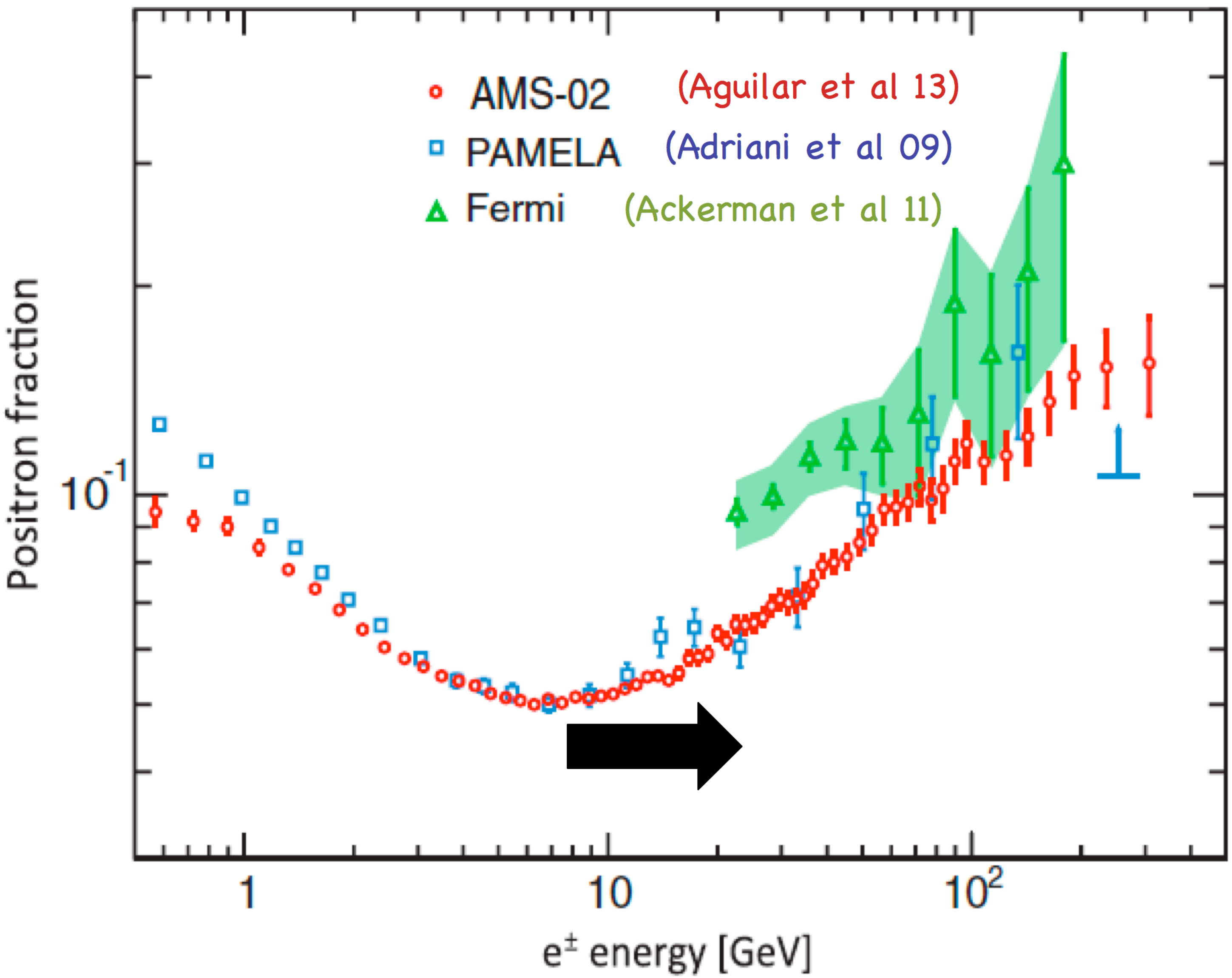
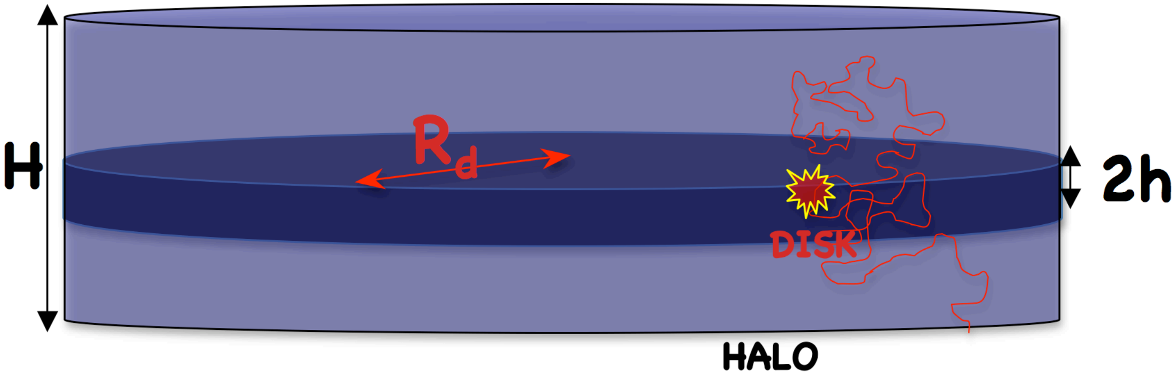
ON THE ORIGIN OF THE POSITRON "EXCESS"

Elena Amato
INAF-Osservatorio Astrofisico di Arcetri

THE POSITRON "EXCESS"



WHAT IS SO PUZZLING?



$$\tau_{LOSS} \propto E^{-1}$$

$$\tau_{ESC} = \frac{H^2}{D(E)} \propto E^{-}$$

$$n_{CR}(E) \approx \frac{N_s(E)\Re\tau_{ESC}}{2\pi R_d^2 H} \propto E^{-\gamma_{inj}-\delta}$$

$$n_{SEC}(E) \approx n_{CR}(E)\Re_{SP}\tau_{ESC} \propto E^{-\gamma_{inj}-2\delta}$$

$$n_{e^-}(E) = \frac{N_S(E)\Re\tau_{LOSS}}{2\pi R_d^2\sqrt{D\tau_{LOSS}}} \propto E^{-\gamma_{inj}-\delta/2-1/2}$$

$$n_{e^+}(E) \propto n_{SEC}(E)\tau_{LOSS} \propto E^{-\gamma_{inj}-3\delta/2-}$$

IF e+ ARE ONLY SECONDARIES $\dfrac{\Phi_{e^+}}{\Phi_{e^-}+\Phi_{e^+}} \approx \dfrac{\Phi_{e^+}}{\Phi_{e^-}} \propto E^{-\delta}$

IN GENERAL: $\dfrac{\Phi_{e^+}}{\Phi_{e^-}} \propto E^{-\left(\gamma_{e^+}-\gamma_{inj}\right)}$

UNLESS SOMETHING MORE SUBTLE IN PROPAGATION....

ASTROPHYSICAL SOURCES OF e

- RADIOACTIVE DECAYS IN SN
- HADRONIC INTERACTIONS WITHIN CR ACCELERATORS
- PAIR PRODUCTION PROCESSES

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$$^{56}Ni \Rightarrow {}^{56}Co \Rightarrow {}^{56}Fe + e^{+} + \gamma$$

$$^{44}Ti \Rightarrow {}^{44}Sc + e^{-} \Rightarrow {}^{44}Ca + e^{+} + e^{-}$$

$T_{1/2,\,Ni}$=6.1 days $T_{1/2,Co}$=77 days

$T_{1/2,Ti}$=63 years

- LOW ENERGY e^{+} PRODUCED FOR A SHORT TIME AND CONFINED IN THE EJECTA
- POSSIBLY ACCELERATED AT REVERSE SHOCK
- SPECTRUM SAME OR STEEPER THAN e^{-}

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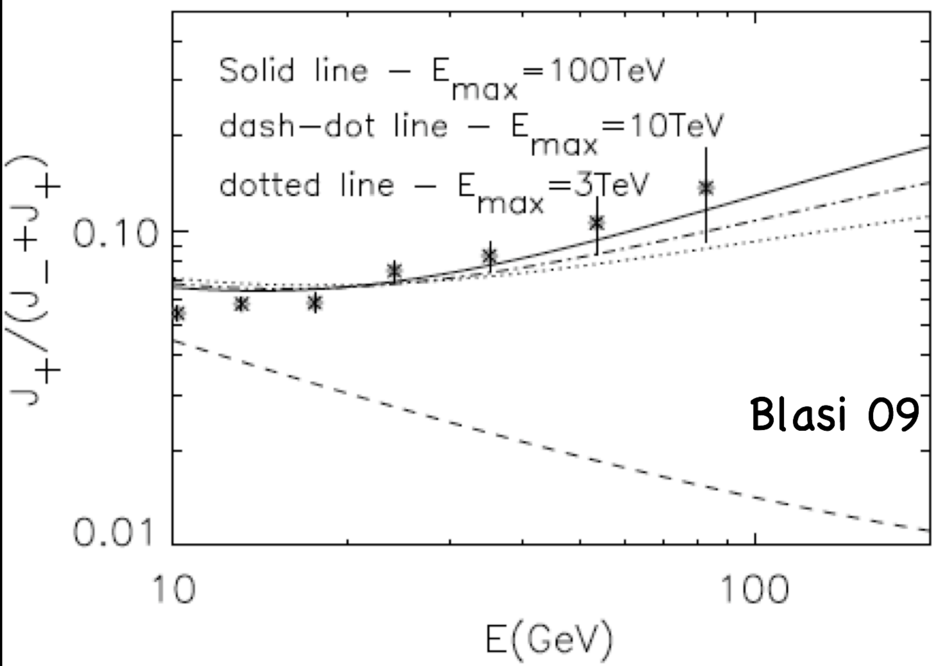
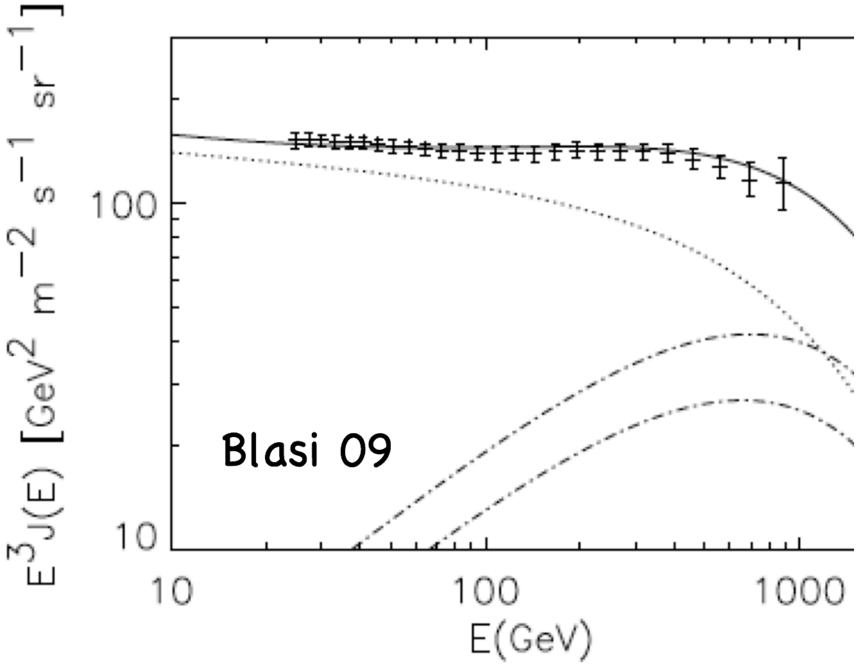
▪SECONDARIES ARE ACCELERATED IN TURN

▪FOR REASONABLE PARAMETERS...





ASTROPHYSICAL SOURCES OF e

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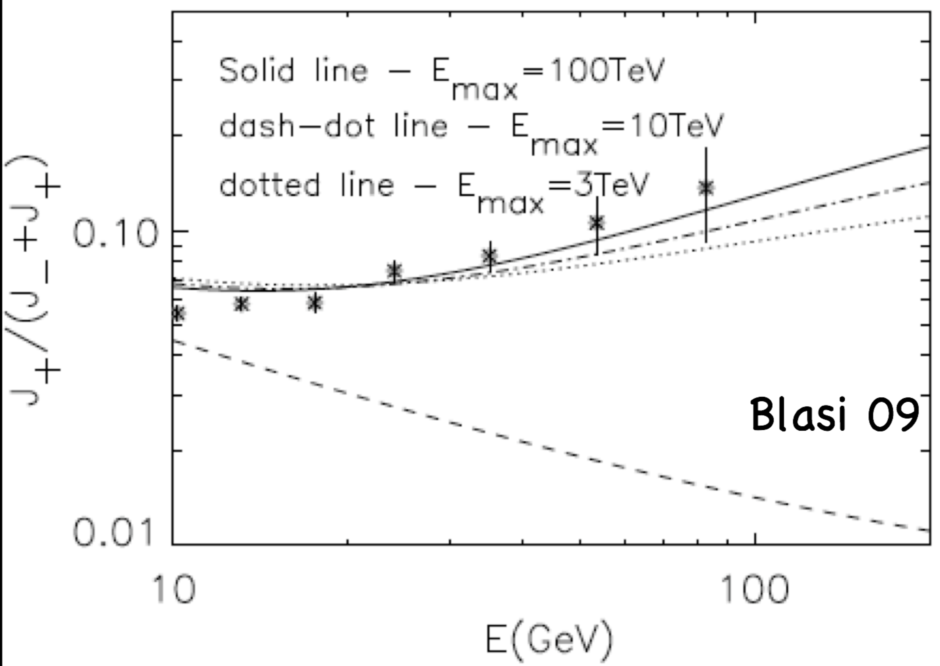

