PARTICLE ACCELERATION

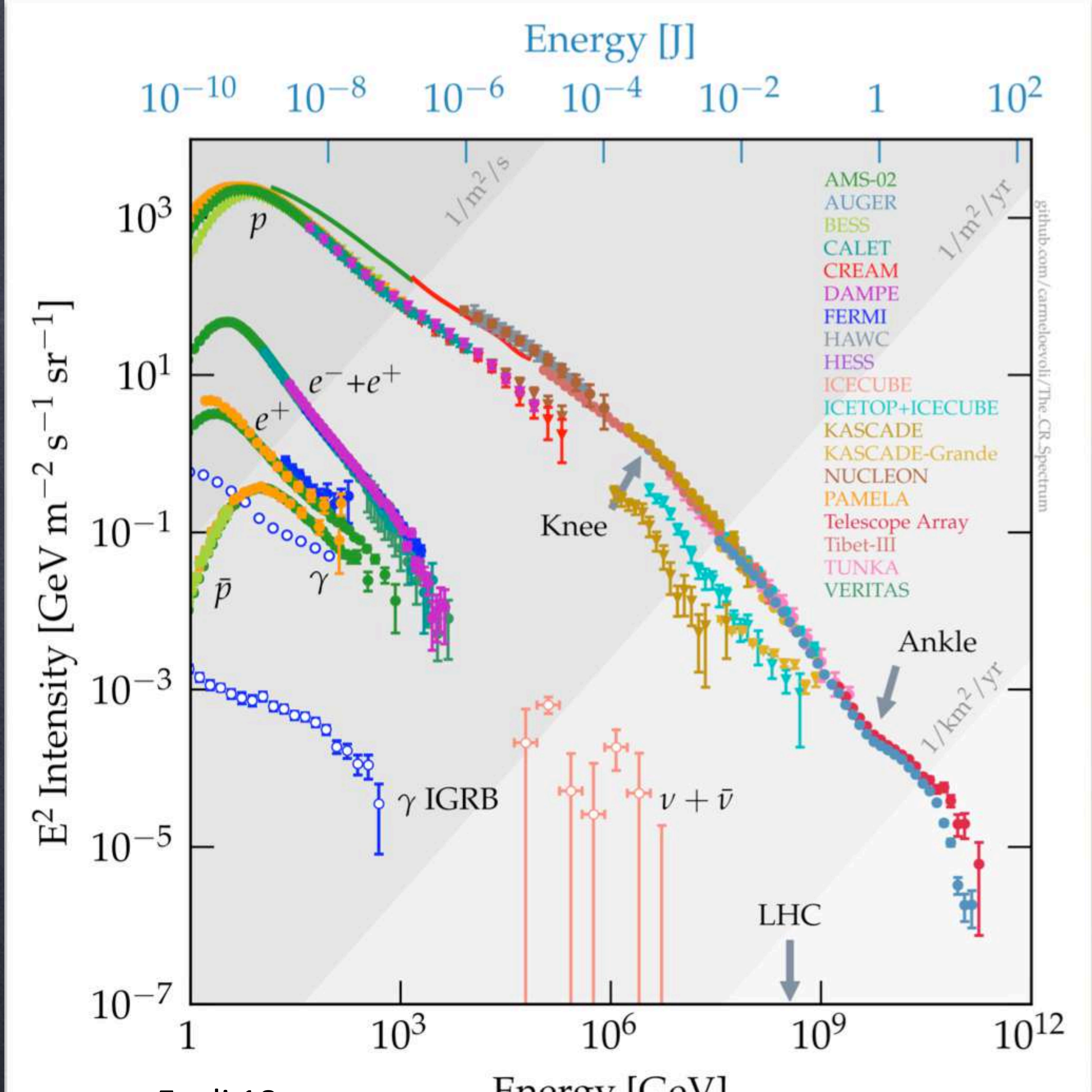
ELENA AMATO
INAF-OSSERVATORIO ASTROFISICO DI ARCETRI

OUTLINE

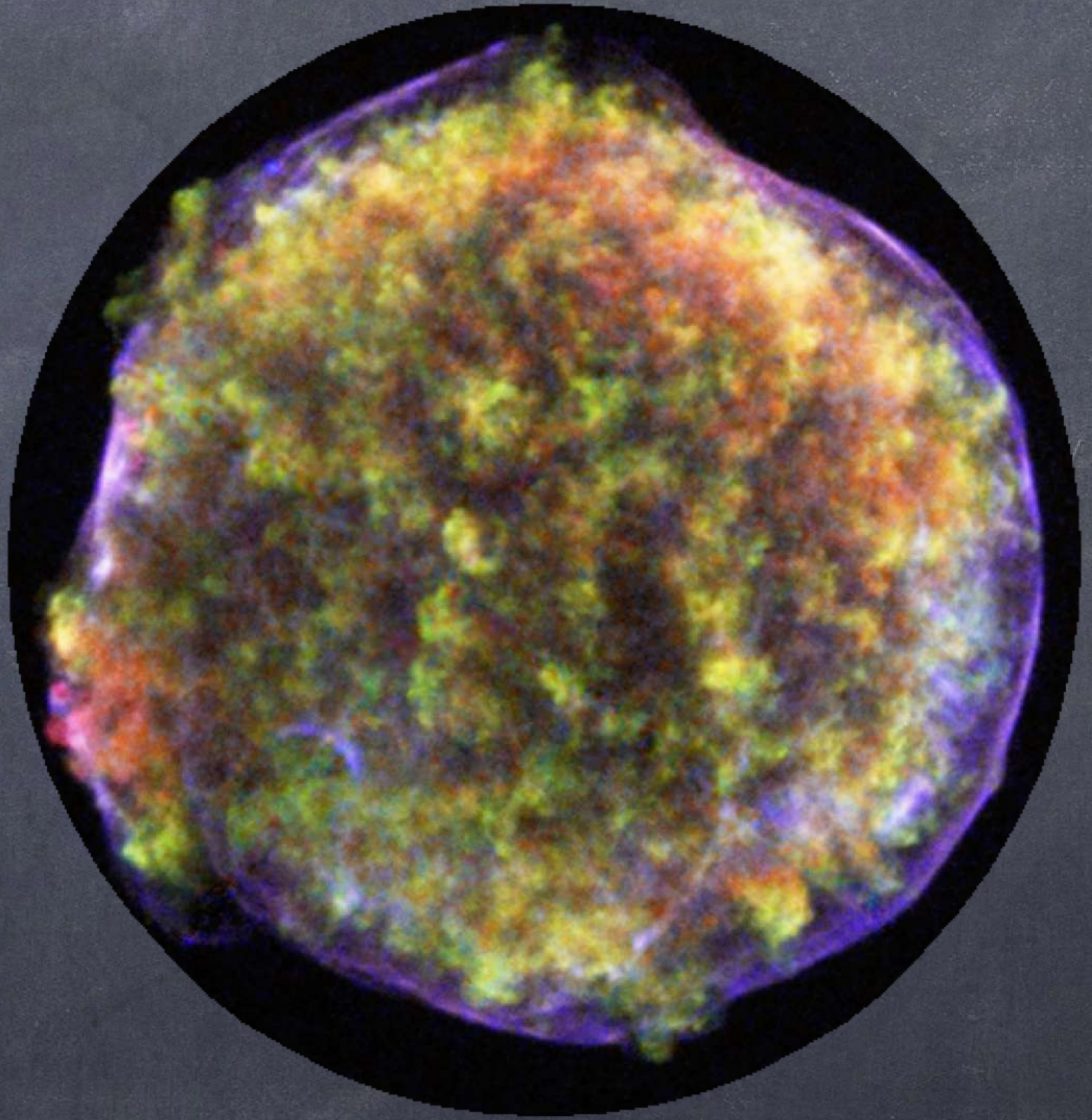
- PARTICLE ACCELERATION IN NON-RELATIVISTIC ENVIRNMENTS
  - EURISTIC DERIVATION OF FERMI ACCELERATION
  - FERMI ACCELERATION THROUGH THE TRANSPORT EQUATION
  - WAVE PARTICLE INTERACTION
  - MAXIMUM ENERGY
  - FERMI ACCELERATION
  - NON-LINEAR EFFECTS
  - PARTICLE INDUCED MAGNETIC TURBULENCE

- PARTICLE ACCELERATION IN RELATIVISTIC ENVIRONMENTS
  - UNIPOLAR INDUCTION
  - PARTICLE ACCELERATION AT RELATIVISTIC SHOCKS
  - GLACTIC PEVATRONS

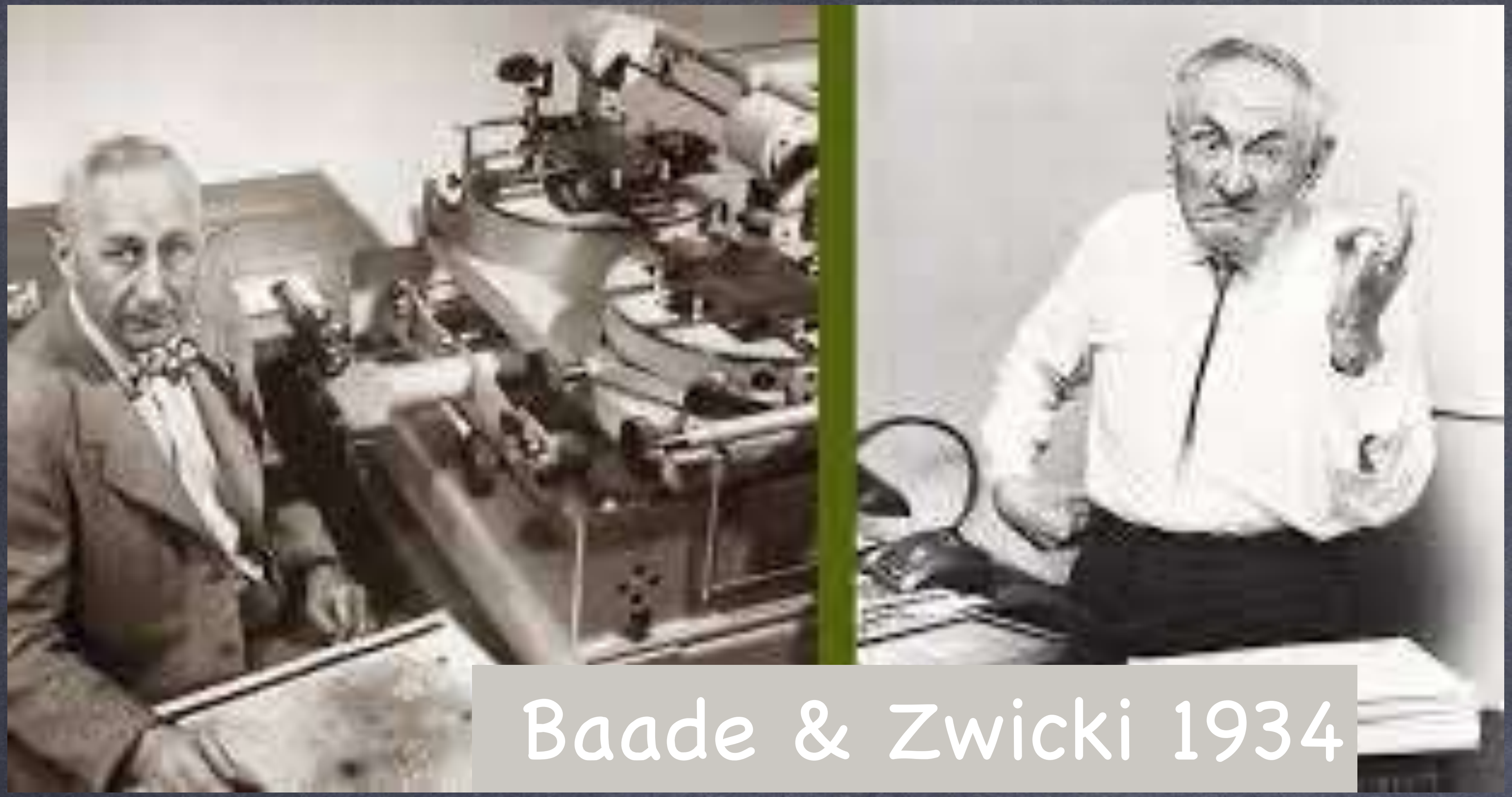
PARTICLE ACCELERATION IN ASTROPHYSICS



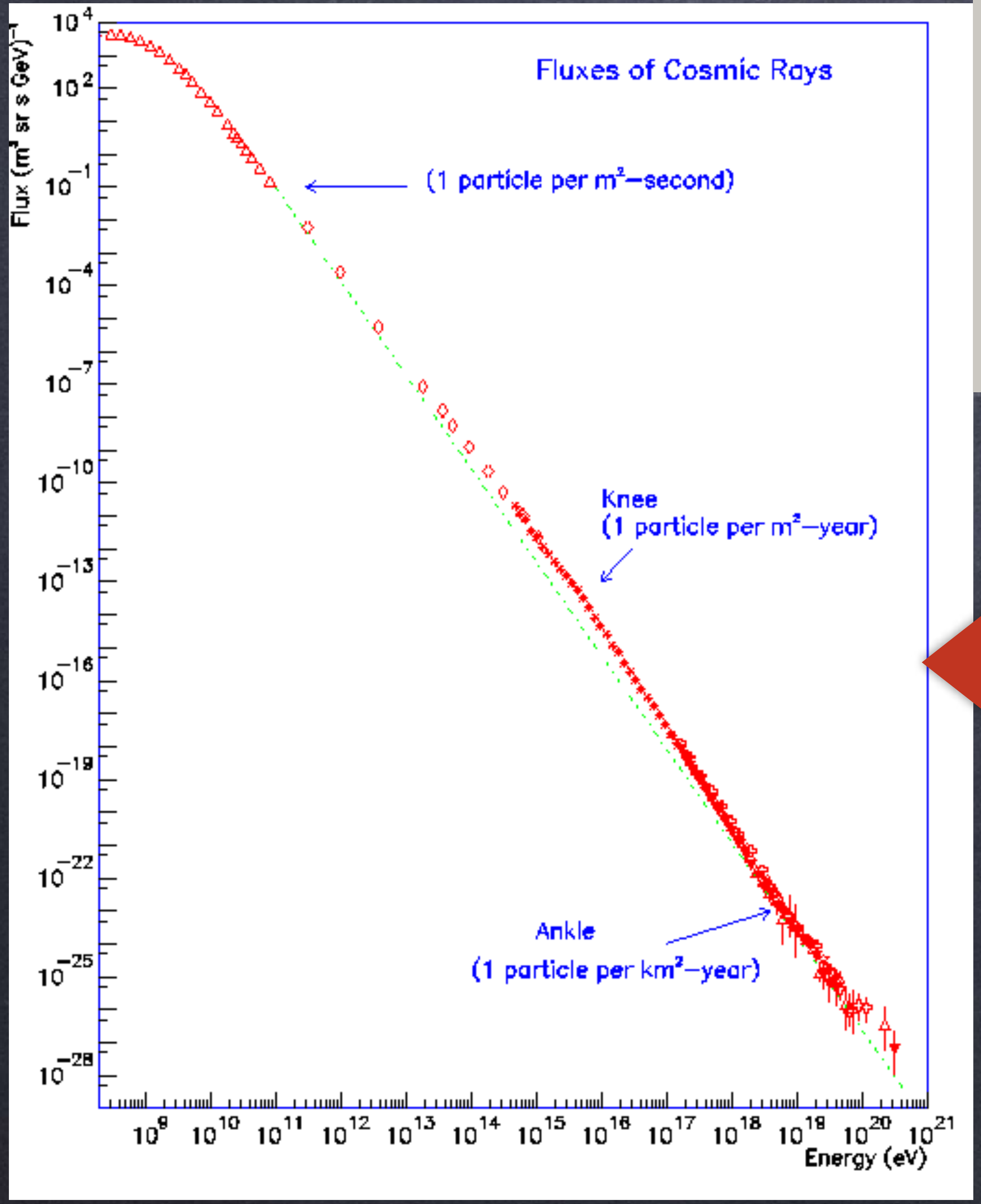
Evoli 18



THE SNR/CR CONNECTION



Baade & Zwicki 1934

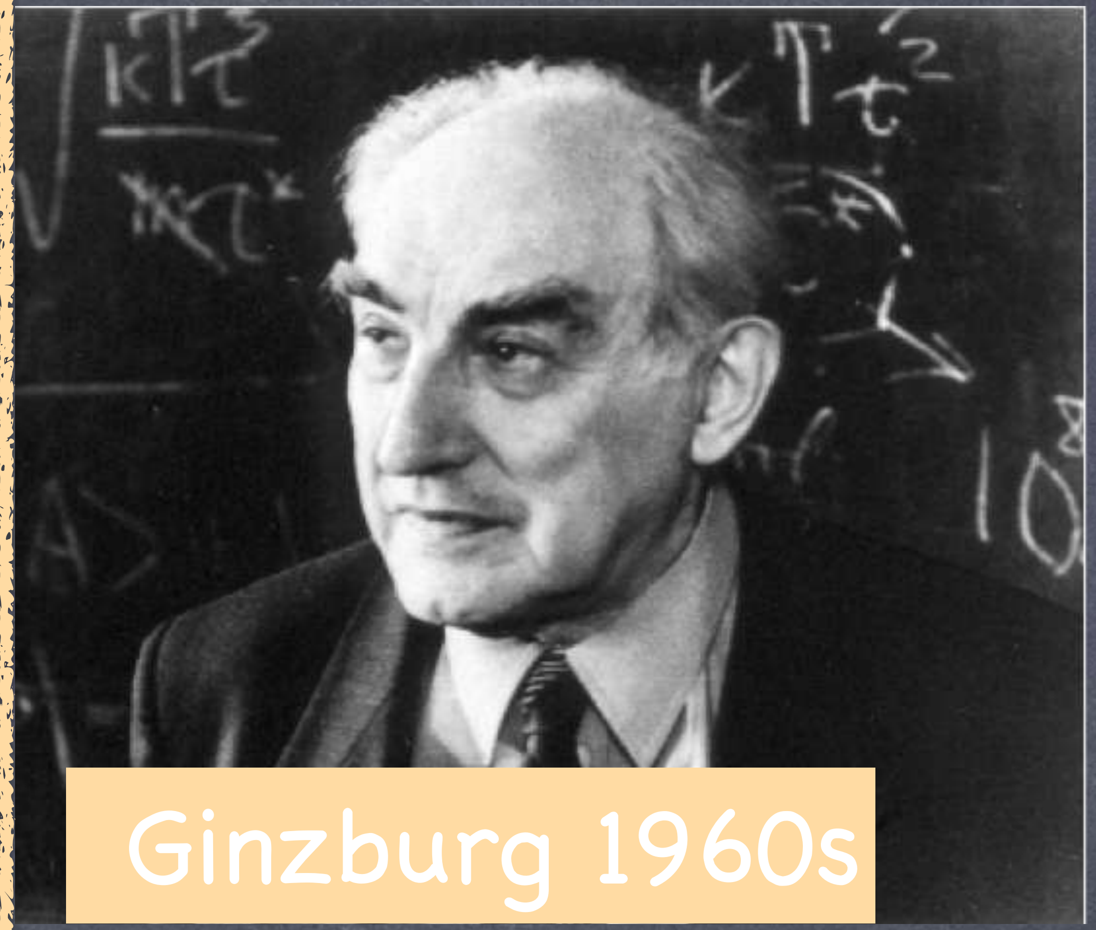


QUALITATIVE SUGGESTION IN BRILLIANT PAPER

$$L_{CR} = \frac{W_{CR} V_{CR}}{\tau_{res}} \approx (3-10) \times 10^{40}\ erg/s$$

$$L_{SN} = \mathscr{R} E_{SN} \approx (3-10) \times 10^{40}\ erg/s$$

$$\frac{L_{CR}}{L_{SN}} = 0.03 - 0.3$$



Ginzburg 1960s

QUANTITATIVE SUGGESTION

$$V_{CR} \approx \pi R_d^2 H \approx \pi\ (15\ kpc)^2\ ((1-3)\ kpc)$$

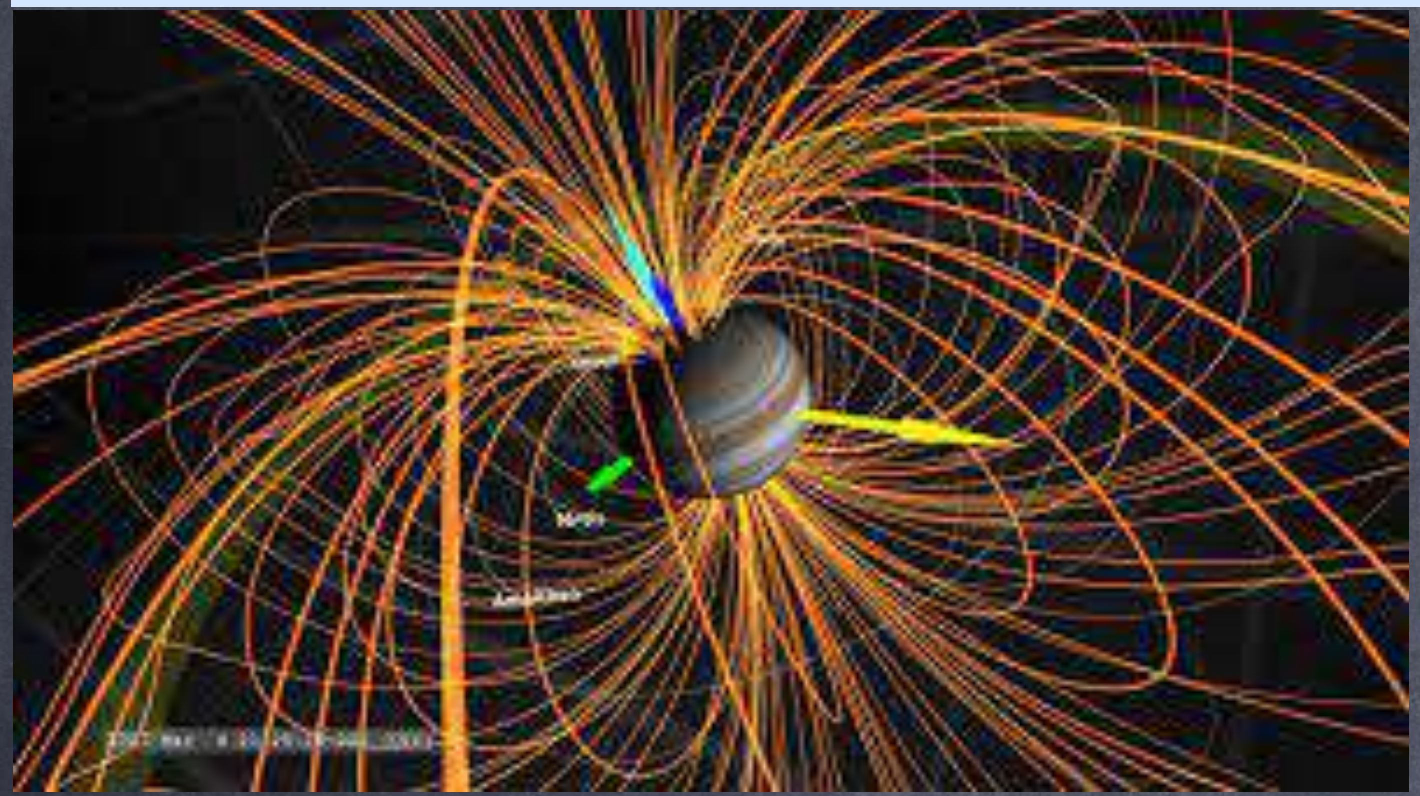
$$W_{CR} \approx 0.5 eV/cm^3$$

$$\mathscr{R} \approx \frac{1}{(30-100)\ yr} \qquad E_{SN} \approx 10^{51} erg$$

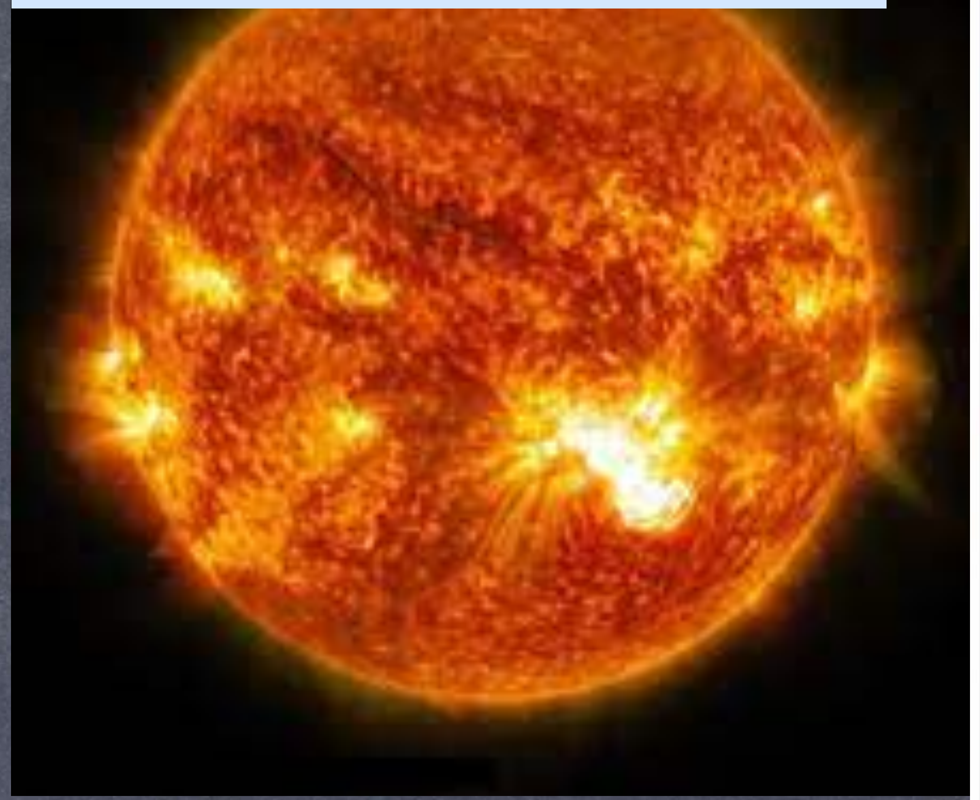
PARTICLE ACCELERATORS IN ASTROPHYSICS

A LARGE AND INCREASING VARIETY

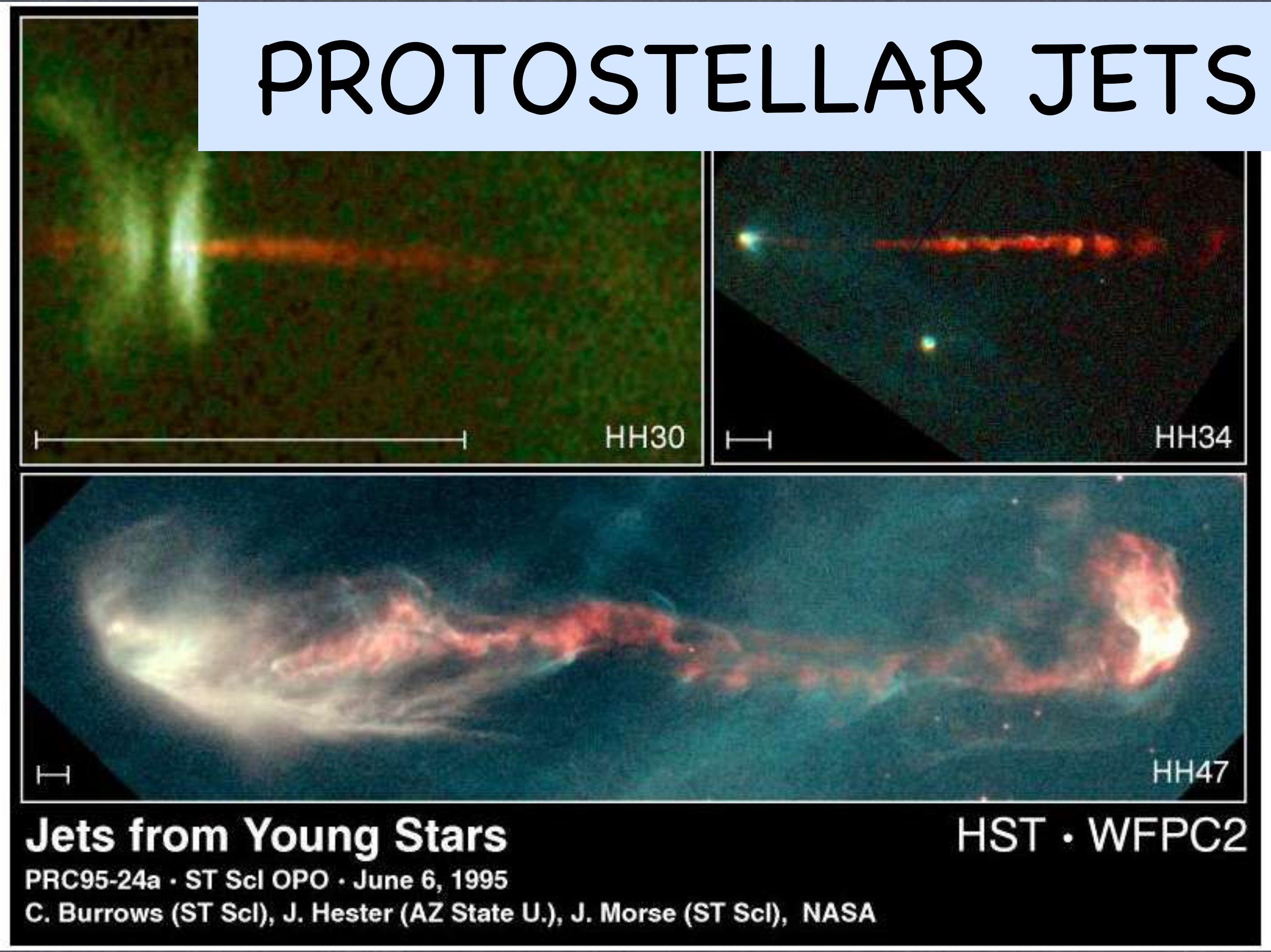
PLANETARY MAGNETOSPHERES



SUN AND STARS

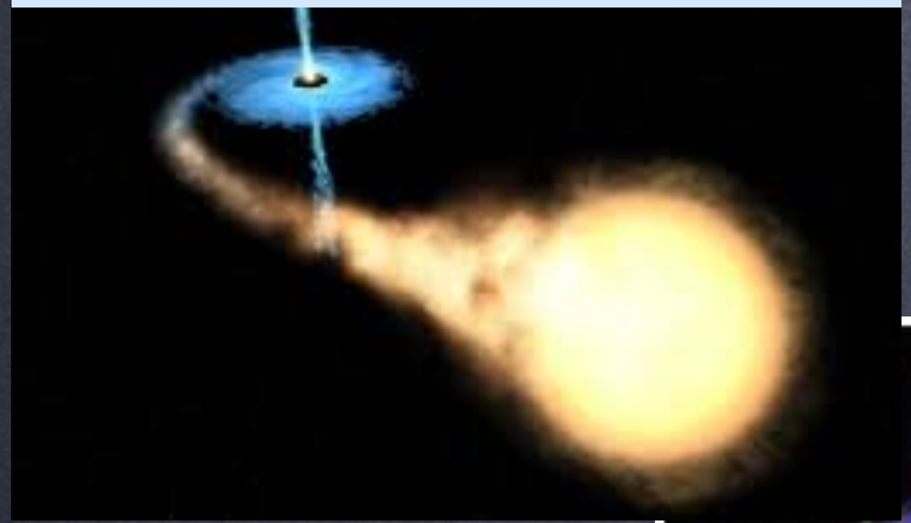


PROTOSTELLAR JETS

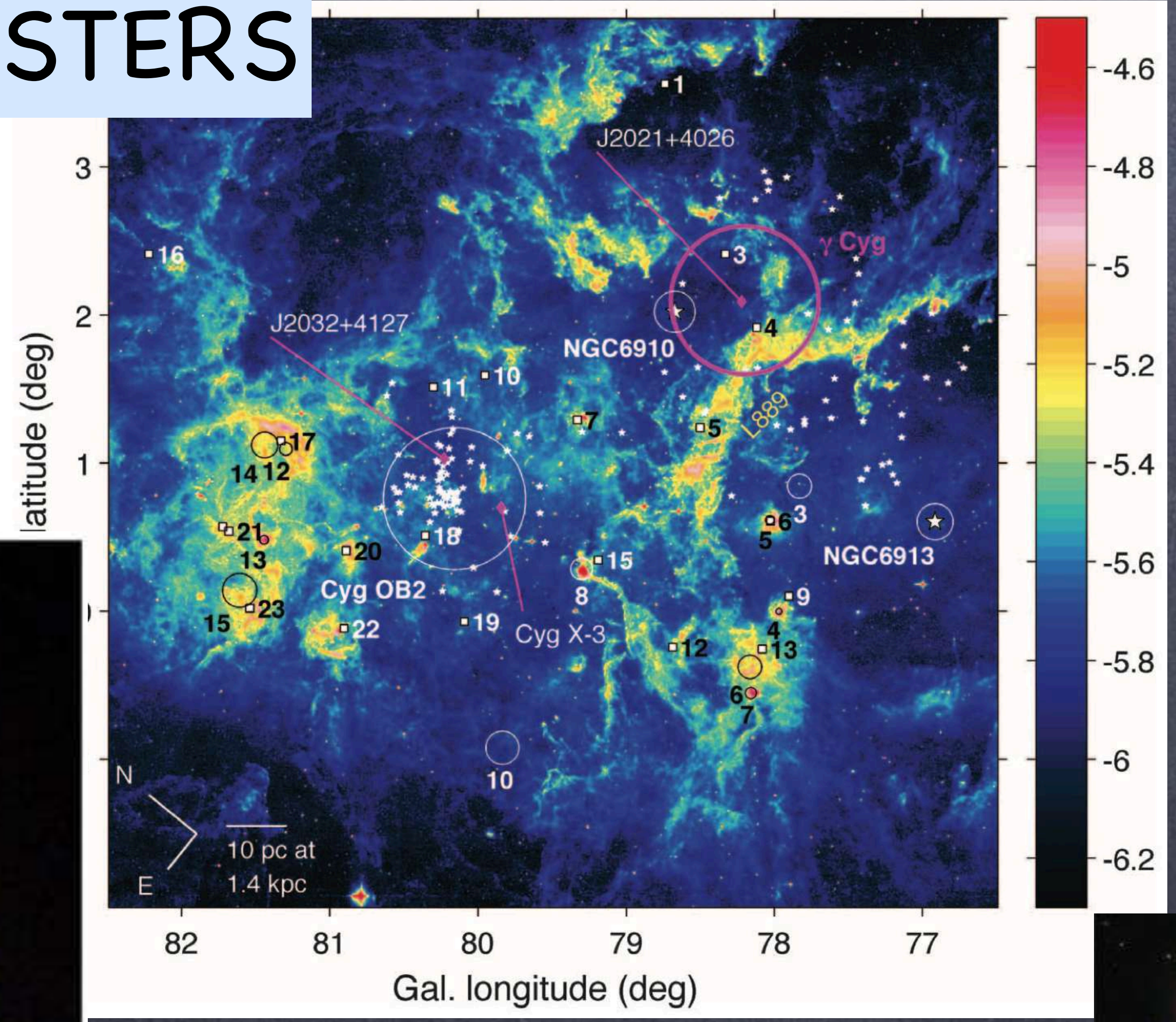


NOVAE

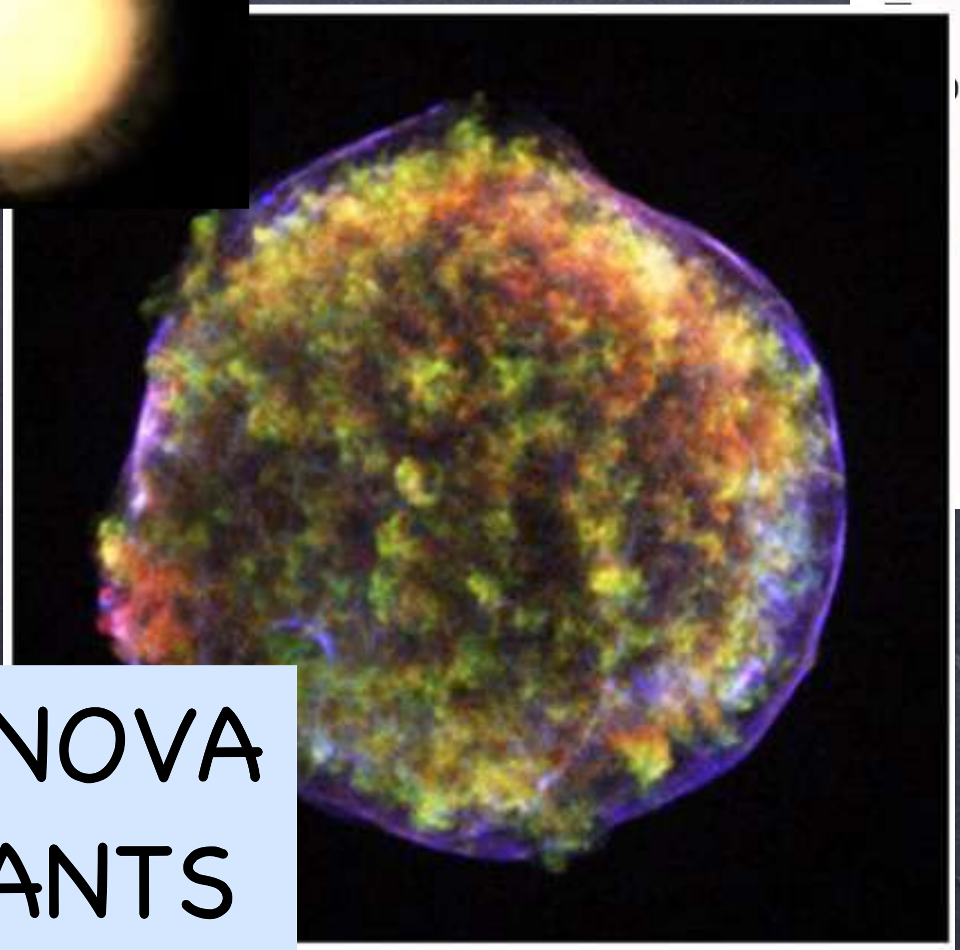
MICROQUASARS



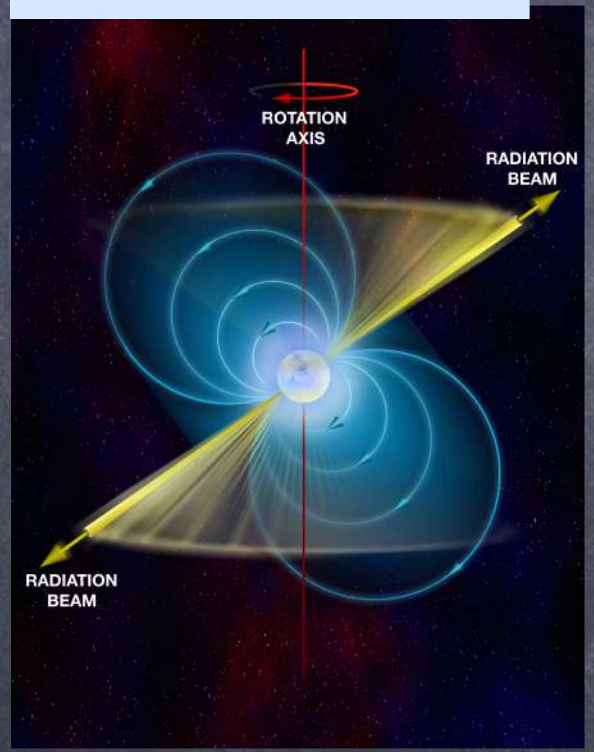
STAR CLUSTERS



SUPERNOVA REMNANTS

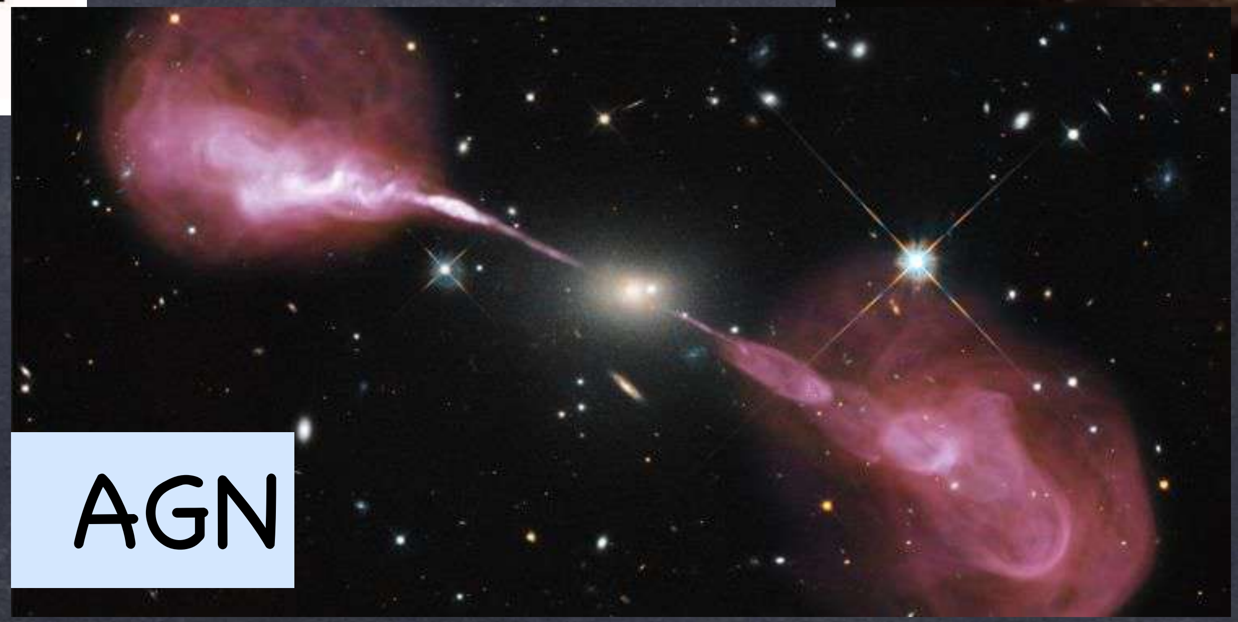


PULSARS

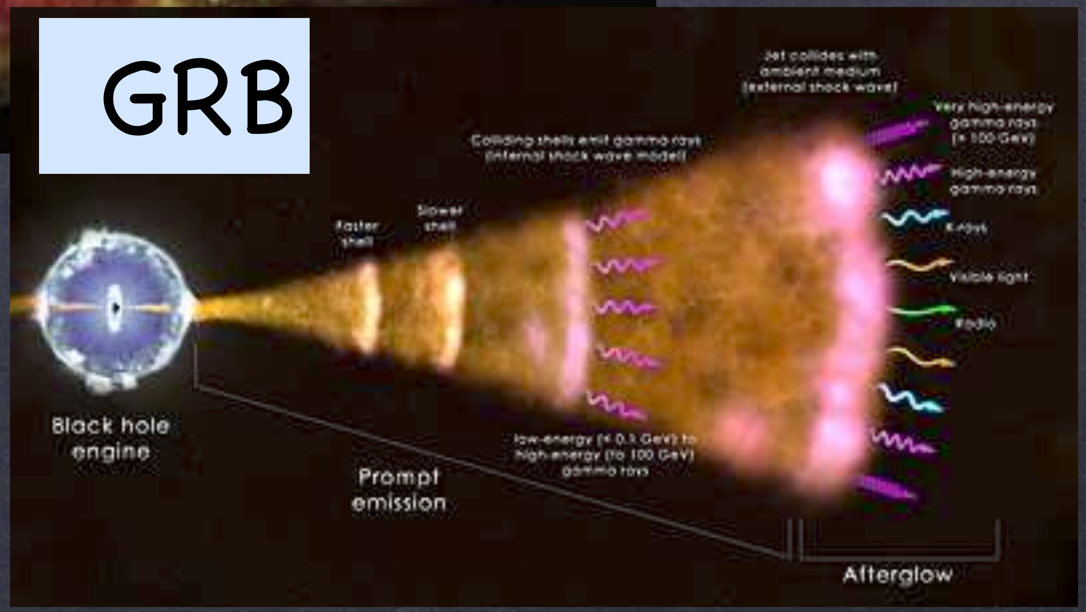


PSR WIND NEBULAE

AGN

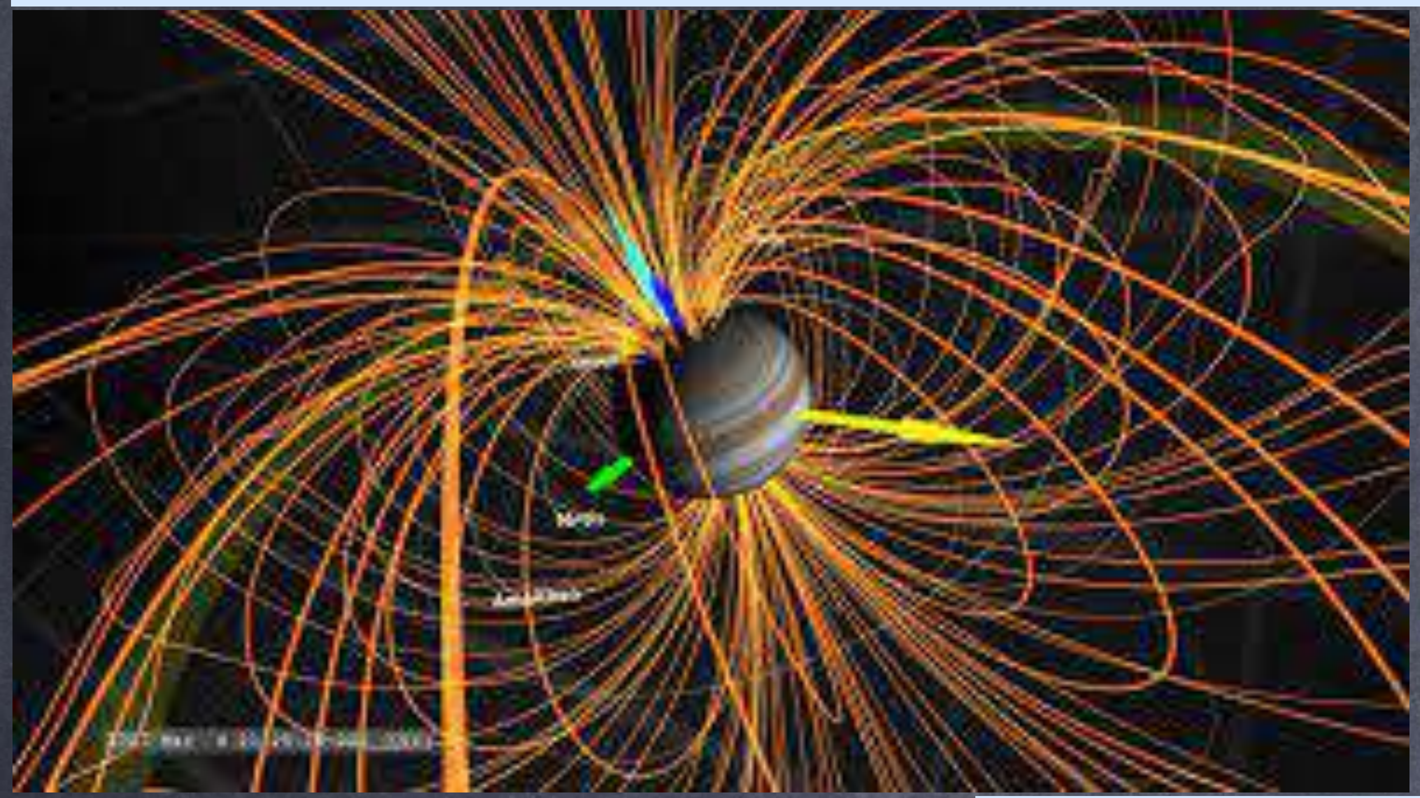


GRB



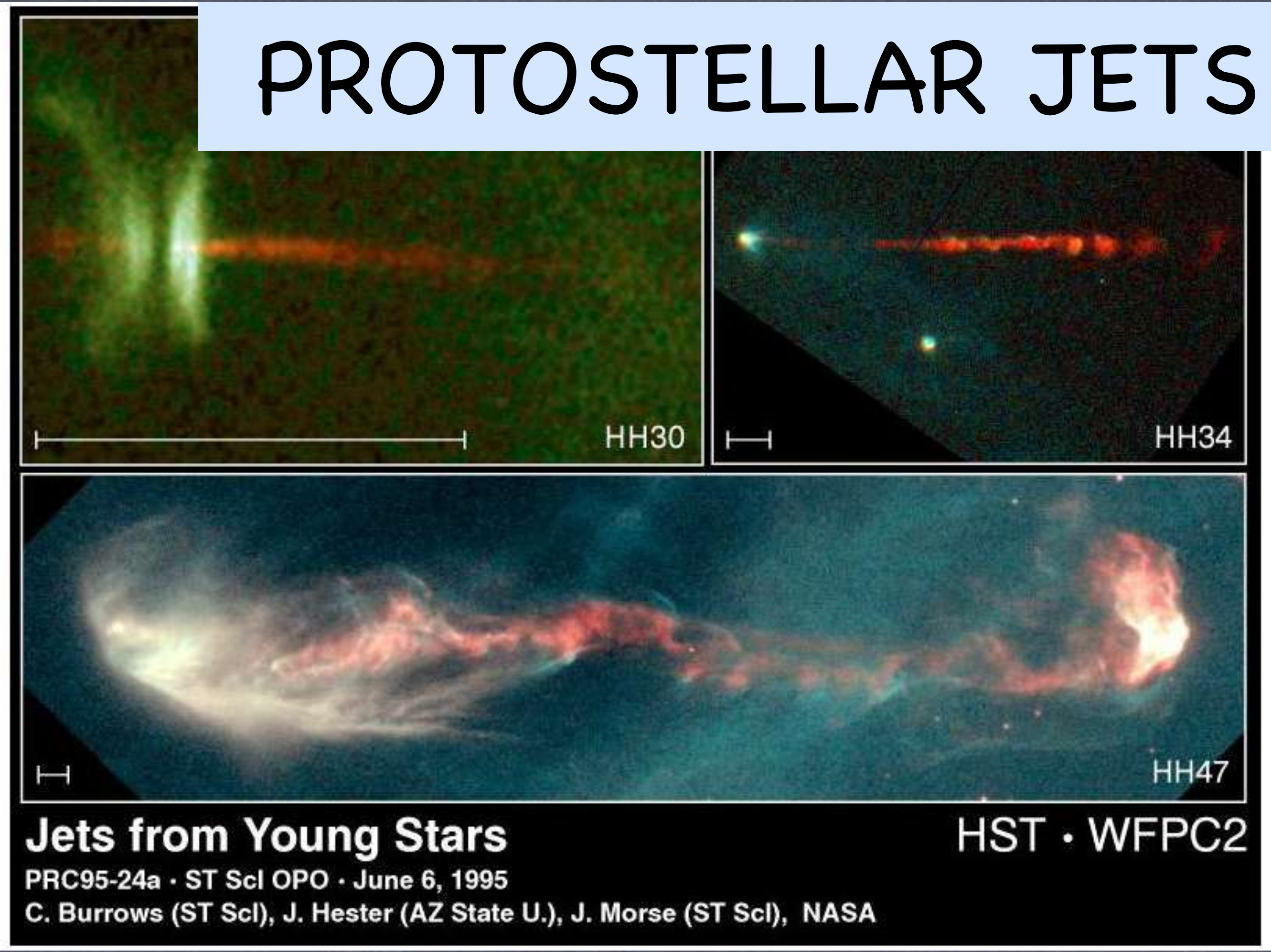
NON-RELATIVISTIC SOURCES

PLANETARY MAGNETOSPHERES



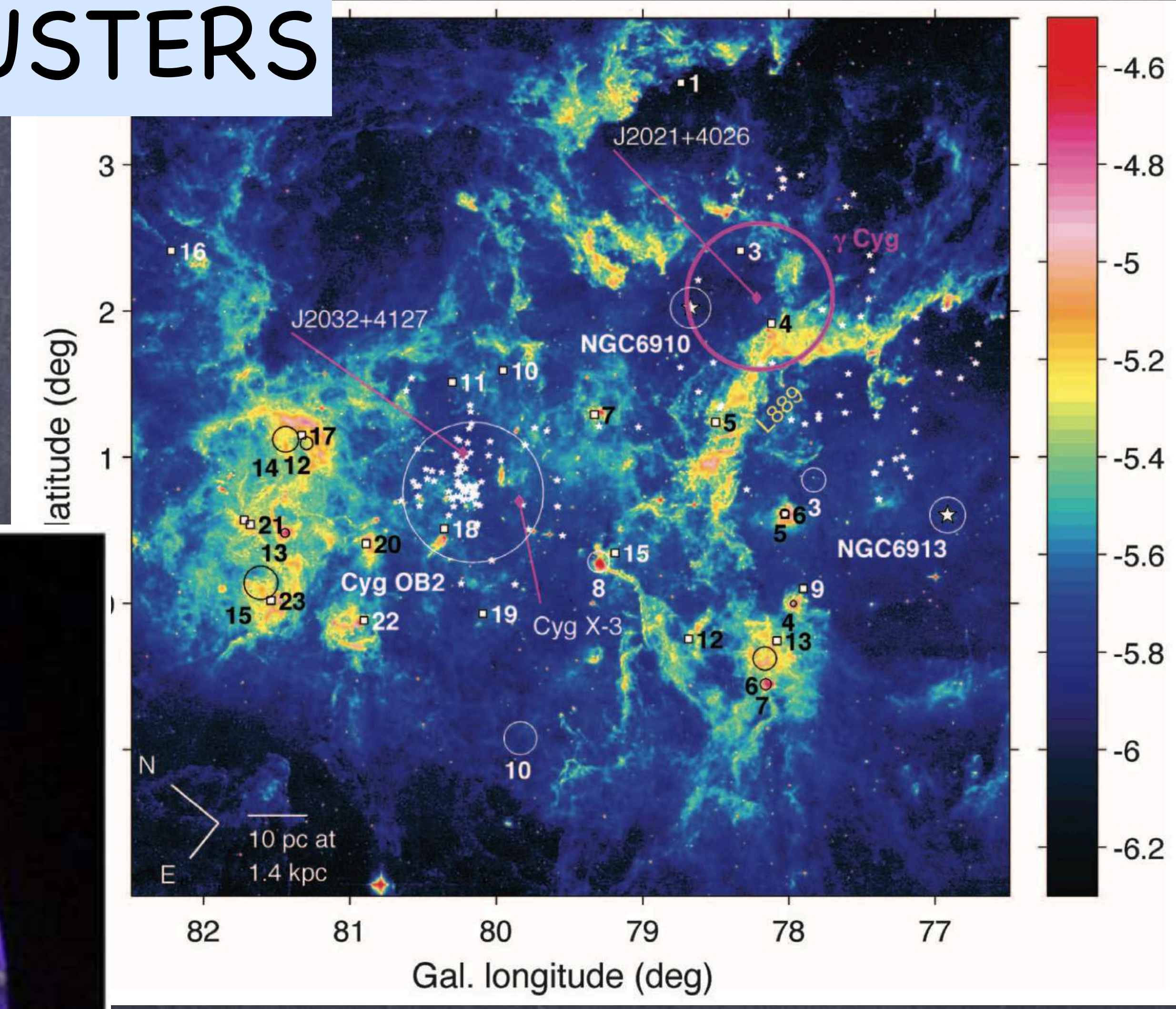
SUN AND STARS

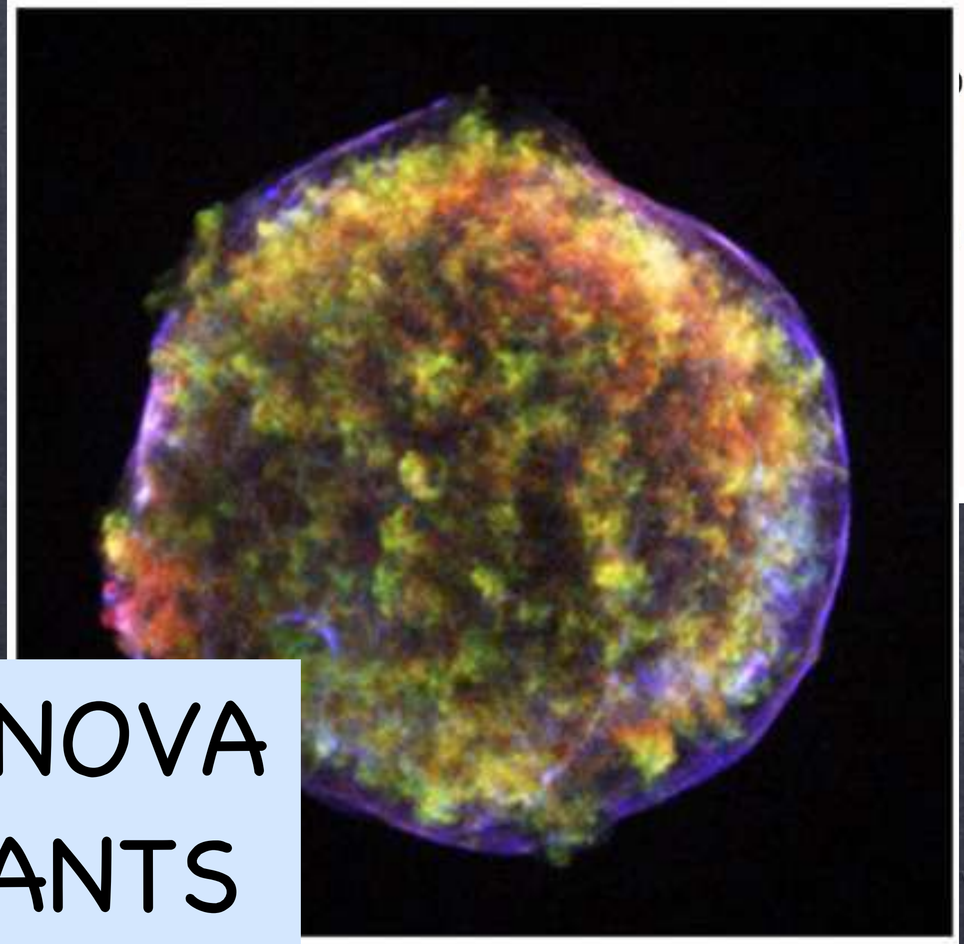
PROTOSTELLAR JETS



NOVAE

STAR CLUSTERS



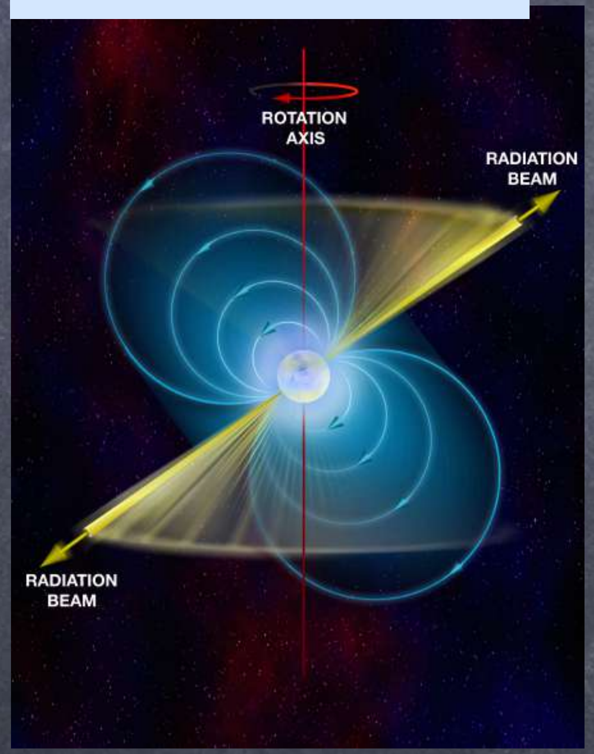


SUPERNOVA REMNANTS

RELATIVISTIC SOURCES

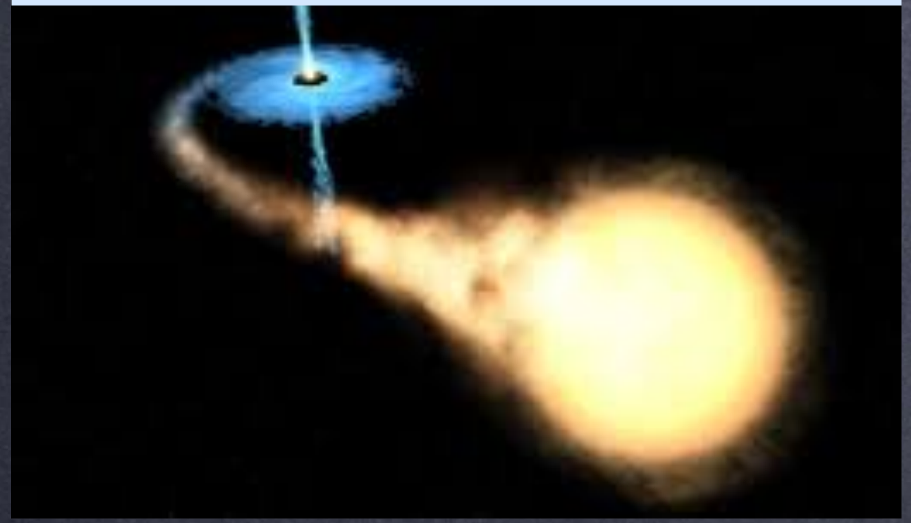
NOVAE

PULSARS

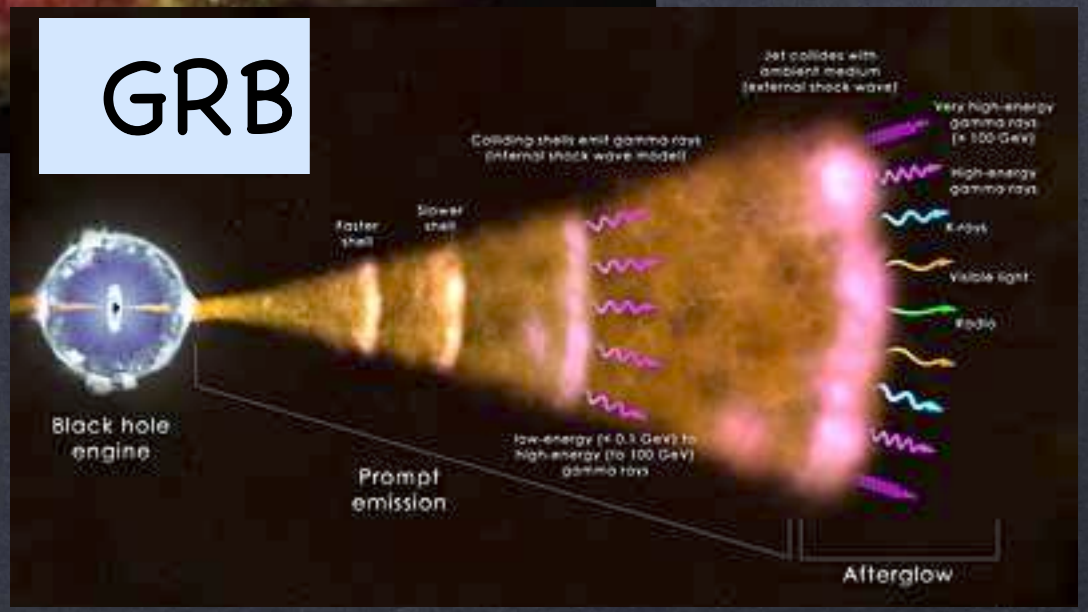


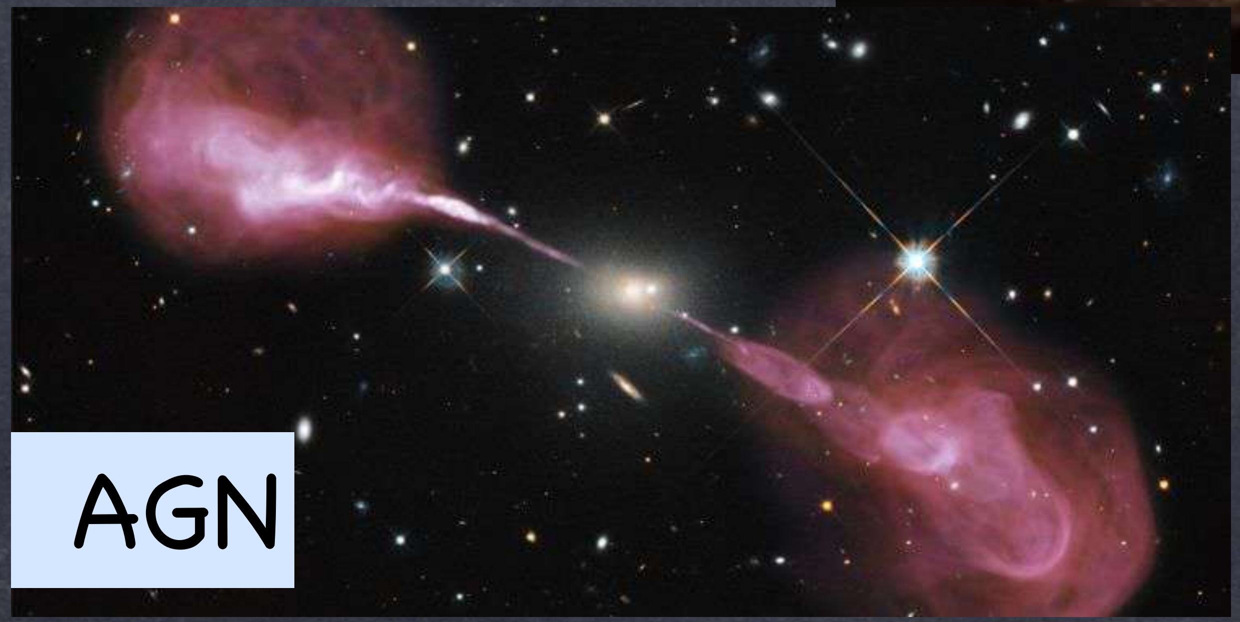
PSR WIND NEBULAE

MICROQUASARS



GRB

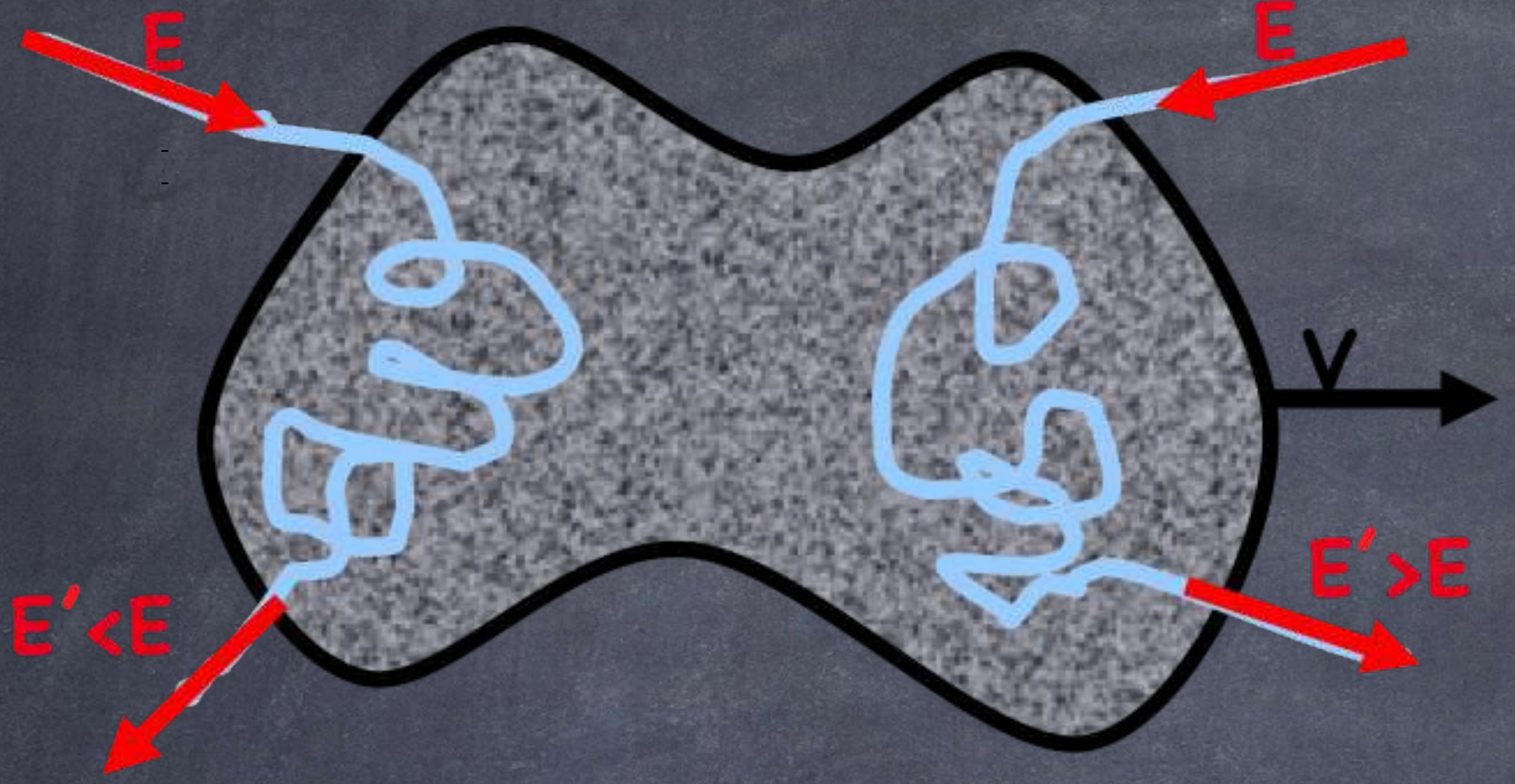




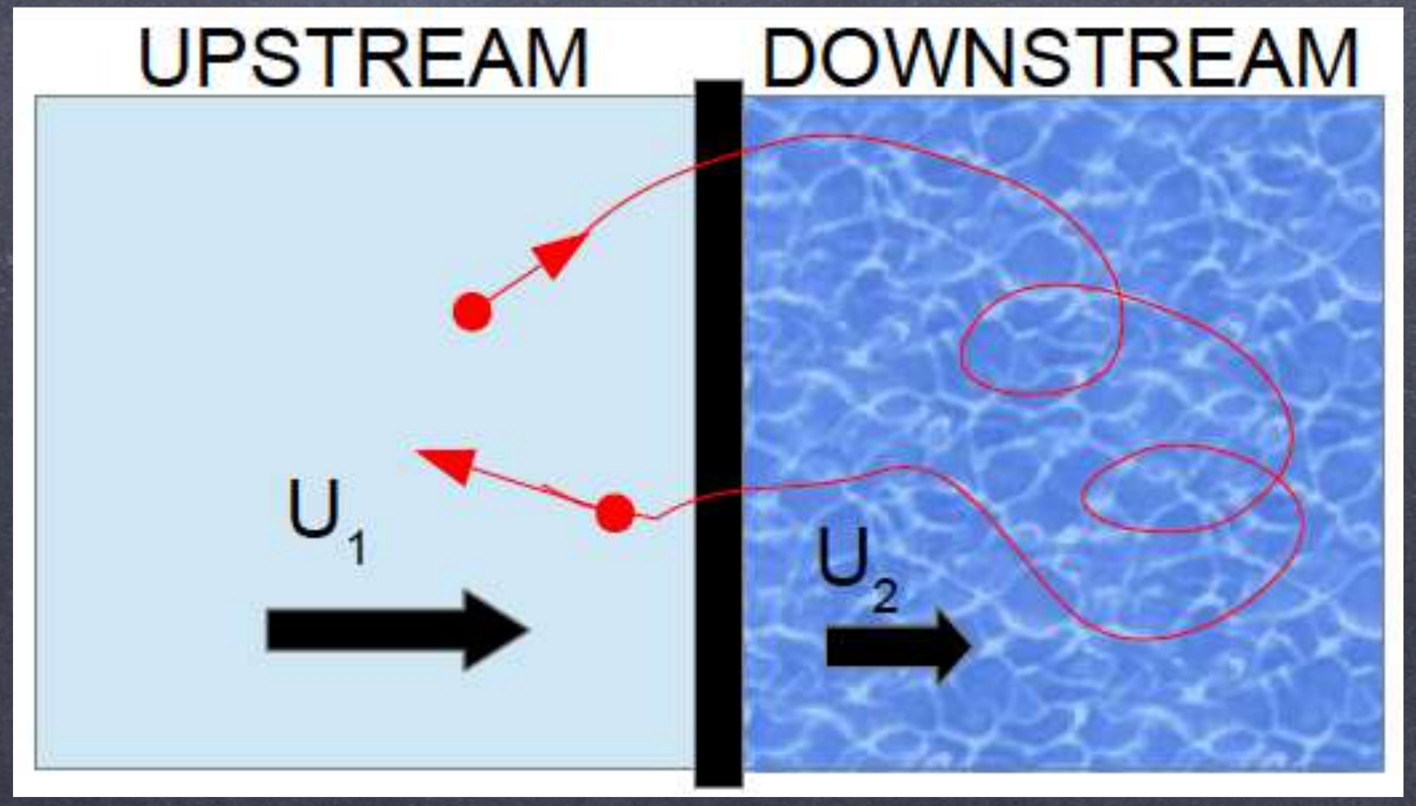
AGN

NON-RELATIVISTIC SOURCES

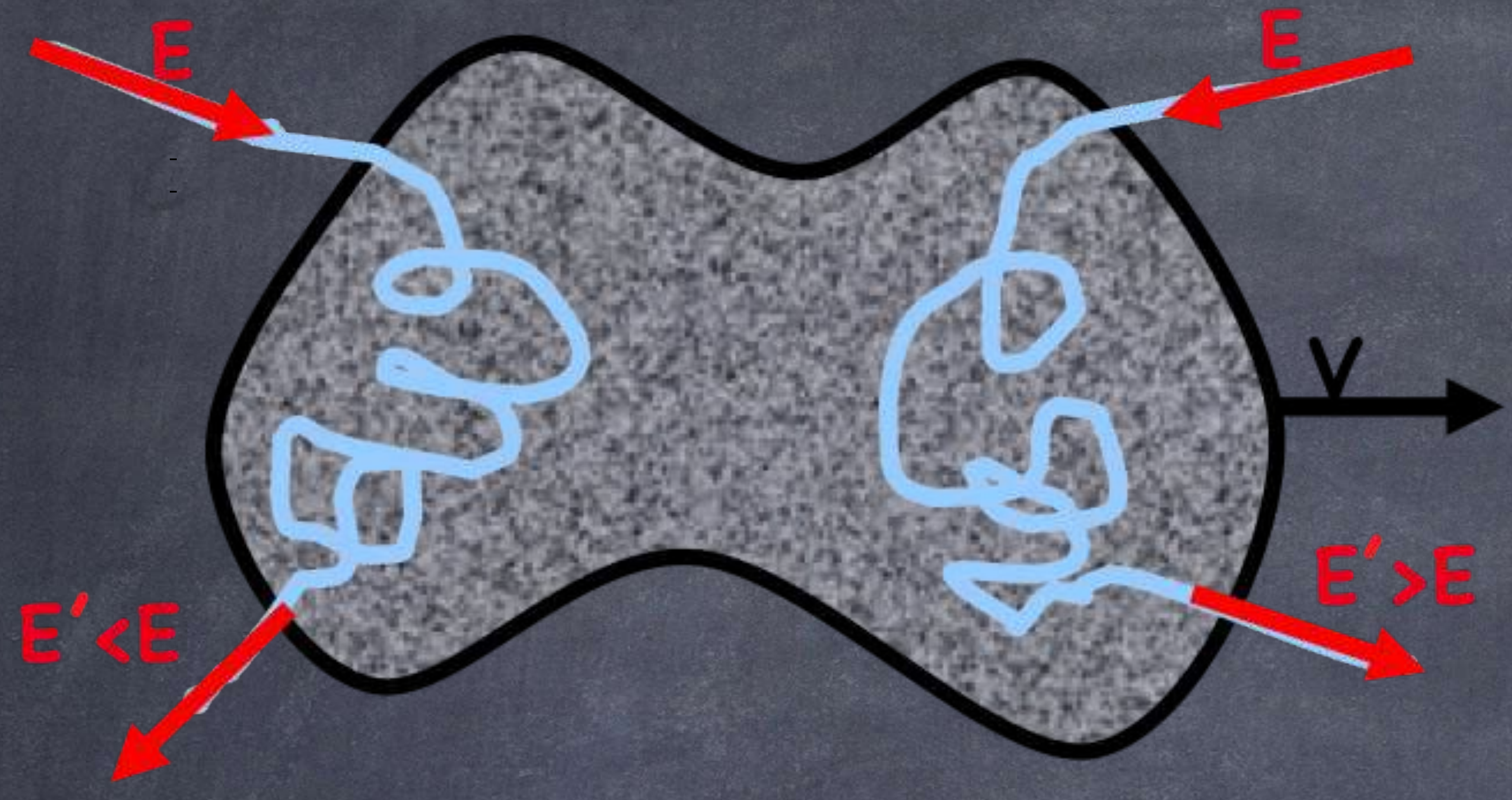
FERMI ACCELERATION MECHANISM



Fermi 1949



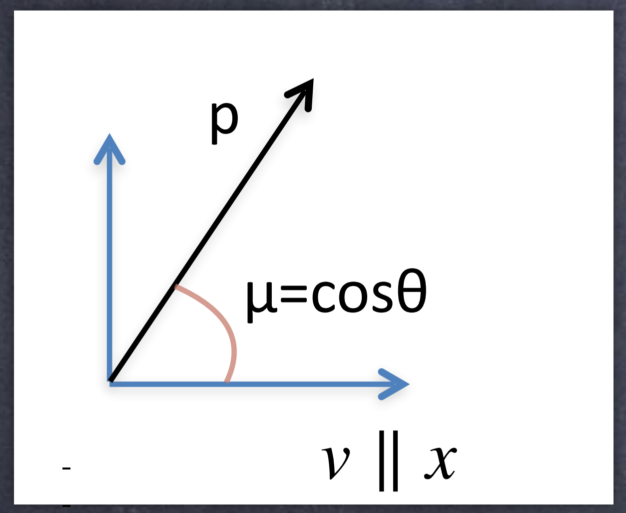
FERMI ACCELERATION MECHANISM



$$E_{ci} = \gamma(E - \beta c p_x) \qquad p_x \approx \frac{E}{c}\mu$$

IN THE CLOUD:
-MULTIPLE SCATTERINGS
-LOSS OF MEMORY OF INITIAL TRAJECTORY

$$E' = \gamma(E_{cf} + \beta c p_{xcf})$$



$$\beta = V/c \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}}$$

$$E_{cf} = E_{ci} \qquad p_{xcf} = \frac{E_{cf}}{c}\mu'$$

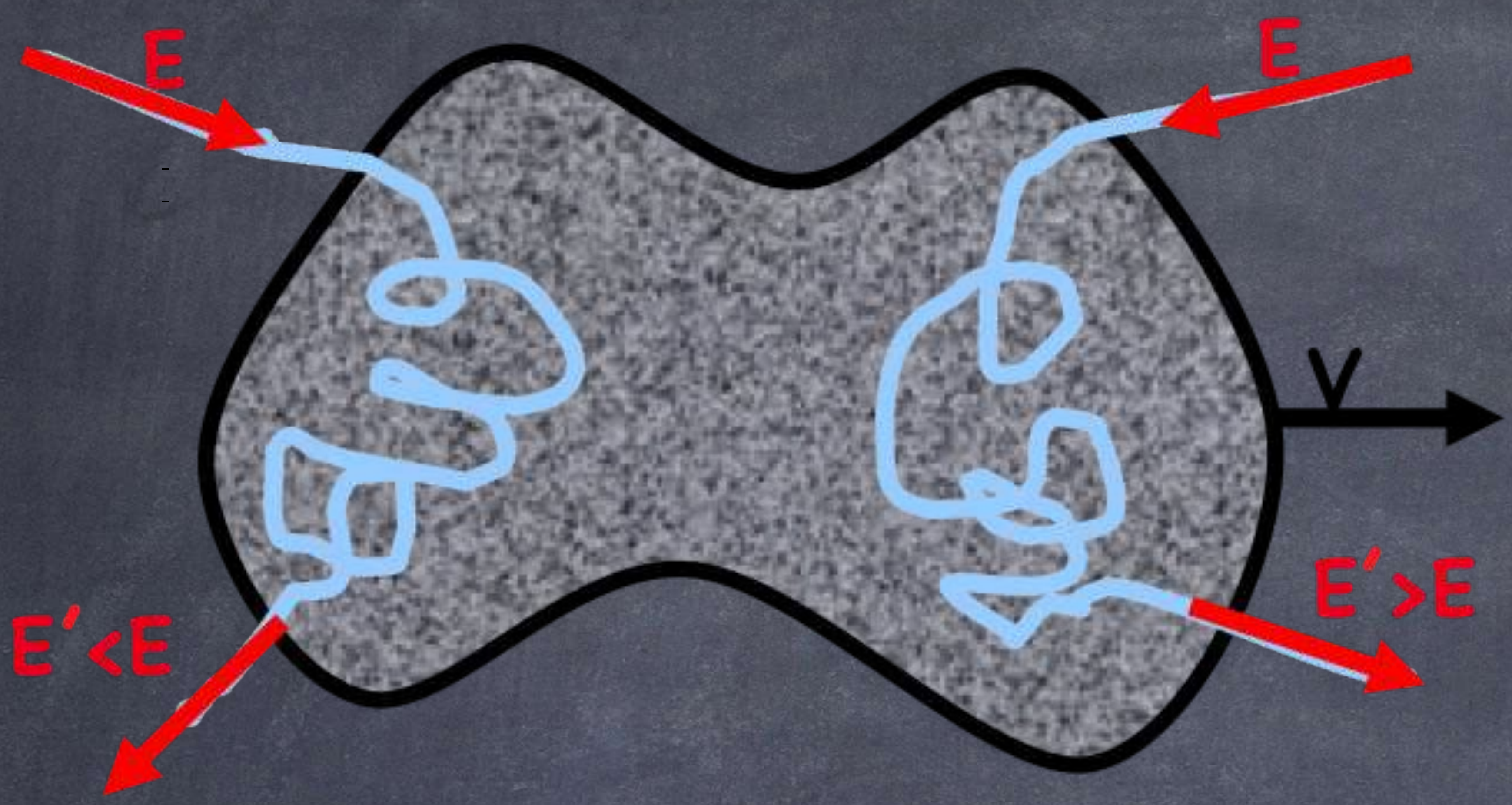
$$E' = \gamma E_{cf}\left(1 + \beta\mu'\right) = \gamma^2 E\left(1 - \beta\mu\right)\left(1 + \beta\mu\right)$$

$$\frac{\Delta E}{E} = \frac{E' - E}{E} = \gamma^2\left[\beta^2\left(1 - \mu\mu'\right) - \beta\left(\mu - \mu'\right)\right]$$

NOTE: IT IS ELECTRIC FIELD THAT DOES THE WORK!!!!

