Summary of the lesson

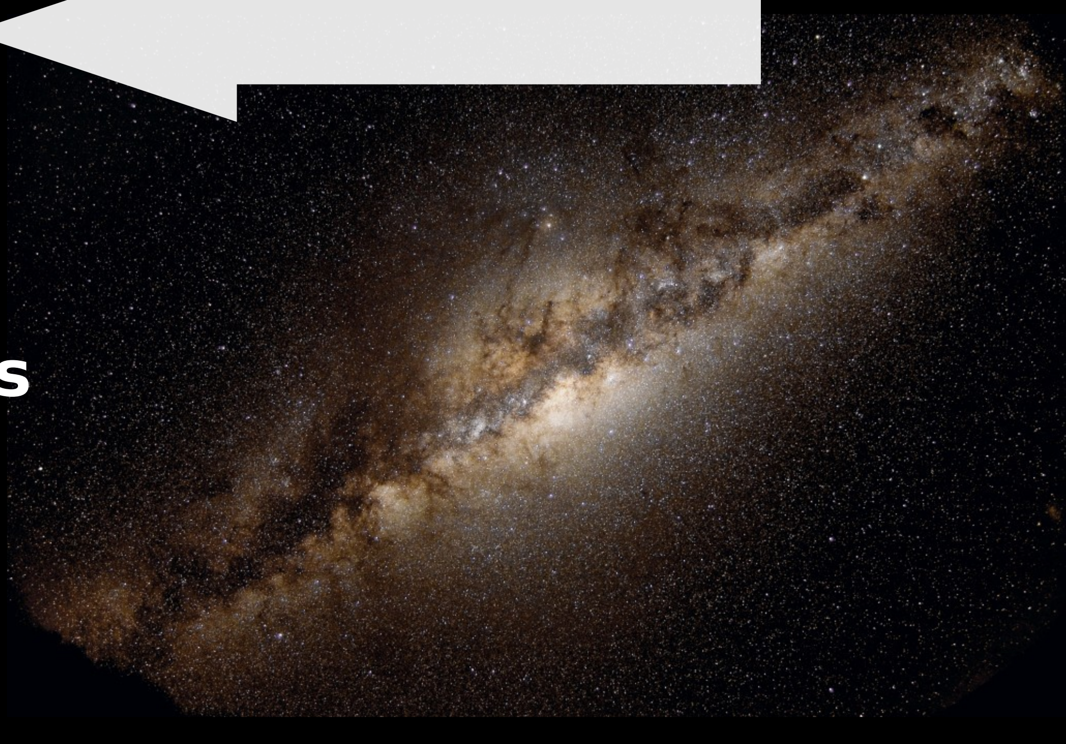
Cosmic Rays

CRs in Galaxies

- **The MilkyWay in ɣ Rays**
  - Diffuse emission
  - Molecular Clouds
- **ɣ Rays from other galaxies**

Supernova Remnants

- Evolution
- MC associations
- Gamma-ray from SNR



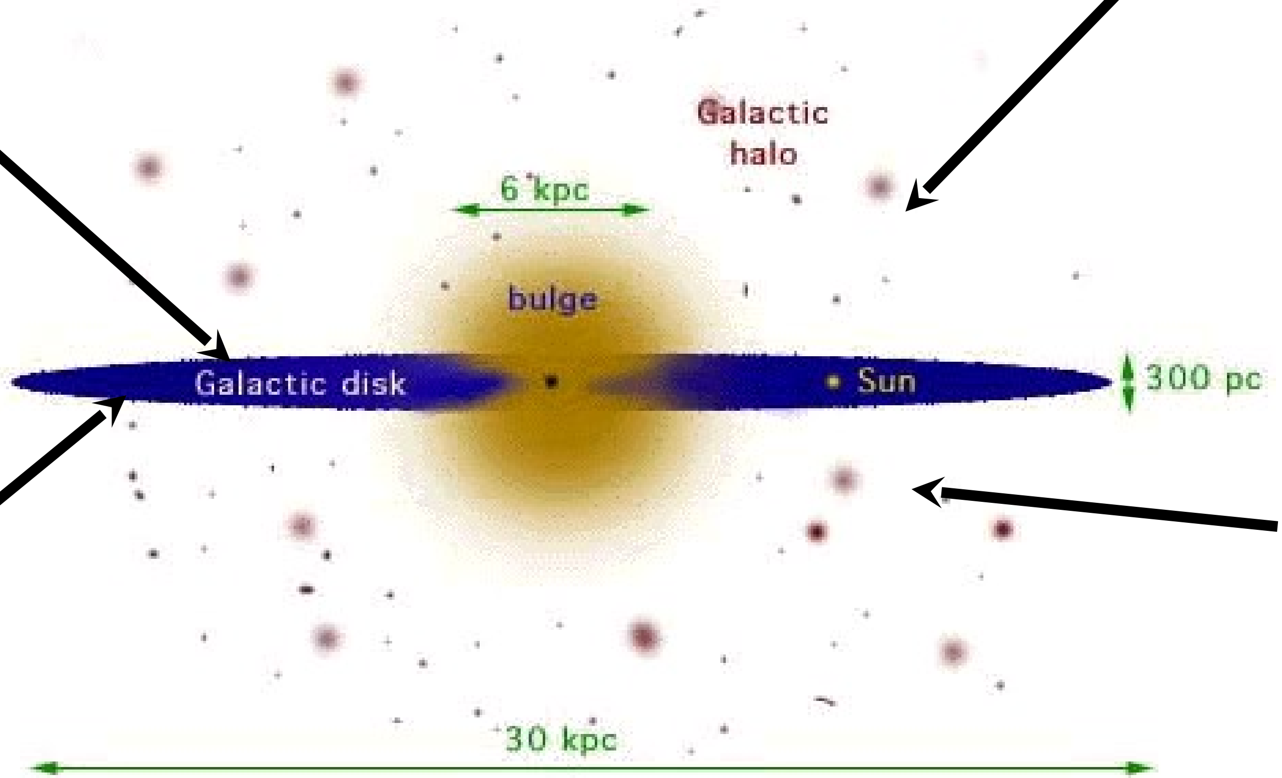
Others possible CRs sources

the Milky Way

gas density

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

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

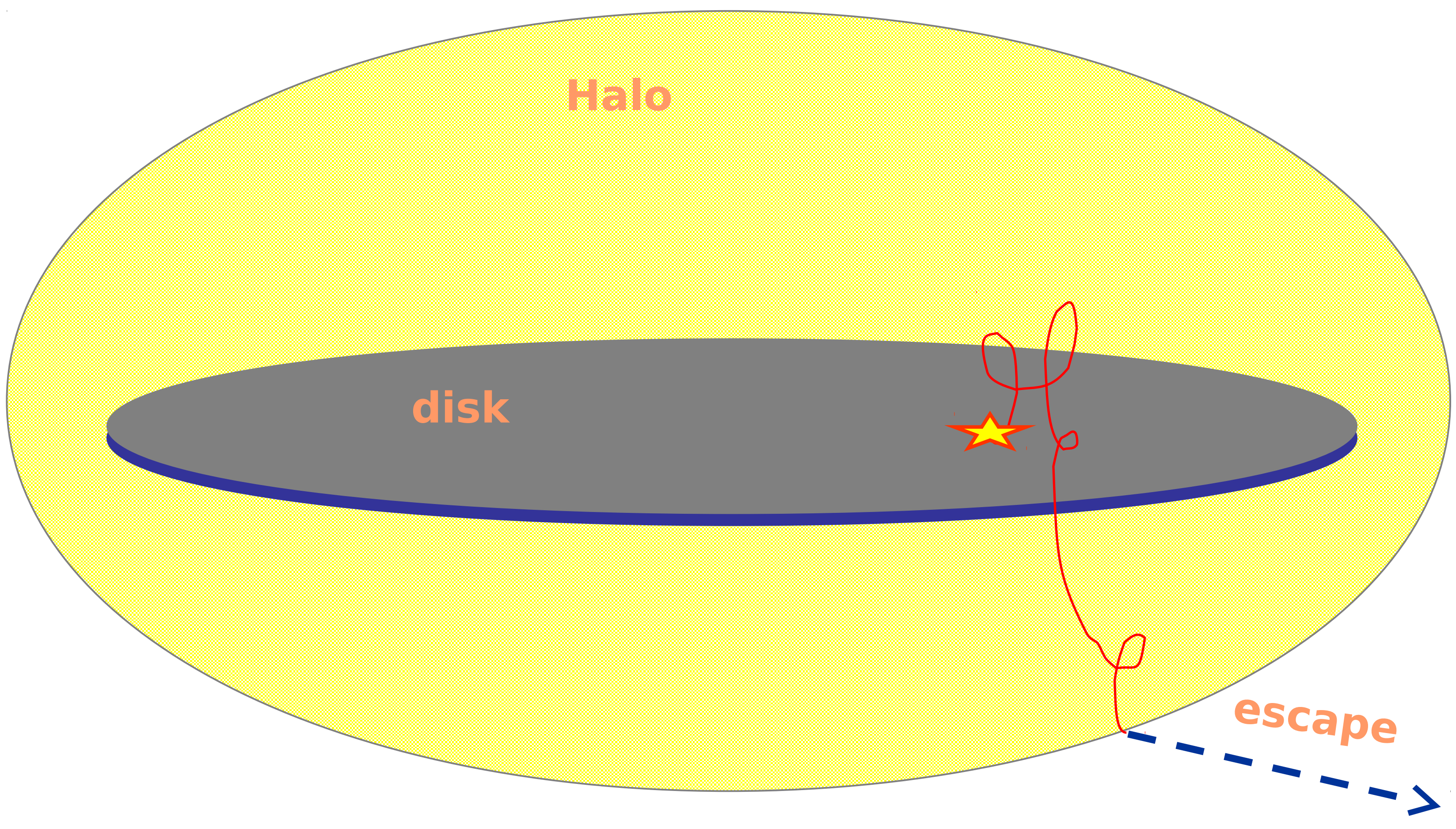


$B < 10\ \mu\mathrm{G}$

magnetic field

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

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

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

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}.

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

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}.

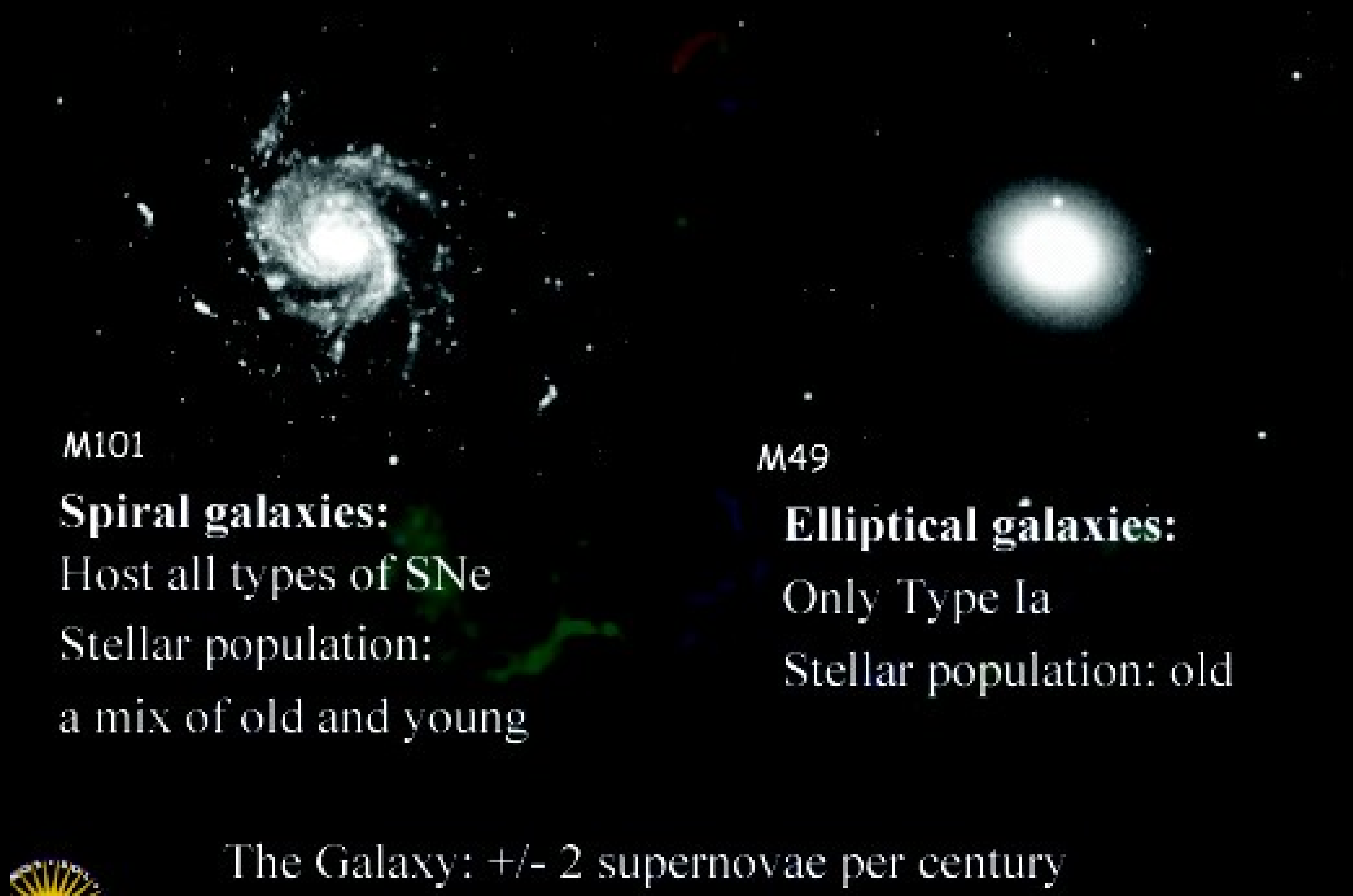
$$P_{SN} = 3 \times 10^{41} \text{ erg/s}$$

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

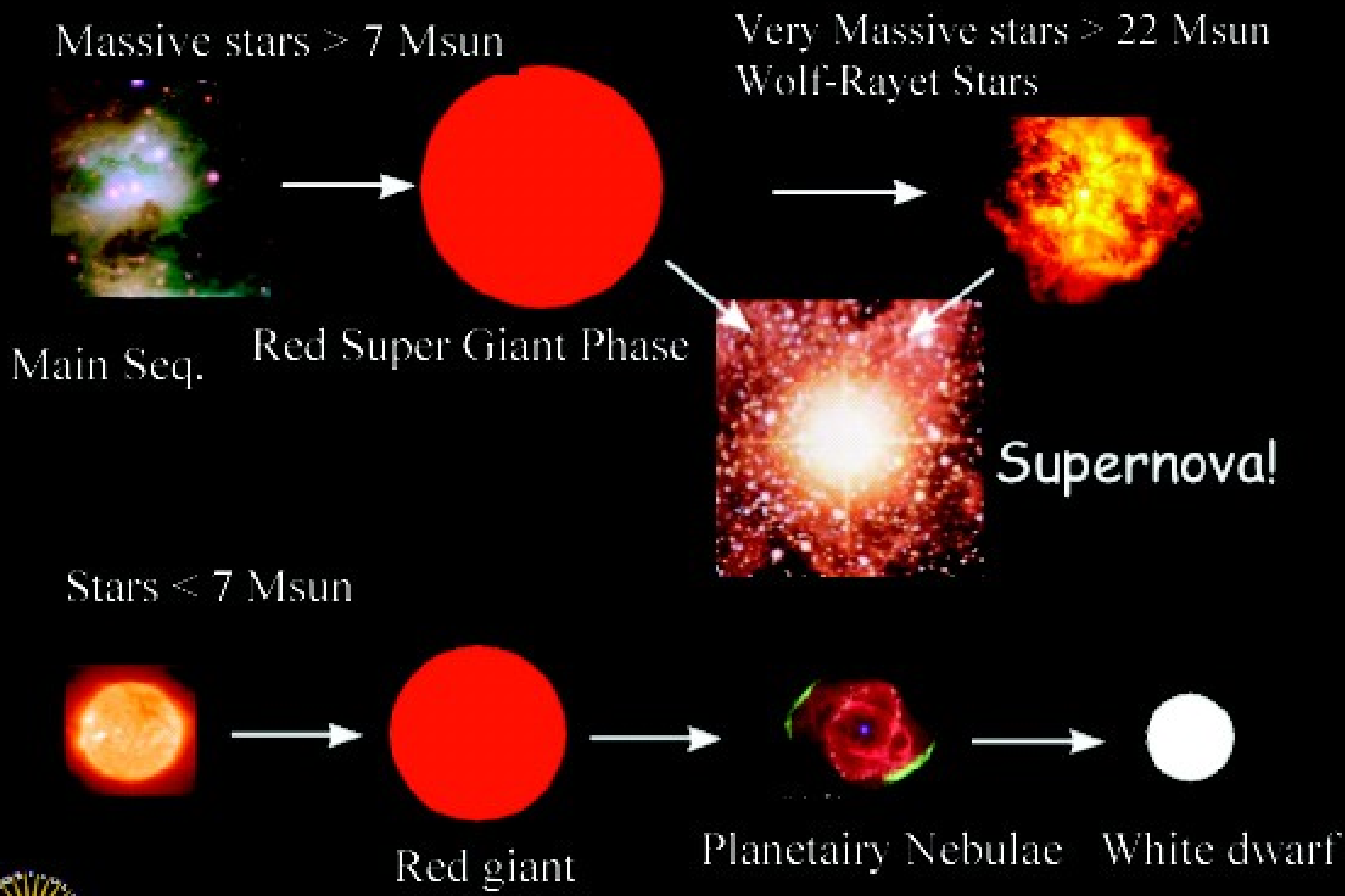
SuperNovae alone could maintain the CR population provided that about **10%** of their kinetic energy is **somehow converted into CRs**

