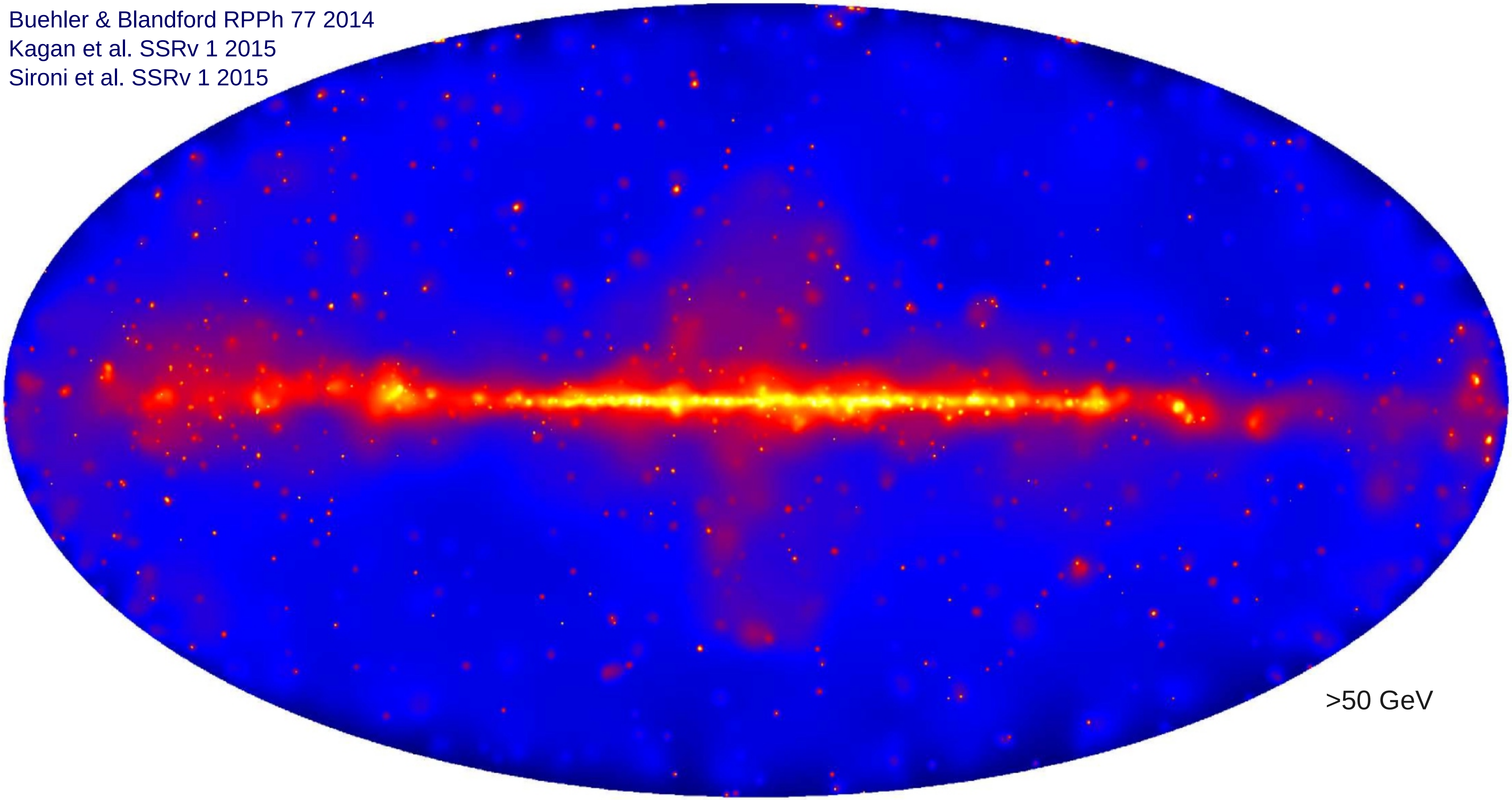
Particle acceleration observed in gamma rays

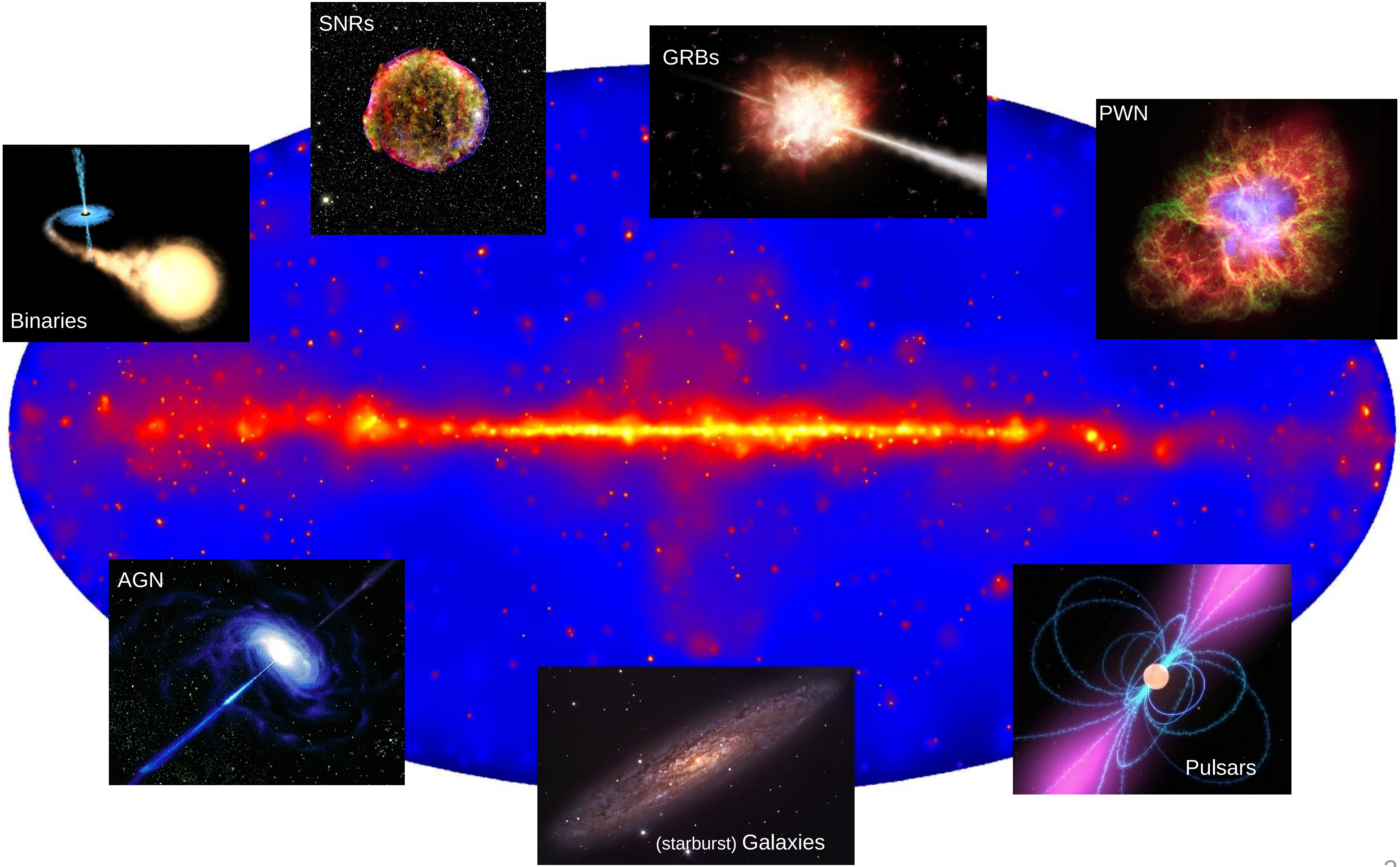
Based on

Buehler & Blandford RPPh 77 2014
Kagan et al. SSRv 1 2015
Sironi et al. SSRv 1 2015

