Cosmic ray production in Supernovae and SNR

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1. cosmic rays

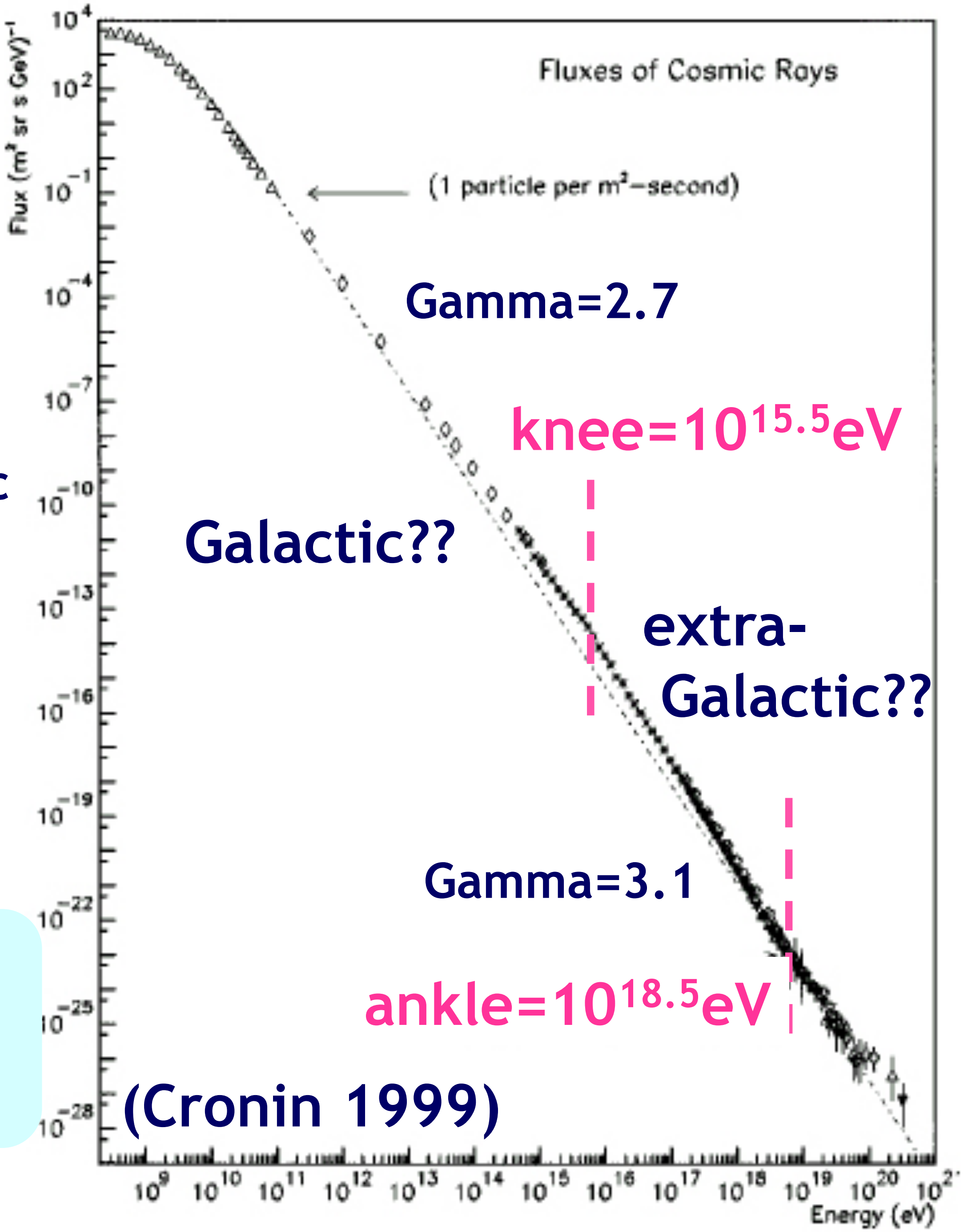
very high energy particles

u_{CR} ~ 1eV/cc

c.f. CMB	0.3 eV/cc
stellar light	< 0.3 eV/cc
magnetic field	0.3 eV/cc
turbulence	0.3 eV/cc
thermal energy	0.01 eV/cc

major component of Galaxy

Origin has been a major astrophysical problem since their discovery



2. Origin of Galactic cosmic rays

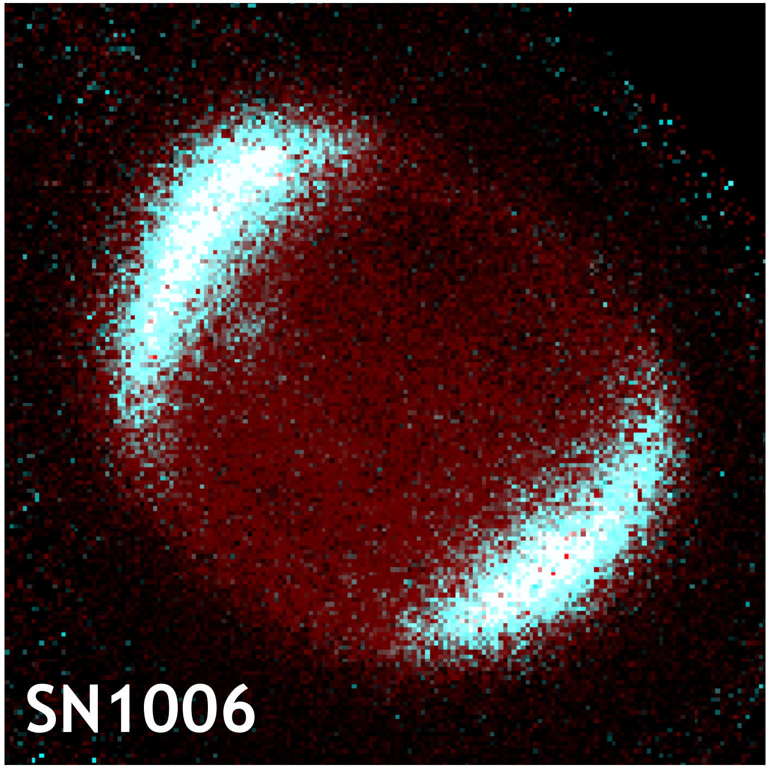
Shocks of SNRs:

the most plausible origin of Galactic cosmic rays

X-ray/gamma-ray observations show us

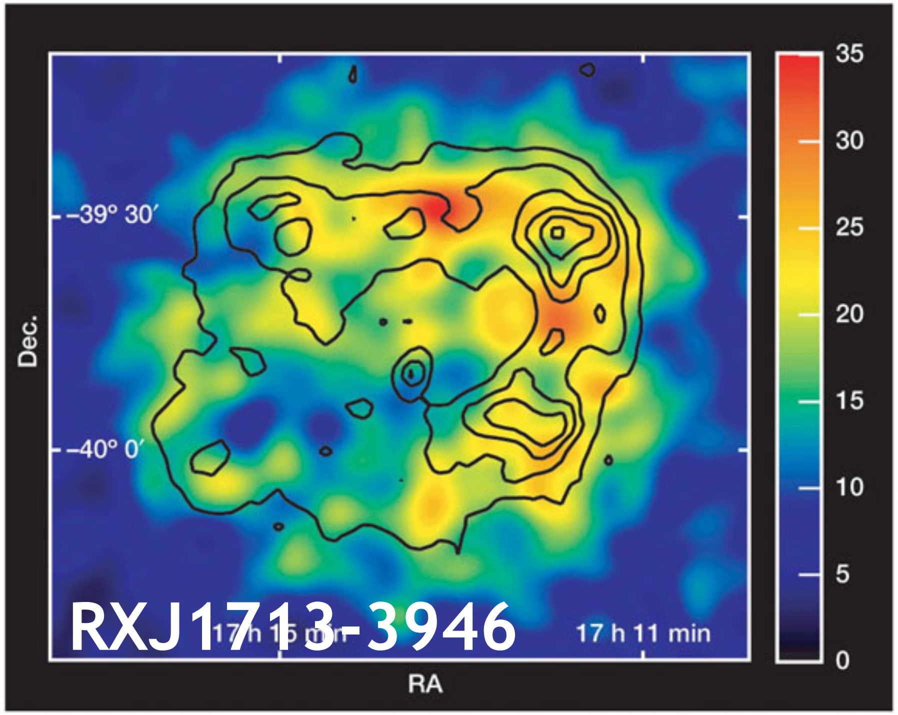
the acceleration history of young SNRs

synchrotron X-ray



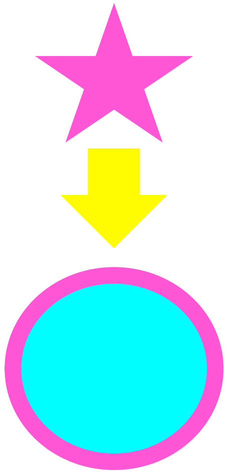
Discovered by ASCA
(Koyama+95)

TeV gamma-ray

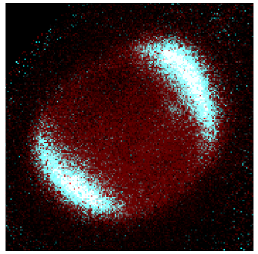


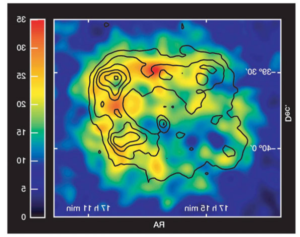
Discovered by HESS
(Aharonian+04)

Acceleration history in SNR shocks



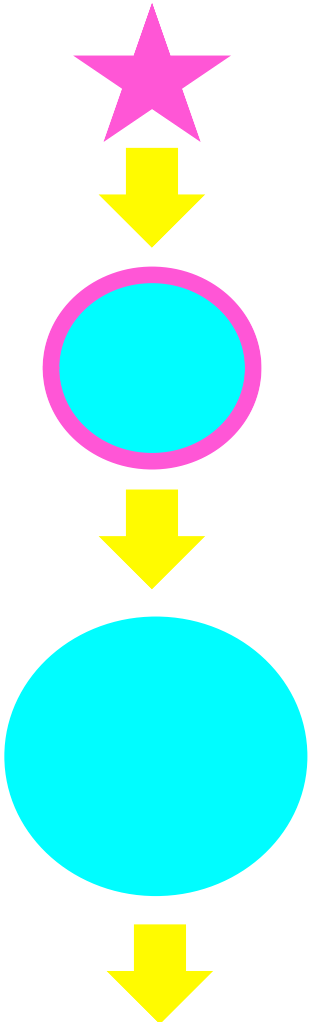
SN explosion
strong shock is formed





Both e and p are accelerated efficiently
strong sync. X-rays
How much energy is injected into particles ?

