THE THEORY OF PULSAR WIND NEBULAE: RECENT PROGRESS

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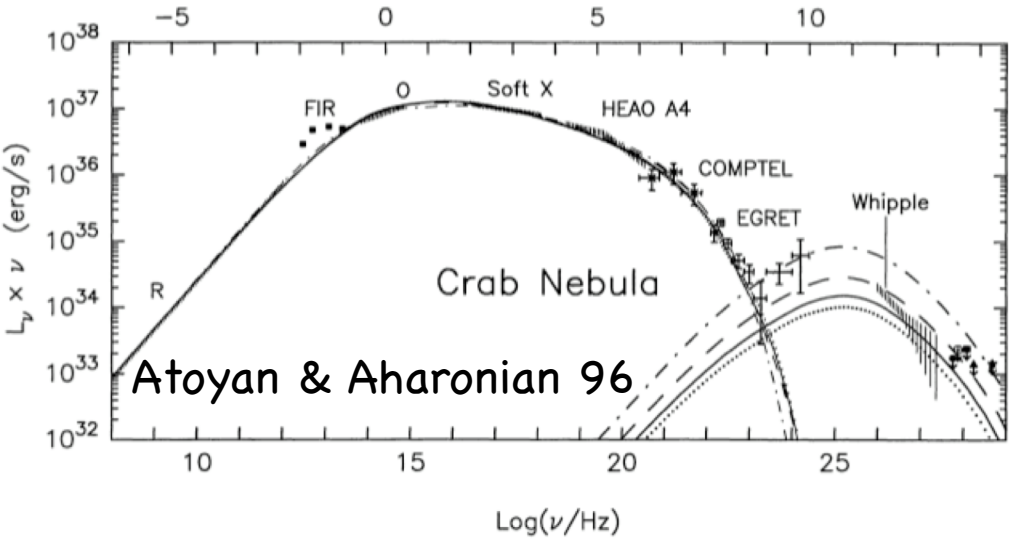
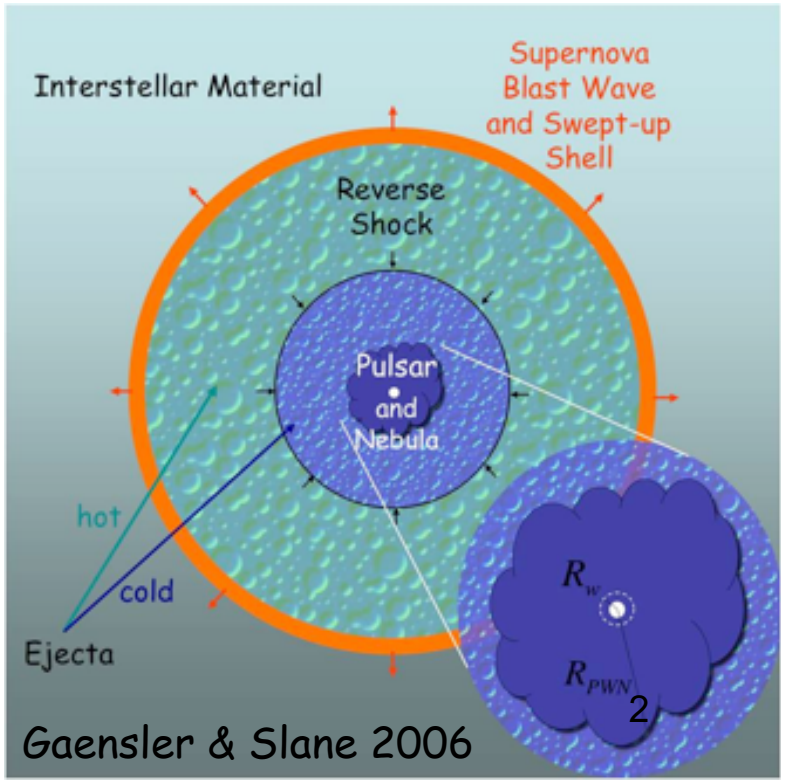
PULSAR WIND NEBULAE

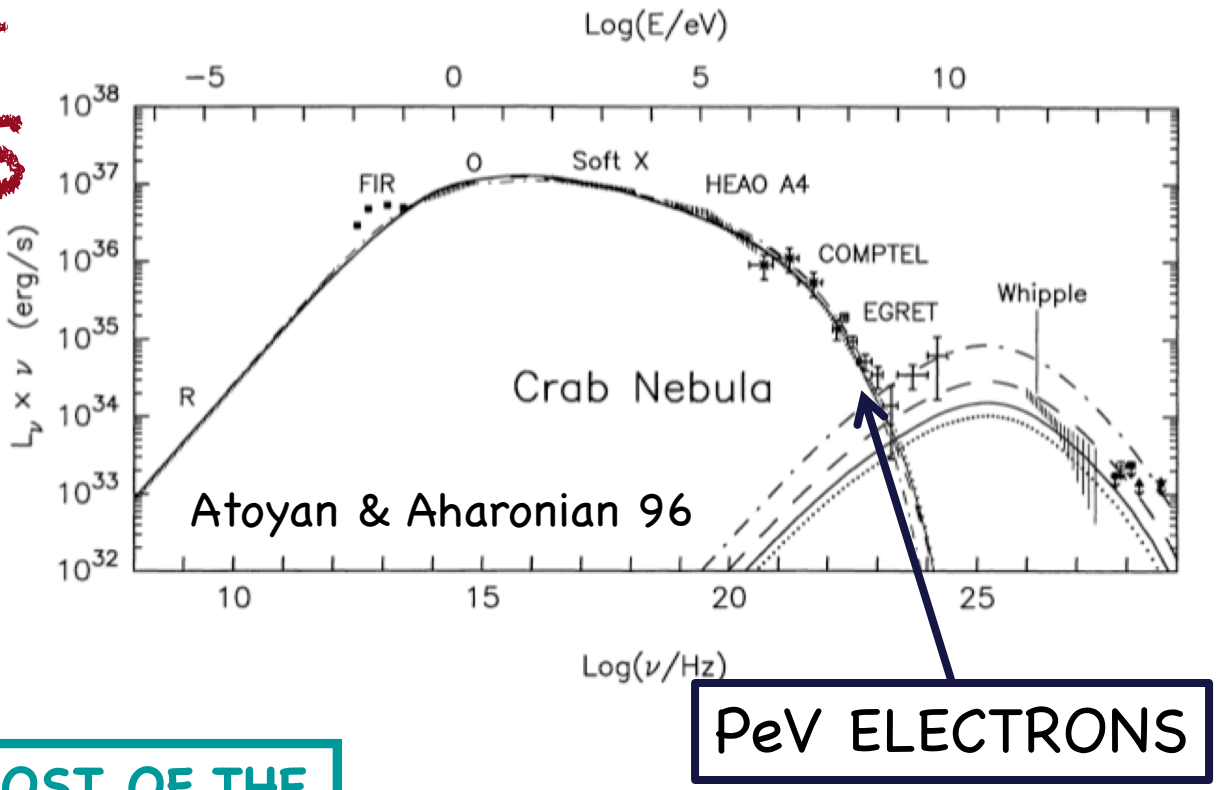
SYNCHROTRON AND ICS RADIATION BY **RELATIVISTIC PARTICLES** IN ***INTENSE*** (>few x 100 B_{ISM}) ***ORDERED*** (HIGH POLARIZATION, IN RADIO, OPTICAL AND EVEN γ-RAYS, Dean et al 08) **MAGNETIC FIELD**





EMITTING PARTICLES

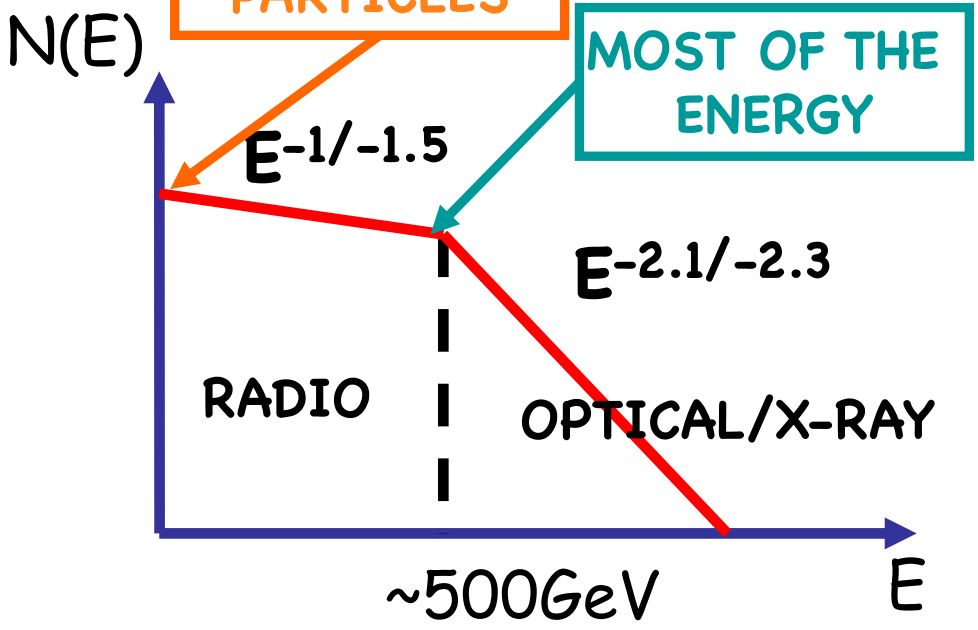
ALREADY FROM 1-ZONE MODELS
(e.g. Pacini & Salvati 74, EA+ 00)



PeV ELECTRONS

MOST OF THE PARTICLES

MOST OF THE ENERGY



B≈100 μG

$L_{CRAB} \approx 30\%\ L_{PSR}$

GREAT ACCELERATOR!!!

MAIN OPEN QUESTIONS

WE KNOW THAT:

- MOST EFFICIENT ACCELERATORS IN NATURE
- ACCELERATION IN THE MOST HOSTILE ENVIRONMENT
- MAIN ANTIMATTER REPOSITORIES IN THE GALAXY
- ENERGY FLUX THAT LEAVES THE PSR

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

WE DO NOT KNOW:

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

IN PRINCIPLE BOTH DEPEND ON WHERE PARTICLE ACCELERATION EXACTLY OCCURS

POSSIBILITIES DEPEND ON:

- COMPOSITION (IONS? MULT.?)
- MAGNETIZATION($\sigma = B^2/4\pi n \Gamma mc^2$)

- HOW PARTICLES ESCAPE

ACCELERATION MECHANISMS

FERMI MECHANISM

MAGNETIZATION

DRIVEN MAGNETIC RECONNECTION

PULSAR MULTIPLICITY AND MAGNETIZATION

RESONANT CYCLOTRON ABSORPTION

PRESENCE OF IONS AND PULSAR MULTIPLICITY

MAGNETIZATION

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

PAIRS

IONS

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

OTHER RECENT PROPOSALS

- **SHOCK CORRUGATION** (Lemoine 17)
  - CURRENTLY FORMULATED TOGETHER WITH B DISSIPATION
  - INTERESTING SCENARIO FOR SPEEDING UP FERMI PROCESS

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

QUANTITATIVELY...

FERMI MECHANISM

- EFFICIENT AT UNMAGNETIZED e^--e^+ RELATIVISTIC SHOCKS
- RIGHT SPECTRUM FOR X-RAYS
- **NO ACCELERATION AT (σ>0.001) SUPERLUMINAL SHOCKS** (Spitkovsky 08, Sironi & Spitkovsky 09, 11)
- **TOO SLOW TO GUARANTEE MAXIMUM ENERGY OBSERVED IN CRAB** (e.g. Pelletier+ 17)

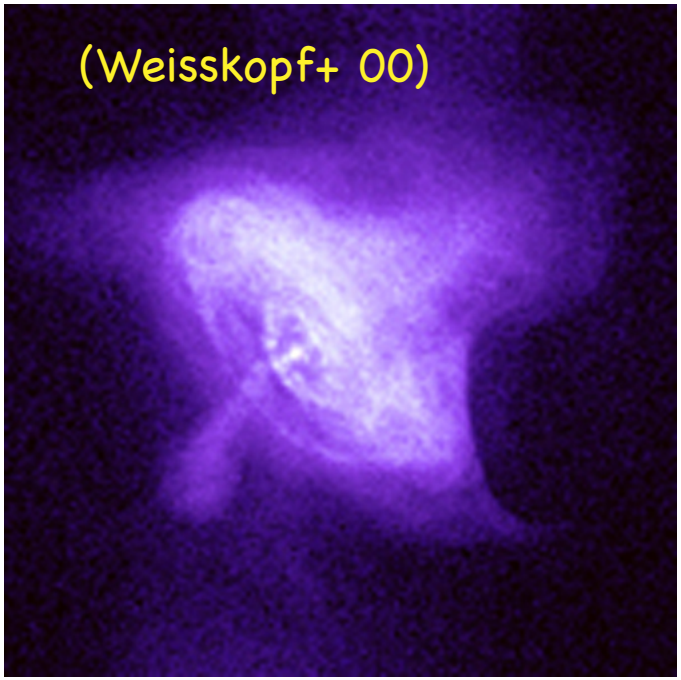
DRIVEN MAGNETIC RECONNECTION:

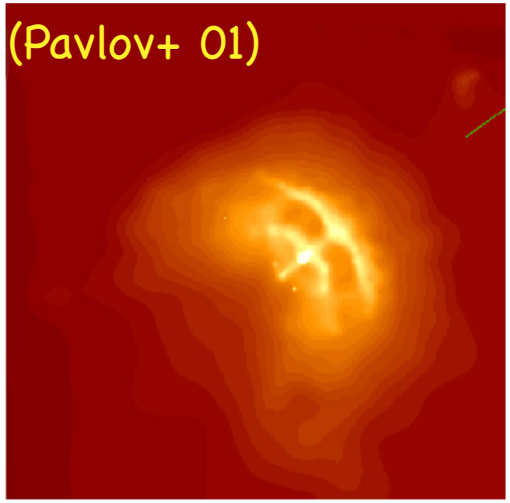
- **BROAD PARTICLE SPECTRA WITH α=-1.5 IF $\sigma\geq$30 AND κ>10^7** (Sironi & Spitkovsky 11)
- **FOR THIS LARGE K WIND LIKELY TO DISSIPATE BEFORE SHOCK FRONT** (Kirk & Skjeraasen 03)

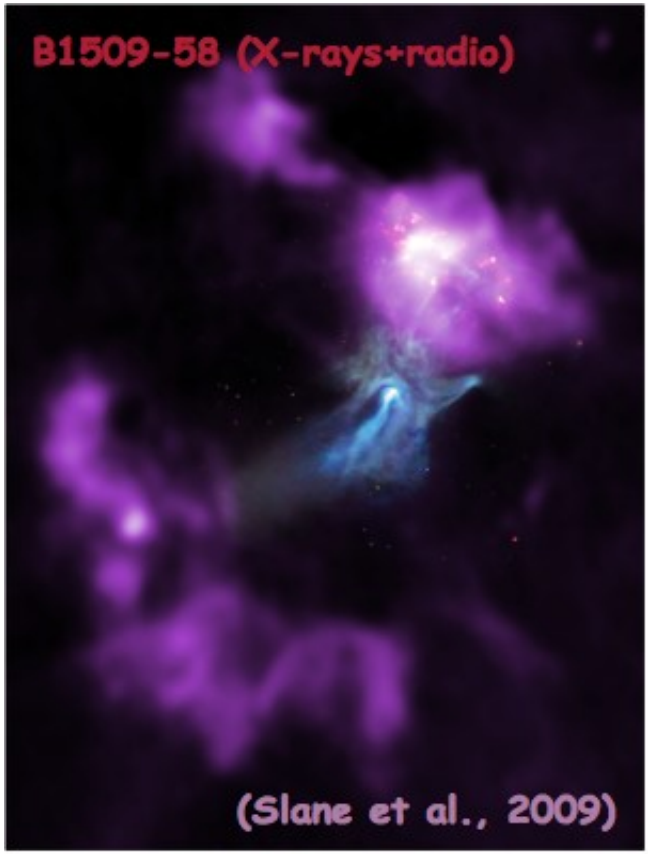
RESONANT CYCLOTRON ABSORPTION:

- SPECTRA AND ACCELERATION EFFICIENCY DEPEND ON THE FRACTION OF ENERGY CARRIED BY IONS: U_i/U_{TOT}=0.8, α=-1.5, ε_{ACC}=0.3, U_i/U_{TOT}=0.6, α=-3, ε_{ACC}=0.03 (EA & Arons 06, Stockem+12)
- **NO ACCELERATION IF k>m_i/m_e**

CONSTRAINING THE WIND MAGNETIZATION AT THE SHOCK





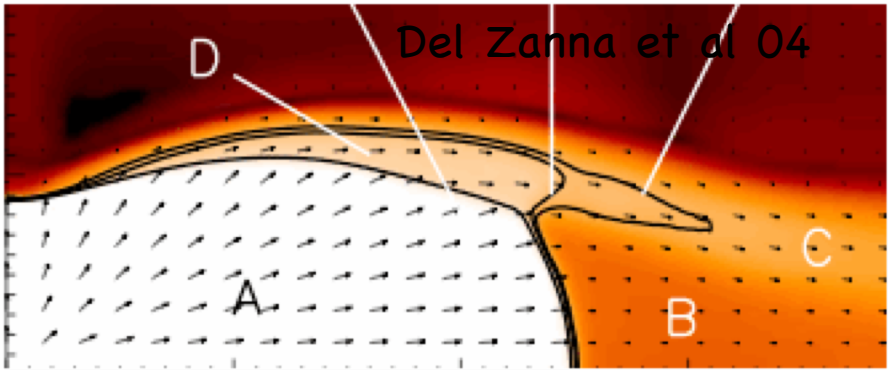


$F \propto \sin^2(\theta)$ $B_\phi \propto \sin(\theta)\, g(\theta)$

Lyubarsky 02, Bogovalov & Khangoulian 02

ANALYTIC SPLIT MONOPOLE SOLUTIONS (Michel 73; Bogovalov 99)
CONFIRMED BY NUMERICAL STUDIES IN THE
FORCE FREE (Contopoulos et al 99, Gruzinov 04, Spitkovsky 06)
AND **RMHD** REGIME (Bogovalov 01, Komissarov 06, Bucciantini+ 06)

