INAF
ISTITUTO NAZIONALE
DI ASTROFISICA

OSSERVATORIO ASTROFISICO DI ARCETRI

On the X-ray features associated to some bow-shock pulsar wind nebulae

Rino Bandiera
Istituto Nazionale di Astrofisica
Osservatorio Astrofisico di Arcetri

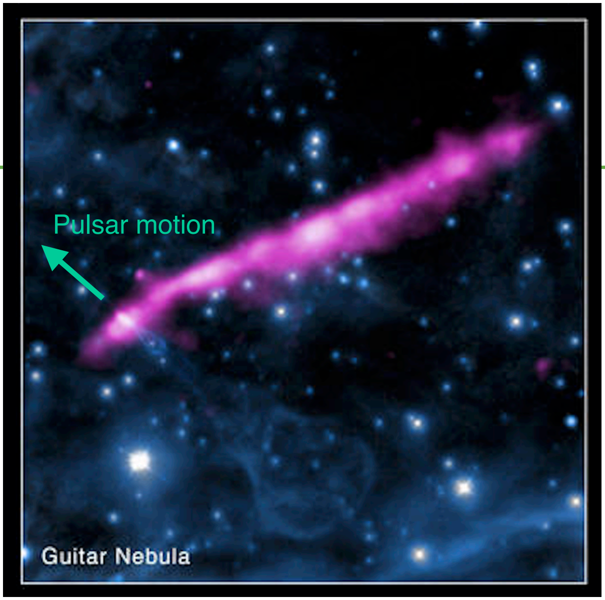
In collaboration with:
Barbara Olmi, Elena Amato, Niccolò Bucciantini

Particle Acceleration in Astrophysical Objects, Rome, 5-7 September 2022

Expected, and unexpected, X-ray emission from pulsars supersonically moving in the ISM

- Pulsars escaped from their birth SNR, but still active
- Pulsar wind nebula confined by the ISM ram pressure. Formation of bow shock.
- Nice bow-shock nebulae in Balmer lines (though with peculiar shapes. *Morlino et al. 2015*)
- Unfruitful search of X-ray emission in the tail of the Guitar Nebula

  (bow shock nebula of PSR 2224+65) *Romani et al. 1997*
- X-ray feature discovered, but in a direction misaligned with the pulsar motion *Hui & Becker 2007*

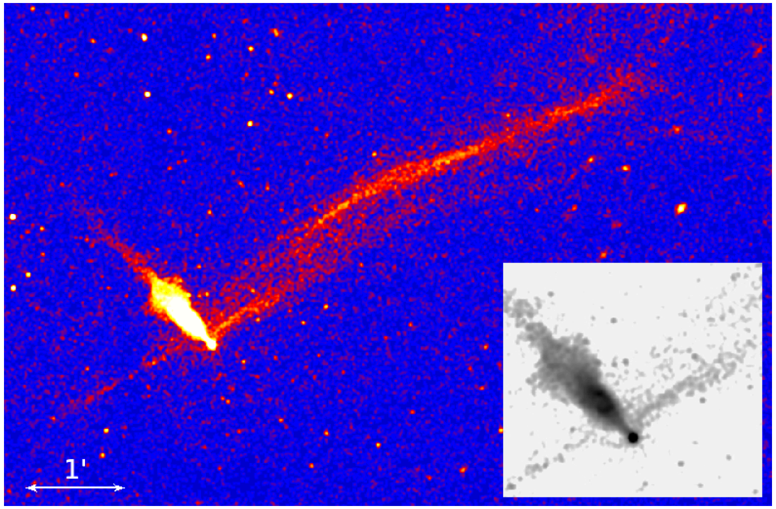


Credit: X-ray: NASA/CXC/UMass/S.Johnson et al,
Optical: NASA/STScI & Palomar Obs 5-m Hale Telescope

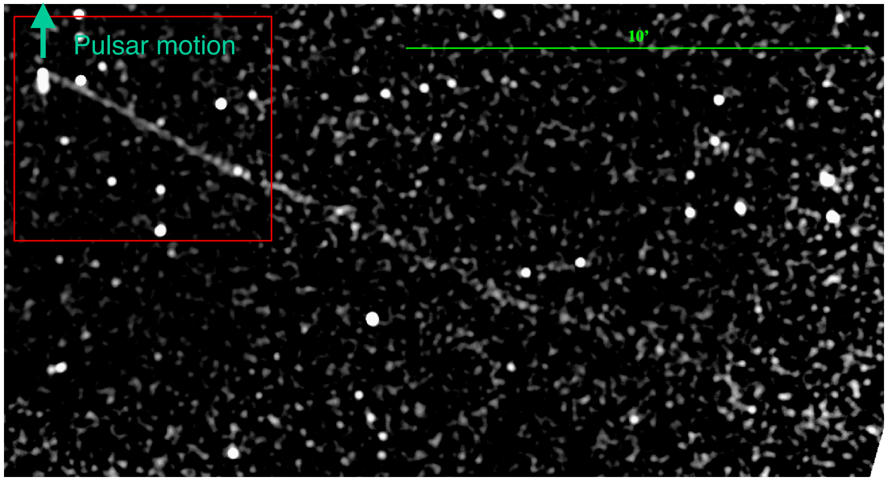
The Guitar Nebula is not alone !

