

A (Galactic) case study: the supernova remnant **RX J1713.7-3946**

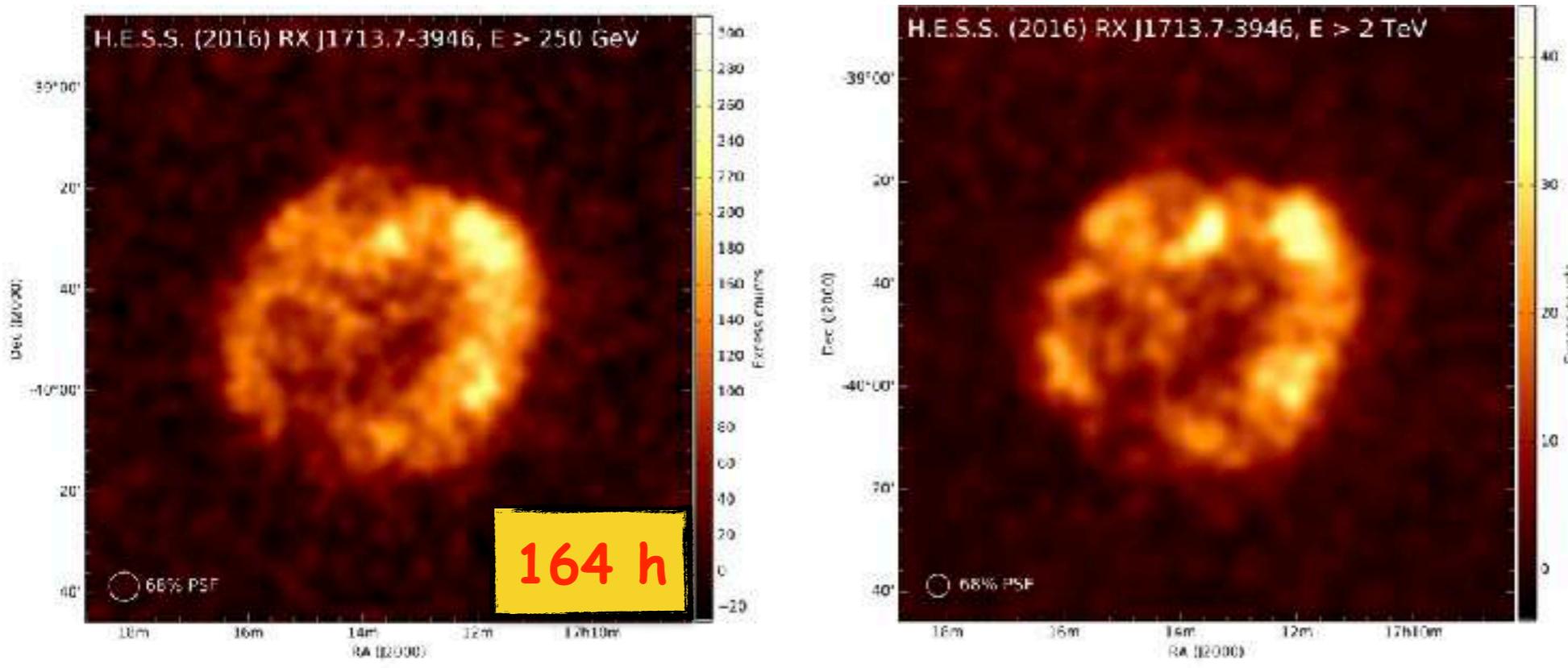


Stefano Gabici
APC, Paris

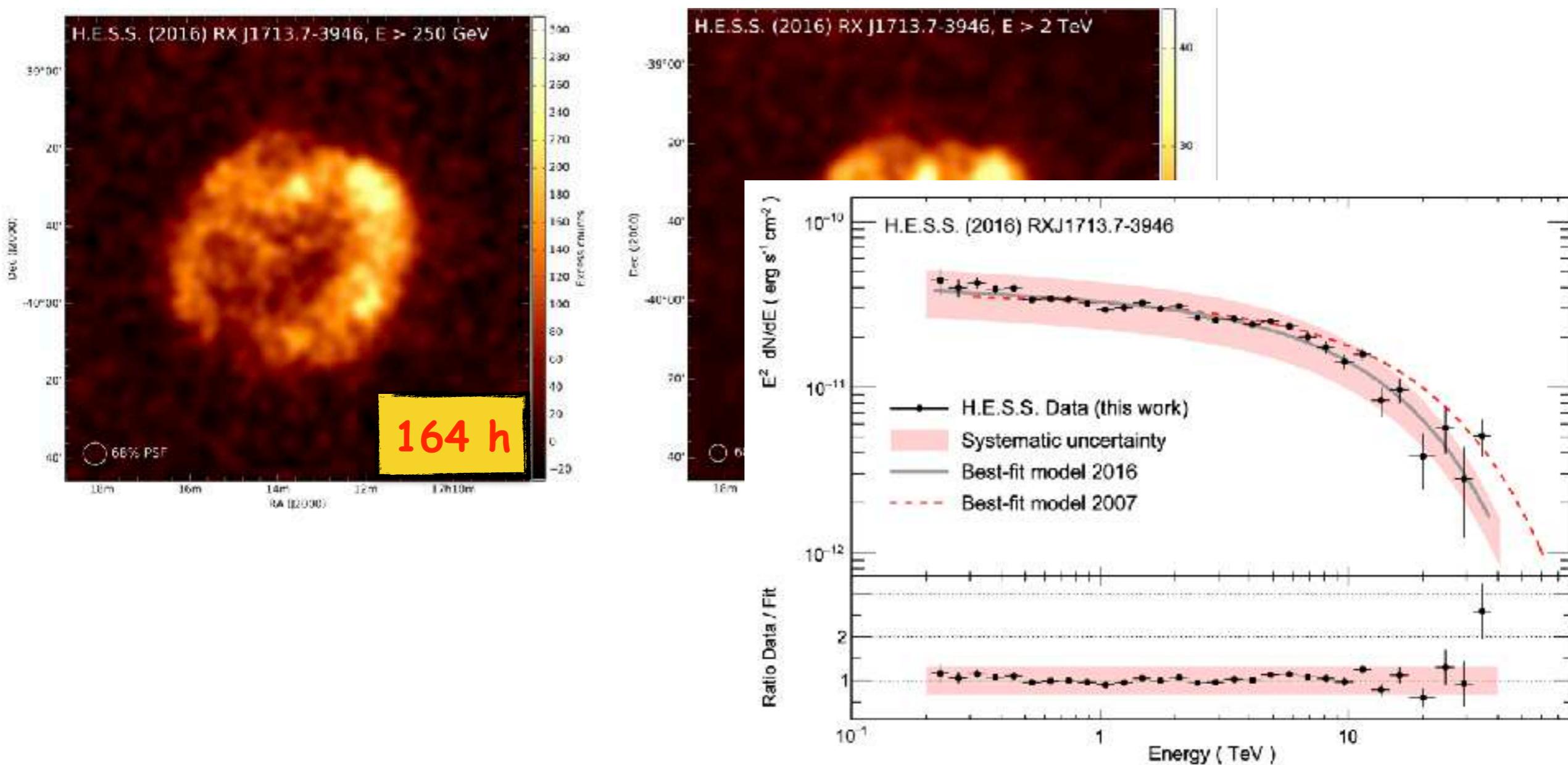


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H.E.S.S. observations of RX J1713.7–3946 with improved angular and spectral resolution: Evidence for gamma-ray emission extending beyond the X-ray emitting shell[★]



H.E.S.S. observations of RX J1713.7–3946 with improved angular and spectral resolution: Evidence for gamma-ray emission extending beyond the X-ray emitting shell[★]



Why do we care?



COSMIC RAYS FROM SUPER-NOVAE

By W. BAADE AND F. ZWICKY

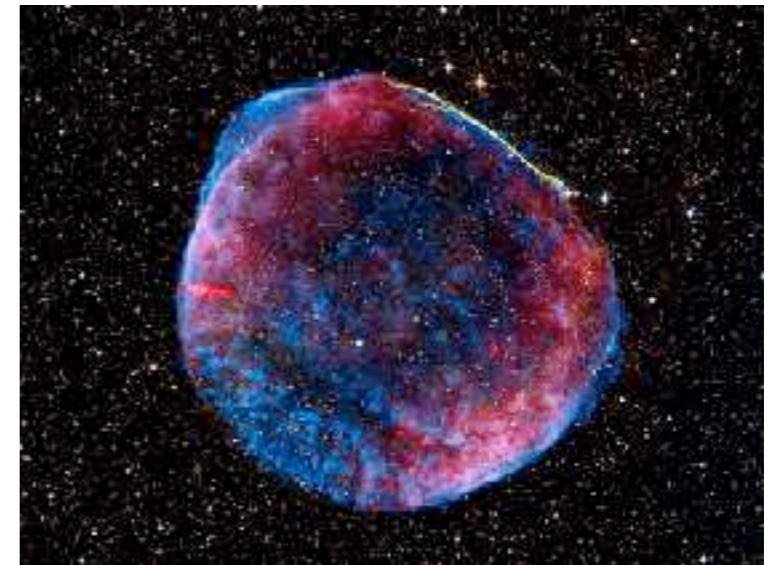
MOUNT WILSON OBSERVATORY, CARNEGIE INSTITUTION OF WASHINGTON AND CALIFORNIA INSTITUTE OF TECHNOLOGY, PASADENA

Communicated March 19, 1934

A. Introduction.—Two important facts support the view that cosmic rays are of extragalactic origin, if, for the moment, we disregard the possibility that the earth may possess a very high and self-renewing electrostatic potential with respect to interstellar space.

to my knowledge, the first paper invoking **Galactic** supernovae as sources of CRs is Ter Haar 1950

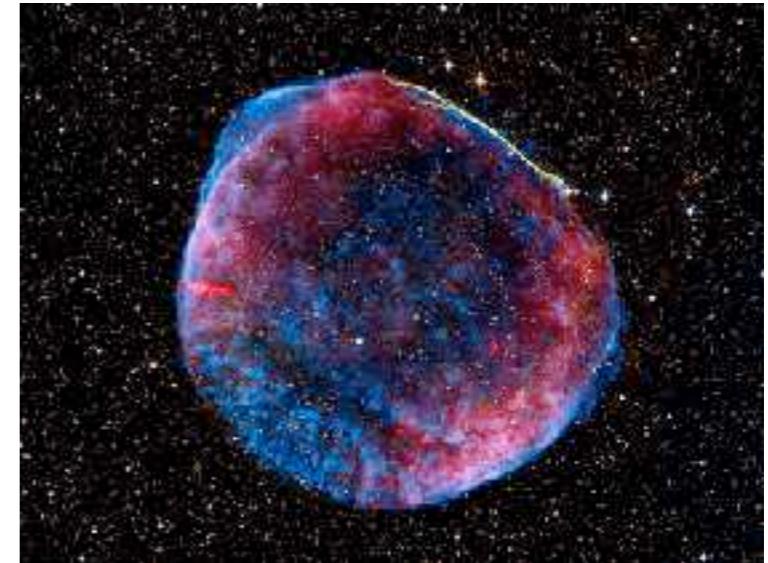
The supernova remnant origin of CRs



The supernova remnant origin of CRs

modern formulation of the hypothesis

3 SN/century in the Galaxy, each one releases
 10^{51} erg in form of kinetic energy.

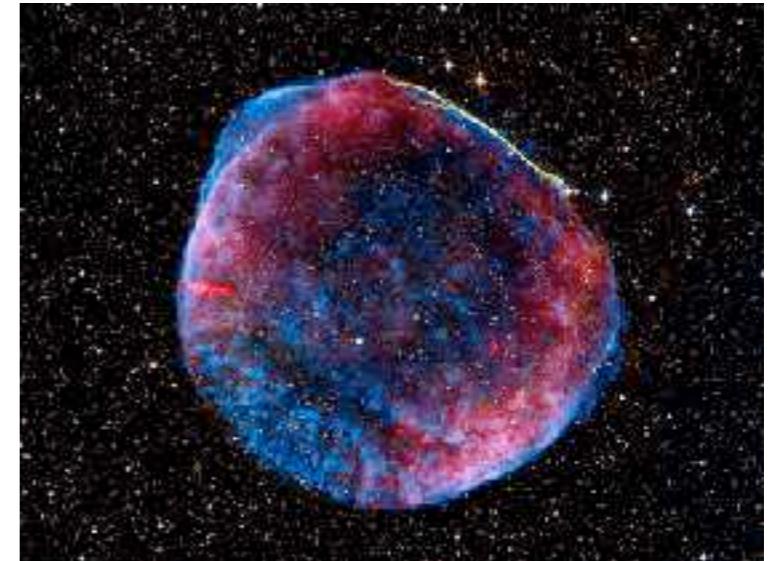


$$W_{SN} = 10^{42} \left(\frac{E_{SN}}{10^{51} \text{erg}} \right) \left(\frac{\nu_{SN}}{3/\text{century}} \right) \text{erg/s}$$

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$$W_{SN} = 10^{42} \left(\frac{E_{SN}}{10^{51} \text{erg}} \right) \left(\frac{\text{century}}{\tau} \right) \text{erg/s}$$

~10% acceleration efficiency

$$W_{CR} = \frac{\omega_{CR} V_{disk}}{\tau_{ISM}} \approx 10^{41} \text{erg/s}$$

The supernova remnant origin of CRs

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$$W_{SN} = 10^{42} \left(\frac{E_{SN}}{10^{51} \text{erg}} \right) \left(\frac{\text{century}}{1} \right) \text{erg/s}$$

~10% acceleration efficiency

$$W_{CR} = \frac{\omega_{CR} V_{disk}}{\tau_{ISM}} \approx 10^{41} \text{erg/s}$$

why remnants? —> radio observations —> particle acceleration at SNR shocks!

Why just one object?

I asked google and...

Success = Focusing on 'One Thing' at a time



- omar itani -

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more seriously: focus on the approach rather than
the details of the object under examination



Let's start from the beginning...

The discovery of RX J1713.7-3946

MPE Report 203, 1996

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ROSAT Observation of a New Supernova Remnant in the Constellation Scorpius

E. Pfeffermann and B. Aschenbach

Max-Planck-Institut für Extraterrestrische Physik, Giessenbachstrasse, D-85740 Garching, Germany

Abstract. During the ROSAT X-ray all-sky survey a previously unknown extended X-ray source has been discovered centered at $\alpha(2000) = 17^{\text{h}}13^{\text{m}}42^{\text{s}}$, $\delta(2000) = -39^{\circ}46'27''$. The source has a slightly elliptical shape with a maximum extent of $\sim 70'$. The size, the morphology and the energy spectrum suggest a thermal, shell-type galactic supernova remnant. The X-ray spectrum of the remnant shows pronounced absorption at low energies with significant variation of the absorbing column density across the emission region. The X-ray flux is 4.4×10^{-10} erg cm $^{-2}$ s $^{-1}$ between 0.1 - 2.4 keV ranking it among the brightest galactic supernova remnants. The Sedov solution with a canonical SN explosion energy of 10^{51} erg puts the remnant at a distance of 1.1 kpc, with a surprising low age of ~ 2100 years. Two X-ray point sources have been detected in the extended emission region. Candidates for the eastern point source are the Wolf-Rayet star WR 85 embedded in an H α region of 13' radius (RCW 118) and a G5IA star. A counterpart for the second source could not yet be found.

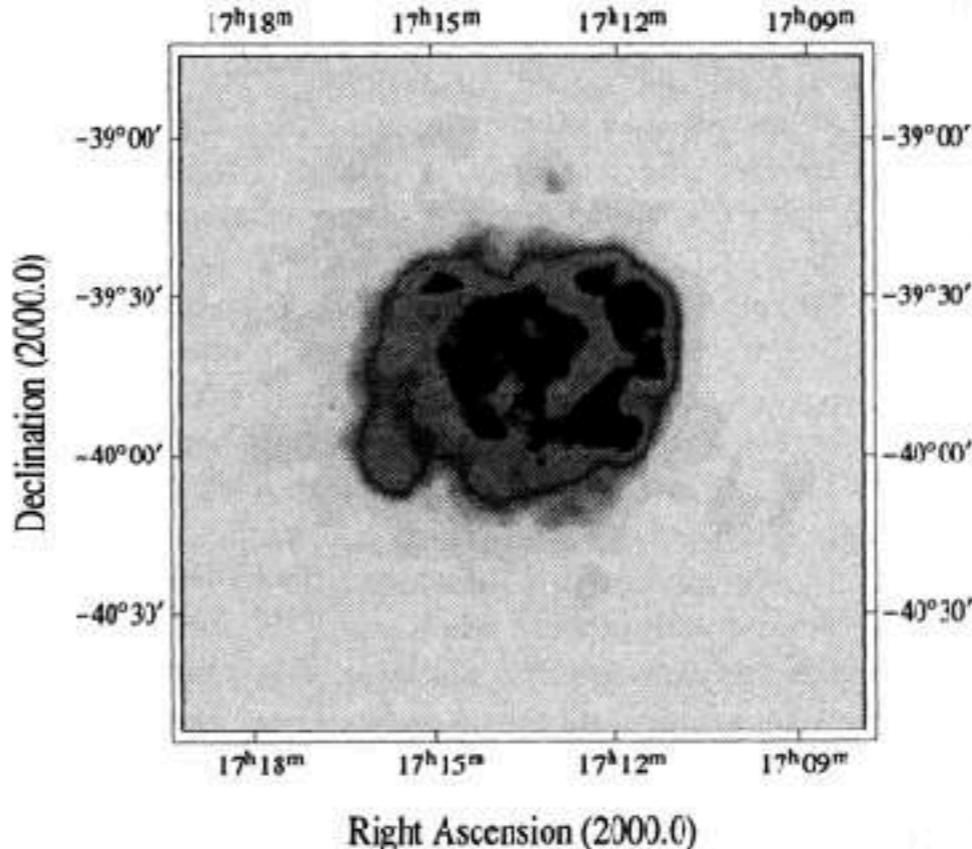


Fig. 1. Smoothed X-ray image of RX J1713.7-3946 in the energy range from 0.5- 2.4 keV.

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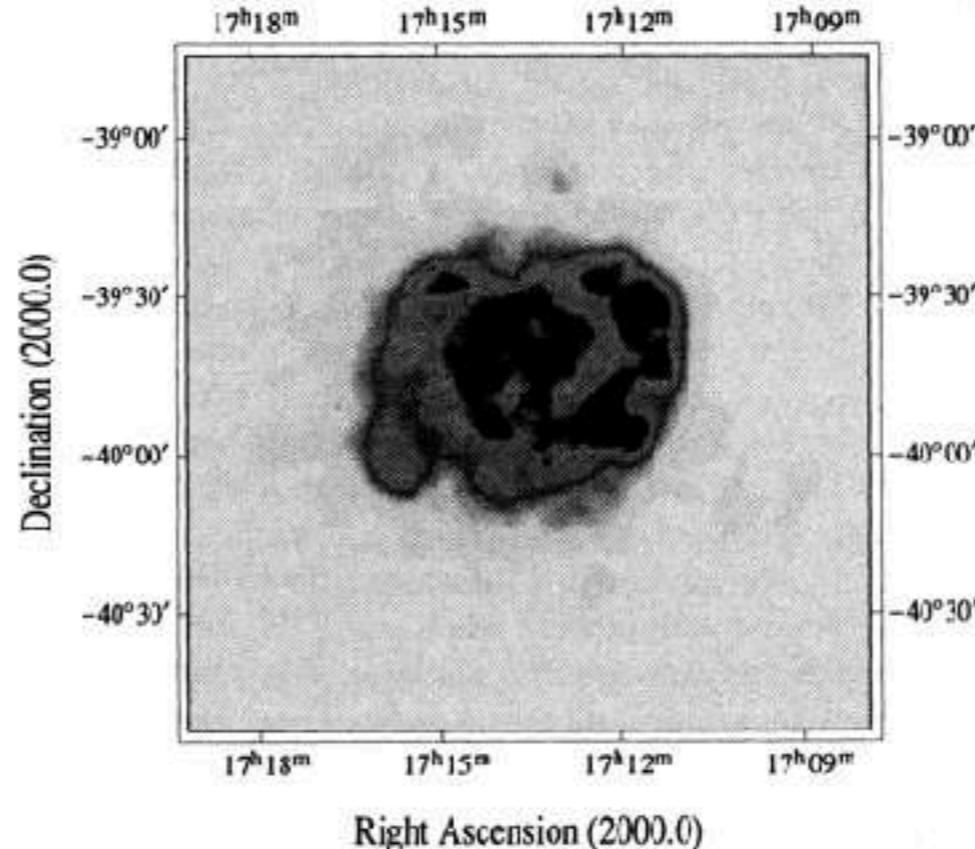


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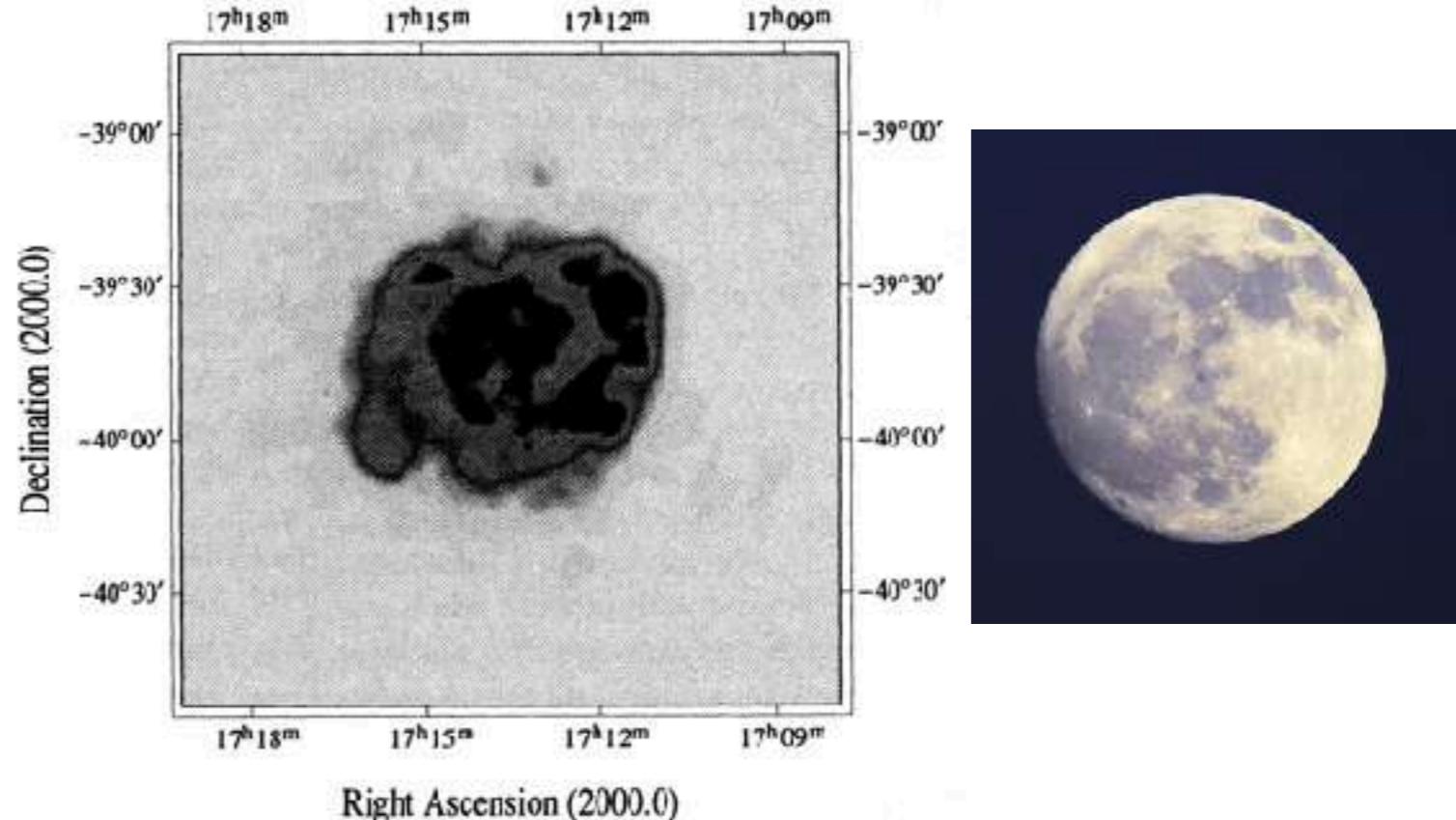