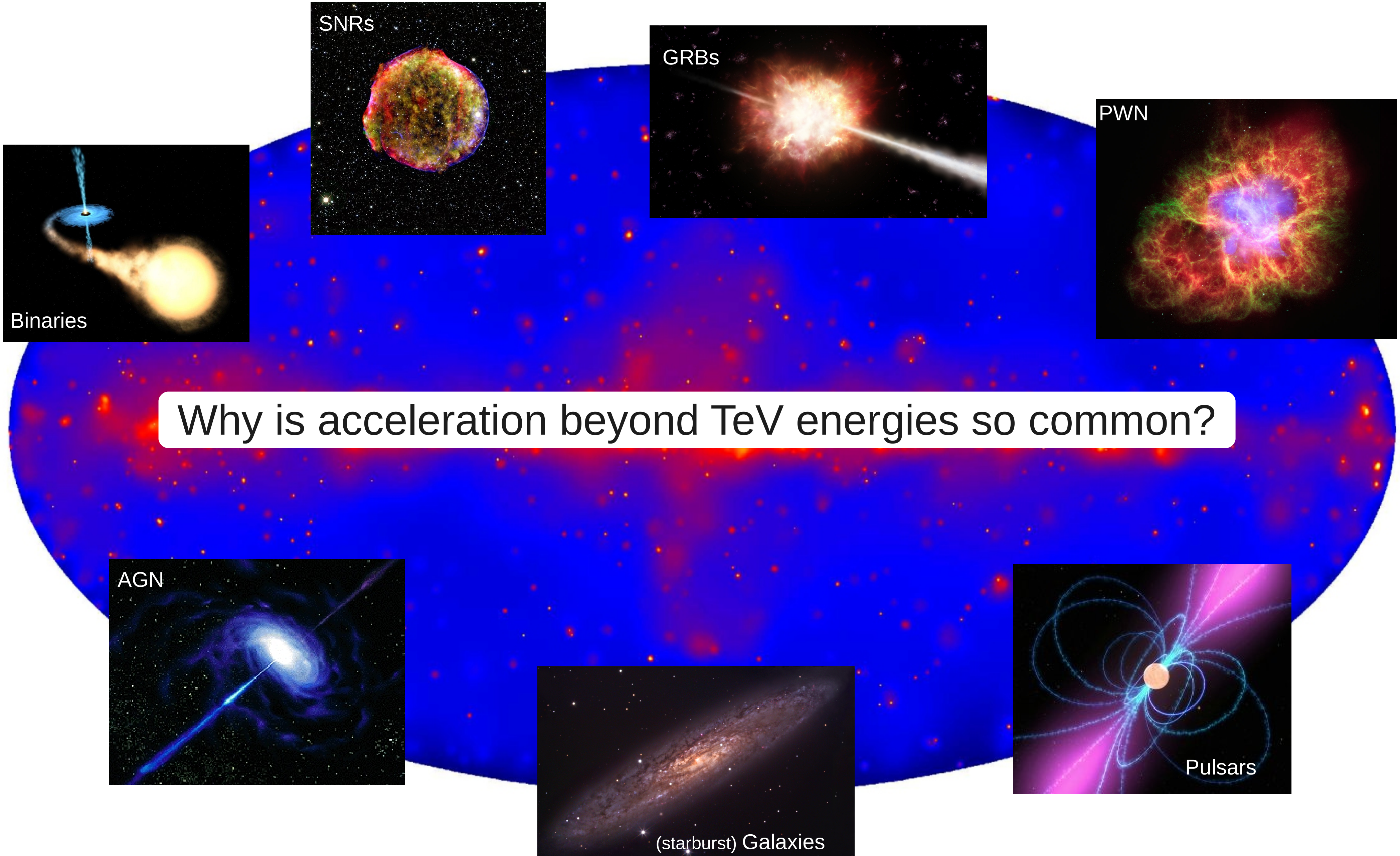


Rolf Bühler • 27th October 2015 • TeVPa Kashiwanoha

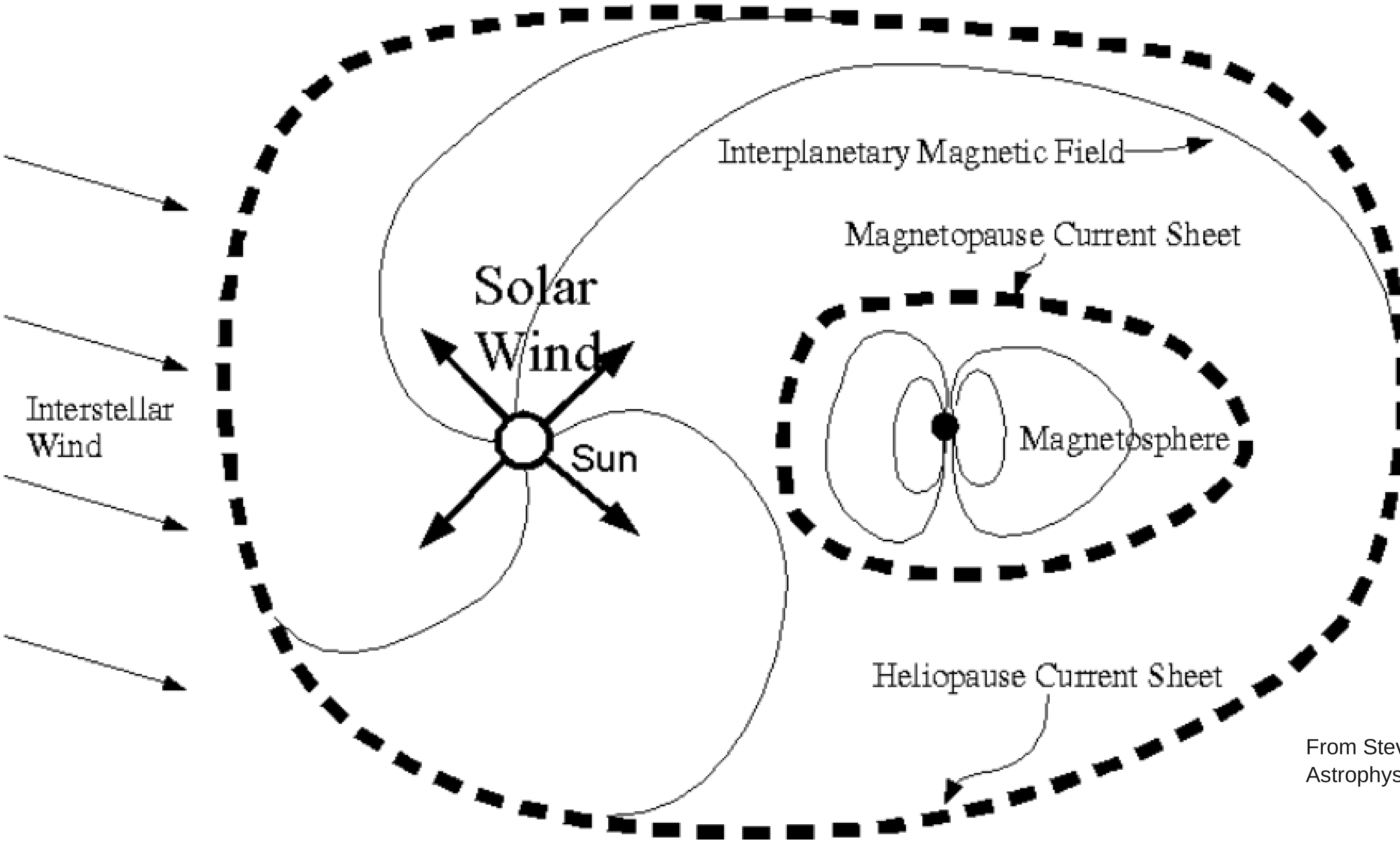
Cosmic accelerators



Cosmic accelerators



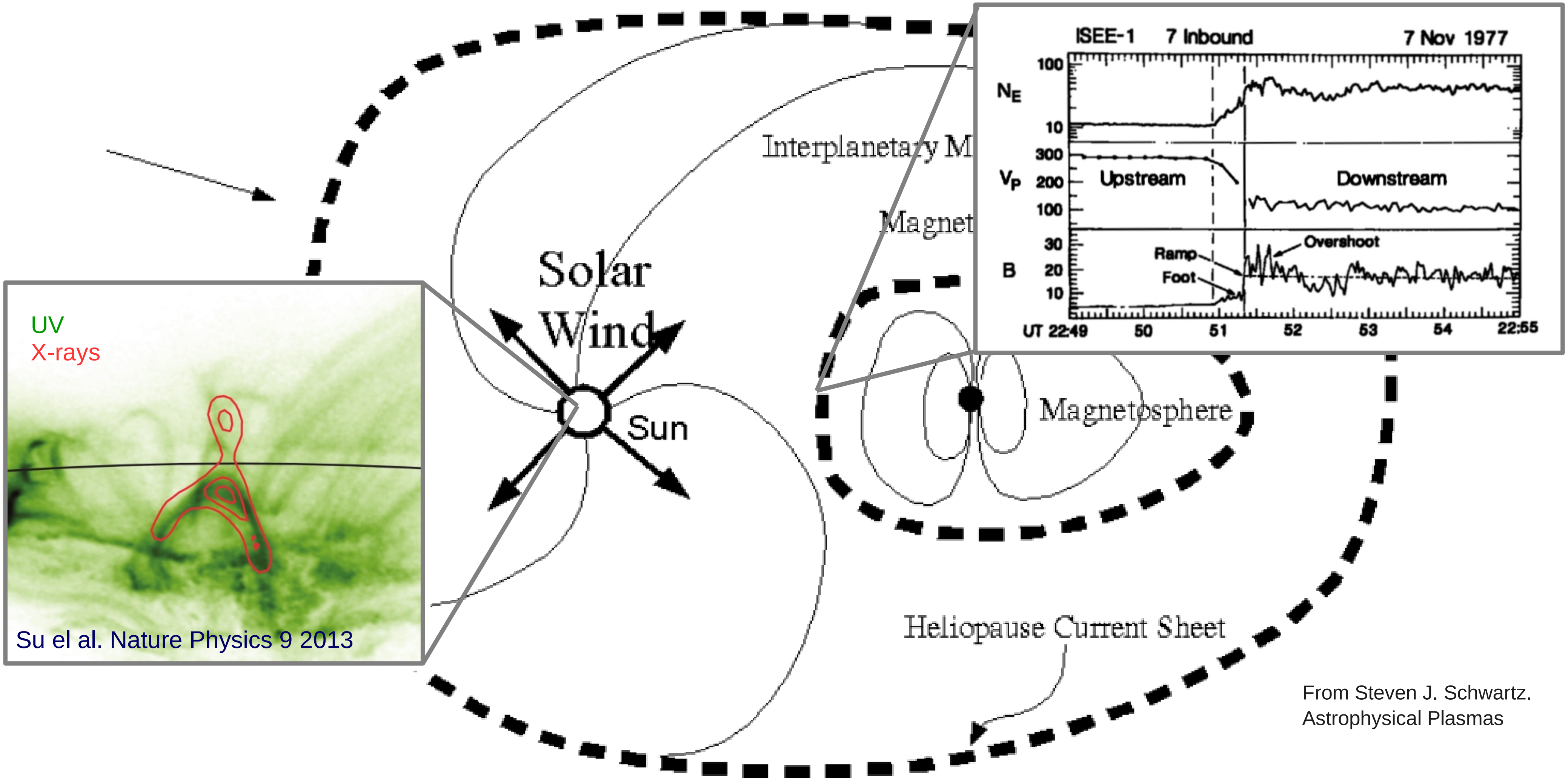
Universe of plasma bubbles



From Steven J. Schwartz. Astrophysical Plasmas

Contact of plasma flows leads to non-thermal particle acceleration, magnetic and bulk flow energies are transferred to particles

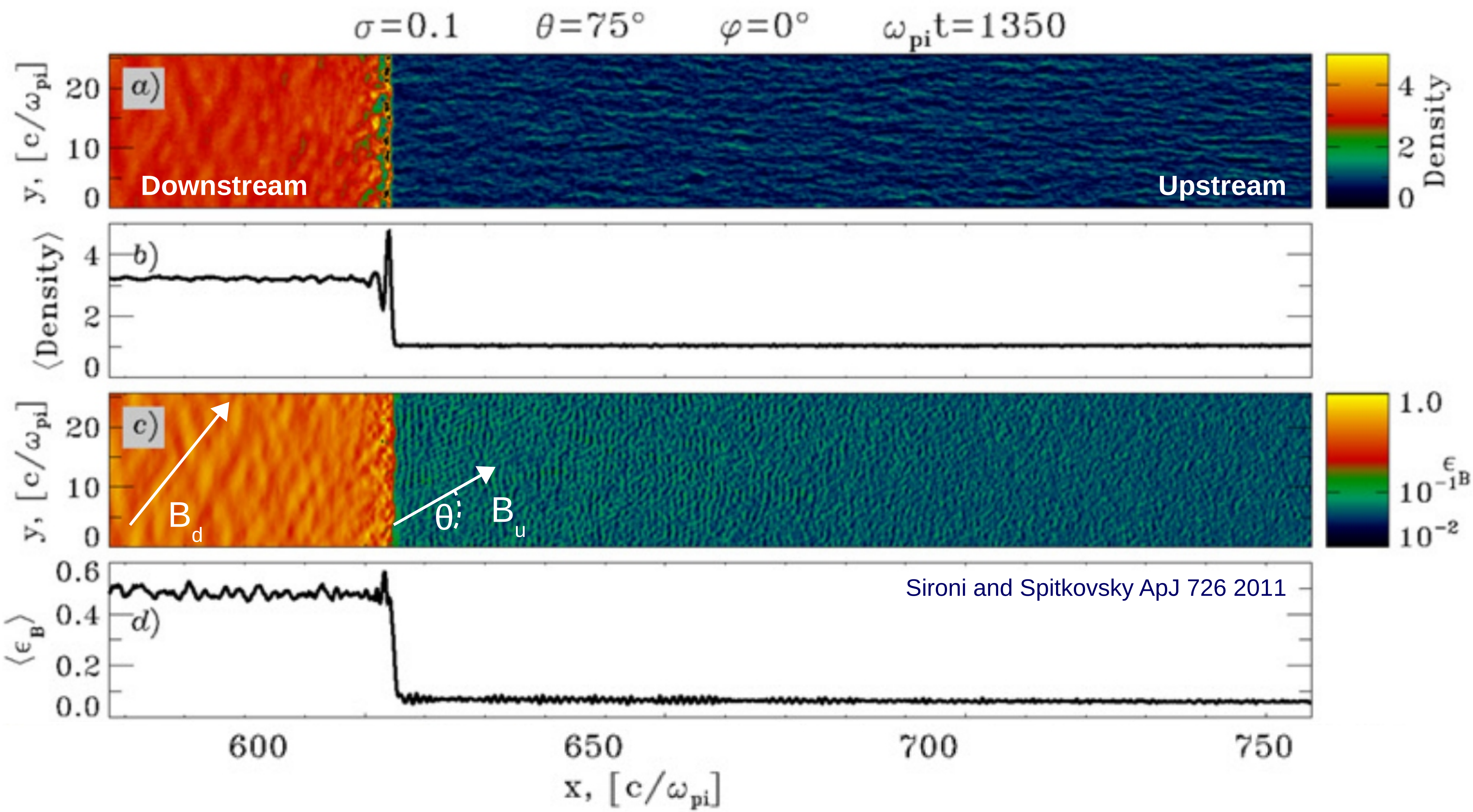
Universe of plasma bubbles



