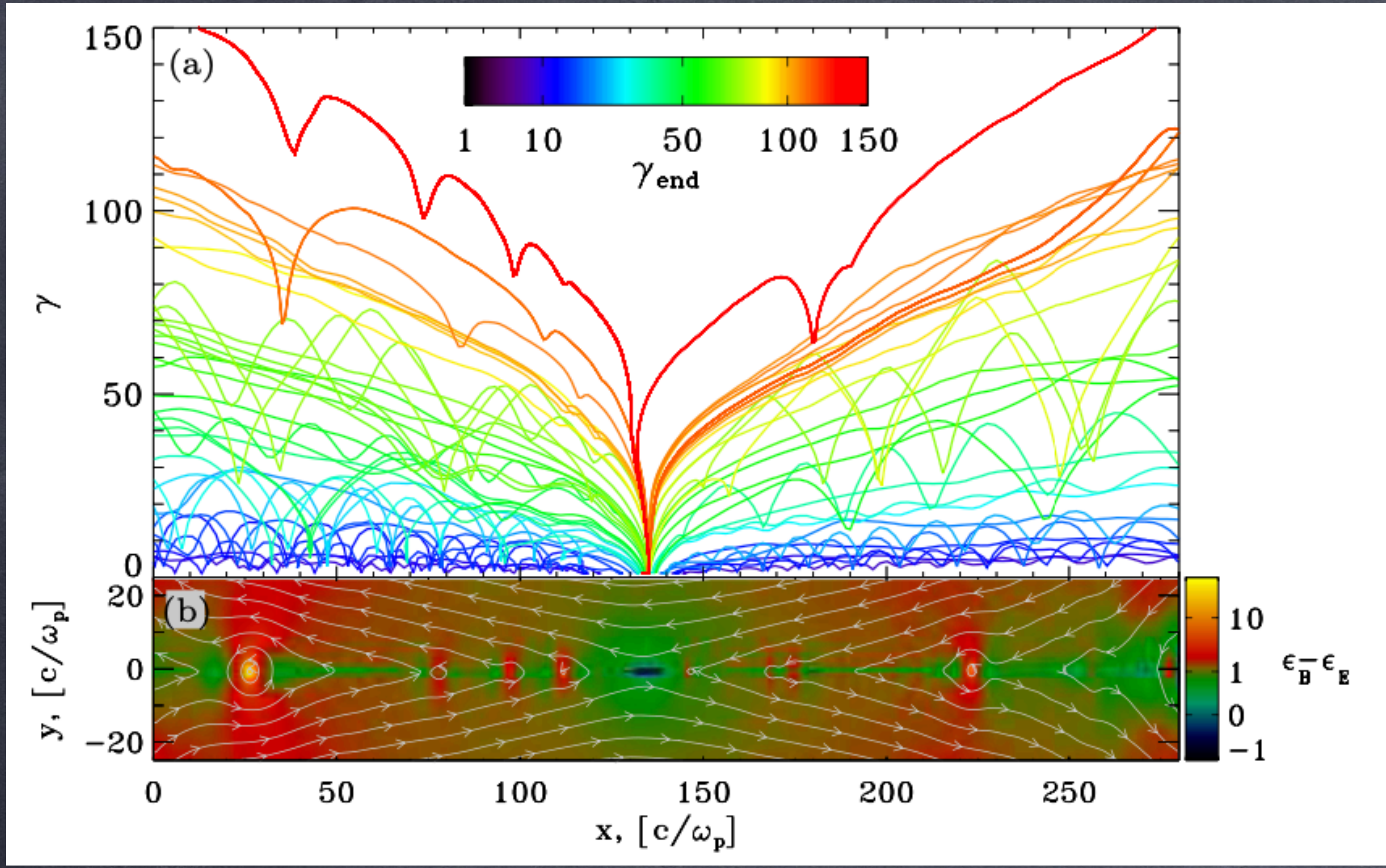
$$\sigma \quad \text{AND} \quad \frac{\lambda}{r_L \sigma}$$

