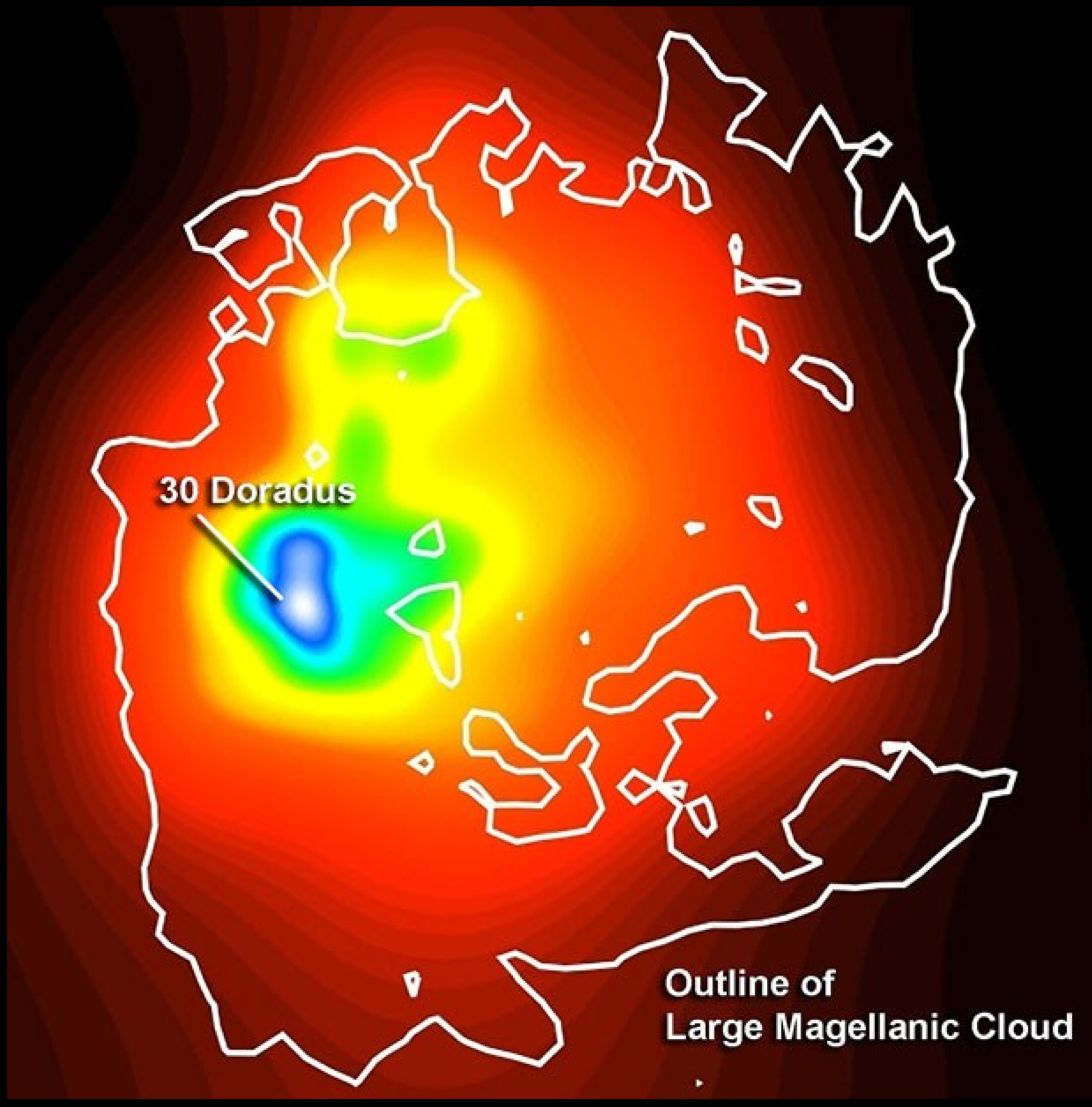
Cosmic Rays in other galaxies


30 Doradus
Outline of
Large Magellanic Cloud

Summary of the lesson

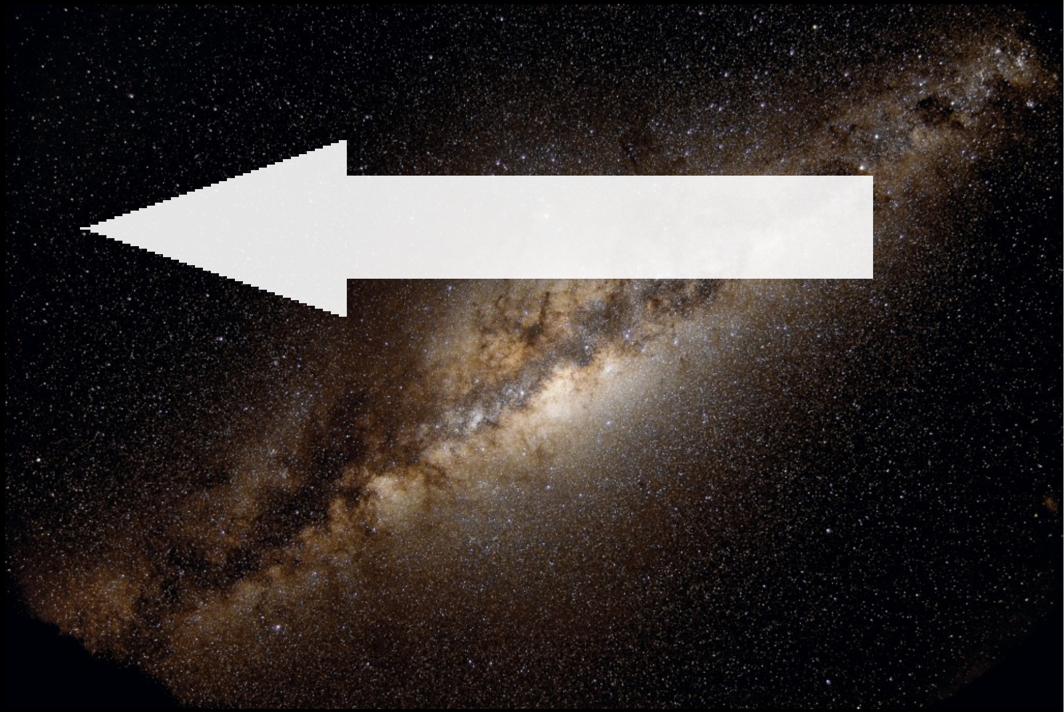
Cosmic Rays

CR and the Galaxy

- **ɣ Rays prod. mech.**
- **The MilkyWay in ɣ Rays**
- Diffuse gas
- Molecular Clouds
- InterStellar Radiation Field

Supernova Remnants

- Evolution
- MC associations
- Gamma-ray from SNR

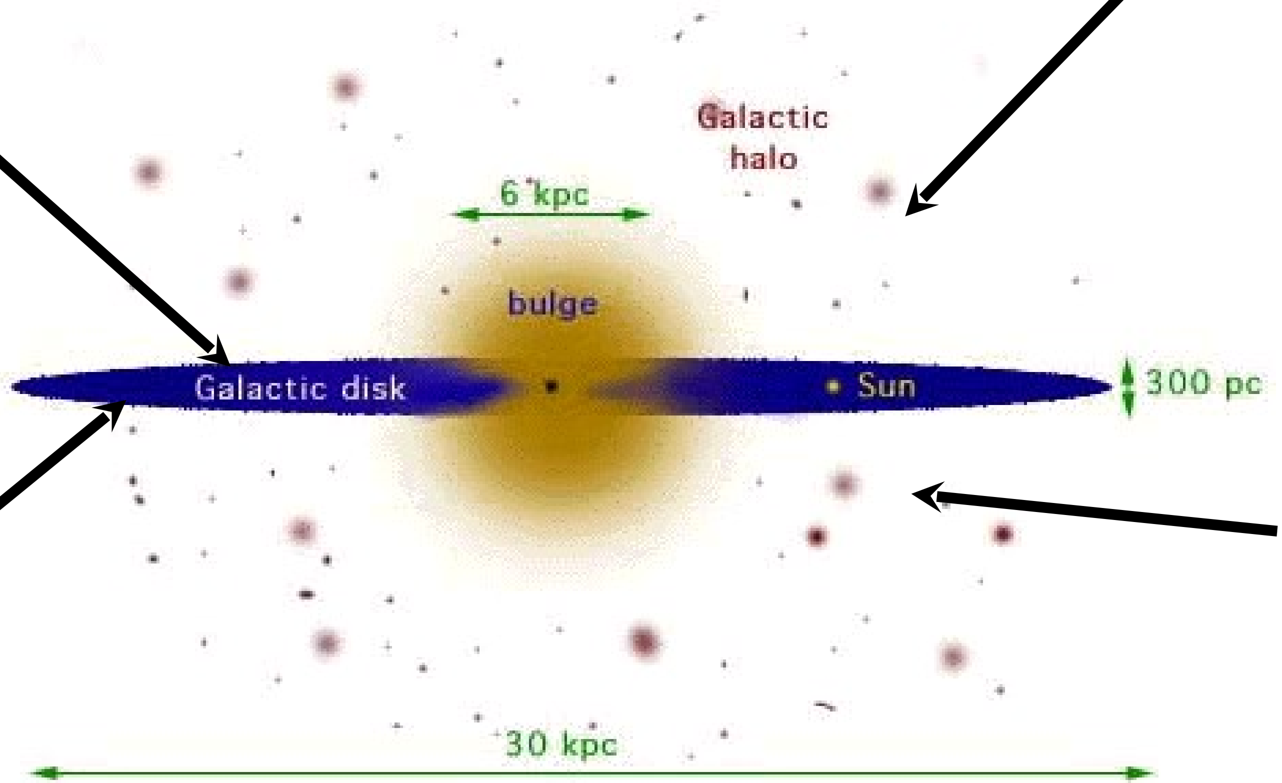


the Milky Way

gas density

$n \approx 1 \text{ cm}^{-3}$

$n \approx 0.01 \text{ cm}^{-3}$

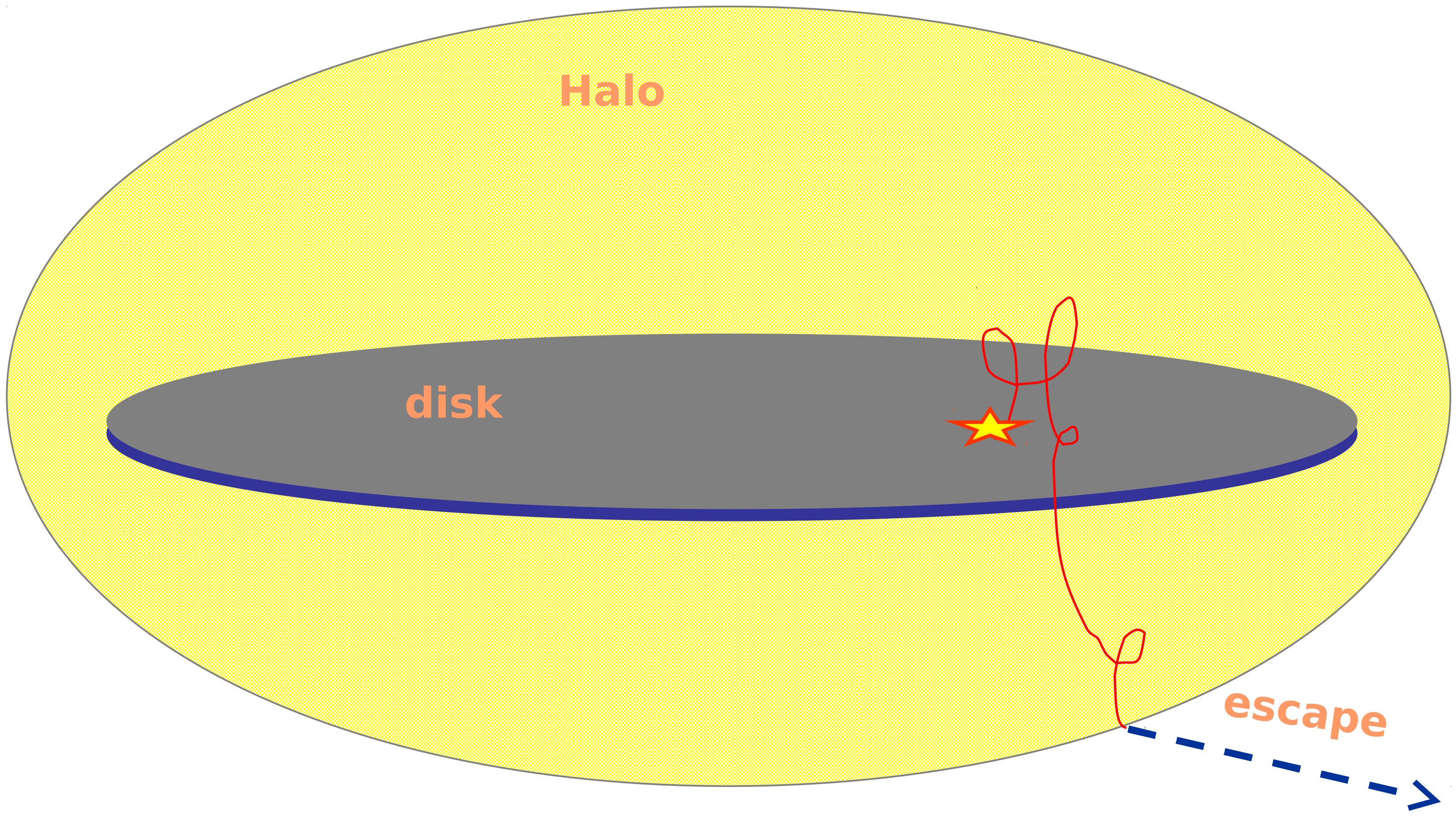


$B < 10 \ \mu\text{G}$

magnetic field

$B \approx 3 \ \mu\text{G}$

CR Propagation



Cosmic Ray power in the Galaxy

$$w_{CR} \sim 1\,\mathrm{eV/cm^3} \longrightarrow \mathcal{E}_{CR} = w_{CR}\,V_{disk}$$

Cosmic Ray power in the Galaxy

$$w_{CR} \sim 1\,\mathrm{eV/cm}^3 \longrightarrow \mathcal{E}_{CR} = w_{CR}\,V_{disk}$$

$$P_{CR} = \frac{\mathcal{E}_{CR}}{t_{disk}} = \frac{w_{CR}V_{disk}}{t_{disk}} = 3 \times 10^{40}\ \mathrm{erg/s}$$

The Supernovae power in the Galaxy

A **supernova** releases ~10^{51} ergs in form of kinetic energy.
In the Galaxy the observed supernova rate is of the order of 1/30 - 1/100 yr^{-1}.

$$P_{SN} = 3 \times 10^{41} \text{ erg/s}$$

The Supernovae power in the Galaxy

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In the Galaxy the observed supernova rate is of the order of 1/30 - 1/100 yr^{-1}.

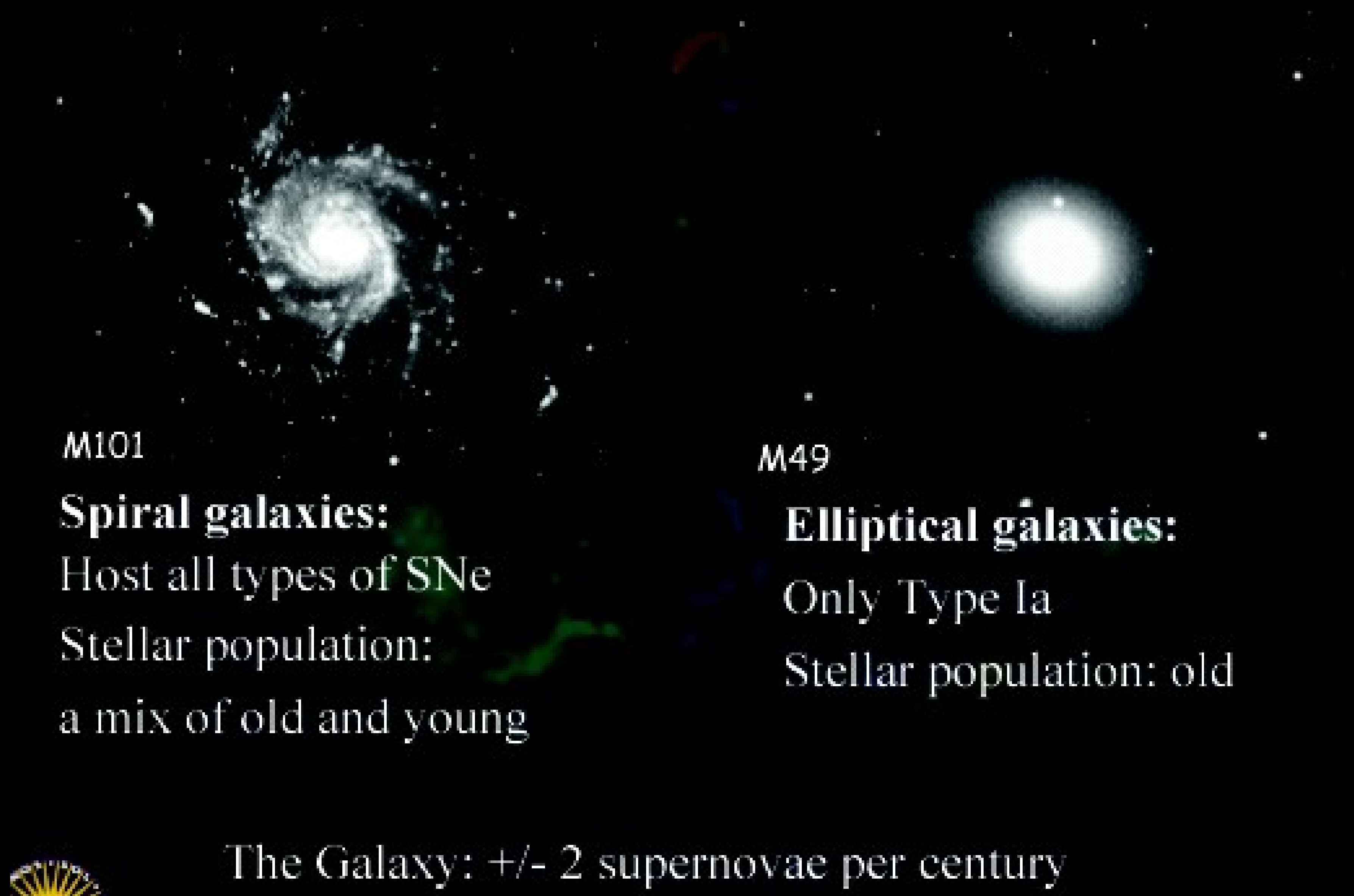
$$P_{SN} = 3 \times 10^{41} \text{ erg/s}$$