VELOCITY DIFFERENCE BETWEEN REGIONS IN THE PLASMA LEAVES UNSCREENED ELECTRIC FIELD

FERMI ACCELERATION MECHANISM



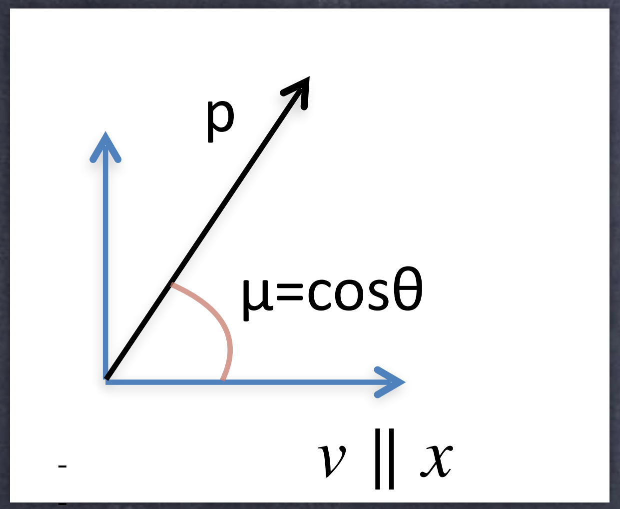
$$\boxed{\frac{\Delta E}{E} = \frac{E' - E}{E} = \gamma^2 \left[\beta^2 \left(1 - \mu\mu'\right) - \beta \left(\mu - \mu'\right)\right]}$$

WHAT HAPPENS ON AVERAGE?

$$\mathscr{P}(\mu) = \propto \mathrm{v}_{\mathrm{rel}} = (\mathrm{v} - V\mu) \qquad \mathscr{P}(\mu') = const$$

$$\int_{-1}^{1} \mathscr{P}(x)dx = 1$$

$$\boxed{\mathscr{P}(\mu) = \frac{(\mathrm{v} - V\mu)}{2\mathrm{v}} \qquad \mathscr{P}(\mu') = \frac{1}{2}}$$



$$\left\langle \frac{\Delta E}{E} \right\rangle = \int_{-1}^{1} d\mu \mathscr{P}(\mu') \int_{-1}^{1} d\mu \mathscr{P}(\mu) \frac{\Delta E}{E}$$

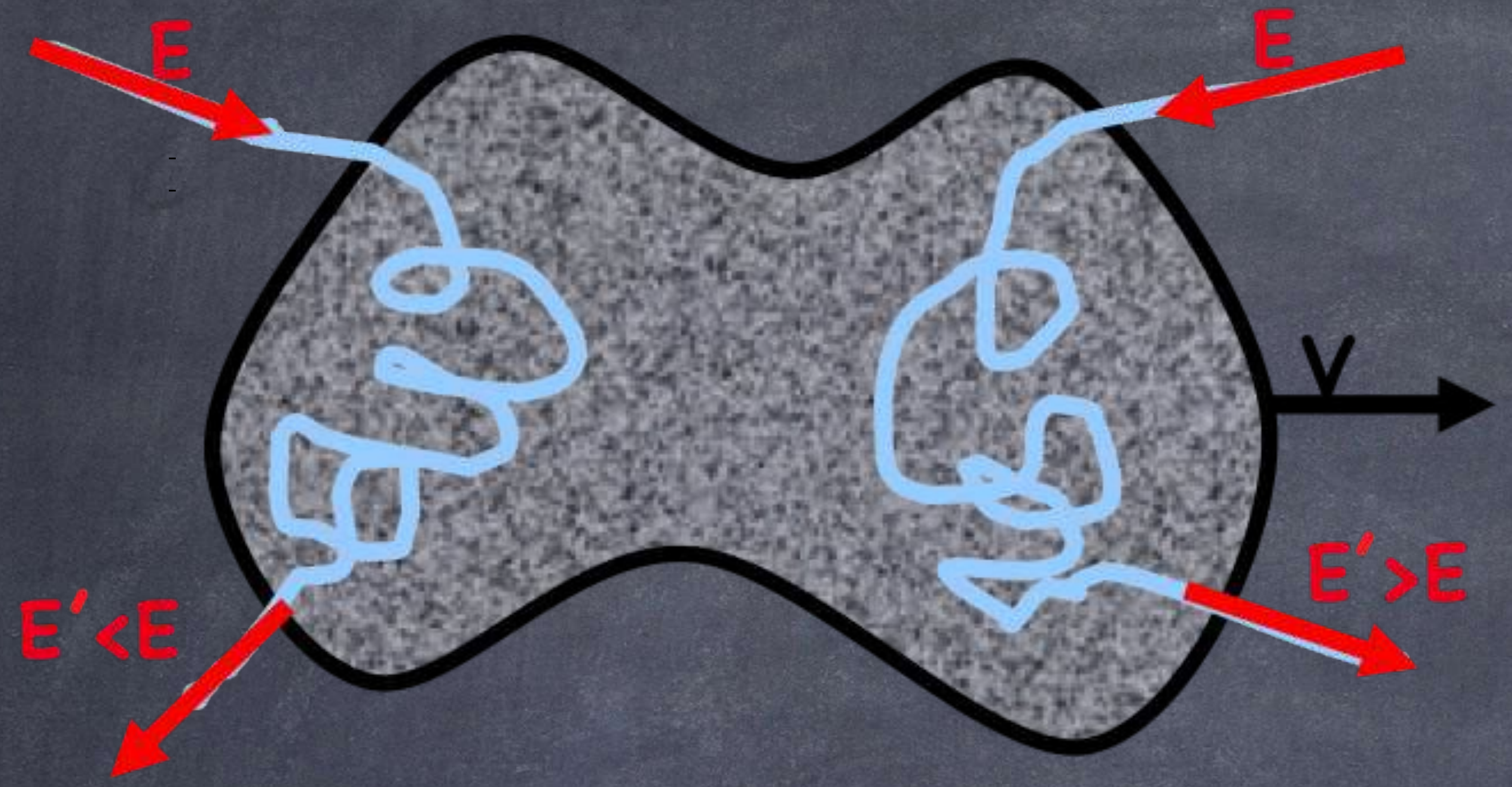
NOTE: IT IS ELECTRIC FIELD THAT DOES THE WORK!!!!

$$\boxed{\left\langle \frac{\Delta E}{E} \right\rangle = \frac{4}{3} \left(\frac{V}{c}\right)^2}$$

VELOCITY DIFFERENCE BETWEEN REGIONS IN THE PLASMA LEAVES UNSCREENED ELECTRIC FIELD

- -ACCELERATION IS SECOND ORDER IN V/c
- -ONLY DUE TO SLIGHTLY LARGER NUMBER OF HEAD-ON COLLISIONS

FERMI ACCELERATION MECHANISM

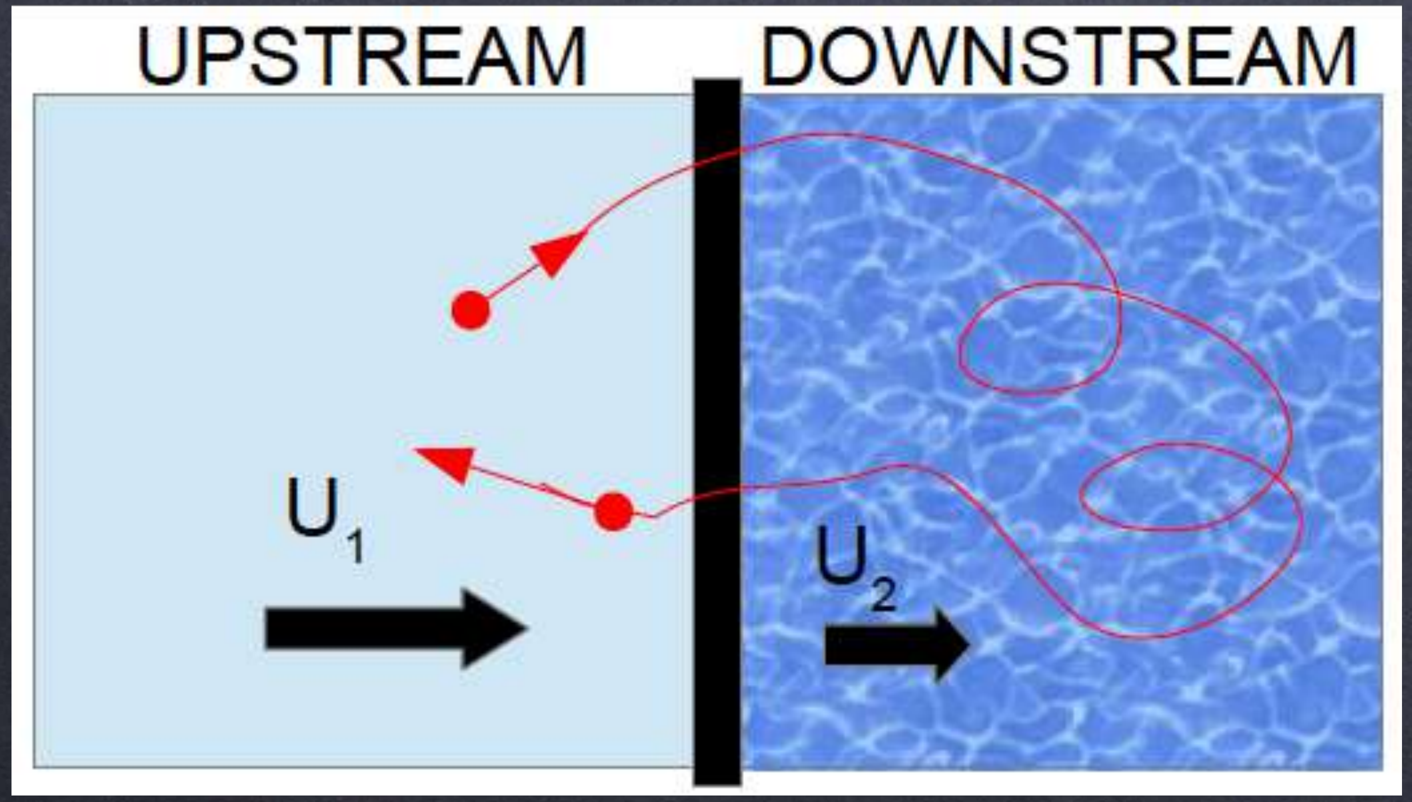


$$\boxed{\left\langle \frac{\Delta E}{E} \right\rangle = \frac{4}{3}\left(\frac{V}{c}\right)^2}$$

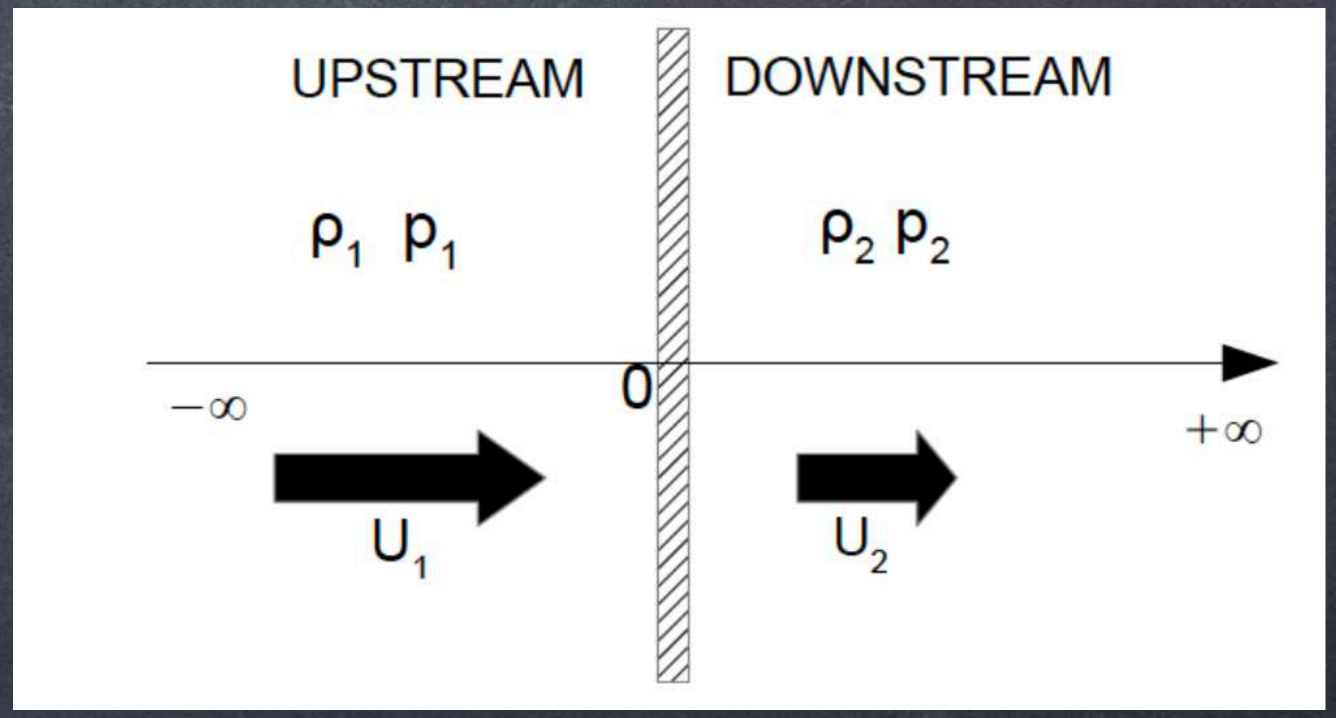
-ACCELERATION IS SECOND ORDER IN V/c

-ONLY DUE TO SLIGHTLY LARGER NUMBER OF HEAD-ON COLLISIONS

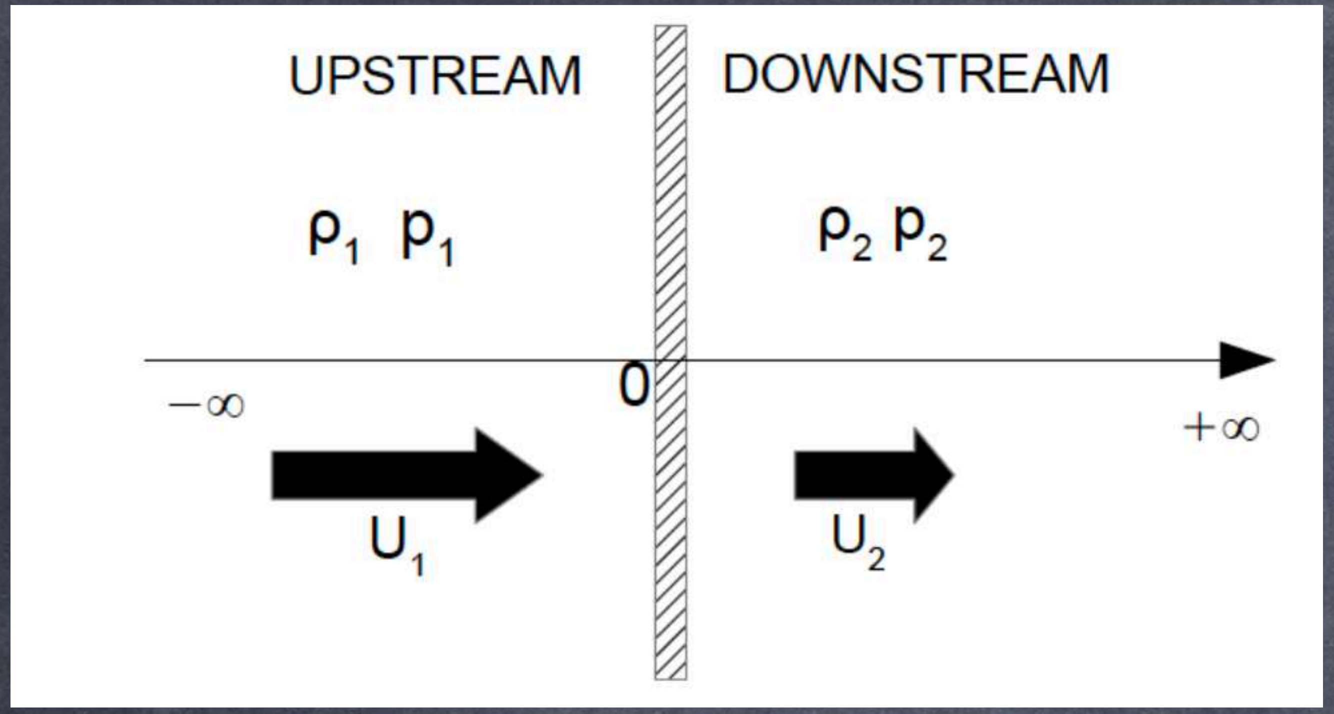
Fermi 1949



-MORE EFFICIENT PROCESS EXPECTED IF COLLISIONS ARE ALL HEAD-ON



FERMI ACCELERATION MECHANISM



HYDRODYNAMIC EQUATIONS

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho U) = 0$$ CONSERVATION OF MASS

$$\frac{\partial}{\partial t}(\rho U) + \frac{\partial}{\partial x}(\rho U^2 + p) = 0$$ CONSERVATION OF MMOMENTUM

$$\frac{\partial}{\partial t}\left(\frac{\rho U^2}{2} + \epsilon\right) + \frac{\partial}{\partial x}\left[\left(p + \epsilon + \frac{\rho U^2}{2}\right)U\right] = 0$$ CONSERVATION OF ENERGY

$$\left[\rho U\right]_{0^-}^{0^+} = 0$$

$$\left[\rho U^2 + p\right]_{0^-}^{0^+} = 0$$

$$\left[\left(p + \epsilon + \frac{\rho U^2}{2}\right)U\right]_{0^-}^{0^+} = 0$$

$\Rightarrow$

$$\rho_2 U_2 = \rho_1 U_1$$

$$\rho_2 U_2^2 + p_2 = \rho_1 U_1^2 + p_1$$

$$\frac{1}{2}\rho_2 U_2^3 + \frac{\Gamma}{\Gamma - 1} p_2 U_2 = \frac{1}{2}\rho_1 U_1^3 + \frac{\Gamma}{\Gamma - 1} p_1 U_1$$

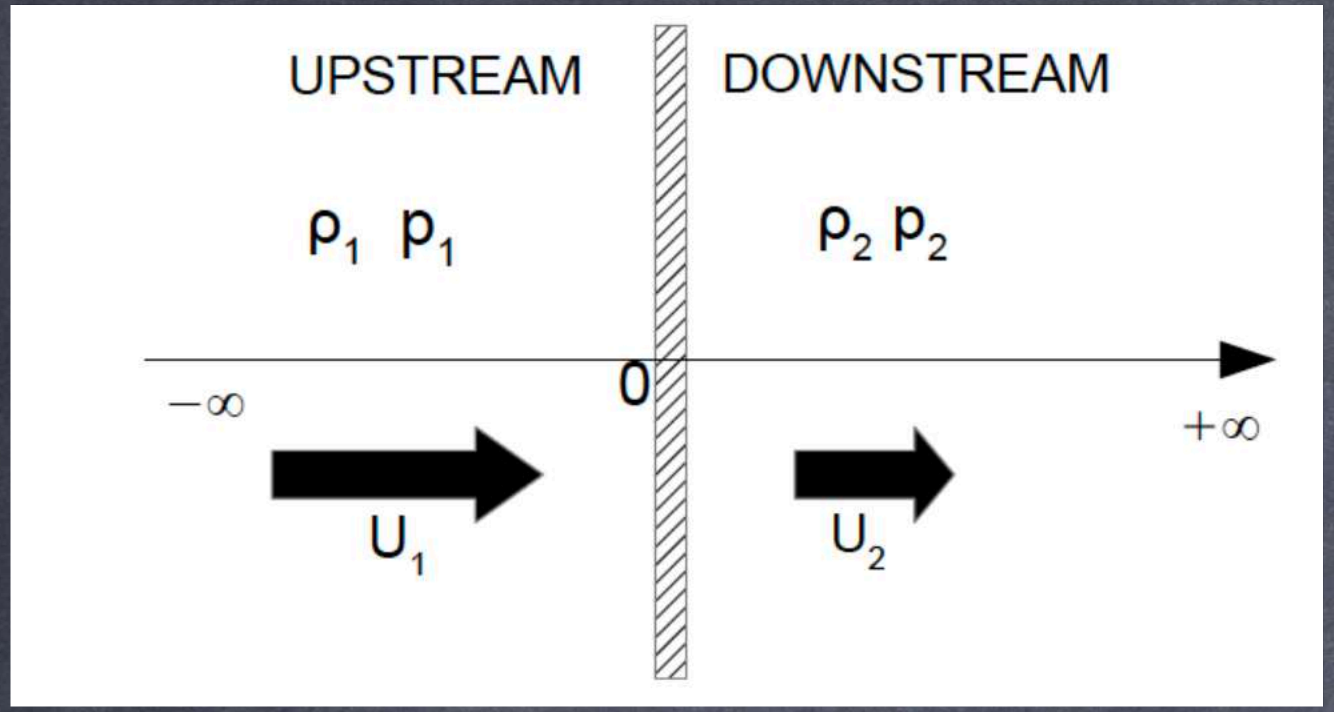
$$\epsilon = \frac{p}{\Gamma - 1}$$

$\Gamma = 5/3$ FOR NON RELATIVISTIC PLASMA

WHERE Γ IS THE ADIABATIC INDEX

$\Gamma = 4/3$ FOR RELATIVISTIC PLASMA

FERMI ACCELERATION MECHANISM



$$\rho_2\, U_2 = \rho_1\, U_1$$

$$\rho_2\, U_2^2 + p_2 = \rho_1\, U_1^2 + p_1$$

$$\frac{1}{2}\rho_2\, U_2^3 + \frac{\Gamma}{\Gamma-1} p_2\, U_2 = \frac{1}{2}\rho_1\, U_1^3 + \frac{\Gamma}{\Gamma-1} p_1\, U_1$$

$$\Rightarrow \quad (R-1)\left[R - \frac{(\Gamma+1)}{\Gamma - 1 + \frac{2}{M_1^2}}\right] = 0$$

$$R = \frac{U_1}{U_2} = \frac{\rho_2}{\rho_1}$$ COMPRESSION RATIO

$$c_s^2 = \Gamma\frac{p}{\rho}$$ SOUND SPEED

$$M_1 = \frac{U_1}{c_{s1}}$$ SONIC MACH NUMBER

SOLUTIONS

$$M_1 \to 1 \quad \Rightarrow \quad R = 1$$

$$M_1 \to \infty \quad \Rightarrow \quad R = \frac{\Gamma+1}{\Gamma-1}$$

$$\frac{\rho_2}{\rho_1} = \frac{U_1}{U_2} = R \qquad \frac{p_2}{\rho_1 U_1^2} = 1 - \frac{1}{R} + \frac{1}{\Gamma M_1^2}$$

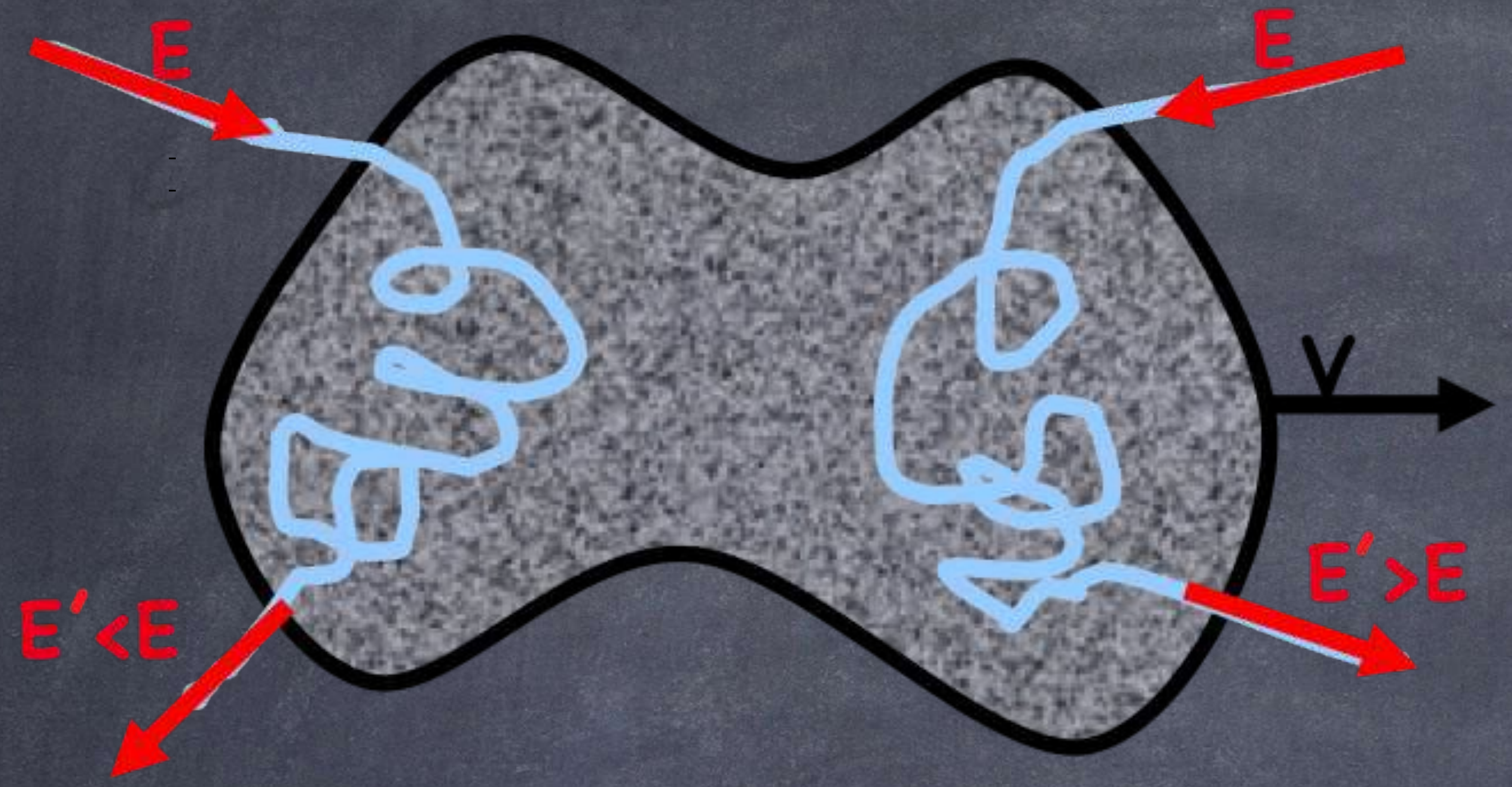
$$\Gamma = 5/3 \quad \Rightarrow$$

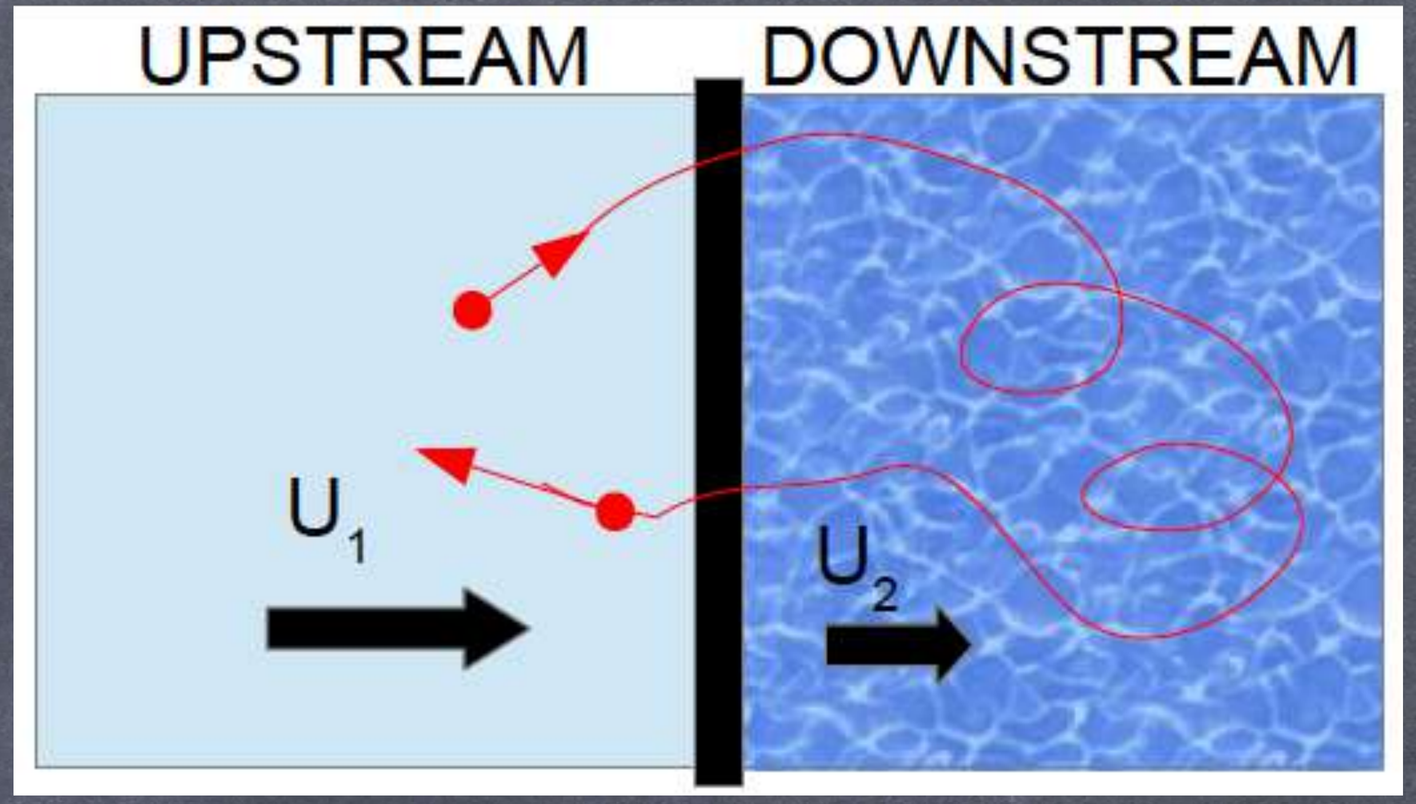
$$\frac{\rho_2}{\rho_1} = \frac{U_1}{U_2} = 4$$

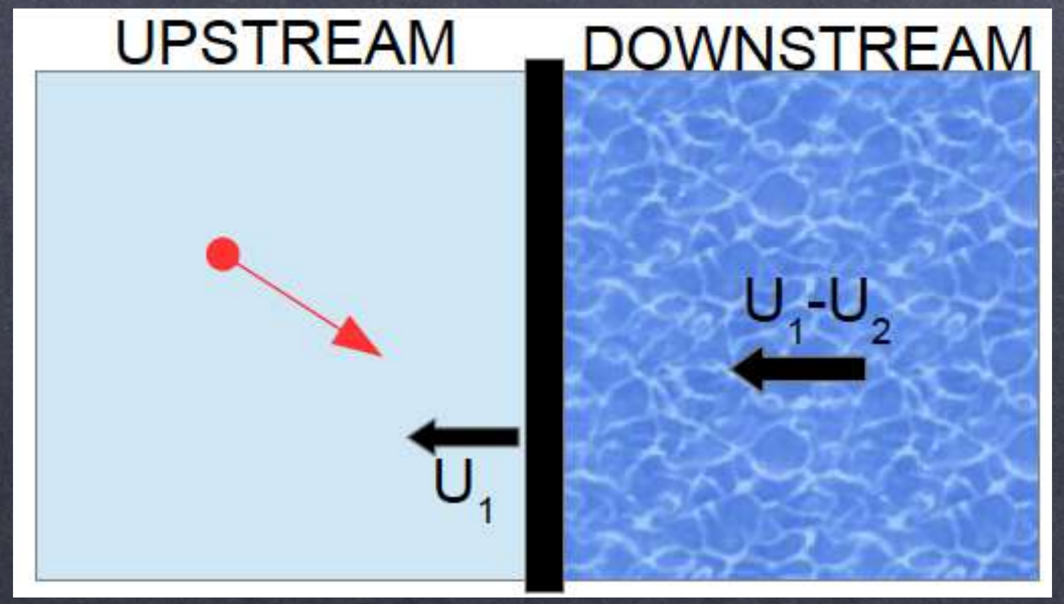
$$\frac{p_2}{\rho_1 U_1^2} = \frac{3}{4}$$

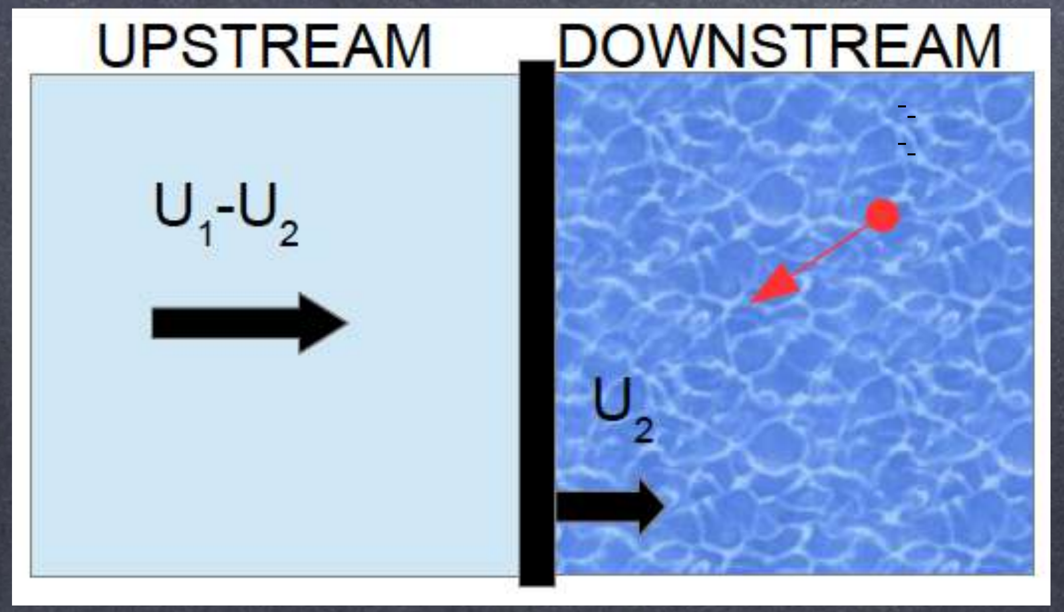
$$\frac{\rho_2 U_2^2}{\rho_1 U_1^2} = \frac{1}{4}$$

FERMI ACCELERATION MECHANISM



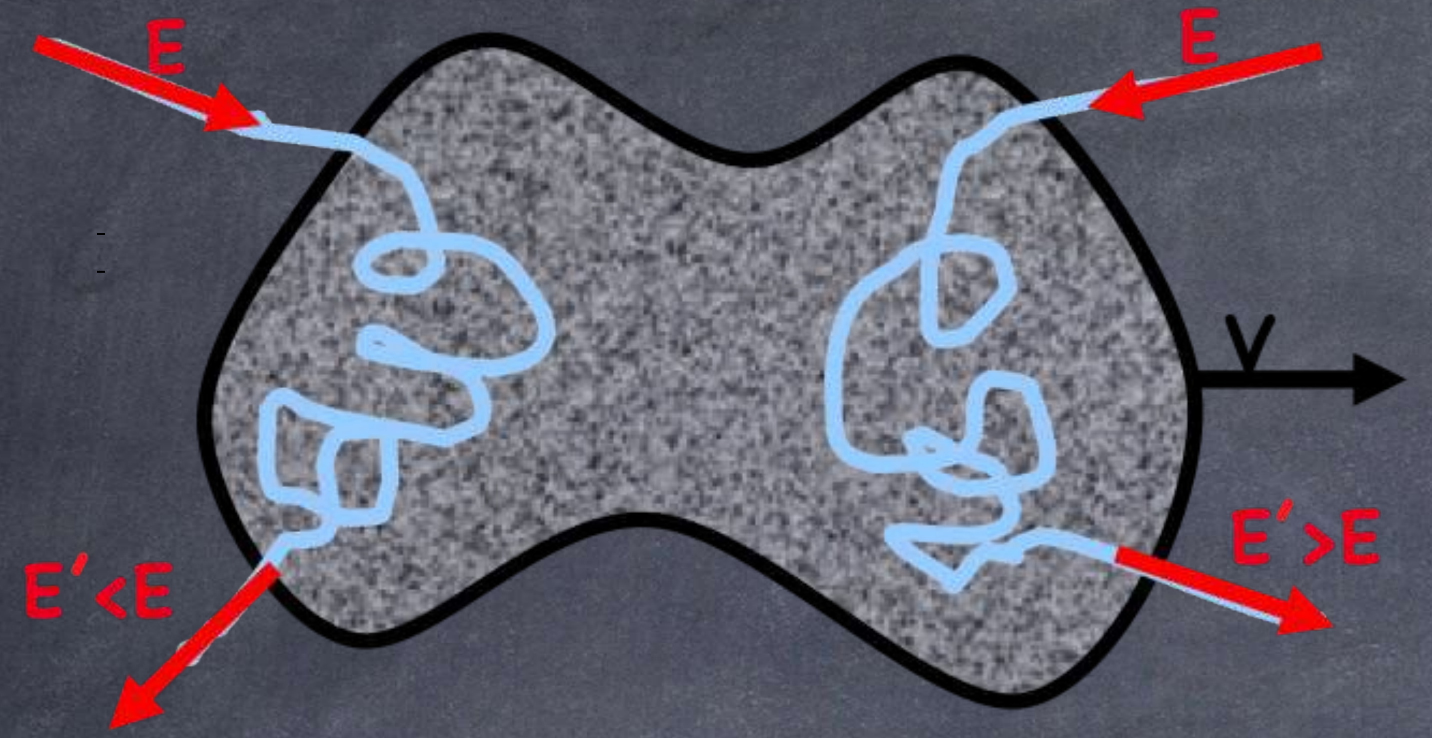






$$V = U_1 - U_2$$

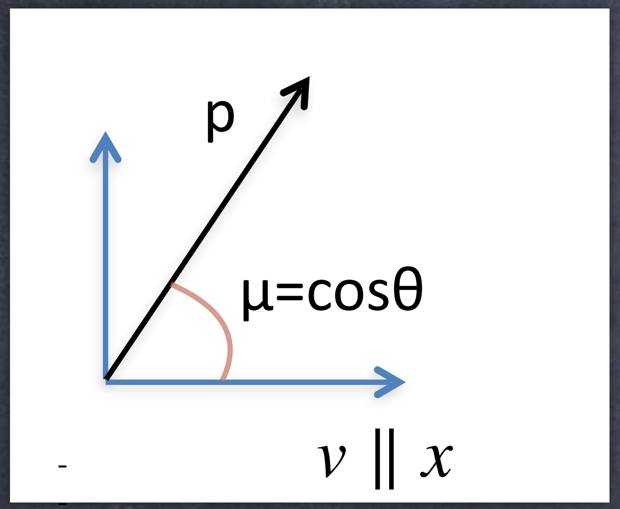
FERMI ACCELERATION MECHANISM



$$\boxed{\frac{\Delta E}{E} = \frac{E' - E}{E} = \gamma^2 \left[\beta^2 \left(1 - \mu\mu'\right) - \beta\left(\mu - \mu'\right)\right]}$$

WHAT HAPPENS ON AVERAGE?

$$\mathscr{P}(\mu) = \propto \mu \quad (0 < \mu < 1) \qquad \mathscr{P}(\mu') \propto \mu' \quad (-1 < \mu' < 0)$$

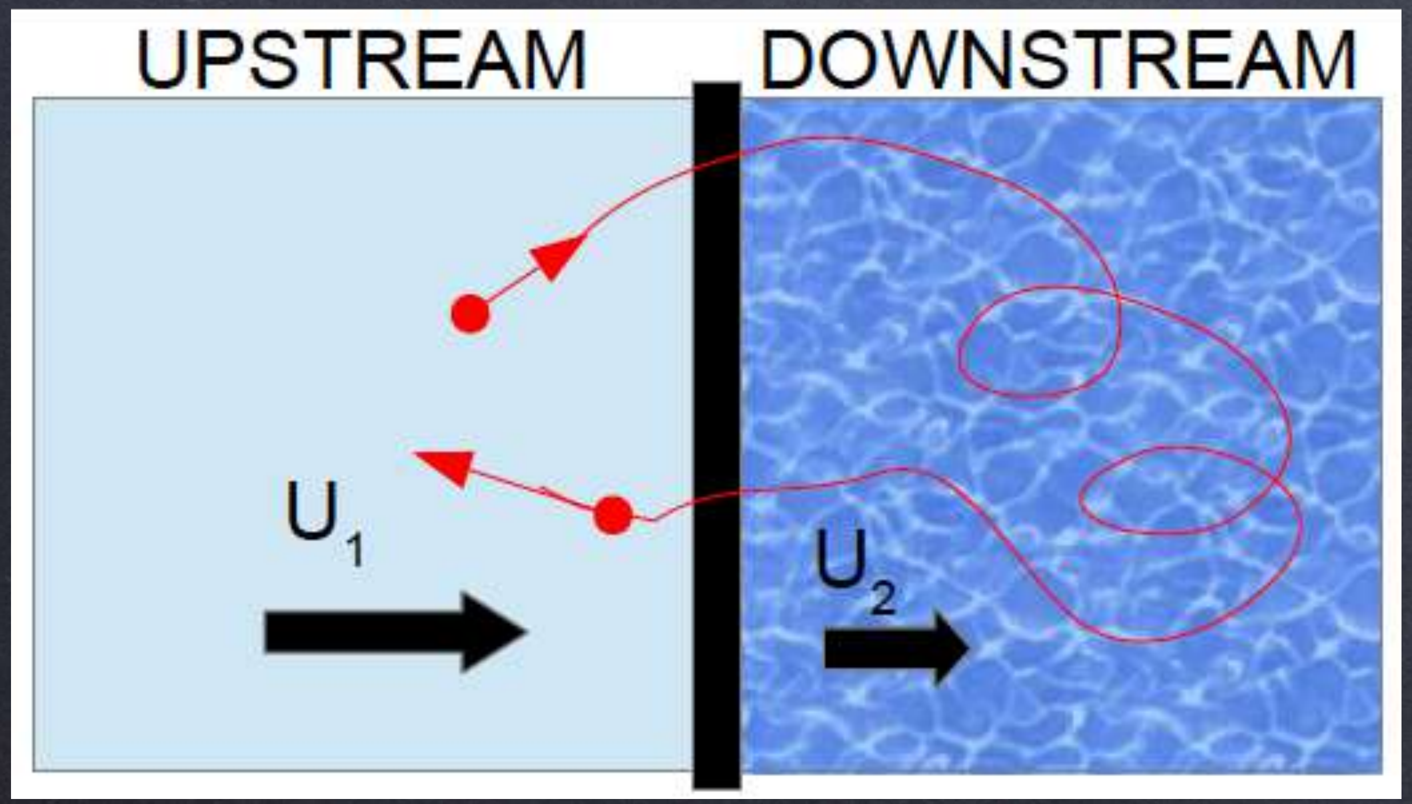


$$\int_{-1}^{1} \mathscr{P}(x)dx = 1$$

$$\mathscr{P}(\mu) = 2\mu$$

$$\mathscr{P}(\mu') = 2\mu'$$

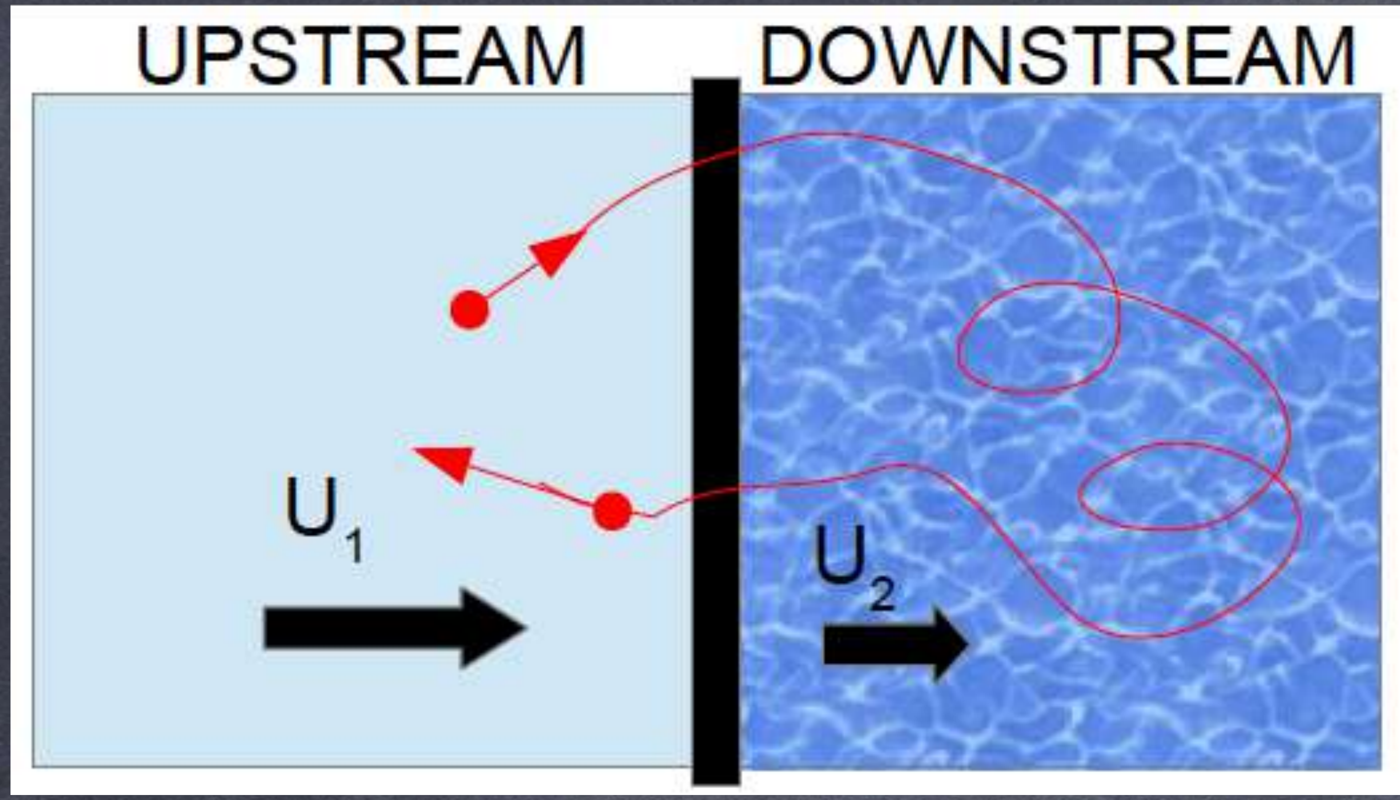
$$\left\langle \frac{\Delta E}{E} \right\rangle = \int_{-1}^{1} d\mu \mathscr{P}(\mu') \int_{-1}^{1} d\mu \mathscr{P}(\mu) \frac{\Delta E}{E}$$



$$\boxed{\left\langle \frac{\Delta E}{E} \right\rangle = \frac{4}{3}\left(\frac{V}{c}\right) - \frac{13}{9}\left(\frac{V}{c}\right)^2}$$

$$V = U_1 - U_2$$

PARTICLE SPECTRUM



PARTICLE ENERGY AFTER k CROSSINGS $\quad E_{k+1} = (1+\xi)E_k \quad \xi = \frac{4}{3}\frac{U_1 - U_2}{c}$

NUMBER OF PARTICLES AFTER k CROSSINGS $\quad N_{k+1} = N_k\, \mathscr{P}_{ret}$

FOR INFINITE PLANAR SHOCK, ALL PARTICLES RETURN FROM UPSTREAM

FOCUS ON DOWNSTREAM: PARTICLES ARE ISOTROPIC $\quad \frac{\partial f_0}{\partial \mu} = 0 \qquad$ RETURNING PARTICLES IF $\mathrm{v}\mu + U_2 < 0$

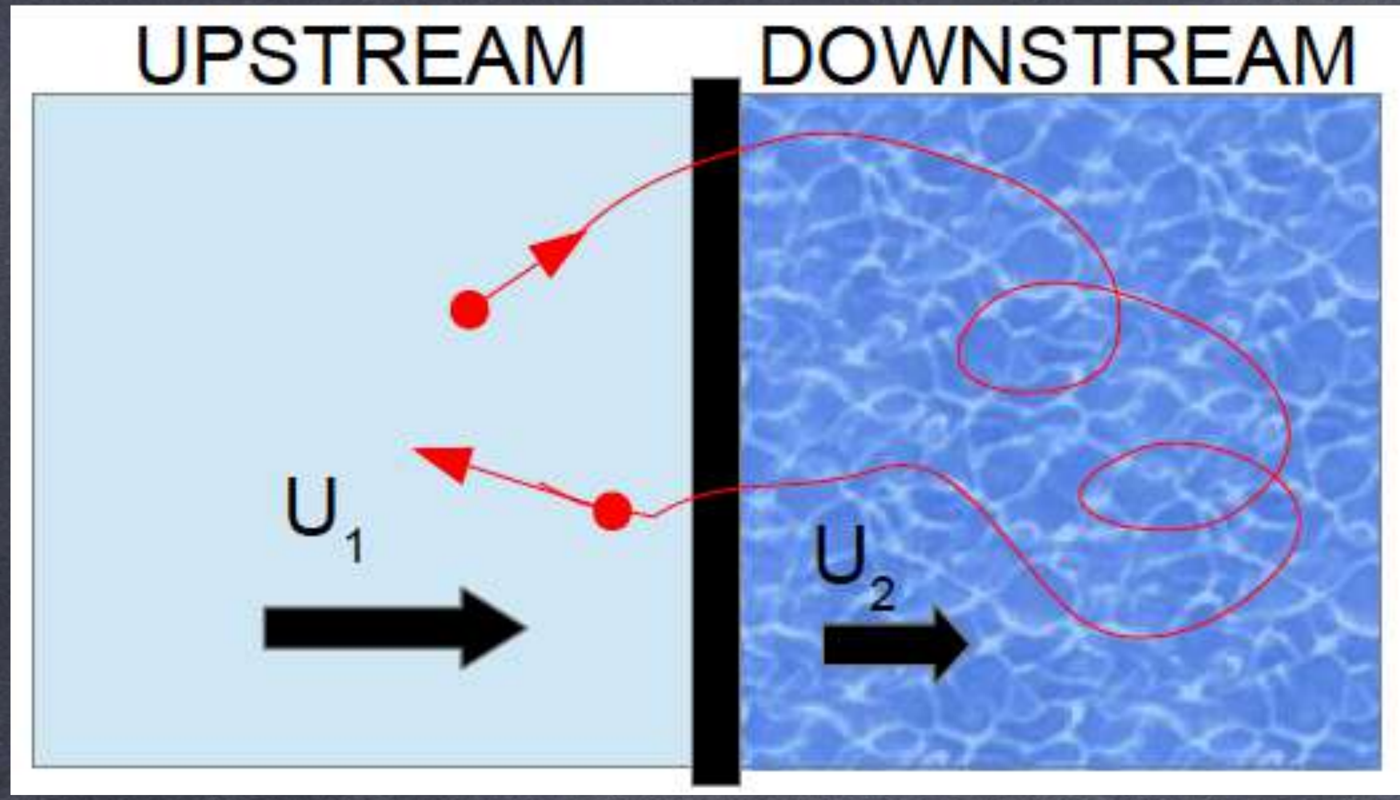
FLUX OF RETURNING PARTICLES

$$\Phi_{\leftarrow} = \int_{-1}^{-U_2/\mathrm{v}} d\mu\, f_0\,(U_2 + \mathrm{v}\mu) = f_0 \frac{(U_2 - \mathrm{v})^2}{2\mathrm{v}}\,.$$

FLUX OF ESCAPING PARTICLES

$$\Phi_{\rightarrow} = \int_{-U_2/\mathrm{v}}^{1} d\mu\, f_0\,(U_2 + \mathrm{v}\mu) = f_0 \frac{(\mathrm{v} + U_2)^2}{2\mathrm{v}}$$

PARTICLE SPECTRUM



PARTICLE ENERGY AFTER k CROSSINGS $E_{k+1} = (1+\xi)E_k \quad \xi = \frac{4}{3}\frac{U_1 - U_2}{c}$

NUMBER OF PARTICLES AFTER k CROSSINGS $N_{k+1} = N_k \, \mathscr{P}_{ret}$

FLUX OF ESCAPING PARTICLES $\Phi_{\rightarrow} = f_0 \frac{(\mathrm{v} + U_2)^2}{2\mathrm{v}}$

FLUX OF RETURNING PARTICLES $\Phi_{\leftarrow} = f_0 \frac{(U_2 - \mathrm{v})^2}{2\mathrm{v}}.$

RETURN PROBABILITY $\mathscr{P}_{ret} = \frac{\Phi_{\leftarrow}}{\Phi_{\rightarrow}} = \frac{(\mathrm{v} - U_2)^2}{(\mathrm{v} + U_2)^2} \approx (1 - 4U_2/\mathrm{v})$

$$N_k = N_0 \, \mathscr{P}_{ret}^{\,k}$$

$$E_k = (1+\xi)^k \, E_0$$

$$\ln\left(\frac{N_k}{N_0}\right) = k \ln P_{ret}$$

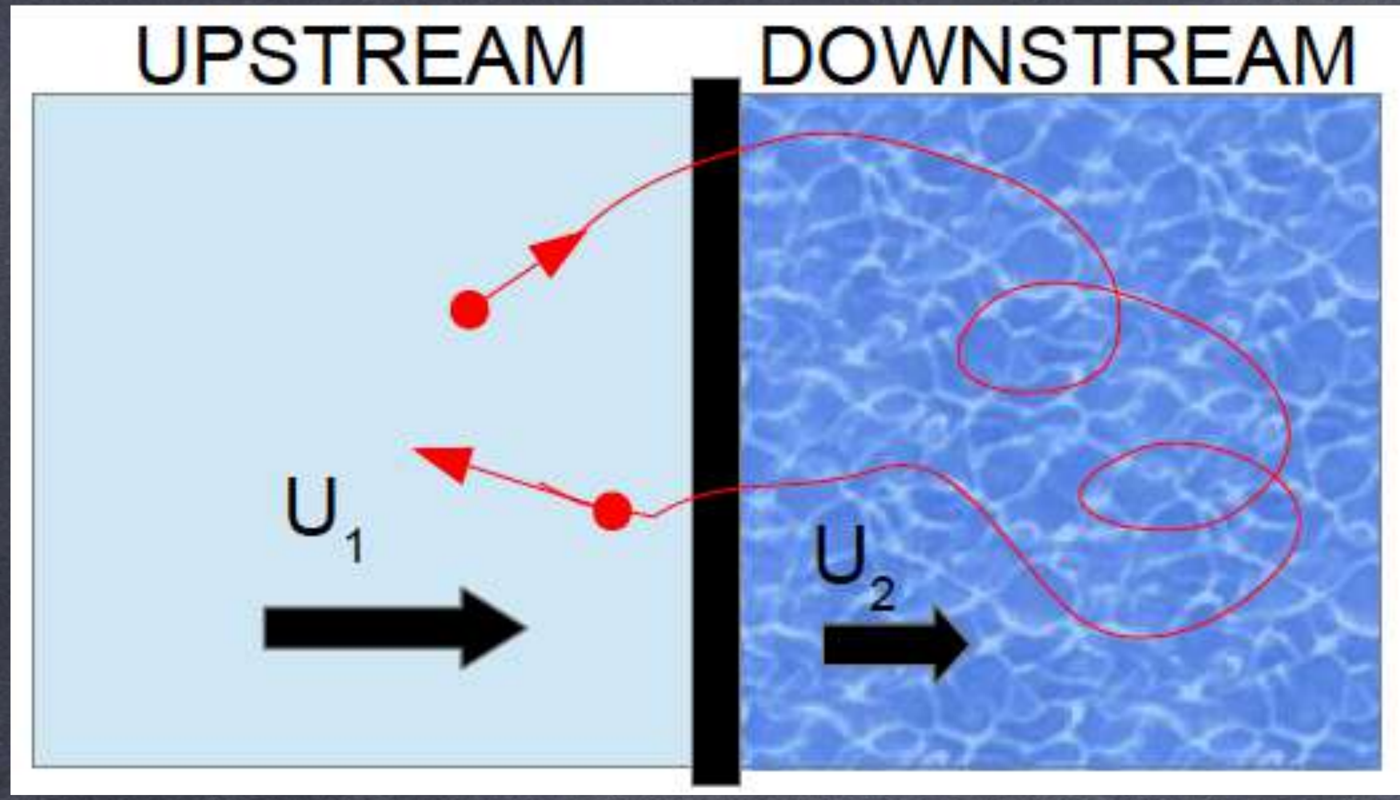
$$\ln\left(\frac{E_k}{E_0}\right) = k \ln(1+\xi)$$

$$\ln\left(\frac{N_k}{N_0}\right) = \frac{\ln \mathscr{P}_{ret}}{\ln(1+\xi)} \ln\left(\frac{E_k}{E_0}\right)$$

$$N_k = N_0 \left(\frac{E_k}{E_0}\right)^{-\gamma_1}$$

$$\gamma_1 = -\frac{\ln P_{ret}}{\ln(1+\xi)}$$

PARTICLE SPECTRUM



PARTICLE ENERGY AFTER k CROSSINGS $E_k = (1+\xi)^k E_0$ $\quad \xi = \frac{4}{3}\frac{U_1 - U_2}{c}$

NUMBER OF PARTICLES AFTER k CROSSINGS $N_k = N_0\, \mathscr{P}_{ret}^{\,k}$ $\quad \mathscr{P}_{ret} = 1 - \frac{4U_2}{c}$

$$N_k = N_0 \left(\frac{E_k}{E_0}\right)^{-\gamma_1}$$

$$\gamma_1 = -\frac{\ln \mathscr{P}_{ret}}{\ln(1+\xi)}$$

$$\gamma_1 = -\frac{\ln \mathscr{P}_{ret}}{\ln(1+\xi)} = -\frac{\ln(1 - 4U_2/c)}{\ln(1 + (4/3)(U_1 - U_2)/c)} \approx \frac{4U_2/c}{(4/3)(U_1 - U_2)/c}$$

RECALLING $\frac{U_1}{U_2} = R \Rightarrow \gamma_1 = \frac{3}{R-1}$

$$\frac{dN}{dE} \propto E^{-\gamma_E} \qquad \gamma_E = \gamma_1 + 1 = \frac{R+2}{R-1}$$

$M_1 \to \infty \Rightarrow R \to 4 \Rightarrow \gamma_E \to 2$

TRANSPORT EQUATION APPROACH

PARTICLE DISTRIBUTION FUNCTION IN 6-DIM SPACE $f(\vec{x}, \vec{p}, t)$

- ASSUME ELASTIC SCATTERING
- ASSUME PROBABILITY OF CHANGE IN MOMENTUM INDEPENDENT OF PARTICLE HISTORY

ADVECTION

INJECTION

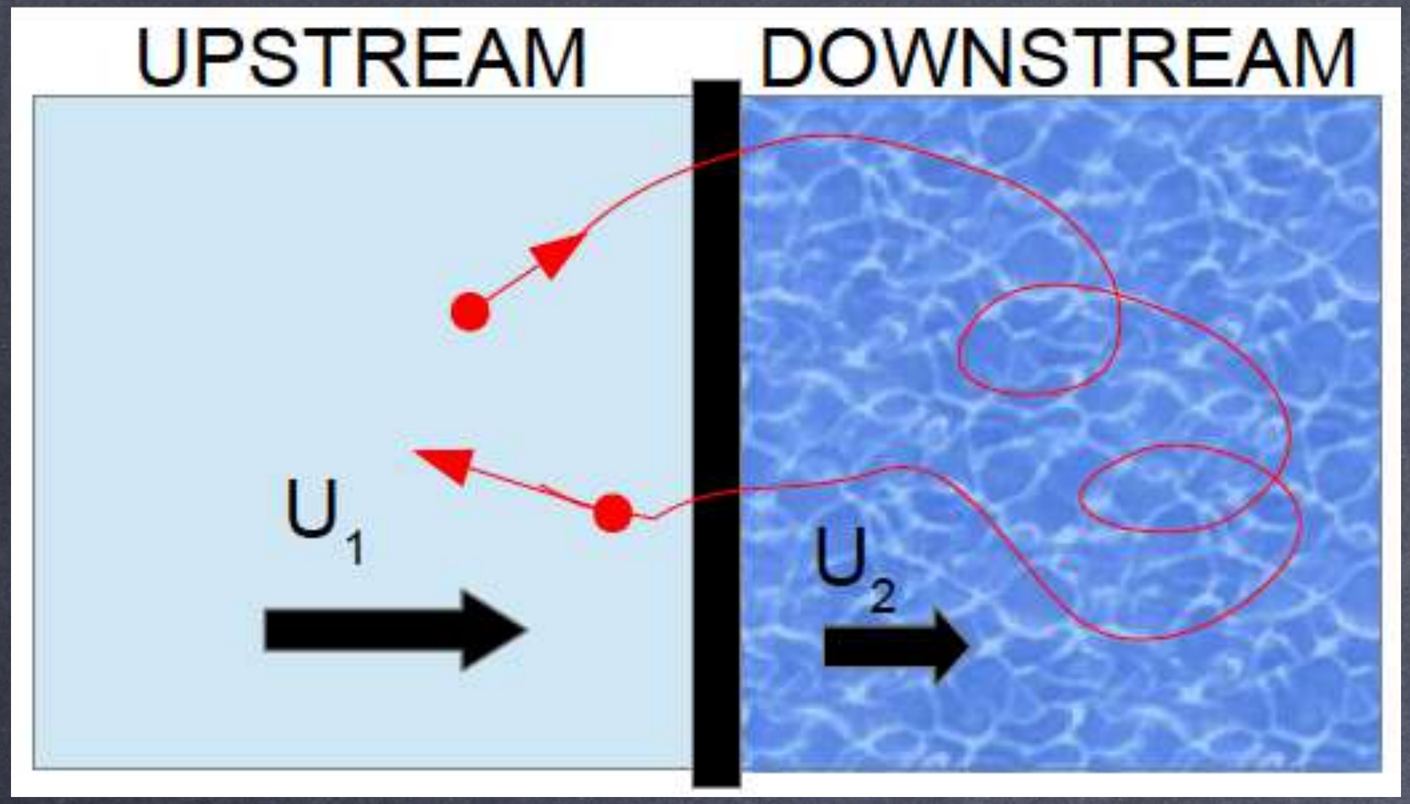
$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial z}\left[D\frac{\partial f}{\partial z}\right] - u\frac{\partial f}{\partial z} + \frac{1}{3}\frac{du}{dz}p\frac{\partial f}{\partial p} + Q(z, p, t),$$

DIFFUSION

ADIABATIC COMPRESSION

- VALID FOR NON-RELATIVISTIC BULK MOTION
- NEARLY ISOTROPIC f
- NEGLECT OF ANGLE TRANSFORMATION (SECOND ORDER ACCELERATION)

TRANSPORT EQUATION APPROACH



$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial z}\left[D\frac{\partial f}{\partial z}\right] - u\frac{\partial f}{\partial z} + \frac{1}{3}\frac{du}{dz}p\frac{\partial f}{\partial p} + Q(z,p,t),$$

STATIONARITY

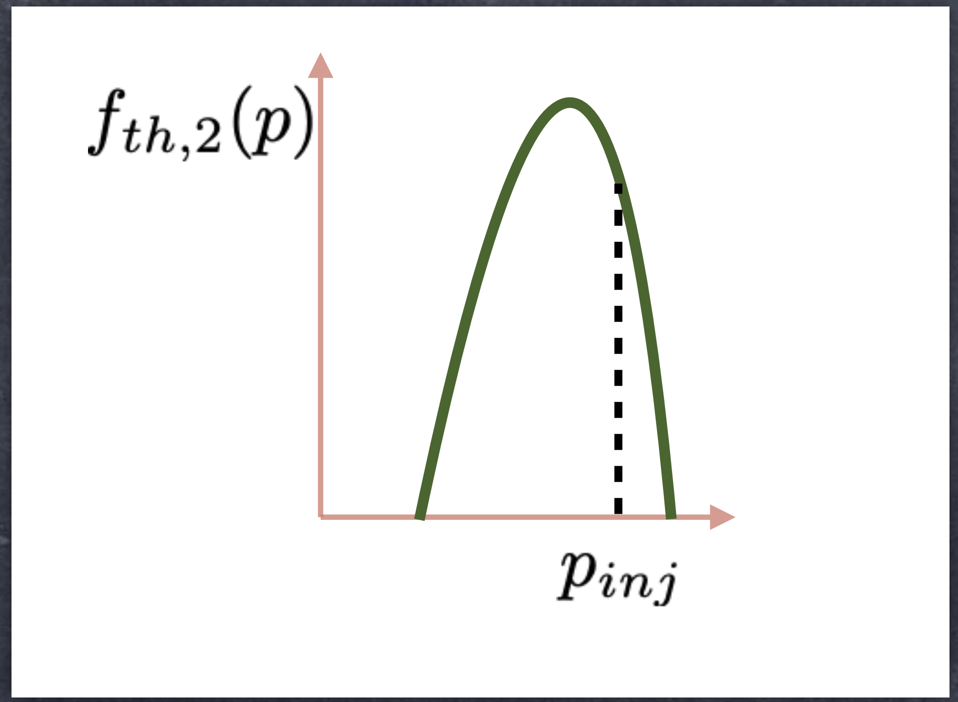
$$\frac{\partial}{\partial z}\left[D\frac{\partial f}{\partial z}\right] - u\frac{\partial f}{\partial z} + \frac{1}{3}\frac{du}{dz}p\frac{\partial f}{\partial p} + Q(z,p,t) = 0$$

INJECTION ONLY AT SHOCK

$f(z=0) = f_0$ CONTINUOUS ACROSS SHOCK

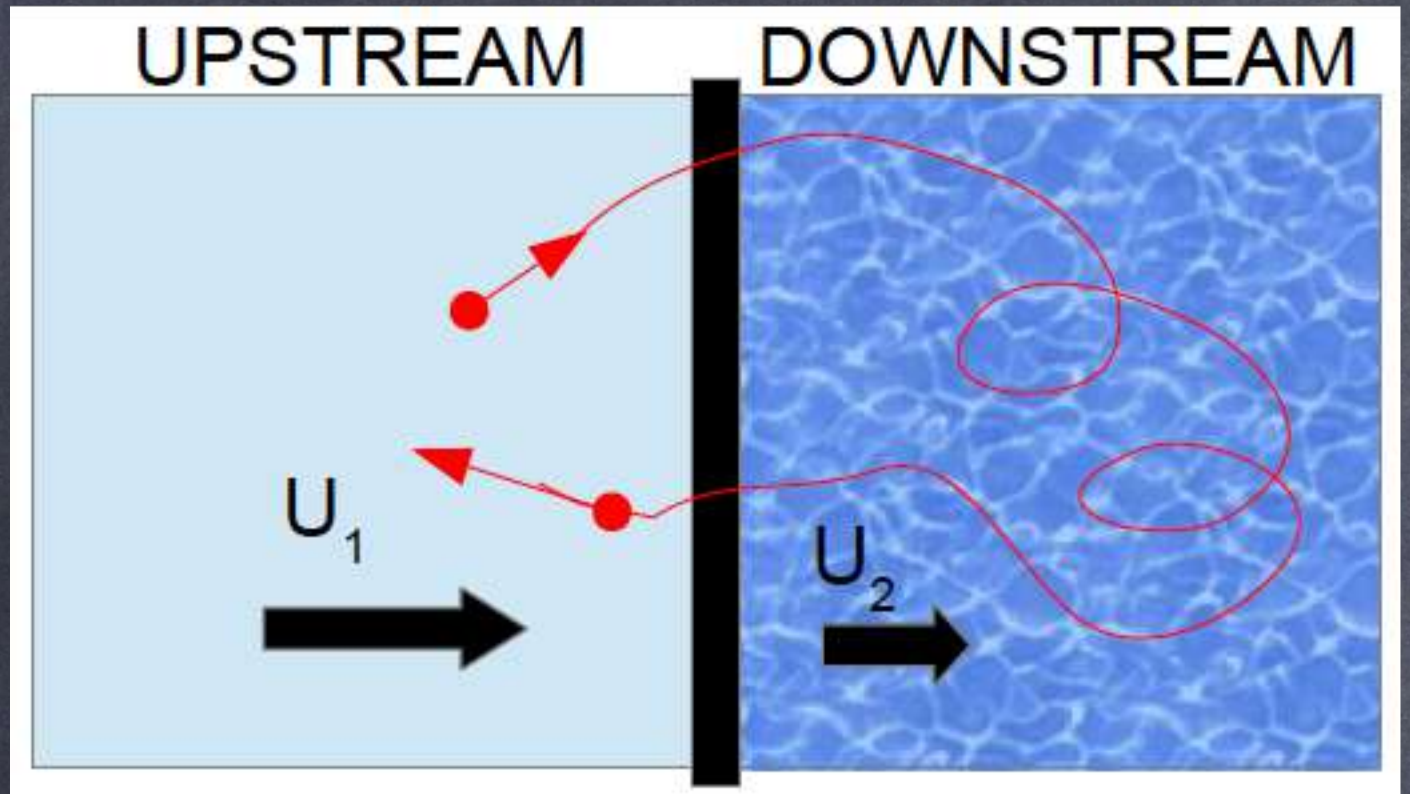
$$Q(z,p,t) = Q_0(p)\delta(z)$$

$$Q_0(p) = \frac{\eta U_1 n_1}{4\pi p_{inj}^2}\delta(p - p_{inj})$$



INJECTION....