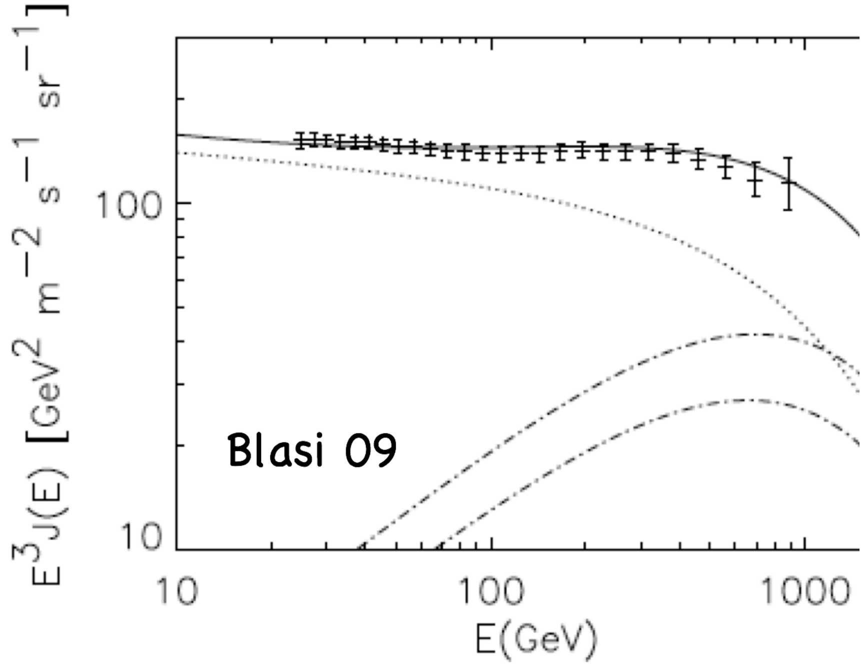

✓OK SO FAR WITH ANTI-PROTONS (Blasi & Serpico 09)

○MAIN CONCERN SECONDARY NUCLEI (Mertsch & Sarkar 09)

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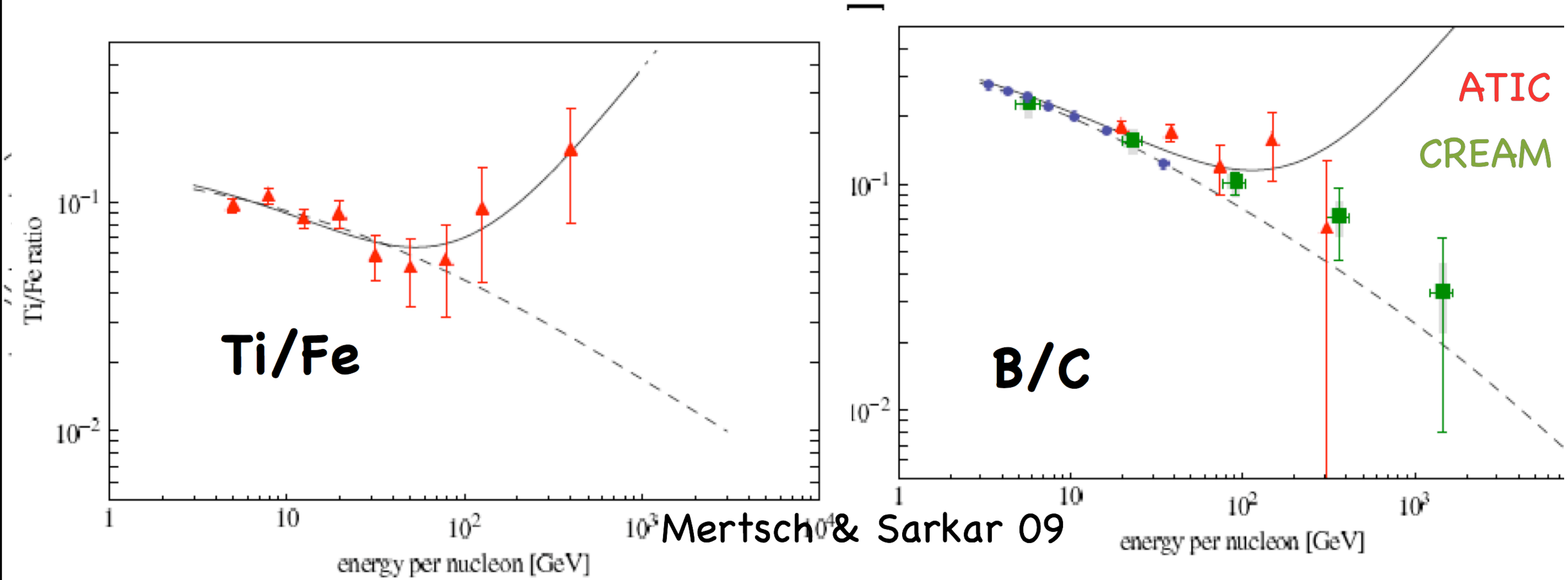

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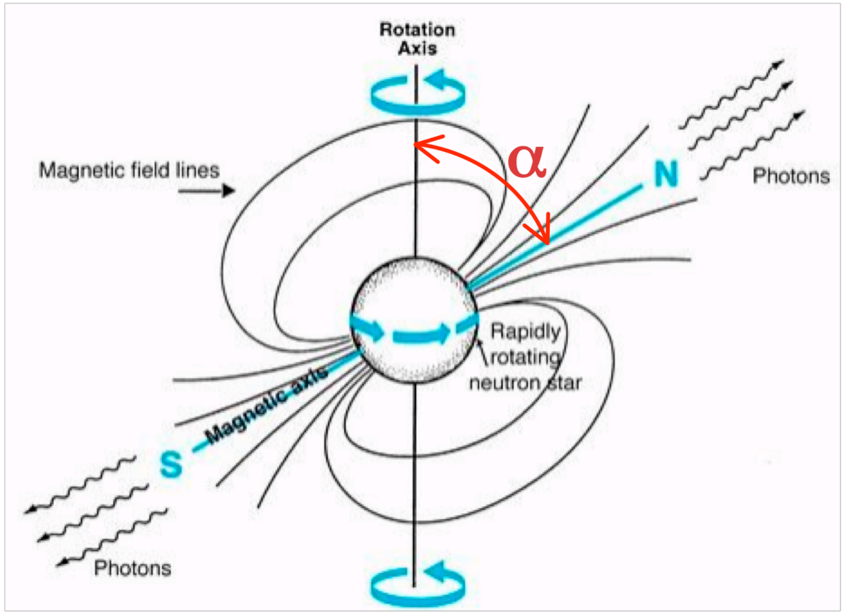
PULSARS



EXCELLENT FACTORIES OF LEPTONIC ANTIMATTER

IMMEDIATELY SUGGESTED AS THE SOURCES OF e^+ EXCESS

(e.g. Hooper, Blasi, Serpico 08, Grasso et al 09, Heyl et al 10)

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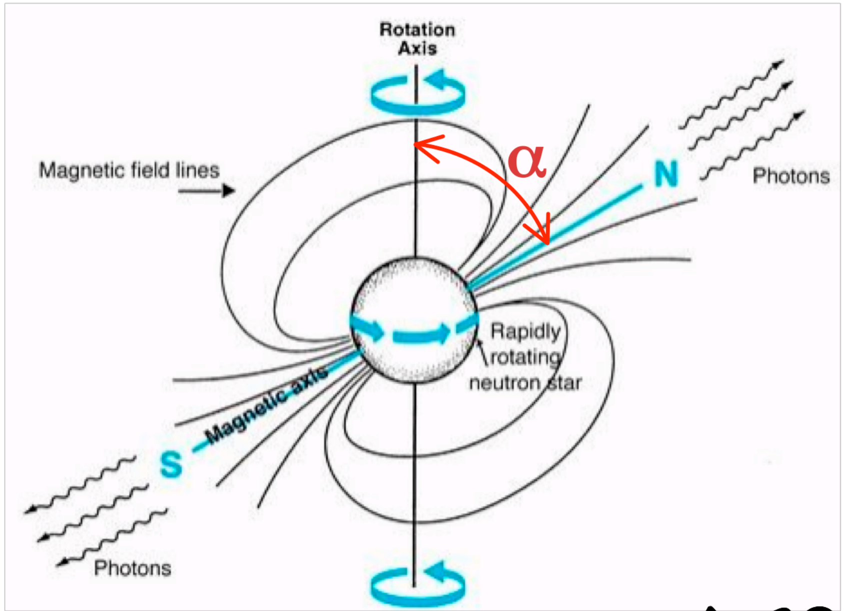

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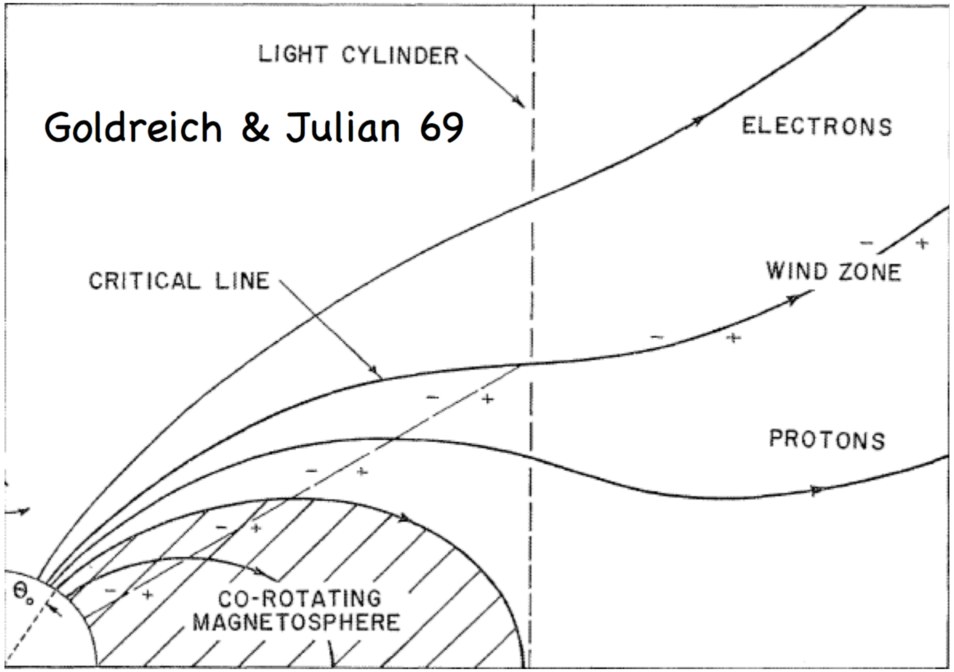
A CONDUCTING ROTATING DIPOLE CANNOT SPIN DOWN IN VACUUM...

PULSARS



STAR IS AN EXCELLENT CONDUCTOR

$$\vec{E} + \frac{\vec{v}}{c} \times \vec{B} = 0$$

$$\Downarrow$$

$$\vec{E}_{in} = -\left(\frac{\vec{\Omega} \times \vec{r}}{c}\right) \times \vec{B}$$

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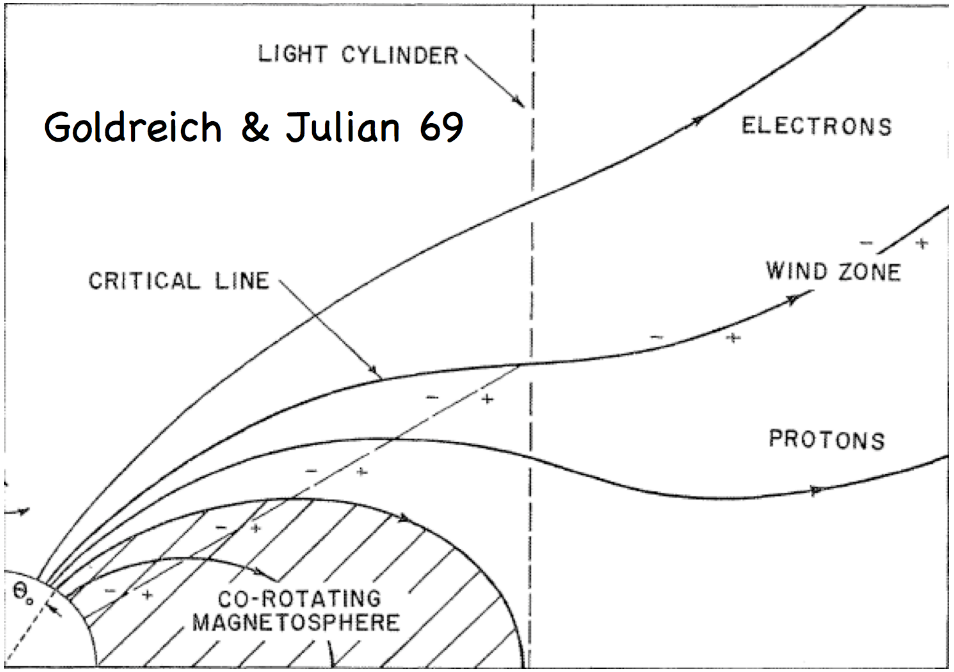

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IF VACUUM OUTSIDE: $\nabla^2 \Phi = 0$

WHERE $\vec{E} = -\vec{\nabla}\Phi$

BOUNDARY CONDITI… AT STAR SURFACE:

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

$\Phi \rightarrow \vec{E}$ $\quad (E_r^{out} - E_r^{in})_{R_*} = 4\pi\sigma \neq 0$ **FINITE SURFACE CHARGE DENSITY**