Ginzburg e Syrovatskii (1964)

SuperNova Remnants

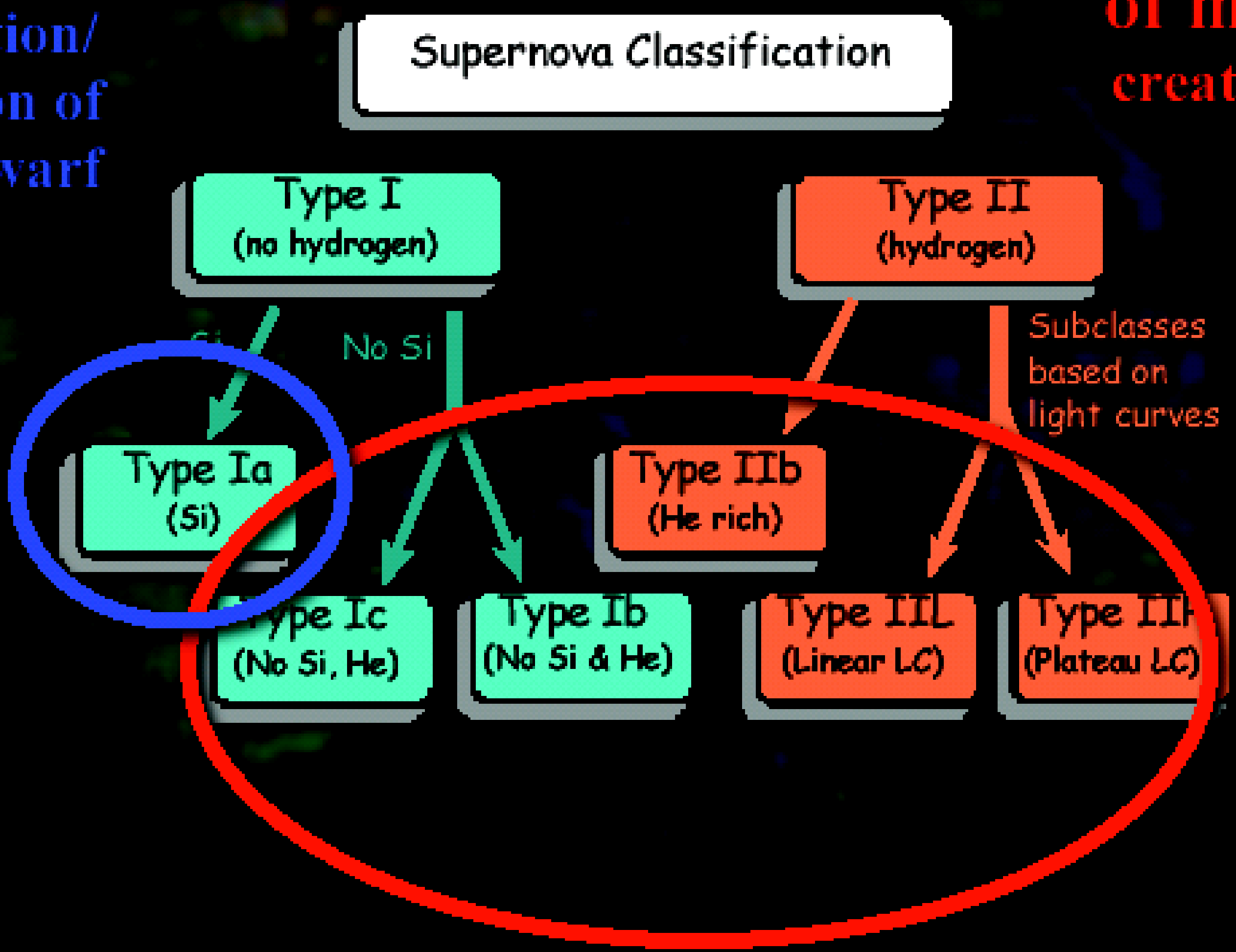


SuperNova Remnants



SuperNova Remnants

Thermonuclear explosion
deflagration/ detonation of White Dwarf



<u>Core collapse</u>
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

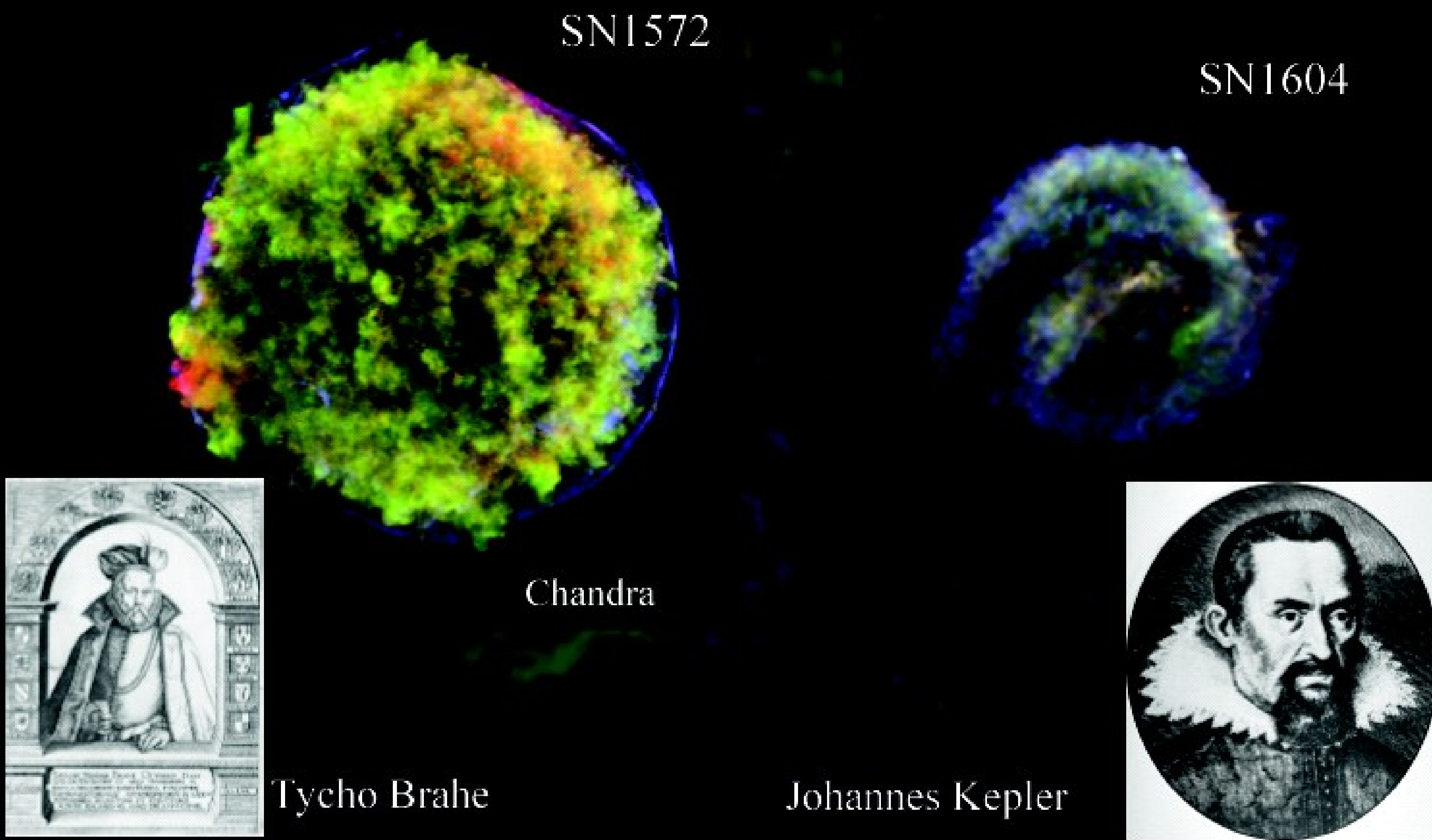
-The source of energy is therefore gravity ($\sim GM^2/R_{NS} \sim 10^{53}$ erg)

-Most of the energy released as neutrinos!

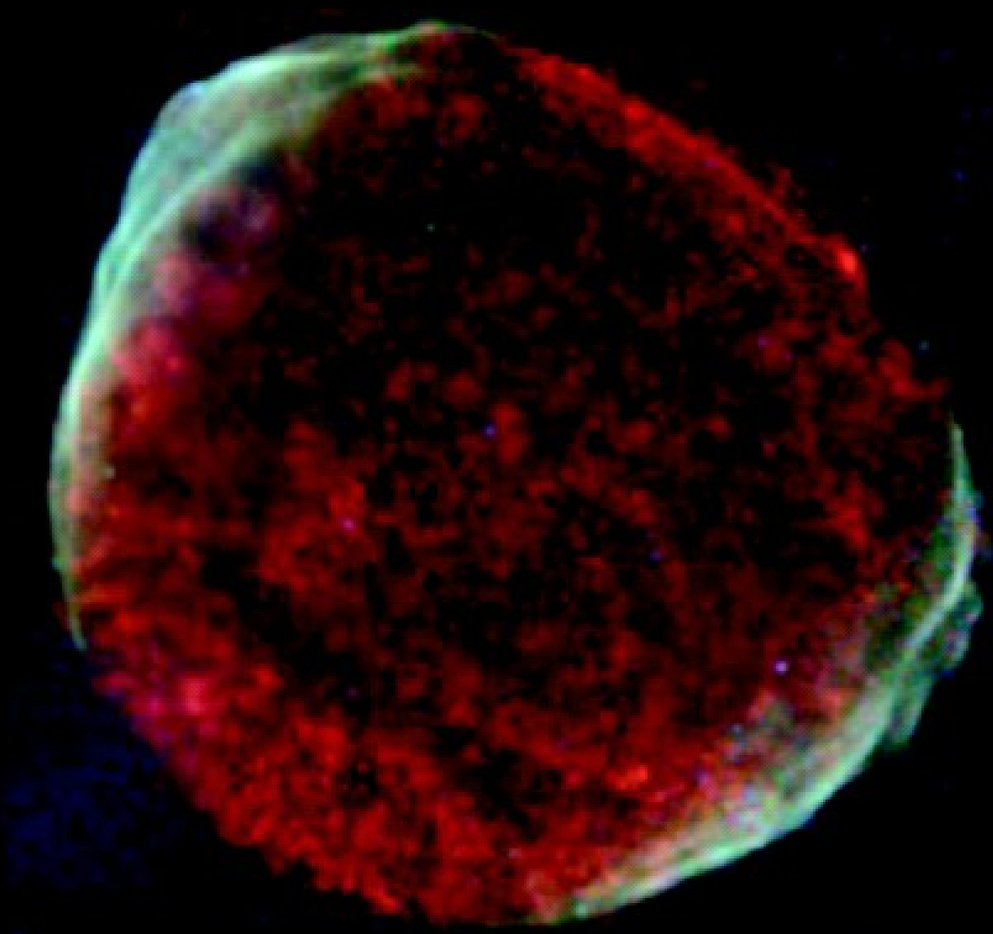
-Only 1% converted to heat/kinetic energy!

-Nuclear fusion: by-product/not source of the explosion

SuperNova Remnants



SuperNova Remnants



Size: 30'

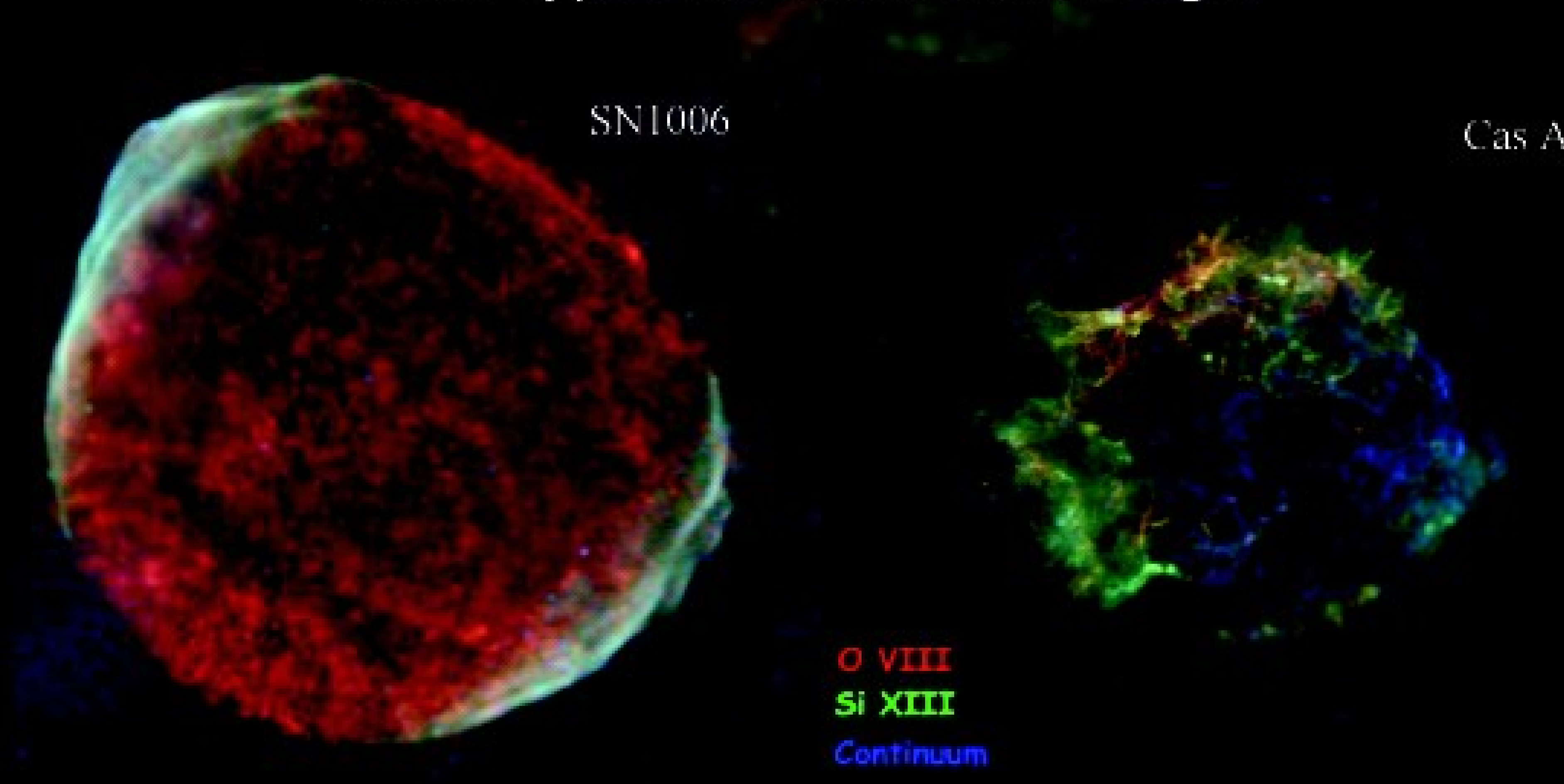
The size of the full Moon

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

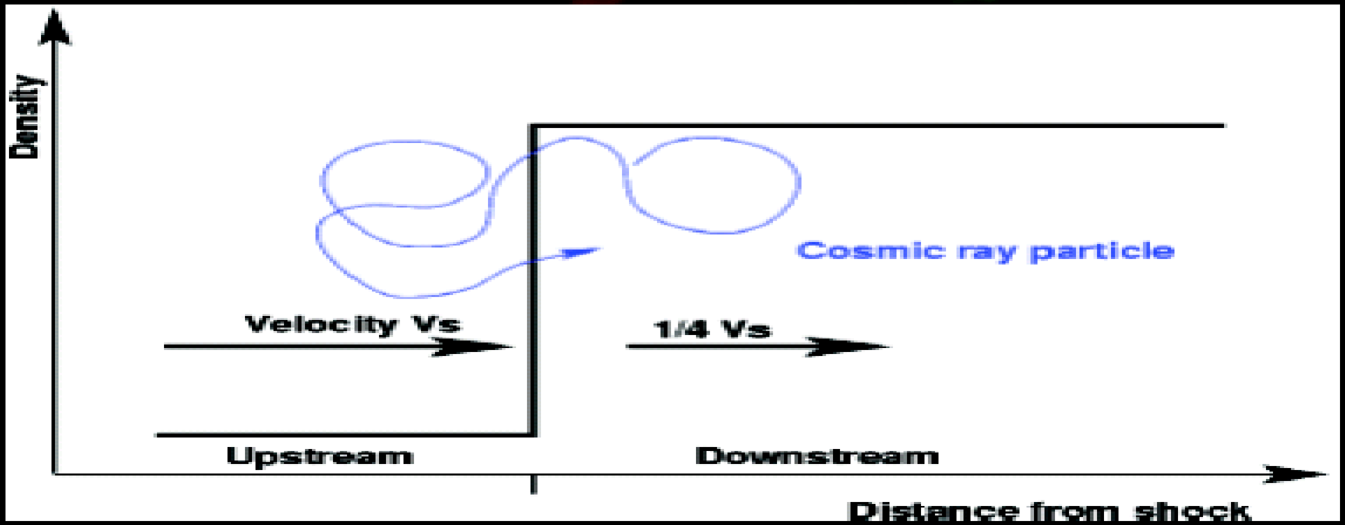
1) Free expansion (less than 200-300 years)

