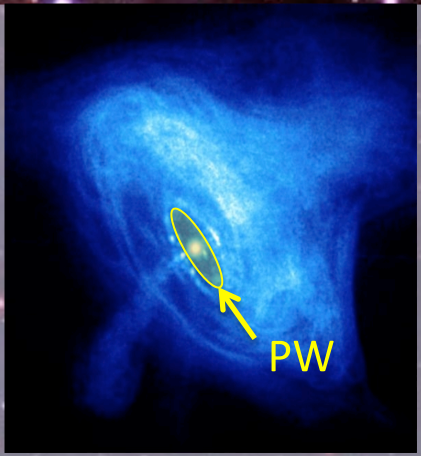
Winds from pulsars: constraints on particle acceleration mechanism(s) at the termination shock through relativistic MHD simulations

B. Olmi[1,2,3], L. Del Zanna[1,2,3], E. Amato[3], N. Bucciantini[2,3]

1 Università degli Studi di Firenze, Italy
2 INFN sezione di Firenze, Italy
3 INAF, Osservatorio Astronomico di Arcetri, Firenze (Italy)

IX CNOC
Monteporzio Catone

Introduction to the problem & outline



Pulsar Wind Nebulae are powered by the spin-down of young neutron stars that lose their energy in the form of a magnetized, relativistic and cold wind.
The fact that the wind is cold makes necessary to use numerical models to investigate it.

- How to construct the numerical model of the Pulsar Wind (PW)
- How to obtain synthetic emission maps from simulations
- Simulation overview: from the beginning to the final stage of the evolution
  - ➥ Some results from the simulation of the Crab nebula
- Investigating the particle acceleration mechanism(s) at the wind termination shock of the Crab nebula
  - ➥ What wisps observations tell us
  - ➥ The wisps multiwavelenghts analysis
  - ➥ Results

How to fix your PW model

Information about the PW properties are obtained following the iterative scheme:

1 Pw model

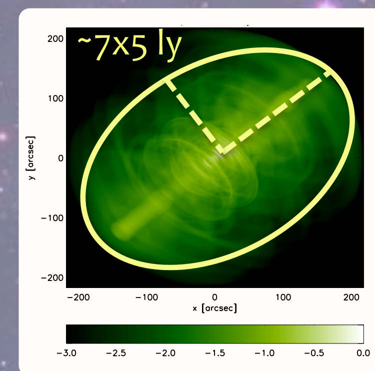
Chose a parametrization

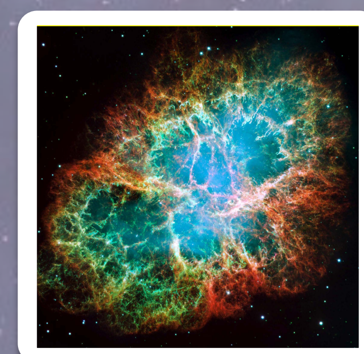
2 Synthetic Nebula

Compare morphology and fine structures

3 Observed Nebula

Determine the best set of the free parameters





Chose your parametrization

PW modelization

[Del Zanna et al 2006, Olmi et al 2014]

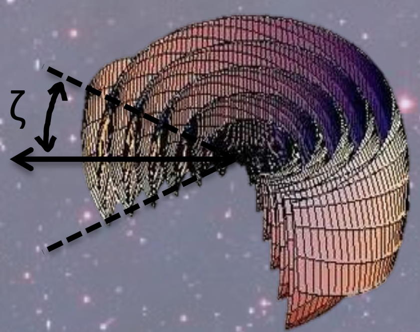
From theoretical models we know that the main properties of the PW must be:

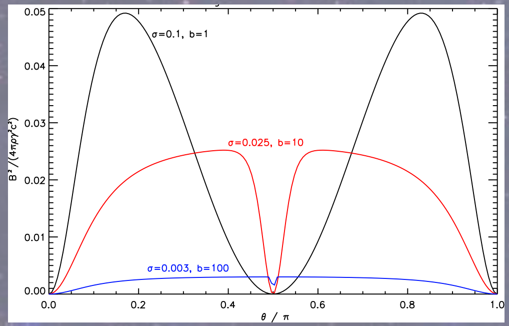
- The wind has an anisotropic energy flux → the most of the energy is in the equatorial plane

$$F(r,\theta) \propto \frac{\alpha + (1-\alpha)}{(2-\alpha)r^2} \Rightarrow \quad F(r,\pi/2) \gg F(r,0) \Rightarrow \alpha \ll 1$$

anisotropy parameter

- The wind is striped in an equatorial belt of extension ≈ 2x(inclination of the magnetic axis ζ)





$$B(r,\theta) \propto \sqrt{\sigma_0} \sin\theta \tanh\left[b\left(\frac{\pi}{2} - \theta\right)\right]$$