JETS AND TORI



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

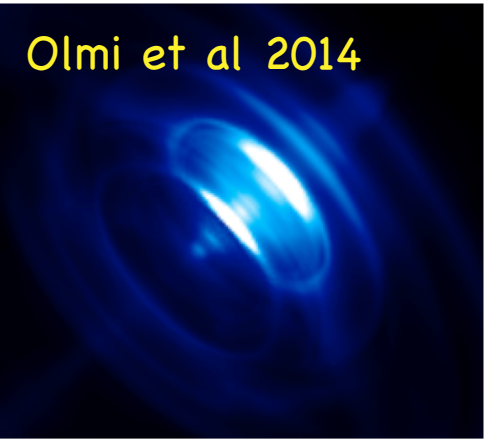
2D RMHD SIMULATIONS

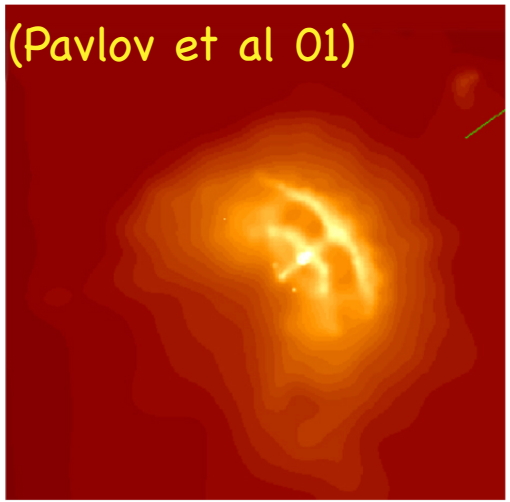
$F \propto \sin^2(\theta)$ $B_\phi \propto \sin(\theta) G(\theta)$

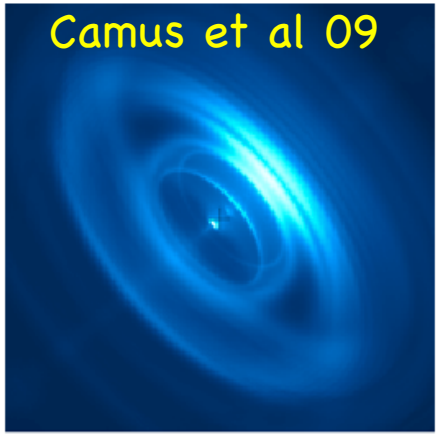
Komissarov & Lyubarsky 03, 04
Del Zanna+ 04, 06
Bogovalov+ 05
Camus+ 09
Volpi+ 08, Olmi+ 14

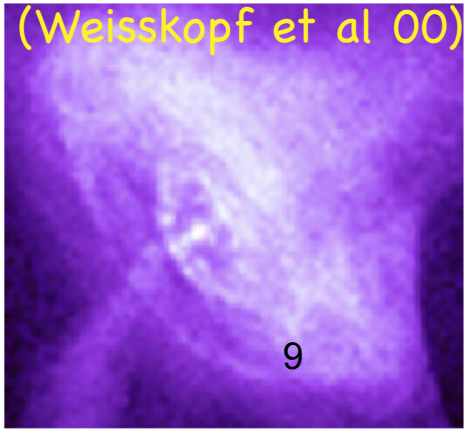
E_{max} IS EVOLVED WITH THE FLOW

$f(E) \propto E^{-\alpha}$, $E < E_{max}$ (Del Zanna+ 06)







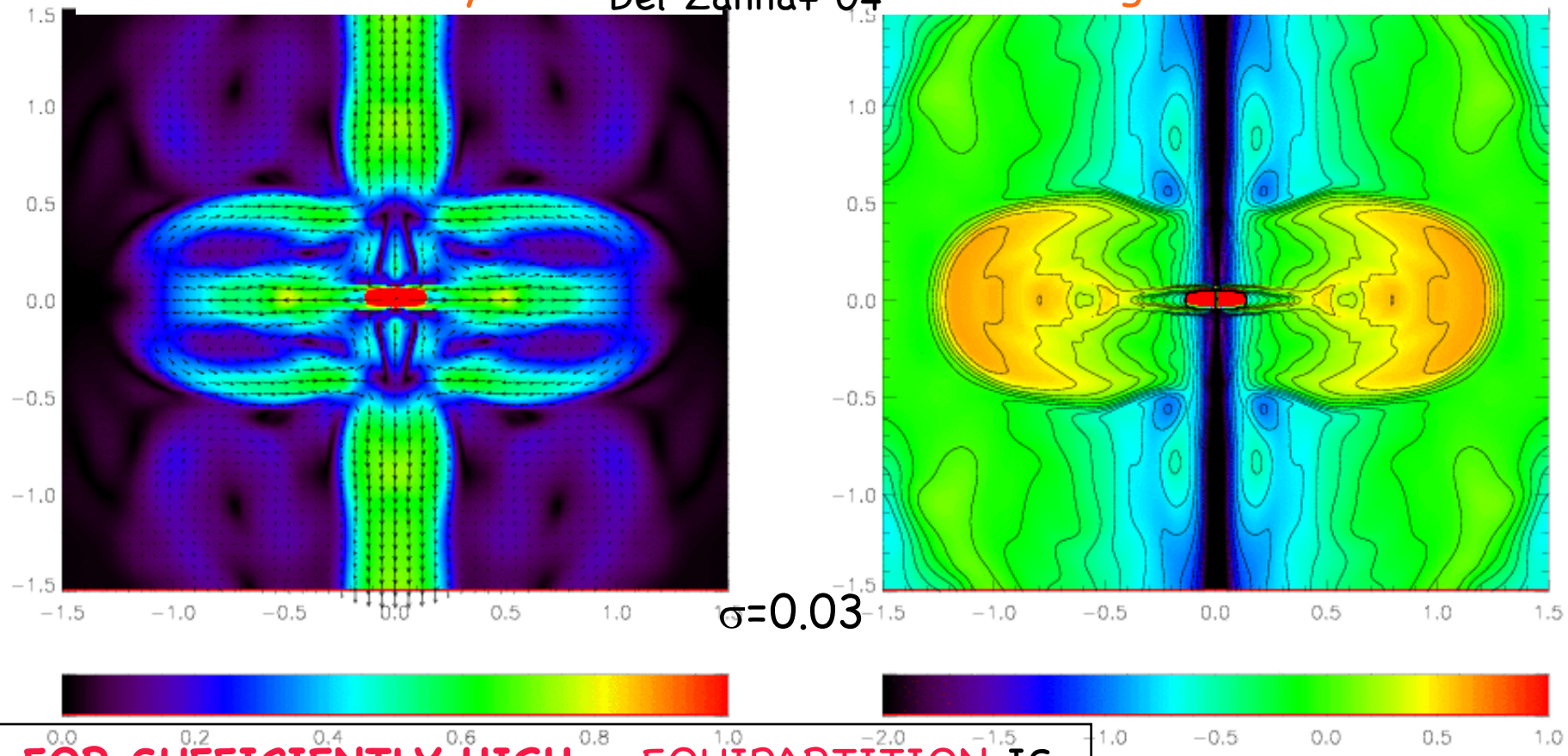


THE PHYSICS BEHIND THEM

Velocity

Del Zanna+ 04

Magnetization

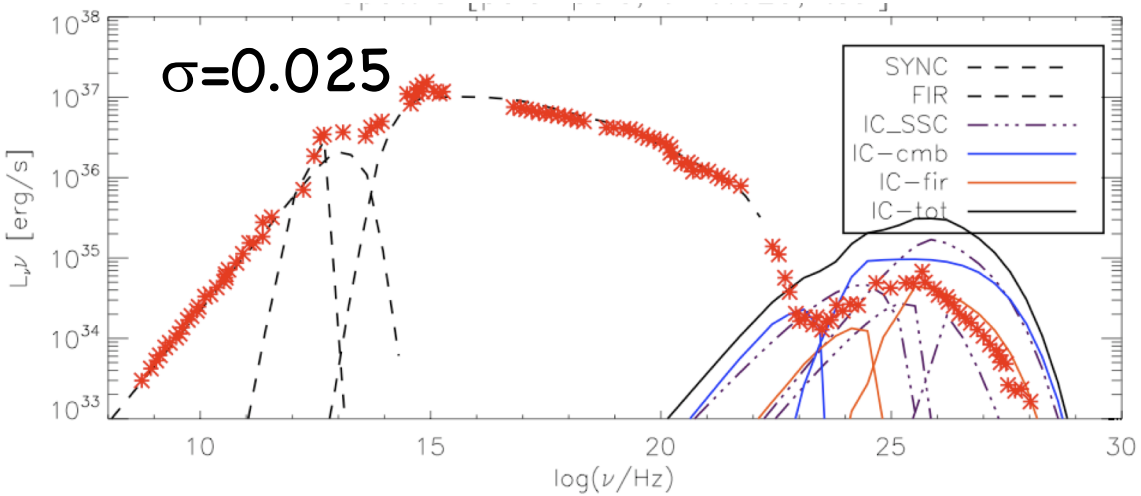


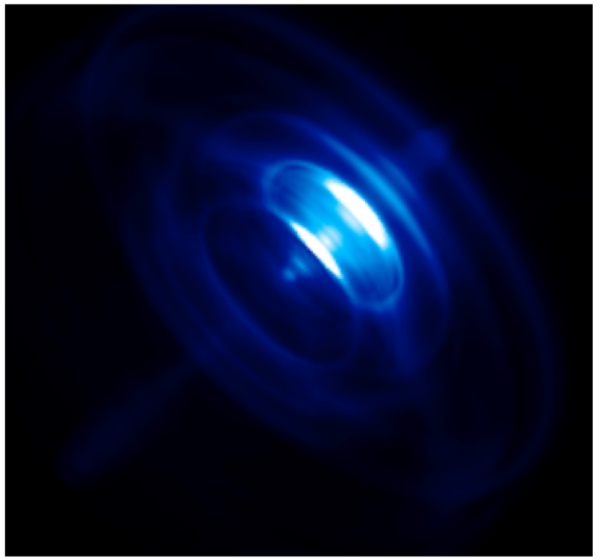
σ=0.03

- **FOR SUFFICIENTLY HIGH σ, EQUIPARTITION** IS REACHED IN EQUATORIAL REGION
- EQUATORIAL FLOW IS DIVERTED TOWARDS HIGHER LATITUDES
- A FAST CHANNEL THEN FORMS ALONG THE AXIS

JET REQUIRES σ>0.03

WHAT σ?

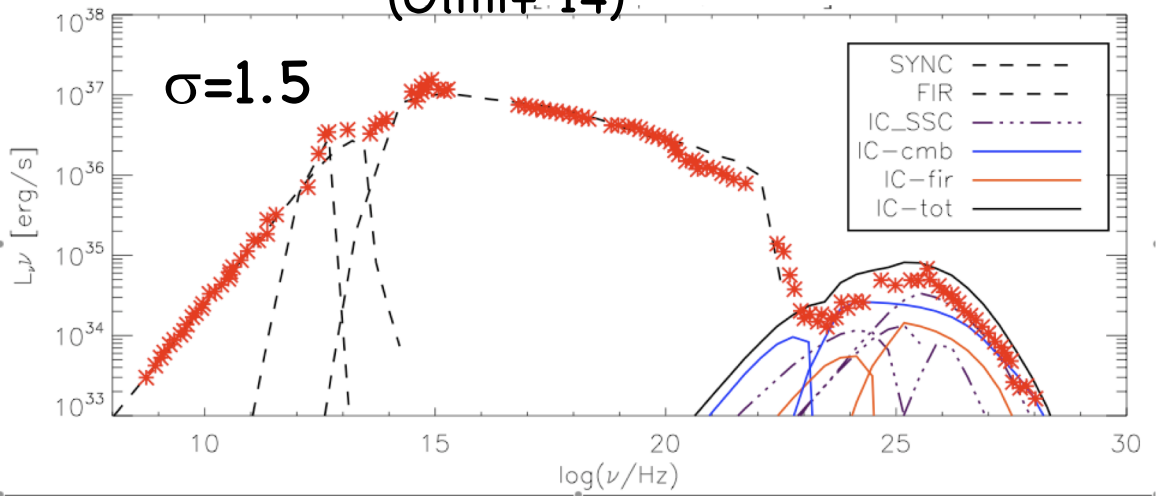


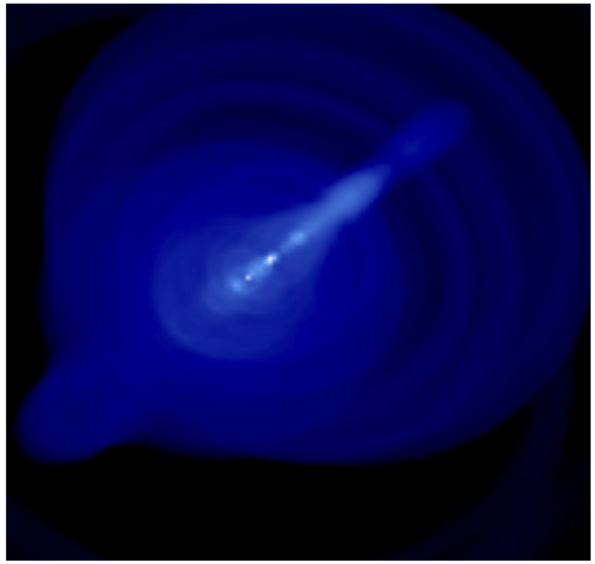


LOW σ LEADS TO LOWER B FIELD THAN REQUIRED TO FIT INTEGRATED SPECTRUM

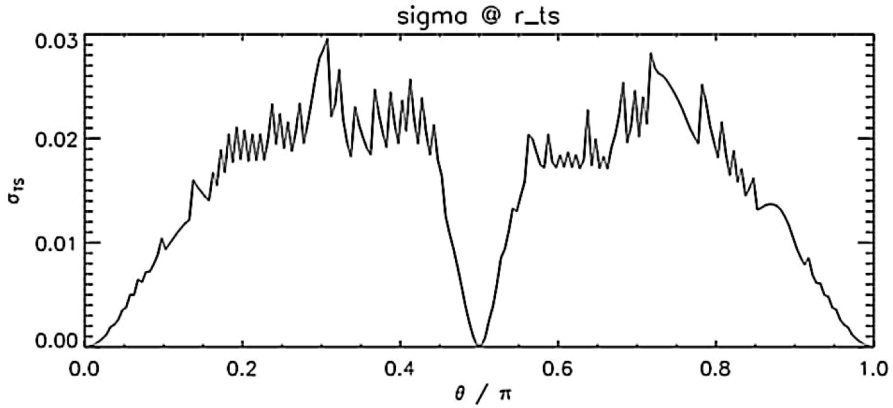
(Volpi+ 08, Olmi+ 14,
Atoyan & Aharonian 96, de Jager & Harding 92)

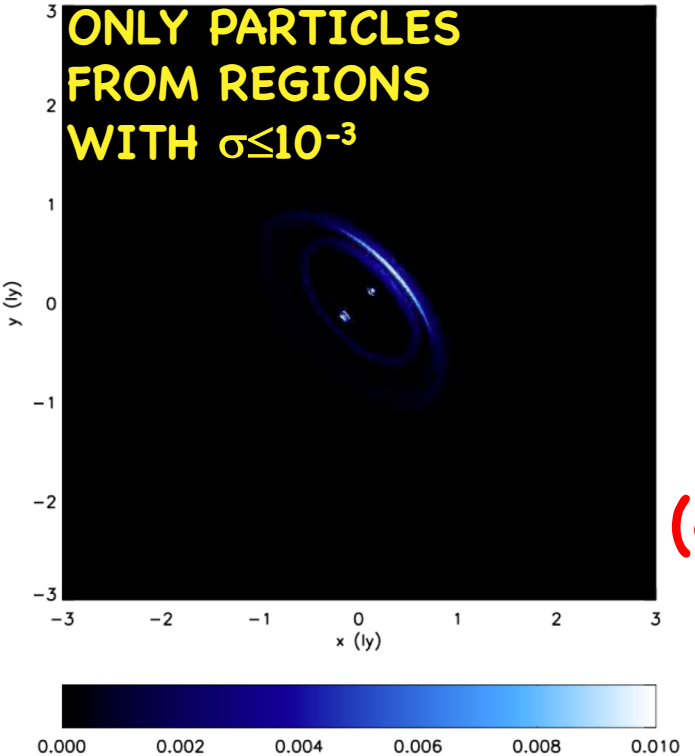
(Olmi+ 14)



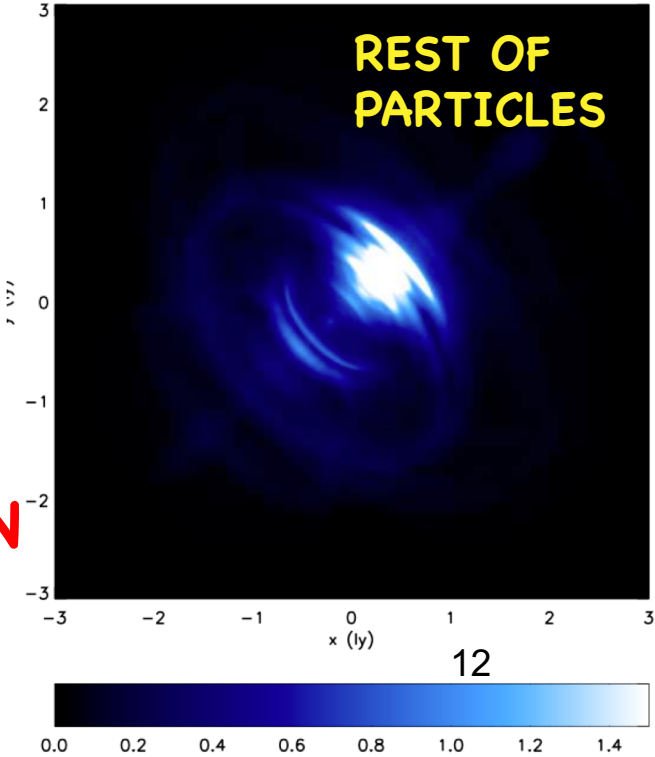


DIFFUSIVE SHOCK ACCELERATION





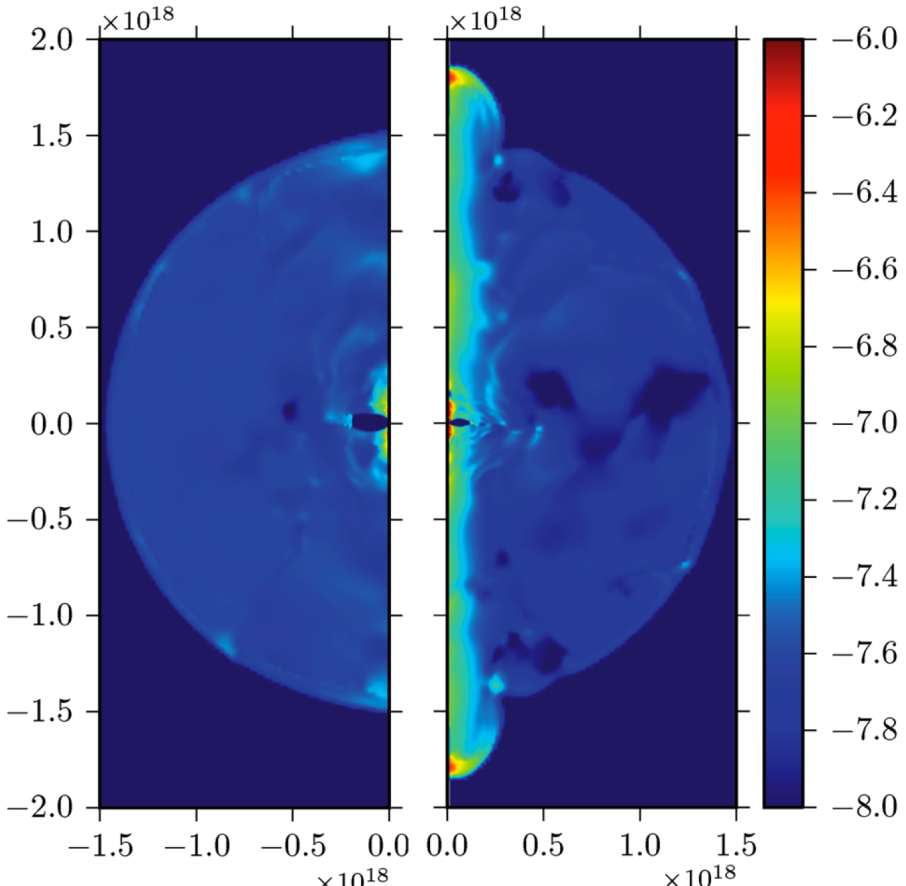
TOO SMALL A FRACTION OF THE FLOW SATISFIES LOW MAGNETIZATION ($\sigma < 10^{-3}$) CONDITION