A handful of sources "similar" to the Guitar Nebula:

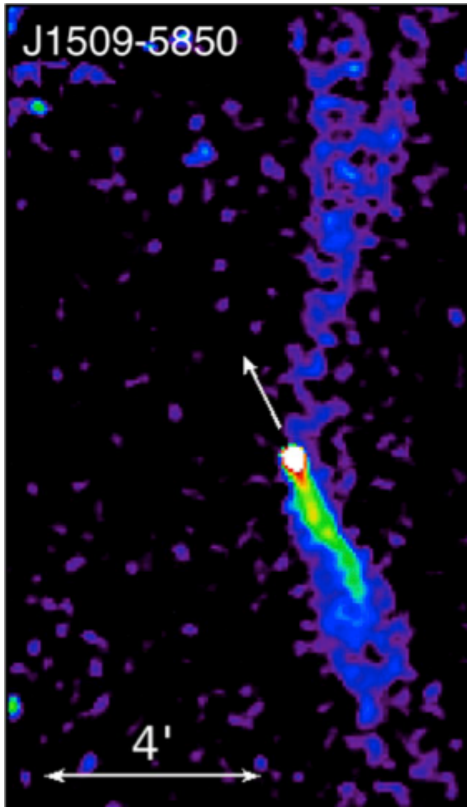
- IGR J1101-6103 (a.k.a. the Lighthouse Nebula) *Pavan et al. 2014, 2016*



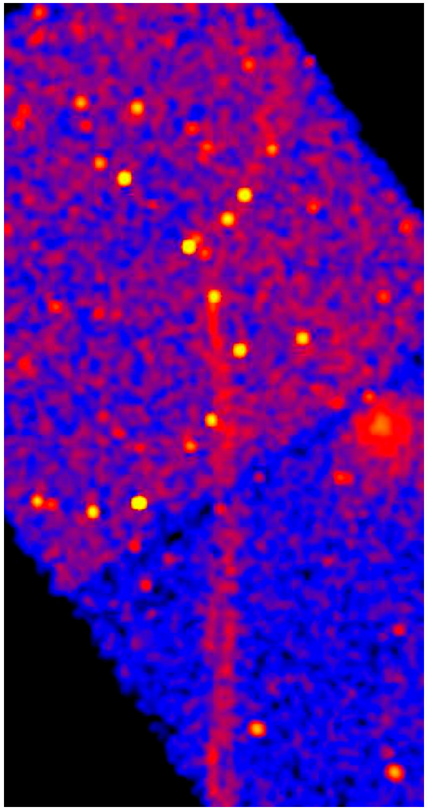
- PSR J2030+4415 *de Vries & Romani 2020*



- PSR J1509-5850 *Klingler et al. 2016*



- PSR J2055+2539 *Marelli et al. 2019*



- + more dubious cases, like PSR B0355+54 *Klingler et al. 2016*
  or PSR J1135-6055 *Bordas & Zhang 2020*

Outlining some “general” properties

but small sample, uncertain identifications, faint sources → photon noise

- Elongated X-ray feature, misaligned with the pulsar motion
- Highly collimated (in some cases)
- Very small curvature, if any
  (but, in one case, some wiggling also interpreted as a helical pattern)
- Very hard X-ray spectrum (power-law with typical photon index $\Gamma \sim 1.7$)
- No sign of spectral downgrading with increasing distance from the pulsar
- Presence of a counter-feature (in some cases)
- Co-existence with a “well-behaved” X-ray pulsar tail (in some cases)
- Possible clumps in the structure (just photon noise ?)
- Possibly dimmer emission close to the pulsar (just photon noise ?)

"Ballistic jets" versus "Kinetic jets" *Barkov et al. 2019*

The Importance of Being Earnest *Wilde 1895*

Names like "Lighthouse Nebula" or "jet" may imply a subliminal expectation. Better to use a generic term like "feature", until their nature will be fully assessed.

A suggested scenario for the feature in the Guitar *Bandiera 2008*

- The highest energy electrons may escape from the pulsar bow shock head.
- Then they passively flow along the pre-existing interstellar magnetic field.
- Due to the pulsar motion, electrons continuously fill new magnetic flux tubes.
- Then from the transverse width of the feature one can compute the synchrotron lifetime of the X-ray emitting electrons.
- A magnetic field $\sim 45\mu G$ and a particle Lorentz factor $\gamma_e \sim 10^8$ are derived.
- This high magnetic field (~ 1 order of magnitude higher than the interstellar value) implies that electrons may effectively amplify the field, on short scales.