Acceleration history in SNR shocks



SN explosion
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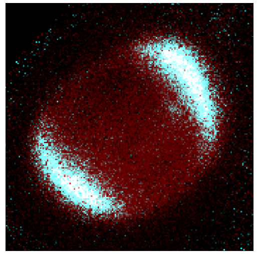
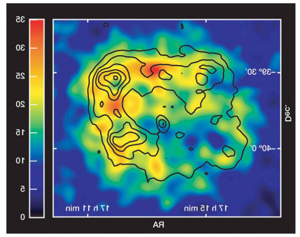




Both e and p are accelerated efficiently
strong sync. X-rays
How large energy is injected into particles ?

High E electrons disappear
due to strong sync. loss
Protons should remain

??

How to escape from shocks to be cosmic rays ??
How about the total energy of
remaining particles ?

3. How much energy is injected into particles ?

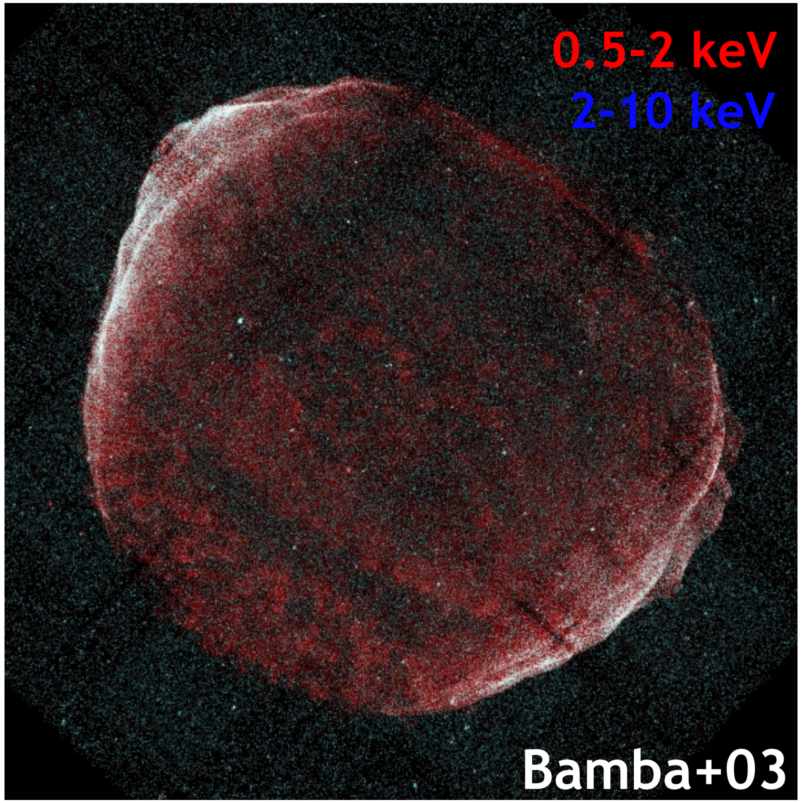
Clues of efficient acceleration

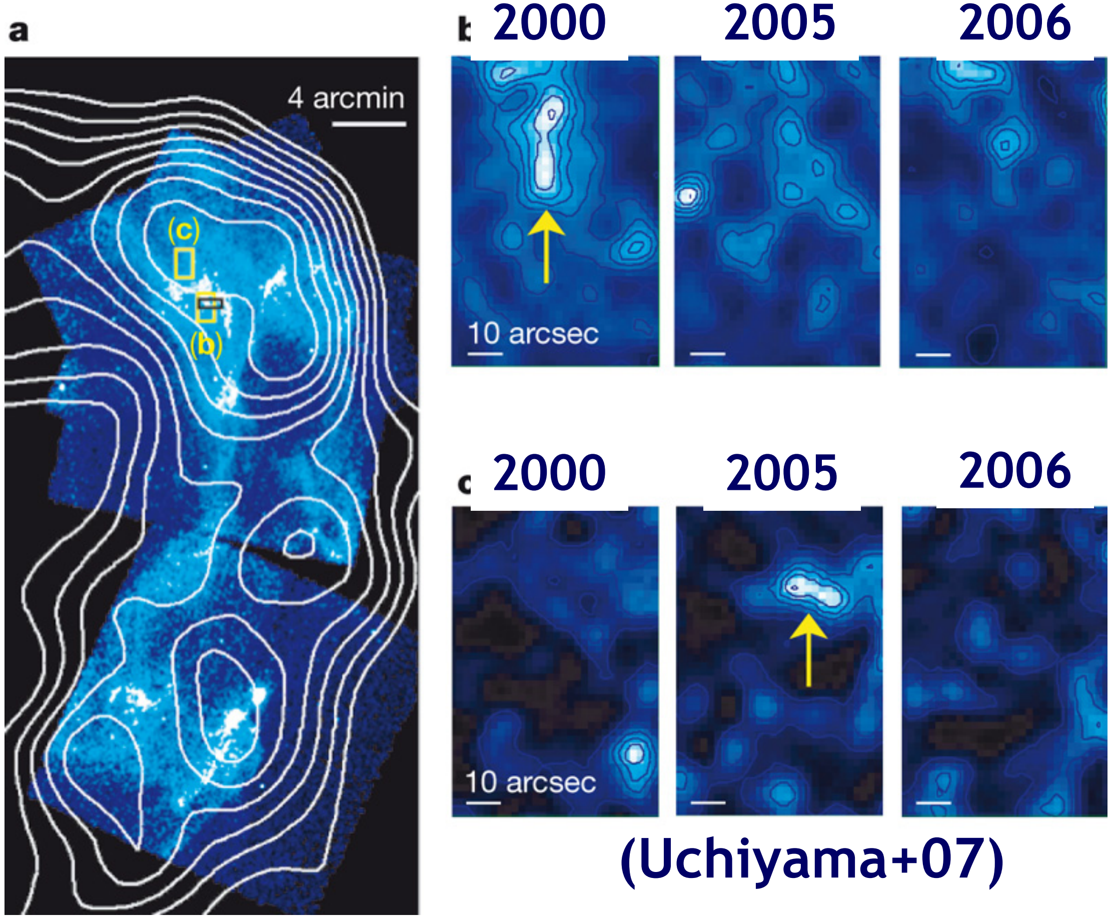
Chandra/XMM era

Discovery of very thin filaments with synchrotron X-rays
Some are time variable.

thin = small gyro radius
small diffusion
rapid time variability

-> amplified and turbulent B
efficient acceleration





(Uchiyama+07)

Very low kT plasma behind the shock

Hughes et al. 00: low temperature in E0102-72

Helder+09: NE rim of RCW86

measured shock velocity using Chandra observations

-> v_{shock} ~ 6000 km/s

-> expected temperature: 40-70 keV

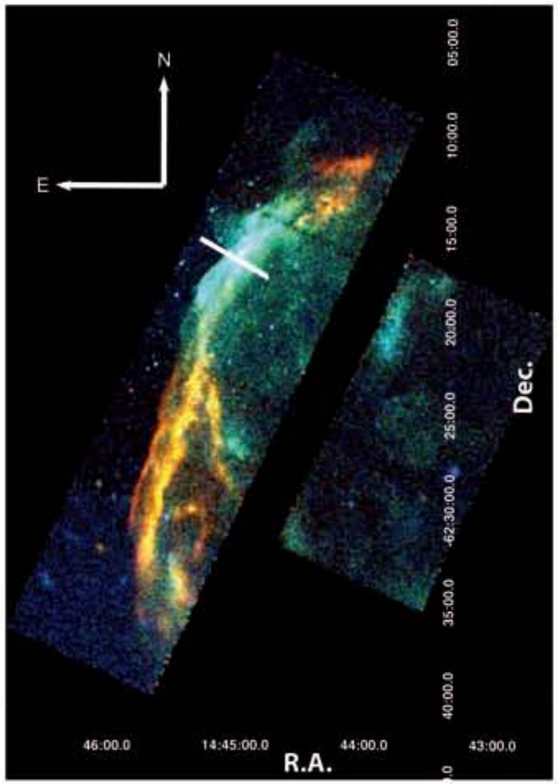
measured kT with H-alpha observations

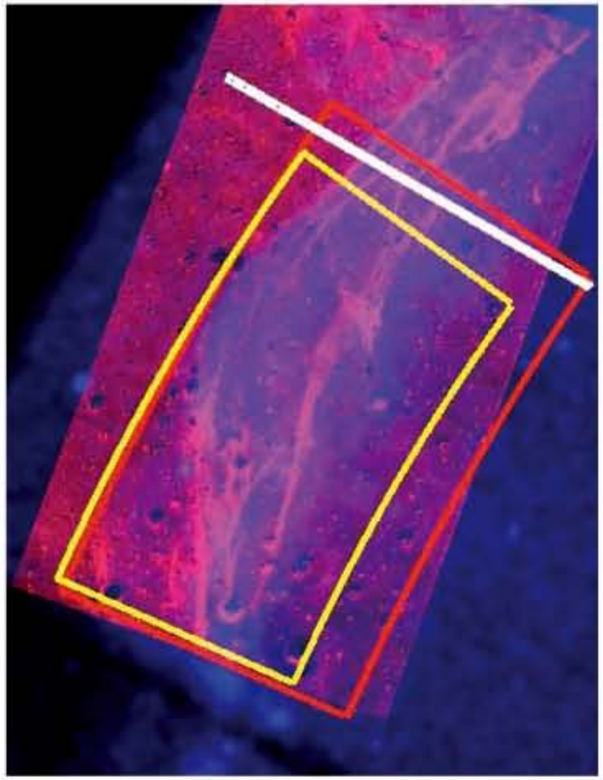
-> kT = 2.3 keV

Helder+09

"disappeared E"

to acceleration?





efficiency:
> 50 % !!

But with large measurement uncertainty.