UPSTREAM SOLUTION



$$\frac{\partial}{\partial z}\left[D\frac{\partial f}{\partial z}\right] - u\frac{\partial f}{\partial z} + \frac{1}{3}\frac{du}{dz}p\frac{\partial f}{\partial p} + Q(z,p,t) = 0$$

IN $(-\infty < z < 0^{-})$

FLUX CONSERVATION

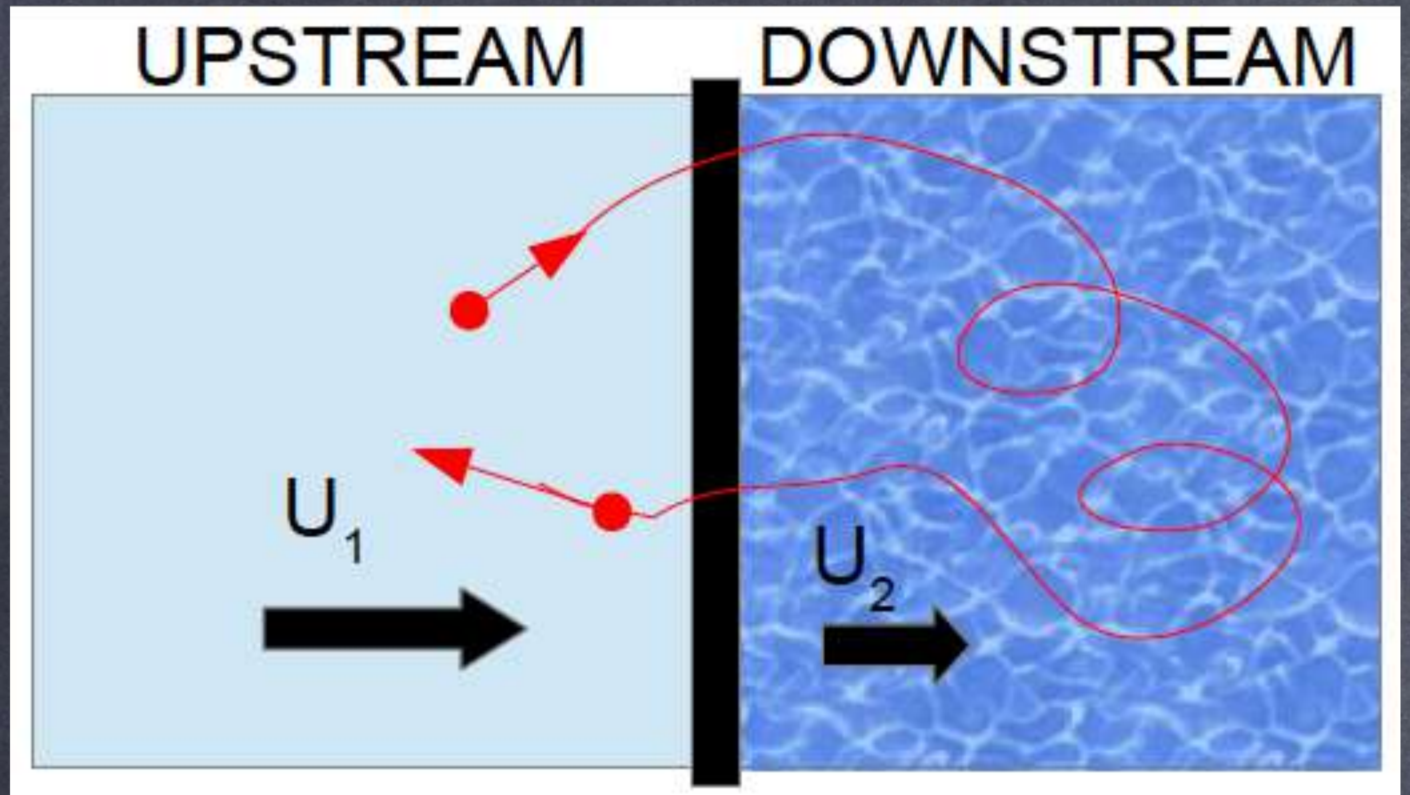
$$\frac{\partial}{\partial z}\left[D\frac{\partial f}{\partial z}\right] - U\frac{\partial f}{\partial z} = 0 \quad \Rightarrow \quad \frac{\partial}{\partial z}\left[D\frac{\partial f}{\partial z} - Uf\right] = 0$$

BOUNDARY CONDITIONS

$$f(z \to \infty) = 0 \qquad \left[\frac{\partial f}{\partial z}\right]_{z\to\infty} = 0 \quad \Rightarrow \quad \boxed{f(z,p) = f_0 \exp\left[\frac{U_1 z}{D}\right]}$$

$$\Rightarrow \quad \boxed{\left(D\frac{\partial f}{\partial z}\right)_{0^-} = U_1 f_0}$$

DOWNSTREAM SOLUTION



$$\frac{\partial}{\partial z}\left[D\frac{\partial f}{\partial z}\right] - u\frac{\partial f}{\partial z} + \frac{1}{3}\frac{du}{dz}p\frac{\partial f}{\partial p} + Q(z,p,t) = 0$$

IN $(z > 0)$

FLUX CONSERVATION

$$\frac{\partial}{\partial z}\left[D\frac{\partial f}{\partial z}\right] - U\frac{\partial f}{\partial z} = 0 \quad \Rightarrow \quad \frac{\partial}{\partial z}\left[D\frac{\partial f}{\partial z} - Uf\right] = 0$$

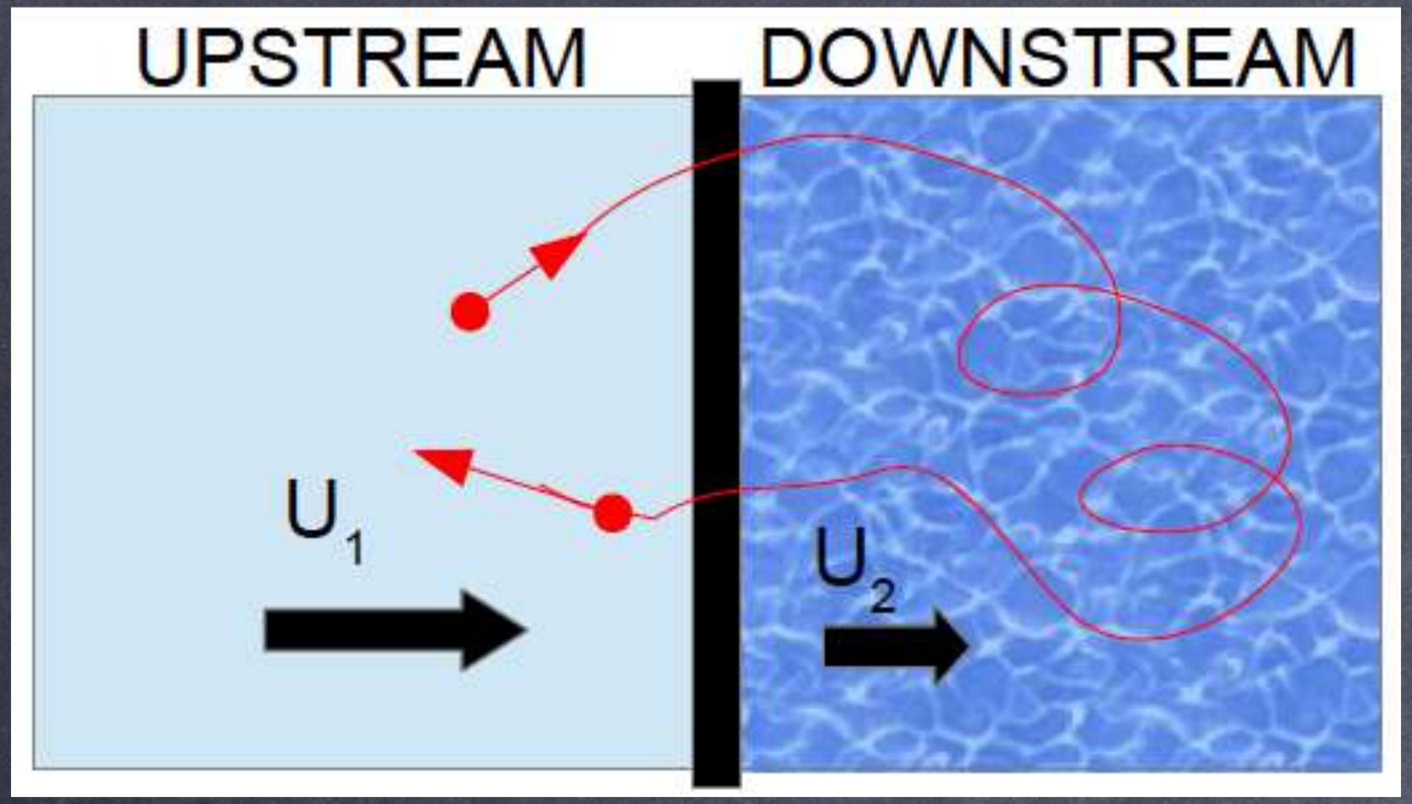
$$f(z,p) = A_1 \exp\left[\frac{U_1 z}{D}\right] + A_2$$

$f(z \to \infty) \to \infty$ UNLESS $A_1 = 0$

$$\Rightarrow \quad f(z,p) = f_0(p)$$

$$\left(D\frac{\partial f}{\partial z}\right)_{0^+} = 0$$

SOLUTION AT THE SHOCK



$$\frac{\partial}{\partial z}\left[D\frac{\partial f}{\partial z}\right] - u\frac{\partial f}{\partial z} + \frac{1}{3}\frac{du}{dz}p\frac{\partial f}{\partial p} + Q(z,p,t) = 0$$

INTEGRATE IN $(0^- < z < 0^+)$

$$\boxed{\left(D\frac{\partial f}{\partial z}\right)_2 - \left(D\frac{\partial f}{\partial z}\right)_1 + \frac{1}{3}\left(U_2 - U_1\right)p\frac{df_0}{dp} + Q_0(p) = 0}$$

$$\boxed{\begin{aligned}\left(D\frac{\partial f}{\partial z}\right)_{0^-} &= U_1 f_0 \\ \left(D\frac{\partial f}{\partial z}\right)_{0^+} &= 0\end{aligned}}$$

$$\boxed{p\frac{df_0}{dp} - \frac{3U_1}{U_2 - U_1}f_0 = -\frac{3}{U_2 - U_1}Q_0}$$

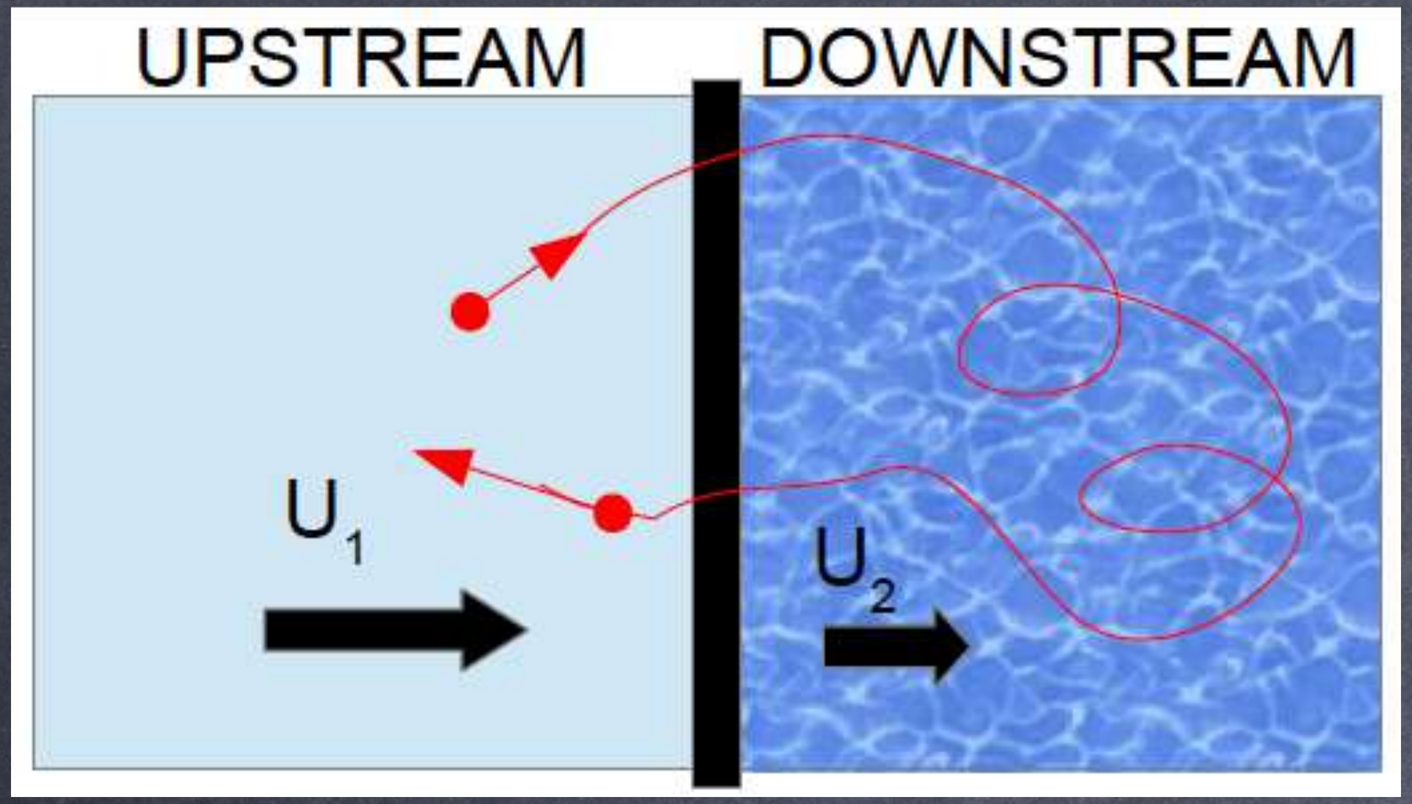
$$\frac{df_0}{dp} + \frac{3R}{R-1}\frac{f_0}{p} = \frac{3R}{R-1}\frac{Q_0}{U_1\,p}$$

$$f_0(p) = e^{-g(p)}\left(\int_{p_0}^{p}\frac{3R}{R-1}\frac{Q_0}{U_1}\frac{dp''}{p''}e^{g(p'')}dp'' + f_0(p_0)\right)$$

$$g(p) = \int_{p_0}^{p}\frac{3R}{R-1}\frac{dp'}{p'}$$

$$\boxed{f_0(p) = \frac{3R}{R-1}\frac{\eta n_1}{4\pi p_{inj}^3}\left(\frac{p}{p_{inj}}\right)^{-\frac{3R}{R-1}}}$$

PARTICLE SPECTRUM



$N(E) \propto E^{-\gamma}$ $\quad \gamma_E = \dfrac{R+2}{R-1}$ $\quad R = U_2/U_1$ RELATIVISTIC PARTICLES!

$f(p) \propto p^{-\gamma_p}$ $\quad \gamma_p = \dfrac{3R}{R-1}$ PARTICLES OF ANY ENERGY!

$N(E) = 4\pi p^2 f(p)\ (dp/dE) \Leftrightarrow \gamma_E = \gamma_p - 2$ ONLY IF dE/dp=c

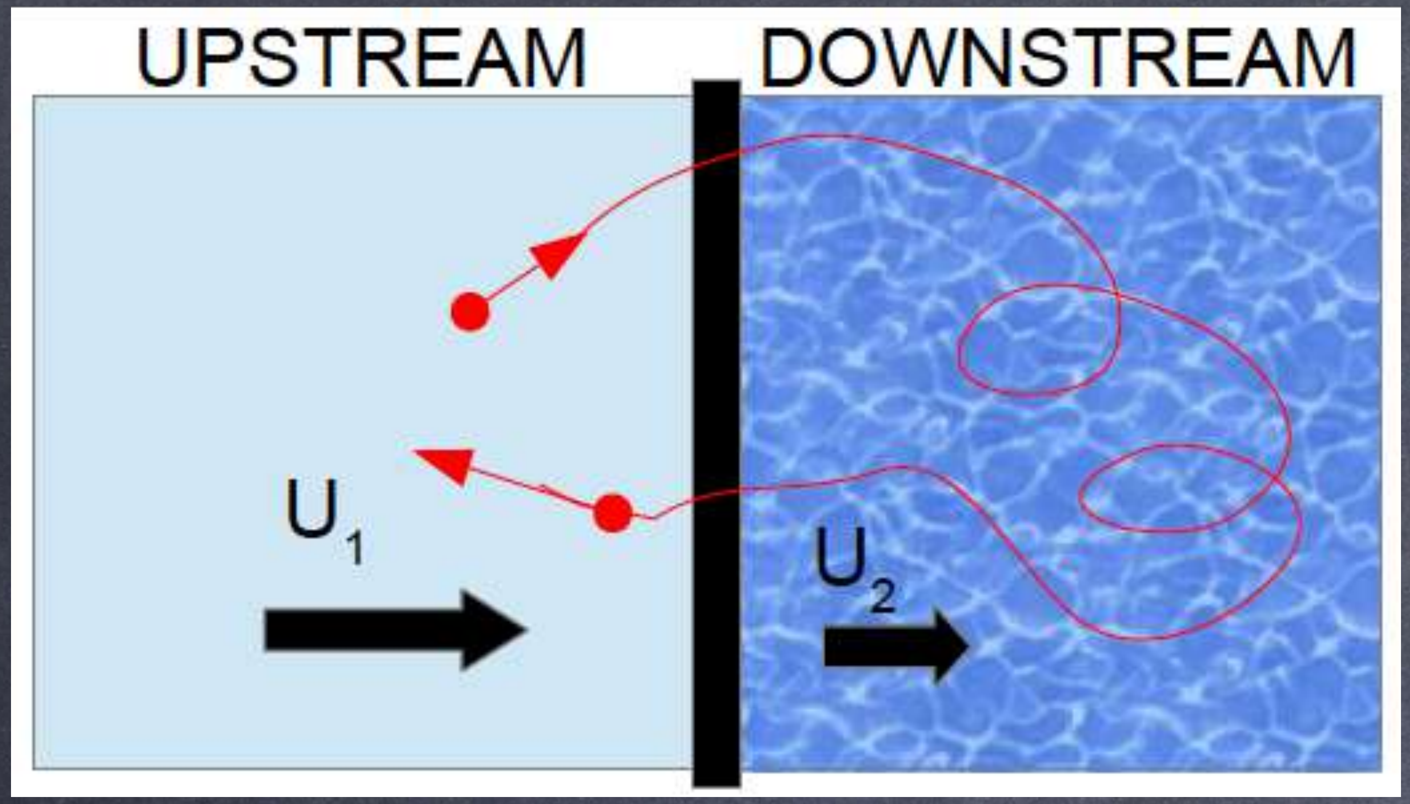
AT A STRONG SHOCK: $R = 4 \;\Rightarrow\; \gamma_p = 4$ VERY SUITABLE TO EXPLAIN MEASURED COSMIC RAY SPECTRUM AFTER PROPAGATION

IMPORTANT: IN FACT POWER LAW IN MOMENTUM, NOT IN ENERGY UNLESS...

ULTRARELATIVISTIC $N(E)dE = 4\pi p^2 f(p)dp \Rightarrow N(E) \propto E^{-2}$

NON-RELATIVISTIC $N(E)dE = 4\pi p^2 f(p)dp \Rightarrow N(E) \propto E^{-3/2}$

PARTICLE SPECTRUM



$N(E) \propto E^{-\gamma}$ $\qquad \gamma_E = \dfrac{R+2}{R-1}$ $\qquad R = U_2/U_1$ RELATIVISTIC PARTICLES!

$f(p) \propto p^{-\gamma_p}$ $\qquad \gamma_p = \dfrac{3R}{R-1}$ PARTICLES OF ANY ENERGY!

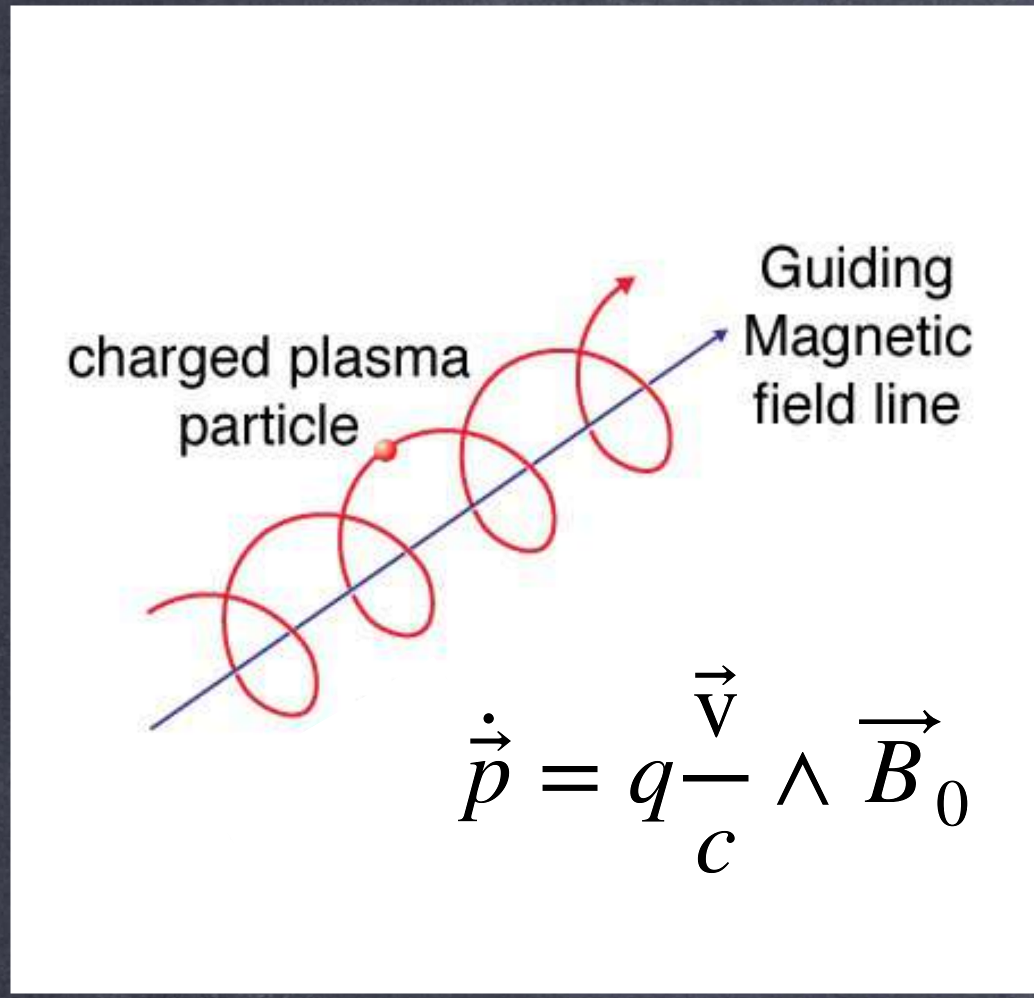
$N(E) = 4\pi p^2 f(p)\ (dp/dE)$ $\Longleftrightarrow$ $\gamma_E = \gamma_p - 2$ ONLY IF dE/dp=c

AT A STRONG SHOCK: $R = 4 \;\Rightarrow\; \gamma_p = 4$ VERY SUITABLE TO EXPLAIN MEASURED COSMIC RAY SPECTRUM AFTER PROPAGATION

IMPORTANT:
DIFFUSION COEFFICIENT PLAYS NO ROLE IN SPECTRUM!!!!!!
IT DOES PLAY A ROLE IN DETERMINING MAXIMUM ENERGY!

PARTICLE TRANSPORT

MOTION OF A PARTICLE IN UNIFORM MAGNETIC FIELD



HELICOIDAL MOTION

$$\vec{B} = B_0\hat{z}$$

$$\mu = \cos\theta = \frac{\vec{B}\cdot\vec{v}}{|\vec{B}|\,|\vec{v}|}$$

$$v_{z0} = v_{0\parallel} = v_0\mu$$

$$v_{0\perp} = v_0(1-\mu^2)$$

$$m\gamma\frac{dv_x}{dt} = \frac{q}{c}v_y\,B_0$$

$$m\gamma\frac{dv_y}{dt} = -\frac{q}{c}v_x\,B_0$$

$$m\gamma\frac{dv_z}{dt} = 0 \quad \Rightarrow v_z = const$$

$$\Downarrow$$

$$v_x(t) = v_0\,(1-\mu^2)\,\cos(\Omega\,t)$$

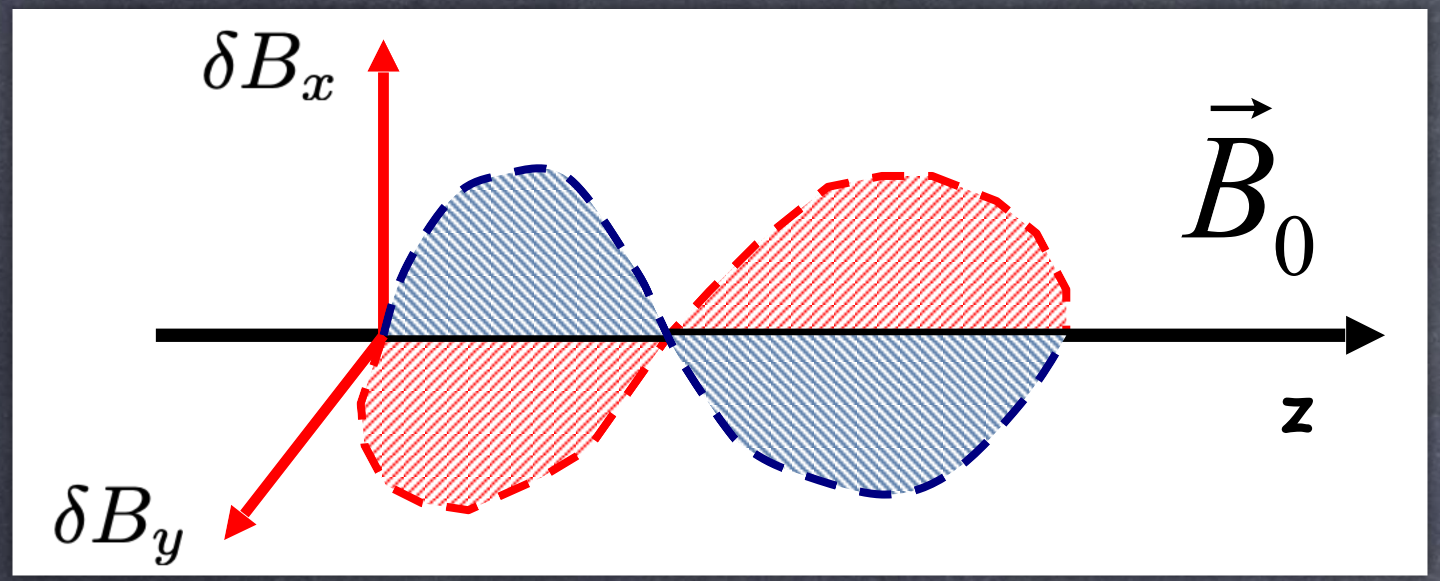
$$v_y(t) = -v_0\,(1-\mu^2)\,\sin(\Omega\,t)$$

$$v_z(t) = v_0\,\mu$$

LARMOR FREQUENCY

$$\Omega = \frac{qB_0}{m\gamma c}$$

WAVE-PARTICLE INTERACTIONS



$$\delta B \ll B_0$$

$$\delta \vec{B} \perp \vec{B}_0$$

$$\vec{k} = k\hat{z}$$

$$\delta B_x(t) = \pm \delta B \sin\left(kz - \omega t + \phi\right)$$

$$\delta B_y(t) = \delta B \cos\left(kz - \omega t + \phi\right)$$

$$\dot{\vec{p}} = q\frac{\vec{\mathrm{v}}}{c} \wedge \left(\vec{B}_0 + \delta\vec{B}\right)$$

AFFECTS $p_{\|}$

$$m\gamma\frac{d\mathrm{v}_x}{dt} = \frac{q}{c}\left(\mathrm{v}_y\, B_0 - \mathrm{v}_z\, \delta B_y\right)$$

$$m\gamma\frac{d\mathrm{v}_y}{dt} = -\frac{q}{c}\left(\mathrm{v}_x\, B_0 - \mathrm{v}_z\, \delta B_x\right)$$

$$m\gamma\frac{d\mathrm{v}_z}{dt} = \frac{q}{c}\left(\mathrm{v}_x\, \delta B_y - \mathrm{v}_y\, \delta B_x\right)$$

$$\Rightarrow$$

$$v_x(t) = \mathrm{v}_0\left(1-\mu^2\right)^{1/2}\cos\left(\Omega\ t\right)$$

$$v_y(t) = -\mathrm{v}_0\left(1-\mu^2\right)^{1/2}\sin\left(\Omega\ t\right)$$

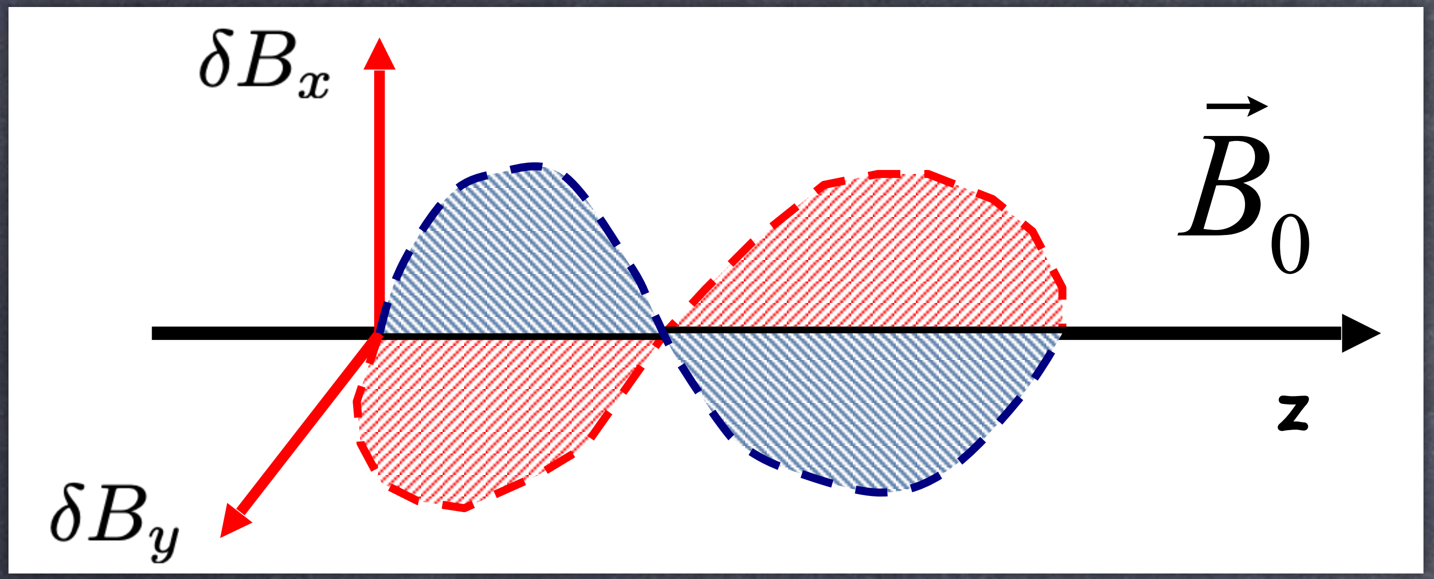
POLARIZATION

$$m\gamma\frac{d\mathrm{v}_z}{dt} = \frac{q}{c}\mathrm{v}_0\delta B\left(1-\mu^2\right)^{1/2} \times \left[\cos\left(\Omega t\right)\cos\left(kz - \omega t + \phi\right) \pm \sin\left(\Omega t\right)\sin\left(kz - \omega t + \phi\right)\right]$$

$$\boxed{v_A = \frac{B_0}{\sqrt{4\pi\rho}} = 3\times 10^5 \left(\frac{B_0}{\mu G}\right)\left(\frac{n}{\mathrm{cm}^{-3}}\right)^{-1/2} \mathrm{cm\ s}^{-1}}$$

$$kz \approx k\mathrm{v}_0\mu t >> k v_a t = \omega t \quad \Rightarrow \quad \frac{d\mathrm{v}_z}{dt} = \frac{q\delta B}{m\gamma c}\mathrm{v}_0\left(1-\mu^2\right)^{1/2}\left[\cos\left(\Omega t\right)\cos\left(k\mathrm{v}_0\mu t + \phi\right) \pm \sin\left(\Omega t\right)\sin\left(k\mathrm{v}_0\mu t + \phi\right)\right]$$

WAVE-PARTICLE INTERACTIONS



$\delta B \ll B_0$

$\delta \vec{B} \perp \vec{B}_0$

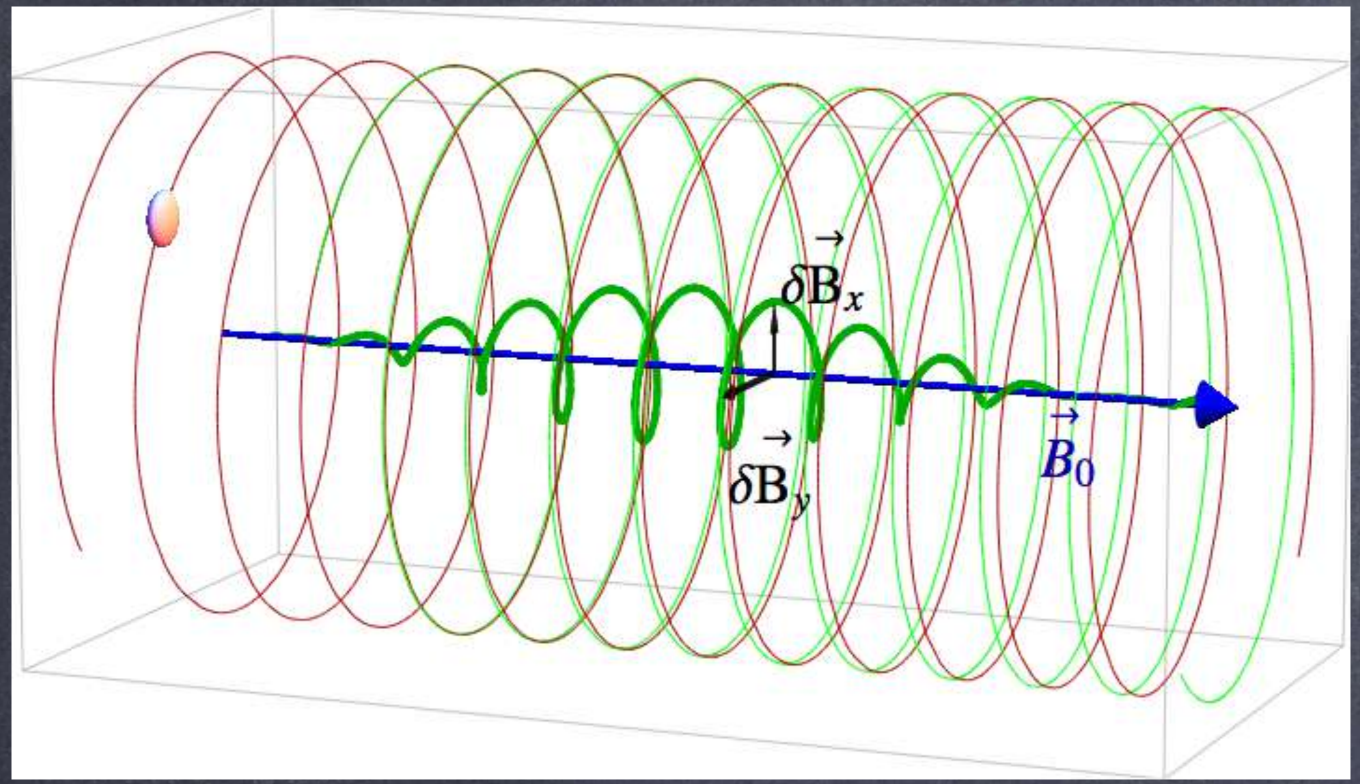
$$\vec{k} = k\hat{z}$$

$$\delta B_x(t) = \pm \delta B \sin\left(kz - \omega t + \phi\right)$$

$$\delta B_y(t) = \delta B \cos\left(kz - \omega t + \phi\right)$$

$$v_x(t) = \mathrm{v}_0 \left(1-\mu^2\right)^{1/2} \cos\left(\Omega\ t\right)$$

$$v_y(t) = -\mathrm{v}_0 \left(1-\mu^2\right)^{1/2} \sin\left(\Omega\ t\right)$$



$$\frac{d\mathrm{v}_z}{dt} = \frac{q\delta B}{m\gamma c}\mathrm{v}_0\left(1-\mu^2\right)^{1/2}\left[\cos\left(\Omega t\right)\cos\left(k\mathrm{v}_0\mu t+\phi\right) \pm \sin\left(\Omega t\right)\sin\left(k\mathrm{v}_0\mu t+\phi\right)\right]$$

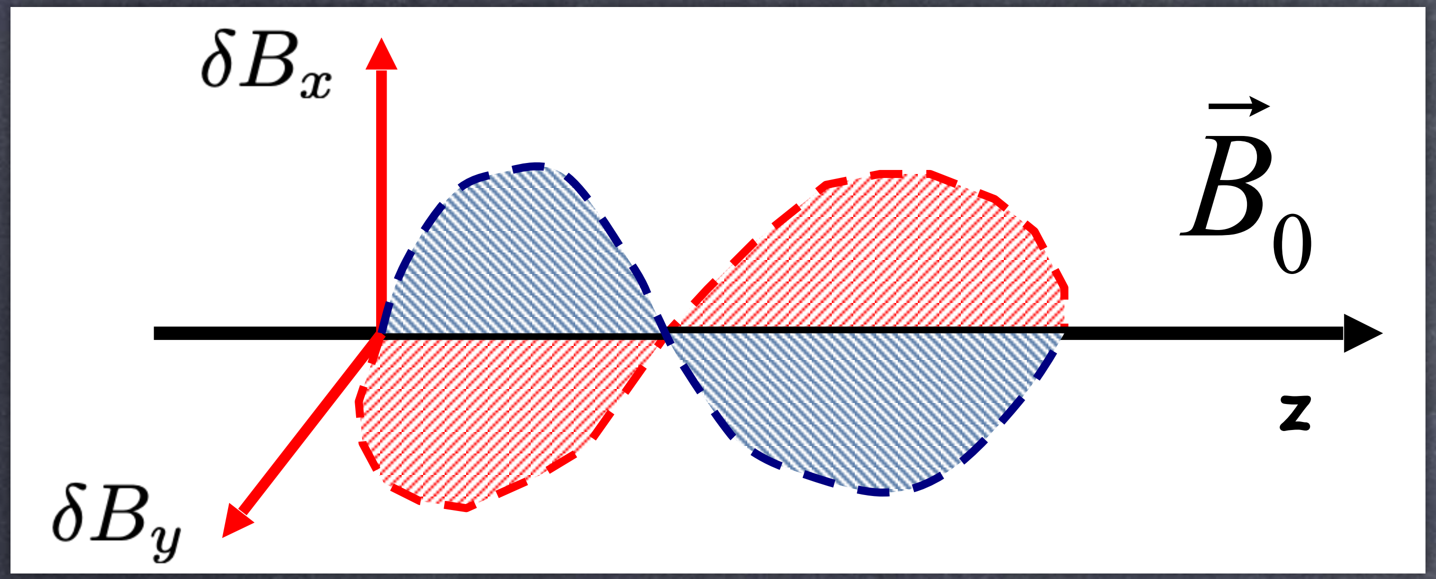
$$\boxed{\frac{d\mu}{dt} = \frac{q\delta B}{m\gamma c}\left(1-\mu^2\right)^{1/2}\left[\cos\left(\Omega t \mp k\mathrm{v}_0\mu t \mp \phi\right)\right]} \Rightarrow \boxed{\langle \Delta\mu \rangle_t = 0}$$

$$\langle \Delta\mu\Delta\mu \rangle_t = (1-\mu^2)\left(\frac{\delta B}{B_0}\right)^2 \frac{\Omega^2}{4\pi^2}\int_0^{2\pi} d\Phi \int_0^{2\pi} d\Phi' \int_0^T dt \cos\left[\left(\Omega \mp k\mathrm{v}_0\mu\right)t \mp \phi\right]\int_0^T dt'\ \cos\left[\left(\Omega \mp k\mathrm{v}_0\mu\right)t' \mp \phi'\right]$$

AVERAGE OVER PHASES

$$\langle \Delta\mu\Delta\mu \rangle_t = (1-\mu^2)\left(\frac{\delta B}{B_0}\right)^2 \frac{\Omega^2}{2}\int_0^T dt \int_0^T dt'\ \cos\left[\left(\Omega \mp k\mathrm{v}_0\mu\right)(t-t')\right]$$

WAVE-PARTICLE INTERACTIONS



$\delta B \ll B_0$

$\delta \vec{B} \perp \vec{B}_0$

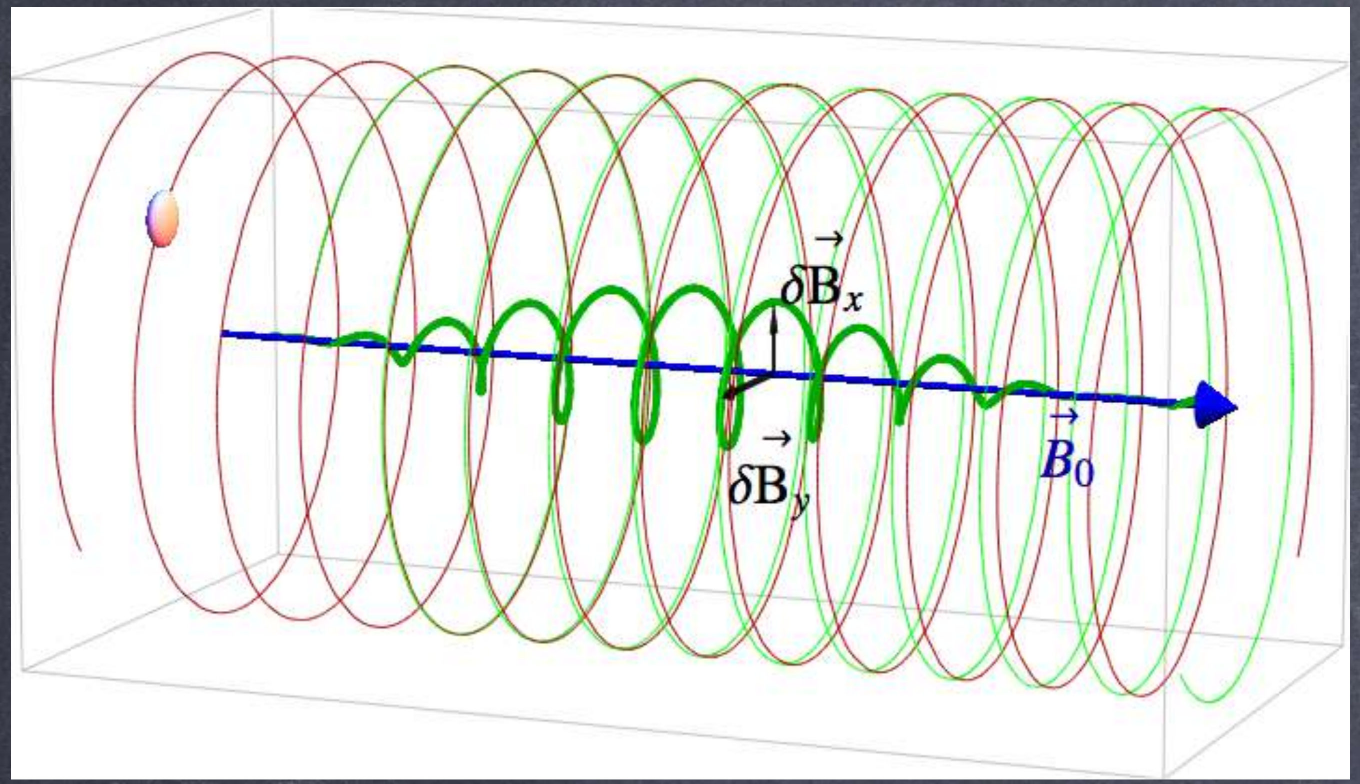
$$\vec{k} = k\hat{z}$$

$$\delta B_x(t) = \pm \delta B \sin\left(kz - \omega t + \phi\right)$$

$$\delta B_y(t) = \delta B \cos\left(kz - \omega t + \phi\right)$$

$$v_x(t) = \mathrm{v}_0 \left(1 - \mu^2\right)^{1/2} \cos\left(\Omega\ t\right)$$

$$v_y(t) = -\mathrm{v}_0 \left(1 - \mu^2\right)^{1/2} \sin\left(\Omega\ t\right)$$



$$\langle \Delta\mu\Delta\mu \rangle_t = (1 - \mu^2) \left(\frac{\delta B}{B_0}\right)^2 \frac{\Omega^2}{2} \int_0^T dt \int_0^T dt' \ \cos\left[\left(\Omega \mp k\mathrm{v}_0\mu\right)(t - t')\right]$$

$$\langle \Delta\mu\Delta\mu \rangle_t = (1 - \mu^2)\ T\ \Omega^2 \left(\frac{\delta B}{B_0}\right)^2 \frac{\pi}{2\mathrm{v}_0\mu} \delta\left(k \mp \frac{\Omega}{\mathrm{v}_0\mu}\right)$$

$$r_L = \frac{cp}{eB_0}$$

$$\boxed{k_{res} = \frac{\Omega}{\mathrm{v}_0\mu} = \frac{1}{r_L\mu}}$$

$$\boxed{D_{\mu\mu} = \left\langle \frac{\Delta\mu\Delta\mu}{2T} \right\rangle = (1 - \mu^2)\ \frac{\pi}{4} \left(\frac{\delta B}{B_0}\right)^2 \Omega\ k_{res}\ \delta\left(k \mp \frac{\Omega}{\mathrm{v}_0\mu}\right)}$$

WAVE-PARTICLE INTERACTIONS

SINGLE WAVE MODE

$$\vec{k} = k\hat{z}$$
$$\delta B_x(t) = \pm\delta B \sin\left(kz - \omega t + \phi\right)$$
$$\delta B_y(t) = \delta B \cos\left(kz - \omega t + \phi\right)$$

$$\Rightarrow \quad D_{\mu\mu} = \left\langle \frac{\Delta\mu\Delta\mu}{2T} \right\rangle = (1-\mu^2)\,\frac{\pi}{4}\left(\frac{\delta B}{B_0}\right)^2 \Omega\; k_{res}\;\delta\left(k \mp \frac{\Omega}{v_0\mu}\right)$$

FULL WAVE SPECTRUM

$$\left(\frac{\delta B}{B_0}\right)^2 = \int_{k_{min}}^{\infty} \mathcal{F}(k)dk$$

$$\Rightarrow \quad D_{\mu\mu} = \left\langle \frac{\Delta\mu\Delta\mu}{2T} \right\rangle = (1-\mu^2)\,\frac{\pi}{4}\Omega\; k_{res} \int dk\; \mathcal{F}(k)\;\delta\left(k \mp \frac{\Omega}{v_0\mu}\right)$$

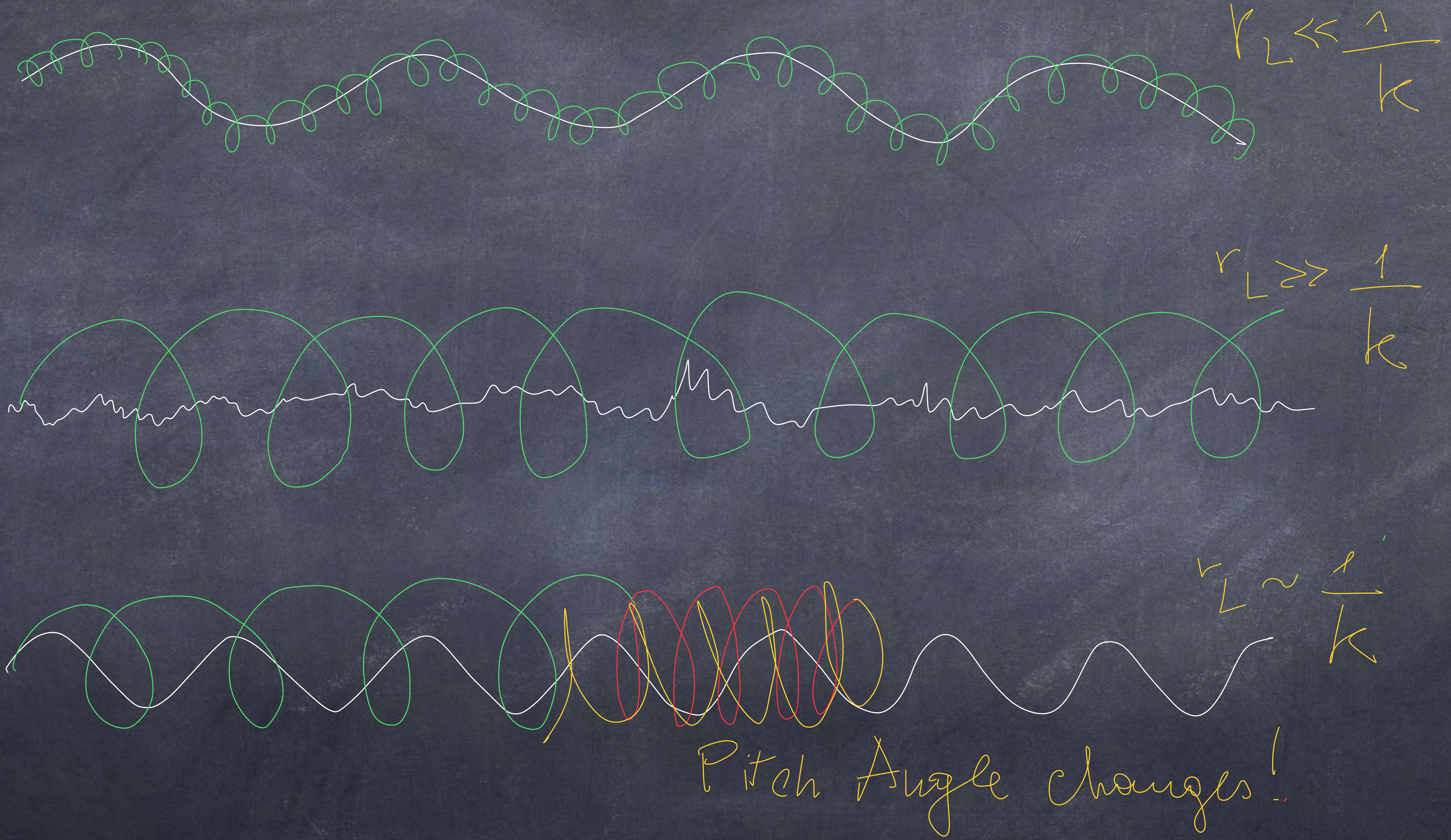
$$\boxed{k_{res} = \frac{\Omega}{v_0\mu} = \frac{1}{r_L\;\mu}}$$

$$\boxed{D_{\mu\mu} = (1-\mu^2)\,\frac{\pi}{4}\Omega\; k_{res}\mathcal{F}(k_{res})}$$

ALSO

$$\boxed{D_{\theta\theta} = \frac{\pi}{4}\Omega\; k_{res}\;\mathcal{F}(k_{res})}$$

IN ALL CASES RELEVANT INTERACTIONS ARE THOSE WITH RESONANT MODES
THE POWER THAT MATTERS IS THAT IN RESONANT PERTURBATIONS!


$r_L \ll \frac{1}{k}$
$r_L \gg \frac{1}{k}$
$r_L \sim \frac{1}{k}$
Pitch Angle changes!

DIFFUSION IN MOMENTUM SPACE

CHANGE IN PITCH ANGLE IMPLIES NO CHANGE OF ENERGY IN WAVE FRAME

IN LAB FRAME $\Delta p \approx p \frac{v_A}{c}$

EITHER POSITIVE OR NEGATIVE….

$$\boxed{\langle \vec{E} \rangle = 0 \qquad \langle \vec{E}^2 \rangle \neq 0}$$

PITCH ANGLE DIFFUSION COEFFICIENT : $D_{\theta\theta} = \frac{\pi}{4} \Omega \; k_{res} \; \mathcal{F}(k_{res})$ $\qquad D_{\mu\mu} = (1-\mu^2)\frac{\pi}{4}\Omega \; k_{res} \; \mathcal{F}(k_{res})$

$$\boxed{D_{pp} = \left\langle \frac{\Delta p \Delta p}{T} \right\rangle \approx p^2 D_{\mu\mu} \left(\frac{v_A}{c}\right)^2}$$

$$\boxed{\tau_{acc,II} = \frac{p^2}{D_{pp}} \approx \left(\frac{c}{v_A}\right)^2 \frac{1}{D_{\mu\mu}}}$$

SPATIAL DIFFUSION

CHANGE IN PITCH ANGLE IMPLIES CHANGE OF TRAJECTORY

CHARACTERISTIC TIME-SCALE: $\tau_{diff} \approx \frac{1}{D_{\theta\theta}}$

MEAN FREE PATH: $\lambda_{diff} \approx \mathrm{v}\tau_{diff}$

$$D_{\parallel} = \left\langle \frac{\Delta z \Delta z}{T} \right\rangle \approx \frac{1}{3}\lambda_{diff}\mathrm{v} = \frac{1}{3}\mathrm{v}^2\tau_{diff} \approx \frac{1}{3}\frac{\mathrm{v}^2}{\Omega k_{res}\mathscr{F}(k_{res})}$$

PITCH ANGLE DIFFUSION: $D_{\theta\theta} = \frac{\pi}{4}\Omega\, k_{res}\, \mathscr{F}(k_{res})$

$$\boxed{D_{\parallel} \approx \frac{cr_L}{3k_{res}\mathscr{F}(k_{res})} \approx \frac{cr_L}{3(\delta B(k_{res})/B_0)^2}}$$

SPATIAL DIFFUSION COEFFICIENT ALONG THE BACKGROUND MAGNETIC FIELD INVERSELY PROPORTIONAL TO TURBULENCE LEVEL

SPATIAL DIFFUSION COEFFICIENT ACROSS THE BACKGROUND MAGNETIC FIELD PROPORTIONAL TO TURBULENCE LEVEL

$$\boxed{D_{\perp} = \left(\frac{r_L}{\lambda_{diff}}\right)^2 D_{\parallel} \approx cr_L\left(\frac{\delta B(k_{res})}{B_0}\right)^2}$$

ENERGY DEPENDENCE OF DIFFUSION COEFFICIENT

$$\boxed{D_{\parallel} \approx \frac{c r_L}{k_{res}\mathcal{F}(k_{res})}}$$

ASSUME $\boxed{\mathcal{F}(k) \propto k^{-\alpha}}$

$$k_{res} = \frac{\Omega}{v_0 \mu} \propto p^{-1}$$

$$k_{res}\mathcal{F}(k_{res}) \propto k_{res}^{1-\alpha} \propto p^{\alpha-1}$$

$$\boxed{D_{\parallel} \propto p^{2-\alpha}}$$

DEPENDS ON TURBULENCE SPECTRAL INDEX

KOLMOGOROV $\alpha = 5/3 \Rightarrow D(E) \propto E^{1/3}$

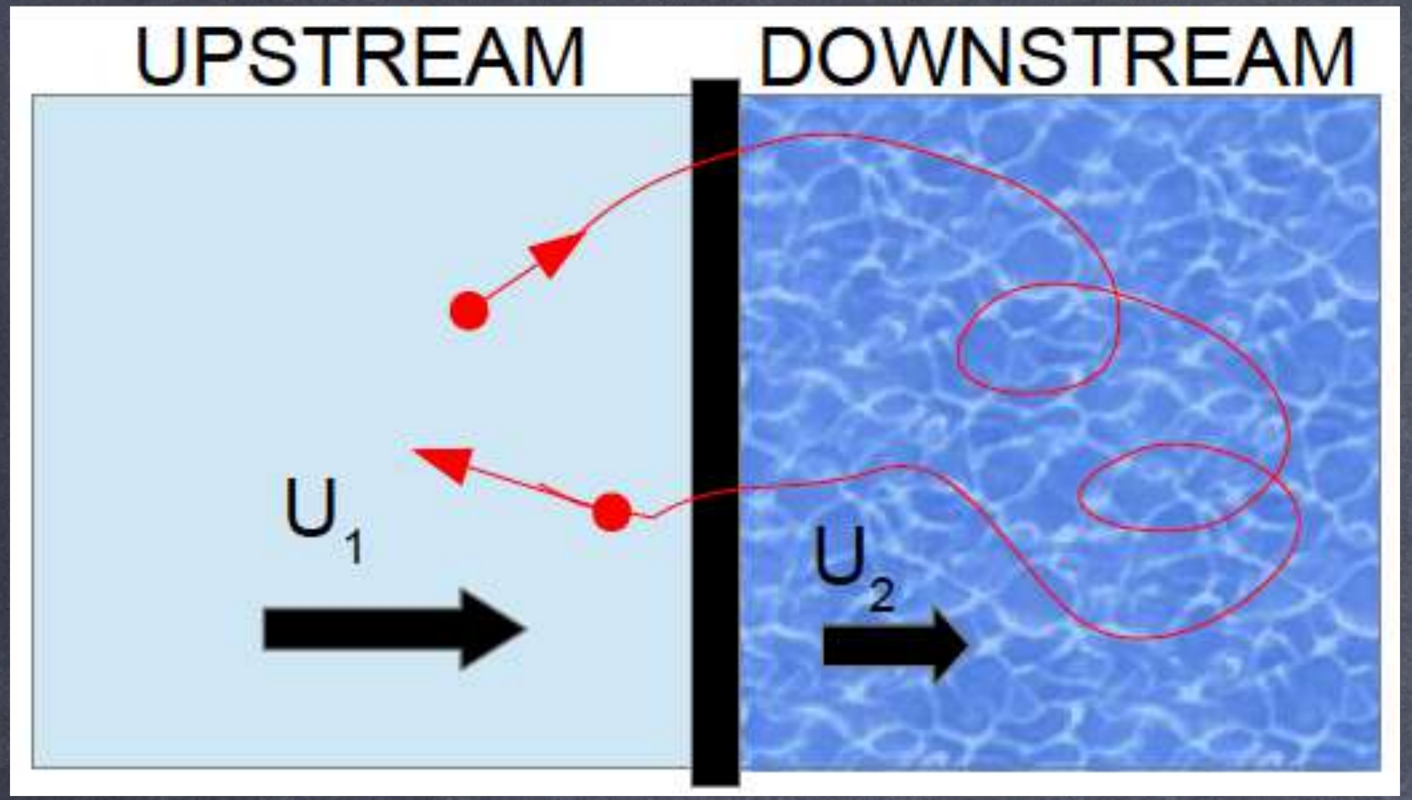
KRAICHNAN $\alpha = 3/2 \Rightarrow D(E) \propto E^{1/2}$

BOHM $\alpha = 1 \Rightarrow D(E) \propto E$

BOHM DIFFUSION COEFFICIENT TYPICALLY SMALLER THAN THE OTHERS BY A FACTOR $(r_L/L_{OUT})^{\alpha-1}$

MOST FAVOURABLE TO REACH HIGH ENERGIES

MAXIMUM ENERGY



ACCELERATED PARTICLE SPECTRUM ONLY DEPENDS ON COMPRESSION RATIO BUT…

$$\boxed{E_{max} \Leftarrow t_{acc}\left(E_{max}\right) = min\left[t_{age}, t_{loss}\left(E_{max}\right)\right]}$$

$$t_{acc} = \frac{E}{dE/dt} = \frac{\tau_{ret}}{\Delta E/E}$$

$$\frac{\Delta E}{E} = \frac{4}{3}\frac{U_1 - U_2}{c}$$

$$\tau_{ret} = \frac{4D_1(p)}{U_1 c} + \frac{4D_2(p)}{U_2 c}$$

(SEE e.g. DRURY '83)

$$\boxed{t_{acc} = \frac{3}{U_1 - U_2}\left(\frac{D_1}{U_1} + \frac{D_2}{U_2}\right)}$$

OFTEN SIMPLIFIED TO

$$t_{acc} \sim \frac{D}{V_s^2}$$

$$(D_2/D_1) \propto B_1/B_2 \approx 1/R \quad \Rightarrow \quad (D_2\ U_2) \approx (D_1\ U_1)$$

HILLAS CRITERION

$$E_{max,H} = q\ \mathscr{E}\ L$$

$$\mathscr{E} \sim \frac{v_{flow}}{c} B$$

$$\boxed{E_{max,H} = q\ \frac{v_{flow}}{c} B\ L}$$

COMPARE SIZE AND TIME LIMITED ACCELERATION

DIFFUSION WITH $D = \xi_B\ D_B$ WITH $\xi_B \gtrsim 1$

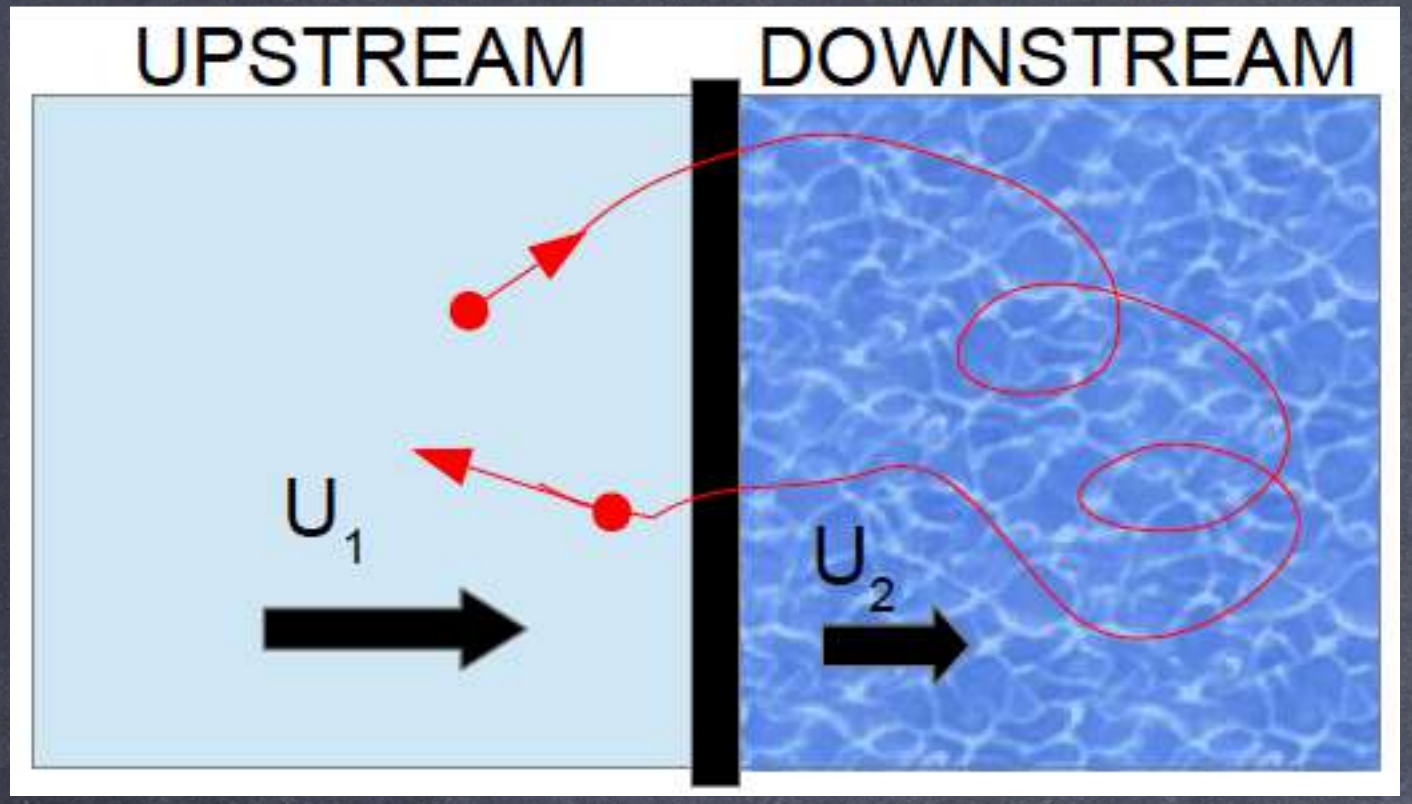
$$t_{acc} \sim \frac{D}{V_s^2} \lesssim t_{age}$$

$$\boxed{E_{max,T} = \xi_B^{-1}\ q\ \frac{V_s}{c} B V_s\ t_{age} \lesssim \xi_B^{-1}\ q\ \frac{V_s}{c} B\ L \lesssim E_{max,H}}$$

FOR SYSTEM IN LINEAR EXPANSION SAME CONSTRAINT IF $D=D_B$

NOTE: SOLVING TRANSPORT EQ. WITH FINITE BOUNDARY UPSTREAM SHOWS EXPONENTIAL CUT-OFF AT E_{max}

AGE LIMITED MAXIMUM ENERGY



E_{max} DEPENDS ON VELOCITY AND SCATTERING EFFICIENCY

$$E_{max} \Leftarrow t_{acc}\left(E_{max}\right) = min\left[t_{age}, t_{loss}\left(E_{max}\right)\right]$$

$$t_{acc} = \frac{E}{dE/dt} = \frac{3}{U_1 - U_2}\left(\frac{D_1}{U_1} + \frac{D_2}{U_2}\right) \approx \frac{8D_1(E)}{V_s^2}$$

SNR SHOCK WITH ISM FIELD

$$V_s \approx 5 \times 10^8 \; cm/s$$

$$D(E) \approx 3 \times 10^{28} E_{GeV}^{1/3} \; cm^2/s$$

$$\Rightarrow \quad t_{acc}(E) \sim 4 \times 10^3 \; E_{GeV}^{1/3} \; yr$$

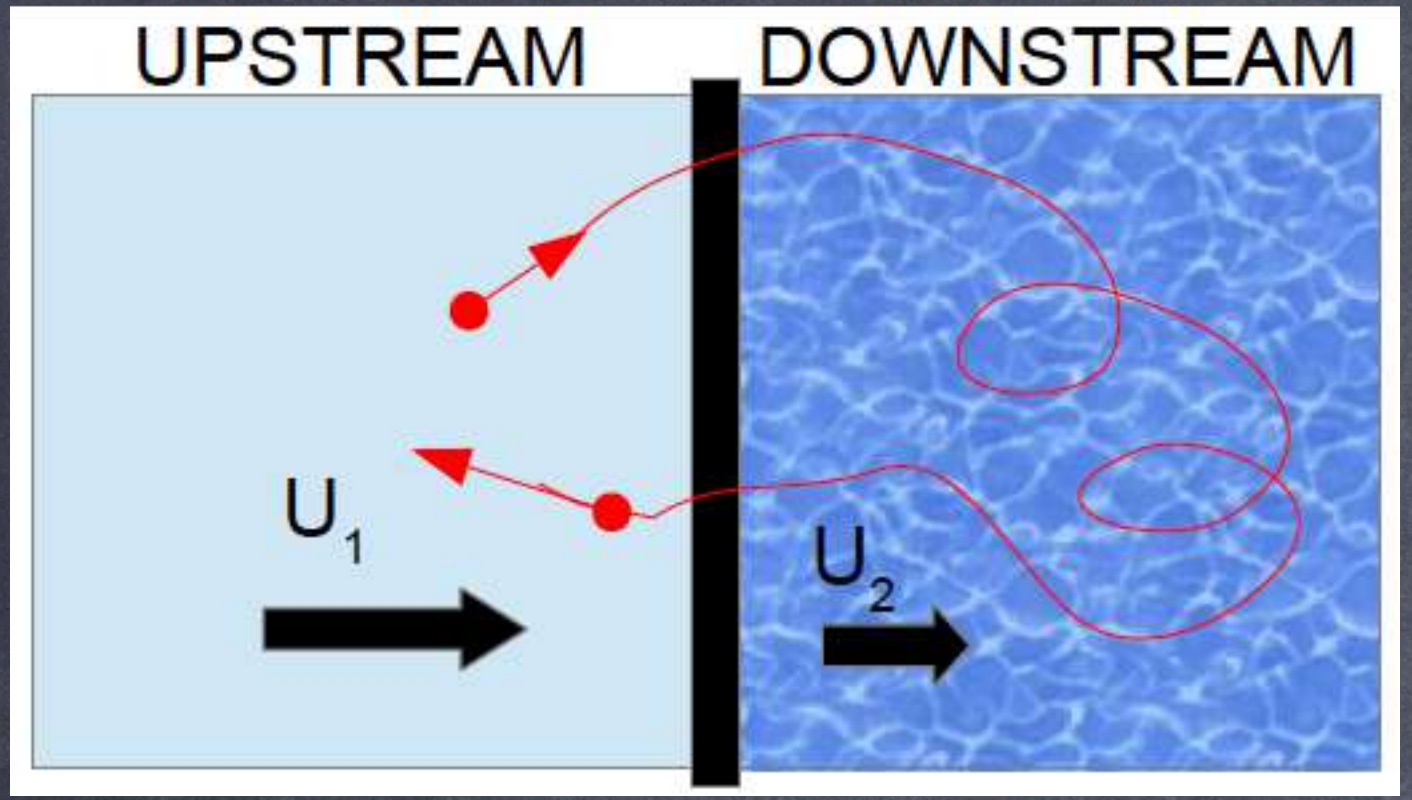
$t_{acc} < t_{age} \Rightarrow$

$E_{max} \sim GeV$ IF SAME D AS IN ISM

(Lagage & Cesarsky 83)

$E_{max} \sim 10^3 - 10^4 GeV$ IF SAME $\delta B \sim B_0$ AT RELEVANT SCALES....