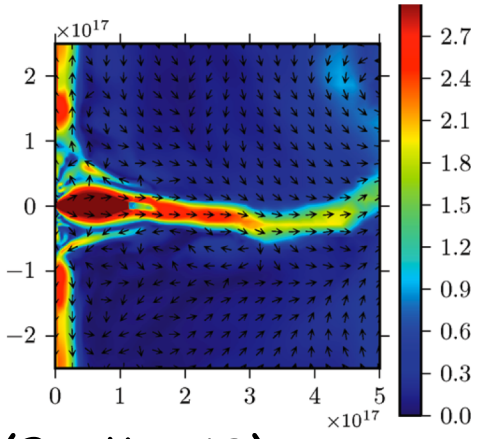


3D RMHD SIMULATIONS

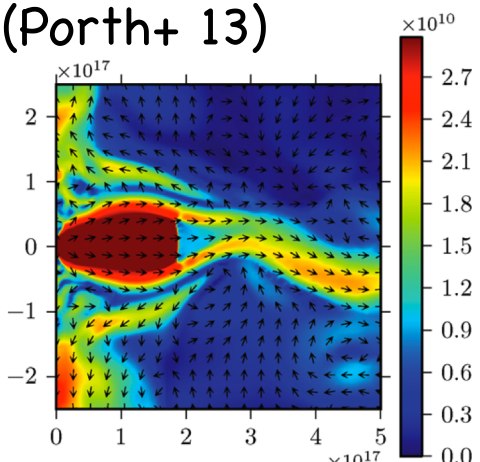
DIMENSIONALITY OF SIMULATIONS:

- IN 3D SAME σ LOOKS VERY DIFFERENT!
- KINKS MAY MESS UP THE FIELD IN THE PWN WITH RELATIVELY LOW DISSIPATION (Begelman 98)



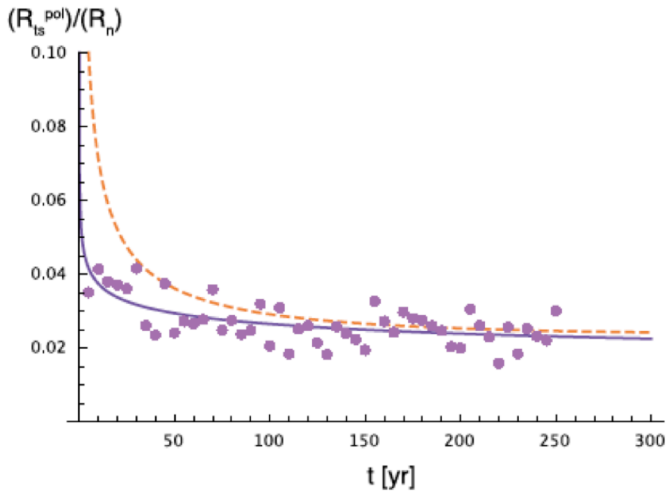


(Porth+ 13)



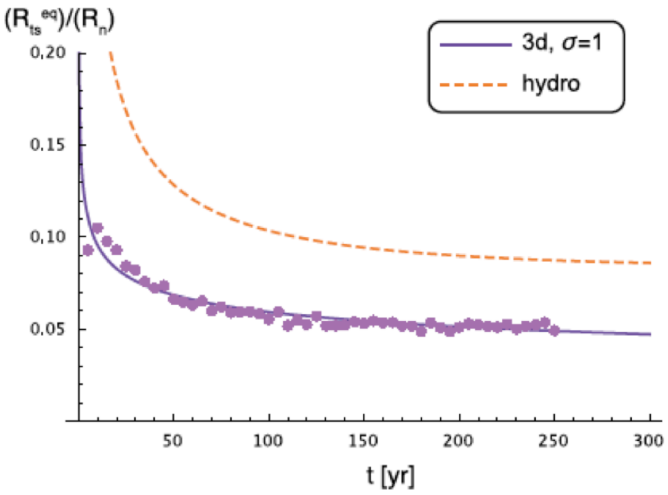
REPRODUCE SPECTRUM AND MORPHOLOGY WITH HIGH σ ?

LONGER 3D RMHD SIMULATIONS

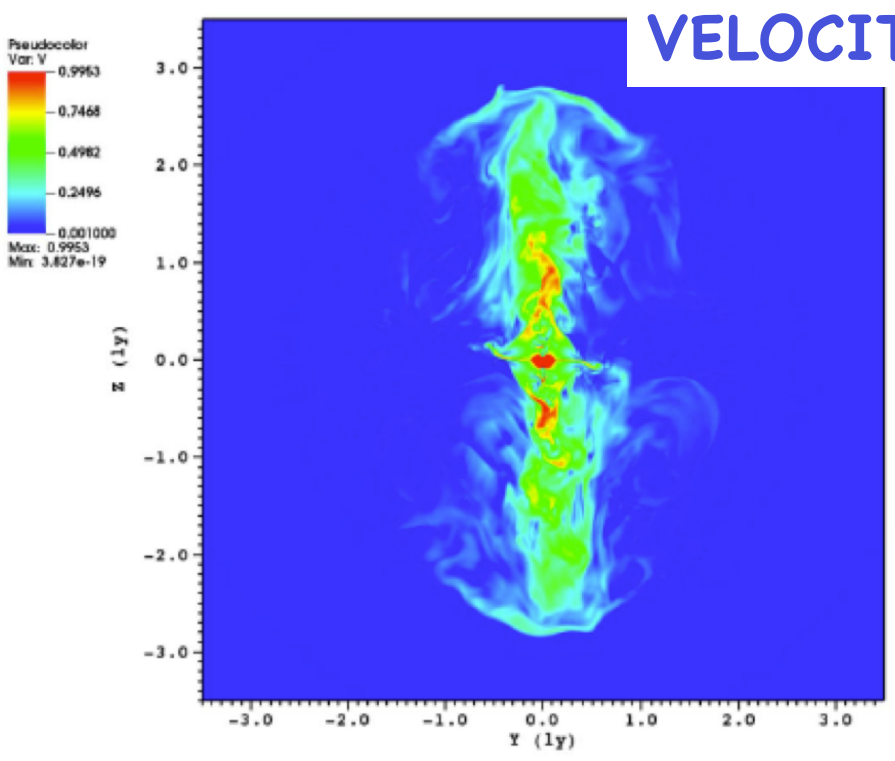


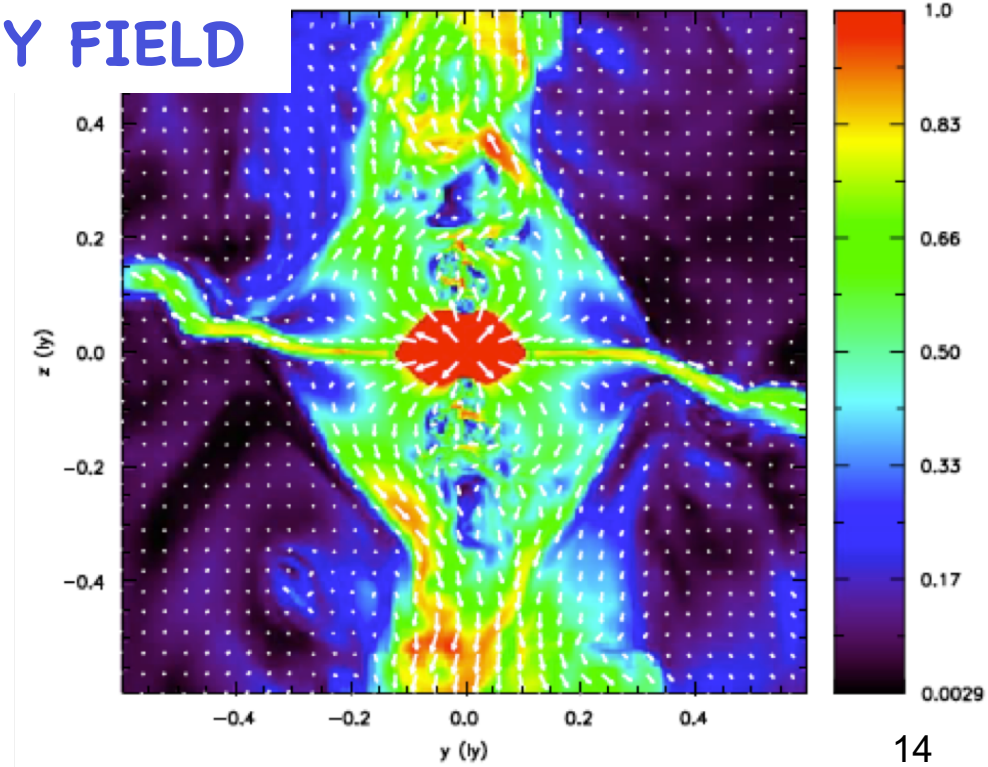
T=500 YR

SELF-SIMILAR PHASE FULLY REACHED (Olmi+ 16)



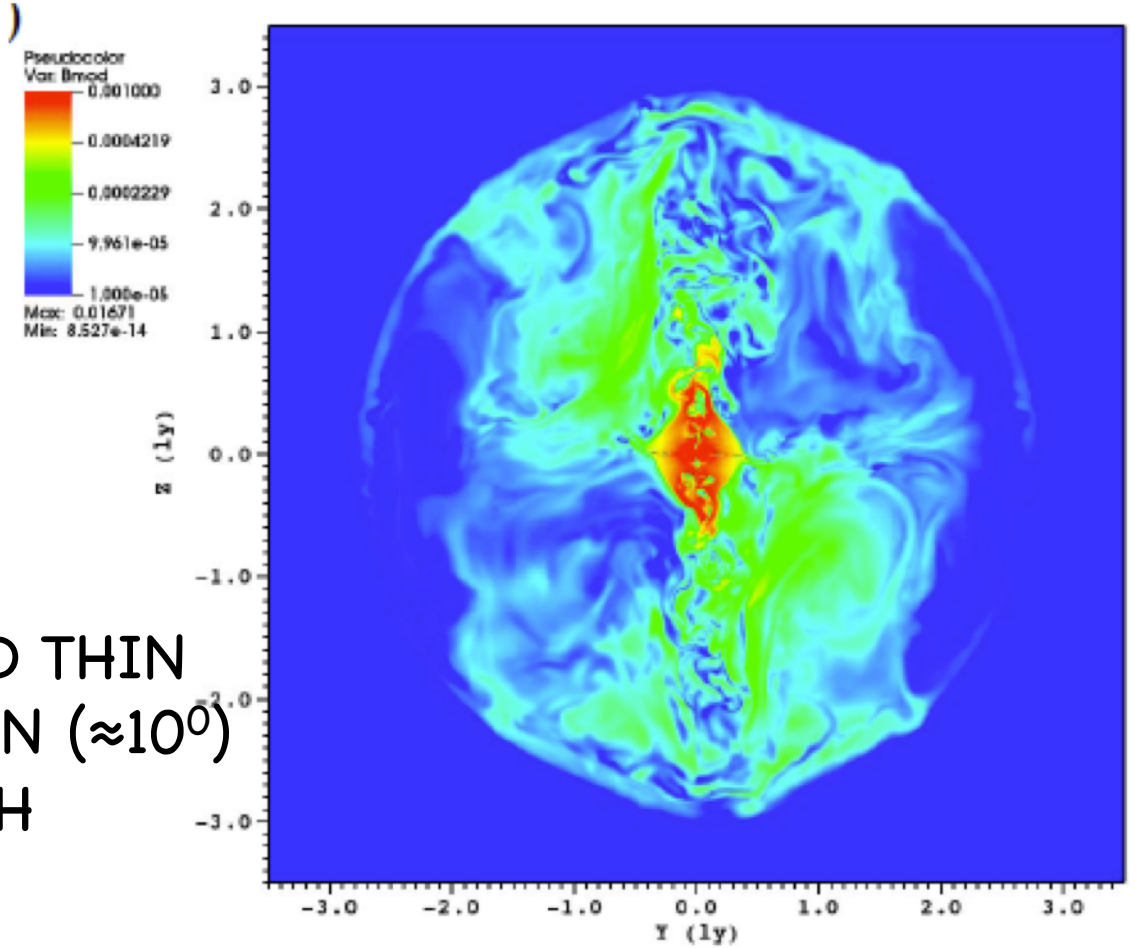
VELOCITY FIELD



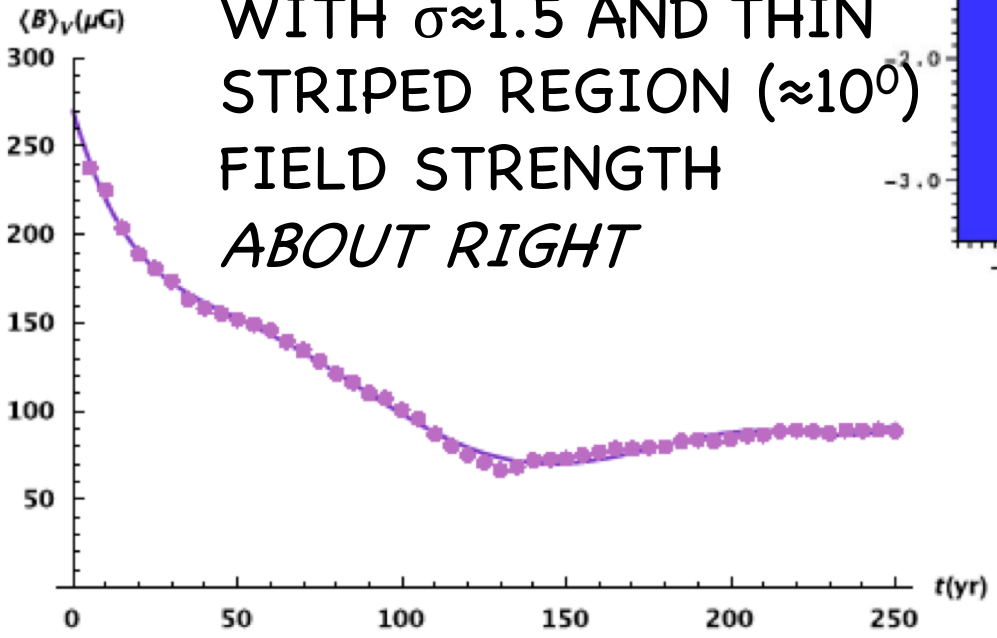


MAGNETIC FIELD STRENGTH

AFTER INITIAL DECREASE
(Porth+ 13,14)
FIELD STRENGTH APPROACHES CONSTANT
(Olmi+ 16)

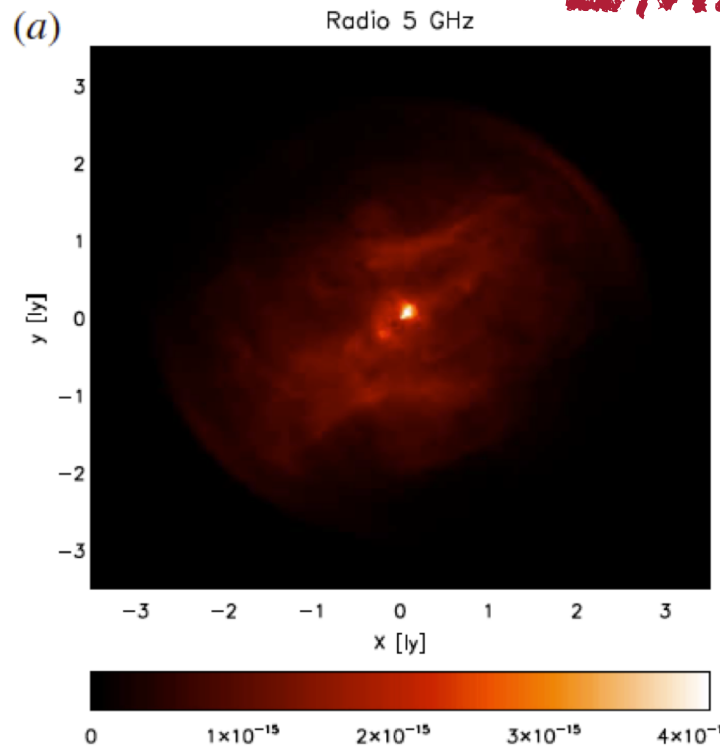


WITH $\sigma \approx 1.5$ AND THIN STRIPED REGION ($\approx 10^0$)
FIELD STRENGTH
ABOUT RIGHT