From Steven J. Schwartz. Astrophysical Plasmas

The most studied acceleration mechanisms are shock acceleration and magnetic reconnection

Shock acceleration



Theoretically studies since the 70's, recently with 2D/3D Particle In Cell simulations

Shock acceleration

The acceleration depends on the shock Lorentz factor and the upstream magnetization

$$\sigma = \frac{B^2}{4\pi \cdot (\gamma - 1) n m c^2}$$

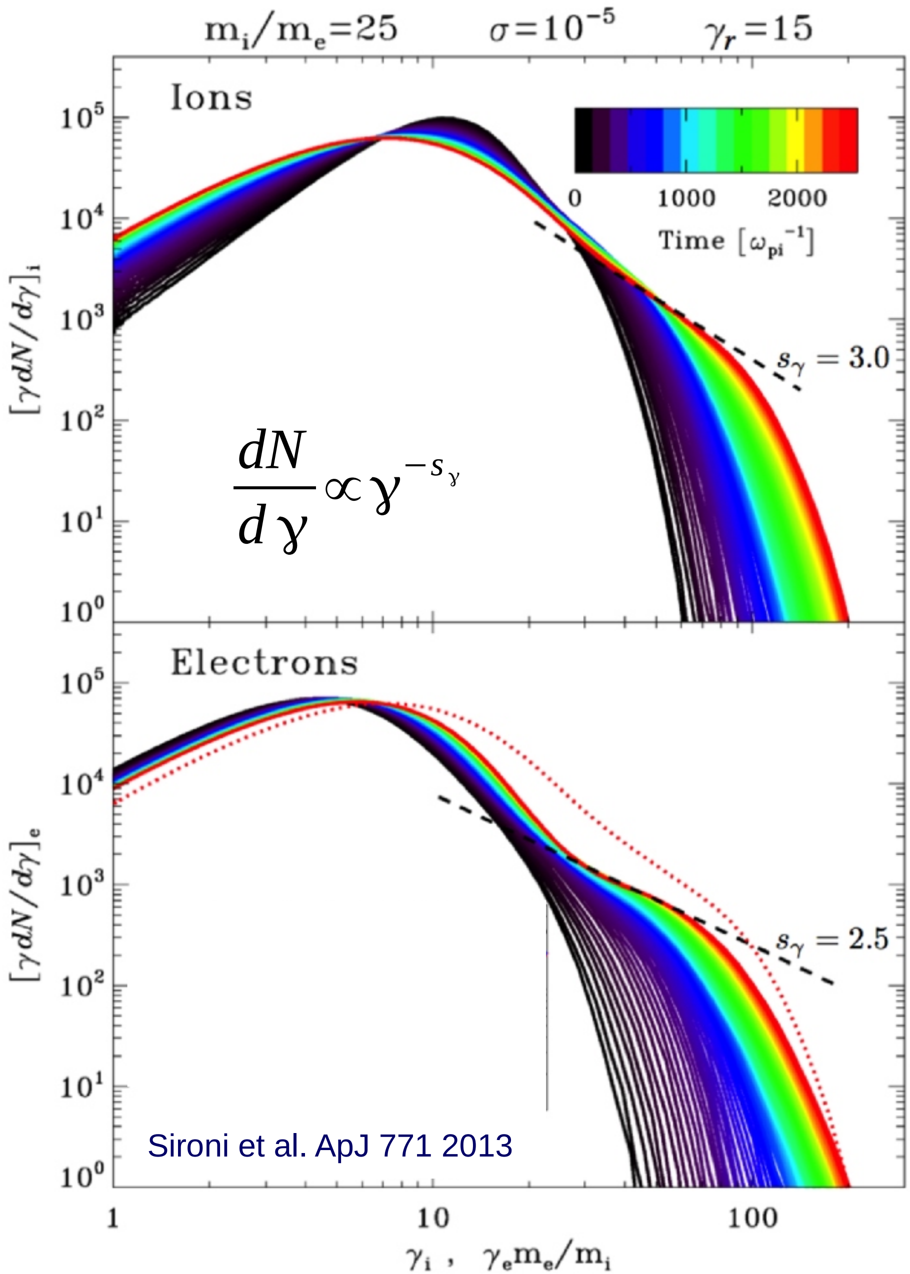
(in the shock frame)