LOSS LIMITED MAXIMUM ENERGY



$$E_{max} \Leftarrow t_{acc}\left(E_{max}\right) = min\left[t_{age}, t_{loss}\left(E_{max}\right)\right] \qquad t_{acc} = \frac{D_1(E)}{V_s^2}$$

FOR LEPTONS E_{max} IS TYPICALLY LIMITED BY SYNCHROTRON LOSSES

$$\frac{dE}{dt} = -\frac{4}{3}\sigma_T c\left(\frac{E}{mc^2}\right)^2\left(\frac{B^2}{8\pi} + U_{rad}\right)$$

$$\tau_{sync} = \frac{E}{(dE/dt)_{sync}} \approx 10^3 yr\left(\frac{E_e}{1TeV}\right)^{-1}\left(\frac{B_2}{100\mu G}\right)^{-2}$$

$$\tau_{ICS} = 1.5\times 10^6 yr\left(\frac{E_e}{1TeV}\right)^{-1}\left(\frac{U_{rad}}{eV\ cm^{-3}}\right)^{-2}$$

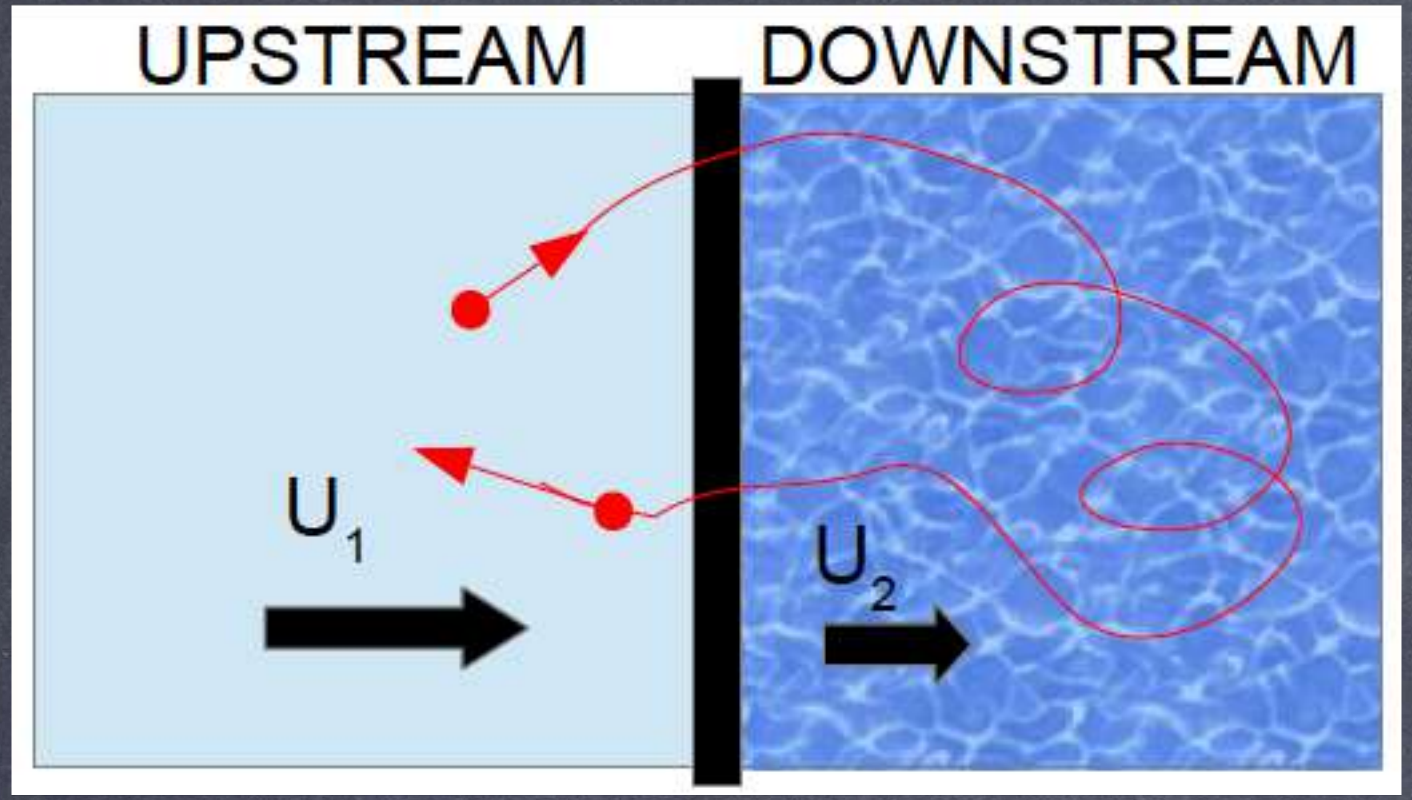
$$t_{acc}(E_{\max}) = t_{\rm sync}(E_{max}) \Longleftrightarrow \frac{c}{V_s^2}\frac{E_{max}}{eB} = \frac{6\pi m^2 c^3}{\sigma_T E_{max} B^2}$$

$$\Rightarrow \quad E_{max,el} = 30TeV\left(\frac{B_2}{100\mu G}\right)^{-1/2}\left(\frac{V_s}{5000km/s}\right)$$

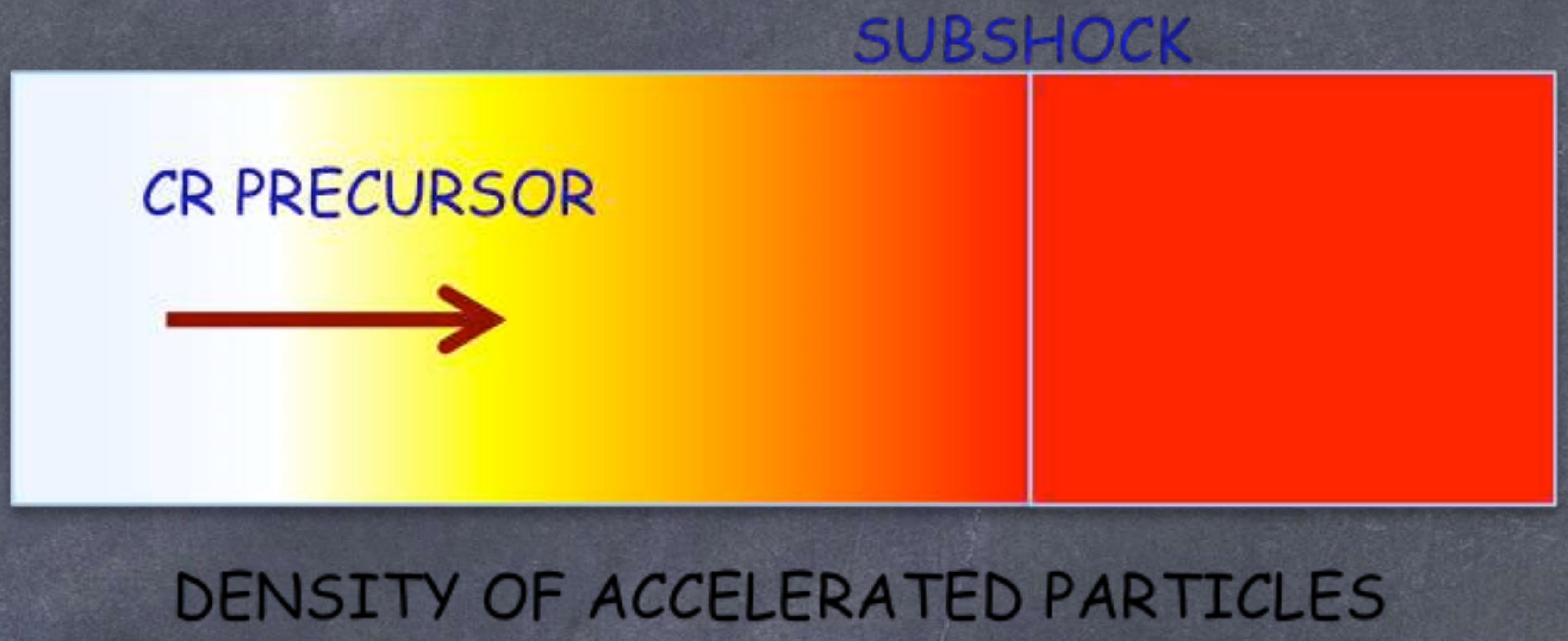
$$\nu_{max,el} = 0.29\frac{eB}{mc}\left(\frac{E_{max}}{mc^2}\right)^2 \approx 1keV\left(\frac{V_s}{5\times 10^8 cm/s}\right)^2$$

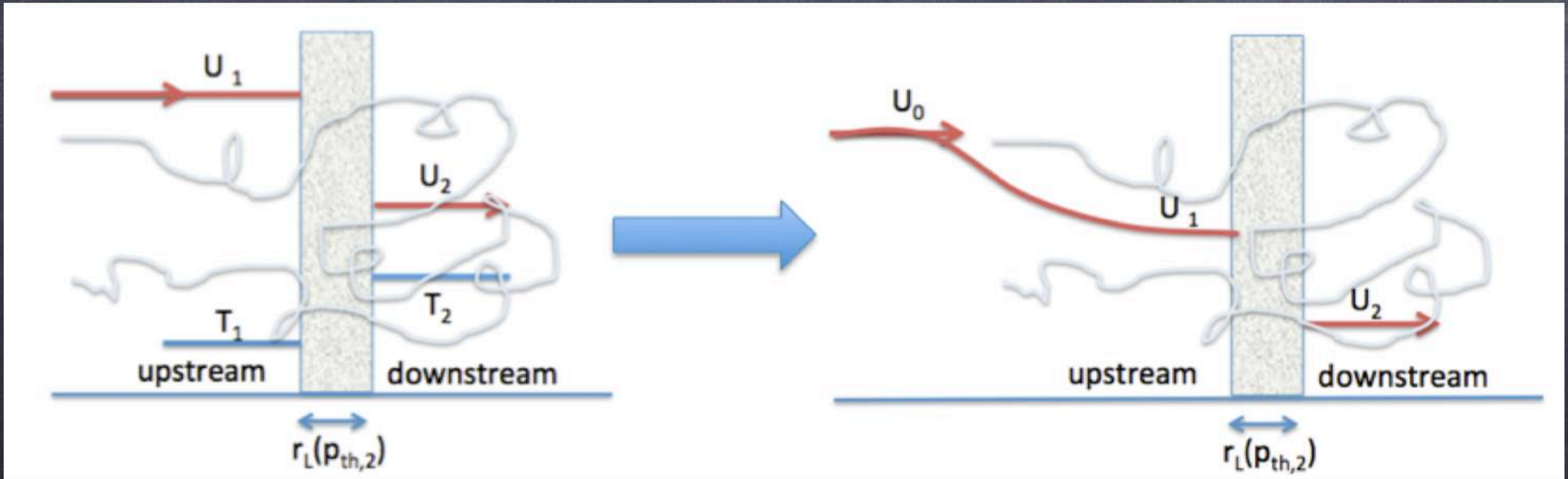
X-RAYS

NON-LINEAR EFFECTS



IF ACCELERATION EFFICIENCY >=10%
ENERGY BUDGET I CRs NON NEGLIGIBLE….



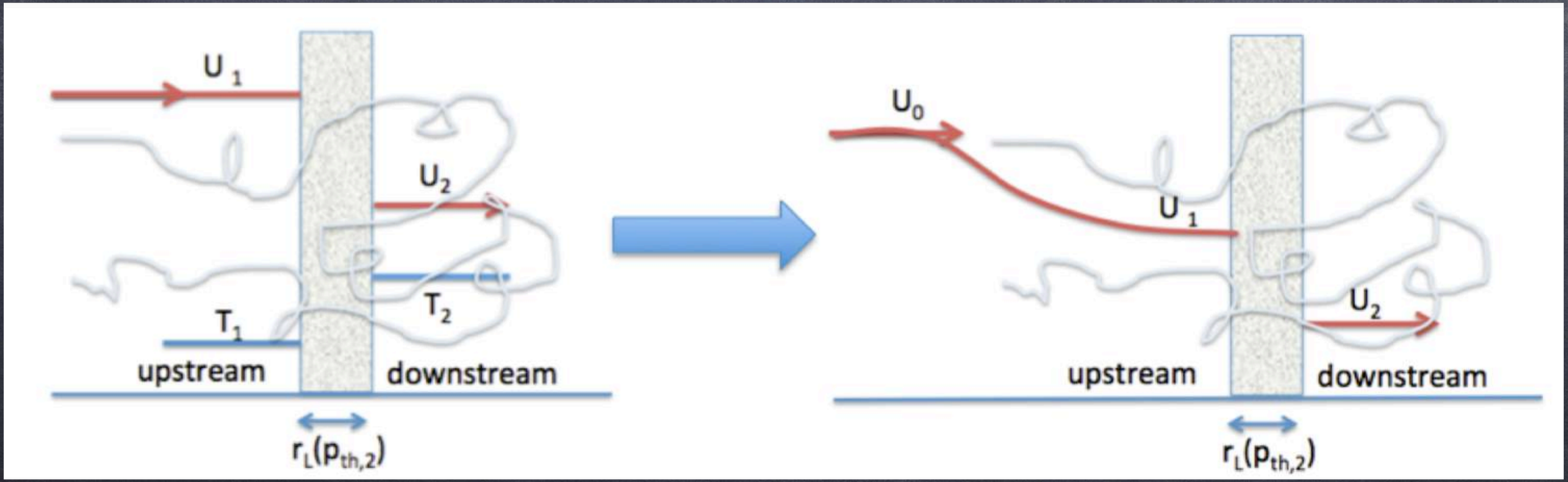


NON-LINEAR EFFECTS

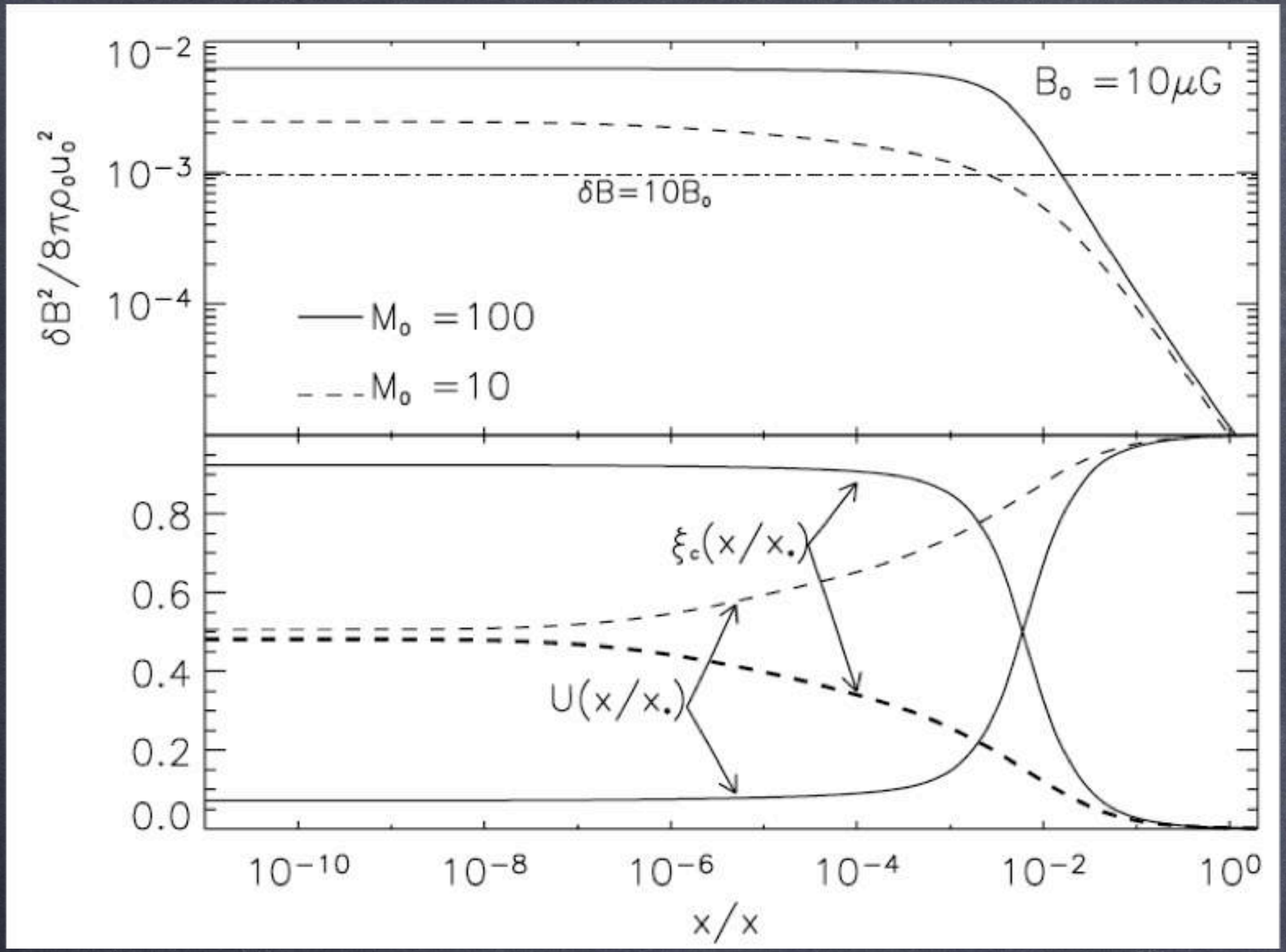
$$\frac{\partial}{\partial x}(\rho U) = 0$$
$$\frac{\partial}{\partial x}(\rho U^2 + p) = 0$$
$$\frac{\partial}{\partial x}\left[\left(p + \epsilon + \frac{\rho U^2}{2}\right)U\right] = 0$$

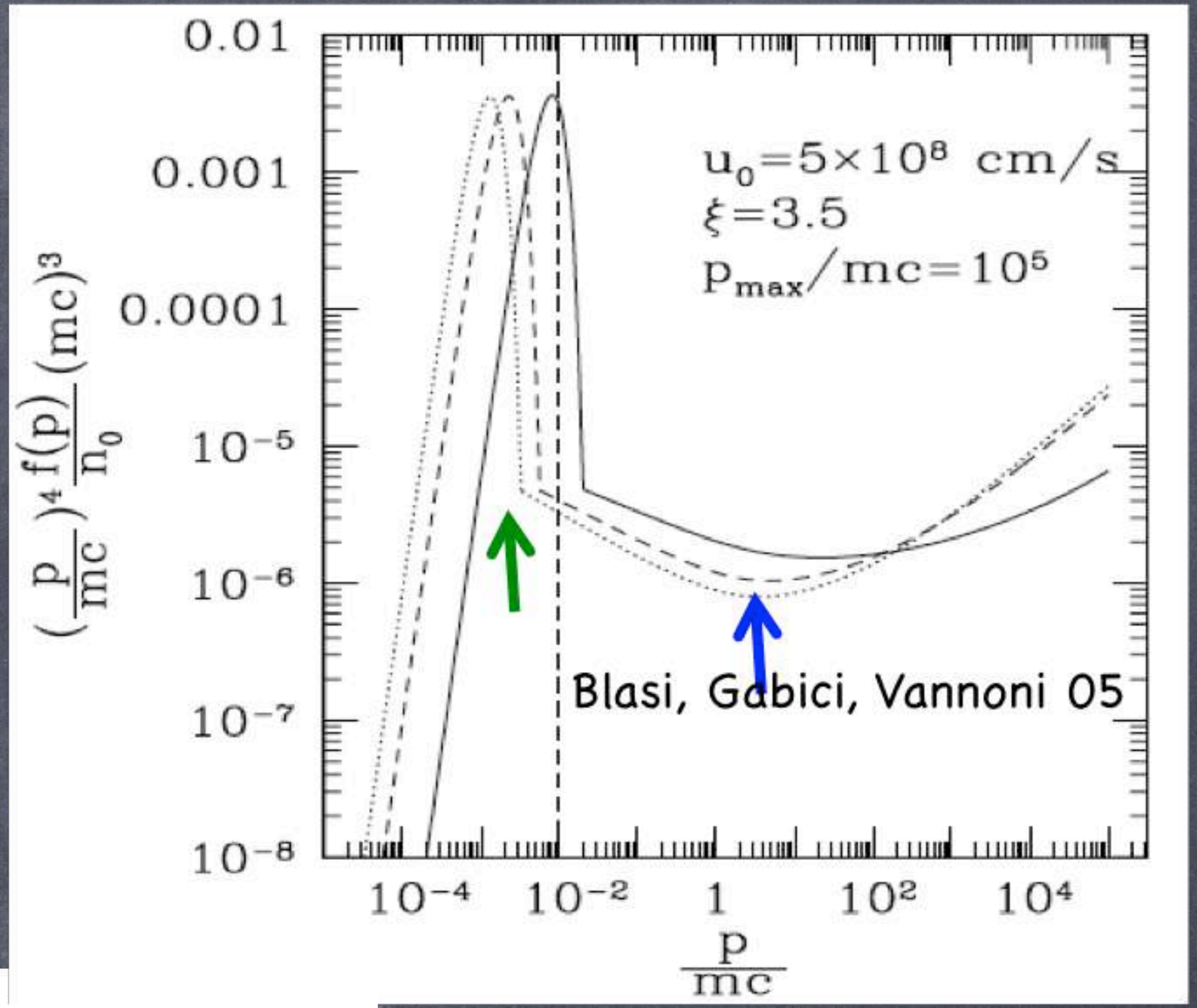
$$\frac{\partial}{\partial x}(\rho U) = 0$$
$$\frac{\partial}{\partial x}\left(\rho U^2 + p_g + p_{CR} + p_w\right) = 0$$
$$-\frac{\partial}{\partial x}\left[\frac{\rho u^3}{2} + \frac{\gamma_g u p_g}{\gamma_g - 1}\right] - u\frac{\partial}{\partial x}\left[p_{CR} + p_w\right] + \Gamma_w E_w = 0$$

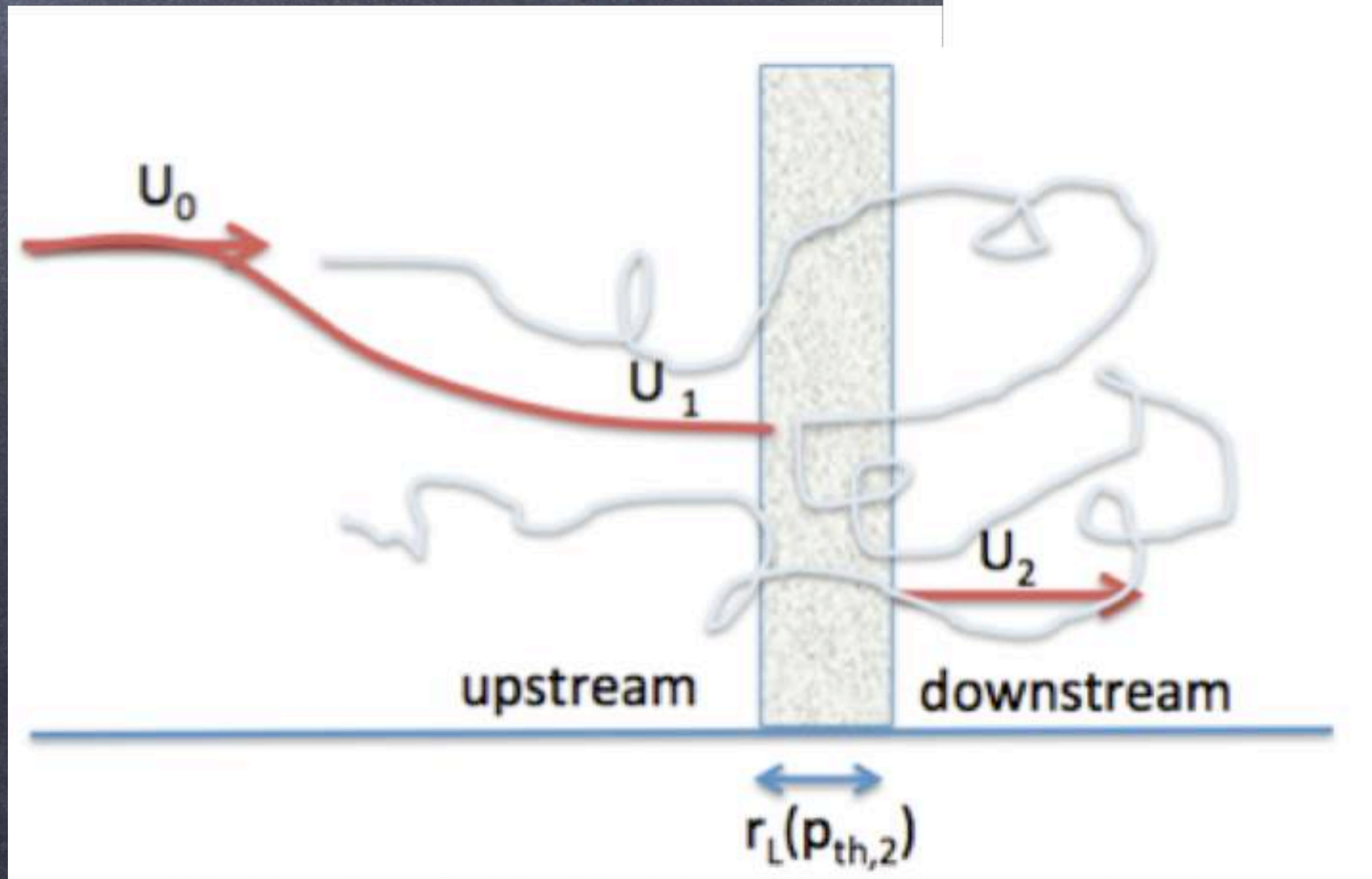
$$+ \quad \frac{\partial F_w}{\partial x} = u\frac{\partial P_w}{\partial x} + \sigma E_w - \Gamma_w E_w$$



CR SPECTRUM IN MODIFIED SHOCKS





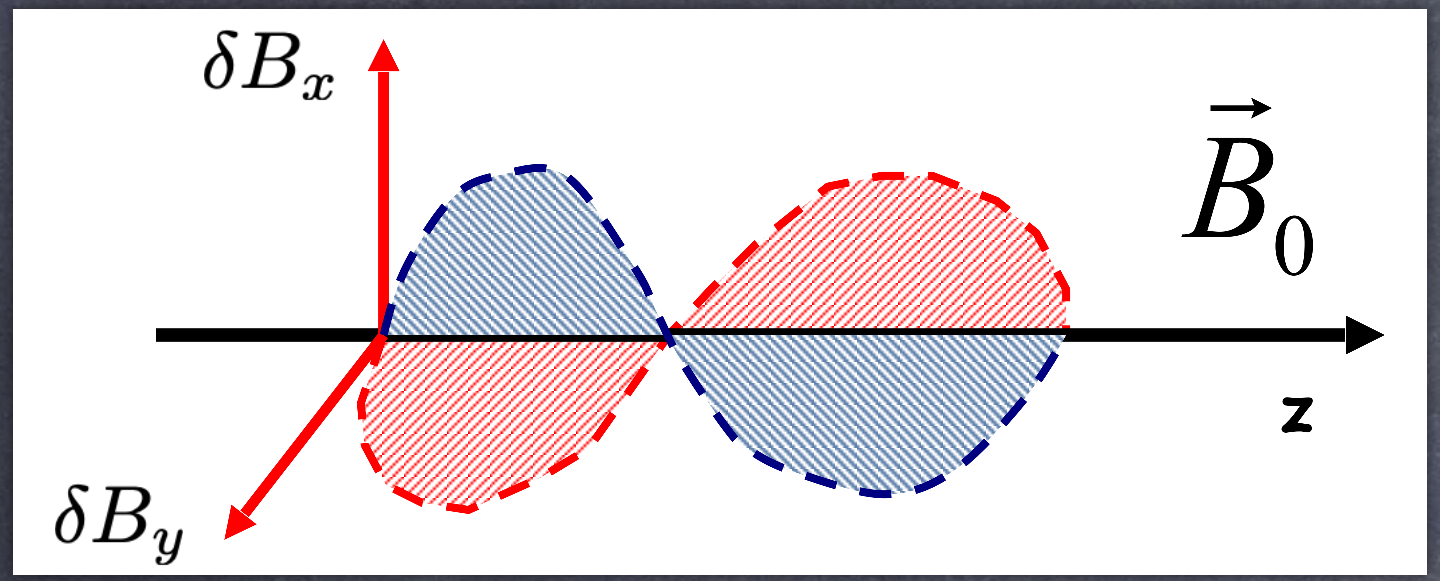


SHOCK BECOMES RADIATIVE —> R>4

PARTICLES OF DIFFERENT ENERGY EXPERIENCE DIFFERENT R —> CONCAVE SPECTRUM

MAGNETIC FIELD AMPLIFICATION…..

MAGNETIC FIELD AMPLIFICATION



PARTICLES MUST LOSE MOMENTUM TO WAVES DURING ISOTROPIZATION

$$\frac{dP_{part}}{dt} = \frac{n_{CR}\, m\, \gamma\, (\mathrm{v}_{bulk} - \mathrm{v}_A)}{\tau_{diff}}$$

$$\delta B \propto e^{i(kz-\omega t)}$$

$$\frac{dP_{wave}}{dt} = \frac{1}{\mathrm{v}_A}\frac{dE_w}{dt} = 2\frac{\Gamma_w}{\mathrm{v}_A}\frac{\delta B^2}{8\pi}$$

$$\omega = \omega_R + i\Gamma_w \longrightarrow \delta B \propto e^{\Gamma_w t}\, e^{i(kz-\omega_R t)}$$

$$\longrightarrow dE_w/dt = 2\Gamma_w \delta B^2/8\pi$$

$$\frac{dP_{wave}}{dt} = \frac{dP_{part}}{dt} \Rightarrow \Gamma_w = \frac{n_{CR}\, m\, \gamma(\mathrm{v}_{bulk} - \mathrm{v}_A)}{\tau_{diff}} \frac{4\pi \mathrm{v}_A}{\delta B^2}$$

$$\tau_{diff} \approx \frac{1}{D_{\theta\theta}} = \frac{4}{\pi\Omega}\left(\frac{B}{\delta B}\right)^2$$

CR STREAMING AT SUPERALFVENIC SPEED AMPLIFIES MAGNETIC TURBULENCE

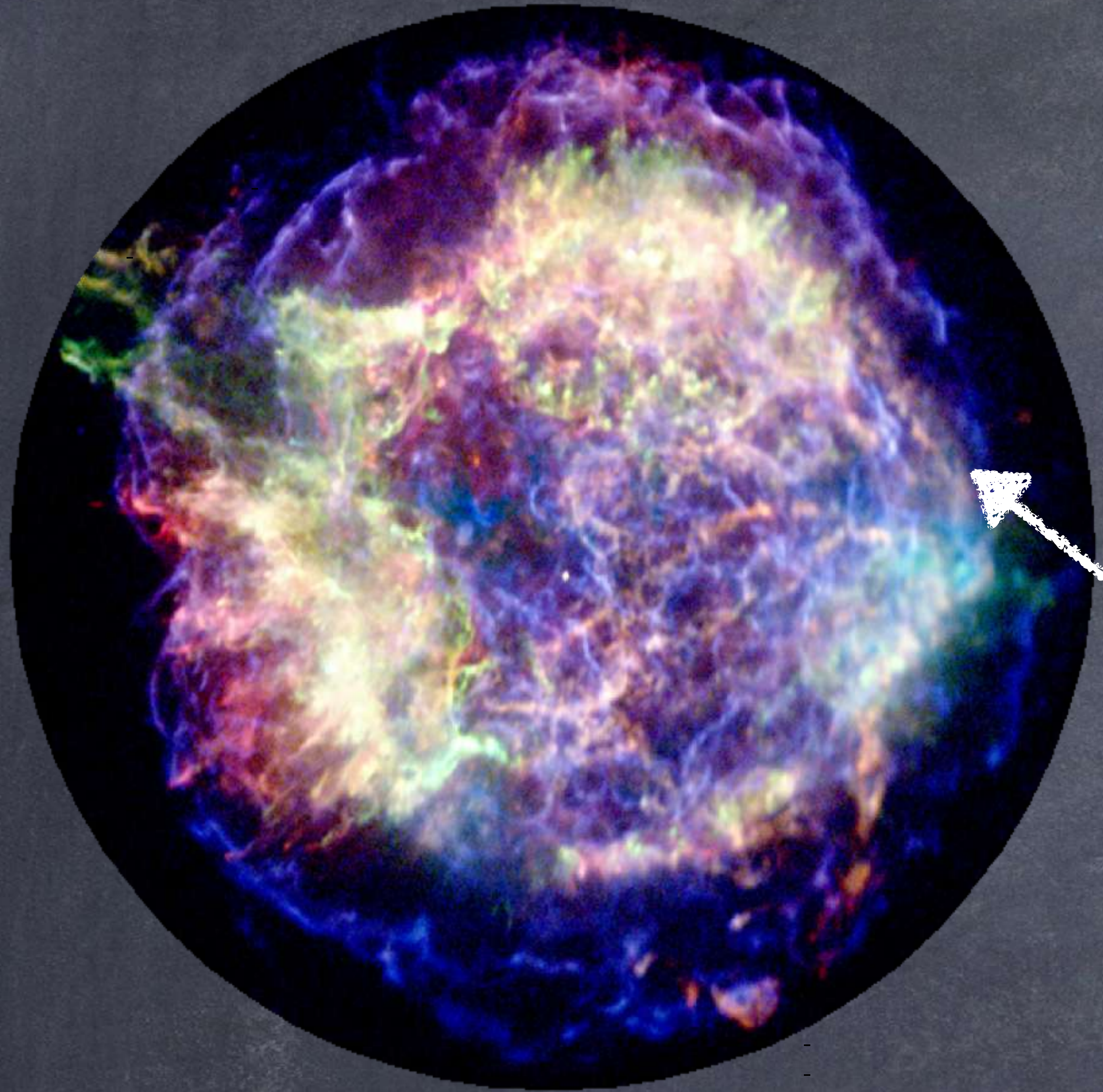
INDUCES AMPLIFICATION UP TO $\delta B/B \lesssim 1$

RESONANT STREAMING INSTABILITY

$$\boxed{\Gamma_w = \frac{\pi}{4}\frac{n_{CR}}{n_i}\frac{(\mathrm{v}_{bulk} - \mathrm{v}_A)}{\mathrm{v}_A}\omega_{ci}}$$

NOTE: GROWTH RATE DEPENDS ON RESONANT CR BUT NOT ON B

AMPLIFIED MAGNETIC FIELDS

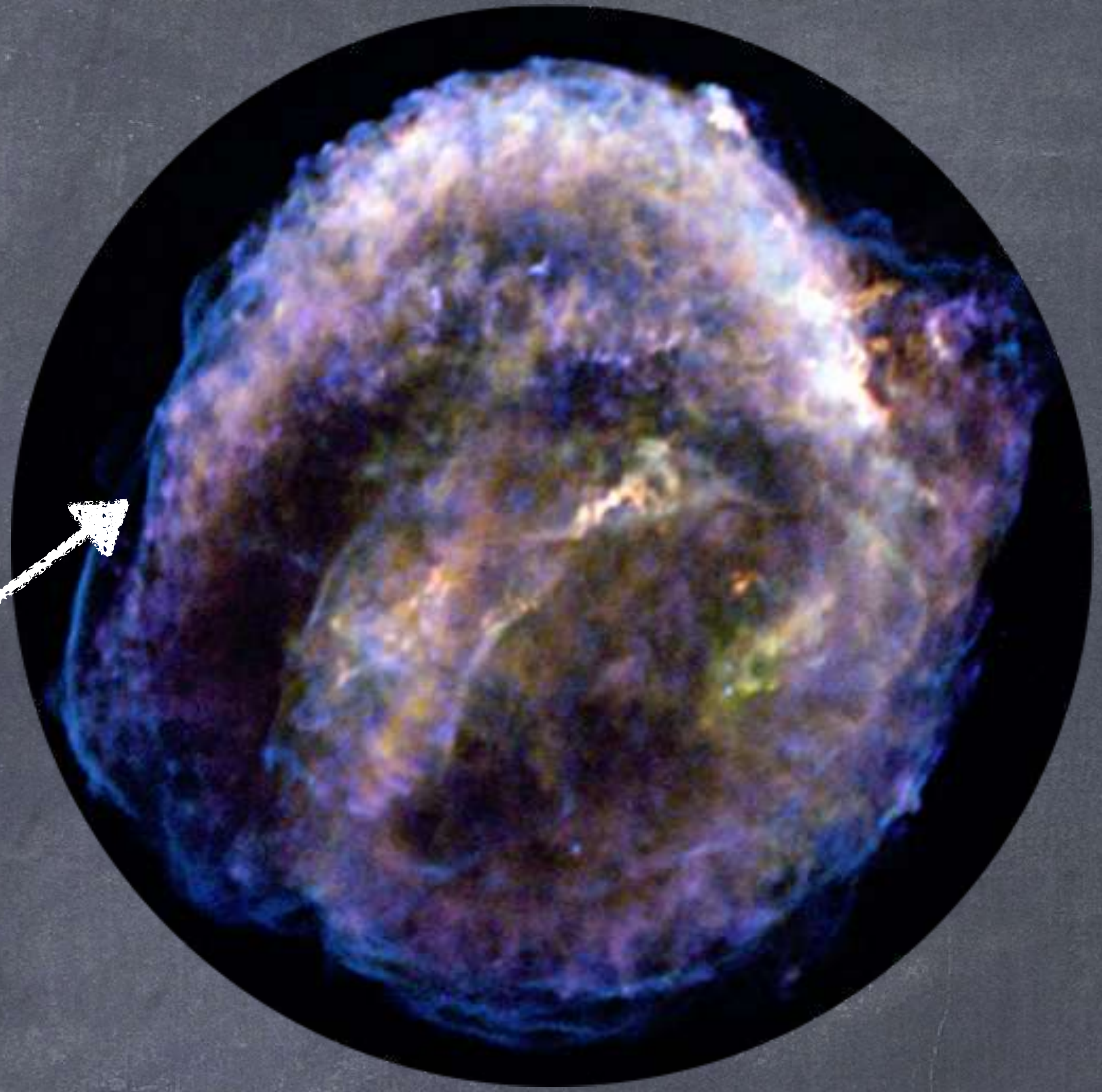


e.g. Vink 12

$$\Delta x \approx 0.01\ pc$$

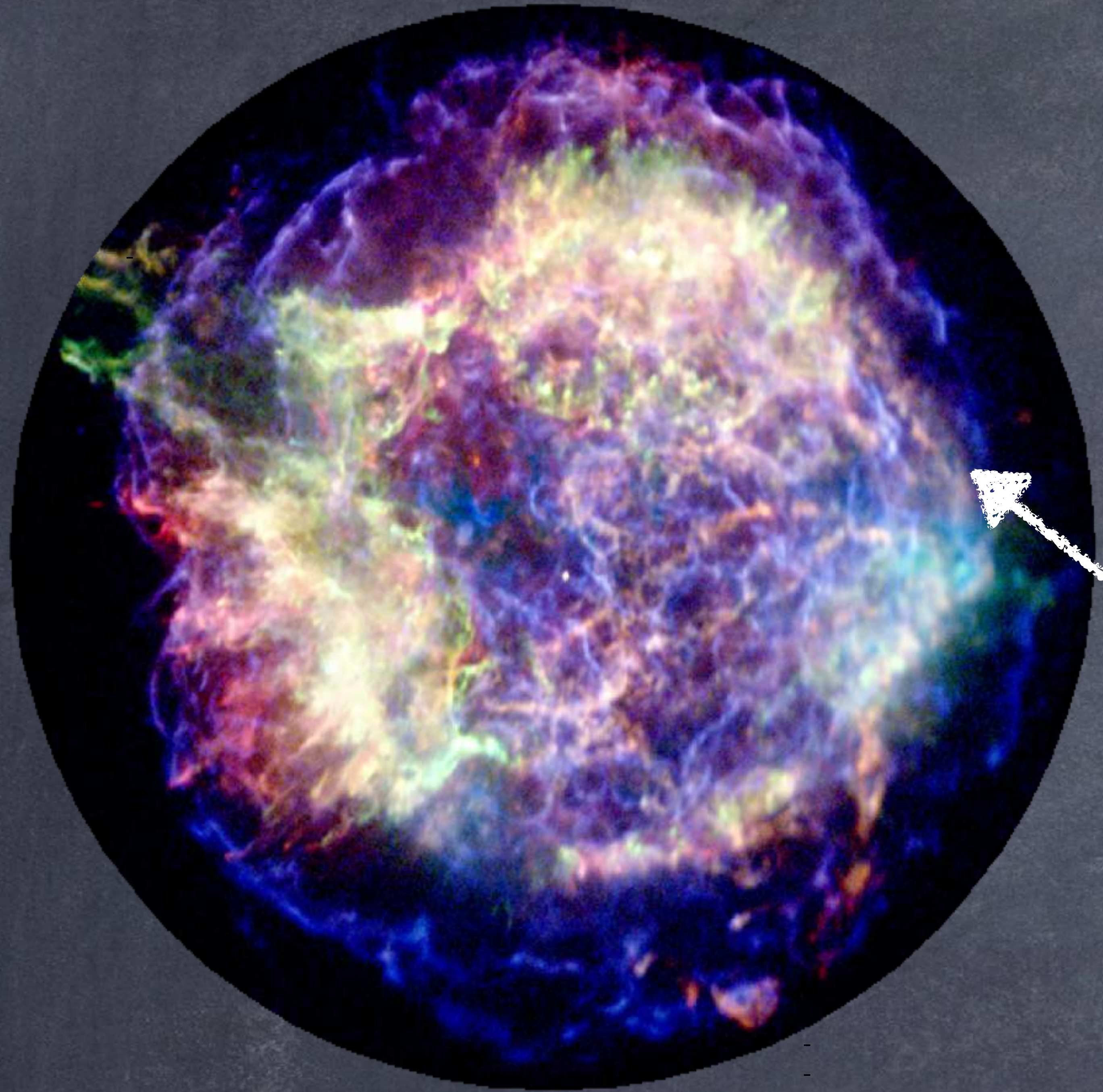
$$\Downarrow$$

$$B \approx 100 - 300\ \mu G$$



INTERPRET THE RIMS AS LOSS-LENGTH OF HIGHEST ENERGY ELECTRONS...

AMPLIFIED MAGNETIC FIELDS



e.g. Vink 12

$$\Delta x = \sqrt{D_B\, \tau_{sync}} = 0.04 B_{100}^{-3/2}\ pc$$

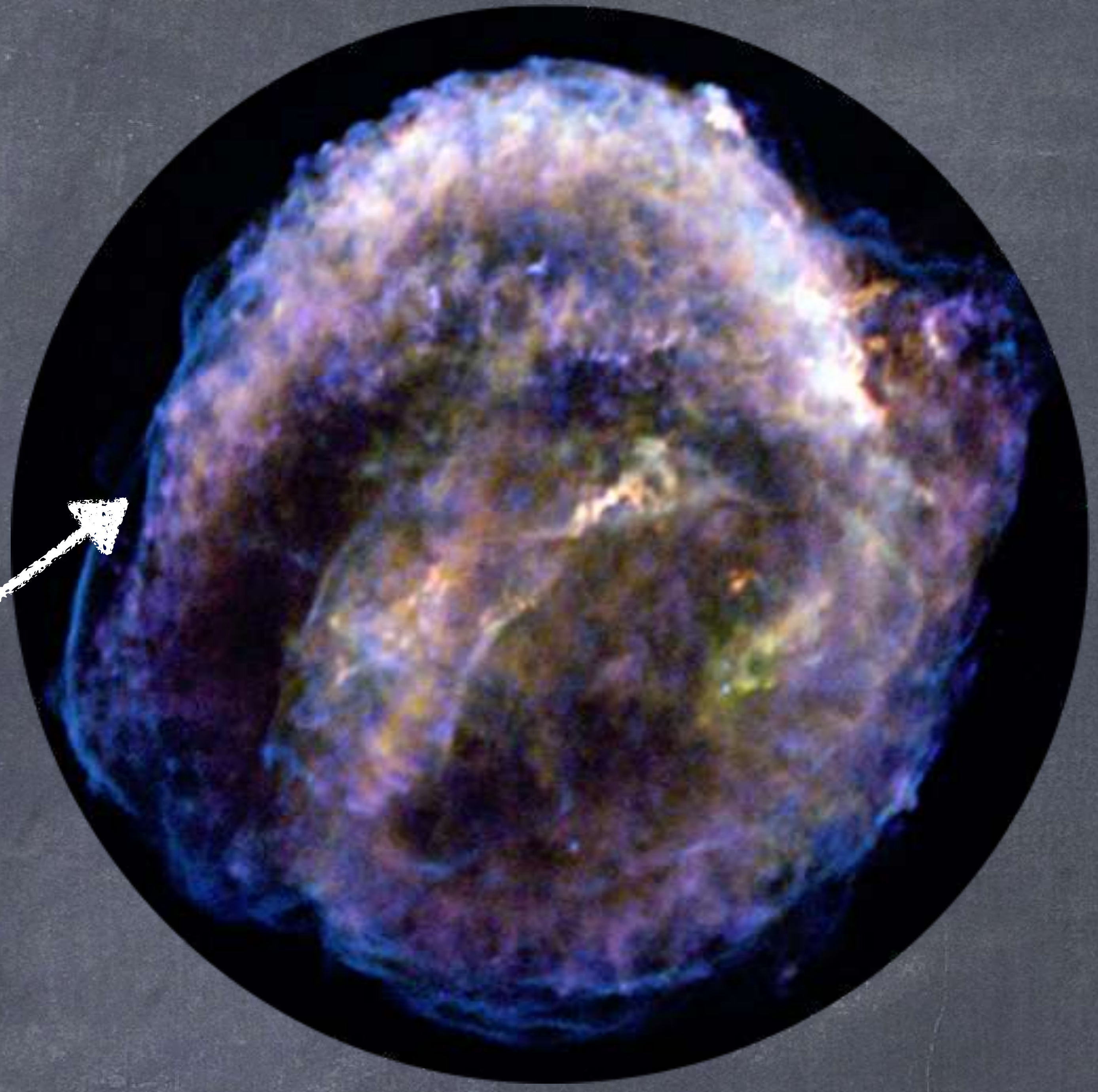
$$D_B = \frac{c}{3} r_L = \frac{c}{3}\frac{E}{eB}$$

$$t_{\rm sync} = \frac{6\pi m^2 c^3}{\sigma_T E B^2}$$

$\Delta x \approx 0.01\ pc$

⬇

$B \approx 100 - 300\ \mu G$



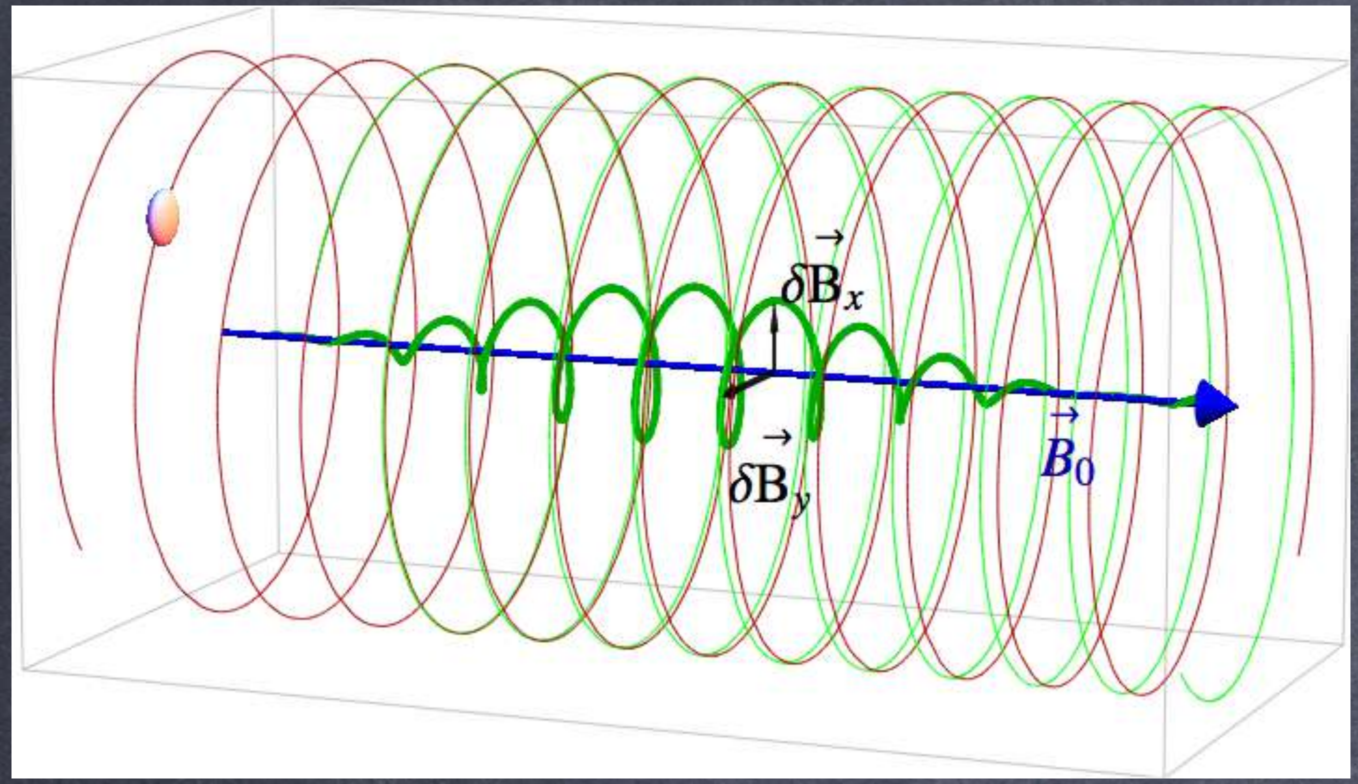
$E_e \approx 10\ \mathrm{TeV}\ \epsilon_{\gamma,\mathrm{keV}}\ B_{100}^{-1/2}$

ϵ_γ=1 keV

➡ 30 TeV ELECTRONS

- ELECTRONS ARE LOSS-LIMITED
- PROTONS COULD REACH HIGHER ENERGIES
- MFA A SIGN OF EFFICIENT PROTON ACCELERATION ITSELF

THE STREAMING INSTABILITY



KNOWN SINCE THE '70S

PARTICLES STREAMING AT $v_d > v_A$

RESONANTLY AMPLIFY AMBIENT ALFVEN WAVES

WAVES AT $k_{res} = 1/r_L$ GROW WITH $\Gamma_{res} = \frac{\pi}{4} \frac{n^*_{CR}}{n_i} \Omega_c \frac{v_d - v_A}{v_d}$

WHERE $n^*_{CR} = n_{CR}\left(p > \frac{eB_0}{ck}\right)$

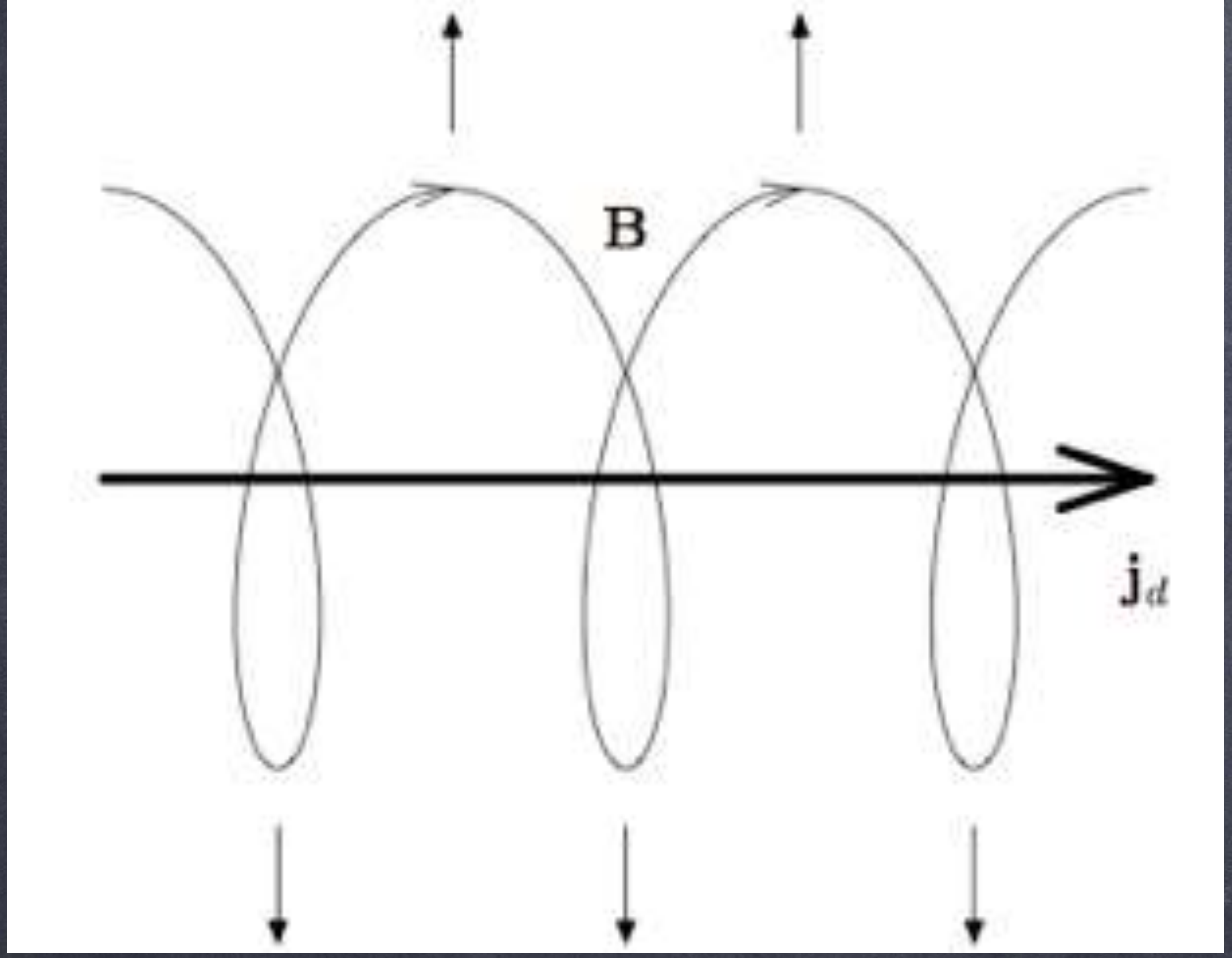
MAGNETIC FIELD CAN BE AMPLIFIED UP TO $\frac{\delta B}{B_0} \lesssim 1$

REANALYSIS BY BELL '04

ABOVE DESCRIPTION CORRECT ONLY IF $\frac{4\pi}{c} J_{CR} < \frac{B_0}{r_{L,0}}$

BELL INSTABILITY

$$\frac{4\pi}{c} J_{CR} > \frac{B_0}{r_{L,0}} \qquad \frac{U_{CR}}{U_B} > \frac{c}{v_d}$$

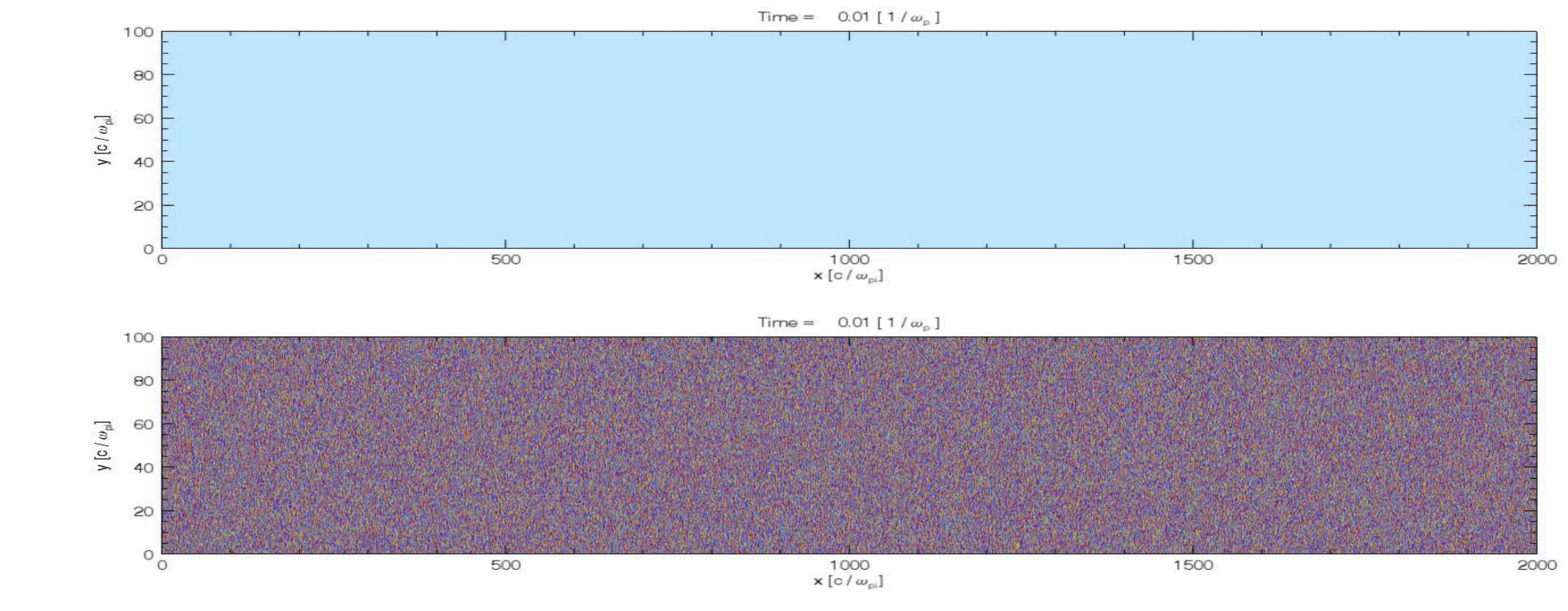


Ptuskin & Zirakashvili 08

- CR CURRENT INDUCES COMPENSATING CURRENT IN THE PLASMA
- $\vec{J}_{ret} \times \vec{B}$ INDUCES TRANSVERSE PLASMA MOTION
- RESULTING CURRENT ACTS AS A SOURCE OF B
- FOR RIGHT-HAND POLARIZED WAVES, FIELD LINES ARE STRETCHED: FIELD IS AMPLIFIED POTENTIALLY WELL ABOVE B_0

BELL INSTABILITY: SATURATION

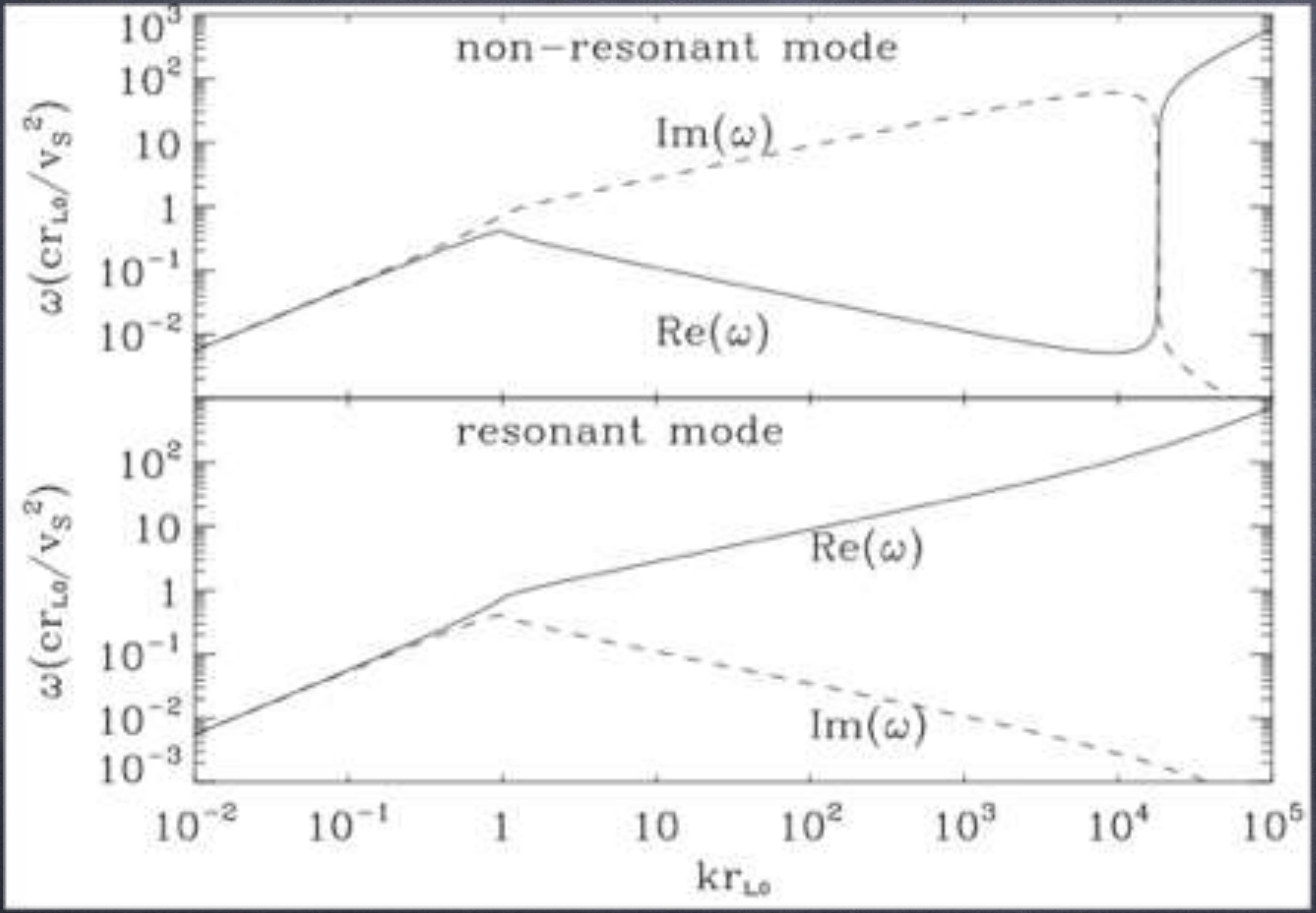
$$\frac{4\pi}{c} J_{CR} > \frac{B_0}{r_{L,0}} \qquad \frac{U_{CR}}{U_B} > \frac{c}{\mathrm{v}_d} \qquad \Rightarrow \qquad \frac{\delta B^2}{4\pi} = \frac{v_s}{c} U_{CR} = \xi_{CR} \rho v_s^2 \frac{v_s}{c}$$

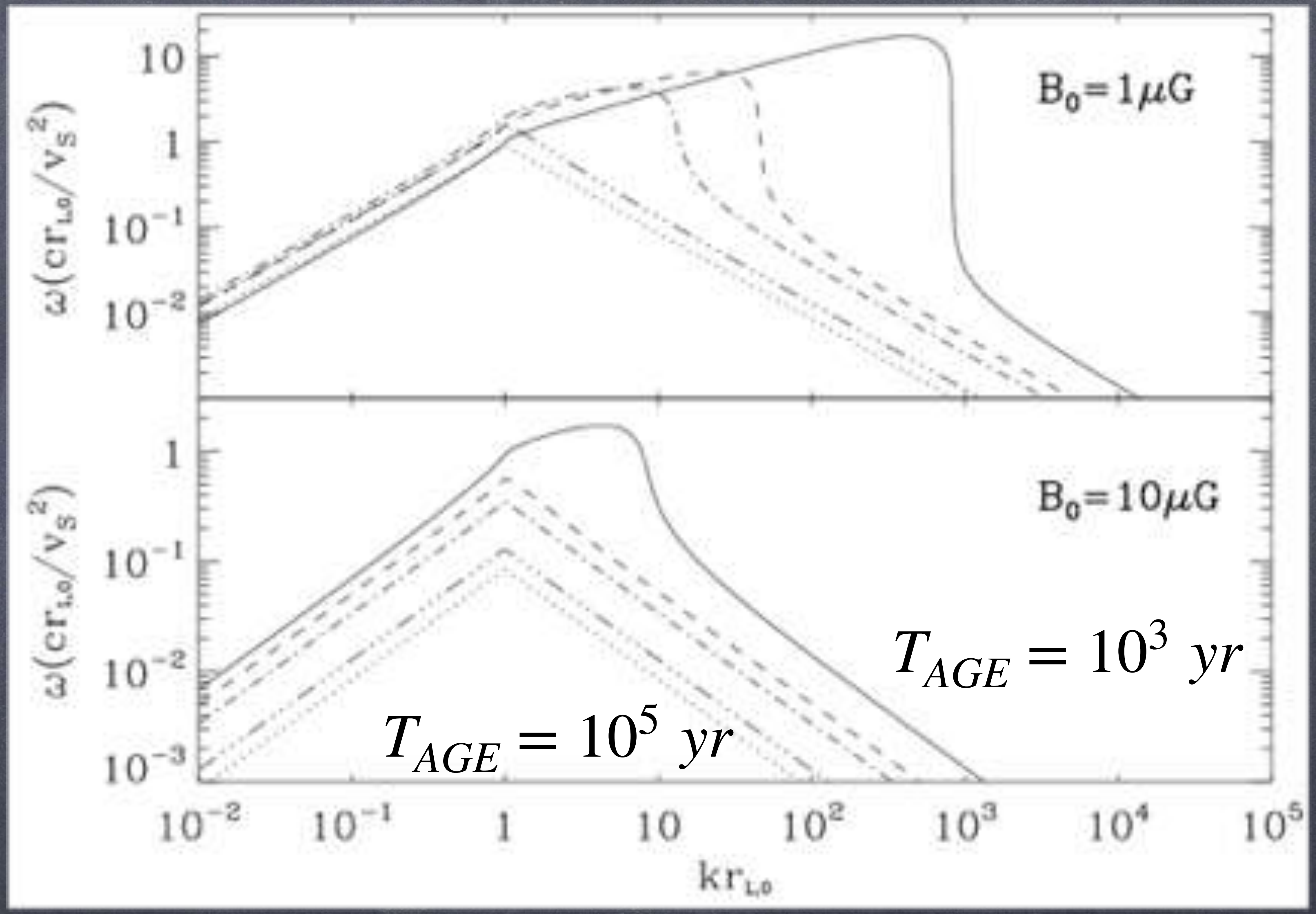


Caprioli & Spitkovsky 13,14

EVOLUTION WITH SNR AGE

$$\gamma_{\max} \propto \xi_{\rm CR} v_s^3$$





EA & Blasi 09

MAXIMUM ENERGY AND PARTICLE ESCAPE

LITTLE UPSTREAM TURBULENCE

MANY PARTICLES ESCAPE

LARGE CURRENT

TURBULENCE INCREASES

PARTICLE ESCAPE IS SUPPRESSED

SELF-REGULATNG MECHANISM

$$E_M \approx 130 \left(\frac{\xi_{\rm CR}}{0.1}\right) \left(\frac{M_{\rm ej}}{M_\odot}\right)^{-\frac{2}{3}} \left(\frac{E_{\rm SN}}{10^{51}{\rm erg}}\right) \left(\frac{n_{\rm ISM}}{{\rm cm}^{-3}}\right)^{\frac{1}{6}} {\rm TeV}$$

TYPE I

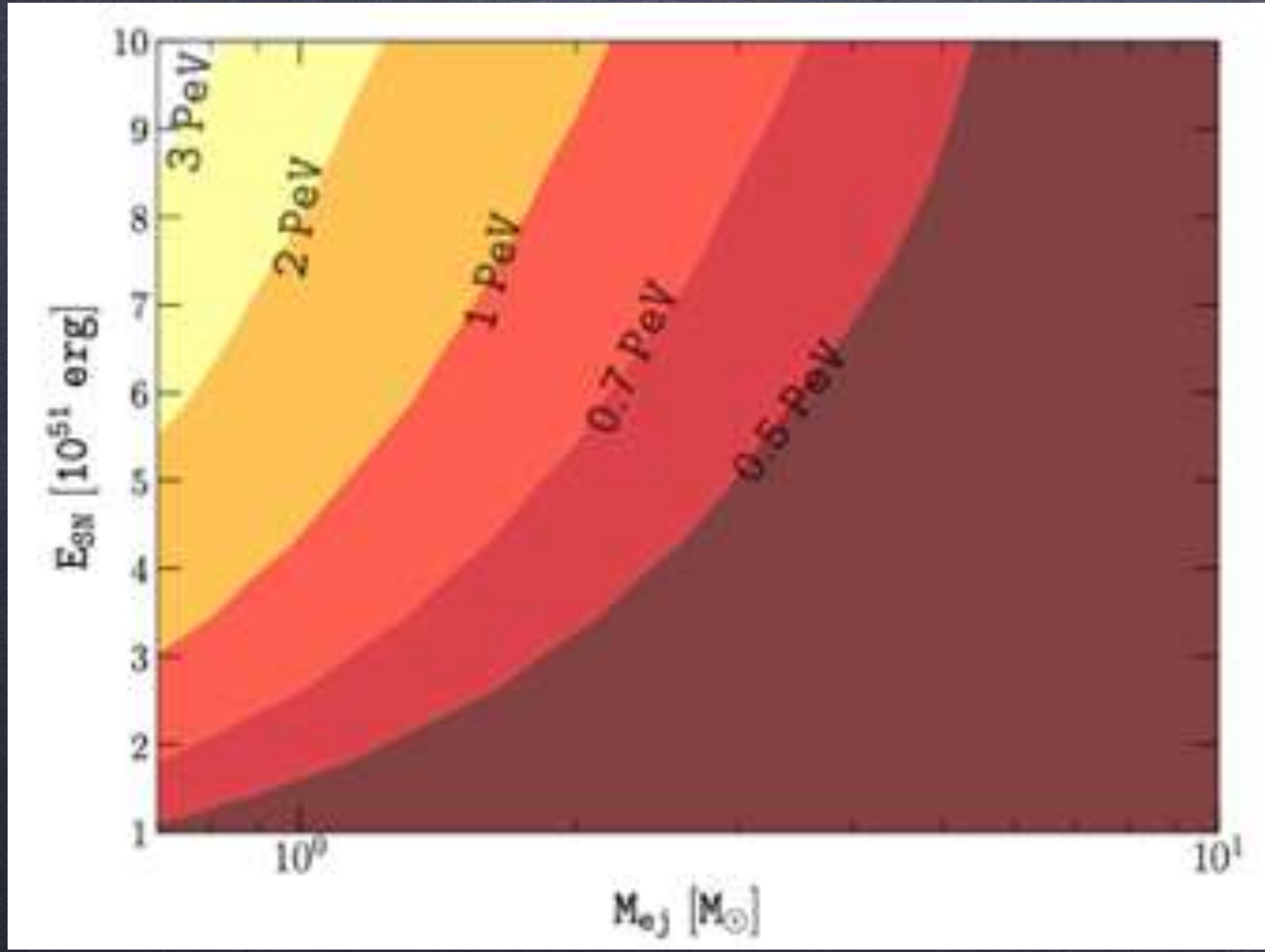
$$E_M \approx 1 \left(\frac{\xi_{\rm CR}}{0.1}\right) \left(\frac{M_{\rm ej}}{M_\odot}\right)^{-1} \left(\frac{E_{\rm SN}}{10^{51}{\rm erg}}\right) \left(\frac{\dot{M}}{10^{-5} M_\odot {\rm yr}^{-1}}\right)^{\frac{1}{2}} \left(\frac{v_w}{10{\rm km/s}}\right)^{-\frac{1}{2}} {\rm PeV}$$

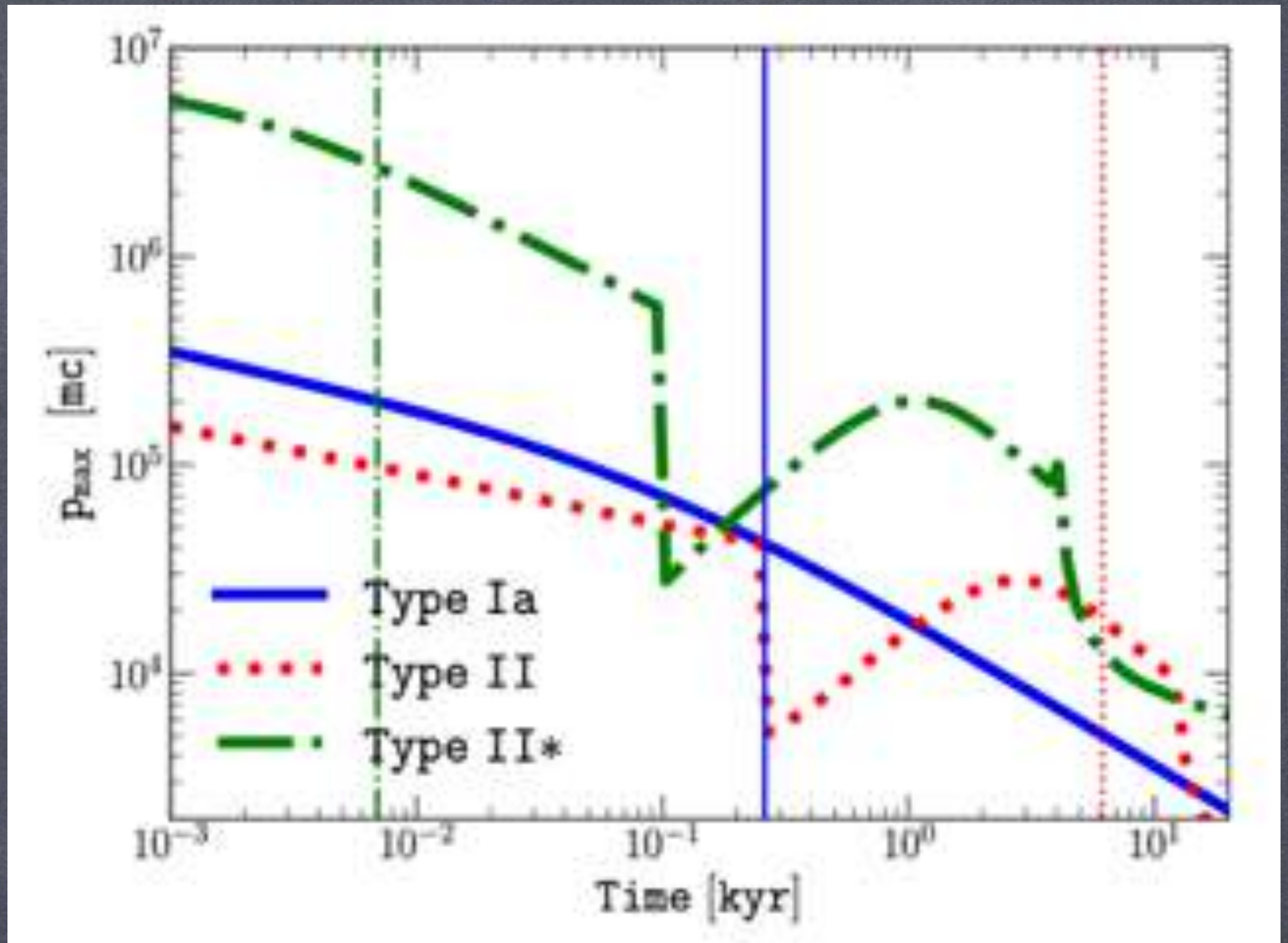
TYPE II

PEVATRON SNRs?

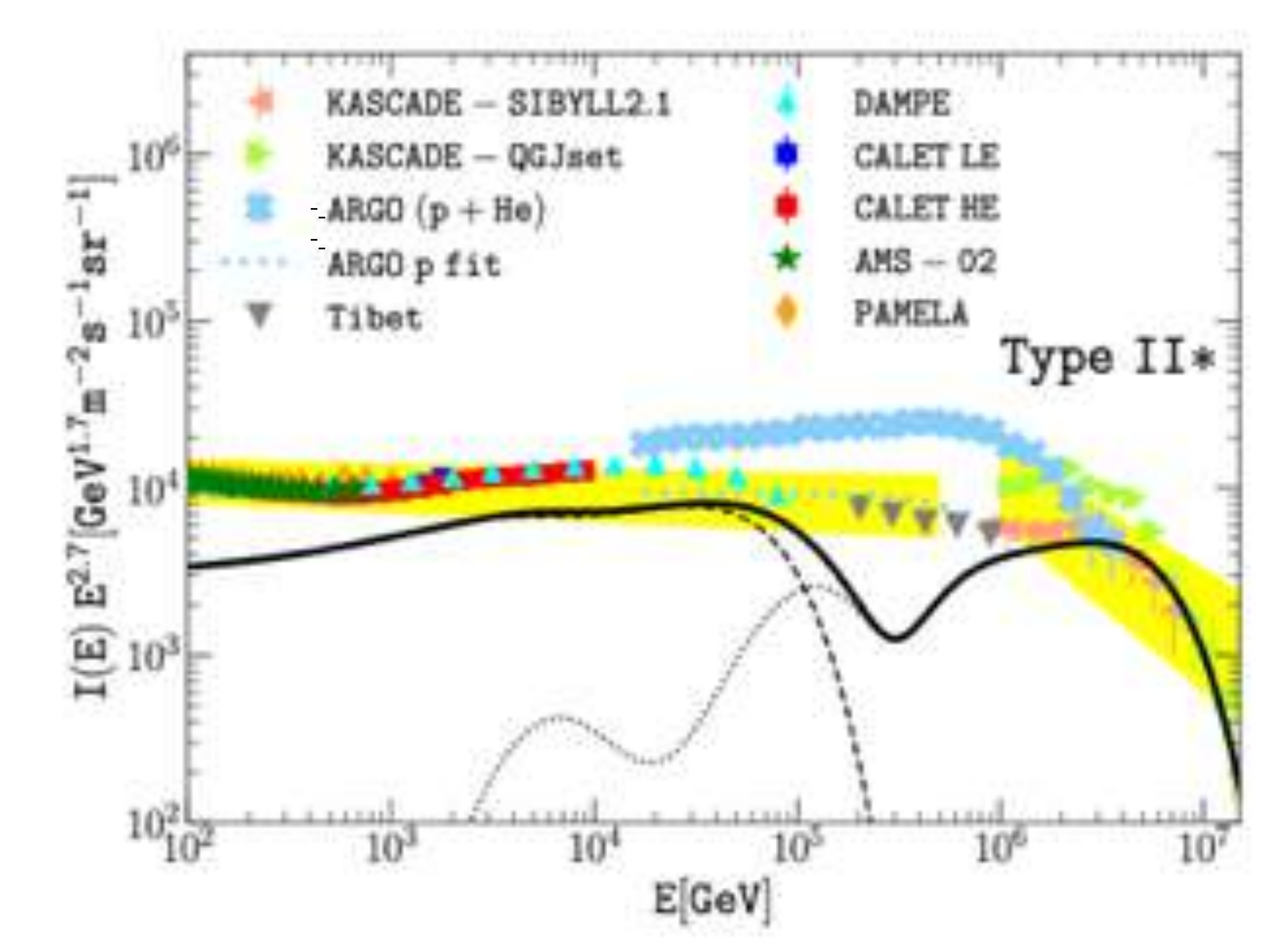
Type	Ia	II	II*
M_{ej} [$M_\odot$]	1.4	5	1
E_{SN} [10^{51} erg]	1	1	10
$\dot{M}$ [10^{-5} $M_\odot$/yr]	–	1	10
u_w [10^6 cm/s]	–	1	1
r_1 [pc]	–	1.5	1.3

TYPE II*



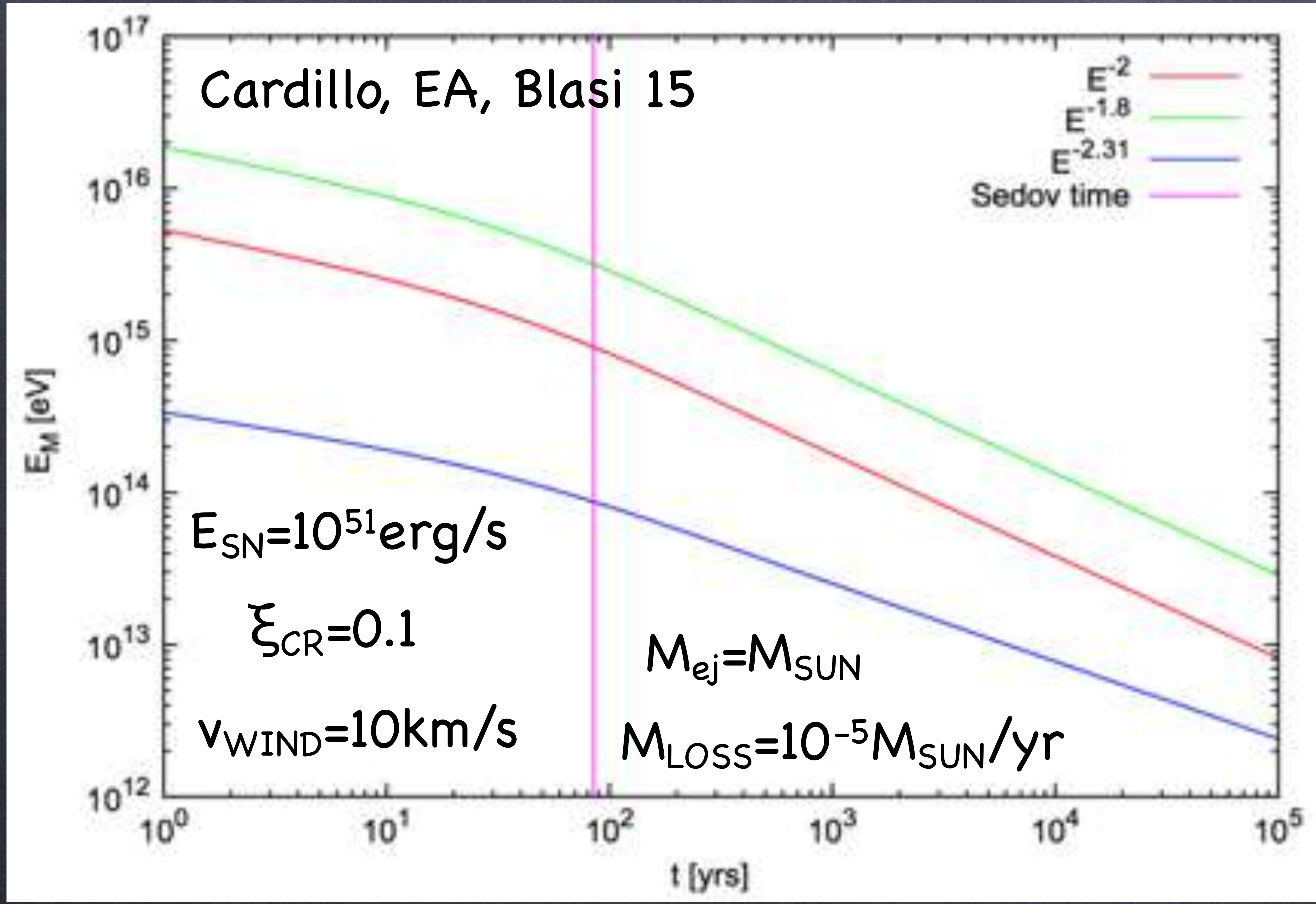


TYPE II* WOULD DOMINATE ALSO AT 10^2–10^4 GeV



Cristofari, Blasi, EA 20

STEEP PARTICLE SPECTRA MAKE IT WORSE!