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

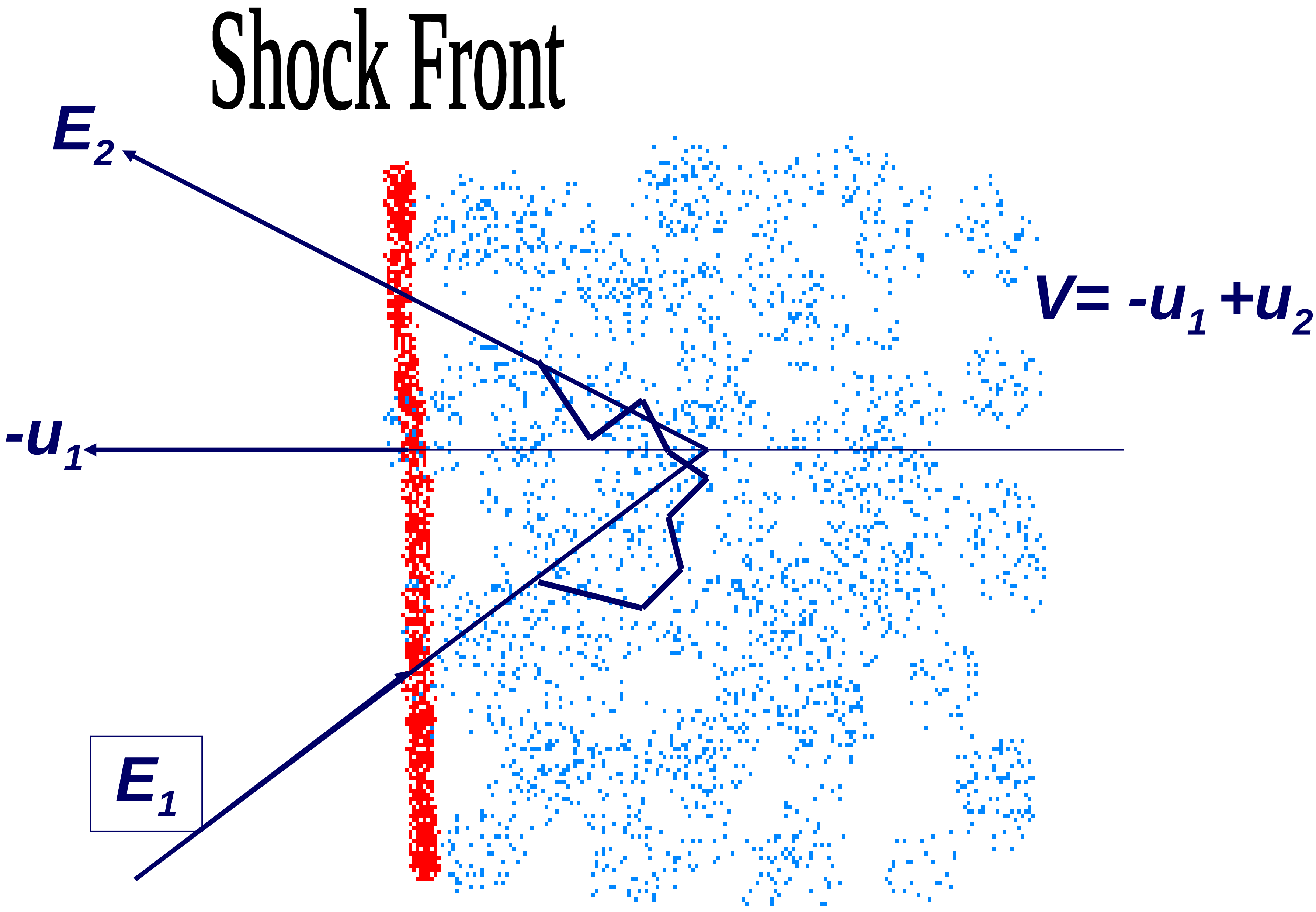
- Simplification: heat sinks (cosmic ray acceleration!), magnetic fields, and radiation losses not taken into account.

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

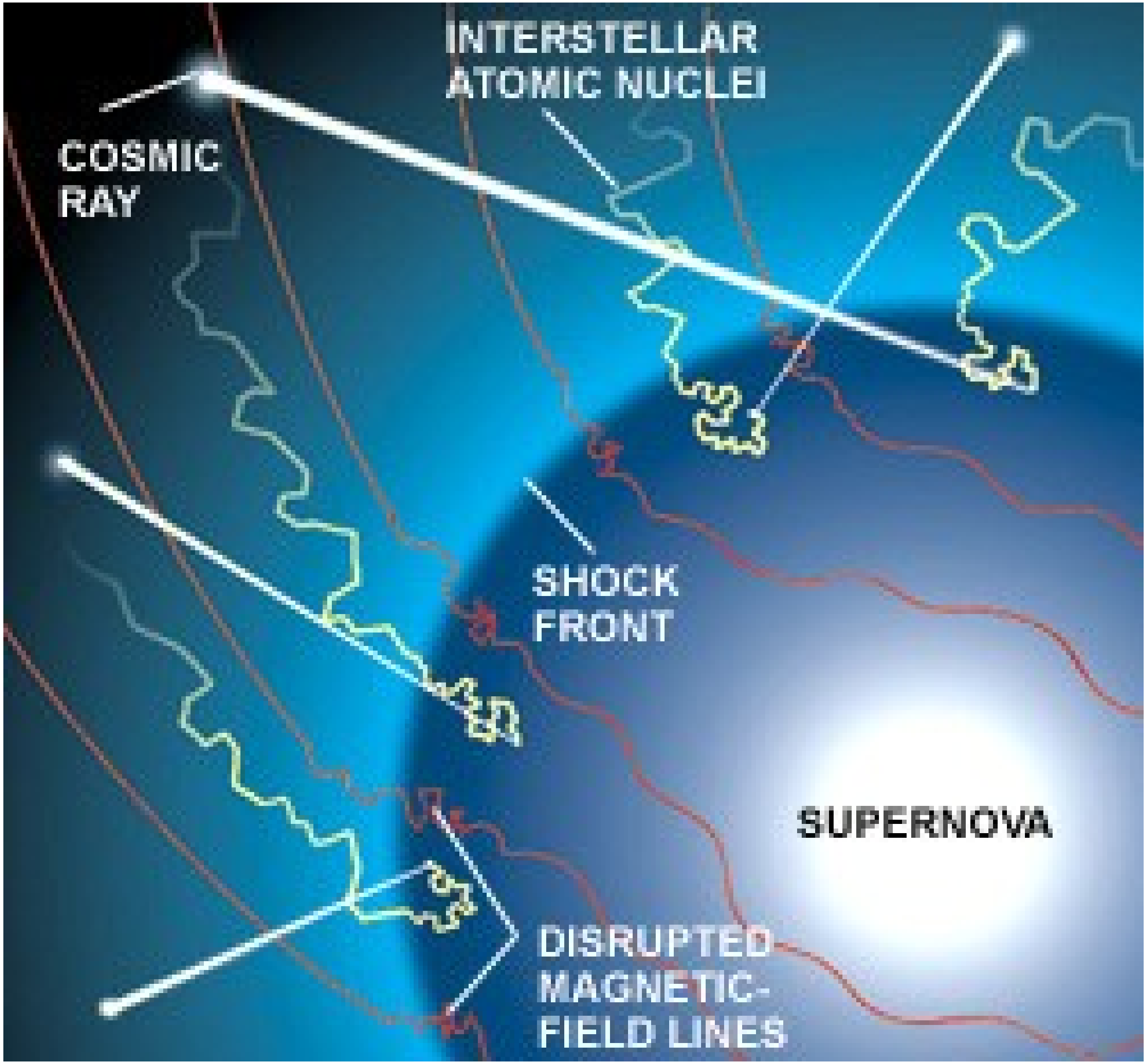
$\rho_2/\rho_1 = (\gamma+1)/(\gamma-1) = 4$, implying $v_2 = 1/4 v_s$

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

Accelerazione di Fermi del primo ordine

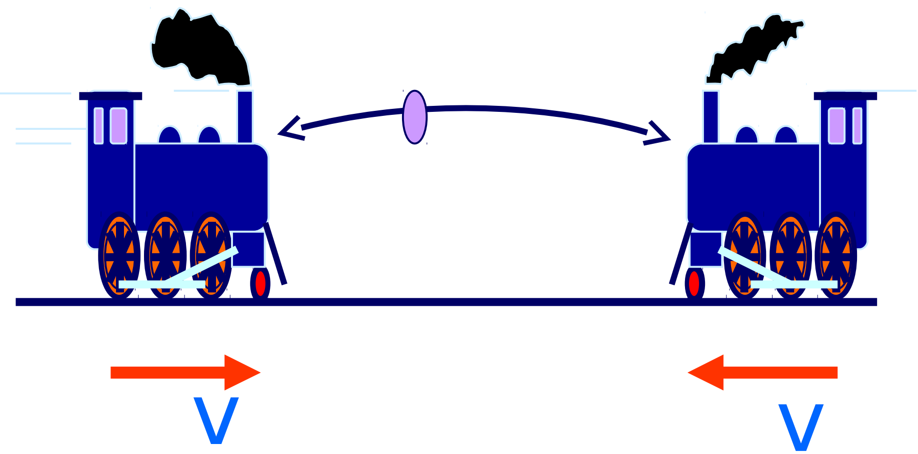


Meccanismo di accelerazione del primo ordine di Fermi



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:

$$\frac{dN(\epsilon)}{d\epsilon} \propto \epsilon^{-p}$$

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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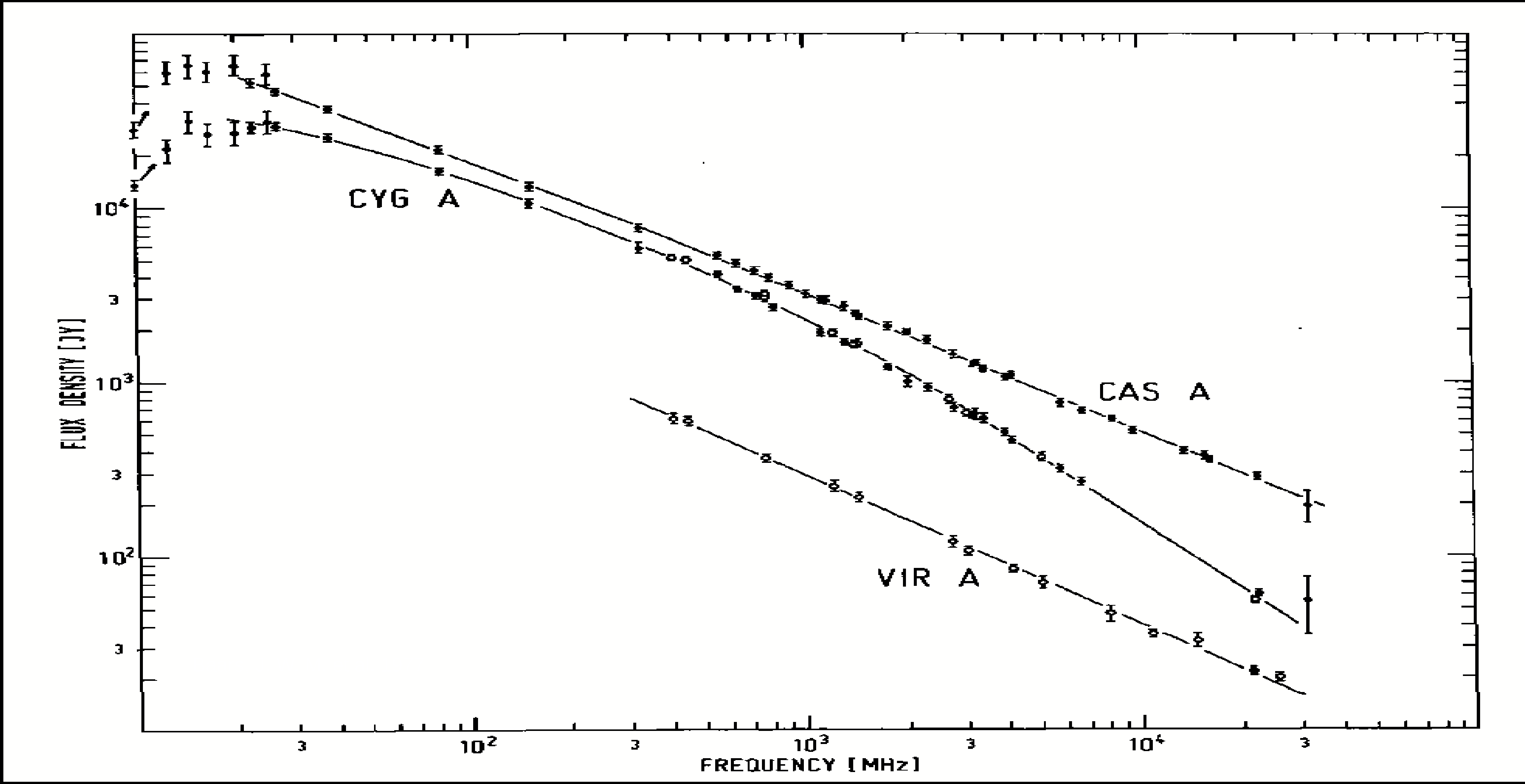