Relativistic MHD 3D models for the electrons escape

Olmi & Bucciantini 2019; Barkov et al. 2019

- Confirmed the general scenario proposed by the analytic model.
- Particle escape may be due to magnetic reconnection on the bow shock head.
- Escape of only the highest energy particles. $\gamma > 10^7 \div 10^8$, close to the theoretical limit of the pulsar maximum potential drop.
- Highly asymmetric structures, which justify cases of one-sided features.
- Electrons and positrons follow different orbits. Effective charge separation.
- Charged flows in ambient medium. Possible current driven instabilities. *Bell 2004*

BUT

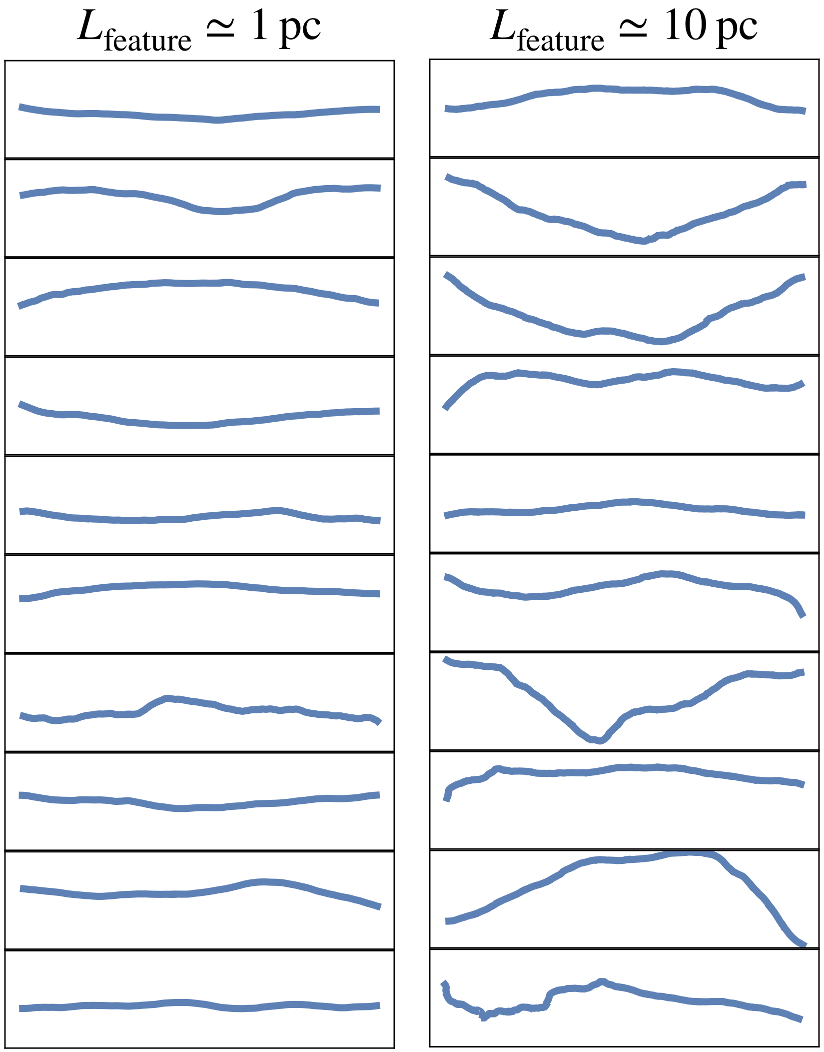
1. Why some features are almost perfectly straight, while others are bent ?

   Is this scenario valid for all objects?

