Use of PLUTO code for High Energy Astrophysical Problems

Dr. Bhargav Vaidya

Dept. of Physics
University of Torino, Italy.

Laser Plasma Accelerator
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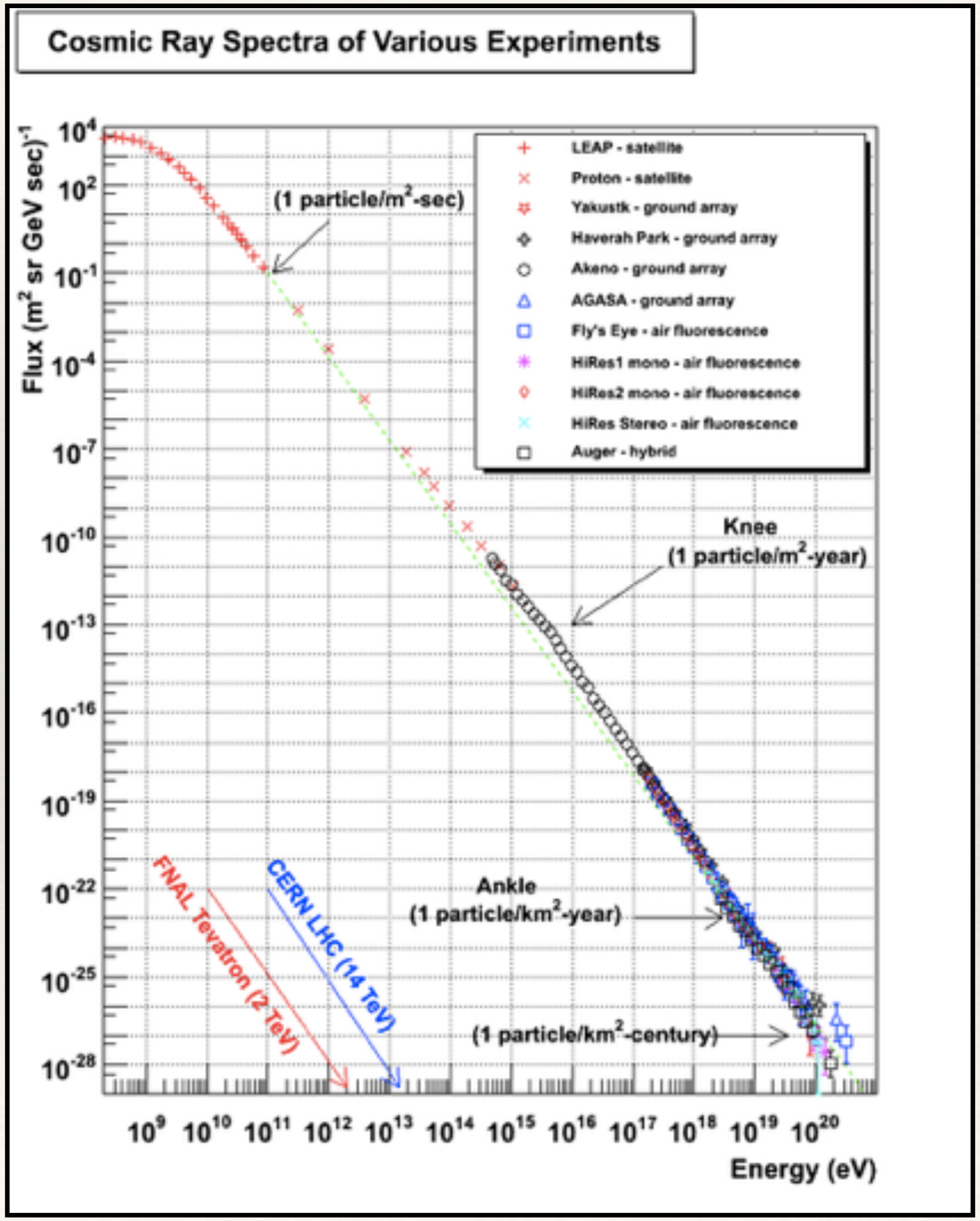
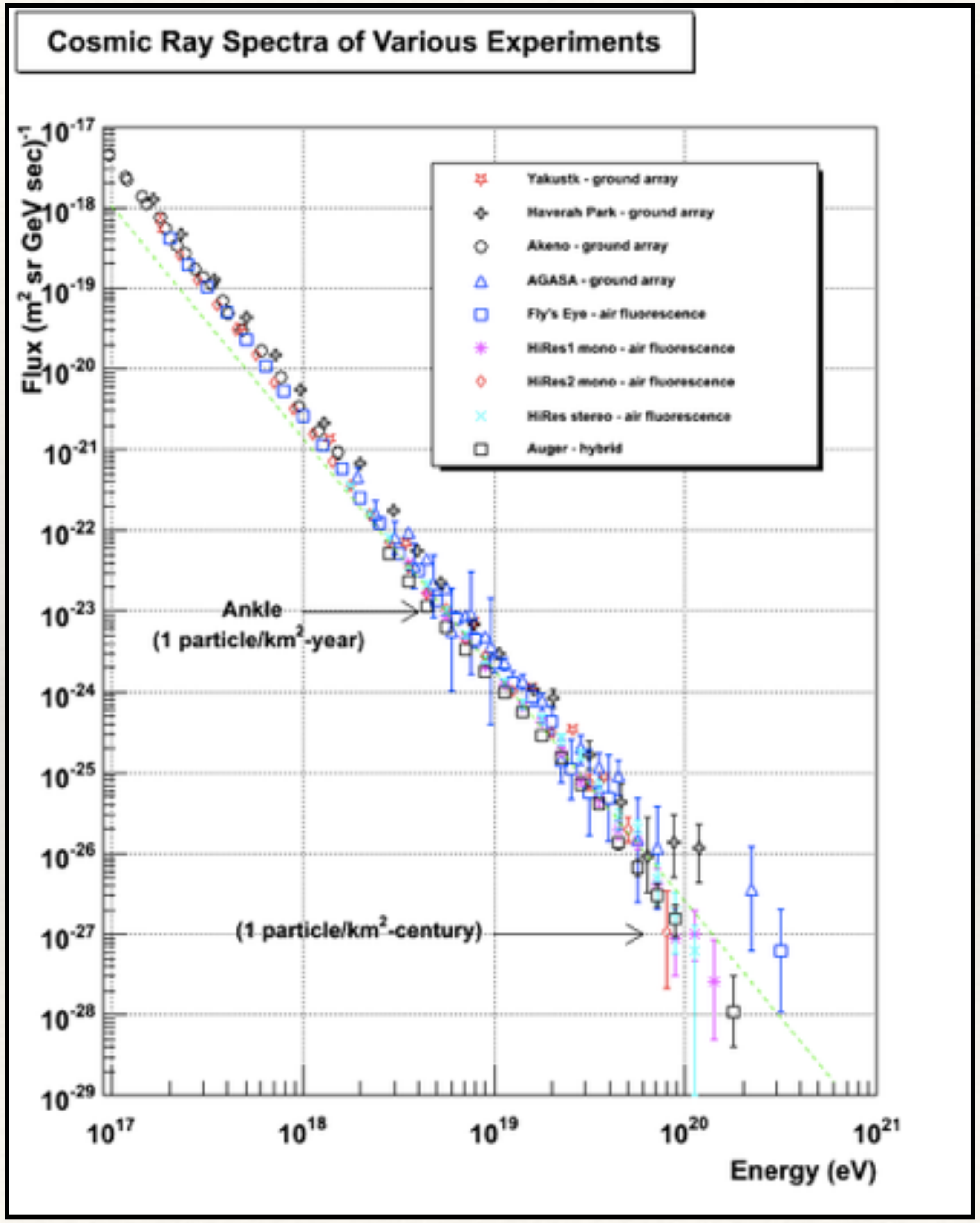
Outline

- *Motivation : Cosmic Accelerators*
- *PLUTO Code : Capabilities and New Features.*
- *Multi-scale Nature*
- *High Energy Astrophysical Sources*
  - Supernova
  - Bright Knots in AGN Jets.
  - Oblique Shocks in Relativistic flows.
- *Summary*

Powerful Power law

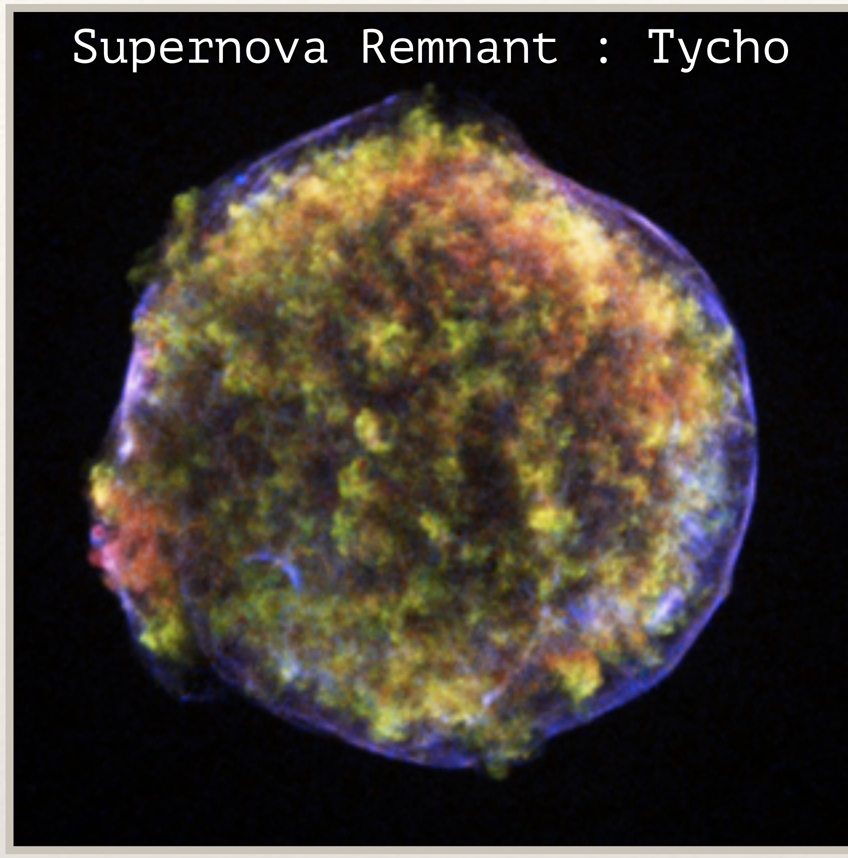
What is the origin of such a power-law cosmic ray spectrum covering about several orders of magnitude in energy?

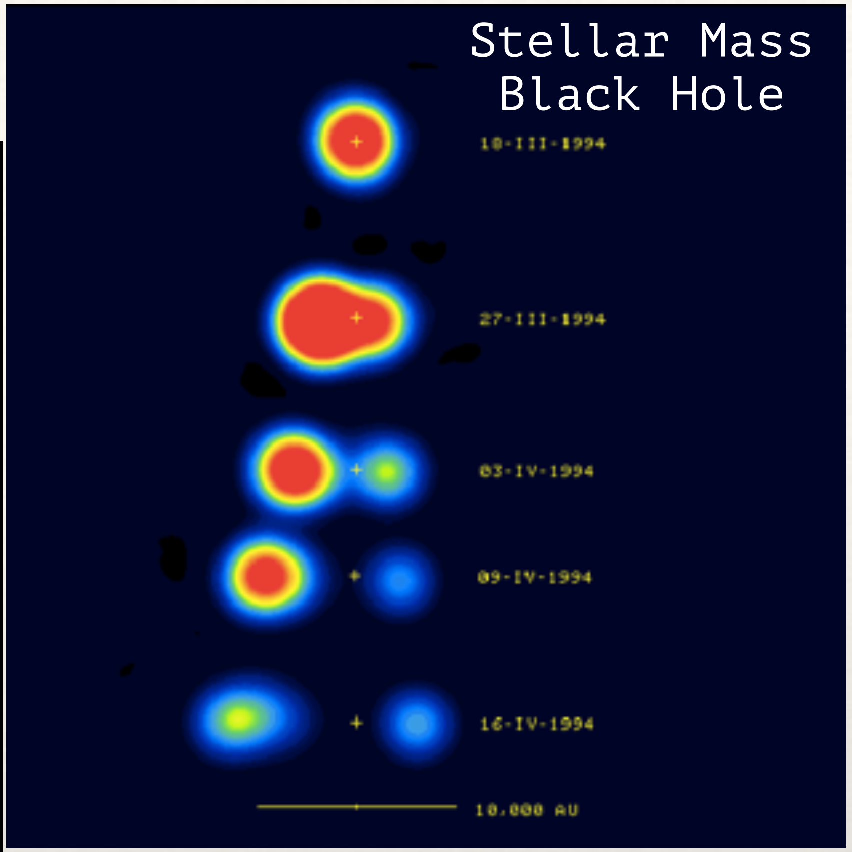


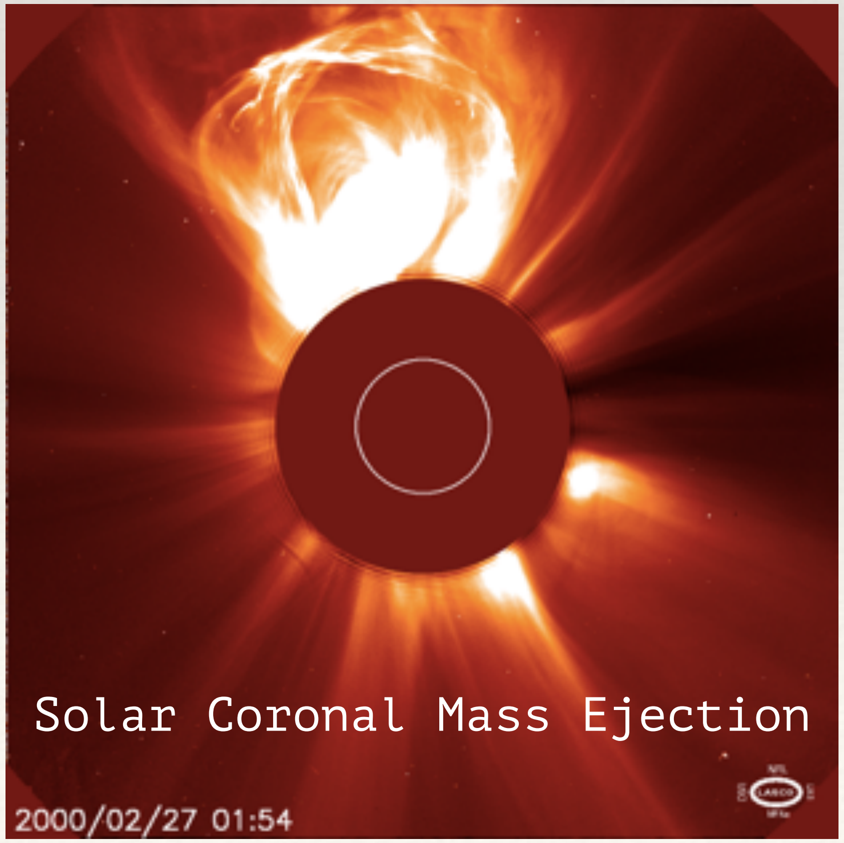


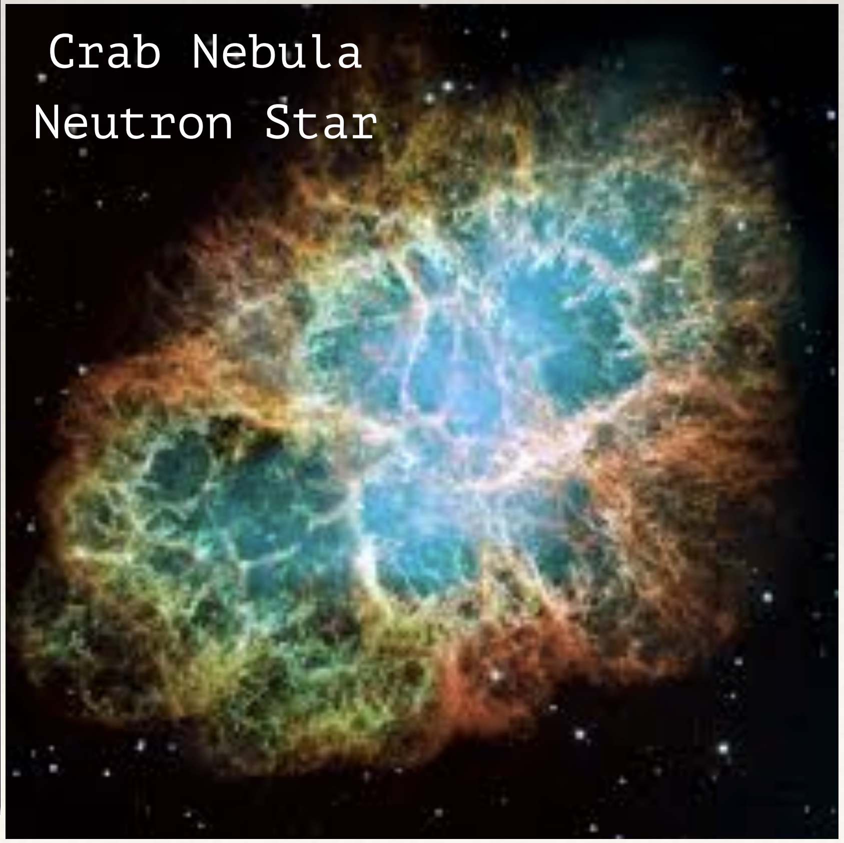
http://www.physics.utah.edu/~whanlon/spectrum.html

Cosmic Accelerators.









PLUTO code : An Overview

- Modular (HD, MHD, RHD, RMHD)
- Conservative, Finite Volume based — Godunov Method
- Static and Adaptive Mesh grid in 1D, 2D and 3D.
- Supports Cartesian, Spherical, Cylindrical and Polar Geometries
- Parallelised using MPI Library
- Written in C, C++
- Used by a very large astrophysical community for wide range of problems.

PLUTO v. 4.2 (Aug 2015)

User's Guide

(http://plutocode.ph.unito.it)

Developer: A. Mignone[1,2] (mignone@ph.unito.it)

Contributors: C. Zanni[2] (AMR) (zanni@oato.inaf.it)
B. Vaidya[1] (EoS, Cooling, pyPLUTO) (bhargav.vaidya@unito.it)
T. Matsakos[3] (Resistivity, Thermal Conduction, STS)
G. Muscianisi[4] (Parallelization, I/O)
P. Tzeferacos[5] (Viscosity, MHD, STS, Finite-Difference)
O. Tesileanu[6] (Cooling)

1 Dipartimento di Fisica, Turin University, Via P. Giuria 1 - 10125 Torino (TO), Italy
2 INAF Osservatorio Astronomico di Torino, Via Osservatorio, 20 10025 Pino Torinese (TO), Italy
3 Dept. of Astronomy & Astrophysics, University of Chicago, 5640 S. Ellis Ave Chicago, IL 60637, USA
4 Consorzio Interuniversitario CINECA, via Magnanelli, 6/3, 40033 Casalecchio di Reno (Bologna), Italy
5 FLASH Center, University of Chicago, USA
6 Department of Physics, University of Bucharest, Str. Atomistilor nr. 405, RO-077125 Magurele, Ilfov, Romania

[Mignone et al. 2007, 2012]

PLUTO code : MHD Equations.