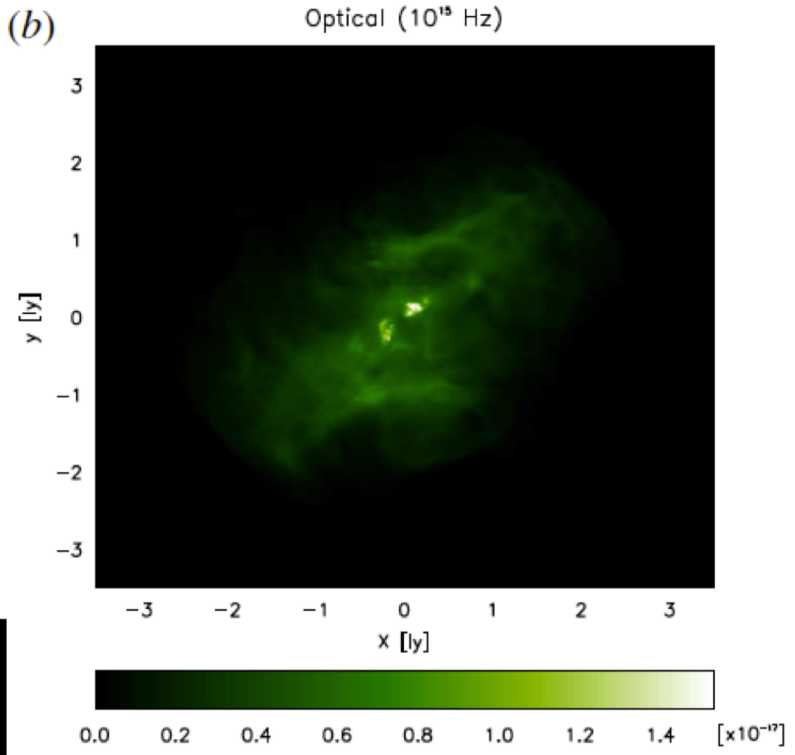
$B(R_{TS}) \approx 1$ mG

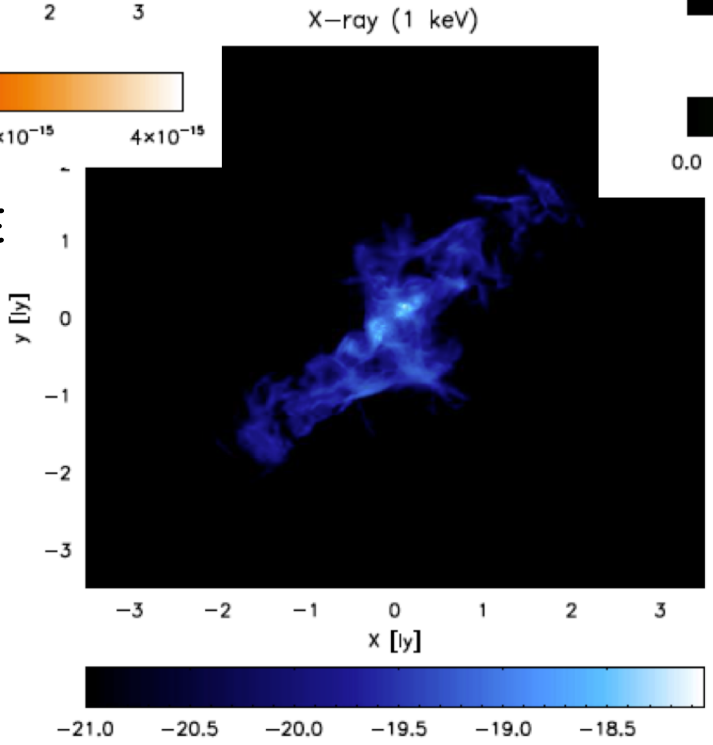
EMISSION MAPS



σ≈1.5
T ≈500 yr

Olmi+ 16



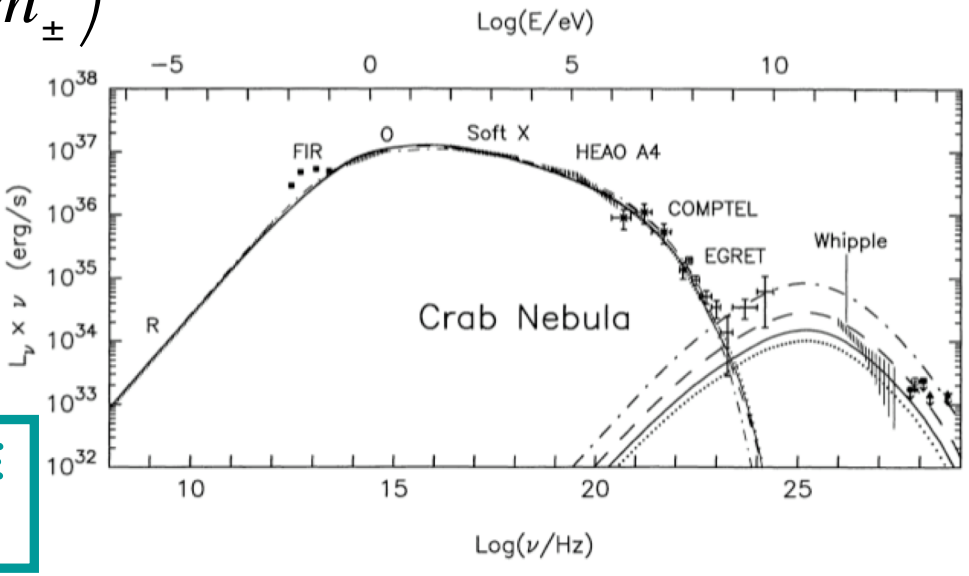


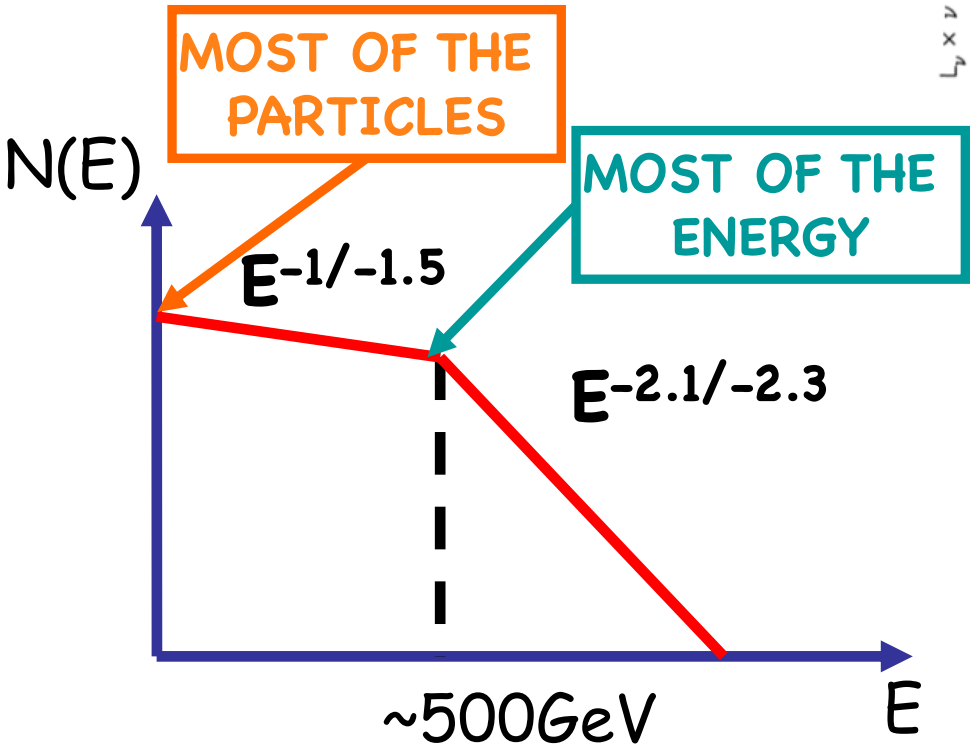
- SIZE SHRINKAGE IN EQUATORIAL PLANE
- LACK OF SHRINKAGE ALONG THE POLAR AXIS

WIND AT THE SHOCK EVEN MORE MAGNETIZED THAN FROM 2D STUDIES

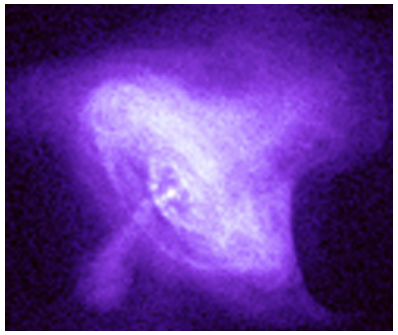
WIND LORENTZ FACTOR & PULSAR MULTIPLICITY

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





X-RAYS VS RADIO EMISSION



$\Gamma \sim 3 \times 10^6$ $k \sim 10^4$
FROM OPTICAL/X-RAY EMISSION
(e.g. Kennel & Coroniti 84)

$\alpha \sim 2.2$
JUST RIGHT FOR FERMI I

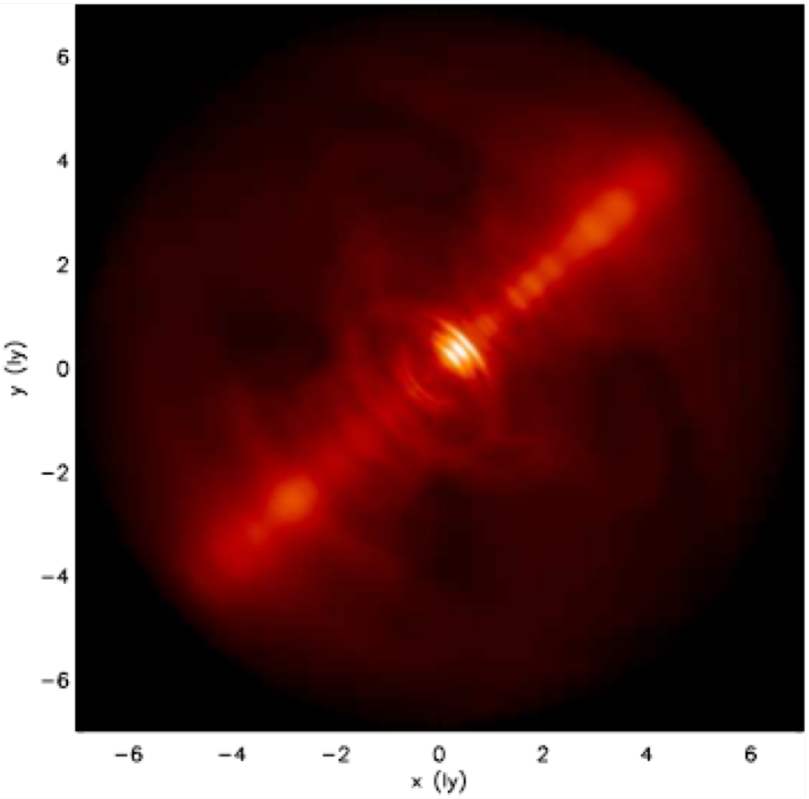
NOTE: A GJ DENSITY OF IONS, IF PRESENT, WOULD DOMINATE THE WIND ENERGY FLOW.
PeV IONS

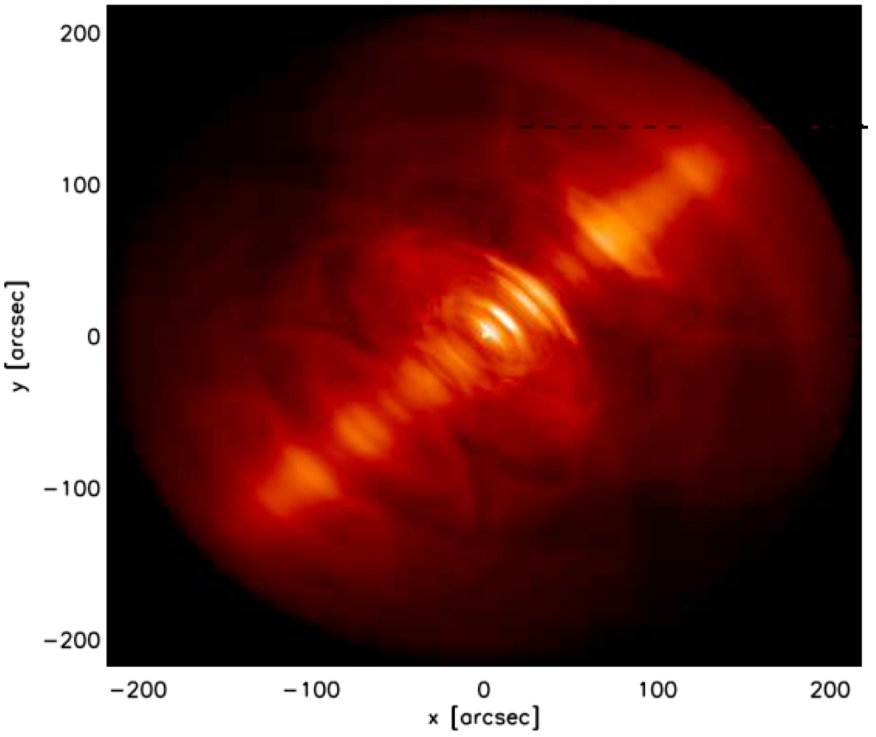
$\Gamma \sim 10^4$ $k \sim 10^6$
FROM RADIO EMISSION
(e.g. Bucciantini, Arons, EA, 12)
unless fossile (Atoyan 99)
or accelerated eslewhere

$\alpha \sim 1.5$
DRIVEN MAGNETIC RECONNECTION?

NOTE: NO WAY FOR IONS TO BE ENERGETICALLY IMPORTANT EVEN IF THEY WERE THERE

RADIO EMISSION MORPHOLOGY





SHOCK ACCELERATION
+
ADVECTION

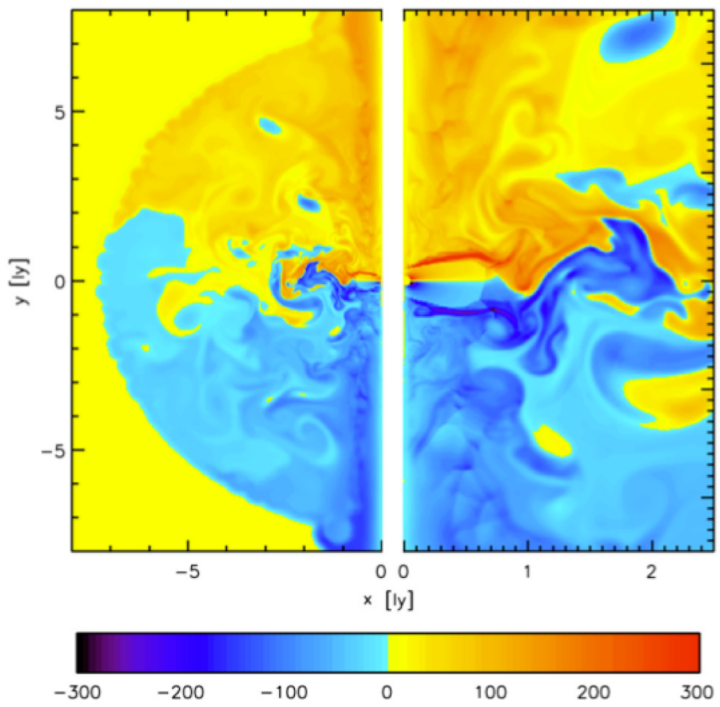
UNIFORM
INJECTION

VERY SIMILAR MAP

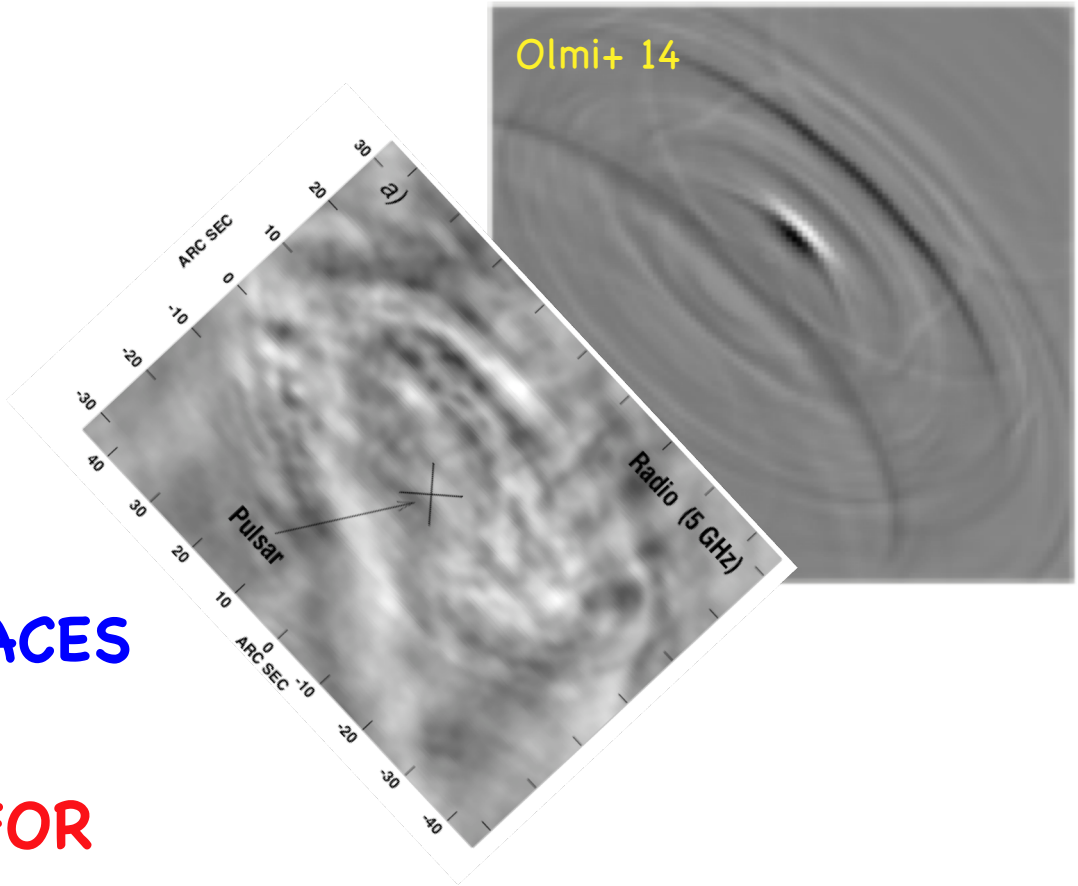
Olmi et al 14

RADIO WISPS

MAGNETIC FIELD



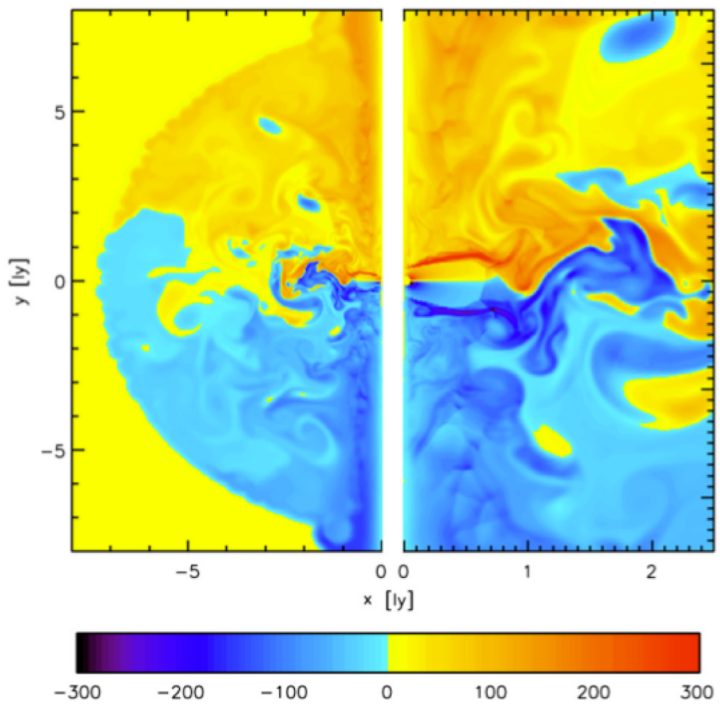
DIFFERENCE BETWEEN IMAGES AT DIFFERENT TIMES



