CTA Japan meeting
Kashiwa Campus of the University of Tokyo
2016-12-16

Particle acceleration in supernova remnants

numerical simulations and high-energy observations

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Outline of the talk

Introduction: particle acceleration in supernova remnants

- SNRs as Cosmic Ray accelerators

Catalogue of high-energy observations

- rationale and objectives
- demo and statistics

3D numerical simulations

- hydro+kinetic code
- thermal and non-thermal emission

SNRs as a key link between stars and the ISM

enrichment in heavy elements

Big Bang: H, He	Cosmic Rays: Li, Be, B	stars: all other elements from C to U

average stars: up to C-O
massive stars: up to Fe
supernovae: everything else?

injection of energy

heating of the gas	hydrodynamic turbulence	magnetic field amplification

impact on subsequent star formation cycles?

acceleration of particles

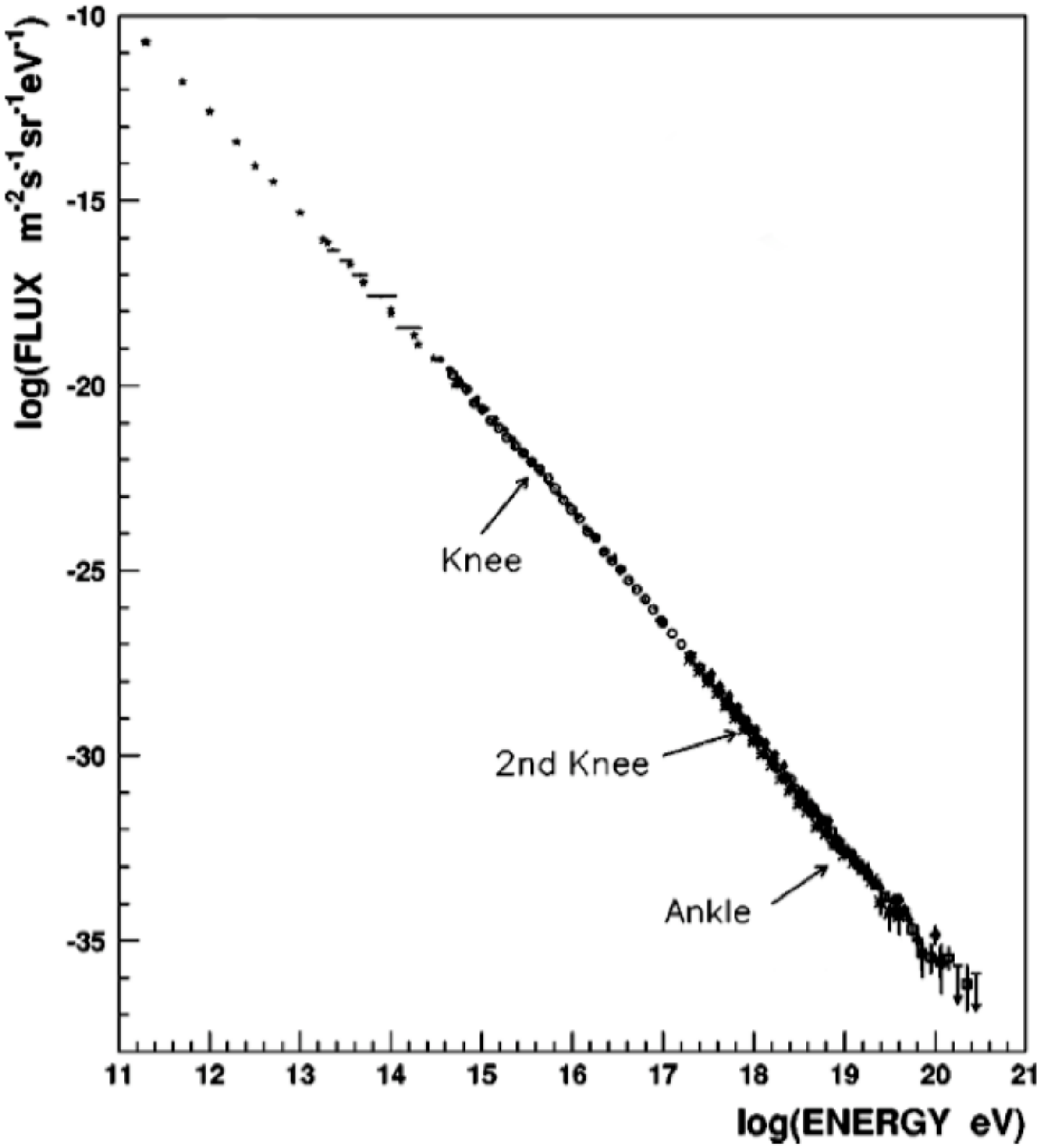
SNRs main sources?
Also PSRs and binaries

$< 10^{15}$ eV: Galactic	$> 10^{18}$ eV: extra-Galactic

the acceleration of charged particles is an important feature of magnetized shocks in collisionless plasma

Supernova Remnants as sources of Cosmic Rays

energy spectrum
of cosmic radiation
(as observed on the Earth)



from Nagano et Watson 2000

acceleration by shock waves
in supernova remnants

- ☺ standard composition
- ☹ some "anomalies"

- ☺ global energetics
- ☹ maximum energy

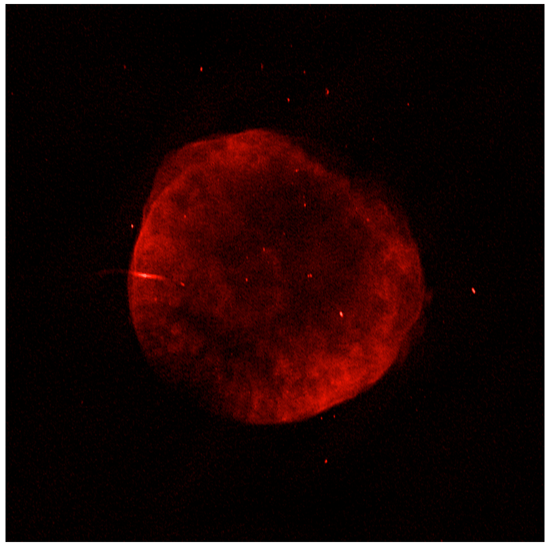
- ☺ power-law (Fermi 1)
- ☹ which slope? (NL effects)

- ☺ radiation from accelerated electrons
- ☹ and protons?

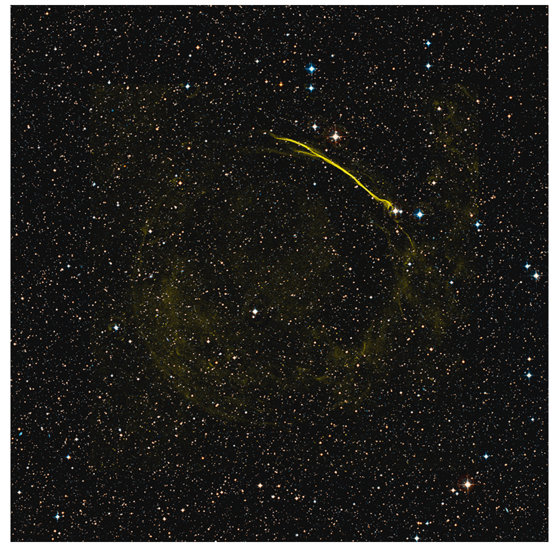
reviews: Drury 2012, Blasi 2013, Bell 2013

SNR broad-band emission

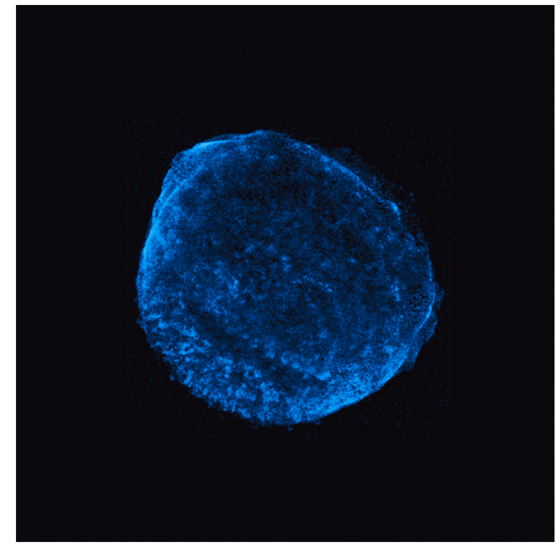
SN 1006



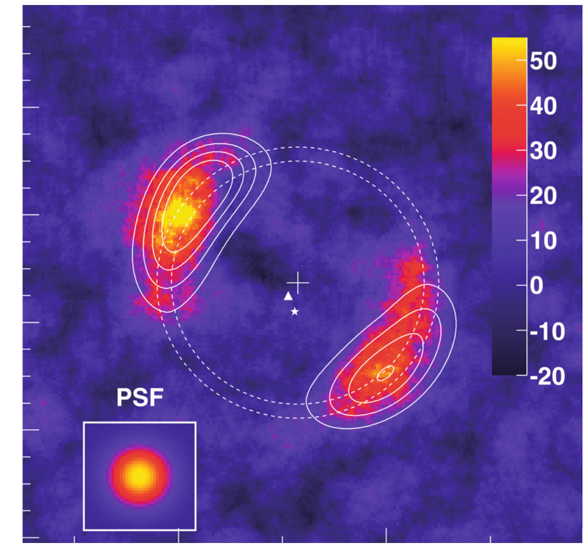
radio



optical



X



gamma

E

cm μm keV TeV

λ

radio	optical	X	gamma
synchrotron in B field	Balmer lines forbidden lines	atomic lines of heavy elements + synchrotron	Inverse Compton ? pion decay ?
↑	↑	↑	↑
GeV e-	blast wave	hot ejecta + TeV e-	> TeV e- ? > TeV p ?