2. What is the behaviour of these electrons once inside the feature?

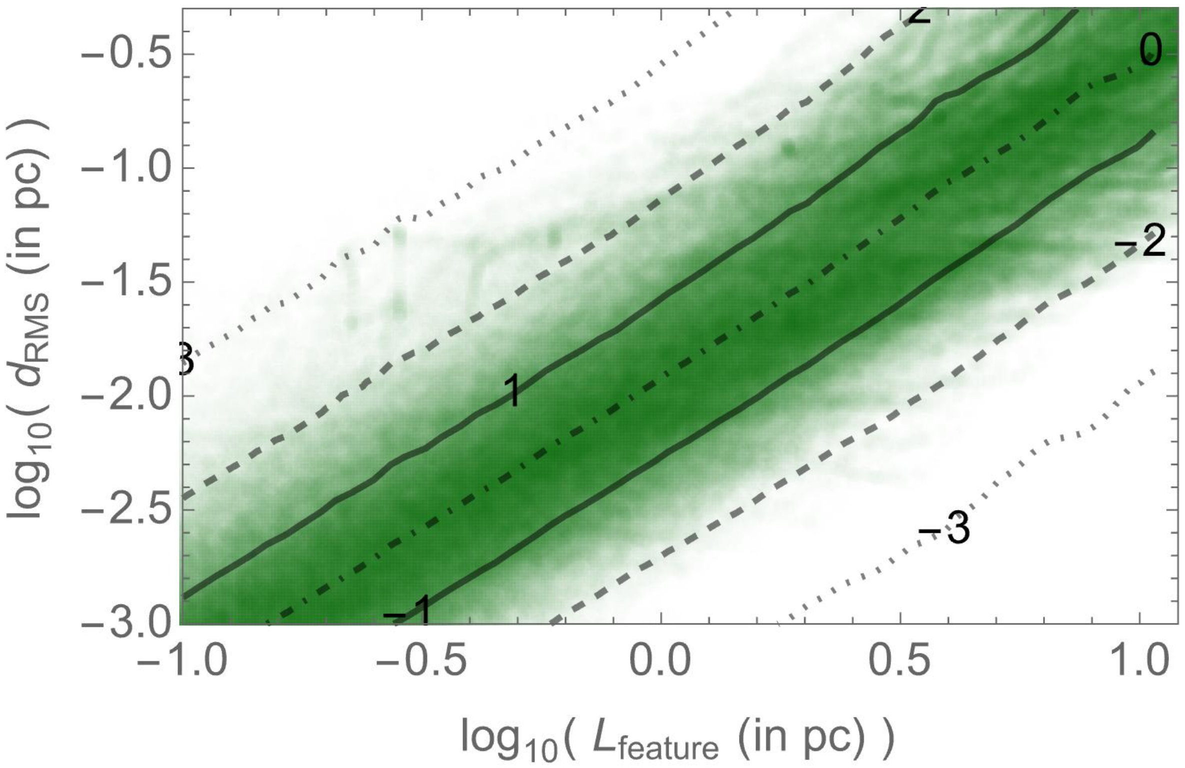
1. Statistical properties of the features bending

- Assume that electrons passively flow along the ambient field.
- Field perturbations simulated with a turbulent power spectrum. Kolmogorov law, scaled to have $\delta B/B \sim 1$ at the maximum scale of the distribution, $L_{\max} \simeq 100$ pc. Simulations in 3-D, then projected patterns. Randomly oriented viewing angles.
- THEN Bending more evident in longer features. ($L_{\rm Guitar} \sim 1.3\,{\rm pc}$, $L_{\rm J2030} \sim 2.2\,{\rm pc}$, $L_{\rm J2055} \sim 4.7\,{\rm pc}$, $L_{\rm J1509} \sim 7\,{\rm pc}$, $L_{\rm Lighthouse} \sim 11\,{\rm pc}$)
- ANYWAY Strong differences expected from case to case.



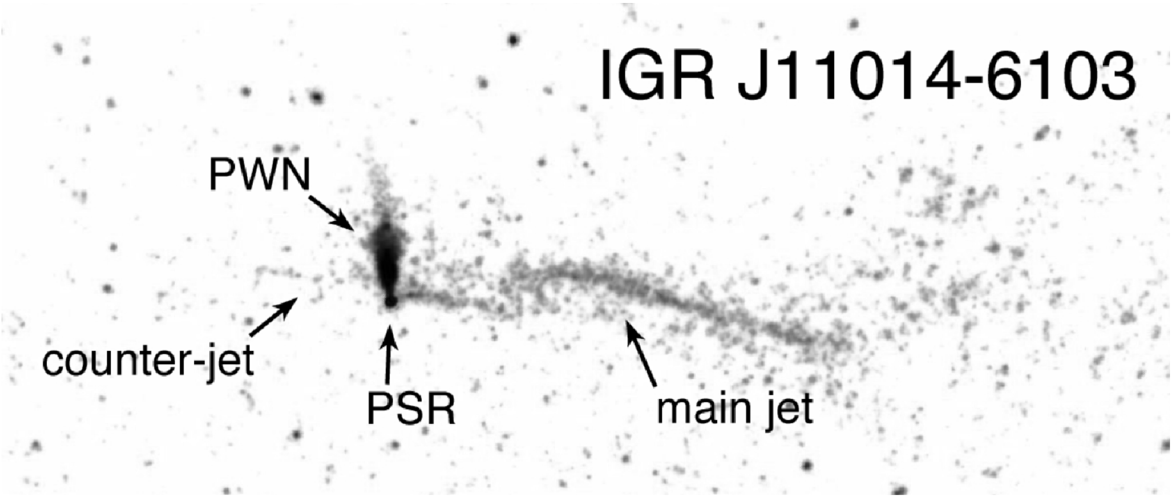
An overall, quantitative approach

- A measurable parameter: RMS dispersion away from the best-fit line.
- Simulated 10^6 measurements. Used to derive theoretical contour lines.