- RADIO EMISSION TRACES MAGNETIC FIELD
- RADIO WISPS EVEN FOR UNIFORM PARTICLE DISTRIBUTION

RADIO WISPS

MAGNETIC FIELD



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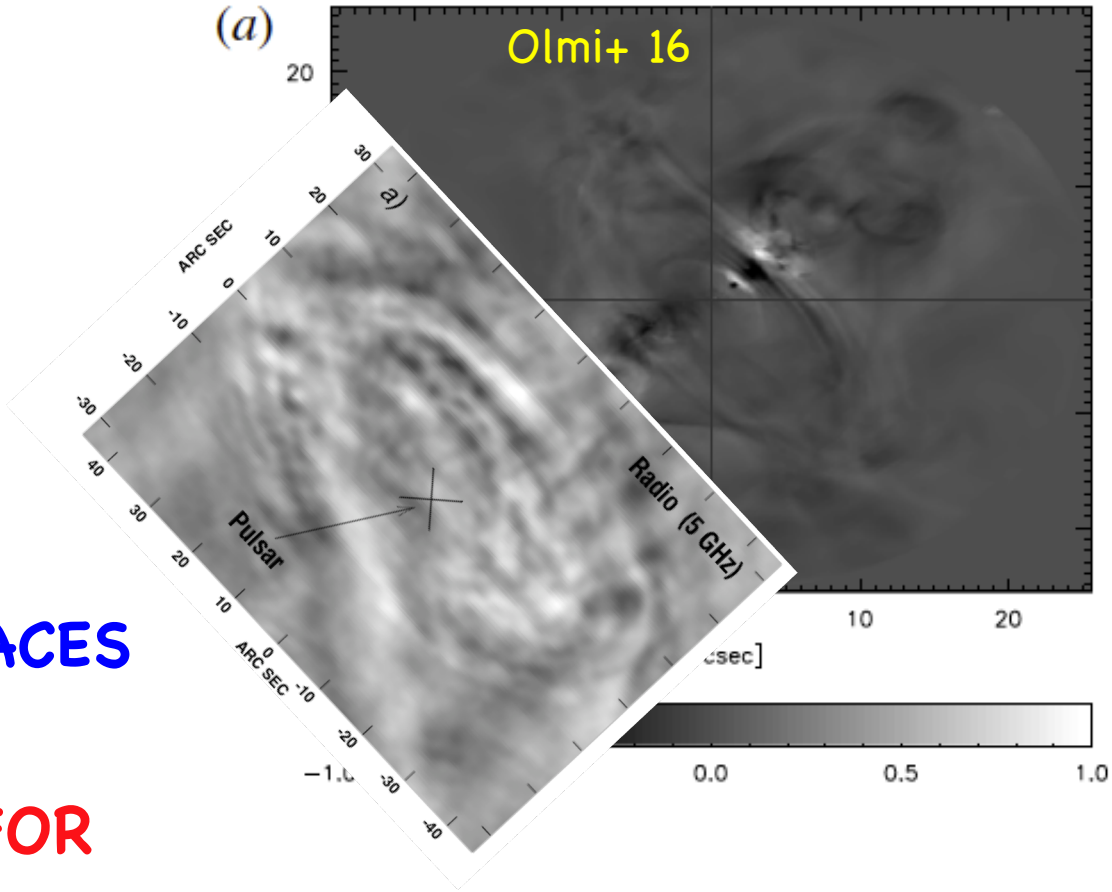
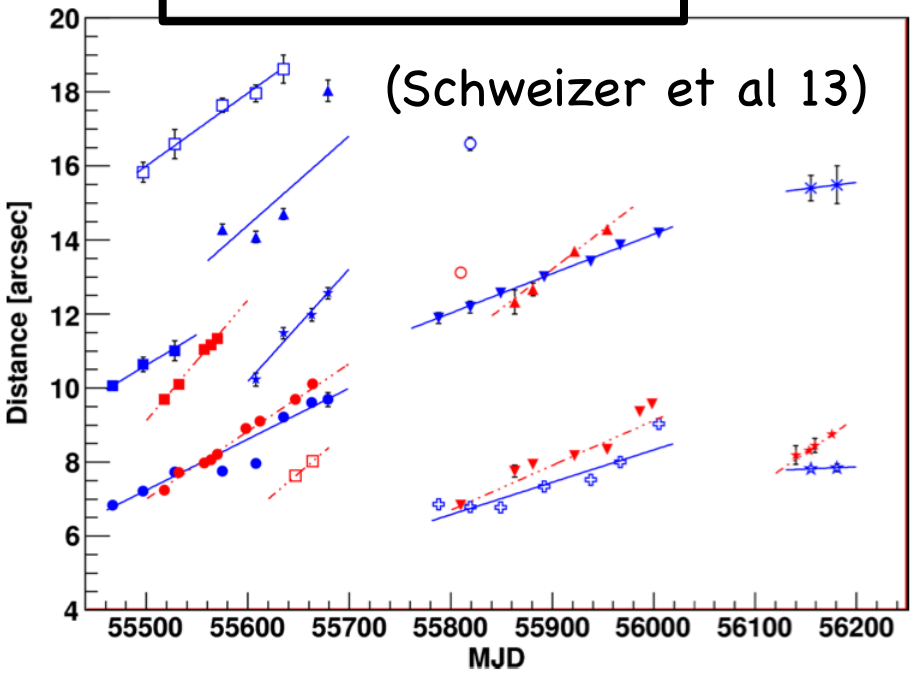


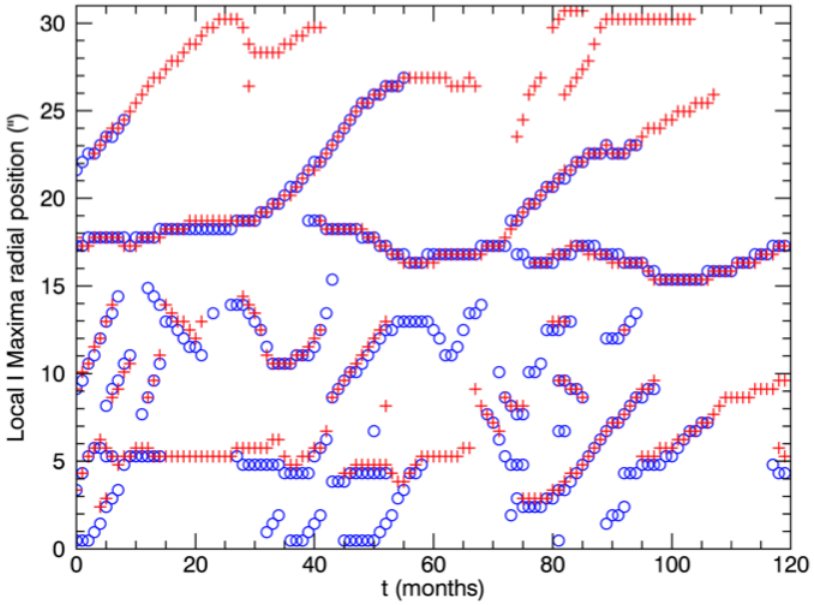
- RADIO EMISSION TRACES MAGNETIC FIELD
- RADIO WISPS EVEN FOR UNIFORM PARTICLE DISTRIBUTION

WISPS AT MULTIWAVELENGTHS

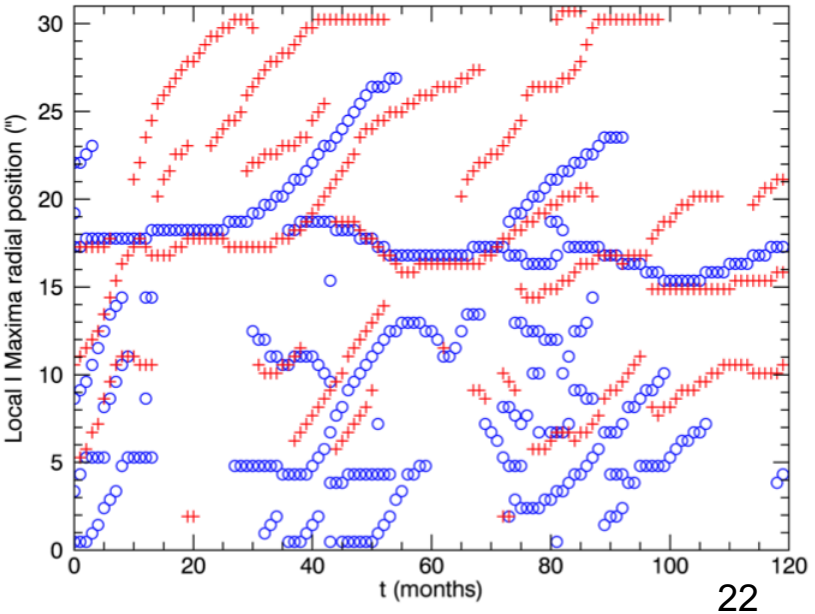
ISOTROPIC ACCELERATION

OBSERVATIONS





Olmi + 15

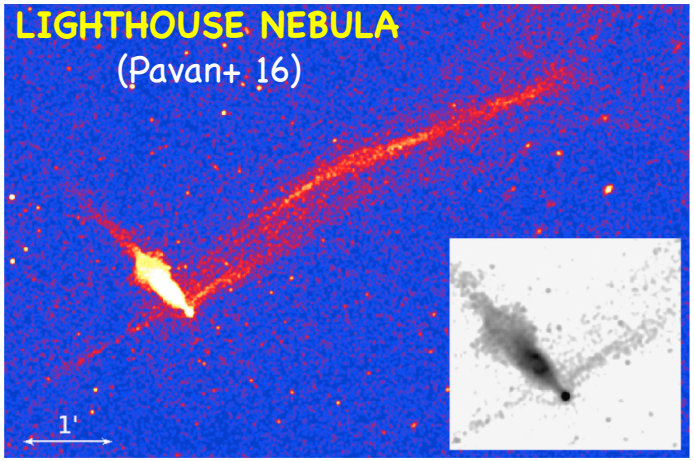


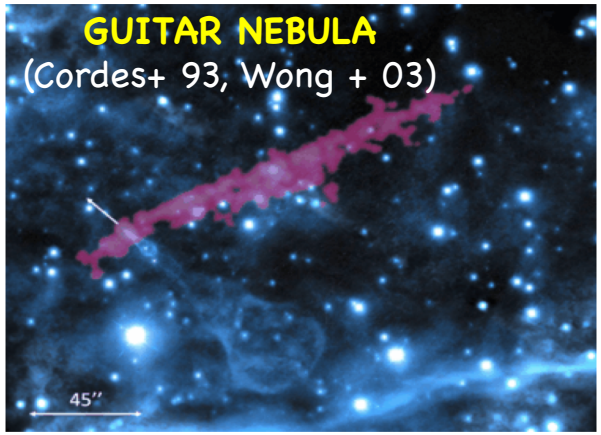
EQUATORIAL X, LOWER EN. ELSEWHERE: BEHAVIOUR AND VELOCITY OK!

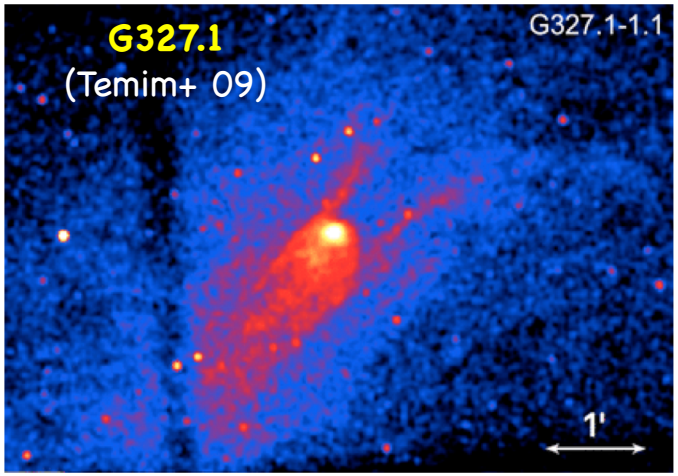
SUMMARY

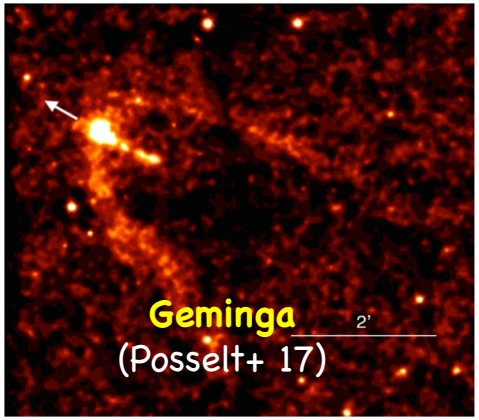
- 3D MHD SIMULATIONS SEEM TO REQUIRE σ>FEW IN ORDER TO REPRODUCE SPECTRUM AND MORPHOLOGY
- FERMI MECHANISM VERY PROBLEMATIC: NOT ONLY HIGH σ BUT ALSO SLOW PROCESS THOUGH LARGE SCALE PERTURBATIONS OF THE SHOCK FRONT (e.g. Lemoine 16) MIGHT SPEED THINGS UP
- DRIVEN MAGNETIC RECONNECTION DIFFICULT TO MAKE SELF-CONSISTENT + IT DISSIPATES B
- WISPS CONSISTENT WITH EQUATORIAL X AND ANY RADIO
- RADIO PARTICLES DO NOT NEED TO BE PART OF THE FLOW
  - MORE COMFORTABLE k FOR PSR THEORIES (e.g. Timokhin & Harding 19)
- MULTIPLICITY CAN BE SMALL ENOUGH FOR ION CYCLOTRON TO WORK: GOOD NEWS ALSO FOR UHECRs

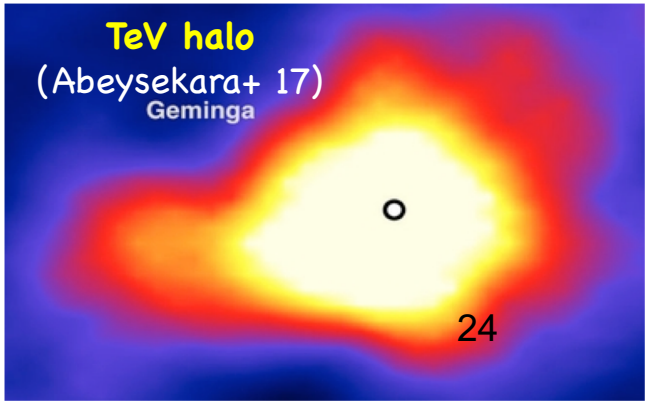
PARTICLE ESCAPE



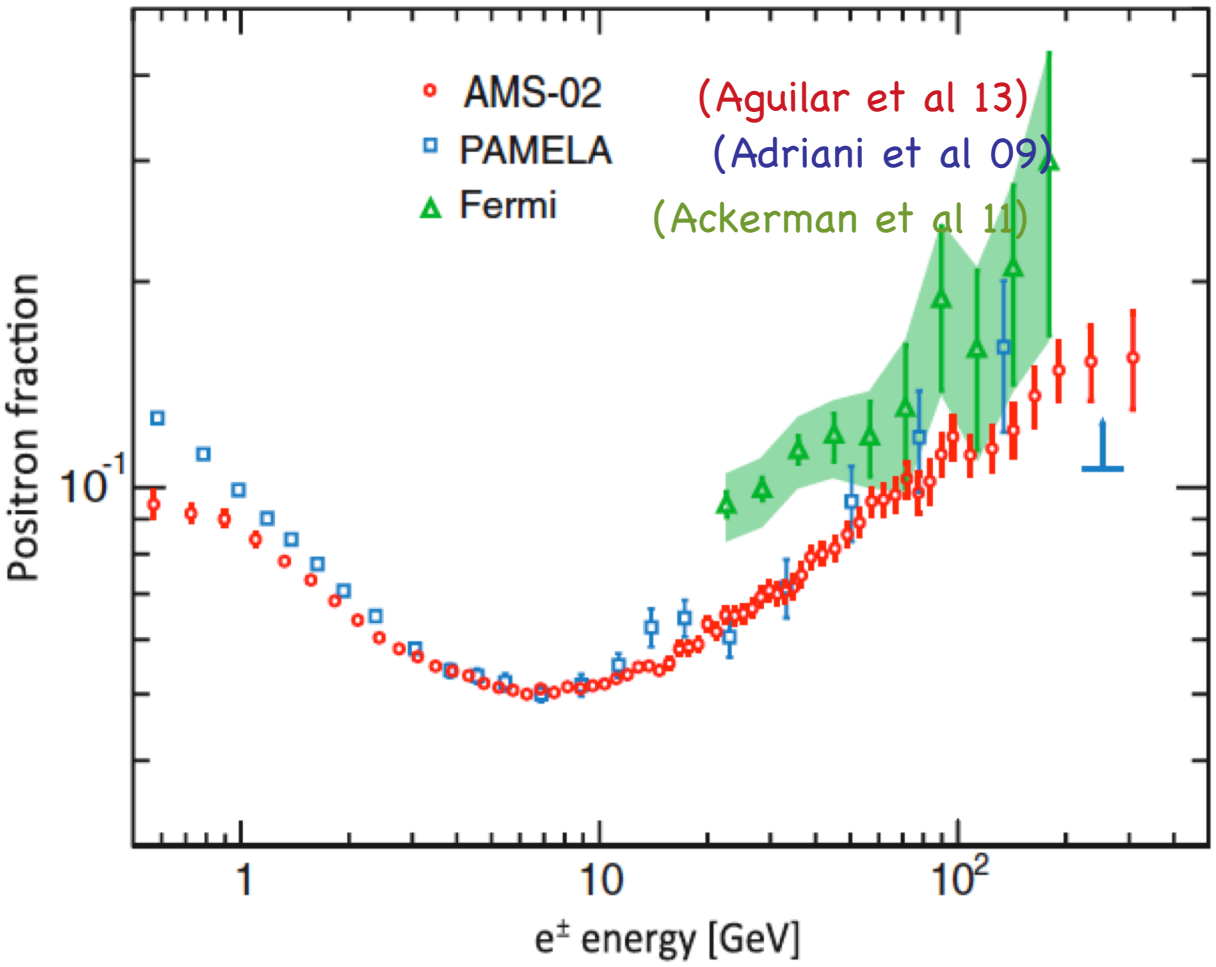








THE POSITRON "EXCESS"