Intensity + striped zone width

$\alpha,\ \sigma,\ b$ ➡ Free parameters of the model

How to obtain synthetic emission maps

(1) **Injecting the emitting particles in the nebula**

Particles are injected at the termination shock with power law (in energy) distribution functions and injection energy $\varepsilon \approx \infty$ (2 families: 1 for radio and 1 for optical/X-ray particles)

(2) **Let it evolves**

The local particle distribution function in the nebula is evaluated by evolving the distribution function at the TS in time and space, taking into account adiabatic and syncrotron losses. The emitting properties at each point are described by dedicated particle tracers (from Del Zanna:2006 and Camus:2009).

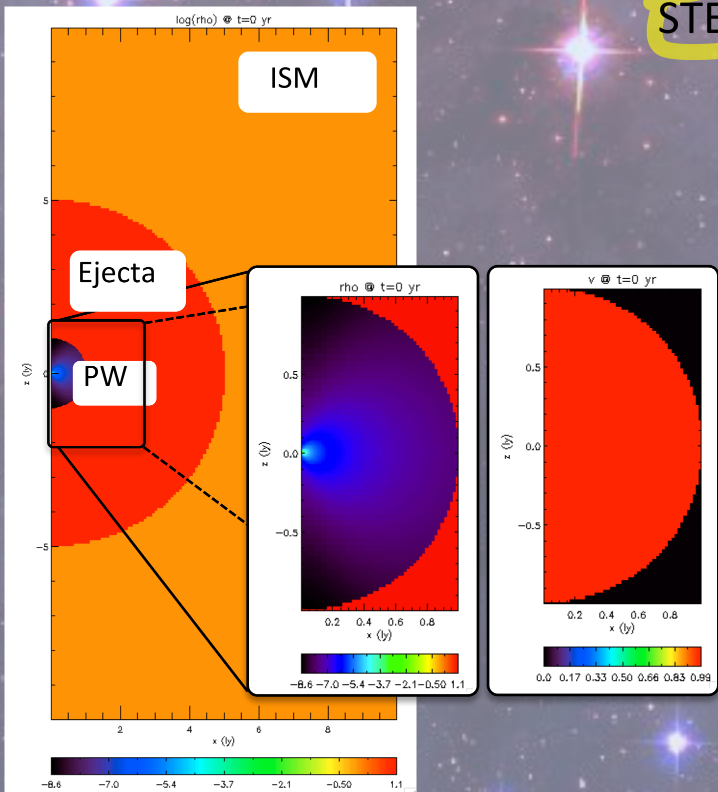
(3) **Compute emission properties**

By applying standard formula for synchrotron emission taking into account relativistic effects (Doppler boosting: enanched emission from fluid elements which move towards the observer and vice versa).

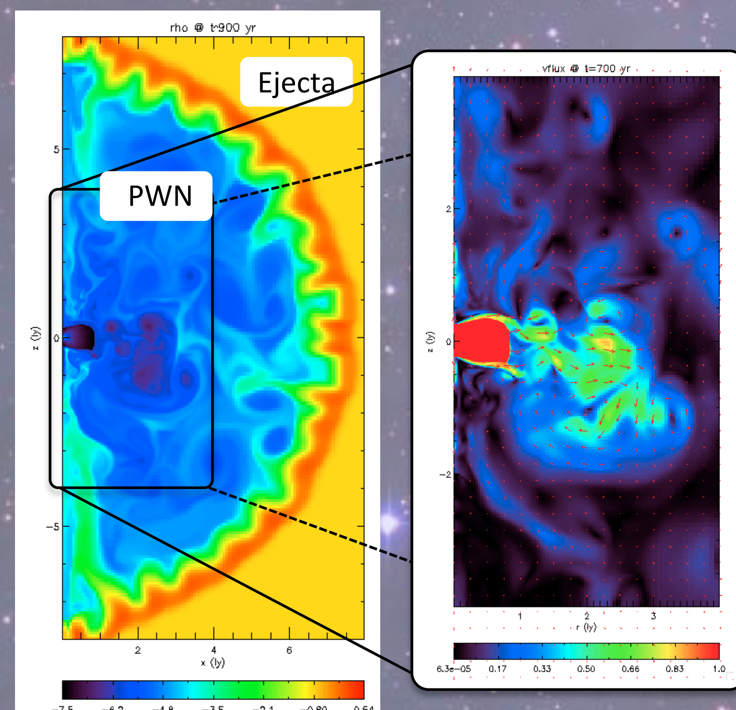
How to obtain the synthetic Nebula

Simulation overview

STEP 0 Initialization of the system @ t=0 yr



STEP>0 System evolved up to $t=t_{Crab}\cong 950$ yr, solving numerically the eqs of the RMHD 2d axy-simmetric model + adiabatic EoS with the shock-capturing numerical code ECHO [Del Zanna 2007].