FORCED MAGNETIC RECONNECTION



Sironi, Spitkovsky 2014

FORCED MAGNETIC RECONNECTION



INTERACTION WITH X-POINT

DC ACCELERATION

THEN ADVECTION INTO MAJOR ISLANDS

BROAD SPECTRUM ⇔

$\sigma > 30$

$\frac{\lambda}{r_L \sigma} > few \times 10$

⇓

BUT

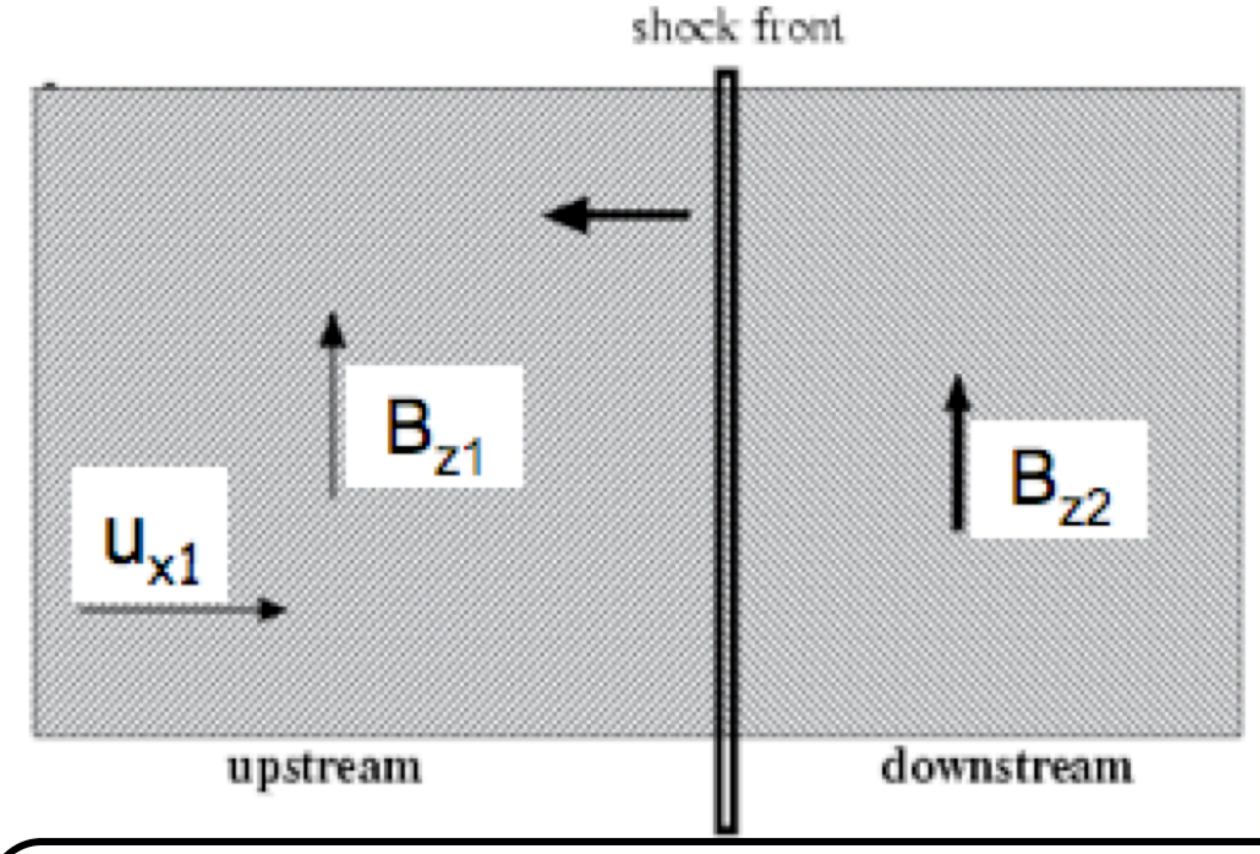
$$\frac{\lambda}{r_L \sigma} = 4\pi\kappa \frac{R_L}{R_{TS}}$$ ⇒ $\kappa > few \times 10^7$

⇐

SUCH LARGE K DIFFICULT TO ACCOUNT FOR

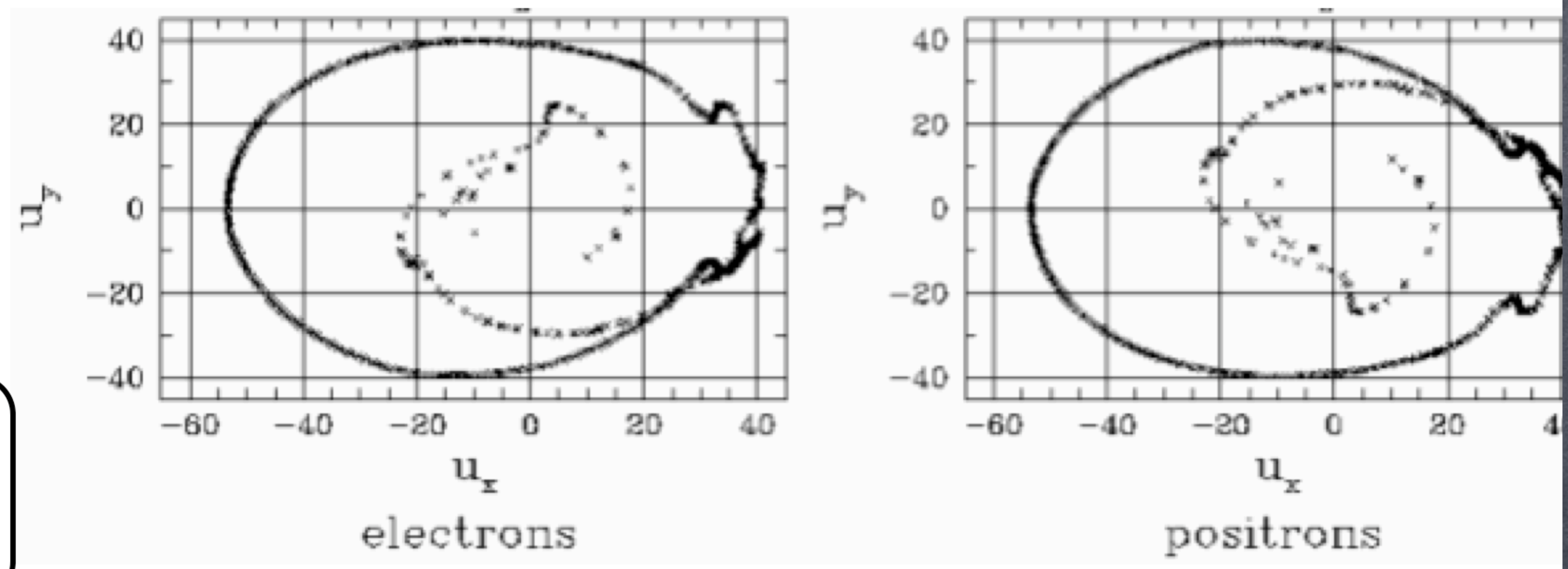
IF REALIZED, RECONNECTION BEFORE THE SHOCK