review for CR evidence: Helder et al 2012

HE catalogue of Galactic SNRs: motivation

- **Focus on high-energies (X, gamma)**

Dave Green's catalogue: identification and typing from radio emission
SNRcat: particle acceleration from broadband X-ray and γ-ray emission

- **Provide a unified view of SNRs**

Some observatories offer dedicated resources
SNRcat: all observations from major relevant observatories presented together

Some other websites present all observations in a specific energy domain
SNRcat: complete and broad-band view of all Galactic SNRs

- **Be up-to-date**

Green's catalogue: last updated in 2014 (294 SNRs, added 87)
SNRcat: weekly/daily updates, to keep pace with the surge in X-ray/γ-ray obs

- **Be easy to manipulate**

SNRcat: stored in a relational database (sorting, filtering, searching,...)

Ferrand & Safi-Harb 2012 (ASR 49 9)

`www.physics.umanitoba.ca/snr/SNRcat`

HE catalogue of Galactic SNRs: statistics

- **381 records of a supernova remnant (SNR)**

. 108 contain a neutron star (NS) or candidate, 108 identified as a pulsar (PSR)
. 6 anomalous pulsars (AXPs) + 5 soft γ-ray repeaters (SGRs) + 2 high-B PSRs = 13 magnetars candidates
. 15 central compact objects (CCOs) or candidates
. pulsar wind nebula (PWN) detected or suggested in 106 cases (not a subset of the SNRs hosting a NS: only 83 SNRs are associated with both)
. interaction of the shell with a molecular cloud (MC) reported in 70 cases

- **14 records of the sighting of a supernova (SN)**

referred to by 14 SNRs records
(non-bijective: some SN have multiple candidates, others have none)

- **1633 records of high-energy observations** made with 40 observatories

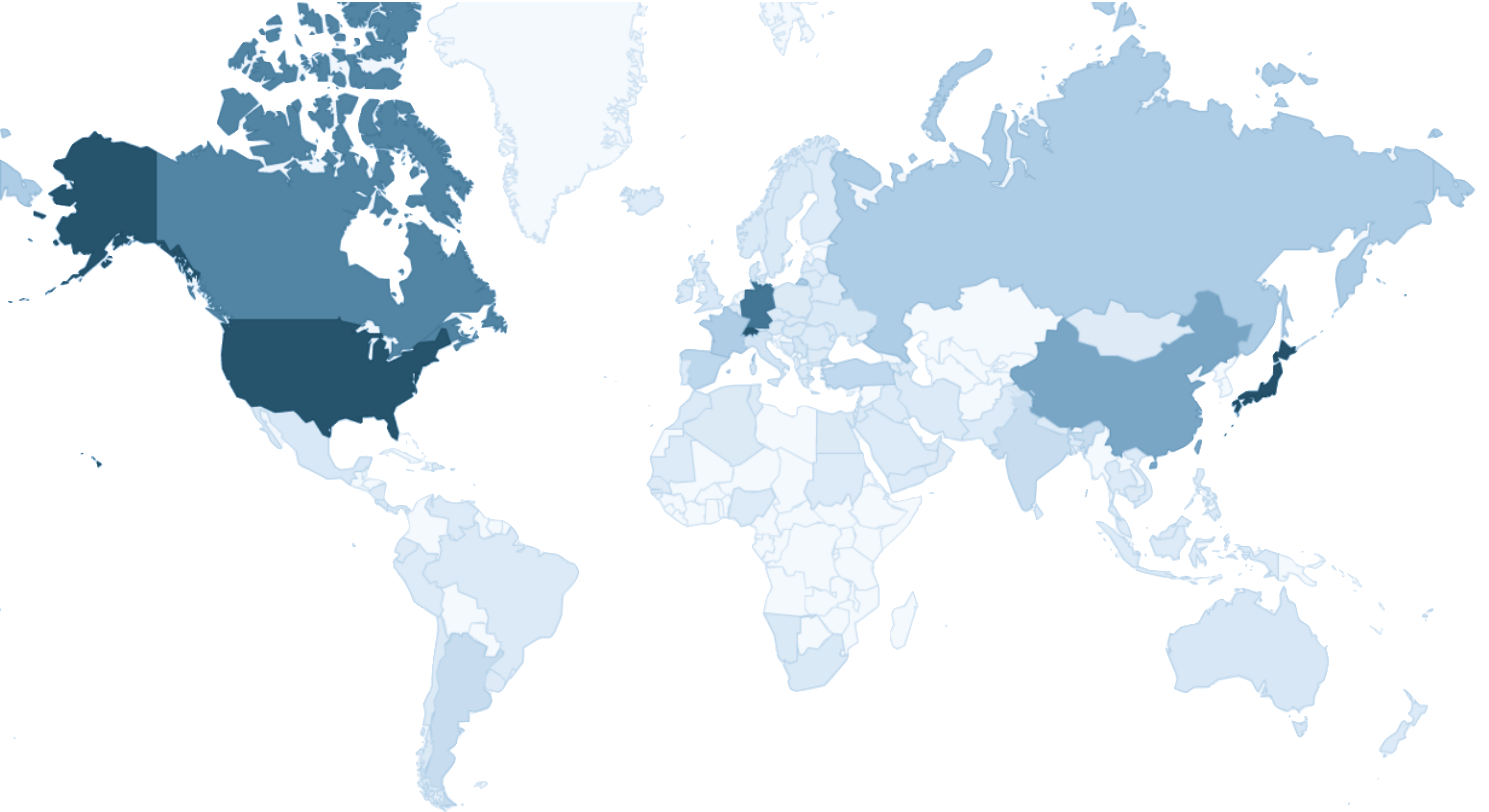
NB: 425 of these are actually non-detections
NB: the emission might not be coming from the SNR itself

- **2235 references as ADS bibcodes** plus 100s of other URLs

OMISSIONS? IDEAS? YOUR FEEDBACK IS WELCOME!

7 HE catalogue of Galactic SNRs: worldwide usage

www.physics.umanitoba.ca/snr/SNRcat



first 2 years statistics (2012/02 – 2014/01)
> 60,000 accesses from > 5,000 unique IPs
(98% of IP addresses can be localized at country level)