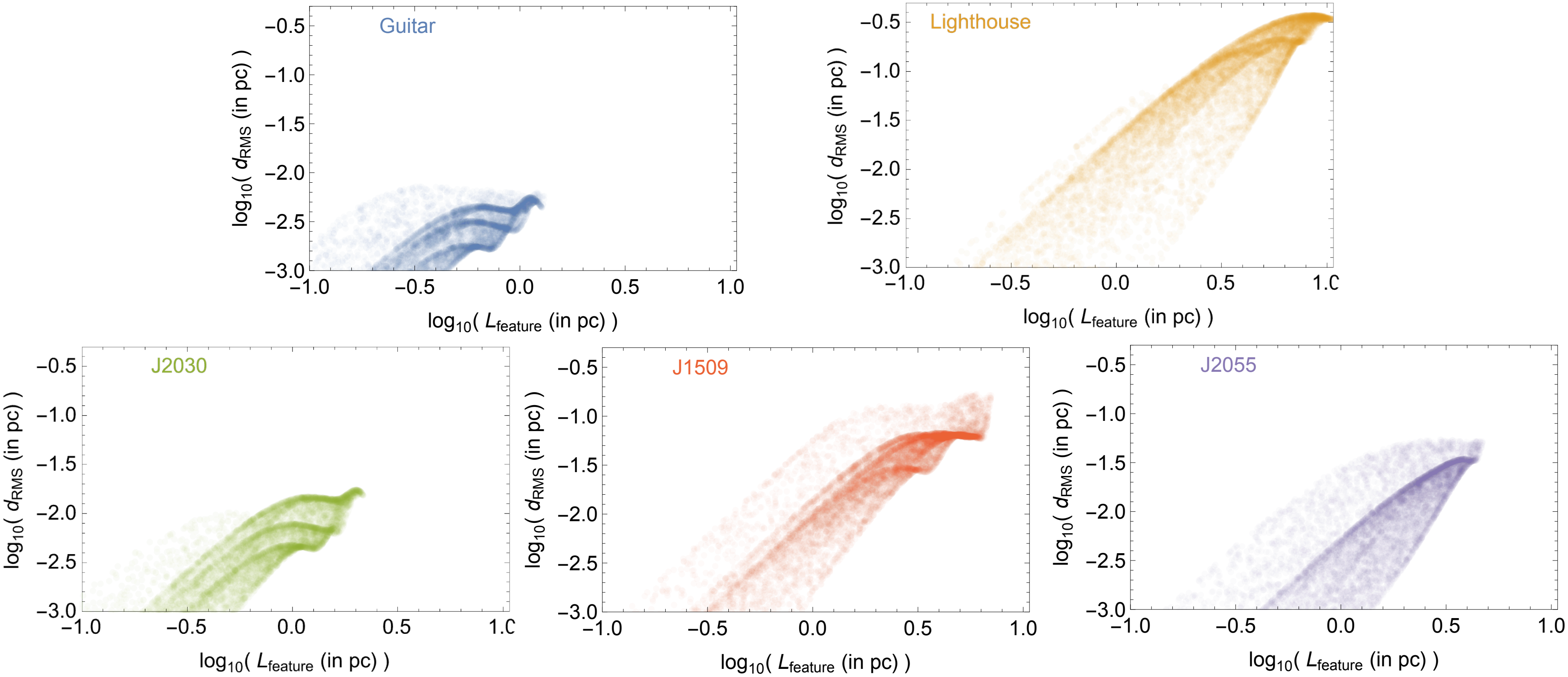
Observational results

Curves derived from published images + semi-automatic procedure.



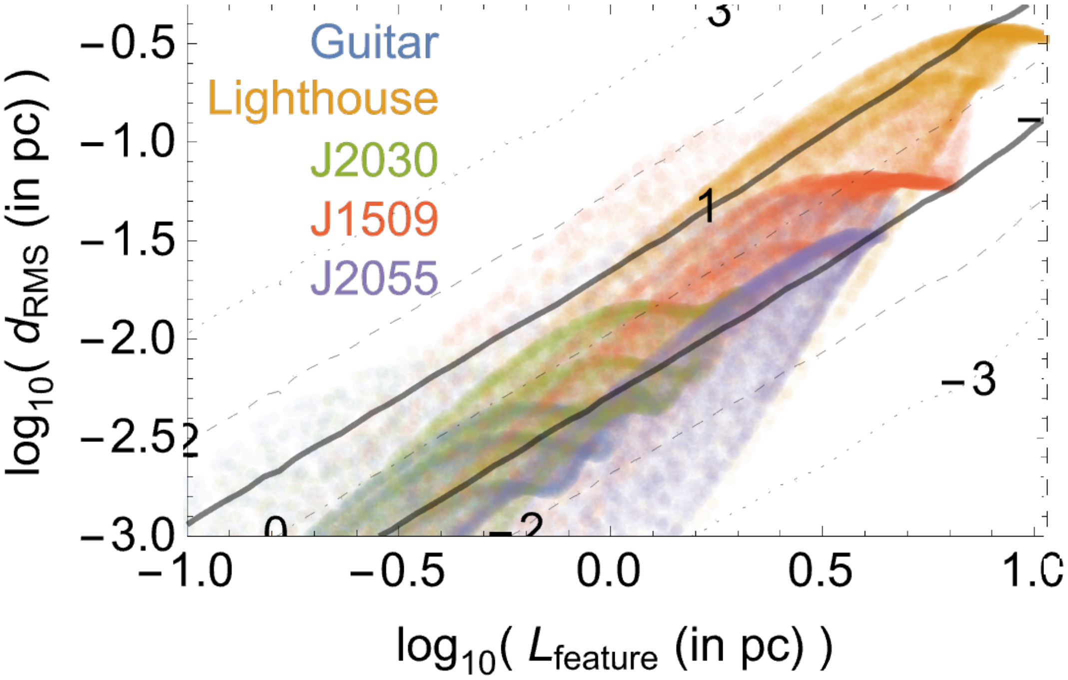
Observational results

- Multiple selection of points → a cloud of points from each individual source.
- Possibly inaccurate fit of the shapes BUT sufficient for a Log-Log plot.