For magnetized relativistic shocks ($\sigma > 10^{-3}$ and $\gamma > 1$) there is no acceleration if

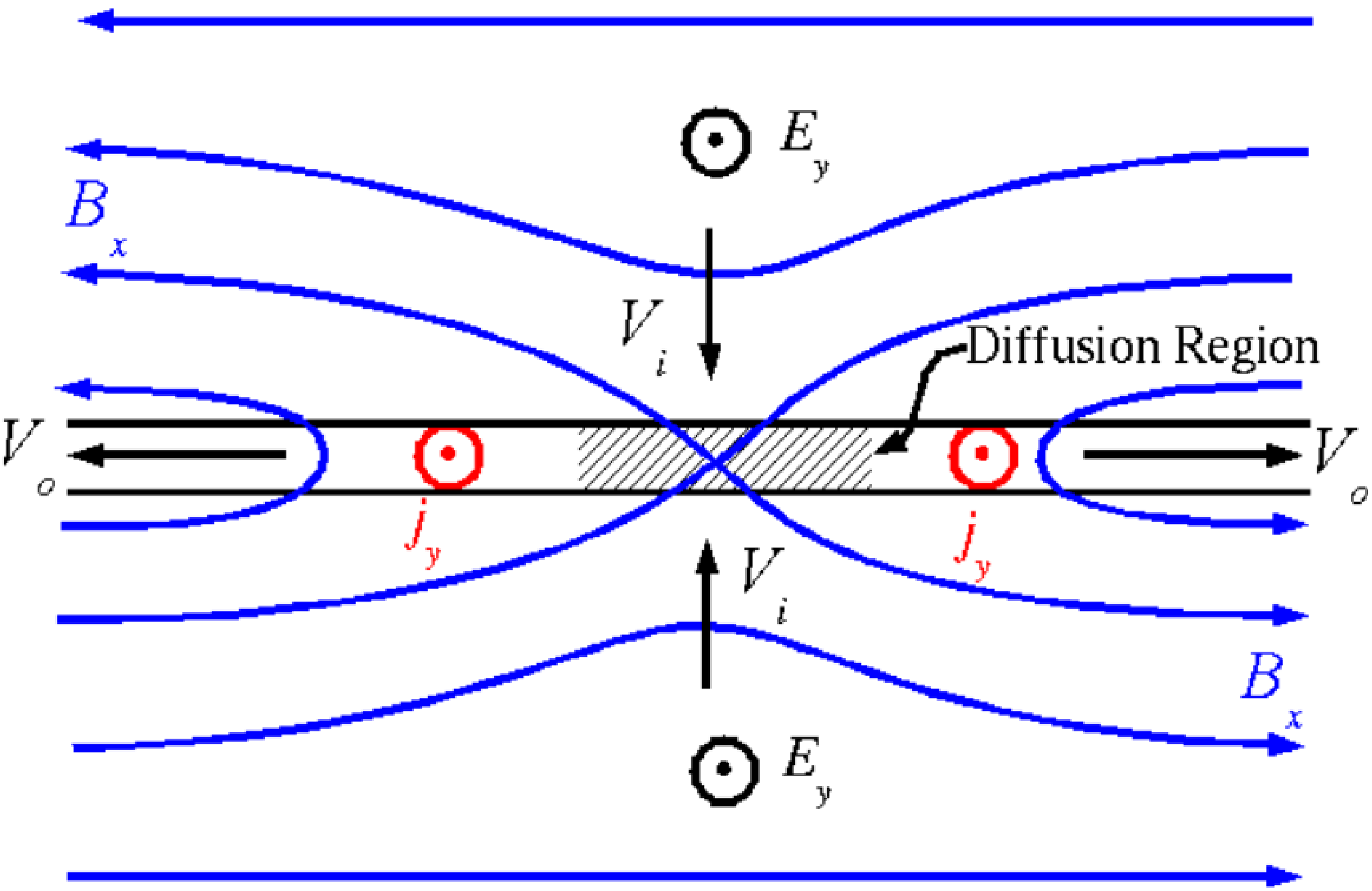
$$\theta > 34° / \gamma$$

(in the upstream frame)

as particles can not come back upstream



Magnetic reconnection



$$\nabla \times \vec{B} \approx \frac{4\pi}{c} \vec{j}$$

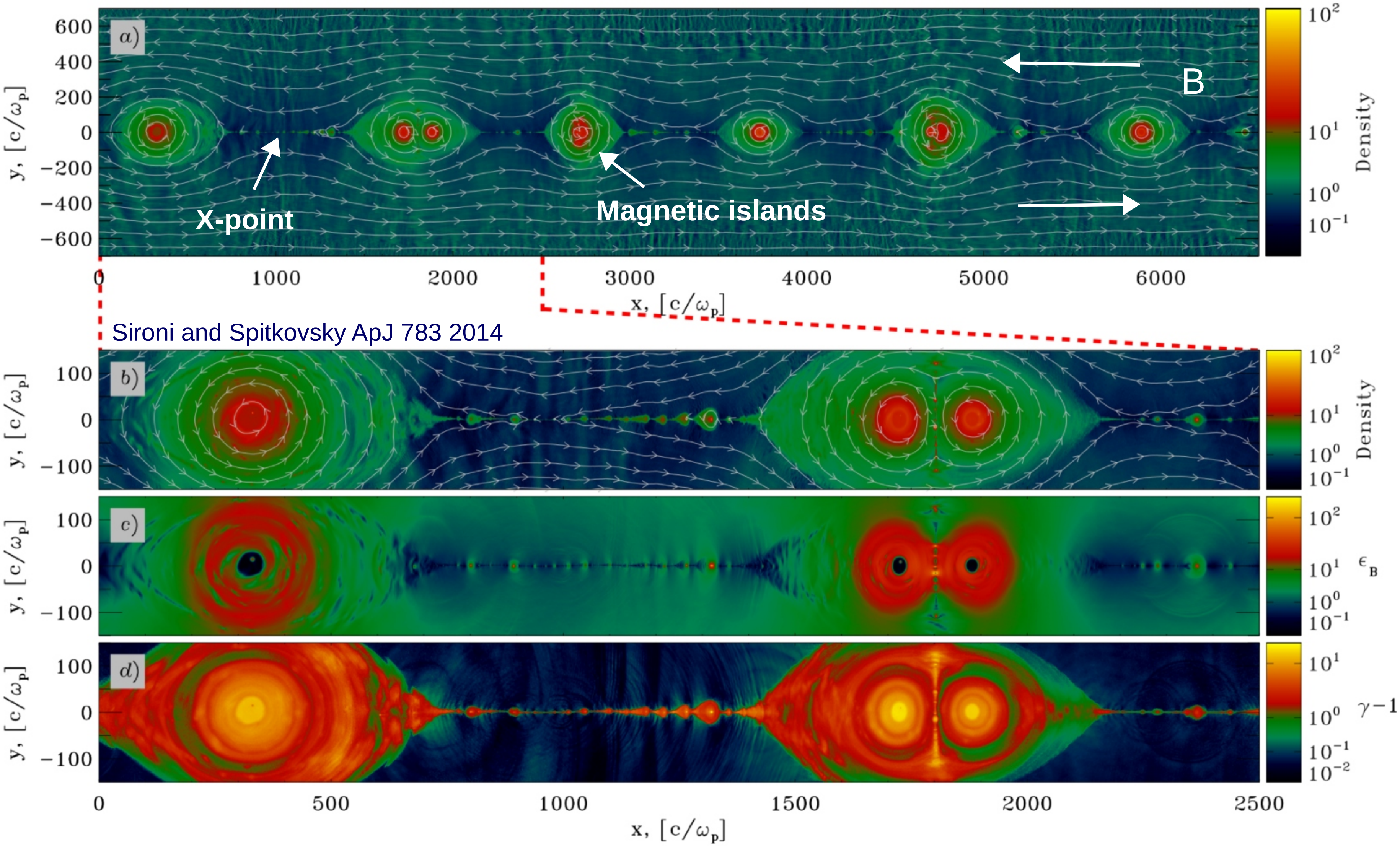
$$\vec{E} = -\frac{\vec{v}}{c} \times \vec{B}$$