HE catalogue of Galactic SNRs: extensions

Database completeness

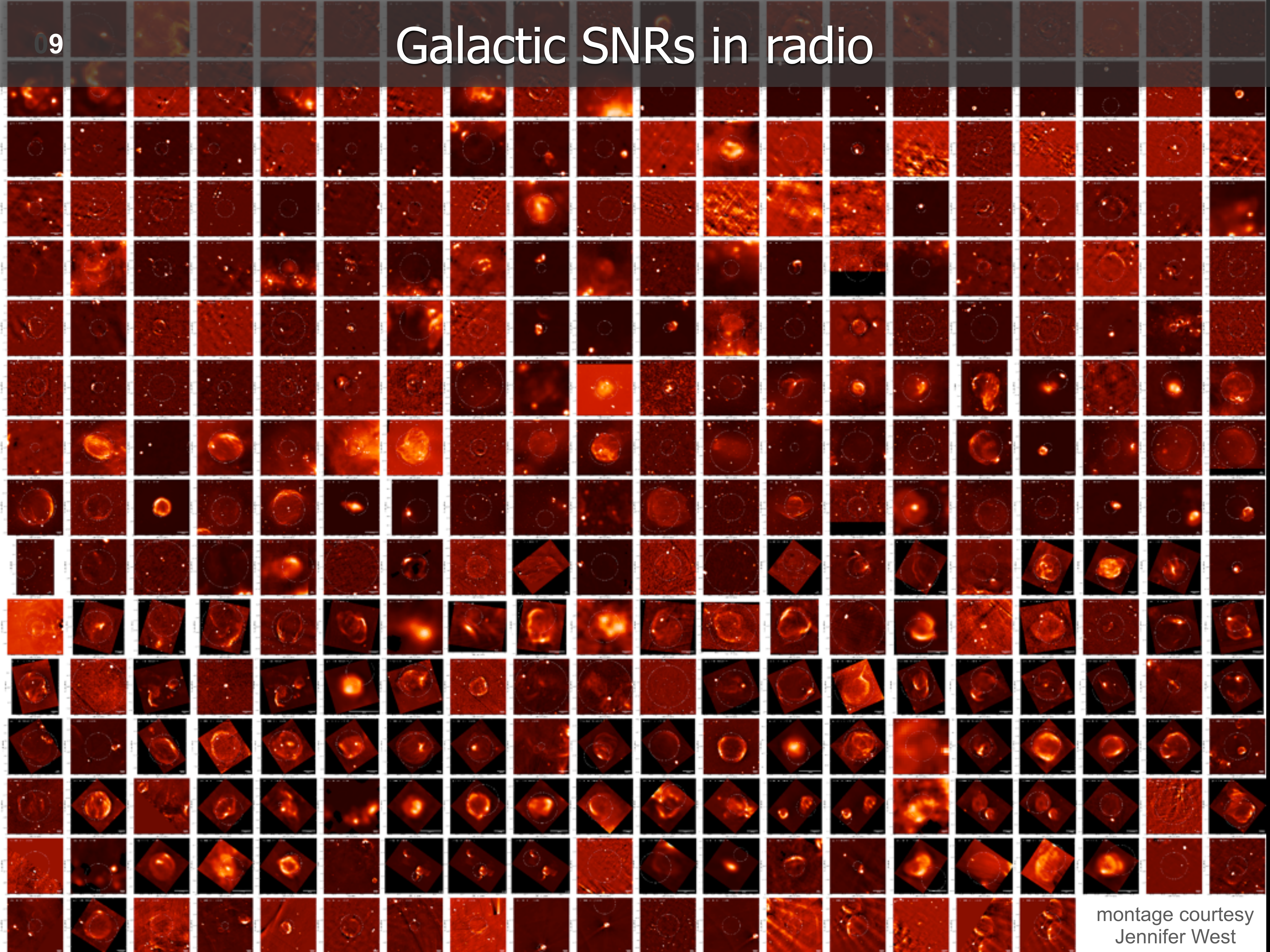
- **Instruments coverage**: to be updated regularly following new results, in particular from instruments having started operations (H.E.S.S. II, NuSTAR, ASTROSAT), satellites about to be launched (eROSITA), as well as planned next-generation observatories (Hitomi recovery mission, CTA)
- **Wavelength coverage**: eventually get a full multi-wavelength view of all SNRs, covering all regions of the electromagnetic spectrum (IR, optical, UV)
- **Objects coverage:** can be extended to nearby LMC and SMC

User interface

- **maps**: add an interactive map of the Galaxy
- **images**: add images in radio and X-rays (maybe γ-rays)

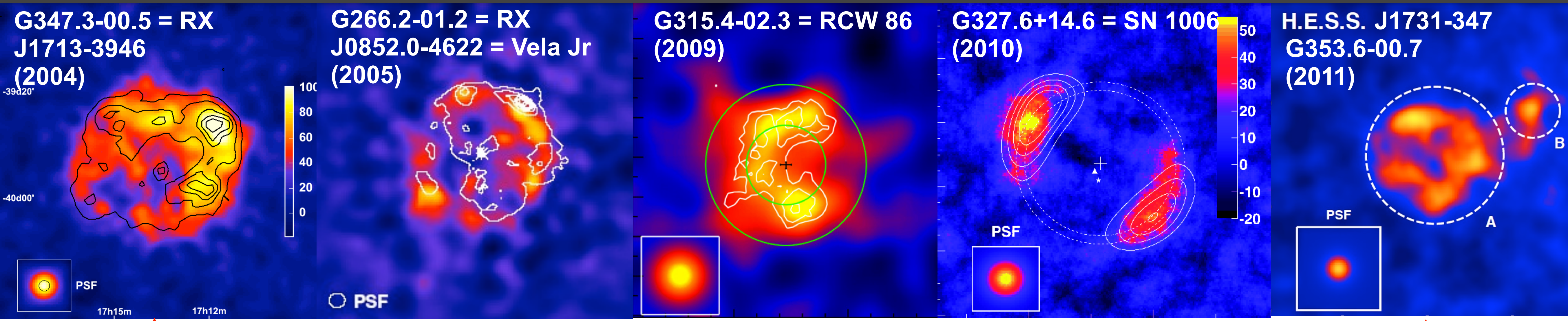
Samar Safi-Harb
U. of Manitoba

Galactic SNRs in radio



montage courtesy
Jennifer West

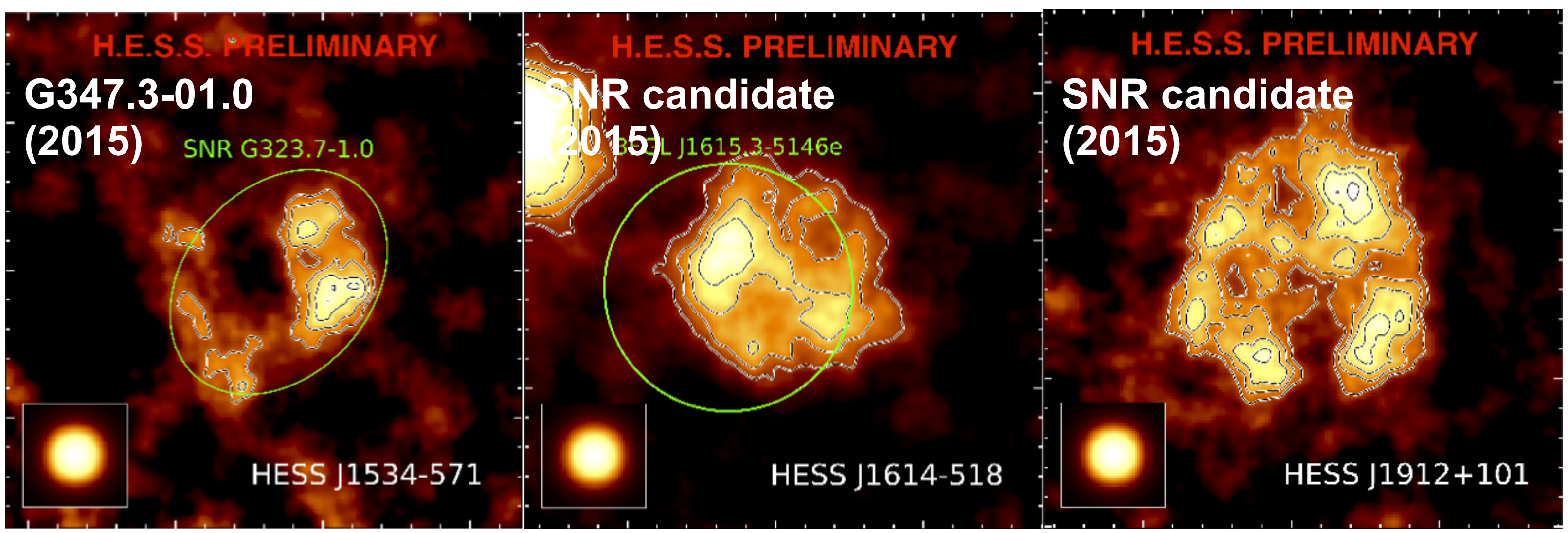
SNRs at TeV: from HESS...



first image at TeV

H.E.S.S. Coll. Nature 2004

a new way of detecting and studying SNRs



Pühlhofer et al 2015 (arXiv:1509.03872P)
Gottschall et al 2016 (arXiv:1612.00261)

discovered in γ-rays!

H.E.S.S. Coll. 2008, 2011

a new way of detecting and studying SNRs

The H.E.S.S. experiment has imaged several TeV shell SNRs in the last decade.
A breakthrough for ground-based astronomy, although still a small sample.

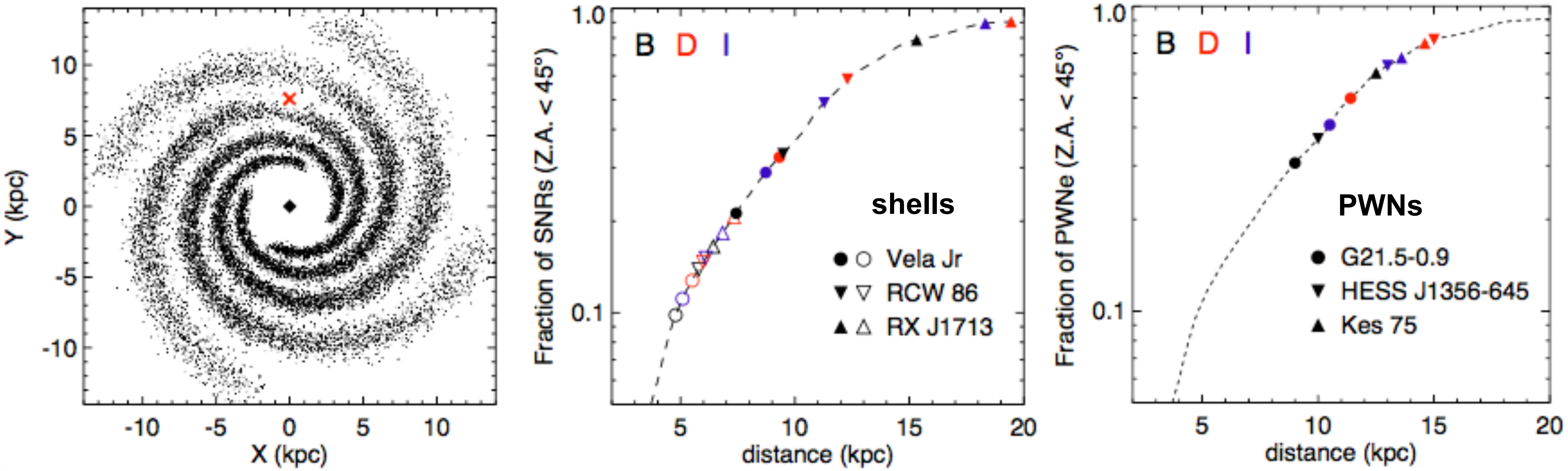
SNRs at TeV: ...to CTA

The CTA observatory will be able to

✓ detect 20-70 SNRs (most of the TeV shells currently shining in the Galaxy)

✓ resolve 7-15 SNRs (depends on their distance...)