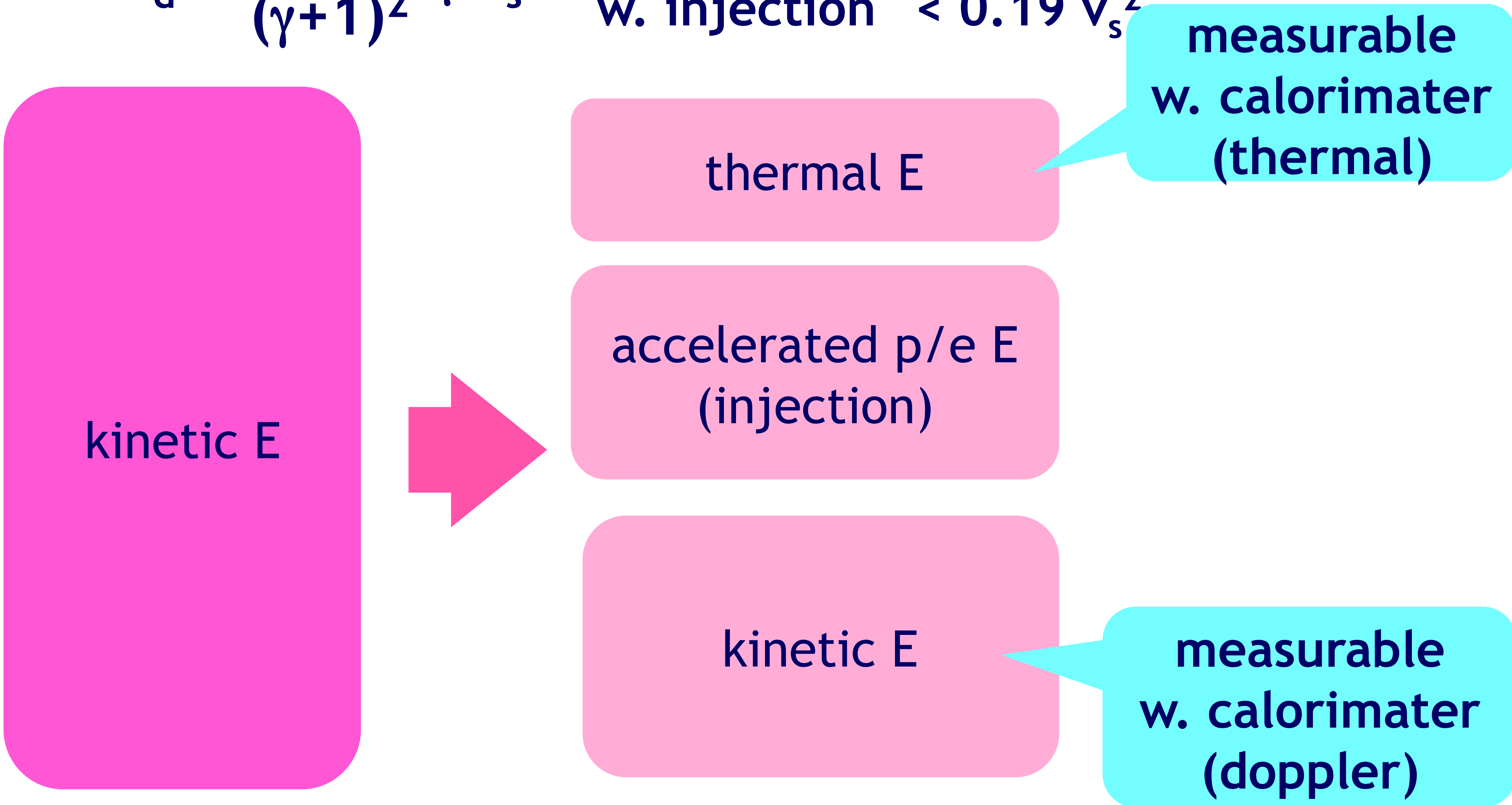
Injection rate measurement with XMS

From Rankine-Hugoniot relation

$$kT_d = \frac{2(\gamma-1)}{(\gamma+1)^2}\mu v_s^2$$

ideal gas $\sim 0.19 v_s^2$

w. injection $< 0.19\ v_s^2$



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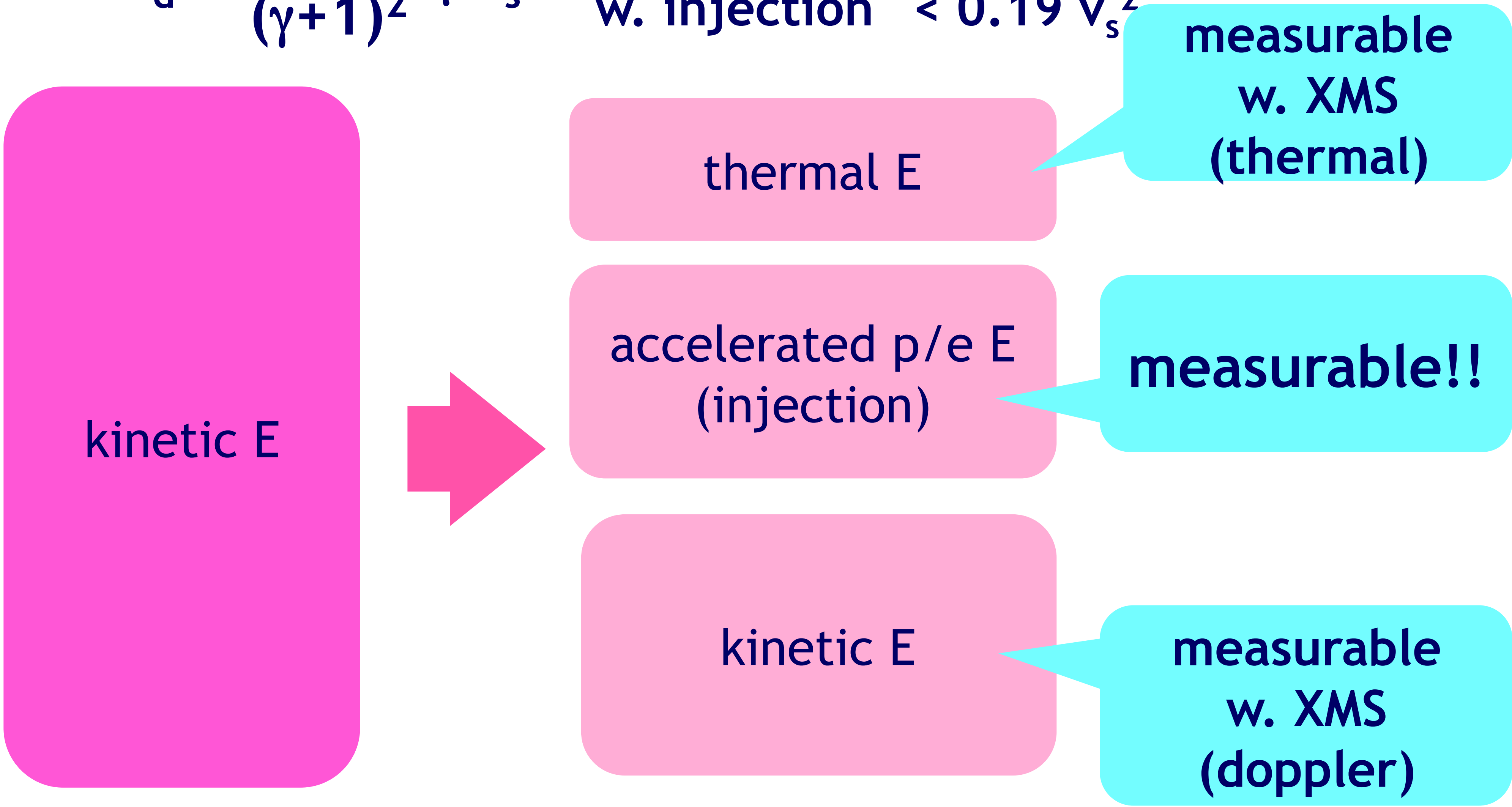
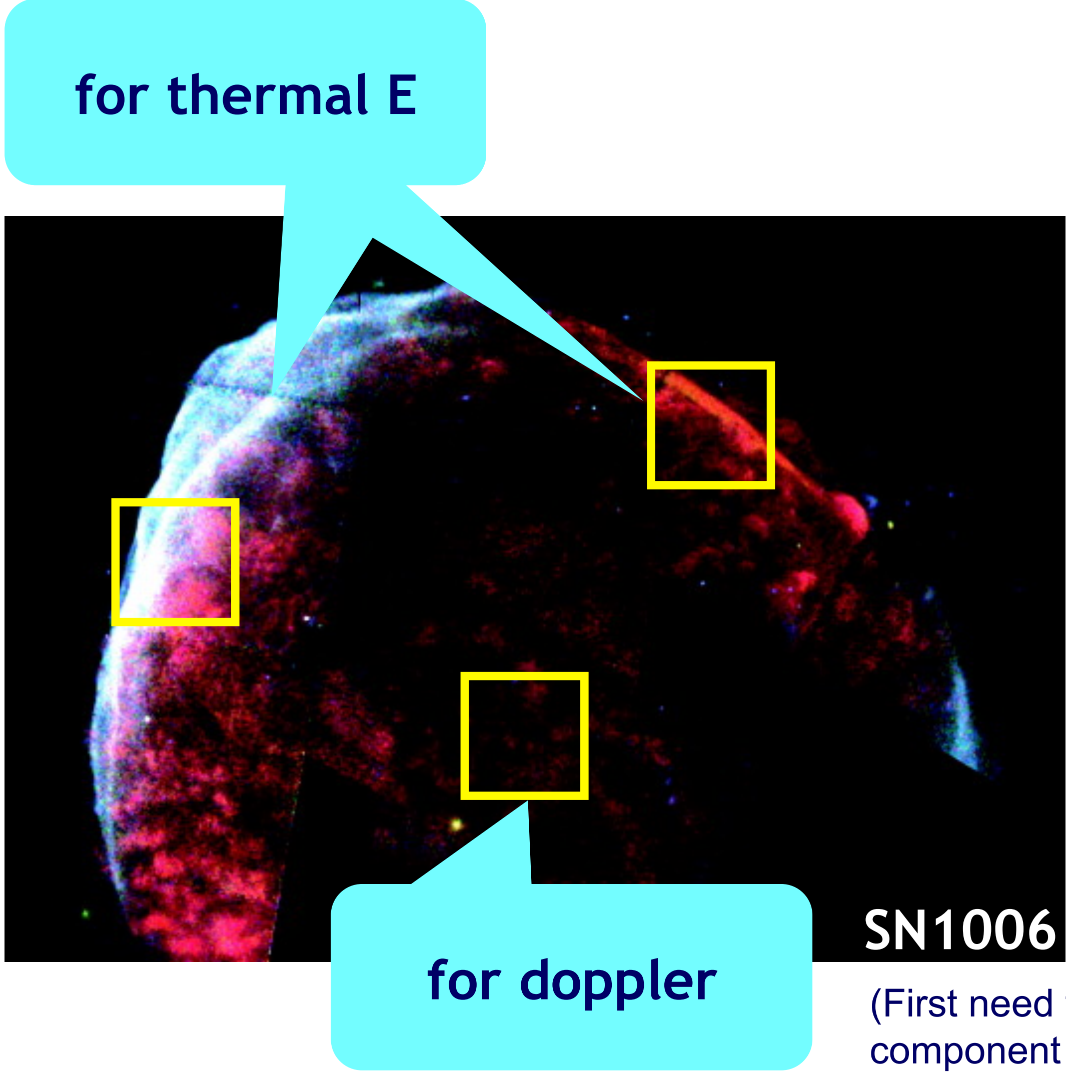
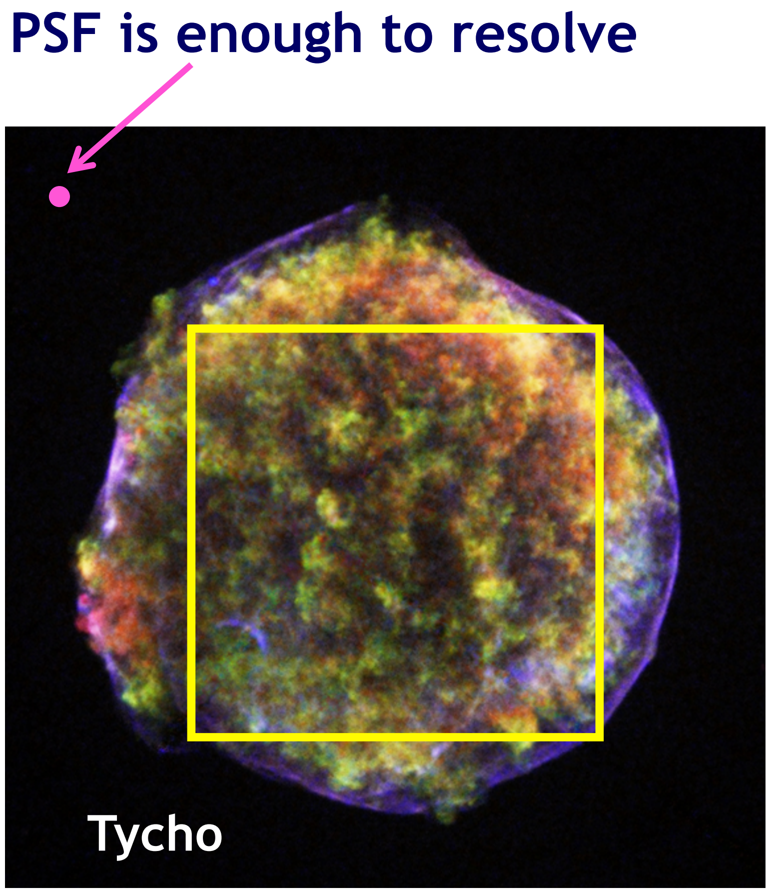