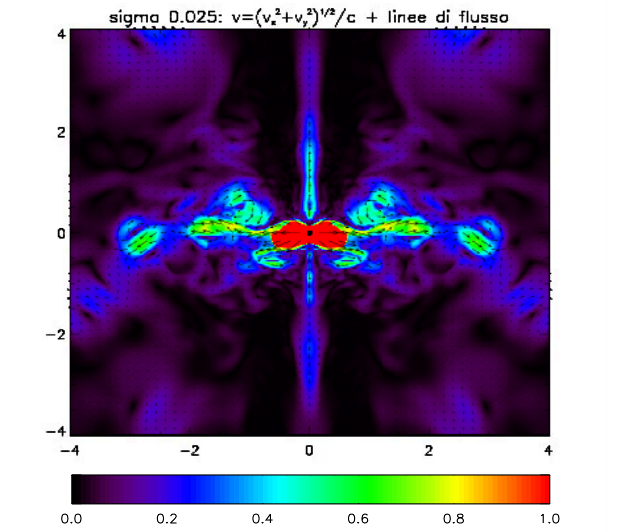


computational time:
1 week with 64 CPUs.

Typical Run:
$N_r=800$, $N_\theta=400$, $0 \le t \le 1000$ yr

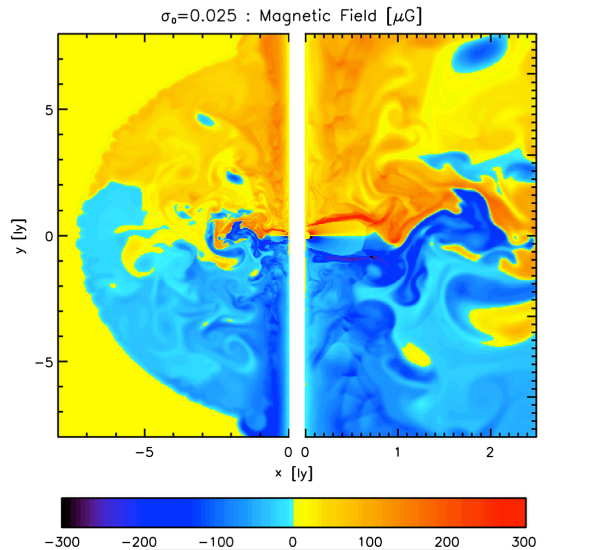
Fix the best set of free parameters

Results @ 950 yr



TS turbulence

Olmi et al 2014 +2015

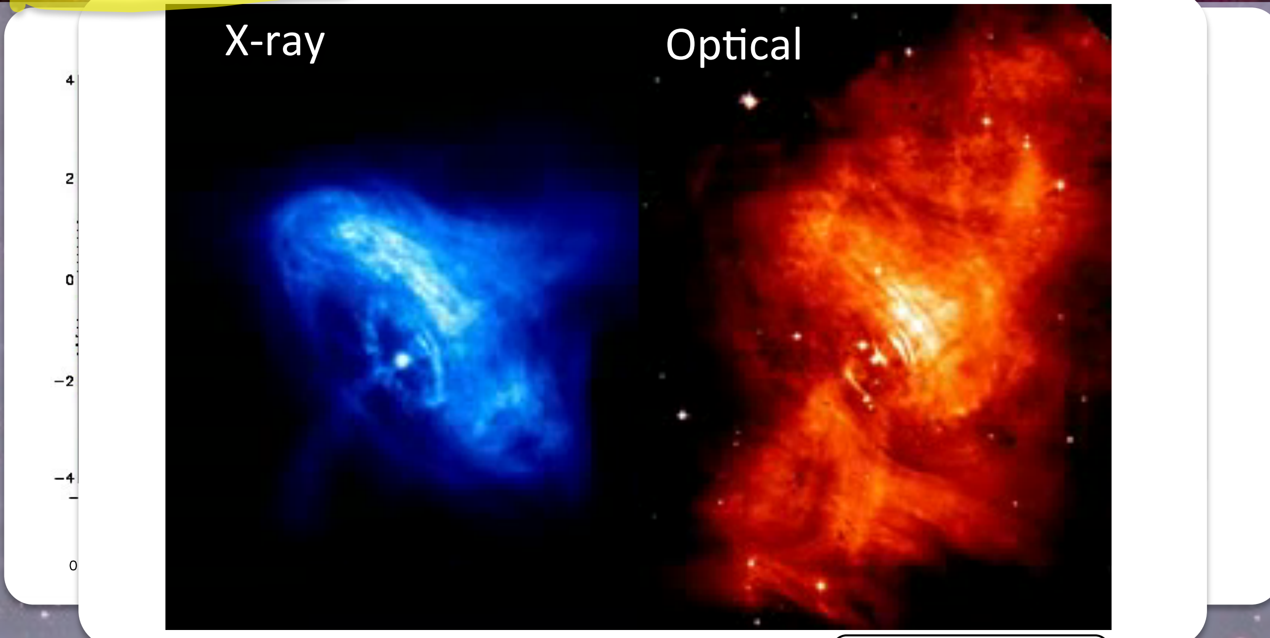


Magnetic field

Dynamics

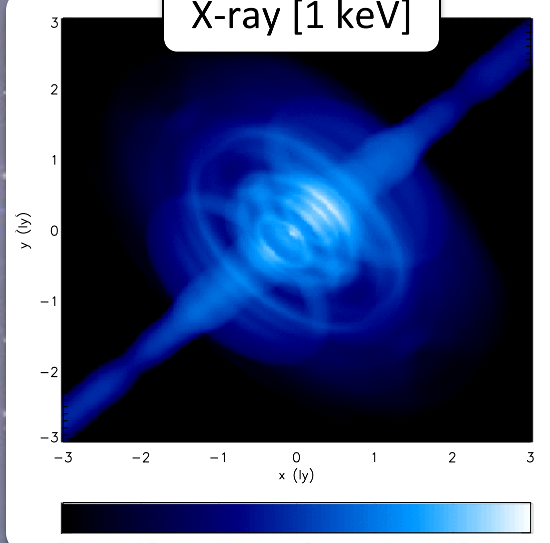
Synthetic data vs observations

Results @ 950 yr