$$P_{CR} = 3 \times 10^{40} \text{ erg/s}$$

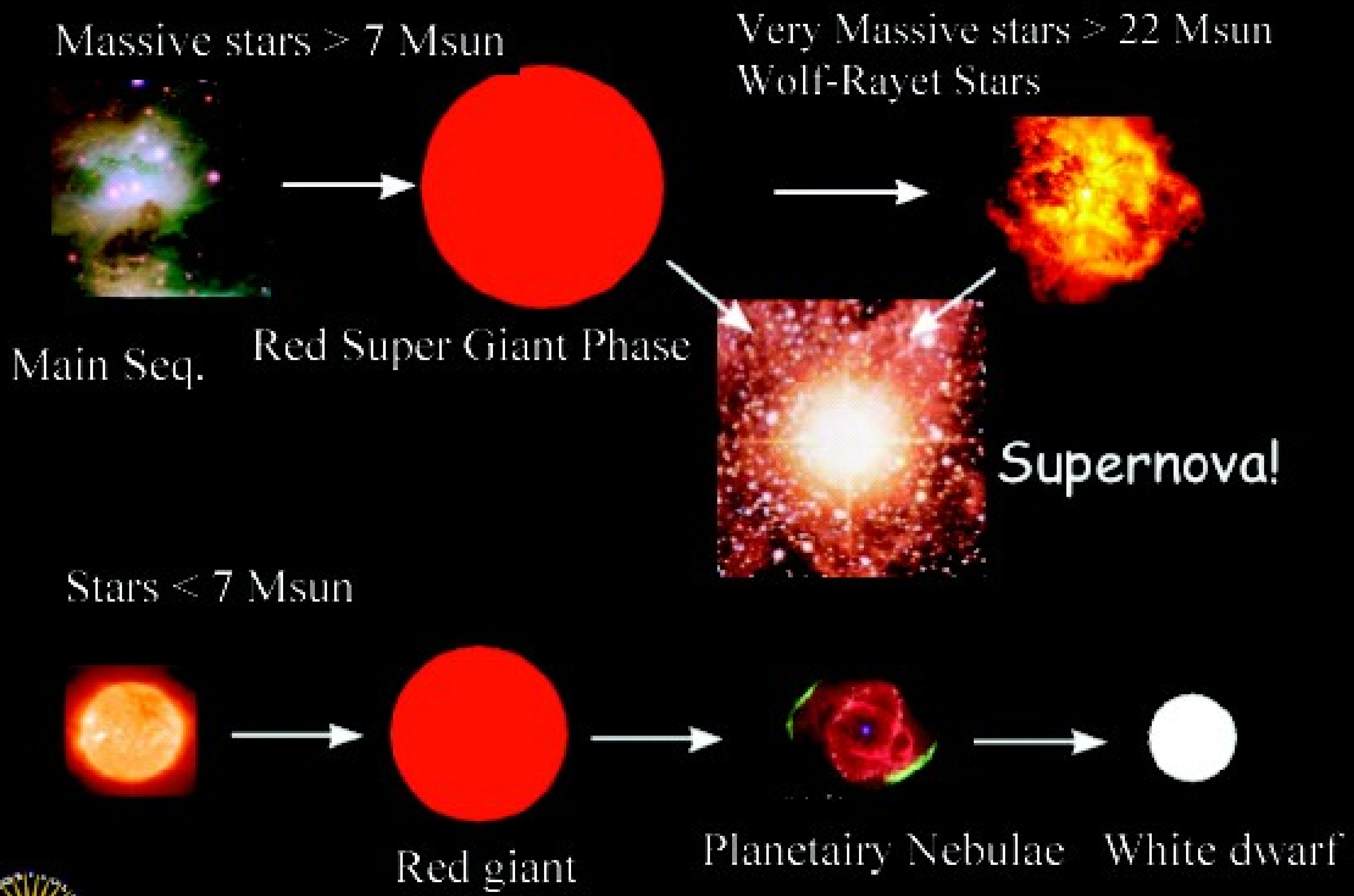
SuperNovae alone could maintain the CR population provided that about **10%** of their kinetic energy is **somehow converted into CRs**

Ginzburg e Syrovatskii (1964)

SuperNova Remnants

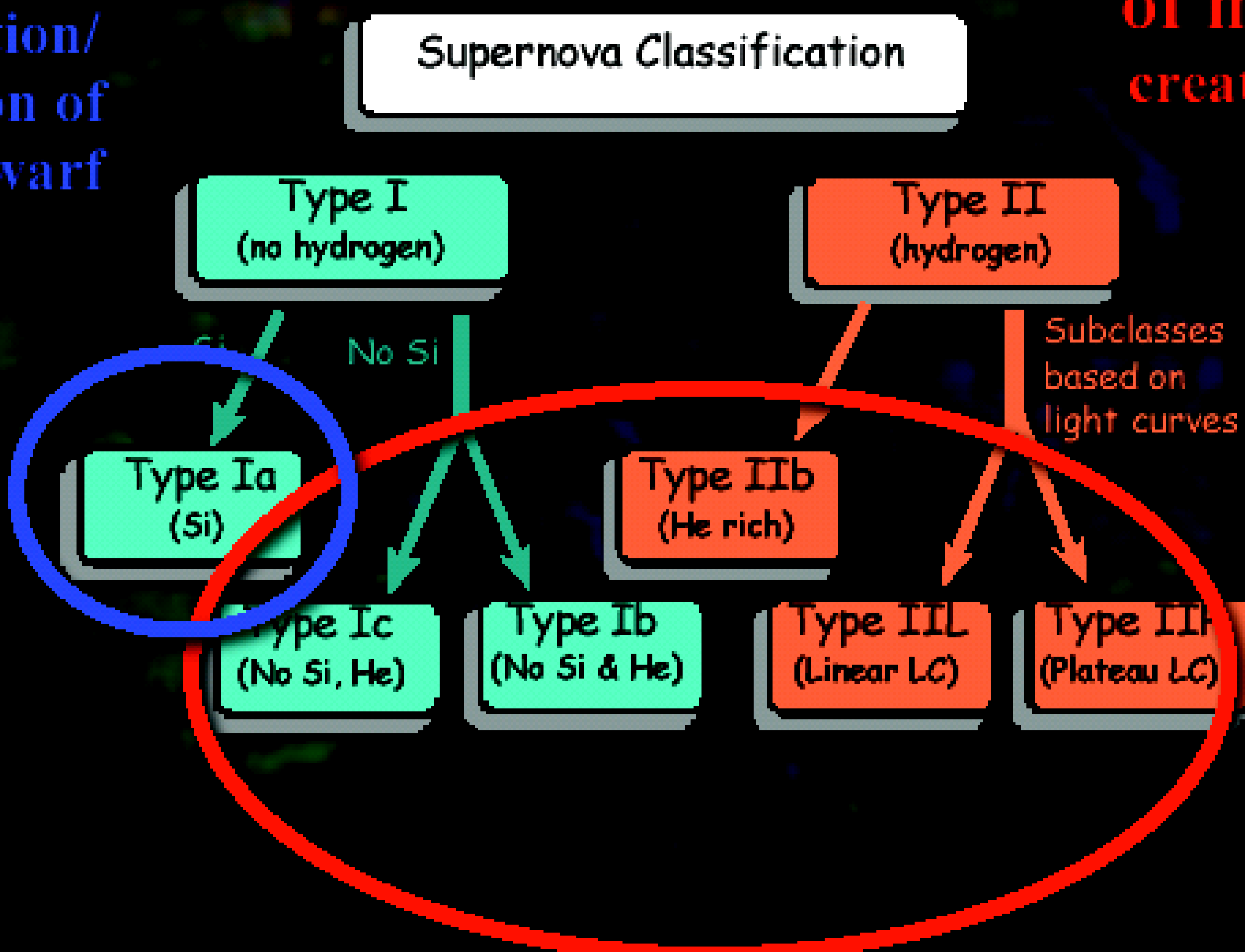


SuperNova Remnants



SuperNova Remnants

Thermonuclear explosion
deflagration/ detonation of White Dwarf



Core collapse of massive star
creation of NS/BH

SuperNova Remnants

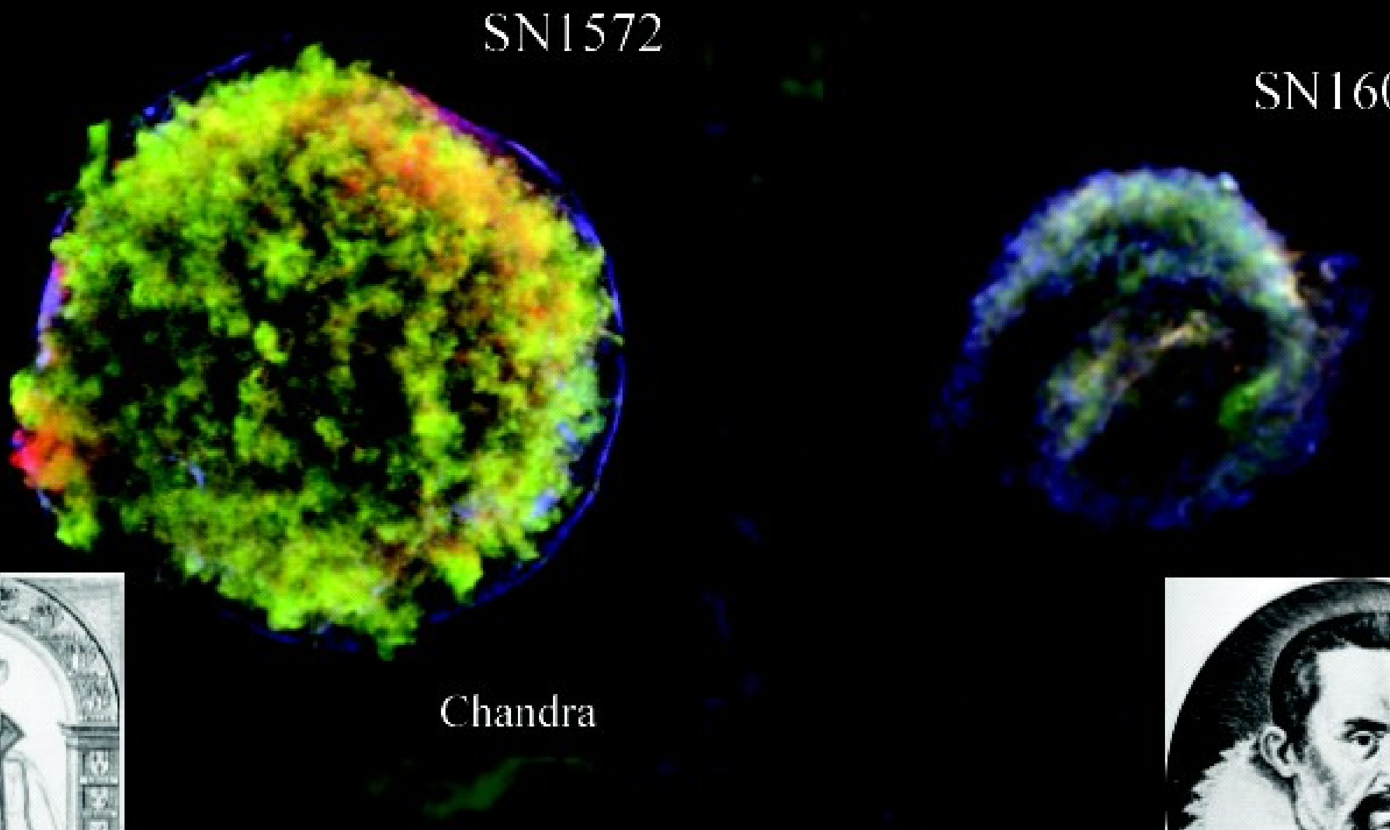
Type Ia: - The whole star is disrupted by the explosion

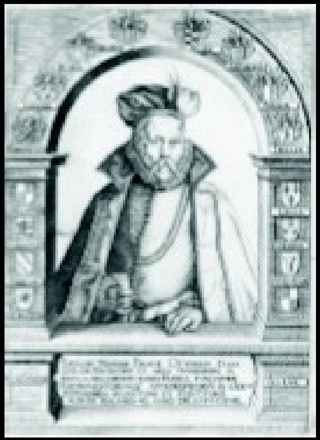
- The source of energy is nuclear fusion, predominantly the burning of C/O into ^{56}Ni
- Most of the energy is in the form of heat (10^{51} erg)

Type II/Ibc: - The core of the star collapses into a neutron star

- The source of energy is therefore gravity ($\sim GM^2/R_{NS} \sim 10^{53}$ erg)
- Most of the energy released as neutrinos!
- Only 1% converted to heat/kinetic energy!
- Nuclear fusion: by-product/not source of the explosion

SuperNova Remnants

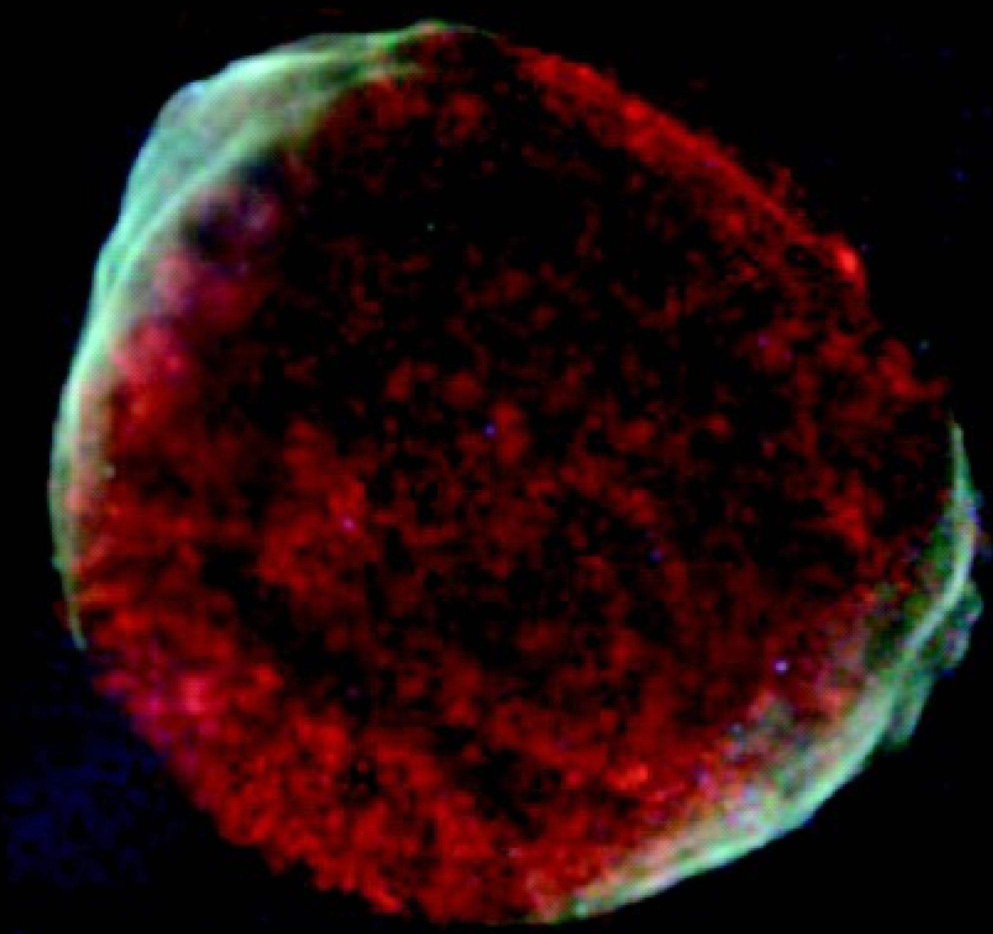




Tycho Brahe

Johannes Kepler

SuperNova Remnants



Size: 30'