Note: identification will still require MWL studies



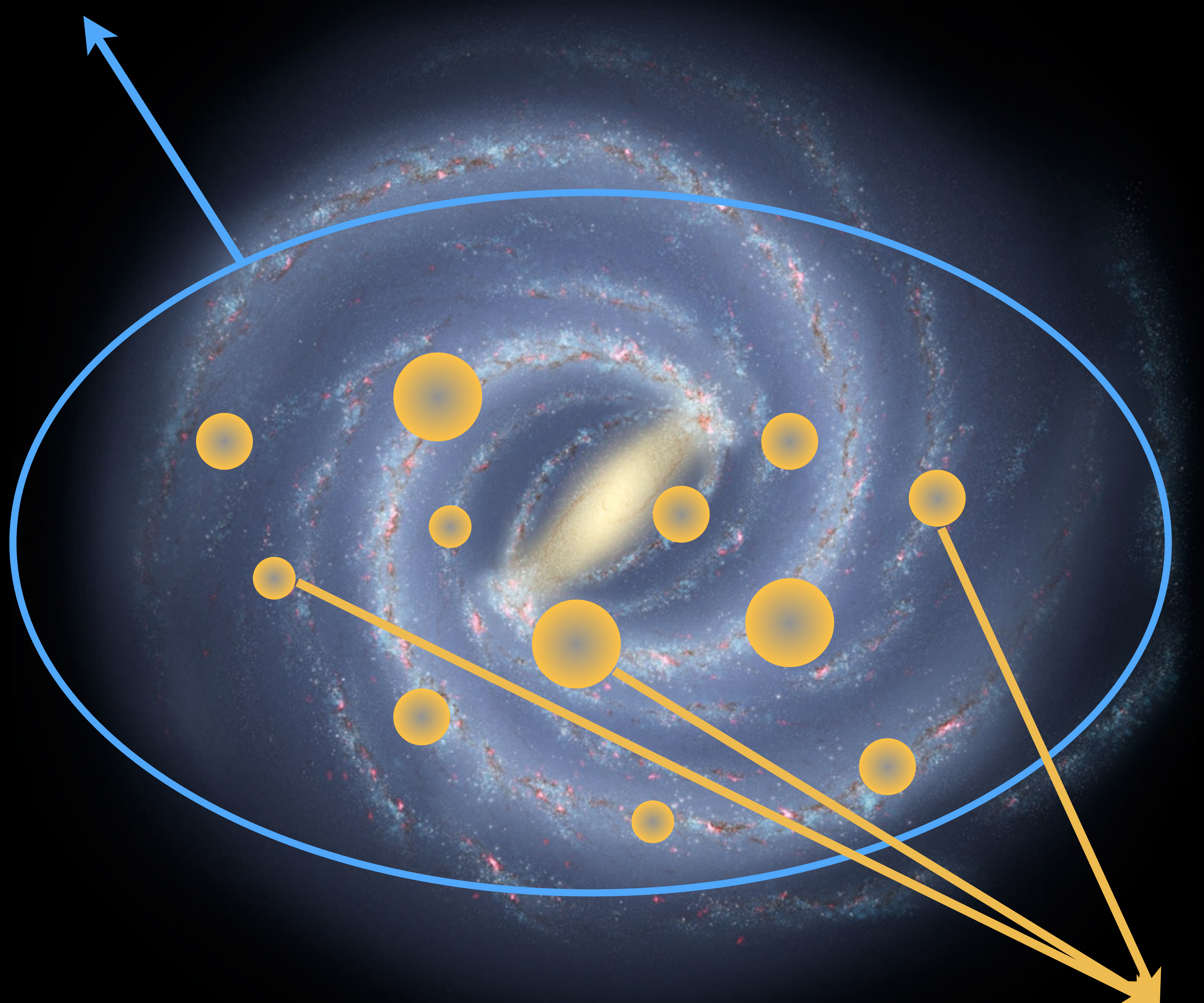
horizons of detectability (filled symbols) and resolvability (open symbols) for different possible configurations of the array

simulations by Renaud 2011, also in Acero et al 2013

2 orthogonal approaches for SNR studies

→ derive statistically significant trends in the Galaxy

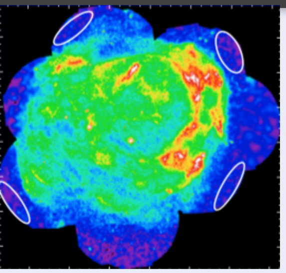
do a **global modeling of all Galactic SNRs**, by doing simpler broad-band spectral fittings



do a **detailed modeling of select SNRs**, by running realistic 3D numerical simulations

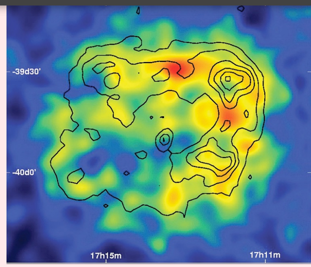
→ study in details the physics of particle acceleration

Diffusive shock acceleration: the coupled system



IR
Opt
UV
X

radio
X
γ



shock wave
(thermal magnetized plasma)

cosmic-rays
(non-thermal population)

magnetic waves
(collective movements of charges)

injection, acceleration
shock modification

damping
heating

generation (instabilities)
diffusion, injection,
stochastic acceleration

conservation laws

$$\frac{\partial \mathbf{X}}{\partial t} + \mathrm{div}\left(\mathbf{F}\left(\mathbf{X}\right)\right) = \mathbf{0}$$

$$\mathbf{X} = \begin{pmatrix} \rho \\ \rho \mathbf{u} \\ P \end{pmatrix} \quad \mathbf{F}\left(\mathbf{X}\right) = \begin{pmatrix} \rho \mathbf{u} \\ \rho \mathbf{u} \otimes \mathbf{u} + p\mathbf{I} \\ (e+P)\,\mathbf{u} \end{pmatrix}$$

particle distribution:

$$n\left(x,t\right) = \int_p f\left(x,p,t\right)\ 4\pi p^2\ \mathrm{dp}$$

transport equation:

$$\frac{\partial f}{\partial t} + \frac{\partial}{\partial x}\left(uf\right) = \frac{\partial}{\partial x}\left(D\frac{\partial f}{\partial x}\right) + \frac{1}{3p^2}\frac{\partial p^3 f}{\partial p}\frac{\partial u}{\partial x}$$

hydrodynamic treatment

kinetic treatment

reviews : Drury 1983, Jones and Ellison 1991, Malkov and Drury 2001

Numerical simulations: hydro + kinetic

from cosmology to supernova remnants
(in both cases: comoving grid to factor out expansion)