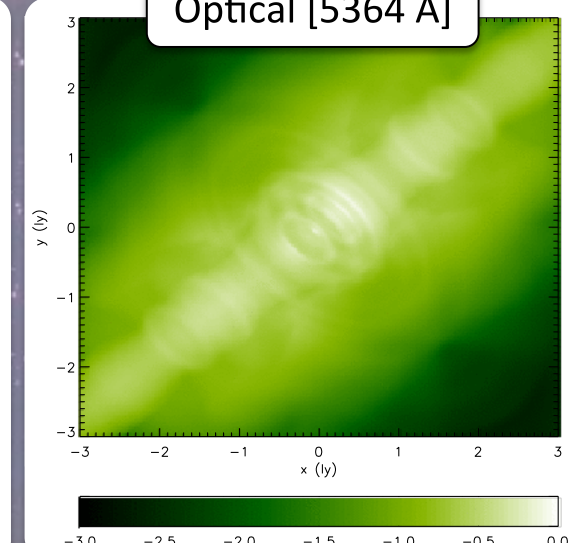


Synchrotron emission and variability

X-ray [1 keV]



Optical [5364 Å]



$\sigma = 0.025$
$\alpha = 0.1$
$b = 10$

Best set for the Crab

Investigating the particle acceleration mechanism

Wisps

RADIO particles ORIGIN

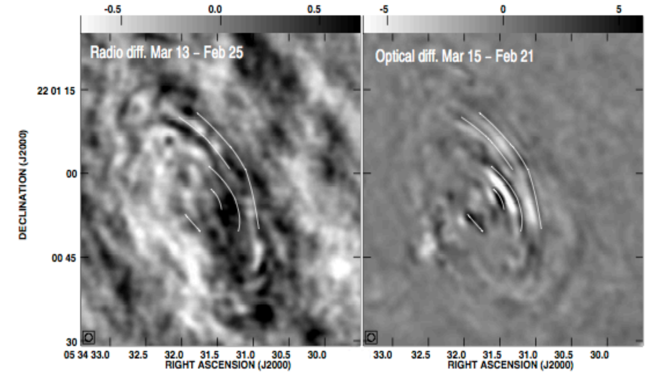
Properties are only due to the fluid and magnetic field structure.

see Olmi et al. 2014

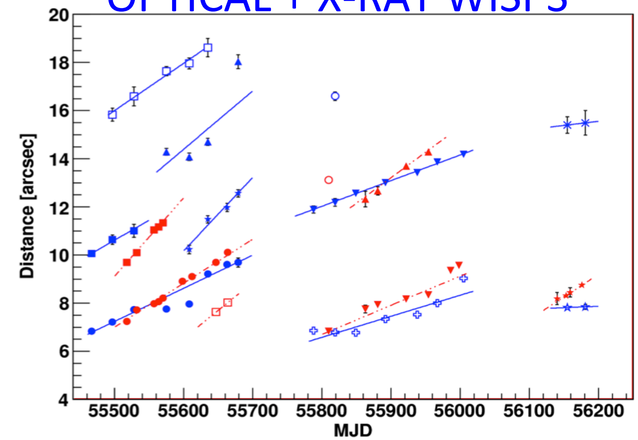
OBSERVATIONS:

- Wisps are seen at multiwavelengths
- Not coicident locations
- Different outward velocities, mildly relativistic $0.1c \lesssim v \lesssim 0.4c$

Bietenholz et al. 2004
RADIO + OPTICAL WISPS



Schweizer et al. 2013
OPTICAL + X-RAY WISPS

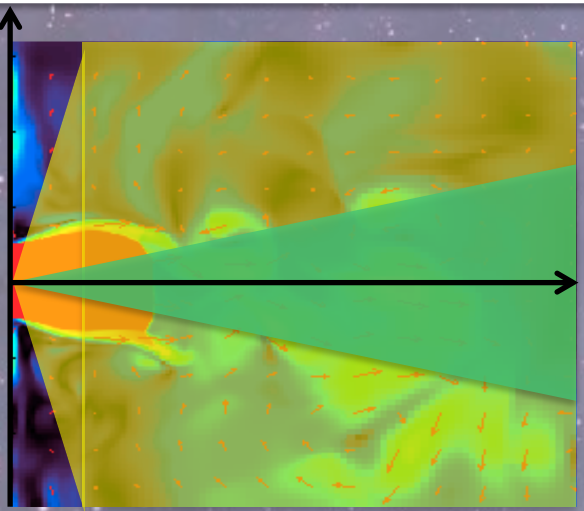


To have not coincident wisps at different wavelengths particles must have different acceleration mechanisms!

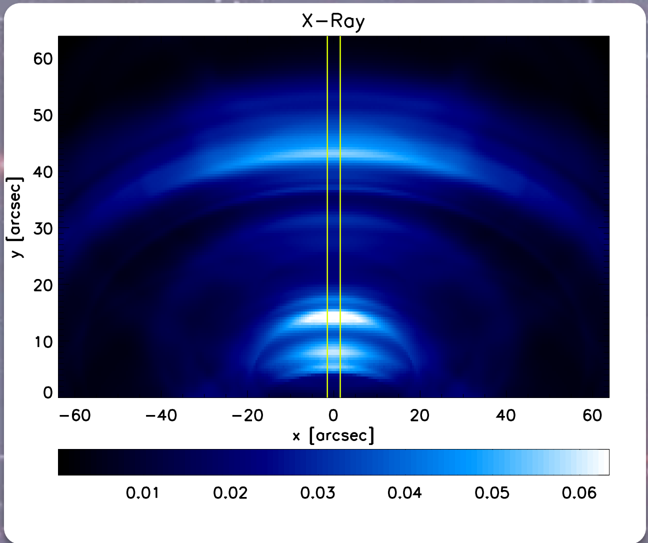
Multi wavelengths wisp analysis

Radio and X-ray families injected at different locations at the TS.
Optical emission = mixed origin (radio + X-ray contribution at optical frequencies)