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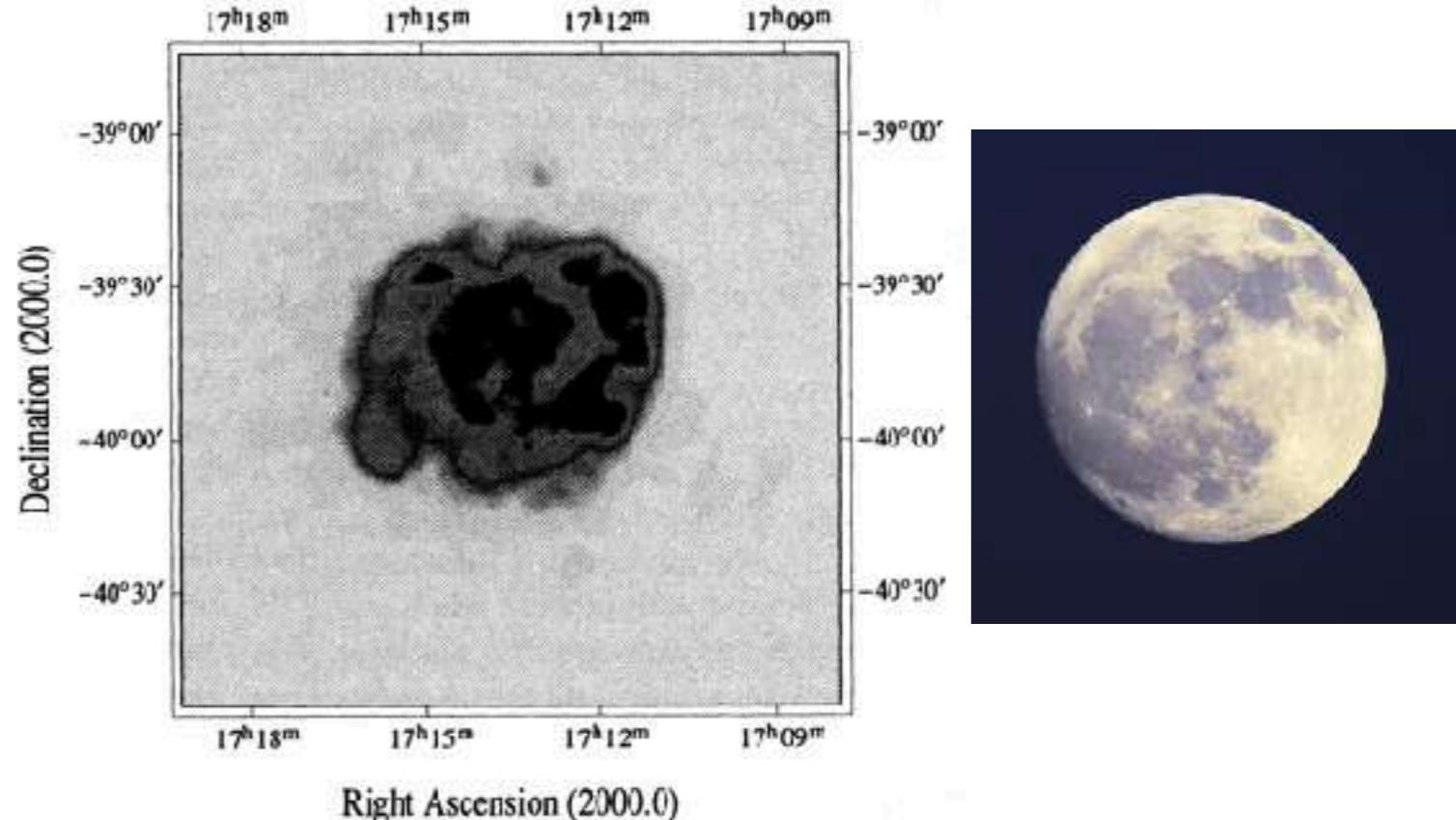
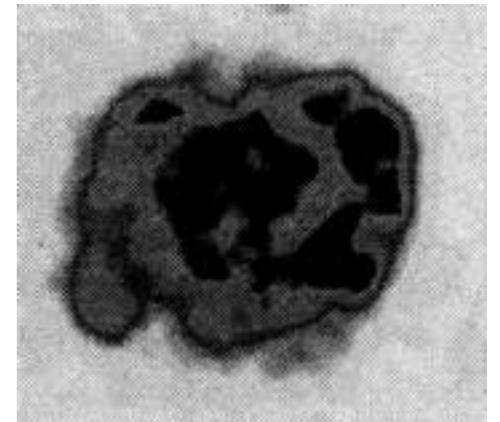


Fig. 1. Smoothed X-ray image of RX J1713.7-3946 in the energy range from 0.5- 2.4 keV.

**[Question 1] What is the
distance to the object we
want to study?**

How far is RX J1713.7-3946 ?

X-rays

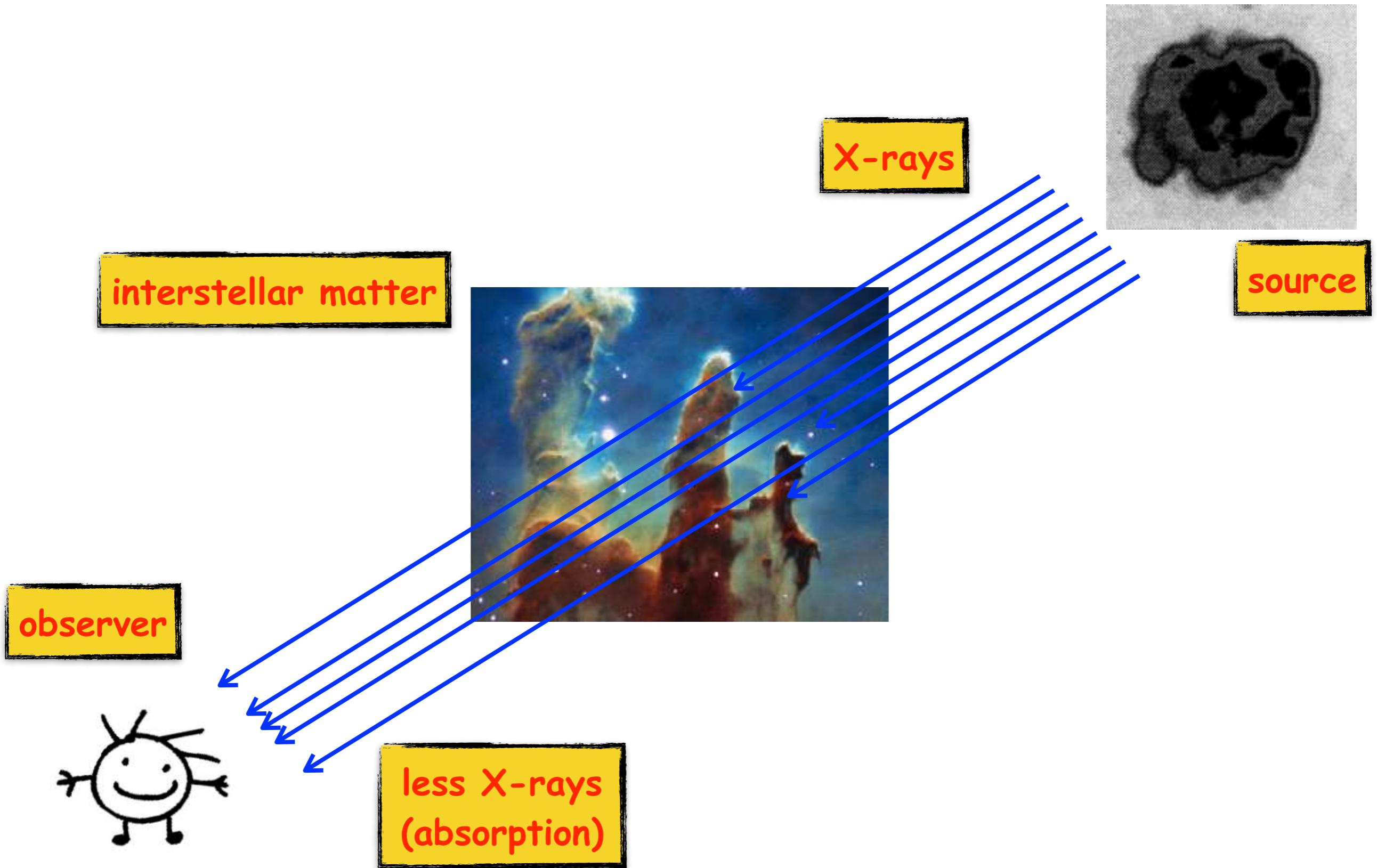


source

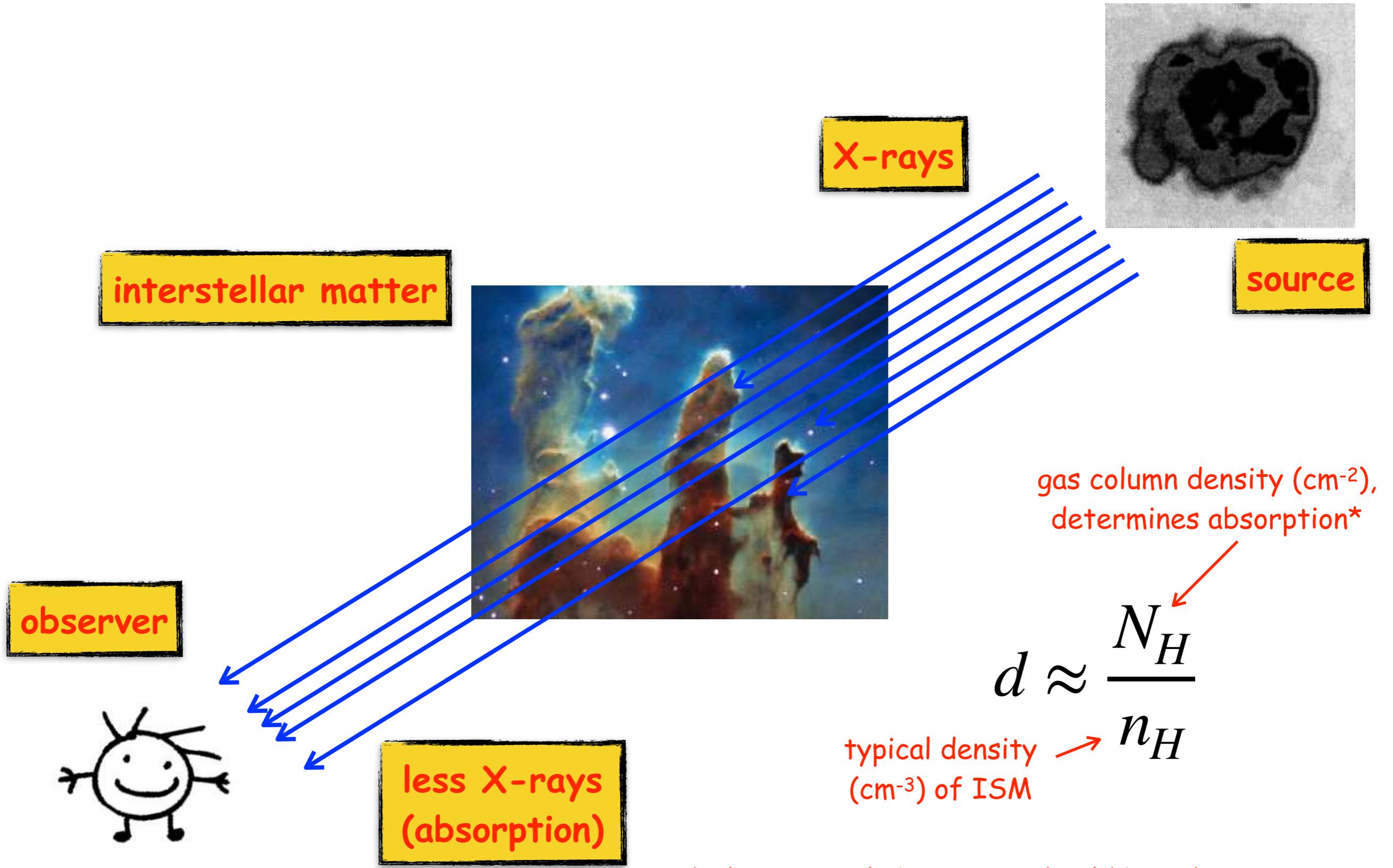
observer



How far is RX J1713.7-3946 ?



How far is RX J1713.7-3946 ?



How far is RX J1713.7-3946 ?

$$d \approx 1 - 2 \text{ kpc}$$

extremely rough, but
measuring distances is tough!

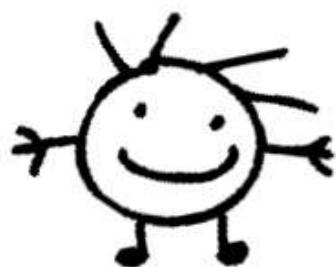
X-rays



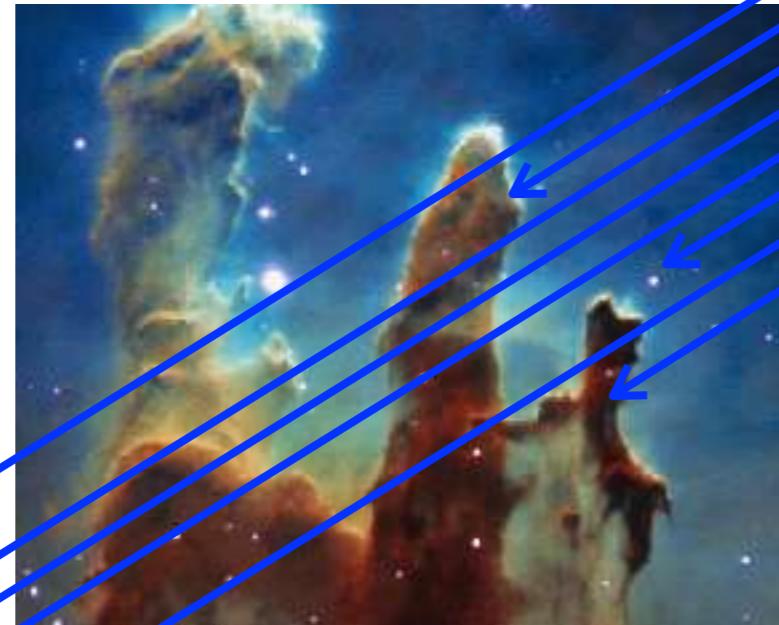
interstellar matter

source

observer



less X-rays
(absorption)



gas column density (cm^{-2}),
determines absorption*

$$d \approx \frac{N_H}{n_H}$$

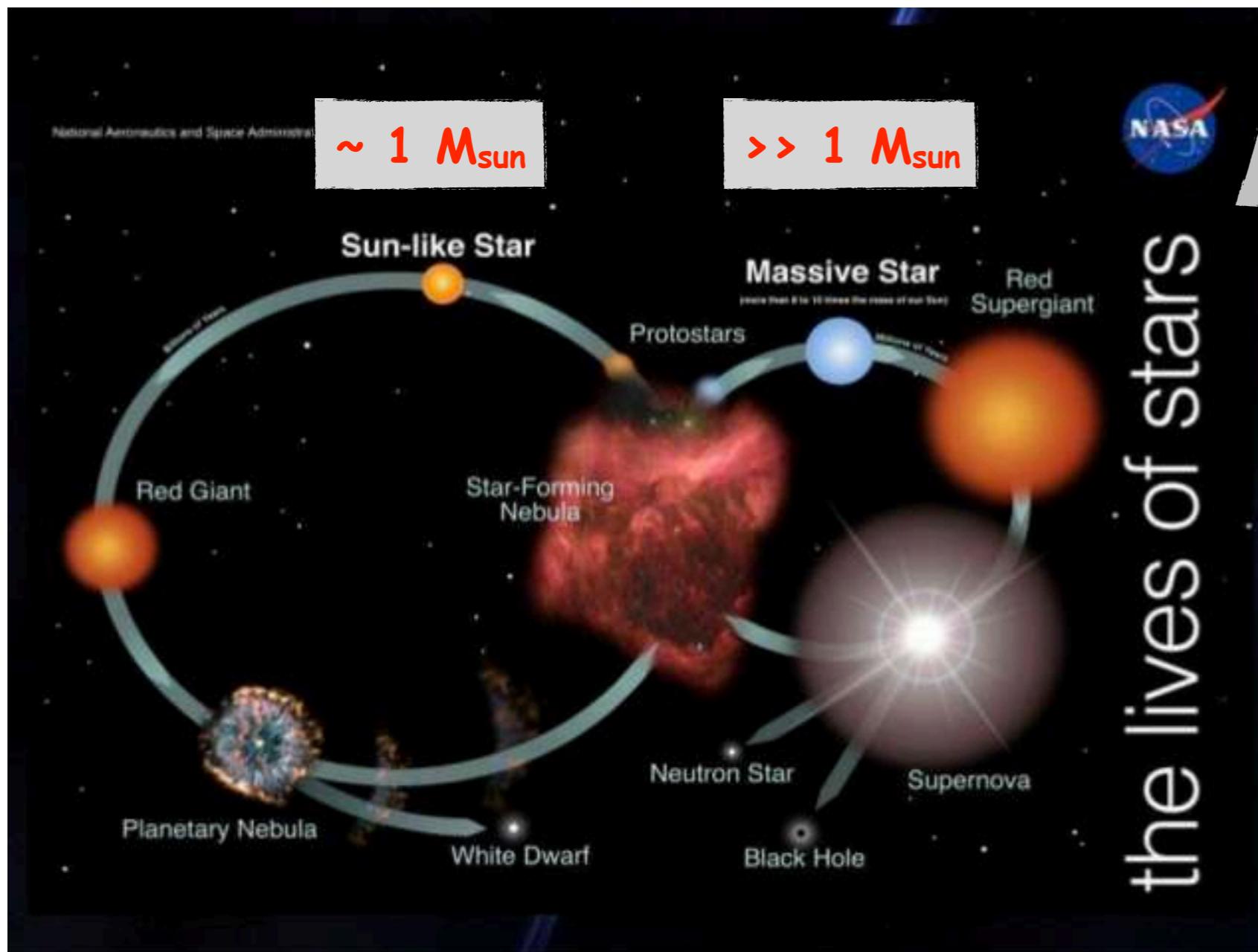
typical density
(cm^{-3}) of ISM

* also internal absorption should be taken into account...

[Question 2] How old is
the object we want to
study?