Chevalier 1982, 1983

SNR initialization:
self-similar profiles
from **`Chevalier`**

Teyssier 2002, Fraschetti et al 2010

SNR evolution:
3D hydro code
`ramses`

shock diagnostics ↓

↑ back-reaction: varying gamma

Ellison et al 2007

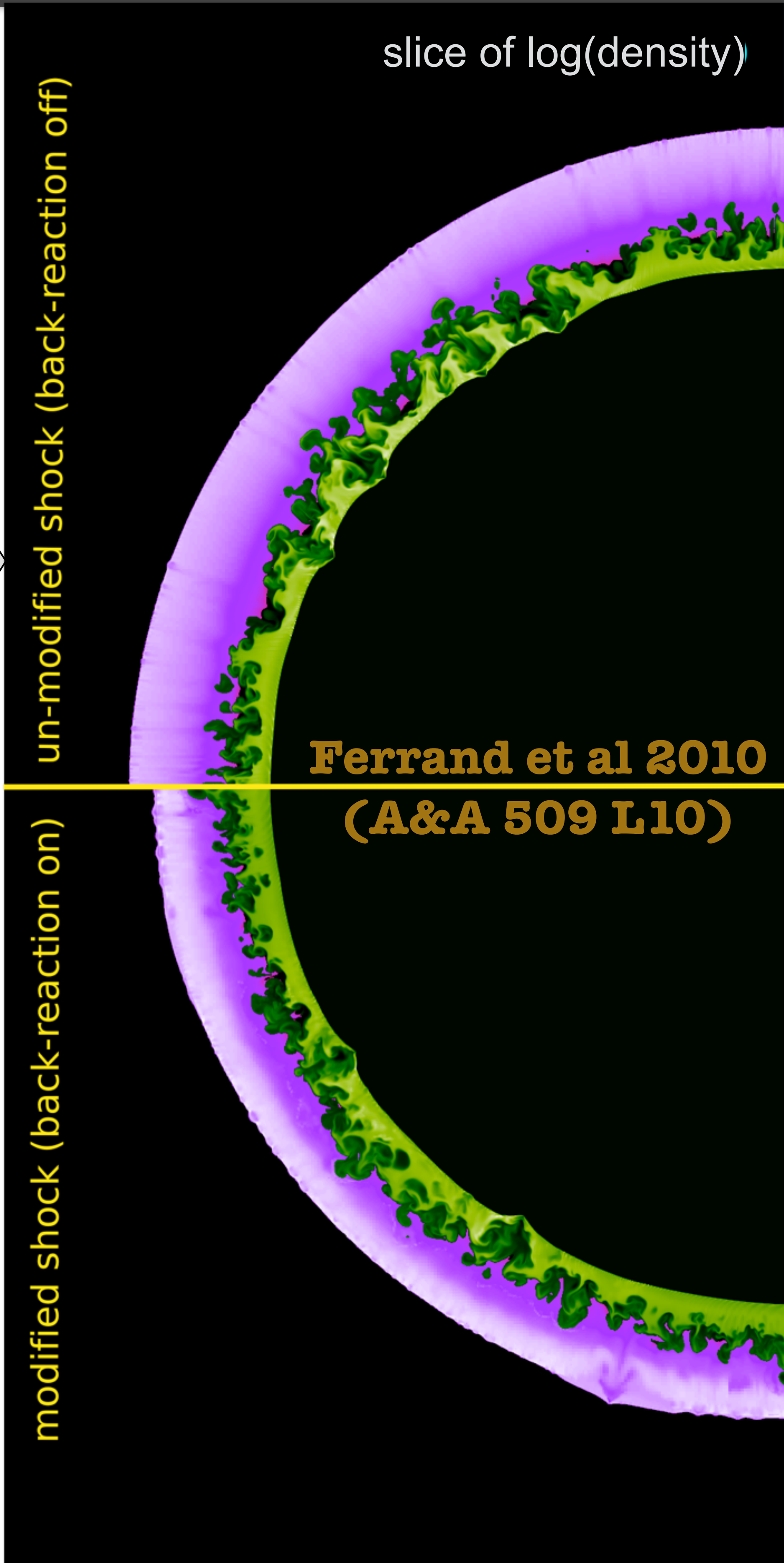
particle acceleration:
non-linear model
of **`Blasi`**

Blasi et al 2002, 2004, 2005
+ Caprioli 2008, 2009

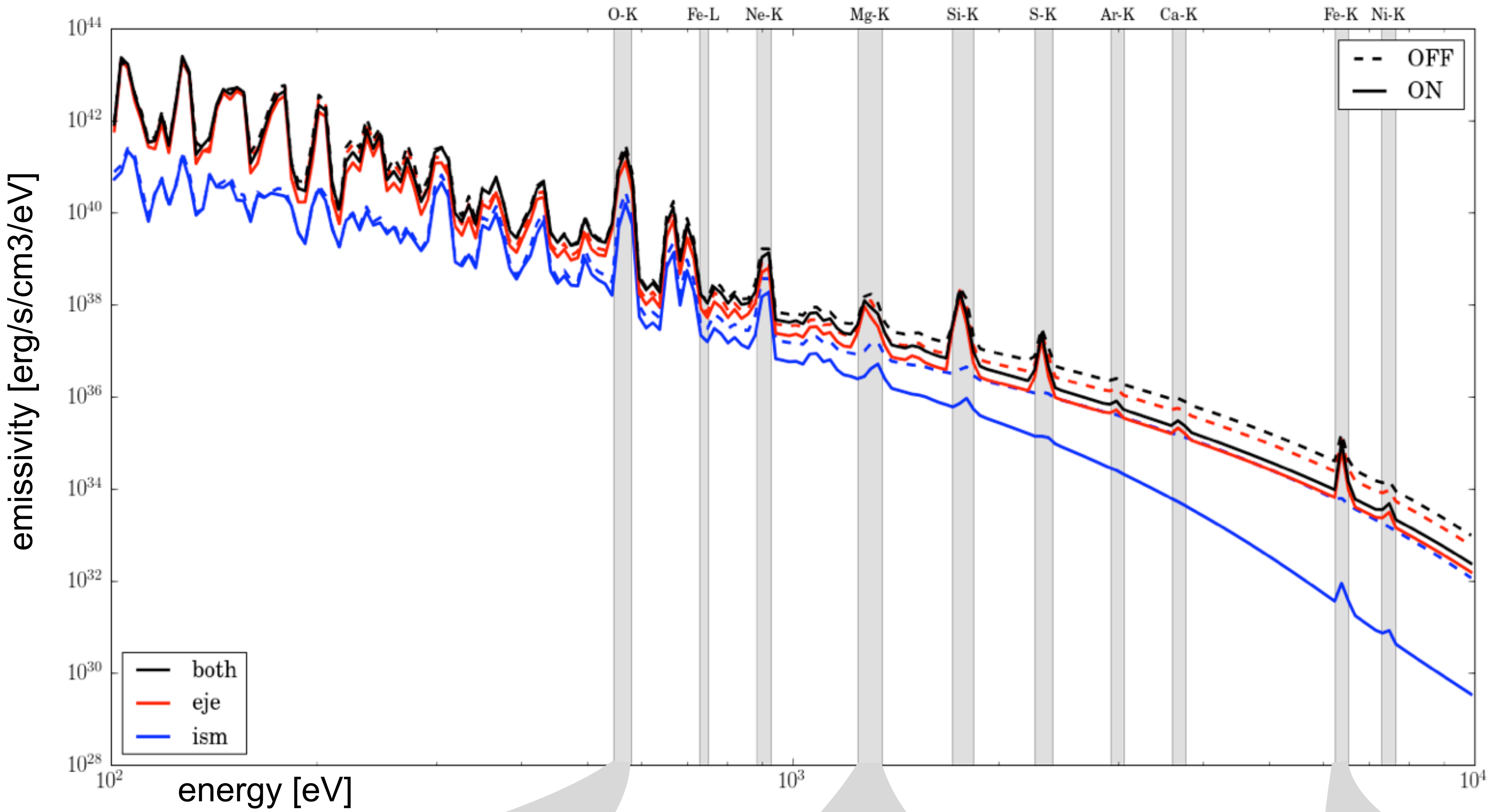
parameters: Tycho (SN Ia)

$$t_{\rm SN} = 440 \text{ years}$$
$$E_{\rm SN} = 10^{51} \text{ erg}$$
$$n = 7\,,\ M_{\rm ej} = 1.4\ {\rm M}_\odot$$
$$s = 0\,,\ n_{\rm H,ISM} = 0.1 \text{ cm}^{-3}$$

Anne Decourchelle
CEA Saclay
Irfu/SAp



Thermal emission from the hot plasma

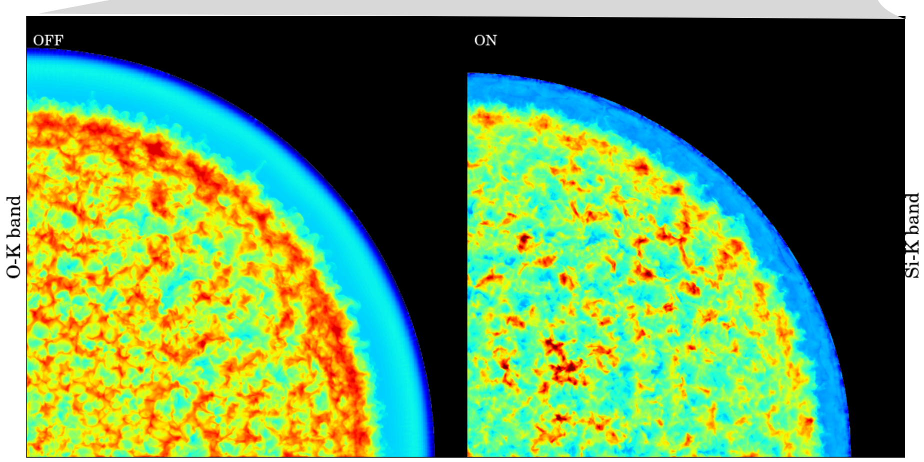


Ferrand, Decourchelle, Safi-Harb 2012 (ApJ 760 34)