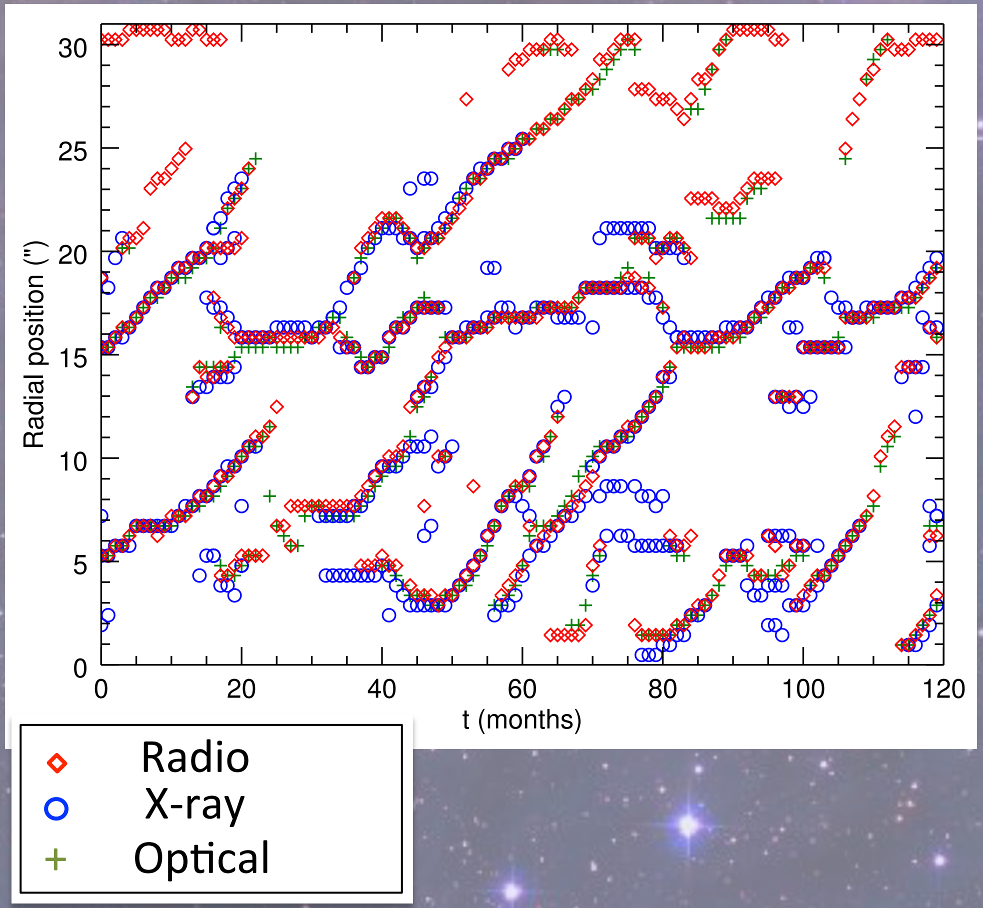
1. Uniform injection → $\theta \in [0^\circ, 90^\circ]$
2. Wide equatorial zone → Equatorial: $\theta \in [20^\circ, 90^\circ]$
   Polar: $\theta \in [0^\circ, 20^\circ]$
3. Narrow equatorial zone → Equatorial: $\theta \in [70^\circ, 90^\circ]$
   Polar: $\theta \in [0^\circ, 70^\circ]$



Wisp profiles extracted as in Schweizer et al 2013 from a 3” slice in the upper hemisphere of intensity maps. Data extracted with monthly frequency during 10 yr. Results shown as plots of wisp local maxima radial positions vs time.

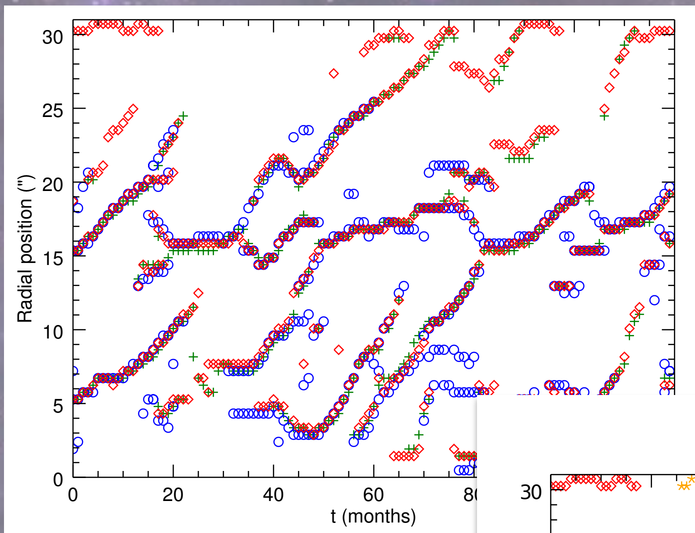


(1). Uniform injection:



Leads to coincident wisps at different ν.