[Inset 1] The life of a supernova remnant

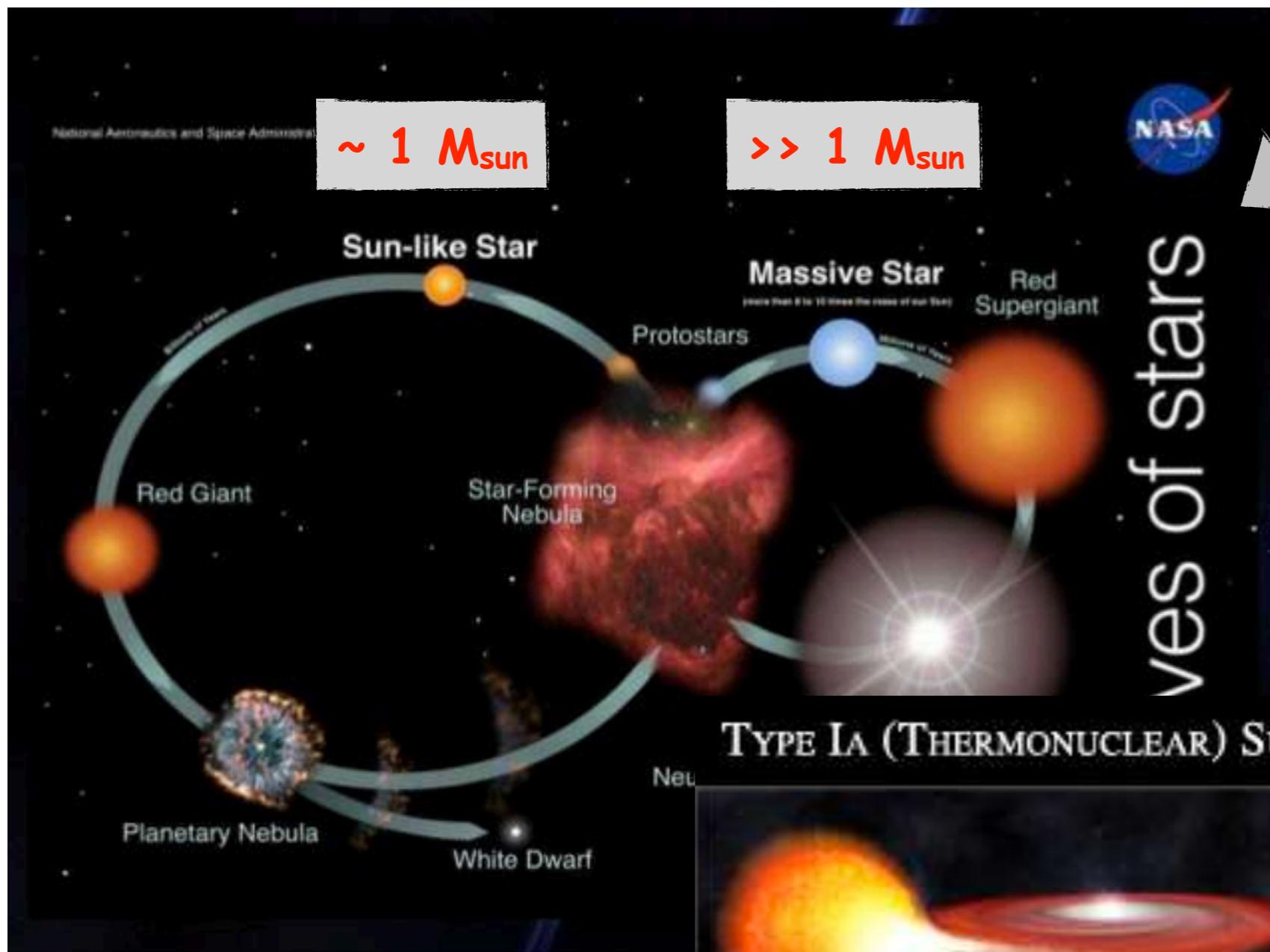
Thermonuclear & core-collapse supernovae



core-collapse

$M_{ej} \sim \text{several } M_{\odot}$

Thermonuclear & core-collapse supernovae



core-collapse

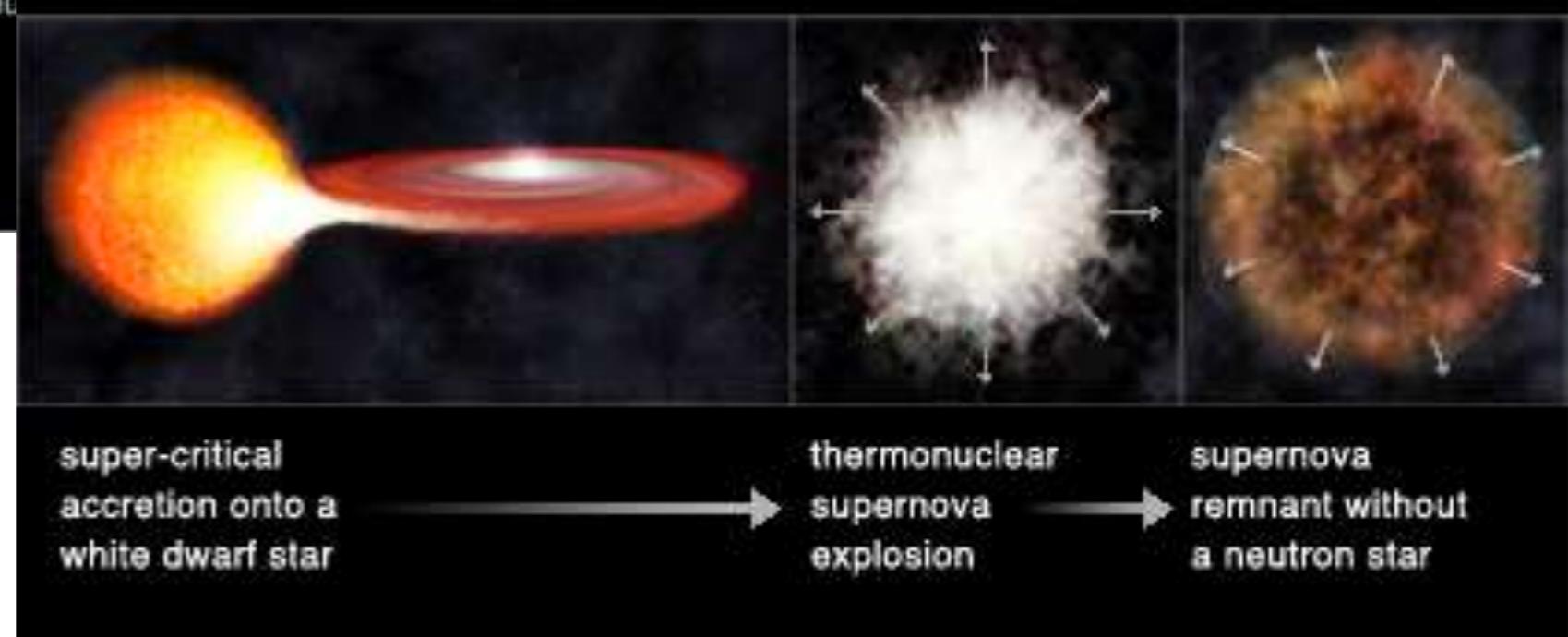
$M_{ej} \sim \text{several } M_{\odot}$

$M_{ej} \sim 1.4 M_{\odot}$

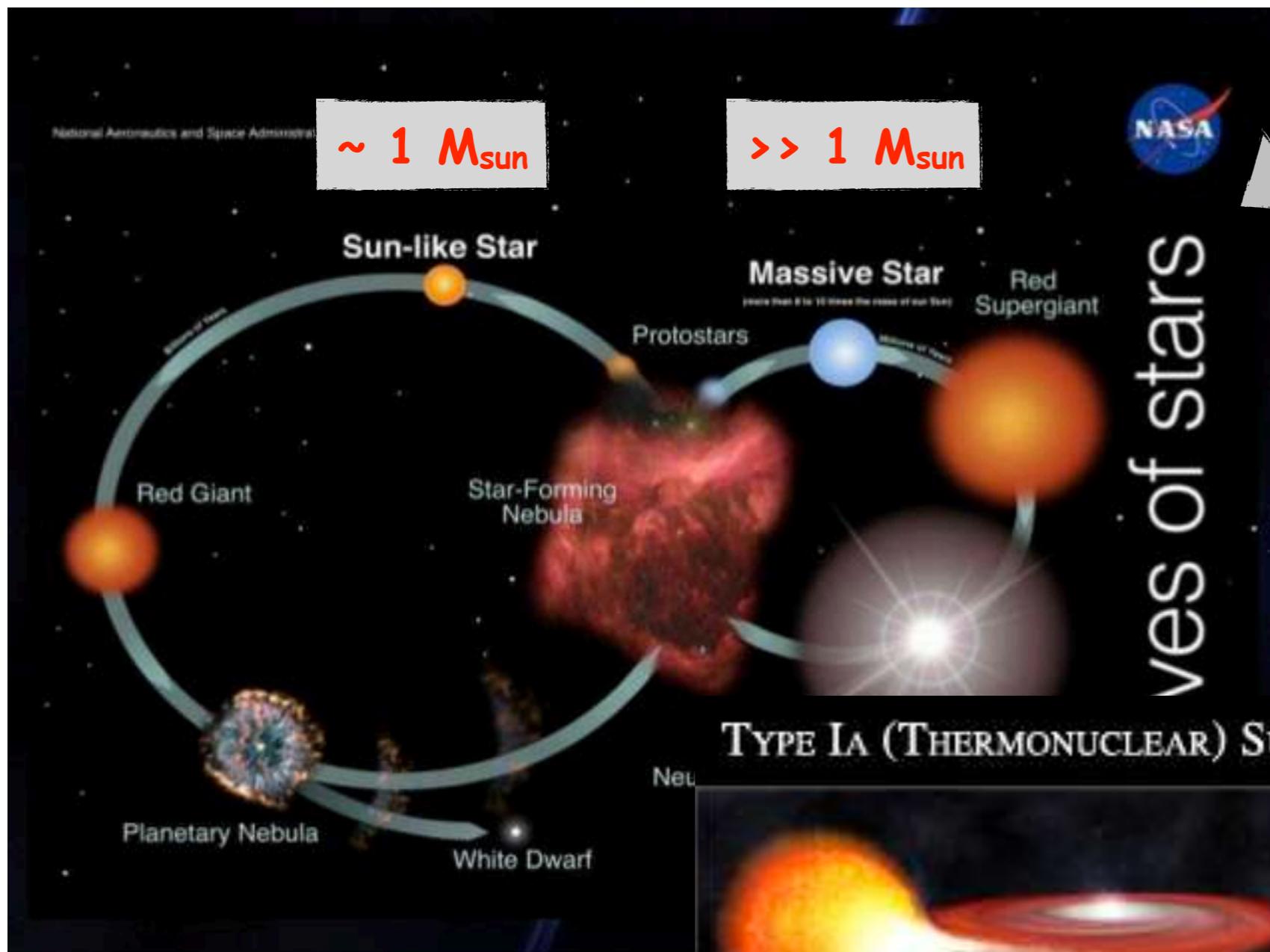
thermonuclear

TYPE Ia (THERMONUCLEAR) SUPERNOVA

(NOT TO SCALE)

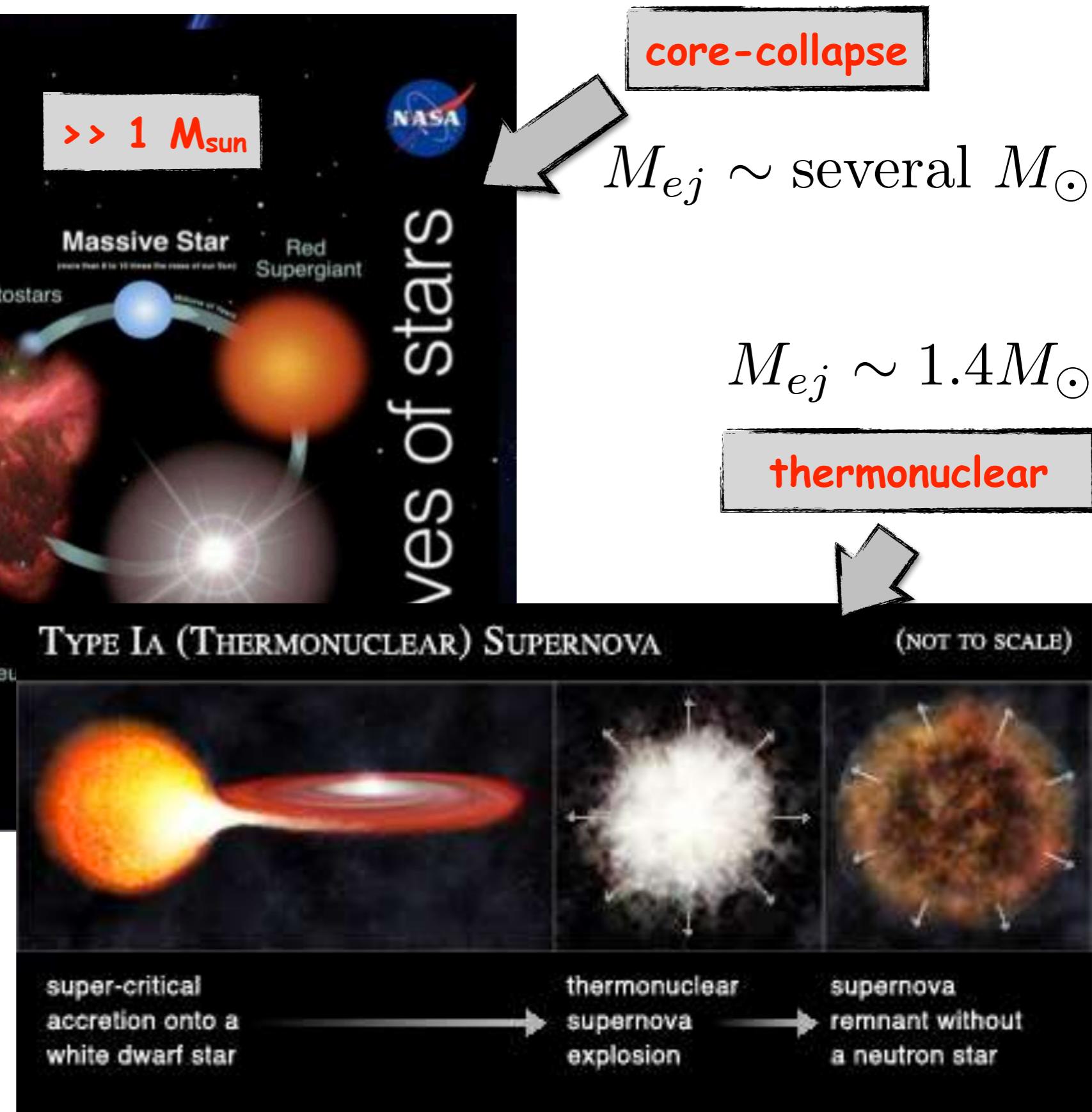


Thermonuclear & core-collapse supernovae



explosion energy

$$E_{SN} \sim 10^{51} \text{ erg}$$



Astrophysical explosions

interstellar medium

pressure
 P density
 ρ



massive star

Astrophysical explosions

interstellar medium

mass of the ejecta

explosion energy

M_{ej}

E_{SN}

P

ϱ

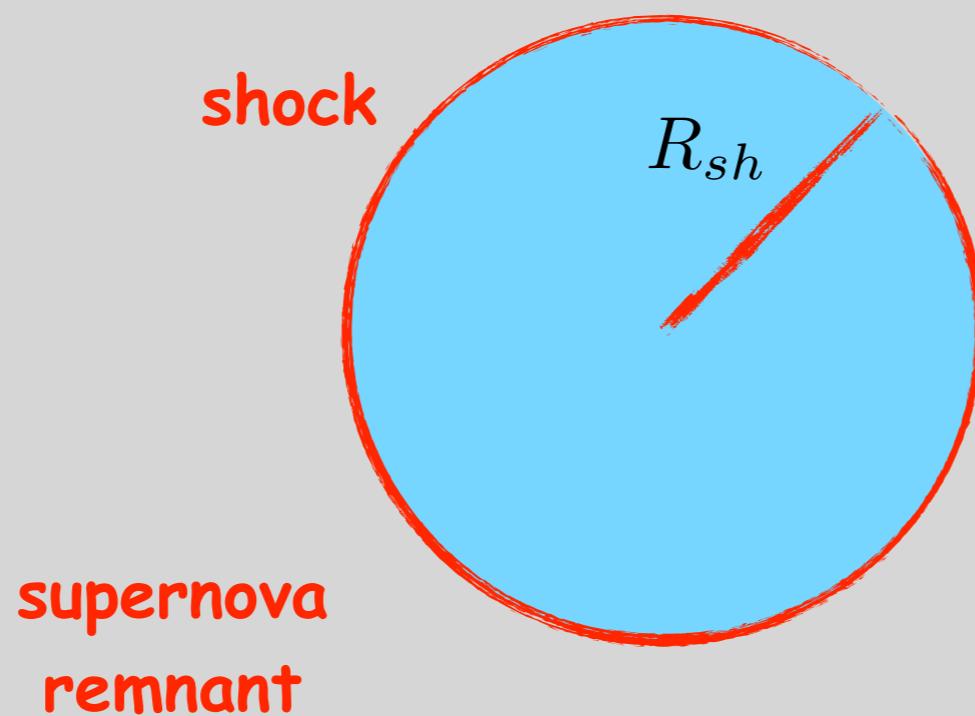
supernova



Astrophysical explosions

interstellar medium

$$M_{ej} \quad E_{SN} \quad P \quad \varrho$$

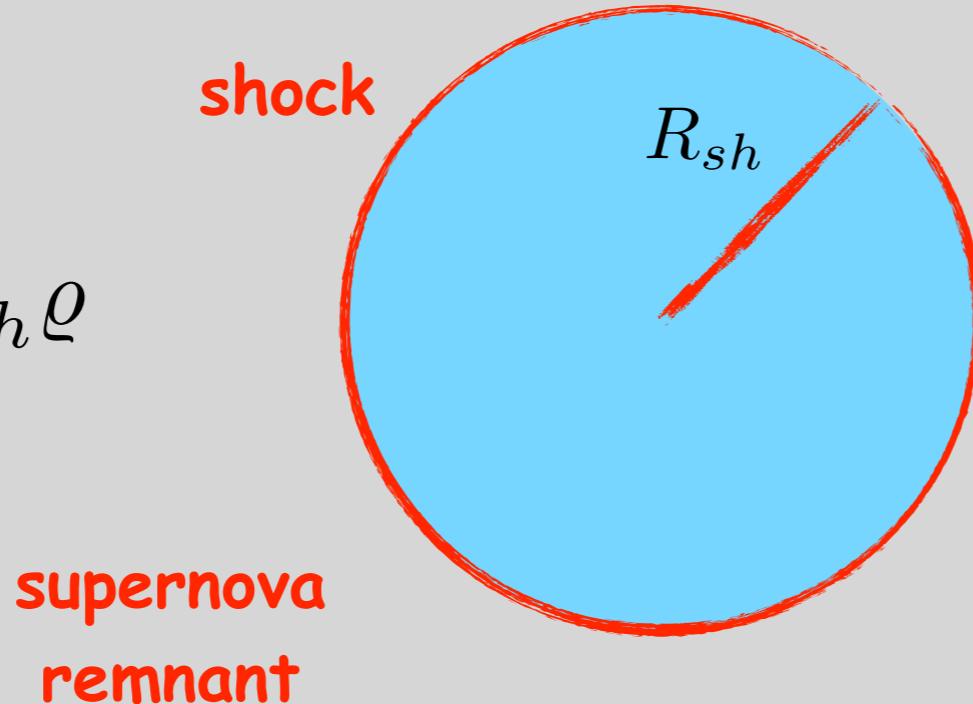


Astrophysical explosions

interstellar medium

$$M_{ej} \quad E_{SN} \quad P \quad \varrho$$

$$M_{sw} = \frac{4\pi}{3} R_{sh}^3 \varrho$$



Astrophysical explosions

interstellar medium

$$M_{sw} = \frac{4\pi}{3} R_{sh}^3 \varrho$$

shock

R_{sh}

supernova
remnant

$$M_{ej}$$

$$E_{SN}$$

$$P$$

$$\varrho$$

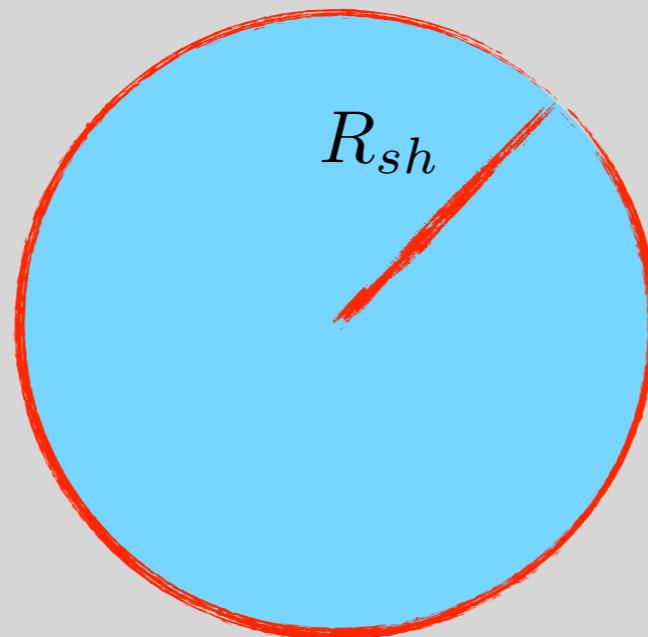
Astrophysical explosions

interstellar medium

$$M_{ej} \gg M_{sw}$$

$$M_{ej} \quad E_{SN} \quad P \quad \varrho$$

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Astrophysical explosions

interstellar medium

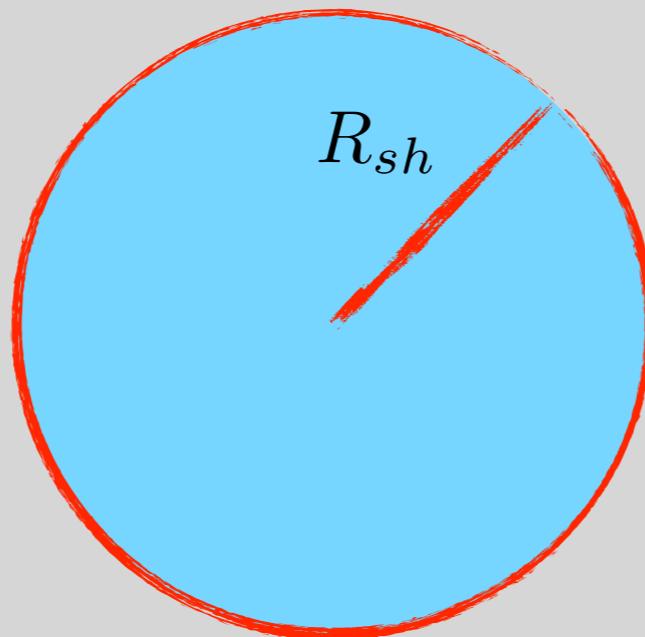
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X

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Astrophysical explosions

interstellar medium

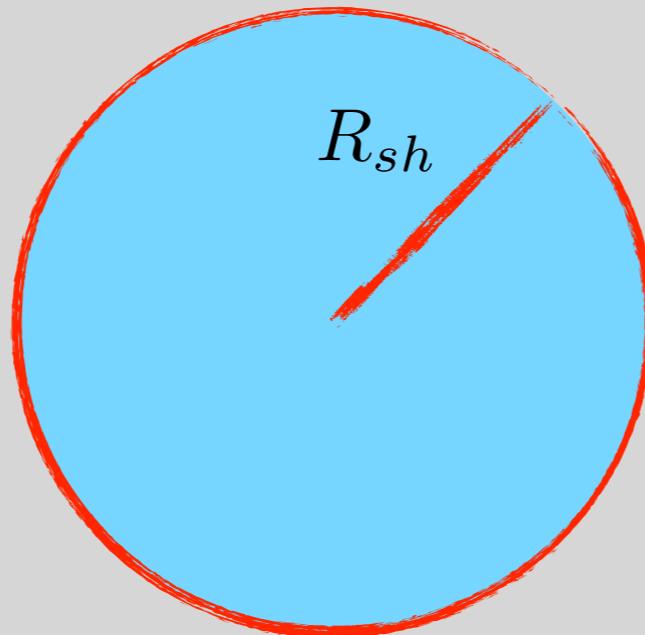
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free expansion
(constant speed)

$$E_{SN} = \frac{1}{2} M_{ej} v_{sh}^2$$

Astrophysical explosions

interstellar medium

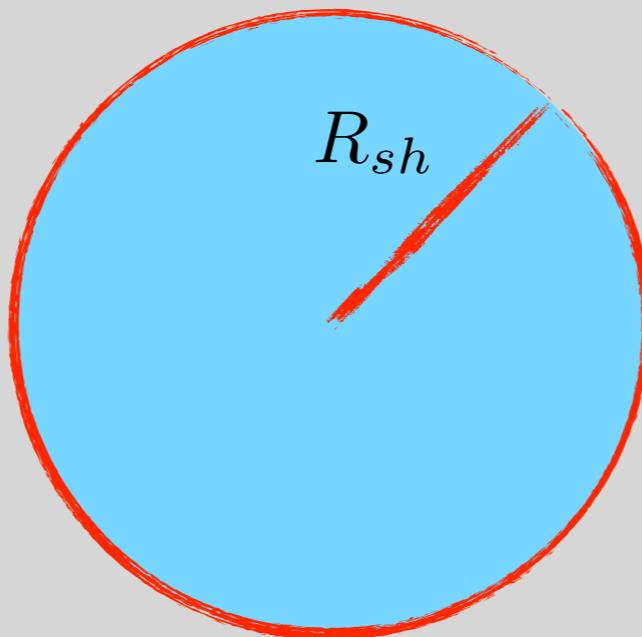
$$M_{ej} \gg M_{sw}$$

$$M_{ej} \quad E_{SN}$$

~~X~~

~~X~~

$$M_{sw} = \frac{4\pi}{3} R_{sh}^3 \varrho$$



free expansion
(constant speed)

$$E_{SN} = \frac{1}{2} M_{ej} v_{sh}^2 \rightarrow v_{sh} = \sqrt{\frac{2E_{SN}}{M_{ej}}} \sim 10000 \left(\frac{M_{ej}}{M_\odot} \right)^{-1/2} \text{ km/s}$$