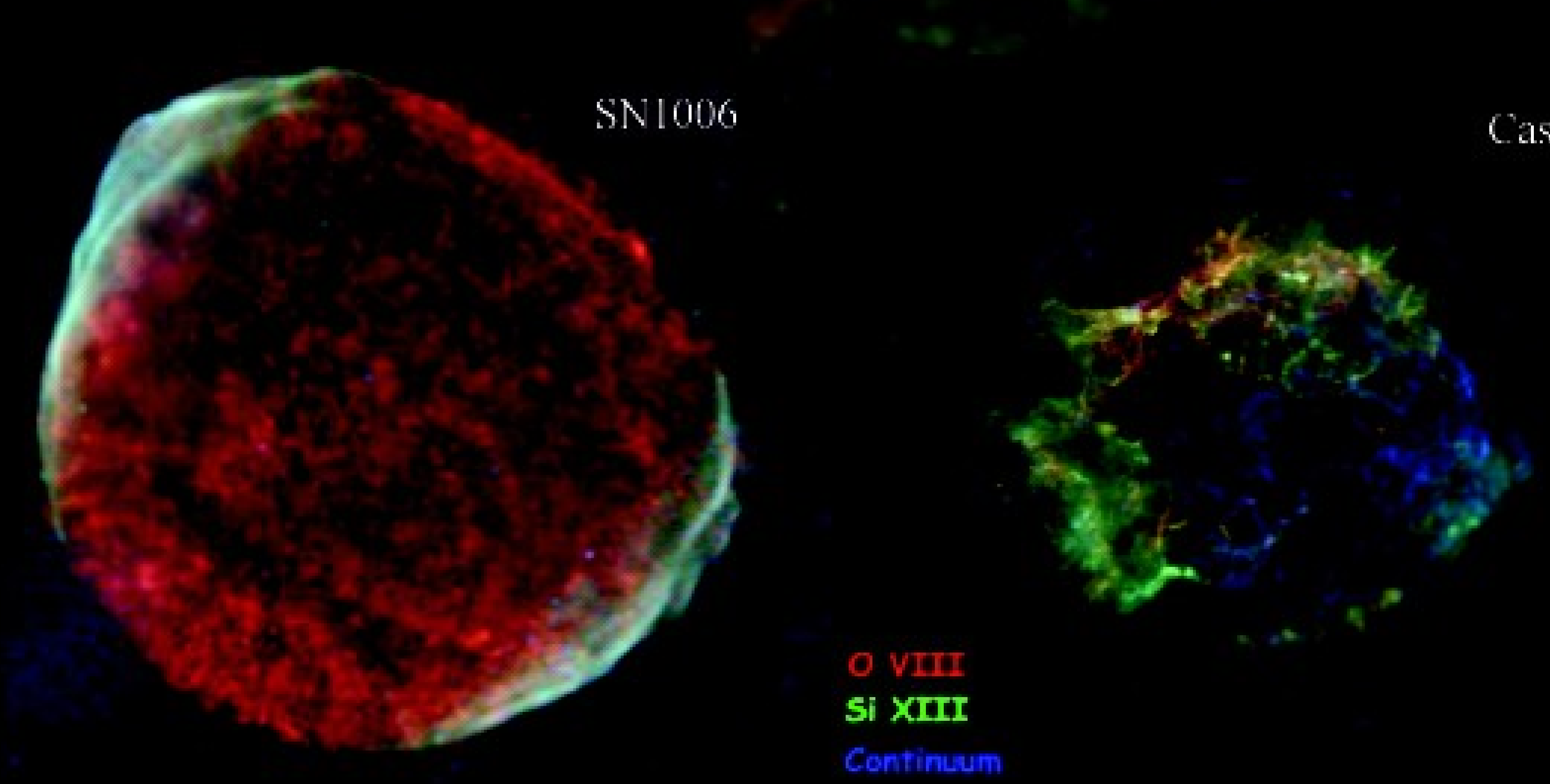
The size of the full Moon

Historical brightness

-6 mag, perhaps -9 mag

SuperNova Remnants

Shell Types: Shell of shock heated gas



Type Ia supernova
Shell Type SNR

Core-collapse supernova (Type Ib)
Shell Type SNR

3 phases in SNR’s life

1) Free expansion (less than 200-300 years)

2) Adiabatic or “Taylor-Sedov” phase

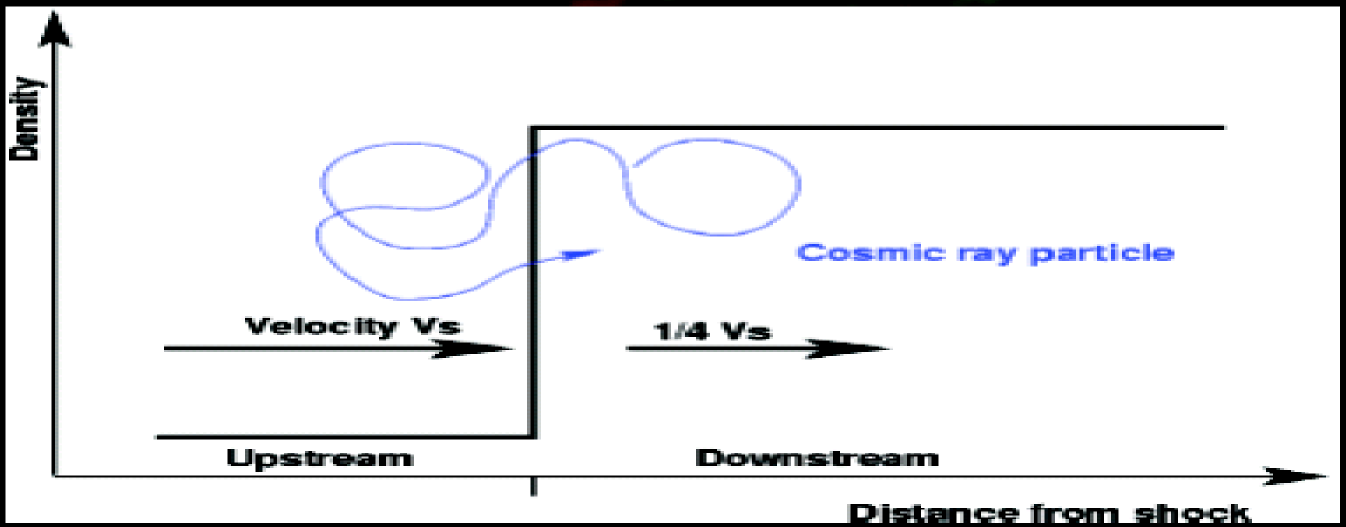
(about 20 000 - 40 000 years)

3) Radiative phase

(up to 500 000 years)

4) ... and then, merge with the ISM

Shocks



- Conservation laws: mass, momentum and energy conservation:
  Use system in which shock is at rest

  $\rho_1 v_1 = \rho_2 v_2$

  $(\rho_1 v_1) v_1 + p = (\rho_2 v_2) v_2 + p$

  $(1/2\rho_1 v_1^2 + u) v_1 = (1/2\rho_2 v_2^2 + u) v_2$

  internal energy $u = p/(\gamma-1)$, $\gamma = 5/3$ for monatomic gas

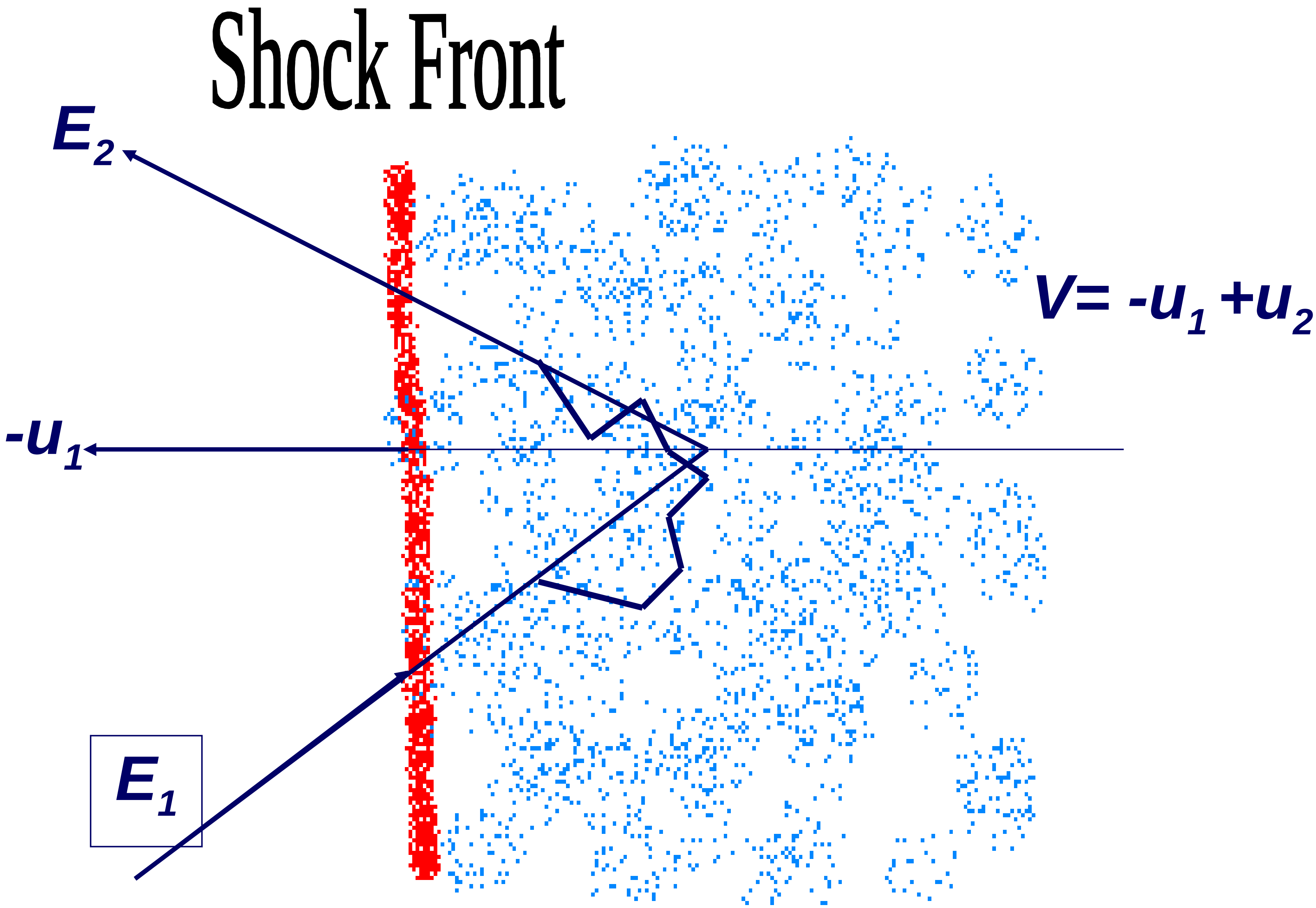
- Simplification: heat sinks (cosmic ray acceleration!), magnetic fields, and radiation losses not taken into account.

- For strong shocks ($M \rightarrow \infty$) one finds:

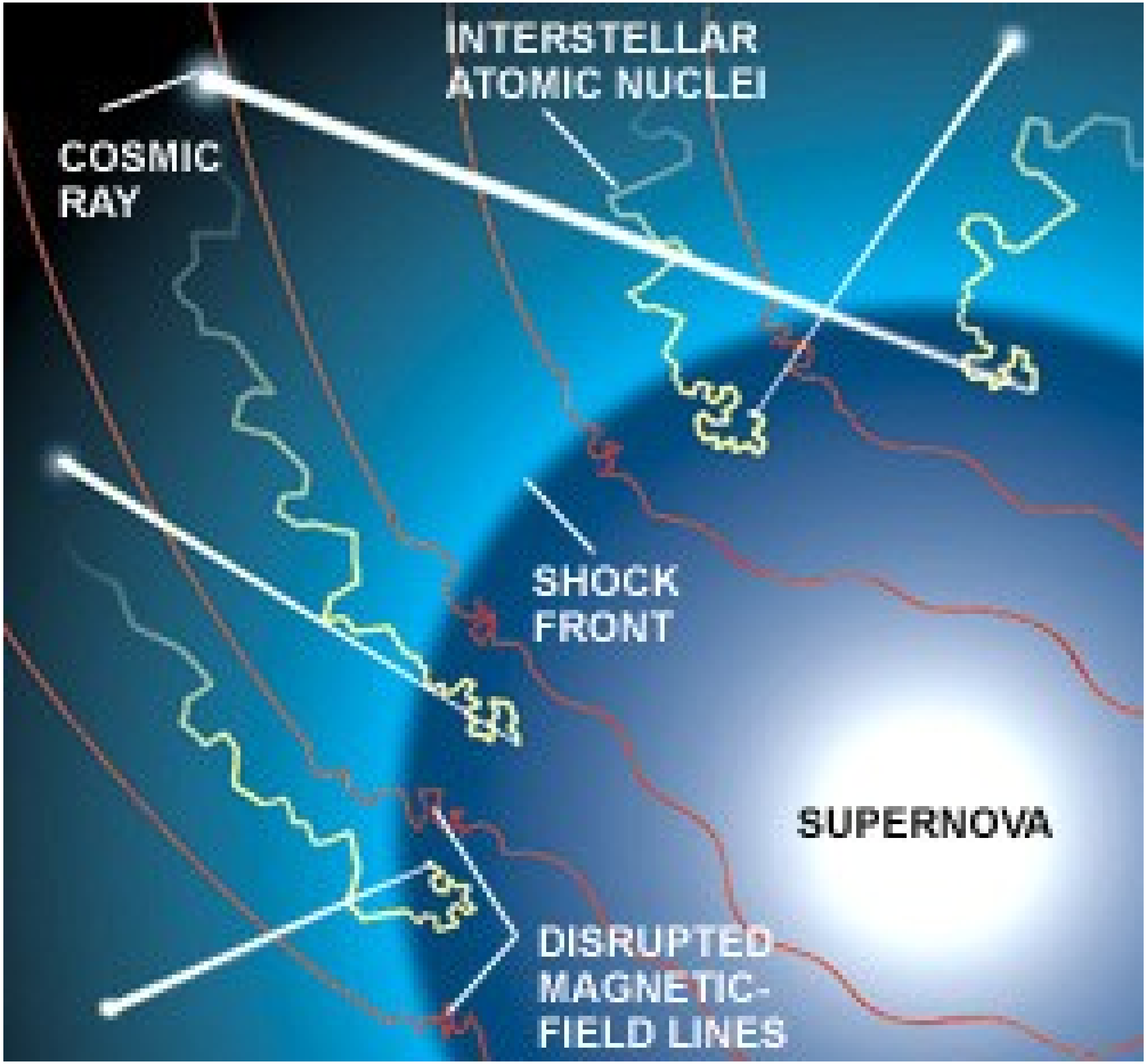
  $\rho_2/\rho_1 = (\gamma+1)/(\gamma-1) = 4$, implying $v_2 = 1/4 v_s$

  $kT_2 = 2(\gamma-1)(\gamma+1)^{-2}\, m\, v_s^2 = 3/16 m\, v_s^2$, with m particle mass

Accelerazione di Fermi del primo ordine

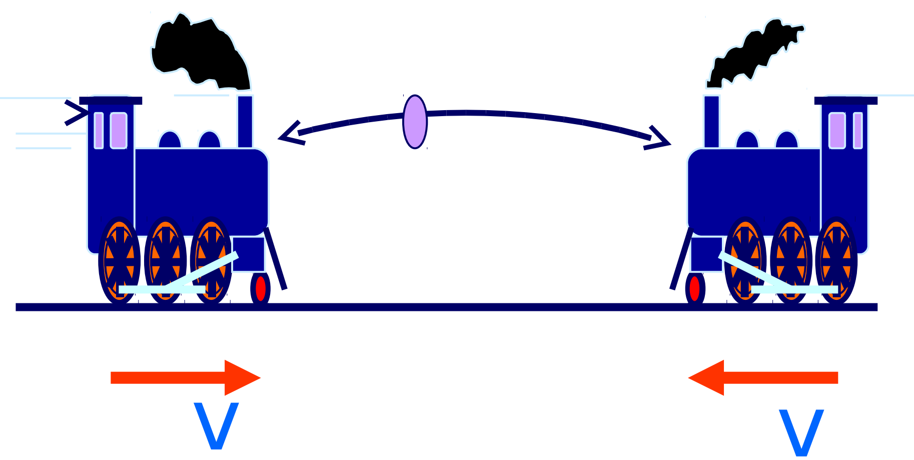


Meccanismo di accelerazione del primo ordine di Fermi



The Fermi acceleration

toy model



Urto n.	Velocità nel lab.
0	0
1	+2V
2	-6v
3	+14v
….	

The resulting energy spectrum of many particles undergoing this process (assuming that they do not influence the structure of the shock) turns out to be a power law:

$$\frac{dN(\epsilon)}{d\epsilon} \propto \epsilon^{-p} \qquad p >= 2$$

where the spectral index depends, for non-relativistic shocks, only on the compression ratio of the shock

SNR Cas A   (2nd brigthest radio source!) Age ~300 yr

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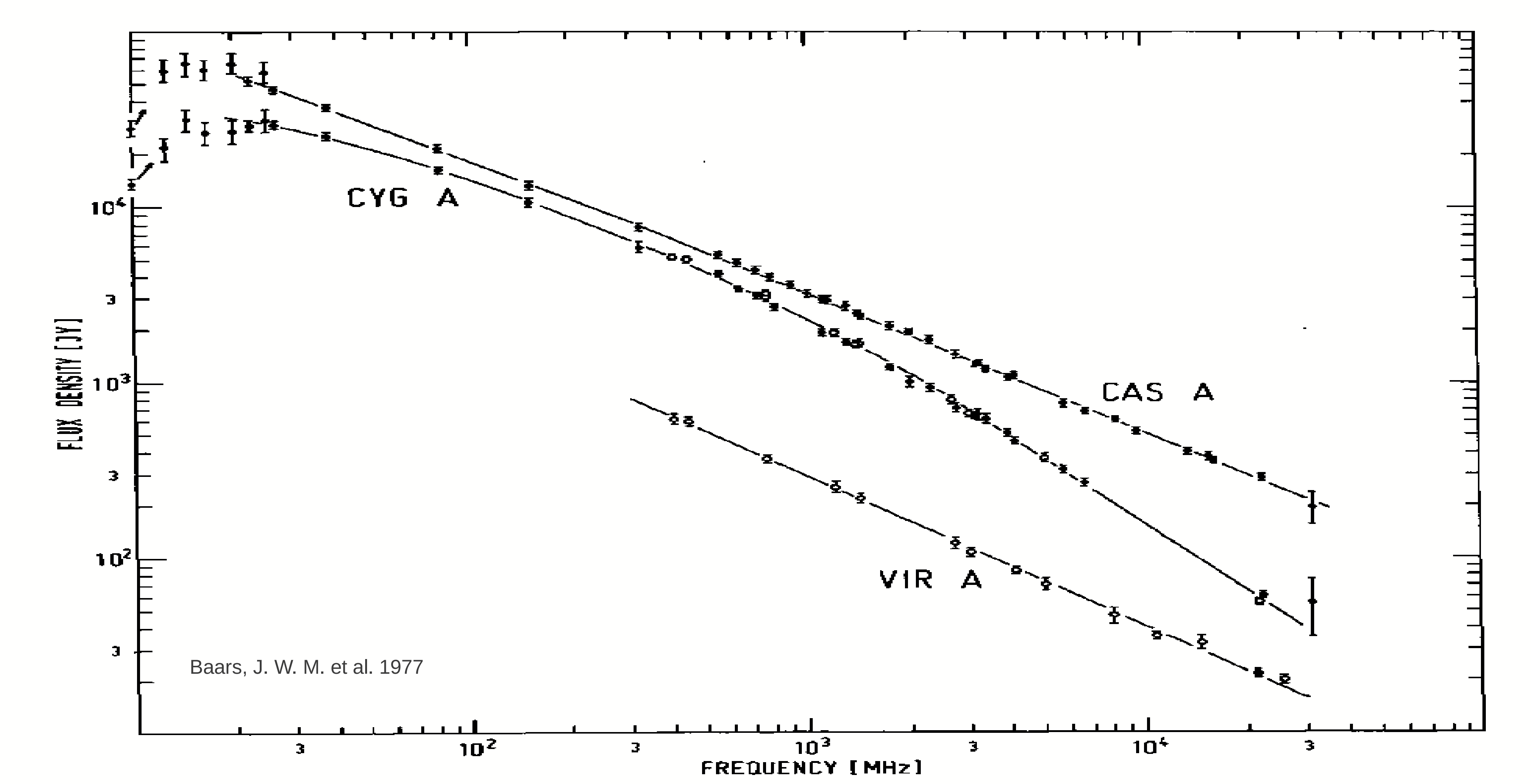