Set of Ideal MHD Equations Solved by PLUTO

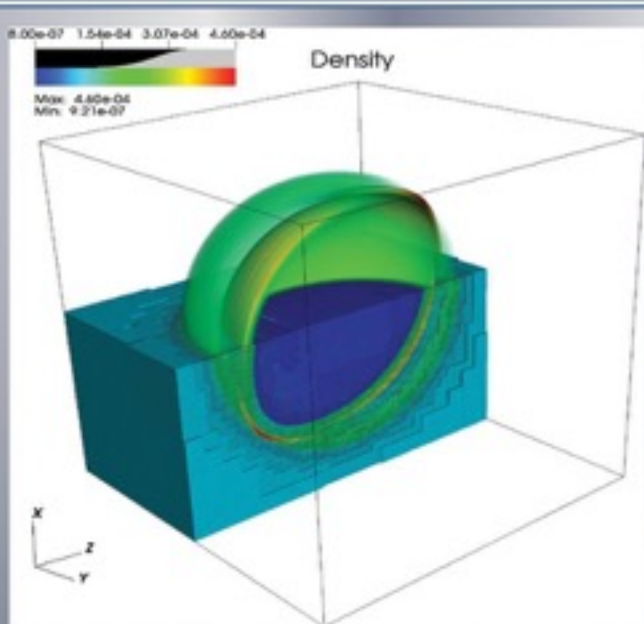
Mass Conservation	$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0,$
Momentum Conservation	$\frac{\partial}{\partial t}(\rho \boldsymbol{v}) + \nabla \cdot (\rho \boldsymbol{v}\boldsymbol{v} - \boldsymbol{B}\boldsymbol{B} + p_t \mathsf{I}) = 0,$
Total Energy Conservation	$\frac{\partial E}{\partial t} + \nabla \cdot [(E + p_t)\boldsymbol{v} - (\boldsymbol{B} \cdot \boldsymbol{v})\boldsymbol{B}] = 0$
Induction Equation	$\frac{\partial \boldsymbol{B}}{\partial t} - \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) = 0$
Total Pressure	$p_t = p + \frac{B^2}{2}$
Total Energy	$E = \rho\epsilon + \frac{\rho v^2}{2} + \frac{B^2}{2}$
Solenoidal Condition	$\nabla \cdot B = 0,$

PLUTO Code : Non-Ideal Effects.

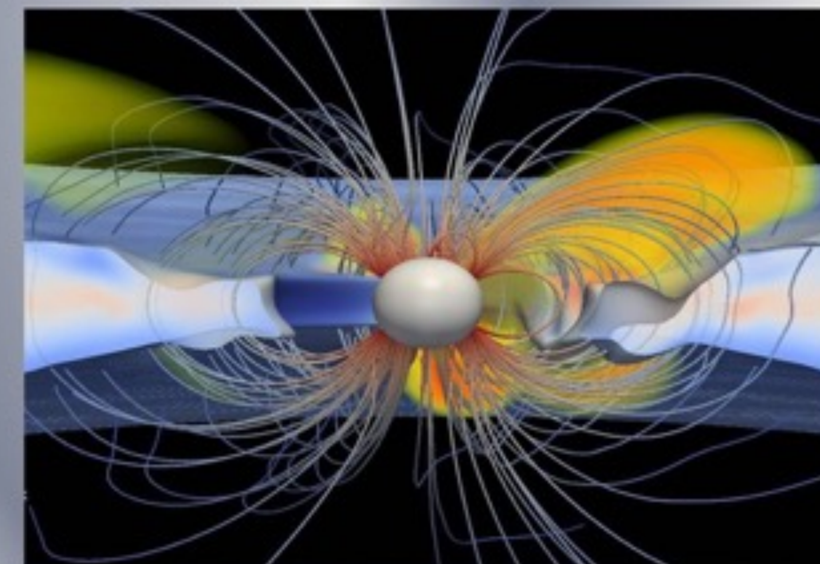
Additional Physics

- Viscosity (Mignone et. al. 2012)
- Thermal Conduction (Mignone et al 2012, Vaidya et. al. 2017)
- Magnetic Resistivity, Hall MHD, Ambipolar Diffusion
- Radiative Cooling. (Tesileanu et. al. 2008)
- Chemistry with Species dependent EoS (Vaidya et. al. 2015)
- Lagrangian Particles : Macro-Particles (Vaidya et. al. 2016)
- Cosmic Rays, Dust : Active Particles

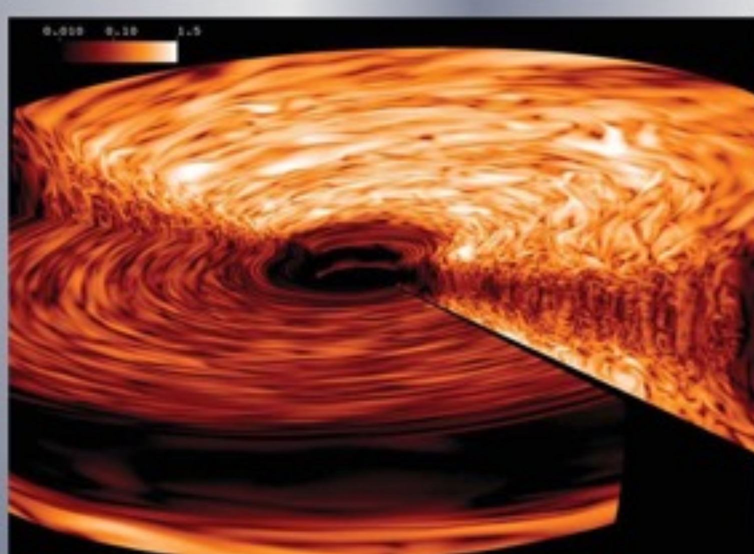
PLUTO Code : Image Suite



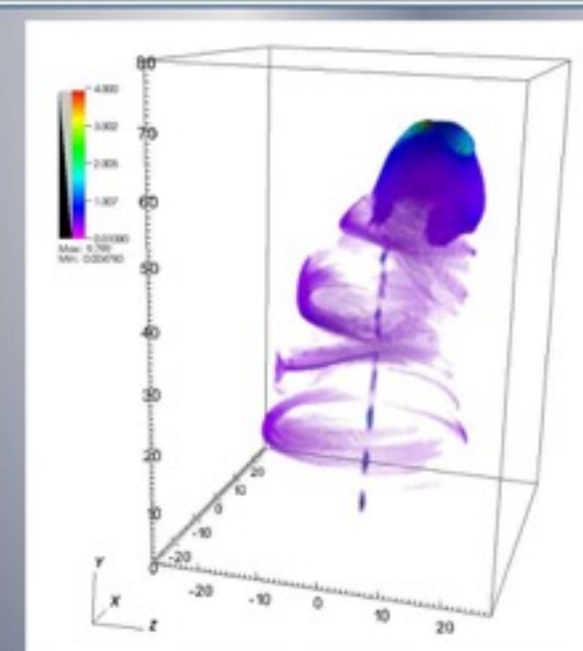
3D relativistic blast explosion in an (initially) oblique magnetic field.



MHD modeling of flares occurring in young stellar objects (YSOs) with the aim to investigate the effects of the flares on the stability of the circumstellar disk surrounding the central protostar, Orlando et al., MNRAS (2011) 415, 3380.



Turbulent r.m.s. velocity field in a 3D magnetized accretion disk. Flock et al., ApJ (2011) 735



3D rendering of the pressure distribution in a relativistic magnetized jet with Lorentz factor 10 and density contrast 10-4. See Mignone et al., MNRAS (2010) 402, 7.

Particle Acceleration in Magnetised Jets

- **Radiative Losses**
  - Adiabatic Expansion, Synchrotron Cooling, Inverse Compton Scattering, Synchrotron Self Compton.
- **X-ray synchrotron emission.**

1 keV radiation — $E_e \sim 10^{13} eV(\gamma \approx 2 \times 10^7)$

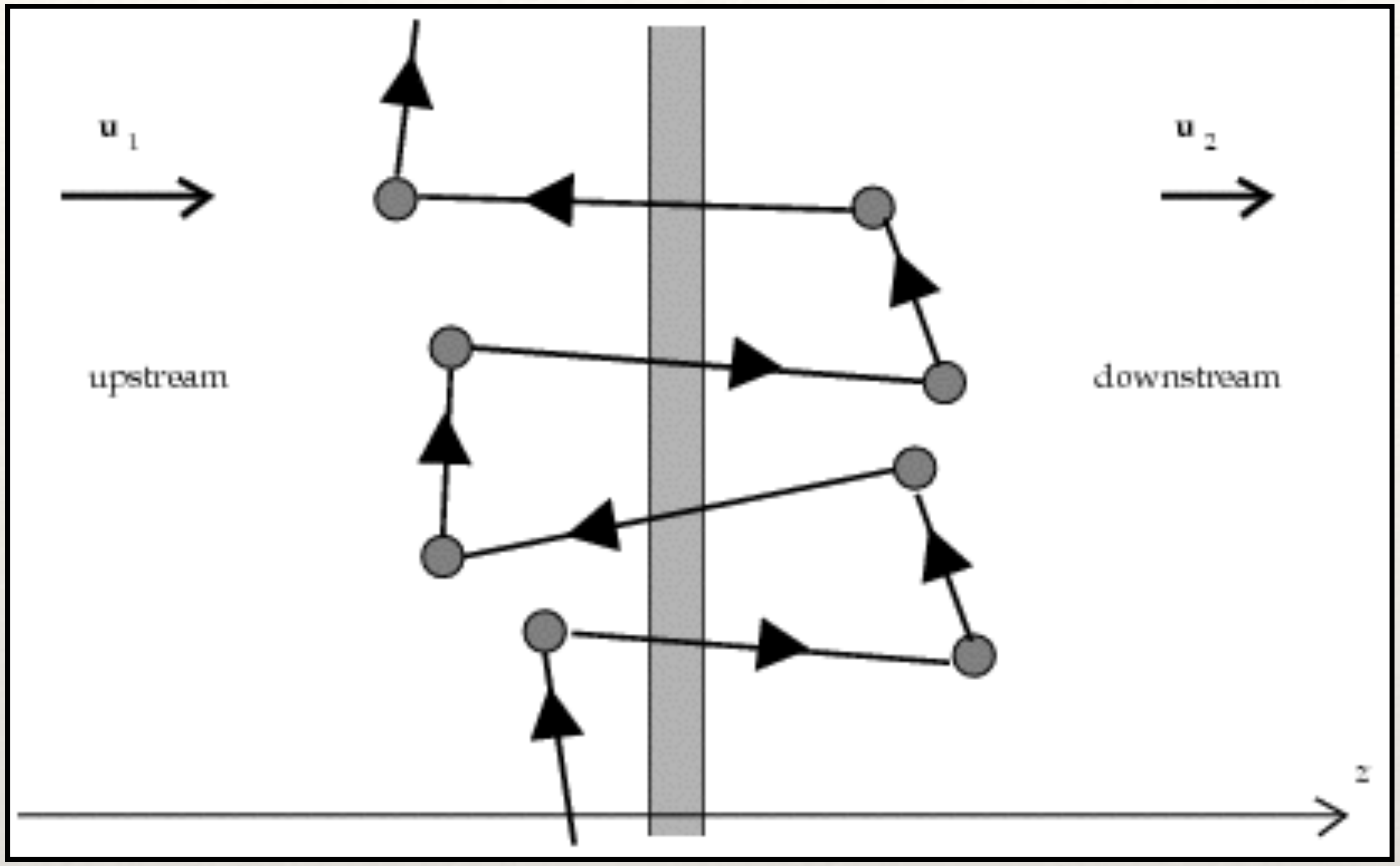
B fields — $200\mu G$

$$\tau_{\rm sync} = \frac{3m_e c}{4\sigma_T u_B \gamma} \sim 30yr(B^{-3/2}) \ll \tau_{dyn}$$

- **MODES of Particle Acceleration**
  - ***Diffusive Shock Acceleration (Fermi Ist Order)***
  - ***Magnetic Reconnection.***
  - ***Stochastic Acceleration.***

Diffusive Shock Acceleration.

Head on collisions of particles with magnetic clouds.



Average Energy Gain

$$\frac{\Delta E}{E} \propto \frac{|u_1 - u_2|}{c}$$

Resultant Power Law

$$f(p) \propto p^{-m}; m = \frac{3r}{r-1}; r = \frac{u_1}{u_2} = \frac{\rho_2}{\rho_1}$$

- Widely applied physical process of particle acceleration.
- Relative energy gain is linear with velocity.
- Naturally gives rise to a power-law spectral distribution.

[Krymsky (1977), Bell (1978), Blandford & Ostriker (1978), Axford (1977), Drury (1983, 1991)]

Hybrid PIC with PLUTO.

Cosmic Rays — Non-Thermal — Particles

Update of CR

$$\frac{d\boldsymbol{x}_p}{dt} = \boldsymbol{v}_p$$

$$\frac{d(\gamma \boldsymbol{v})_p}{dt} = \left(\frac{e}{mc}\right)_p (c\boldsymbol{E} + \boldsymbol{v}_p \times \boldsymbol{B})$$

Current & Force

$$\boldsymbol{F}_{CR} = \left(\frac{q_{\rm CR}}{c}\right) c\boldsymbol{E} + \frac{1}{c}\boldsymbol{J}_{\rm CR} \times \boldsymbol{B}$$

$$\boldsymbol{J}_{\rm CR}/c = q_{\rm CR}\boldsymbol{v}_{\rm CR}/c$$

Electron — Thermal — Massless fluid

Fluid Particle Feedback

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}_g) = 0$$

$$\frac{\partial (\rho \boldsymbol{v}_g)}{\partial t} + \nabla \cdot [\rho \boldsymbol{v}_g \boldsymbol{v}_g - \boldsymbol{B}\boldsymbol{B} + \mathsf{I} p_t] = \boxed{-\boldsymbol{F}_{\rm CR}}$$

$$\frac{\partial \boldsymbol{B}}{\partial t} + c\nabla \times \boldsymbol{E} = \mathbf{0}$$

$$\frac{\partial \mathcal{E}}{\partial t} + \nabla \cdot \left[\left(\frac{1}{2}\rho \boldsymbol{v}_g^2 + \rho e + p\right)\boldsymbol{v}_g + \frac{c\boldsymbol{E} \times \boldsymbol{B}}{4\pi}\right] = \boxed{-\boldsymbol{v}_g \cdot \boldsymbol{F}_{\rm CR}}$$

Electric Field : Ohms Law

$$c\mathbf{E} = -\mathbf{v}_g \times \mathbf{B} + \boxed{\frac{q_{CR}}{|q_e|}(\mathbf{v_{CR}} - \mathbf{v_g}) \times \mathbf{B}}$$

Cosmic Ray Driven Instability.

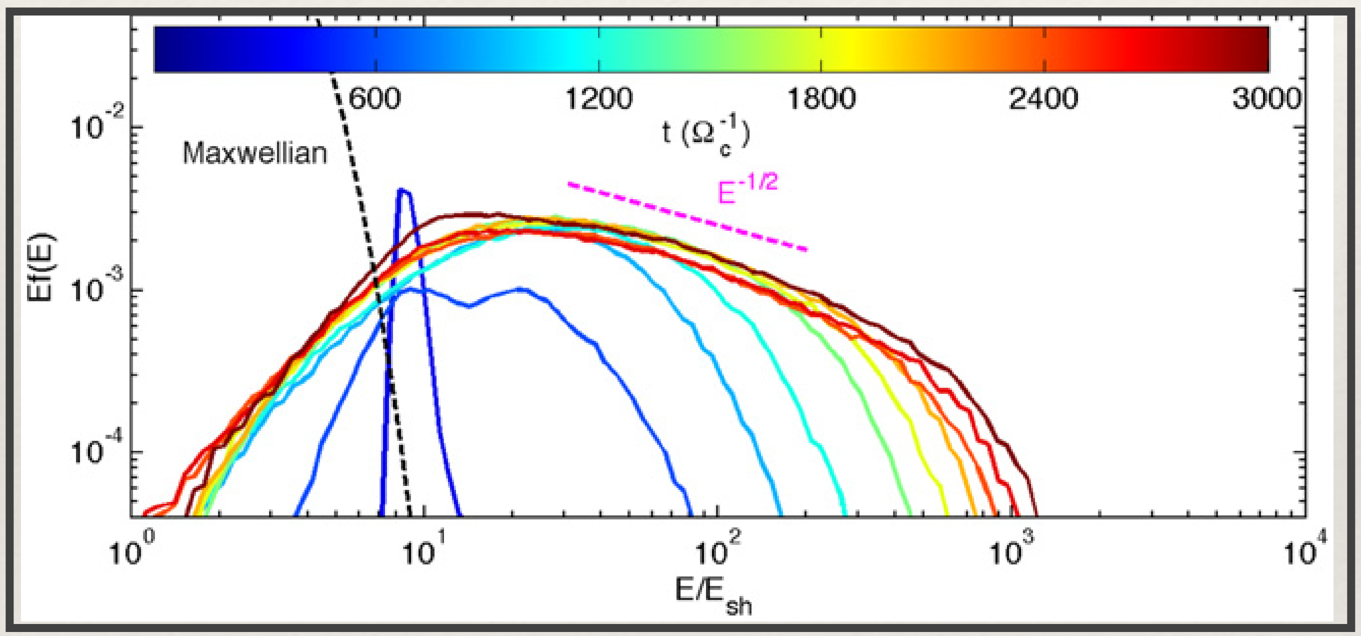
Simulation Setup

Vx = -Ma = -30

$L_y = 3 \times 10^3 c/\omega_{pi}[256pts]$

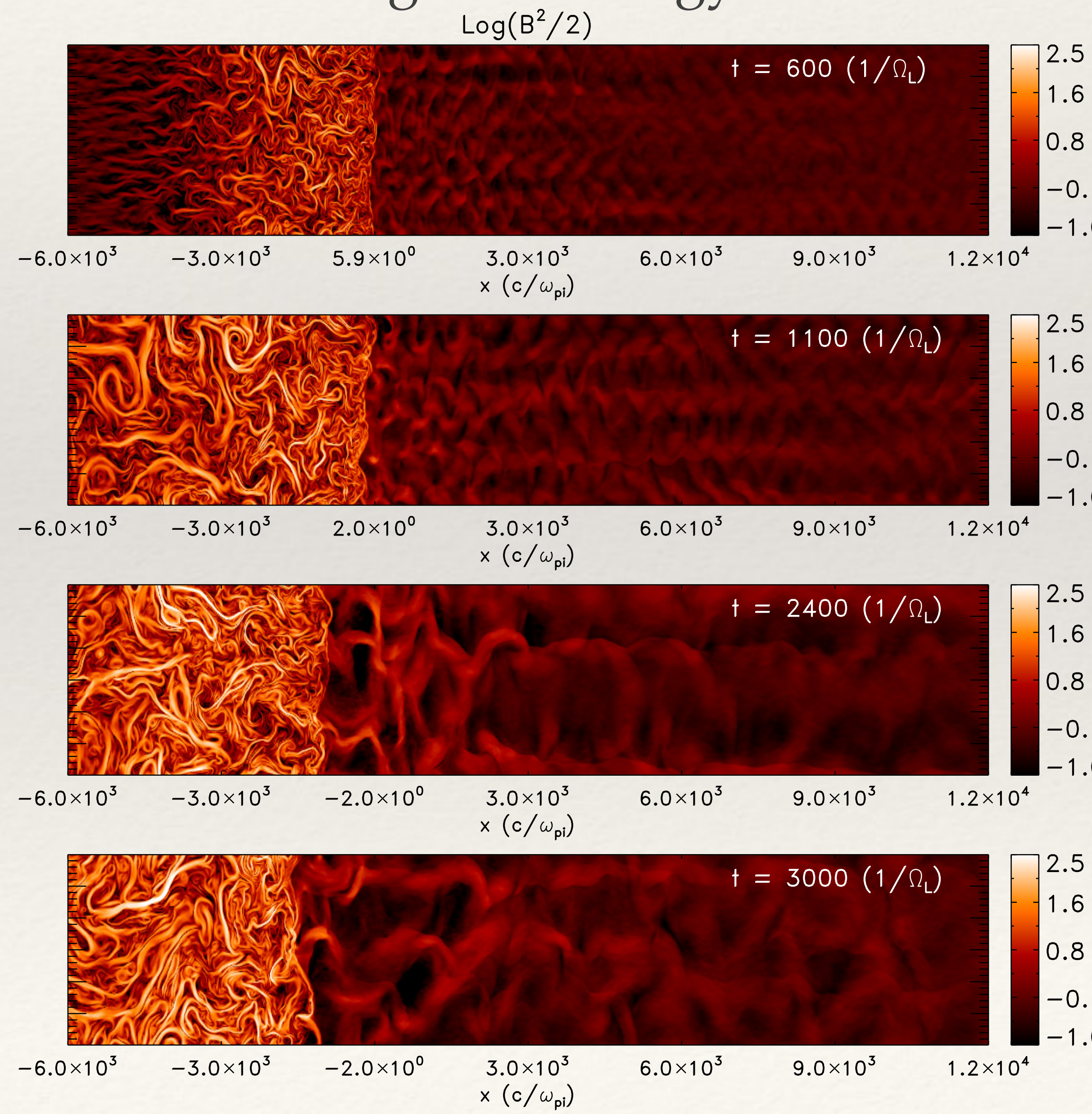
B = (1.0, 0, 0) $\rho_0 = 1 = p_0$

$L_x = 1.2 \times 10^5 c/\omega_{pi}[10240pts]$



Energy Spectra.