Astrophysical explosions

interstellar medium

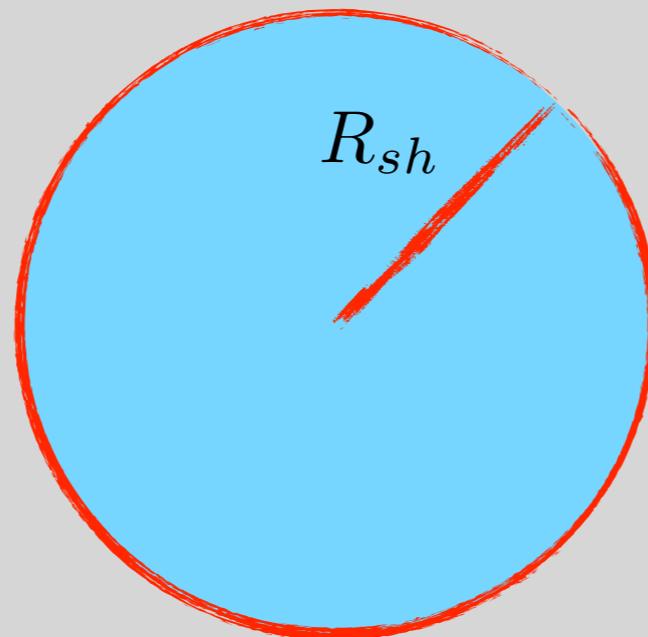
$$M_{ej} = M_{sw}$$

$$M_{ej} \quad E_{SN}$$

~~X~~

~~X~~

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Astrophysical explosions

interstellar medium

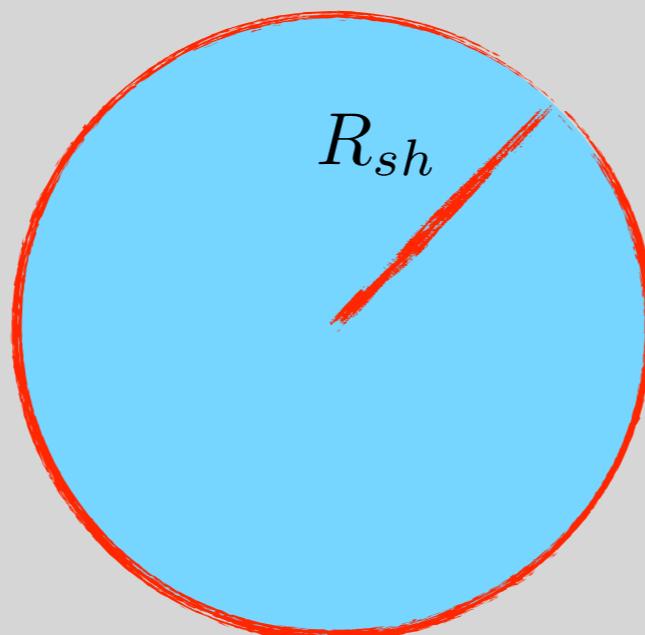
$$M_{ej} = M_{sw}$$

$$M_{ej} \quad E_{SN}$$

~~X~~

~~X~~

$$M_{sw} = \frac{4\pi}{3} R_{sh}^3 \varrho$$



$$R_* = \left(\frac{3M_{ej}}{4\pi\varrho} \right)^{1/3} \sim 2 \left(\frac{M_{ej}}{M_\odot} \right)^{1/3} \left(\frac{n}{\text{cm}^{-3}} \right)^{-1/3} \text{pc}$$

Astrophysical explosions

interstellar medium

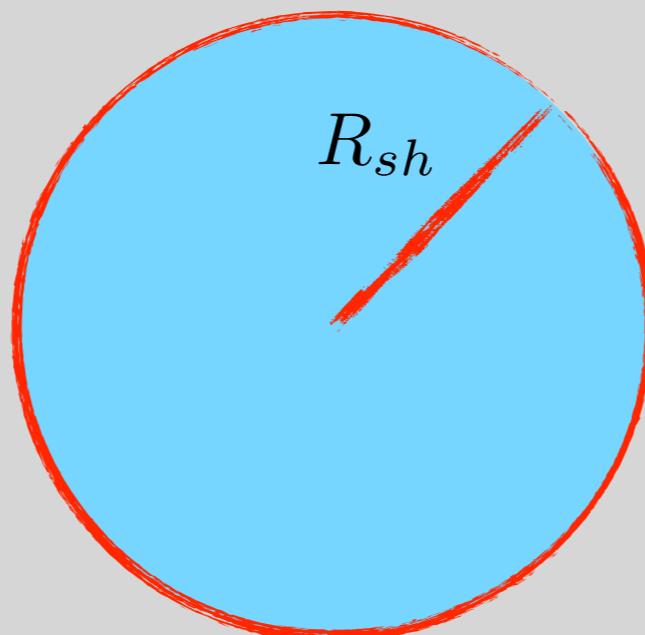
$$M_{ej} = M_{sw}$$

$$M_{ej} \quad E_{SN}$$

~~X~~

~~X~~

$$M_{sw} = \frac{4\pi}{3} R_{sh}^3 \varrho$$



it takes few centuries
to reach this moment

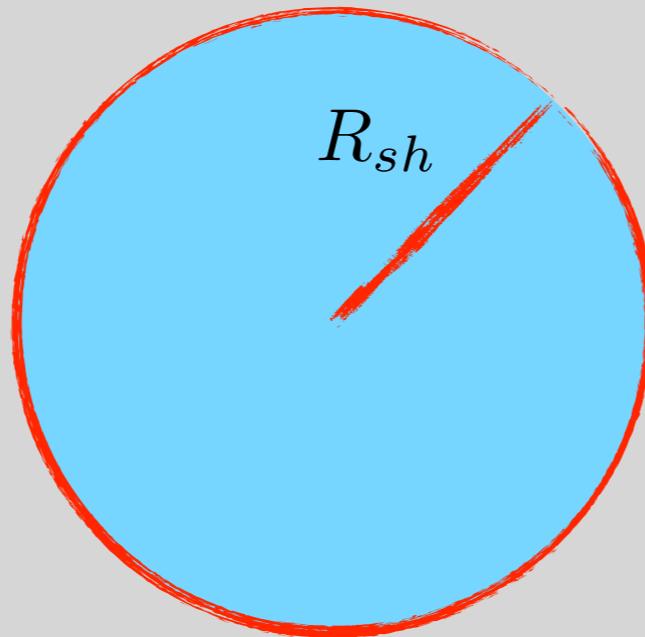
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Astrophysical explosions

interstellar medium

$$M_{ej} \ll M_{sw}$$

$$M_{ej} \quad E_{SN} \quad P \quad \varrho$$

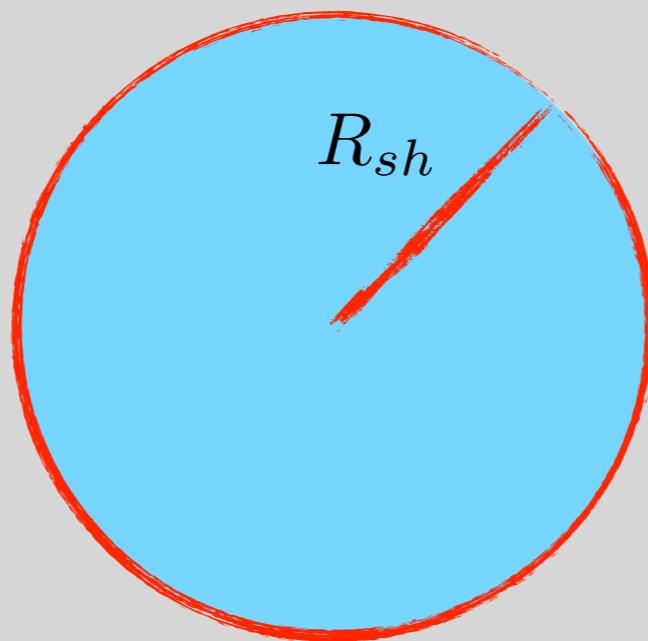


Astrophysical explosions

interstellar medium

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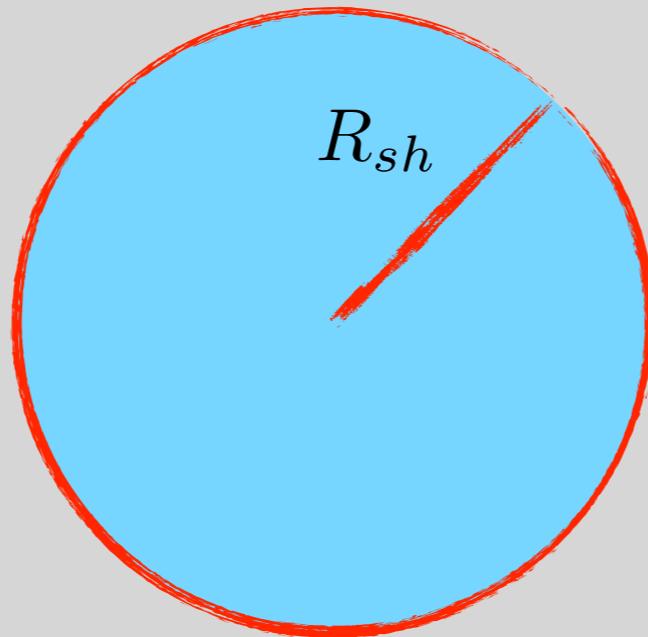
the shock begins to
feel the presence of
the ambient gas and
decelerates

Astrophysical explosions

interstellar medium

$$M_{ej} \ll M_{sw}$$

$$\cancel{M_{ej}} \quad E_{SN} \quad P \quad \varrho$$



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Astrophysical explosions

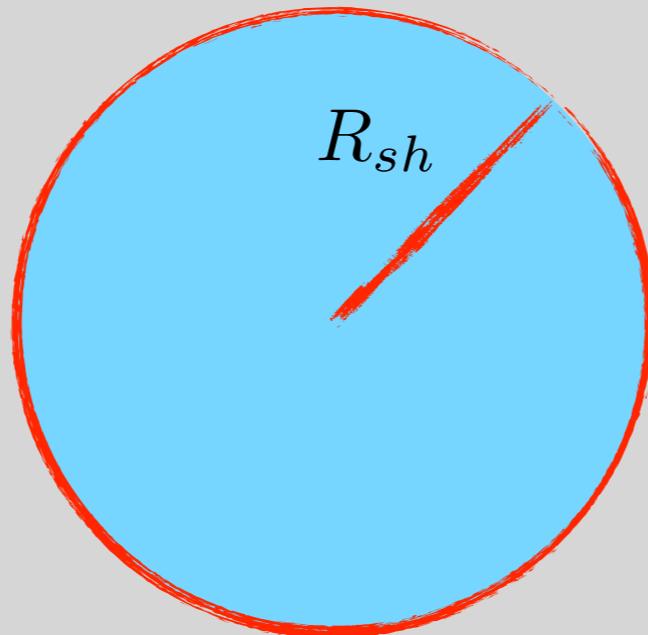
interstellar medium

$$M_{ej} \ll M_{sw}$$

$$\cancel{M_{ej}} \quad E_{SN} \quad P \quad \varrho$$

$$c_s \approx 10 \text{ km/s}$$

strong shock



the shock begins to feel the presence of the ambient gas and decelerates

Astrophysical explosions

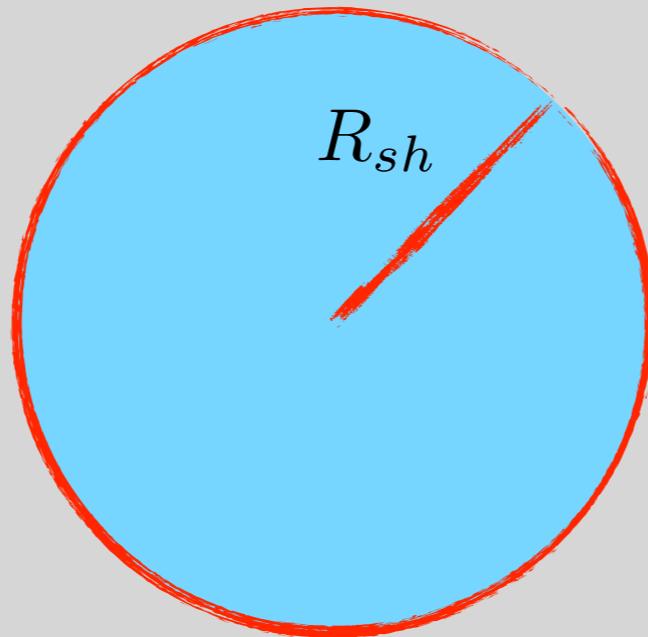
interstellar medium

$$M_{ej} \ll M_{sw}$$

$$\cancel{M_{ej}} \quad E_{SN} \quad \cancel{\times} \quad \cancel{\rho}$$

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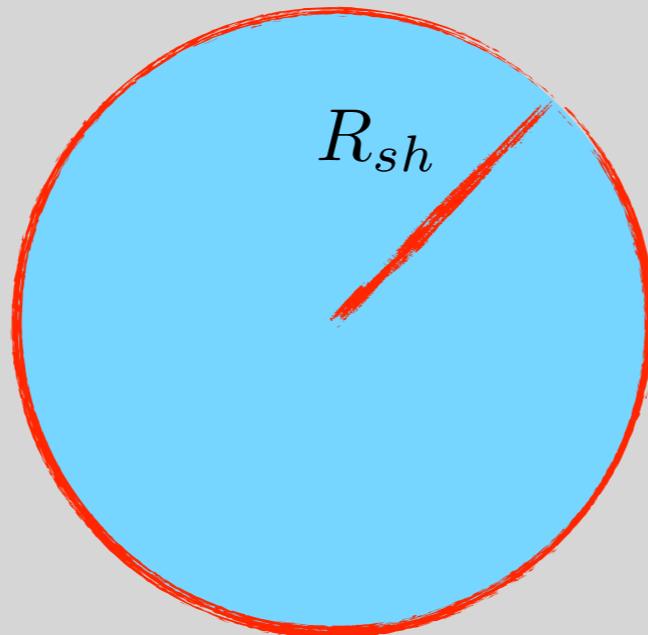
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$$\cancel{M_{ej}} \quad E_{SN} \quad \cancel{\times} \quad \cancel{\rho}$$

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strong shock



the shock begins to feel the presence of the ambient gas and decelerates

non-dimensional quantity: $a = \frac{\varrho R_{sh}^5}{E_{SN} t^2}$

Astrophysical explosions

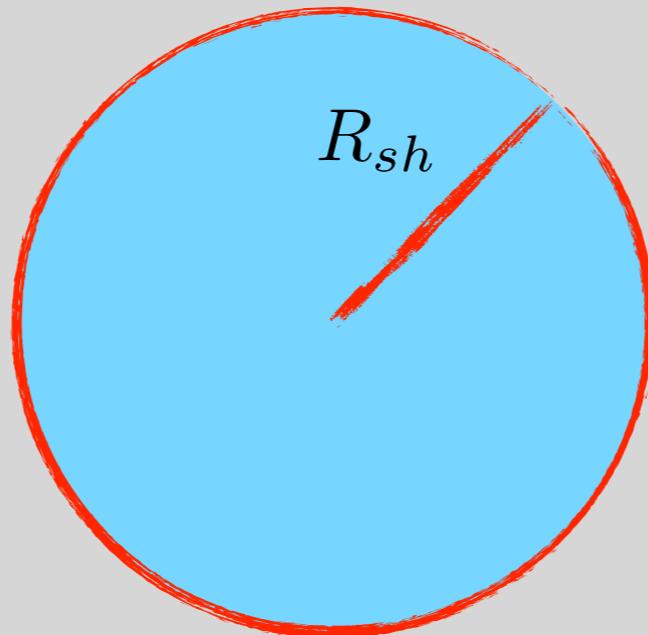
interstellar medium

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$$\cancel{M_{ej}} \quad \cancel{E_{SN}} \quad \cancel{\rho}$$

$$c_s \approx 10 \text{ km/s}$$

strong shock



the shock begins to feel the presence of the ambient gas and decelerates

non-dimensional quantity: $a = \frac{\rho}{E_{SN}} \frac{R_{sh}^5}{t^2} \rightarrow R_{sh} = a \left(\frac{E_{SN}}{\rho} \right)^{1/5} t^{2/5}$

order unity

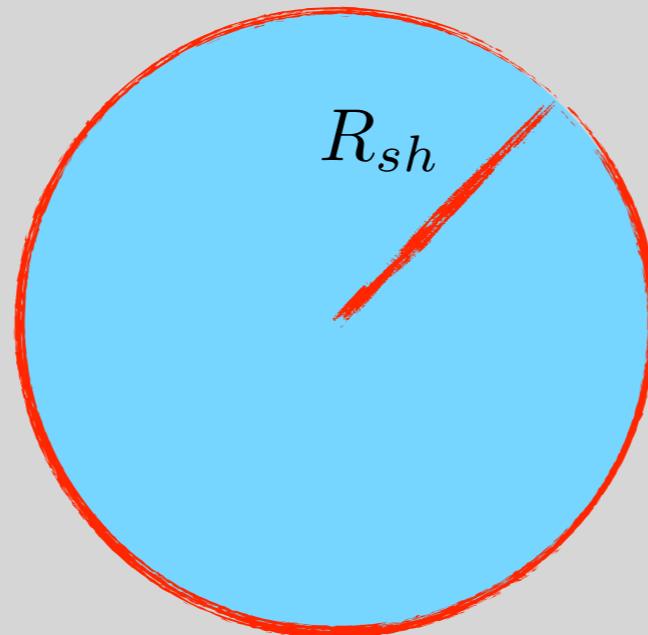
Astrophysical explosions

interstellar medium

$$M_{ej} \ll M_{sw}$$

$$\cancel{M_{ej}} \quad E_{SN} \quad \cancel{\varrho}$$

Sedov-Taylor solution



$$R_{sh} = a \left(\frac{E_{SN}}{\varrho} \right)^{1/5} t^{2/5}$$

$$u_{sh} = \frac{2}{5} \frac{R_{sh}}{t} \propto t^{-3/5}$$

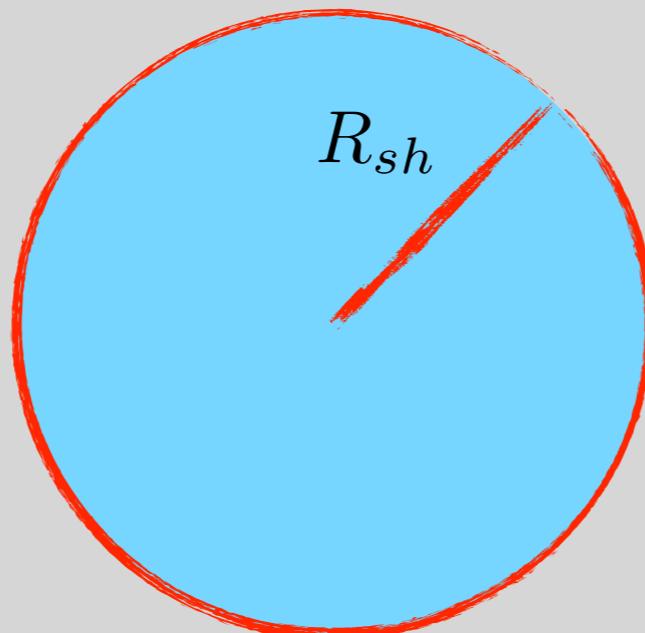
Astrophysical explosions

interstellar medium

$$M_{ej} \ll M_{sw}$$

$$\cancel{M_{ej}} \quad E_{SN} \quad \cancel{\rho}$$

Sedov-Taylor solution



This solution holds until $t \sim 10^4 - 10^5$ yr, after that the SNR cools due to emission of X-ray photons

$$R_{sh} = a \left(\frac{E_{SN}}{\rho} \right)^{1/5} t^{2/5}$$

$$u_{sh} = \frac{2}{5} \frac{R_{sh}}{t} \propto t^{-3/5}$$

SNR shocks in one slide



stellar explosion of energy $E_{SN} = 10^{51}$ erg ejecting M_{ej} solar masses

early times \rightarrow

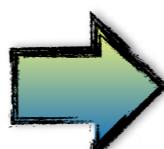
$$M_{ej} \gg M_{sw}$$

mass of the ISM swept up
by the shock

$$E_{SN} = \frac{1}{2} M_{ej} v_{sh}^2 \rightarrow v_{sh} = \sqrt{\frac{2E_{SN}}{M_{ej}}} \sim 10000 \left(\frac{M_{ej}}{M_{\odot}}\right)^{-1/2} \text{ km/s}$$

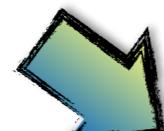
late times \rightarrow

$$M_{ej} \ll M_{sw}$$



solution must depend on ρ
(ISM density) and not M_{ej} !