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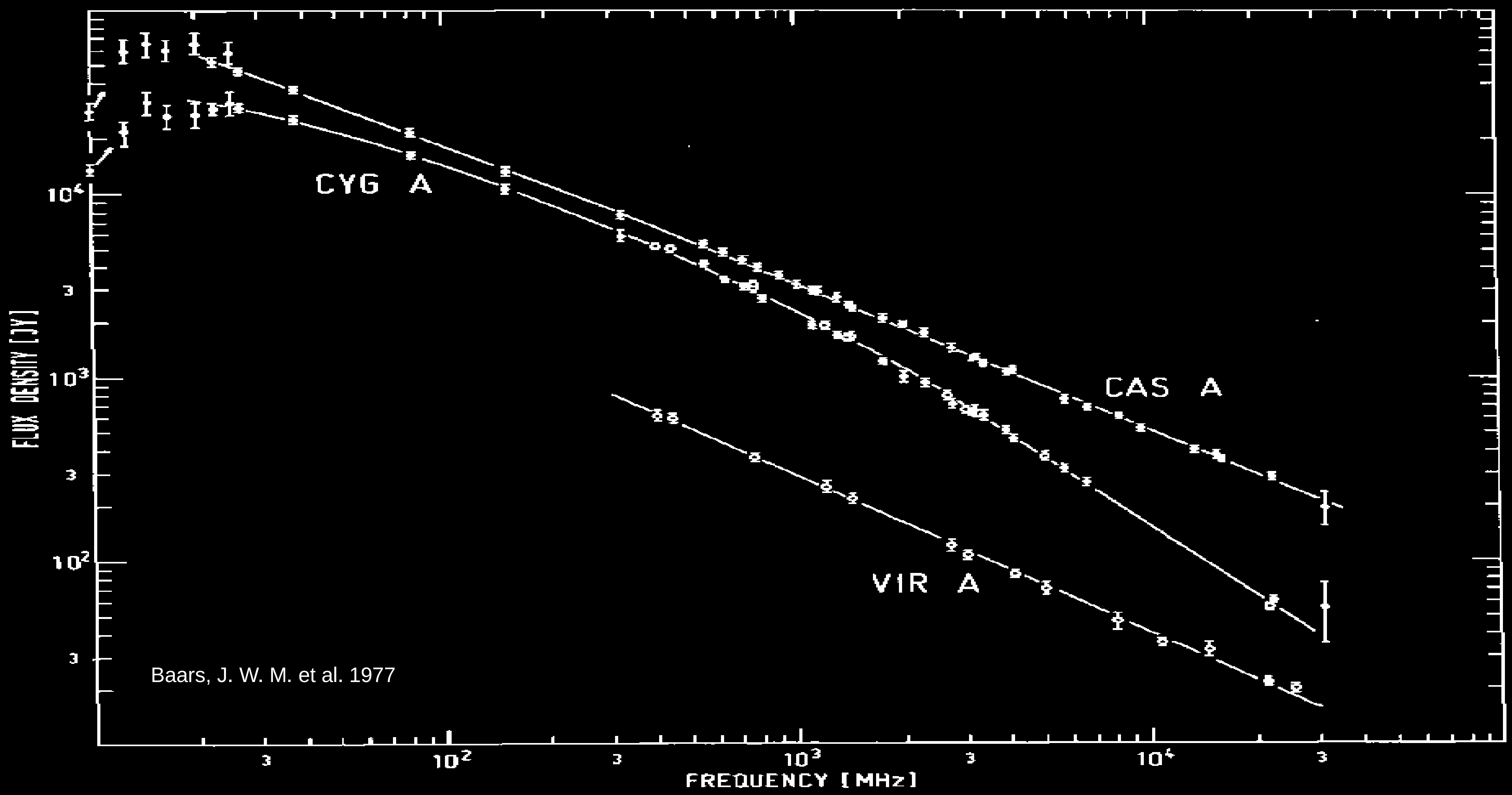
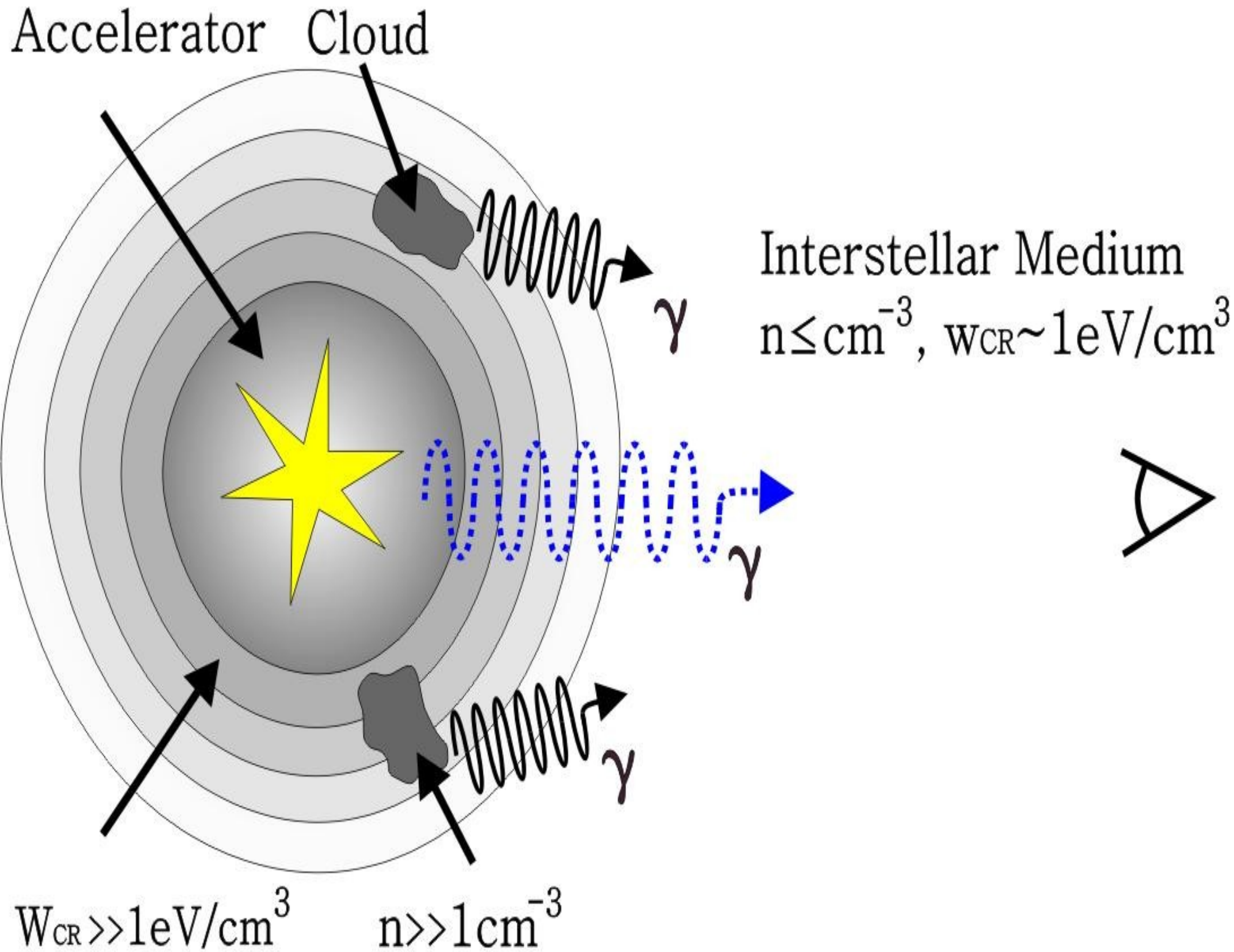


Featurless pl spectrum --> Non-thermal emission
-->Sync. emission from ultrarel. electrons

$F \sim E^{-p}$ 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

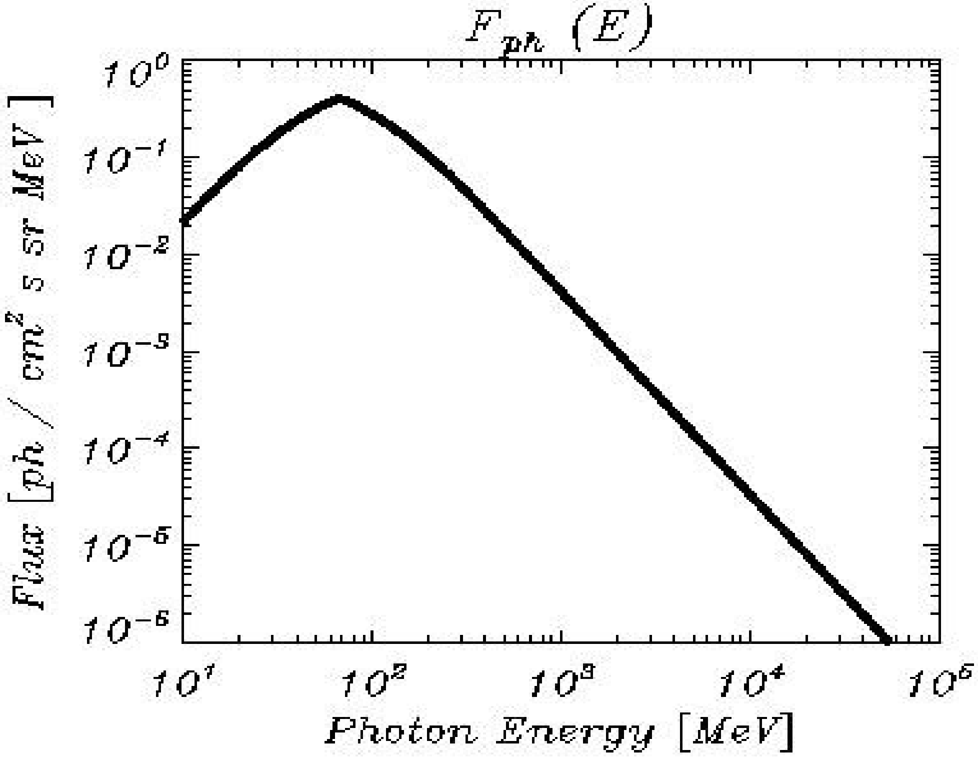
Electron Bremsstrahlung:
electrons + ISM nuclei
→ γ rays

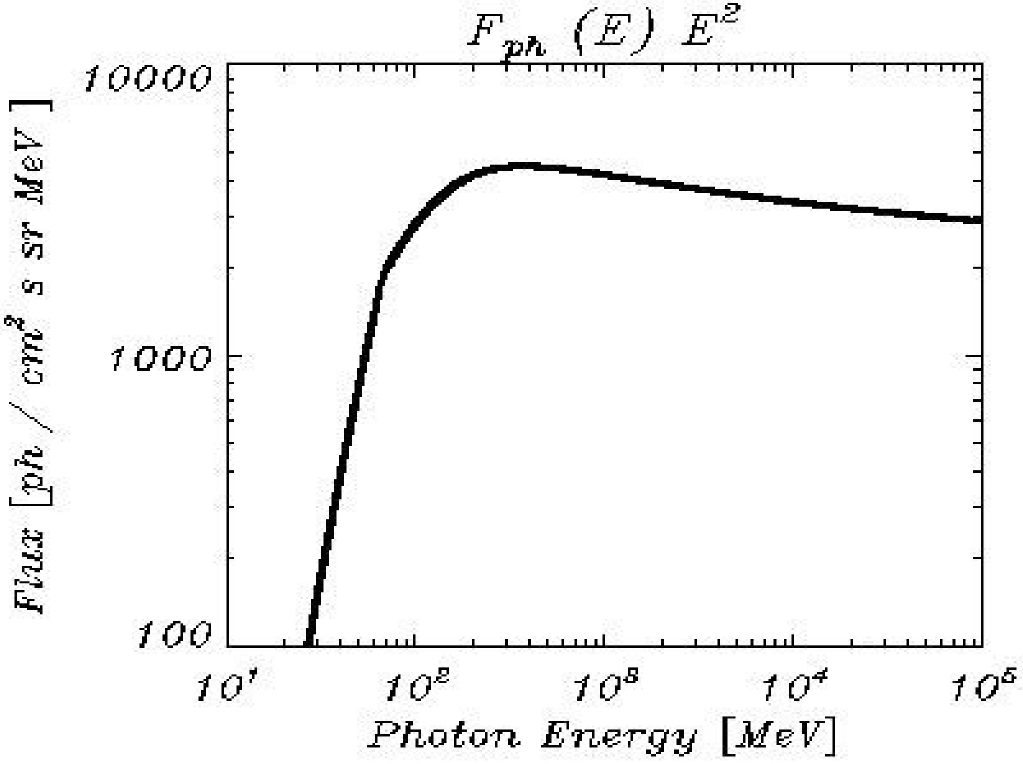
What about protons ?

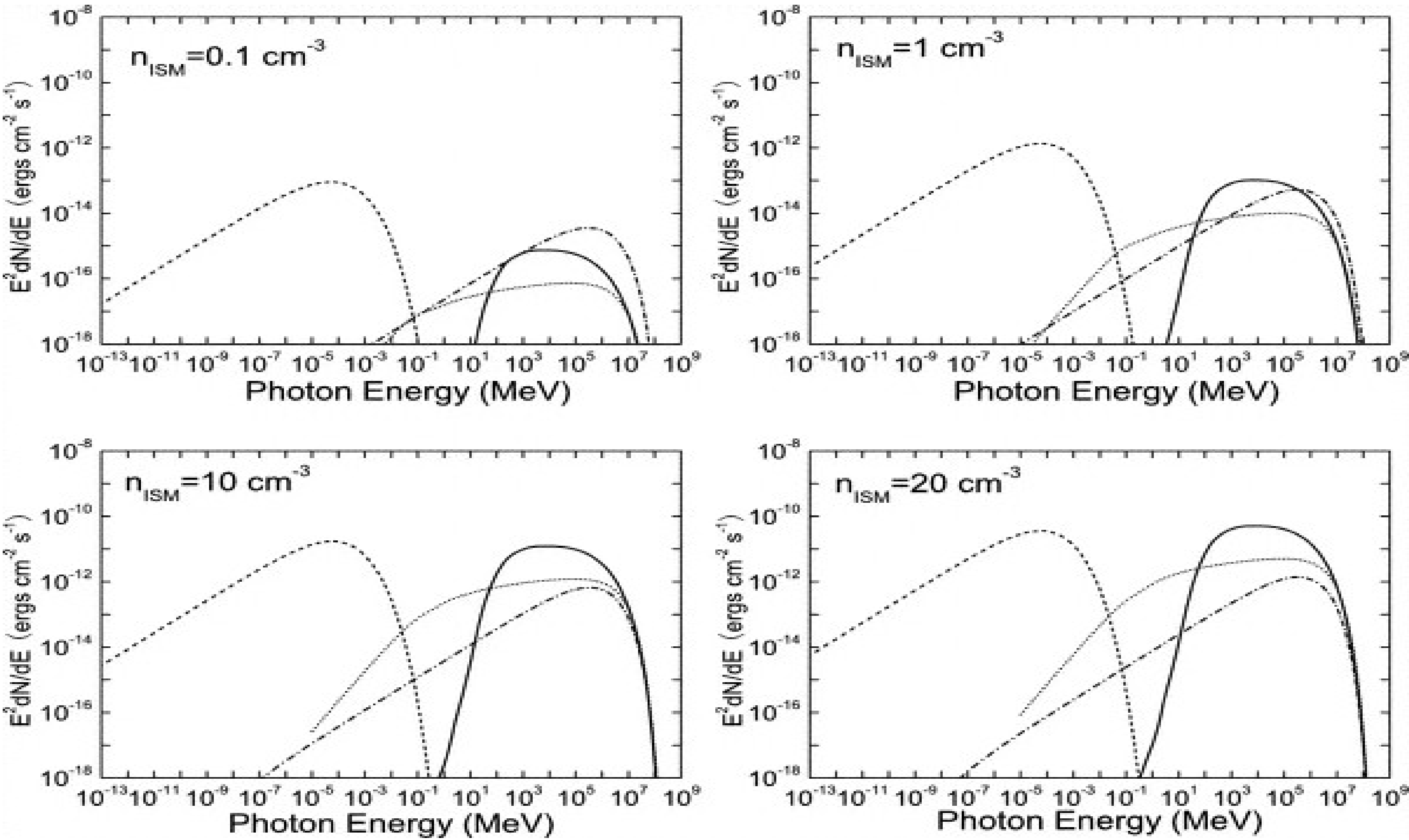
protons + ISM nuclei → π^0 → γ rays

Emission in the hard gamma ray band

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







Zhang et al 2007

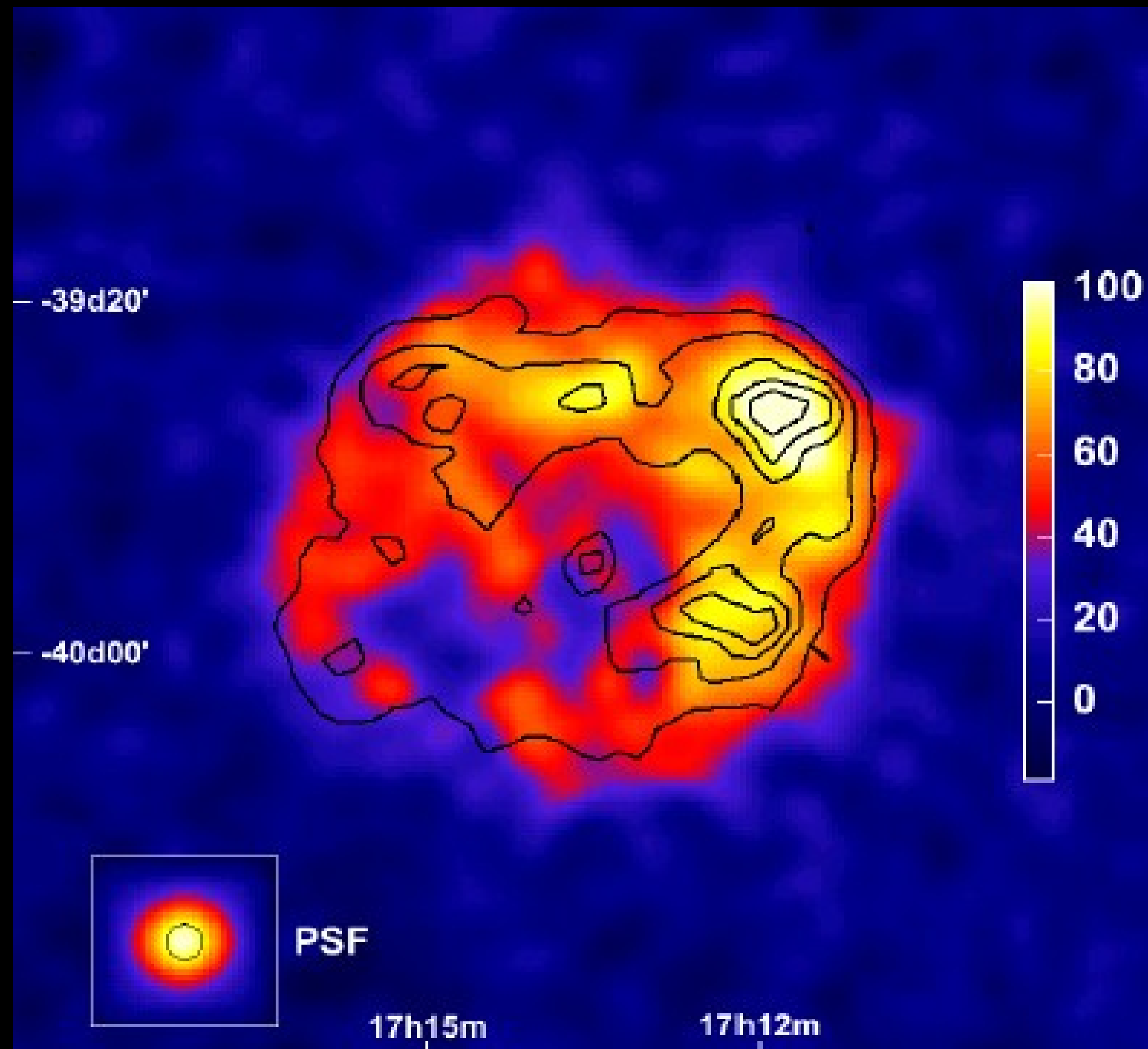
New generation of Cherenkov telescopes
(HESS, MAGIC, VERITAS)