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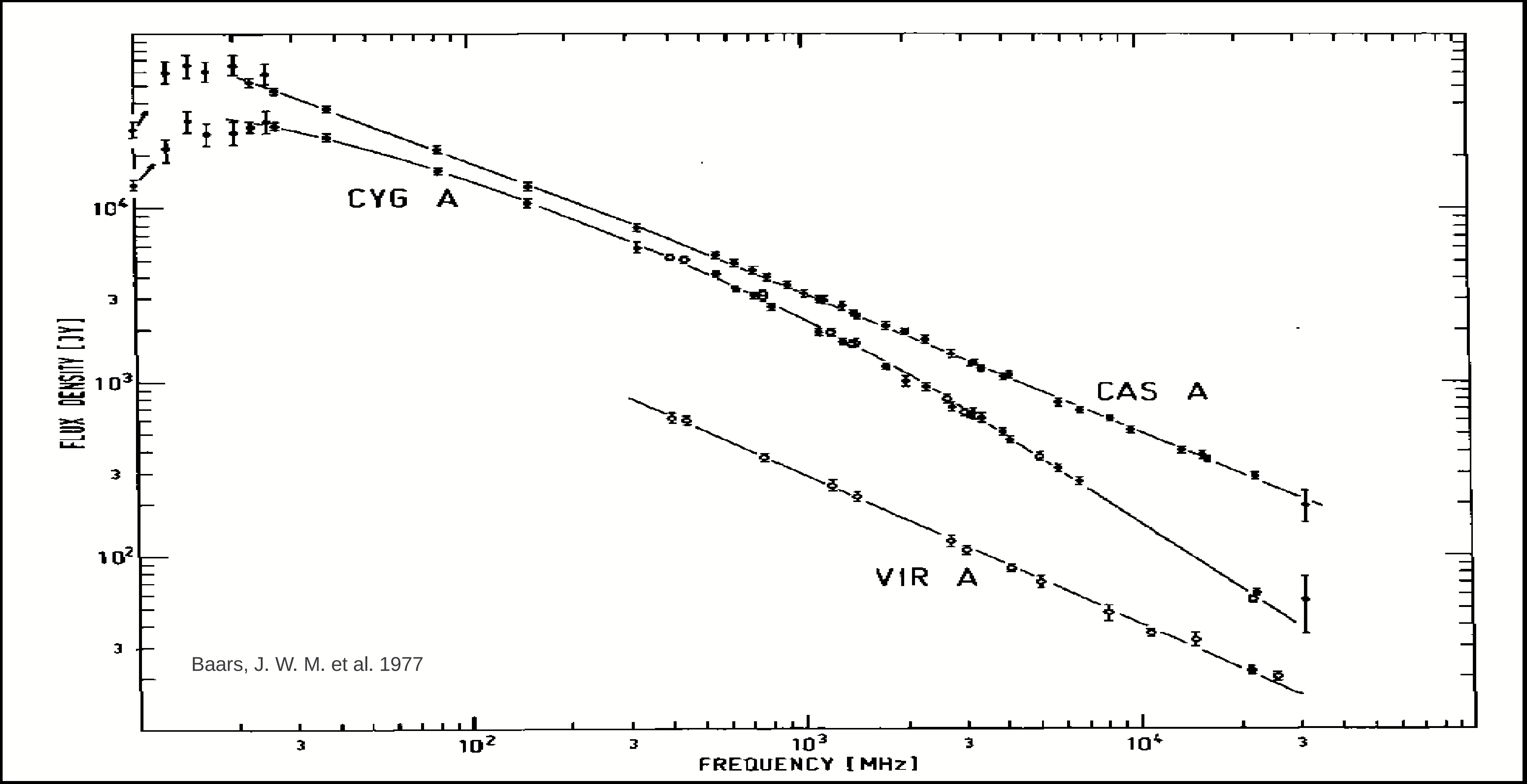
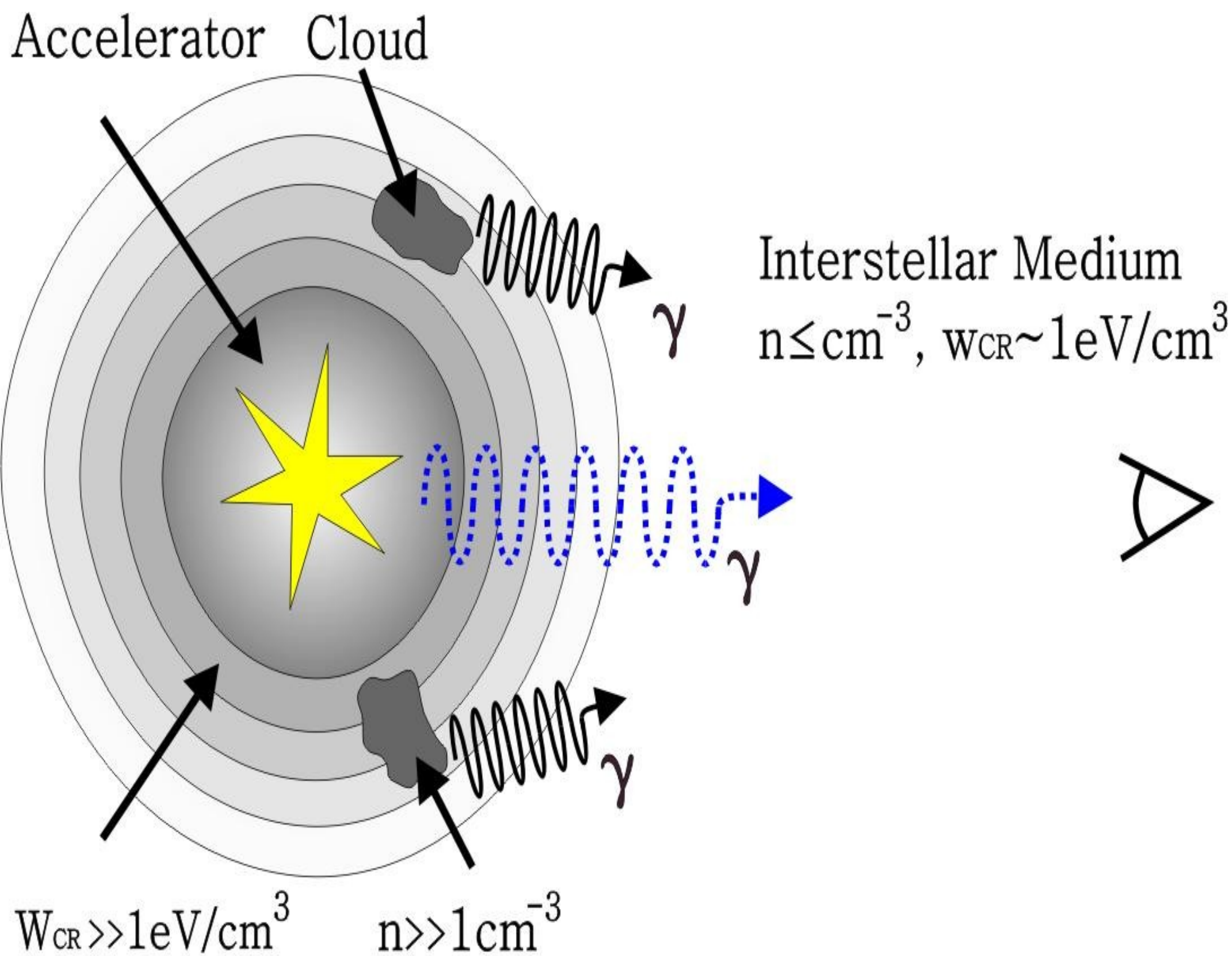


Featurless pl spectrum --> Non-thermal emission
-->Sync. emission from ultrarel. electrons

$F \sim E^{-p}$ p = 1-5 - 2.5   Emax ~ 1 -10 TeV

SNRs in gamma-rays



Neutral π decay :
protons + ISM nuclei → π^0
→ γ rays

But also

Inverse Compton :
electrons + ISRF photons
→ γ rays

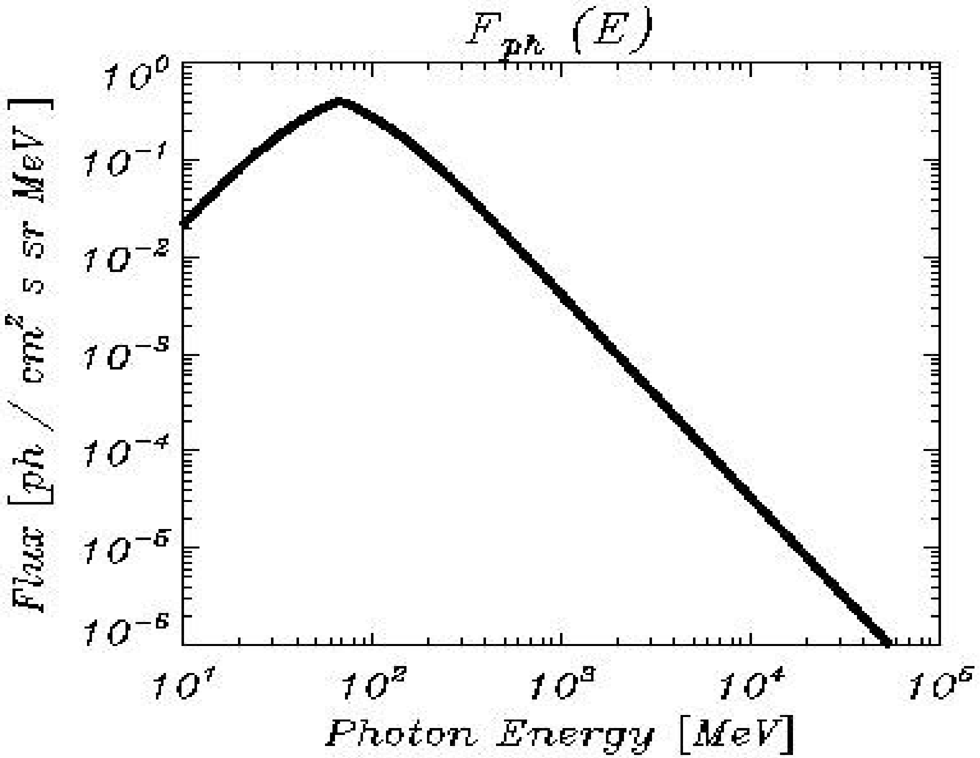
Electron Bremsstrahlung:
electrons + ISM nuclei
→ γ rays

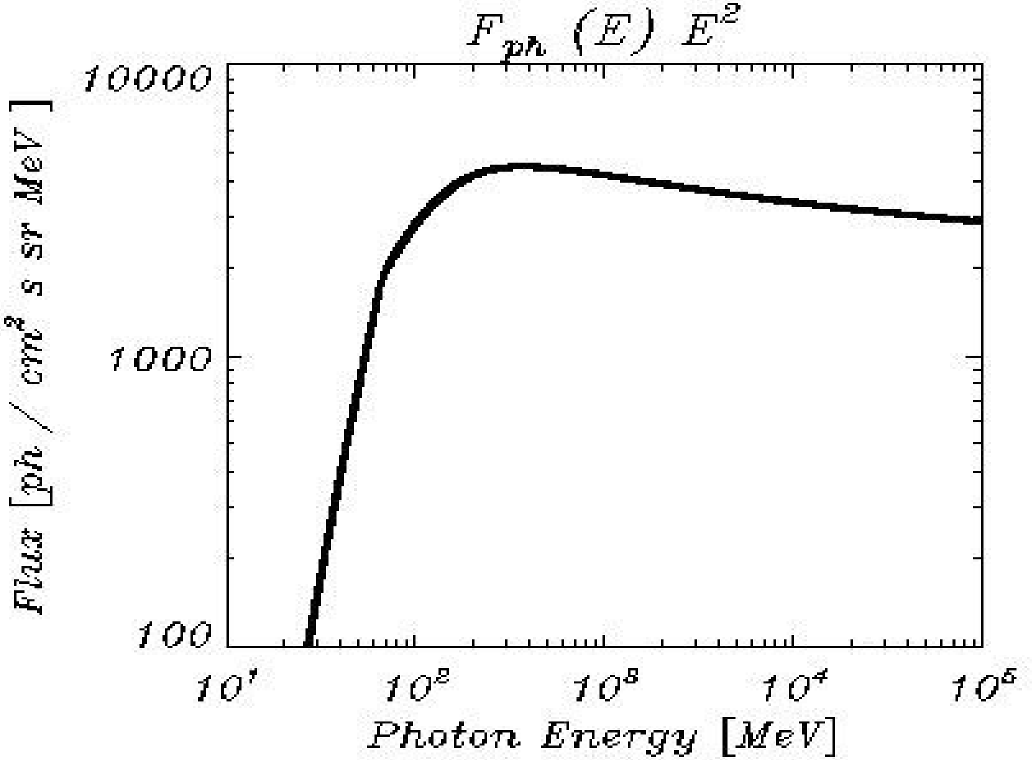
What about protons ?

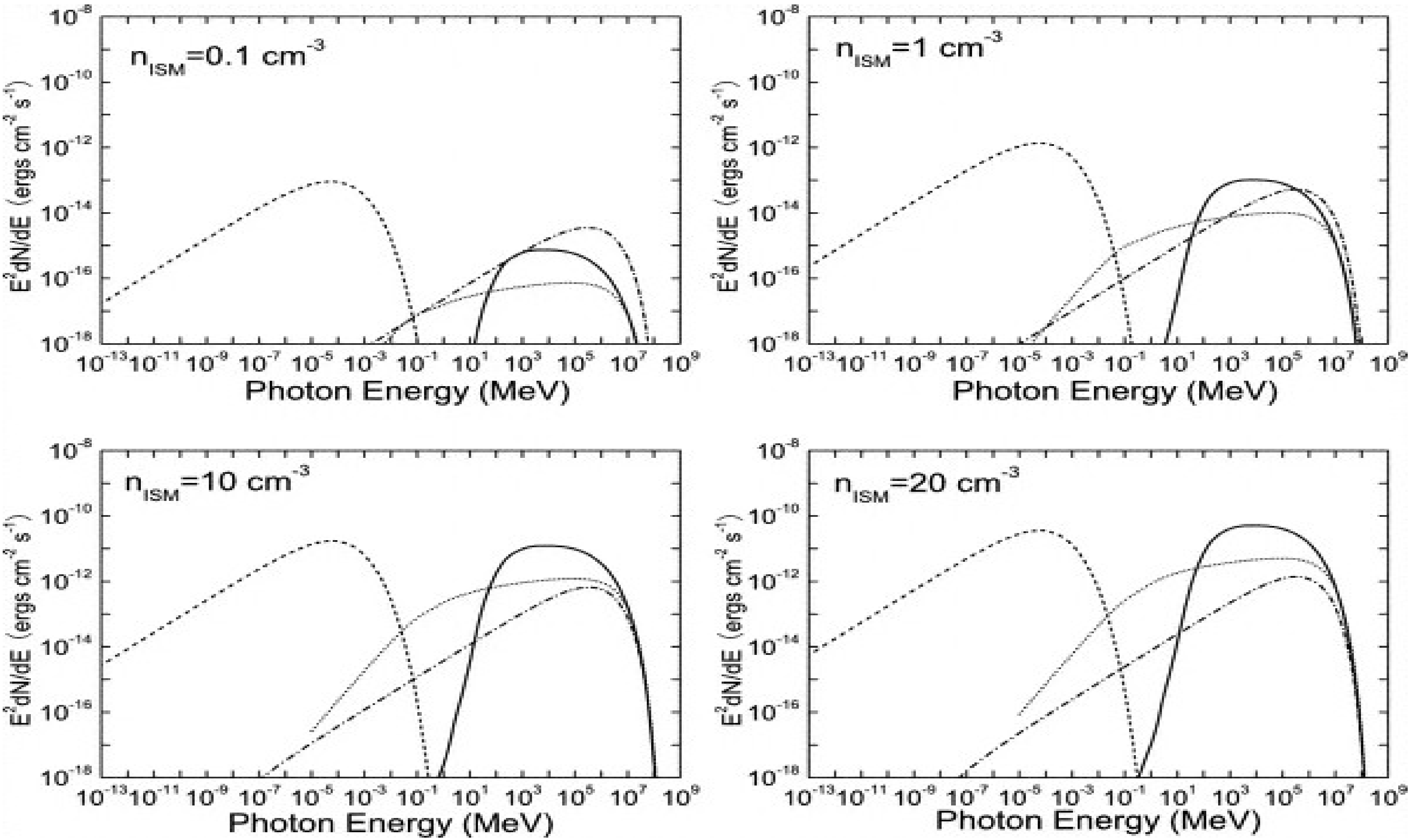
protons + ISM nuclei → π^0 → γ rays

Emission in the hard gamma ray band

$F_{gamma} \sim f_p * n$ (density of ISM nuclei)