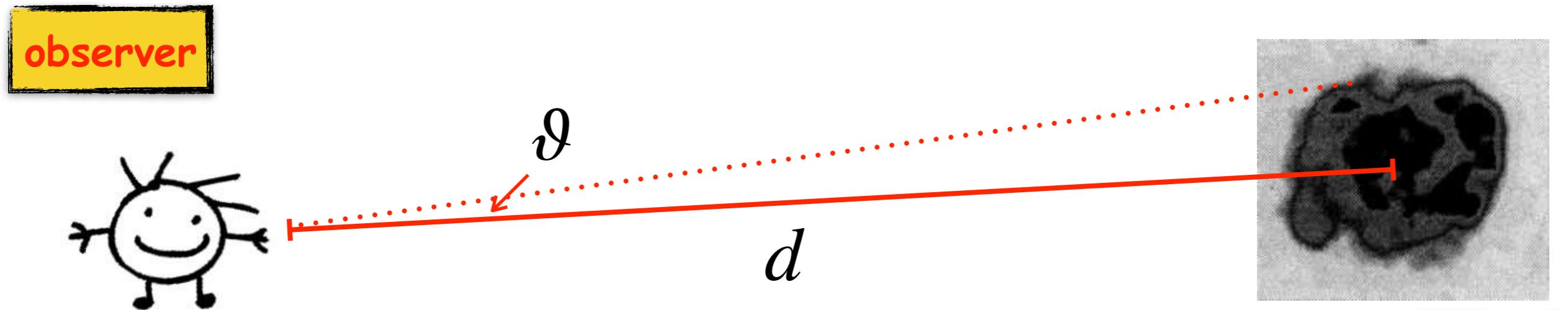
$$R_{sh} \sim \left(\frac{E_{SN}}{\rho}\right)^{1/5} t^{2/5}$$



$$u_s \sim 2 \times 10^3 \left(\frac{E_{SN}}{10^{51} \text{ erg}}\right)^{1/5} \left(\frac{n_{ISM}}{\text{cm}^{-3}}\right)^{-1/5} \left(\frac{t}{\text{kyr}}\right)^{-3/5} \text{ km/s}$$

[End of Inset 1]

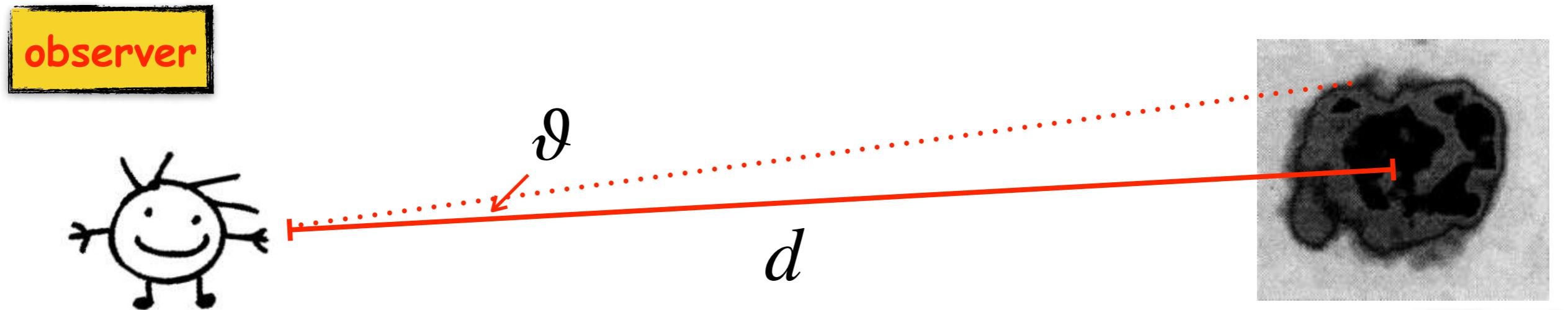
How old is RX J1713.7-3946 ?



$$R \sim d \times \vartheta \sim 10 \left(\frac{d}{\text{kpc}} \right) \text{ pc}$$

source

How old is RX J1713.7-3946 ?

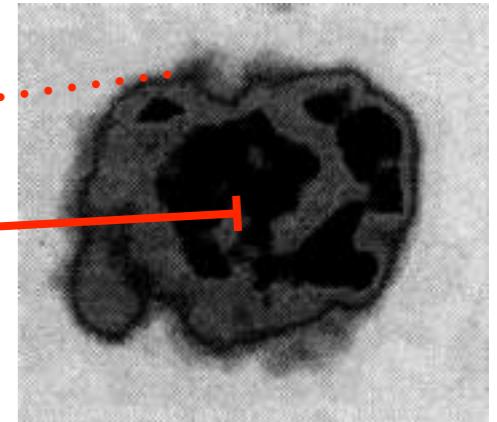
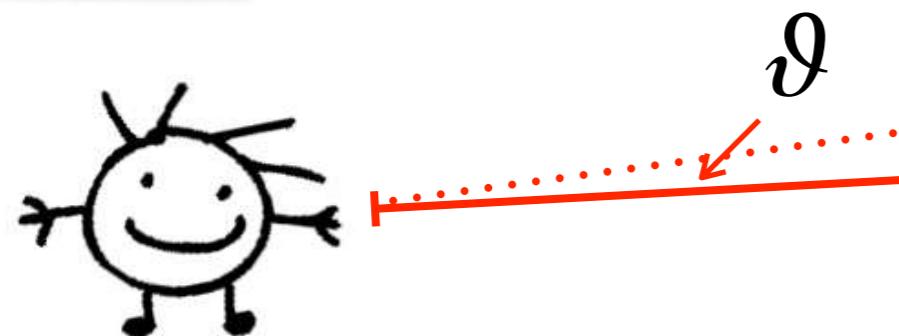


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How old is RX J1713.7-3946 ?

observer



source

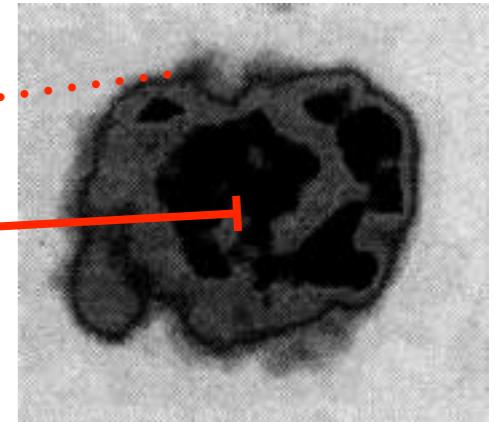
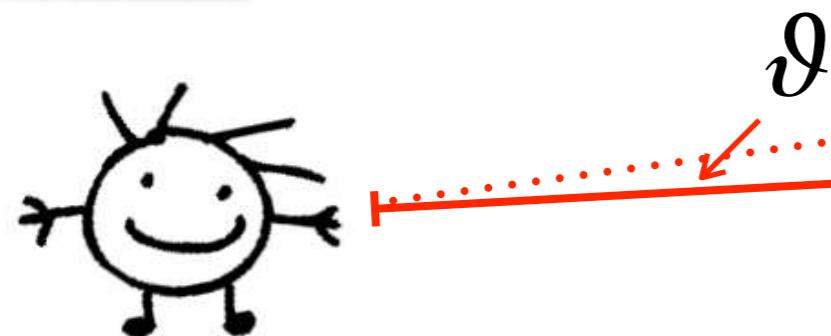
uncertainty on d is
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$$t \sim 2 \text{ kyr} \rightarrow d \sim 1 \text{ kpc}$$

→ early Sedov phase

$$t \sim 10^4 \text{ yr} \rightarrow d \sim 2 \text{ kpc}$$

→ late Sedov phase

Multiwavelenght

Mult~~x~~elenght

Mult~~x~~elenght
Multimessenger

Multilevel

Multimessenger

Mult~~ele~~length

Mult~~in~~ger

Multi-alphabet astronomy

Mult~~ele~~length
Multi~~en~~ger

Multi-alphabet astronomy

之并斬其從弟緒司馬道子由是失勢禍亂成矣
太元十六年十一月癸巳月奄心前星占曰太子憂是
時太子常有篤疾

太元十七年九月丁丑歲星熒惑填星同在亢氐占曰
三星合是謂驚位絕行內外有兵喪與飢改立王公
太元十八年正月乙酉熒惑入月占曰憂在宮中非賊
乃盜也一曰有亂臣若有戮者二十一年九月帝暴崩
內殿兆庶宣言夫人張氏潛行大逆于時朝政闇緩不
加顯戮但黜責而已又王國寶邪狡卒伏其辜

太元十八年二月有客星在尾中至九月乃滅占曰燕

Mult~~ele~~length Multi~~en~~ger

"Tài yuán shíbā nián èr yuè"

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~~Mult~~Ele~~ngh~~Multi~~zenger~~

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Multi-alphabet astronomy

Tai Yuan
reign period

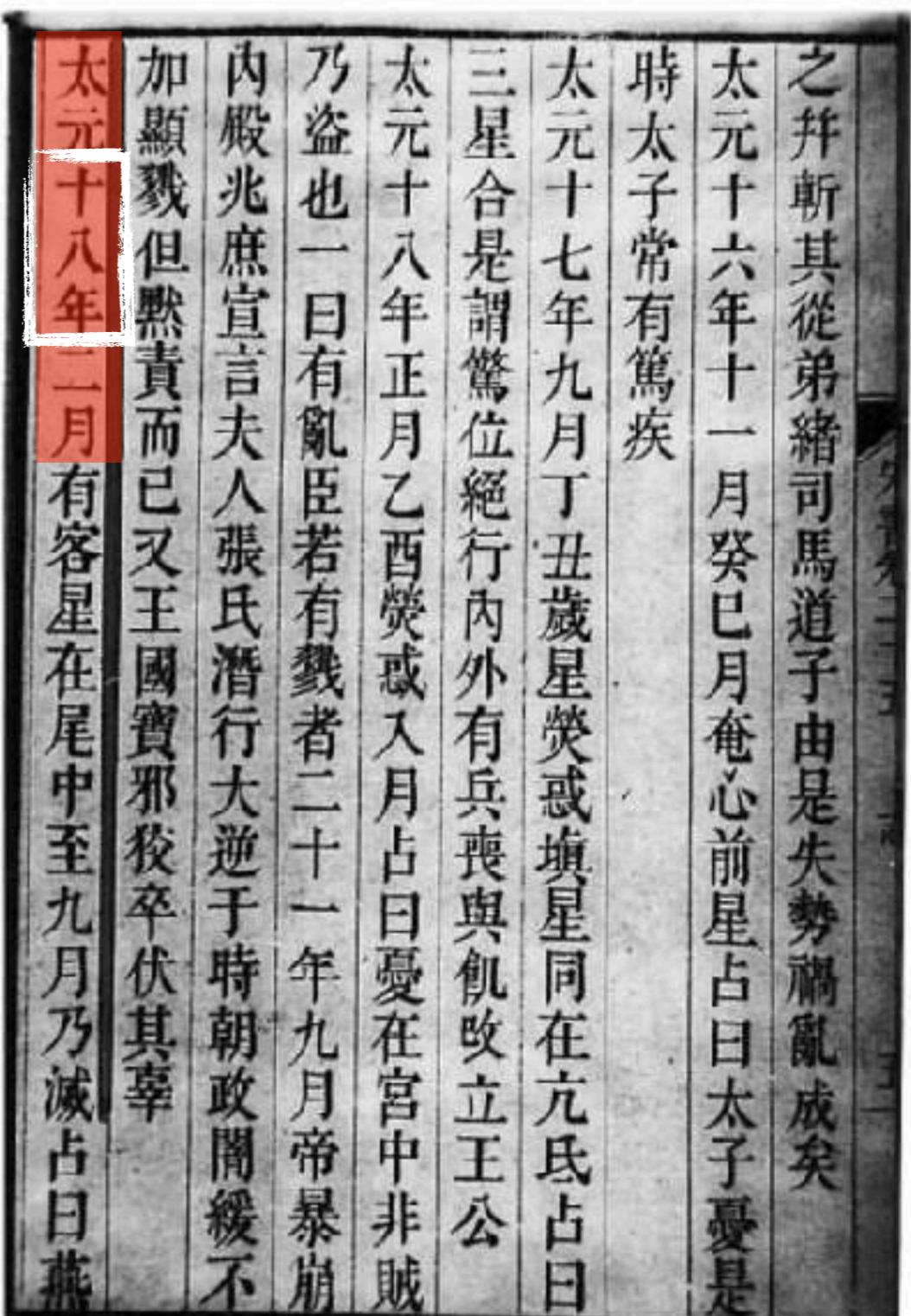
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~~Mult~~ele~~ngh~~linger~~~~

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"Tài yuán shíbā nián èr yuè"

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18th year

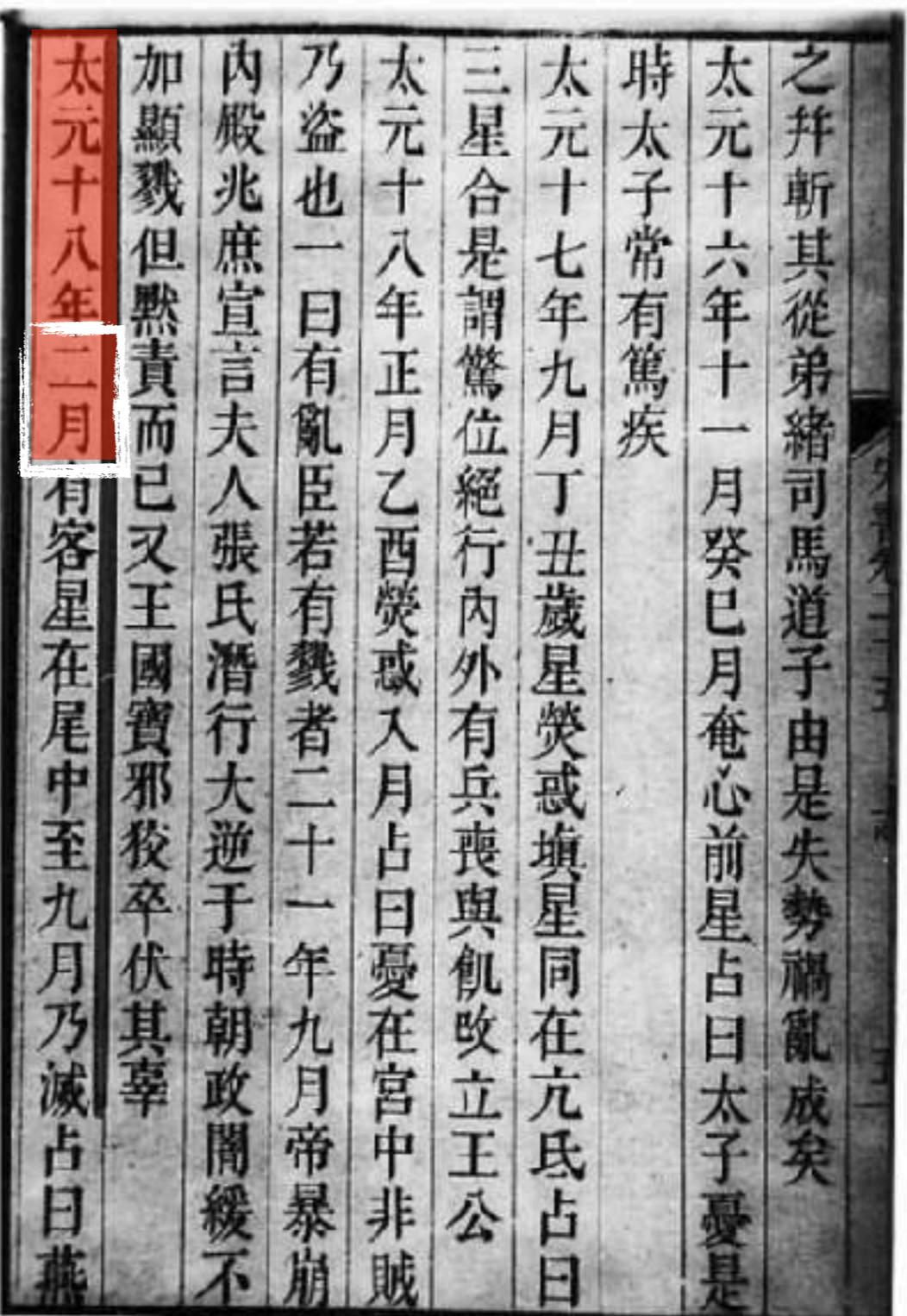


~~Mult~~Elephant ~~Multim~~Zenger

"Tài yuán shíbā nián èr yuè"

Multi-alphabet astronomy

Tai Yuan
reign period
18th year
2nd (lunar) month



~~Mult~~Ele~~n~~ght Multi-~~in~~ger

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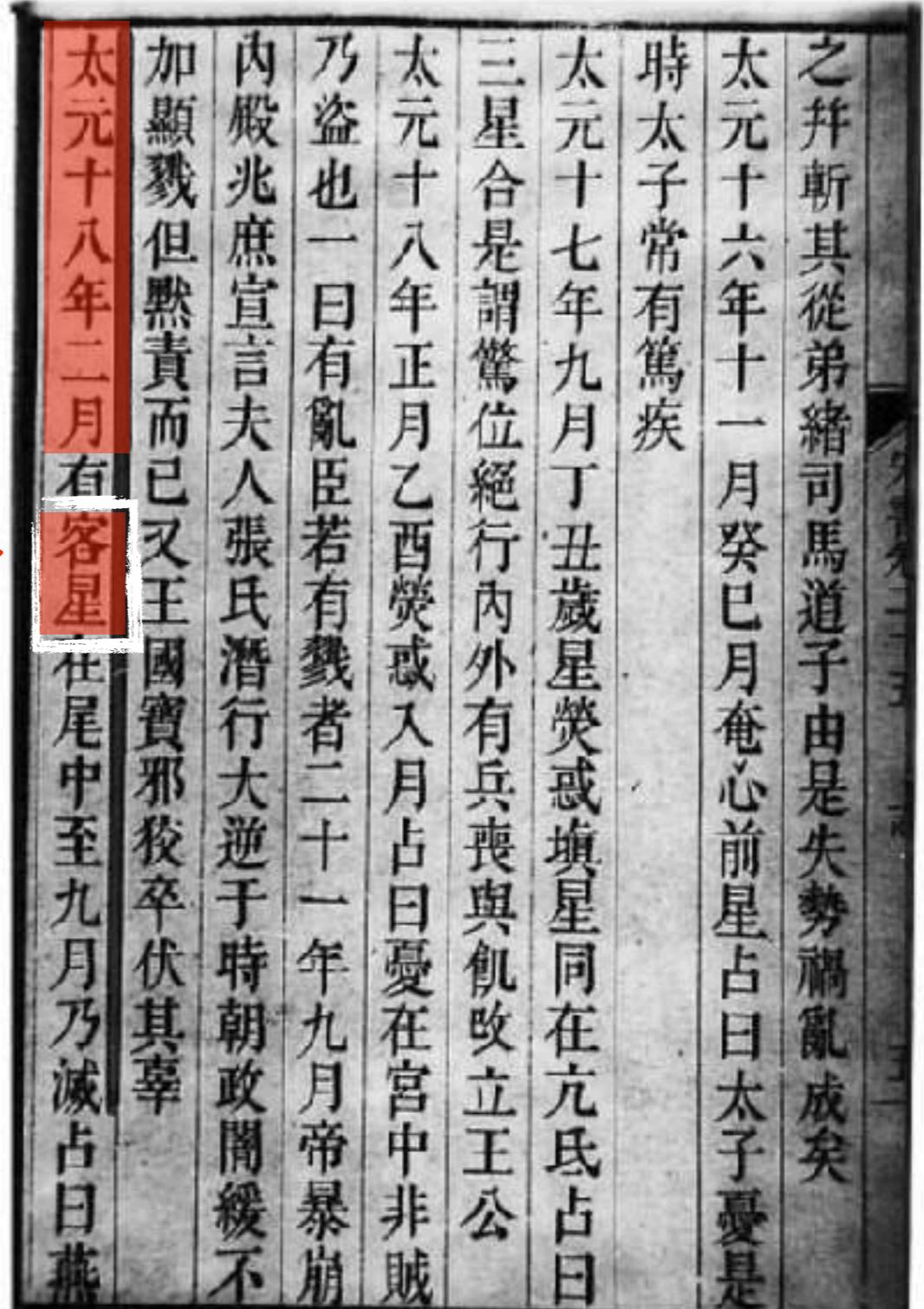
"Kè xīng"

Tai Yuan
reign period

18th year

2nd (lunar) month

guest star



~~Mult~~Ele~~n~~ght Multi-~~in~~ger

"Tài yuán shíbā nián èr yuè"

"Kè xīng"

"jiǔ yuè"

Multi-alphabet astronomy

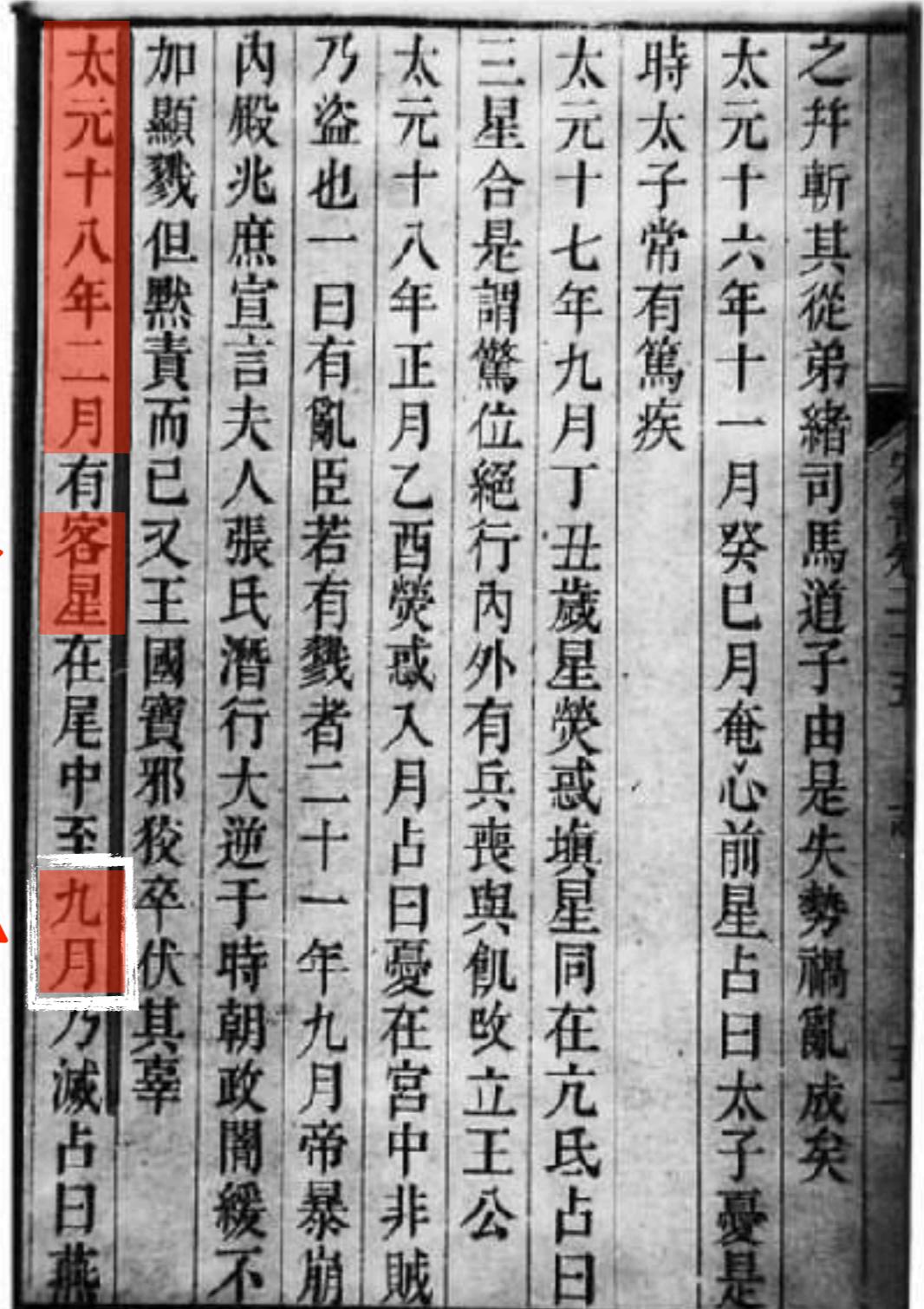
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guest star