Energy Range : 100 GeV – 10 TeV

RX J1713.7–3946

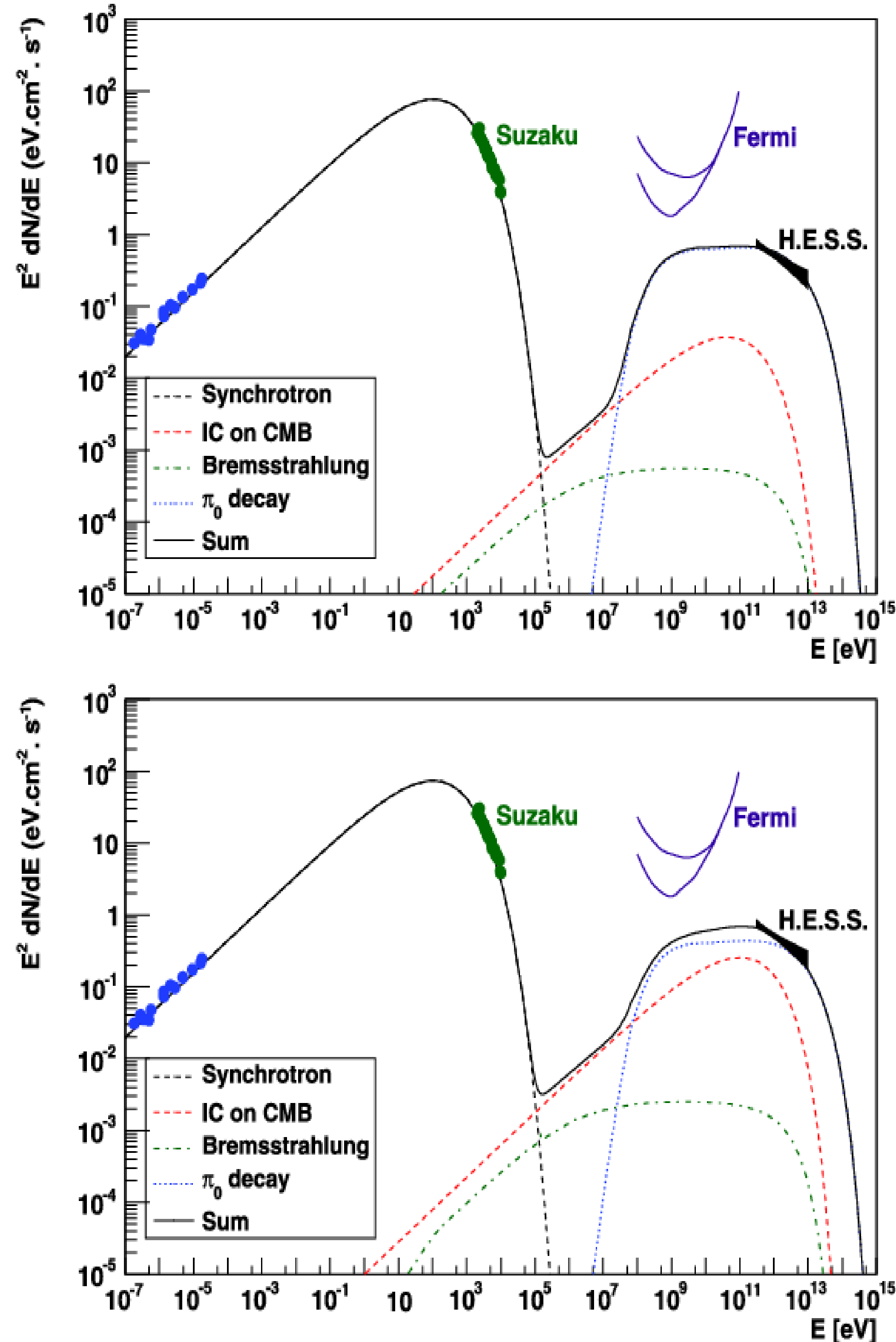
Distance : 1.2 kpc
Age : 2 kyrs
Size : 65'

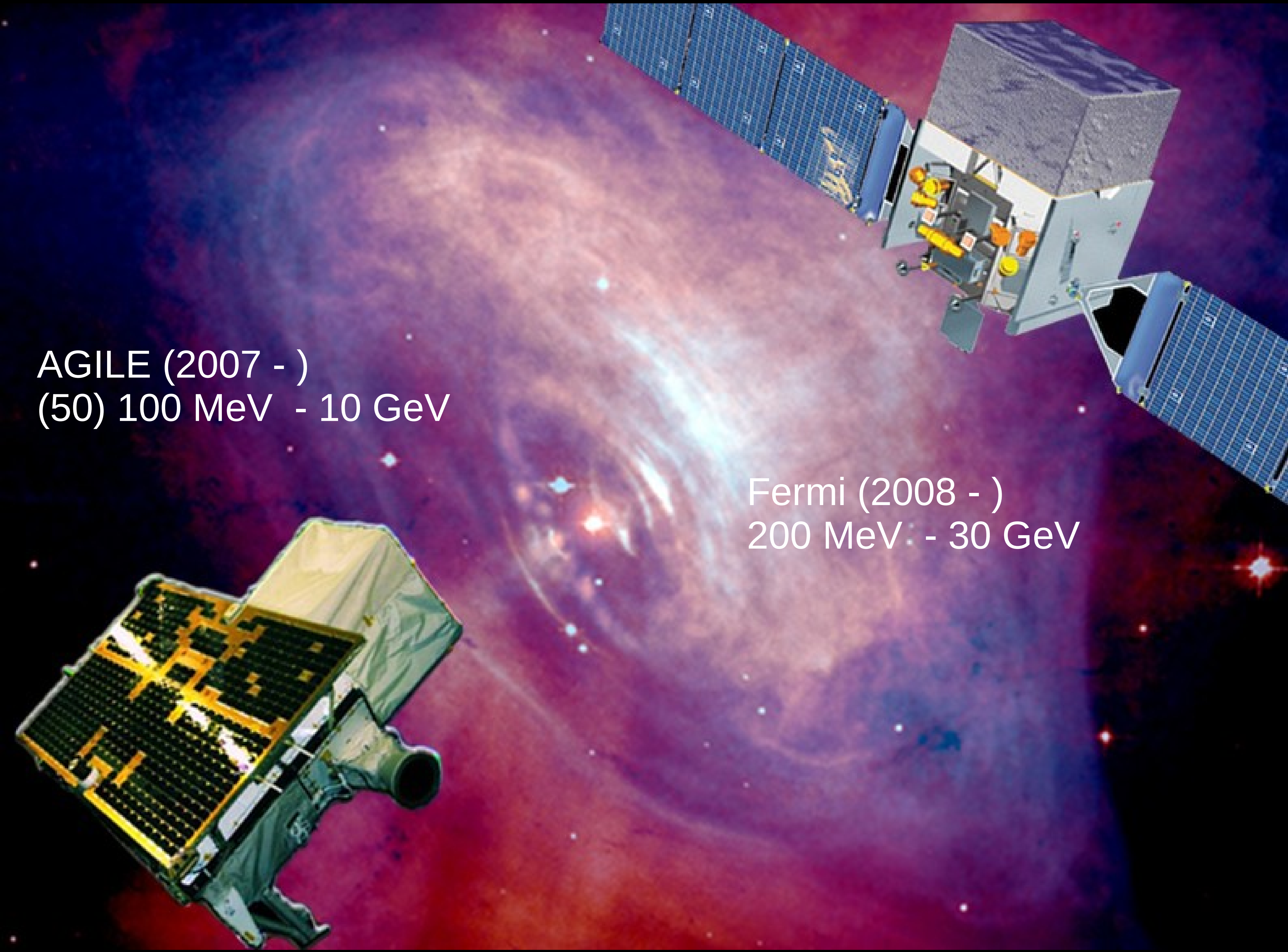
Good X-ray-TeV correlation

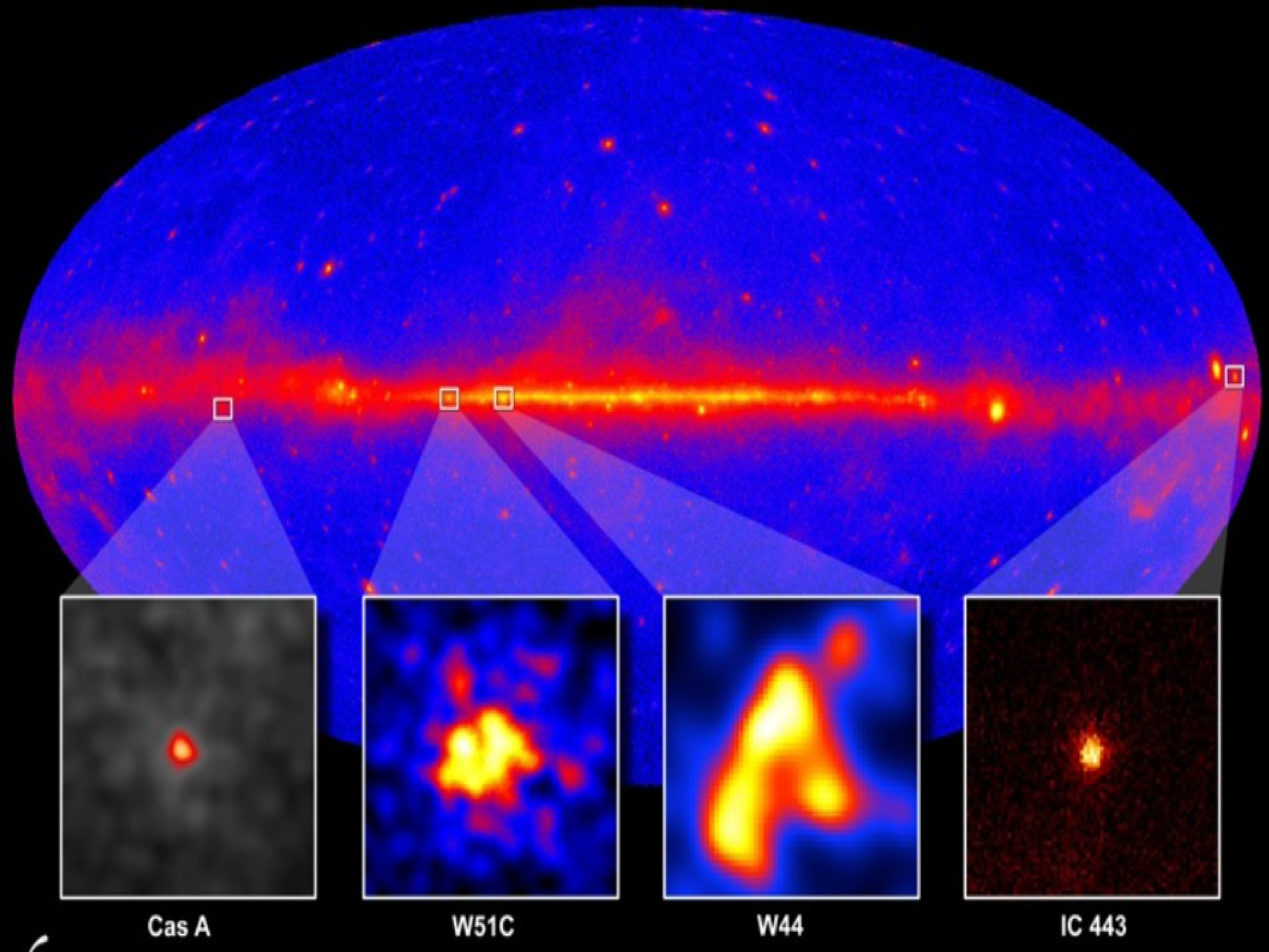


ASCA-HESS data of RX 1713.7-3946 (Goumard et al. 2006)