AND A LARGE FIELD TO EXTRACT IT $(\vec{E} \cdot \vec{B})_{R_*} \neq 0$

$$\frac{eE_\parallel}{GM_* m/R_*^2} = 8 \times 10^{12} \frac{B_1…}{P_1…}$$

PAIR PRODUCTION

LARGE POTENTIAL DROP AVAILAB

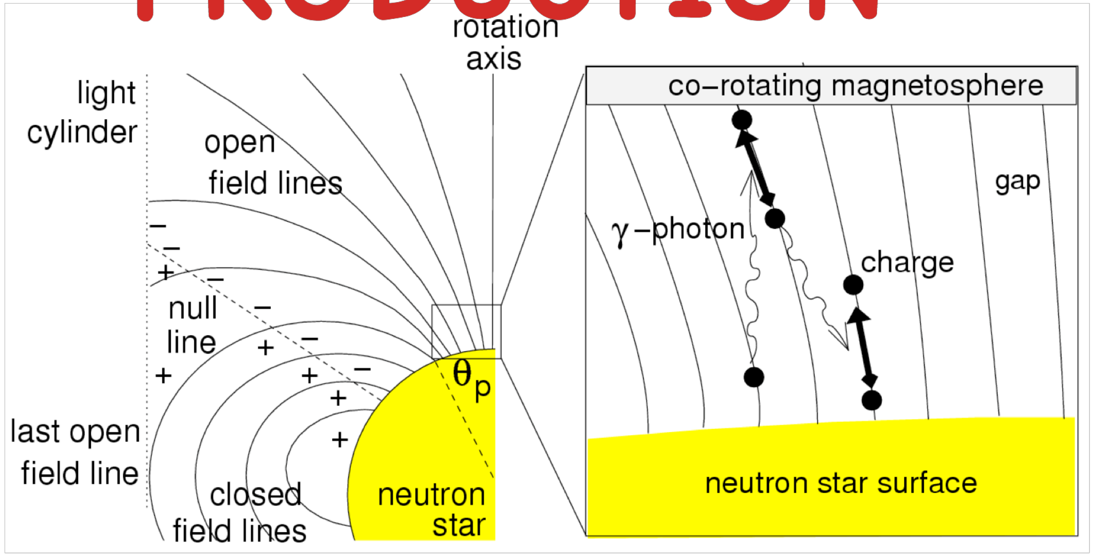
$$E_{max} = e\Phi = 2 \times 10^{15} \frac{B_{12}}{P_{100}^2} eV$$

SCREENING OF THE FIELD REQUIRES:

$$\rho_{GJ} = \frac{\vec{\nabla} \cdot \vec{E}}{4\pi} \approx -\frac{\vec{\Omega} \cdot}{2\pi}$$

BUT $J \propto B$ AND $J_{GJ} \propto B_Z$

PAIR PRODUCTION



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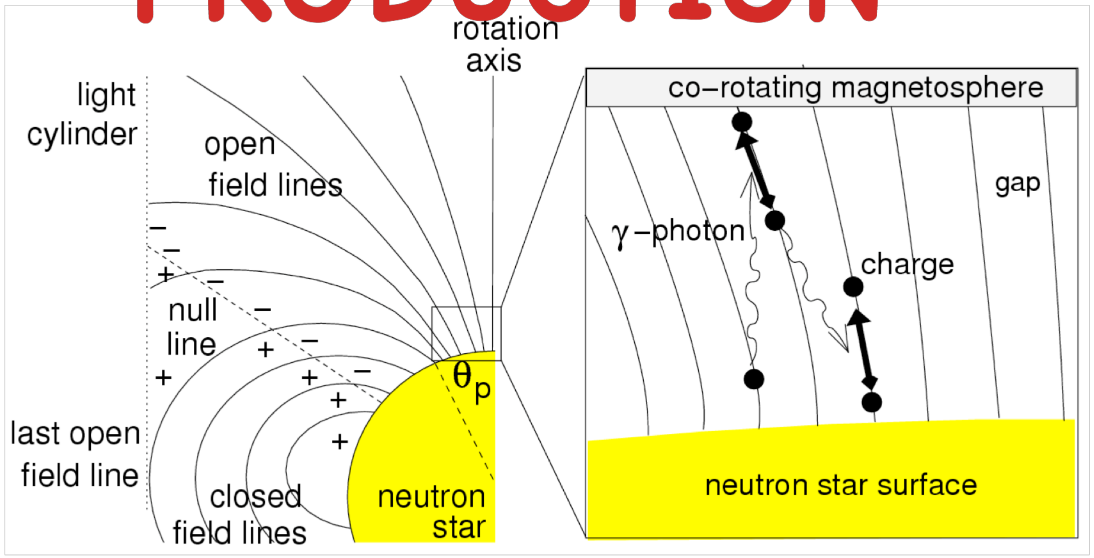

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e^- $\Rightarrow$ Curvature or ICS on star X-rays $\Rightarrow$ γ (E_γ>50 MeV) $\Rightarrow$ $\gamma + B \rightarrow e^+ + e^-$

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

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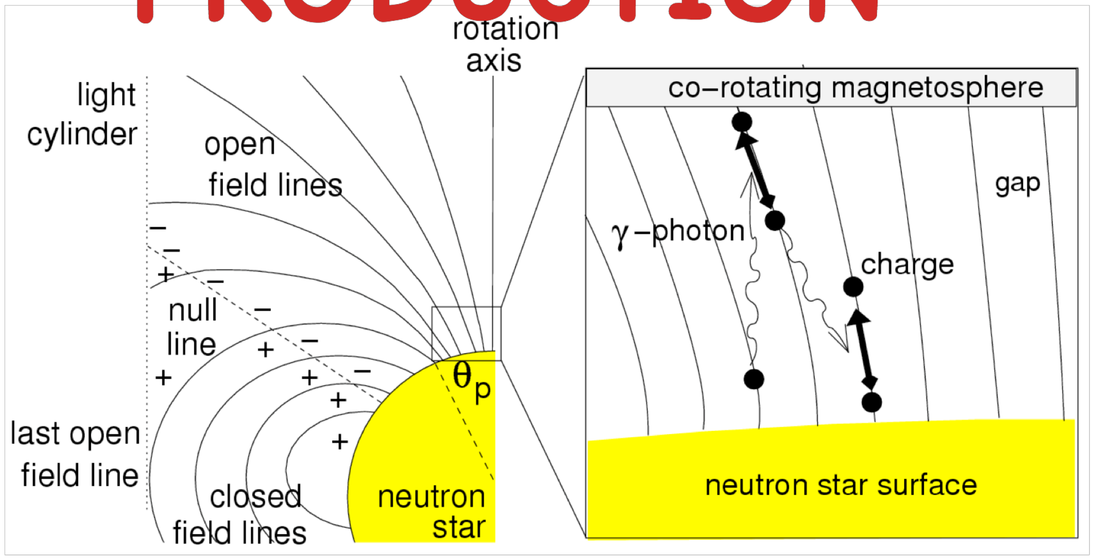

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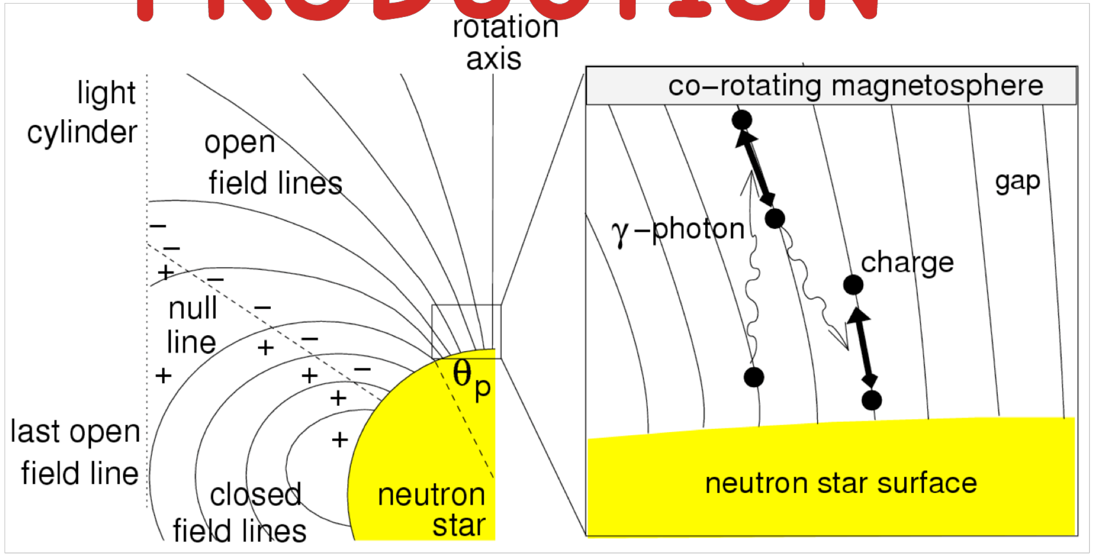
PAIR MULTIPLICITY: $\kappa \approx 10^3 - 10^4$ FROM PSR THEORY (e.g. Hibshmann & Arons 01, Timhokin & Arons 11), EVEN HIGHER FROM PWN MODELING (Bucciantini, Arons, Amato 11)

RECENT γ-RAY OBSERVATION CONFUSING…

PAIR PRODUCTION



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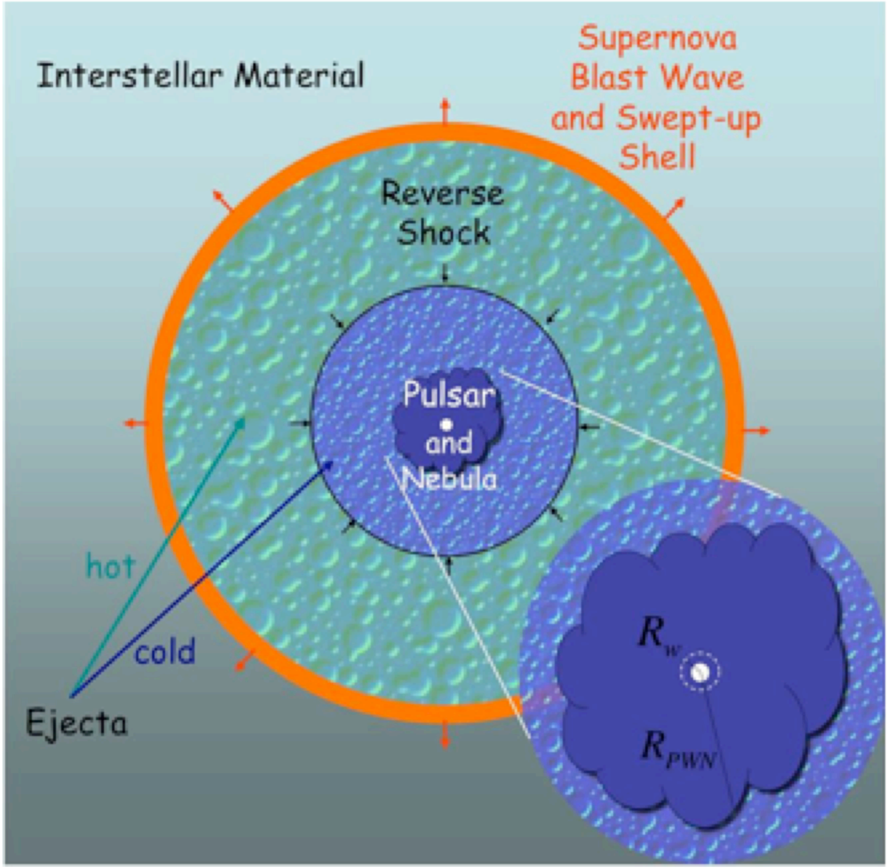
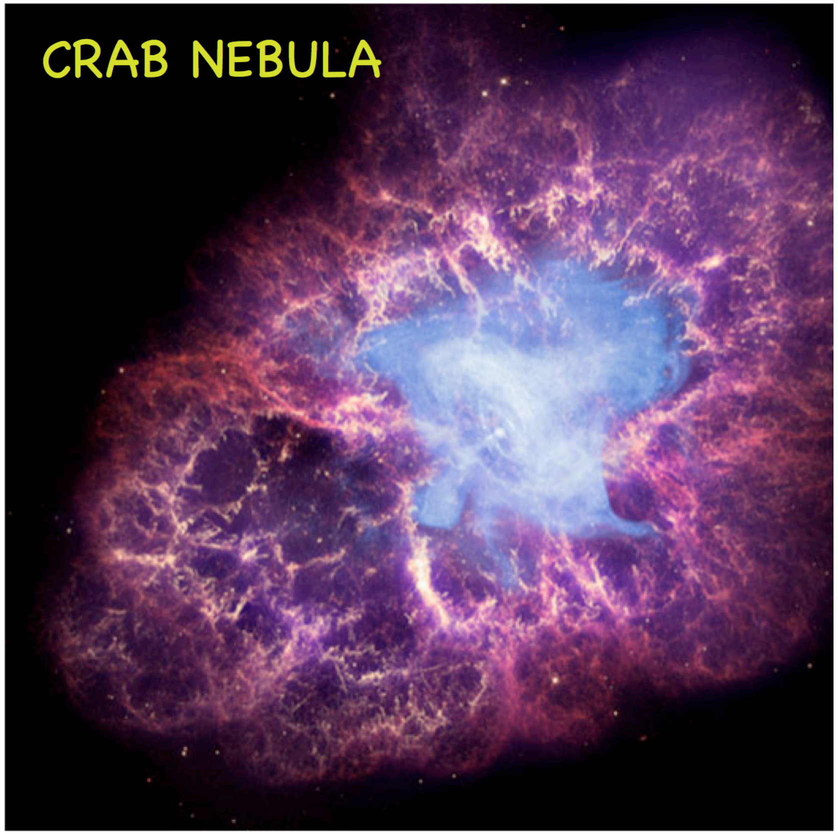
RECENT γ-RAY OBSERVATION CONFUSING...