9th month



~~Mult~~Elephant ~~Mult~~enger

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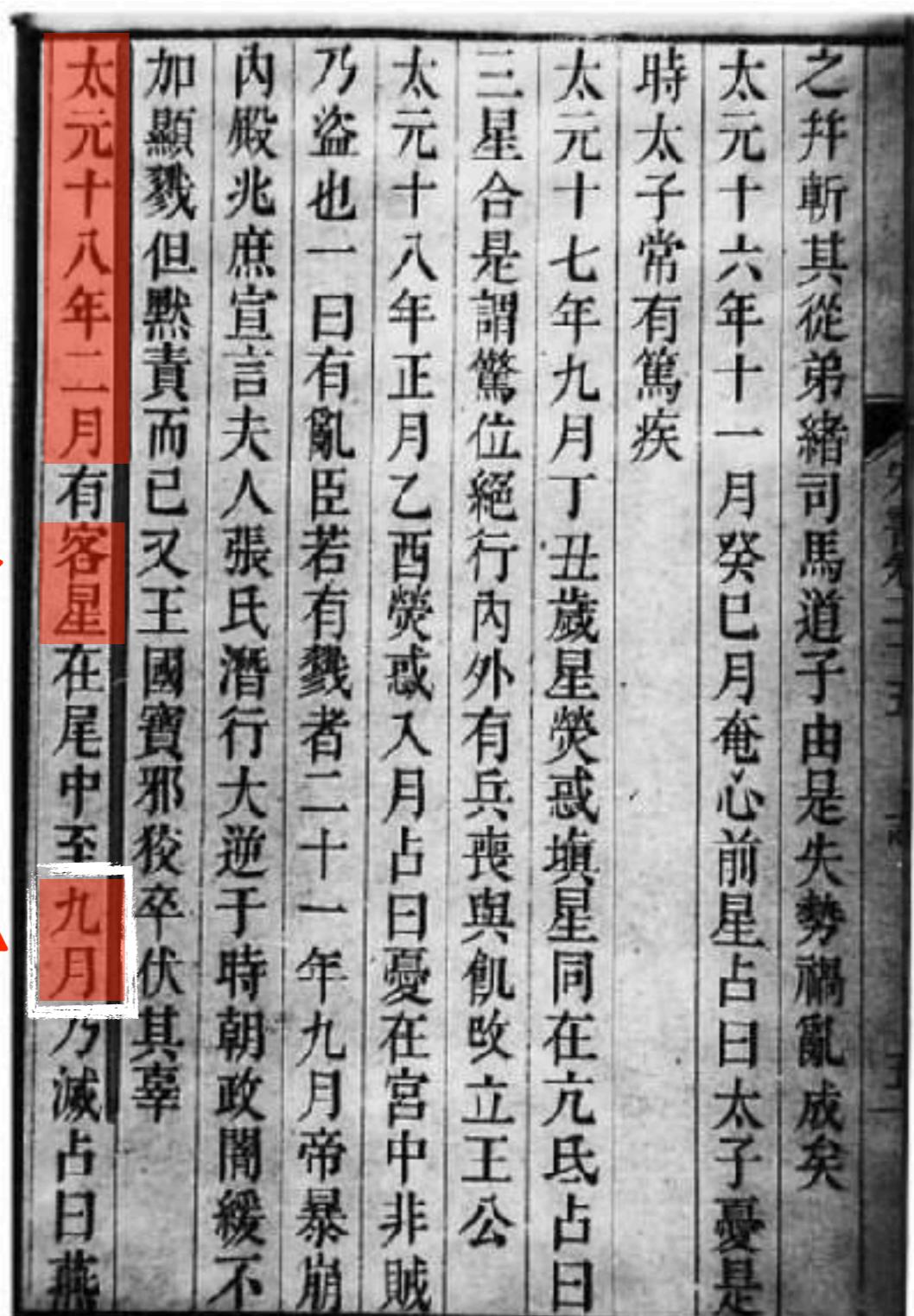
18th year

2nd (lunar) month

guest star

9th month

this corresponds to year 393, and the position in the sky also seems to match!

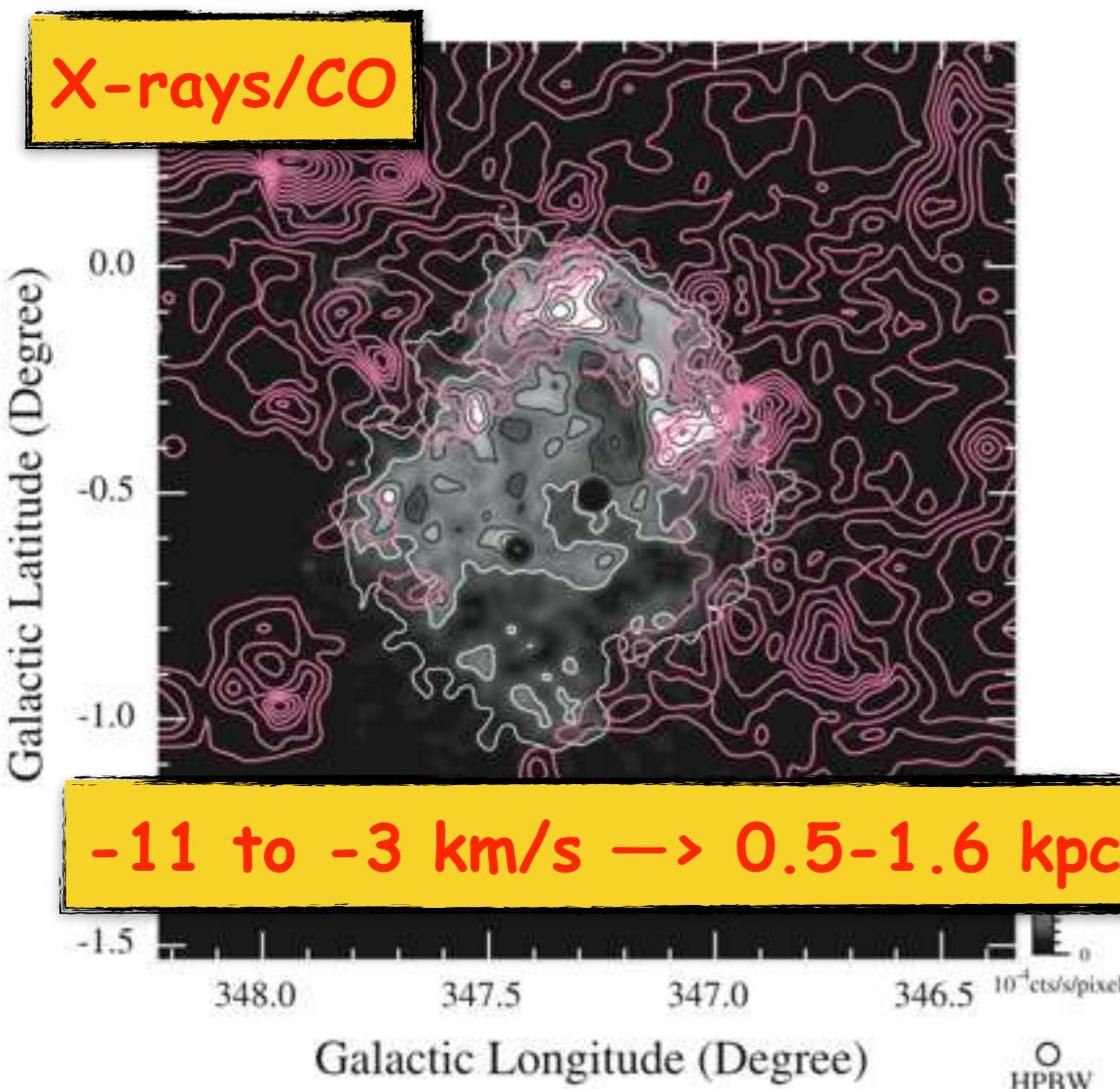


How distant & old is RXJ1713.7-3946?

d ~ 6 kpc was adopted for some time, based on a spatial association with a molecular cloud characterised by that distance (Slane+99) —> t >> 10⁴ yr!

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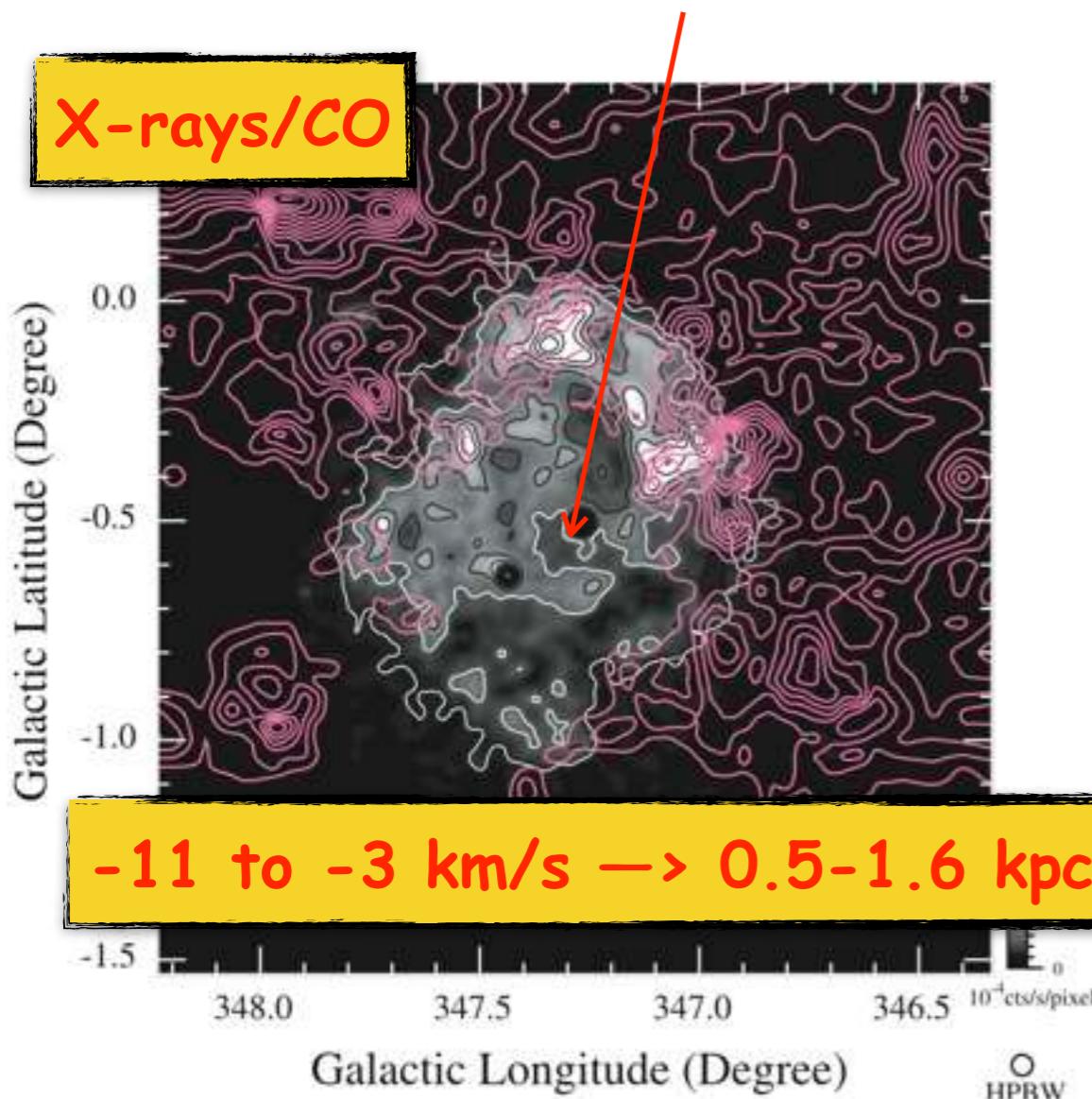
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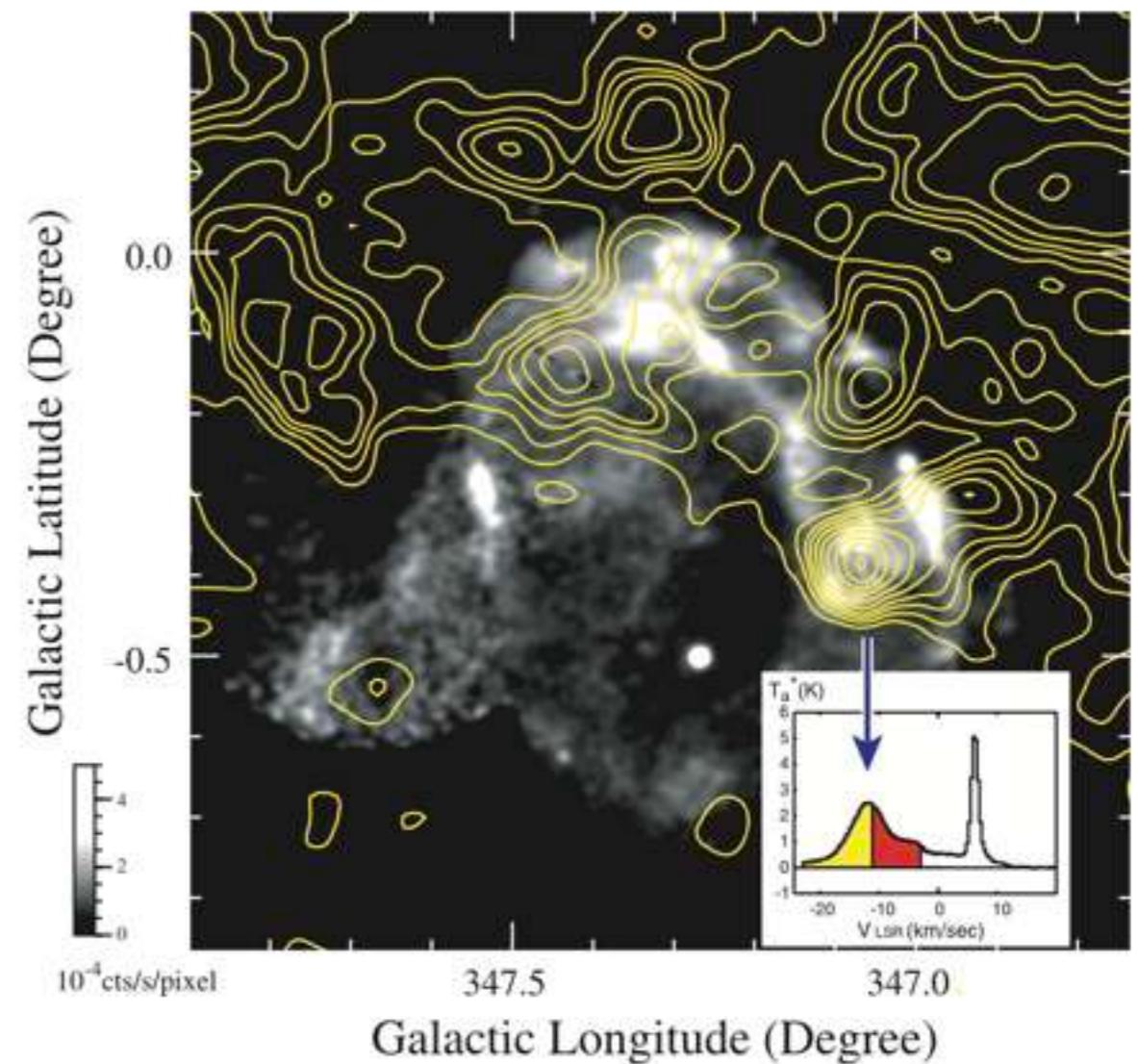
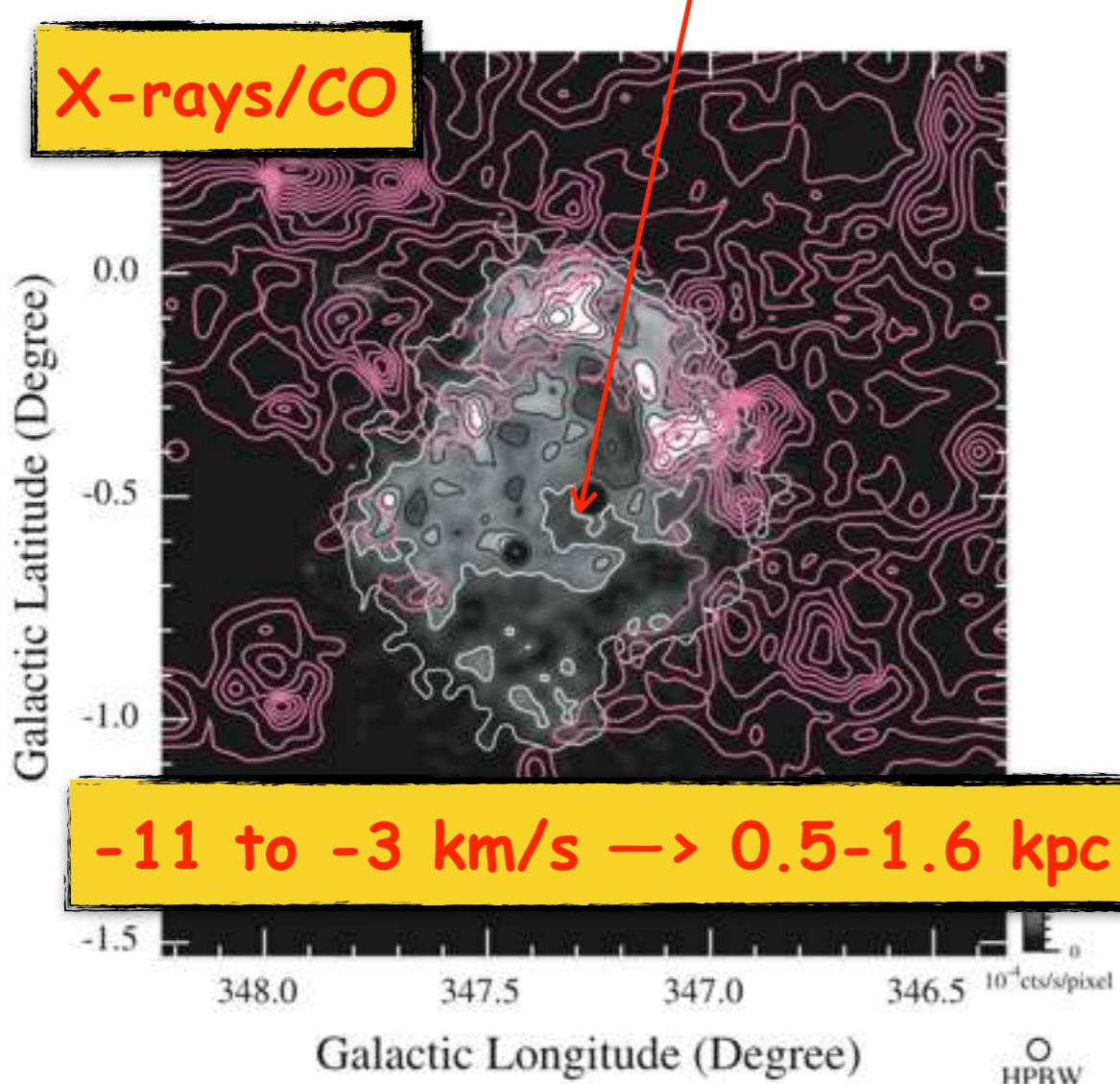
hole in CO distribution \rightarrow gas swept by the SNR or by the parent stellar wind?



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hole in CO distribution \rightarrow gas swept by the SNR or by the parent stellar wind?



high velocity tail in the distribution \rightarrow typical of SNR/cloud interactions