New diagnostics in young SNRs using XMS



(First need to find thermal component in forward shock)



shock speed ~ 3000 km/s ~ 18 eV @ He-like Si

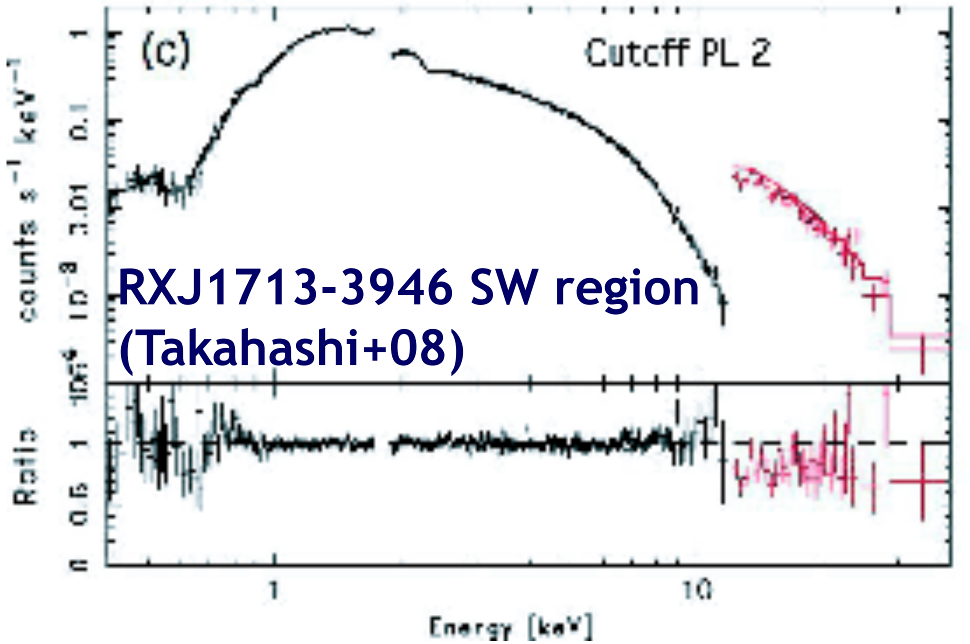
~ 6 eV @ He-like O

We can determine the kinetic and thermal E at shocks

The Maximum E of accelerated electrons

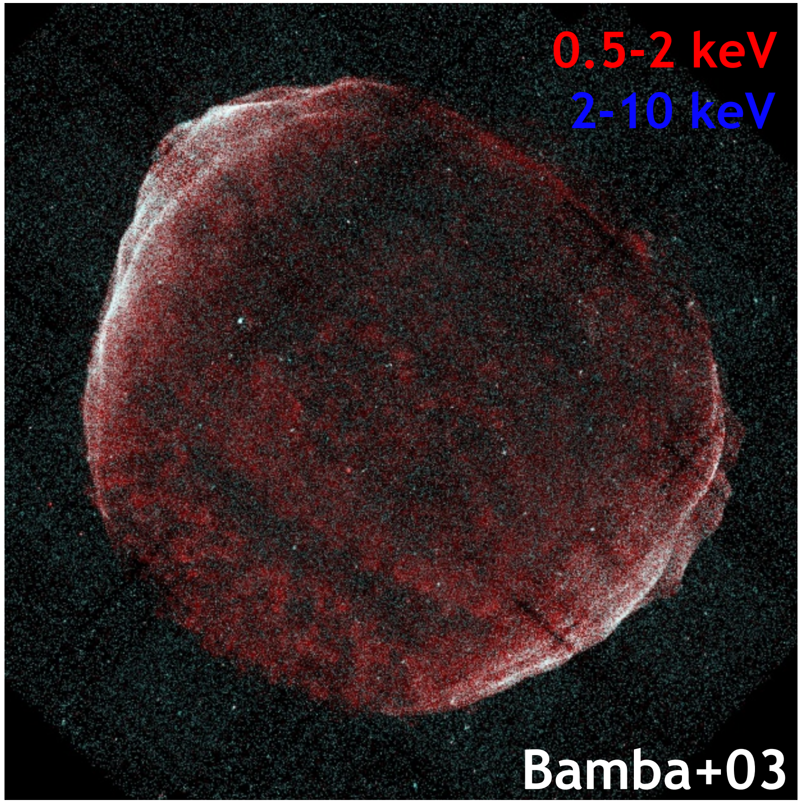
The only observational clue of E_{max}: cut-off of sync. X-rays

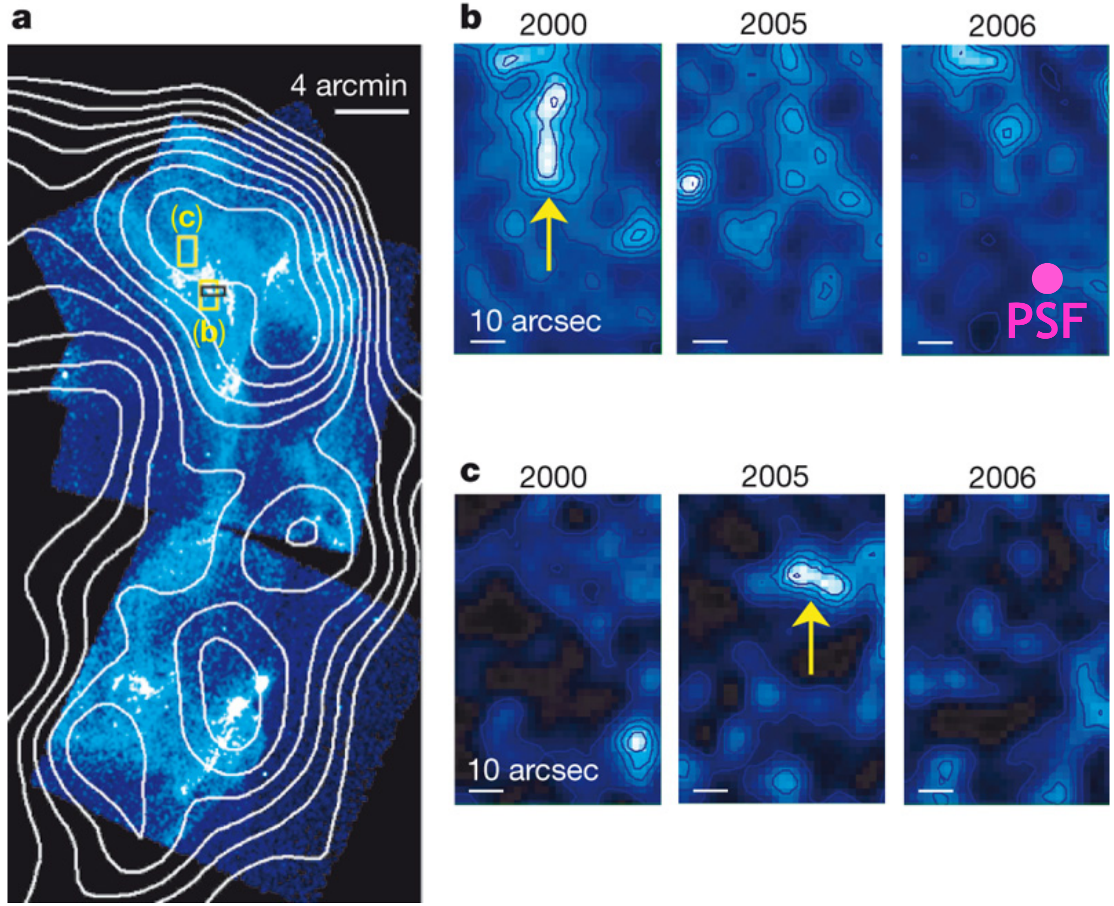
We need sensitivity at E > 10 keV
-> WFI to 15 keV
-> HXI with area at goal



Suzaku/HXD found the cut-off,
but could not resolve where is the best site.
ASTRO-H/HXI can make images,
Could do much better using IXO/HXI
(but only if angular resolution <30 arcsec and area >150 cm^2!)