MANY MANY IDEAS (& PAPERS):

- DARK MATTER
- NEW CR PROPAGATION SCENARIOS
- ASTROPHYSICAL SOURCES

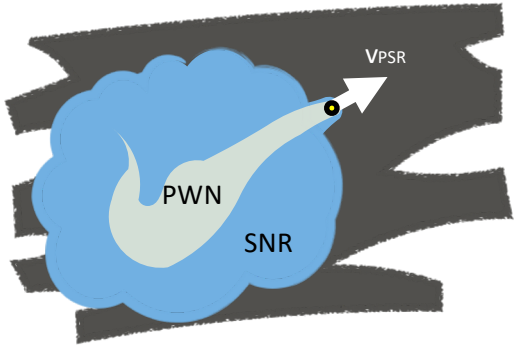
(e.g. Serpico 12, Di Mauro et al 17, EA & Blasi 17, Bykov, EA+ 17)

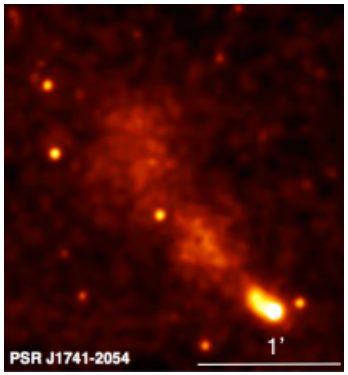
- e^+ ONLY SECONDARIES
- e^- SPECTRUM SAME AS p SPECTRUM

$$\frac{\Phi_{e^+}}{\Phi_{e^+} + \Phi_{e^-}} \propto E^{-\delta}$$

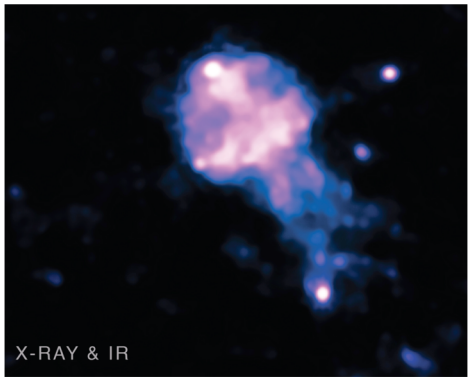
BOW SHOCK PULSAR WIND NEBULAE

$$t_{\rm esc} = \left(\frac{3E_{SN}}{2\pi\rho_{\rm ism}V_{\rm psr}^5}\right)^{1/3} \approx 10^5{\rm yr}\left(\frac{E_{51}}{n_1 V_{200}^5}\right)^{1/3}$$

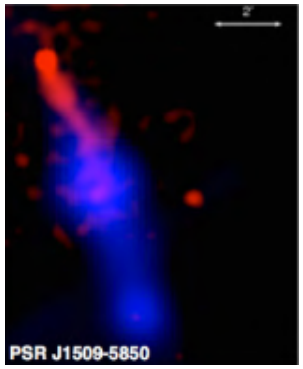




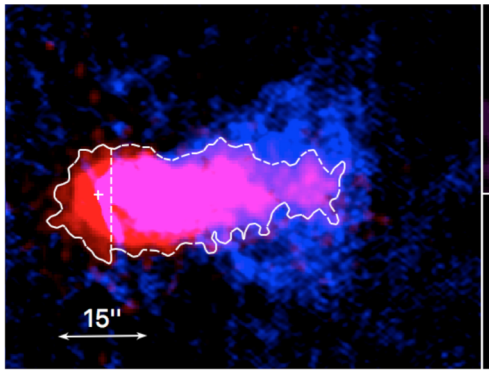
PSR J1741-2054
(Kargaltsev+ 2016)

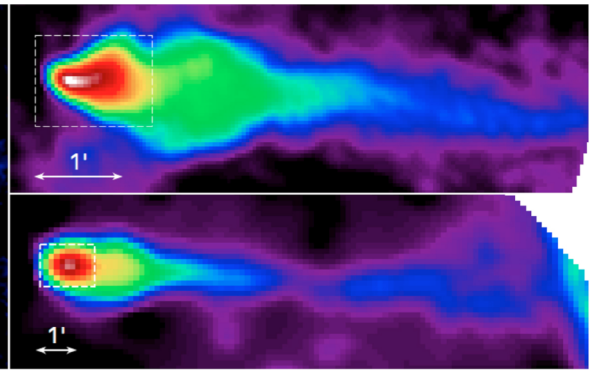


PSR B0355+54
(Emre+ 2005)



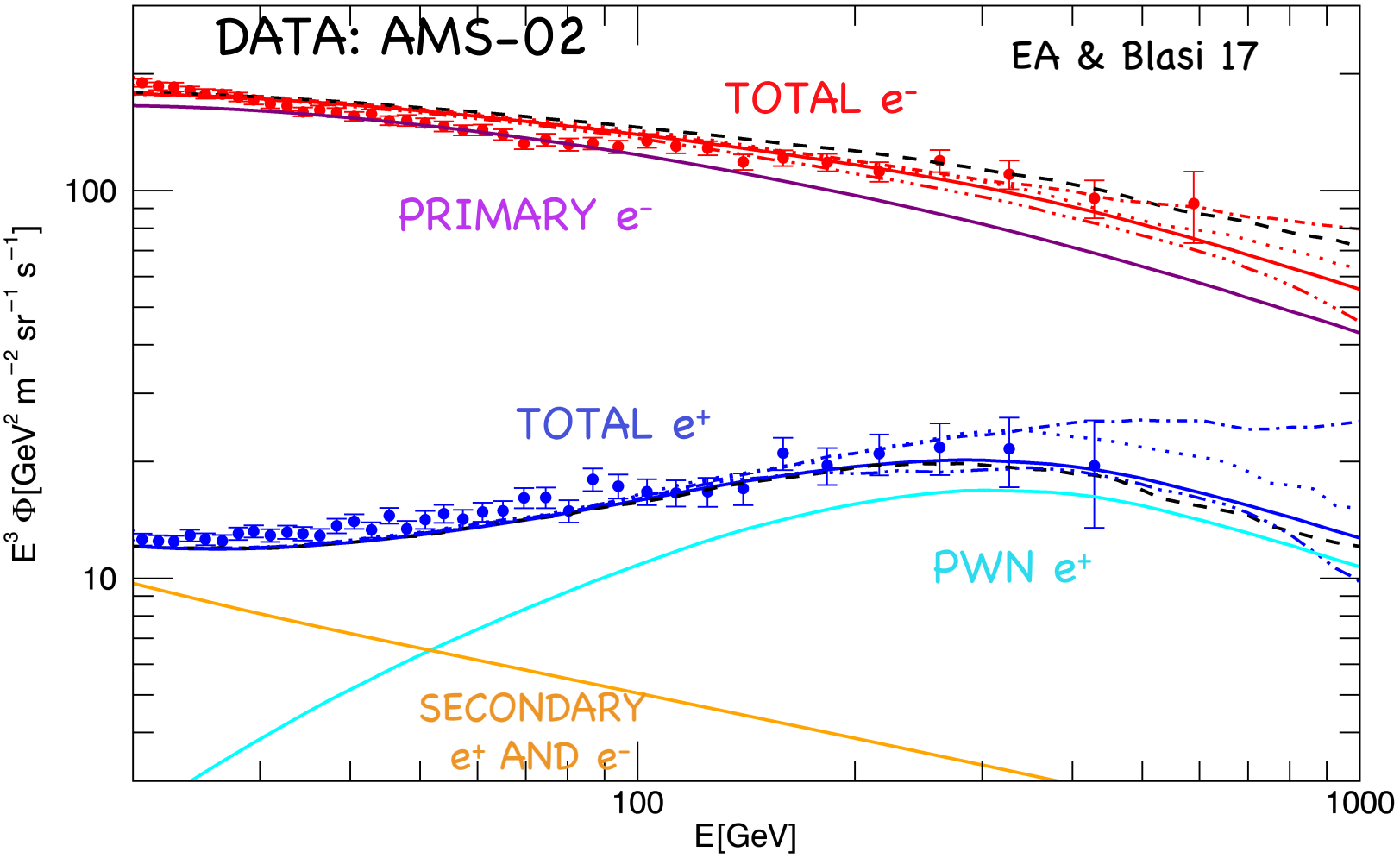
PSR J1509-5850
(Hui & Becker 07, Klinger+ 16)





MOUSE PWN
(Yusef-Zadeh & Bally 1987, Yusef-Zadeh & Gaensler 05, Klinger+ 18)