PAIRS FORM A RELATIVISTIC MAGNETIZED WIND

PULSAR WINDS AND NEBULAE



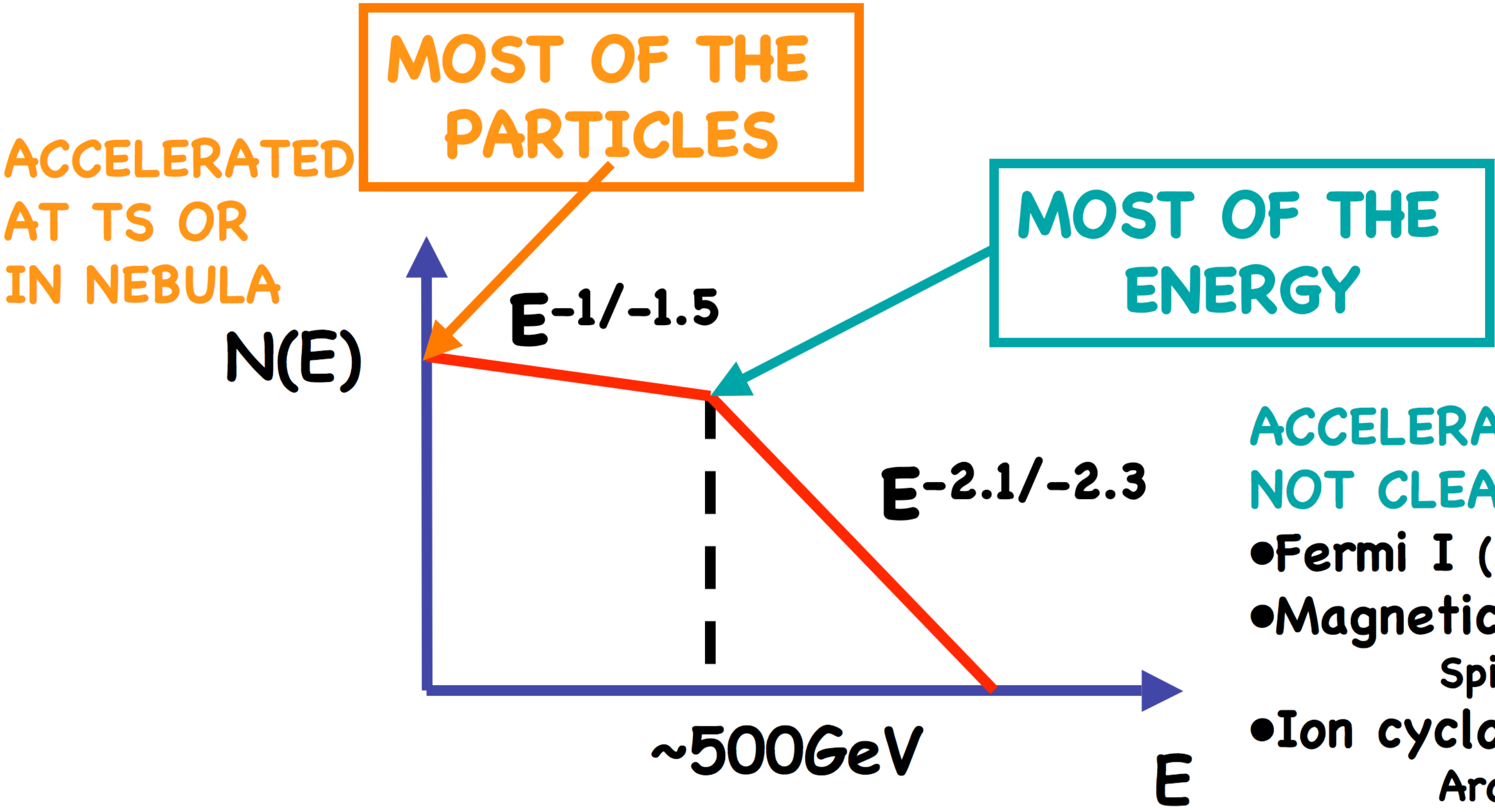
WIND CARRIES AWAY ALL THE ROTATIONAL ENERGY FROM THE PSR, SOMEHOW SPLIT BETWEEN PARTICLES AND B-FIELD



$$\dot{E}_R = \kappa \dot{N}_{GJ} m_{\pm} c^2 \Gamma_{wind} \left(1 + \frac{m_i}{\kappa m_{\pm}}\right)(1+\sigma)$$

$$\sigma = \frac{B^2}{4\pi m_{eff} n_{eff} c^2 \Gamma_{wind}^2}$$

PAIRS IN PWNe



ACCELERATED AT TS
NOT CLEAR HOW

- Fermi I (Spitkovsky 08)
- Magnetic rec.(Sironi & Spitkovsky 11)
- Ion cyclotron (Amato & Arons 06)

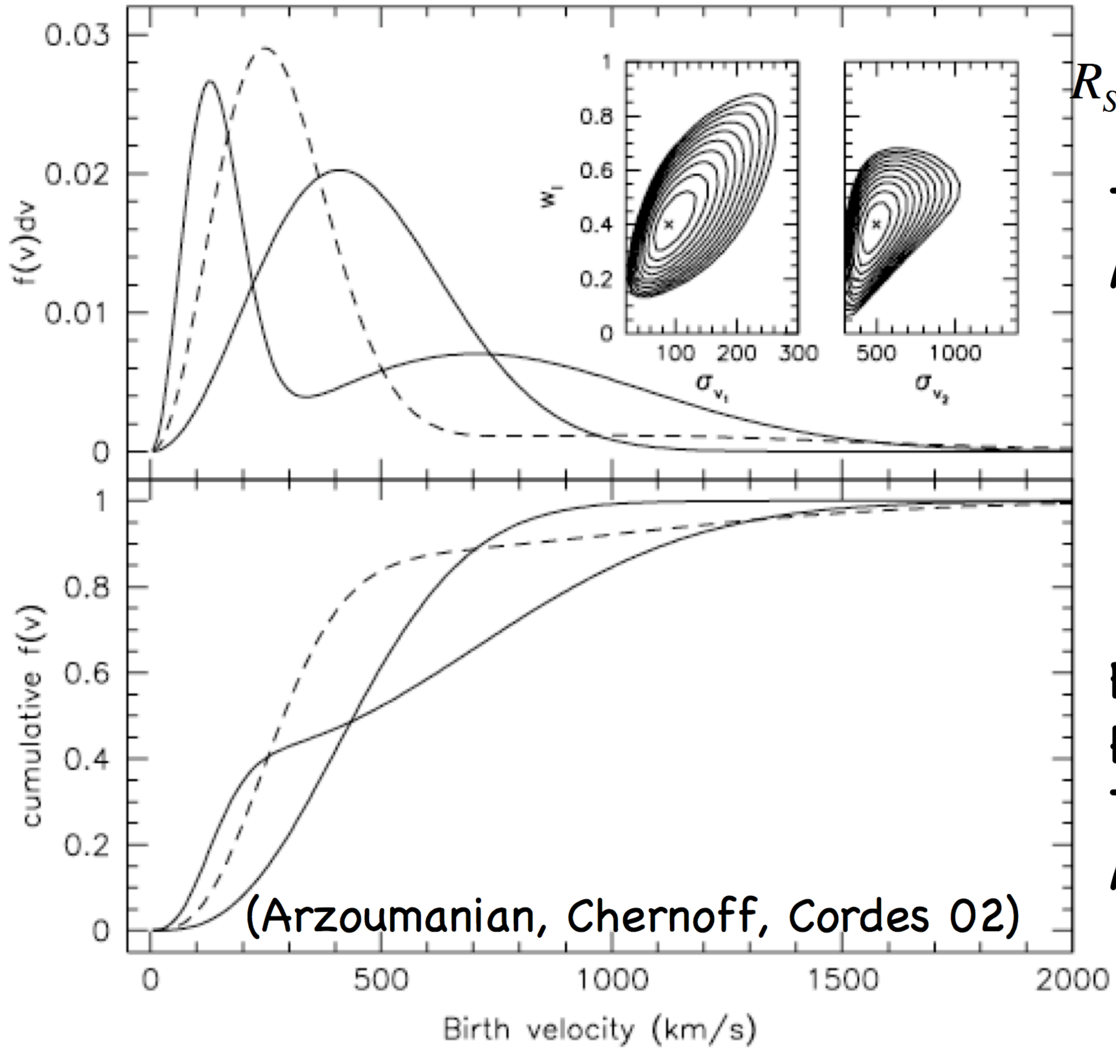
$L_{PAIRS} \approx 30\text{-}40\% \ L_{PSR}$

ALL LOOSE ENERGY DUE TO RADIATION AND EXPANSION WHILE CONFINED IN THE NEBULA

HOW DO WE GET THEM OUT OF THERE?

A HIGH VELOCITY POPULATION

PEAK VELOCITY 400-500 km/s



A SIMPLE ESTIMATE:

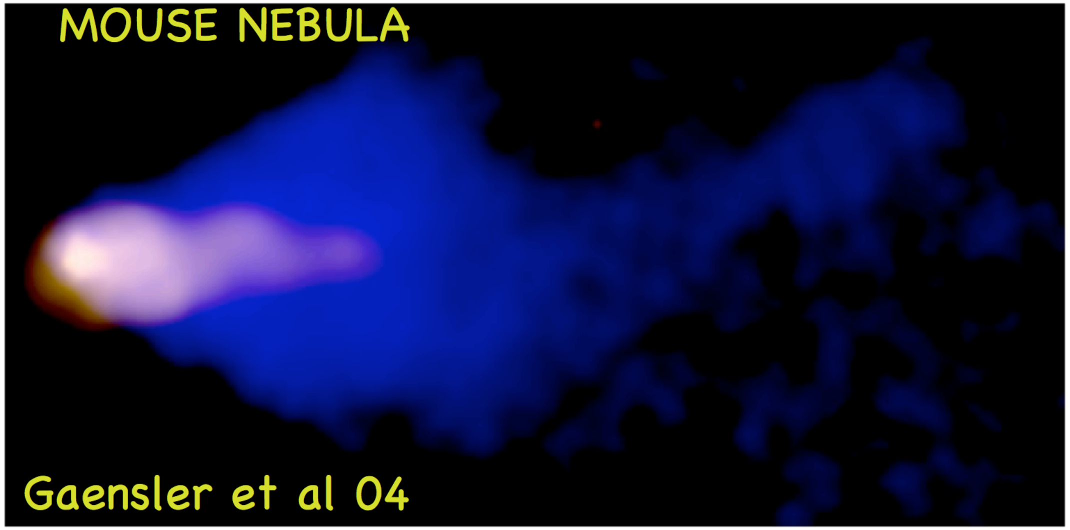
$$R_{SNR}(t) \approx R_{ST}\left(\frac{t}{T_{ST}}\right)^{2/5} \qquad \mathrm{R_{NS}}(t) = \mathrm{V}$$

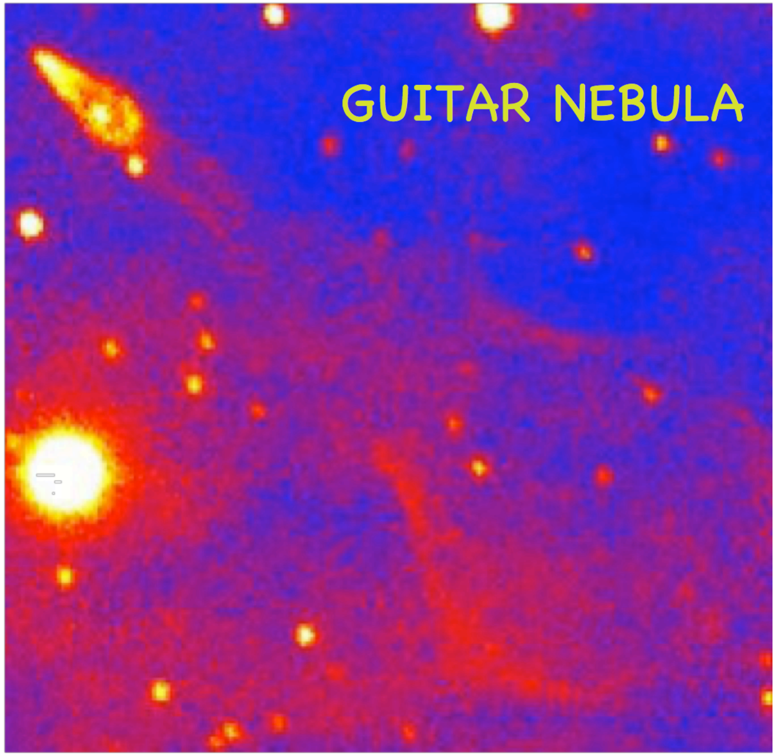
THE NS LEAVES THE REMNAN
AT

$$t \approx T_{ST}\left(\frac{R_{ST}}{T_{ST}V_{NS}}\right)^{5/3}$$

FOR TYPICAL VALUES OF PARAMETERS THE NS LEAVES THE SNR ABOUT 40,000 years AFTER EXPLOSION

PULSAR BOW SHOCK NEBULAE





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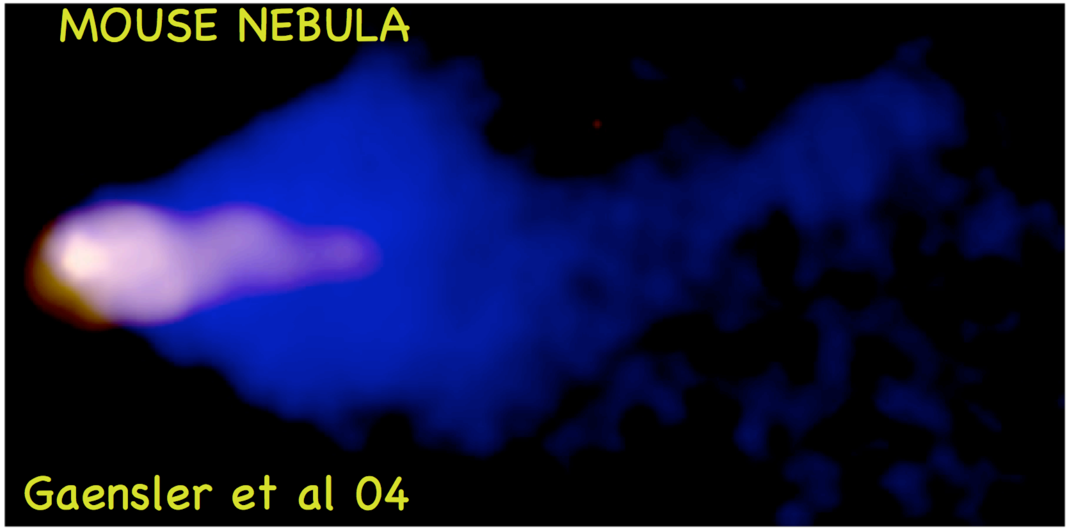