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

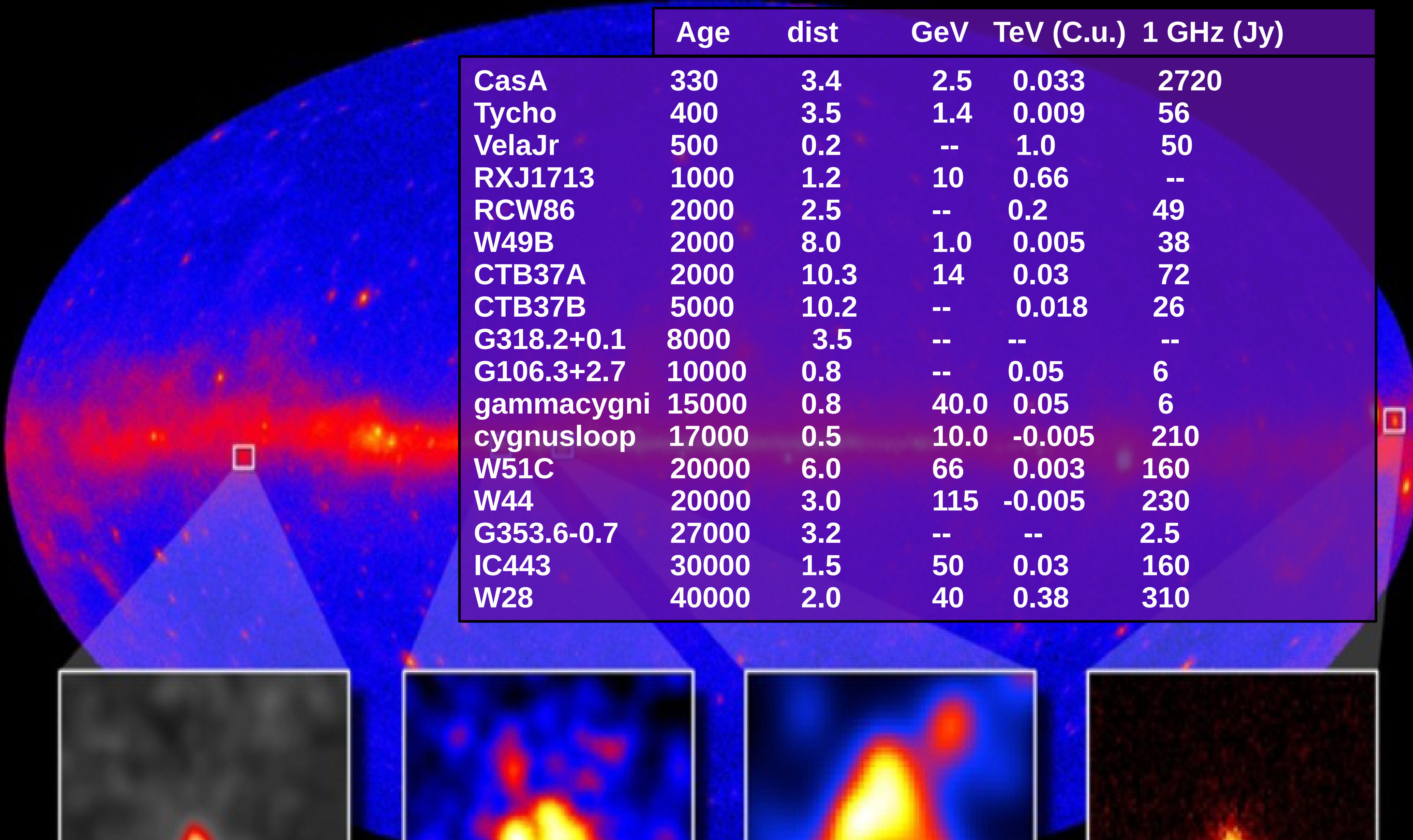


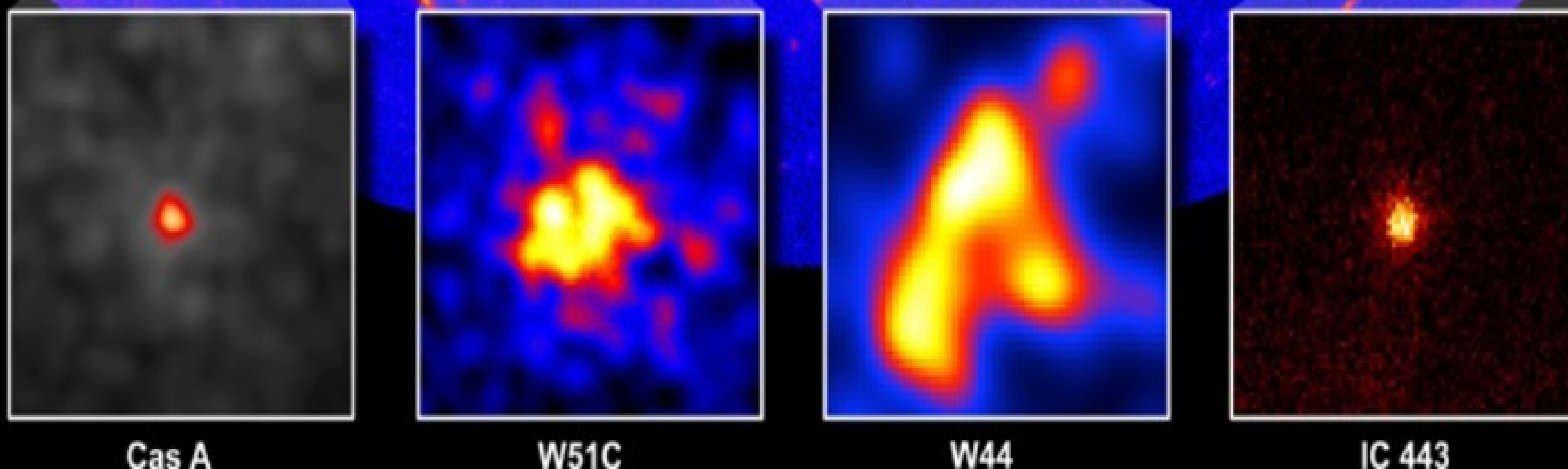

AGILE (2007 -)
(50) 100 MeV - 10 GeV
Fermi (2008 -)
200 MeV - 30 GeV



Cas A
W51C
W44
IC 443

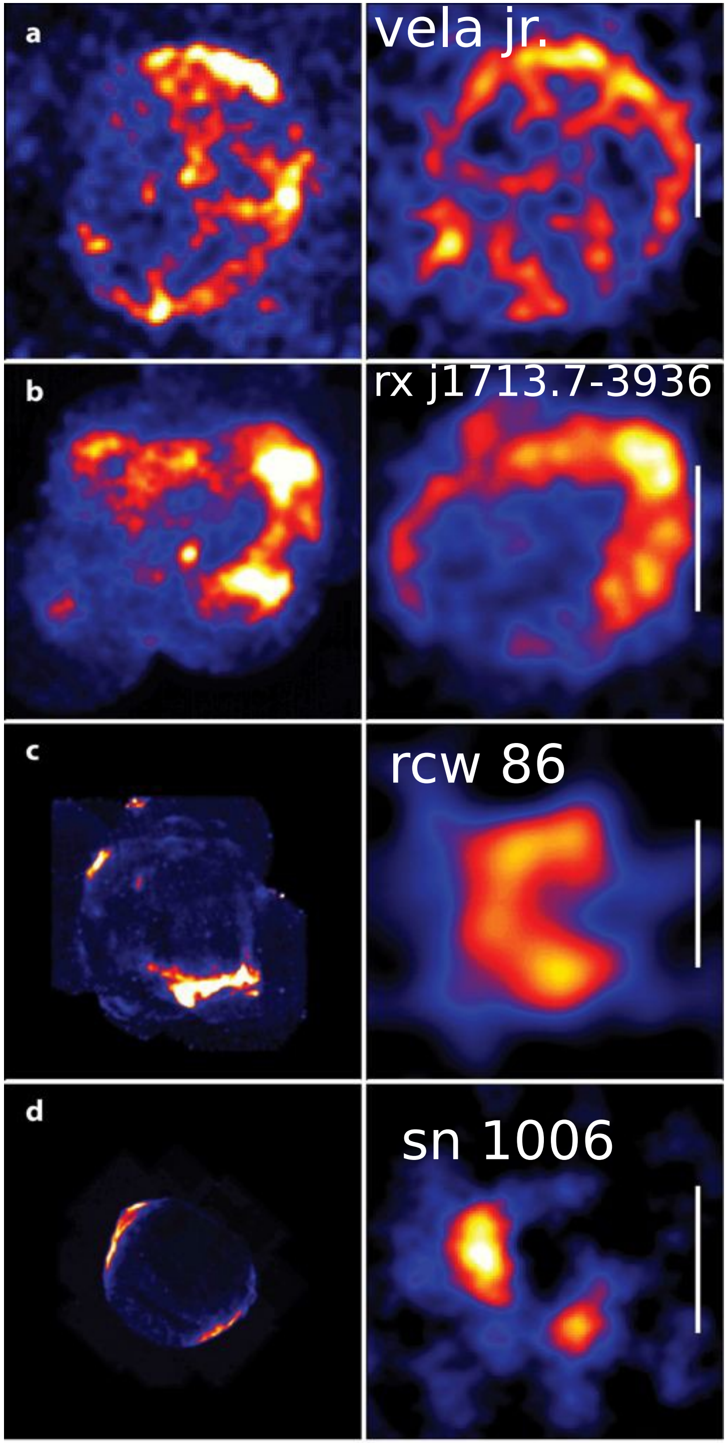
	Age	dist	GeV	TeV (C.u.)	1 GHz (Jy)
CasA	330	3.4	2.5	0.033	2720
Tycho	400	3.5	1.4	0.009	56
VelaJr	500	0.2	--	1.0	50
RXJ1713	1000	1.2	10	0.66	--
RCW86	2000	2.5	--	0.2	49
W49B	2000	8.0	1.0	0.005	38
CTB37A	2000	10.3	14	0.03	72
CTB37B	5000	10.2	--	0.018	26
G318.2+0.1	8000	3.5	--	--	--
G106.3+2.7	10000	0.8	--	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

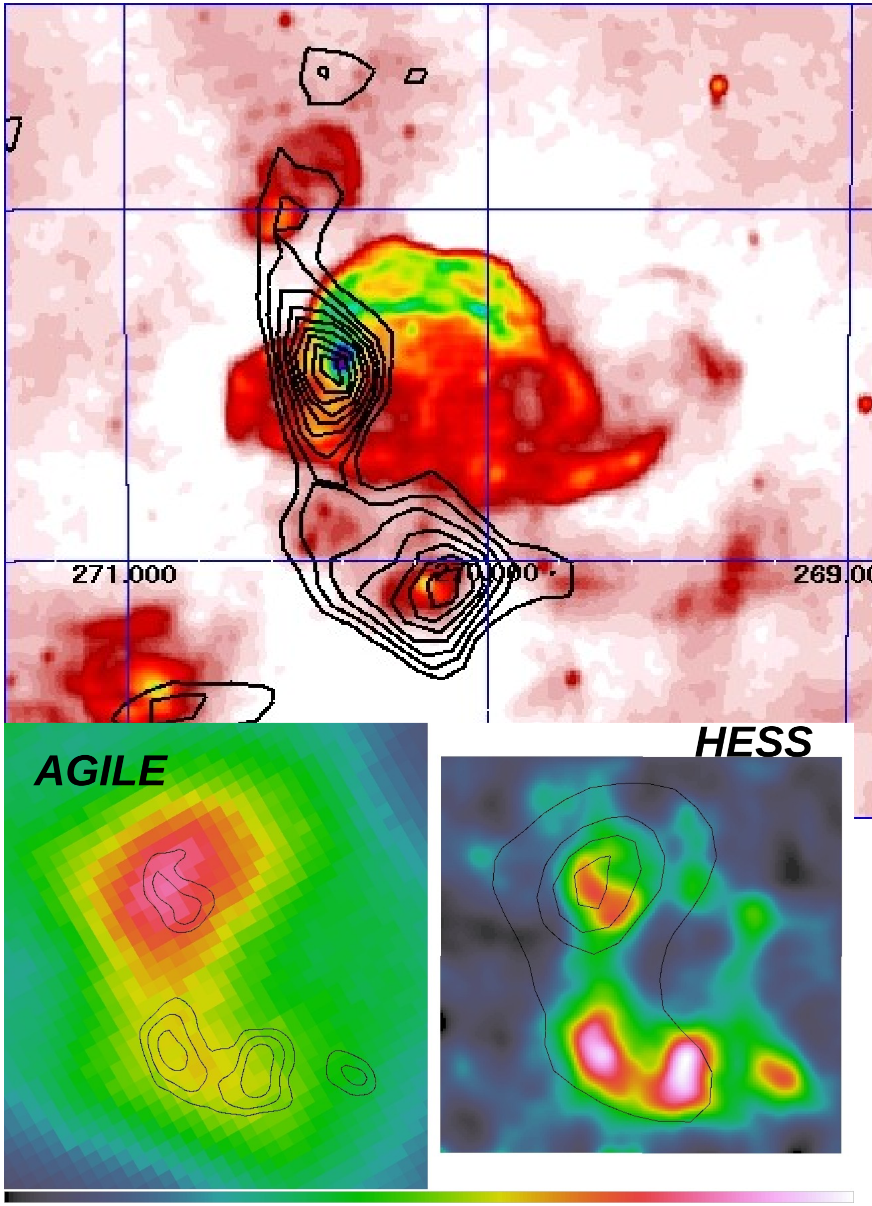


Hinton JA, Hofmann W. 2009.
Annu. Rev. Astron. Astrophys. 47:523–65

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.



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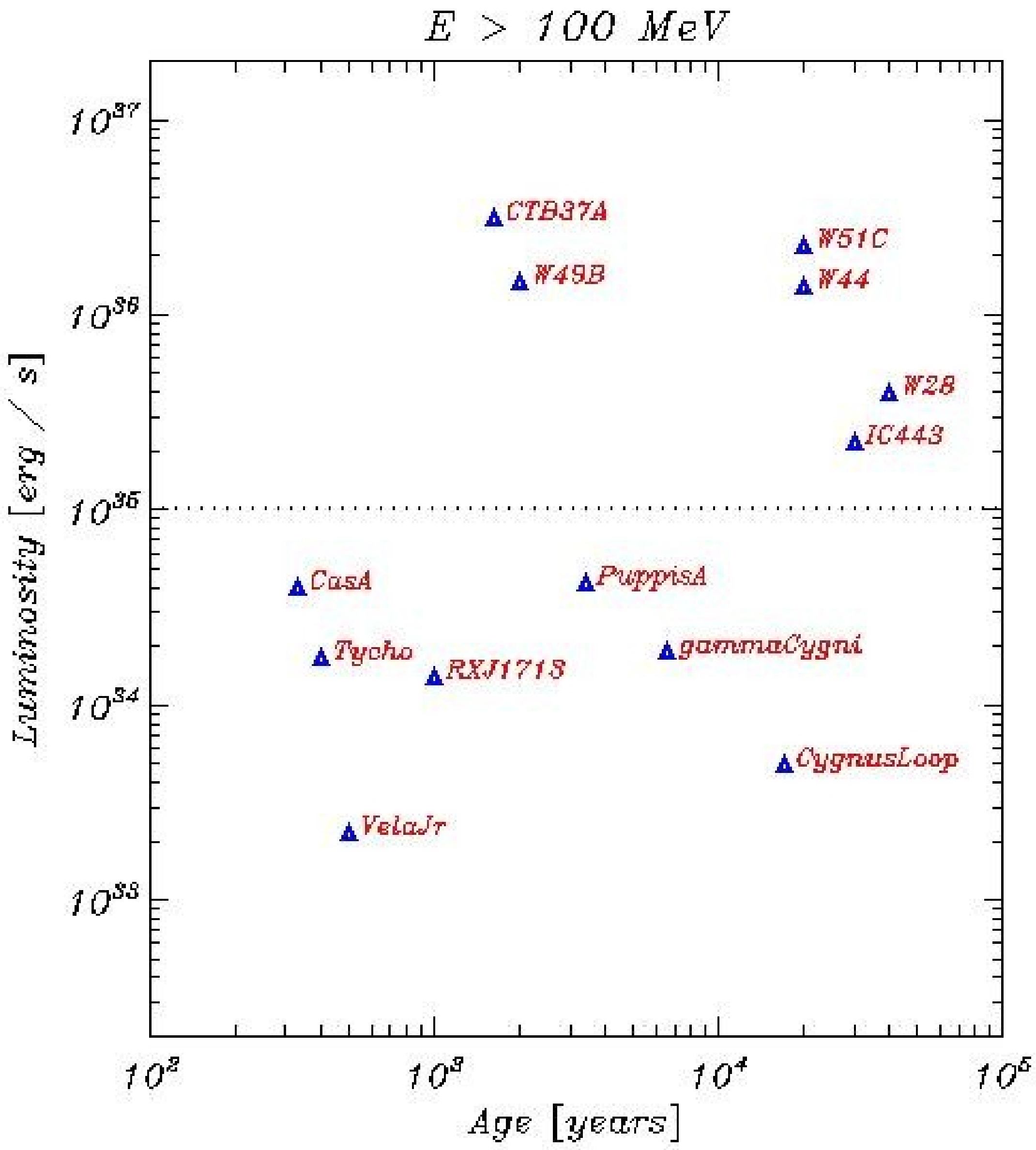