$$\nabla \times \vec{E} = -\frac{1}{c} \frac{\partial \vec{B}}{\partial t} \approx 0$$

$$\nabla \vec{E} = 4\pi\rho \approx 0$$

Particles are accelerated predominantly at X-points and concentrated into magnetic islands

Magnetic reconnection



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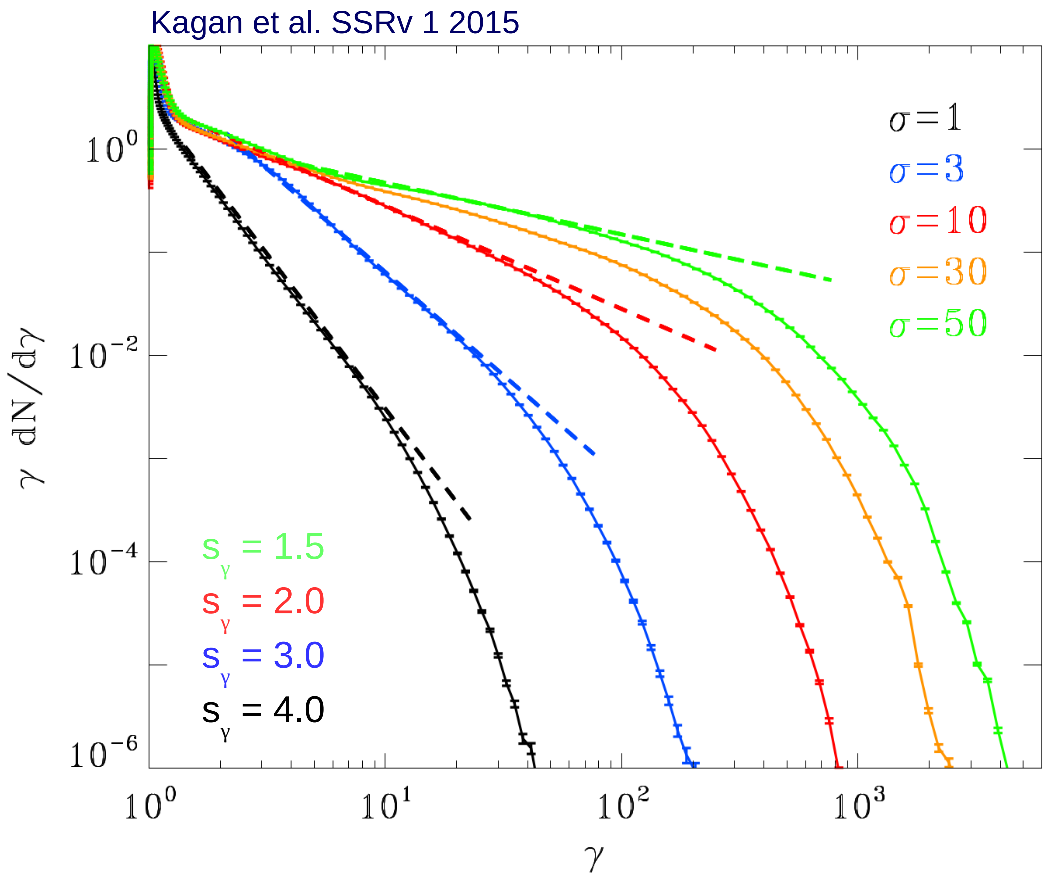
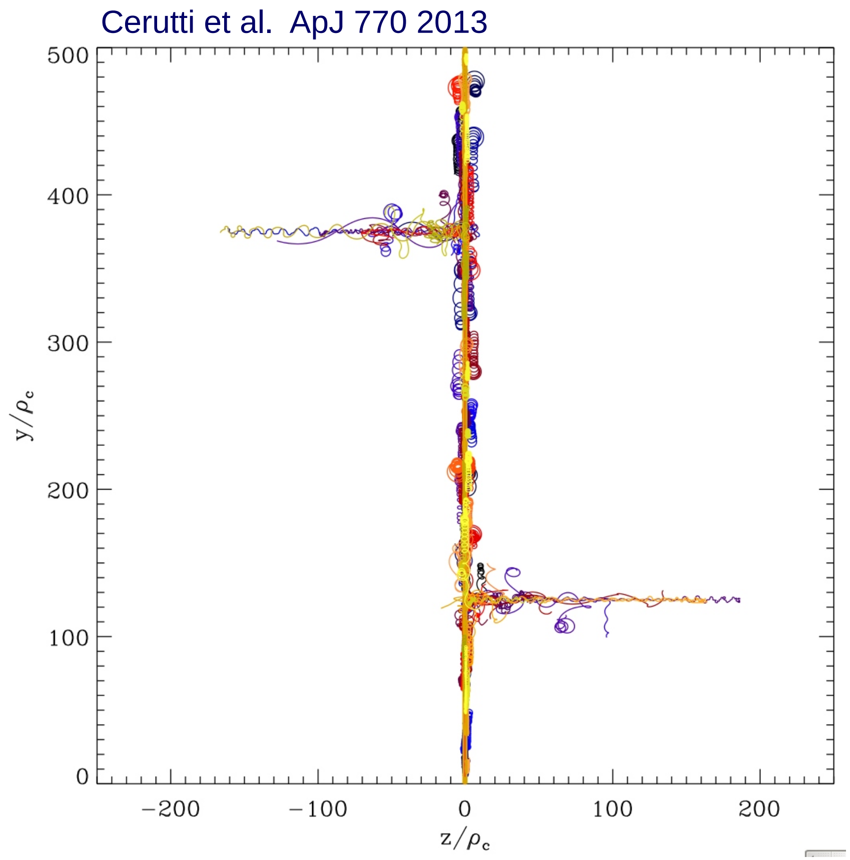
Magnetic reconnection