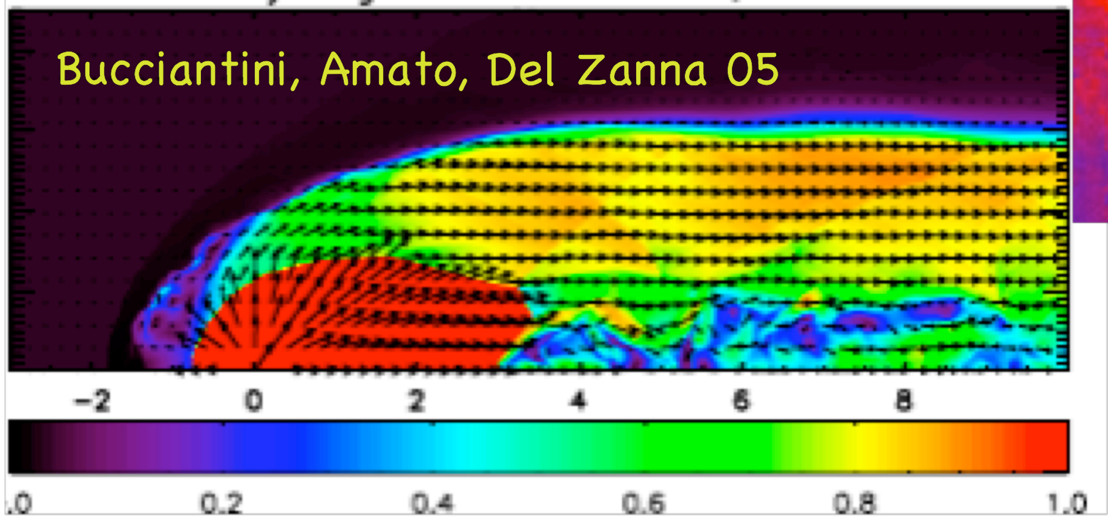

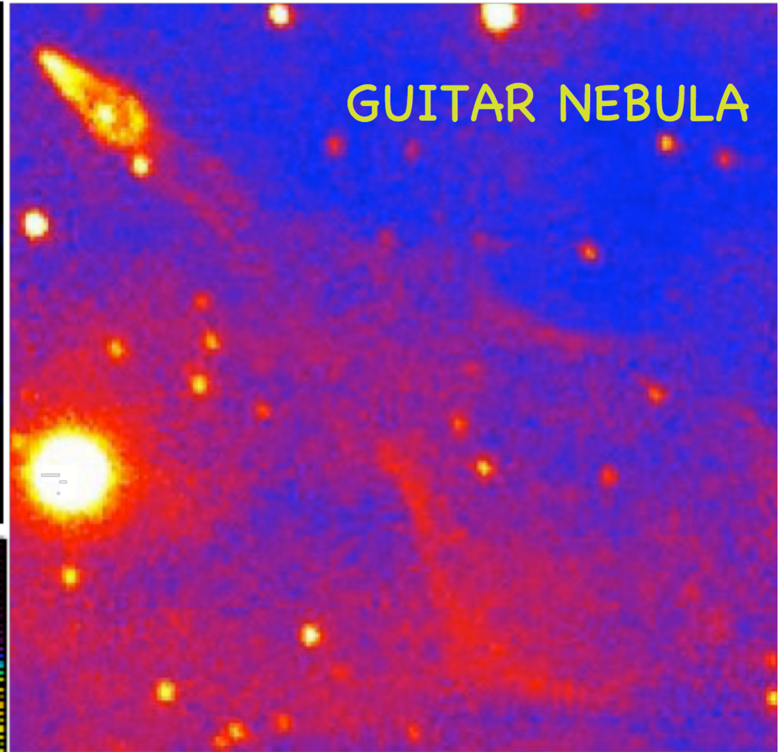

MAIN UNKNOWN:

HOW MUCH ENERGY IS LEF
IN PAIRS AT THIS TIME?

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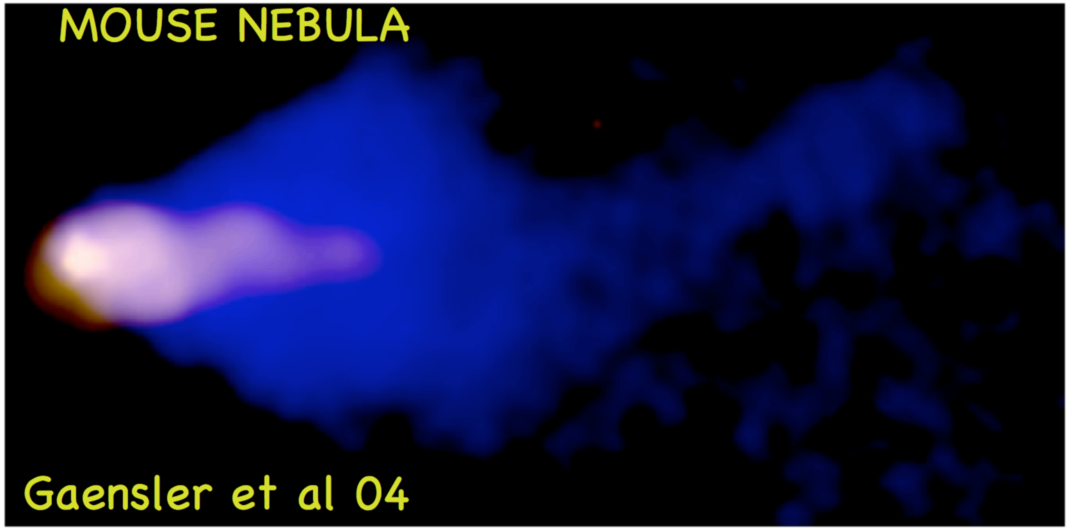

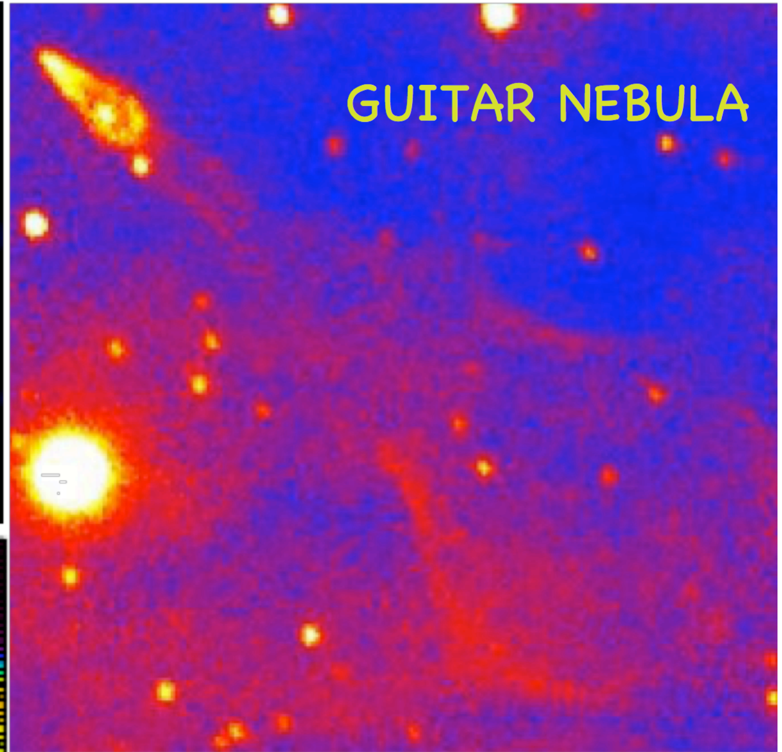

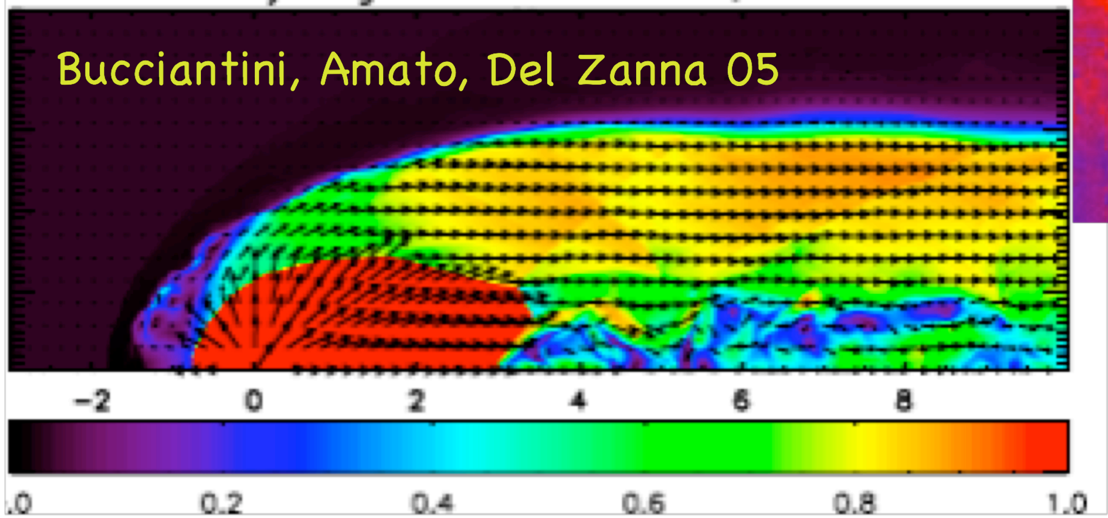

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DEPENDS ON SPIN-DOWN: $L = I\Omega\dot{\Omega} \propto \Omega^{n+1}$

- n=3 FOR DIPOLE
- OBSERVED VALUES: ALWAYS n<

PULSAR SPIN DOWN

FOR ARBITRARY INCLINATION α BETWEEN **B** AND Ω

$$\dot{E} = cB_*^2 R_*^2 \left(\frac{R_* \Omega}{c}\right)^4 (1 + \sin^2 \alpha)$$

$$\dot{E} = I\Omega\dot{\Omega} = -a\Omega^4$$

MORE GENERALLY: $\dot{\Omega} = -a\Omega^n$ $\quad$ $\dot{E} = I\Omega\dot{\Omega} = aI\Omega^{n+1}$

AFTER INTEGRATION $\Omega(t) = \dfrac{\Omega_0}{[1 + t/\tau_0]^{1/(n-1)}}$ $\quad$ $\tau_0 = \dfrac{\Omega_0^{1-n}}{a(n-1)}$

$$\Rightarrow \quad \dot{E} = \frac{aI\Omega_0^{n+1}}{[1 + t/\tau_0]^{\frac{n+1}{n-1}}}$$

n=BRAKING INDEX

n=3 FOR A DIPOLE FIELD

n<3 FOR OTHER CASES

DERIVING n IMPLIES MEASURING d^2P/dt^2

MEASURED FOR 4 PSRs ONLY: ALWAYS LESS THAN 3!!!!

ENERGETICS

THE ENERGY AVAILABLE AFTER A TIME T_* WHEN THE NS IS OUTSIDE THE SNR IS

$$E_* = E(t > T_*) = \frac{1}{2} I\Omega_0^2 \left(1 + \frac{T_*}{\tau_0}\right)^{-\frac{2}{n-1}} = E_{tot}\left(1 + \frac{T_*}{\tau_0}\right)^{-\frac{2}{n-1}}$$

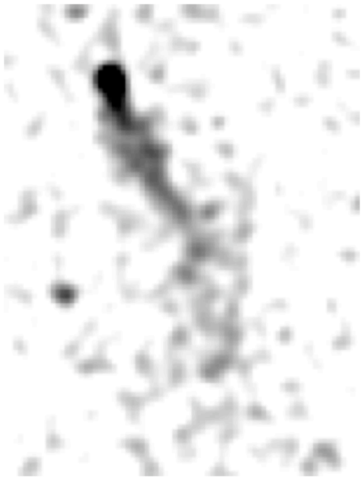
FOR $T_* \approx 40{,}000$ YEARS, ONE HAS:

$$\frac{E_*}{E_{tot}} \approx 0.5 \qquad \text{For dipole n} = 3$$

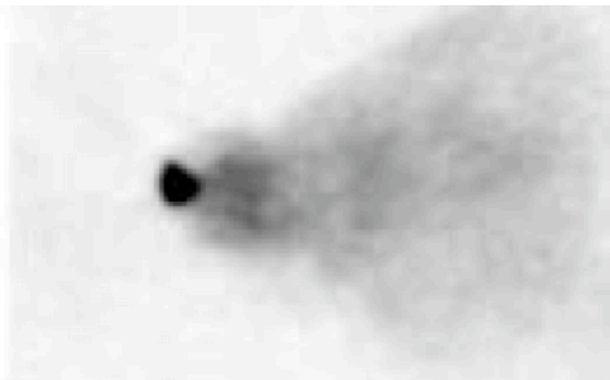
$$\frac{E_*}{E_{tot}} \approx 0.02 \qquad \text{For n} = 2.5$$

PARTICLE SPECTRA FROM OBSERVATIONS

IN THE TWO CASES of BSPWN OUTSIDE A SNR IN WHICH WE HAVE RADIO MEASUREMENTS WE INFER A SPECTRUM OF ACCELERATED PARTICLES WITH SLOPE ≈-1.5