(2). Narrow polar cone + wide equatorial zone

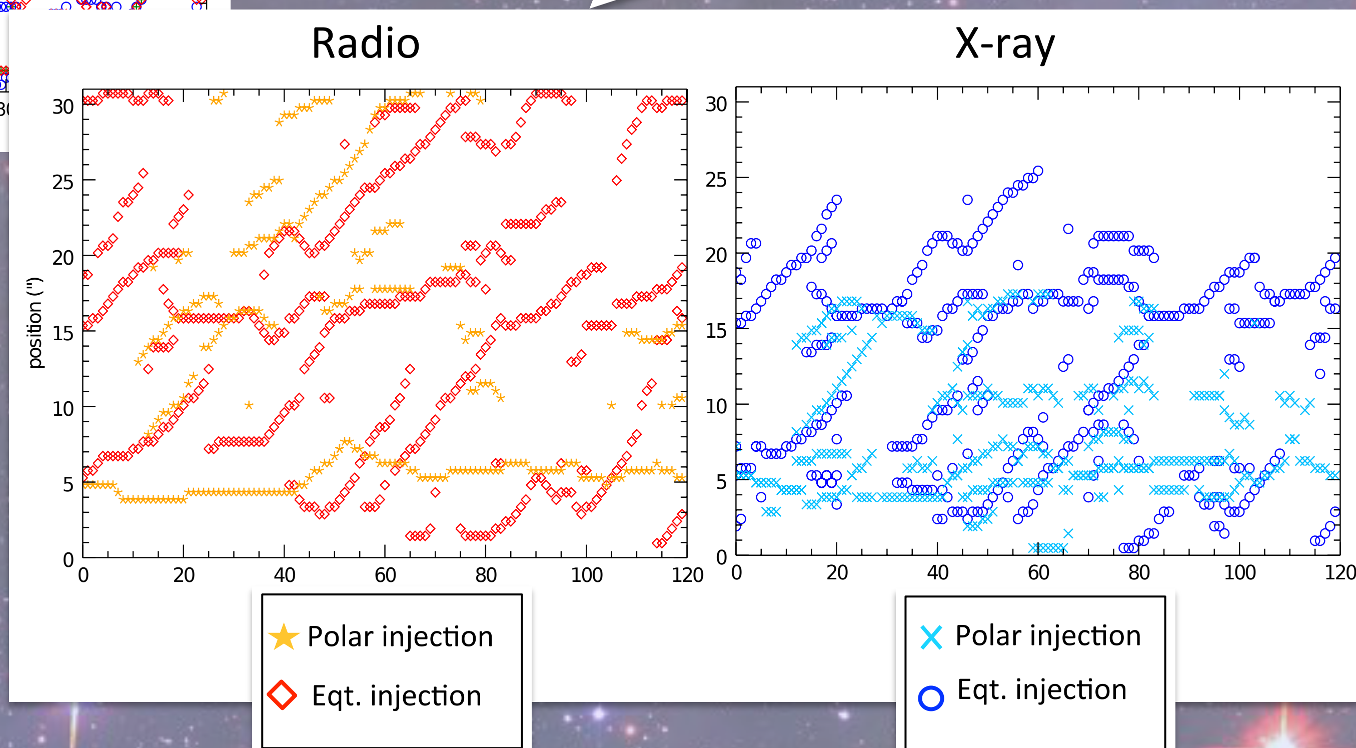


Polar injection:
× and ★

➡ Basically NO wisps appear

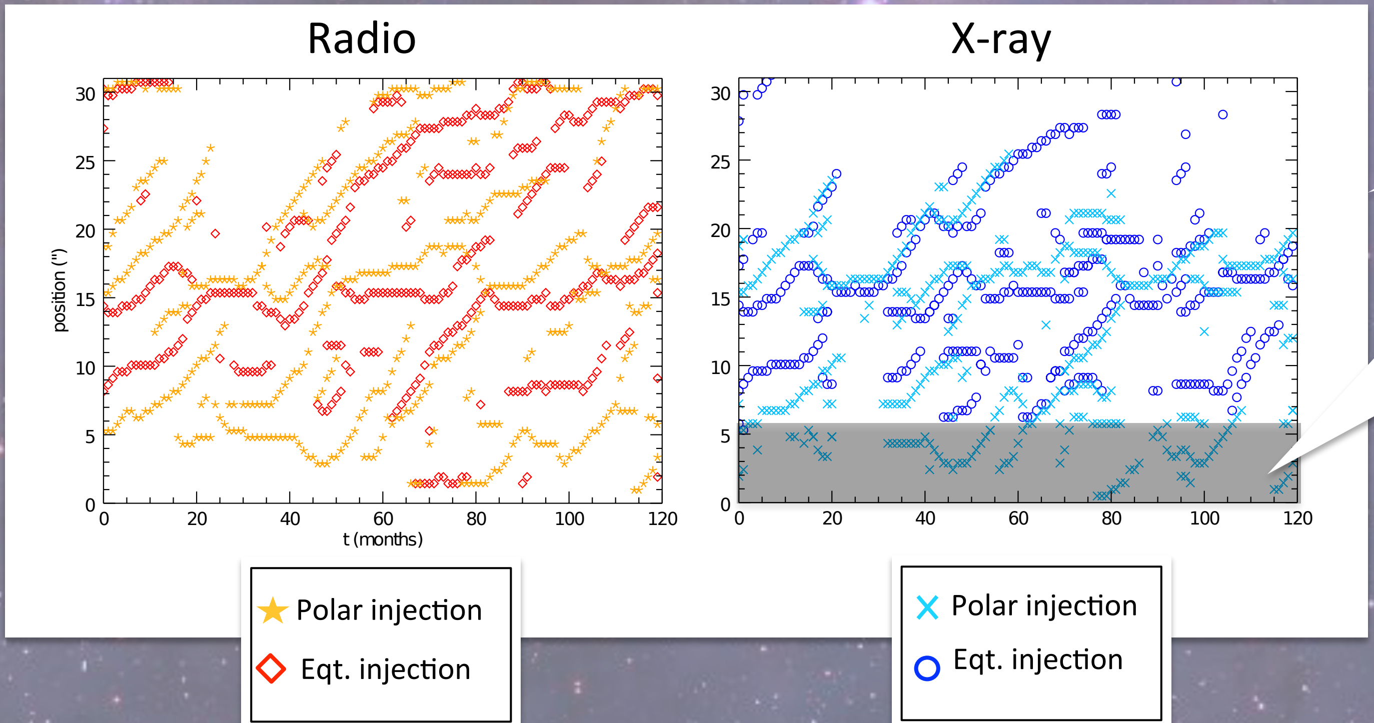
Eqt. injection:
◇ and ○

➡ Same wisps as in case (1)



➡ Impossible to reproduce observations under case (2) assumptions!

(3). Narrow equatorial zone + wide polar cone



wisps appear in both cases

In Schweizer et al. no wisps are seen within 6" in X-rays and optical

Deprojected velocity range:

$0.08c \leq v \leq 0.38c$

From observations

$0.1c \lesssim v \lesssim 0.4c$

Best case for X-ray wisps: equatorial injection in a narrow region

→ $\theta \in [70°, 90°]$

In order to have not coincident radio wisps → injection in complementary zone or a wider equatorial one (difficult to make stronger constraints).

Possible scenario:

X-ray particles accelerated in a narrow, low σ, equatorial belt via Fermi I.
Radio particles accelerated in a wider equatorial zone via driven magnetic reconnection.

Summary and conclusions

GOALS of NUMERICAL MHD 2D AXISYMM. MODELS

☑ **High energy emission** well reproduced