Zhang et al 2007

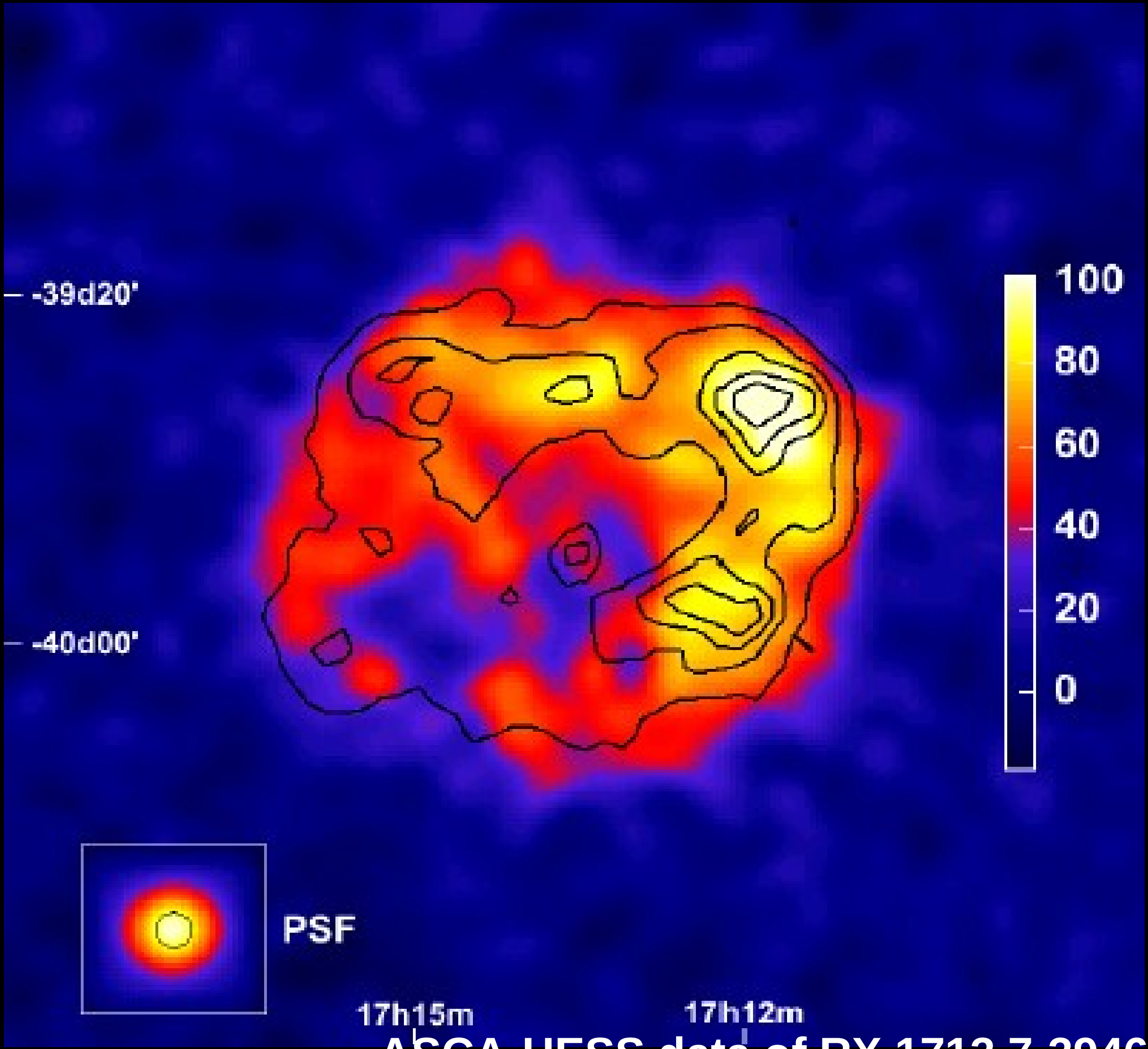
New generation of Cherenkov telescopes
(HESS, MAGIC, VERITAS)

Energy Range : 100 GeV – 10 TeV

RX J1713.7–3946

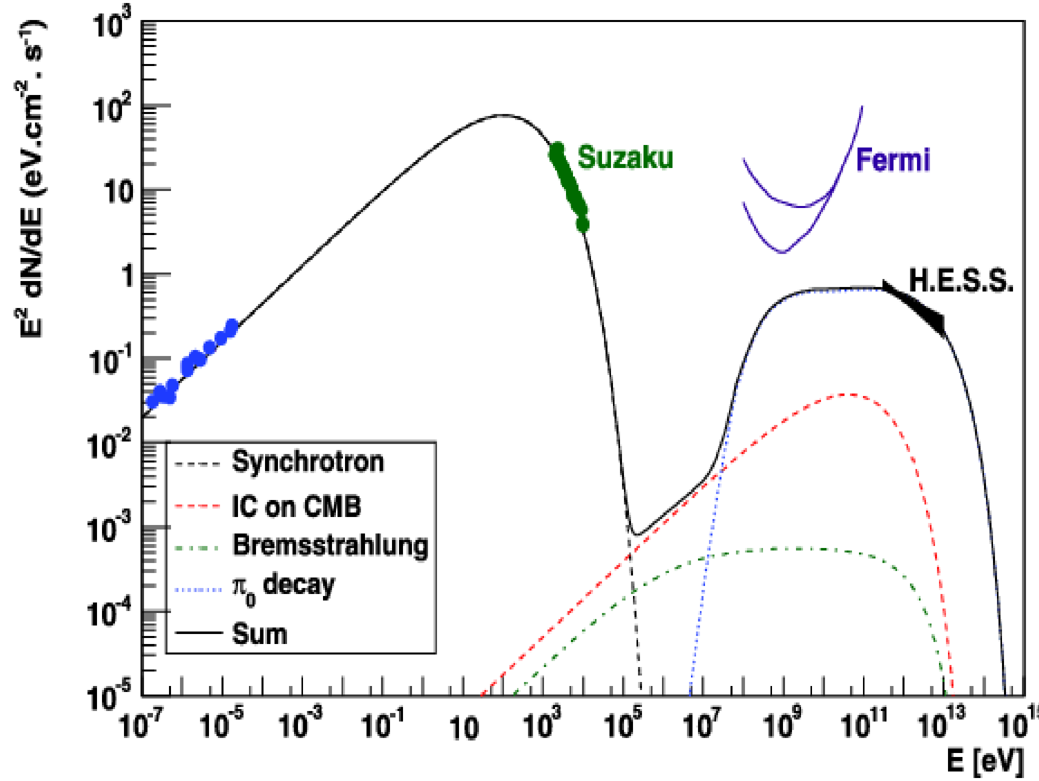
Distance : 1.2 kpc
Age : 2 kyrs
Size : 65'

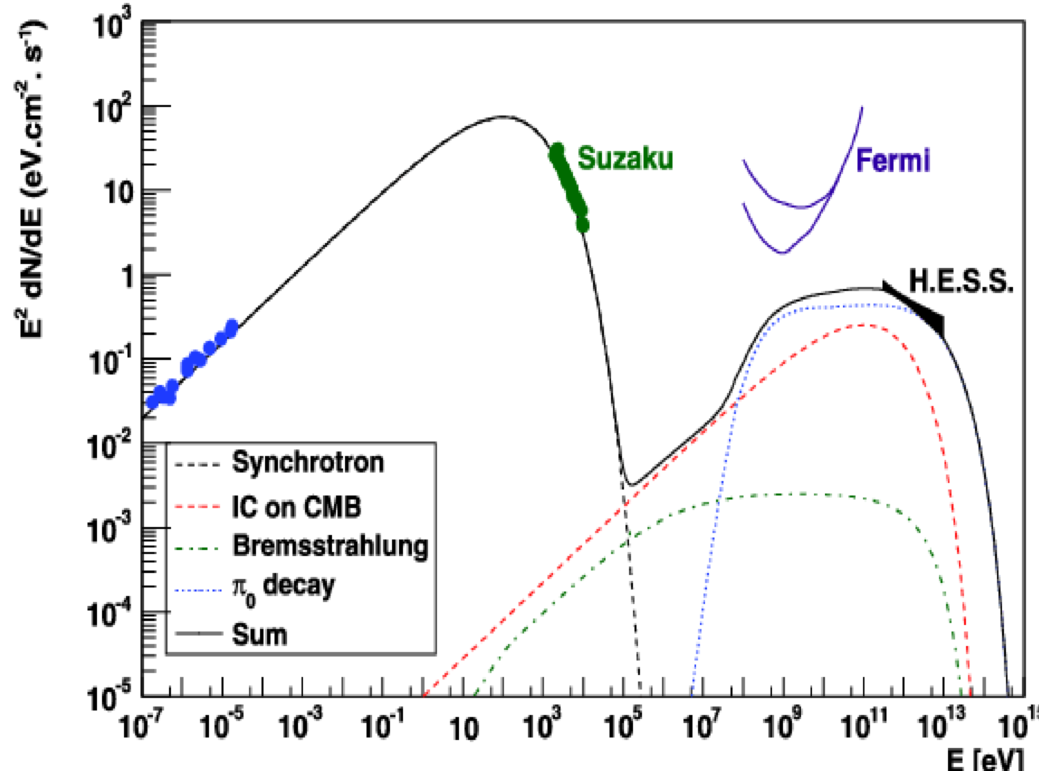
Good X-ray-TeV correlation

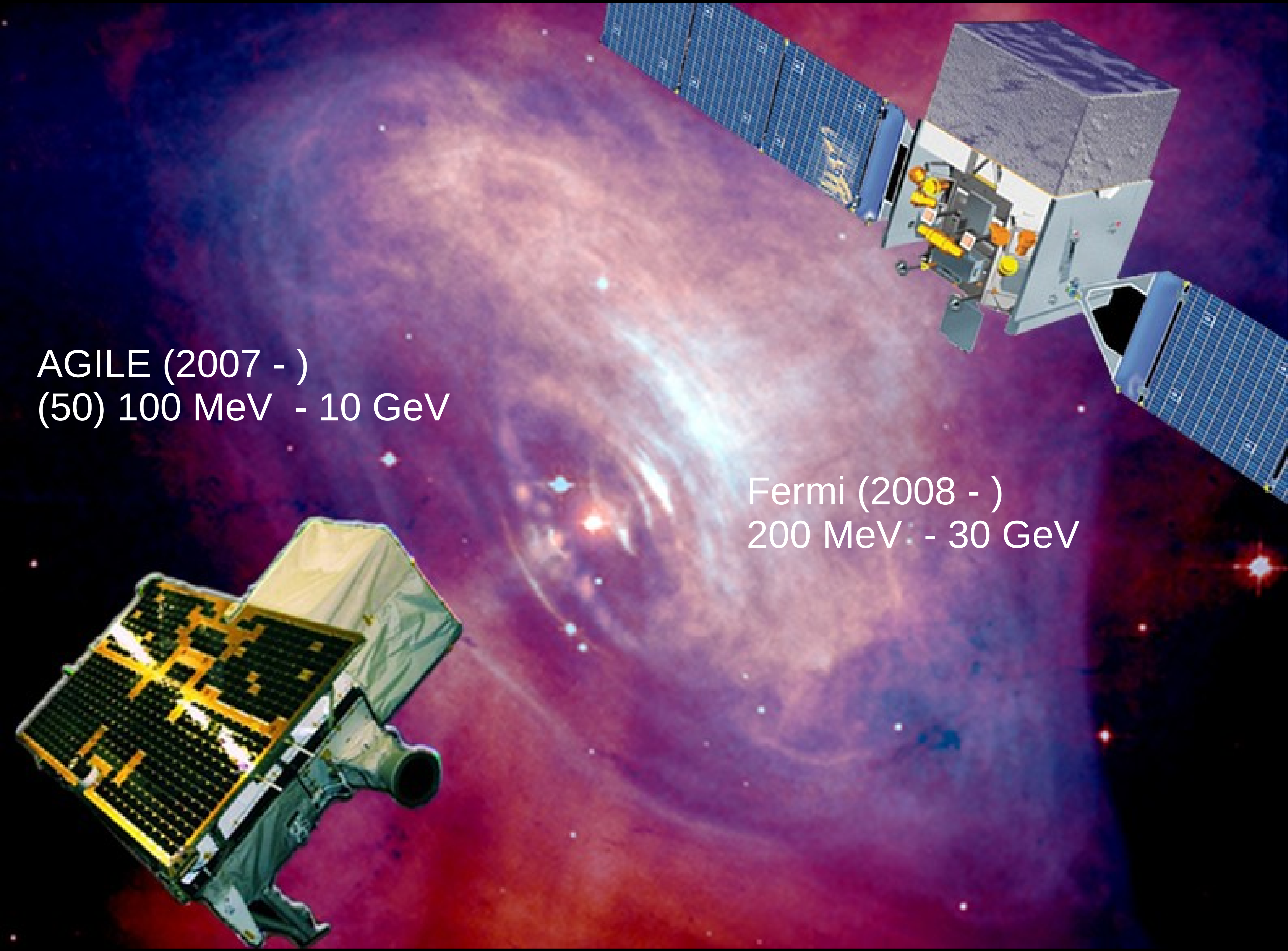


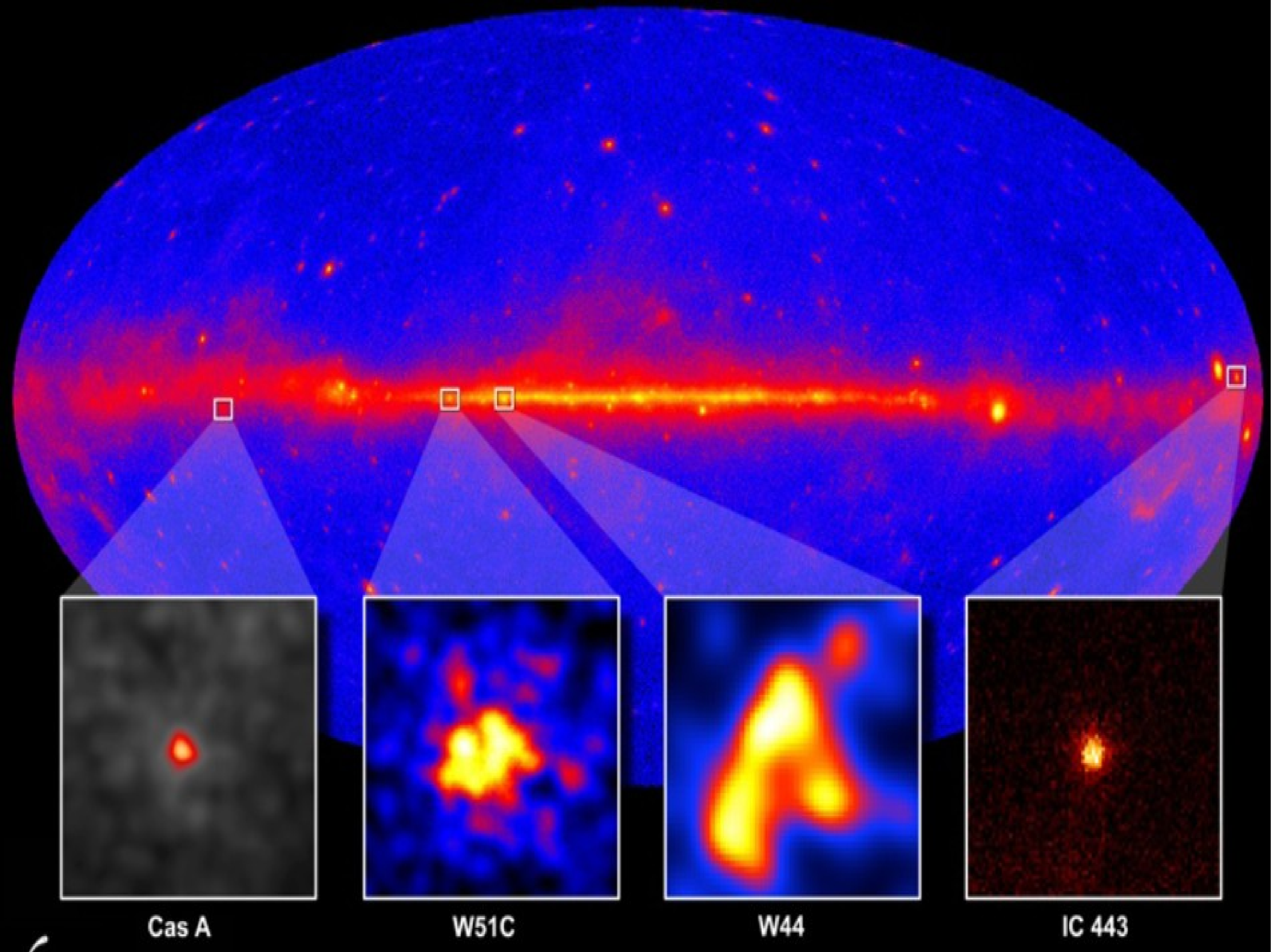
ASCA-HESS data of RX 1713.7-3946 (Goumard et al. 2006)