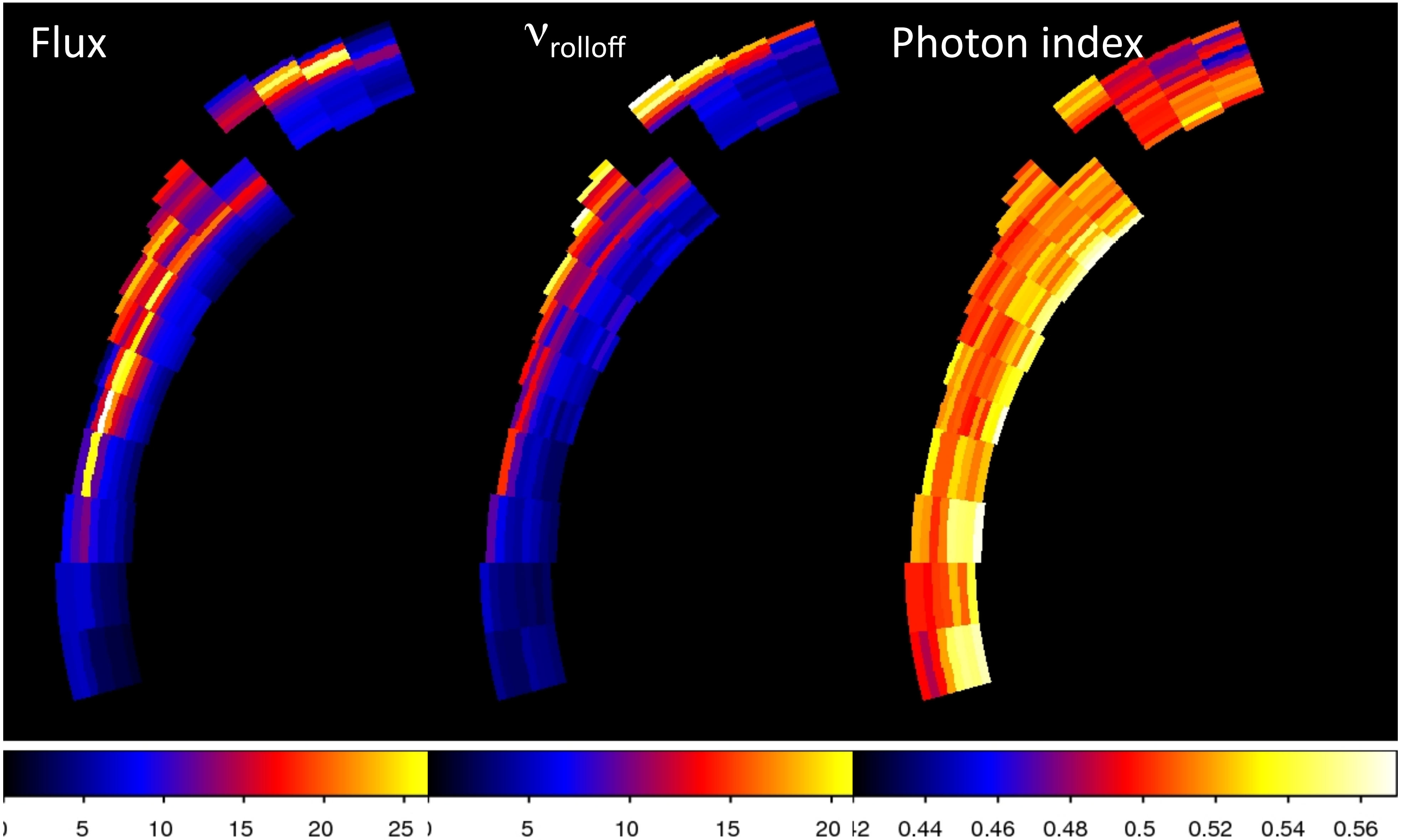
IXO allows detailed study of filaments and knots





Is the maximum energy position dependent ?
Do time variable knots have time variable E_{max} ?
What is the spatial structure of the magnetic field?
-> possible answer to “where is the Pevatron ??”
(Really need more hard X-ray capability to do this right)

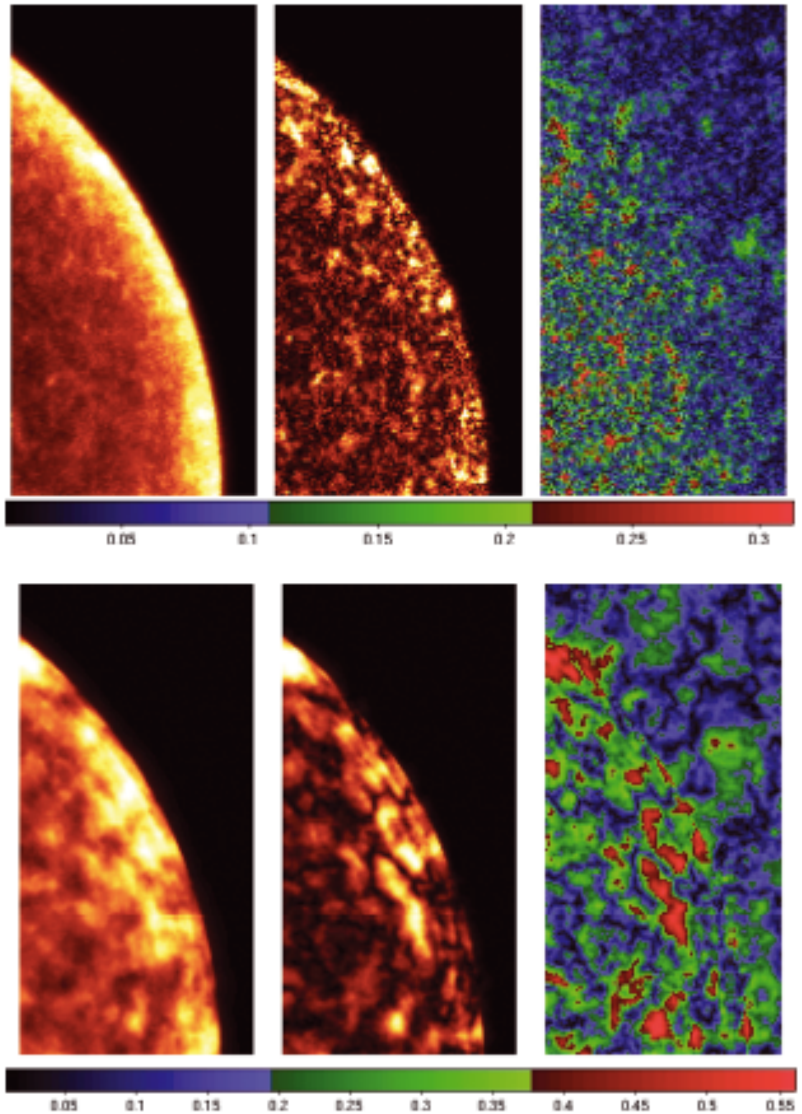
Spatial Spectral Variations in SN 1006

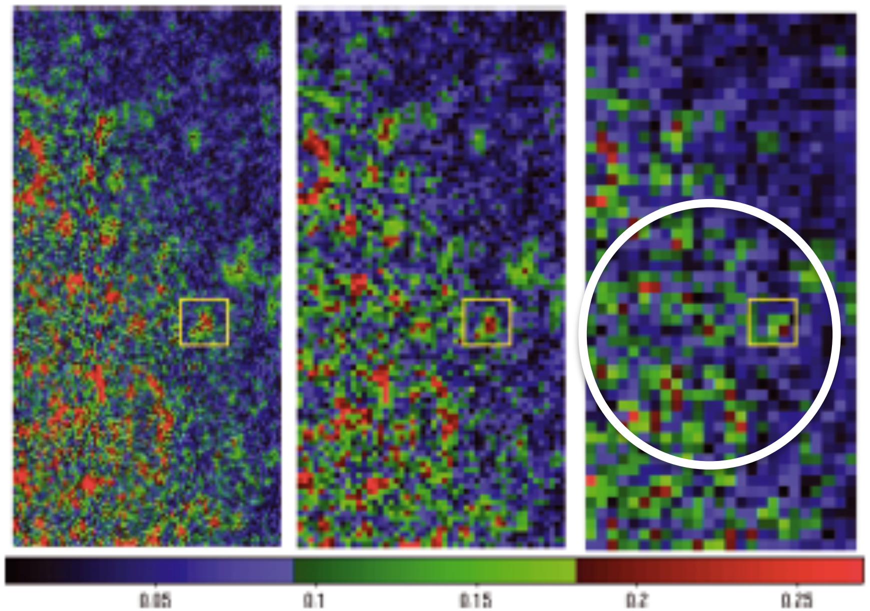


X-ray Polarization in SNRs

- **Detection of polarization will prove synchrotron origin of nonthermal flux**
- Primary magnetic field component in young SNRs is radial (from radio)
- Expect high polarization (up to 80%) from ordered B field at rim
- But field **must** be turbulent if diffusive shock acceleration is to operate
- Turbulence will reduce average polarization (Strohman & Pohl 2009; Bykov et al. 2009)
- Turbulence can also produce locally high B-field fluctuations
  - Results in locally high X-ray polarization
  - X-rays particularly sensitive, since degree of polarization sensitive to electron spectral index, and those producing X-rays in exponential rolloff tail
  - **Fluctuations, thus flux and polarization will be time variable**
- **Imaging polarization measurements can be used to determine degree and spatial scale of B field fluctuations**
  - Radio modeling suggests $\delta B < B$ in young SNRs (Strohman & Pohl 2009)
  - Radio polarization too large to be produced by purely stochastic fields; must be ordered component

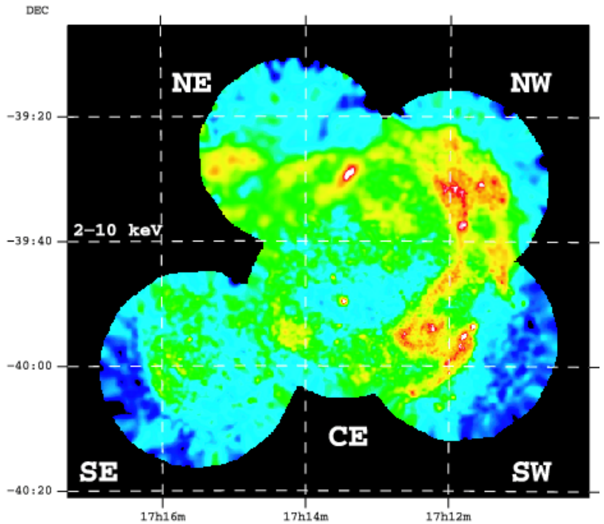
Polarization could be dominated by short term B-field fluctuations (Bykov et al. 2009)