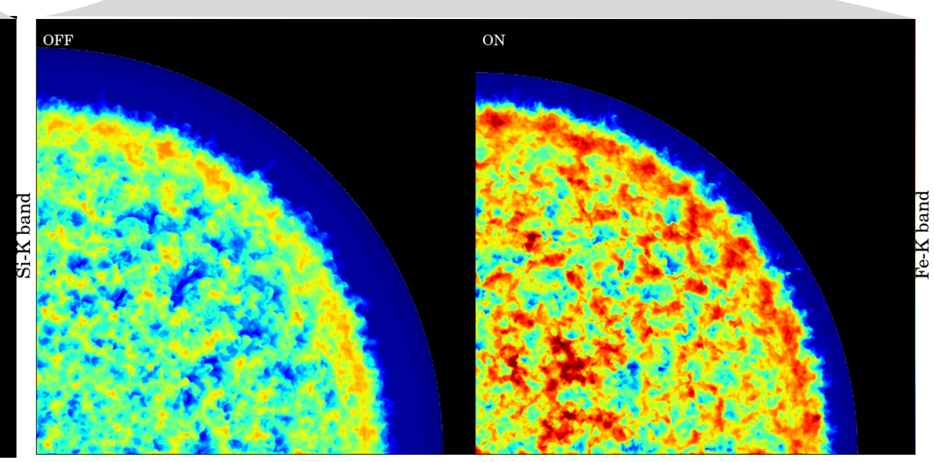
using the emission code from Mewe (depends on density, temperature and ionisation states)

1024^3 cells

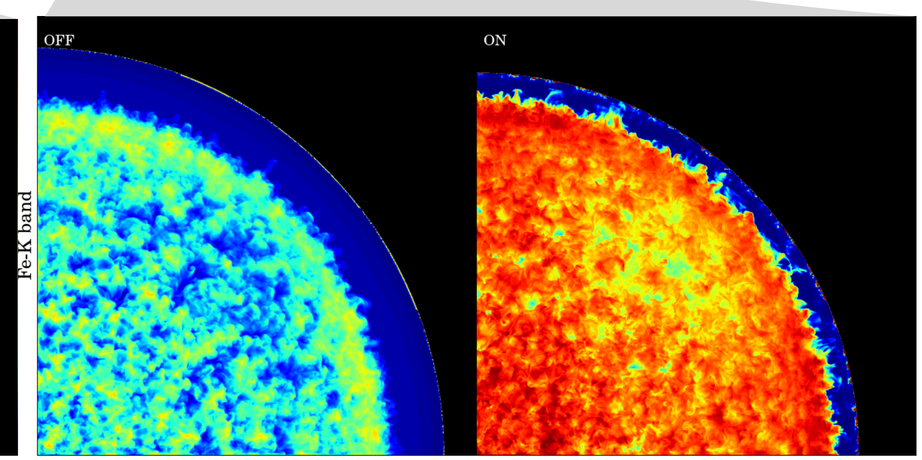
t = 500 yr



test particle vs. back-reaction

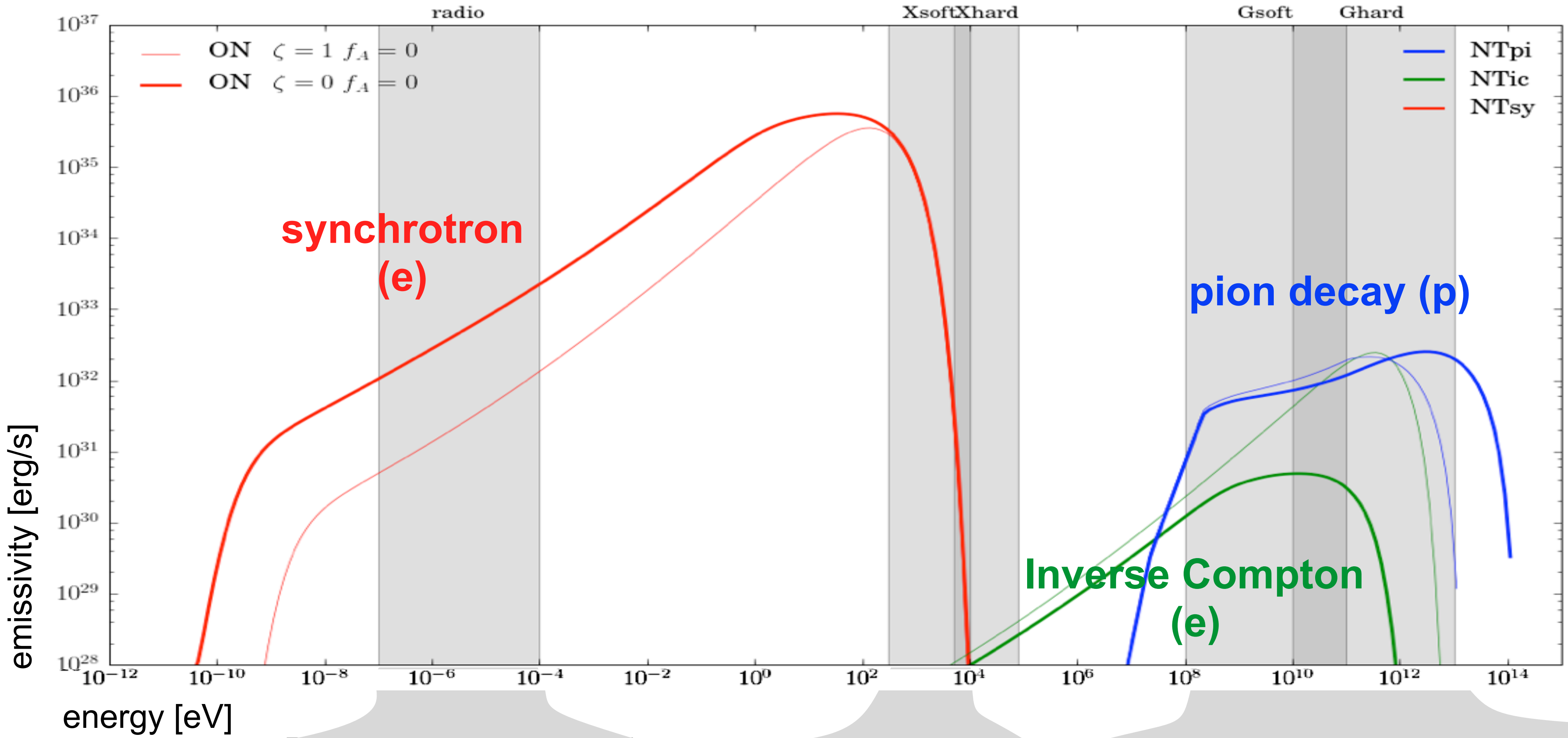


test particle vs. back-reaction



test particle vs. back-reaction

Non-thermal emission from the particles

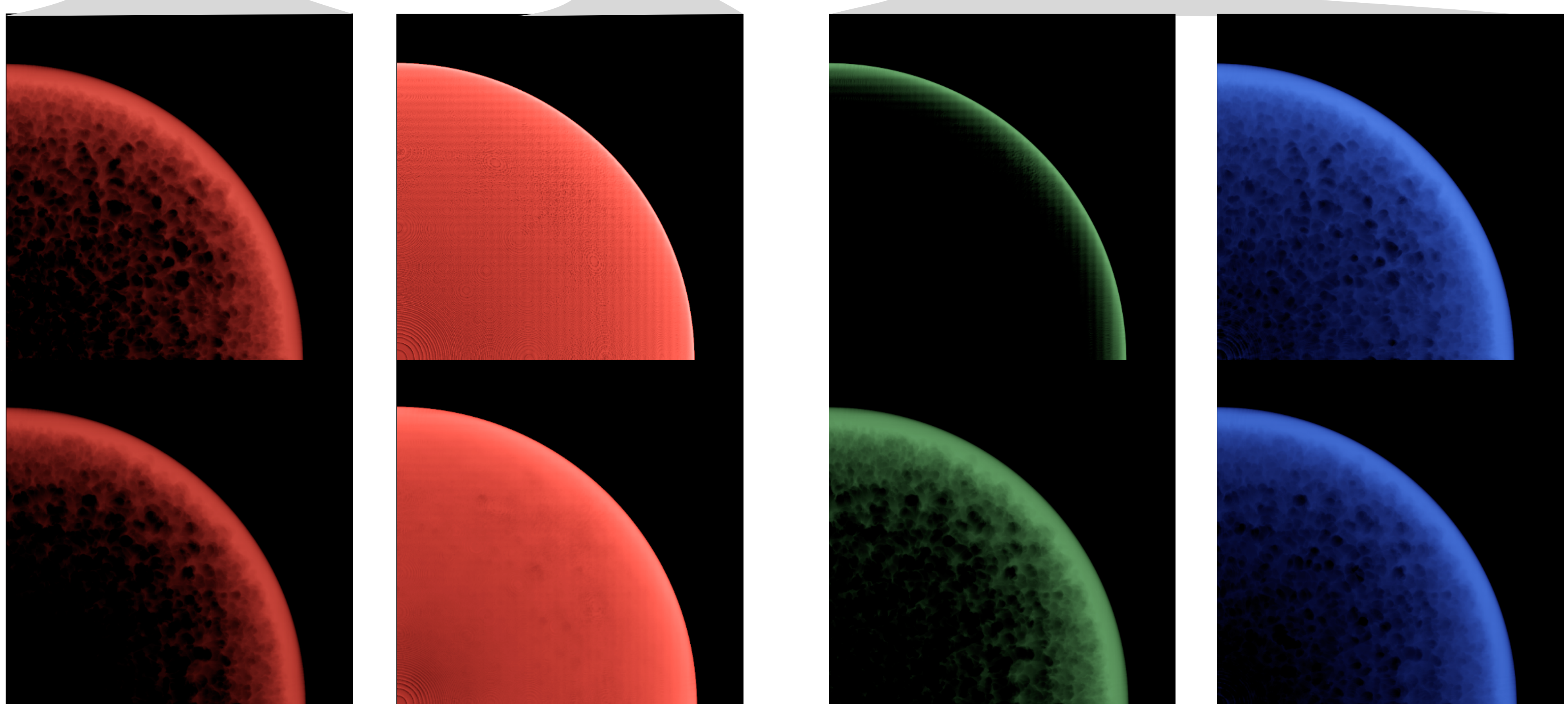


Ferrand, Decourchelle, Safi-Harb 2014 (ApJ 789 49)

using the emission code from P. Edmon (depends on density and magnetic field)