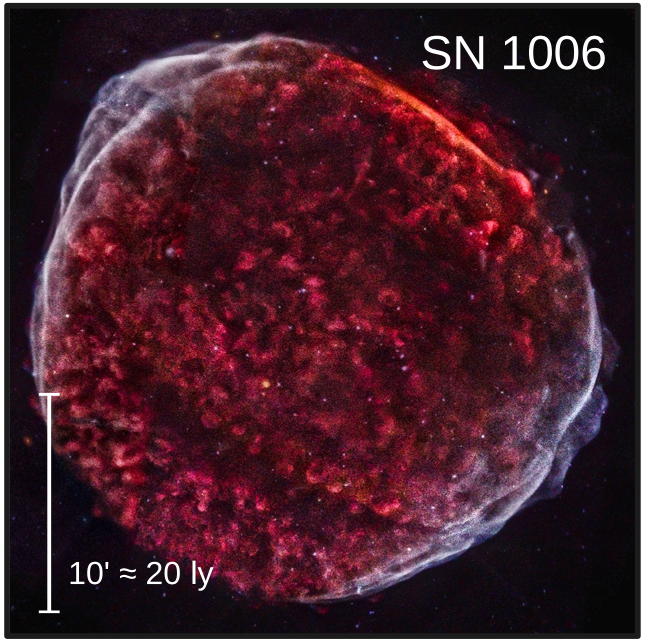


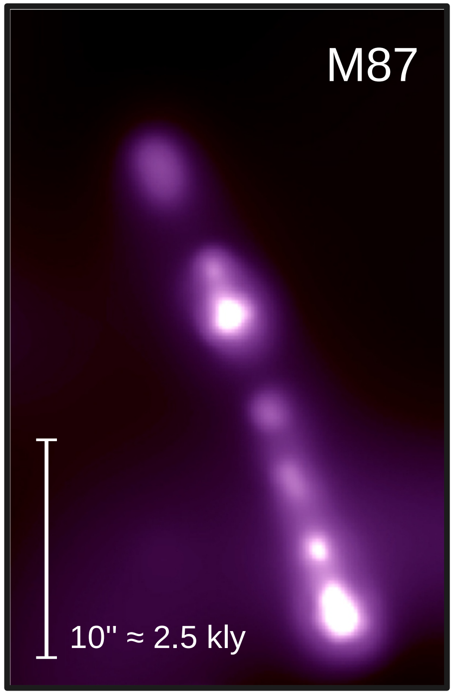


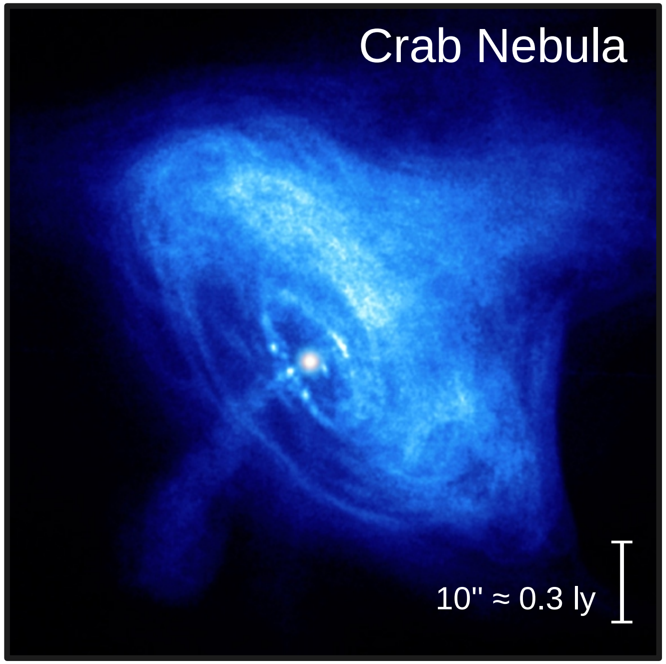
Large magnetization (σ > 1) are required. Hard spectra ($s_\gamma < 2$) are possible. Highest energy particles are beamed into z-direction

Accelerator property estimates

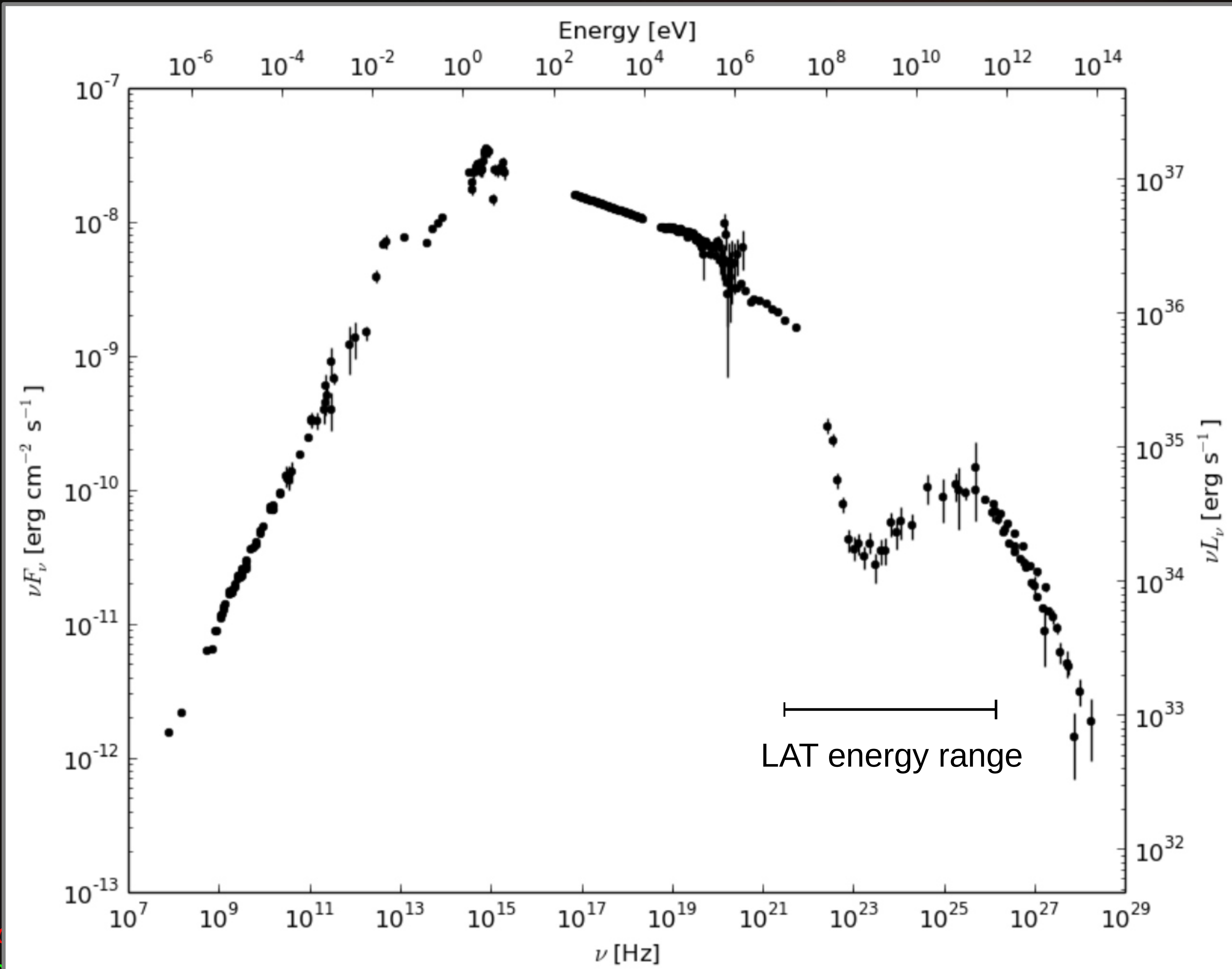
	Supernova Remnant shock	Active Galactic Nuclei jet	Pulsar Wind reverse shock
γ-1	10^{-6} - 10^{-3}	~10	10^{4} - 10^{6}
σ	$<10^{-3}$	$>10^{-3}$	0.01 - >1
Reconnection	no	(yes)	yes
Shock	yes	(no)	no