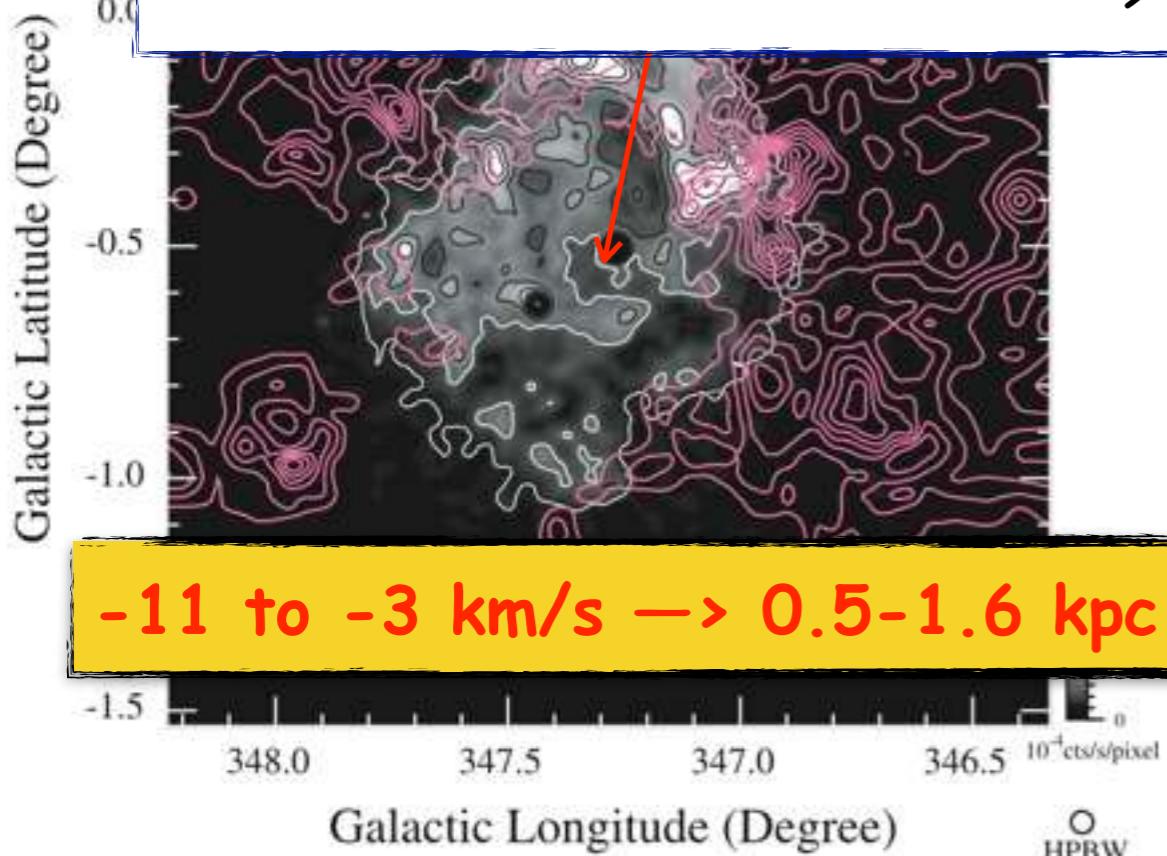
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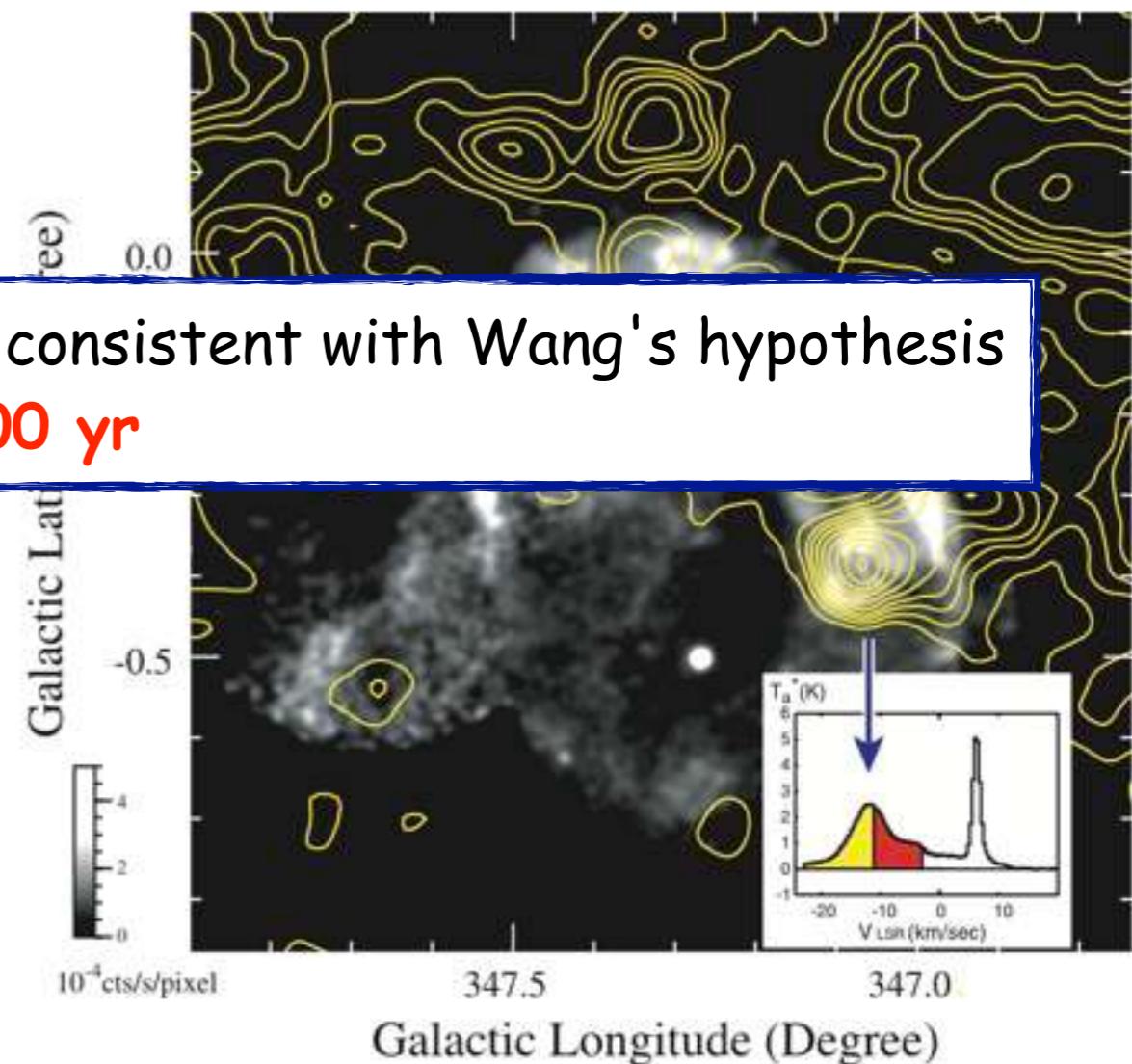
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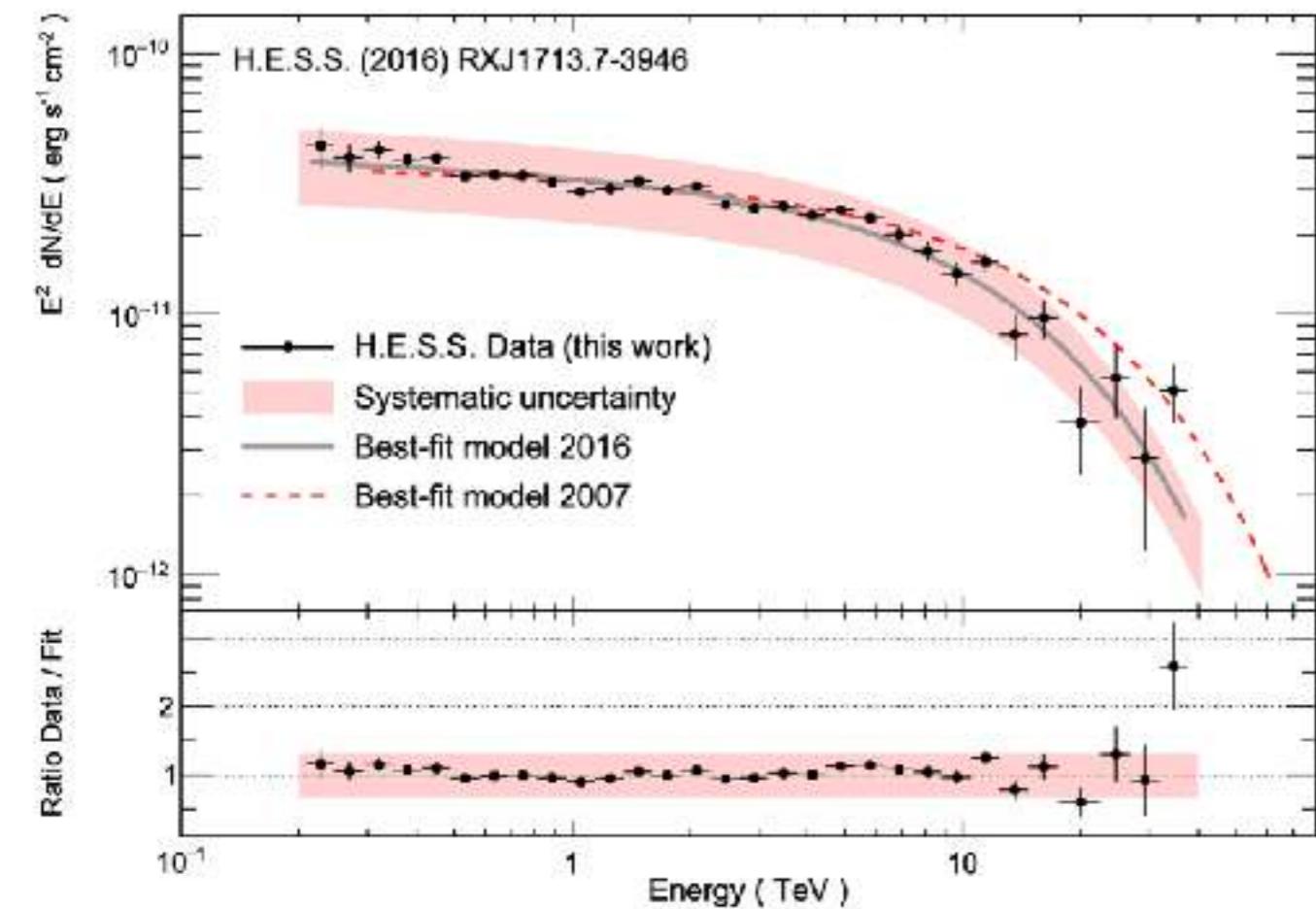
so let's take 1 kpc as a fiducial distance, consistent with Wang's hypothesis
 $\rightarrow t \sim 1600$ yr



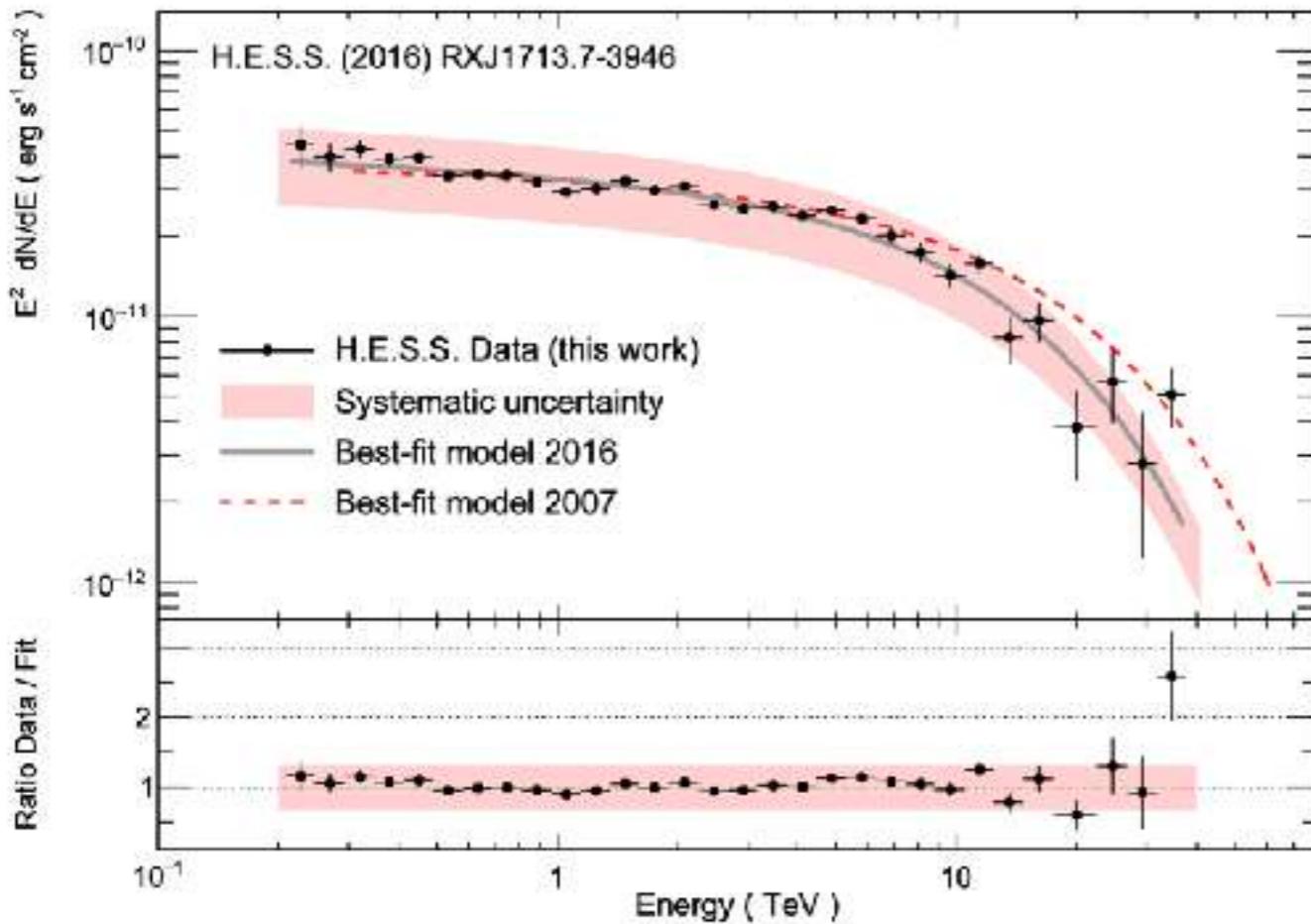
-11 to -3 km/s \rightarrow 0.5-1.6 kpc



VHE gamma ray luminosity



VHE gamma ray luminosity

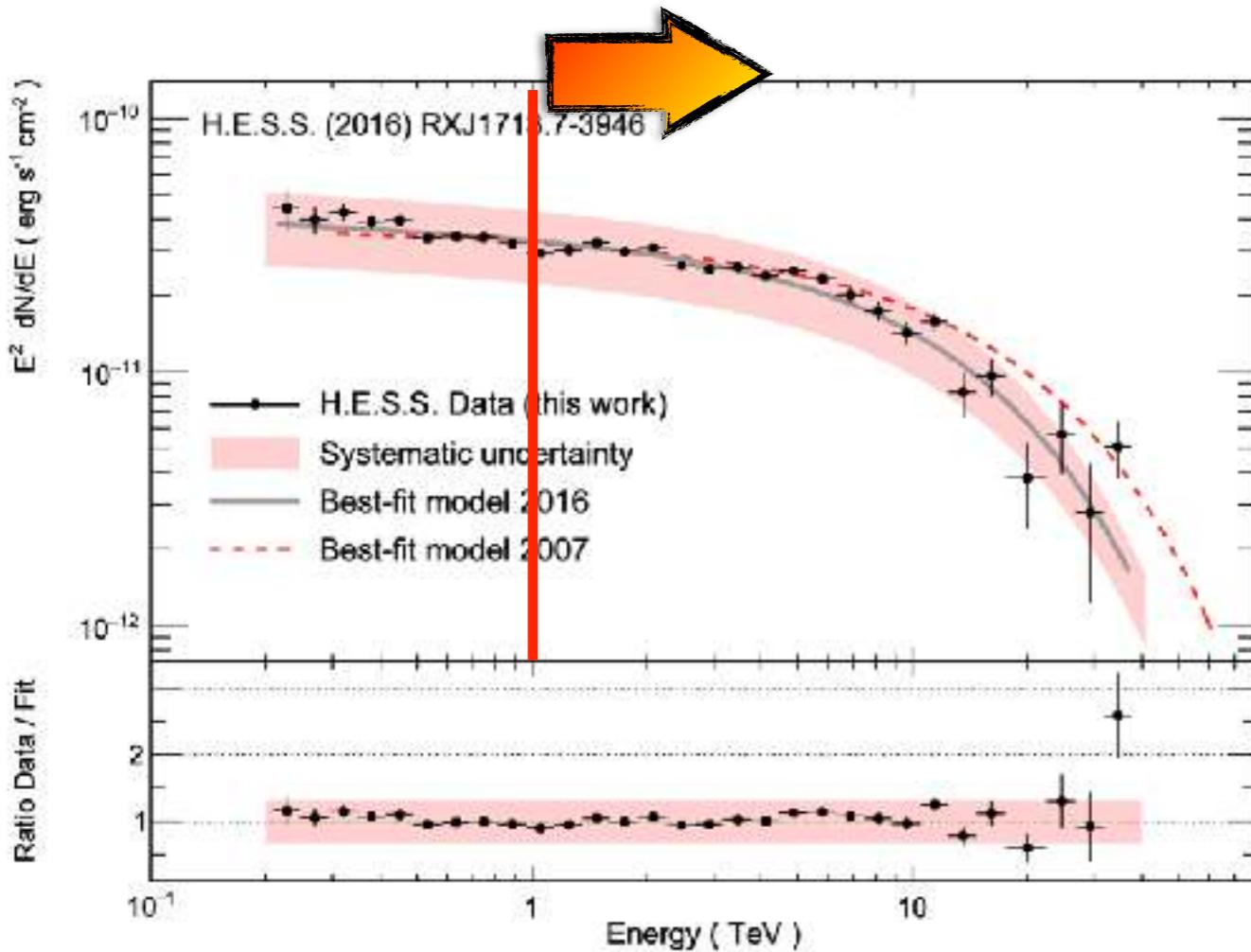


$$F(E) = F_0 E^{-\Gamma} e^{-\left(\frac{E}{E_{cut}}\right)}$$

$$\Gamma = 2.06 \pm 0.02 \quad E_{cut} = 12.9 \pm 1.1 \text{ TeV}$$

$$F_0 = (2.3 \pm 0.1) \times 10^{-11} \text{cm}^{-2}\text{s}^{-1}\text{TeV}^{-1}$$

VHE gamma ray luminosity



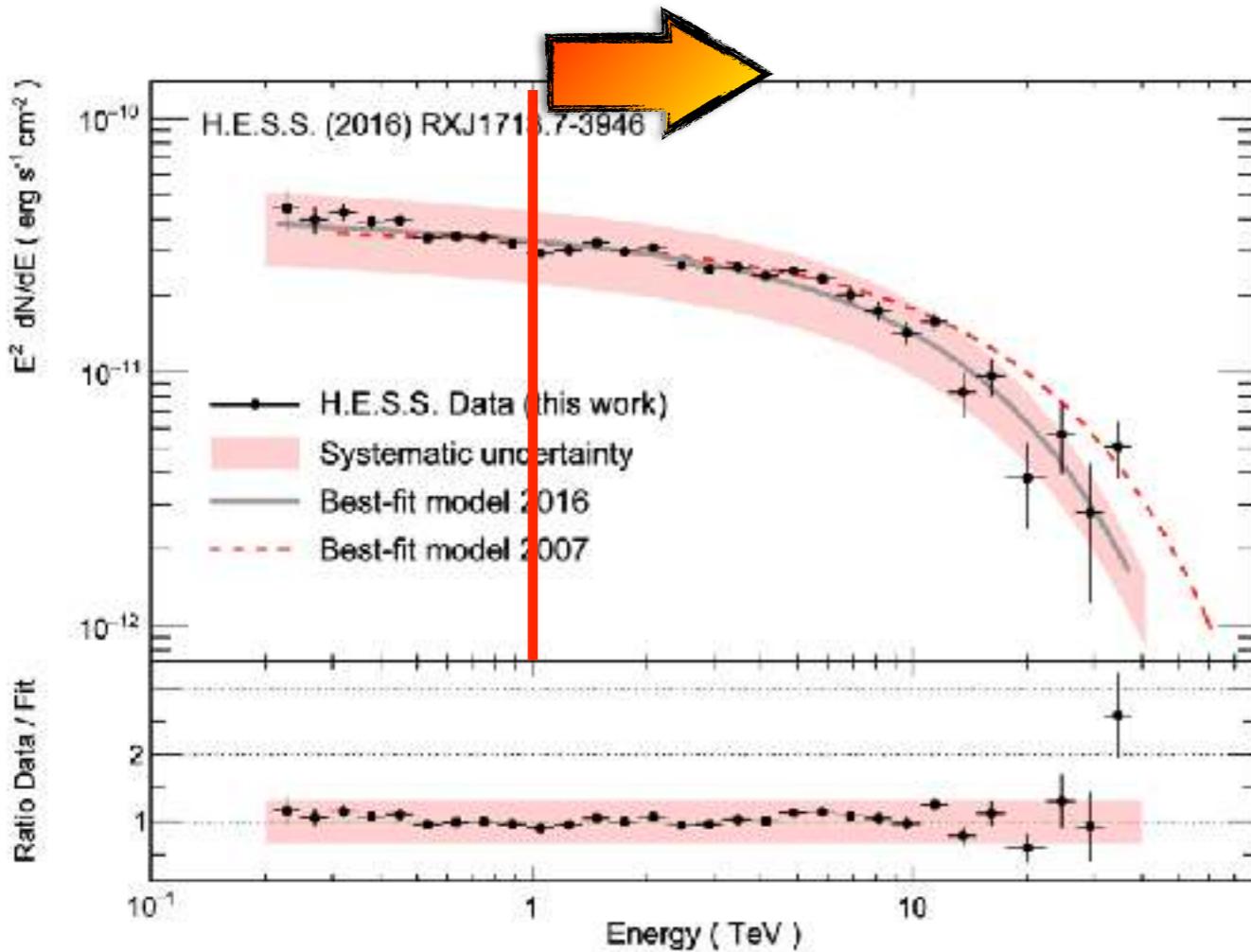
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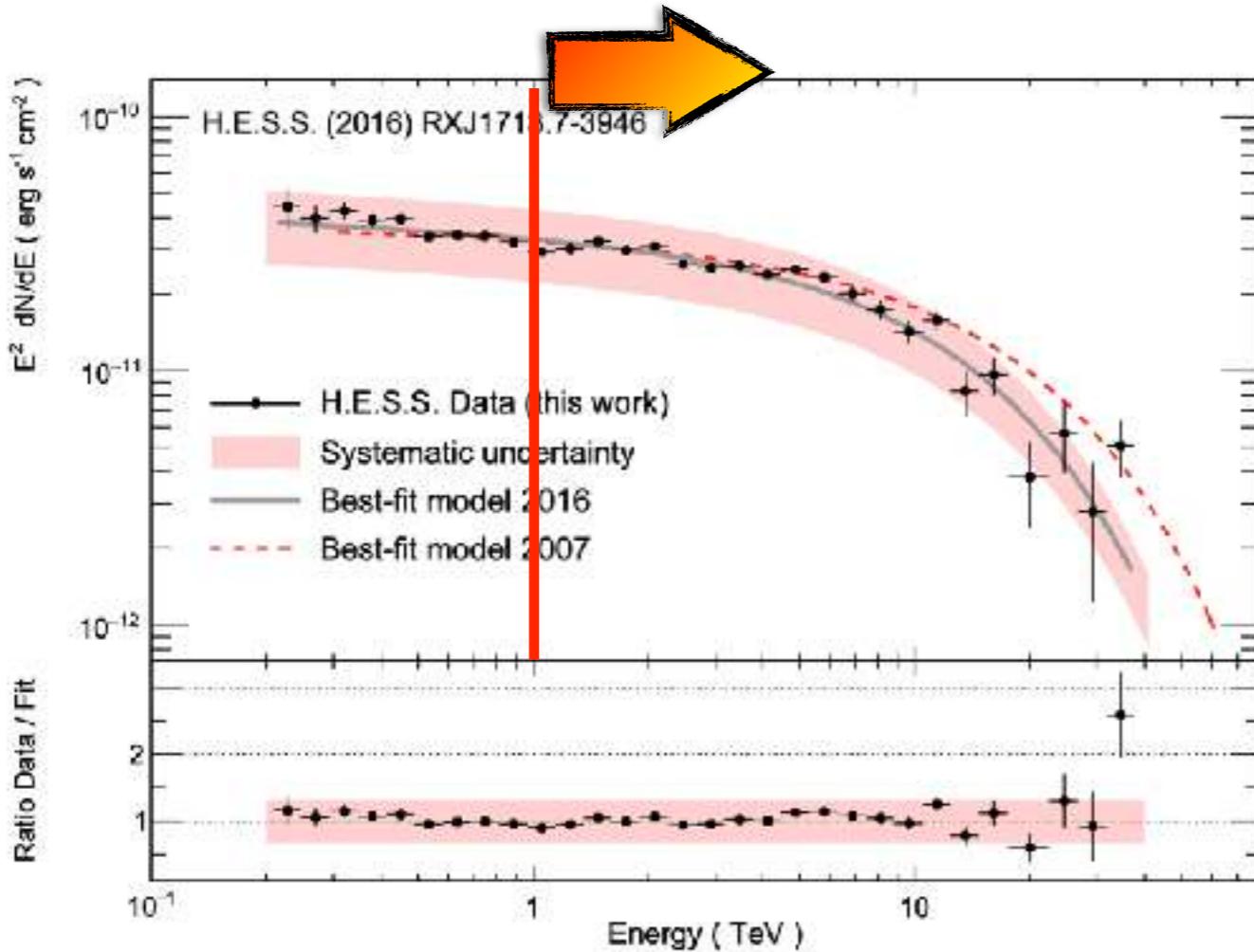
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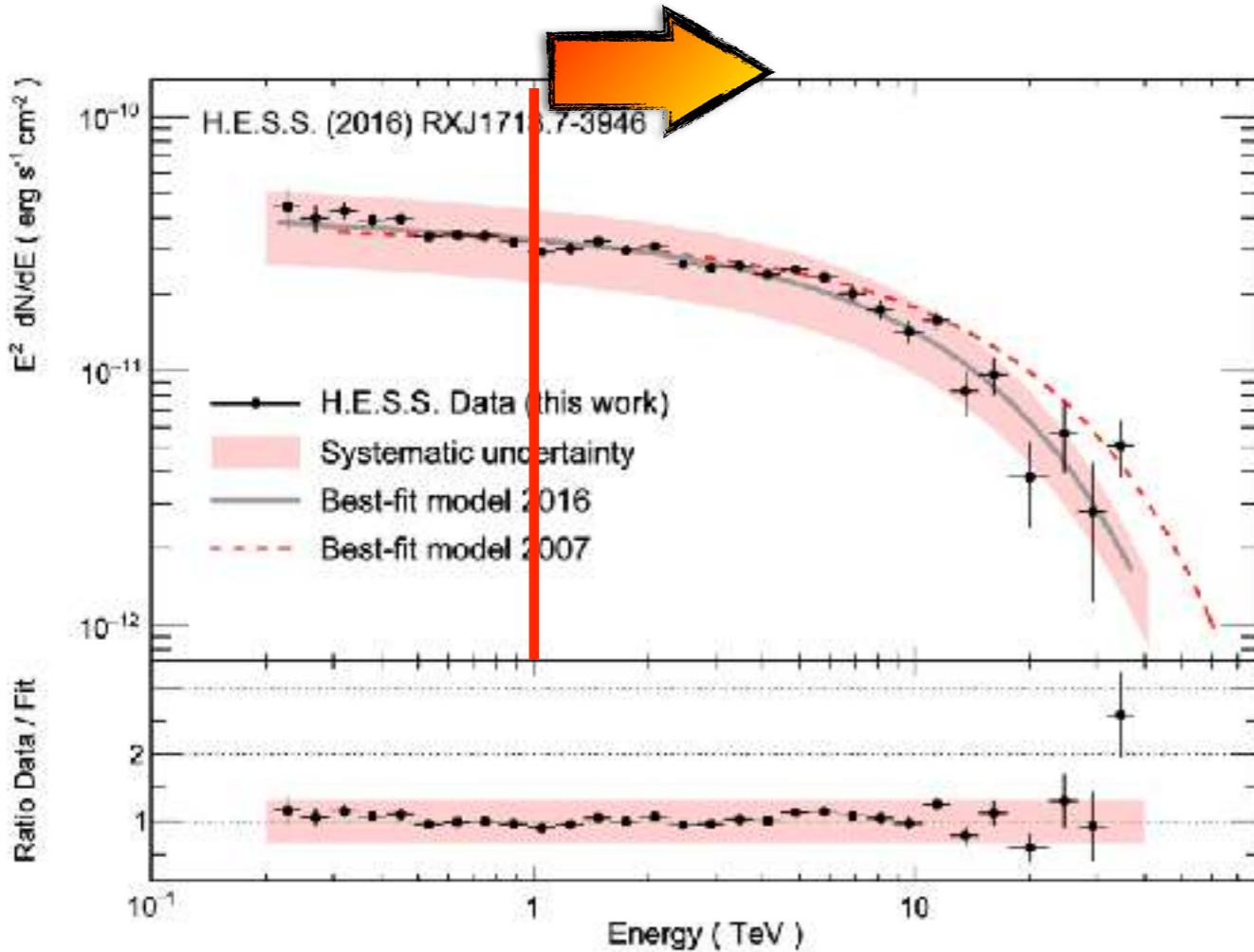
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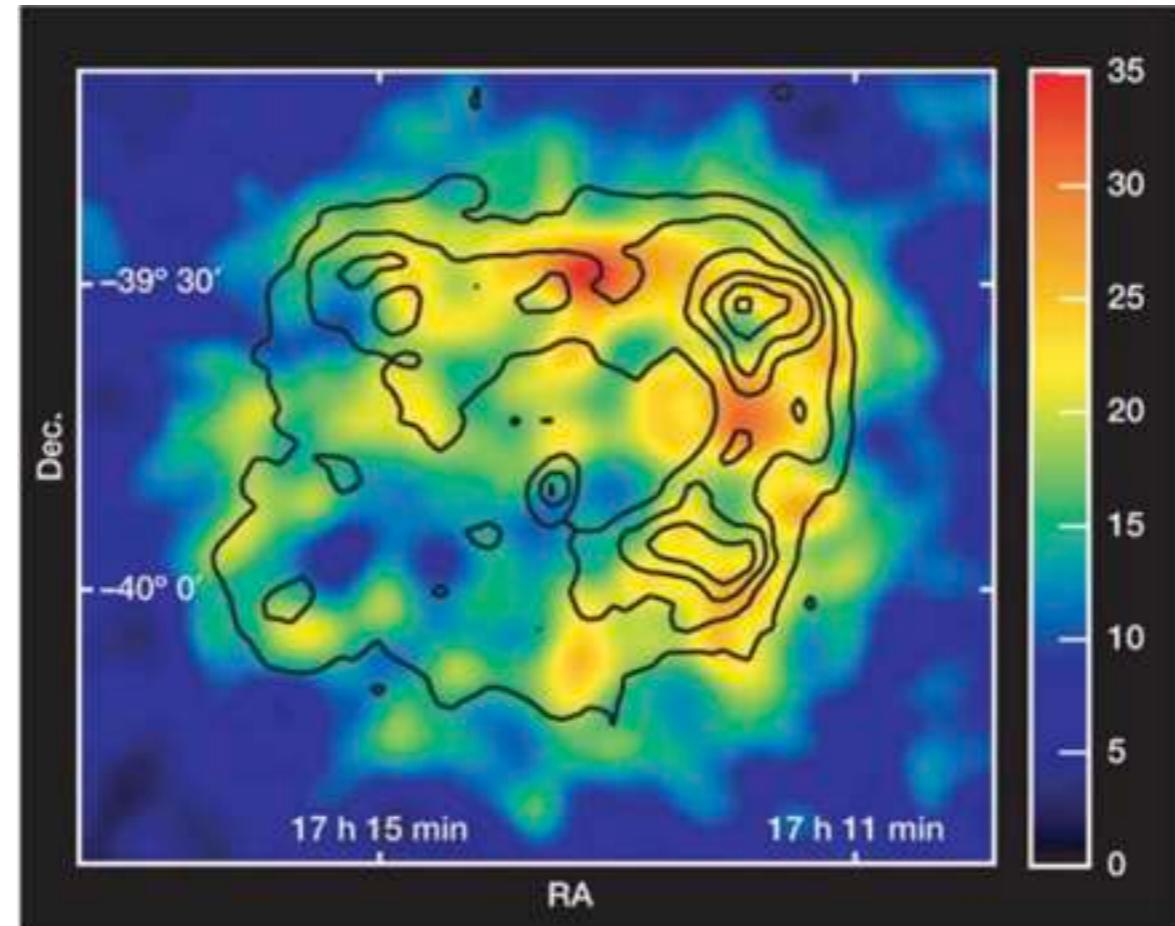
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[Question 3] How much
energy we need to explain
the TeV emission?