1024^3 cells

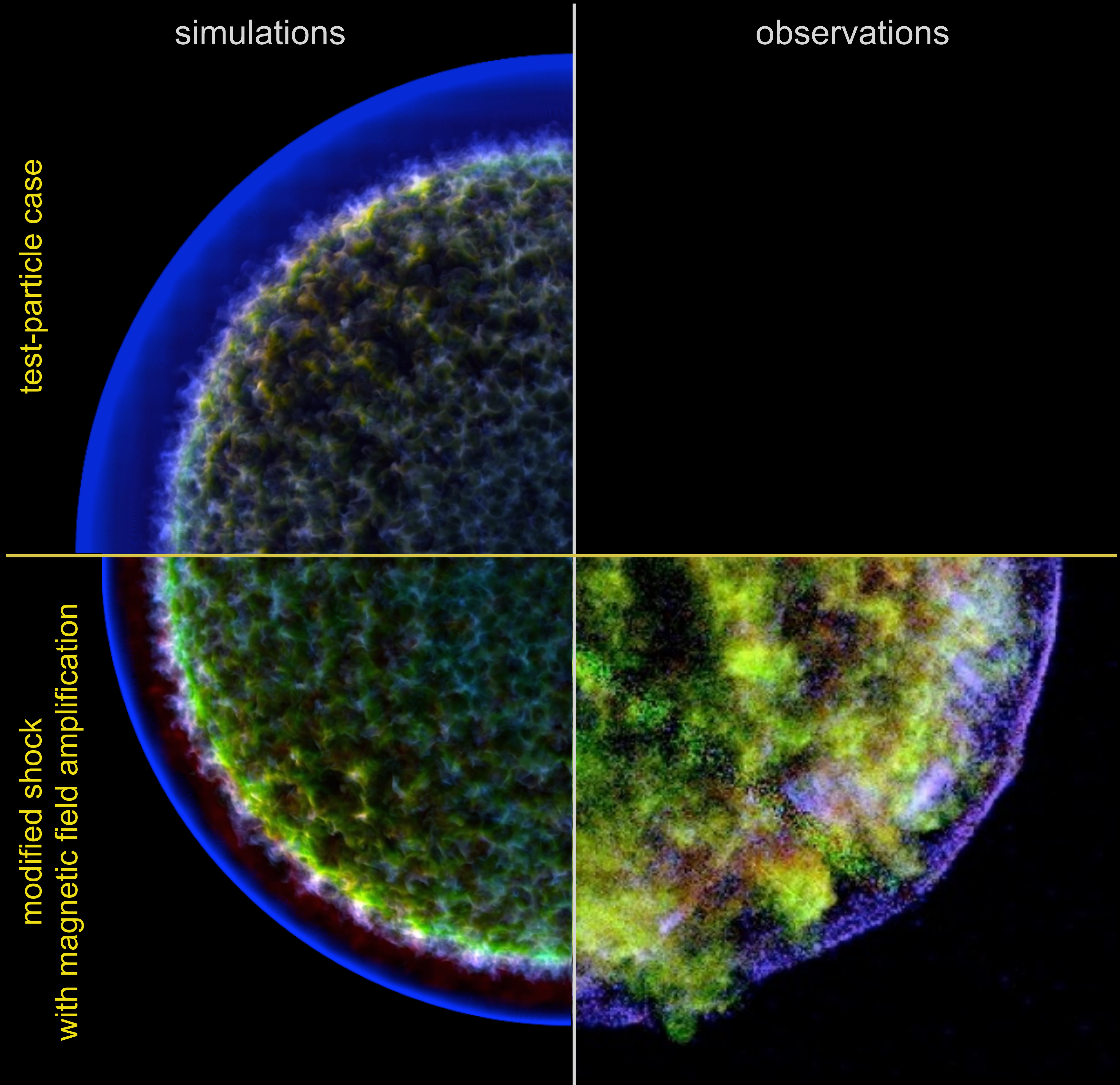
t = 500 yr



efficient MF amplification → high B

no net MF amplification → low B

Thermal + non-thermal emission in X-rays



Energetic protons, accelerated at the shock front, don't radiate as efficiently as electrons, however:

1/ they impact the dynamics of the shock wave, and therefore the **thermal emission** from the shell (optical, X-rays)

2/ they impact the evolution of the magnetic field, and therefore the **non-thermal** emission from the electrons (radio – X-rays – γ-rays)

Non-thermal emission: maps at TeV energies

assuming efficient acceleration and MFA

thermo-nuclear supernova

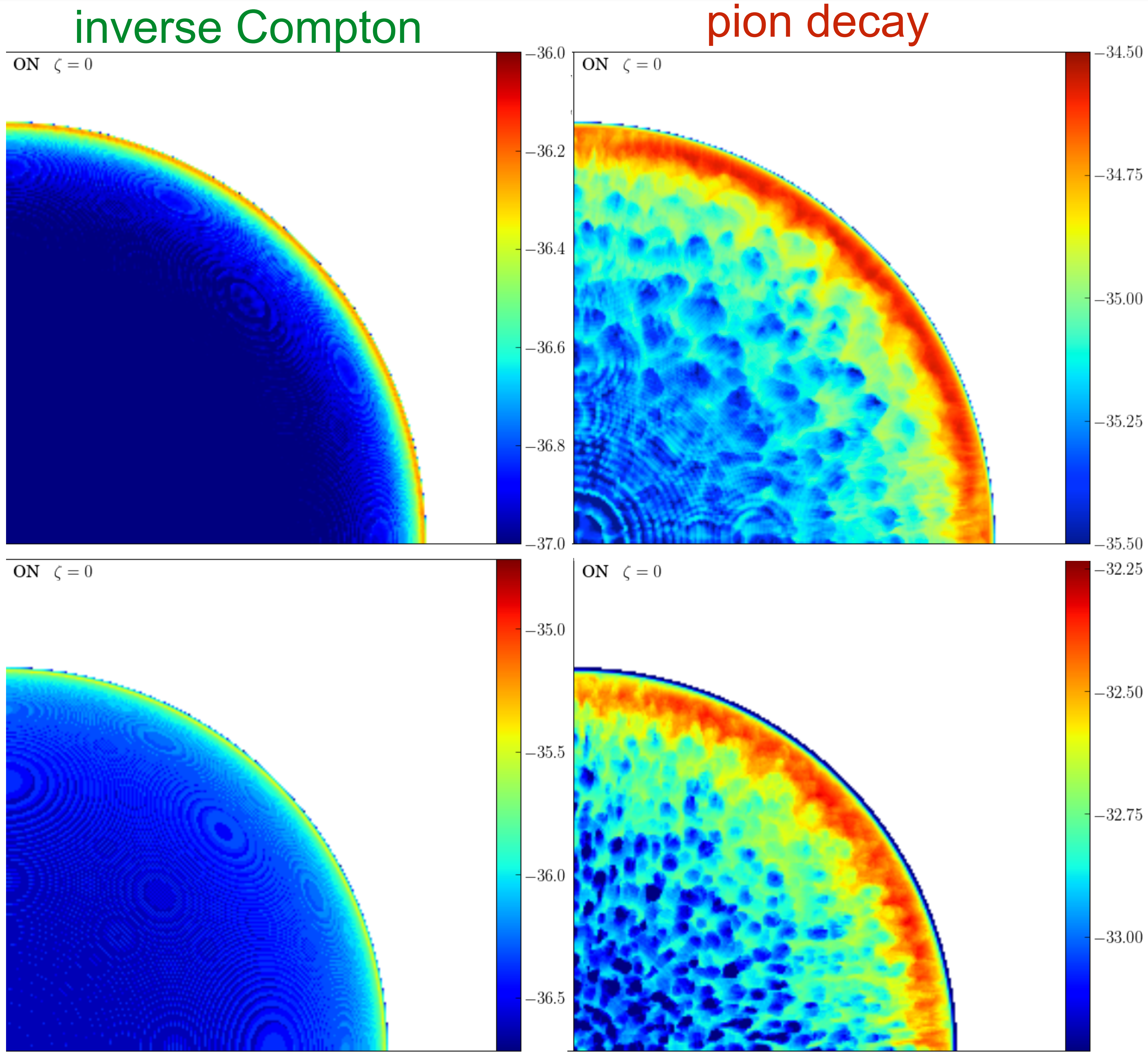
type Ia in a uniform ISM
n=7, s=0
(t = 500 yr)