Non-thermal spectrum
well fitted by both leptonic
and hadronic models

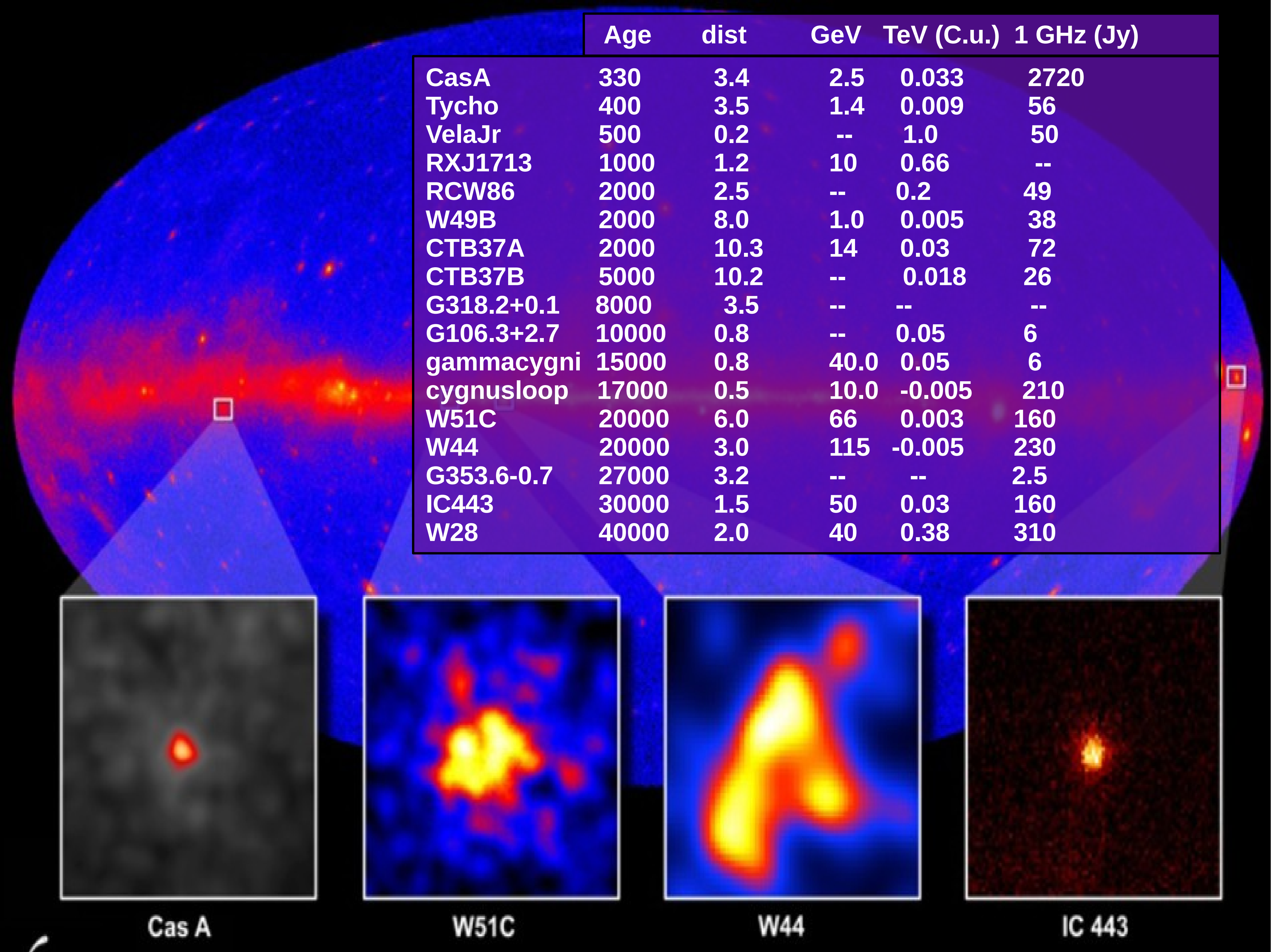





AGILE (2007 -)
(50) 100 MeV - 10 GeV
Fermi (2008 -)
200 MeV - 30 GeV



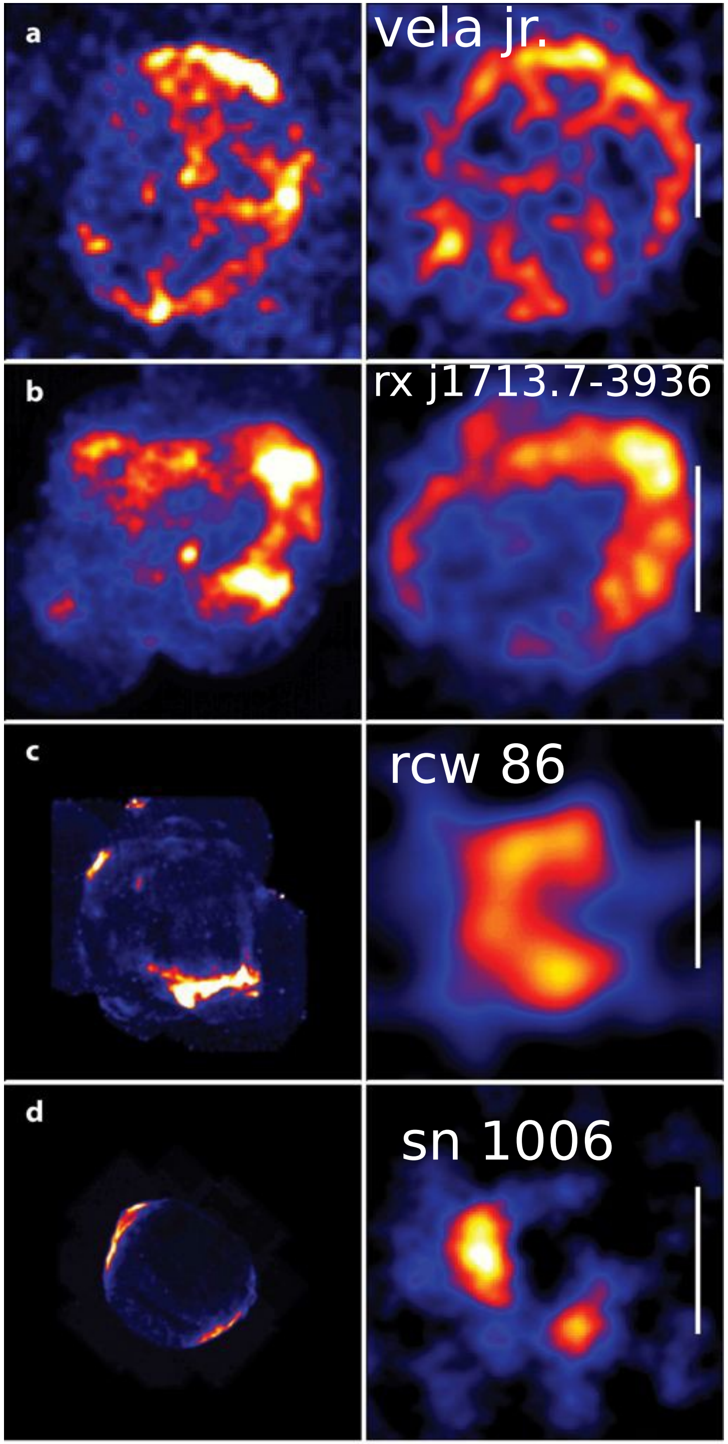
Cas A
W51C
W44
IC 443



	Age	dist	GeV	TeV (C.u.)	1 GHz (Jy)
CasA	330	3.4	2.5	0.033	2720
Tycho	400	3.5	1.4	0.009	56
VelaJr	500	0.2	--	1.0	50
RXJ1713	1000	1.2	10	0.66	--
RCW86	2000	2.5	--	0.2	49
W49B	2000	8.0	1.0	0.005	38
CTB37A	2000	10.3	14	0.03	72
CTB37B	5000	10.2	--	0.018	26
G318.2+0.1	8000	3.5	--	--	--
G106.3+2.7	10000	0.8	--	0.05	6
gammacygni	15000	0.8	40.0	0.05	6
cygnusloop	17000	0.5	10.0	-0.005	210
W51C	20000	6.0	66	0.003	160
W44	20000	3.0	115	-0.005	230
G353.6-0.7	27000	3.2	--	--	2.5
IC443	30000	1.5	50	0.03	160
W28	40000	2.0	40	0.38	310

2 classes of gamma-rays SNRs

1) the young SNRs (10^2 - 10^3 yrs) are shell-like object, expanding in a relatively low density medium, with gamma emission morphology typically very nicely correlated with the radio (and often X) shell

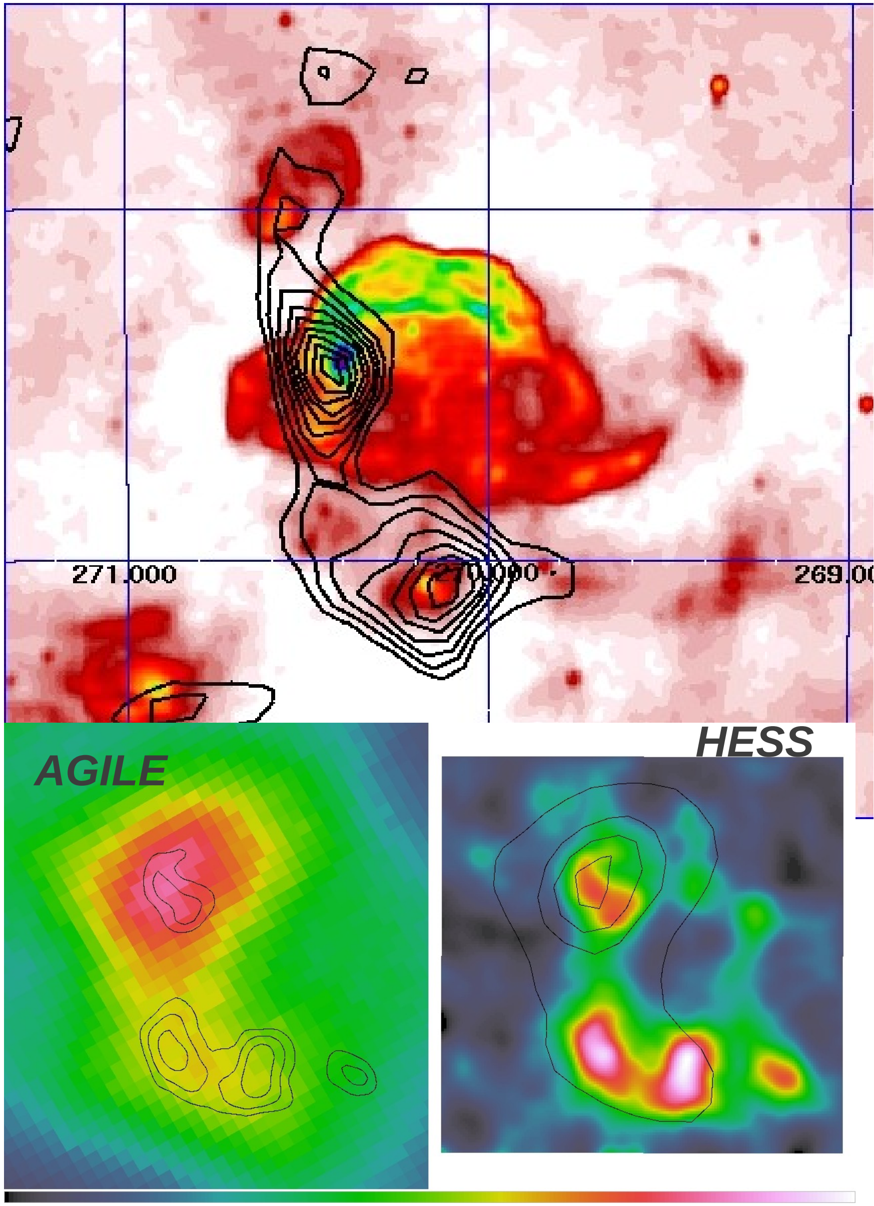


Hinton JA, Hofmann W. 2009.
Annu. Rev. Astron. Astrophys. 47:523–65

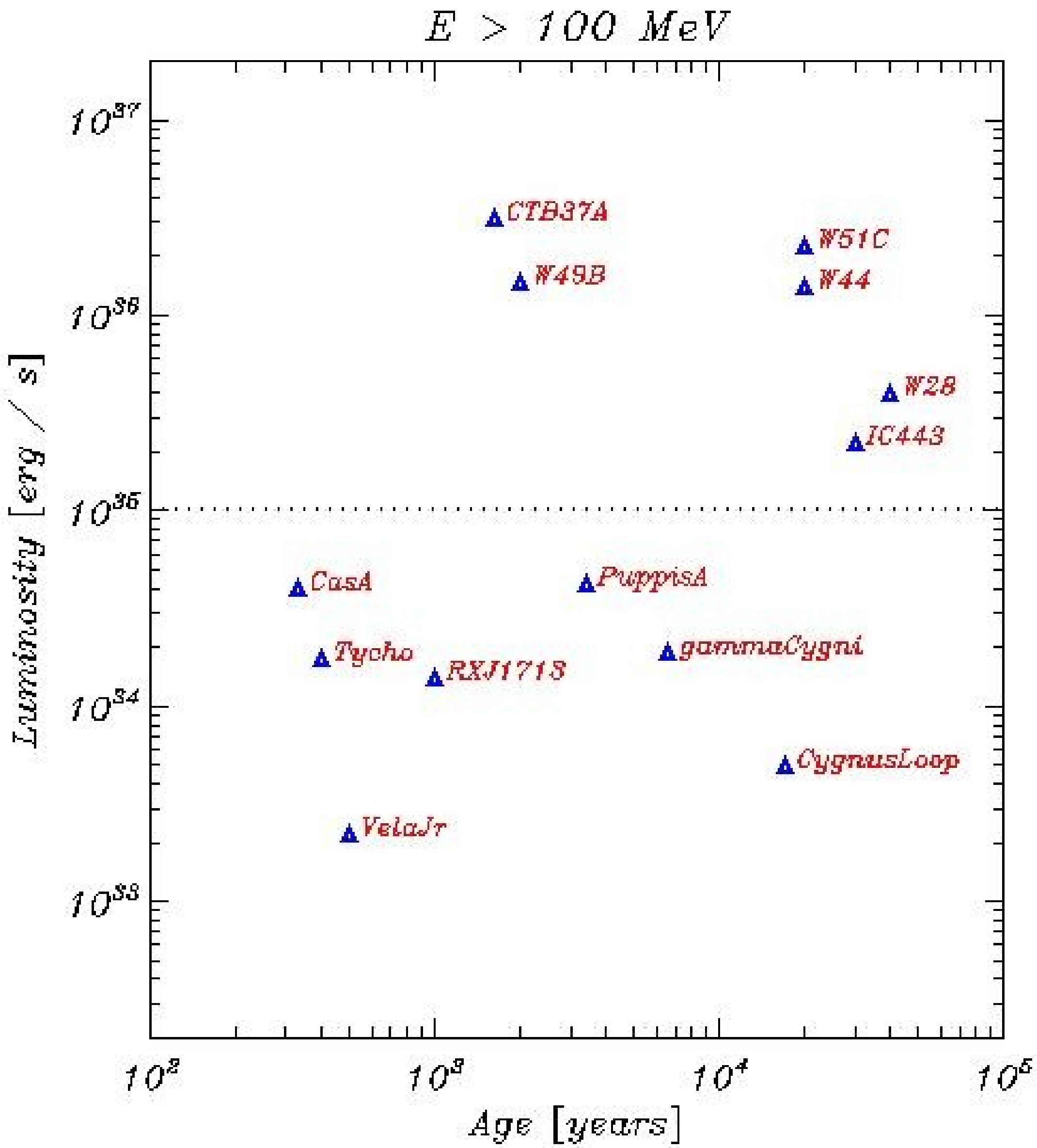
2 classes of gamma-rays SNRs

1) the young SNRs (10^2 - 10^3 yrs) are shell-like object, expanding in a relatively low density medium, with gamma emission morphology typically very nicely correlated with the radio (and often X) shell

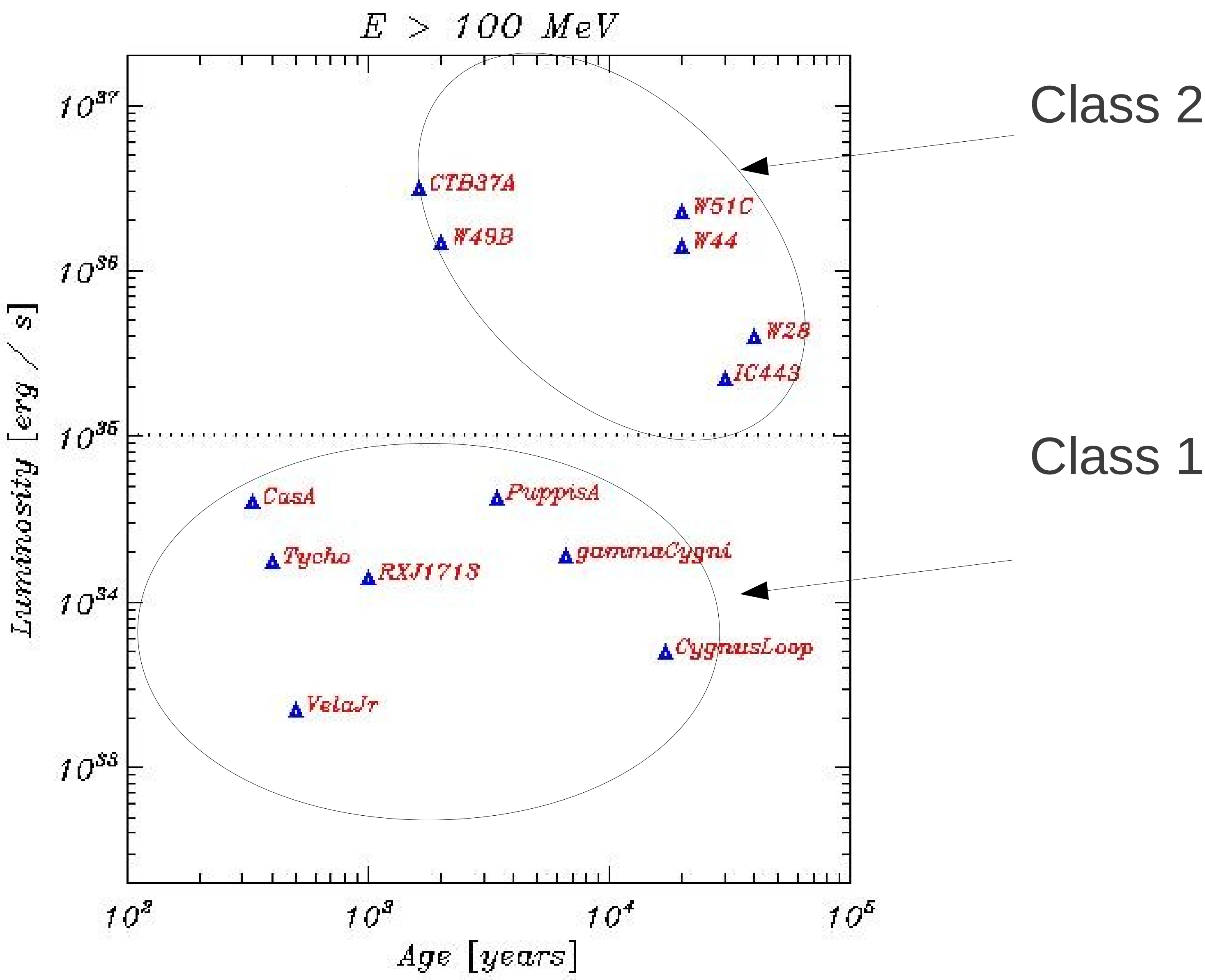
2) the middle-aged SNRs (10^3 - 10^4 yrs) are mixed-morphology objects, interacting with giant molecular clouds and with a gamma morphology that correlates with M.C. better than with the radio shell.