RARE (<1/10000 yr^{-1})

EXTREME EVENTS ($E_{SN}>10^{52}$erg)

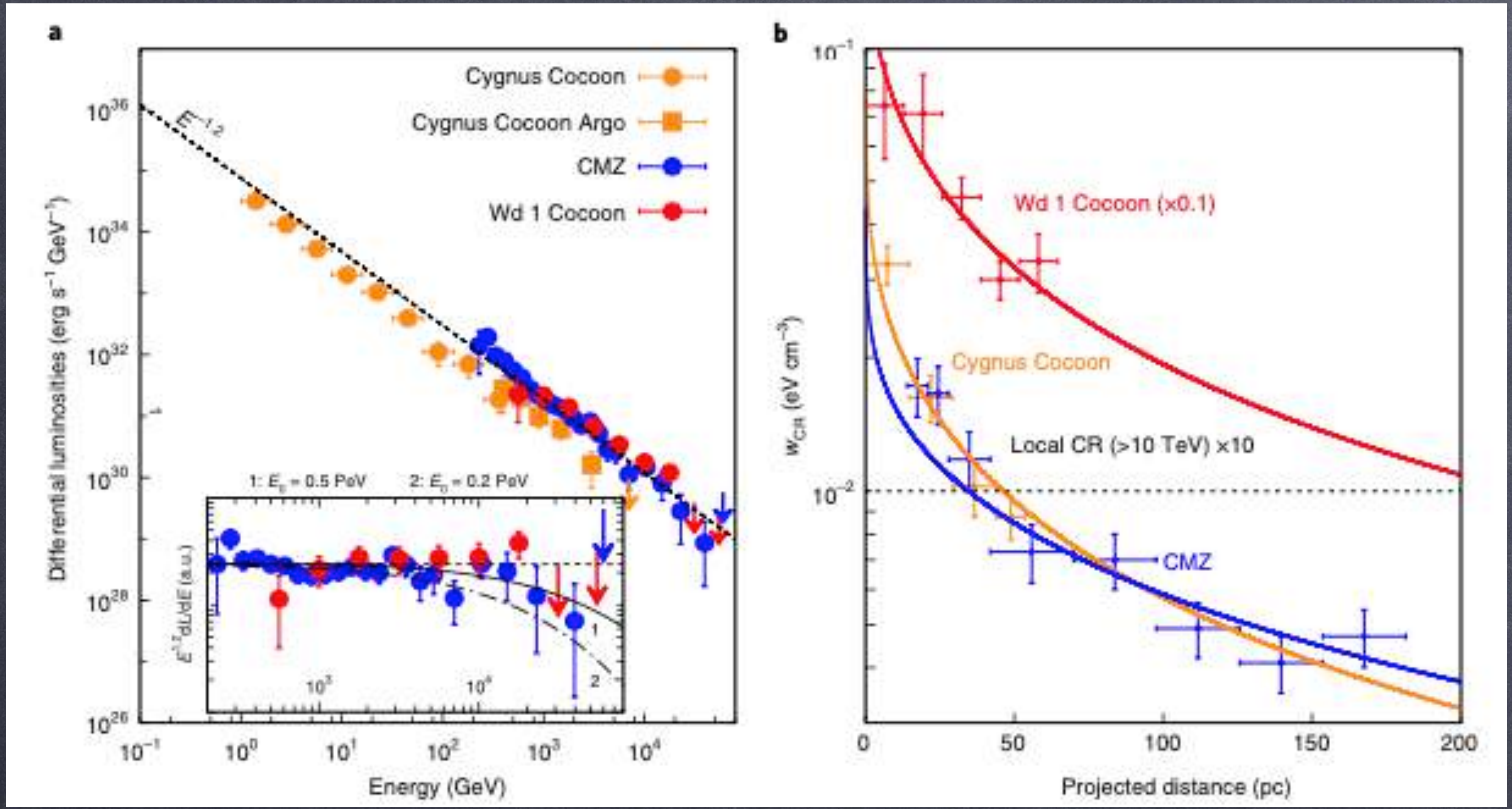
EXTREME EFFICIENCY ($\xi_{CR}>30\%$)

NO HOPE IF SPECTRUM STEEP

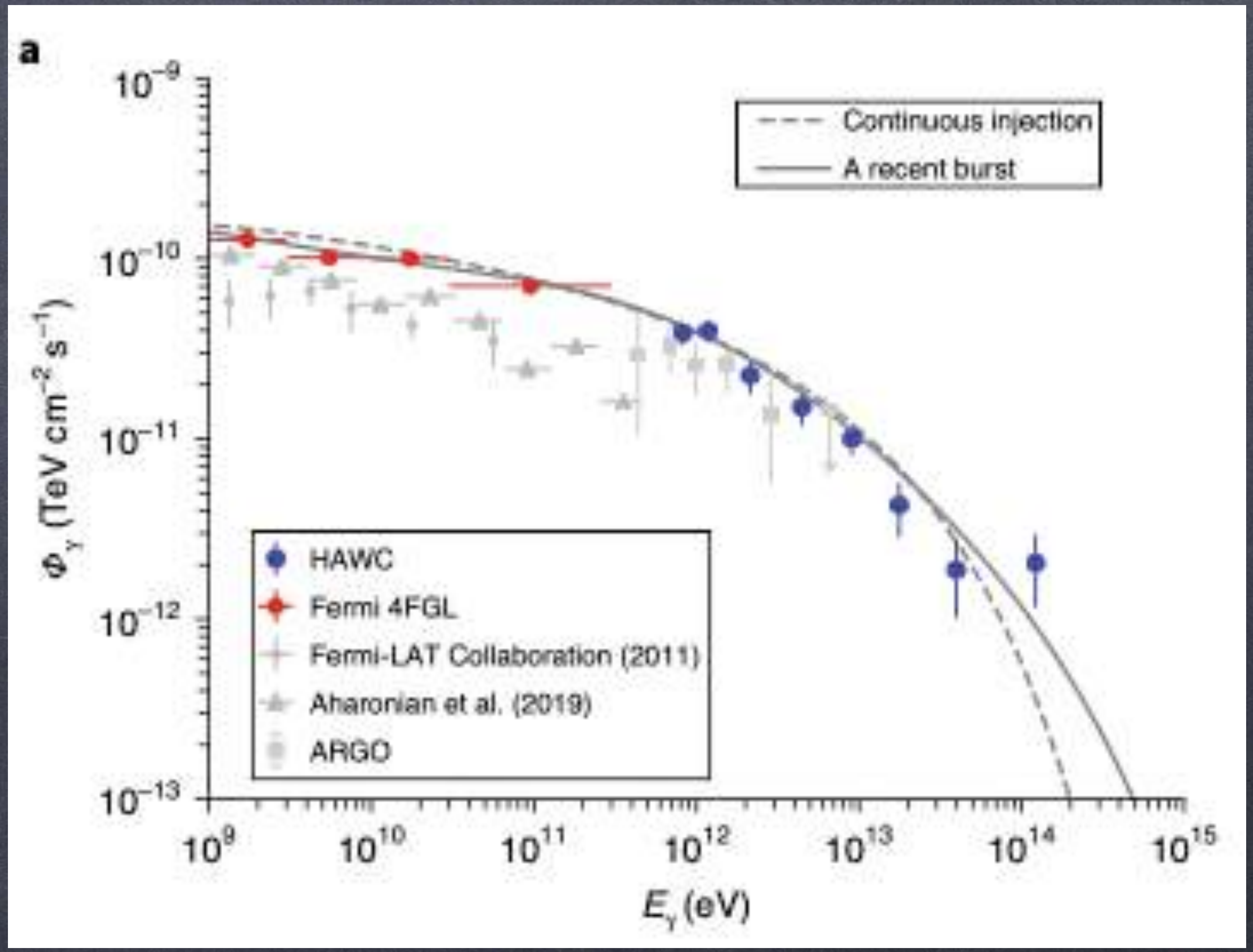
- PROPAGATION POINTS TO STEEP INJECTION SPECTRA (Aguilar+ 16; EA & Blasi 18)
- INJECTED PARTICLE SPECTRA STEEP ONLY IF SOURCE SPECTRA STEEP (Schure & Bell 14; Cardillo, EA, Blasi 15)

ALTERNATIVE PEVATRONS

STAR FORMING REGIONS?



Aharonian+ 19

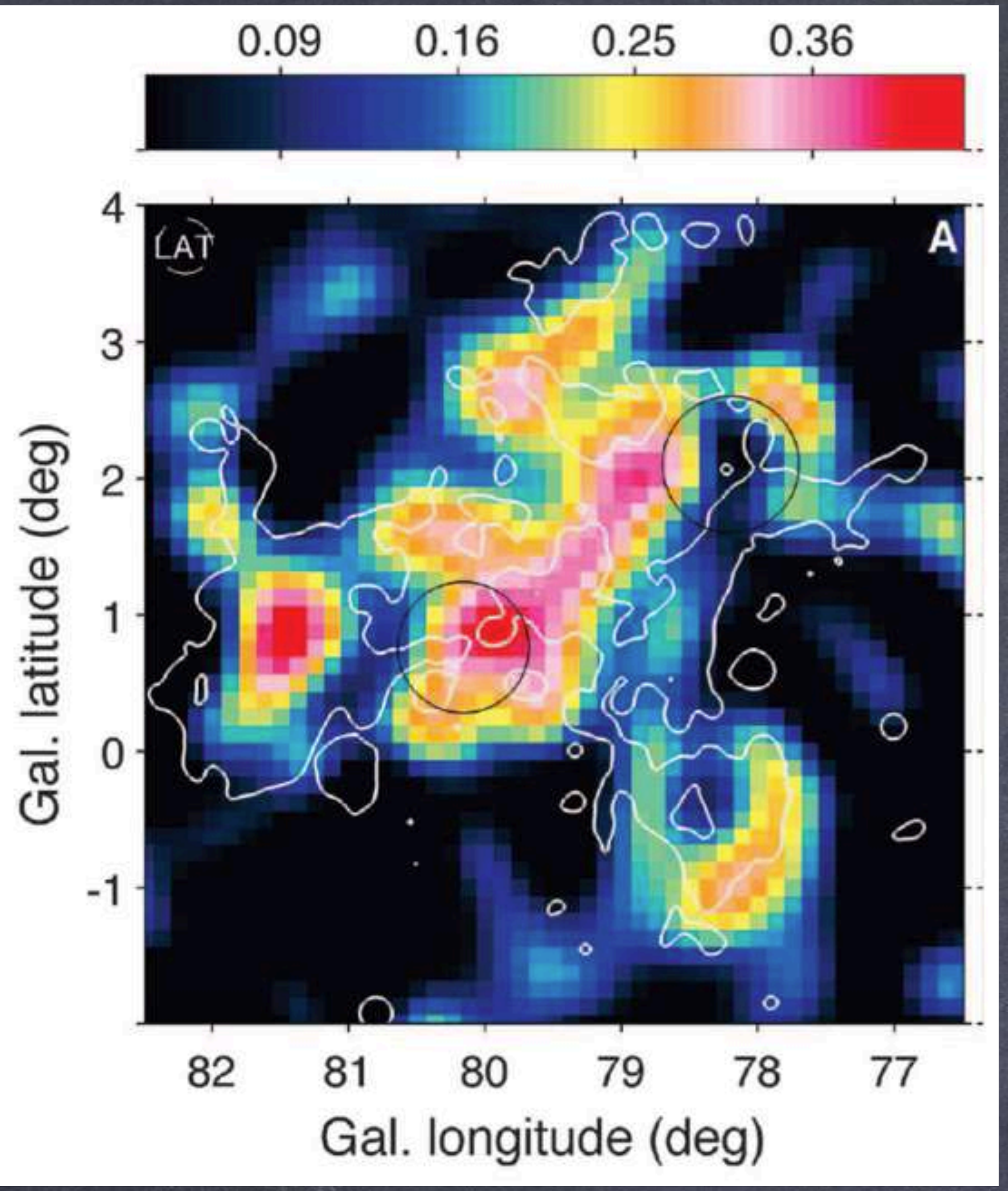


Abeysekara+ 21

$$E_p \approx 300\ TeV$$

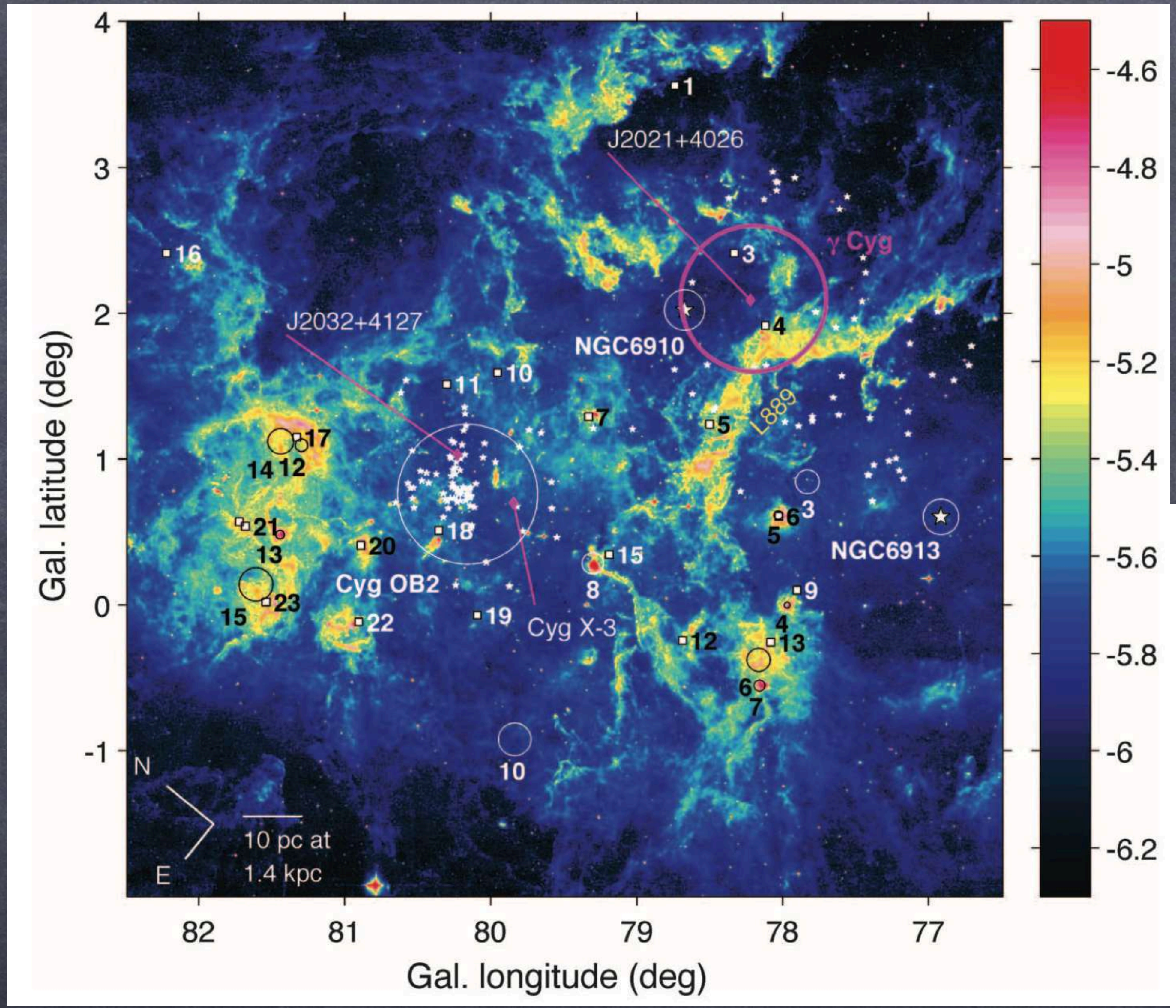
THE CYGNUS REGION

FERMI VIEW

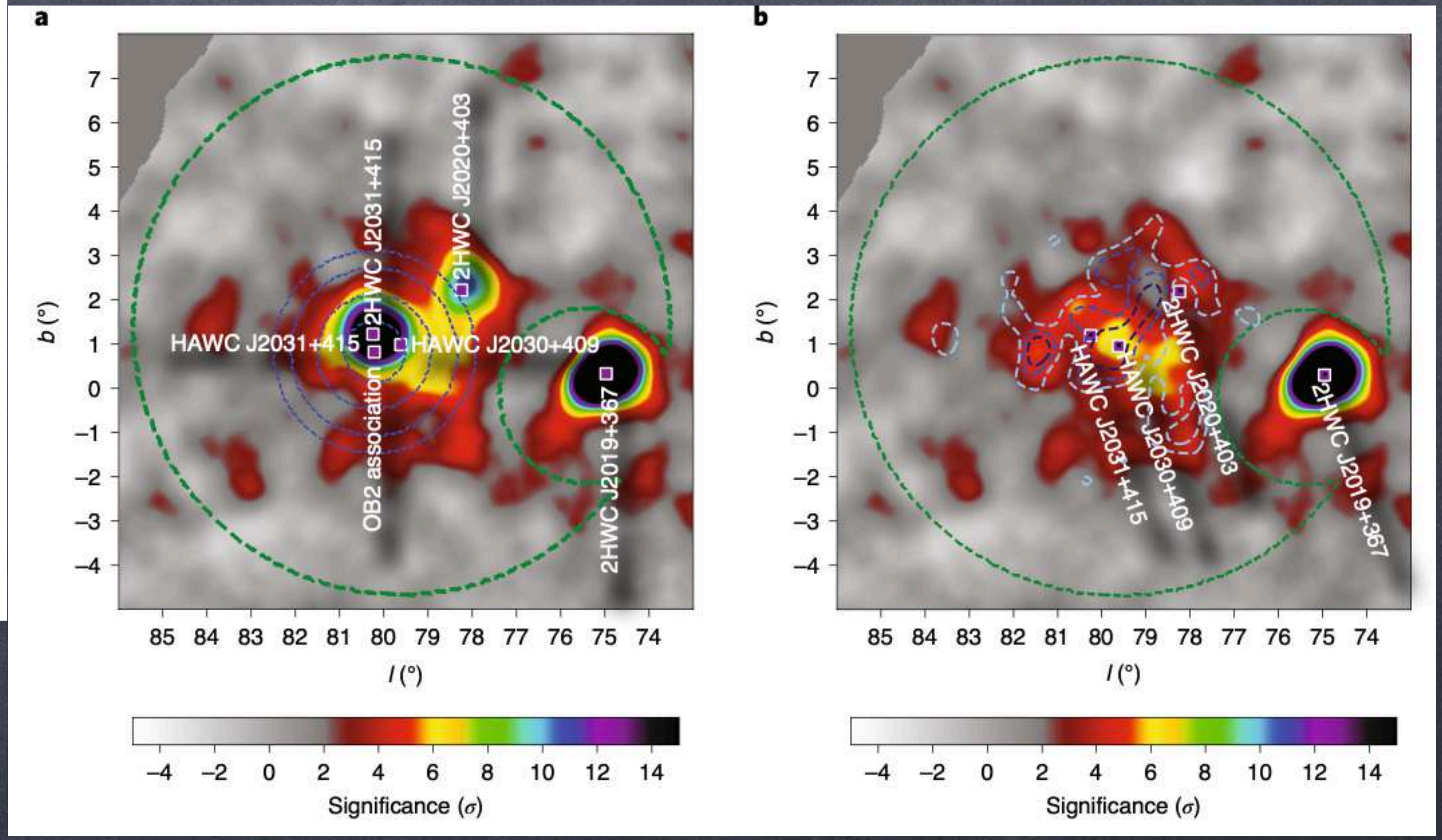


Ackermann+ 11

AN EXTREMELY CROWDED REGION



HAWC VIEW



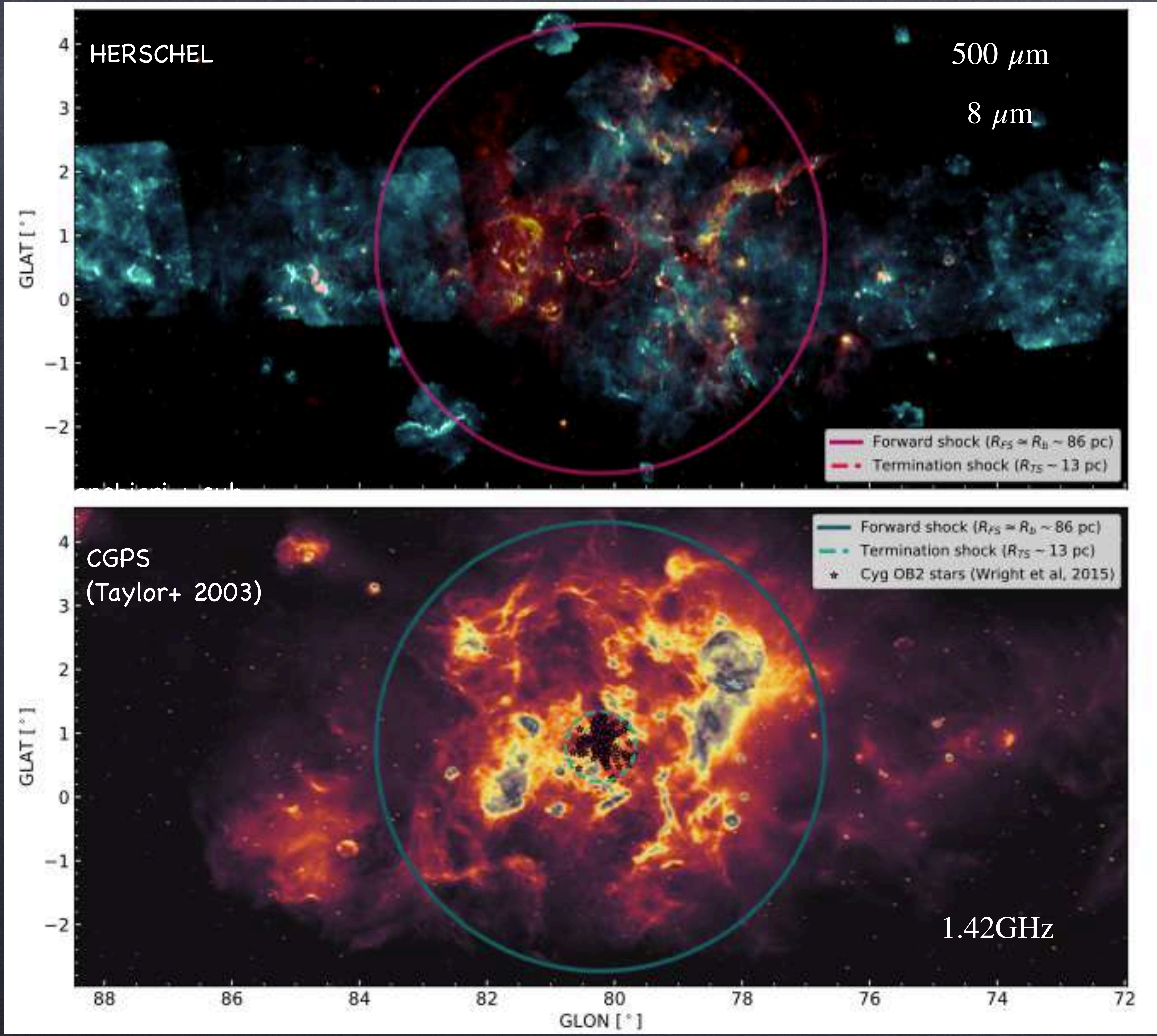
Abeysekara+ 21

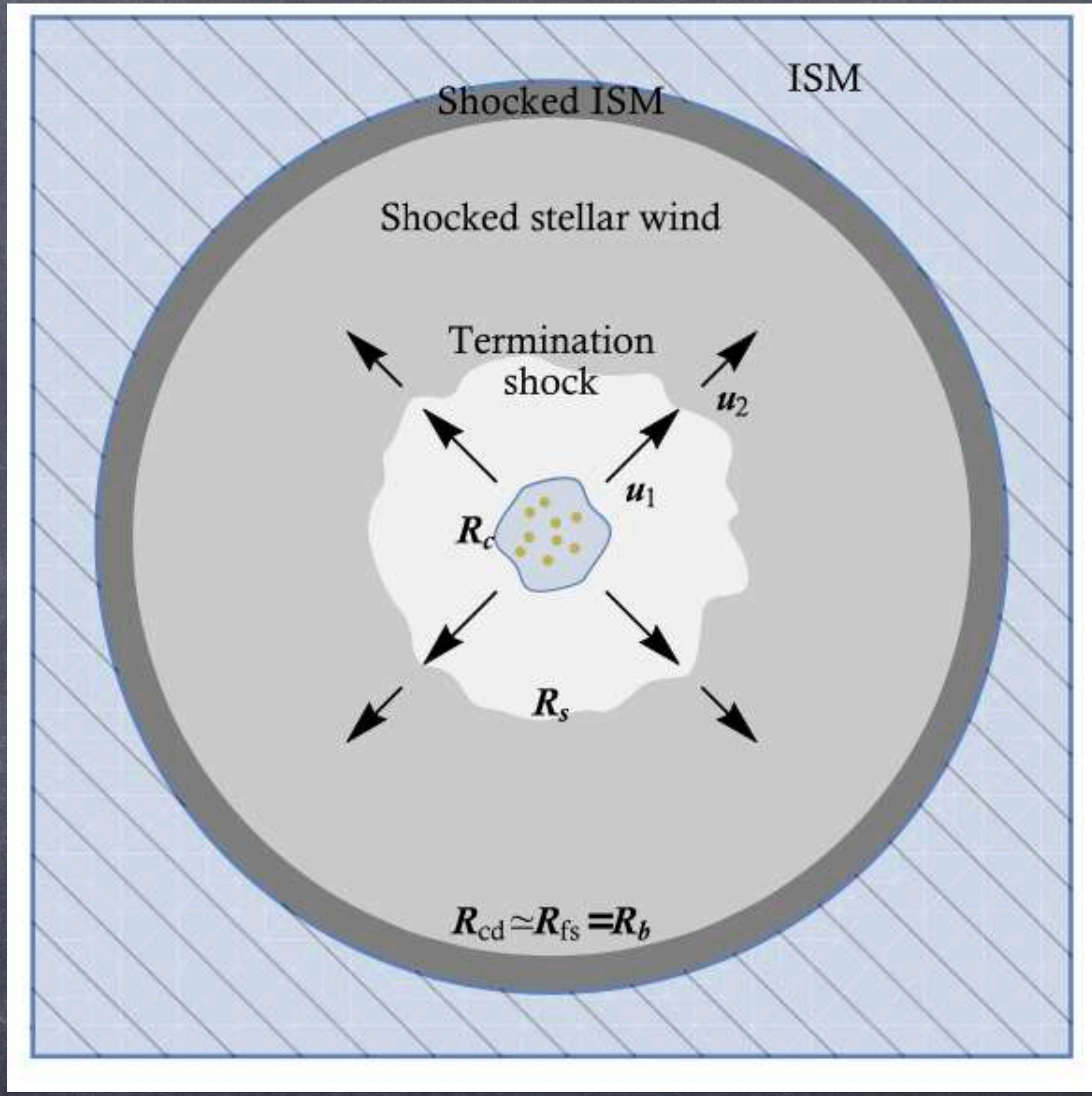
CTA (Bykov+20, Morlino+21) AND

ASTRI-MiniArray (Vercellone+ 22)

NEEDED TO DISENTANGLE SOURCES AT 1-100 TeV

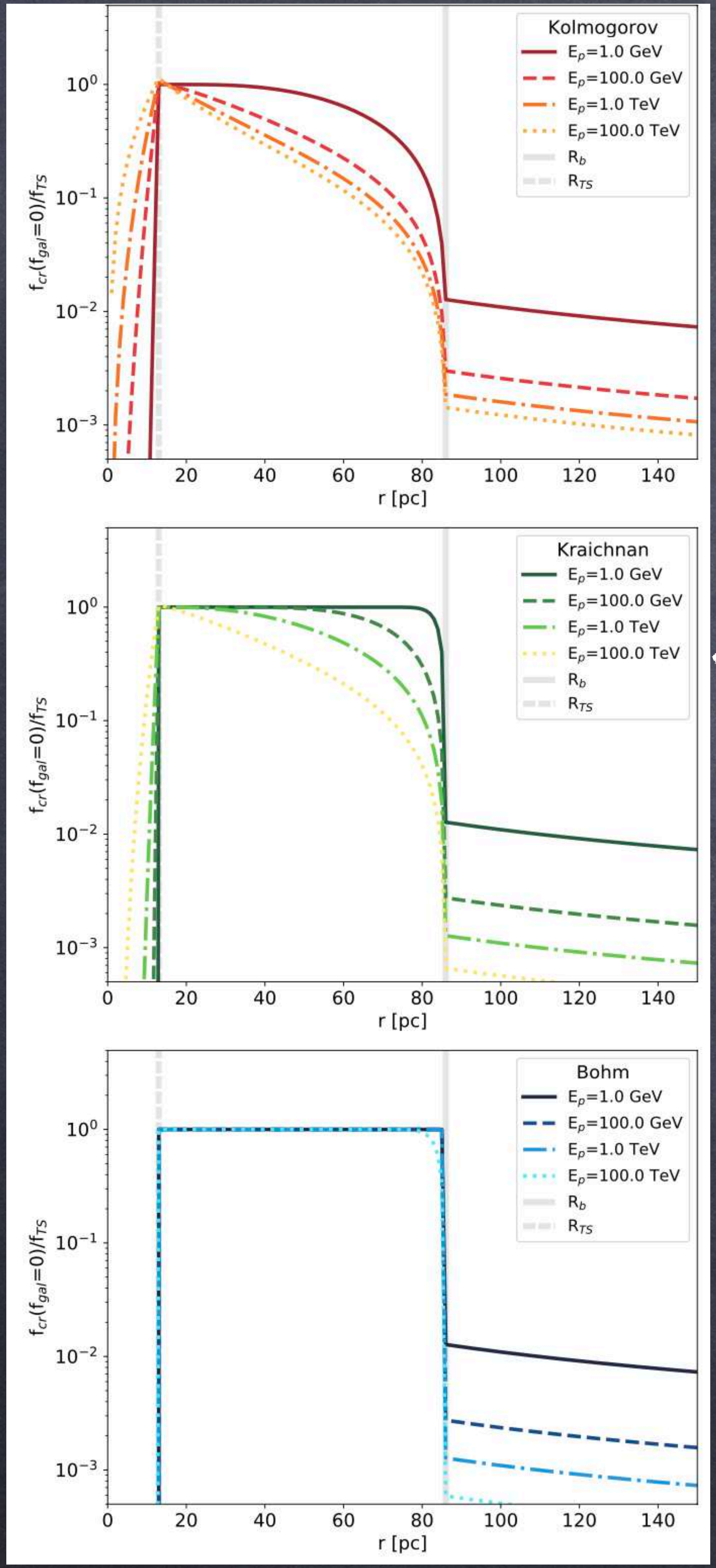
THE CYGNUS COCOON





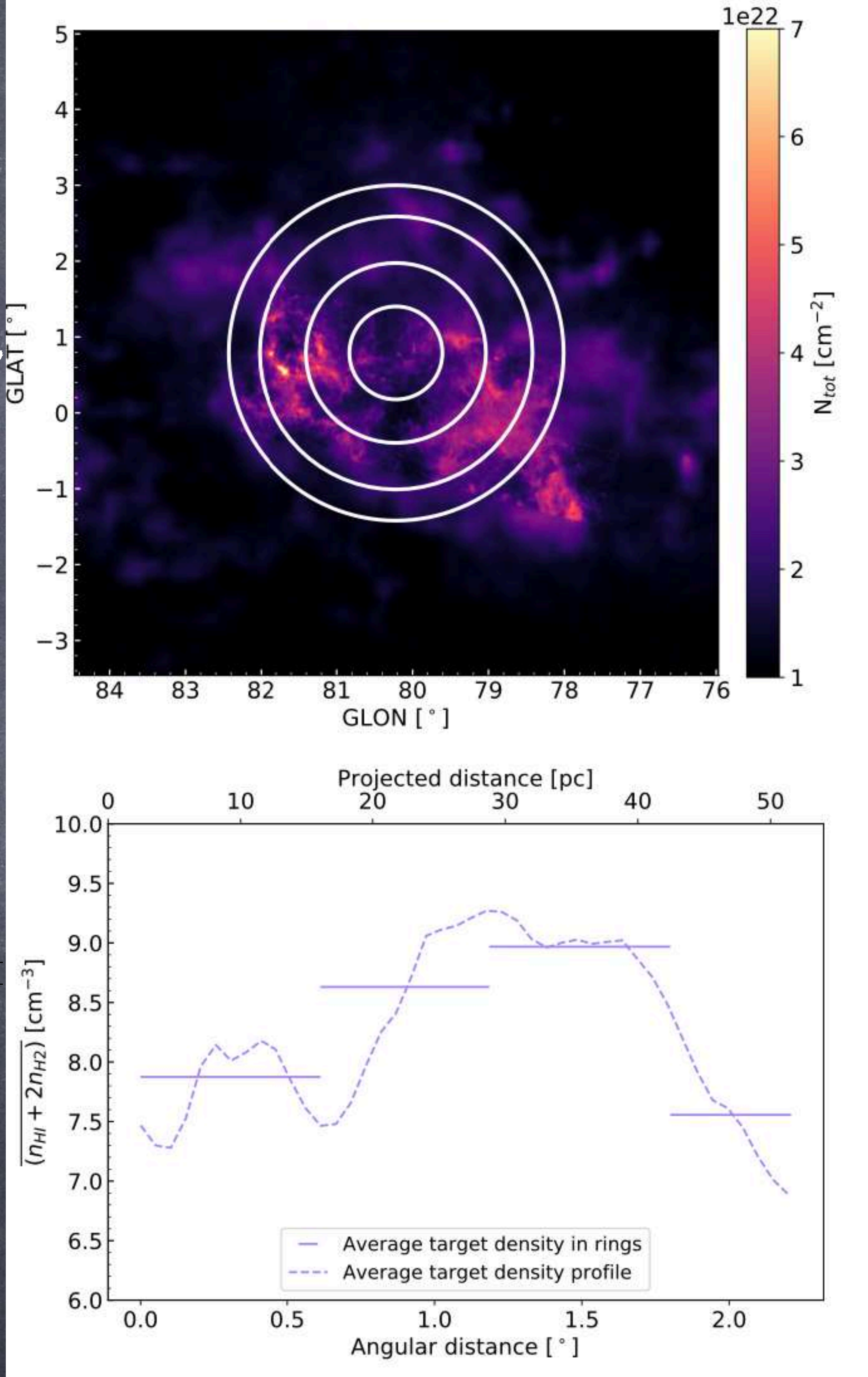
Morlino+ 2021

COSMIC RAYS AND GAS



CR DISTRIBUTION
(based on Morlino+ 2021)

TOTAL GAS DENSITY
(Menchiari+ sub.)

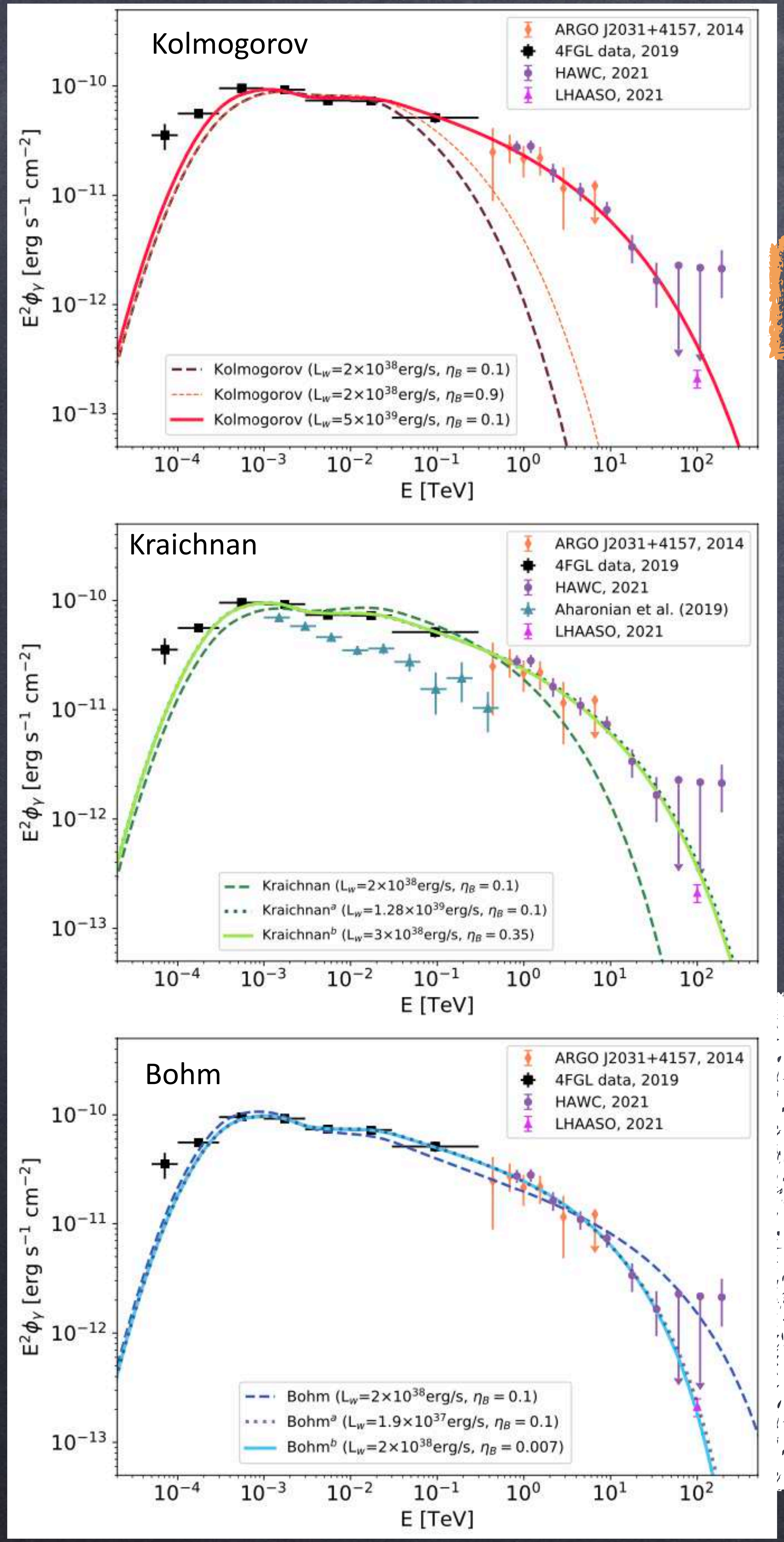


HI from 21cm (CGPS)

HII from Nobeyama and ^{12}CO GPS (Dame+ 2001)

Circles from Fermi (Aharonian+ 2019) and HAWC analyses (Abeysekara+2021)

GAMMA-RAY SPECTRUM AND SPATIAL PROFILE

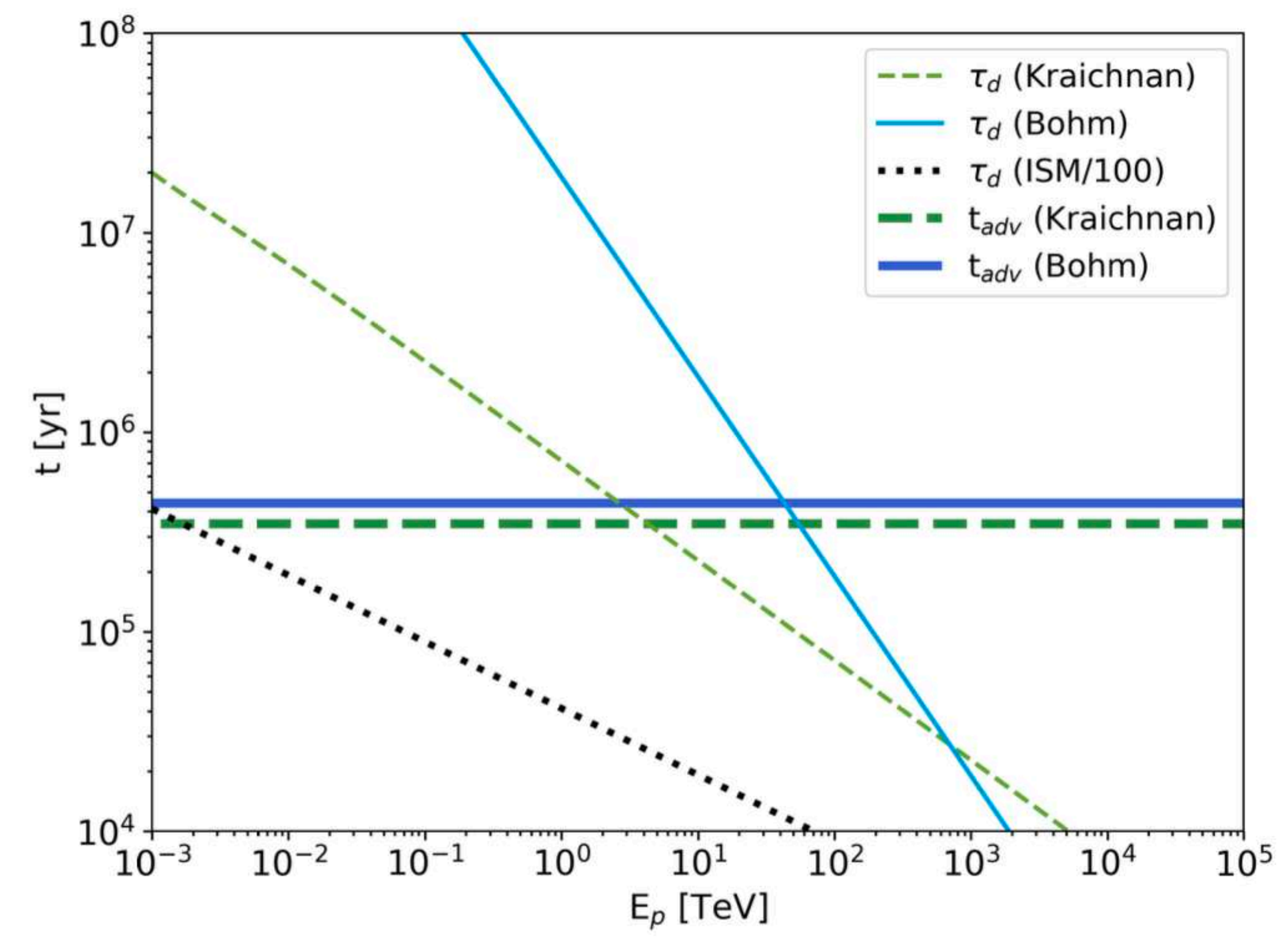


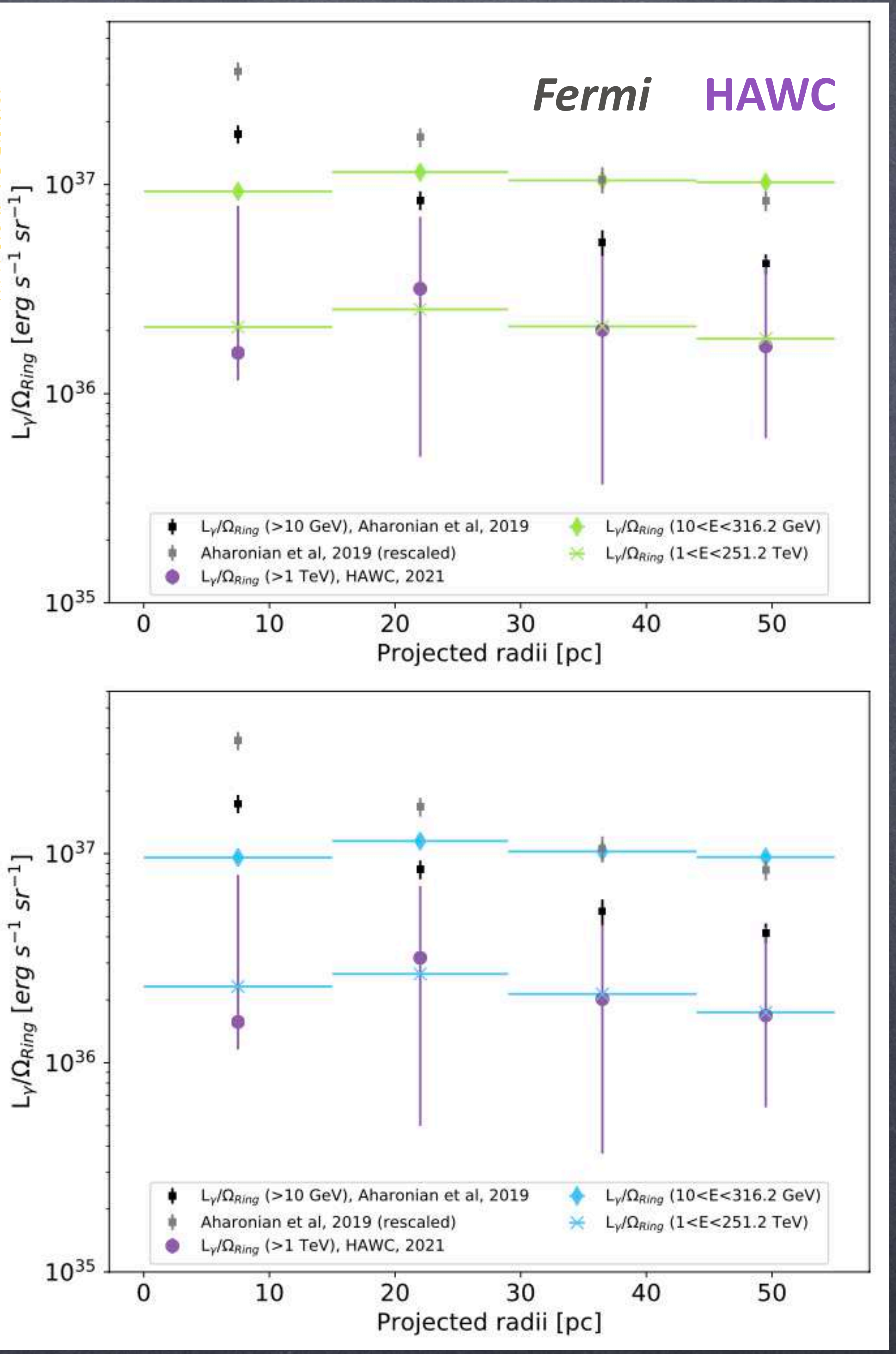
SPECTRA

SPATIAL PROFILES

- HAWC SPATIAL PROFILE OK FOR BOTH KRAICHNAN ($D \propto E^{1/2}$) AND BOHM ($D \propto E$)
- CENTRAL PEAK IN Fermi BAND?

KOLMOGOROV ($D \propto E^{1/3}$) IMPLIES TOO LOW $E_{\max}$ UNLESS $L_w \sim 10^{39}$erg/s

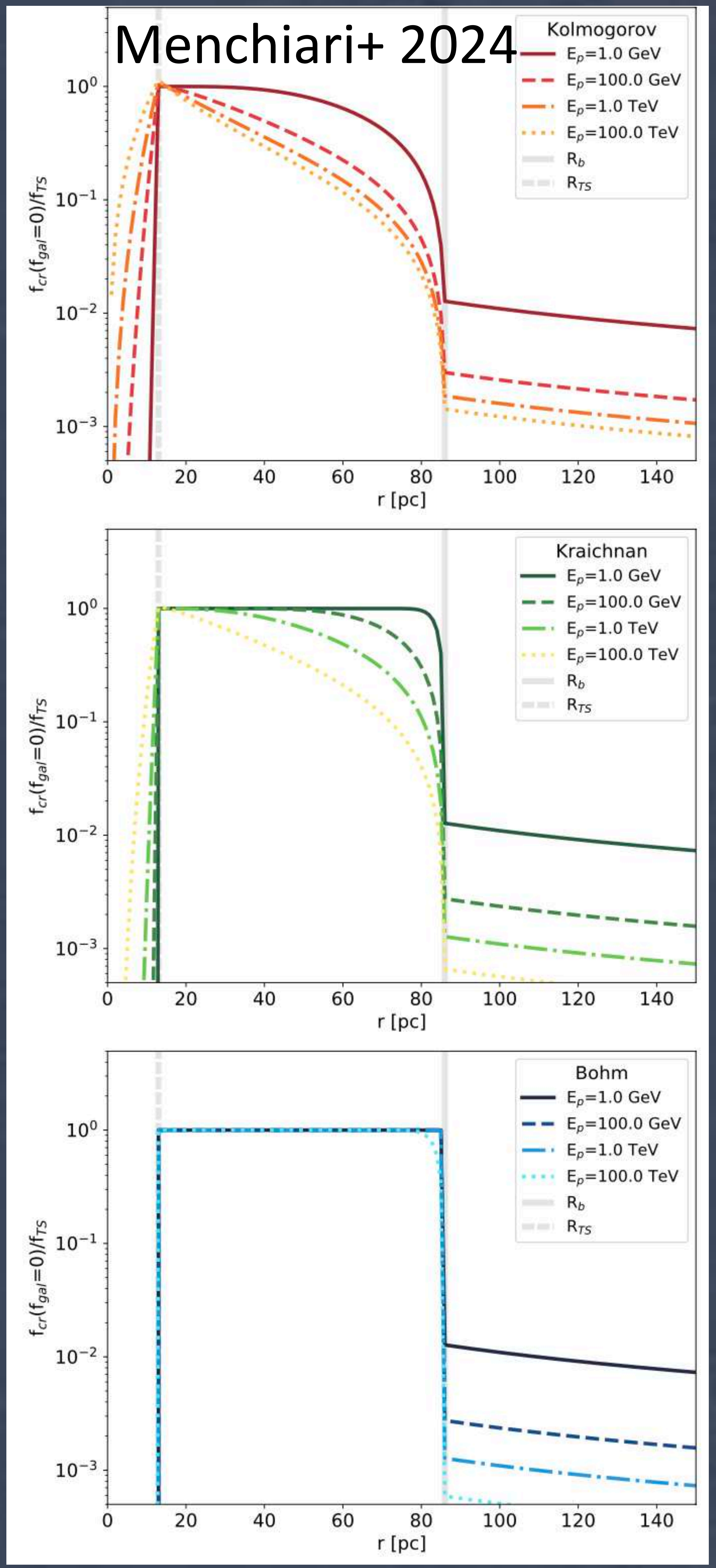




ADVECTION DOMINANT UNLESS... (e.g. Vieu+ 2023)

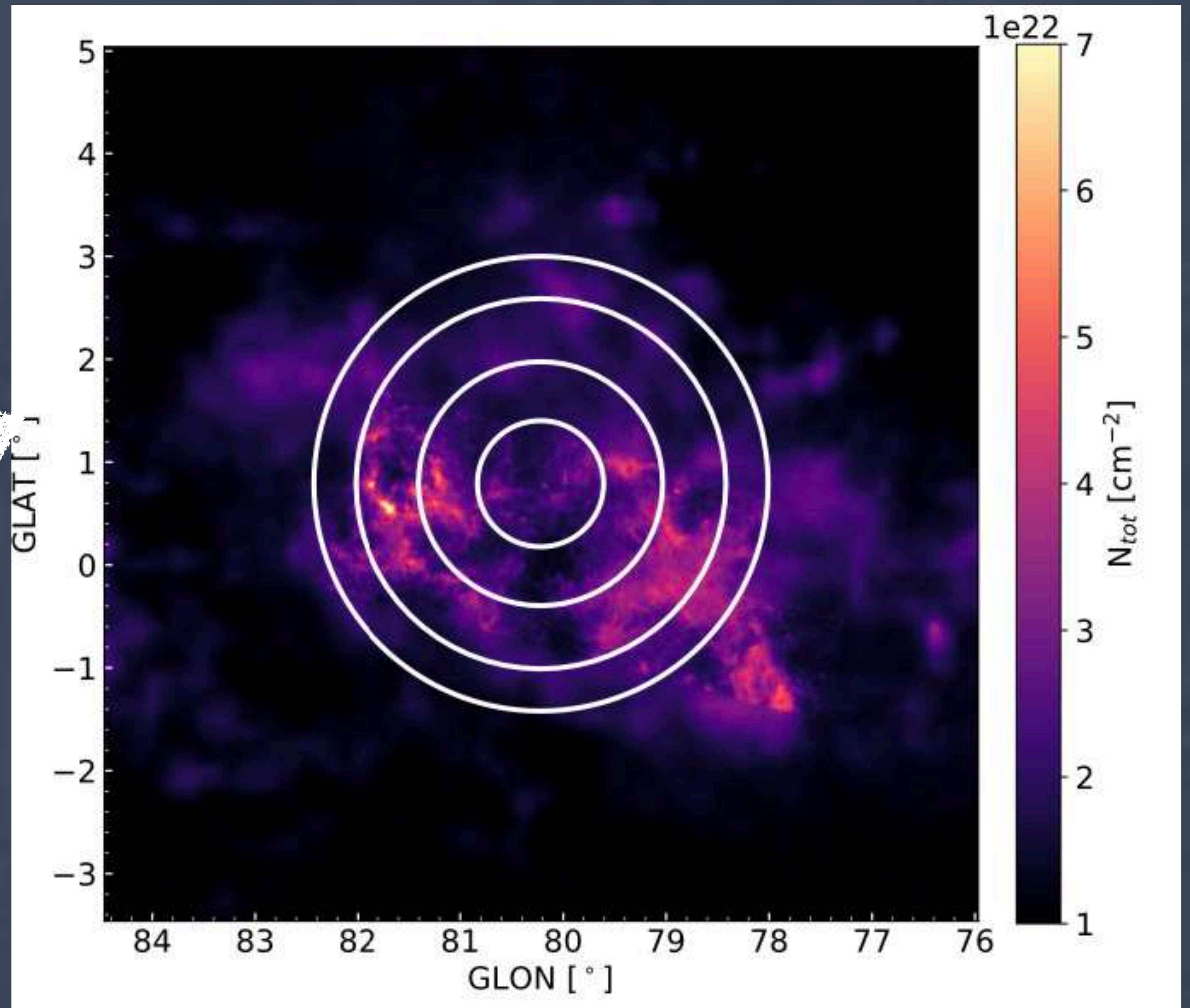
THE FUTURE

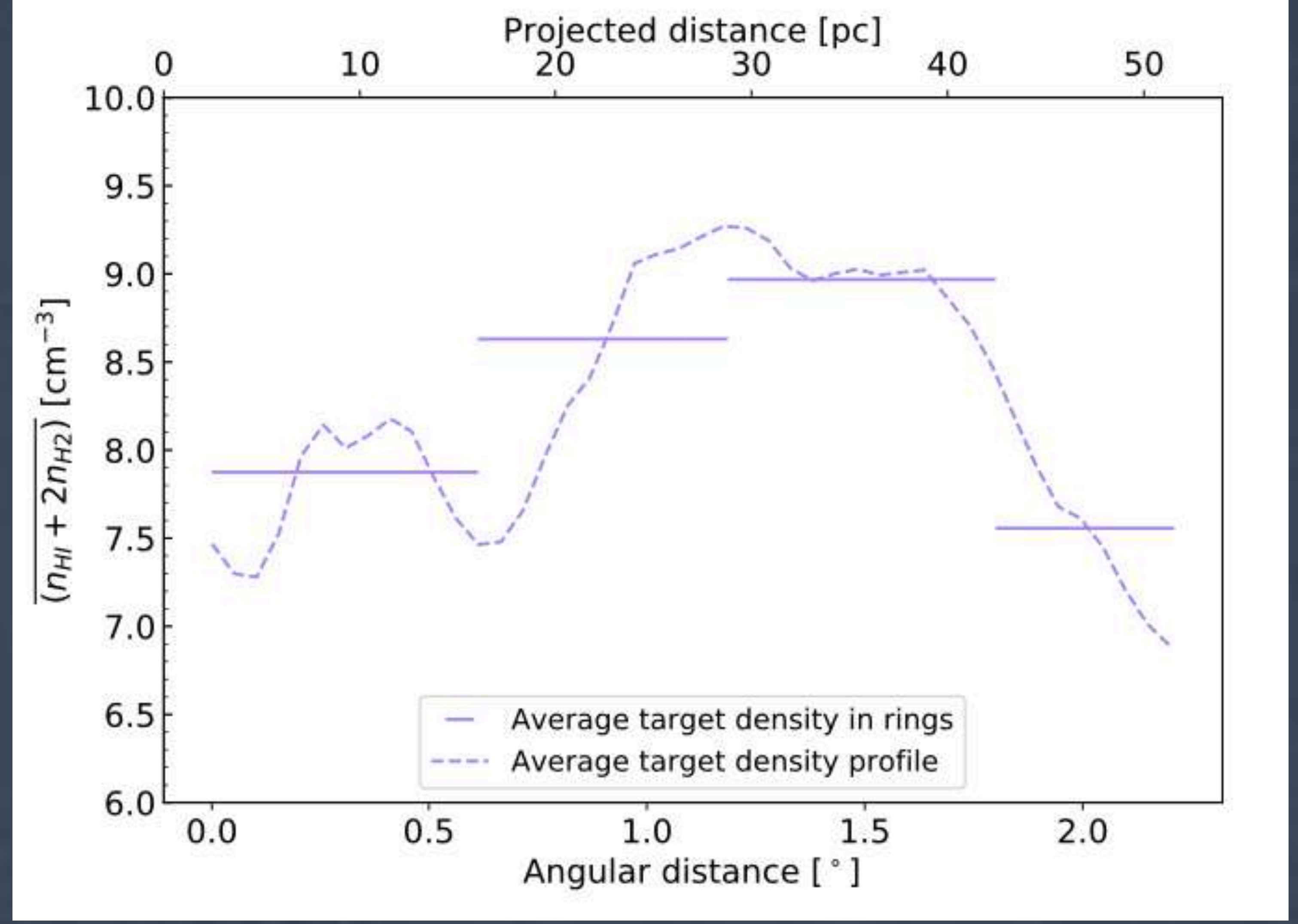
CRs AND GAS MAPS



CR DISTRIBUTION
(based on Morlino+ 2021)

TOTAL GAS DENSITY
(Menchiari+ 2024)





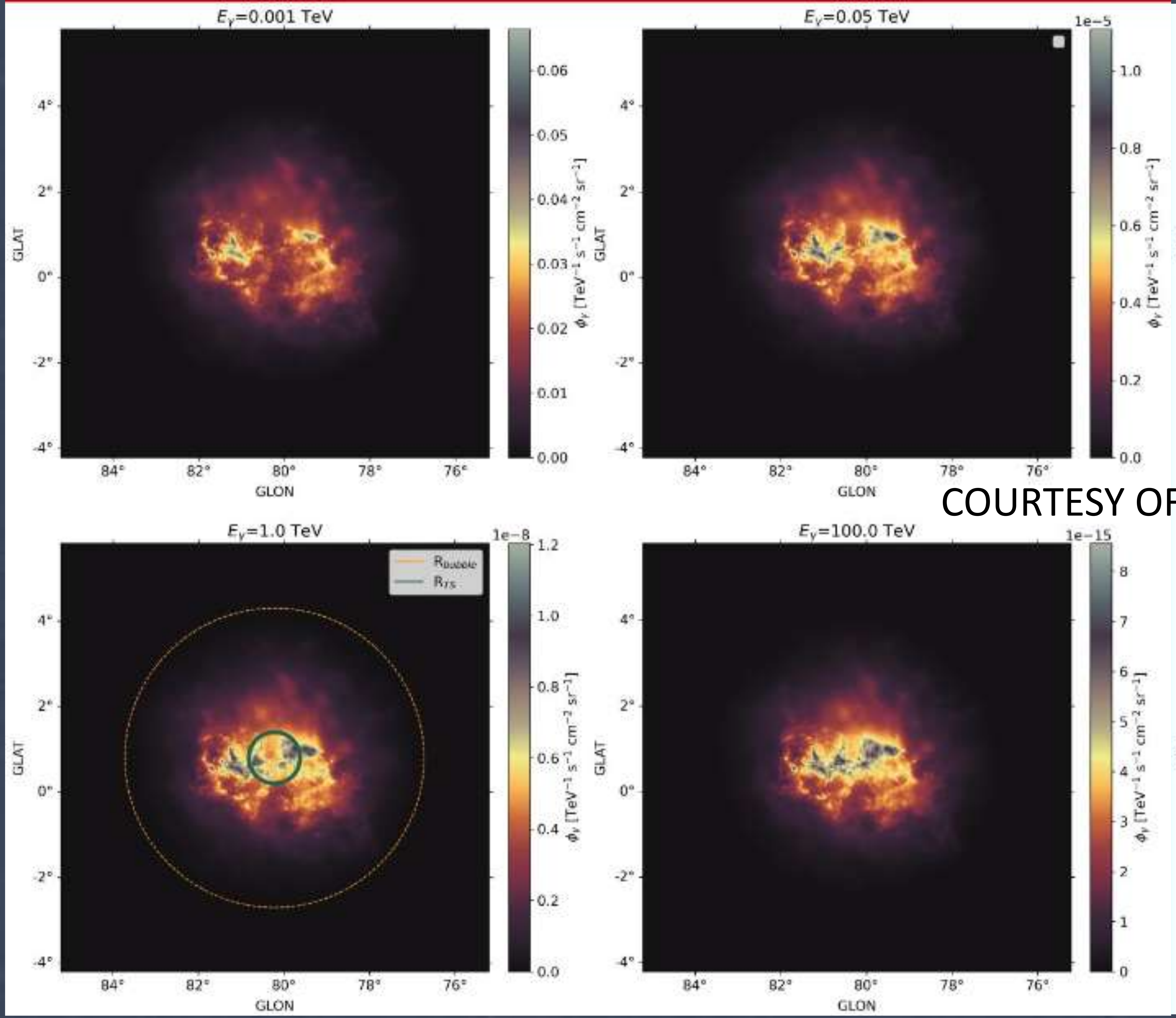
HI from 21cm (CGPS)

HII from Nobeyama and ^{12}CO GPS (Dame+ 2001)

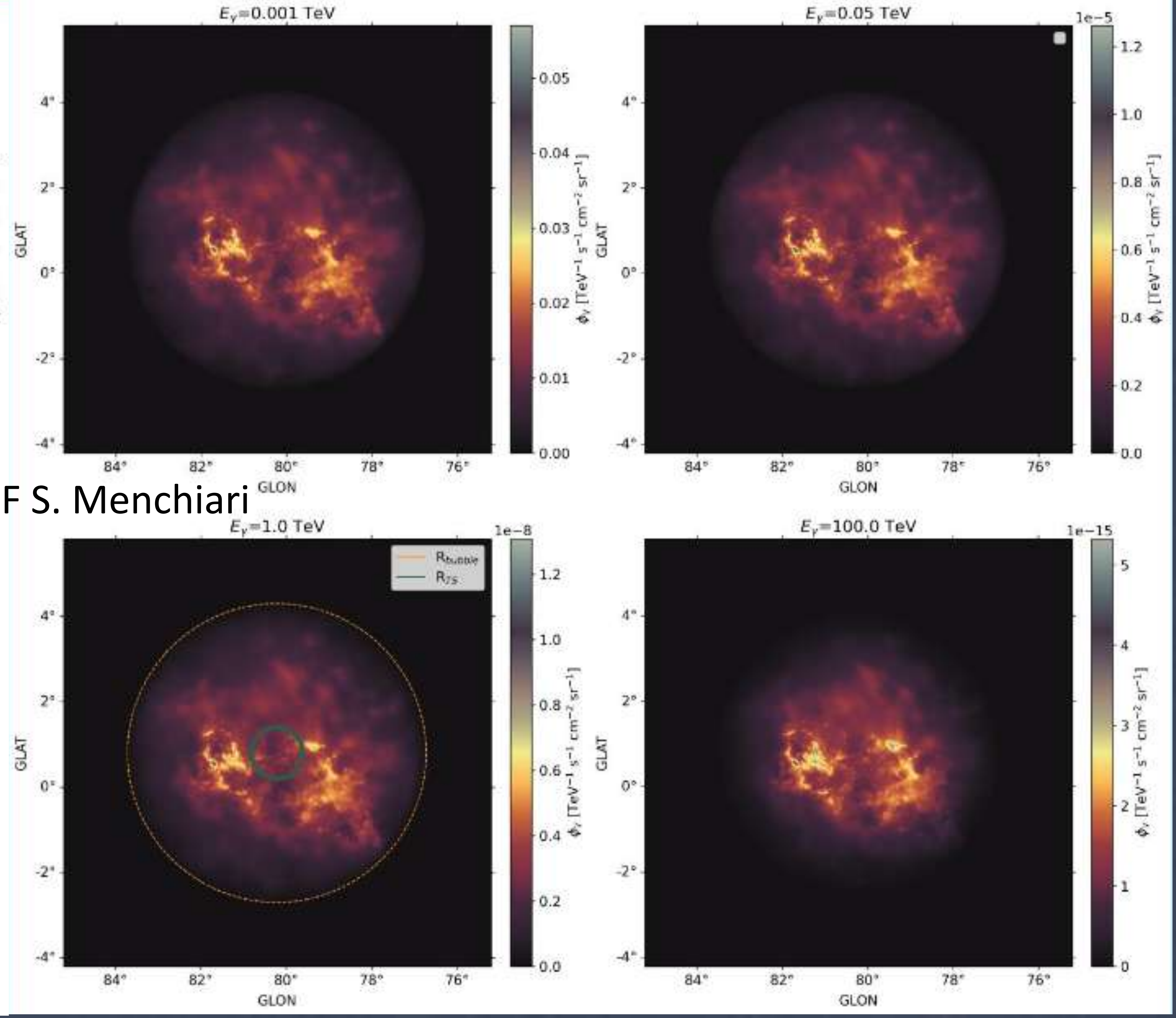
Circles from Fermi (Aharonian+ 2019) and HAWC analyses (Abeysekara+2021)

SIMULATED EMISSION MAPS: CYGNUS

KOLMOGOROV



BOHM

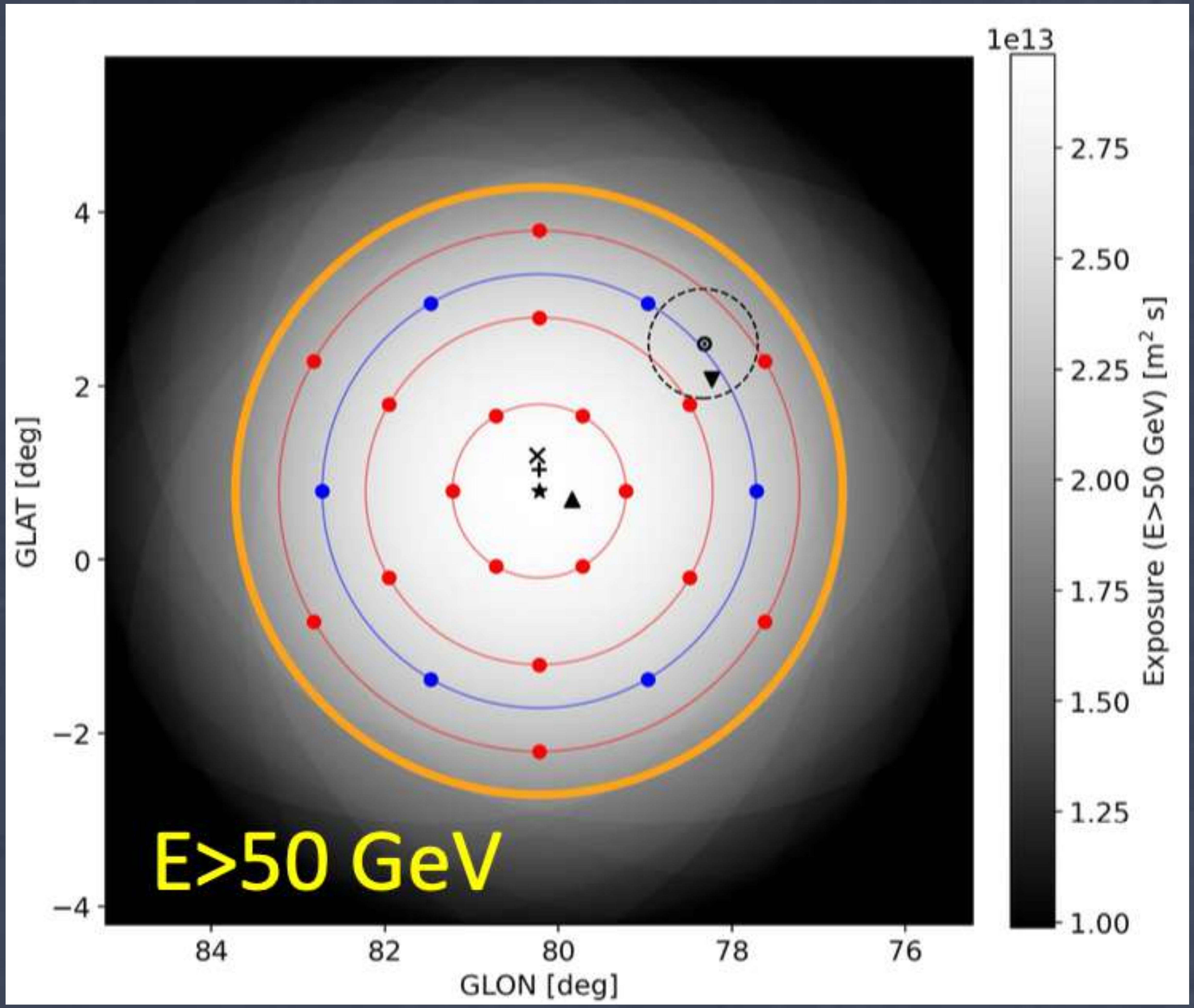


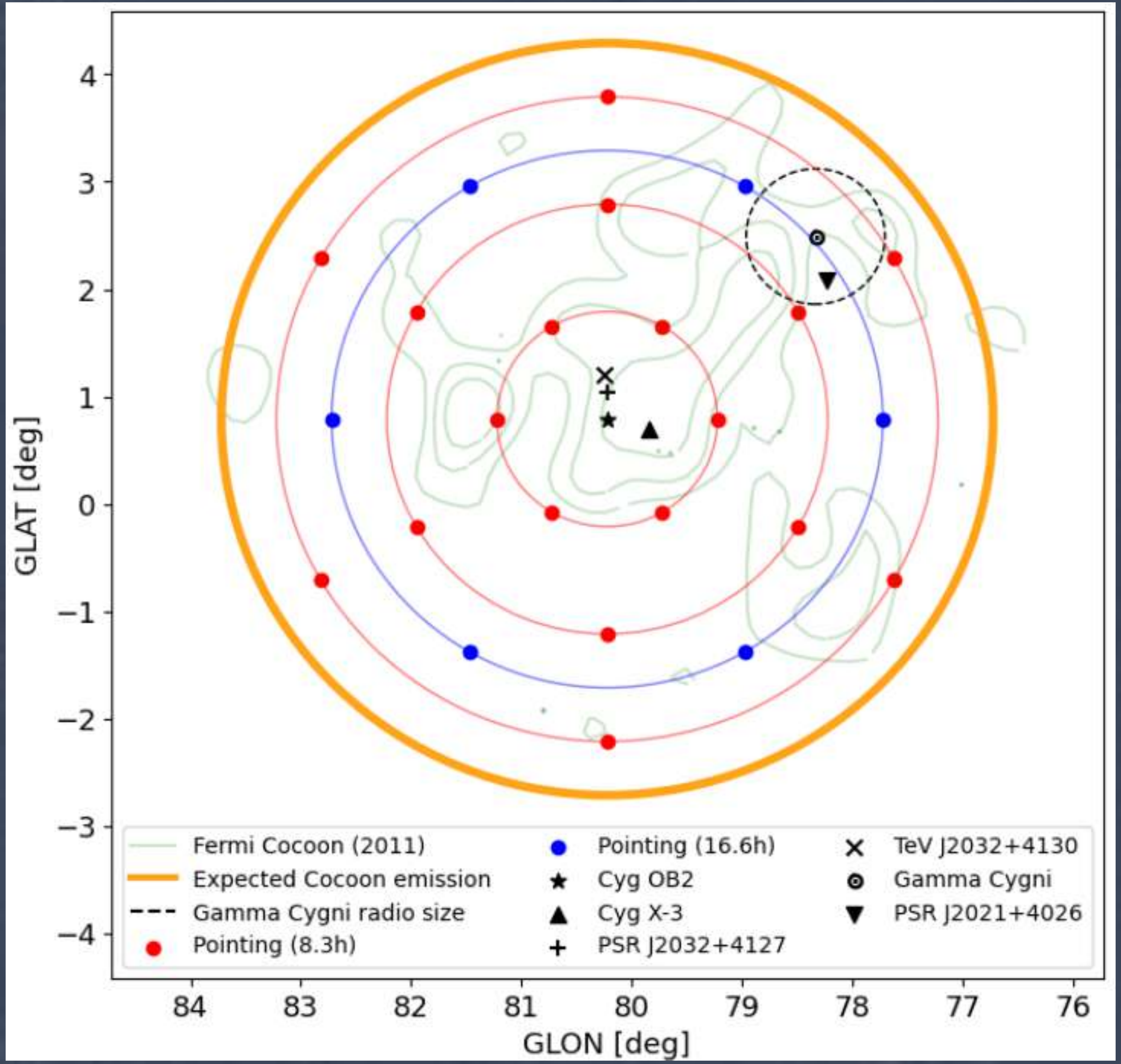
COURTESY OF S. Menchiari

H2: 12CO(J=1-0) CfA (Dame et al, 2001) Lowres. + NRO (Takekoshi et al, 2019) Highres.
(Xco=1.68 1020 mol. cm-2 K-1 km-1 ; -20km/s<v<20km/s)