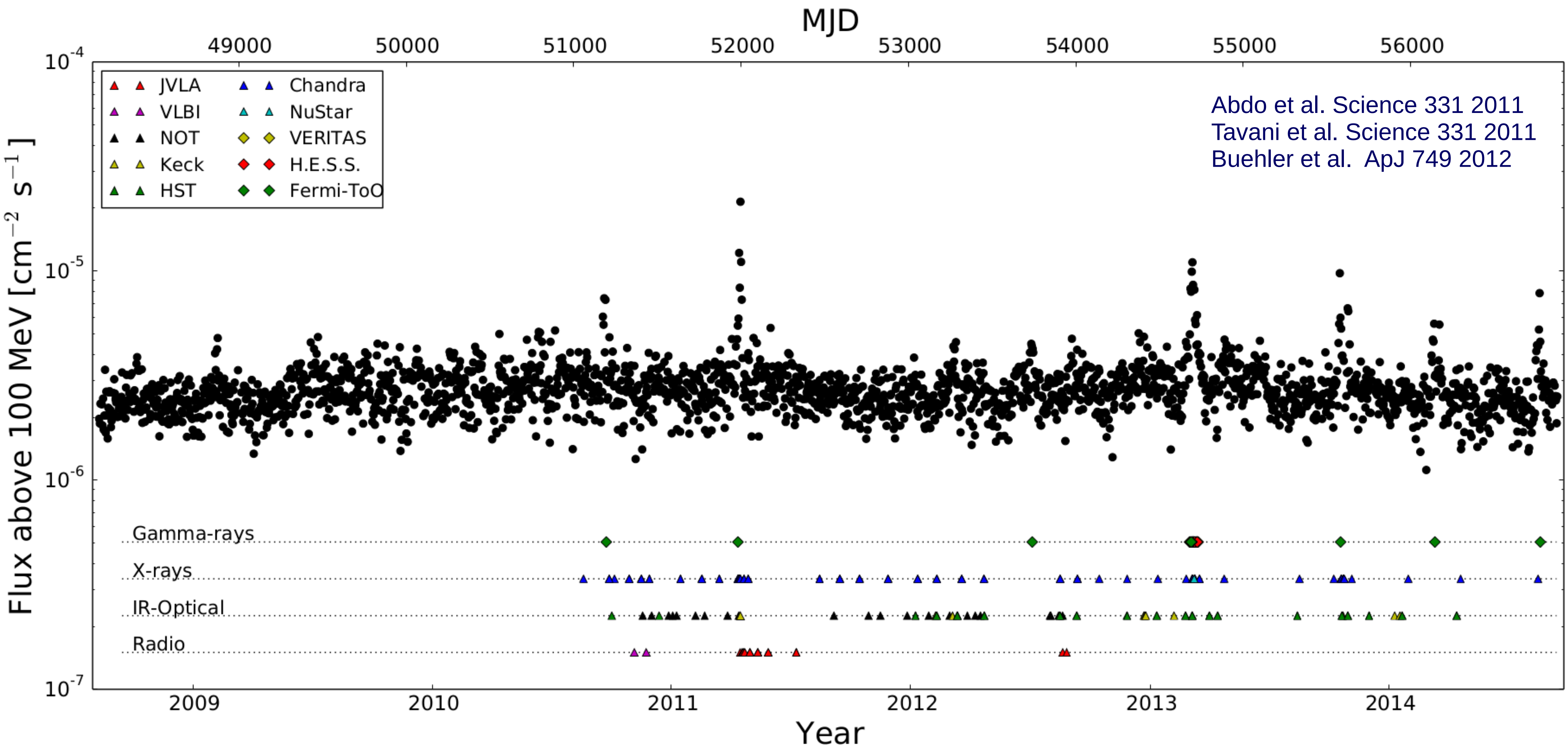

Radio VLA
Optical HST
X-rays Chandra
10'' ≈ 0.3 ly

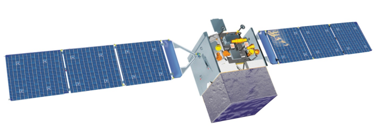


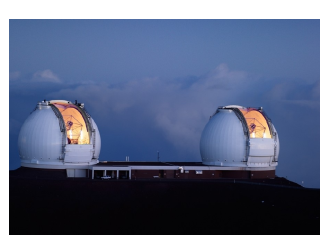
Radio
Optical HST
X-rays Chandra

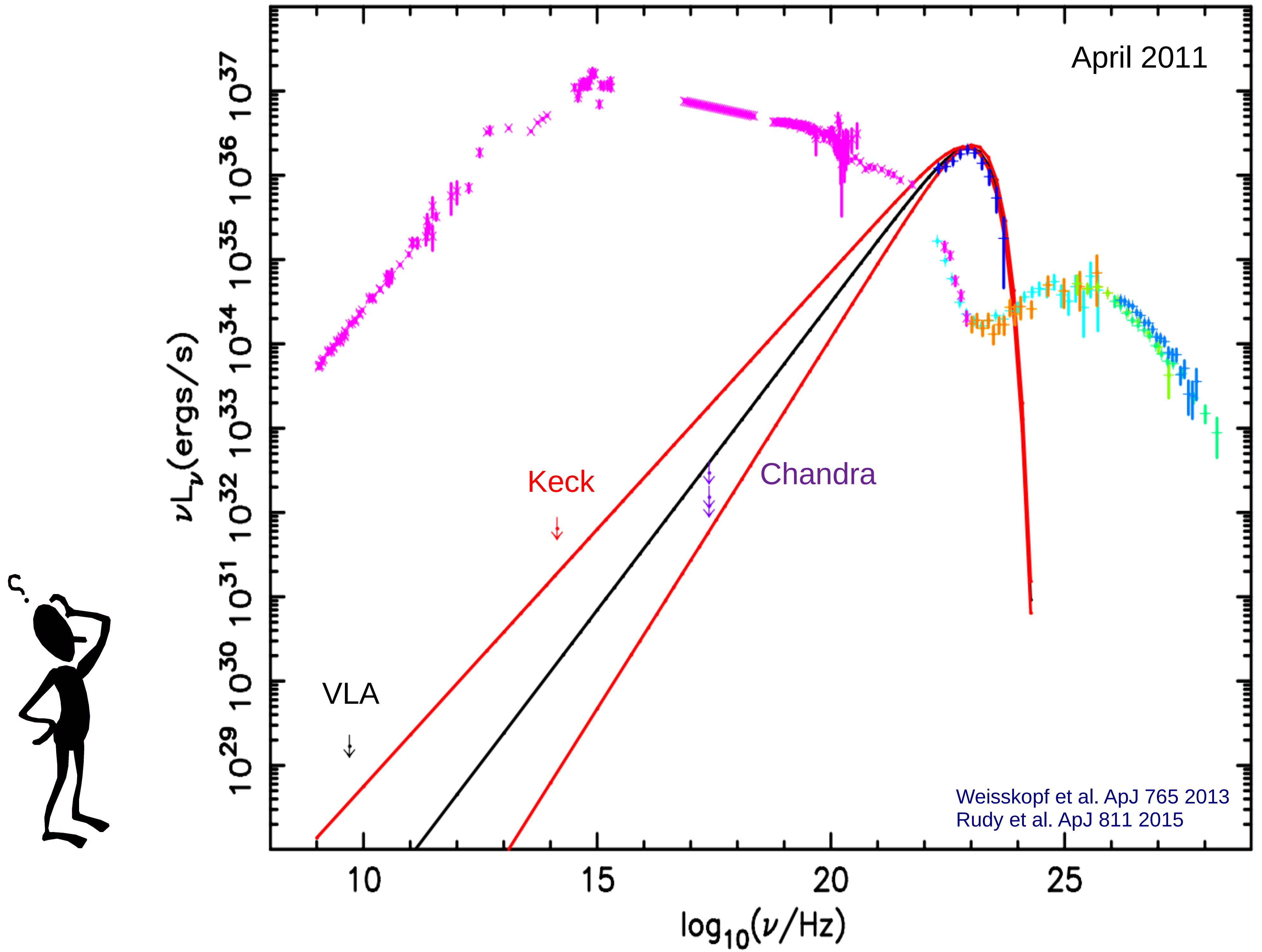
≈ 0.3 ly

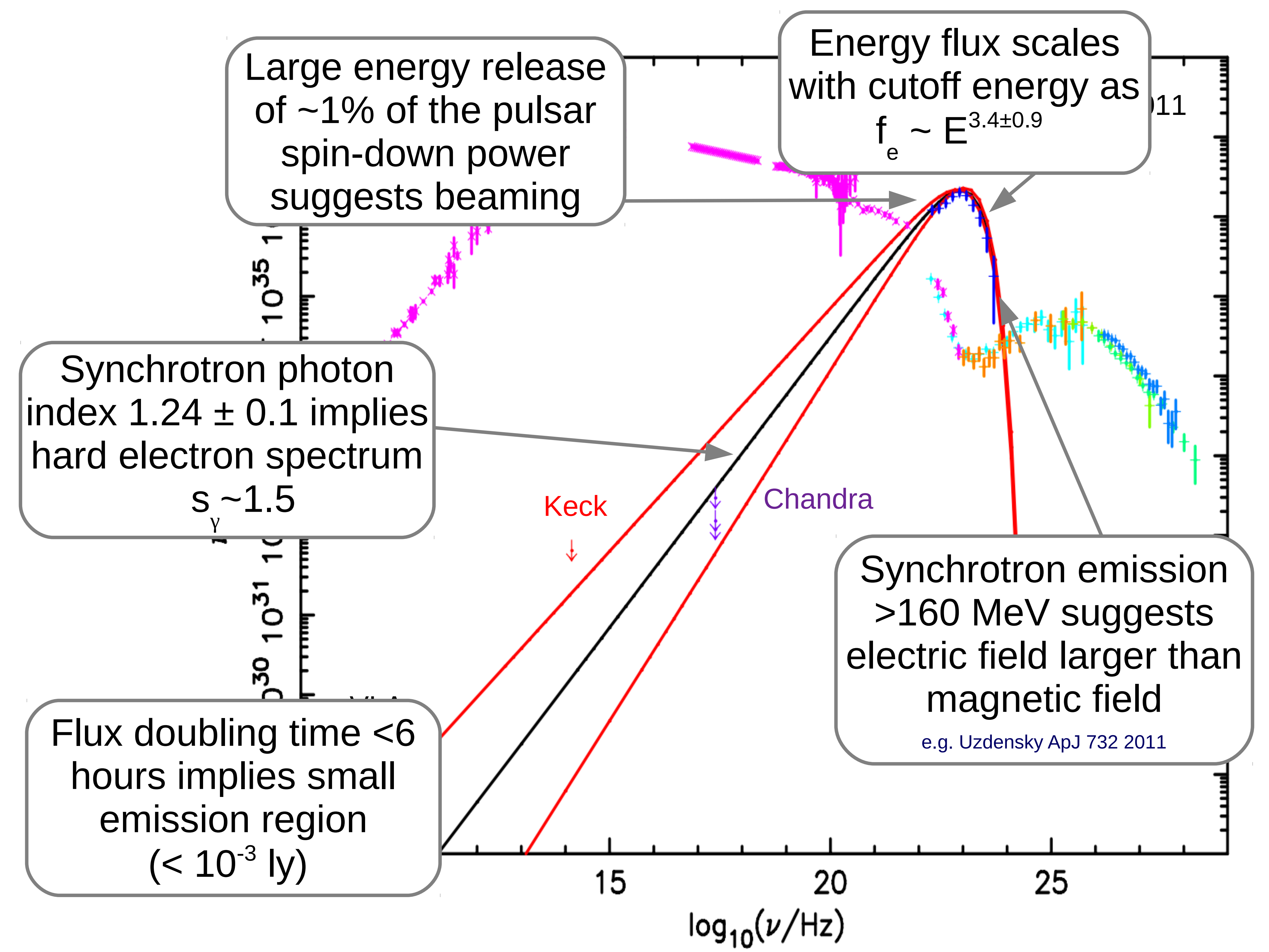
The gamma-ray flares







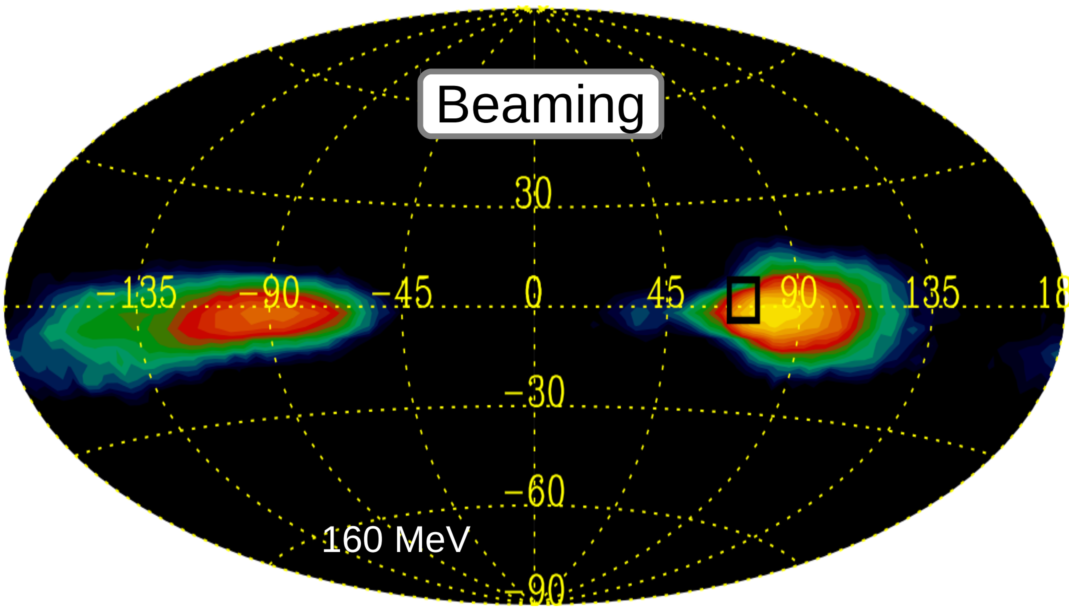

April 2011
Keck
Chandra
VLA
νLν(ergs/s)
log10(ν/Hz)
10
15
20
25
10^29
10^30
10^31
10^32
10^33
10^34
10^35
10^36
10^37
Weisskopf et al. ApJ 765 2013
Rudy et al. ApJ 811 2015

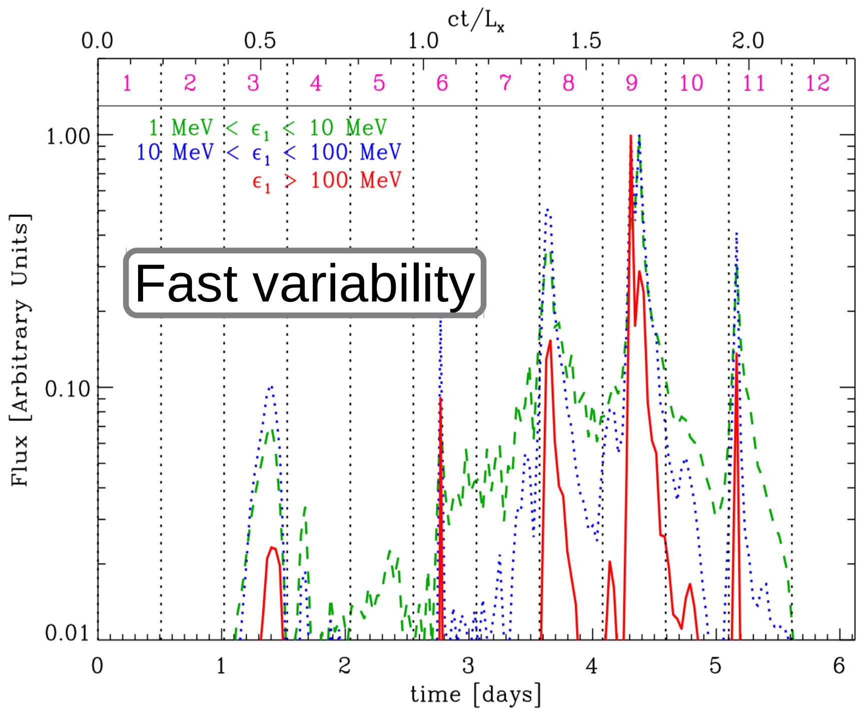

Large energy release of ~1% of the pulsar spin-down power suggests beaming
Energy flux scales with cutoff energy as $f_e \sim E^{3.4\pm0.9}$
Synchrotron photon index 1.24 ± 0.1 implies hard electron spectrum s_γ~1.5
Keck
Chandra