Synoptic plot

- NOT A PROOF BUT SIMPLY A CONSISTENCY CHECK
- WITH MORE SOURCES, MORE INFORMATION ON THE B TURBULENCE ?



2. Electron evolution inside the feature

(WORK IN PROGRESS)

- Very large electron gyration radius: for an ordered $B \simeq 3\,\mu\mathrm{G}$ and $\gamma \simeq 10^8$ (case of Guitar) one obtains $R_{\mathrm{gyr}} \simeq 2 \cdot 10^{-2}\,\mathrm{pc}$, compared to $L_{\mathrm{fea}} \sim 1.3\,\mathrm{pc}$.
- In the case of effective non-resonant instabilities *Bell 2004*, turbulent fields (up to $B \simeq 45\,\mu\mathrm{G}$) at scales smaller than R_{gyr} .
- Regime inconsistent with standard MHD orbit theory. Standard diffusion cannot explain observed properties (no spectral downgrading away from the pulsar)

ANSATZ: electrons injected, at a base of the feature, with a small pitch angle

Analytic approach. Defining:

$$\omega_D = \left(\frac{\delta B}{B_{\mathrm{ISM}}}\right)^2 \left(\frac{c}{R_{\mathrm{gyr}}}\right)^2 \delta t_{\mathrm{coherence}}$$

Then:

$$\frac{d}{dt}\mu[\cos\alpha] = -\,\omega_D \cos\alpha; \qquad \frac{d}{dt}\sigma^2[\cos\alpha] = \omega_D \sin^2\alpha$$

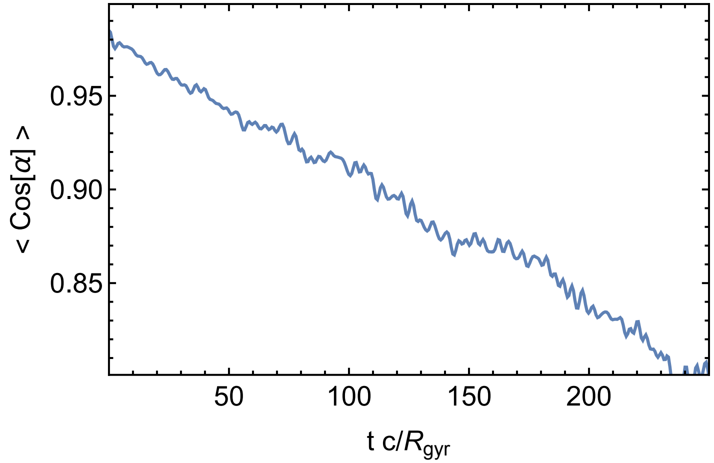
If: $\delta t_{\mathrm{corr}} = \dfrac{\epsilon R_{\mathrm{gyr}}}{c}$ (with ϵ small), then $t_{\mathrm{iso}} = \dfrac{R_{\mathrm{gyr}}}{\epsilon c}\left(\dfrac{B_{\mathrm{ISM}}}{\delta B}\right)^2$.

Persistence of small pitch angles for a rather long time.

TOY MODEL

Fluctuations: $\delta B \sim B_{\mathrm{ISM}}$; $< k_{\delta B} > = 10/R_{\mathrm{gyr}}$; $\sigma(k_{\delta B}) = 0.1 < k_{\delta B} >$

Initial pitch angle $\alpha = 10°$. Averaged values (over 100 particles)