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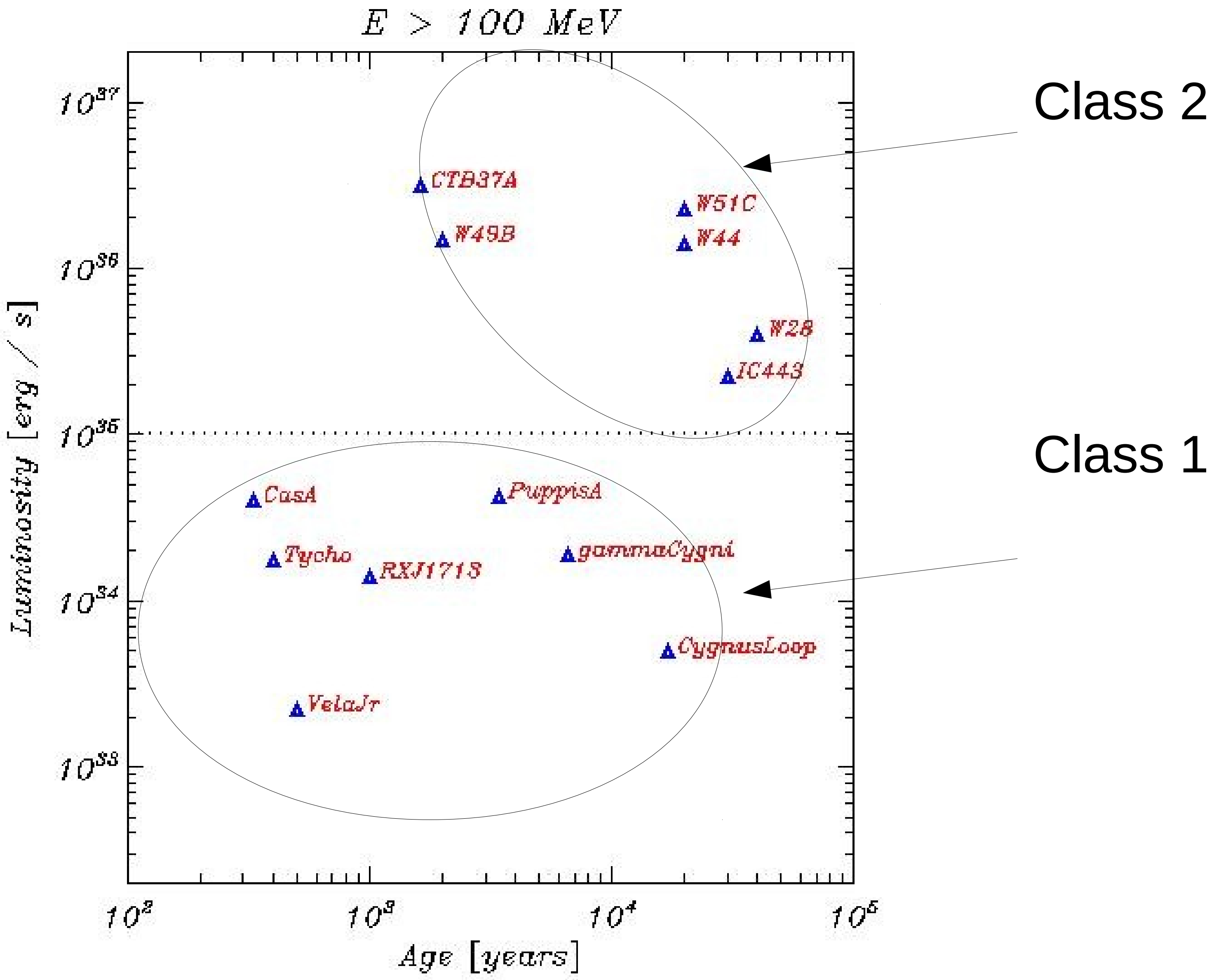
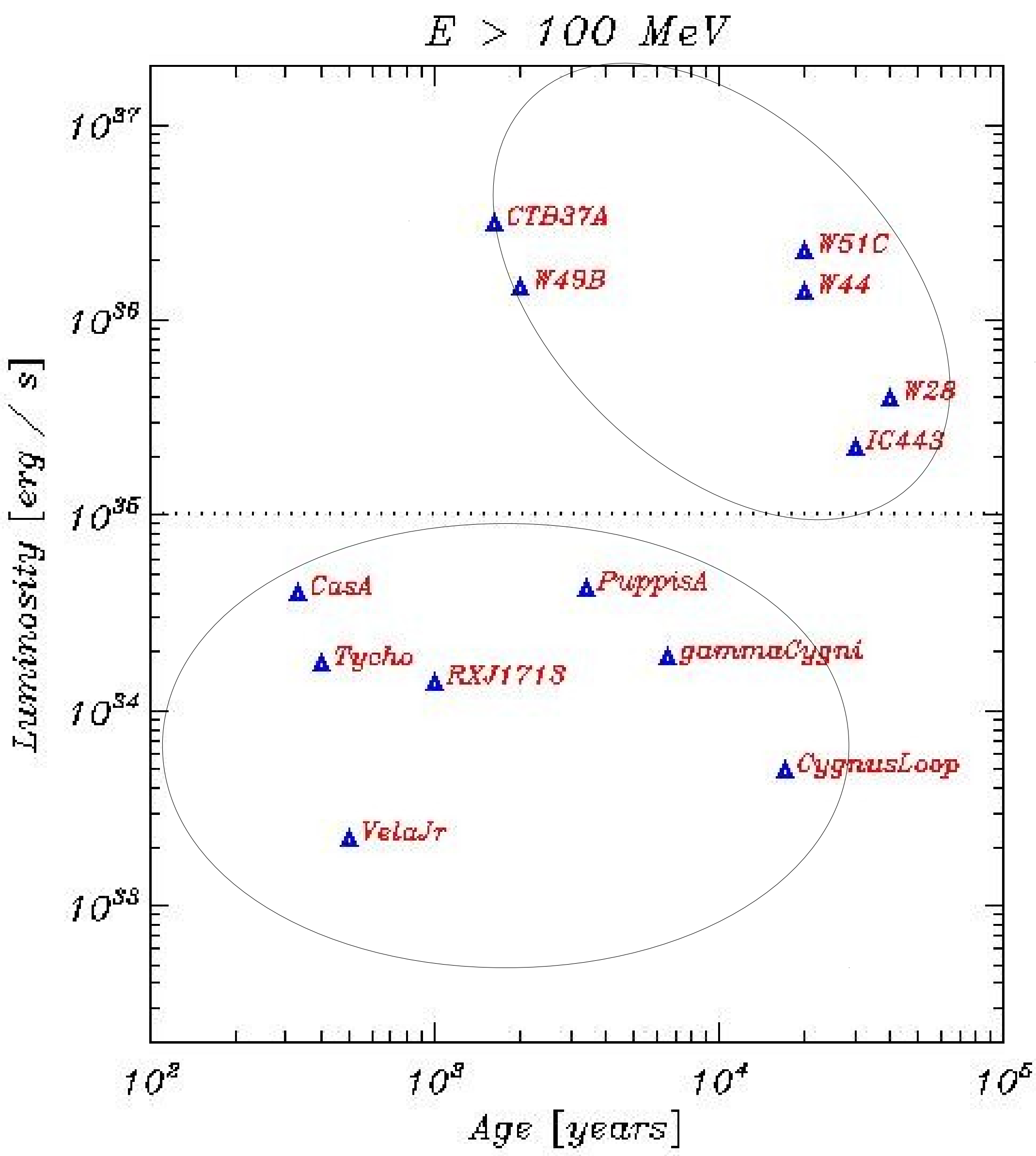
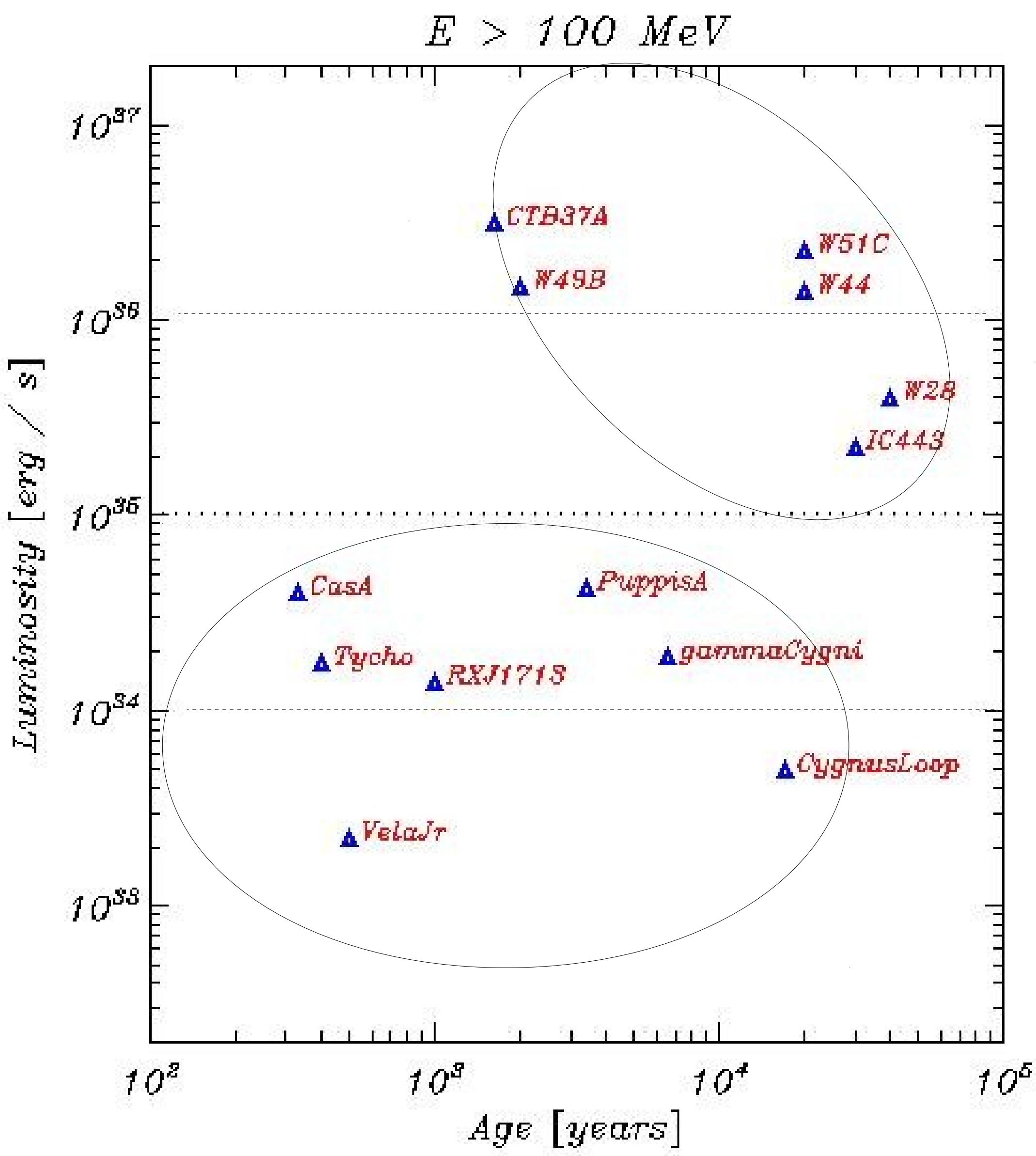