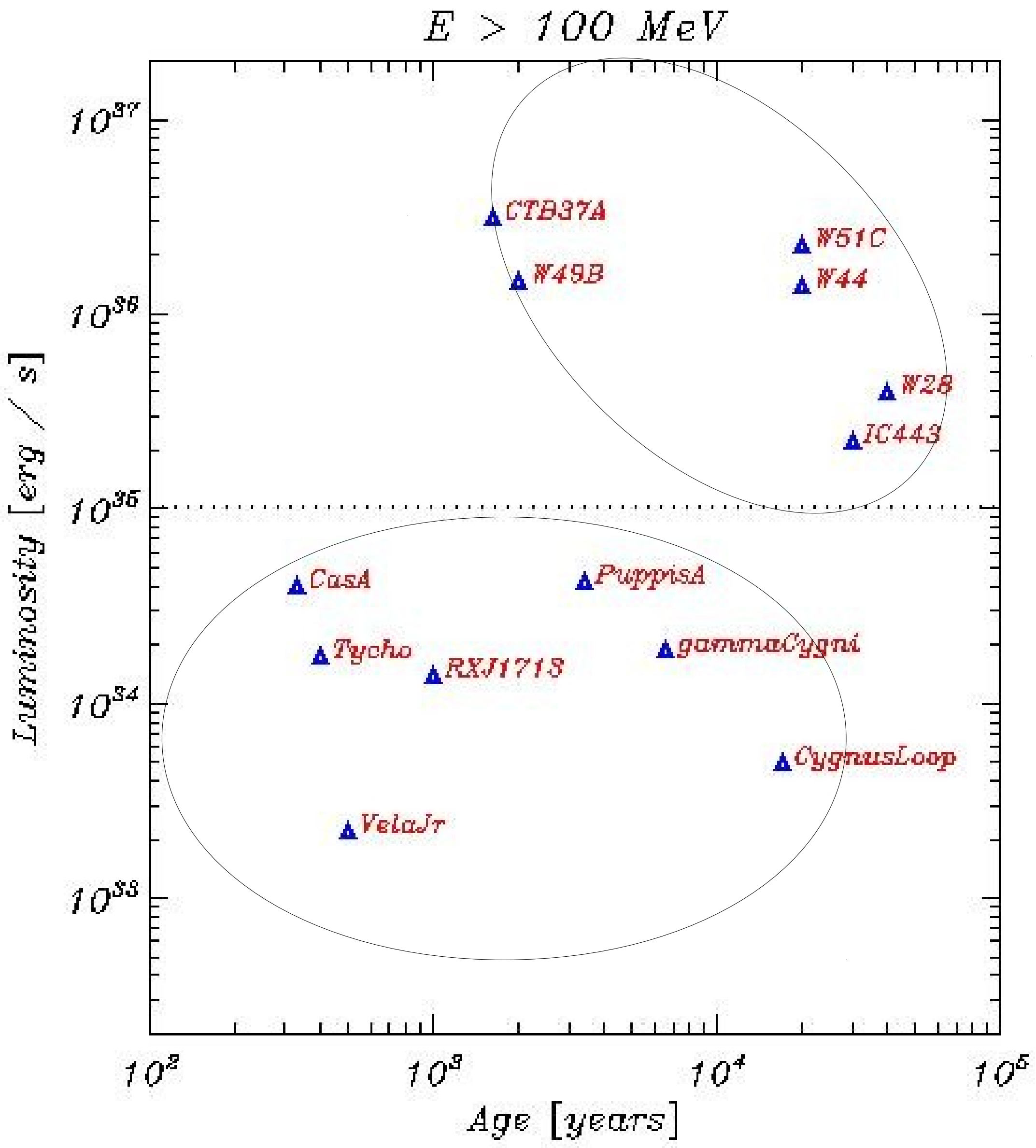
2 classes of gamma-rays SNRs



2 classes of gamma-rays SNRs

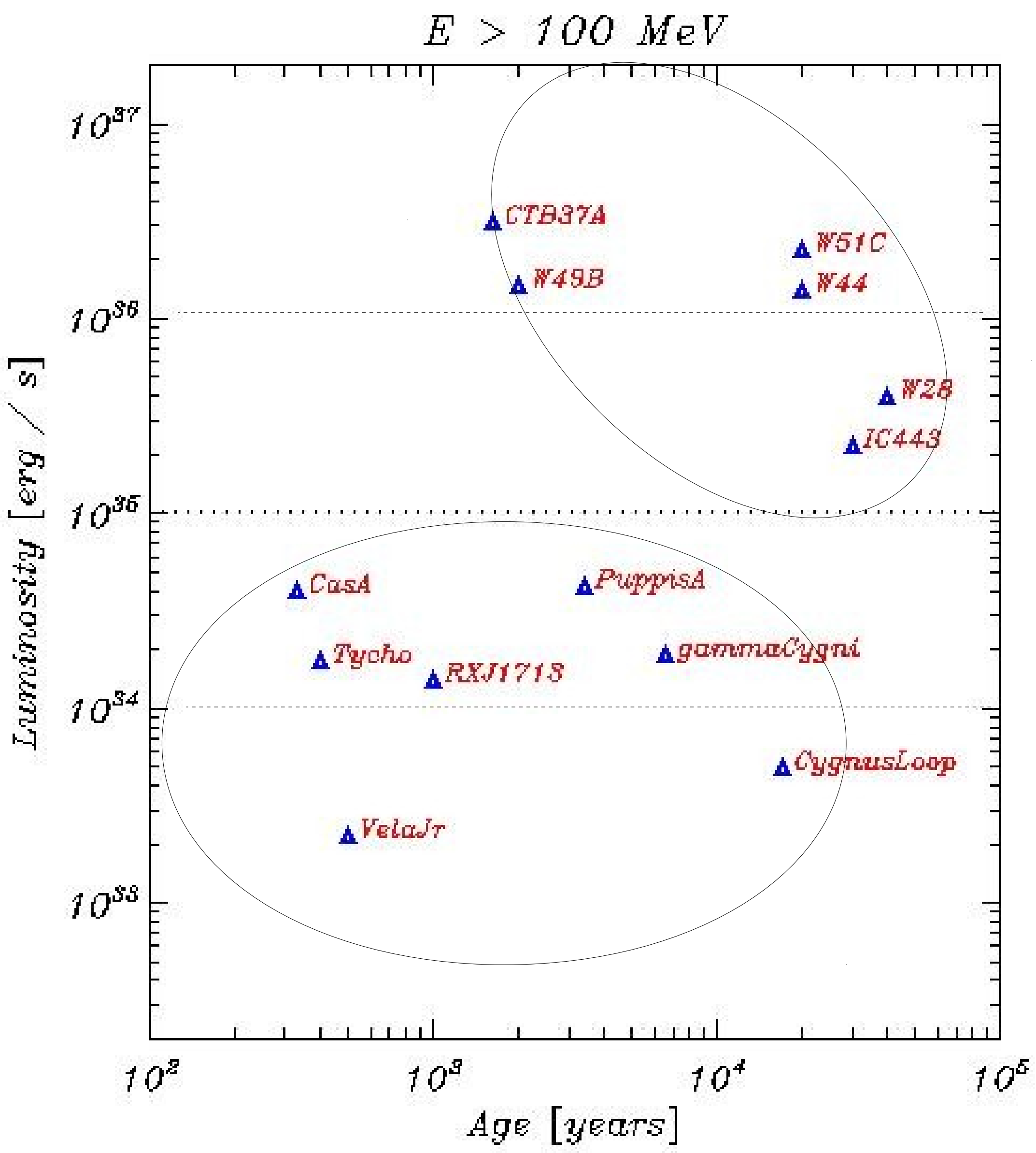


2 classes of gamma-rays SNRs



$L_{gamma}(E) = \sigma(E)\ c\ N_p(E)\ n$

2 classes of gamma-rays SNRs

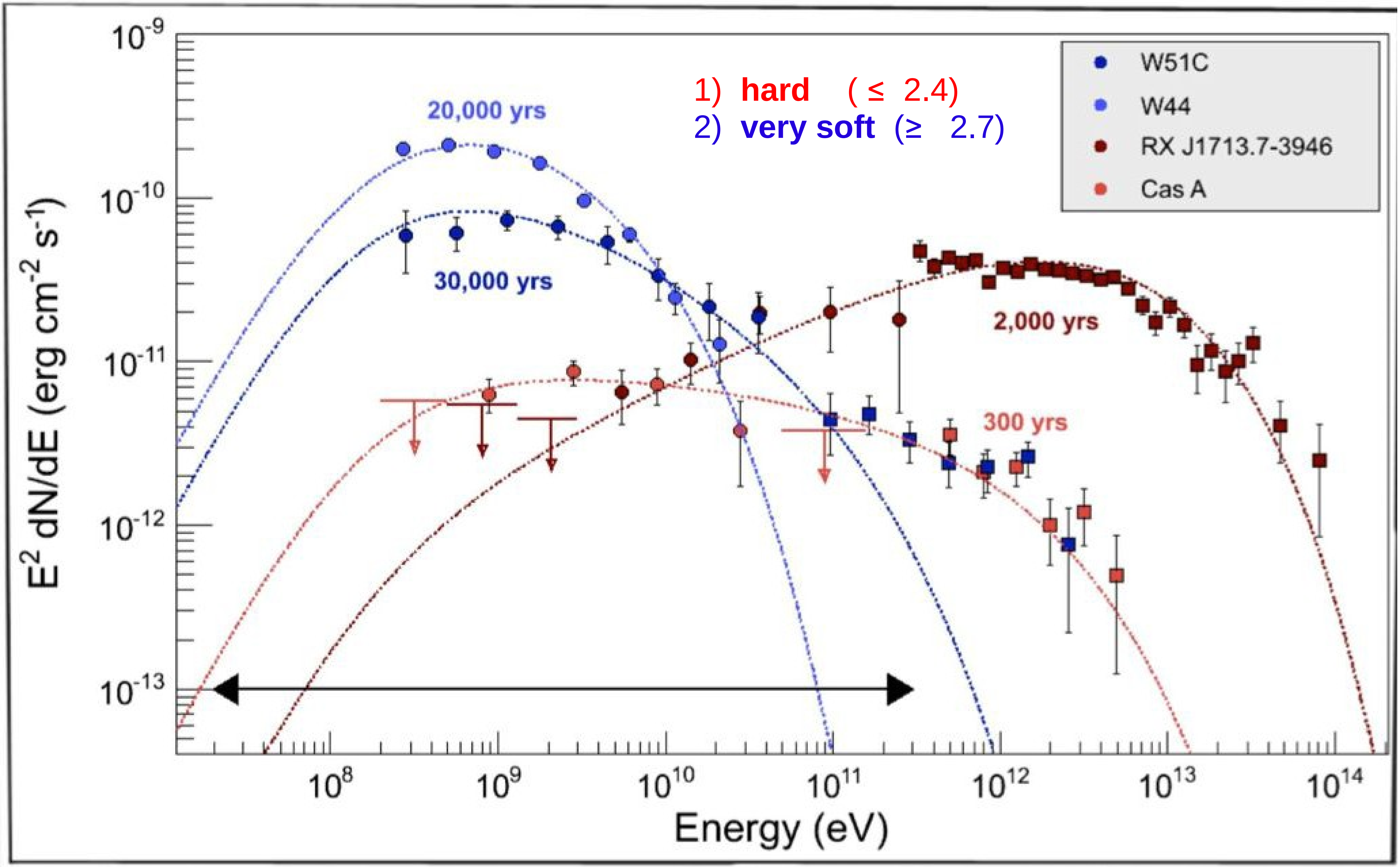


$L_{gamma}(E) = \sigma(E)\ c\ N_p(E)\ n$

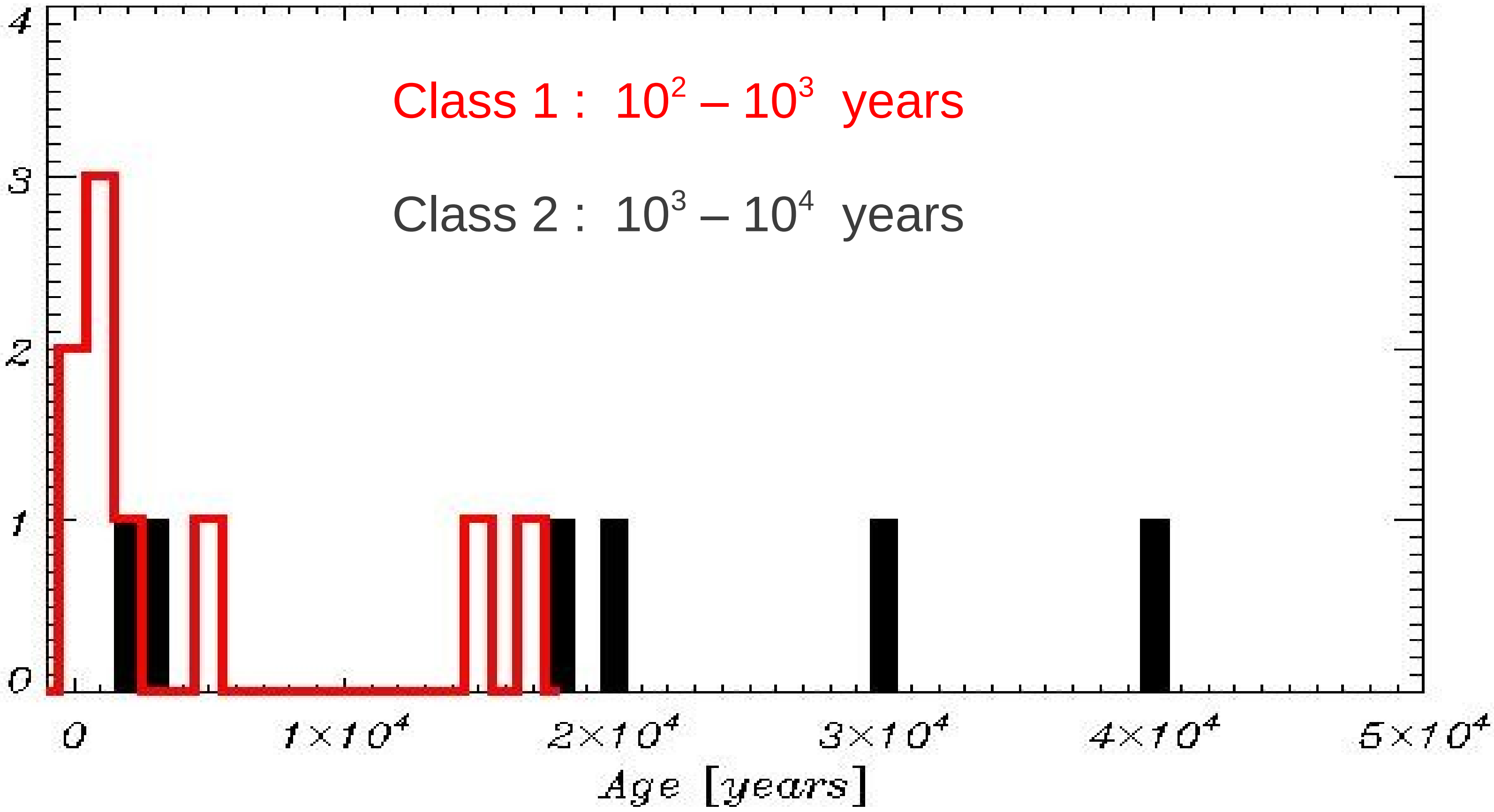
100 cm^{-3}

1 cm^{-3}

Different spectrum



Different Ages



Different frequency

Class 1 : Very common
(All the historical SNRs emit gamma-rays!)