HI: 21cm from CGPS (Taylor et al, 2003)
(T=150°K ; -20km/s<v<20km/s)

SIMULATED CTA OBSERVATIONS



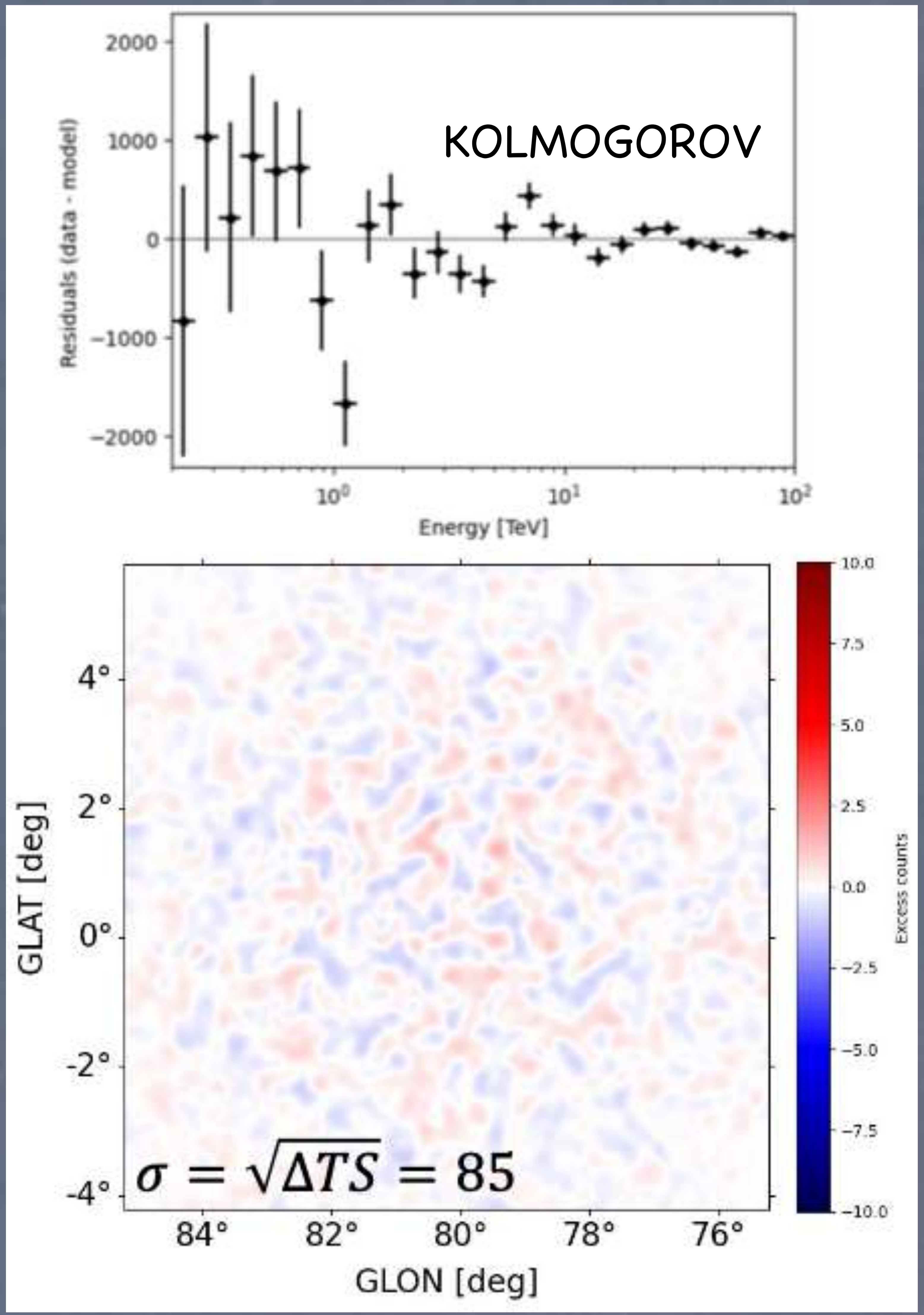


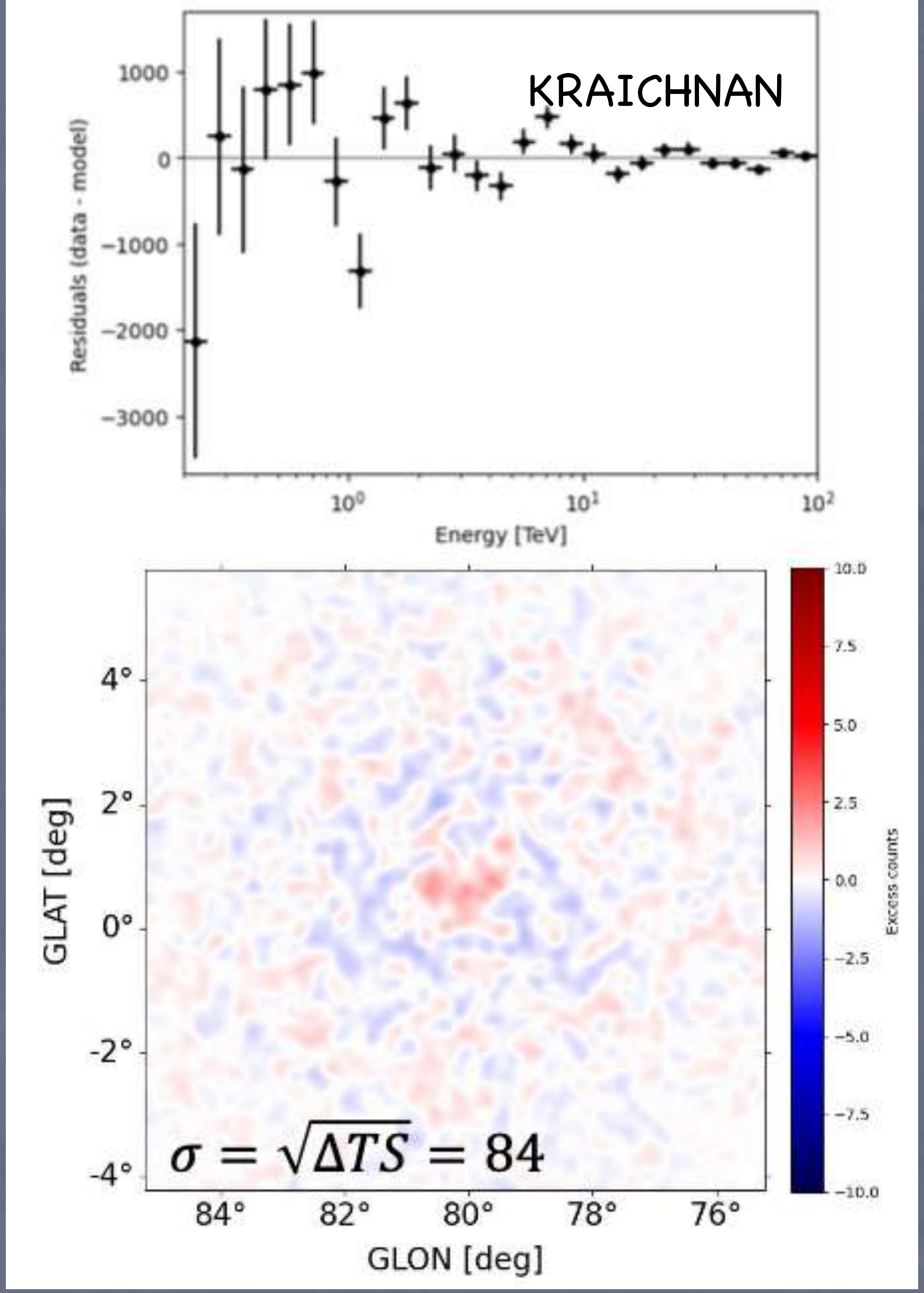
CTAO CP on *Star Forming Regions* COURTESY OF S. Menchiari
CTA coll (c.a. Marcowith)

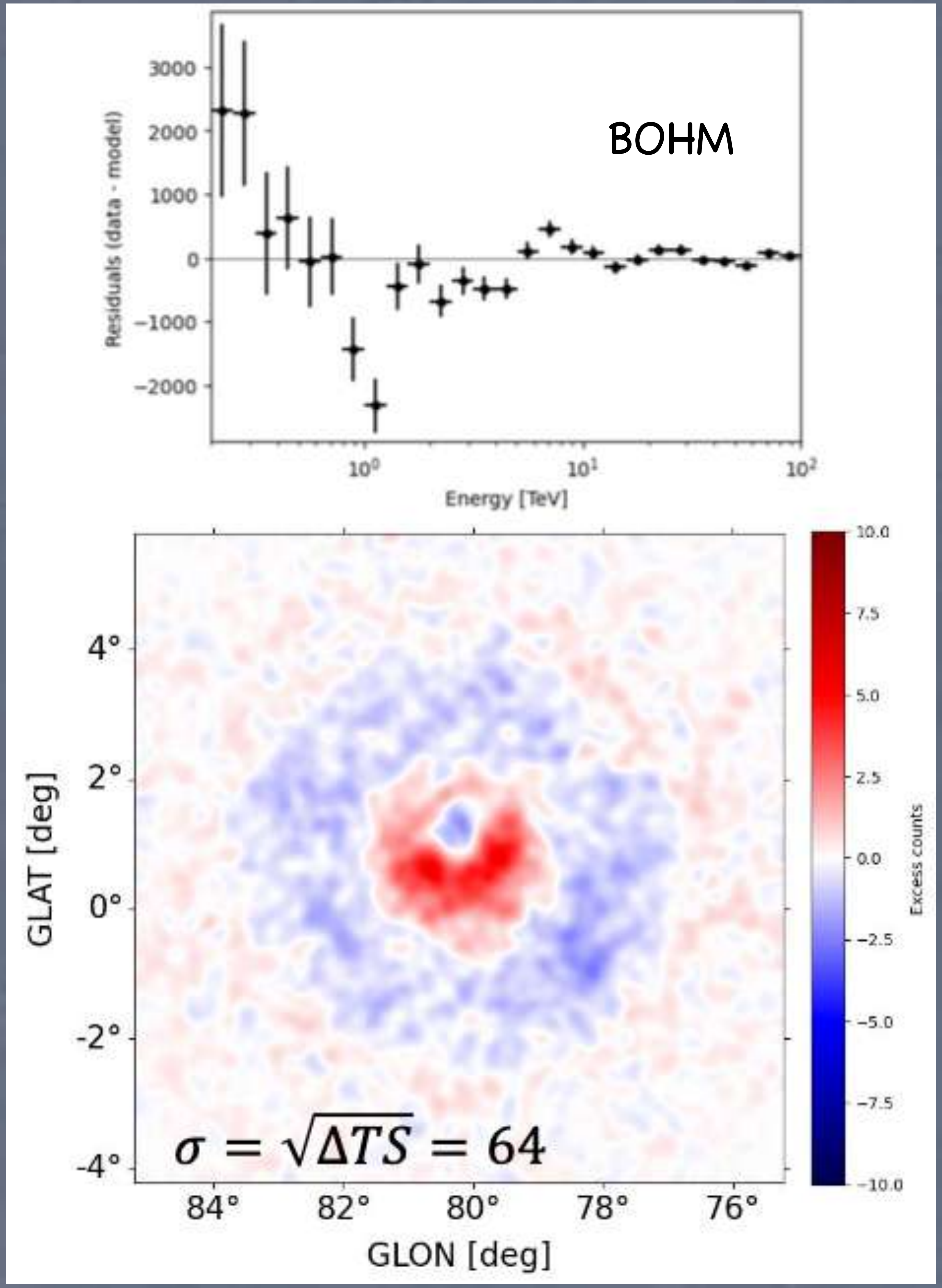
Pointings: Hexagonal grid
(average distance ≈1°, time=200h)

UNVEILING THE TURBULENCE IN CYGNUS OB2

UNDERLYING KOLMOGOROV SPECTRUM







CTAO CP on *Star Forming Regions*
CTA coll (c.a. Marcowith)

COURTESY OF S. Menchiari

The Present

DETECTED PEVATRONS: LEPTONS OR HADRONS?

12 SOURCES DETECTED BY LHAASO ABOVE 100 TeV

Table 1 | UHE γ-ray sources

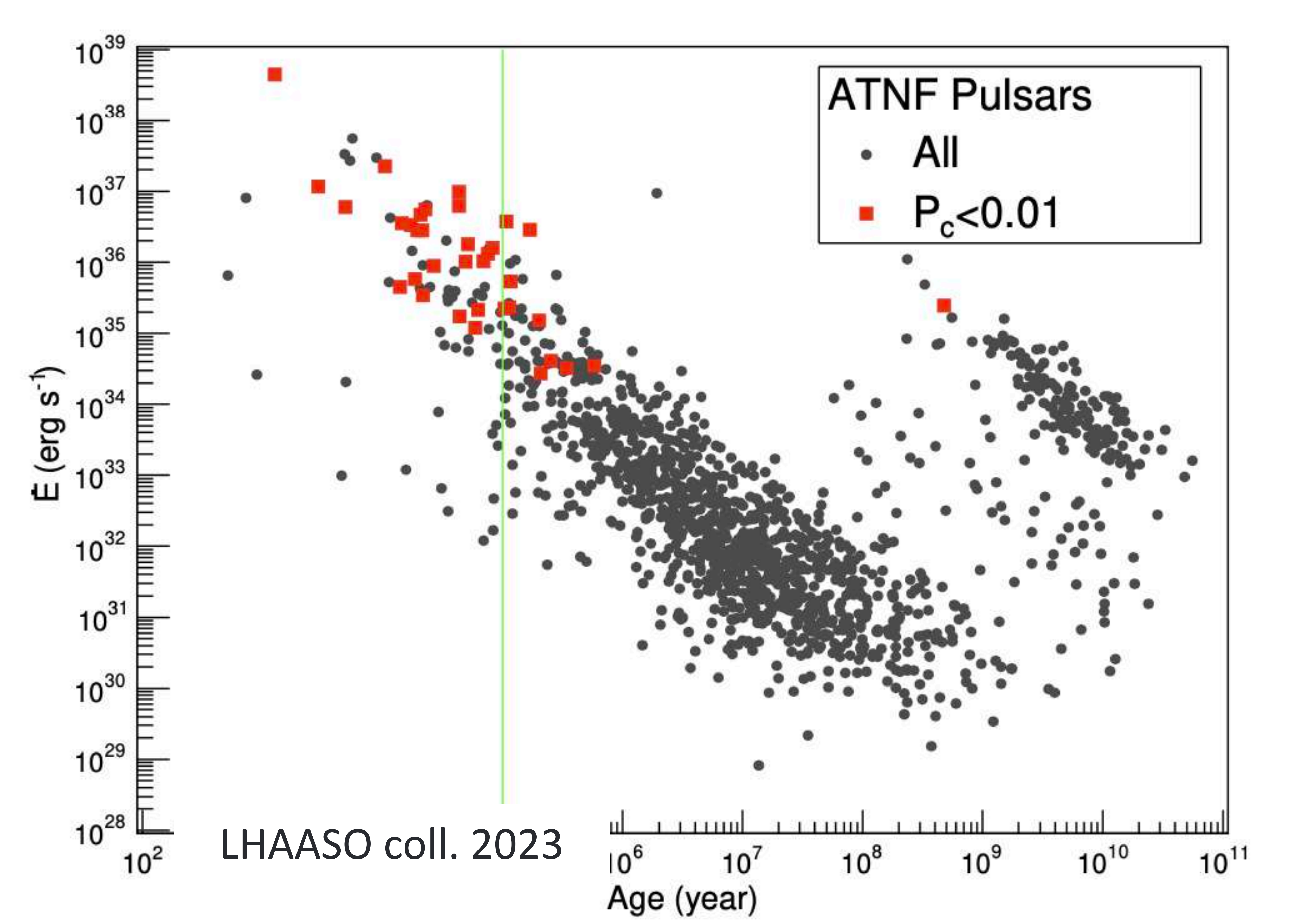
Cao+ 2021

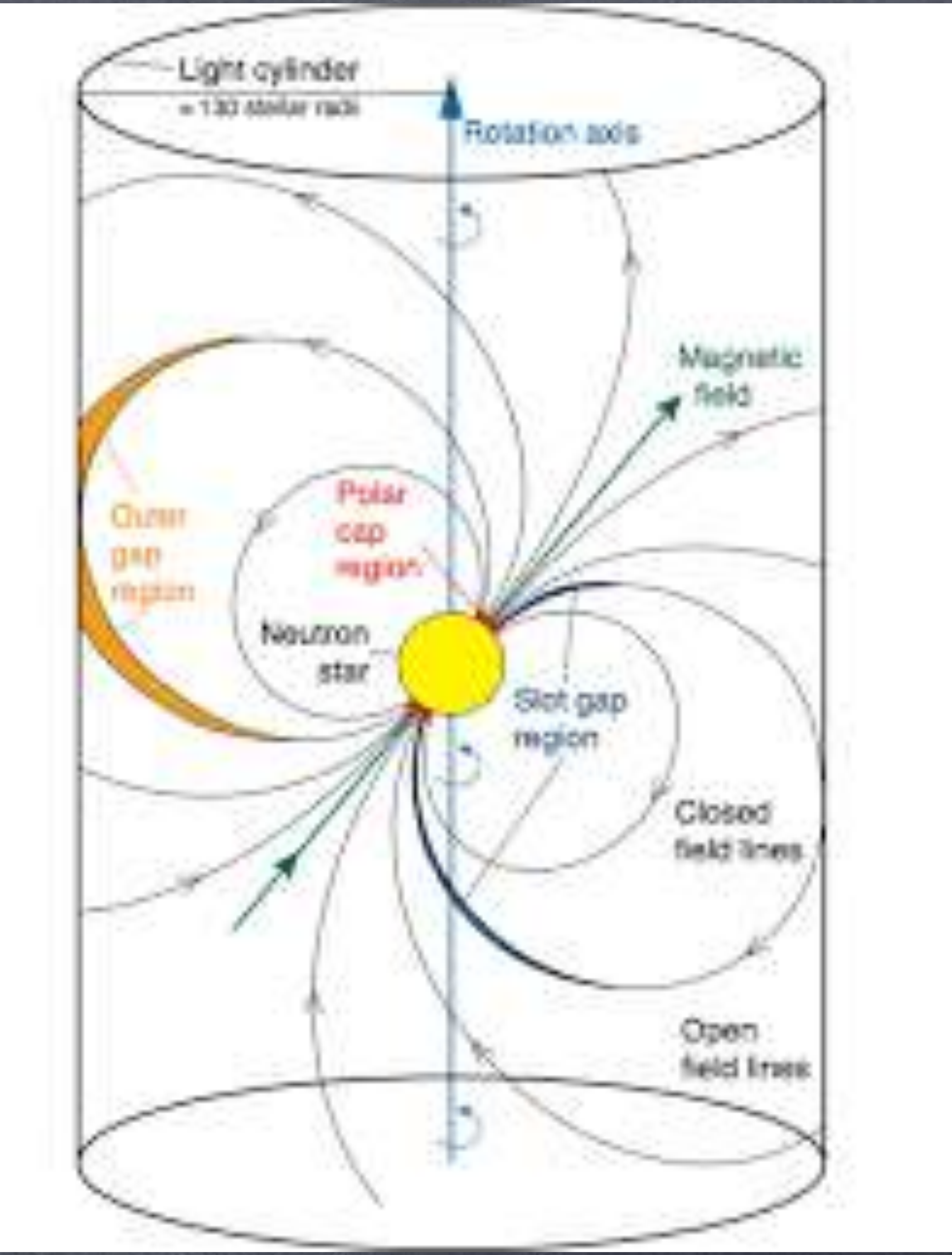
Source name	RA (°)	dec. (°)	Significance above 100 TeV (×σ)	E_{max} (PeV)	Flux at 100 TeV (CU)	
LHAASO J0534+2202	83.55	22.05	17.8	0.88 ± 0.11	1.00(0.14)	
LHAASO J1825-1326	276.45	−13.45	16.4	0.42 ± 0.16	3.57(0.52)	
LHAASO J1839-0545	279.95	−5.75	7.7	0.21 ± 0.05	0.70(0.18)	
LHAASO J1843-0338	280.75	−3.65	8.5	$0.26\,{}_{-0.10}^{+0.16}$	0.73(0.17)	
LHAASO J1849-0003	282.35	−0.05	10.4	0.35 ± 0.07	0.74(0.15)	
LHAASO J1908+0621	287.05	6.35	17.2	0.44 ± 0.05	1.36(0.18)	
LHAASO J1929+1745	292.25	17.75	7.4	$0.71\,{}_{-0.07}^{+0.16}$	0.38(0.09)	
LHAASO J1956+2845	299.05	28.75	7.4	0.42 ± 0.03	0.41(0.09)	
LHAASO J2018+3651	304.75	36.85	10.4	0.27 ± 0.02	0.50(0.10)	
LHAASO J2032+4102	308.05	41.05	10.5	1.42 ± 0.13	0.54(0.10)	Cygnus
LHAASO J2108+5157	317.15	51.95	8.3	0.43 ± 0.05	0.38(0.09)	NO PSR
LHAASO J2226+6057	336.75	60.95	13.6	0.57 ± 0.19	1.05(0.16)	G106.3+2.7

PeV ELECTRONS REQUIRE SUFFICIENT DROP AND $v_{flow} \sim c$

ALL SOURCES BUT ONE HAD 1+ PSR IN THE FIELD....

PULSAR ASSOCIATIONS IN 1LHAASO

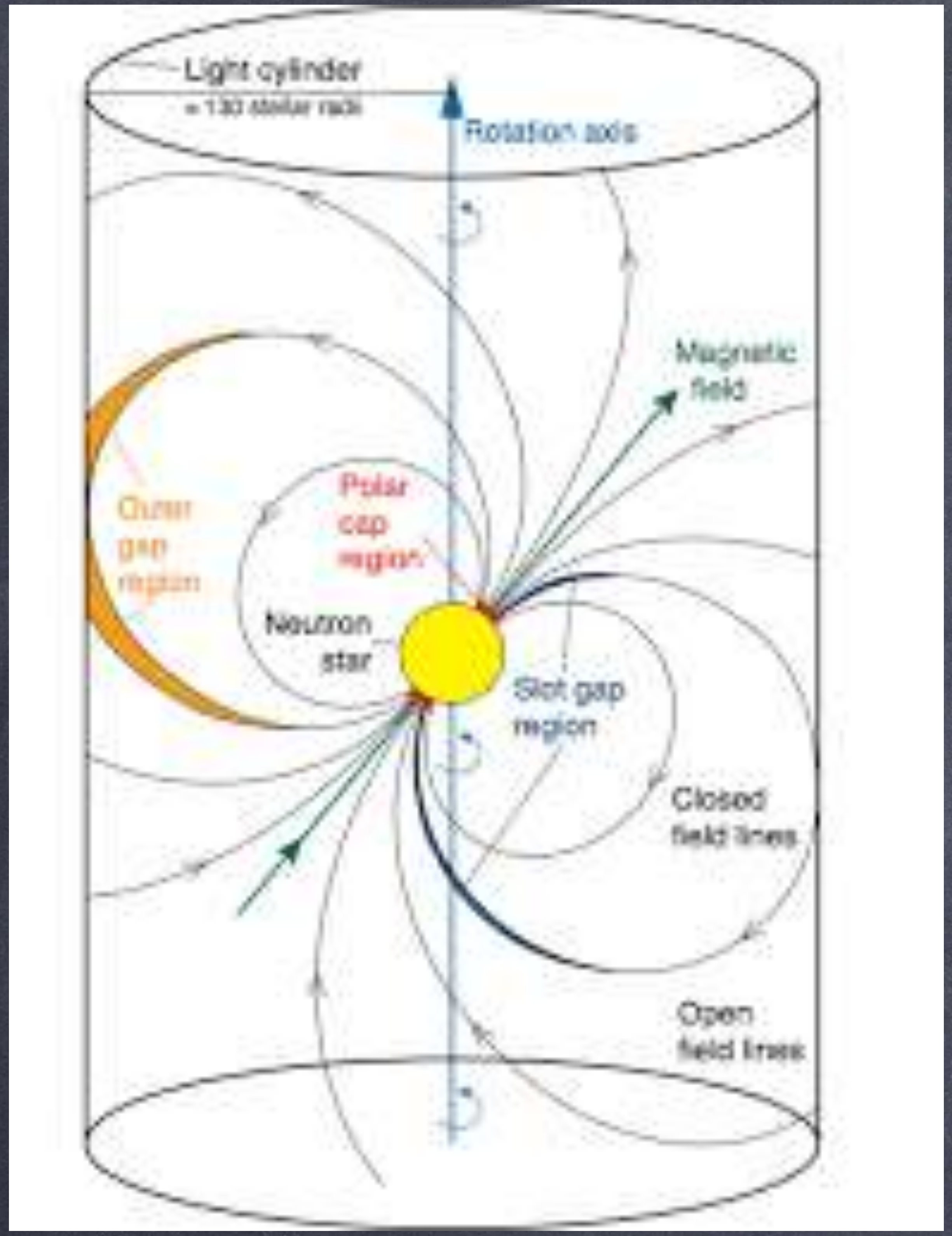


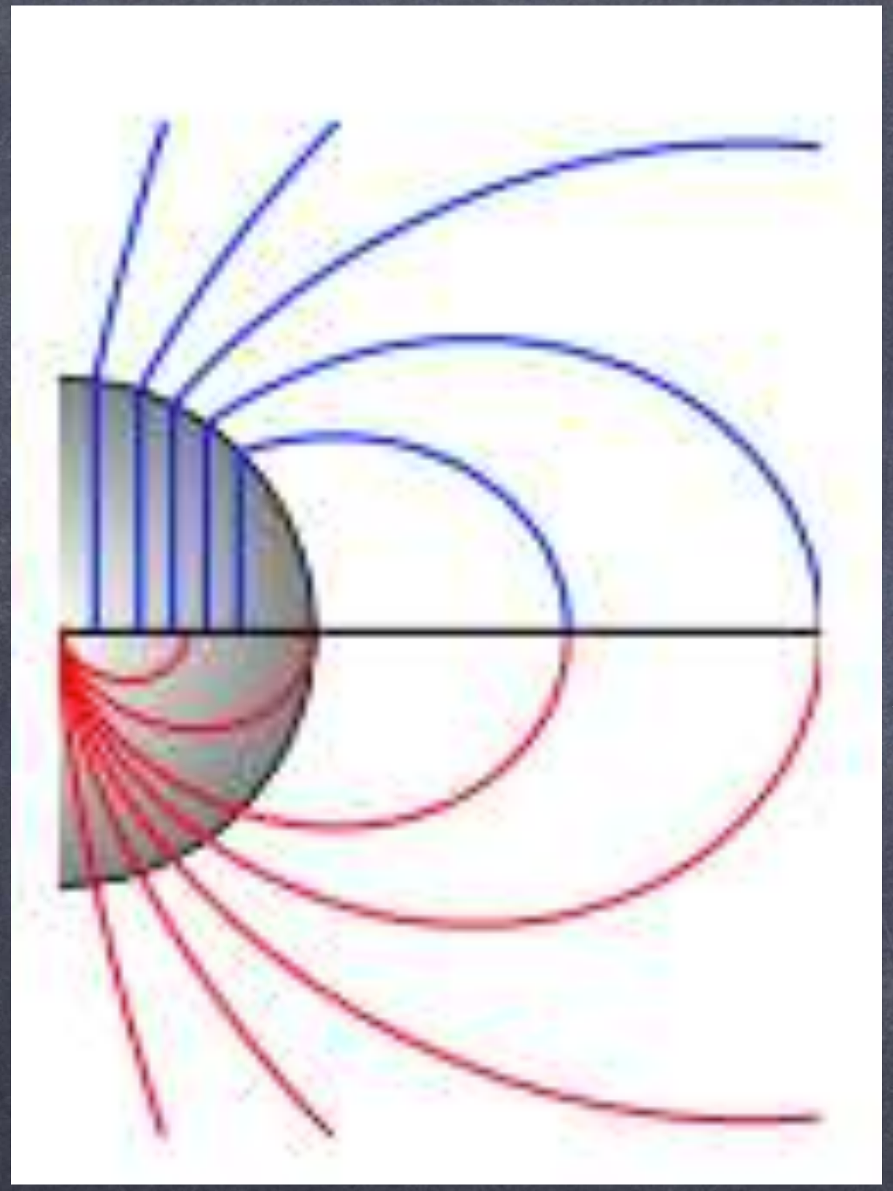


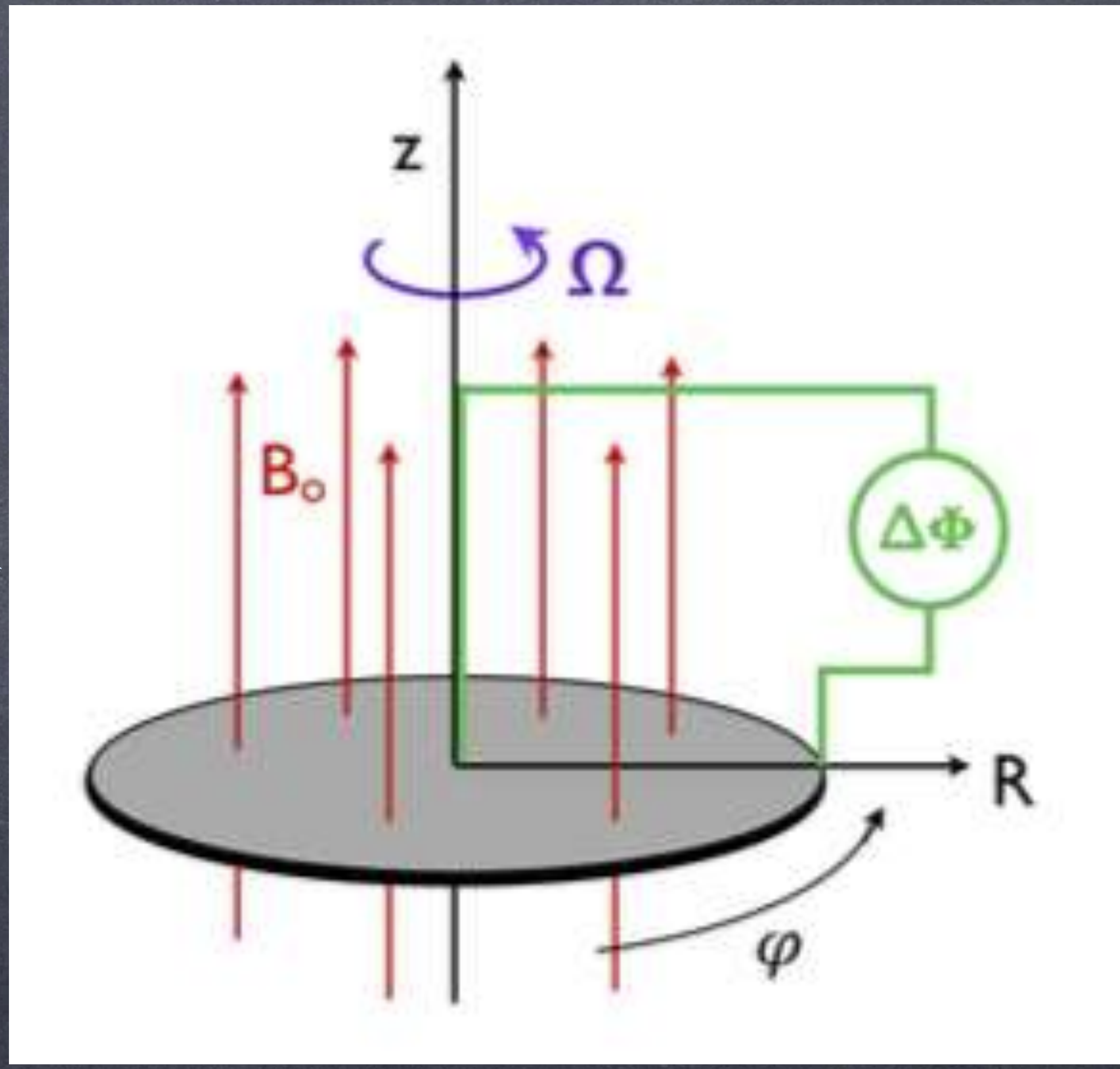
- 35 ASSOCIATIONS WITH PULSARS OUT OF 90 SOURCES
- 22 OUT OF 43 AT UHE
- MANY BUT NOT ALL THE MOST ENERGETIC PSRs: WHY?
- ONE ms PSR: NEW CLASS? ms PSR WIND NEBULAE?

PULSARS AS UNIPOLAR INDUCTORS

UNIPOLAR INDUCTION







$$\Delta\Phi^{PC} \approx \frac{B_\star \Omega R_\star^2}{c}\frac{R_\star}{R_L} \approx \sqrt{\frac{\dot{E}}{c}}$$

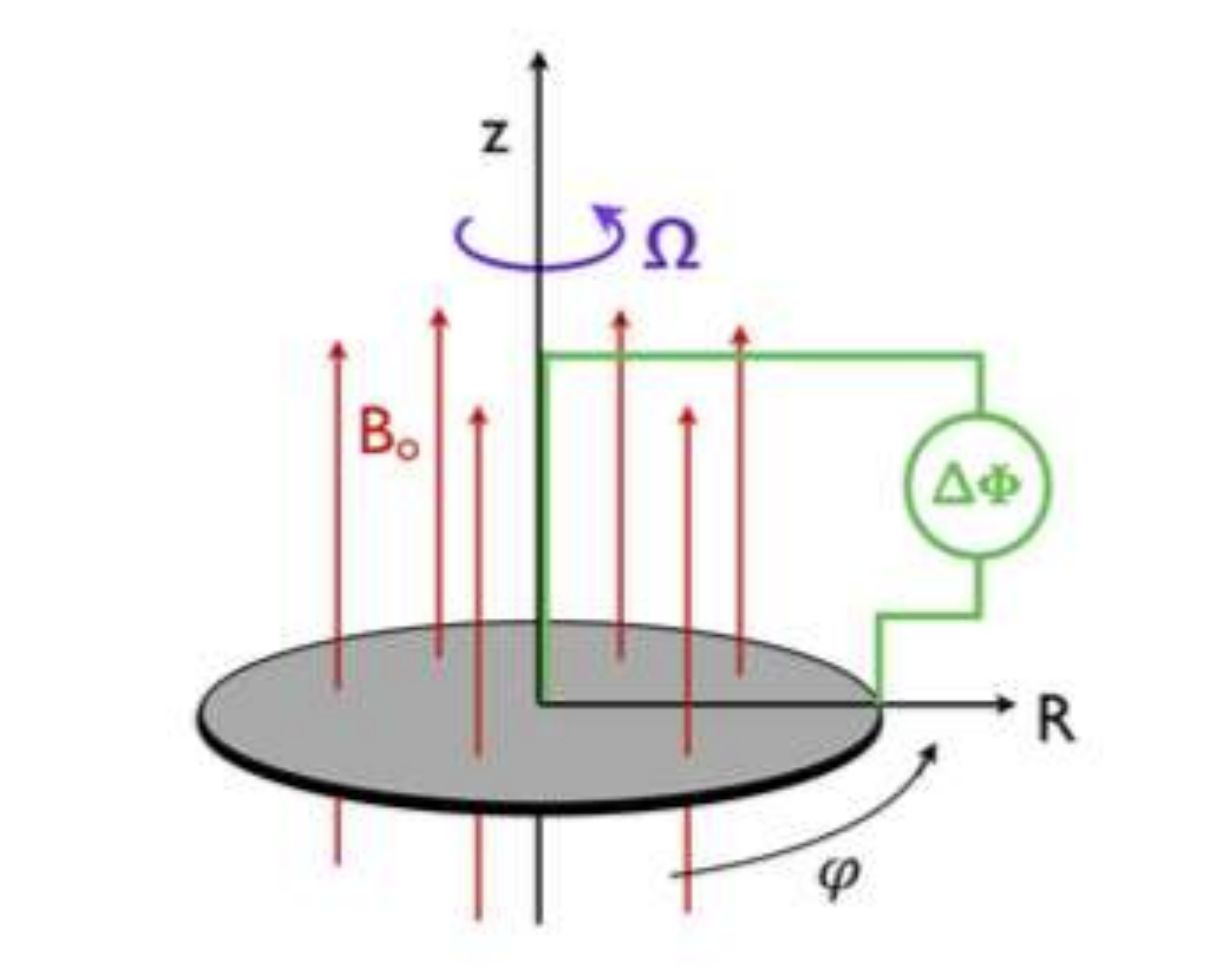
$$\Delta\Phi^{FD} \approx B_d \frac{\Omega R_d}{c} R_d$$

FARADAY DISK

$$\boxed{\begin{gathered}\vec{E} = -\frac{\vec{v}}{c} \wedge \vec{B} \\ \vec{v} = \Omega\, r\, \hat{e}_\phi\end{gathered}}$$

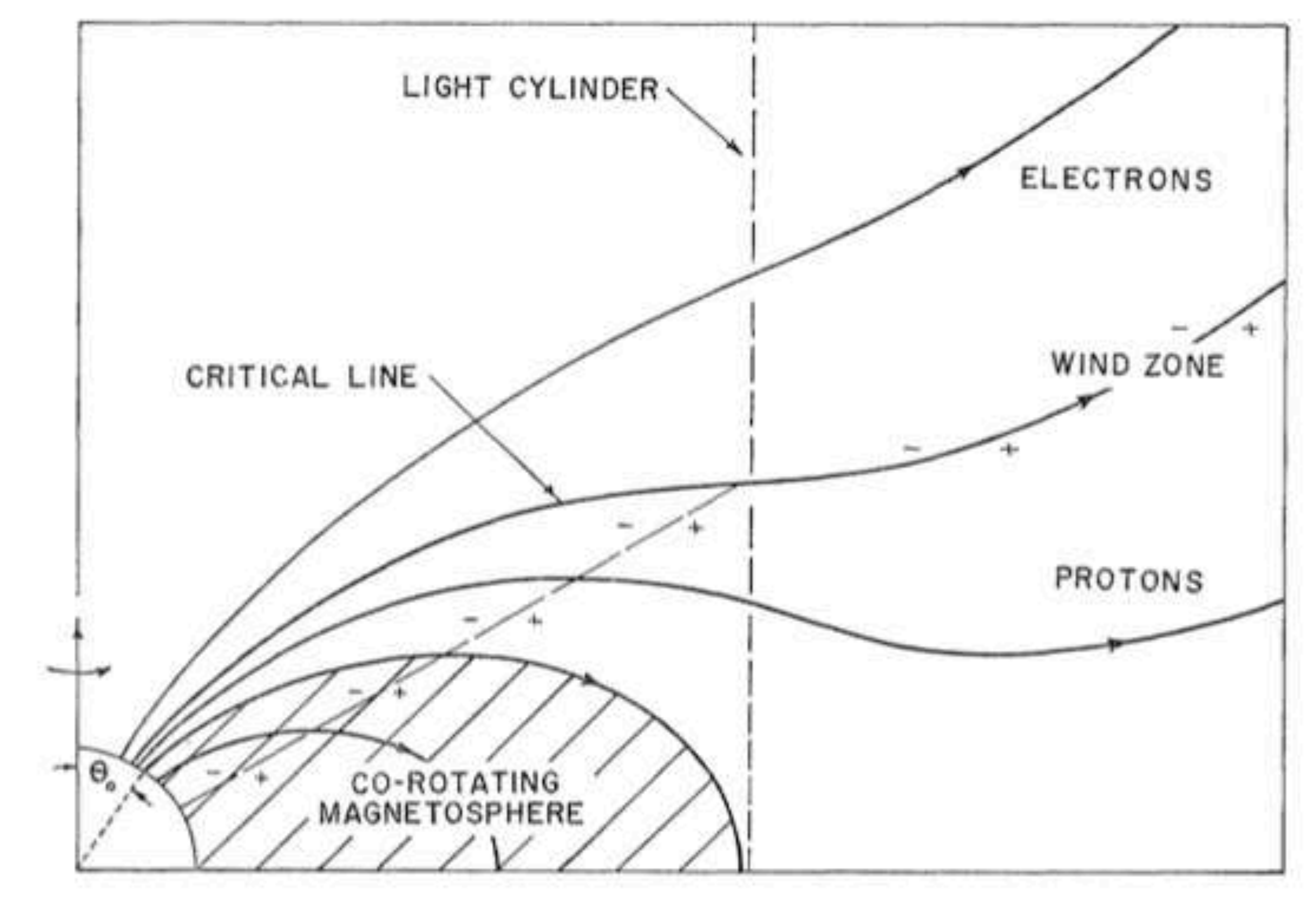
$$\vec{E} = -\frac{\Omega r}{c} B_0 \hat{e}_r$$

$$\boxed{\Delta\Phi = \frac{B_0 \Omega R_d^2}{2c}}$$



$$4\pi\rho_e = \vec{\nabla} \cdot \vec{E} \Rightarrow \boxed{\rho_e = -\frac{\Omega\ B_0}{2\pi c}}$$

THE GOLDREICH AND JULIAN MAGNETOSPHERE

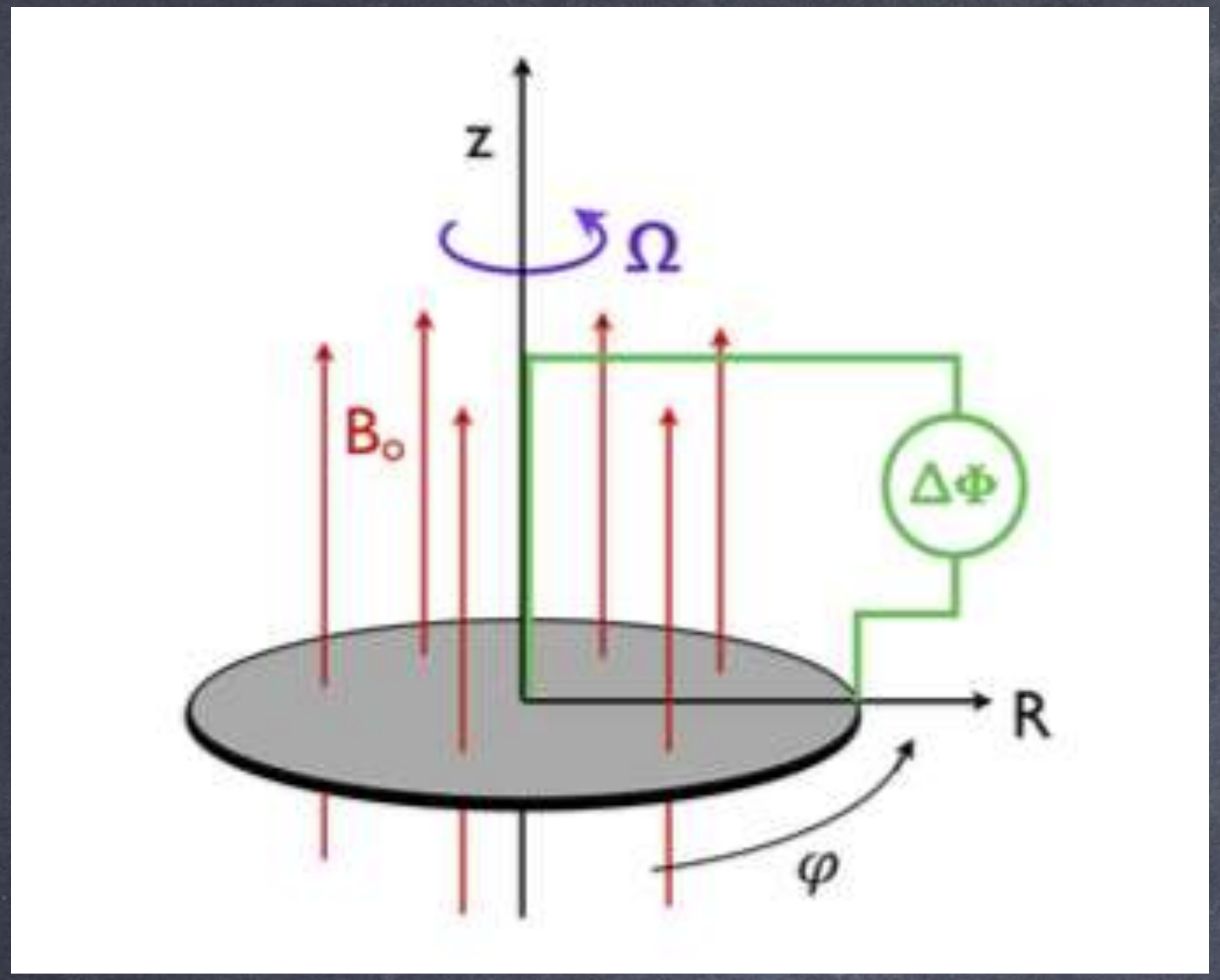


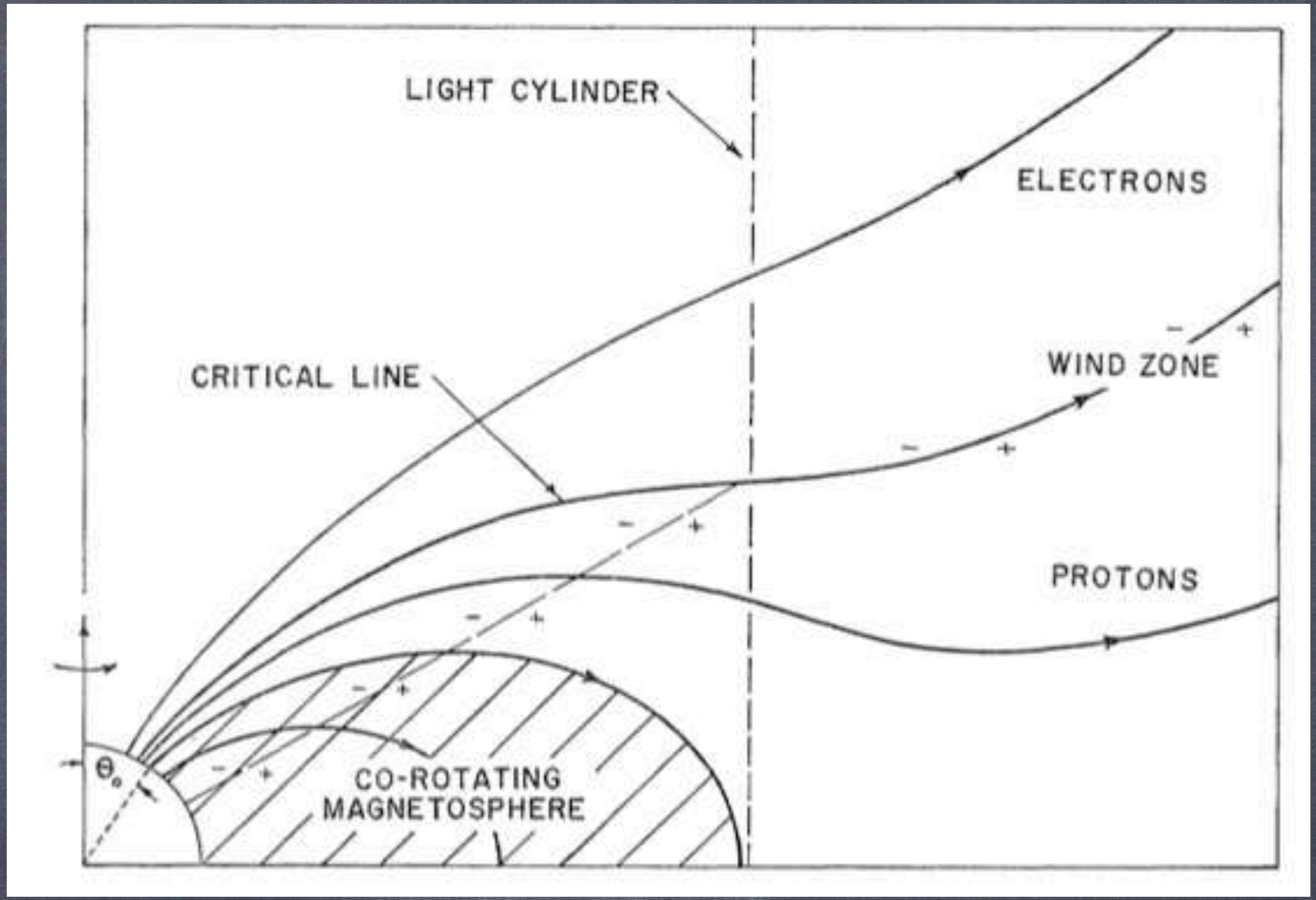
Goldreich & Julian 1969

$$\theta_{\mathrm{PC}} = \sqrt{\frac{R_\star}{R_L}}$$

$$\theta_{\mathrm{c}} = ArcCos\sqrt{\frac{1}{3}}$$

PULSAR BASIC ELECTRODYNAMICS





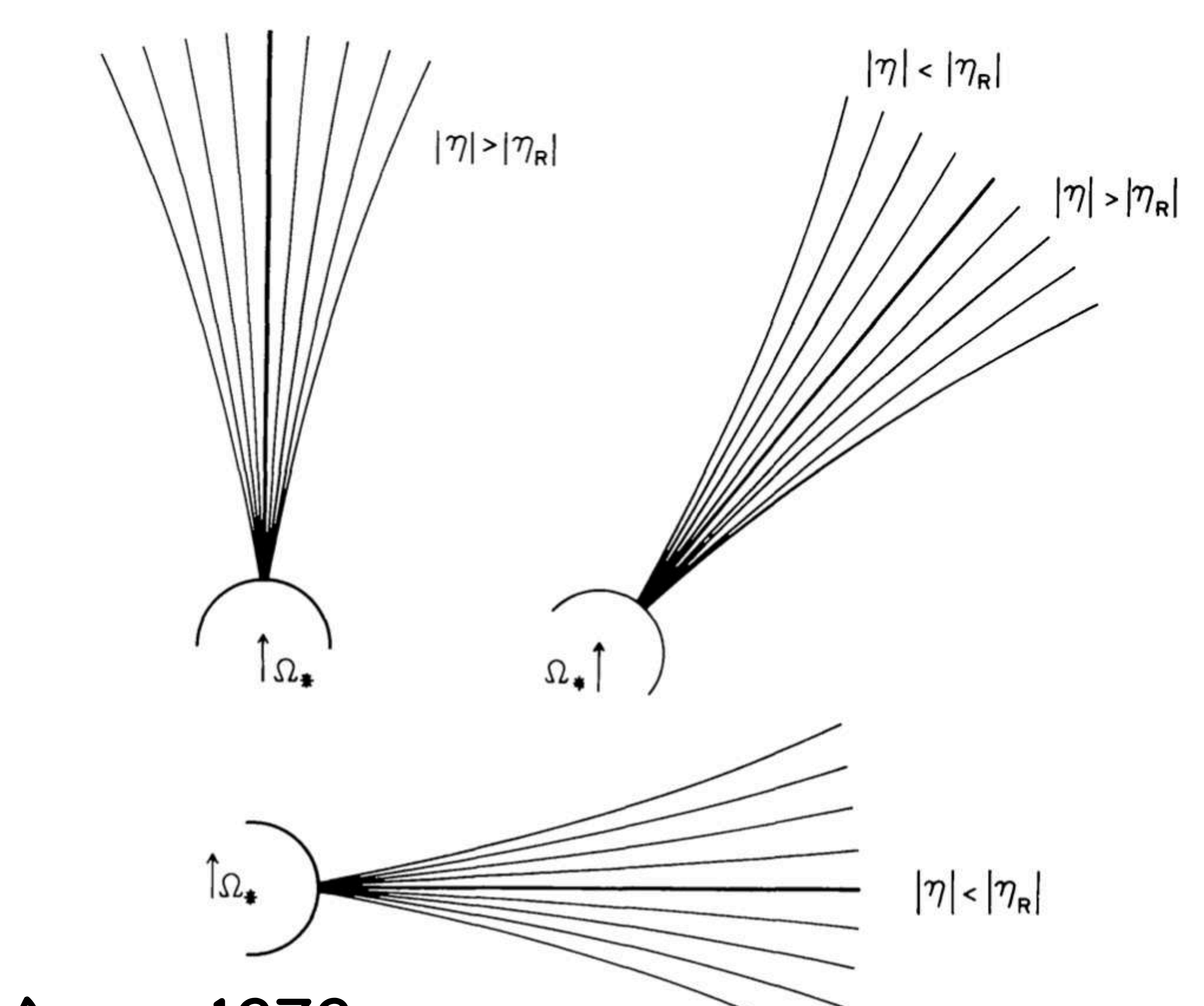
$$\Delta\Phi = \frac{B_0 \Omega R_d^2}{2c}$$

$$\rho_e = -\frac{\Omega\ B_0}{2\pi c}$$

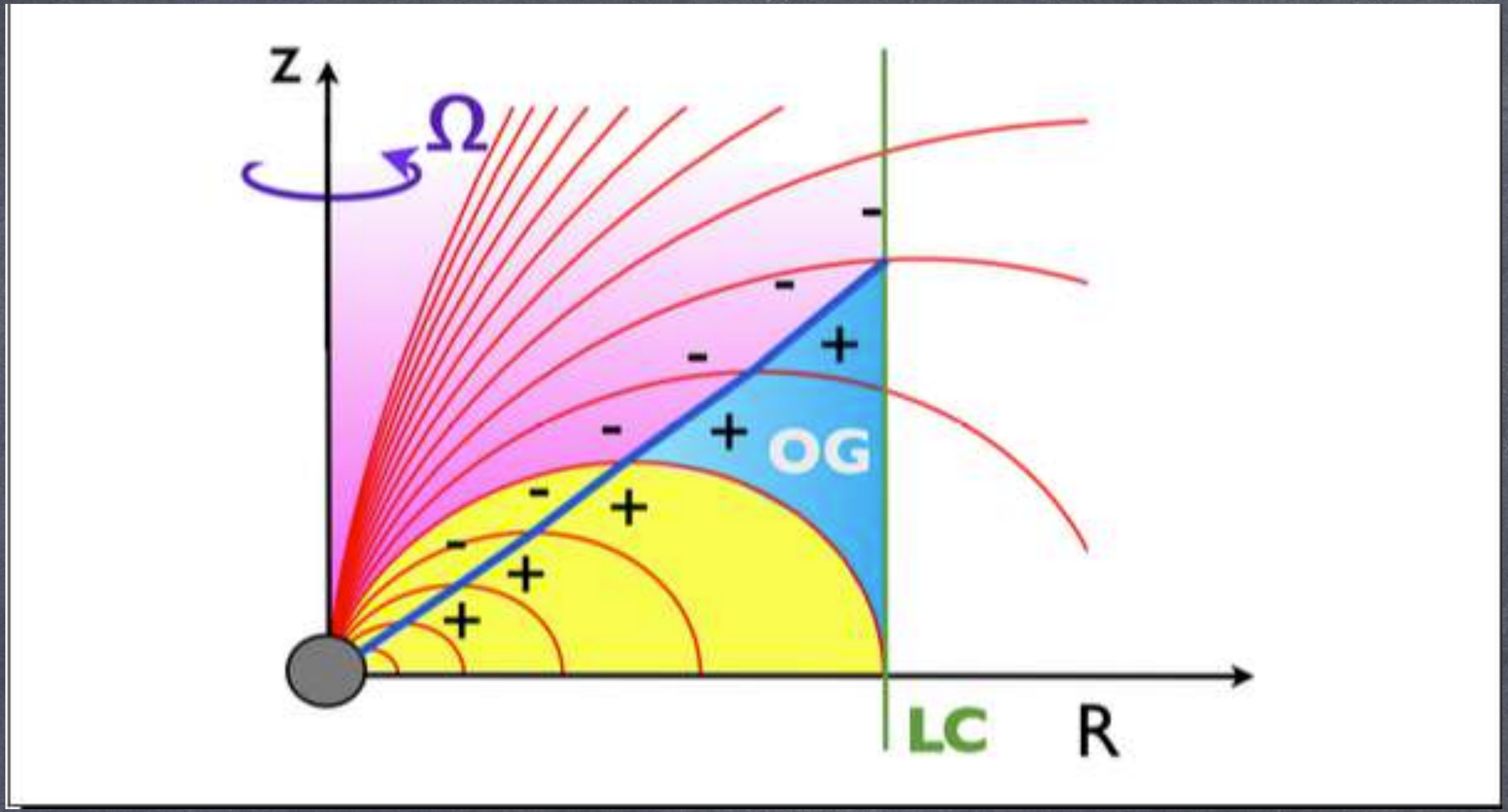
$$\Delta\Phi_{\rm Tot} = \frac{B_\star \Omega R_\star^2}{3c} \qquad \Delta\Phi_{\rm pc} = \frac{B_\star \Omega^2 R_\star^3}{2c^2}$$

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

GAPS IN THE MAGNETOSPHERE



Arons 1979

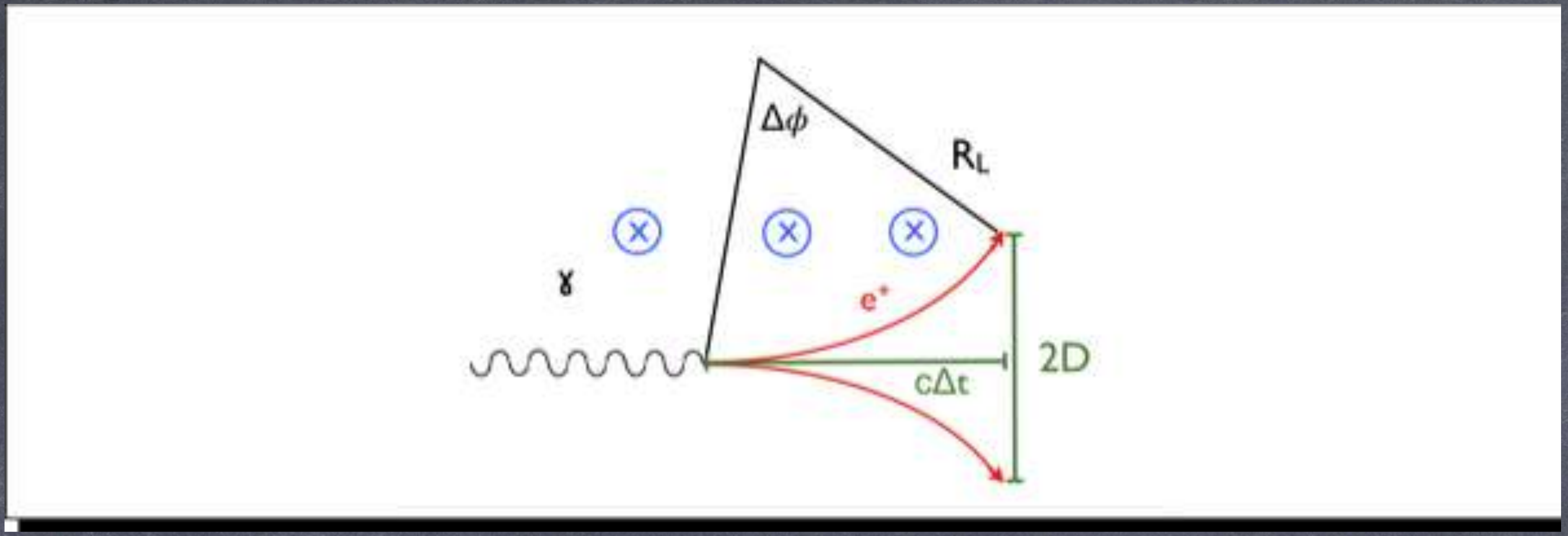


Cheng & Ruderman 1977

$$J_\star = \rho_{\rm GJ}^\star c \qquad J = J_\star \frac{B}{B_\star} \qquad J_{GJ} = c\rho_{GJ} \propto B_z$$

UNSCREENED ELECTRIC FIELD IS LEFT IN ALL CASES IF PARTICLES FROM STAR SURFACE ONLY

PAIR PRODUCTION

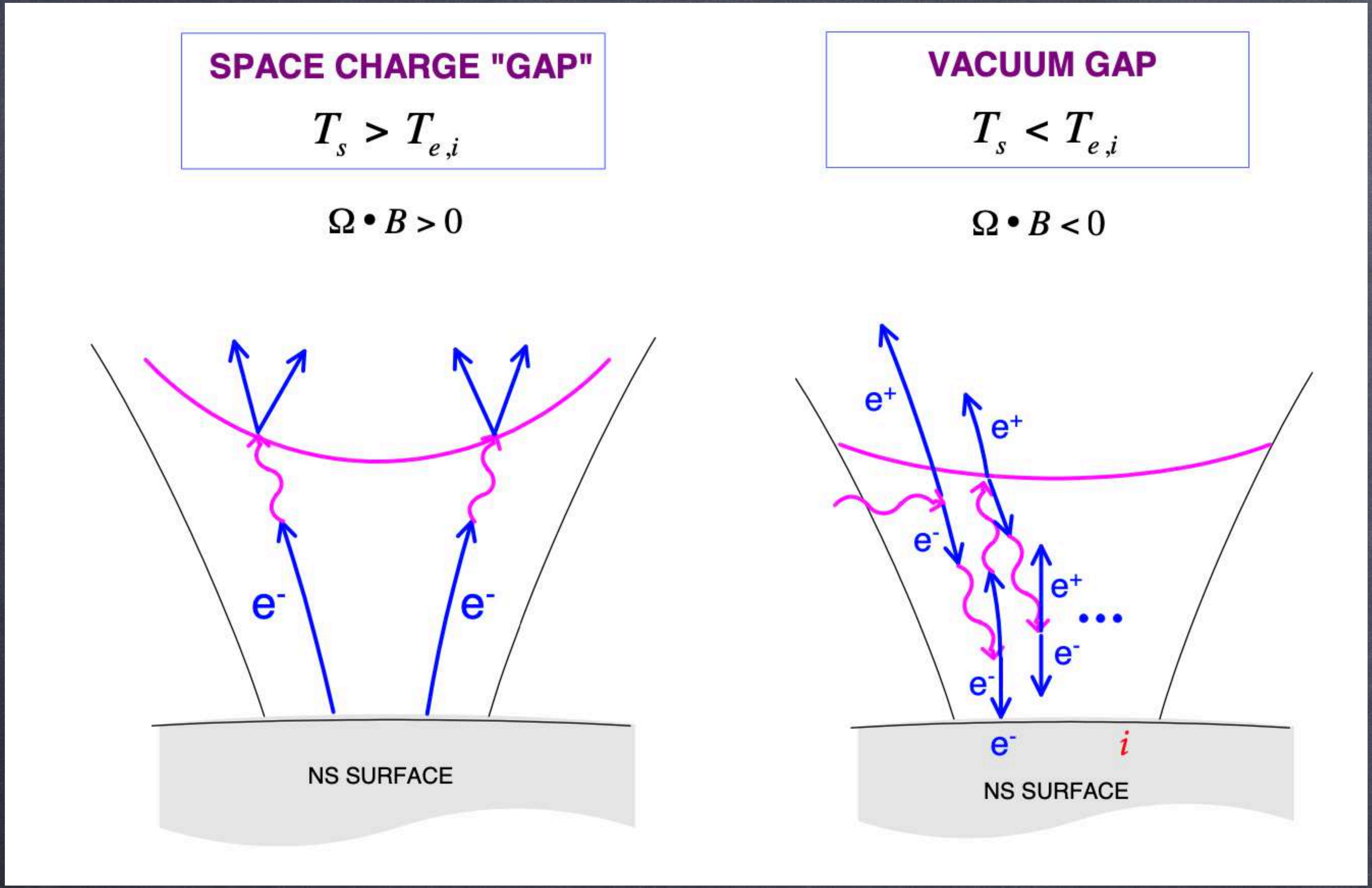


Erber 1966

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

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

POLAR GAPS

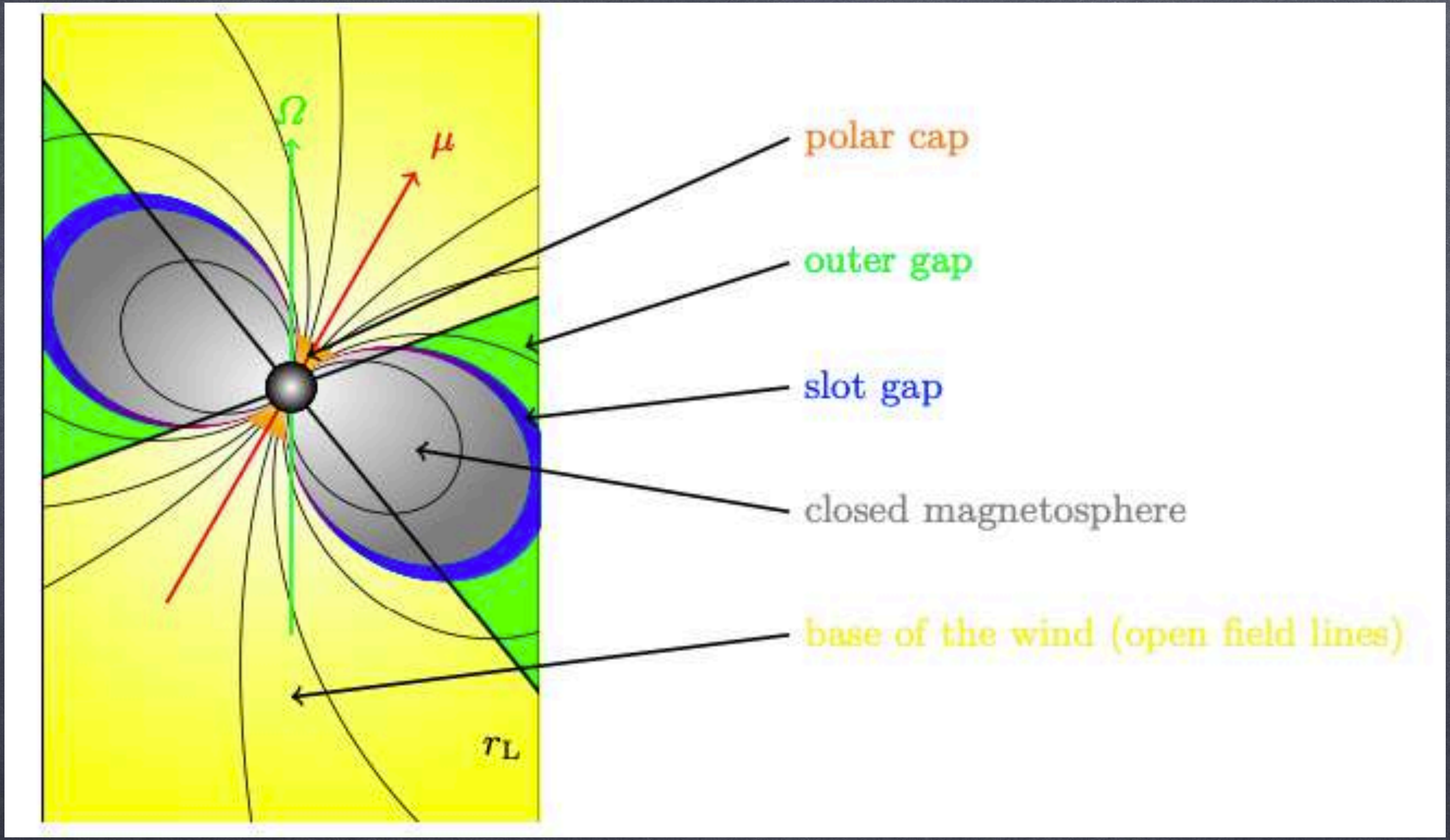


$$T_e \approx 3.6 \times 10^5 \text{ K} \left(\frac{Z}{26}\right)^{0.8} \left(\frac{B_\star}{10^{12}\text{G}}\right)^{0.4}$$