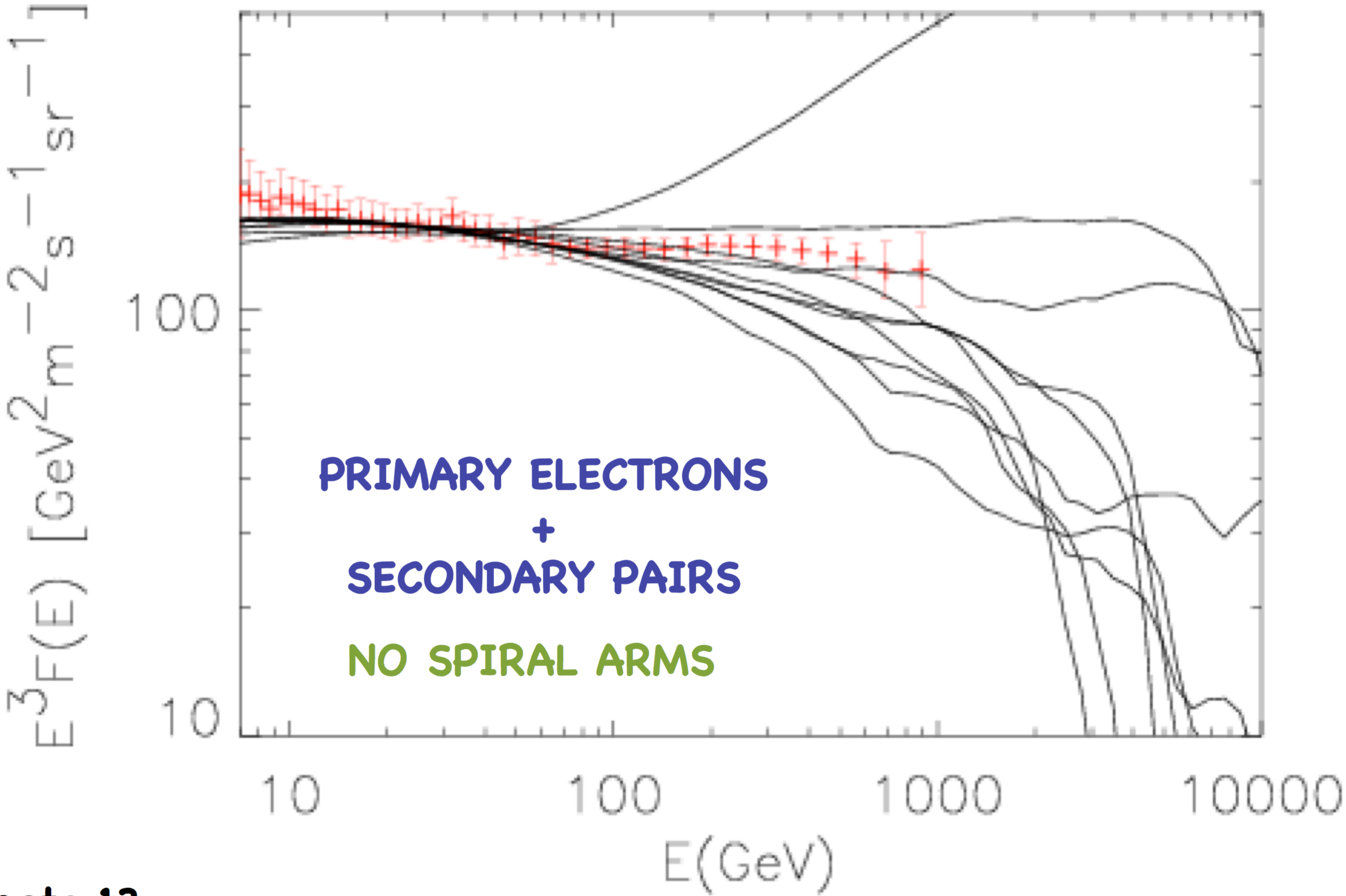
PSR J1509—5850
SLOPE RADIO: -0.26
SLOPE ELECTRONS: -1.52
Ng et al. 2010



THE MOUSE
SLOPE RADIO: -0.3
SLOPE ELECTRONS: -1.6
Gaensler et al. 2004

PROPAGATION "SUBTLETIES" FIRST

DISCRETENESS OF THE SOURCE DISTRIBUTION

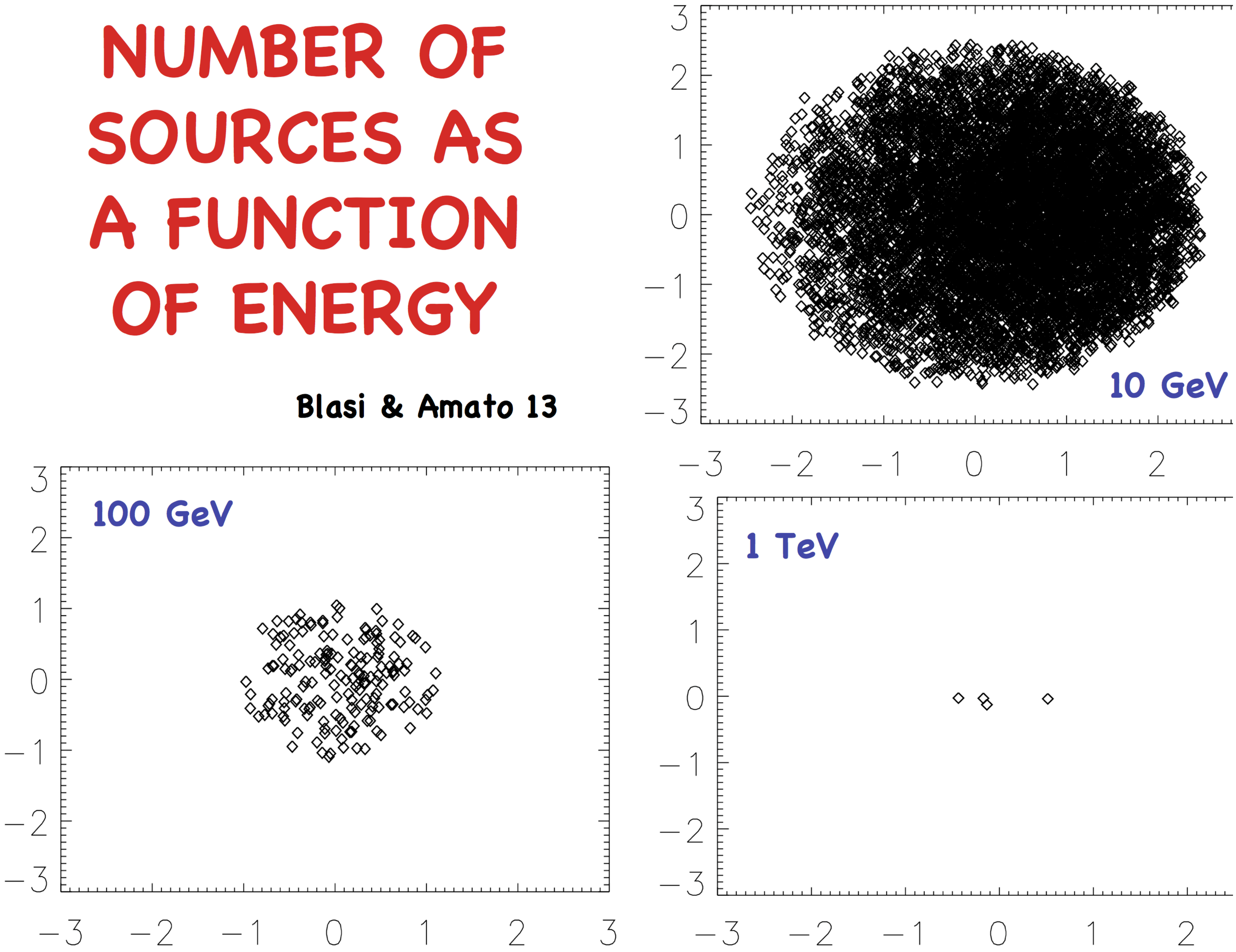


Blasi & Amato 13

DATA from Fermi (Abdo et al 09)

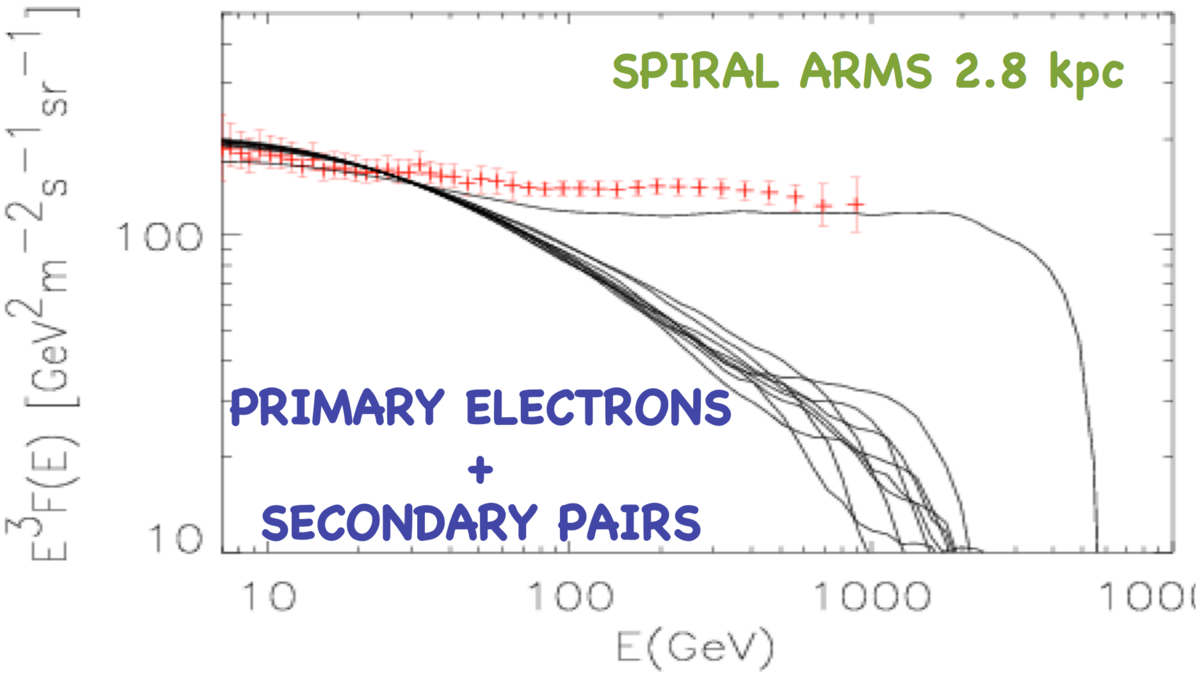
NUMBER OF SOURCES AS A FUNCTION OF ENERGY