Magnetic Energy



Bai et. al 2015, Mignone et. al 2017 (in prep)

Physical Scales in Jets

Physical Quantity	Young Stellar Outflows (YSOs)	Active Galactic Nuclei Jets (AGN Jets)
Length Scale	0.1-1 pc (1 pc = 3 x 10^{18} cm)	1 - 10 kpc
Jet Radius	10s of AU (1 AU = 1.5 x 10^{13} cm)	100 pc
Velocity	Supersonic : 100-500 km/s	Relativistic, Bulk Lorentz Factor : 3 - 10
Opening Angles	5 - 30 degrees	1 - 10 degrees.
Mass Outflow Rates	10^{-5} - 10^{-7} Msun/yr	0.1-10 Msun/yr
Radiation Emission	Largely Thermal	Dominated by Non-thermal emission.

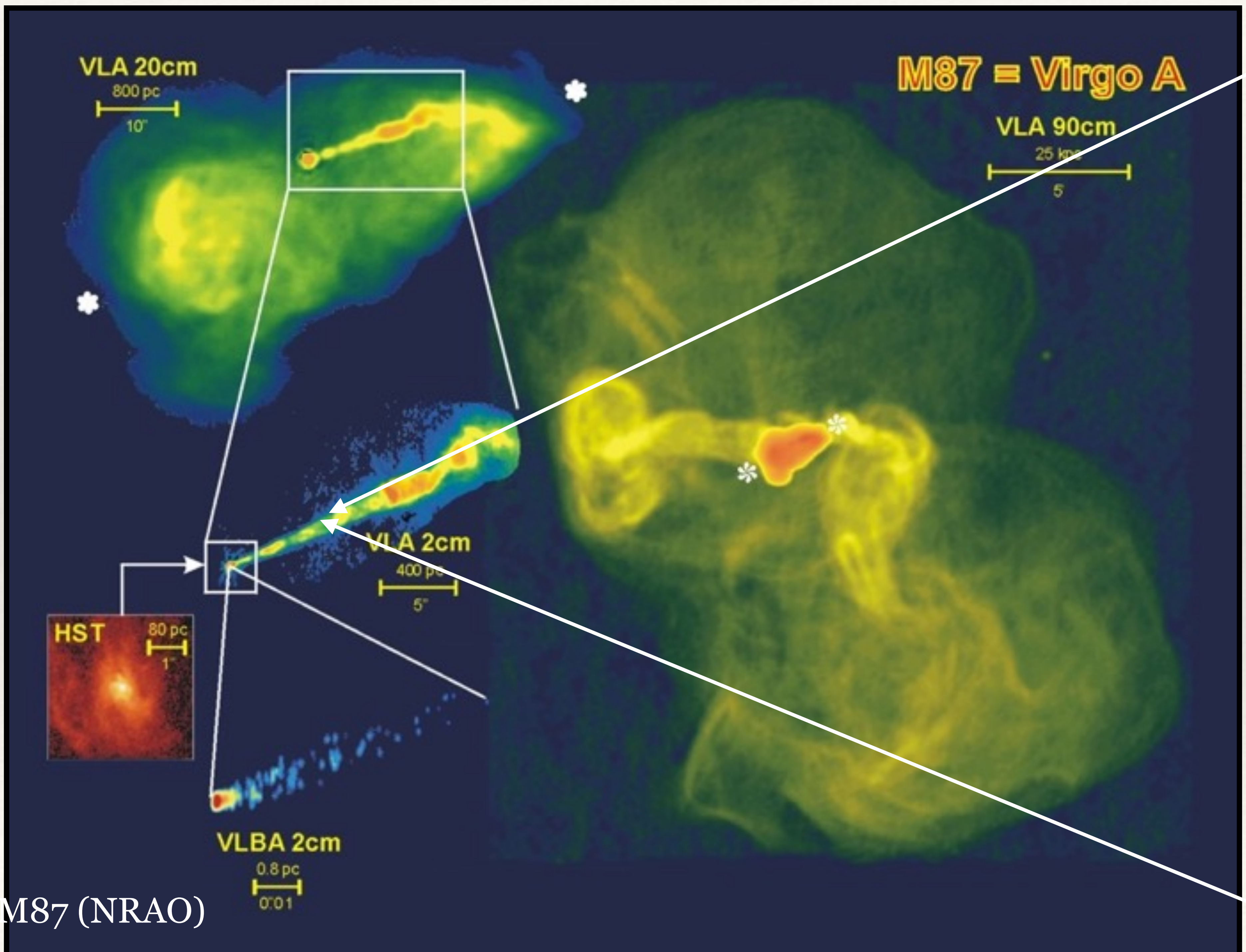
Multi Wavelength AGN Jets

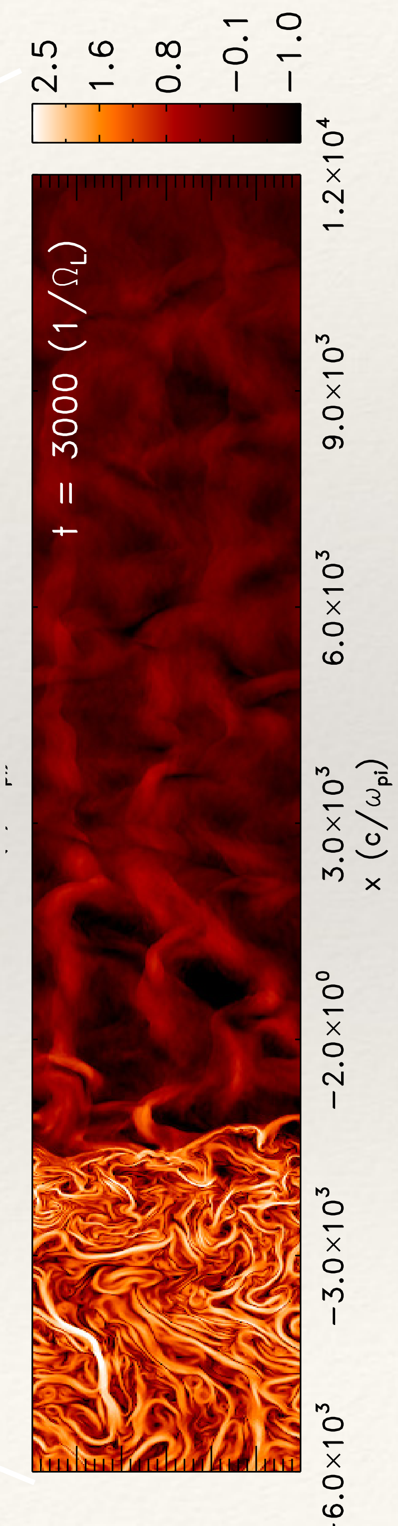
Observed Scale : Few Kilo Parsec

$\approx 10^{21} cm$

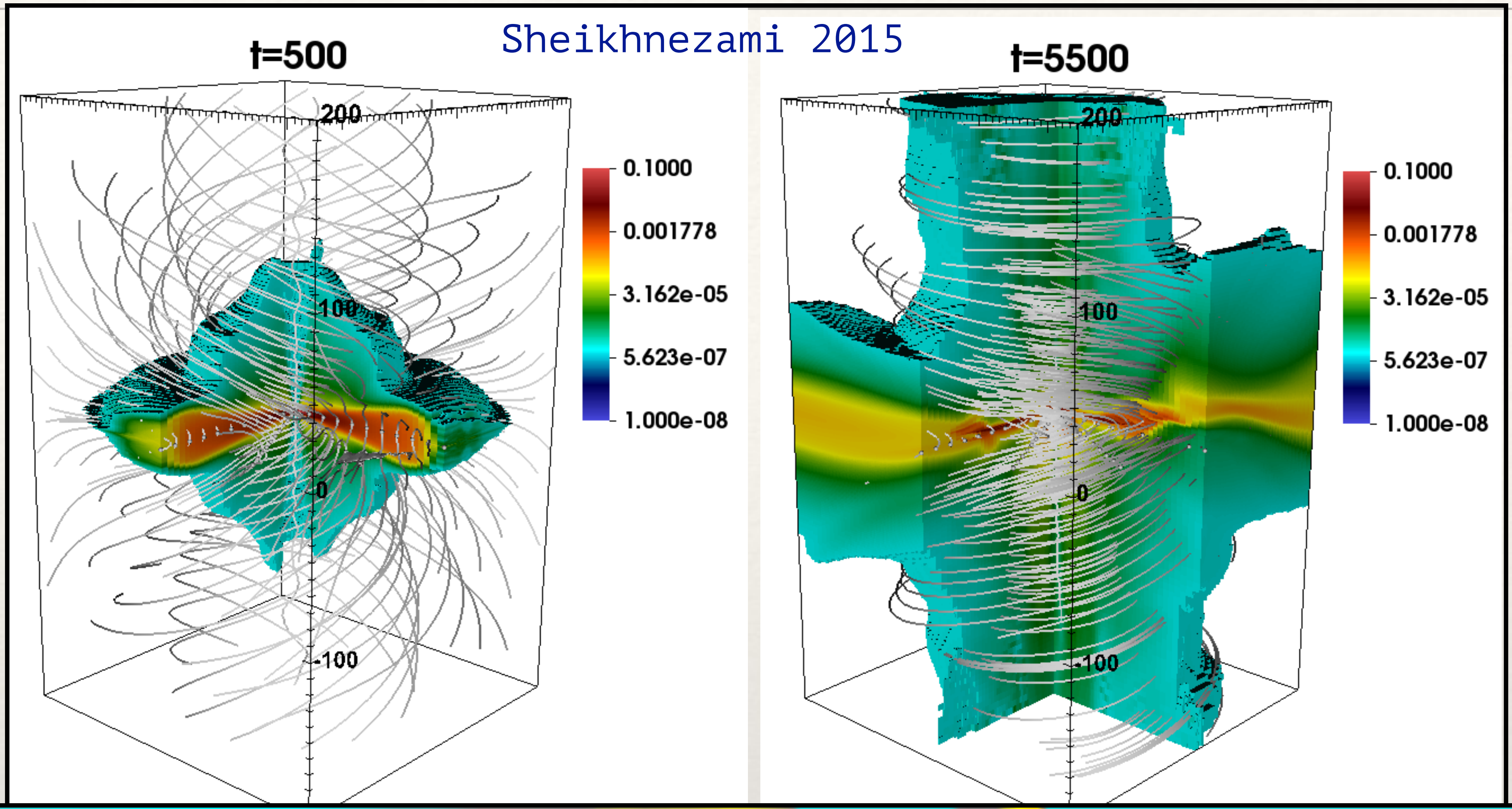
DSA Scale : Thousand Ion Inertial Scale

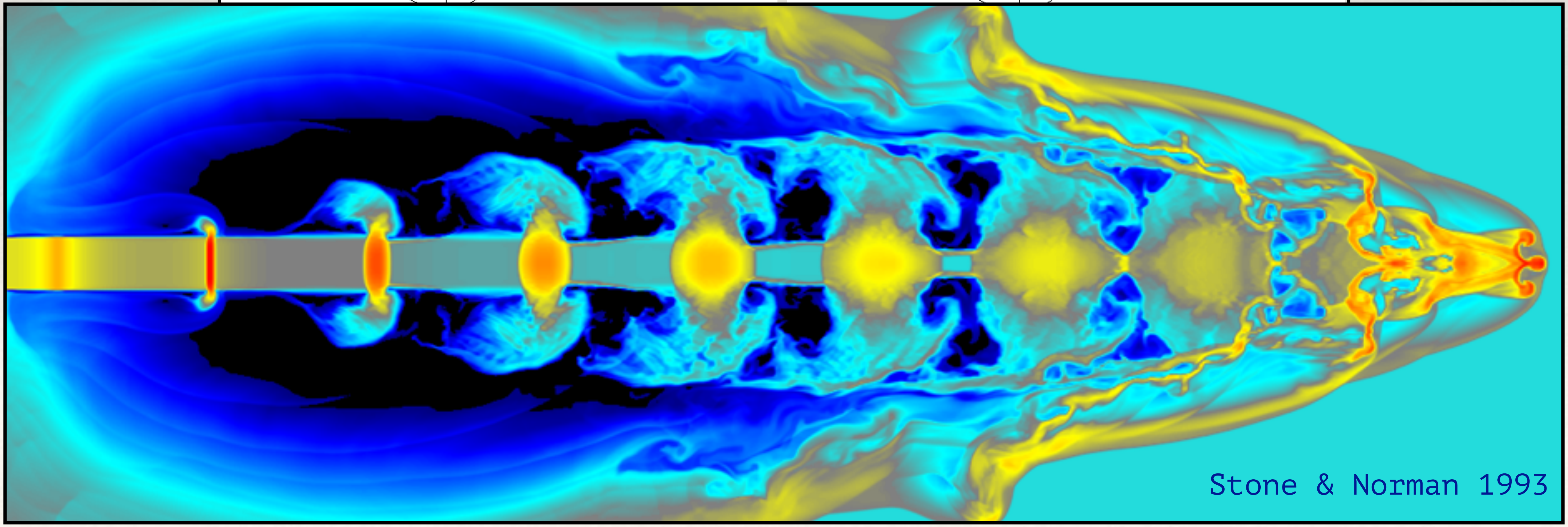
$\approx 10^{8-9} cm$



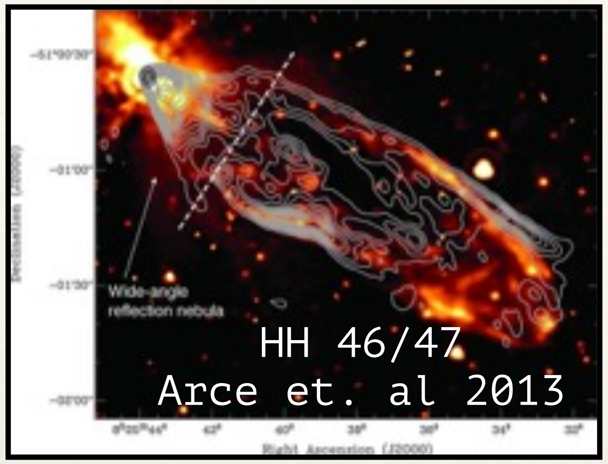


Multi-Scale Nature.





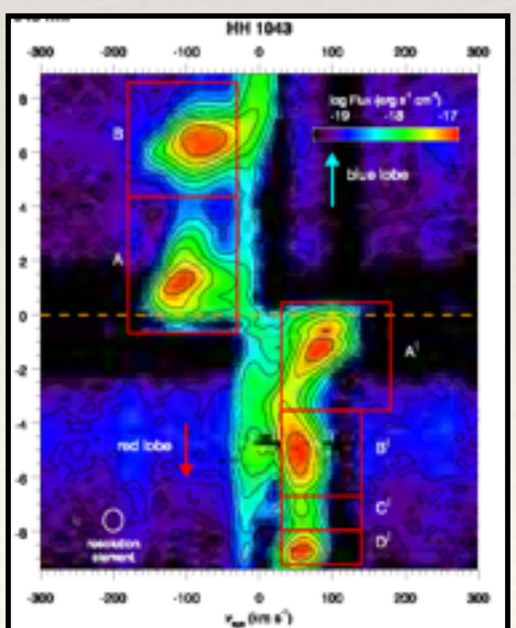
A much needed bridge!