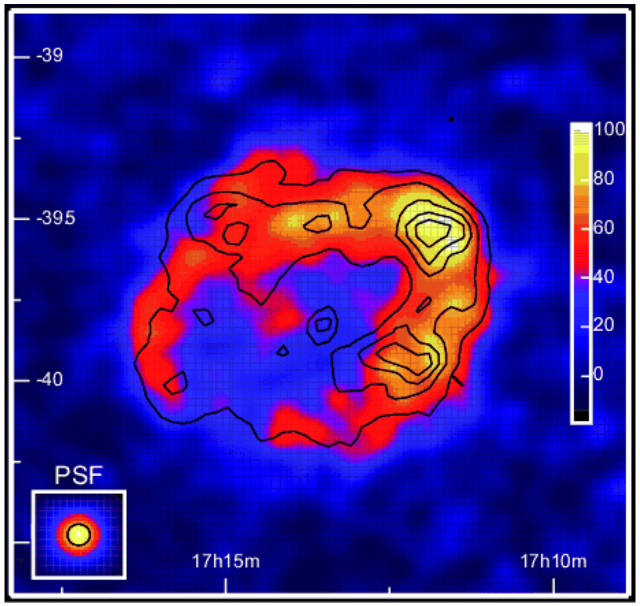


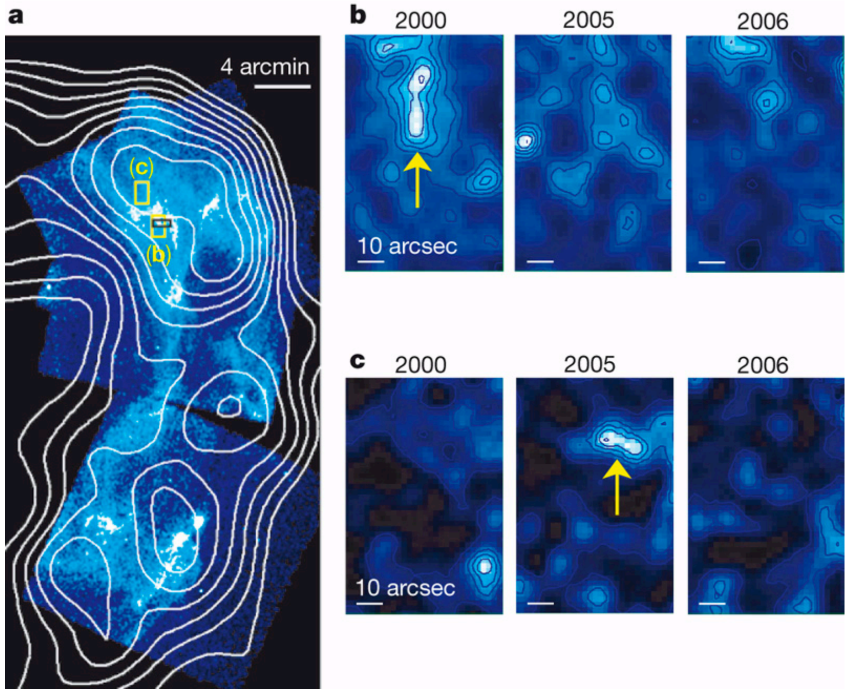


- Polarization at 5 keV from purely stochastic B field
- Strong dependence on electron spectrum
- Random polarization directions
- Strength of polarization dependent on angular resolution
- Polarization will be time variable

RX J1713.7-3946: Poster child for twinkling polarization

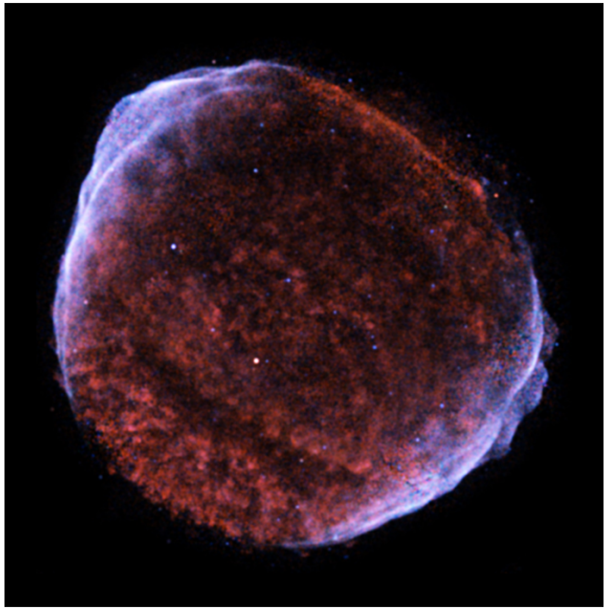




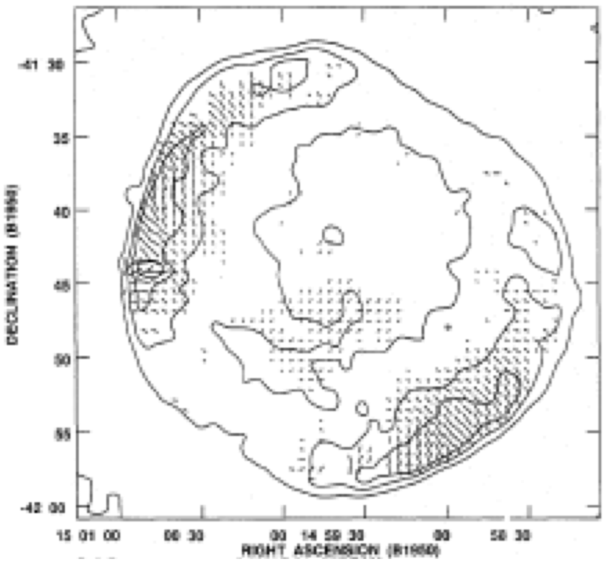


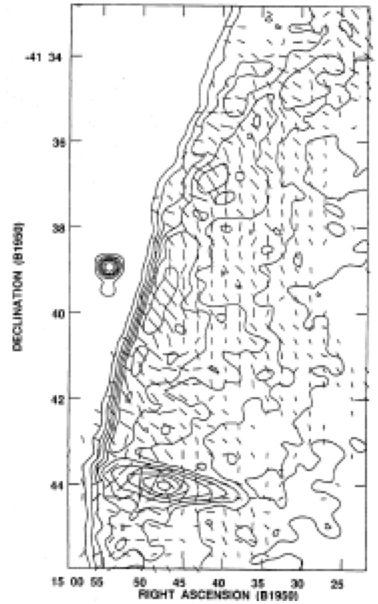
- Spectrum is entirely nonthermal
- Stimulus for Bykov et al. model
- Small features have 1y timescales (Uchiyama et al. 2007)
- These features should be highly polarized

SN 1006 could be different



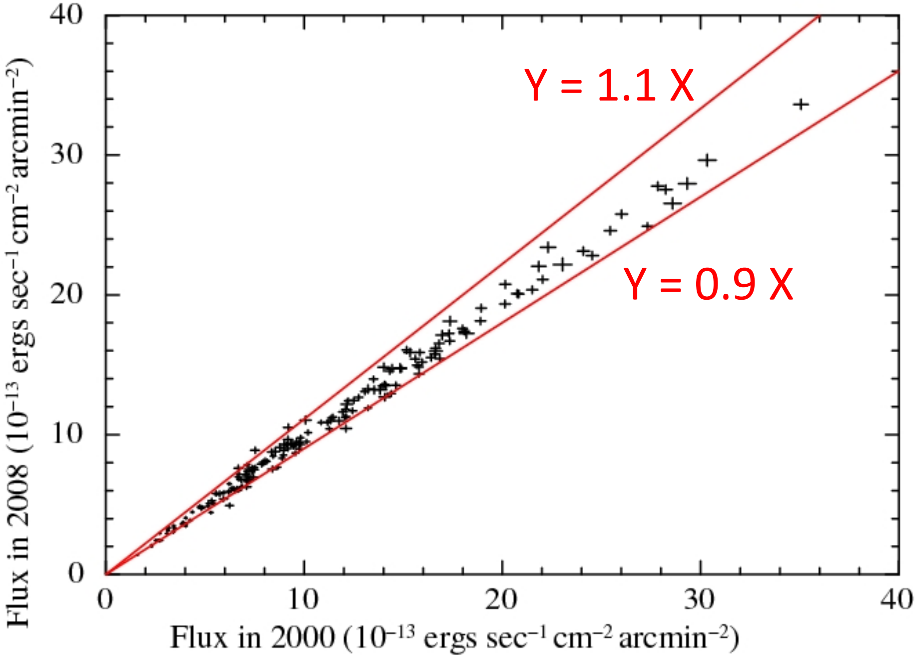
- Intrinsic magnetic field is radial, as expected in young SNR
- Relatively well ordered but some evidence of structure
- Average polarization only 13%, peak of 30%
- Polarized fraction suggests field is mostly disordered, with only 20% of the total magnetic energy density in the radial component
- Radio ordered field polarization would be 71% (X-ray >80%)
- Radio and X-ray probe different scales
  - X-ray synchrotron originates only in outermost shock region
  - *No evidence of X-ray variability* (<10%).
  - Is field there more ordered?