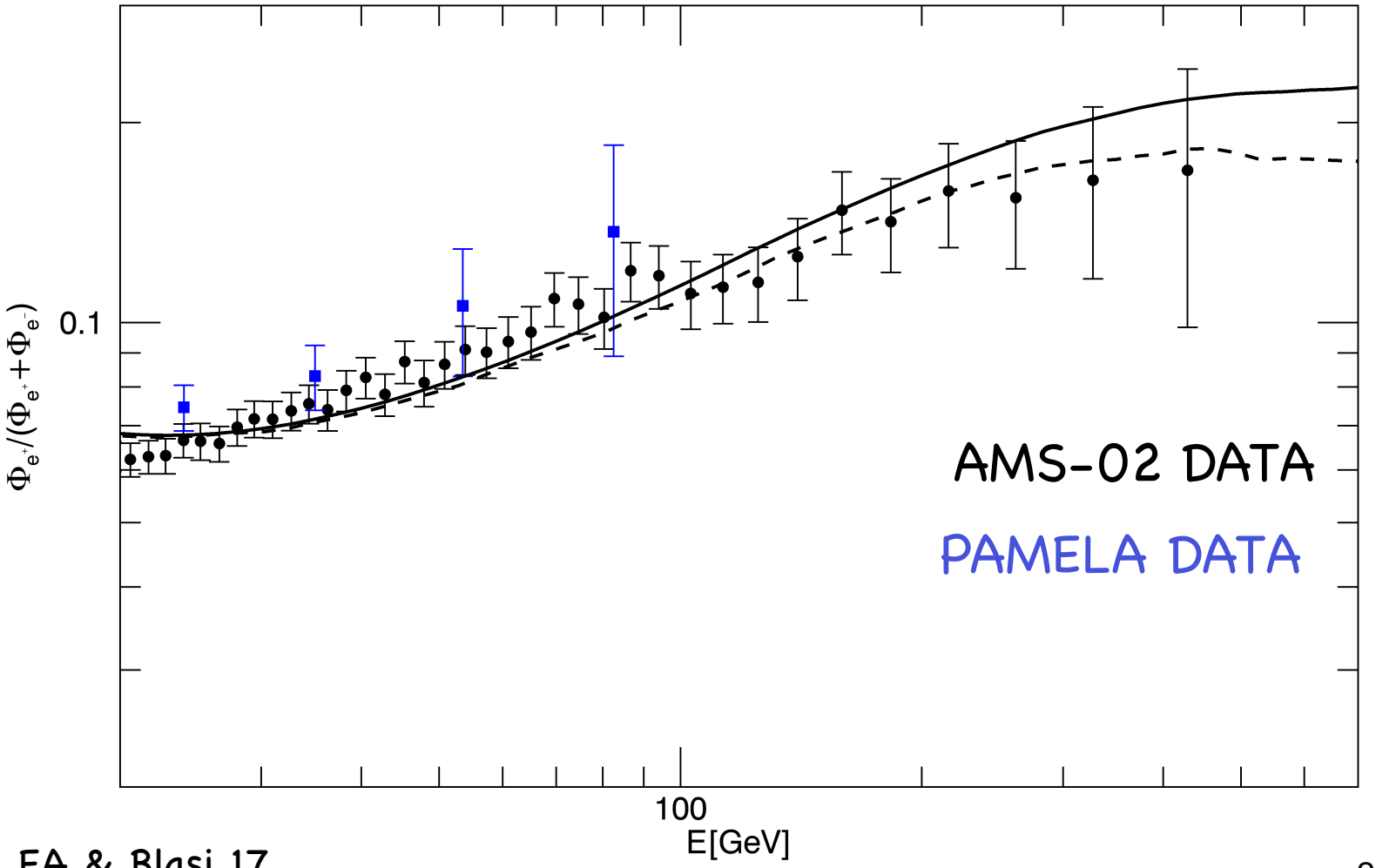
POSITRONS FROM PWNe



PWN ACCELERATION EFFICIENCY 12%

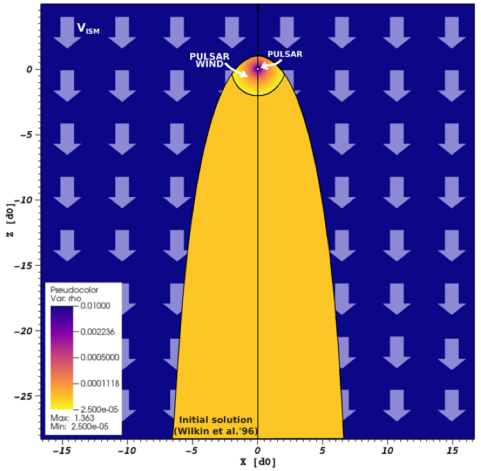
INJECTED SPECTRUM $E^{-1.5}$ E<500 GEV

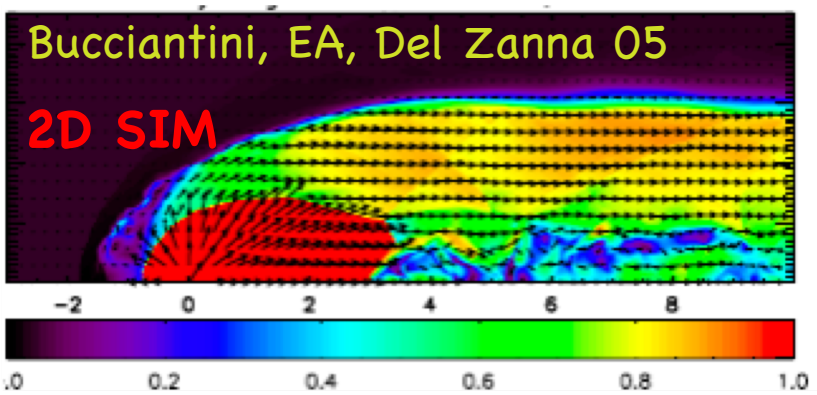
POSITRON FRACTION



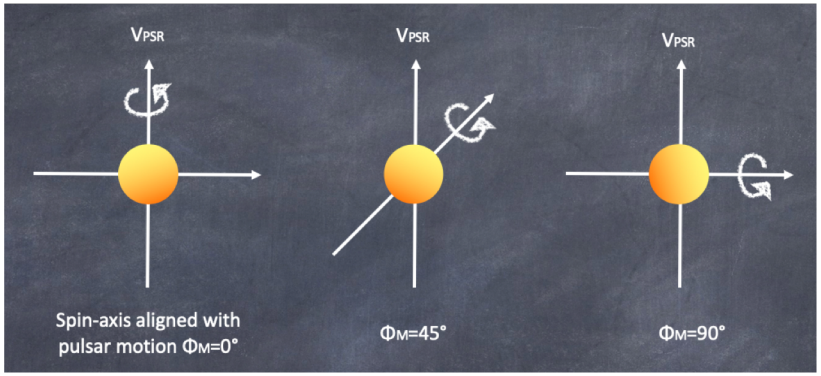
EA & Blasi 17

3D MHD SIMULATIONS OF BSPWNe

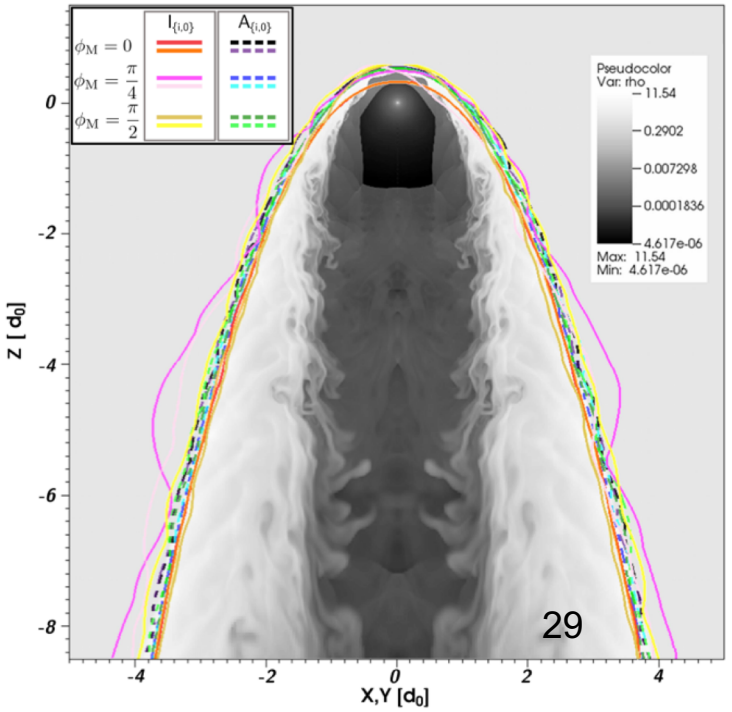




BOTH **ISOTROPIC** AND **ANISOTROPIC** PSR WIND WITH DIFFERENT **MAGNETIZATION** AND **GEOMETRY**

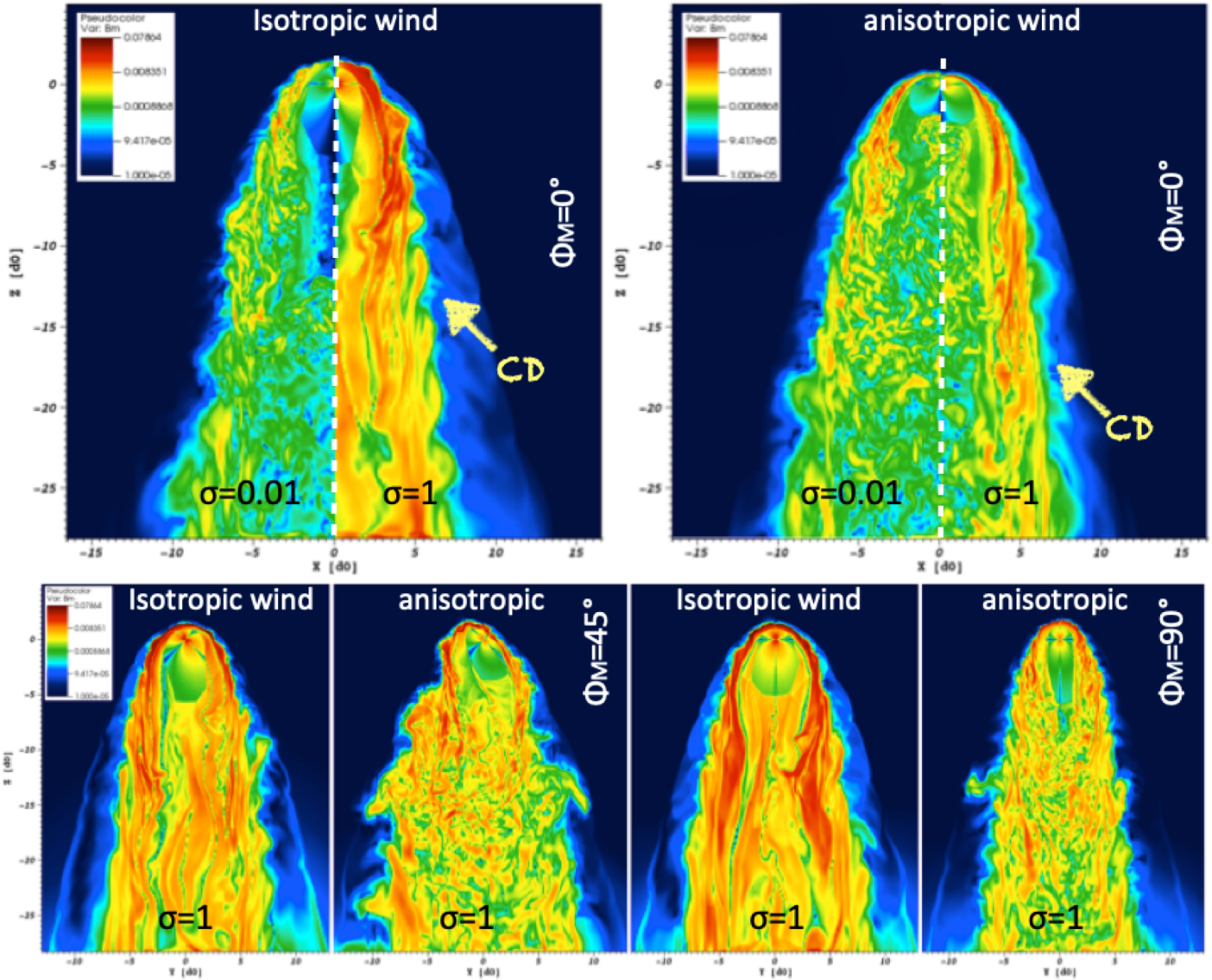


Olmi & Bucciantini 19



OVERALL SHAPE NOT MUCH AFFECTED

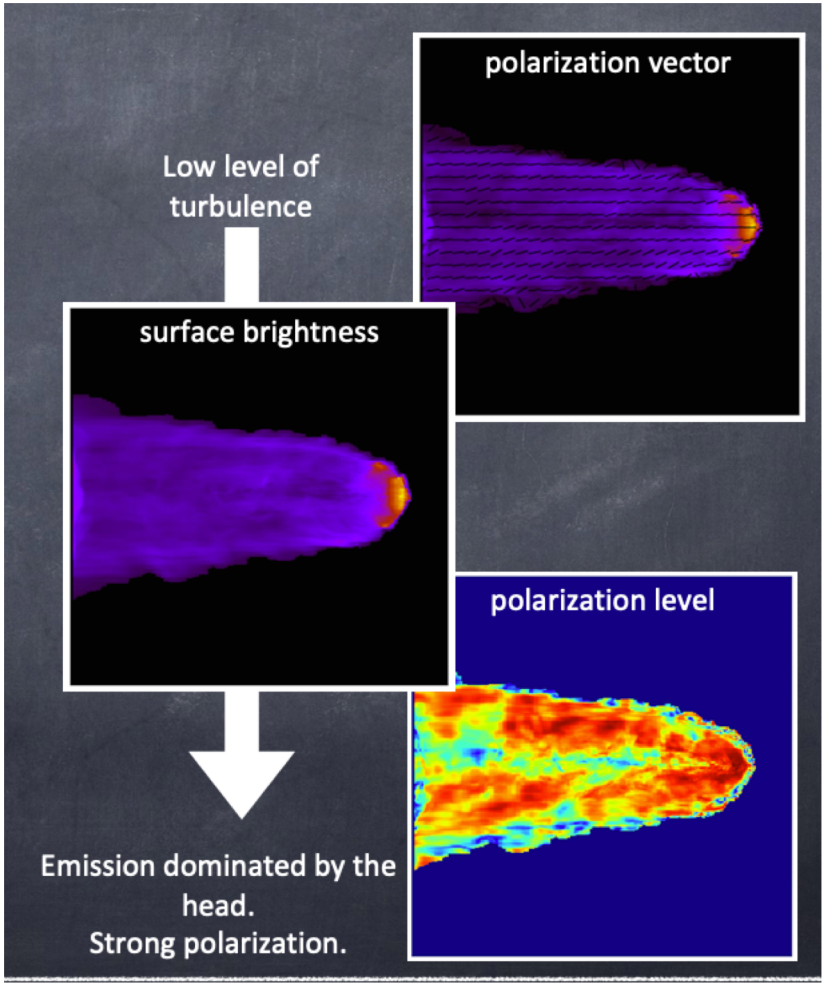
INTERNAL FLOW STRUCTURE



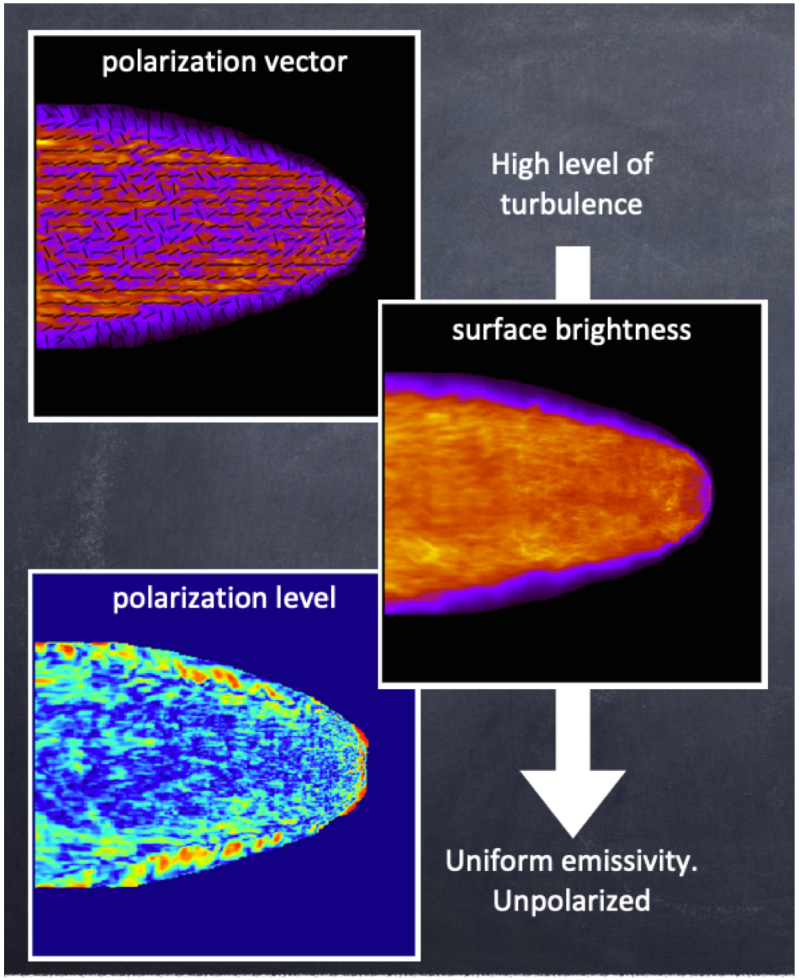
Olmi & Bucciantini 19

EMISSION PROPERTIES

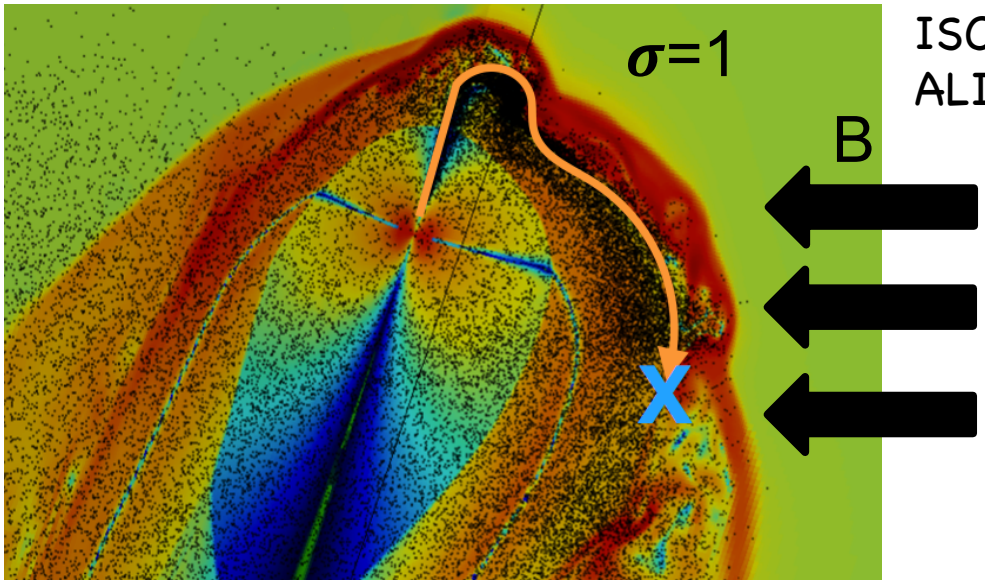
ISOTROPIC σ=1



ANISOTROPIC σ=0.01

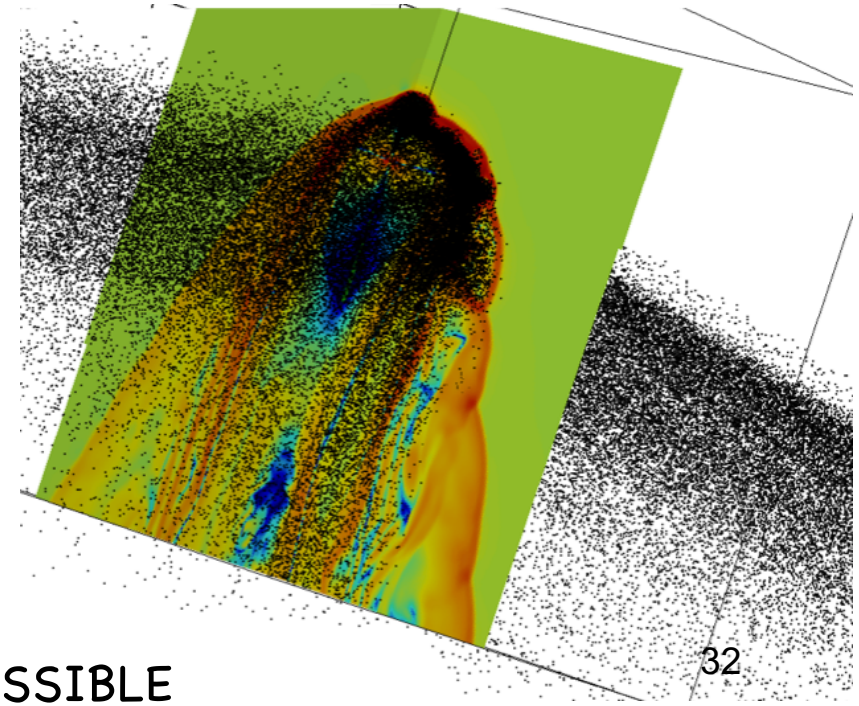


PARTICLE ESCAPE



ISOTROPIC WIND
ALIGNED ROTATOR

CONFINEMENT IN
MAGNETOPAUSE UP TO
RECONNECTION REGION



ONE-SIDED JETS POSSIBLE

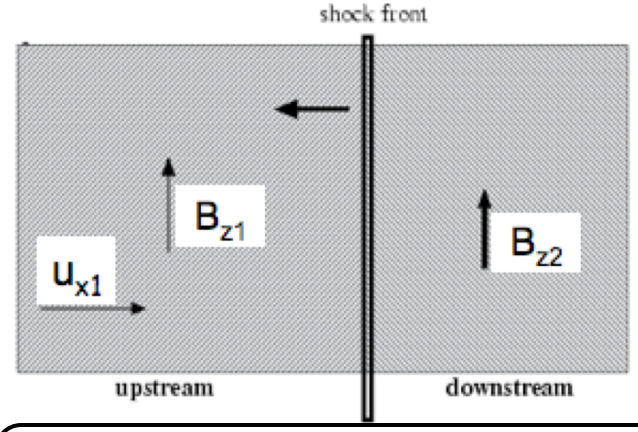
SUMMARY FOR EVOLVED SYSTEMS

- BSPWNe SEEM ABLE TO ACCOUNT FOR 'POSITRON EXCESS' WITH VERY REASONABLE PARAMETERS AND RATHER LOW EFFICIENCIES

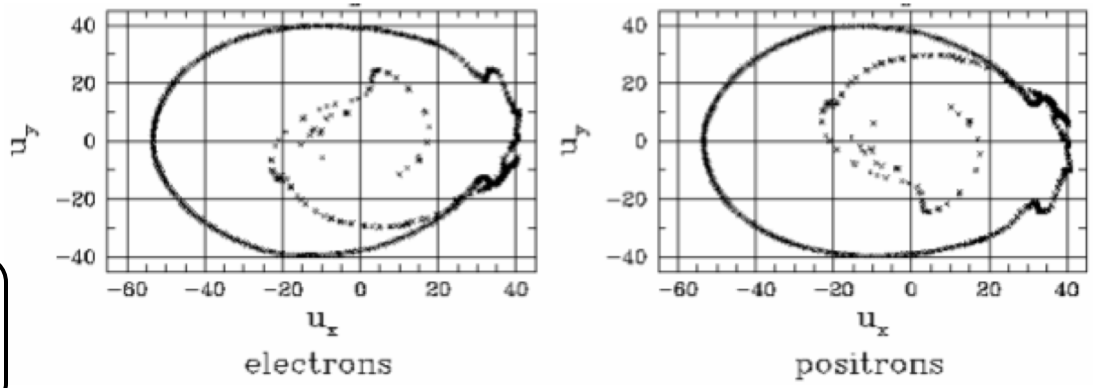
- THEIR CONTRIBUTION SEEMS MANDATORY TO ACCOUNT FOR WHEN MODELING CR LEPTONS

- BETTER MODELING OF DYNAMICS, PARTICLE EVOLUTION AND PARTICLE ESCAPE URGENTLY NEEDED!!!