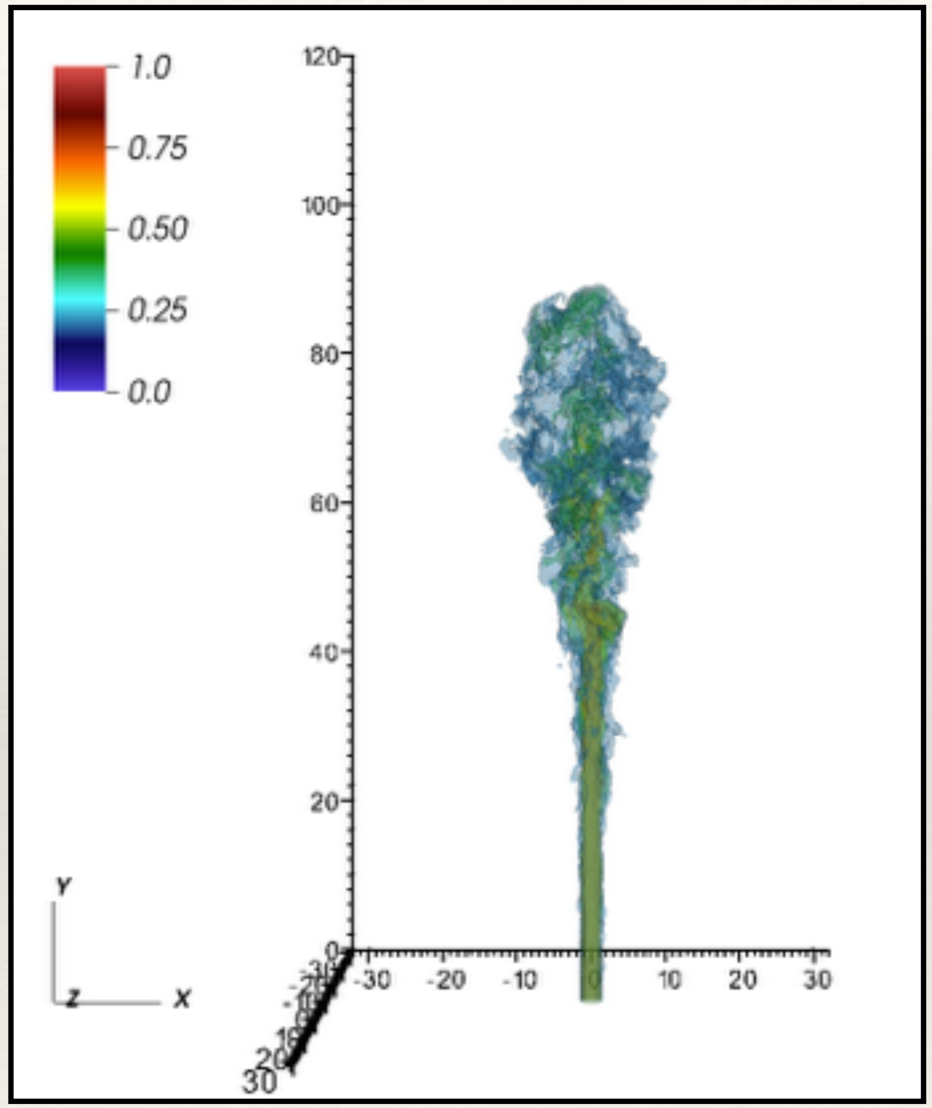
HH 46/47
Arce et. al 2013

IR H_2 Emission HH211
McCaughrean et. al 1994

FeII PV Diagram HH 1043
Ellerbroek et. al. 2013

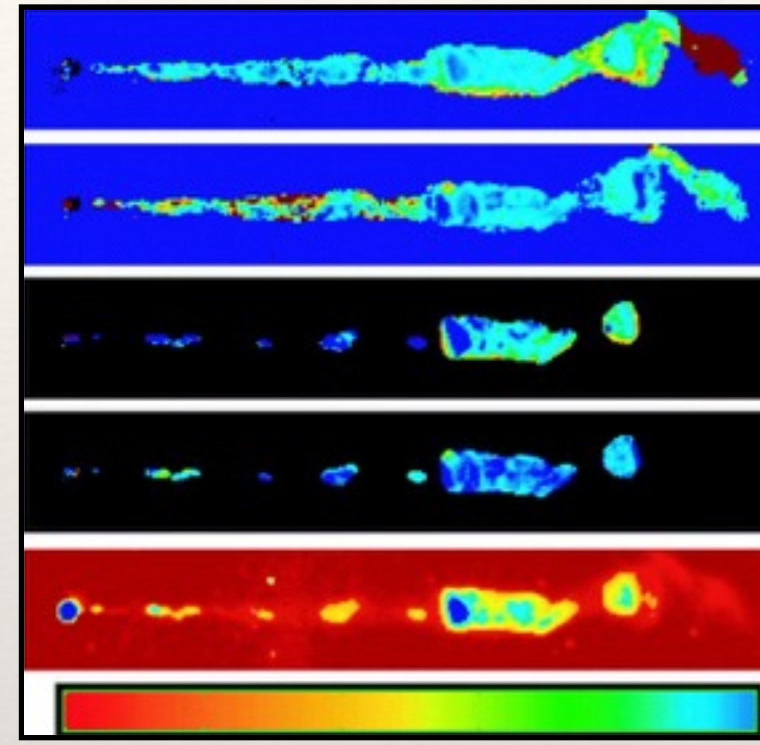


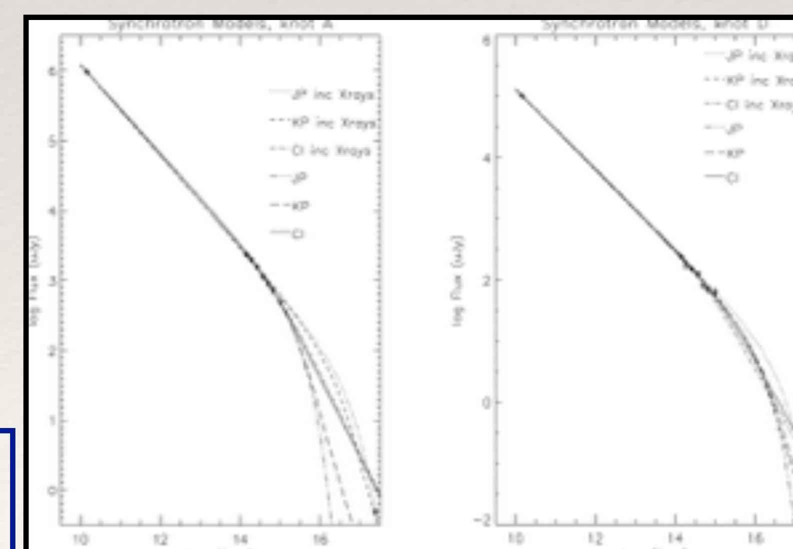
Simulations (MacroPhysics)
Density, Velocity, Temperature, Magnetic field strengths.



Bridging Factor (MicroPhysics)
Chemistry, Thermodynamics, Radiative processes, Particle Acceleration, Polarisation.

Multi-wavelength Emission
and Spectra from M87



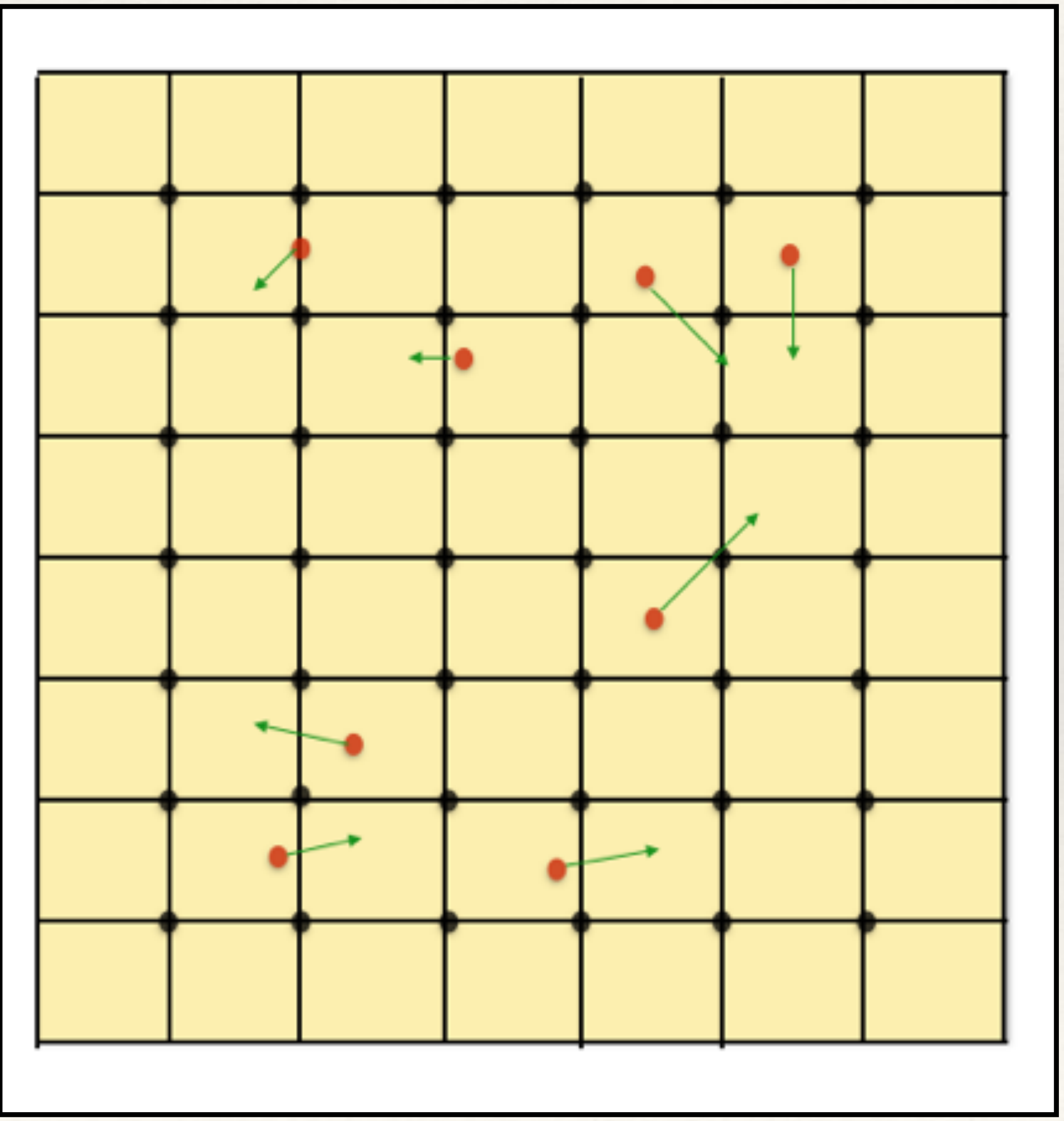


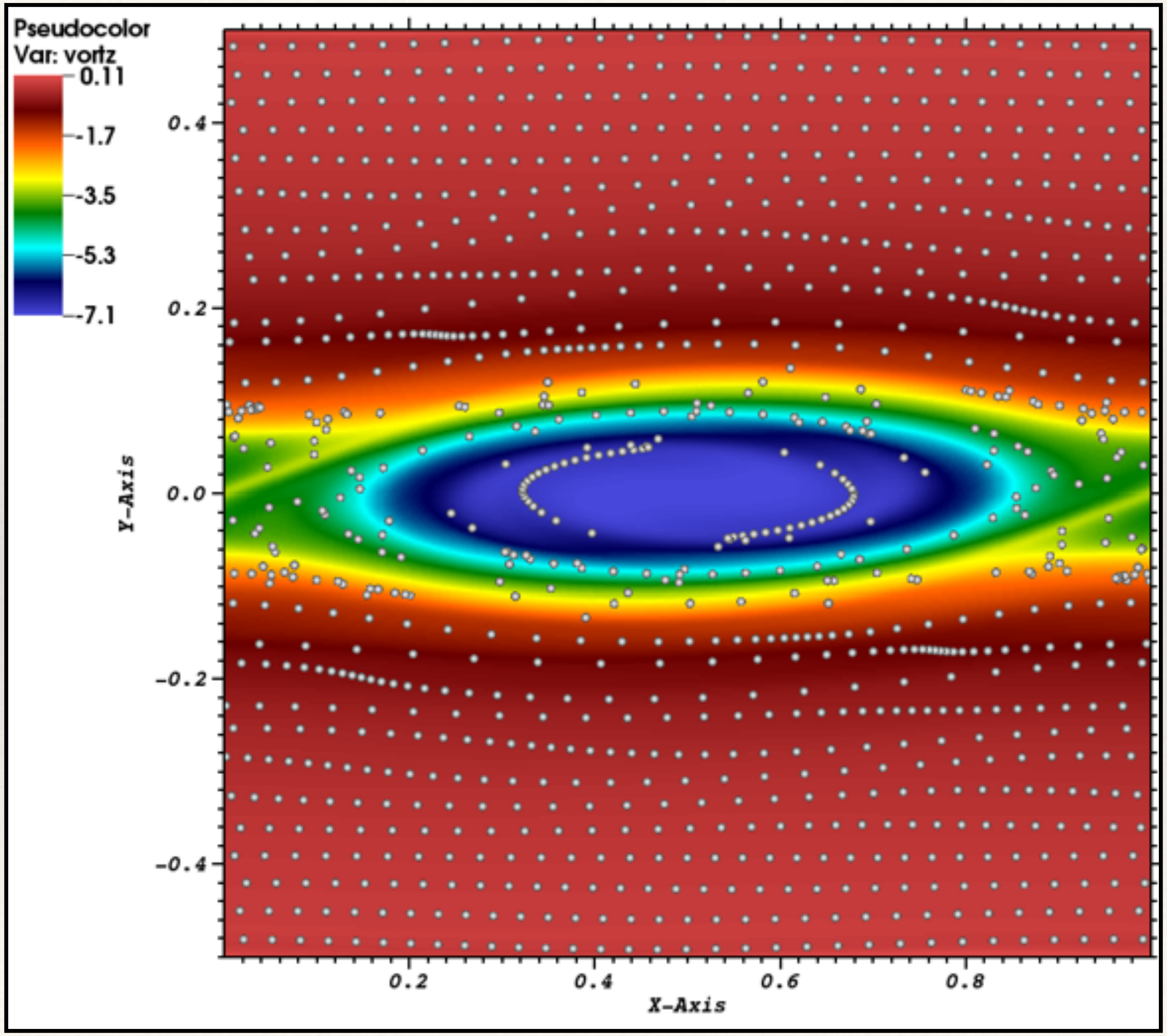
Lagrangian Particle Entities

(Vaidya et. al. 2016)

Particles <u>follow</u> the fluid passively : Proxies for ***<u>unresolved microphysics.</u>***

$$\boxed{\frac{d\mathbf{x_p}}{dt} = \mathbf{v_p} = \mathbf{v_{f\rightarrow p}}}$$

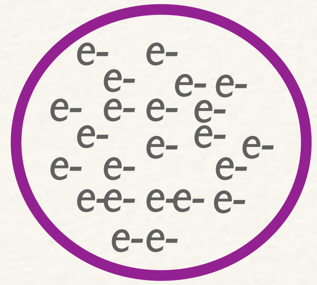




MacroParticles and Sub-grid Physics

Macro Particles are an ensemble

of (say) electrons having a wide energy spectrum but located in a nearby physical space.



Grid in Particle Energy Space — Initial E_{min} to E_{max} with log-spaced bins.

Particle Density — Initial Power Law distribution $N(E) = N_0\, E^{-p}$;

Fokker-Planck Equation :

$$\boxed{\frac{\partial f}{\partial t} = -(\mathbf{u}.\nabla)f + \frac{1}{3}(\nabla\cdot\mathbf{u})p\frac{\partial f}{\partial p} + \nabla_i(D_{ij}\nabla_j f) + \frac{1}{p^2}\frac{\partial}{\partial p}\left(D_{pp}p^2\frac{\partial f}{\partial p} + a_{syn}p^4 f\right)}$$

$$\boxed{a_{syn} = \frac{\sigma_T B_\perp^2}{6\pi m_e^2 c^2}}$$

Synchrotron Losses

Adiabatic (de-)compression.

Second Order Fermi (sub-grid physics??)

First Order Fermi : Asymptotic Limit

$$\boxed{f_+(p) = bp^{-q}\int_0^p p'^{(q-1)} f_-(p')dp'; \quad b = \frac{3u_1}{u_2-u_1}; \quad q = \frac{3r}{r-1}}$$

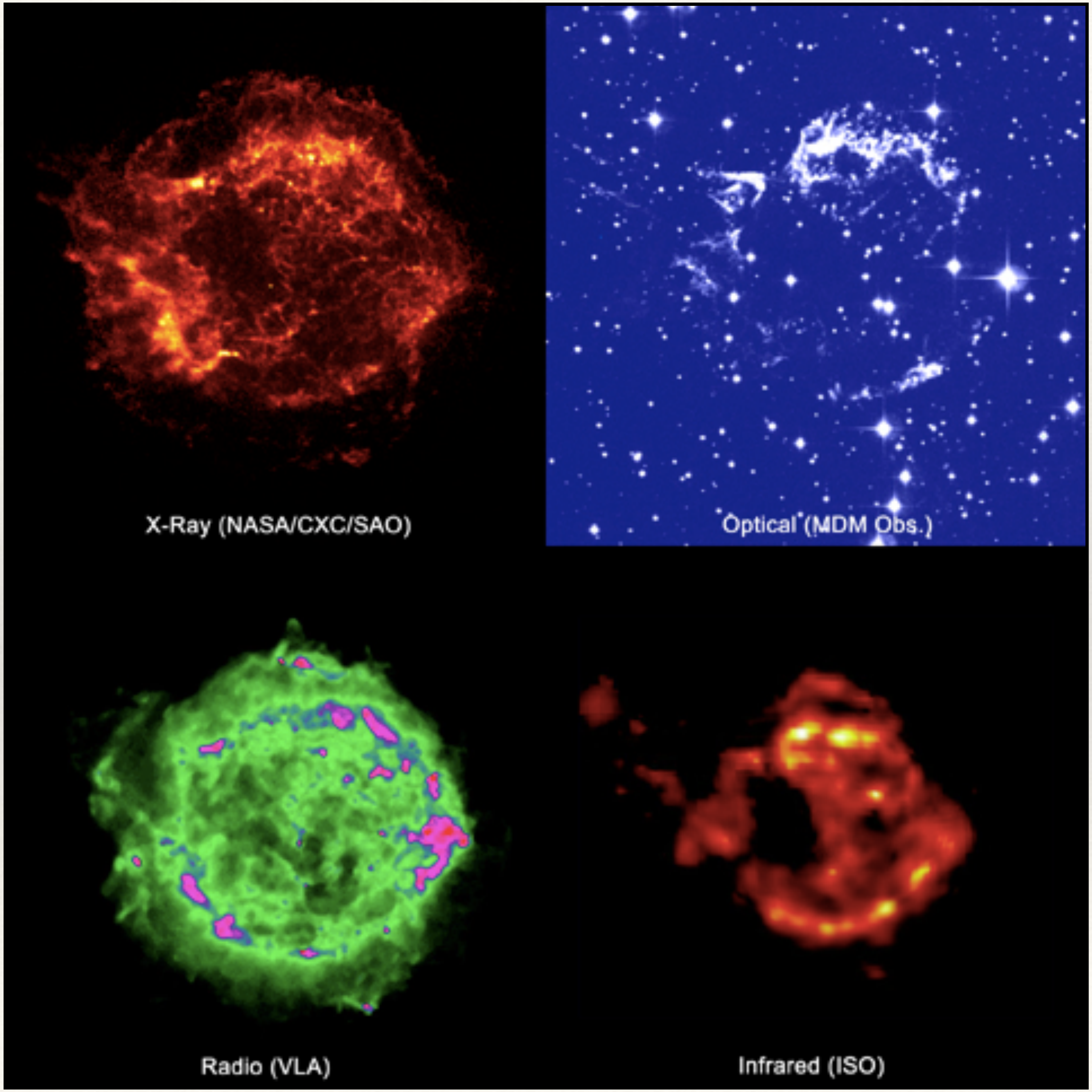
$$\boxed{D_{pp} = 0}$$

(Melrose & Pope 1993, Micono 1999, Parker 2014)

Compression Ratio.

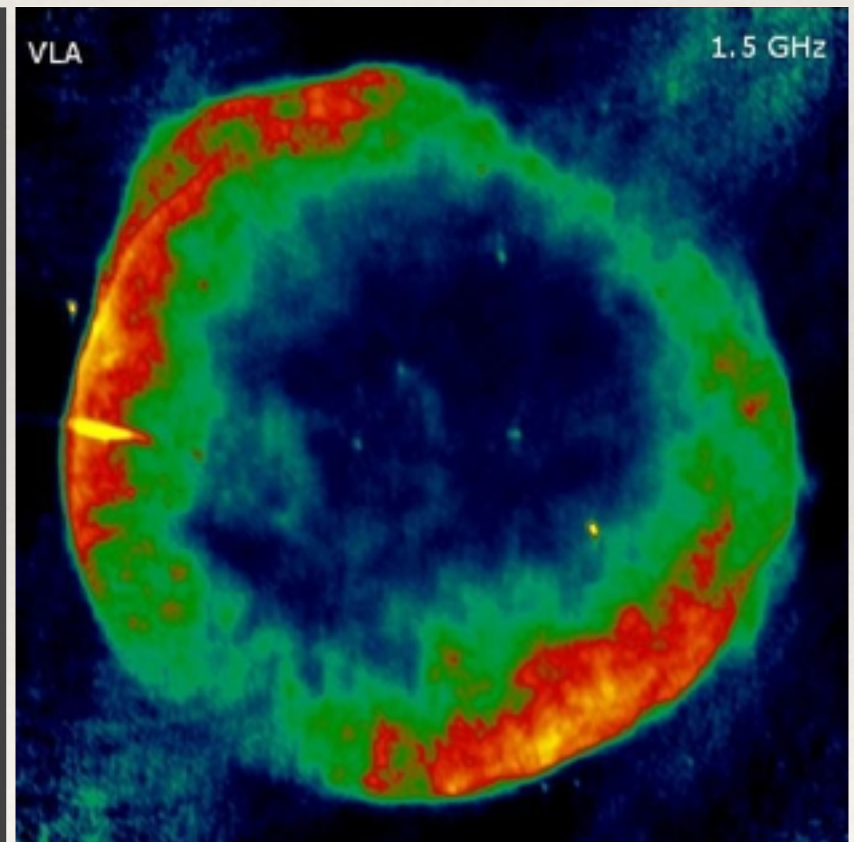
SNR & Shocks

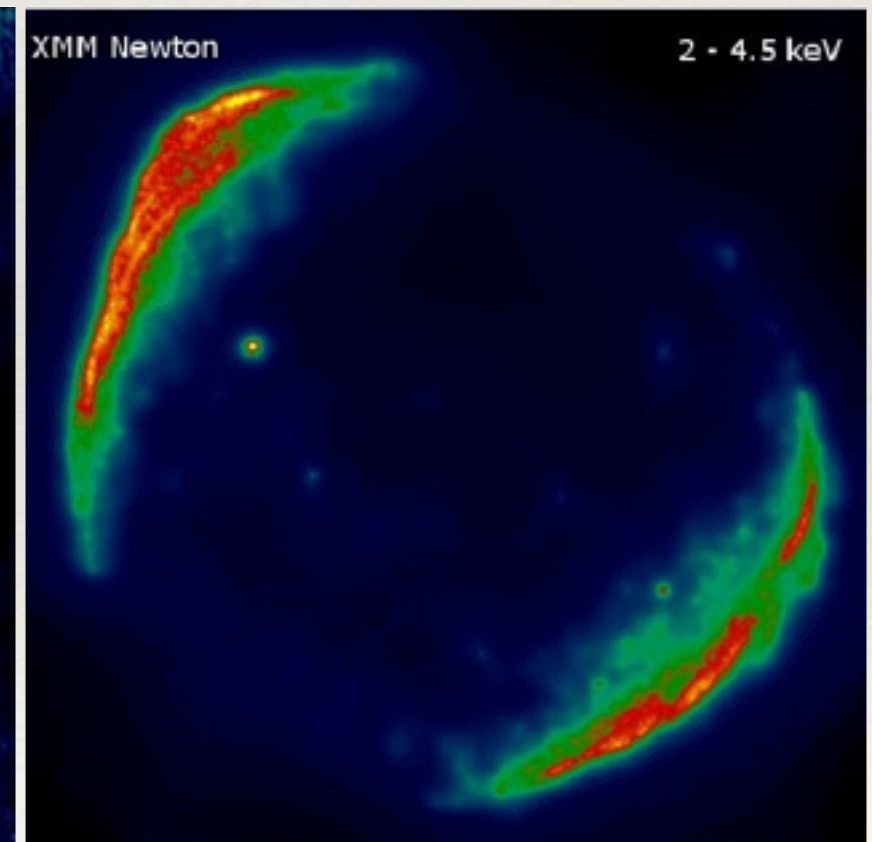
- Late stages of massive stars results in an energetic explosion forming shocks.
- Thermal radiation [IR, and Optical] dominated by heating due to shocks.
- Non-thermal radiation [Radio & Xray] due to synchrotron processes.
- Believed to be sources of Galactic Cosmic rays up to the knee.