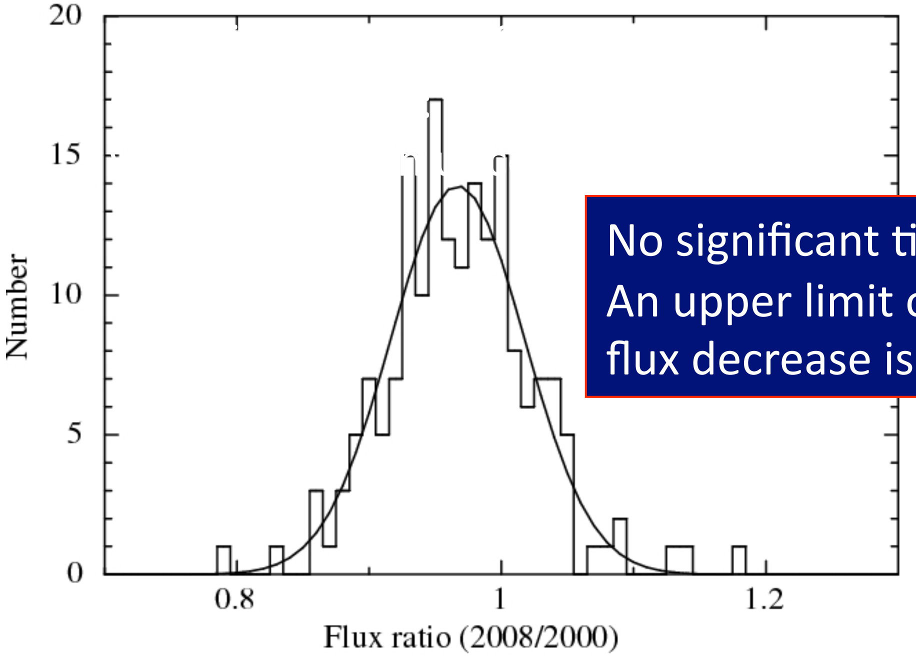




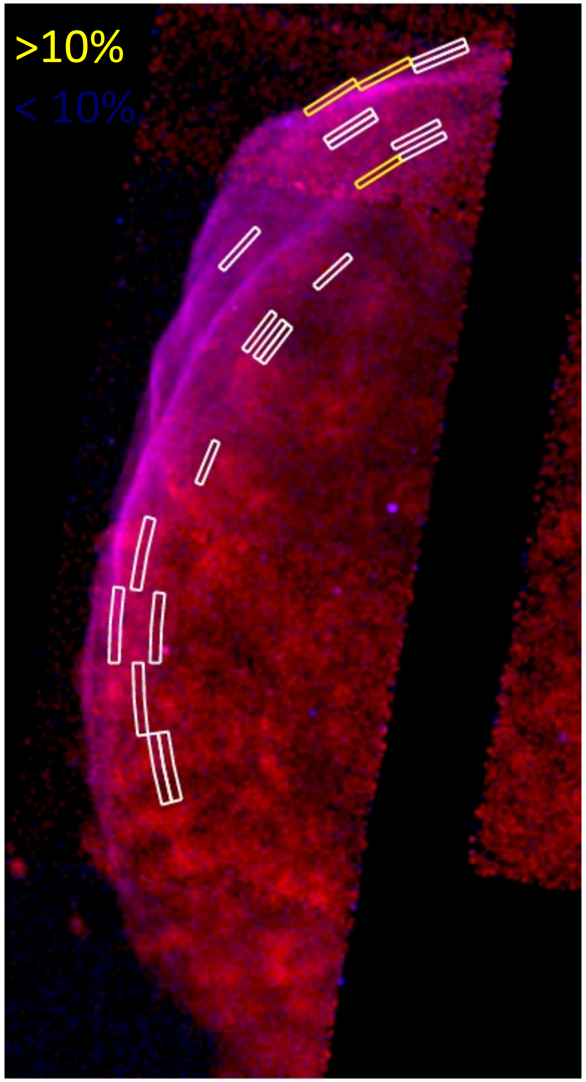
Reynolds & Gilmore 1993

No Time Variation of Flux in SN 1006





No significant time variation.
An upper limit of the global flux decrease is 8%.



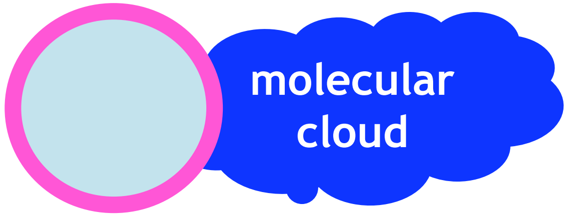
These regions are scattered. => fluctuation?

4. How can particle escape from shocks to be cosmic rays ??

2. How to see the cosmic ray acceleration in old SNRs?

X-rays: sync. X-rays disappear (e^- escape or lose energy)

Gamma-rays: Emission from protons via pion decay
if we have dense targets
(Molecular clouds)



Old SNRs are detected in TeV/GeV gamma-rays

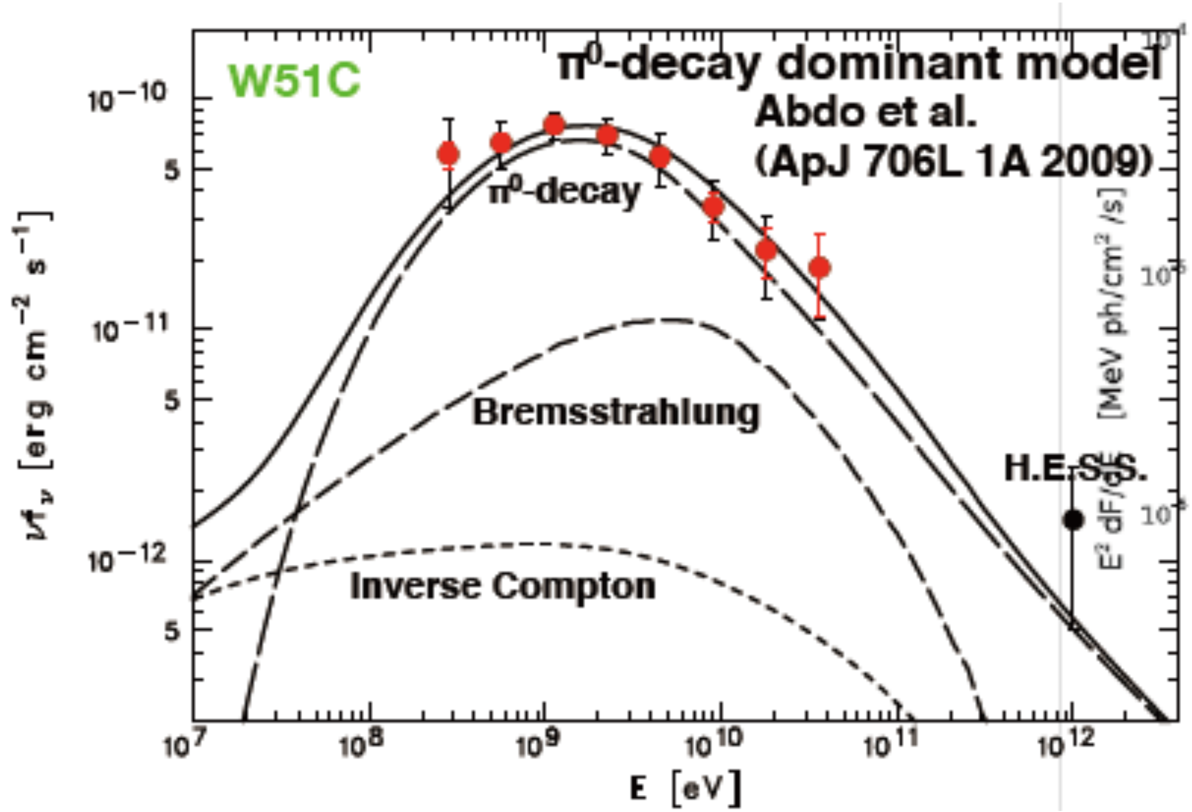
W28: age ~ a few tens thousand years
TeV(HESS) / GeV(Fermi) (offset from SNR!)
IC443: TeV(VERITAS) / GeV(Fermi)
Plus many others...

-> proton accelerators ?
Can we measure the maximum energy of protons ?

Fermi old SNRs have lower cut-off E than cosmic rays

Some old SNRs w. MC are detected by Fermi.
W44, IC443, W51C, …
Their spectra have cut-off in the Fermi band.

In the proton model
E_{max}^{p} ~ 10 GeV/c



The spectrum of RXJ1713 also has cut-off at 150 TeV.

They are not cosmic-ray accelerators ???

Only young SNRs can be accelerators ??

Parameters of acceleration:
- shock speed -> slower in older SNRs
- magnetic field -> smaller in older SNRs

(Ptuskin+03, Bamba+05, ...)

Only young SNRs can accelerate up to the knee

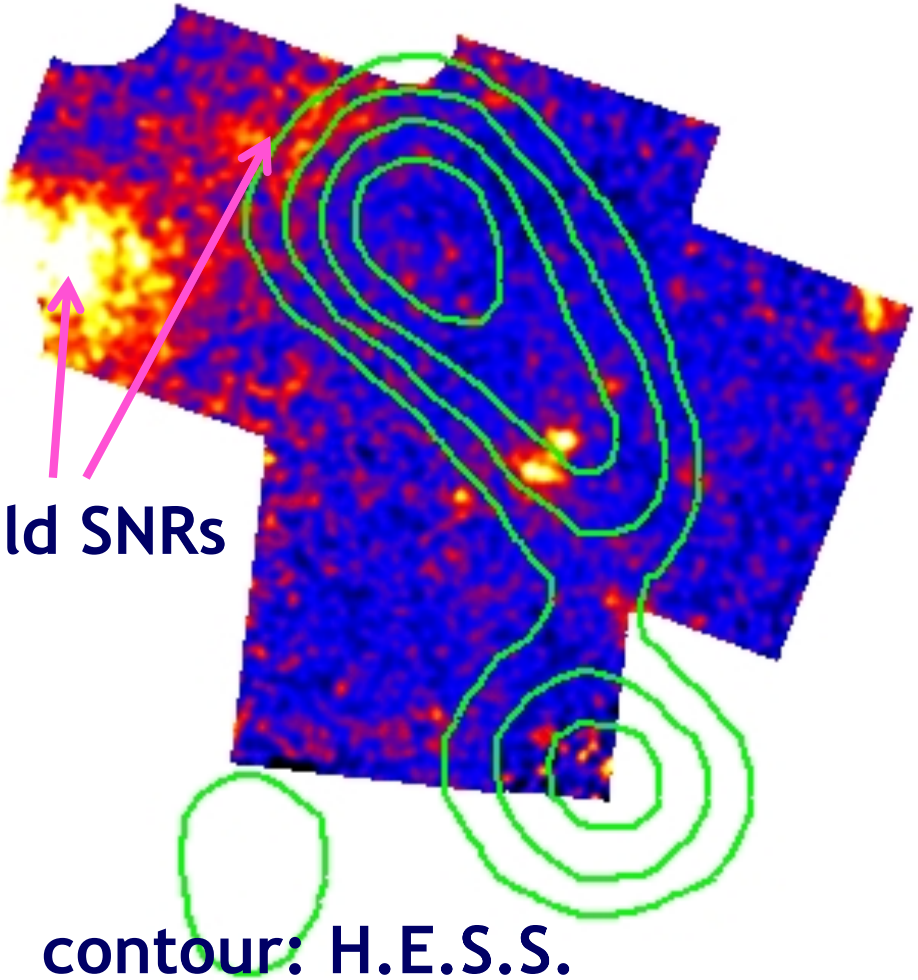
At some point, the accelerated particles should escape to be cosmic rays.