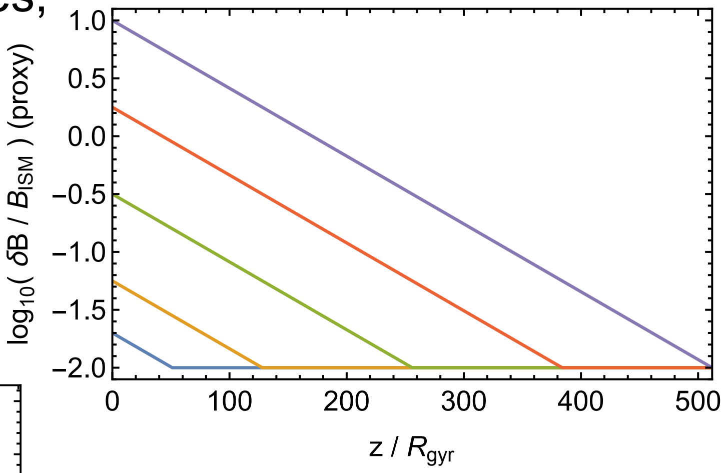
$\epsilon \sim 6 \cdot 10^{-4}$

PRELIMINARY MODEL

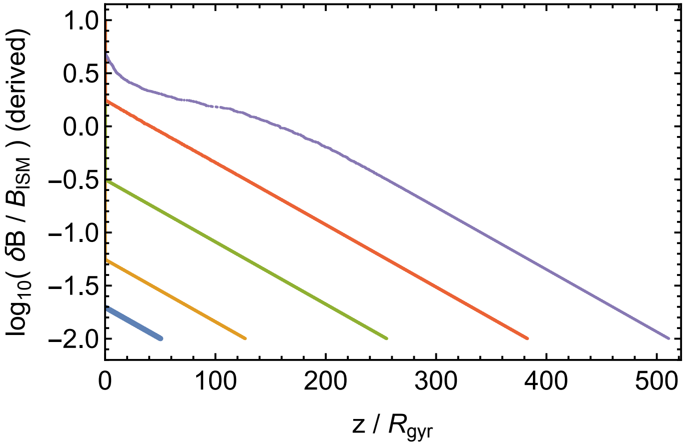
- Continuous flow of particles in the ambient field, with initial $\alpha = 0°$;
- Field amplification by current driven instabilities,

  is proportional to $\exp\left(K \int j(t')\, dt'\right)$.

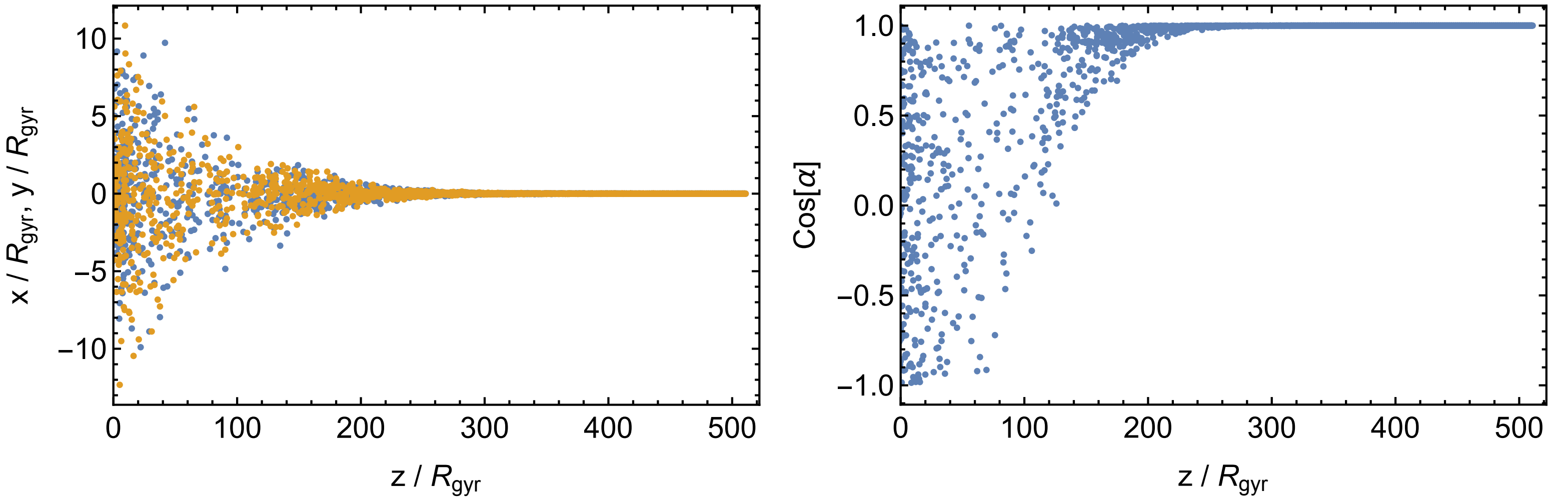
  Proxy used, assuming free flow of particles:



- Orbits simulation (2000 particles).
- Particles slowed down if higher B.
- Lower current.
- B is lower.