Blasi & Amato 13

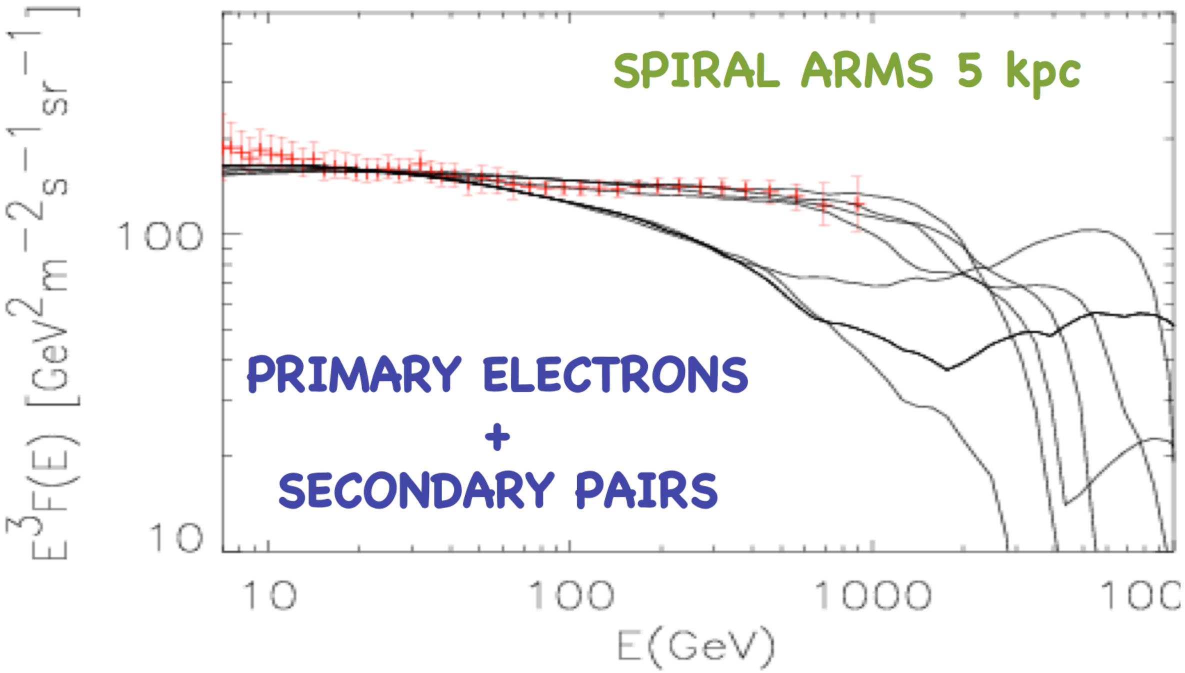


SPIRAL ARMS

TIGHT SPIRAL



BROAD SPIRAL



Blasi & Amato 13

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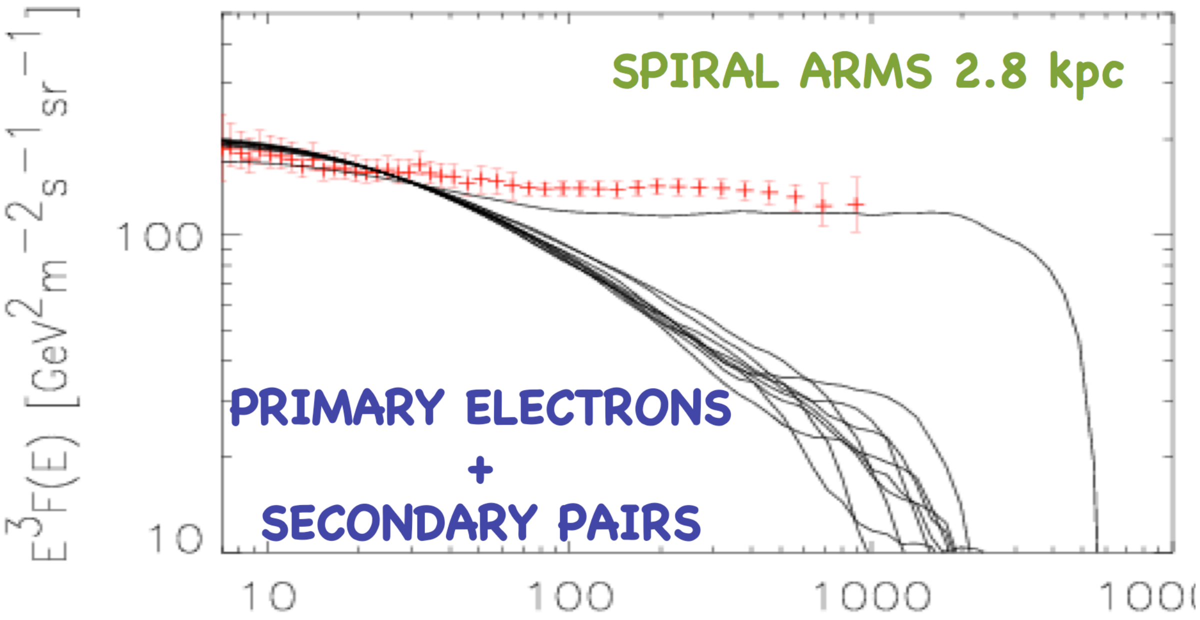
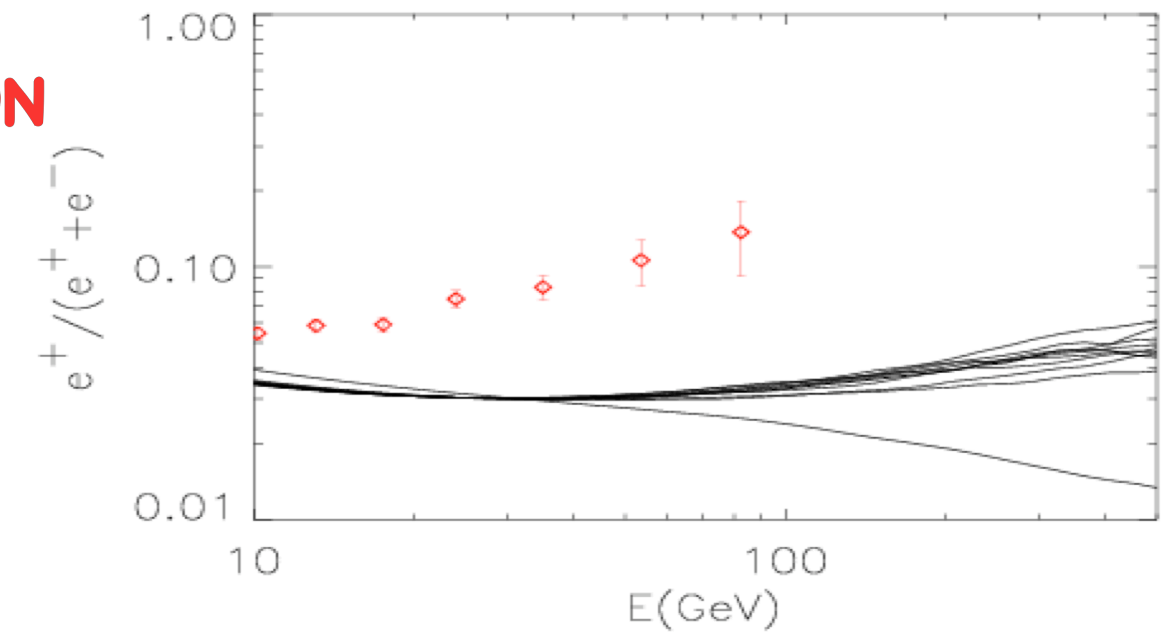


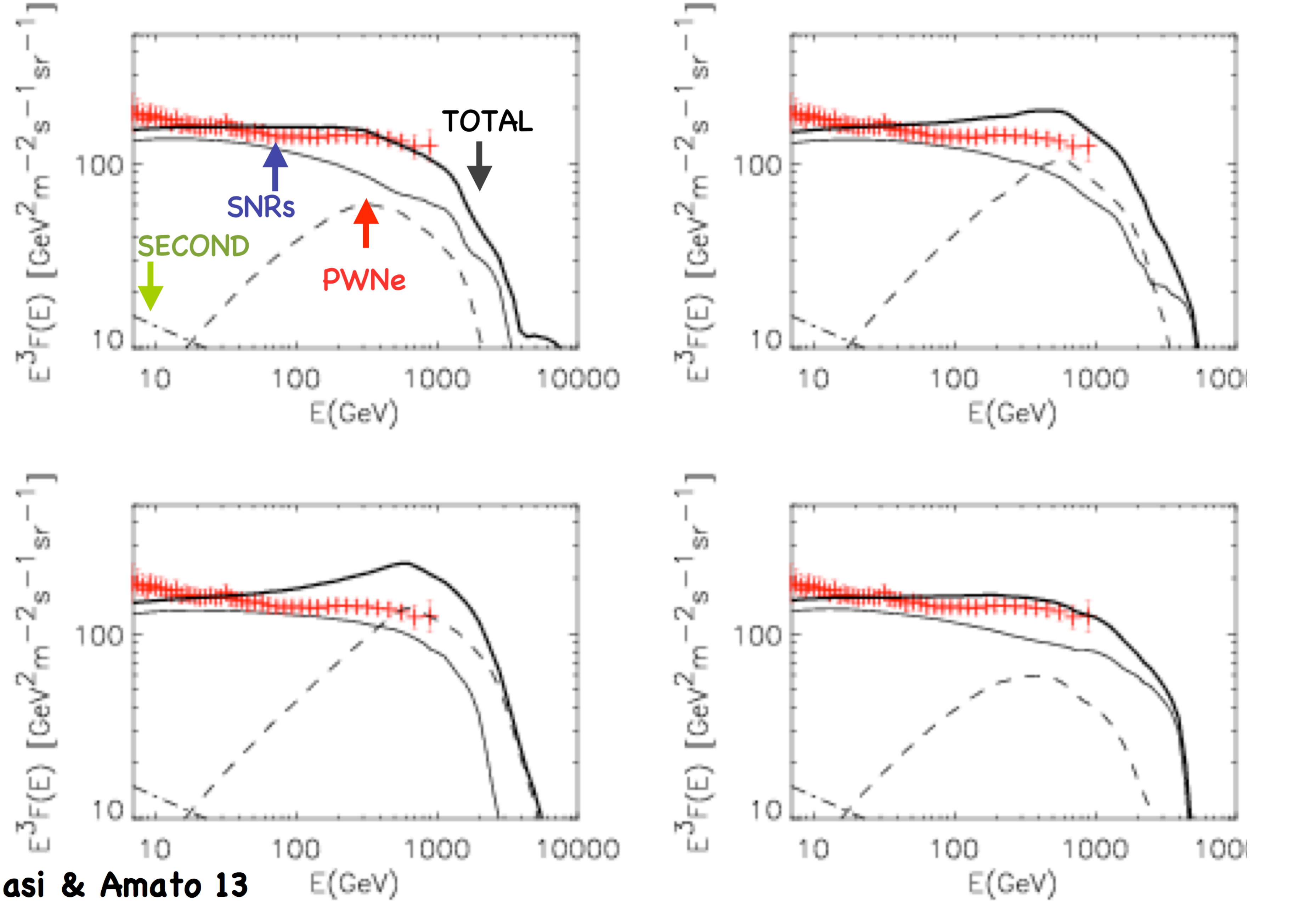
POSITRON FRACTION

RISE DUE TO
DECREASE OF
ELECTRON FLUX



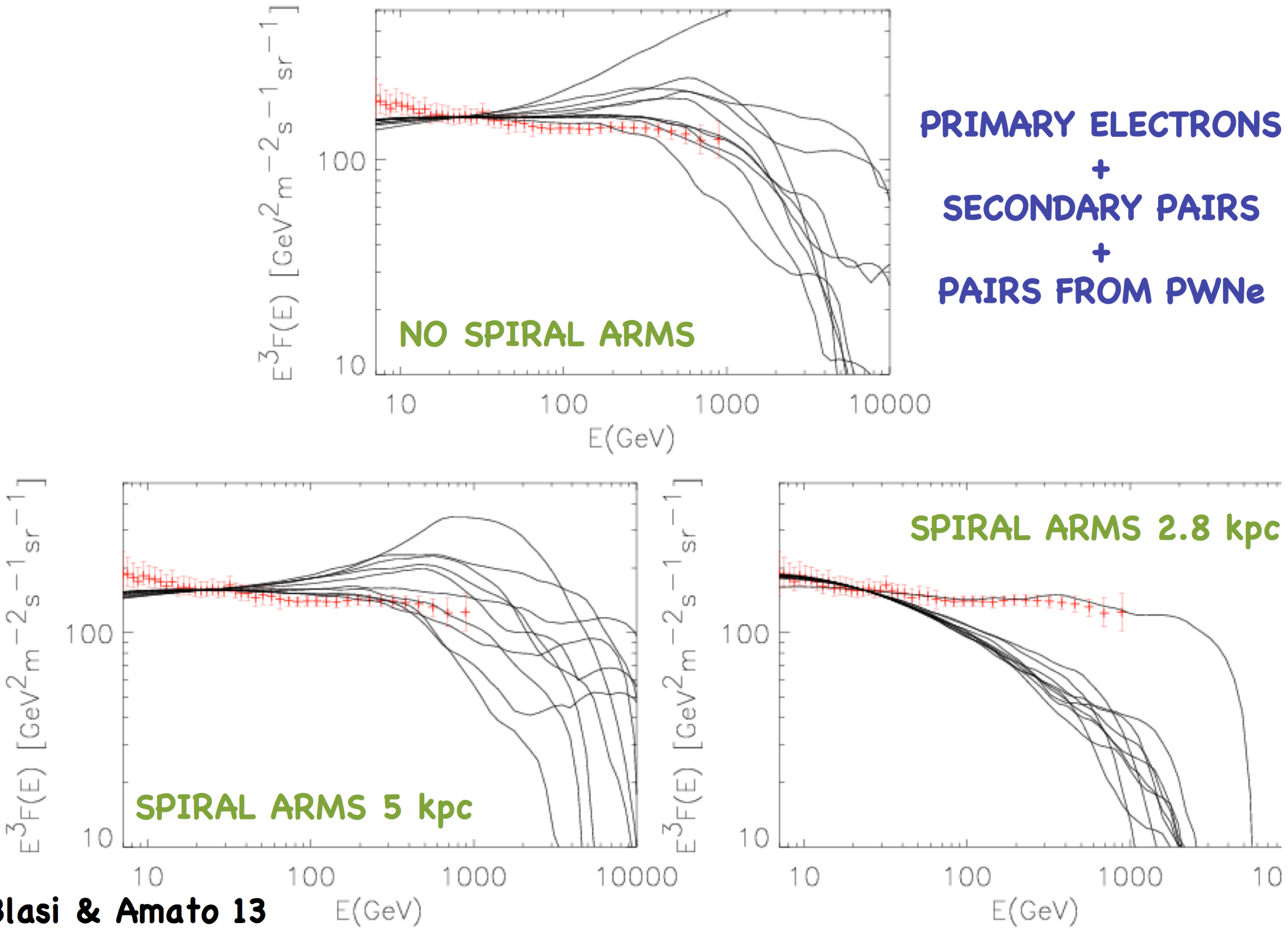
Blasi & Amato 13

THE CONTRIBUTION OF PWNe



Blasi & Amato 13

STRUCTURE OF THE GALAXY



PRIMARY ELECTRONS
+
SECONDARY PAIRS
+
PAIRS FROM PWNe

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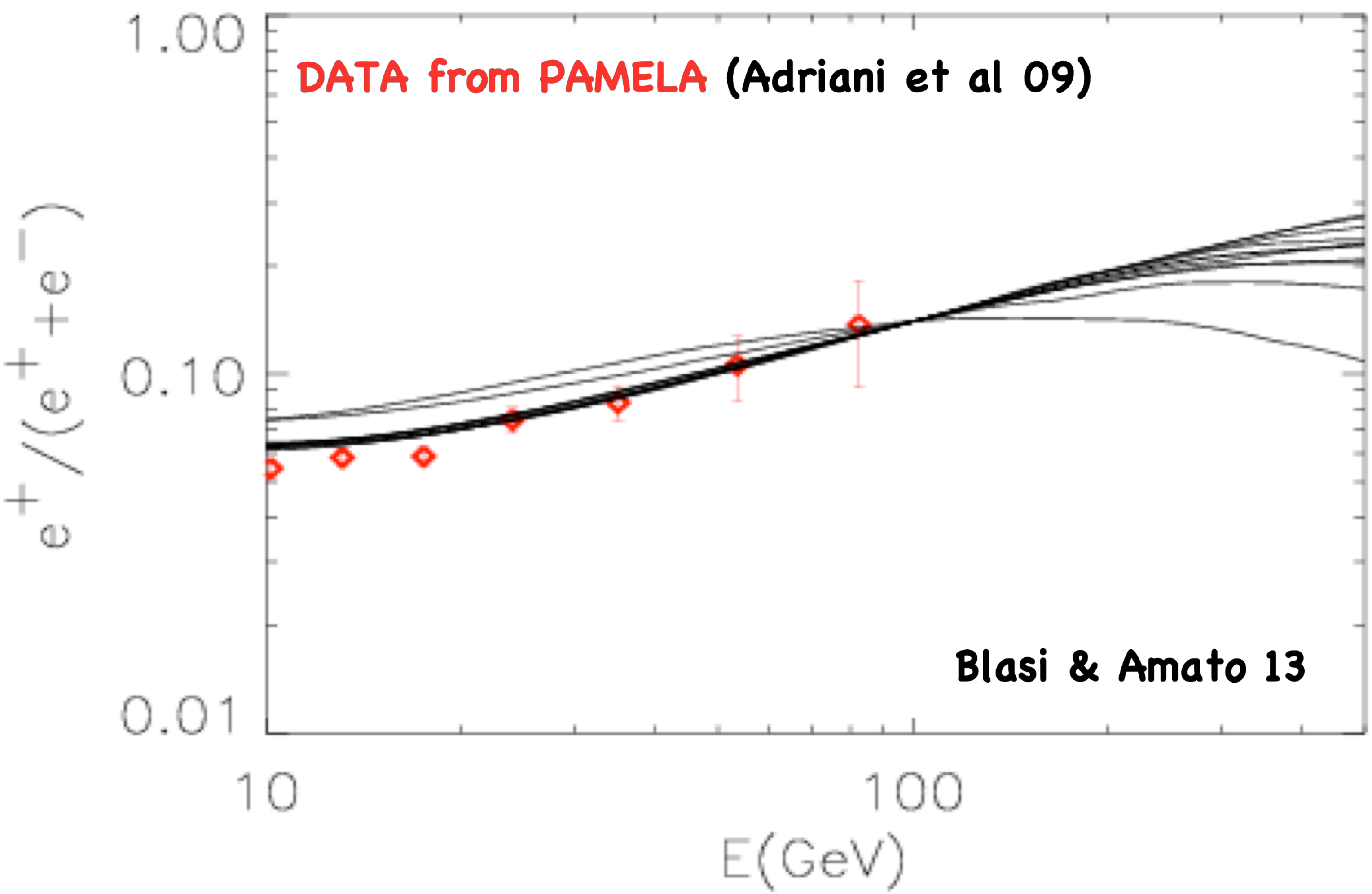
THE POSITRON FRACTION