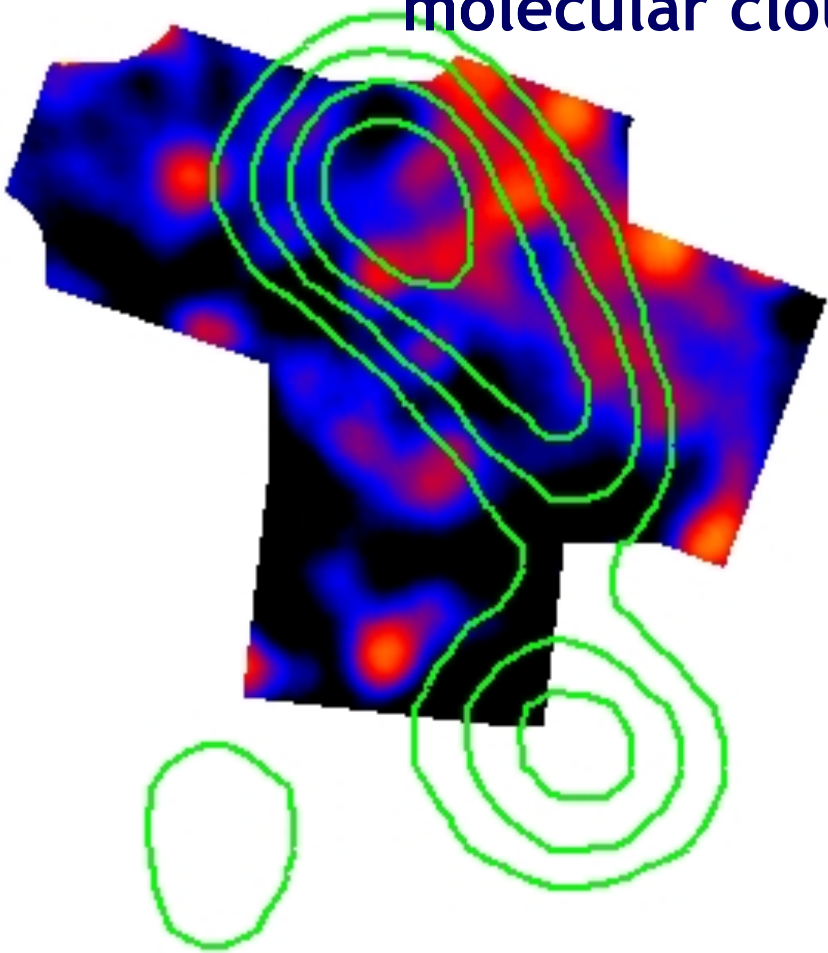
Interaction w. molecular cloud make particles escape?

Fast escape of high energy particles with damping of magnetic turbulence due to the dense environment ??

(Ptuskin & Zirakashvili 03)

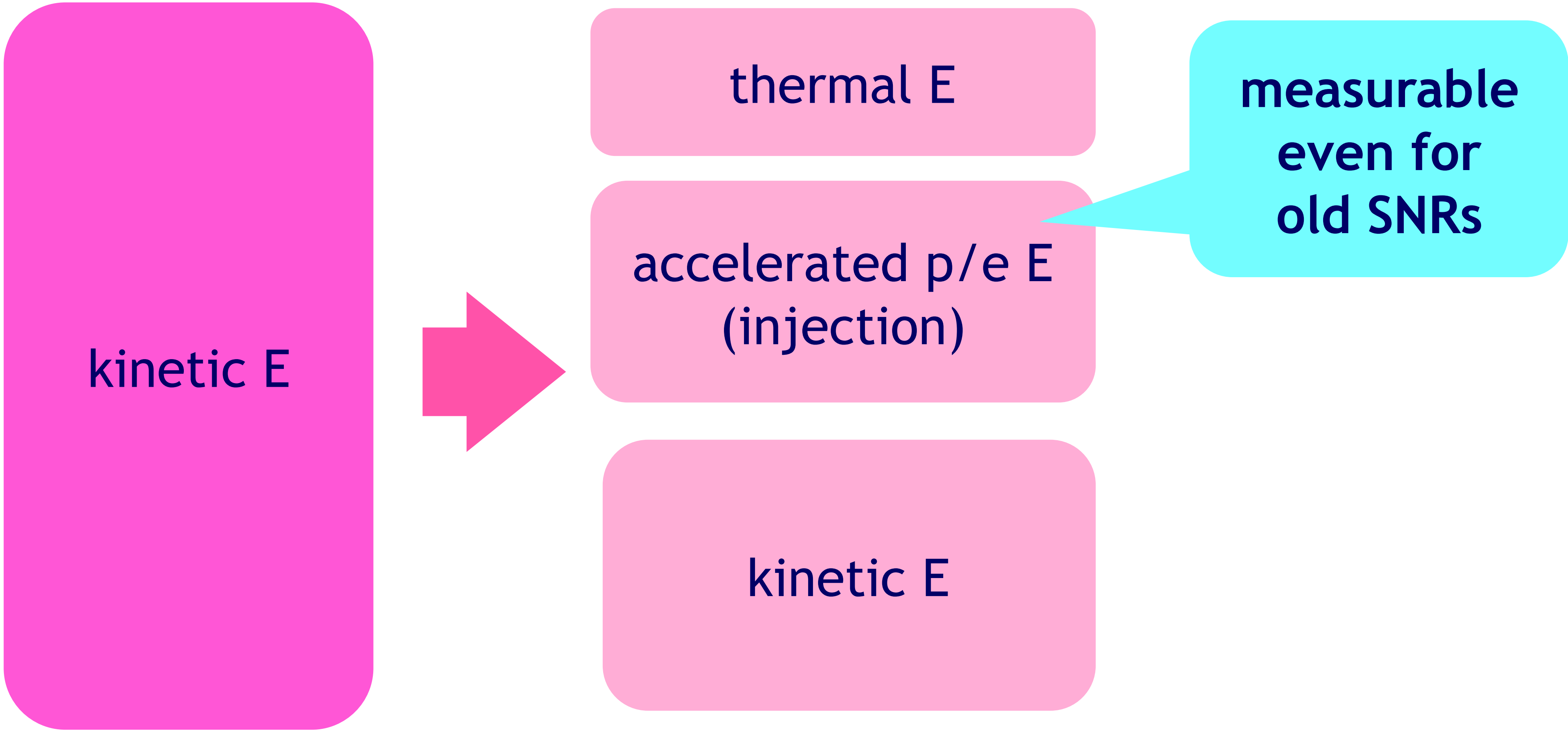
Another example: TeV unID source HESS J1745-303 (Bamba+09)





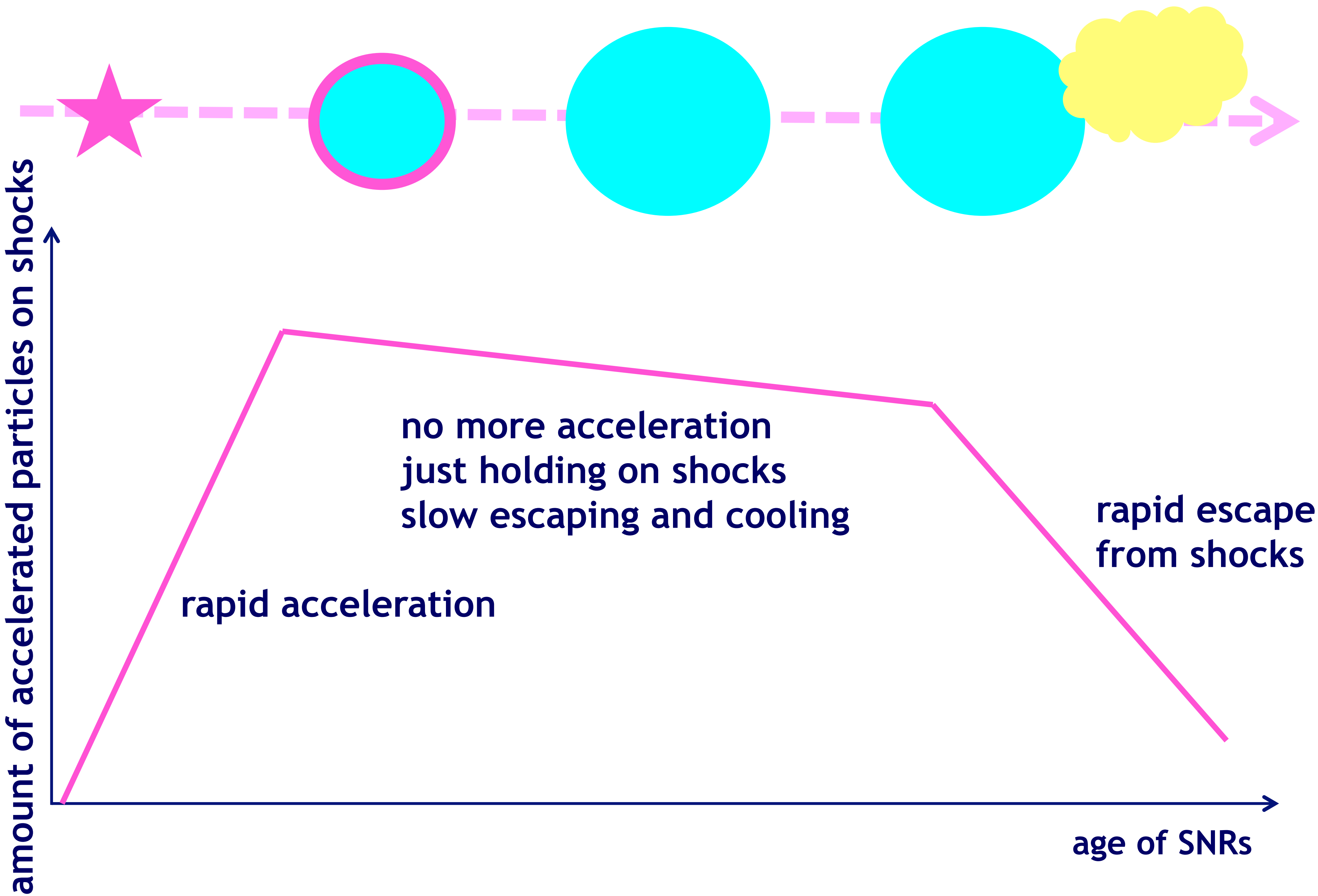
TeV emission w. old SNRs and molecular cloud
-> emission from protons?

How to estimate the amount of escaped particles ?



energy resolution = 2.5 eV -> 400 km/s
measurable even for old SNRs >> 10^4 yrs,
or colliding with molecular cloulds

Expected history of cosmic ray acceleration and escape



Summary

- Origin of cosmic rays is one of the most important problems in astrophysics.
- IXO/XMS will resolve the kinetic and thermal E in shocks, Providing a new way to infer the energy injected into accelerated particles.
- IXO/XPOL will allow us to characterize the magnetic field structures in the acceleration region
- IXO will resolve the most efficient acceleration sites in shocks (but HXI needs better than 30” resolution).
- IXO/XMS will show us how accelerated particles escape from shocks of old SNRs. This is the first direct evidence of CR acceleration in SNRs.