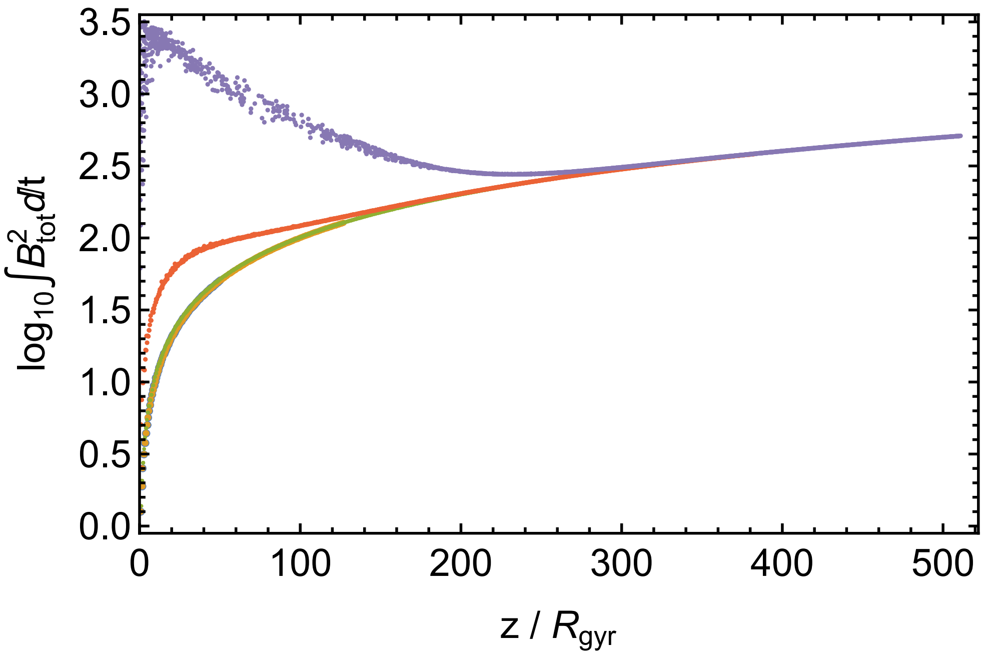


- Evolved distributions (at final time of calculations)

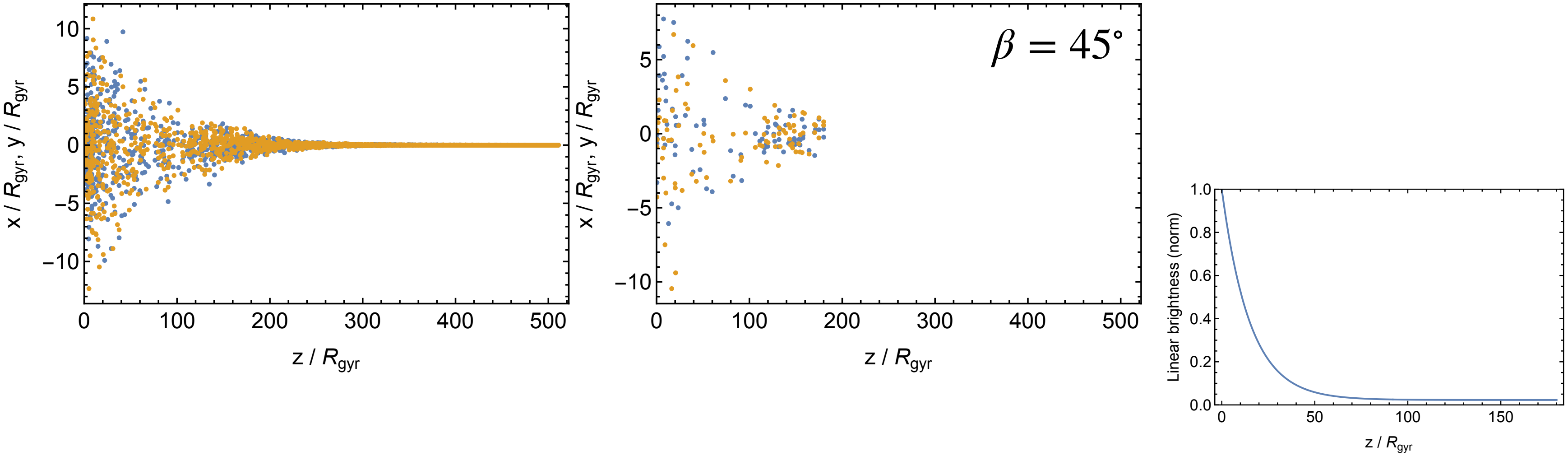


- At $z/R_{\rm gyr} \sim 100 \div 200$ transition between collimated and random pitch angles.
- Particles emitted earlier are further out, and still collimated.

- Relative effectiveness of synchrotron losses



- Oblique / transverse viewing angle → collimated particles are missing !



- The physical feature likely extends beyond the maximum detected distance.
- The invisible particles have contributed to the current necessary to the turbulent field amplification.
- Unclear the saturation level of the turbulent magnetic field amplification.

Summary

X-ray features associated to pulsar bow shocks

1. Statistical analysis of their curvatures

- Compatible with Galactic turbulence.

2. Evolution of particles once injected into the feature

- Fact: very long gyration radii.
- Assumption: they are injected with small pitch angles.
- Dimensionless model (lengths in units of R_{gyr}).
- Some promising preliminary results BUT:
- Still to perform extended analysis in the parameter space.
- Still to investigate some claimed observational details
  (e.g. possibly dimmer near the pulsar, possible clumpization).
- Still to compute the maximum field amplification that can be obtained.
- Maybe corrections to our statistical analysis, if visibility is not isotropic.