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

Harding 07

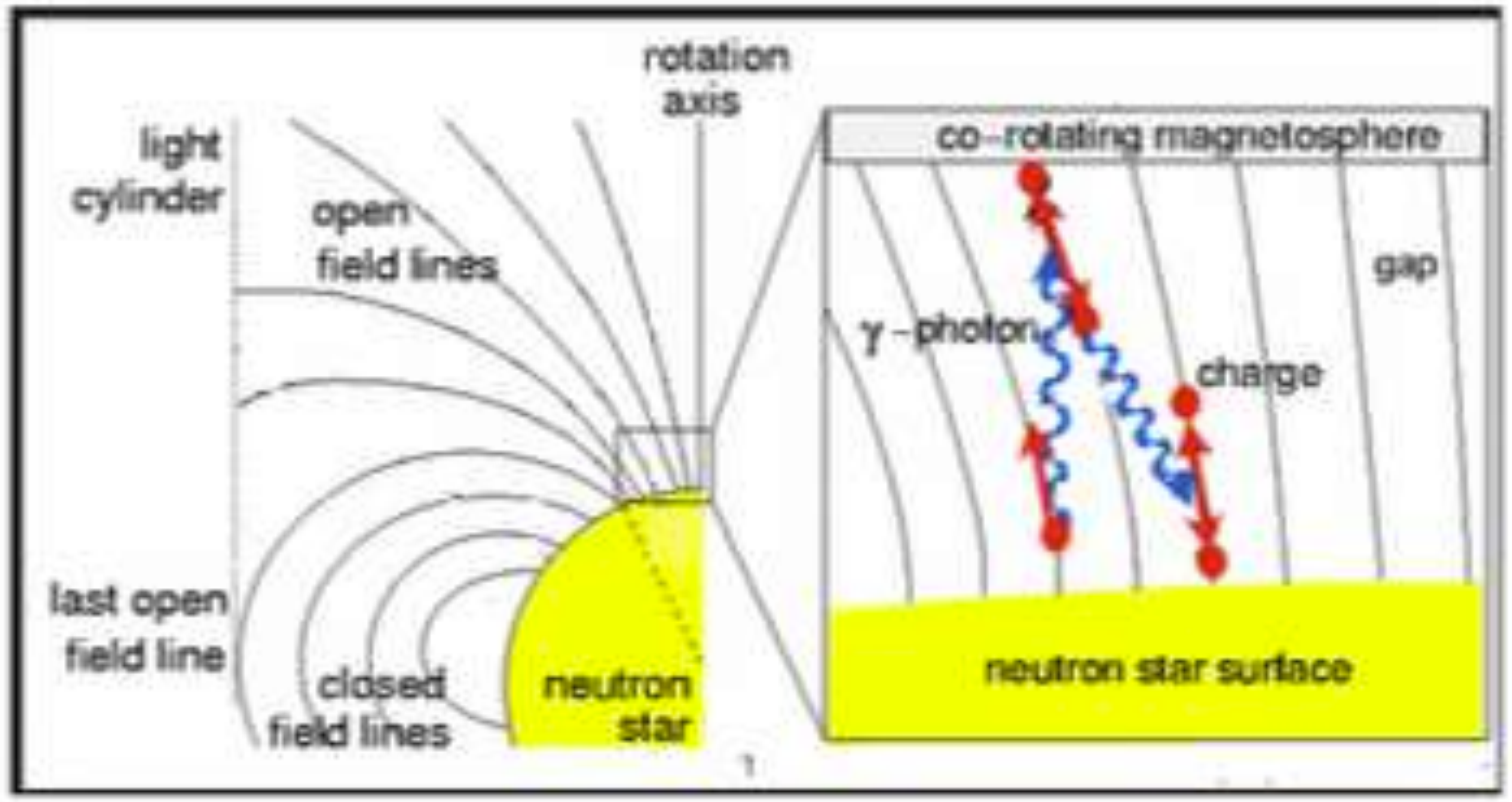
ALL GAPS

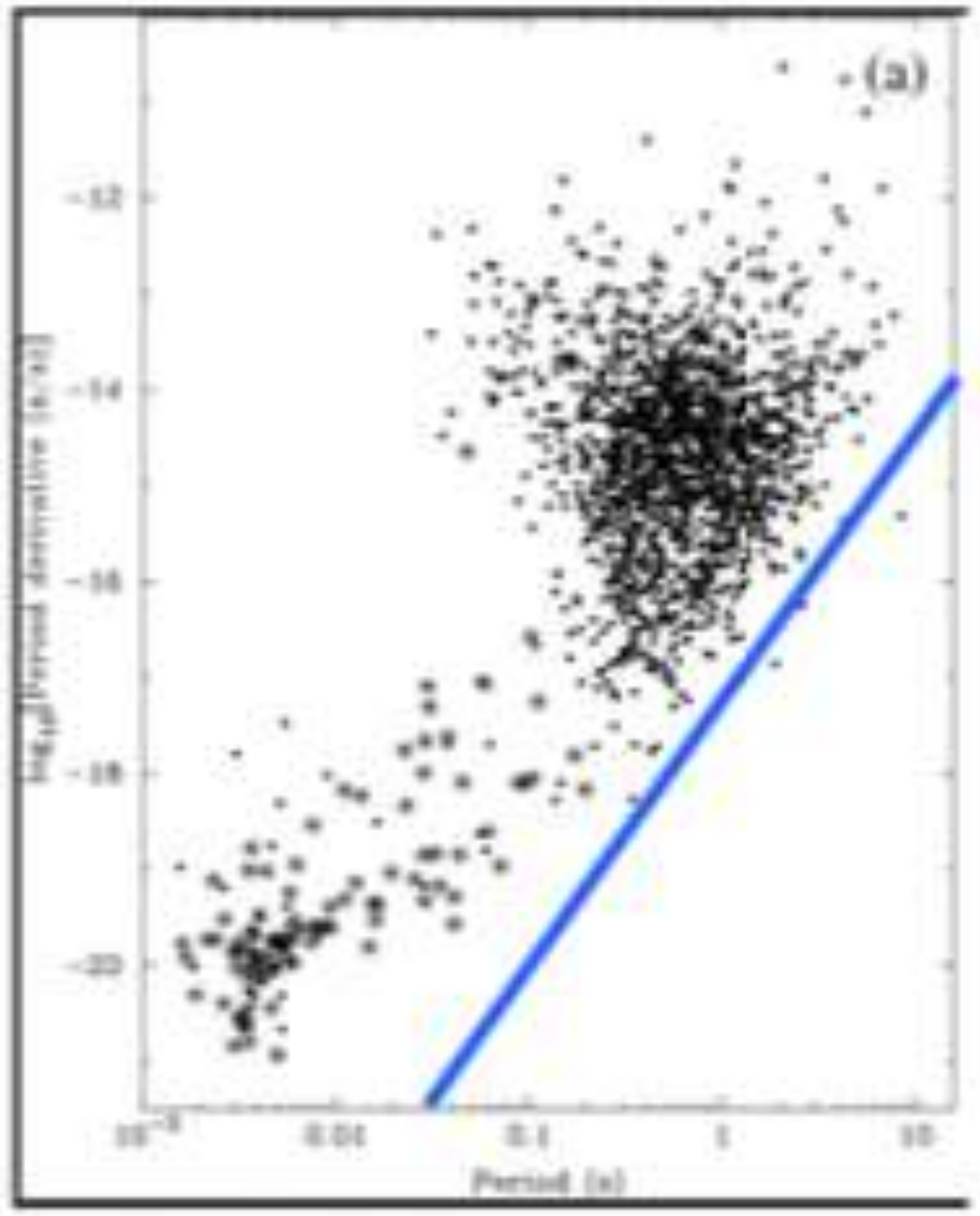


Petri 2017

DIAGNOSTICS OF THE CASCADE

DEATHLINE GAMMA-RAYS MULTIPLICITY





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

$\gamma_{primary} \sim 10^7$

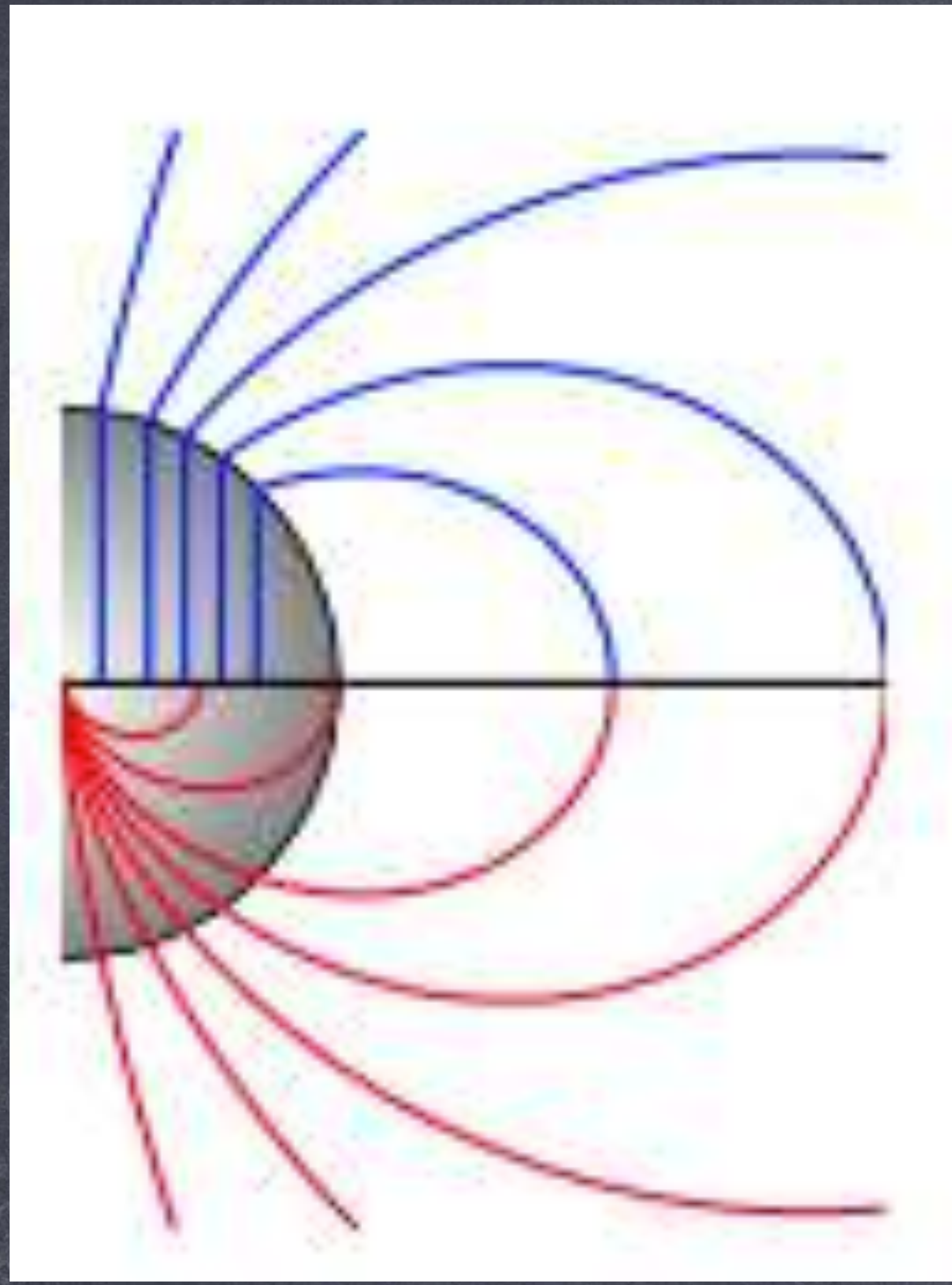
$\gamma_{secondary} \sim 10^{2-3}$

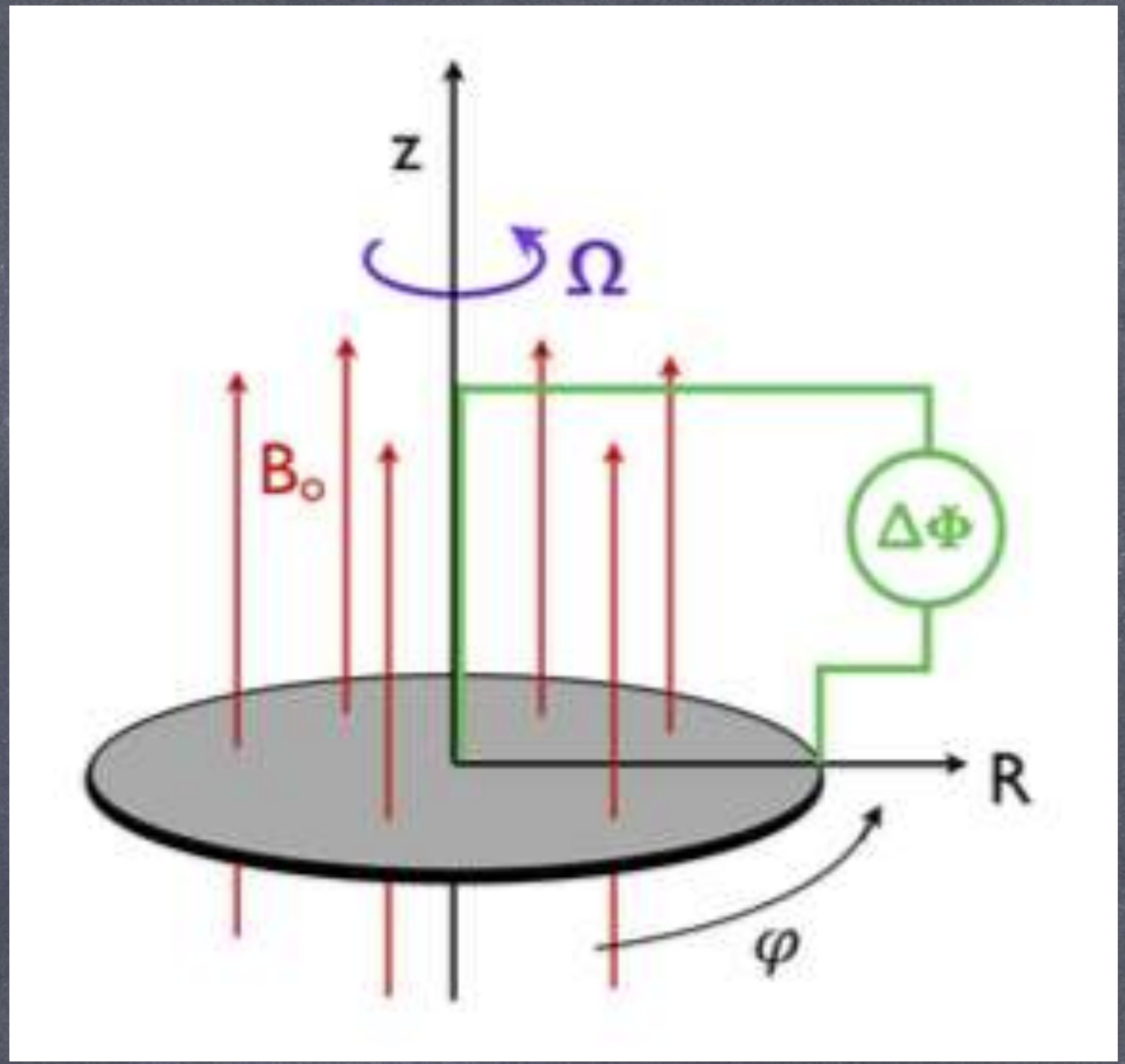
γ-RAYS

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

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

THE PULSAR POTENTIAL DROP



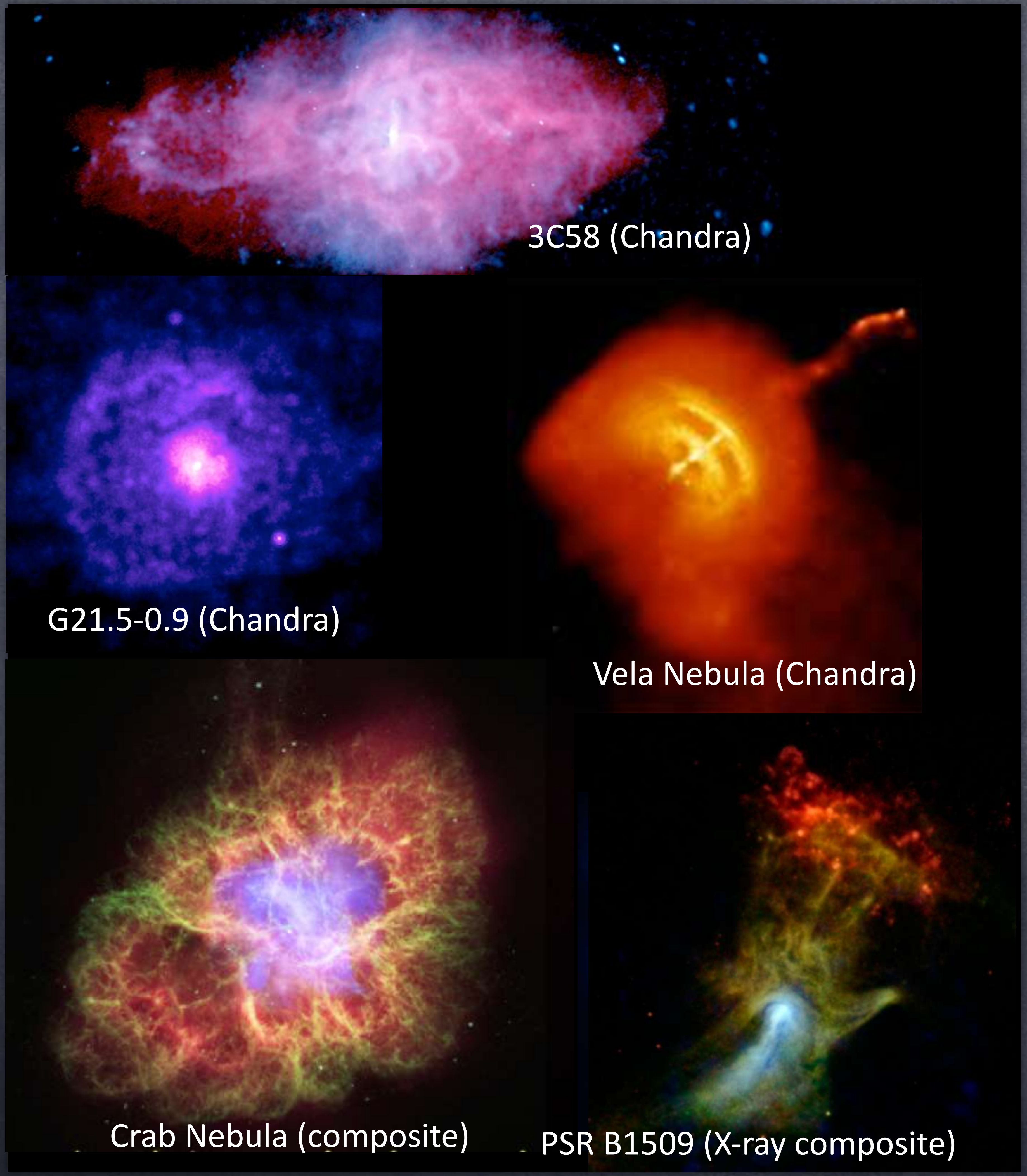


$$\Delta\Phi^{PC} \approx \frac{B_\star \Omega R_\star^2}{c}\frac{R_\star}{R_L} \approx \sqrt{\frac{\dot{E}}{c}}$$

$$\rho_e^{FD} = -\frac{\Omega\ B_0}{2\pi c}$$

$$\Delta\Phi^{FD} \approx B_d \frac{\Omega R_d}{c} R_d$$

PULSAR WIND NEBULAE



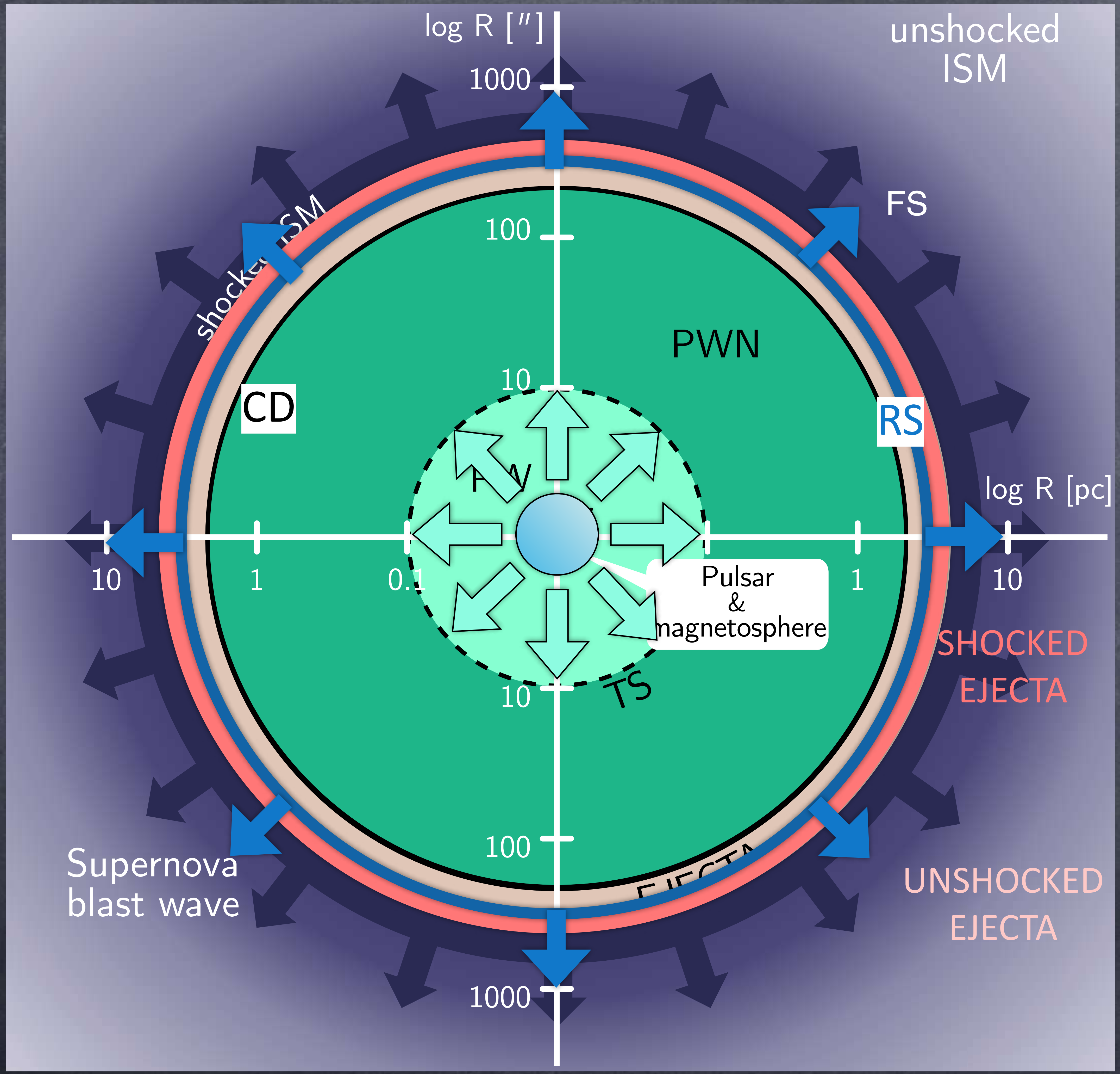
PULSAR WIND NEBULAE OR PLERIONS

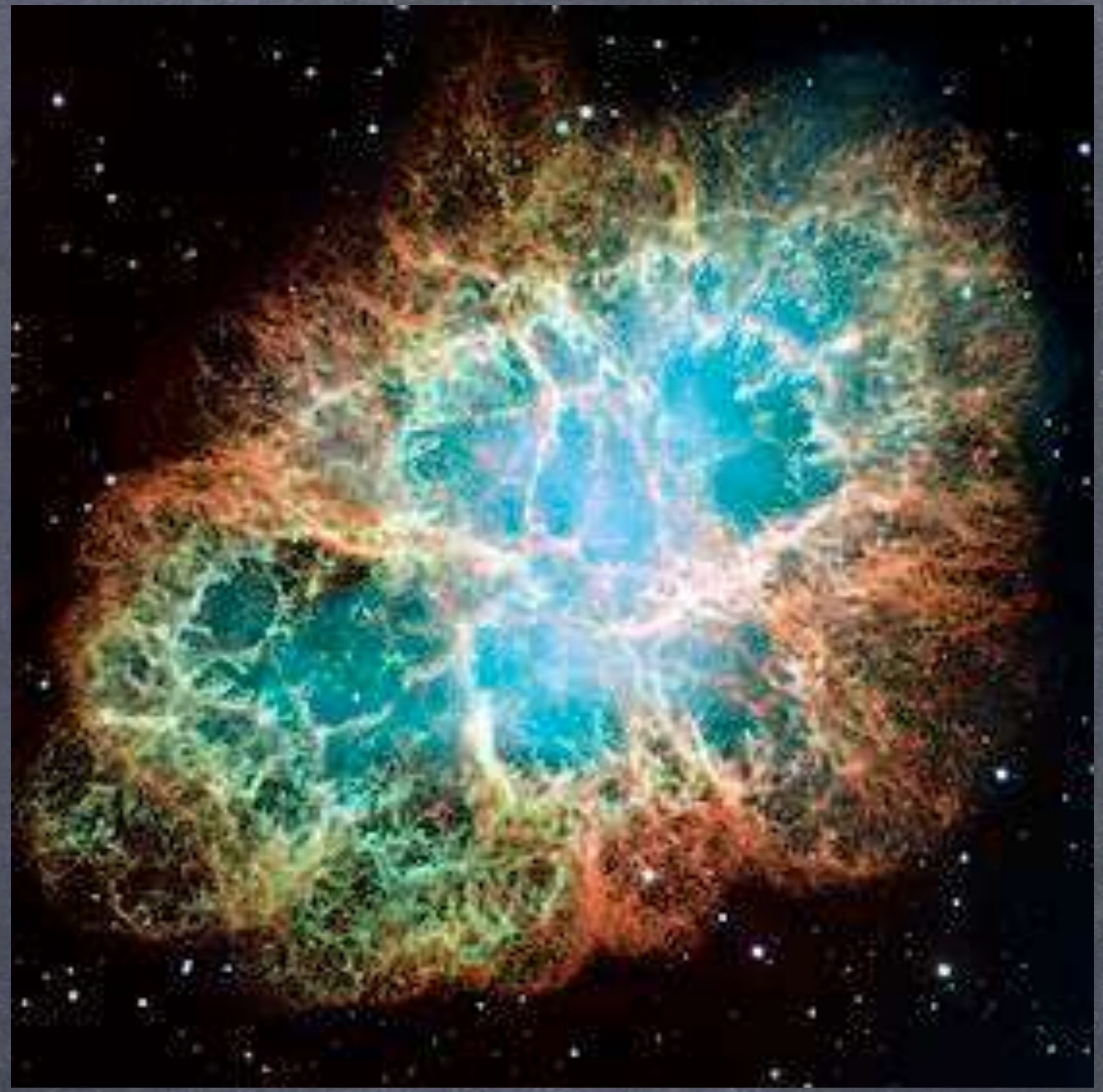
SNRs WITH

- CENTER FILLED MORPHOLOGY
- BROAD NON THERMAL SPECTRUM
- FLAT RADIO SPECTRUM

$$F_\nu \propto \nu^{-\alpha}, \quad \alpha < 0.5$$

PULSAR WIND NEBULAE: THE CRAB NEBULA AS A PROTOTYPE

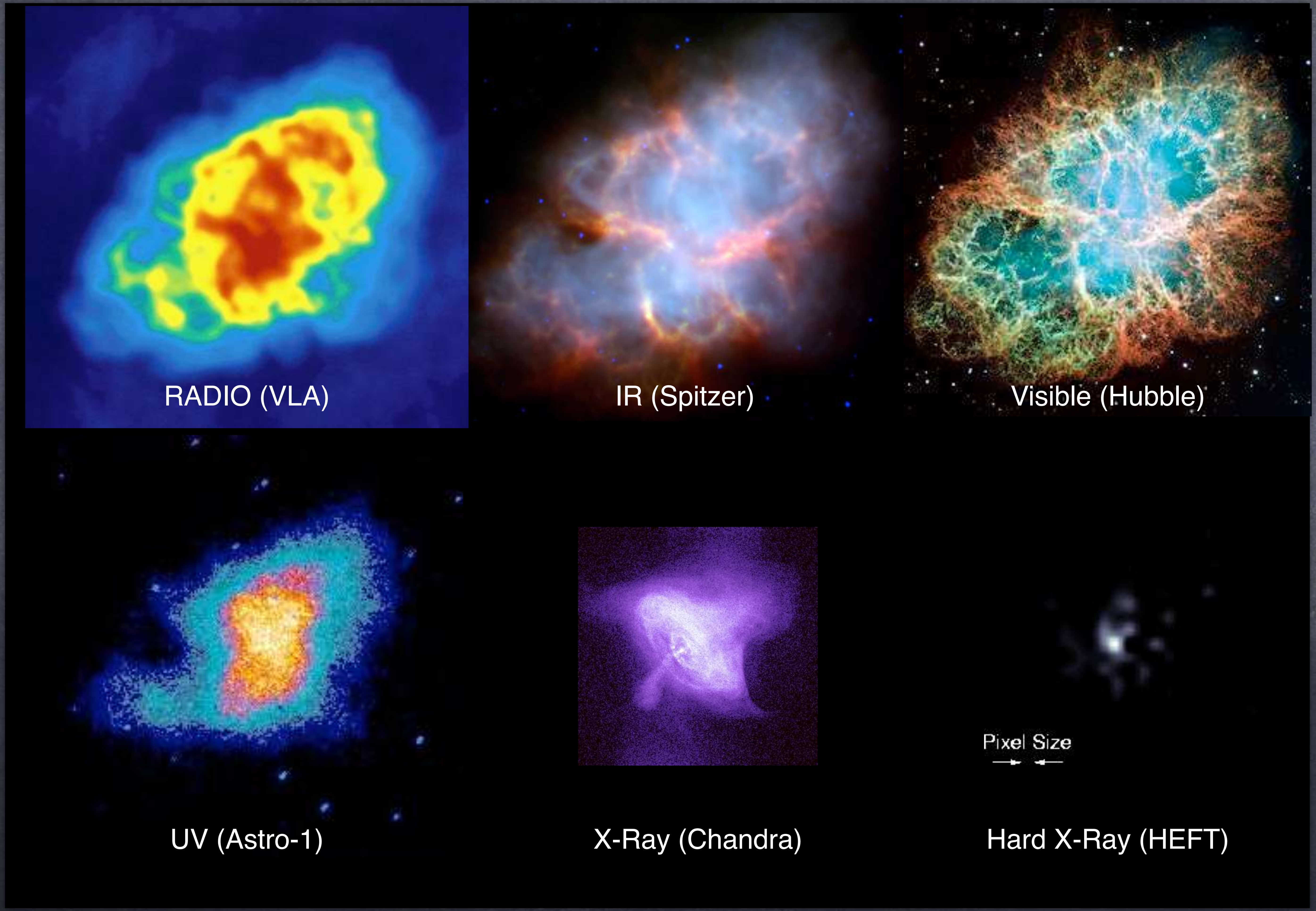




Adapted from Kennel & Coroniti 1984

[Del Zanna & Olmi 2017]

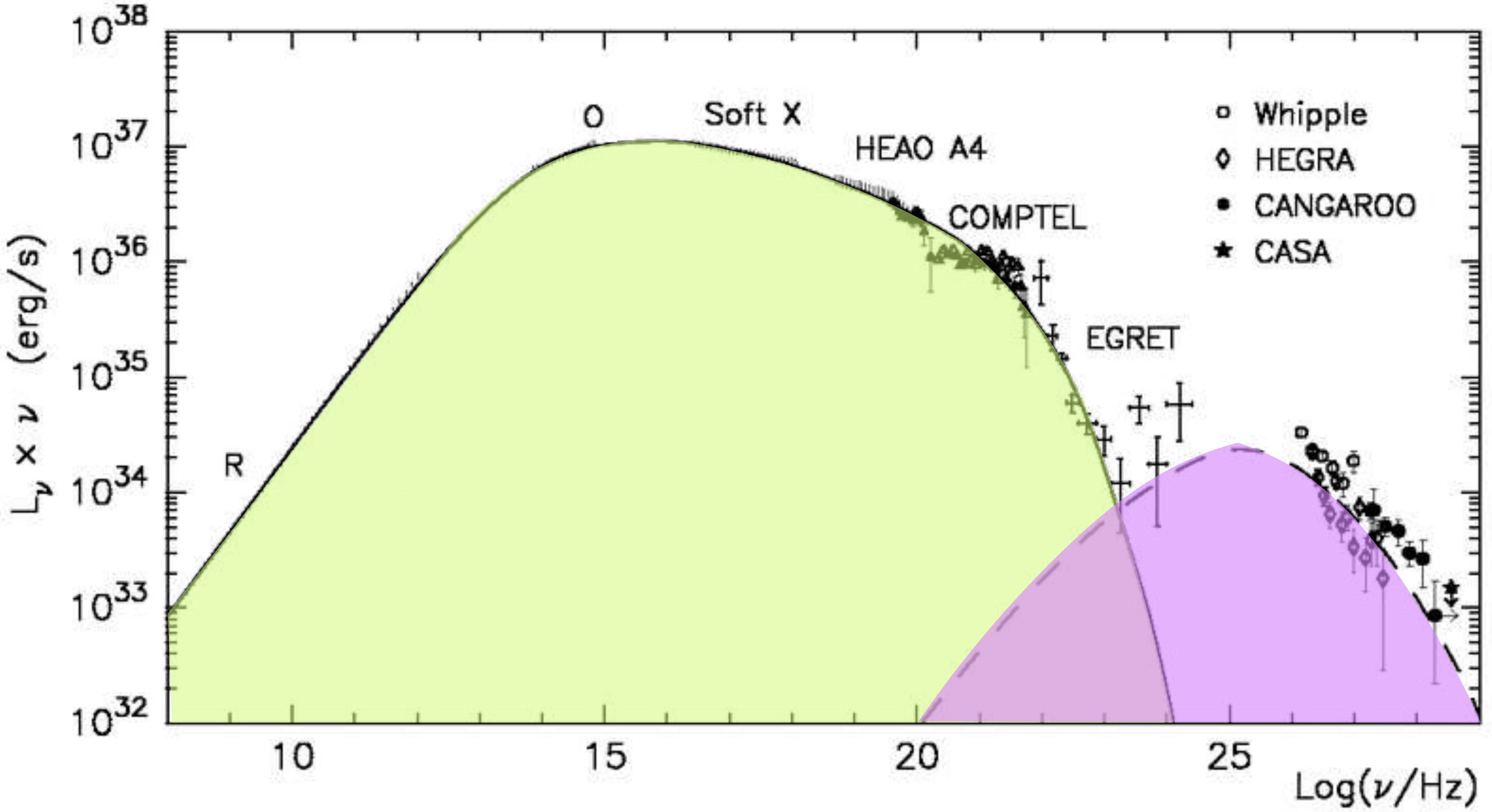
THE CRAB NEBULA AT DIFFERENT FREQUENCIES



THE CRAB NEBULA SPECTRUM

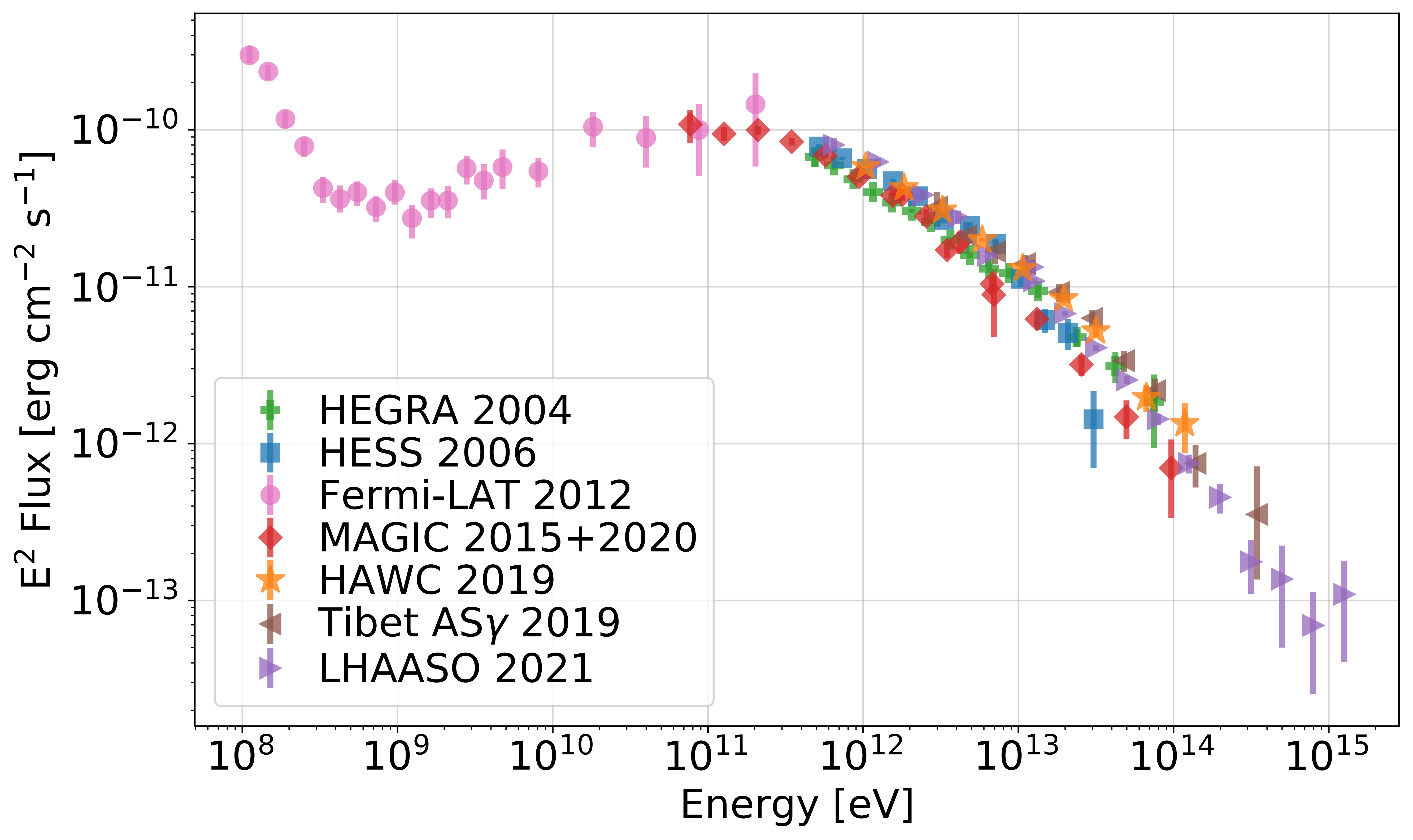
BROAD BAND NON-THERMAL SPECTRUM

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!!!

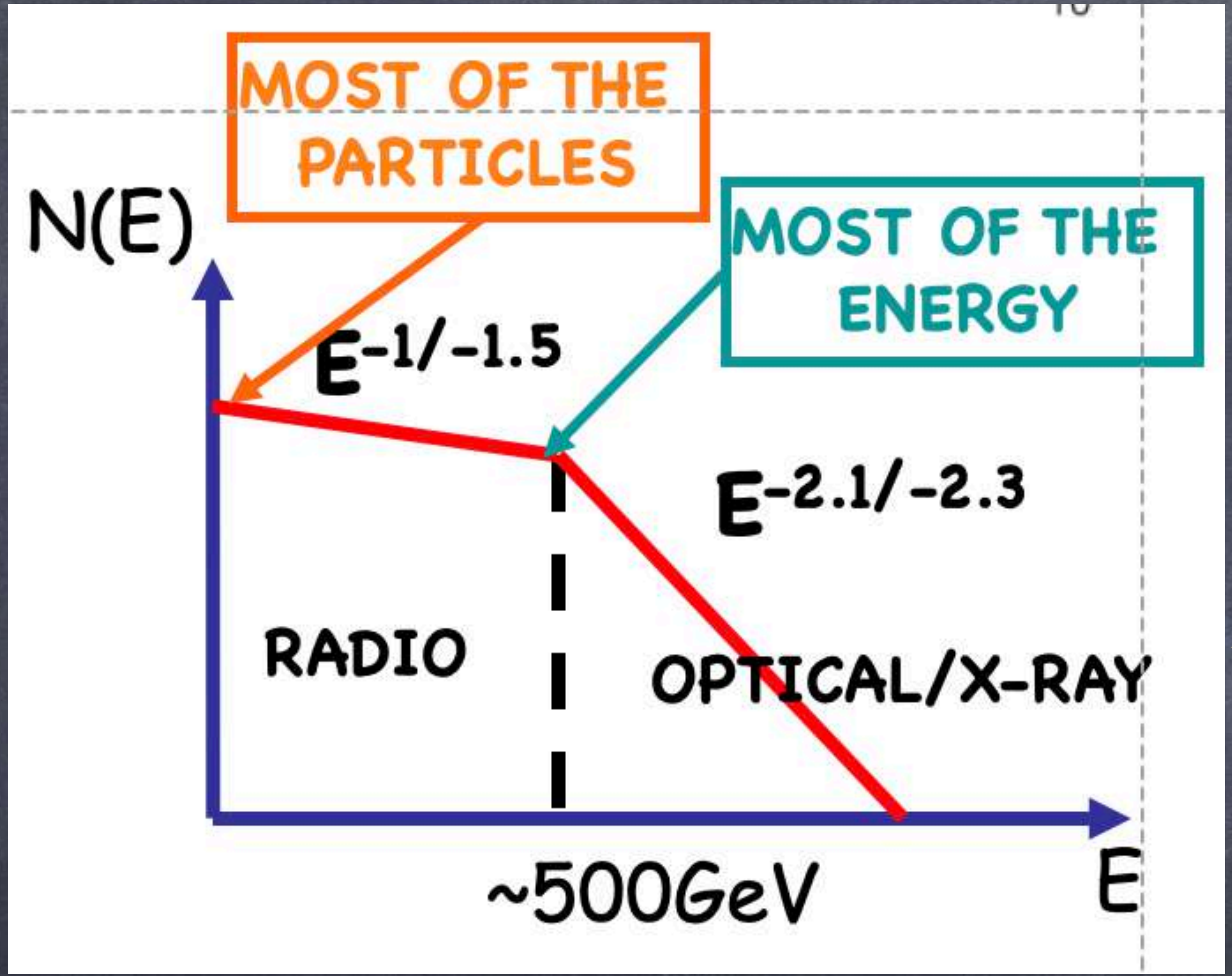
FOR ICS ON CMB

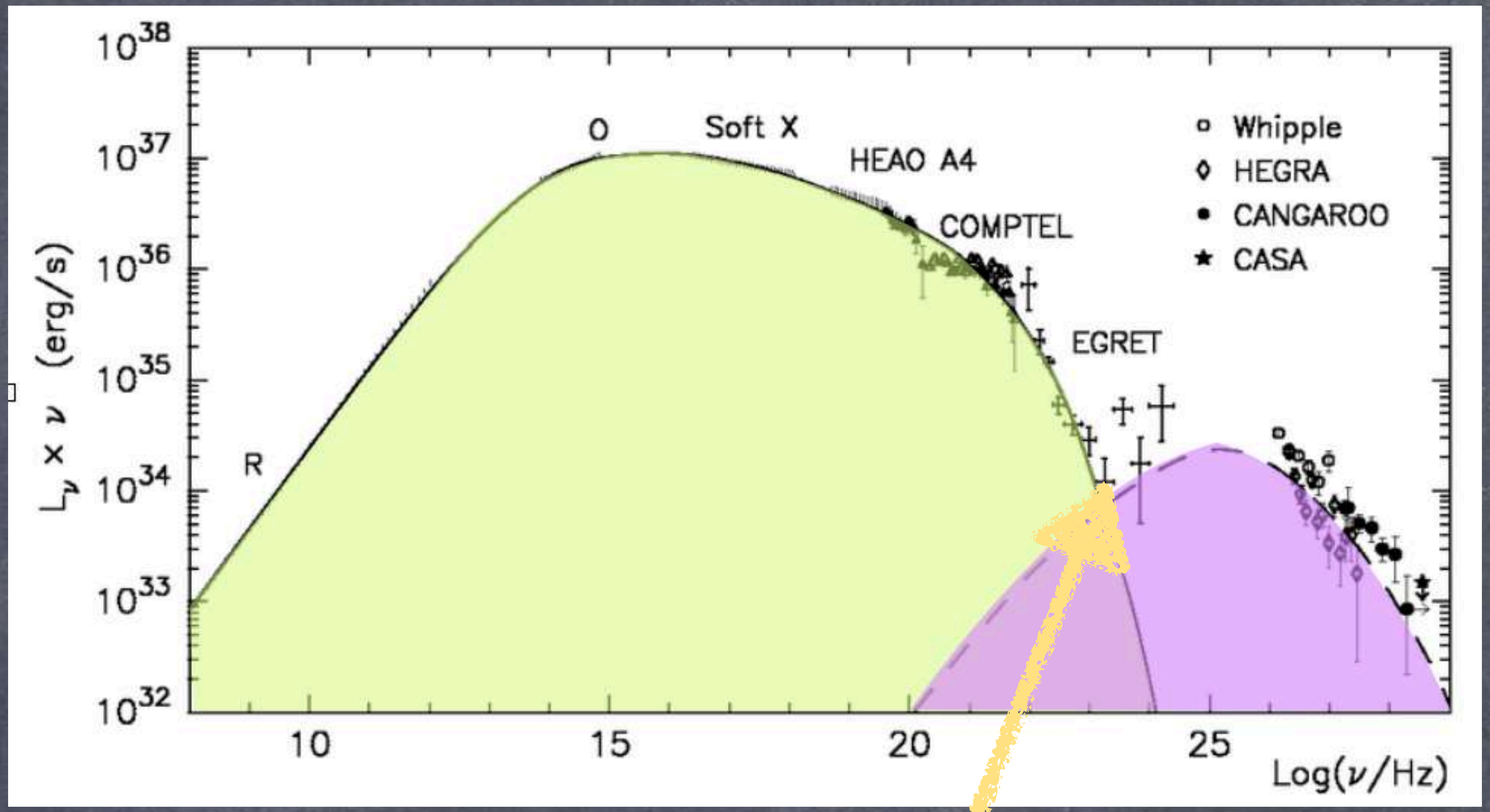
$$\epsilon_\gamma \approx 0.37\ (E_e/\mathrm{PeV})^{1.3}\ \mathrm{PeV}$$

HIGHEST ENERGY LHAASO DATA POINT

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

EMITTING PARTICLES





PeV ELECTRONs

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

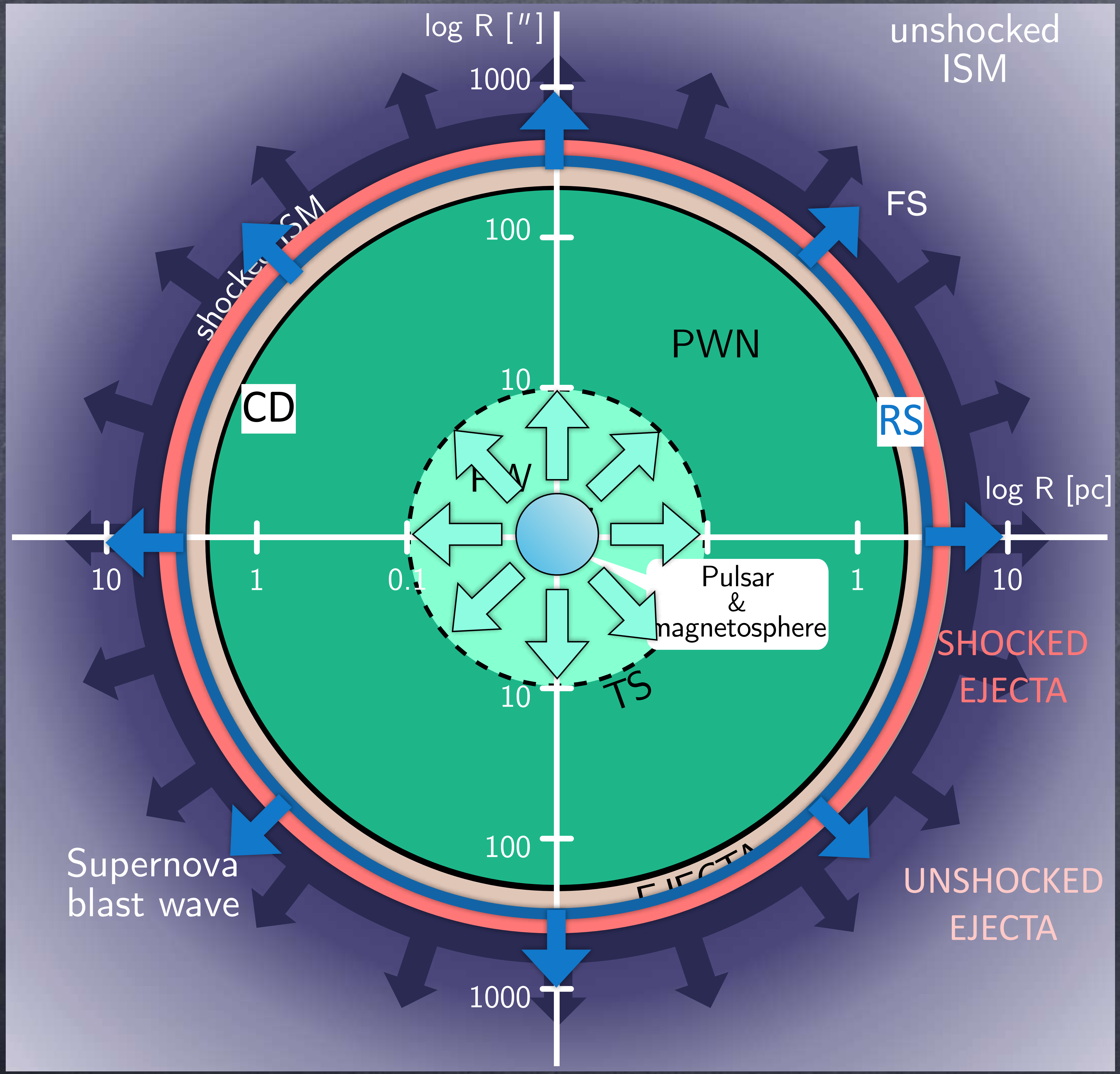
$L_{NEB} > 20\,\%\,\dot{E}$

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

EXTRAORDINARY ACCELERATOR!

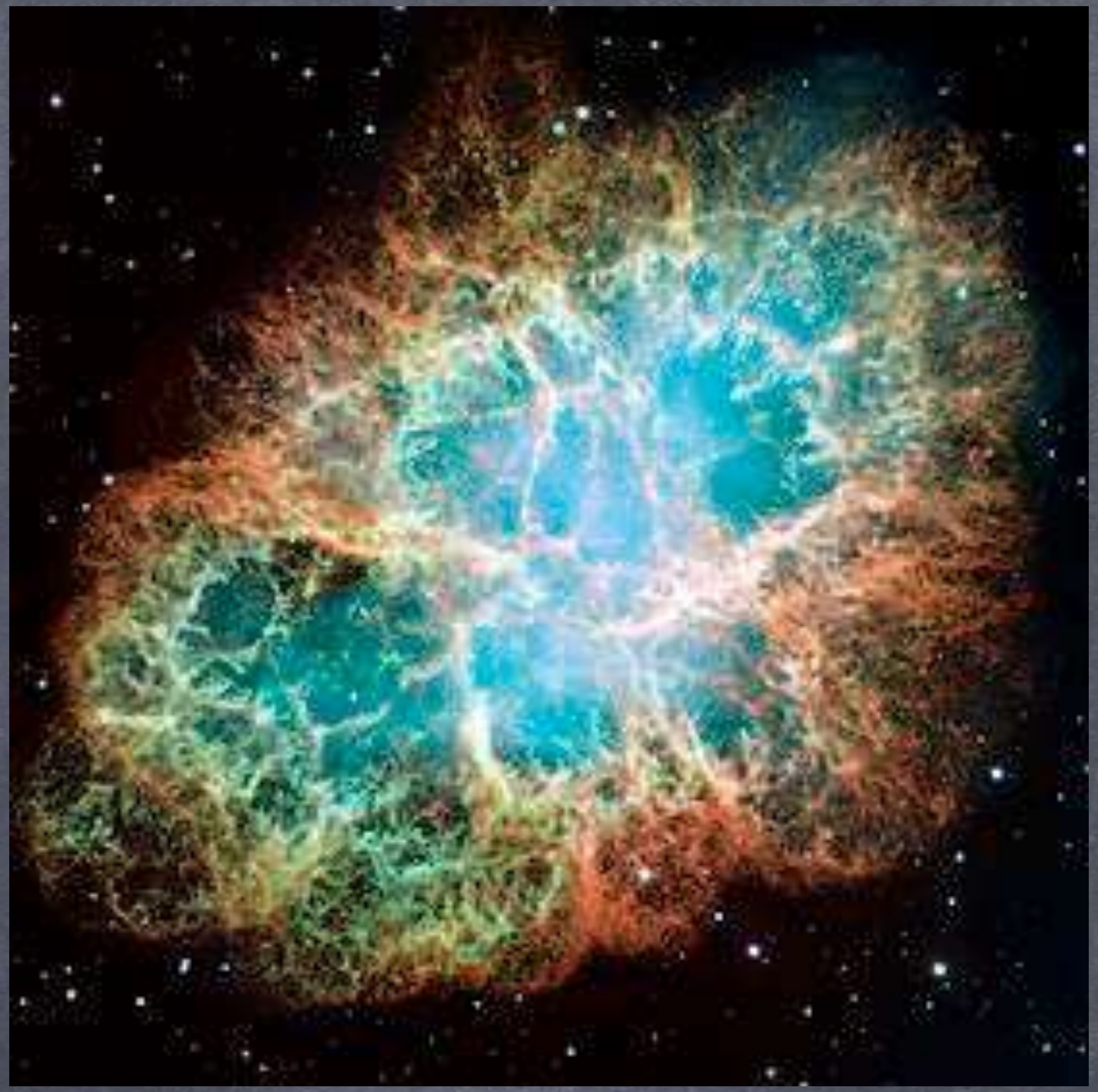
BUT....

BASIC PICTURE OF A YOUNG PWN



Adapted from Kennel & Coroniti 1984

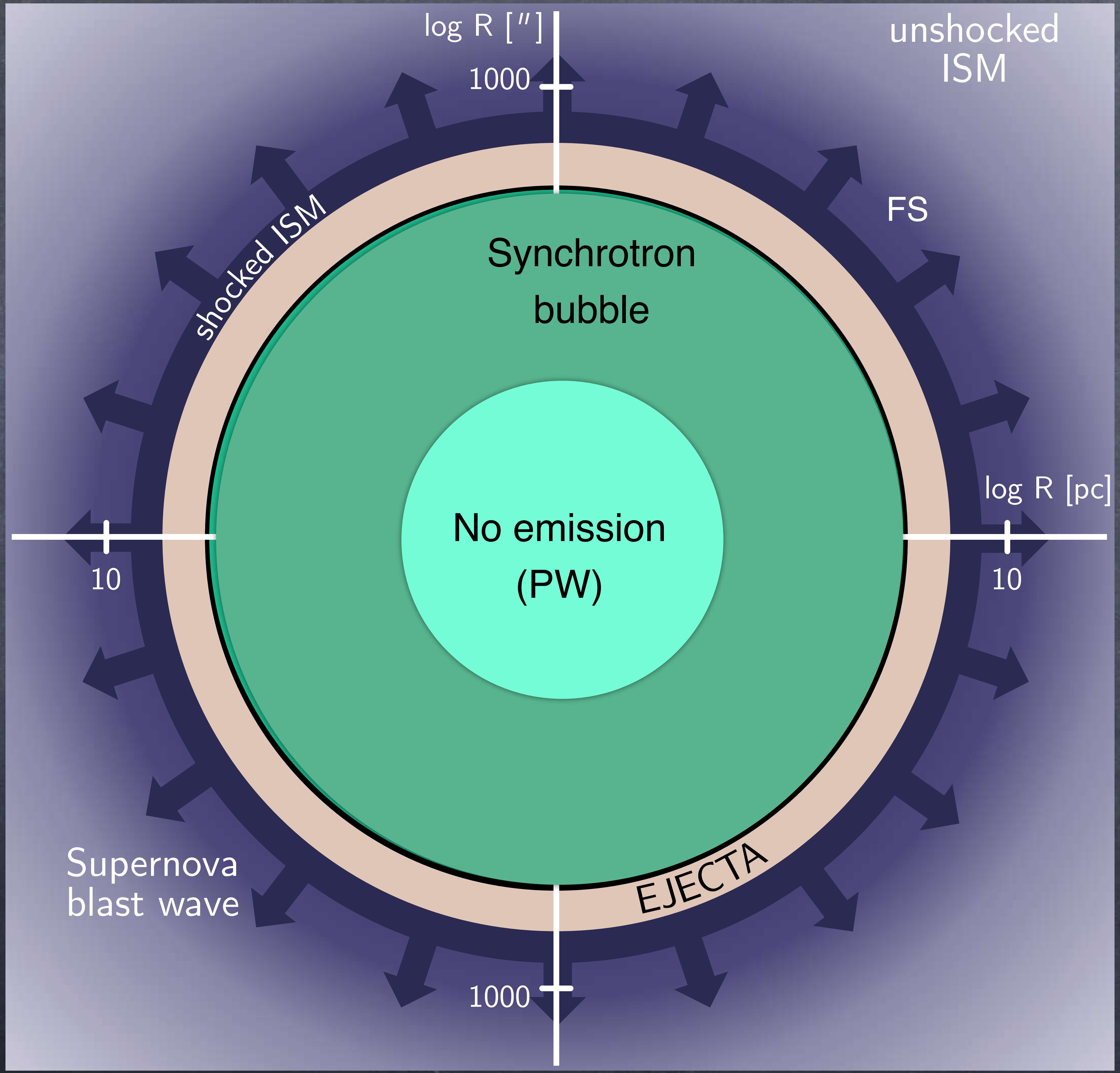
[Del Zanna & Olmi 2017]



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

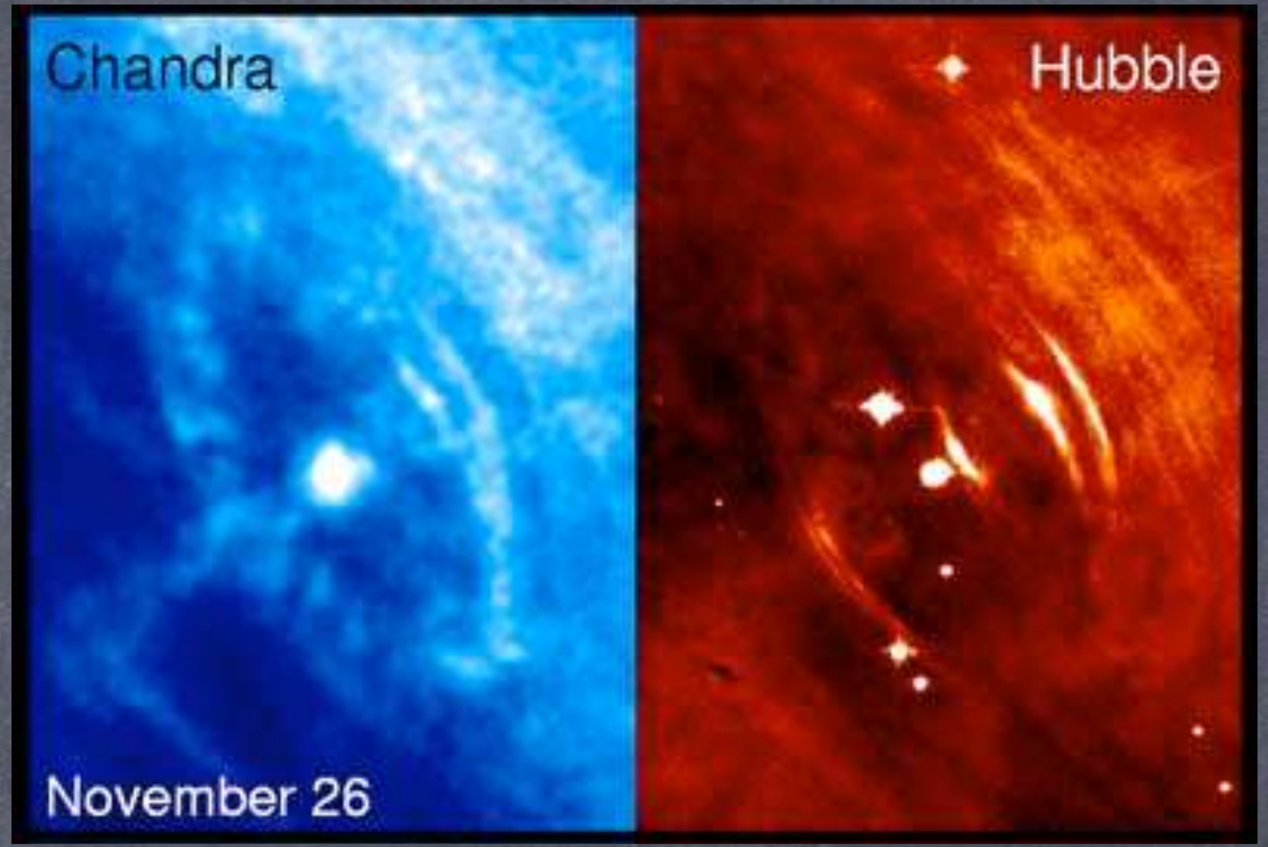
$$R_{TS} = \left(\frac{v_N}{c}\right)^{1/2} R_N$$

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 ACCELERATION AT TS

PARTICLE ACCELERATION AT RELATIVISTIC SHOCKS

- FERMI ACCELERATION
- MAGNETIC RECONNECTION
- ION CYCLOTRON ABSORPTION

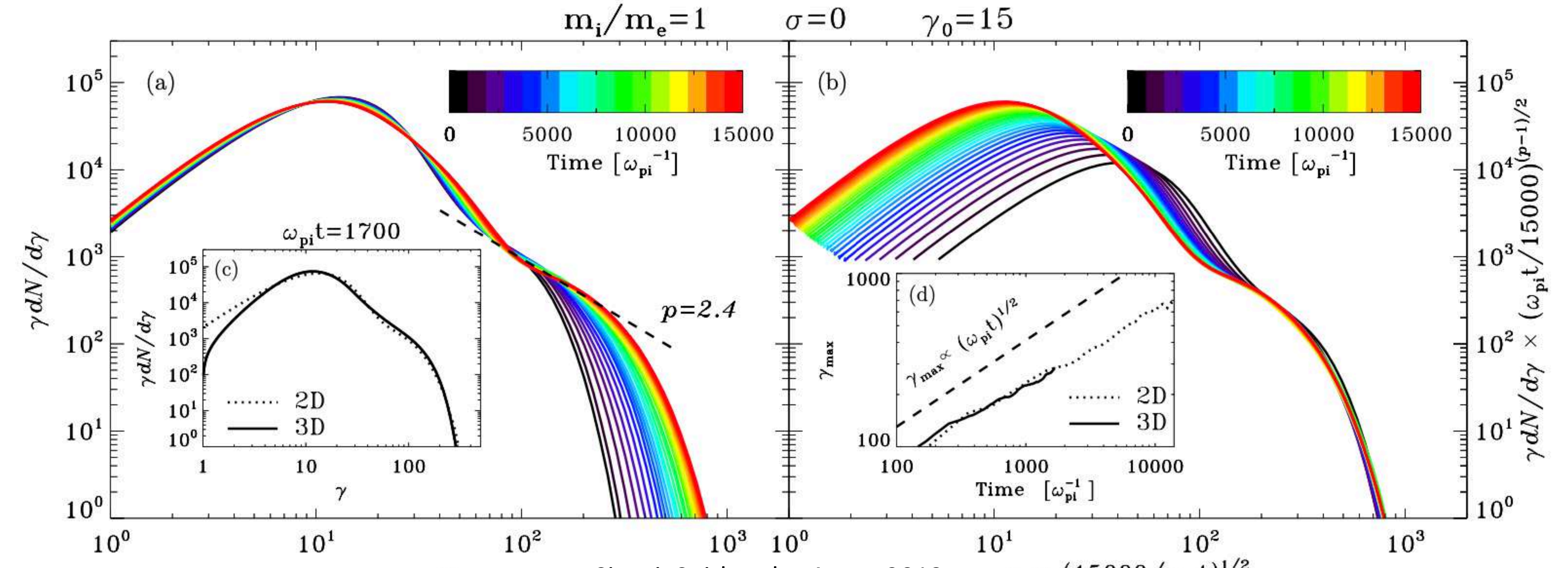
THE PROBLEM

- RELATIVISTIC SHOCKS ARE PERPENDICULAR UNLESS $\theta < 1/\Gamma$ WHERE θ IS THE ANGLE BETWEEN $\overrightarrow{B}$ AND THE SHOCK NORMAL: VERY RARE CONFIGURATION!!!!

- PERP. DIFFUSION IS SUPPRESSED $\Rightarrow$ VERY FEW PARTICLES COME BACK TO THE SHOCK FROM DOWNSTREAM, WHILE THE MAJORITY IS ADVECTED AWAY

- DIFFUSIVE SHOCK ACCELERATION REQUIRES VERY HIGH TURBULENCE LEVEL!

FERMI ACCELERATION (RELATIVISTIC UNMAGNETIZED!)

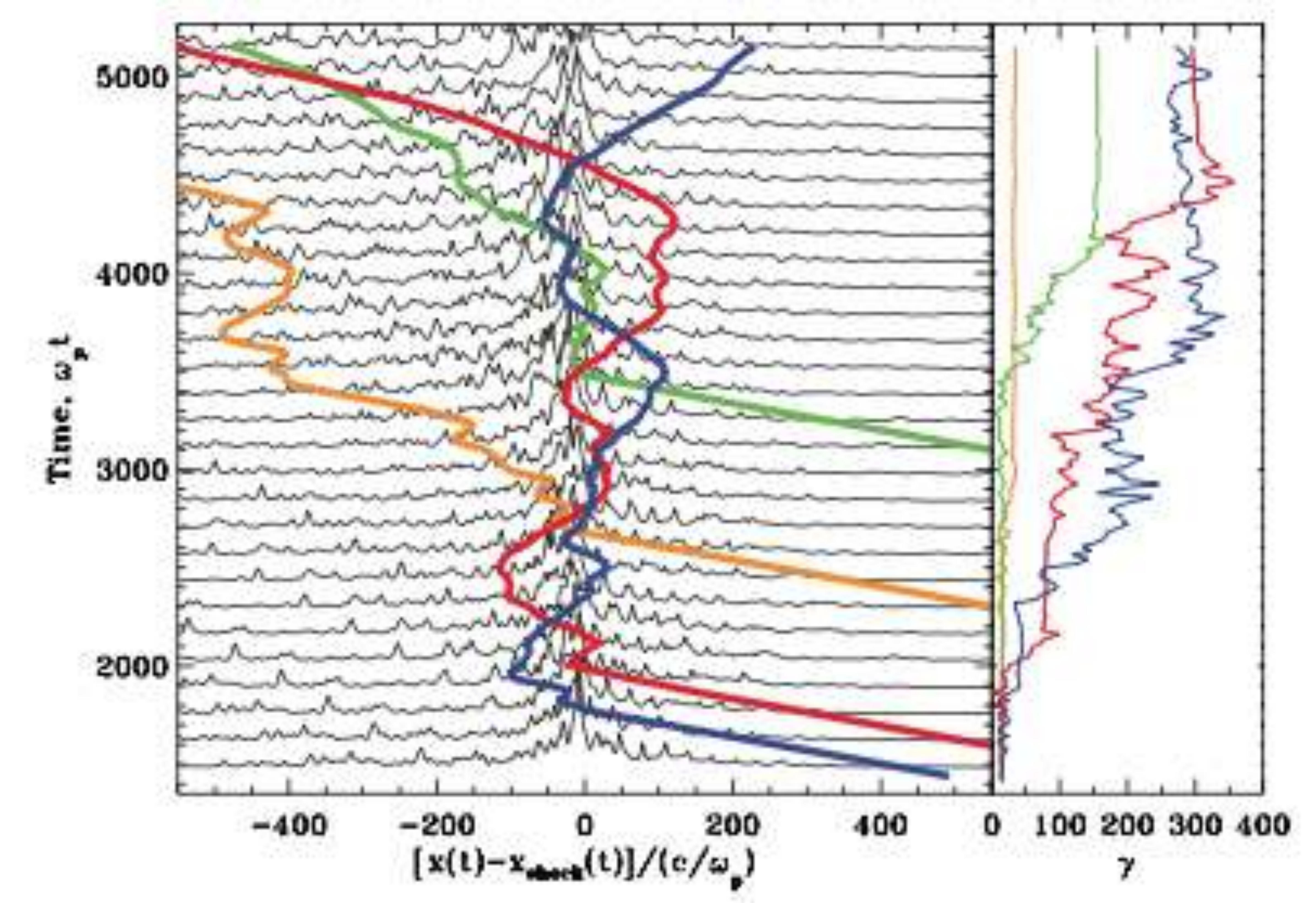


Sironi, Spitkovsky, Arons 2013

POWER-LAW DEVELOPS BUT SLOW PROCESS!

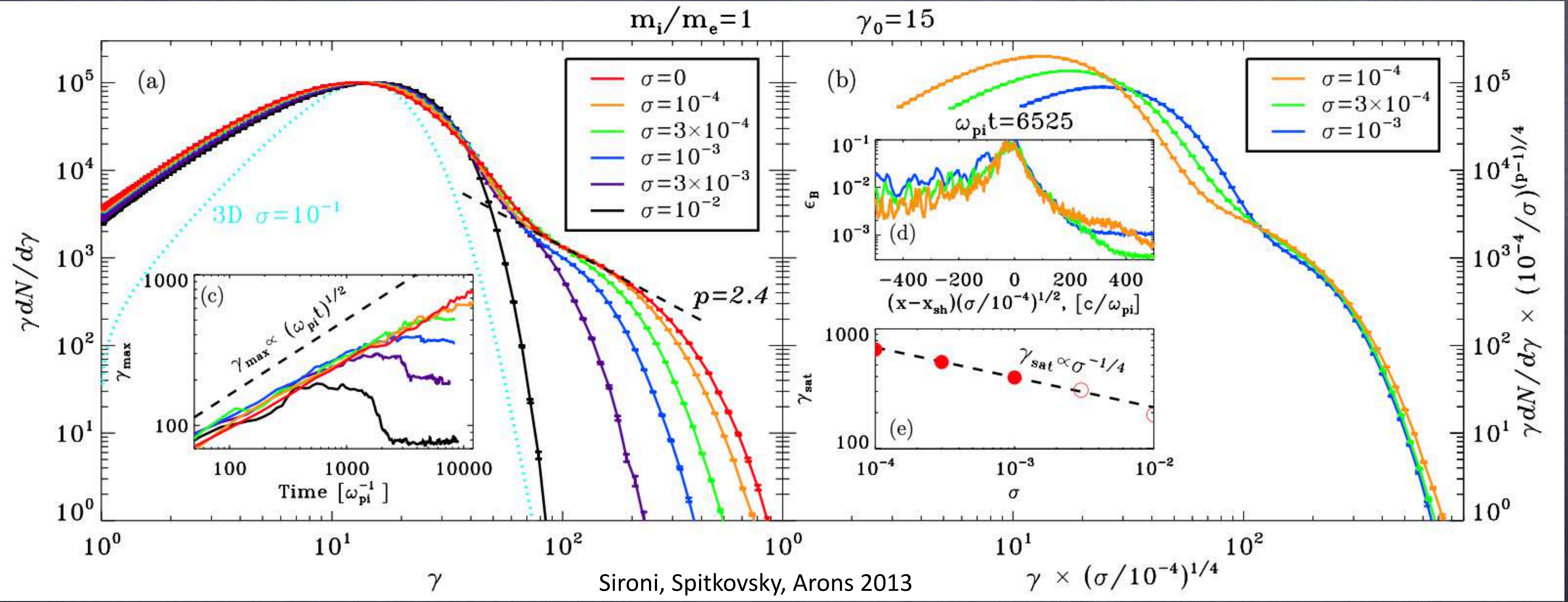
SCATTERING ON SMALL-SCALE TURBULENCE: $E_{MAX} \propto t^{1/2}$

FERMI ACCELERATION (RELATIVISTIC MAGNETIZED!)



Sironi, Spitkovsky, Arons 2013

FERMI ACCELERATION (RELATIVISTIC MAGNETIZED!)