SN 1006 : A Textbook Case

- Distance of 7000 light years : (Documented by Chinese Astronomers : 1st May 1006)
- After 1001 years — Radial extent is about 10 pc.
- Non-thermal synchrotron X rays (Koyama et. al. 1995, Dyer et. al. 2001)
- IC Scattering of Synchrotron electron with CMB —> TeV Gamma (Pohl 2008).





Simulation Setup.

- Numerous 2D and 3D models for SN1006 without the use of Particles.
  [Orlando 2007, Bocchino 2011, Schneiter 2010]
- For our first simple application of Lagrangian particle module, we adopt the 2D model with isotropic injection.

Grid:

$$r \times z = 12 \times 24\,pc; \Delta r = \Delta z = 1.56 \times 10^{-2} pc$$

Ambient:

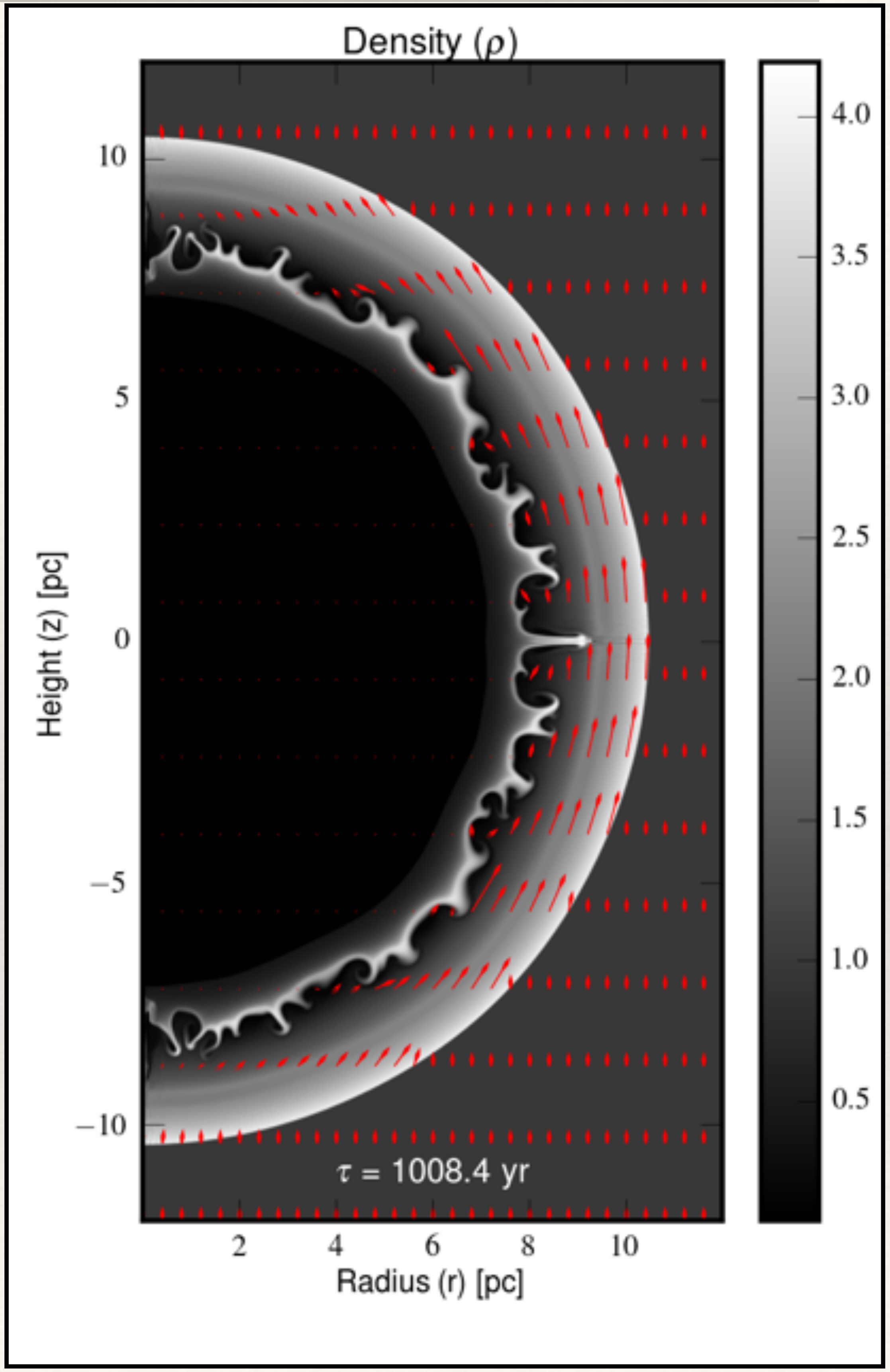
$$n_0 = 0.05cm^{-3}, \vec{B} = 2\mu G\hat{z}$$

Ejecta:

$$r_0 = 0.65pc, M_0 = 1.4M_\odot$$

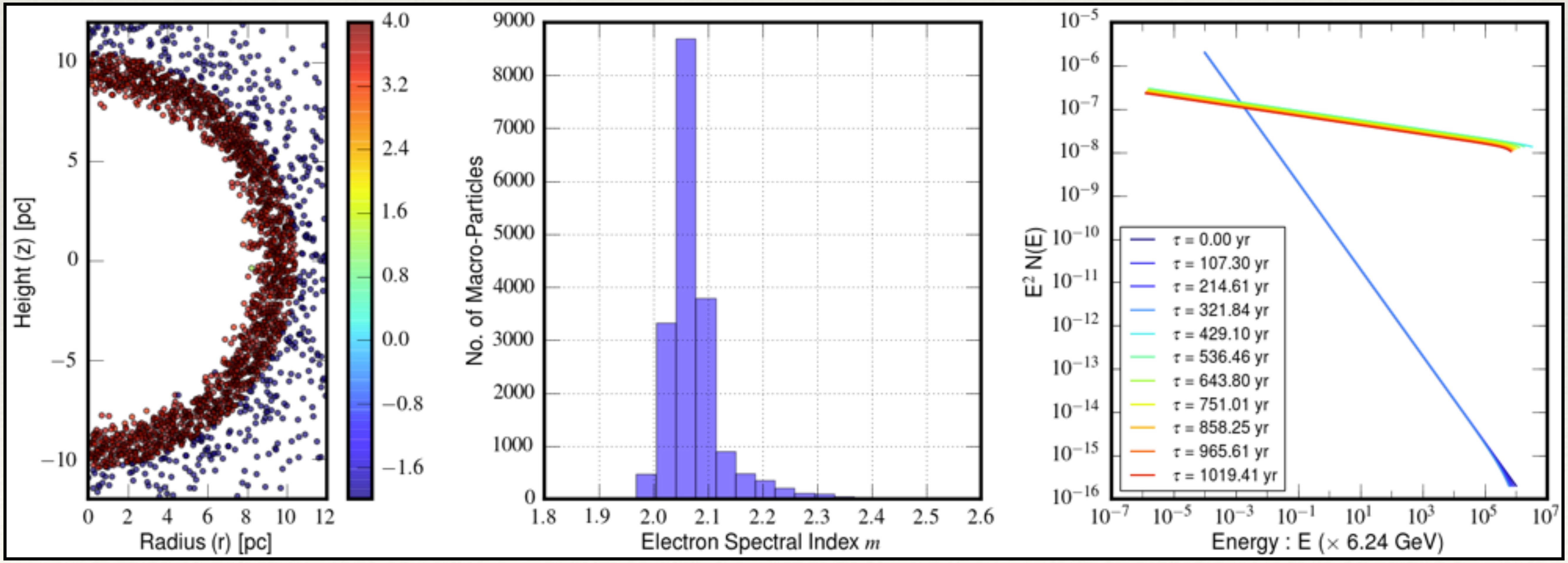
EoS:

$$\gamma = 5/3$$



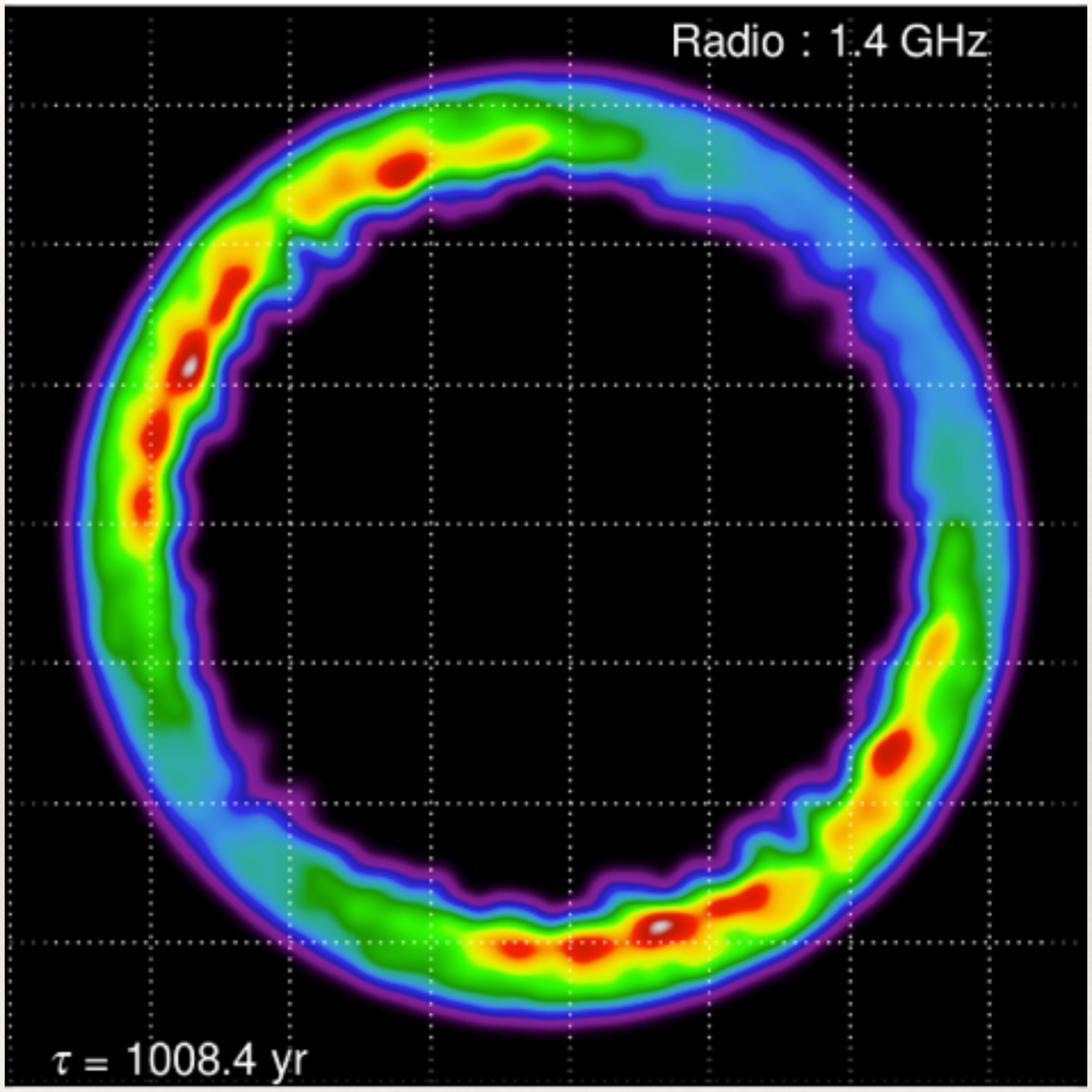
Strong SN1006 Shock.

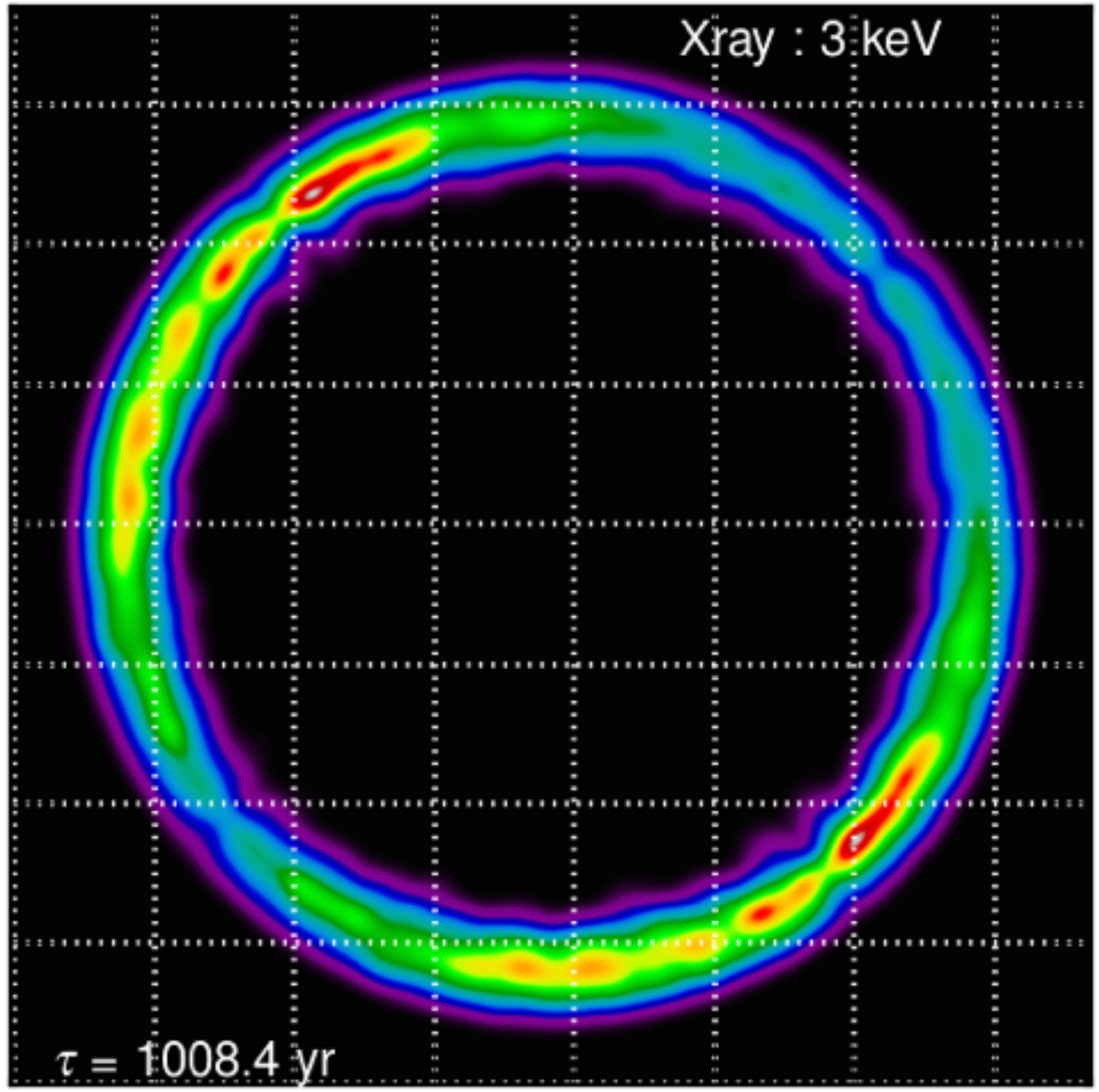
- Random distribution of 10^5 Macro particles in ambient medium.
- Strong Adiabatic Shock : $r = \frac{\rho_d}{\rho_u} \approx 4 \Longrightarrow q \gtrsim 2.$
- Observed spectral index : $S_v \propto \nu^{-\alpha}; \alpha = 0.5 - 0.6 \Rightarrow q = 2.0 - 2.2$