RESONANT CYCLOTRON ABSORPTION IN ION DOPED PLASMA



Magnetic reflection mediates the transition

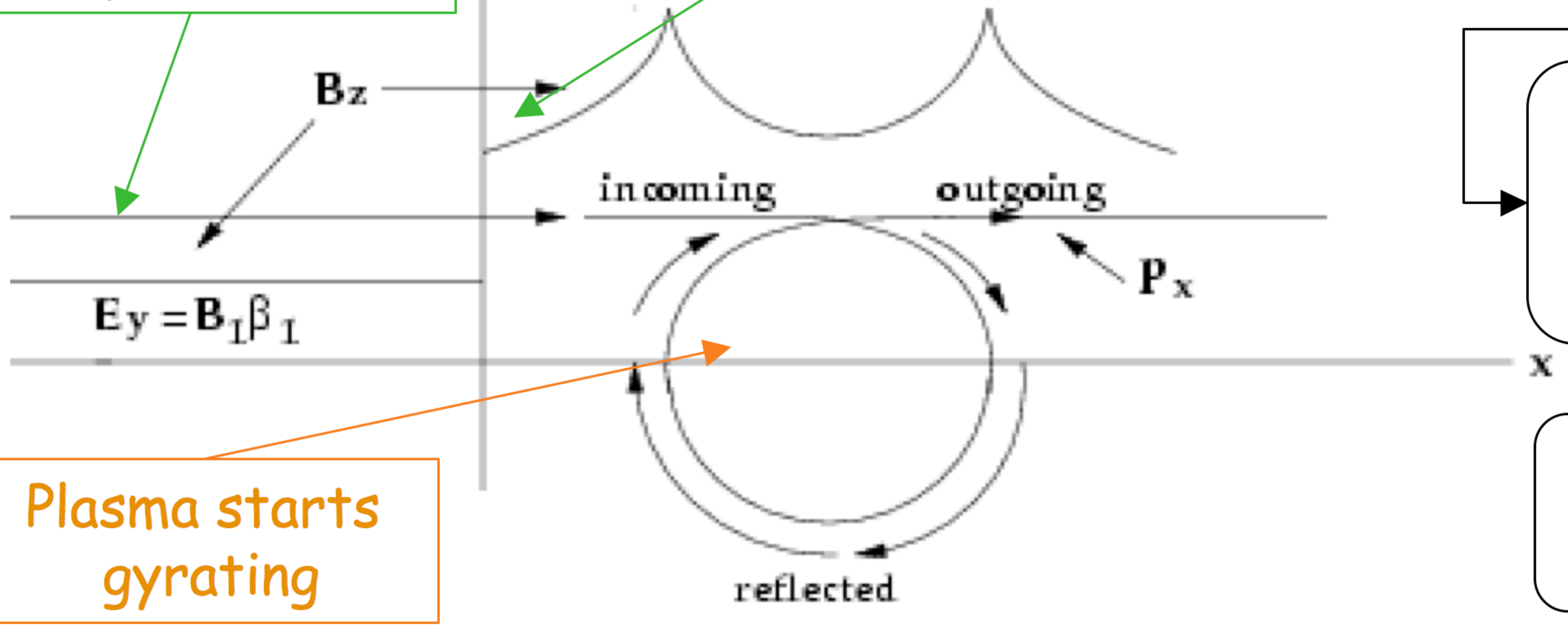
Configuration at the leading edge ~ cold ring in momentum space



Coherent gyration leads to collective emission of cyclotron waves

Drifting e^{+}-e^{-}-p plasma

B increases



Plasma starts gyrating

Pairs thermalize to $kT \sim m_e \Gamma c^2$ over $10\text{-}100 \times (1/\Omega_{ce})$

Ions take their time: m_i/m_e times longer

PARTICLE ACCELERATION MECHANISMS: SUMMARY OF REQUIREMENTS