Synchrotron emission >160 MeV suggests electric field larger than magnetic field
e.g. Uzdensky ApJ 732 2011
Flux doubling time <6 hours implies small emission region (< 10^{-3} ly)
15
20
25
$\log_{10}(\nu/\mathrm{Hz})$

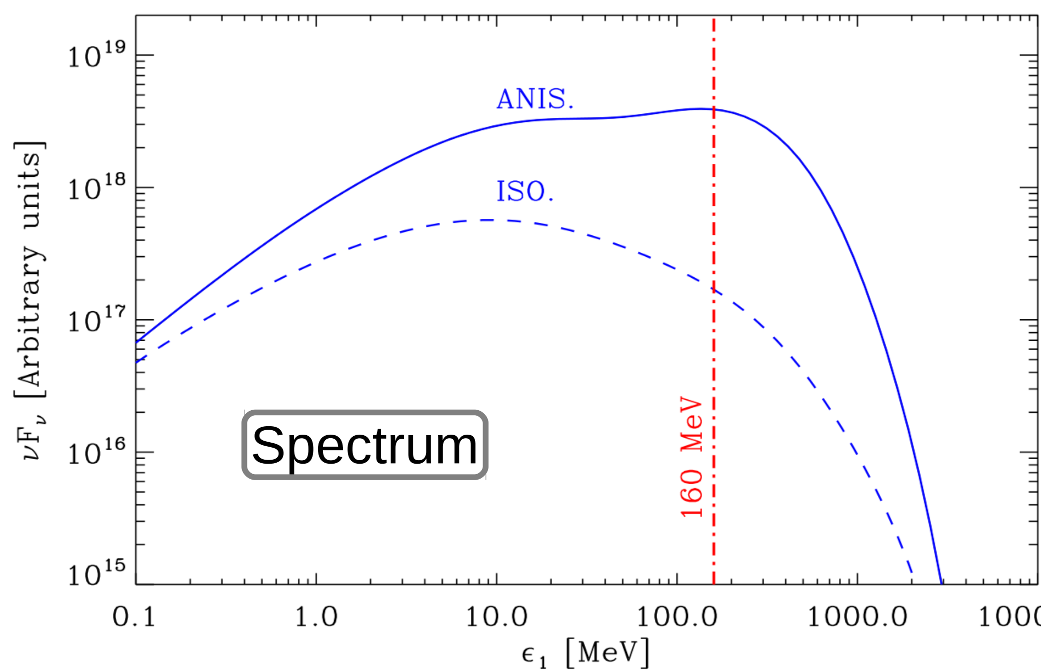
Flares from reconnection?

3D Particle In Cell simulations can reproduce the flare properties

Cerutti et al. ApJ 770 2013
Cerutti et al. ApJ 782 2014







Summary

At the contact point of plasma flows, shock acceleration and magnetic reconnection can accelerate non-thermal particles

Shock acceleration is inefficient at magnetized relativistic shocks. Magnetic reconnection appears more natural in relativistic flows (as AGN, PWN or GRBs)

The Crab nebula flare properties can be well explained as explosive reconnection events in Particle In Cell simulations