2 classes of gamma-rays SNRs



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

2 classes of gamma-rays SNRs

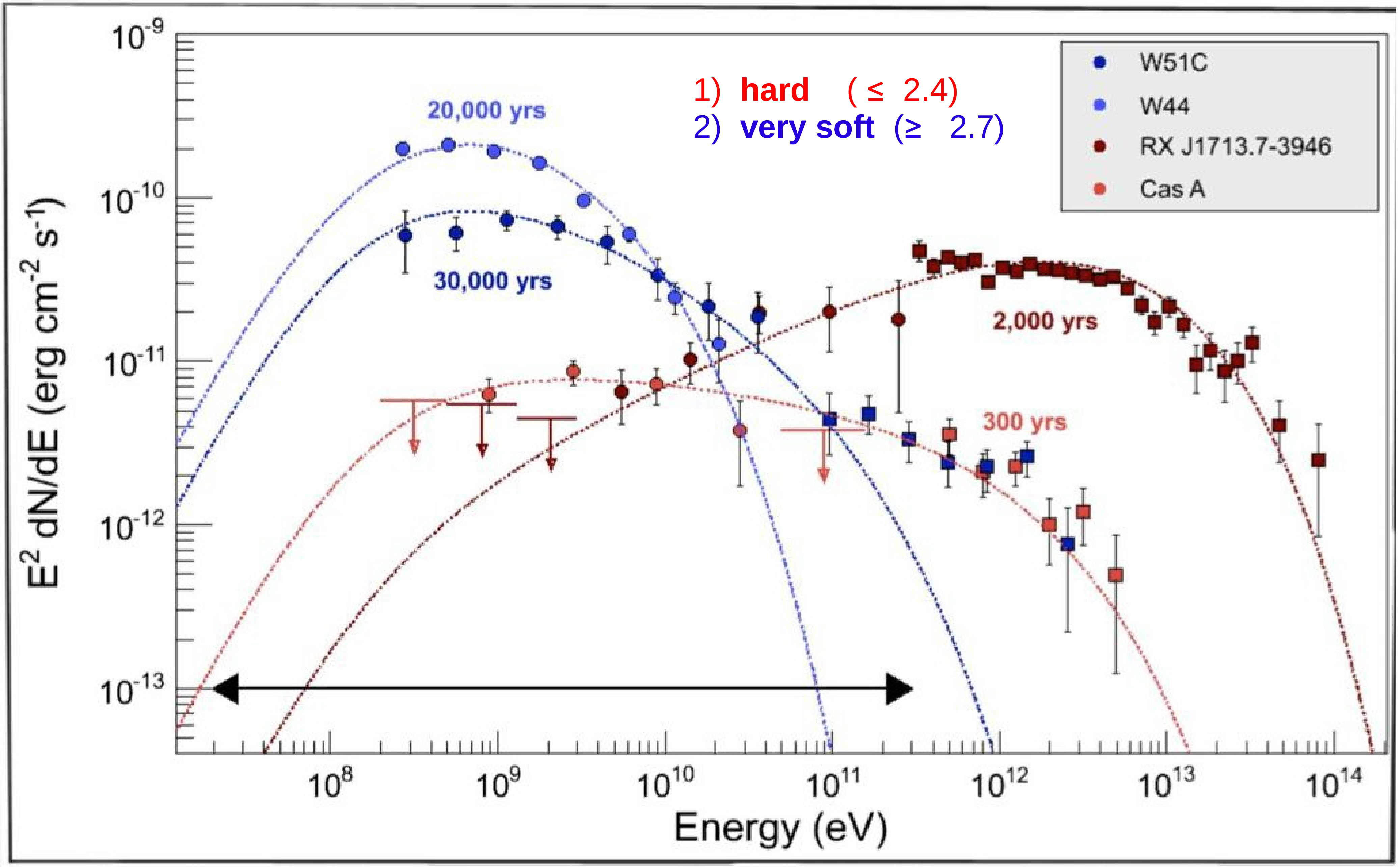


$L_{gamma}(E) = \sigma(E)\ c\ N_p(E)\ n$

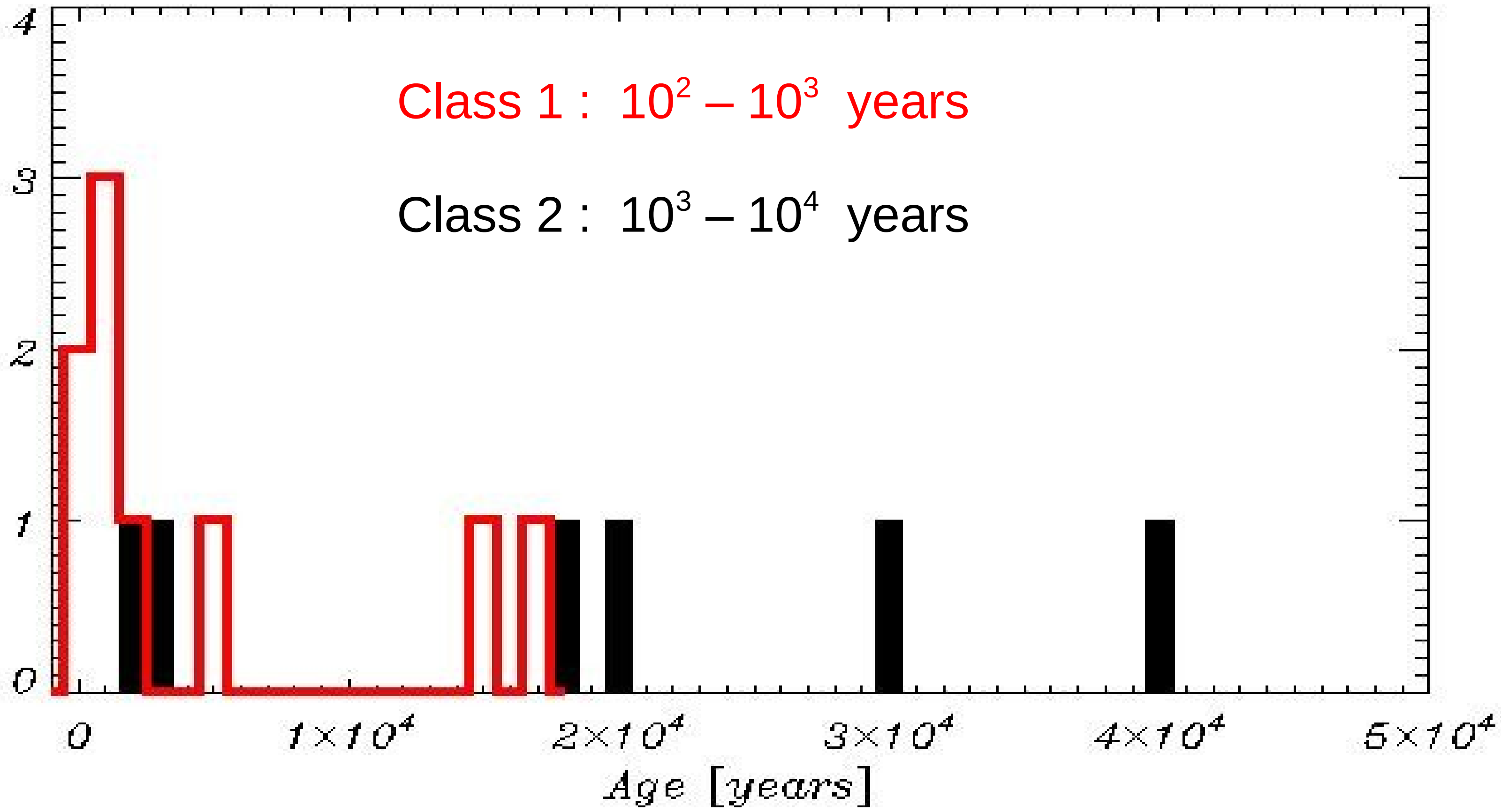
100 cm^{-3}

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

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

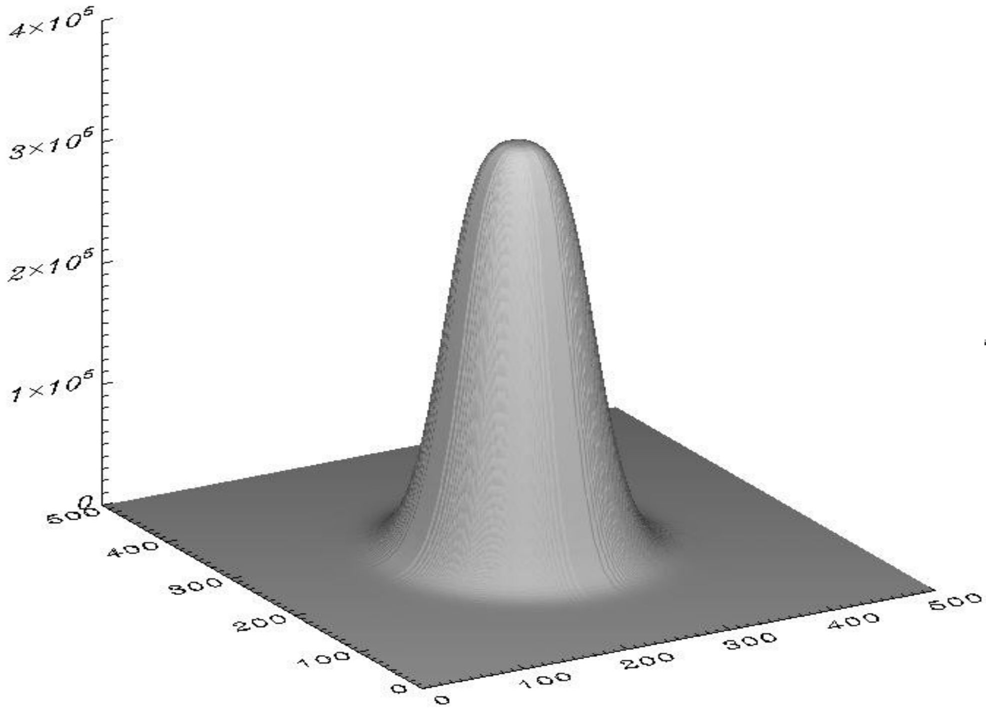
Diff. in physical space

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

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

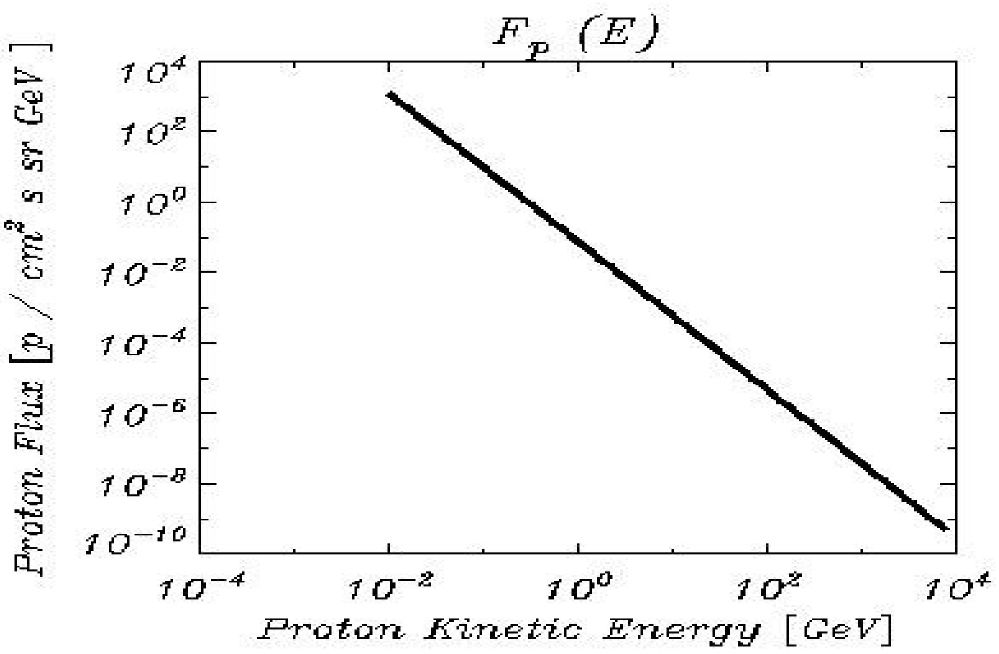
$$D(E) = D_0 E^{\delta} \simeq 10^{26} \left(\frac{E}{10\ GeV} \right)^{0.5}\ cm^2\ s$$

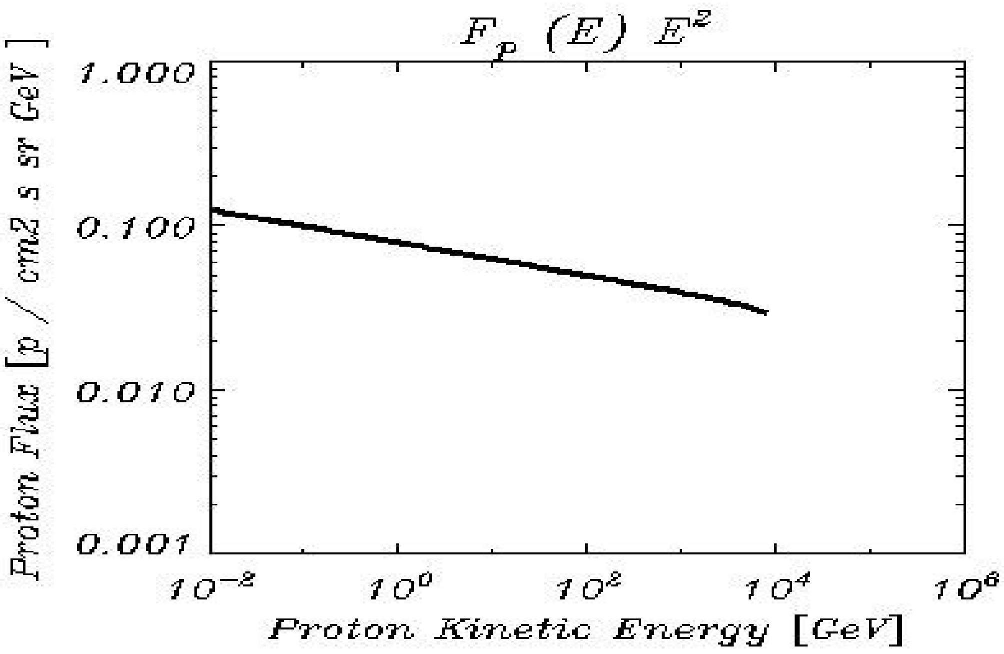
--> Slow !

--> Faster diffusion for high energy CR

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

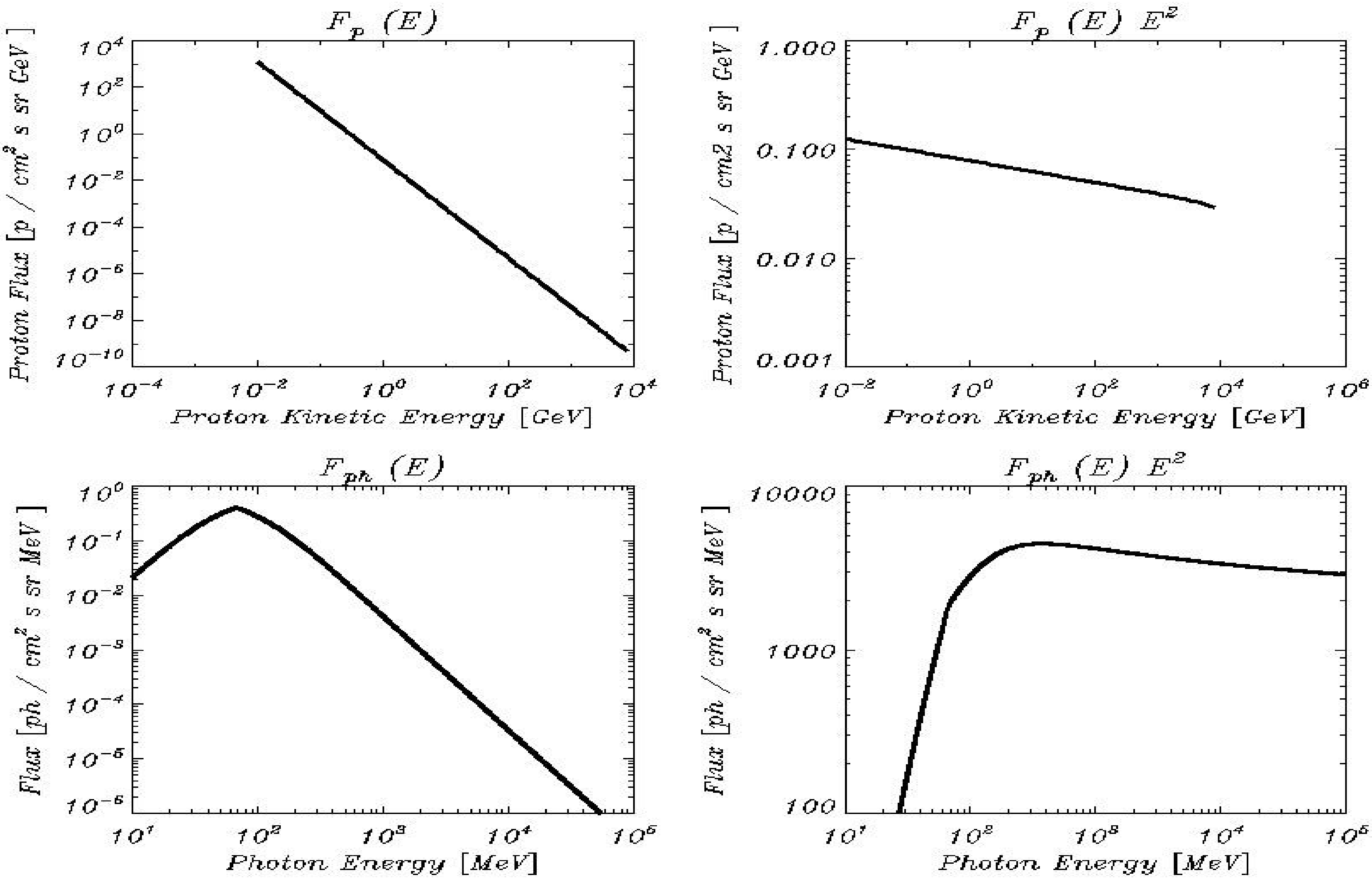
: protons + ISM nuclei → π^0 → γ rays

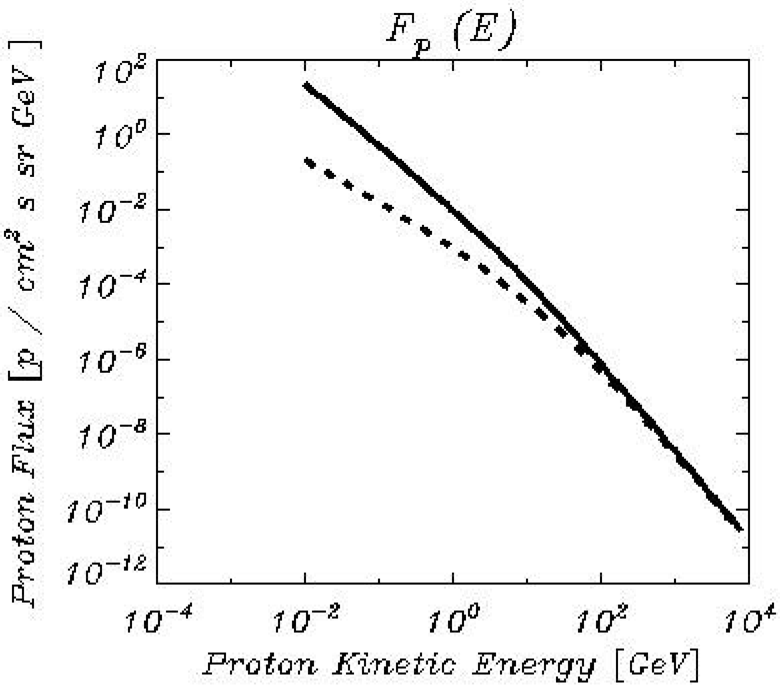


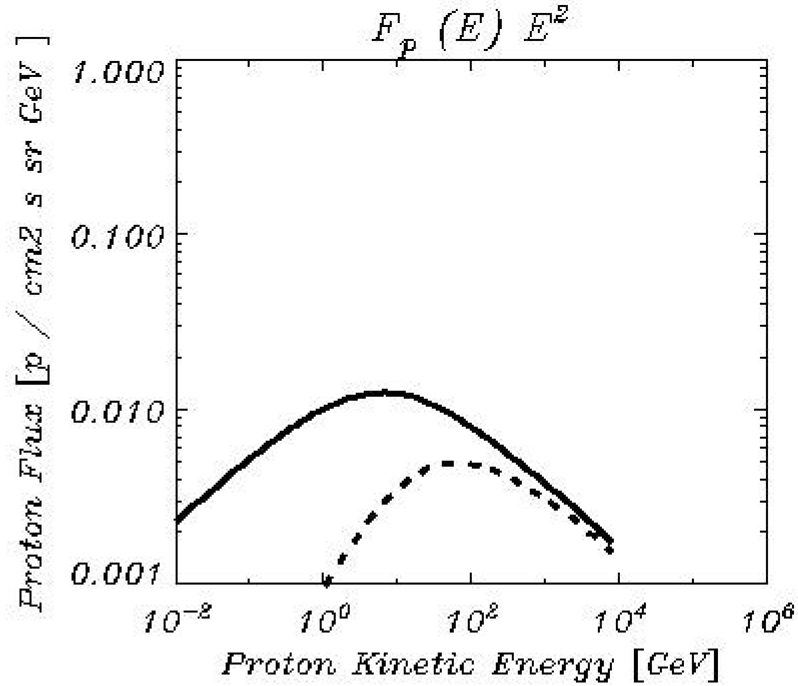


$$F(E) = K\,E^{-p} \qquad [\text{ particles / cm}^2 \text{ s sr GeV }]$$

: protons + ISM nuclei → π^0 → γ rays

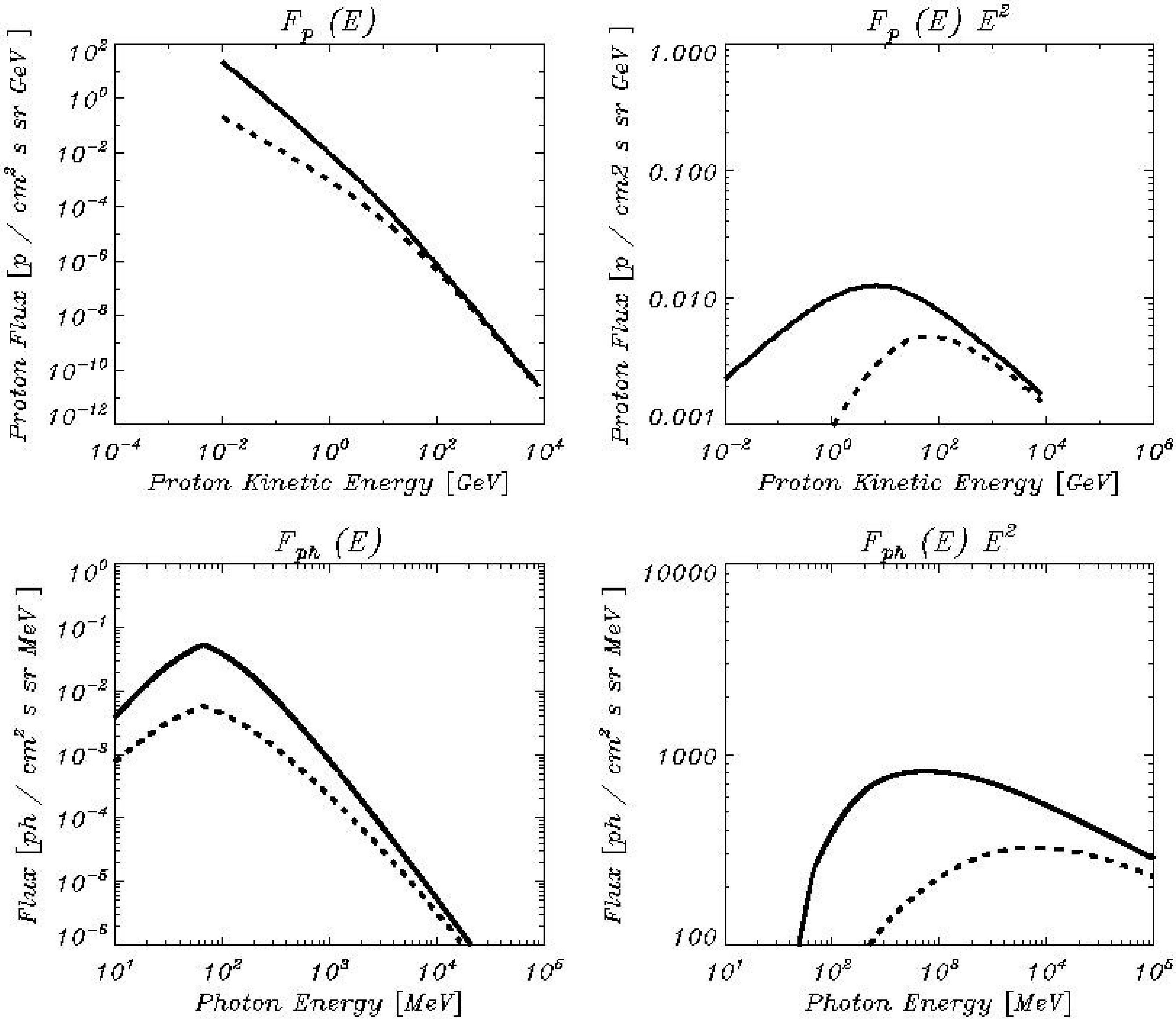






For a given R and D :

$$E_{cut} = \left(\frac{R^2}{4tD_0} \right)^{\frac{1}{\delta}}$$



$F_p\ (E)$
Proton Flux [p / cm^2 s sr GeV]
Proton Kinetic Energy [GeV]
$F_p\ (E)\ E^2$
Proton Flux [p / cm2 s sr GeV]
Proton Kinetic Energy [GeV]
$F_{ph}\ (E)$
Flux [ph / cm^2 s sr MeV]
Photon Energy [MeV]
$F_{ph}\ (E)\ E^2$
Flux [ph / cm^2 s sr MeV]
Photon Energy [MeV]