Class 2 : Quite rare
(~ 1 %, only those SNRs close to a GMC)

Diffusion of CR in the ISM

$$\frac{dn(E,r)}{dt} = D(E)\nabla^2 n(E,r) - \frac{\partial}{\partial E} n(E,r) b(E) + Q(E,r)$$

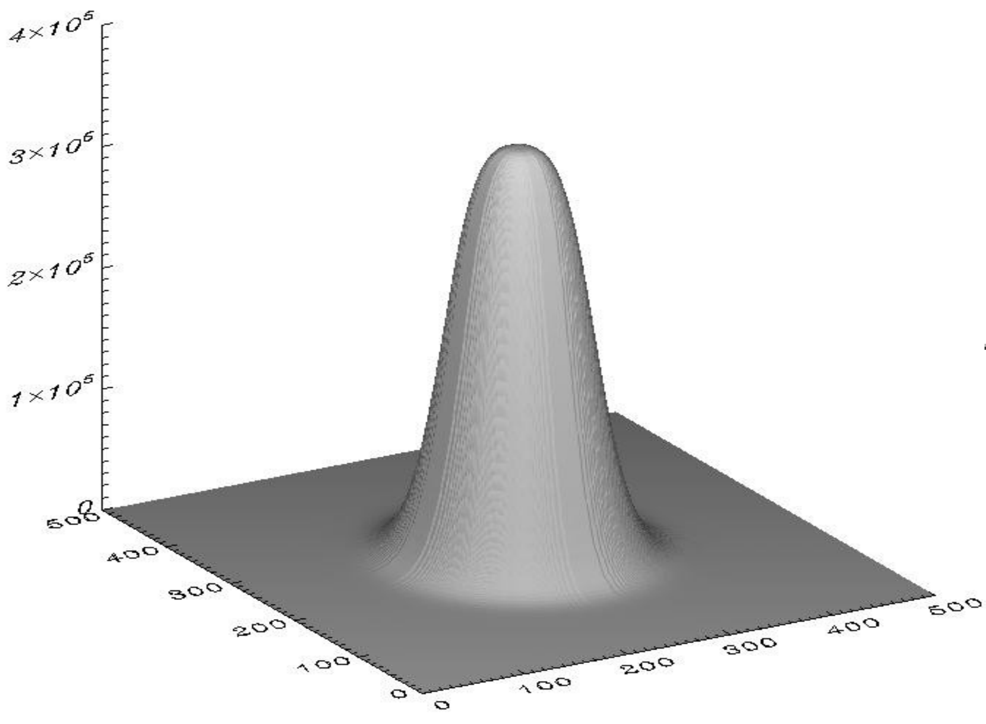
Diff. in physical space

Energy losses

Source

Diffusion of CR in the ISM

$$\frac{dn(E,r)}{dt} = D(E)\nabla^2 n(E,r) - \frac{\partial}{\partial E} n(E,r) b(E) + Q(E,r)$$



For an impulsive source
and ignoring E losses

$$R_{diff}(E,t) = 2\sqrt{D(E)t}$$

see **Aharonian & Atoyan**, A&A, 309, 1996

Diffusion of CR in the ISM

$$R_{diff}(E,t) = 2\sqrt{D(E)t}$$

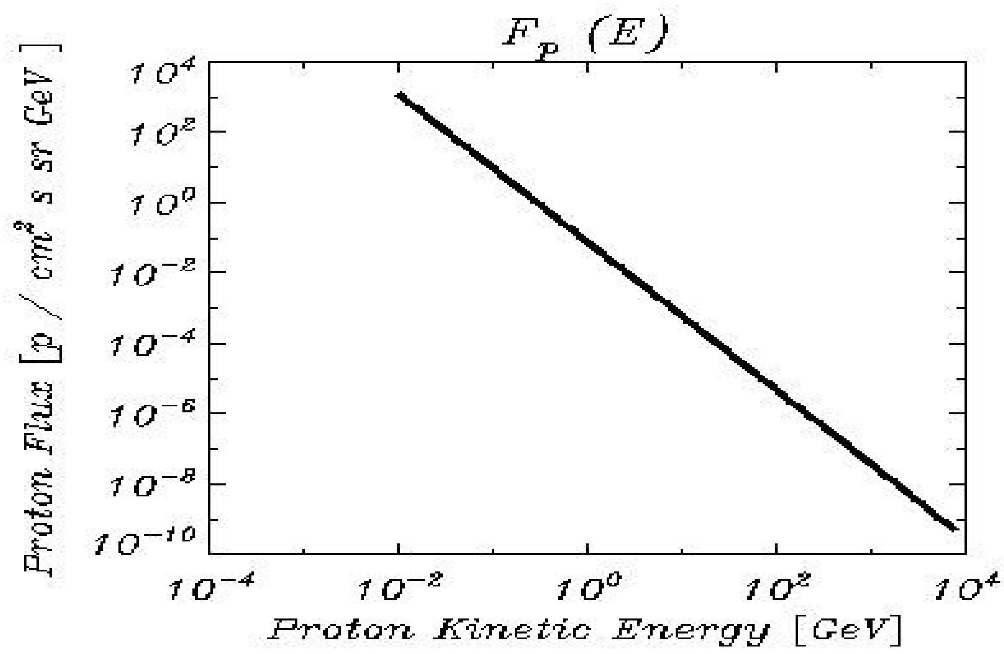
$$D(E) = D_0 E^{\delta} \simeq 10^{26} \left(\frac{E}{10\ GeV}\right)^{0.5}\ cm^2\ s$$

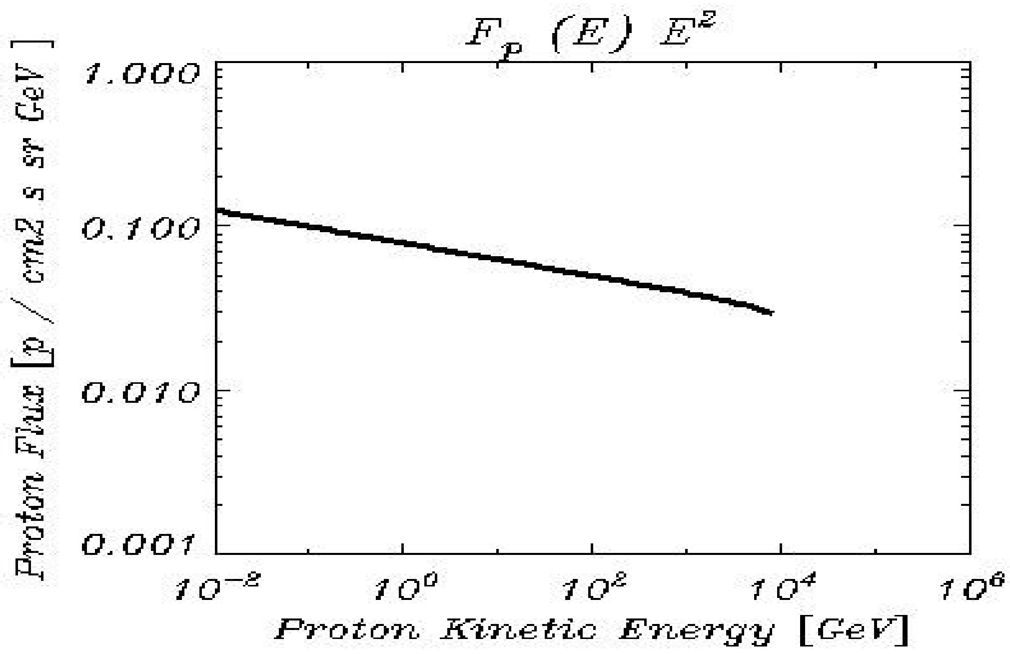
--> Slow !

--> Faster diffusion for high energy CR

see **Aharonian & Atoyan**, A&A, 309, 1996

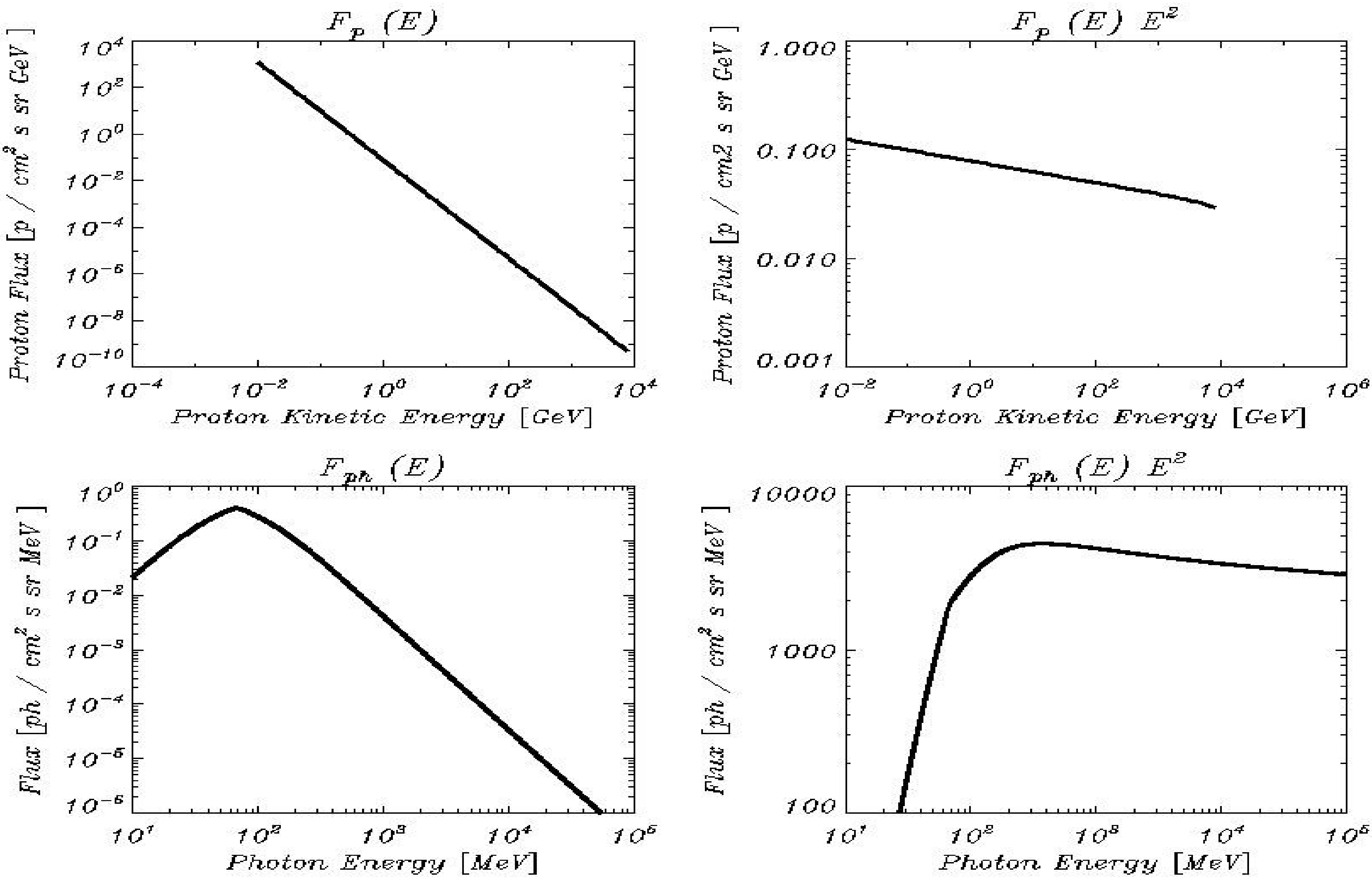
: protons + ISM nuclei → π^0 → γ rays

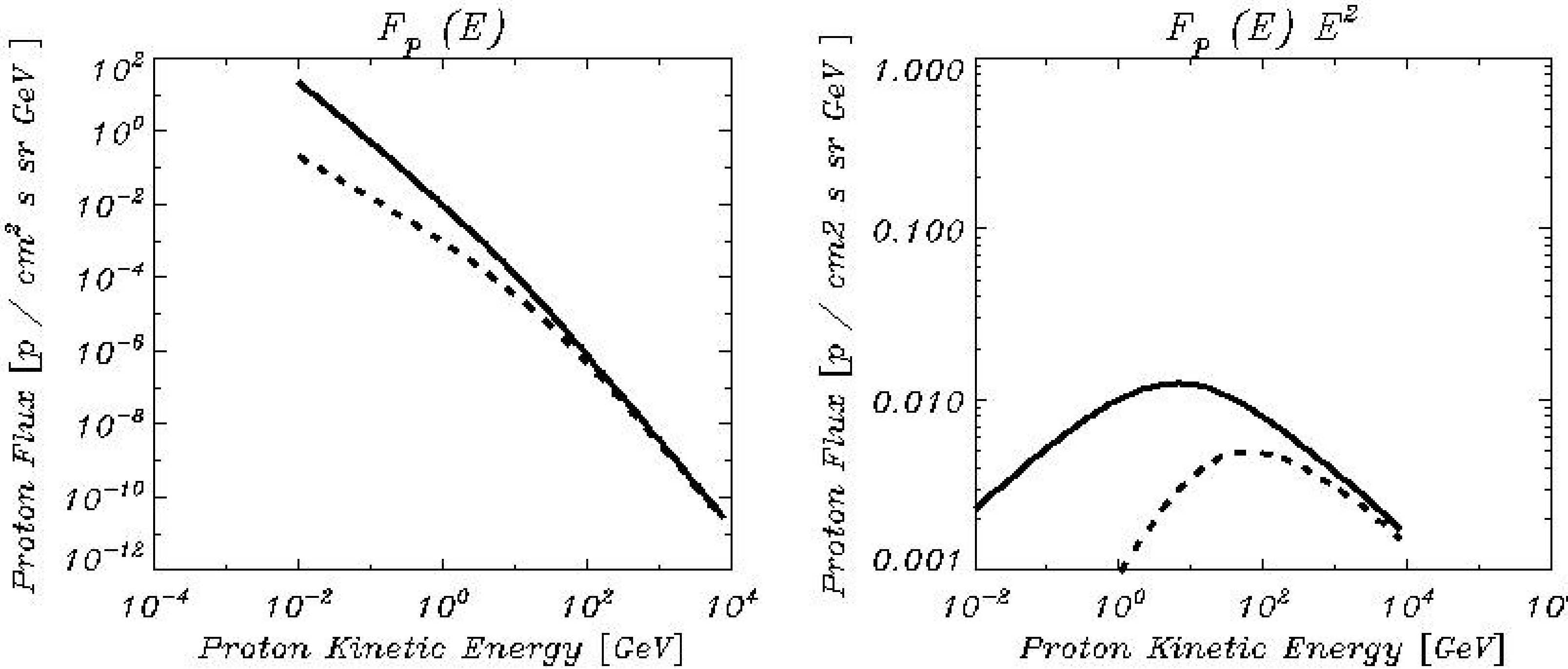




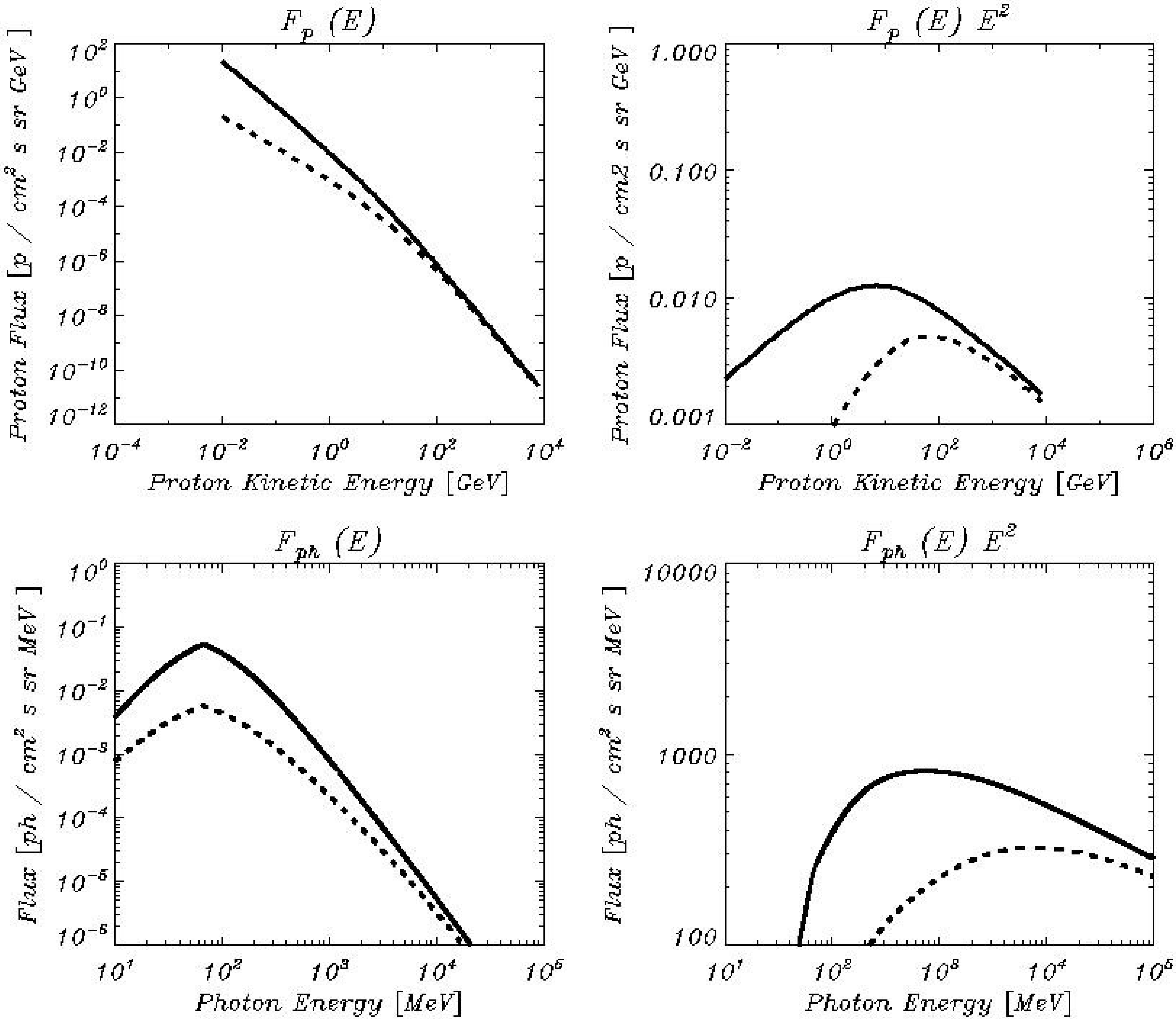
$$F(E) = K\,E^{-p}$$ [particles / cm^2 s sr GeV]

: protons + ISM nuclei → π^0 → γ rays





For a given R and D : $$E_{cut} = \left(\frac{R^2}{4tD_0} \right)^{\frac{1}{\delta}}$$



$F_p\ (E)$
Proton Flux [p / cm^2 s sr GeV]
10^{2}
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
Proton Kinetic Energy [GeV]
$F_p\ (E)\ E^2$
Proton Flux [p / cm2 s sr GeV]
1.000
0.100
0.010
0.001
10^{-2}
10^{0}
10^{2}
10^{4}
10^{6}
Proton Kinetic Energy [GeV]
$F_{ph}\ (E)$
Flux [ph / cm^2 s sr MeV]
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
Photon Energy [MeV]
$F_{ph}\ (E)\ E^2$
Flux [ph / cm^2 s sr MeV]
10000
1000
100
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
Photon Energy [MeV]