RESONANT CYCLOTRON ABSORPTION IN e^+-e^--p PLASMA



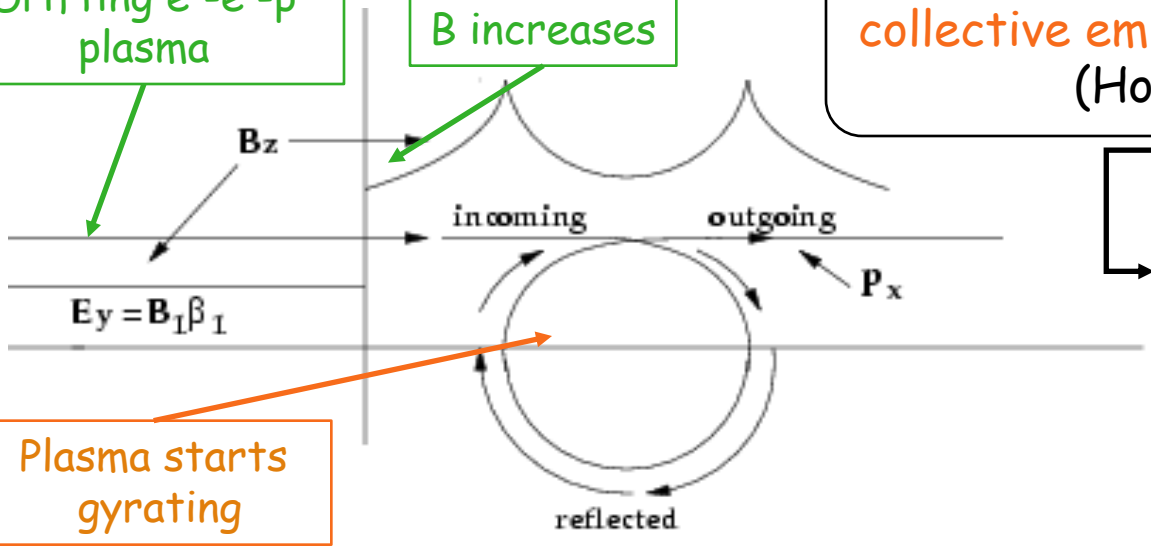
Configuration at the leading edge
~ cold ring in momentum space



Magnetic reflection mediates the transition

Drifting e^+-e^--p plasma

B increases



Plasma starts gyrating

Coherent gyration leads to collective emission of cyclotron waves (Hoshino et al 92)

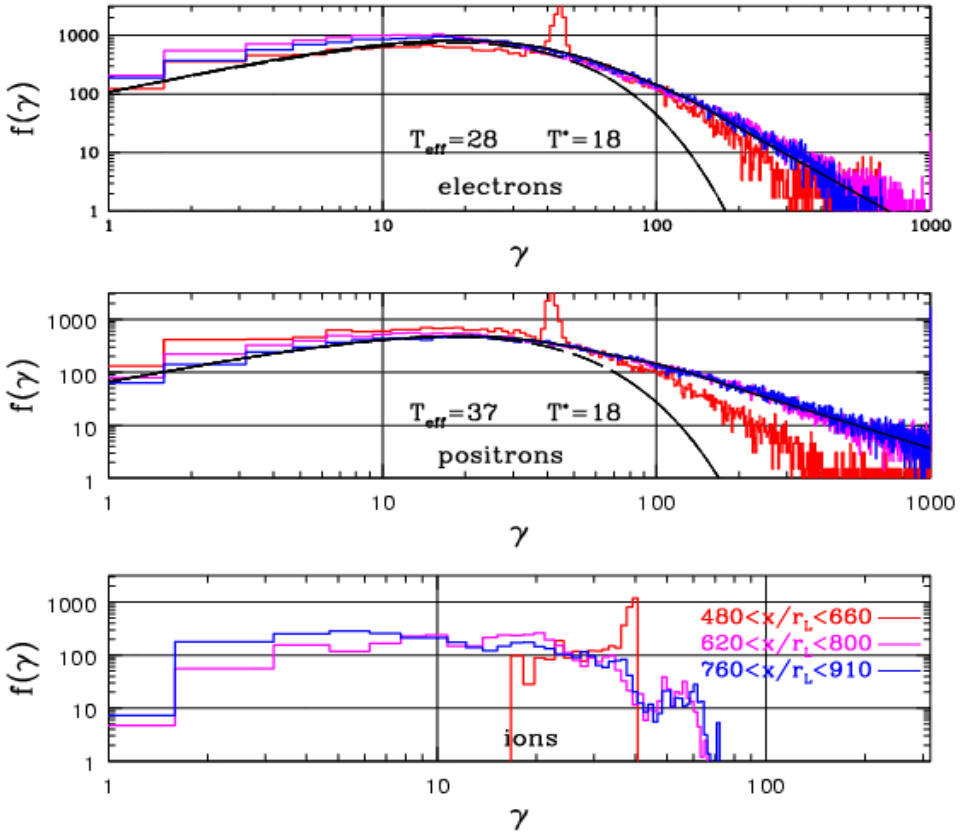
Pairs thermalize to $kT \sim m_e \Gamma c^2$ over 10-100 $\times (1/\Omega_{ce})$

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%

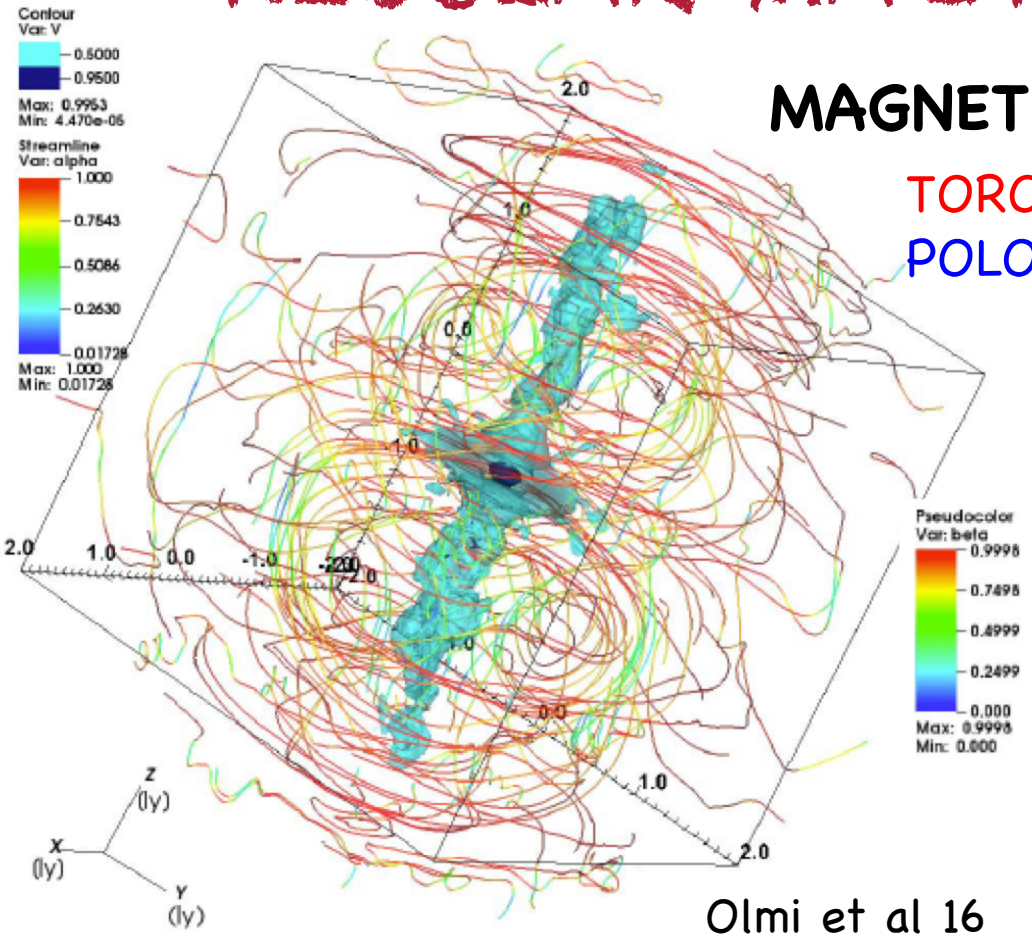
MAXIMUM ENERGY:

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

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

RESULTS BY Amato & Arons 06 RECENTLY CONFIRMED BY Stockem et al 12

NEBULAR MAGNETIC FIELD

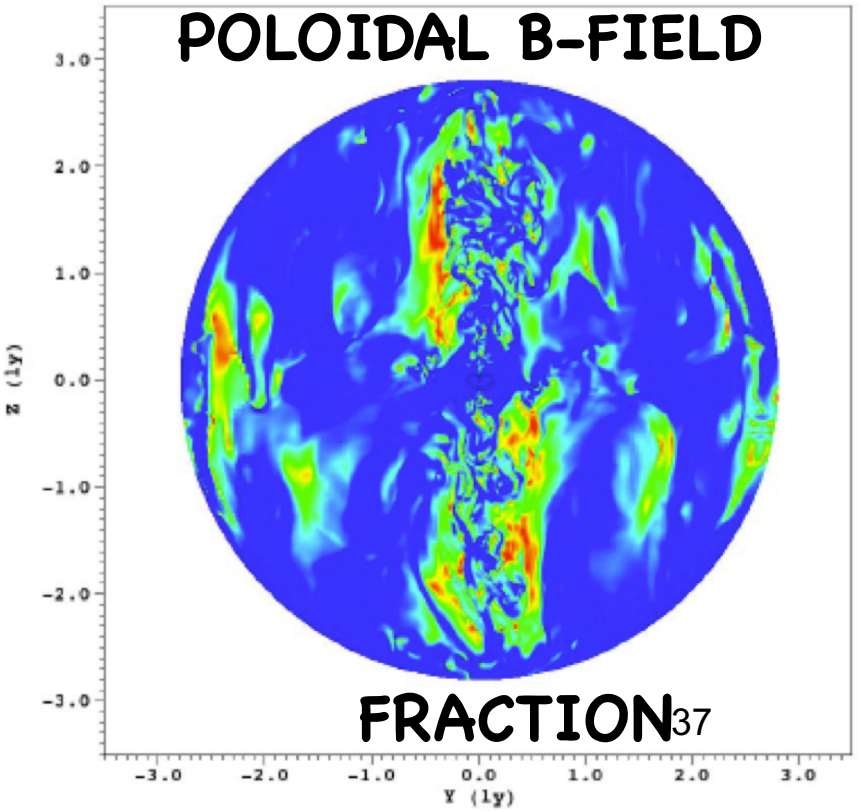


MAGNETIC FIELD LINES

TOROIDAL

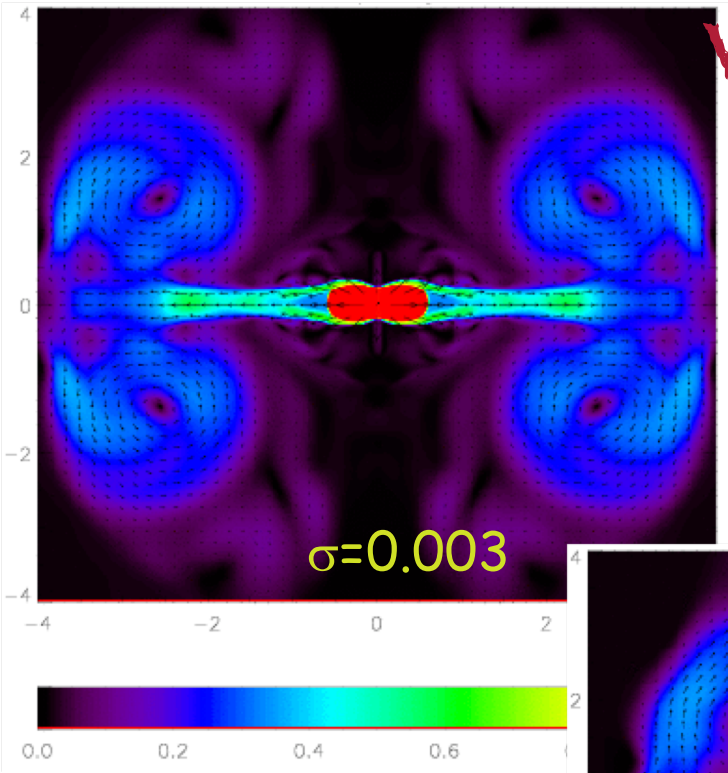
POLOIDAL

Olmi et al 16

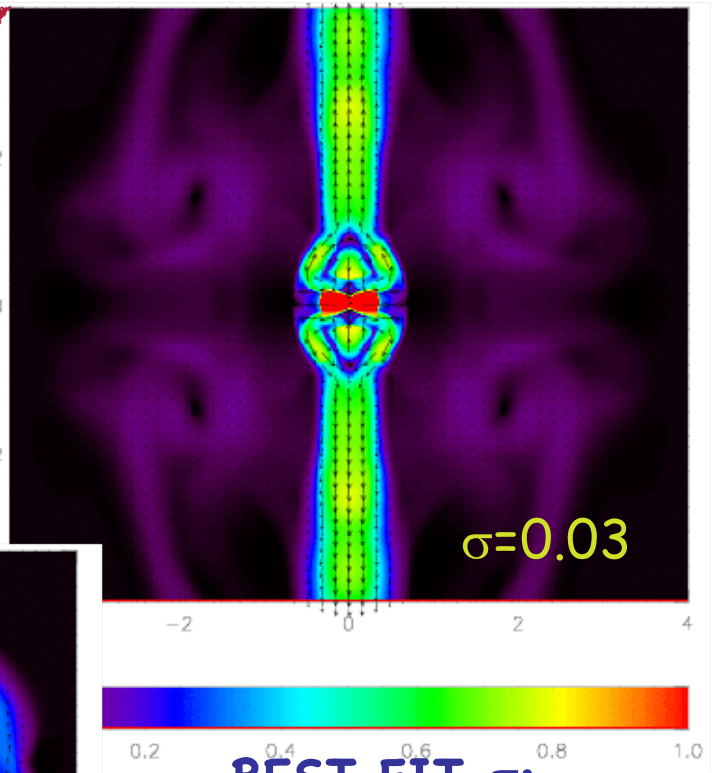


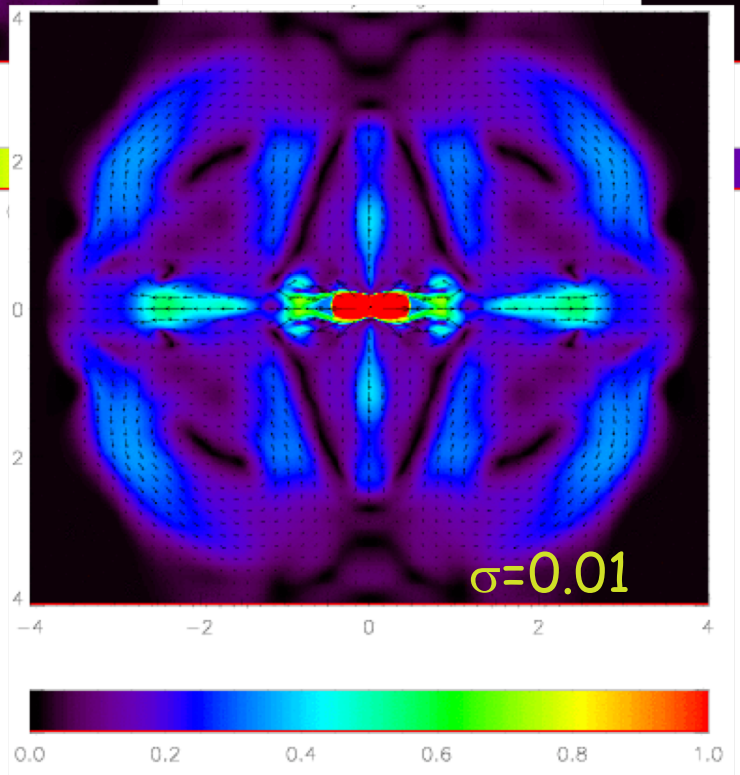
B_p PEAKS SOME DISTANCE FROM AXIS AND OUT OF EQUATORIAL PLANE

DEPENDENCE ON σ OF FLOW VELOCITY



(Del Zanna et al 04)



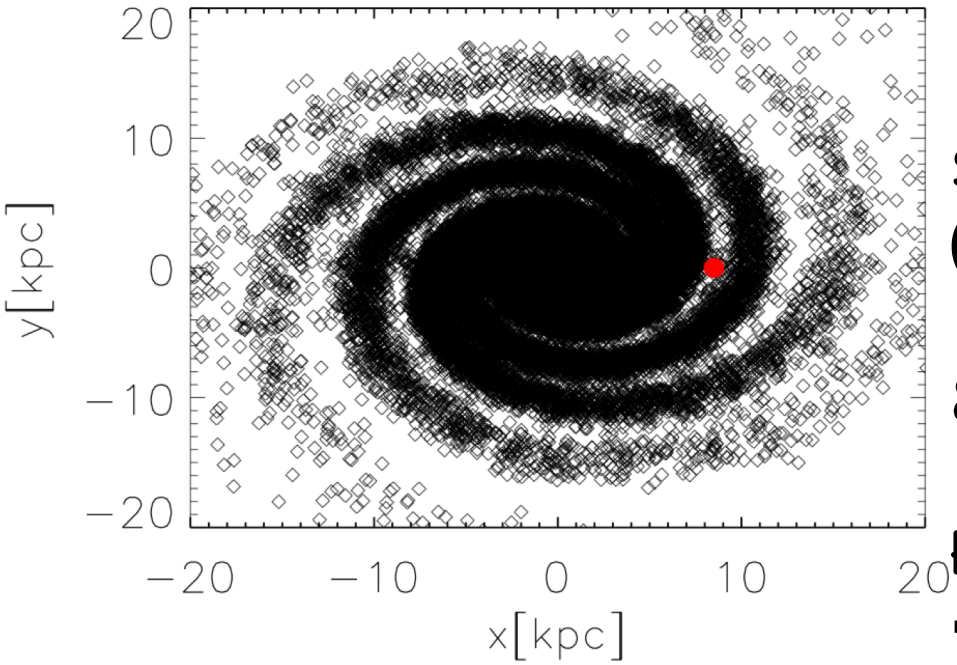


LOWER LIMIT ON σ:

σ>0.01 **REQUIRED FOR JET FORMATION**

BEST FIT σ: 10 X LARGER THAN WITHIN 1D MHD MODELING (Kennel & Coroniti 84) BUT STILL <<1

SNRs AND PSRs IN THE GALAXY



SNR DISTRIBUTION
(Green 05, Faucher-Giguere & Kaspi 06)

80% SNRs HOST A PSR

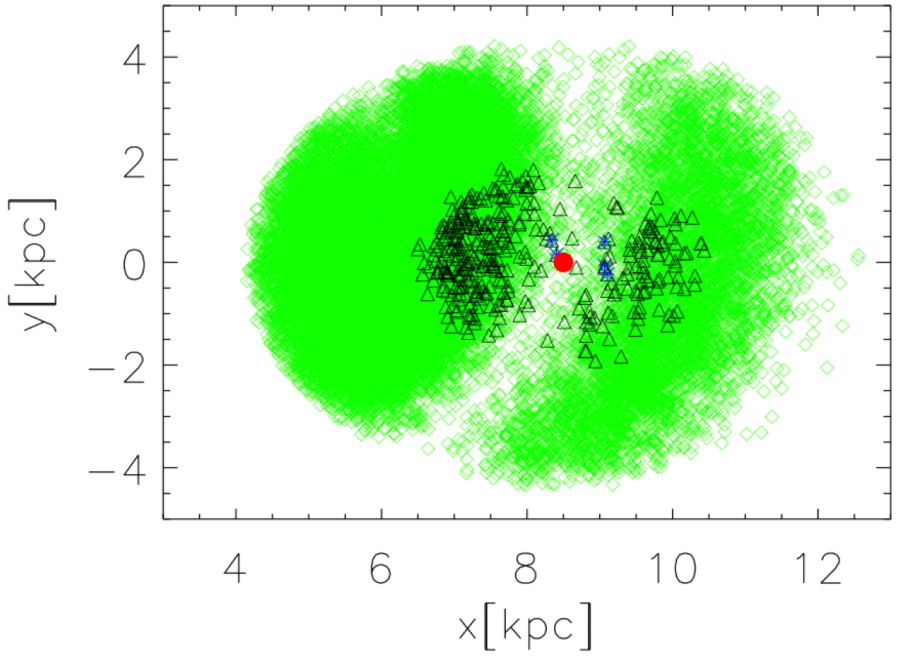
PSR PARAMETERS (B_*,P_0,V_p)
➔ESCAPE AT≈5X10^{4}yr

PROTONS AND PRIMARY ELECTRONS INJECTED FROM SNRS WITH SPECTRUM AS FROM NEWEST AMS-02 DATA (Aguilar et al 15) AND 10% EFFICIENCY

DIFFUSION THROUGH THE GALAXY *A LA KOLOMOGORON*: $D(E)\approx E^{1/3}$ (Aguilar et al 16)

LOSSES THROUGH ICS AND SYNCHROTRON IN 3 μG FIELD

CONTRIBUTING SOURCES



10 GeV

100 GeV

1 TeV