Supernova SN 1006

Simulated Emissivity for two bands

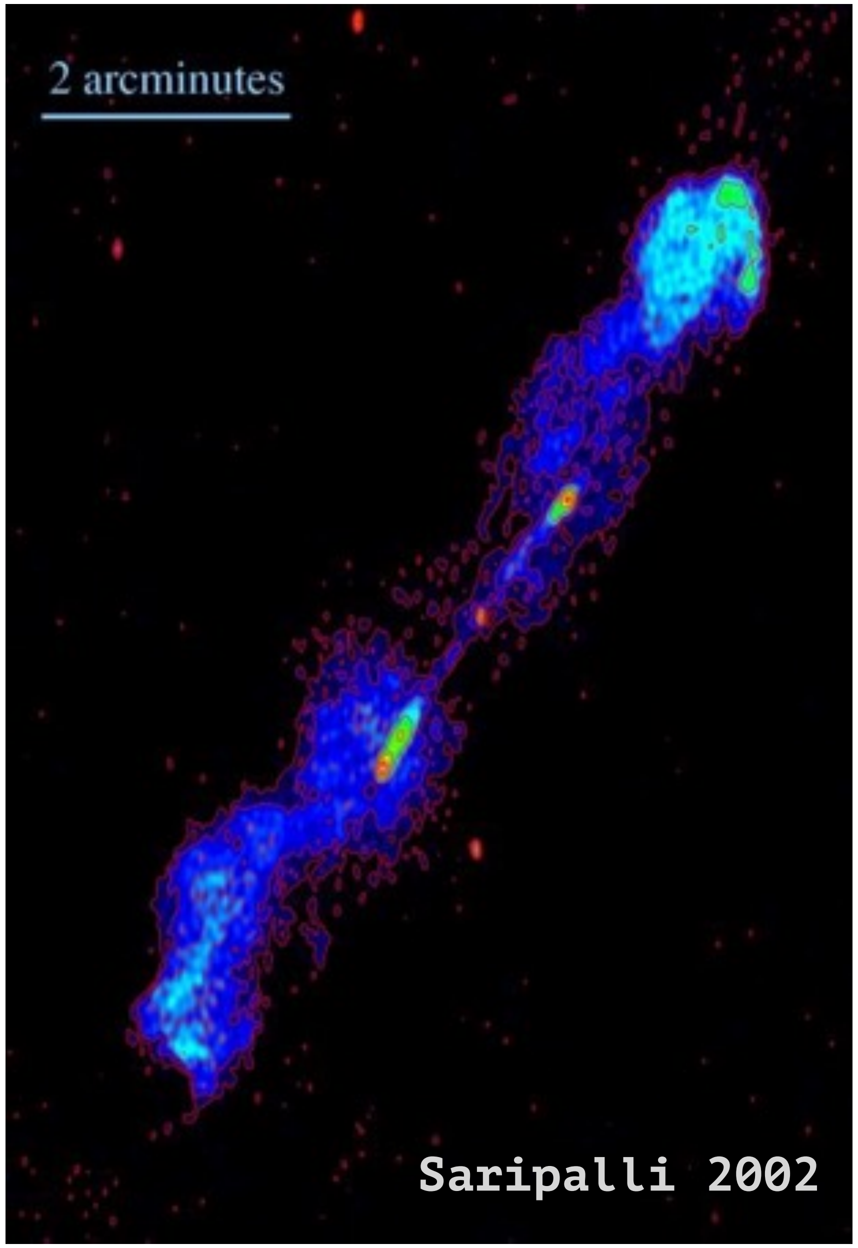




Bright rim features : Qualitative Comparison

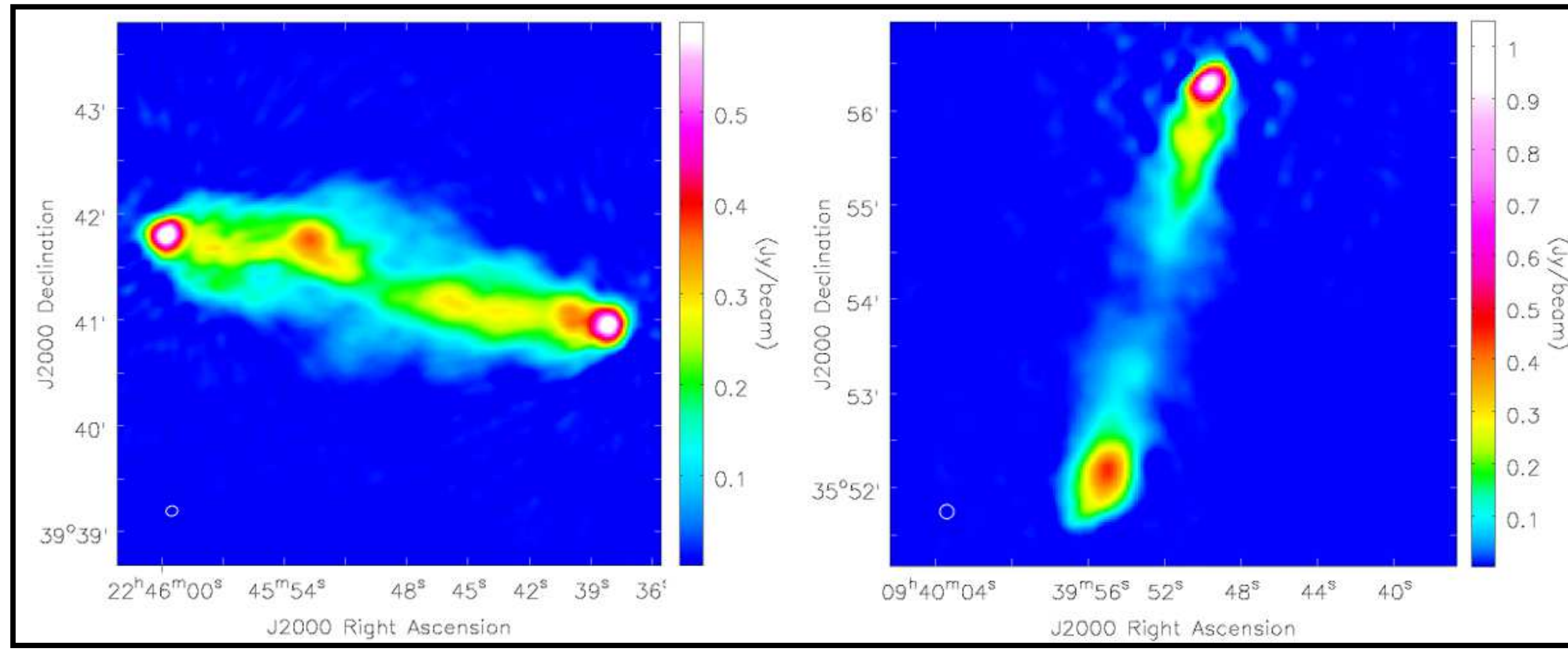
A proper Quantitative Comparison would require **3D models** in future.

Kilo Parsec Scale Radio Jets



Giant radio galaxy B1545-32 : 13 cm wavelength ATCA image

Safouris et. al. 2008

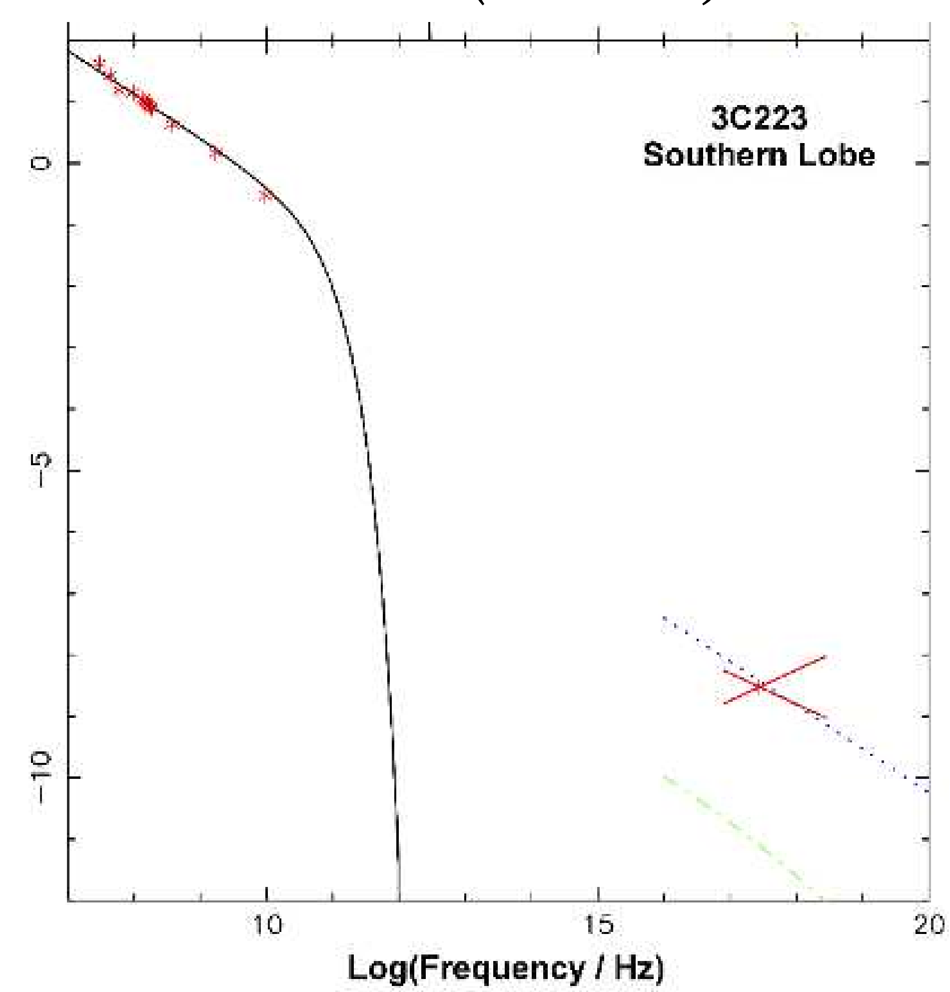


3C452 (138 MHz)

3C233 (147 MHz)

Dying, Fading Radio Remnants with LOFAR

ASTRON Group, Harwood 2016



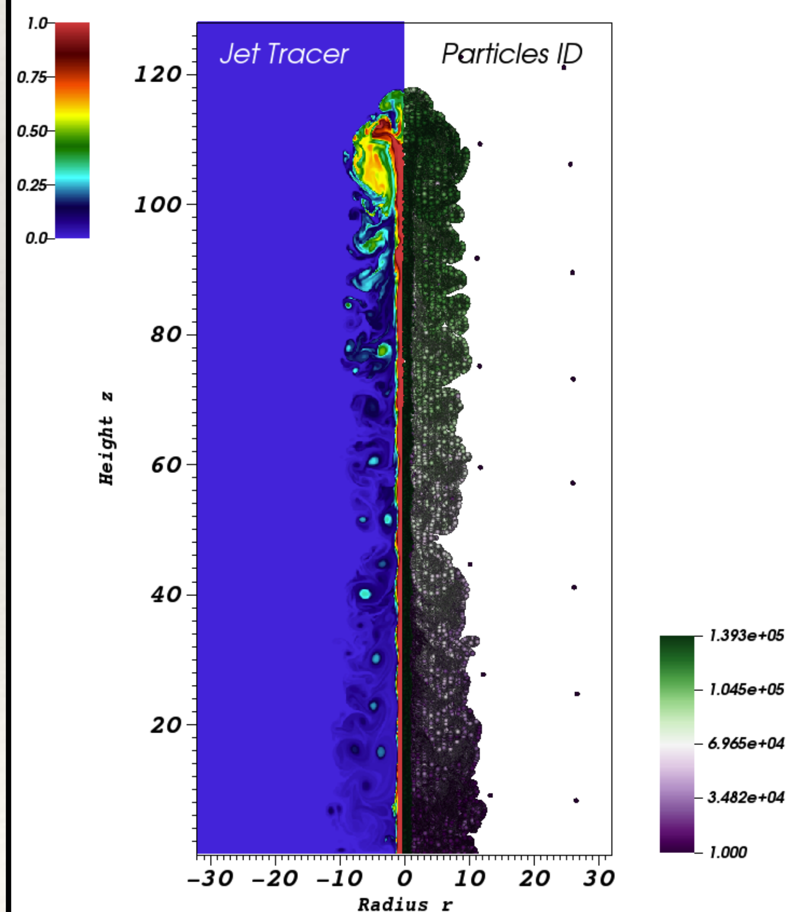
Application in MHD Jets.

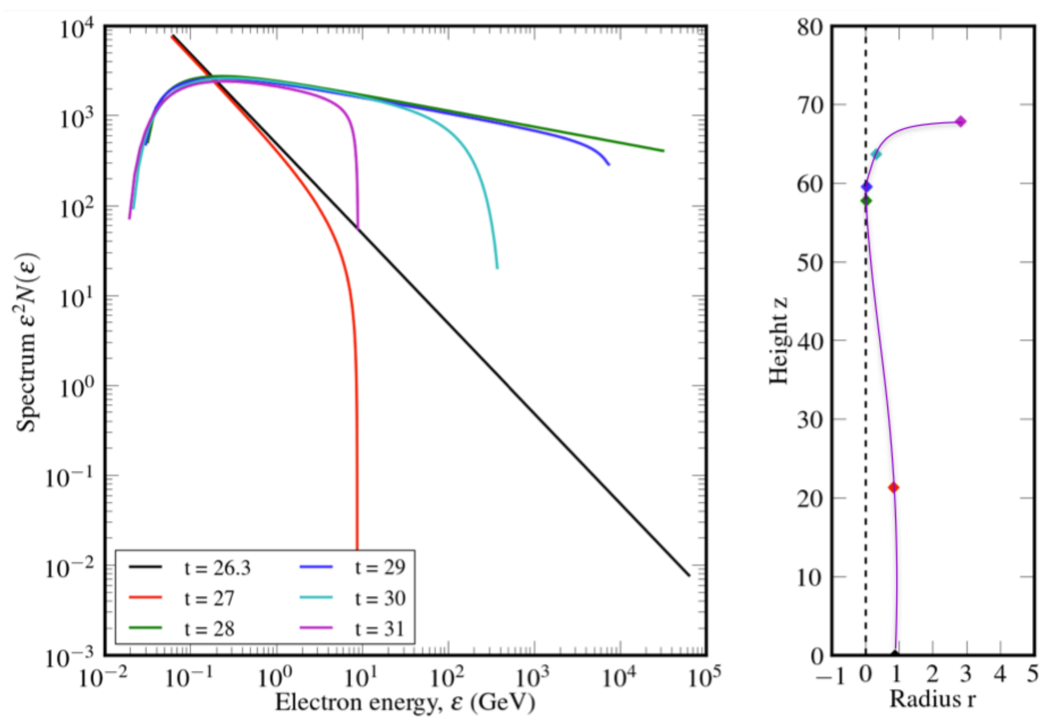
Vaidya et. al 2016

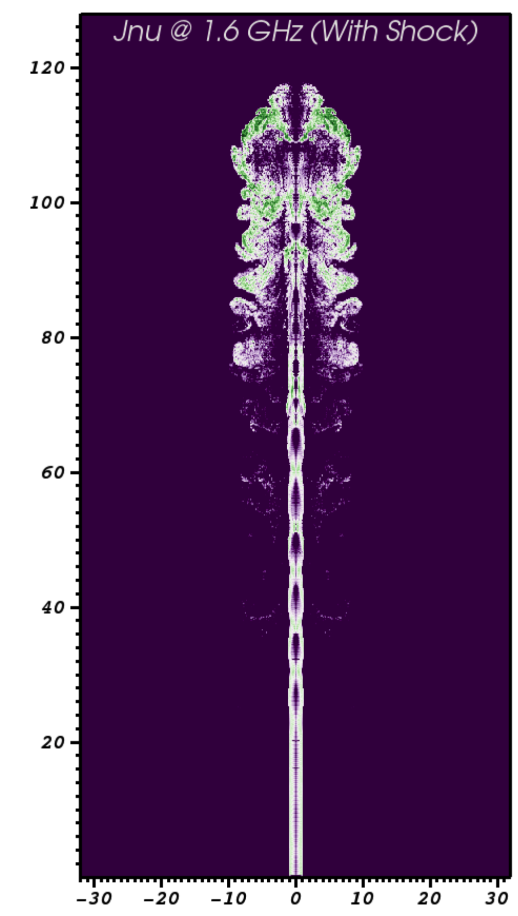
Axisymmetric MHD Jet

Grid : $[r_{\max}, z_{\max}] = [3.2, 12.8]$ kpc ;
$\Delta r = \Delta z = 12.5$ pc., $R_{\rm jet} = 100pc$
$\rho_{\rm j} = 10^{-2} cm^{-3}; \mathcal{M}_s = 4$
Toroidal Field Dominated : $\vec{B}_{\rm j} = 100\mu G\hat{\phi}$

Particles Injected amounting to
$N_{\rm p} = 1.3 \times 10^5$MPs. Initial Spectrum a power
law : $N(E,t) \propto E^{-3}$,
$[E_{\min}, E_{\max}] = [10^{-4}, 100]$ ergs