Ferrand and Safi-Harb 2016

core-collapse supernova

PRELIMINARY

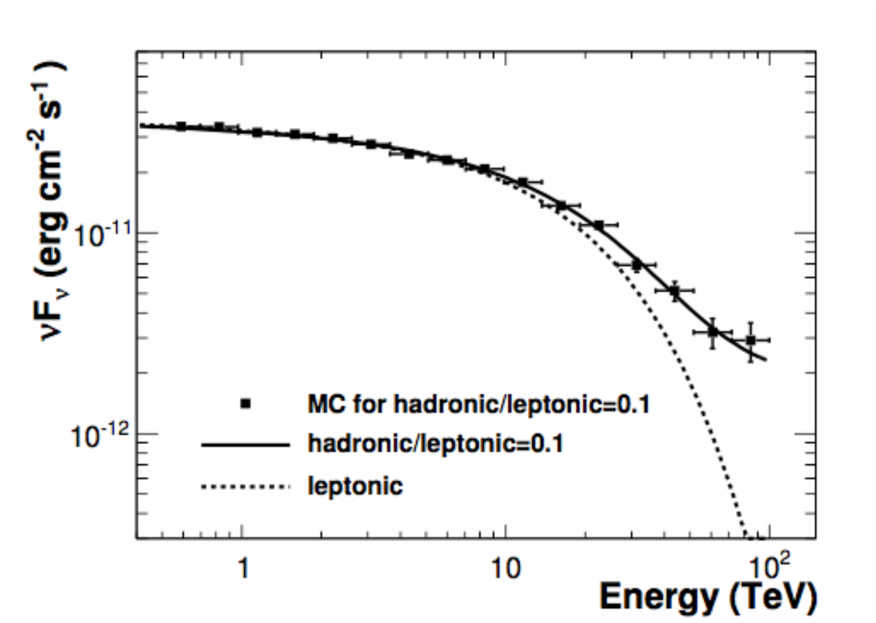
type II in the progenitor's wind
n=9, s=2
(t = 300 yr)



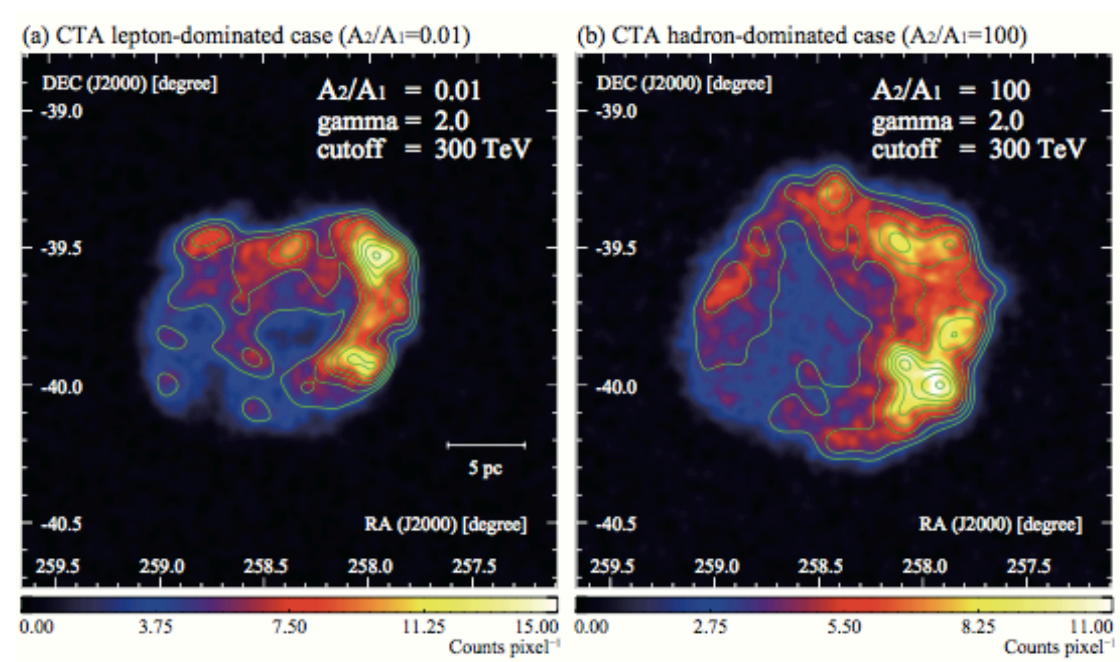
Observational perspectives with CTA

Fermi SNRs: mostly middle-aged remnants interacting with molecular clouds
H.E.S.S. SNRs: still difficult to disentangle hadronic and leptonic contributions
→ we want to (finally) find the "PeVatrons"!

see the **spectrum** cut-off	see the shell **morphology**
✓ wide energy range from 20 GeV to 300 TeV ✓ with sensitivity x10 @ 1 TeV	✓ angular resolution ≃ 1' above 1 TeV ✓ large field of view >5–8°



CTA can detect a (even small) hard hadronic component

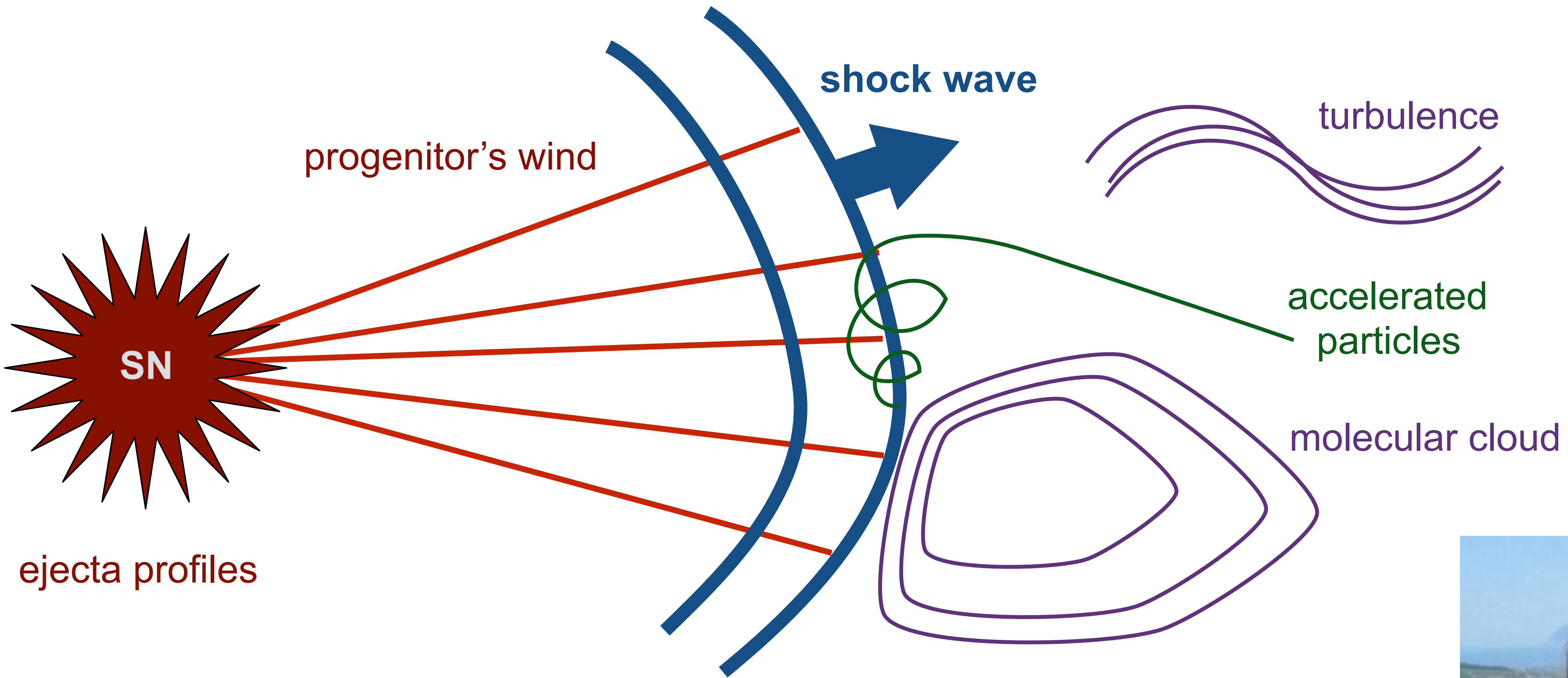


CTA can distinguish between hadronic and leptonic emission

upcoming CTA Collaboration paper on RX J1713.7–3946
Nakamori, Katagiri, Sano, Yamazaki, Ohira

Modelling perspectives: the shock in context

- impact of the **progenitor** : | ejecta profiles (stratification, asymmetries)
  stellar wind (for core-collapse)
- impact of the **environment** : | molecular clouds (radiative? ionized?)
  ISM turbulence (hydro + mag)



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