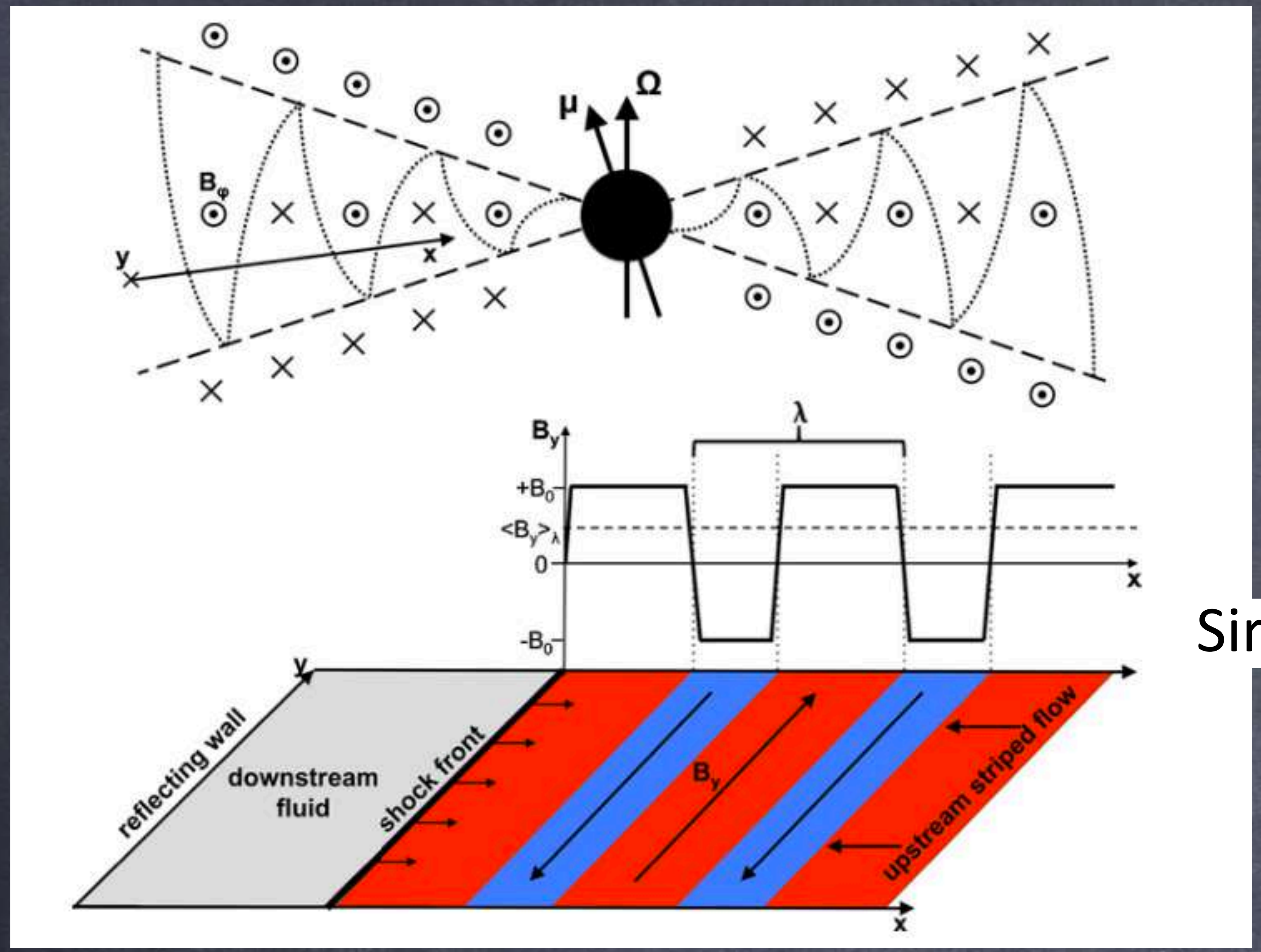


Sironi, Spitkovsky, Arons 2013

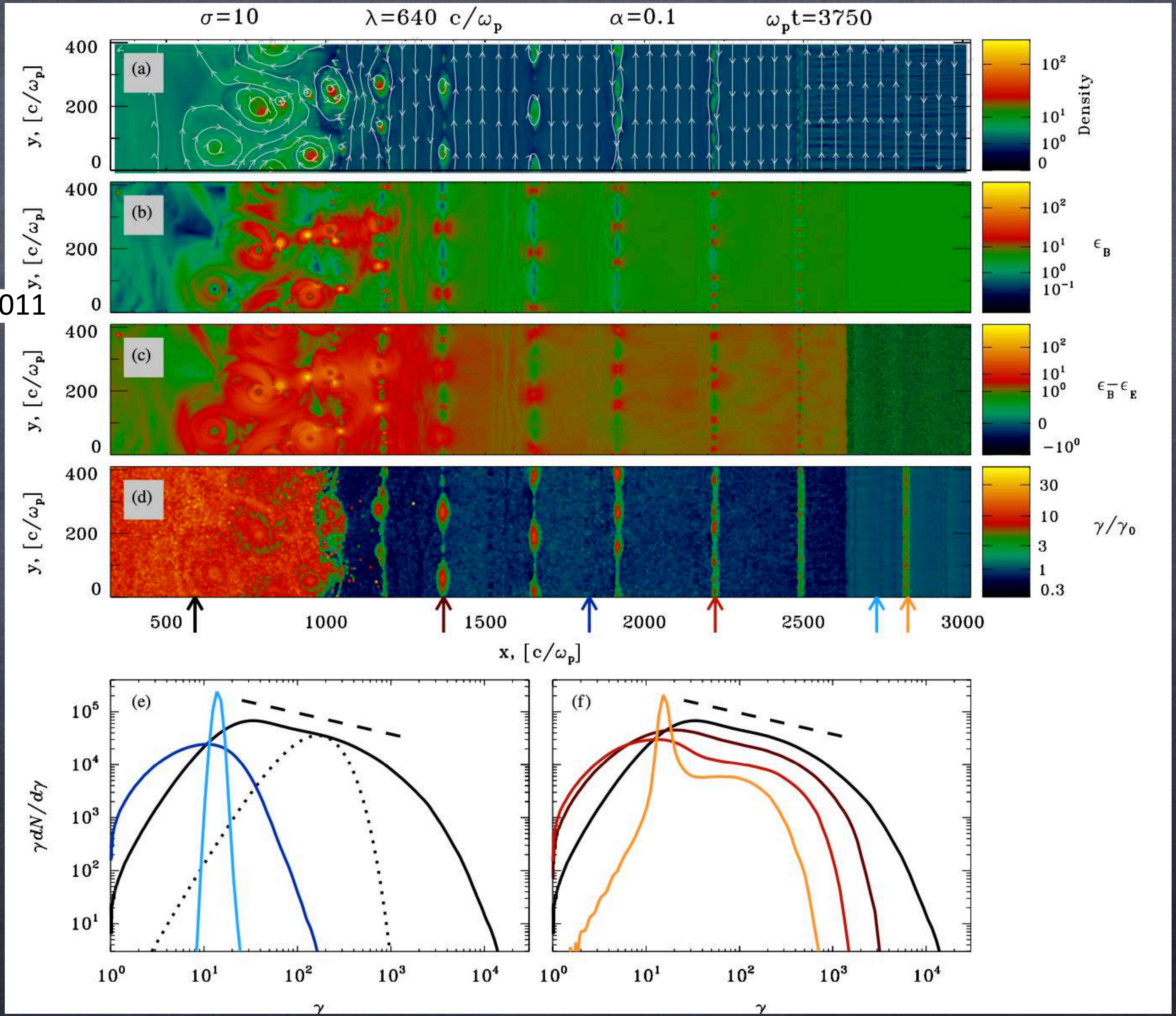
ACCELERATION COMPLETELY SUPPRESSED FOR $\sigma > 10^{-3}$

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

FORCED MAGNETIC RECONNECTION



Sironi, Spitkovsky 2011



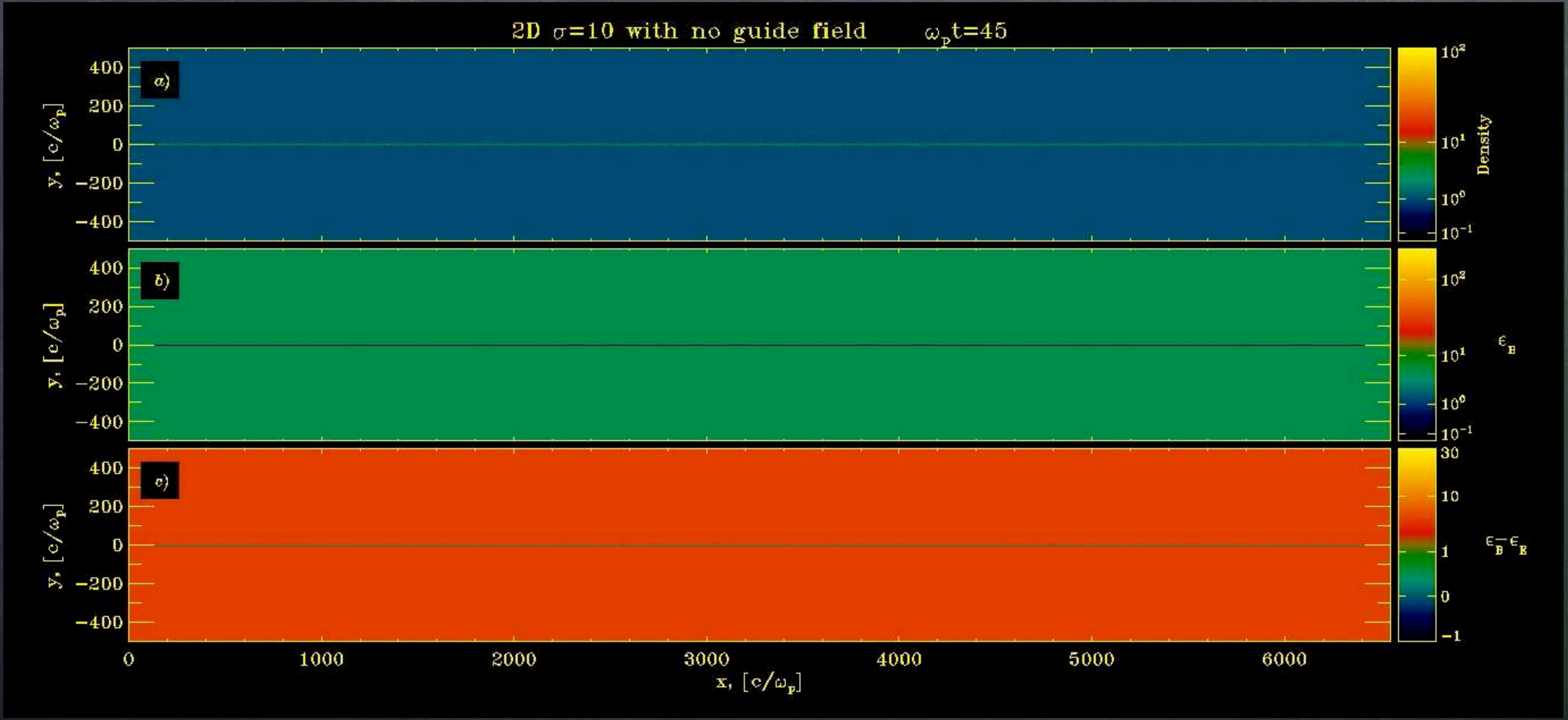
IN PRINCIPLE VERY FLAT SPECTRA AT LOW ENERGY

FERMI ACCELERATION IN UNMAGNETIZED PLASMA AFTERWARDS

RESULTS DEPEND ON

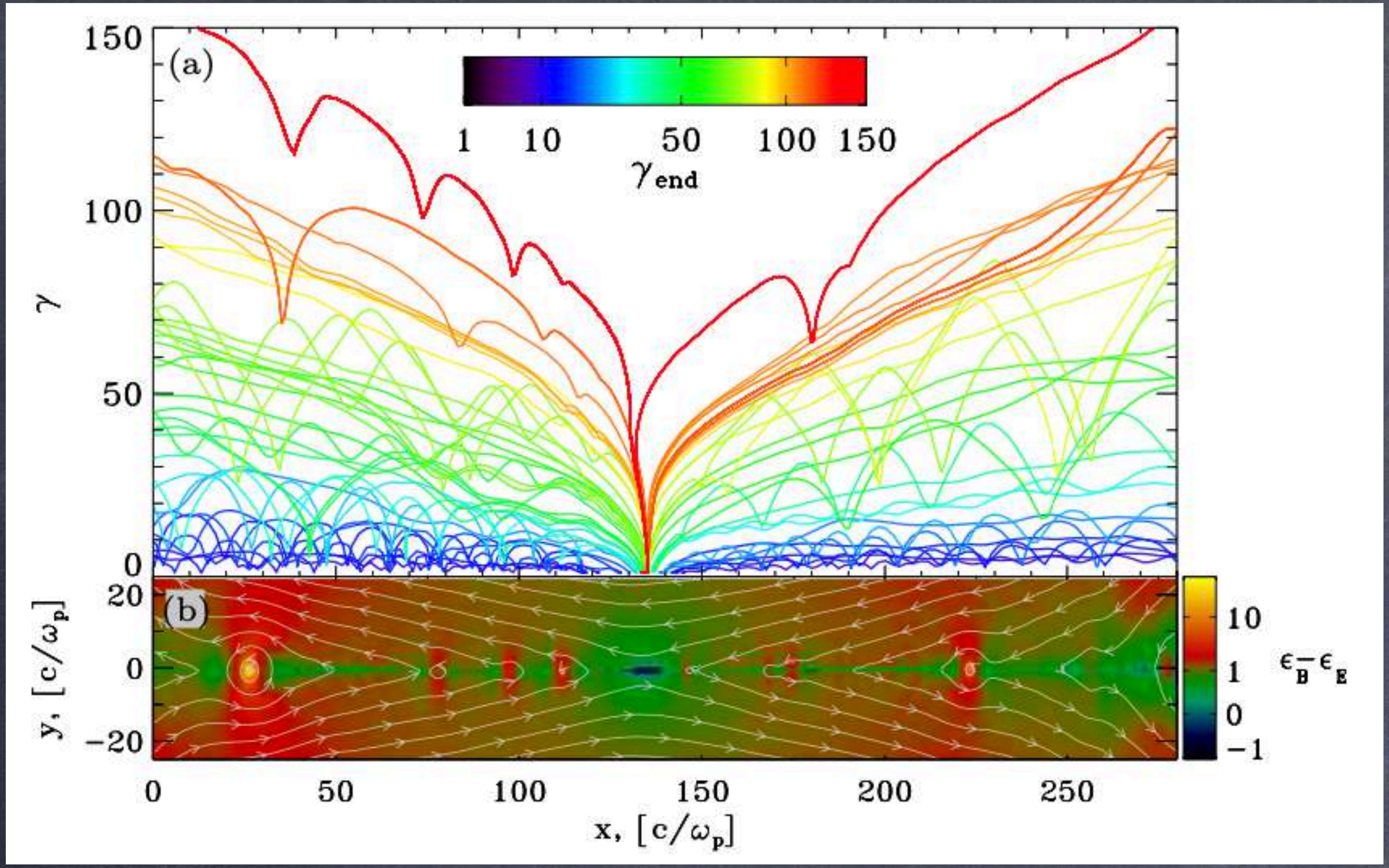
$$\sigma \quad \text{AND} \quad \frac{\lambda}{r_L \sigma}$$

FORCED MAGNETIC RECONNECTION



Sironi, Spitkovsky 2014

FORCED MAGNETIC RECONNECTION



INTERACTION WITH X-POINT

DC ACCELERATION

THEN ADVECTION INTO MAJOR ISLANDS

BROAD SPECTRUM $\Leftrightarrow$

$$\sigma > 30$$

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

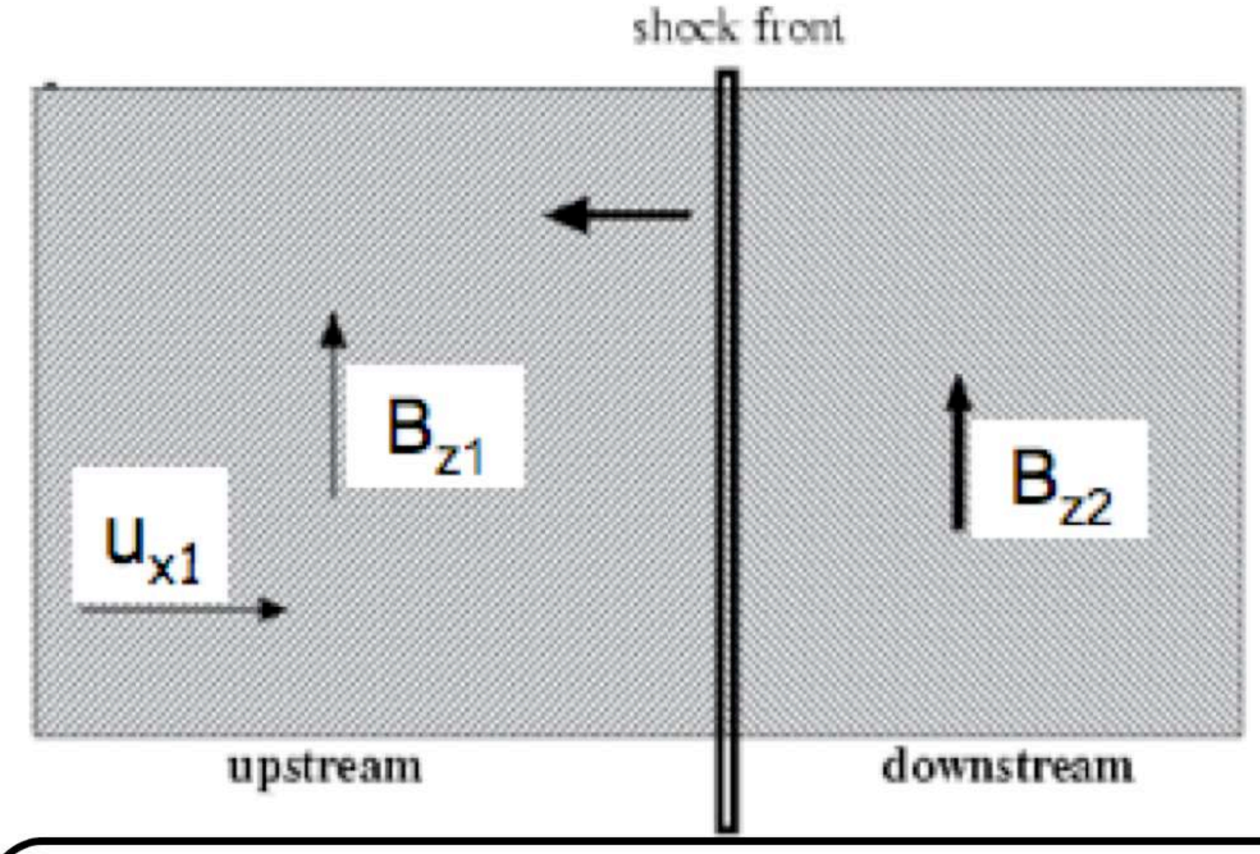
BUT

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

SUCH LARGE K DIFFICULT TO ACCOUNT FOR [Timokhin & Harding 19]

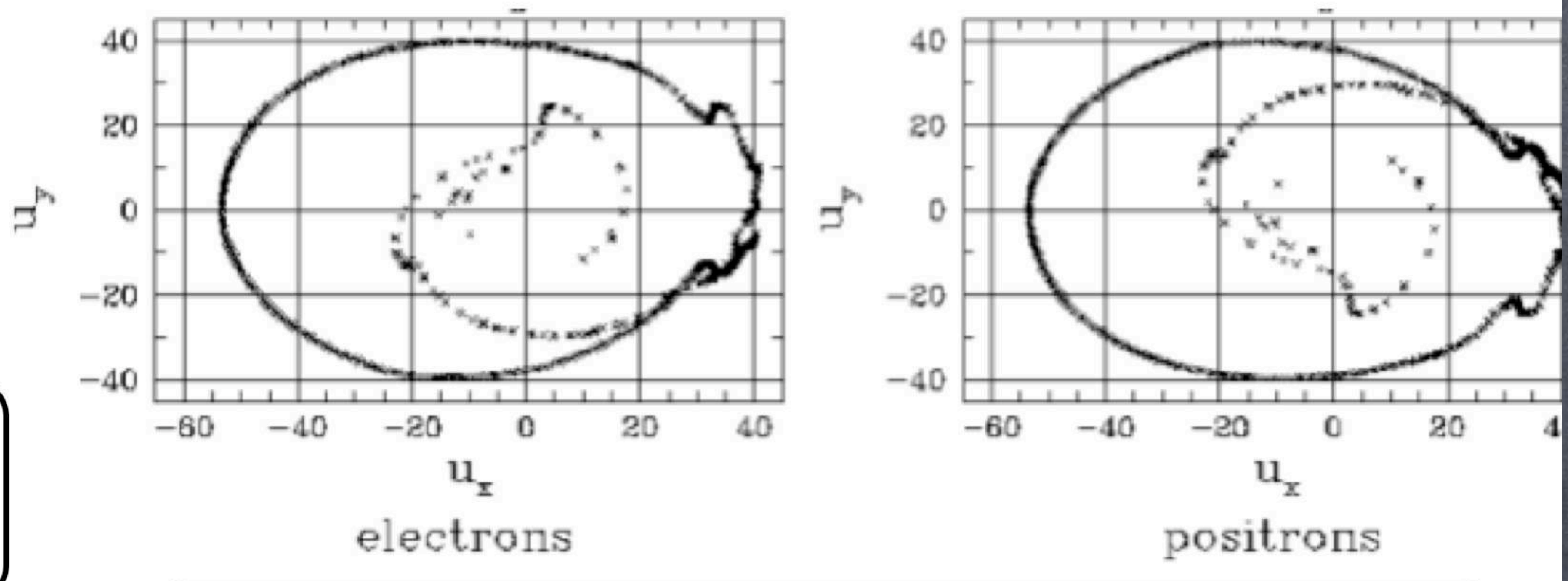
IF REALIZED, RECONNECTION BEFORE THE SHOCK

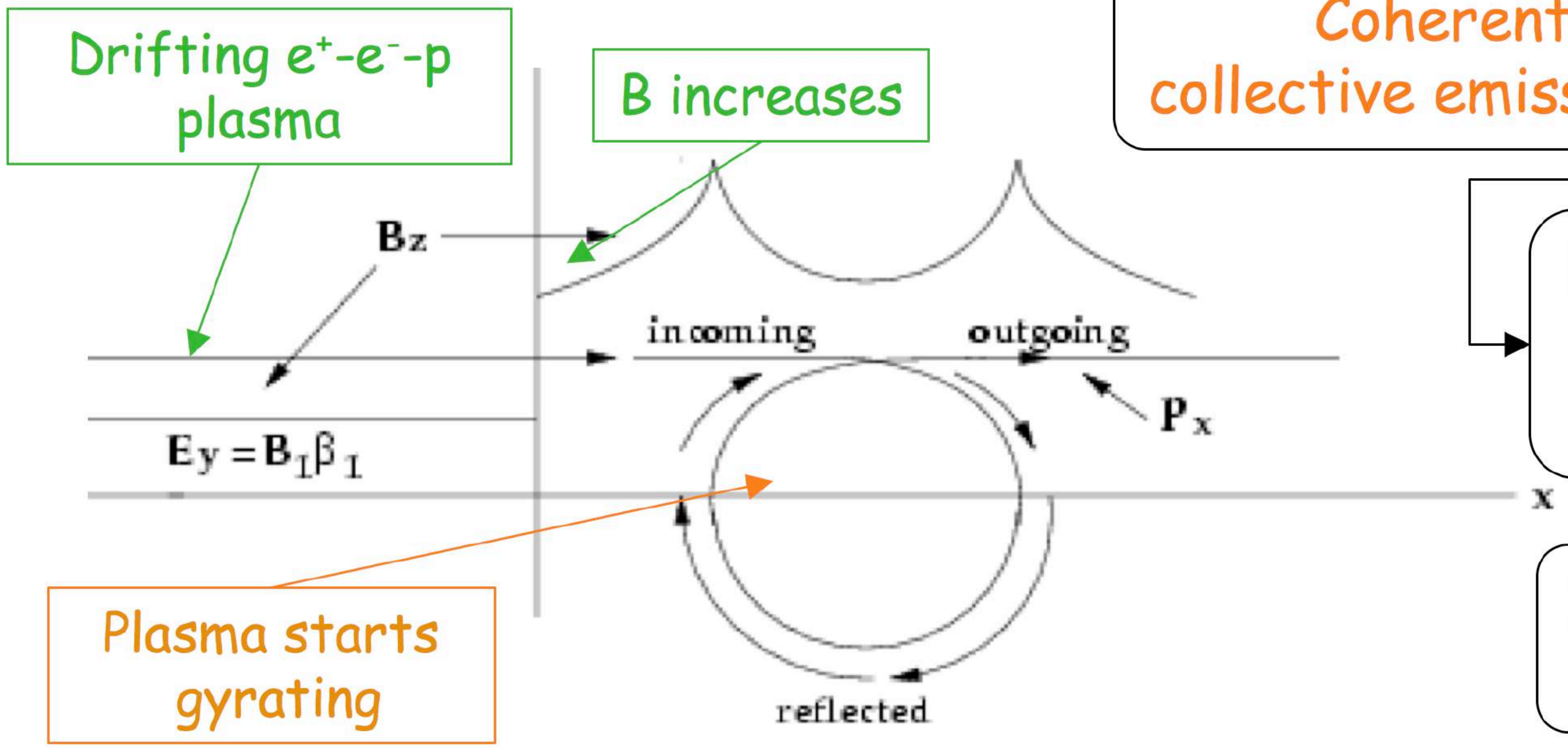
RESONANT CYCLOTRON ABSORPTION IN ION DOPED PLASMA



Magnetic reflection mediates the transition

Configuration at the leading edge ~ cold ring in momentum space





Coherent gyration leads to collective emission of cyclotron waves

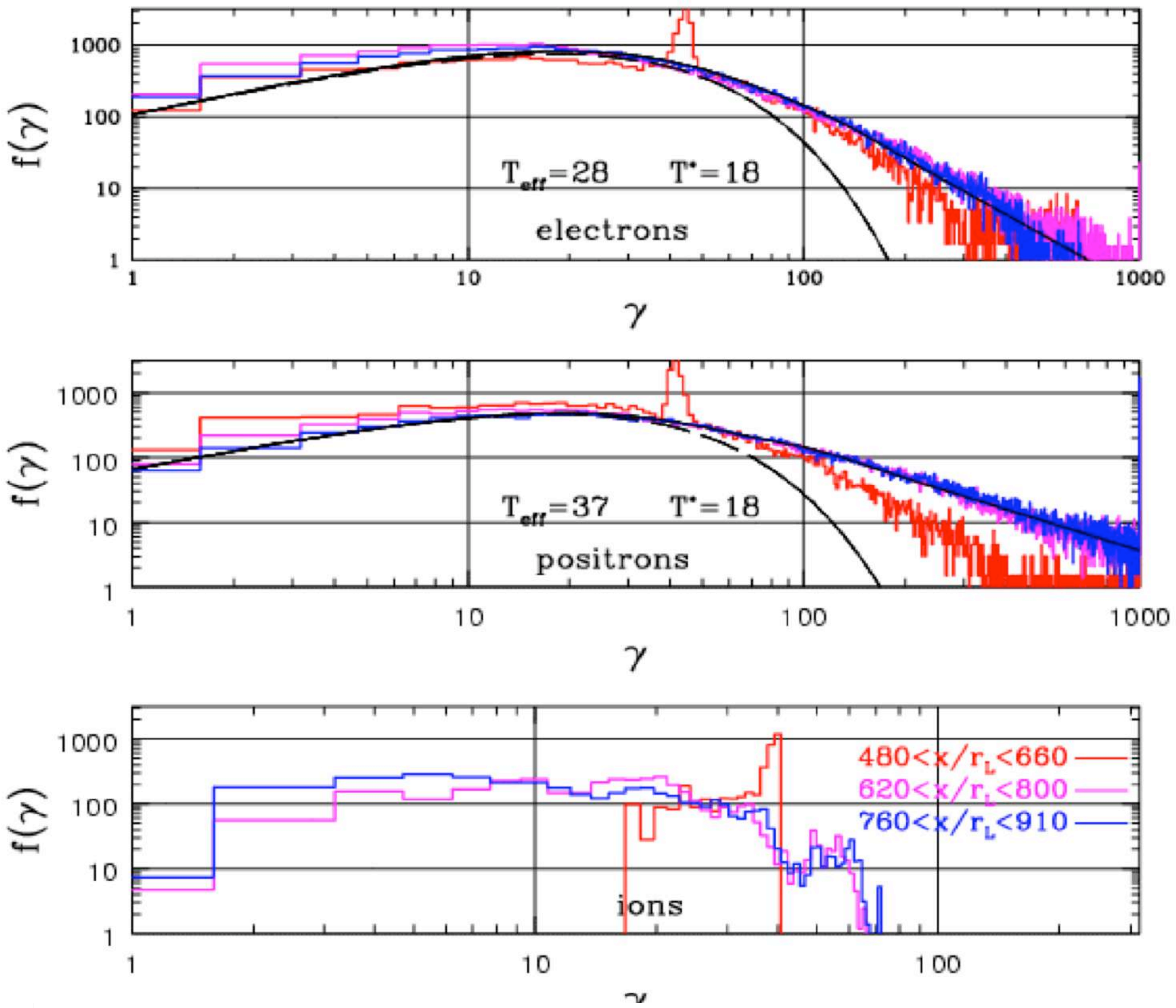
Pairs thermalize to $kT \sim m_e \Gamma c^2$ over $10\text{-}100 \times (1/\Omega_{ce})$

Ions take their time: m_i/m_e times longer

PARTICLE SPECTRA AND ACCELERATION EFFICIENCY

IF

- IONS CARRY MOST OF THE ENERGY: $\kappa < m_i/m_e$
- WIND SUFFICIENTLY COLD: $\delta u/u < m_e/m_i$



ACCELERATION EFFICIENCY:

~few% for U_i/U_{tot}~60%

~30% for U_i/U_{tot}~80%

SPECTRAL SLOPE:

>3 for U_i/U_{tot}~60%

<2 for U_i/U_{tot}~80%

MAXIMUM ENERGY:

~20% $m_i c^2\Gamma$ for U_i/U_{tot}~60%

~80% $m_i c^2\Gamma$ for U_i/U_{tot}~80%

PARTICLE ACCELERATION MECHANISMS (MORE RECENTLY PROPOSED)

SHOCK CORRUGATION
- FORMULATED TOGETHER WITH B DISSIPATION [Lemoine 17, Lyutikov+12]
- INTERESTING SCENARIO FOR SPEEDING UP FERMI PROCESS

TURBULENT ACCELERATION AT THE SHOCK
- ASSUMES DIFFERENT TURBULENCE LEVELS AT DIFFERENT SHOCK LATITUDES [Giacinti & Kirk 18]
- PRODUCES HARD (STEEP) SPECTRA FOR LOW (HIGH) TURBULENCE LEVEL
- INTERESTING LATITUDE DEPENDENCE OF SPECTRAL INDEX
- ACCELERATES ONE SIGN OF CHARGES PREFERENTIALLY

- ANISOTROPIC FIELD HELPS PROVIDING THE TURBULENCE [Cerutti & Giacinti 20]
- SPECTRUM HARDENS WITH INCREASING MAGNETIZATION

ACCELERATION BY HIGH σ TURBULENCE
- ENERGY DEPENDENT ANISOTROPY OF PARTICLE DISTRIBUTION MIMICS FLAT PARTICLE SPECTRA AT LOW ENERGY [Comisso+ 18,19,20, Luo+21]
- WHERE? ON WHAT SCALES? MAXIMUM ENERGY?
- IMPORTANT BROAD IMPLICATIONS!

PARTICLE ACCELERATION MECHANISMS SUMMARY

FERMI MECHANISM

✓EFFICIENT AT UNMAGNETIZED e^+–e^- RELATIVISTIC SHOCKS [Spitkovsky 08]

– NO ACCELERATION AT σ>0.001 SUPERLUMINAL SHOCKS [Sironi & Spitkovsky 09, 11]

– TOO SLOW TO GUARANTEE MAXIMUM ENERGY OBSERVED IN CRAB [Pelletier+ 17]

✓POSSIBLY EFFICIENT AT HIGHLY TURBULENT MODERATELY MAGNETIZED SHOCKS [Lemoine 17, Giacinti & Kirk 18, Cerutti & Giacinti 20]

✓RIGHT SPECTRUM FOR X-RAYS

DRIVEN MAGNETIC RECONNECTION:

✓BROAD AND HARD PARTICLE SPECTRA IF $\sigma \geq 30$ AND $\kappa > 10^8$ [Sironi & Spitkovsky 11b]

– FOR THIS LARGE κ WIND LIKELY TO DISSIPATE BEFORE SHOCK [Kirk & Skjeraasen 03]

RESONANT CYCLOTRON ABSORPTION:

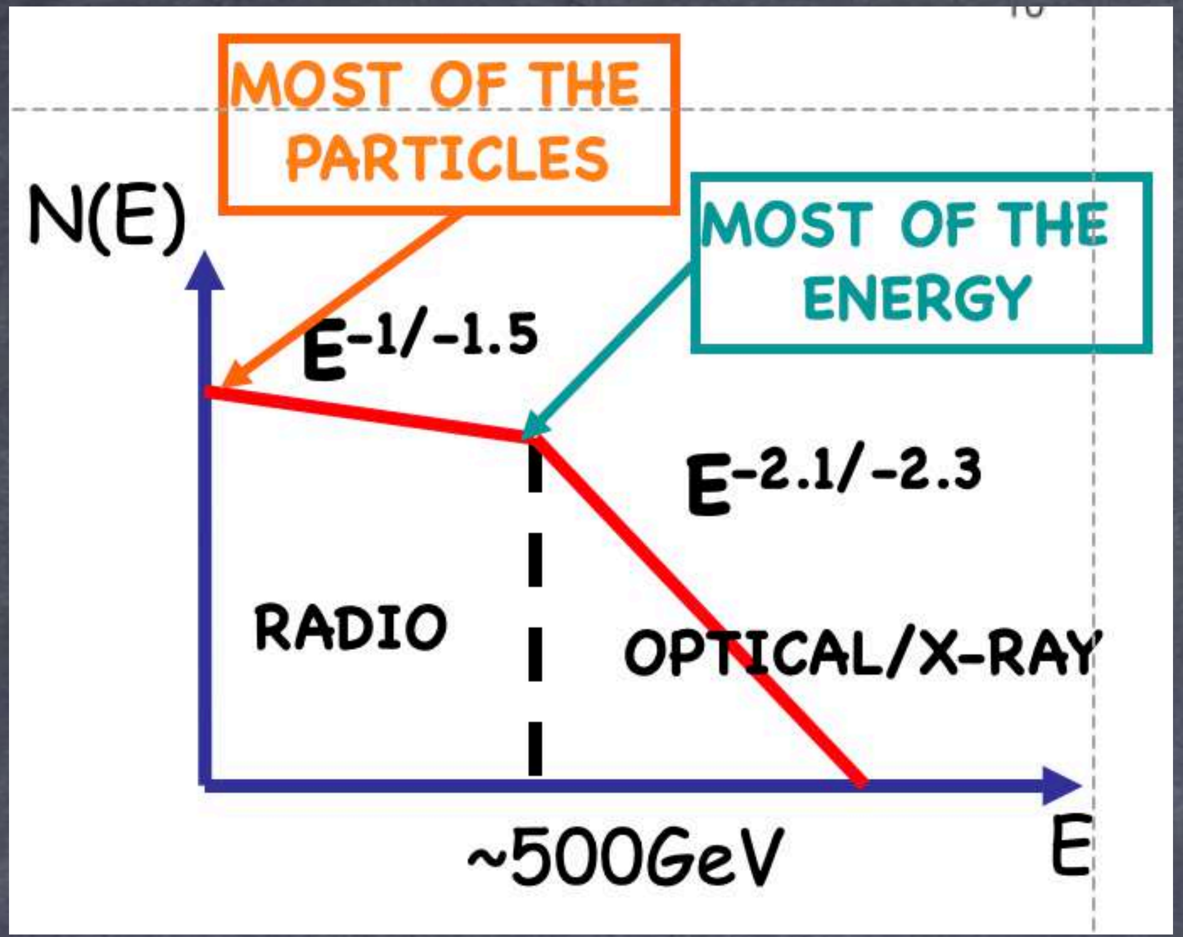
✓SPECTRA AND ACCELERATION EFFICIENCY DEPEND ON ENERGY FRACTION IN IONS: U_i/U_{TOT}=0.8–0.6, γ=1.5–3, ε_{ACC}=0.3–0.03 [Hoshino+ 92, EA & Arons 06; Stockem+ 12]

✓HIGHER σ IMPLIES FASTER ACCELERATION

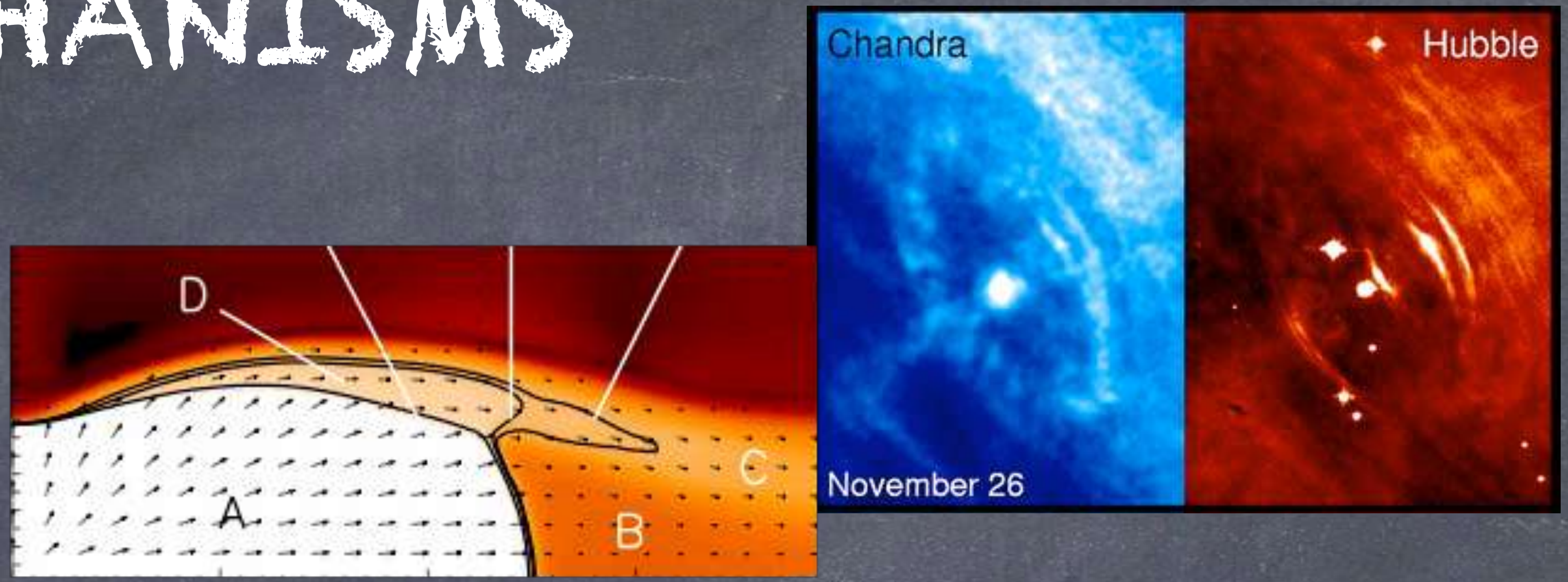
– NO ACCELERATION IF $\kappa > m_i/m_e$

HOW TO CONSTRAIN PARTICLE ACCELERATION MECHANISMS IN PWNe

PARTICLE ACCELERATION MECHANISMS



[Amato & Olmi 22]



Del Zanna, Amato, Bucciantini 04

FERMI MECHANISM → MAGNETIZATION: REQUIRES LOW

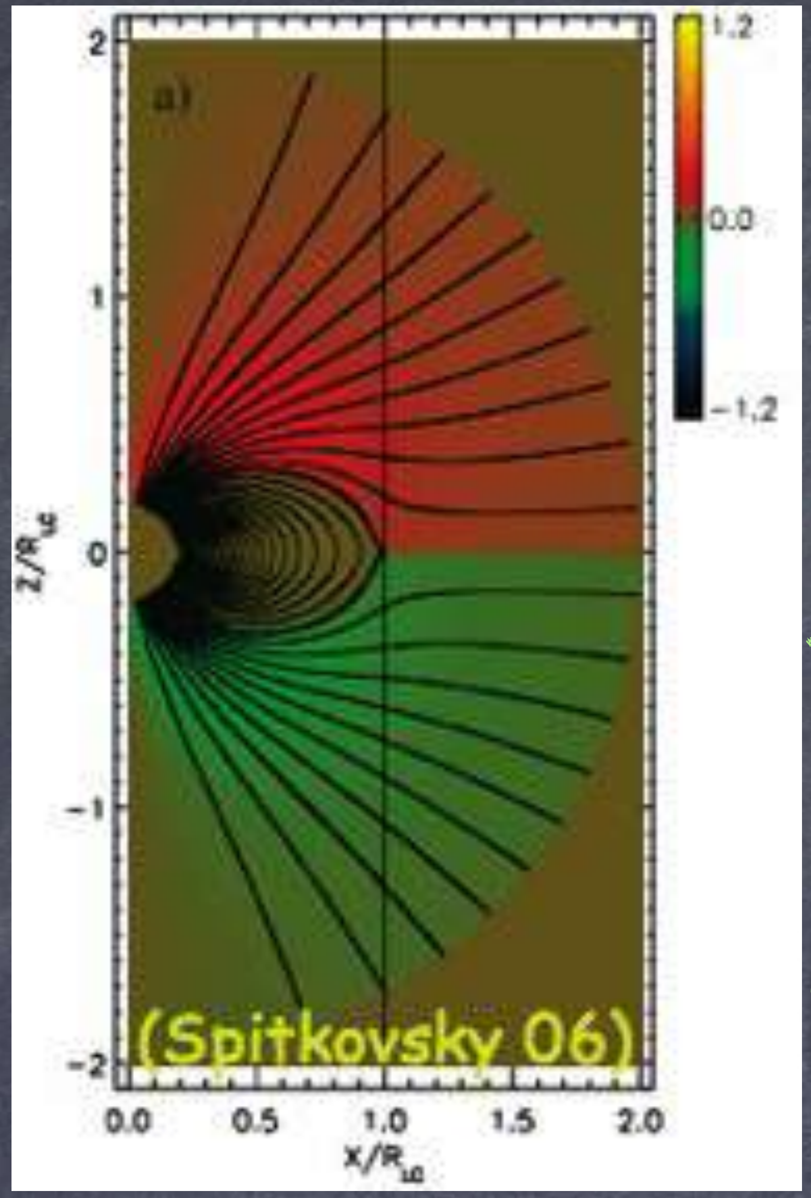
HOWEVER SEE VARIANTS

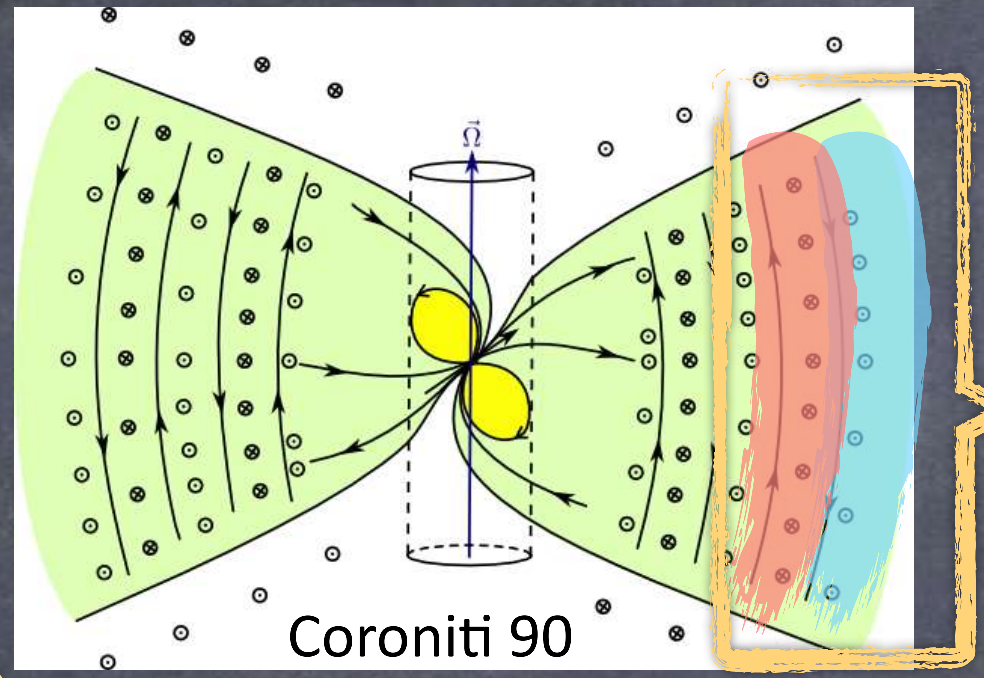
DRIVEN MAGNETIC RECONNECTION → MAGNETIZATION: REQUIRES HIGH

DRIVEN MAGNETIC RECONNECTION → PLASMA MULTIPLICITY: REQUIRES HIGH

ION CYCLOTRON ABSORPTION IN ION DOPED PLASMA → PLASMA MULTIPLICITY: REQUIRES LOW

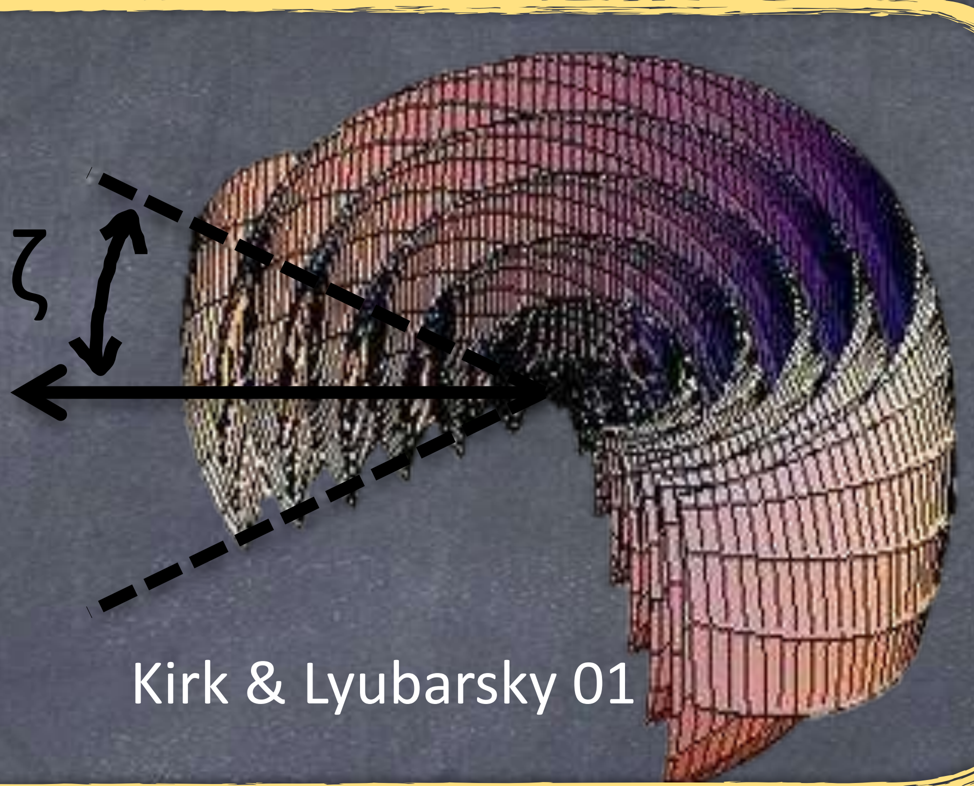
PSR WIND AND PWN DYNAMICS





alternating stripes of opposite B polarities

dissipation in current sheet

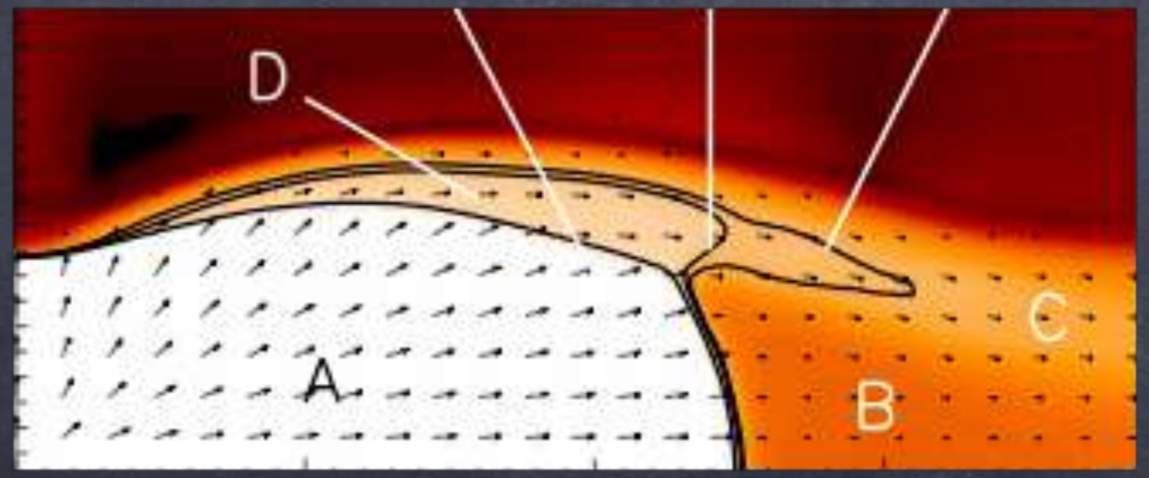


$$F(\theta) \propto \sin^2(\theta)$$

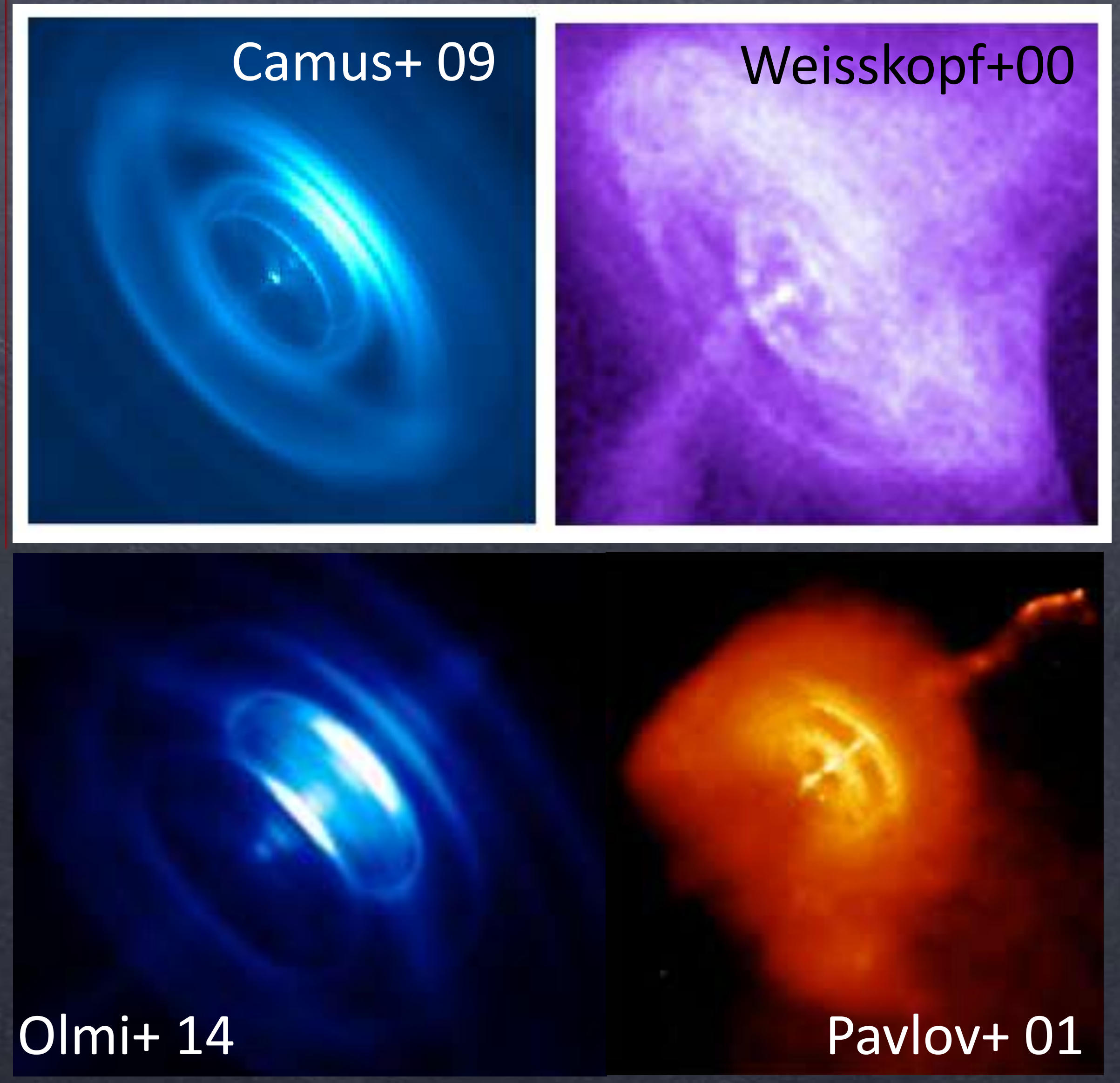
$$B(\theta) \propto \sqrt{\sigma}\ \sin\theta\ G(\theta)$$

DYNAMICS AND RADIATION MODELING

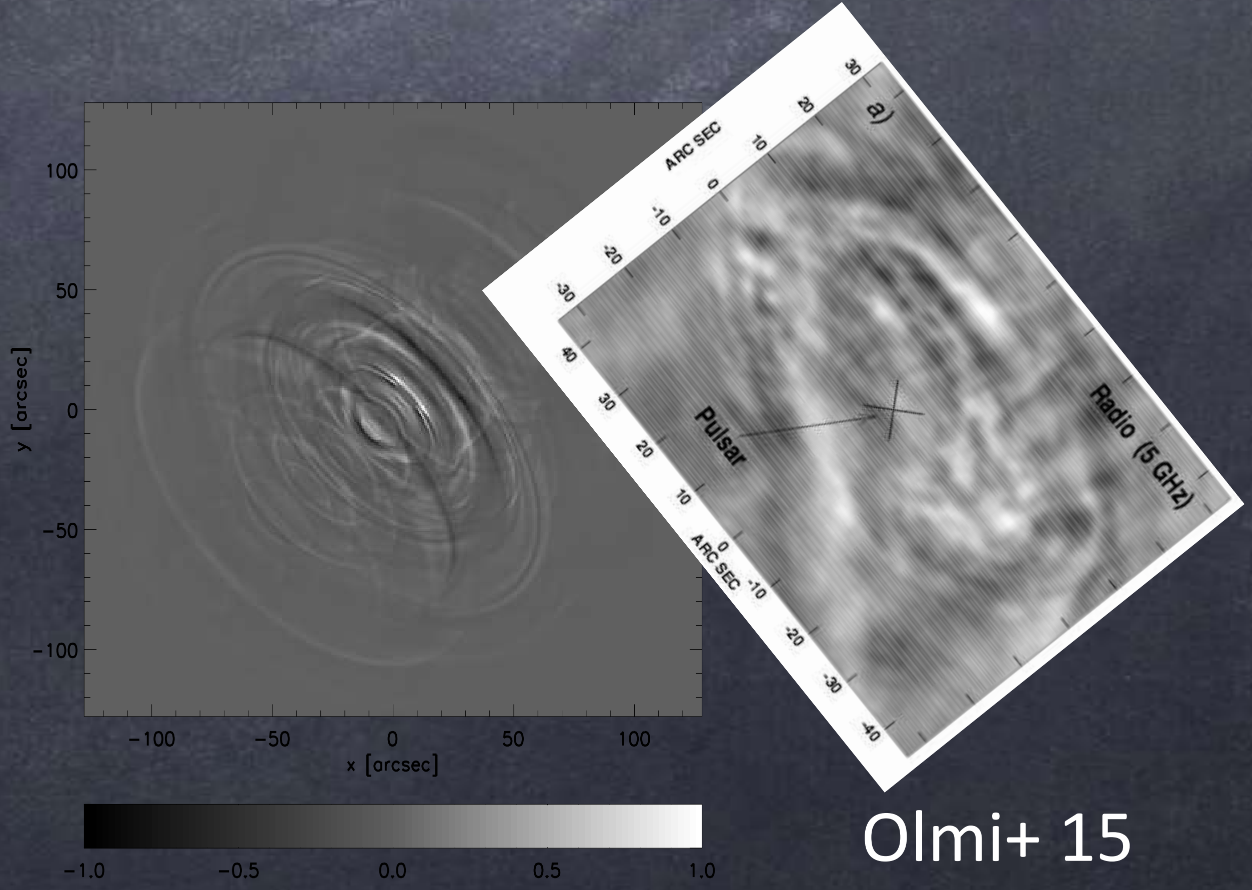
TERMINATION SHOCK



A: ULTRARELATIVISTIC WIND
B: SUBSONIC OUTFLOW
C: SUPERSONIC FUNNEL



MULTI-WAVELENGTH VARIABILTY



Olmi+ 15

[Komissarov & Lyubarsky 03,04; Del Zanna+ 04,06; Bogovalov+ 05;Camus+ 09; Volpi+ 08; Olmi+ 14,15,16;Porth+ 13,14]

IMPLICATIONS ON ACCELERATION MECHANISMS

NEBULAR DYNAMICS AND HIGH ENERGY EMISSION PROPERTIES → $\sigma \gtrsim 1$ → TOO LARGE FOR FERMI ACCELERATION BUT TURBULENCE MIGHT HELP

MODELLING OF RADIO EMISSION → $\kappa \approx \text{few} \times 10^3$ AND $\Gamma > \text{few} \times 10^6$ VIABLE → ION CYCLOTRON VIABLE

MODELLING OF MULTIFREQUENCY VARIABILITY OF INNER NEBULA → ACCELERATION OF LOW AND HIGH ENERGY PARTICLES IN DIFFERENT REGIONS → LOW ENERGY FROM TURBULENT ACCELERATION IN THE NEBULA?

MAXIMUM ENERGY IN A PWN

IN YOUNG ENERGETIC SYSTEMS ACCELERATION IS LOSS LIMITED

$$\boxed{t_{acc} = \frac{E}{e\eta_E B c} < t_{loss} = \frac{6\pi(mc^2)^2}{\sigma_T c B^2 E}} \Rightarrow \boxed{E_{max} \approx 6\ PeV\ \eta_E^{1/2}\ B_{-4}^{-1/2}}$$

REMEMBER $E_{max,el} = 30TeV \left(\frac{B_2}{100\mu G}\right)^{-1/2} \left(\frac{V_s}{5000km/s}\right)$

STRICT LIMIT FROM THE PSR POTENTIAL DROP $\Phi_{PSR} = \sqrt{\dot{E}/c}$

$$E_{max,abs} = e\eta_E B_{TS}\ R_{TS}$$

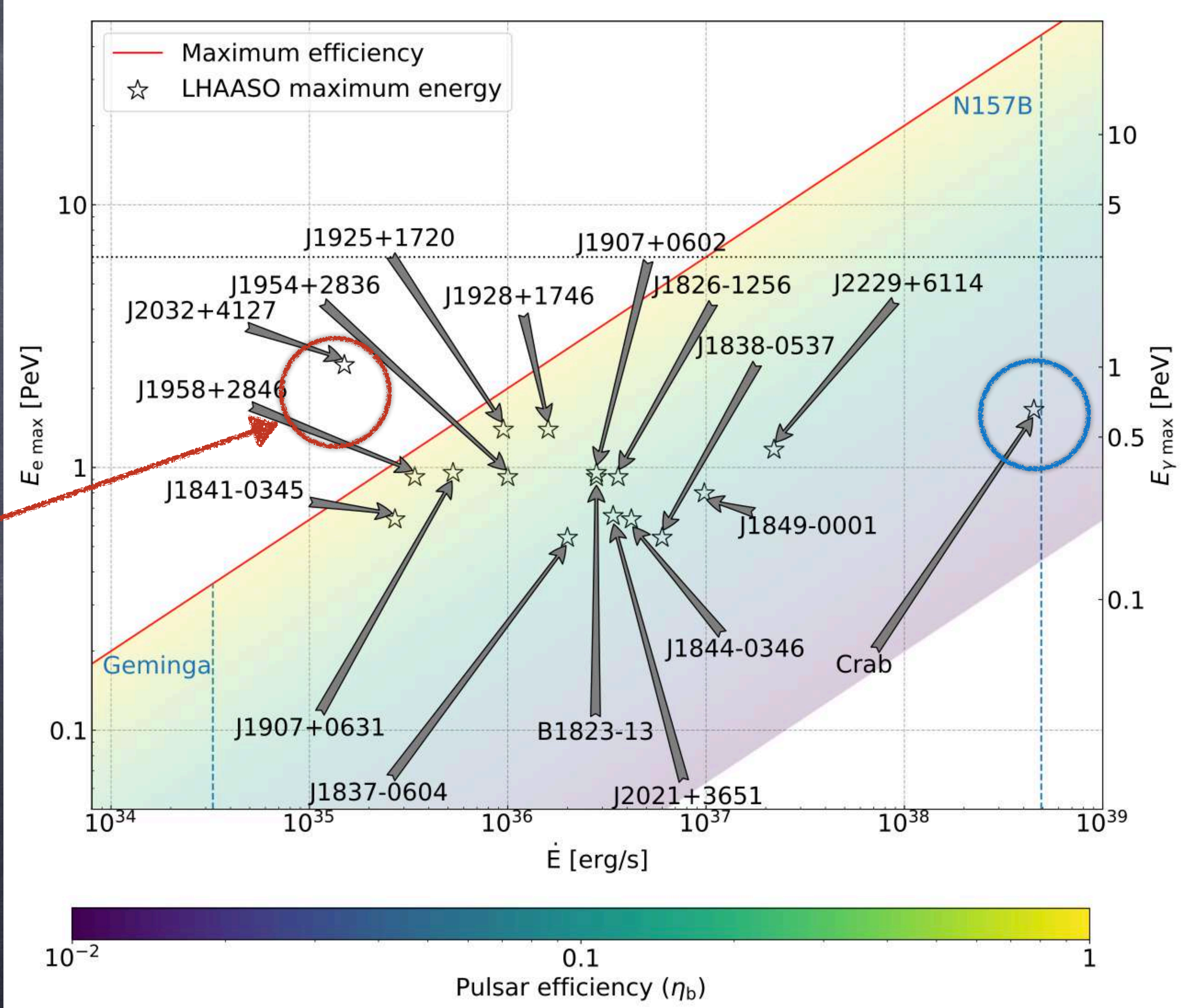
$$\frac{B_{TS}^2}{4\pi} = \eta_B \frac{\dot{E}}{4\pi R_{TS}^2 c}$$

$$\Rightarrow \boxed{E_{max,abs} = e\eta_E\ \eta_B^{1/2}\sqrt{\dot{E}/c} \approx 1.8\ PeV\ \eta_E\ \eta_B^{1/2}\ \dot{E}_{36}^{1/2}}$$

LHAASO PEVATRONS AND PWNe

MAXIMUM
ELECTRON ENERGY
AS A FUNCTION
OF PSR POTENTIAL DROP
AND LHAASO SOURCES

CYGNUS



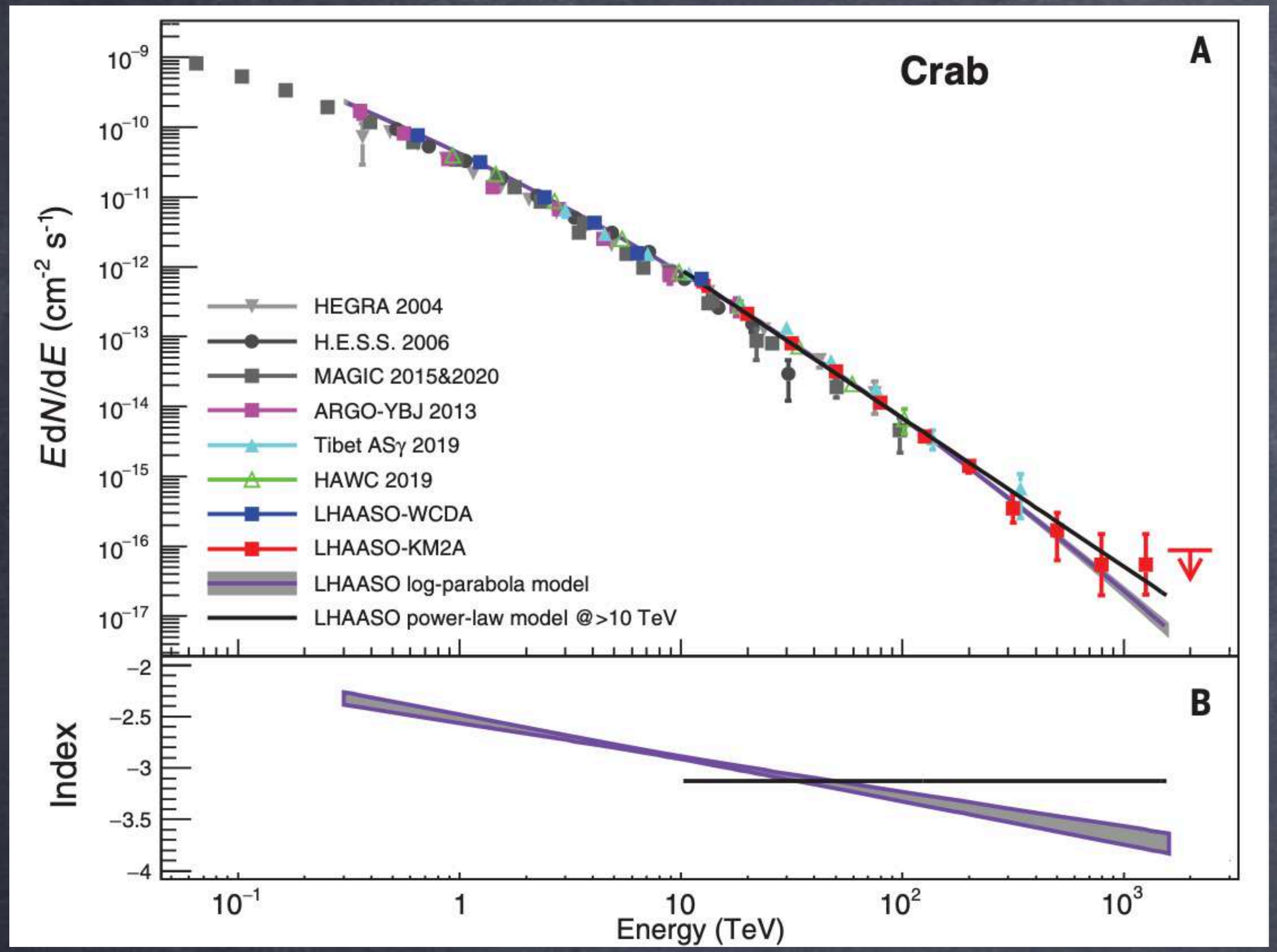
de Ona Wilhelmi + 2022

IF LEPTONS THEN PULSARS!

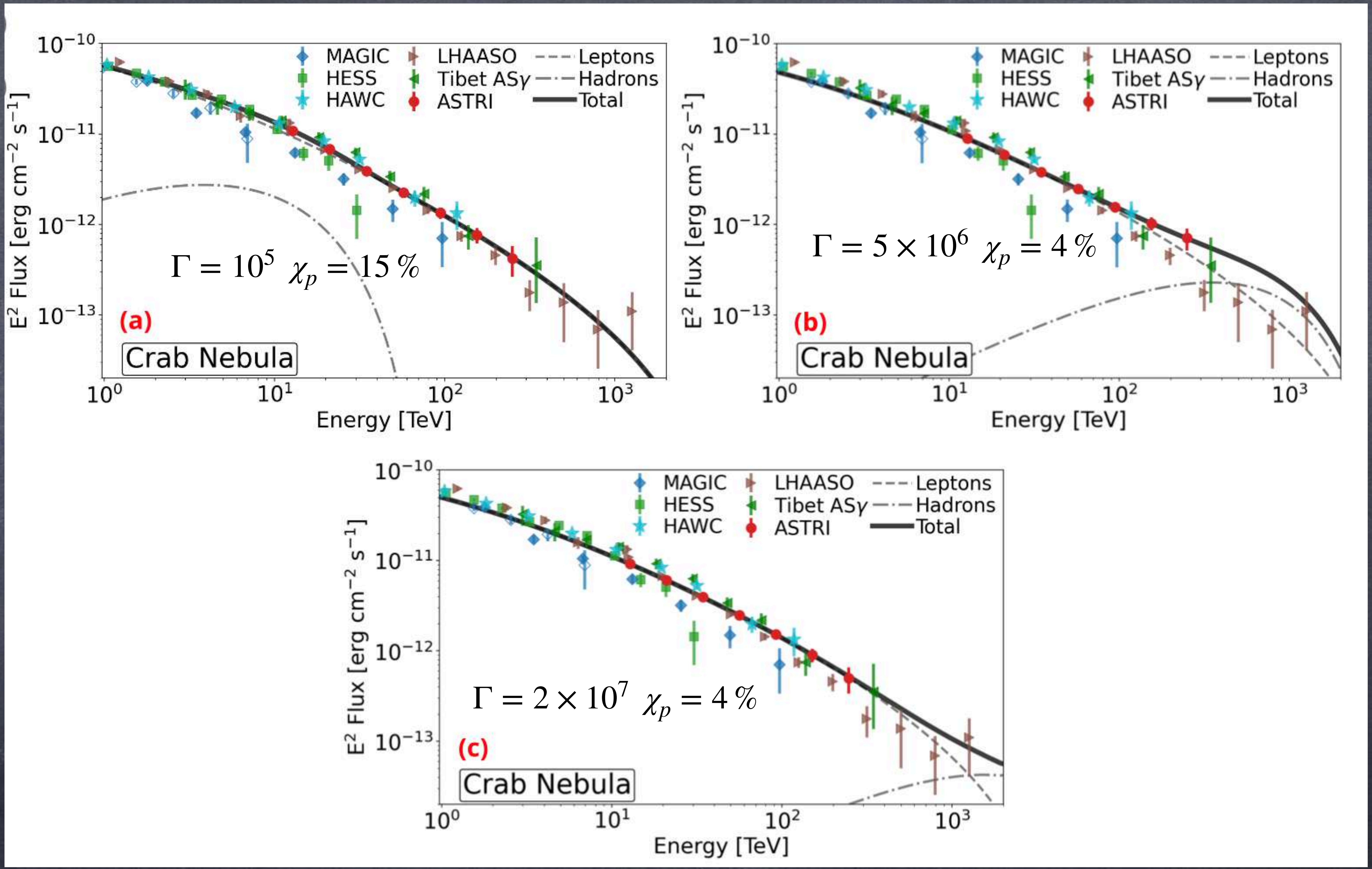
BUT

IF PULSARS THE LEPTONS?

HADRONS IN CRAB?



Cao+, LHAASO Coll. 21



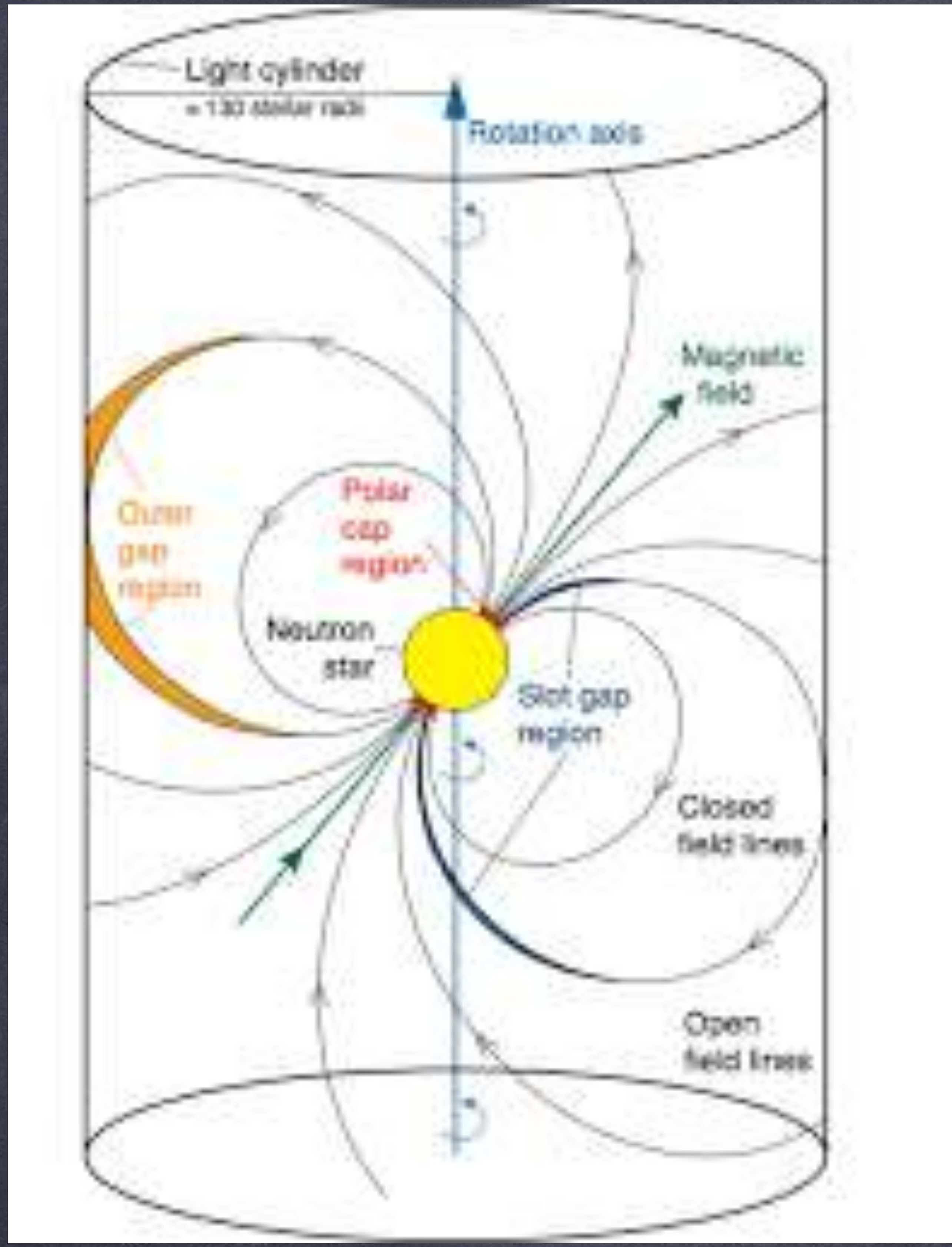
Vercellone+ 22; Fiori, EA + in prep.

$Q_p(E) \propto \delta(E - m_p c^2 \Gamma)$ (EA & Arons 06; EA, Guetta, Blasi 03)

UHCRs FROM NEW BORN MAGNETARS

UHECRs FROM MAGNETARS?

Blasi, Olinto, Epstein 00; Arons 03; Kotera & Olinto; Kotera, EA, Blasi 15



DIRECT E-FIELD ACCELERATION IN GAP OF SIZE ξR_L

WITH POTENTIAL DIFFERENCE Φ VS CURVATURE

$$\frac{\mathrm{d}\gamma}{\mathrm{d}t} = \frac{Ze\Phi}{Am_{\mathrm{p}}c^2}\frac{2\pi}{\xi P} - \frac{8\pi^2}{3cP^2}\frac{Z^2e^2}{Am_{\mathrm{p}}c^2}\gamma^4$$

$$\gamma_{\mathrm{curv}} = \left(\frac{3\pi B R_\star^3}{2ZecP\xi}\right)^{1/4} \sim 1.1\times 10^8 Z_{26}^{-1/4}\xi^{-1/4}B_{13}^{1/4}P_{-3}^{-1/4}R_{\star,6}^{3/4}$$

$$\gamma_{max} = \max(\gamma_w, \min(\gamma_\Phi, \gamma_{curv}))$$

PURE IRON EXTRACTION

+ PHOTODISINTEGRATION

$$\frac{\mathrm{d}N_A}{\mathrm{d}t} + \frac{N_A}{t_A} = \frac{N_{A+1}}{t_{A+1}}$$

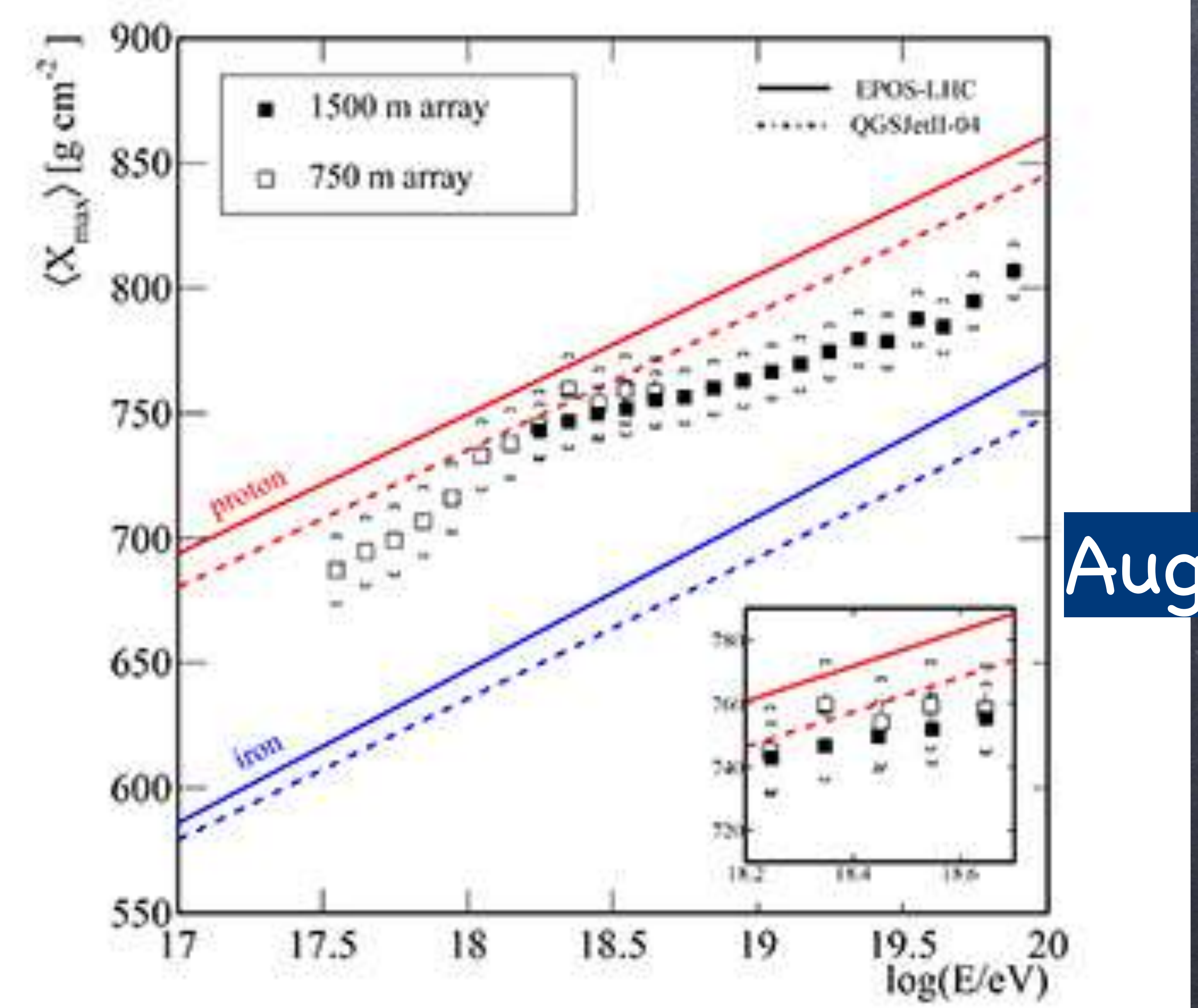
AUGER CORRELATION: AGN:2.7σ; AGN+SBG: 3.7σ; SBG: 4σ

PARTICLE SPECTRUM

$$E_{\rm CR}(t) = E_0\,(1+t/t_{\rm sd})^{-1}$$
$$\sim 1.2\times10^{20}\,{\rm eV}\,\eta A_{56}\kappa_4 I_{45} B_{13}^{-1} R_{\star,6}^{-3}\, {t_{7.5}}^{-1} \qquad \text{for} \quad t > t_{\rm sd}$$

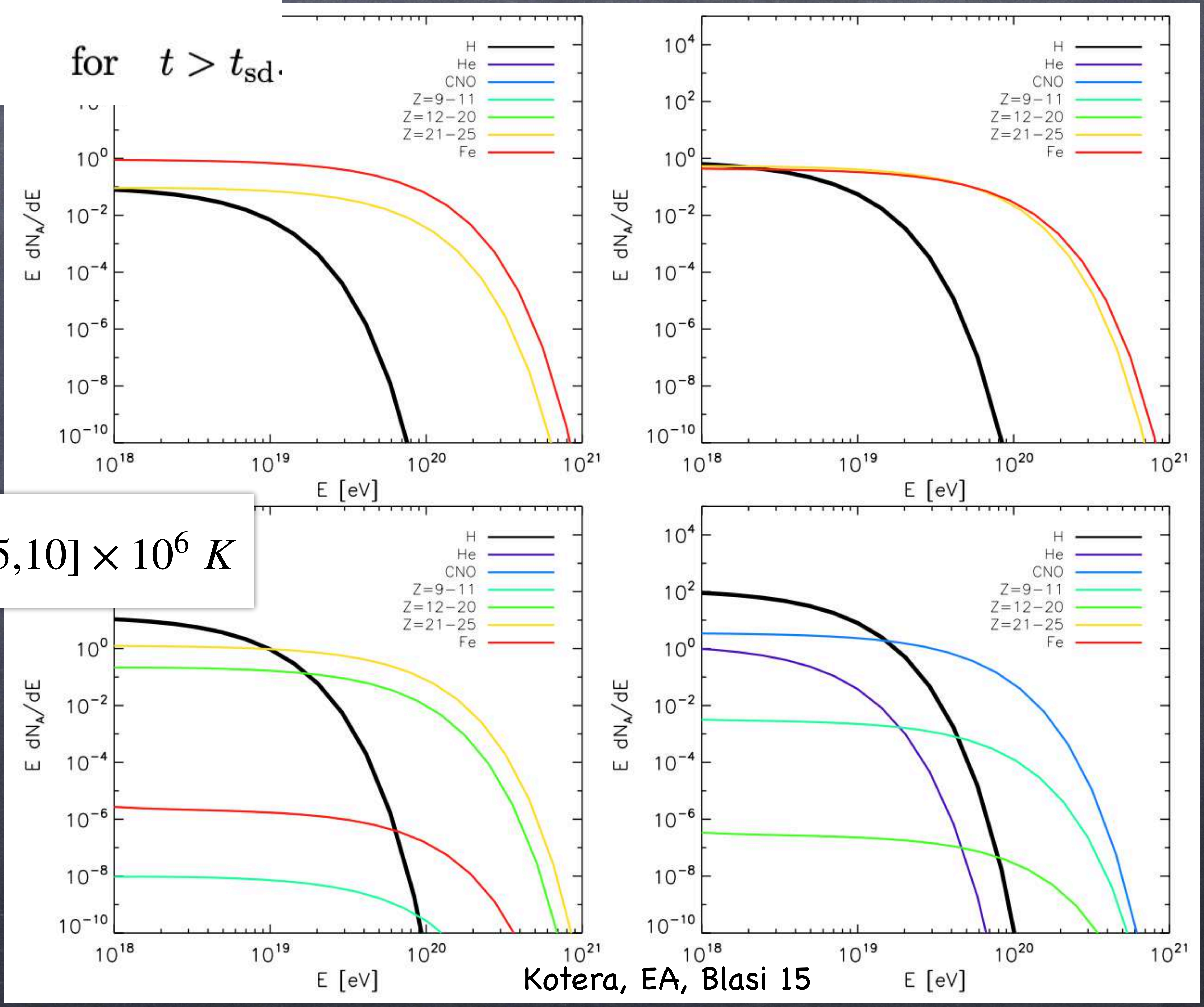
$$\frac{{\rm d}N_{\rm CR}}{{\rm d}E} = \int_0^\infty {\rm d}t \dot{N}_{\rm GJ}(t)\,\delta\left(E - E_{\rm CR}(t)\right) = \frac{\dot{N}_{\rm GJ}(0)t_{\rm sd}}{E}$$

$$t_{\rm sd} = \frac{9Ic^3P_{\rm i}^2}{8\pi^2B^2R^6} \sim 3.1\times10^7\,{\rm s}\,I_{45}B_{13}^{-2}R_{\star,6}^{-6}P_{\rm i,-3}^2$$



Auger 20

$T_{NS} = [1,2,5,10]\times10^6\ K$



Kotera, EA, Blasi 15

SUMMARY

- STILL MUCH TO UNDERSTAND ABOUT PARTICLE ACCELERATION IN ASTROPHYSICS
- AT NON-RELATIVISTIC SHOCKS THE MAIN PROBLEM STAYS THAT OF ACHIEVING THE MAXIMUM ENERGIES DEDUCED FROM CR OBSERVATIONS
- AT RELATIVISTIC SHOCKS (BETTER DISSIPATION REGIONS?) THE ACCLERATION PROCESS IS STILL OBSCURE
- SPECTRO-MORPHOLOGICAL INFORMATION FROM IACTS MOST POWERFUL TOOL TO CLARIFY THE PROBLEM

UP TO YOU! ENJOY THE WORK!

REFERENCES

-FERMI ACCELERATION (EURISTIC VERSION): book “High Energy Astrophysics” by M. Longair

-WAVE-PARTICLE INTERACTIONS: book “Plasma Physics for Astrophysics” by R. Kulsrud

-FERMI ACCELERATION THROUGH TRANSPORT EQUATION: Blandfold & Eichler 1987, Physics Reports 154, 1

-RELATIVISTIC SHOCKS: Sironi, Keshet, Lemoine, 2015, Space Science Review 191, 519