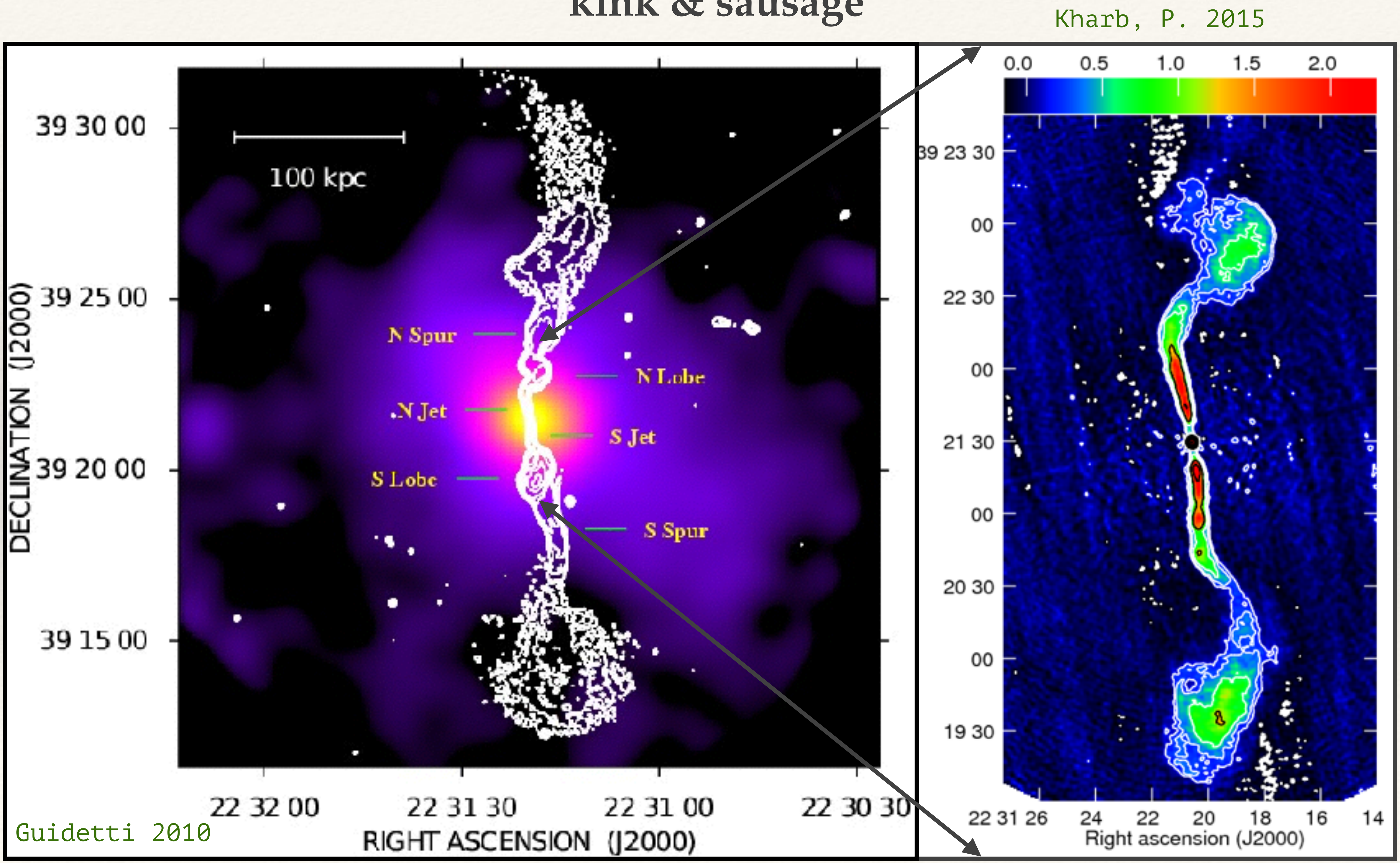






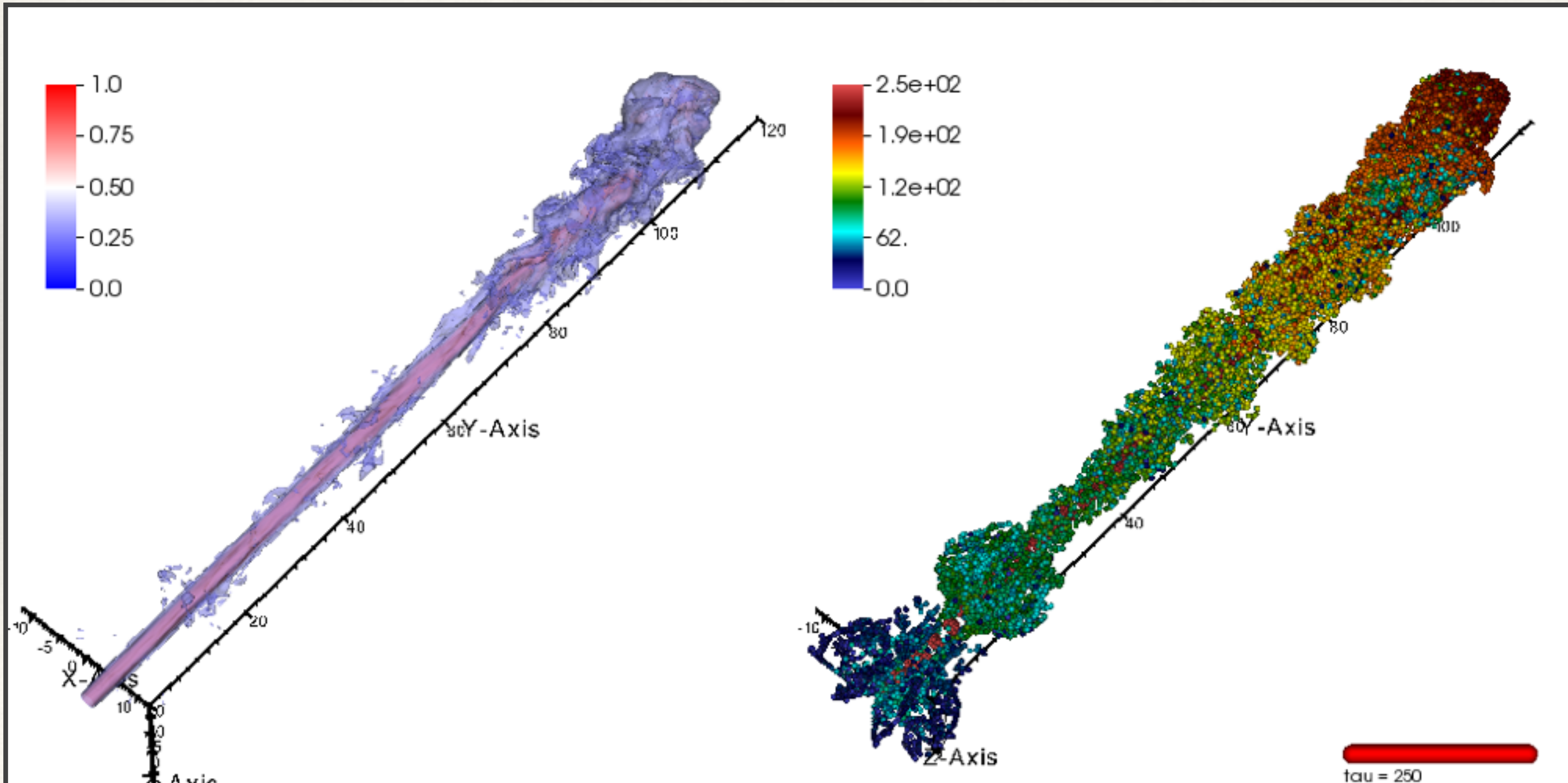
Instabilities in 3C 499

Magnetised jets are subject to non axisymmetric instability : kink & sausage



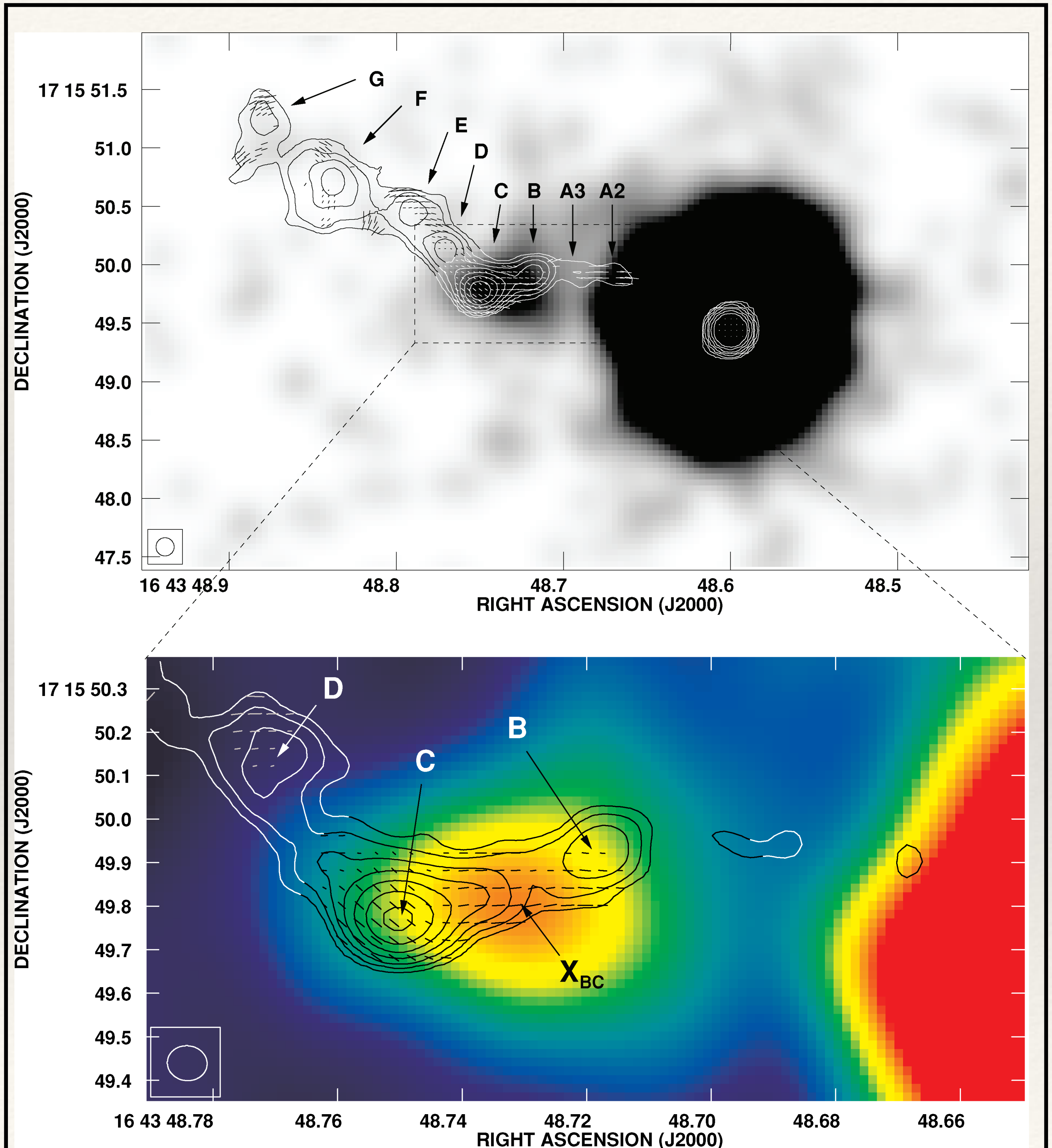
Going to 3D!

Extending the 2D Axisymmetric jet to 3D results in formation of turbulent head.

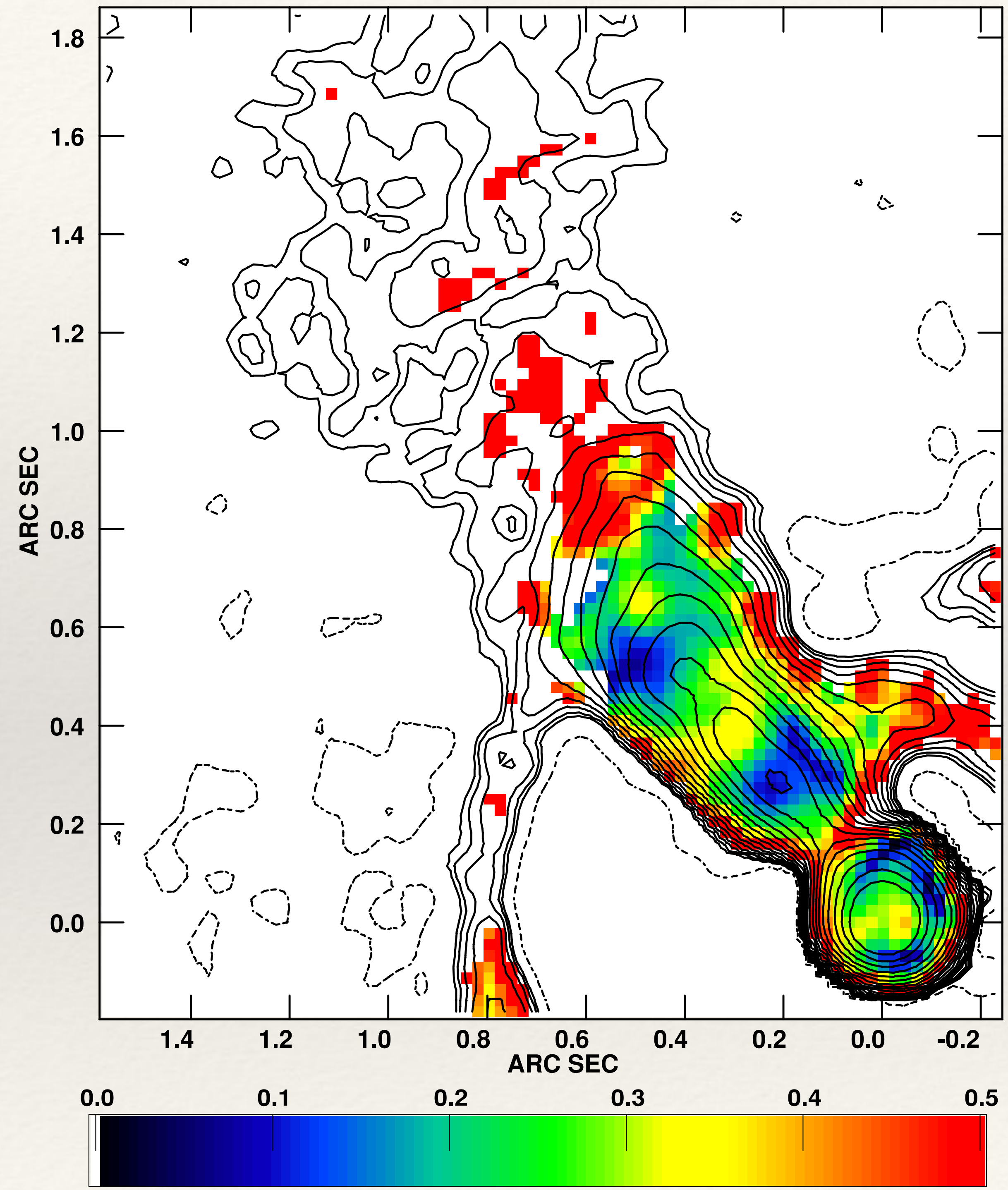


Close to the Black hole!

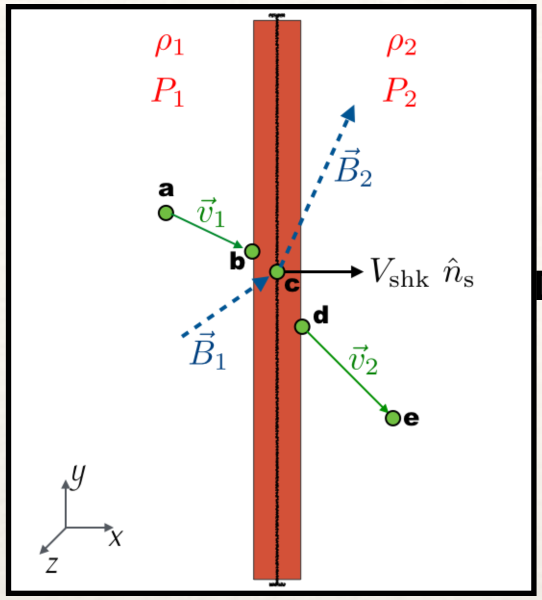
A Case of 3C 346 (Worrall 2005, Dulwich 2009)



Polarisation 3C 264 (Perlmann 2010)



DSA Relativistic Shocks.



Shock Rest Frame

Normal Incidence Frame

Compression

$$r = \frac{\beta_u^{NIF}}{\beta_d^{NIF}}$$

Injection of High Energy Particles.

$$N_{\rm inj}(E) \propto E^{-m}$$

$$m = \frac{3r}{r-1} - 2 + \delta$$

Monte Carlo Simulations.

$$m = 2.23$$

Dependence on orientation of B fields.

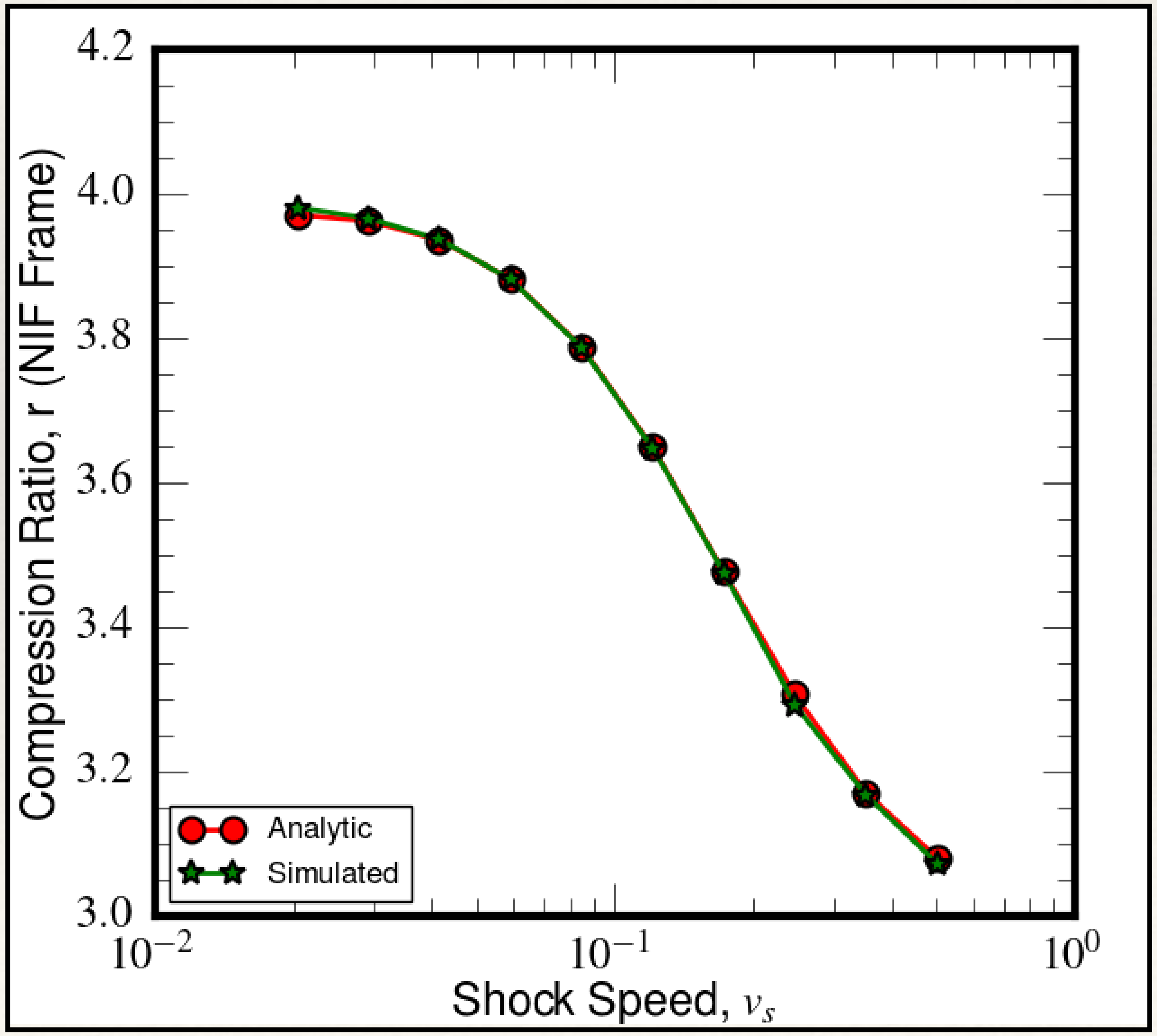
$$B \parallel \hat{n}_{\rm shk} \rightarrow \delta = \left(\frac{1-2r}{r-1}\right)\beta_d^2$$

Keshet & Waxman 2005

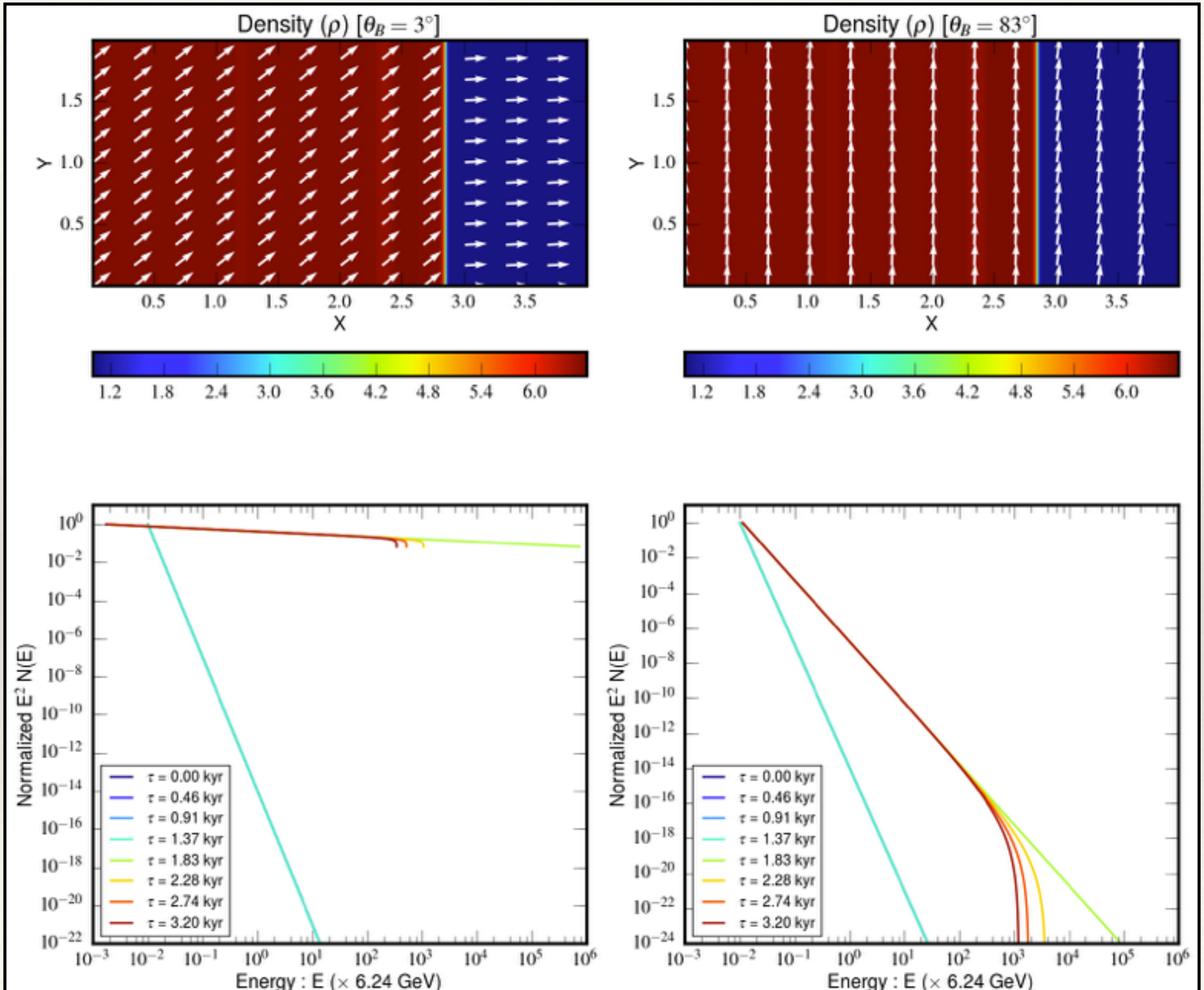
$$B \perp \hat{n}_{\rm shk} \rightarrow \delta = \frac{9}{20}\left(\frac{r+1}{r(r-1)}\right)\eta^2\beta_u^2$$