☑ Analysis of **low energy emission** → not strong constraints on radio particles nature, but shows that wisps arise as a fluid property

☑ **Multi band wisps analysis** → Best case for X-ray wisps is injection in a narrow equatorial belt (→ Fermi I acceleration?), no strong constraint for radio particles. They can be accelerated in a wider equatorial zone via driven magnetic reconnection.

OPEN PROBLEMS:

☐ Radio particles origin → no strong constraints are found

☐ Magnetic field compression around polar axis → only due to simulation dimensionality?

➡ Complete 3D models needed!

First attempt by Porth et al 2014 (but only 70 yr of the Crab evolution are simulated…)

Summary and conclusions

GOALS of NUMERICAL MHD 2D AXISYMM. MODELS

☑ **High energy emission** well reproduced

☑ Analysis of **low energy emission** → not strong constraints on radio particles nature.

☑ **Multi band wis**

equatorial belt (

They can be acce

OPEN PROBLEMS:

☐ Radio particles o

☐ Magnetic field c

dimensionality?

C

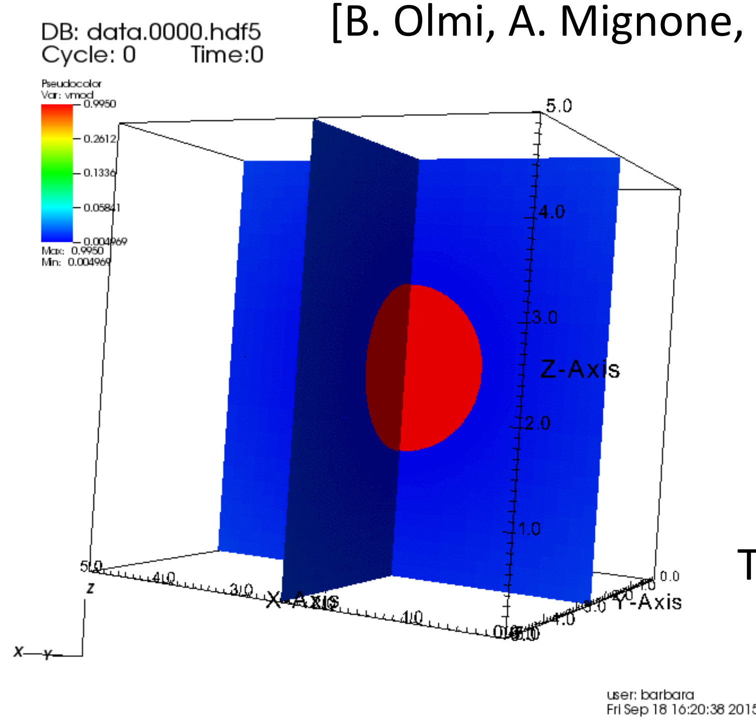
F

a

Preliminary!

Results of complete Crab's 3D simulation with PLUTO® are coming soon

[B. Olmi, A. Mignone, L. Del Zanna]



Thank you for your attention!