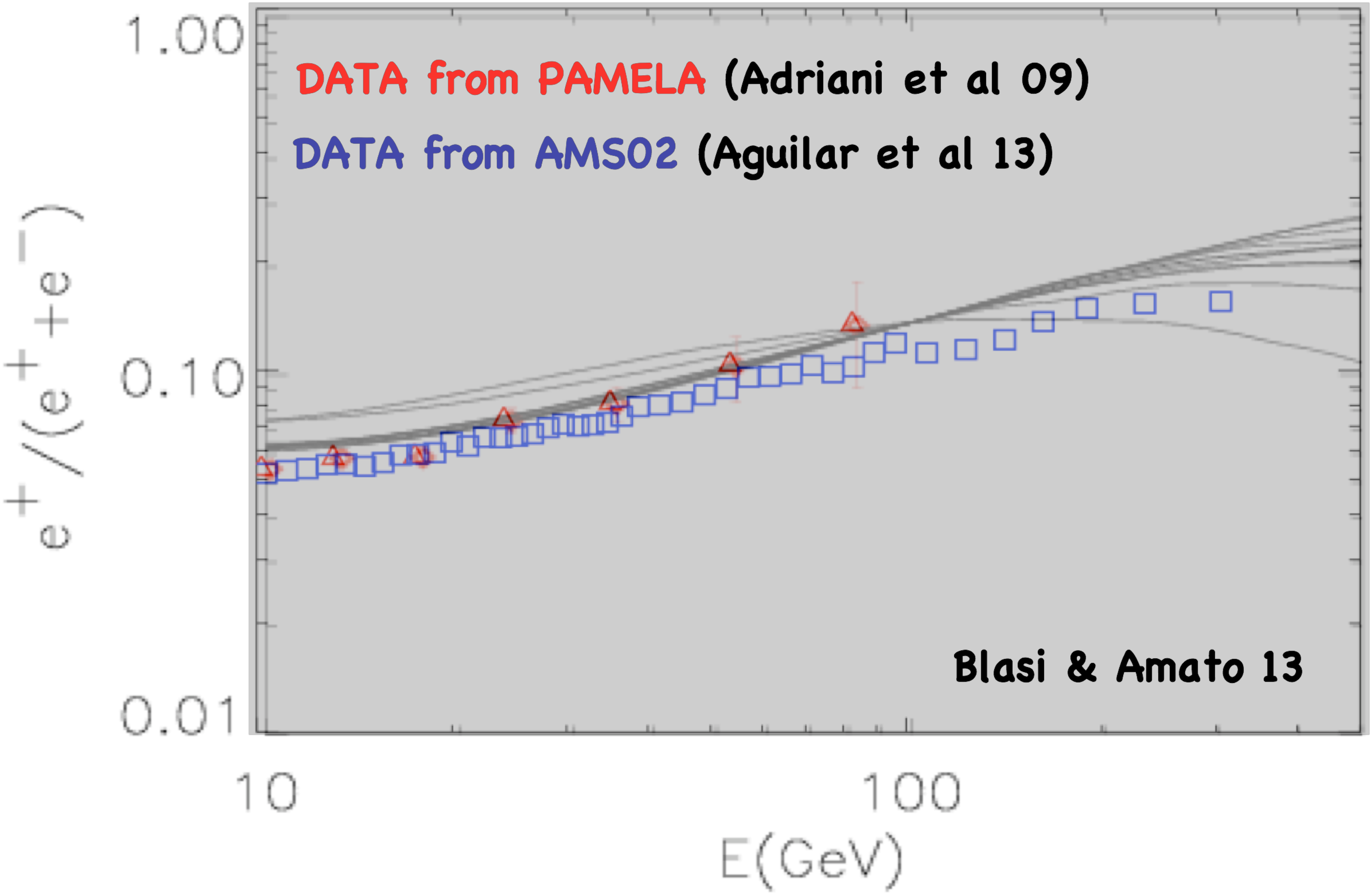


25% EFFICIENCY FOR n=2.5

1% EFFICIENCY FOR n=3

CONTRIBUTION FROM PULSARS MUST BE THERE AT SOME LEVEL!!!!

THE POSITRON FRACTION

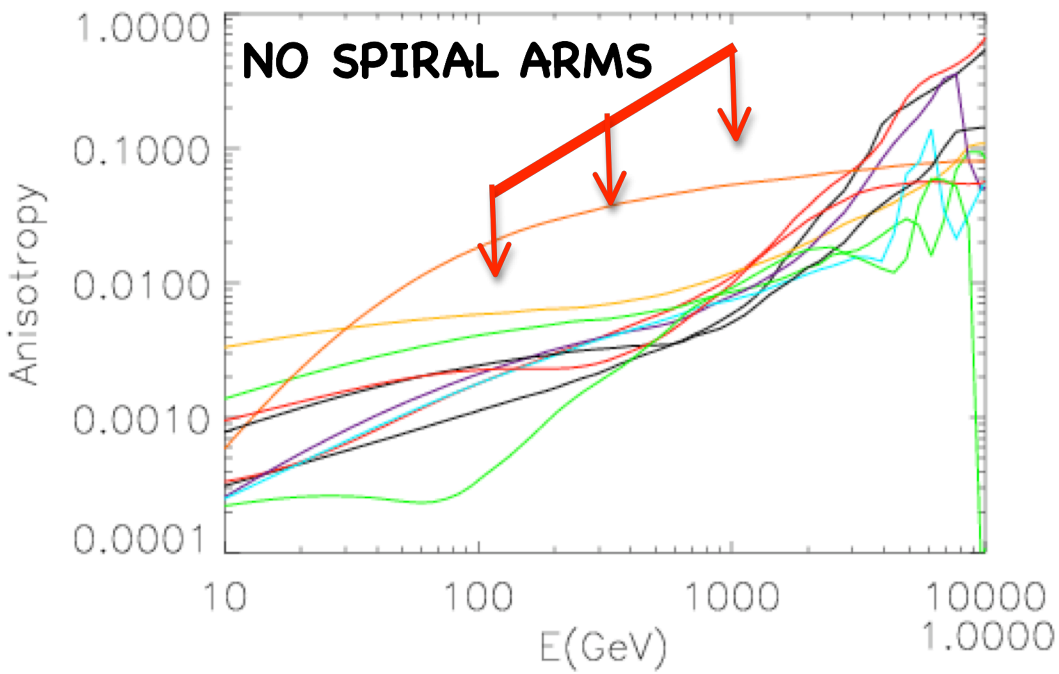


25% EFFICIENCY FOR n=2.5

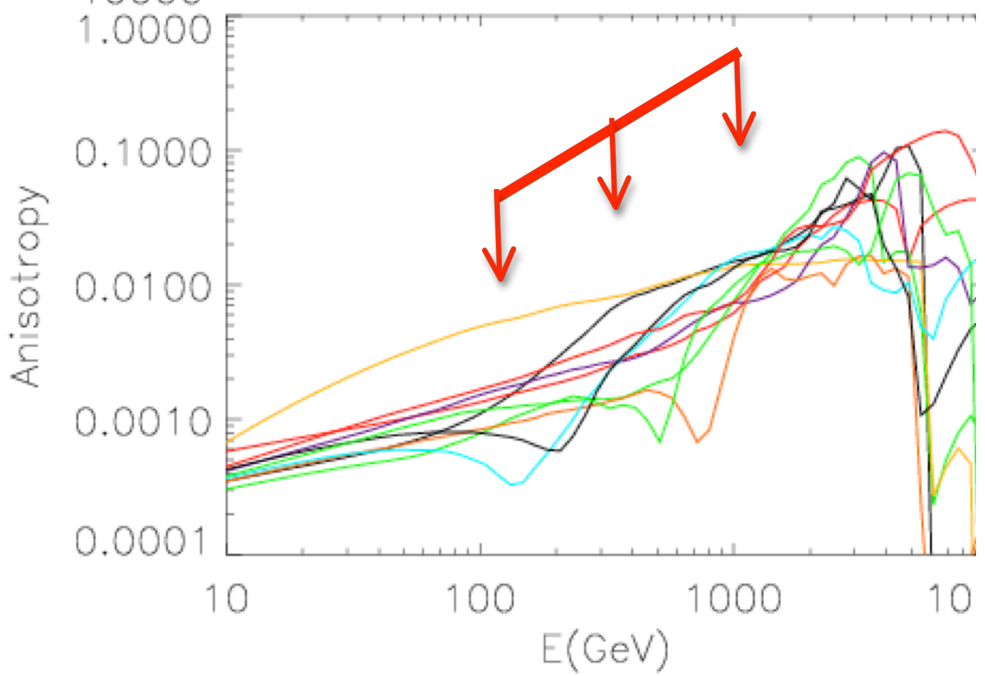
1% EFFICIENCY FOR n=3

CONTRIBUTION FROM PULSARS MUST BE THERE AT SOME LEVEL!!!!

ANISOTROPY



TIGHT SPIRAL
ARMS 2.8 kpc



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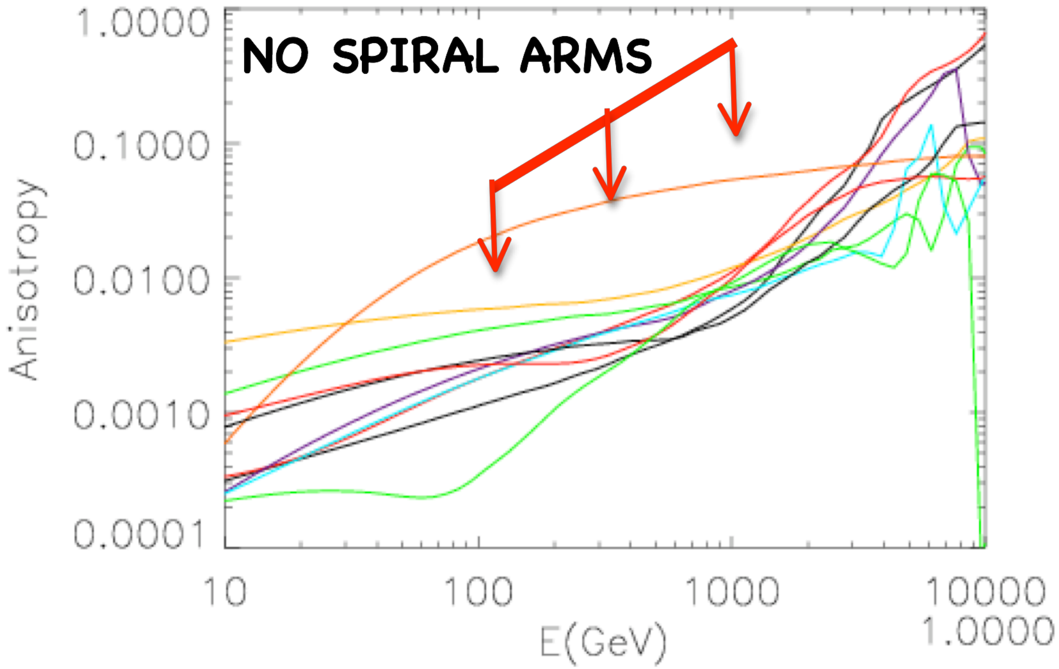
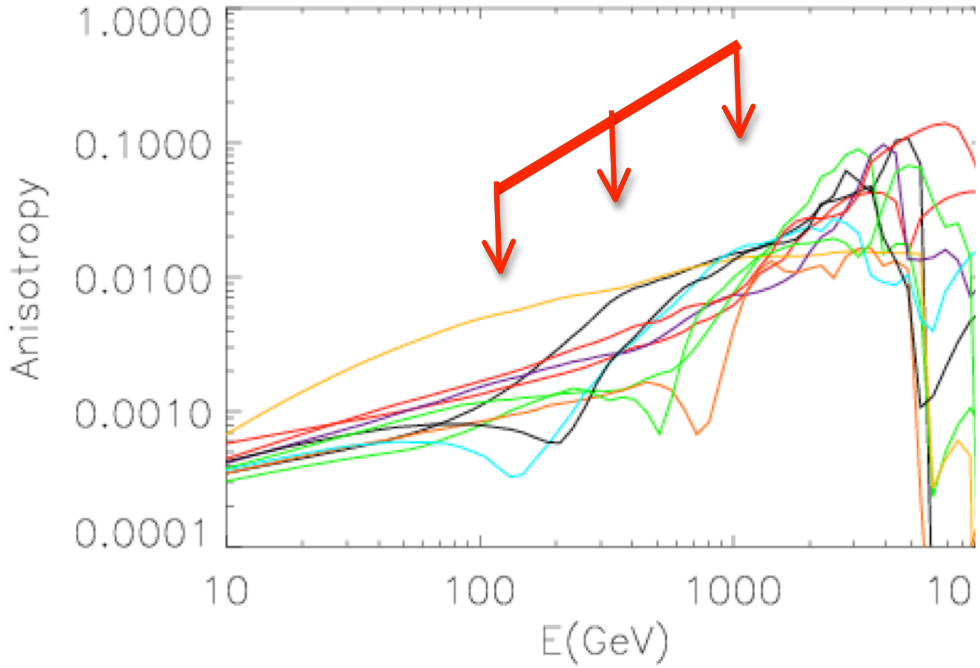
ANISOTROPY



UPPER LIMITS from Fermi
(Ackerman et al 11)

TIGHT SPIRAL
ARMS 2.8 kpc



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CONCLUSIONS

PAIR PRODUCTION IN PSRs AND SUBSEQUENT RELEASE OF THESE PAIRS IN THE ISM PROVIDES A VERY NATURAL EXPLANATION FOR THE POSITRON EXCESS

IN A SENSE THE POSITRON FRACTION PUTS A CONSTRAINT ON PULSAR SPIN-DOWN SUGGESTING SOMETHING FASTER THAN DIPOLE IN AGREEMENT WITH CURRENT DATA

OBSERVATION OF THESE POSITRONS SHOULD HAVE BEEN PREDICTED: TOO BAD THAT SUCH CALCULATIONS WERE NOT CARRIED OUT BEFORE PAMELA OBSERVATIONS!!!!