Takamoto & Kirk 2015

Free Turbulence Parameter



DSA Relativistic Shocks



Emissivity and Polarisation

(Longair, M. 1994, Lyutikov, M. 2005)

Total observed emissivity due to synchrotron emission : (Prime Quantities in Co-moving Frame)

$$\boxed{J_{sy}(\nu; E, \boldsymbol{B}, \hat{\boldsymbol{n}}_{los}) = \int_{E_i}^{E_f} \mathcal{D}^2 j'_\nu(E, \boldsymbol{B}', \hat{\boldsymbol{n}}'_{los}) \mathcal{N}(E,t) dE}$$

where the Doppler Factor, line of sight unit vector and Magnetic field are given by

$$\mathcal{D}(\boldsymbol{\beta}, \hat{\boldsymbol{n}}_{los}) = \frac{1}{\Gamma(1 - \boldsymbol{\beta}\cdot\hat{\boldsymbol{n}}_{los})} \qquad \hat{\boldsymbol{n}}'_{los} = \mathcal{D}\left[\hat{\boldsymbol{n}}_{los} + \left(\frac{\Gamma^2}{\Gamma+1}\boldsymbol{\beta}\cdot\hat{\boldsymbol{n}}_{los} - \Gamma\right)\boldsymbol{\beta}\right] \qquad \boldsymbol{B}' = \frac{1}{\Gamma}\left[\boldsymbol{B} + \frac{\Gamma^2}{\Gamma+1}(\boldsymbol{\beta}\cdot\boldsymbol{B})\boldsymbol{\beta}\right]$$

and the single electron emissivity,

$$\boxed{\begin{aligned} j'_\nu(E, \boldsymbol{B}', \hat{\boldsymbol{n}}'_{los}) &= \frac{\sqrt{3}e^3}{m_e c^2}|\boldsymbol{B}' \times \hat{\boldsymbol{n}}'_{los}|F(x) \\ &\approx 23.44|\boldsymbol{B}' \times \hat{\boldsymbol{n}}'_{los}|F(x)\ \mathrm{Jy\,cm}^2 \end{aligned}}$$

where,

$$x \approx \frac{1.6\times 10^{-9}\nu'_{GHz}}{E^2|\mathbf{B}' \times \hat{\mathbf{n}}'_{\mathbf{los}}|}$$

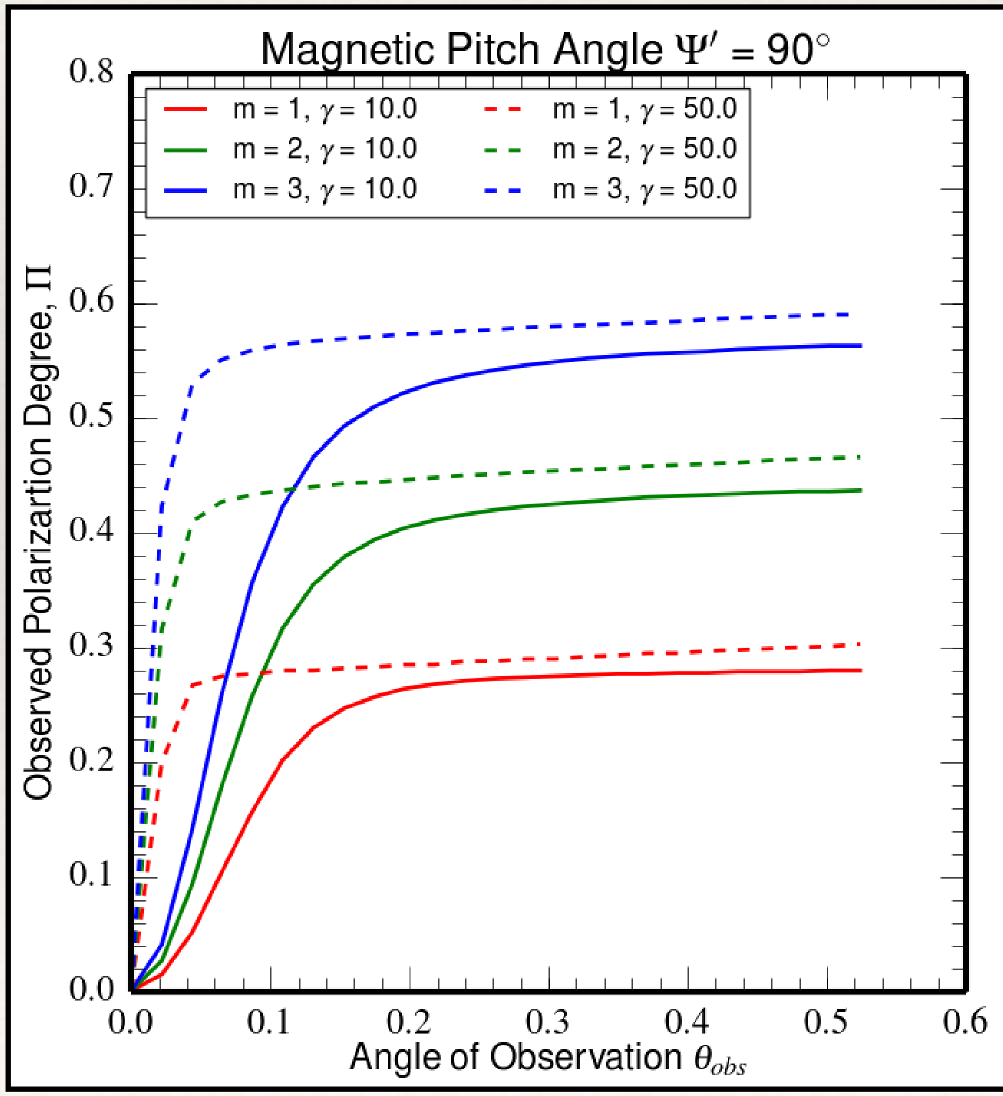
Synchrotron emission is polarised,

$$J_{pol}(\nu; E, \boldsymbol{B}, \hat{\boldsymbol{n}}_{los}) = \int_{E_i}^{E_f} \frac{G(x)}{F(x)}(\mathcal{D}^2 j'_\nu(E, \boldsymbol{B}')\hat{\boldsymbol{n}}'_{los})\mathcal{N}(E,t)dE,$$

and the polarisation degree

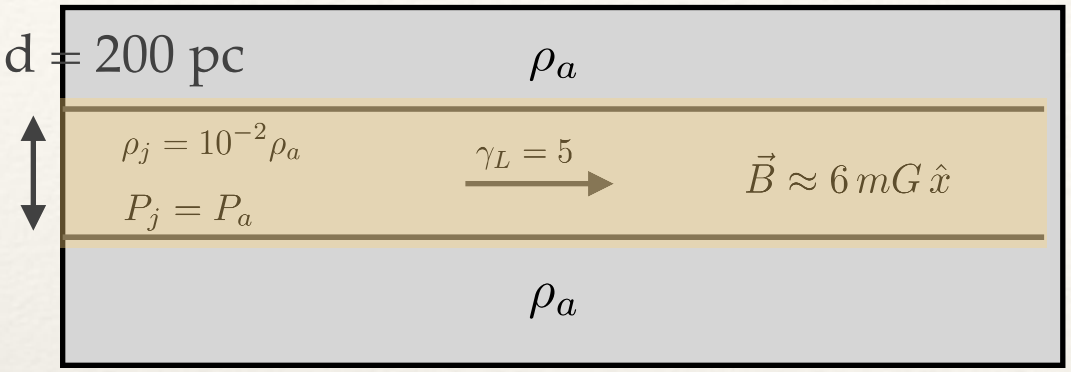
$$\Pi(\nu) = J_{pol}/J_{sy} = \frac{m+1}{m+7/3}$$

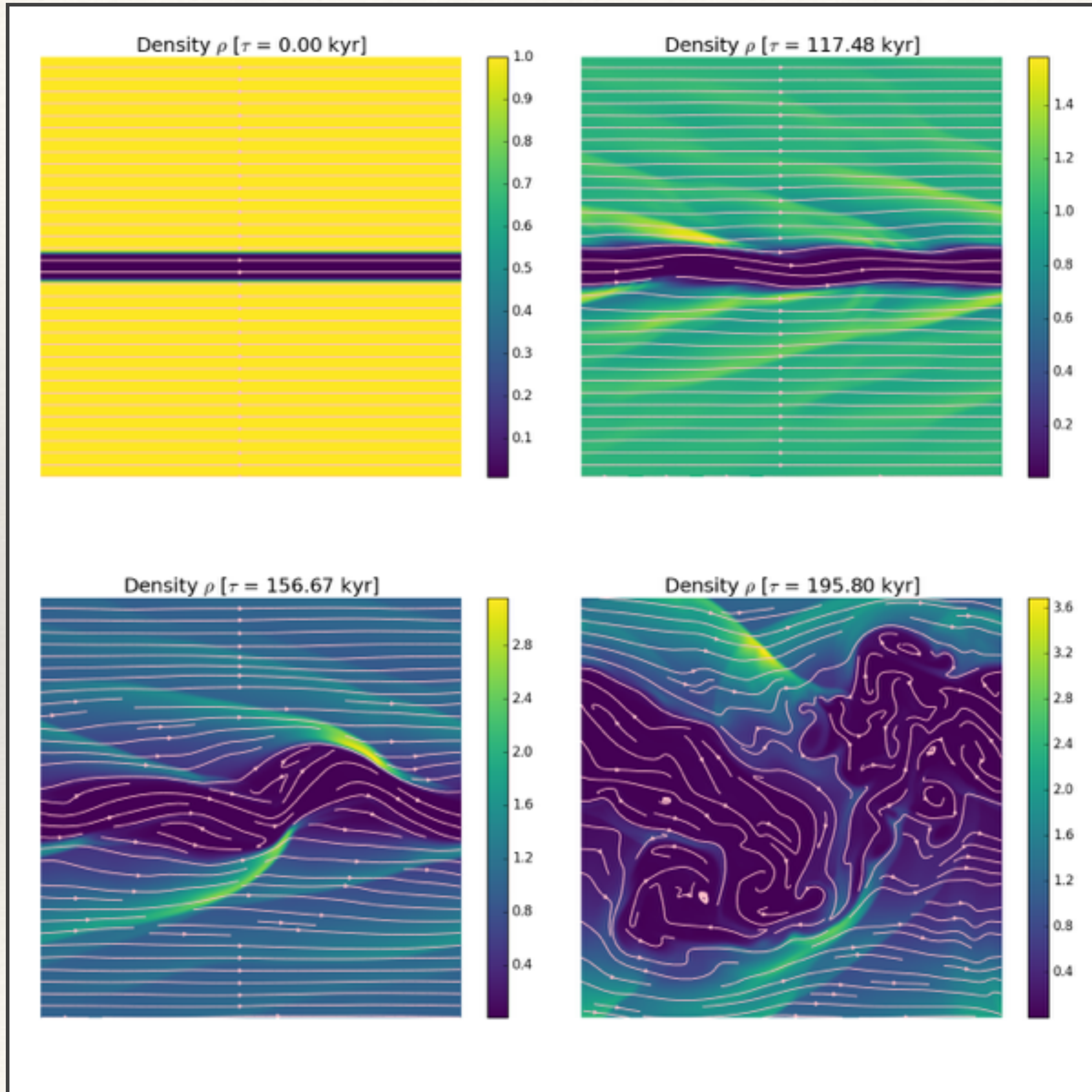
$$m = 3 \rightarrow \Pi \sim 75\%$$



Slab Jets and Shocks.

Initial Conditions

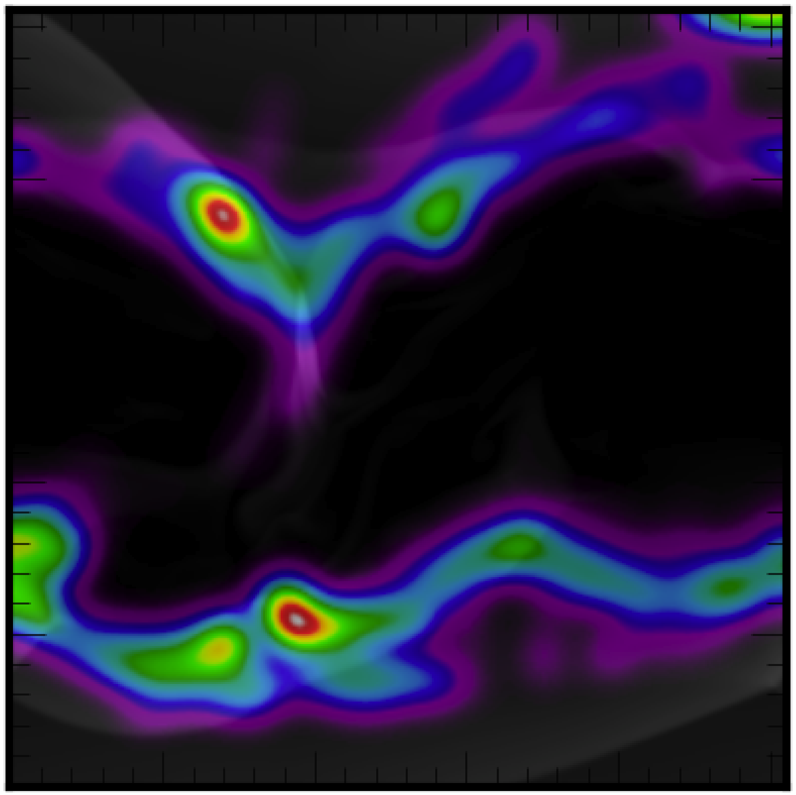




- Development of KH Instability due to shear.
- Eventually builds up oblique shocks
- Represents jets interacting with ambient.

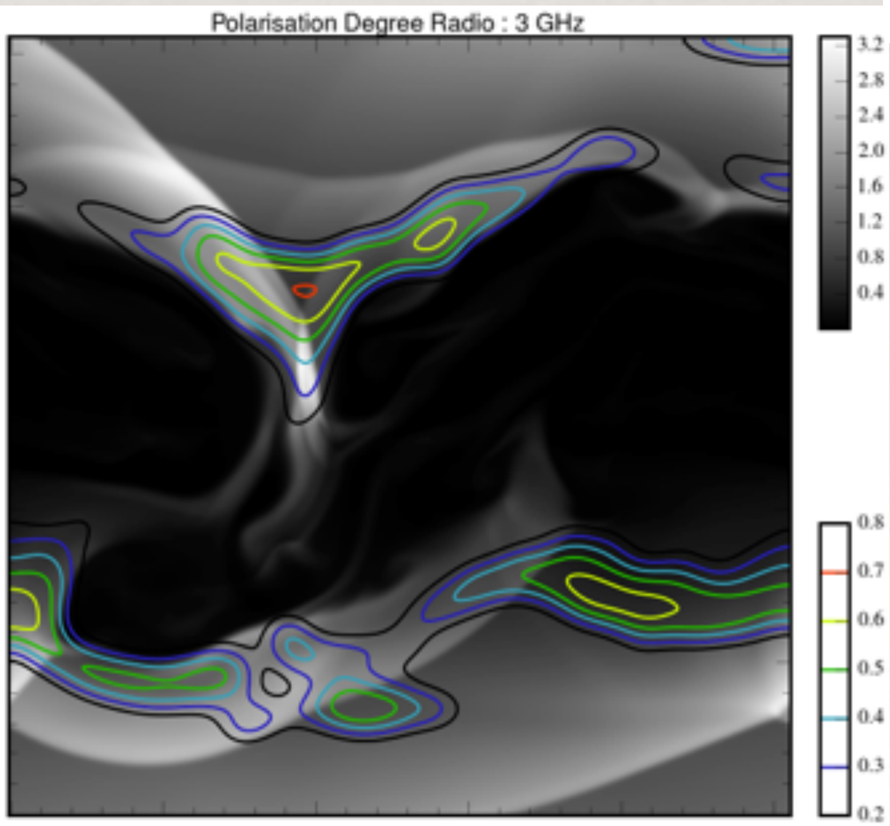
Emission from Slab jets!

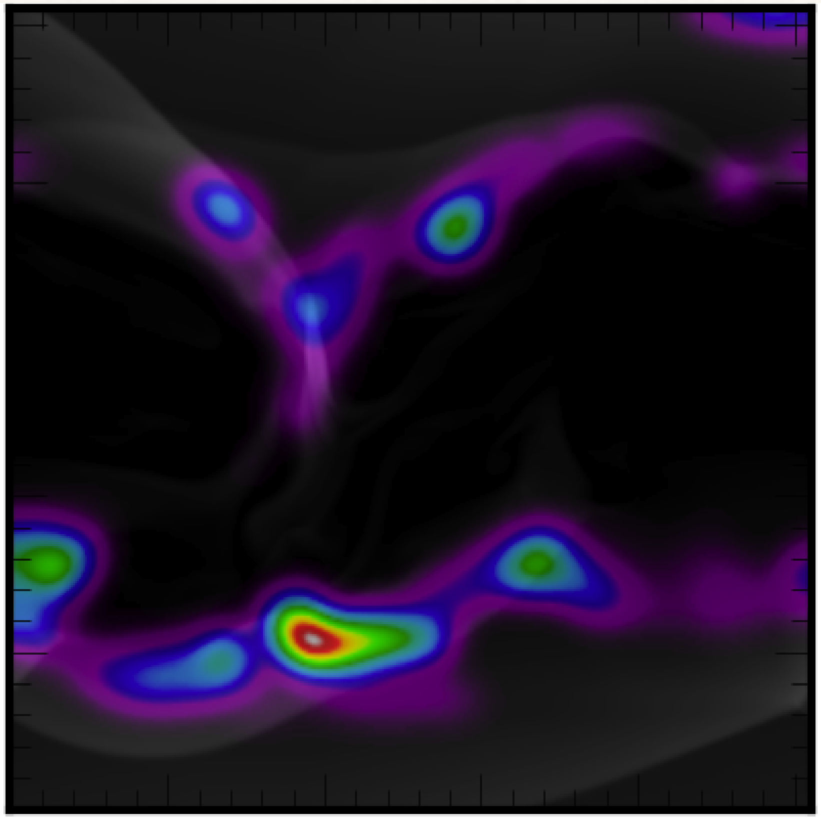
SYNTHETIC RADIO MAP (3 GHz)



Power law index kept fixed
m = 2.23

Polarisation Maps.





Power law index dependent
on B field orientation

Summary

- ***Multi-scalar Nature of Astrophysical High Energy Sources —***
  - Observations (up-till now) can't resolve regions close to the central source.
  - Simulations (up-till now) can not consistently resolve the micro-physical scales.
- Complex Interplay of Physics — Requires Numerical Simulations with sub-grid physical modules
- Developed a versatile ***Hybrid Particle Module*** for the PLUTO code.
- Applications to High Energy Astrophysical problems using 2D simulations are qualitatively consistent with observations.
- Orientation of Magnetic fields play a crucial role in determining the Emission and Polarisation.
- **Final goal** : Apply these modules to build a ***Synthetic Observatory*** that may provide templates to up-coming telescopes using 3D simulations.

THANK YOU