[Inset 2] Hadronic versus leptonic dichotomy in gamma-ray astronomy

Hadronic or leptonic? This is the question

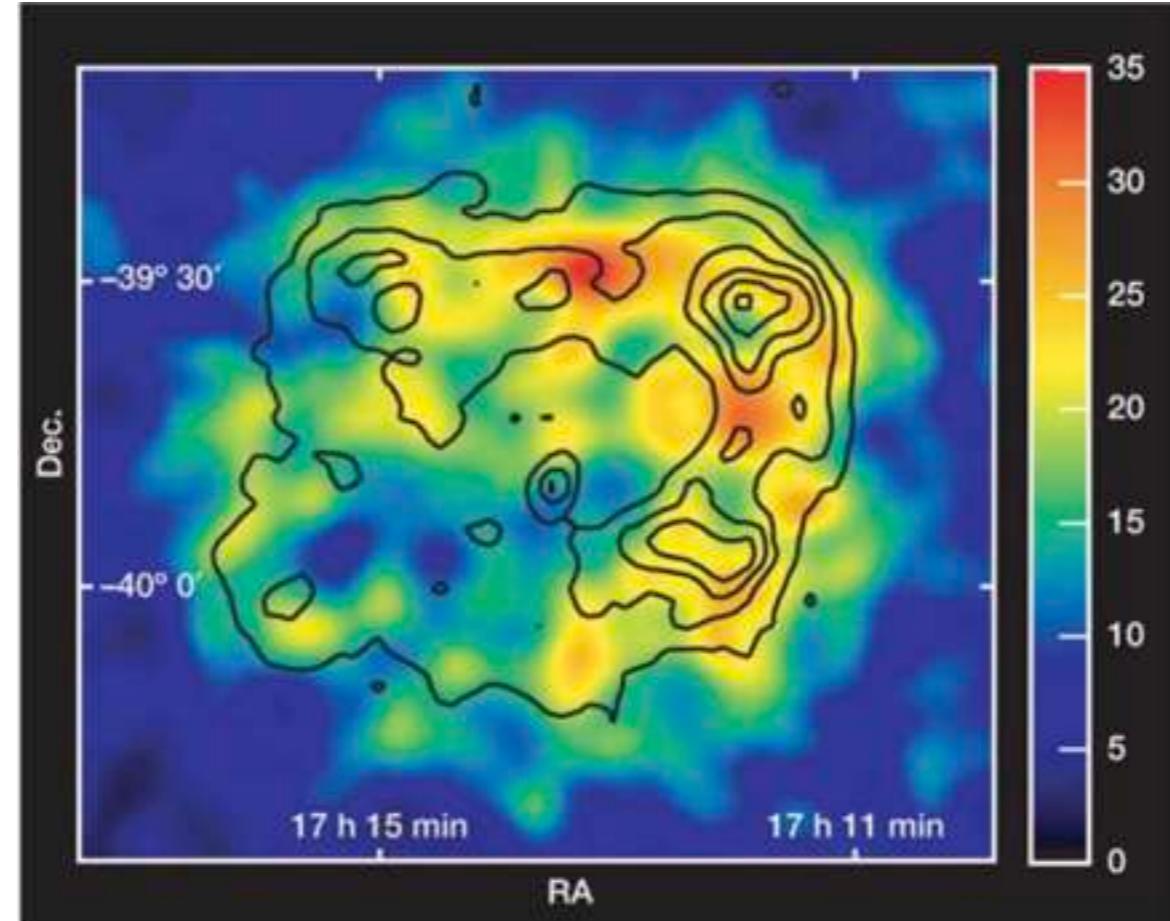


Hadronic or leptonic? This is the question



p-p interactions

target: ambient gas



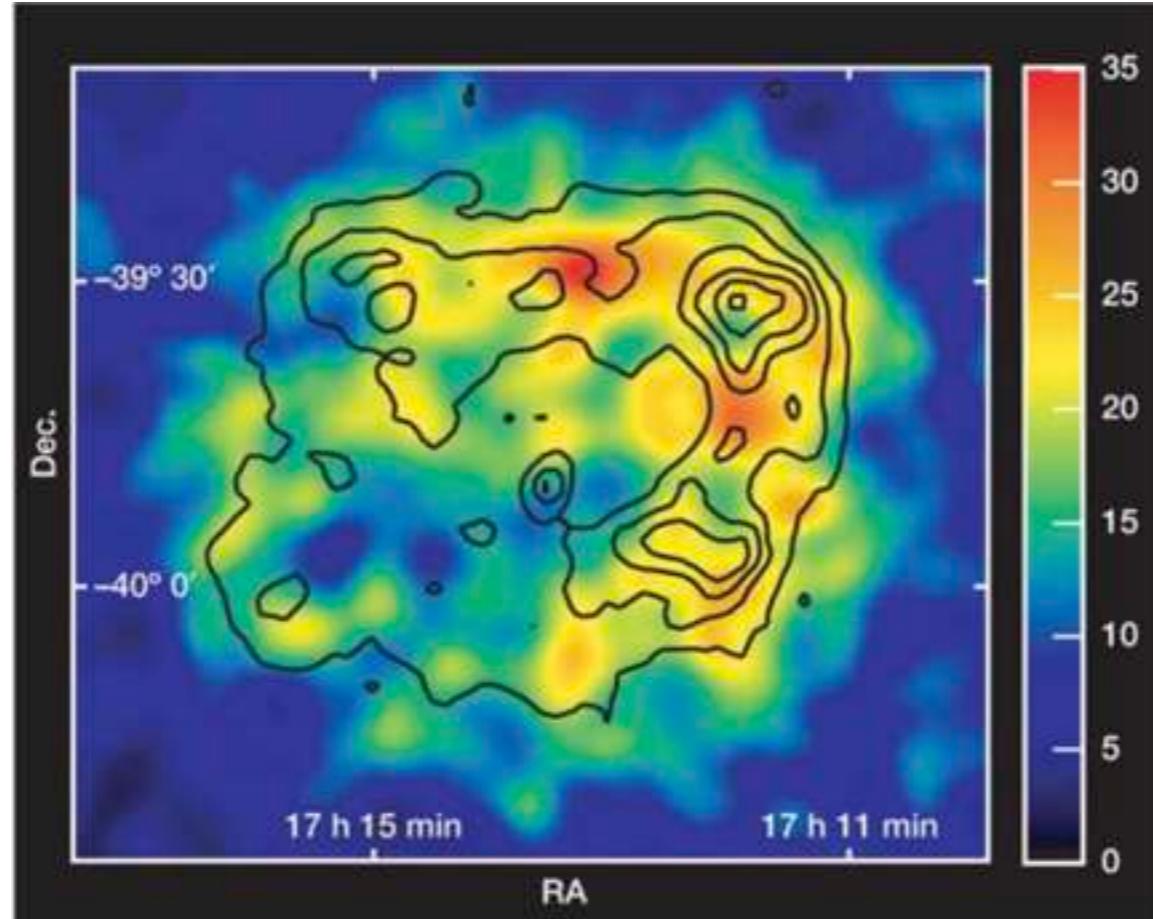
Hadronic or leptonic? This is the question



p-p interactions

target: ambient gas

need protons of energy



$$E_p \sim 10 \left(\frac{E_\gamma}{\text{TeV}} \right) \text{ TeV}$$

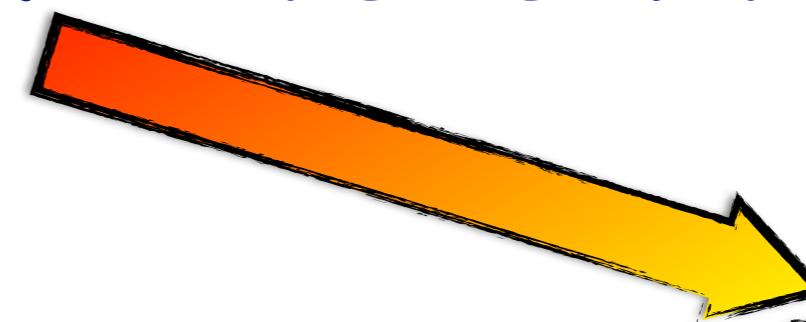
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p-p interactions

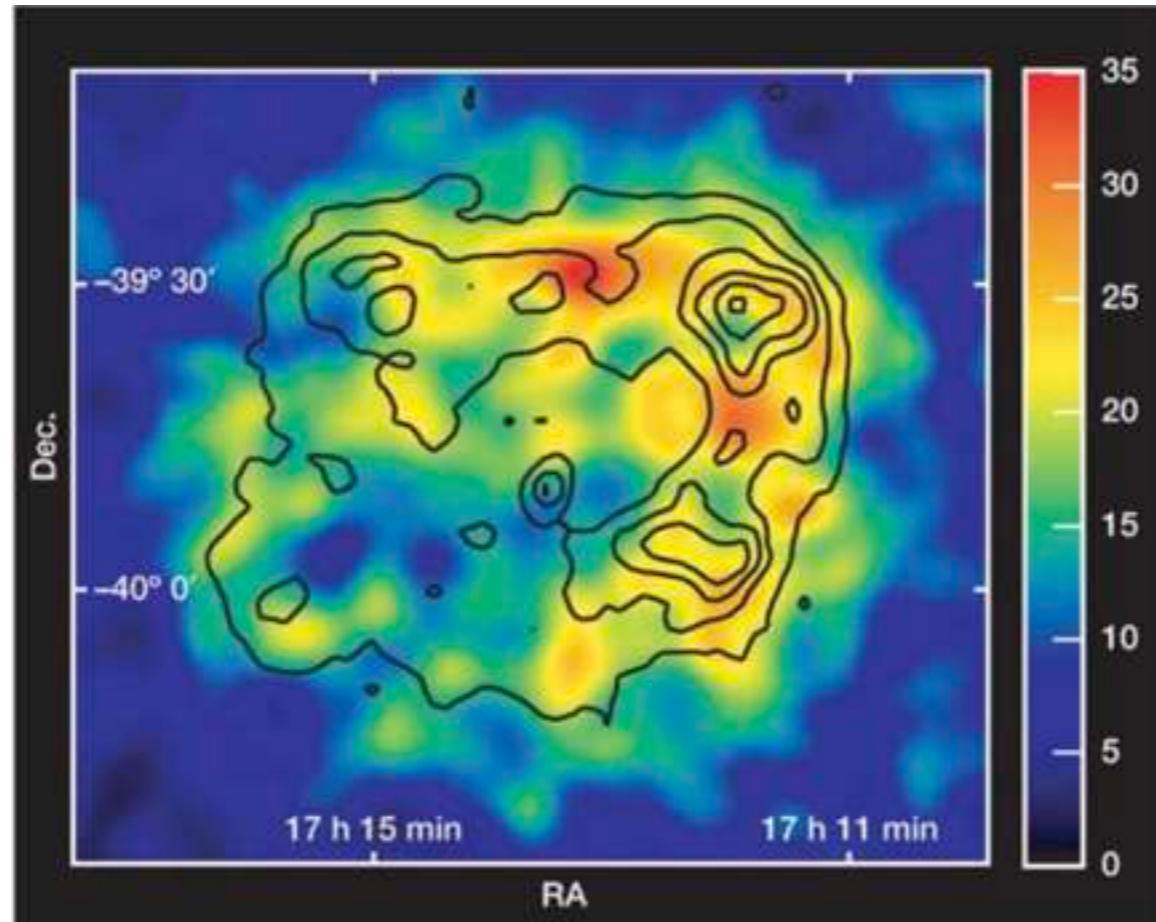
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inverse Compton

target: CMB photons



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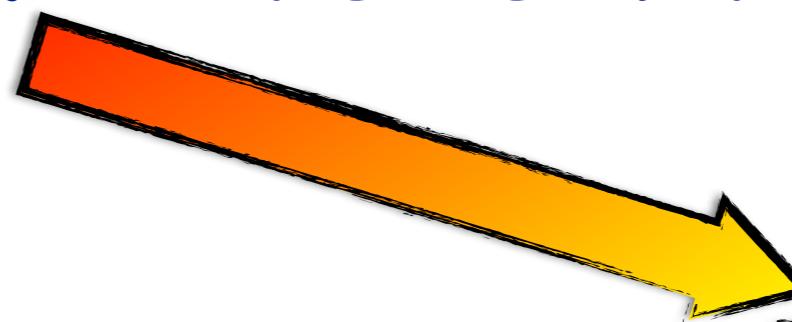
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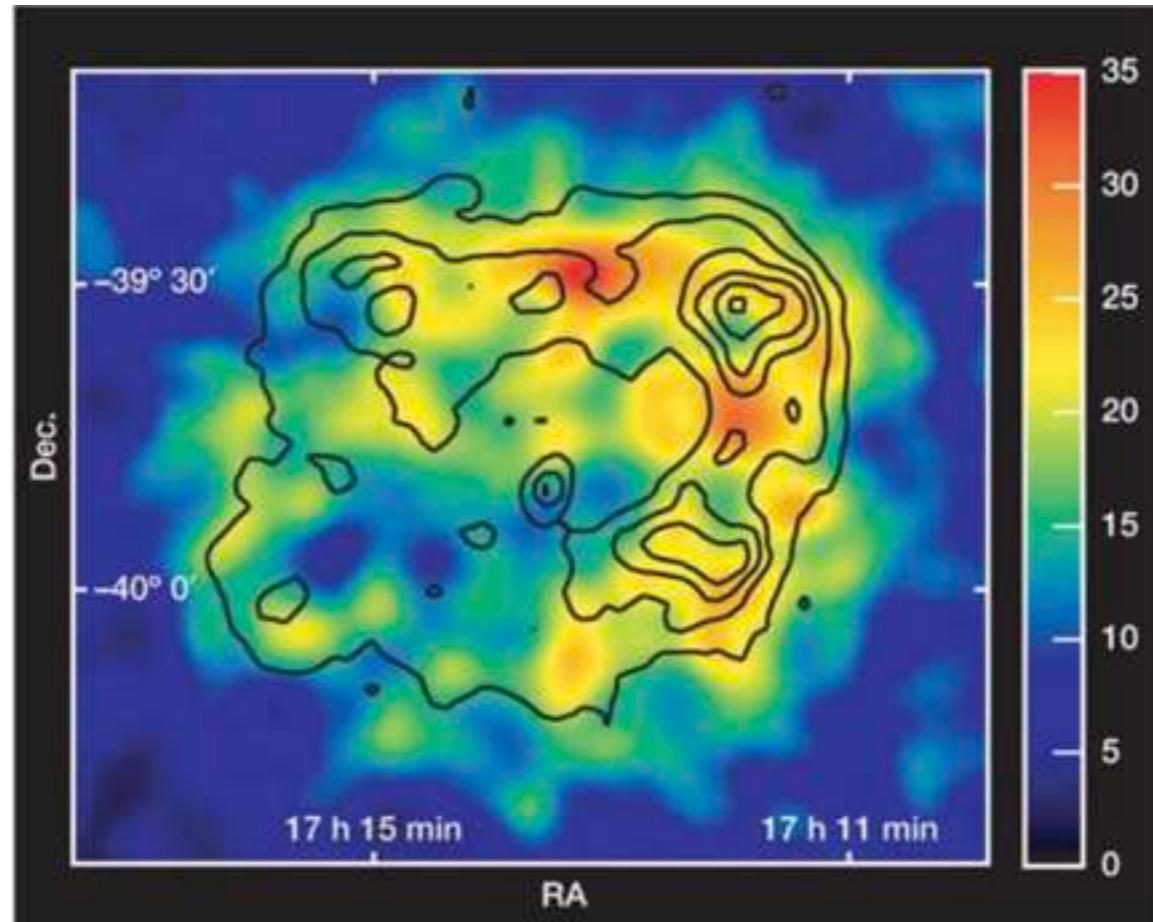
target: CMB photons

need electrons
of energy

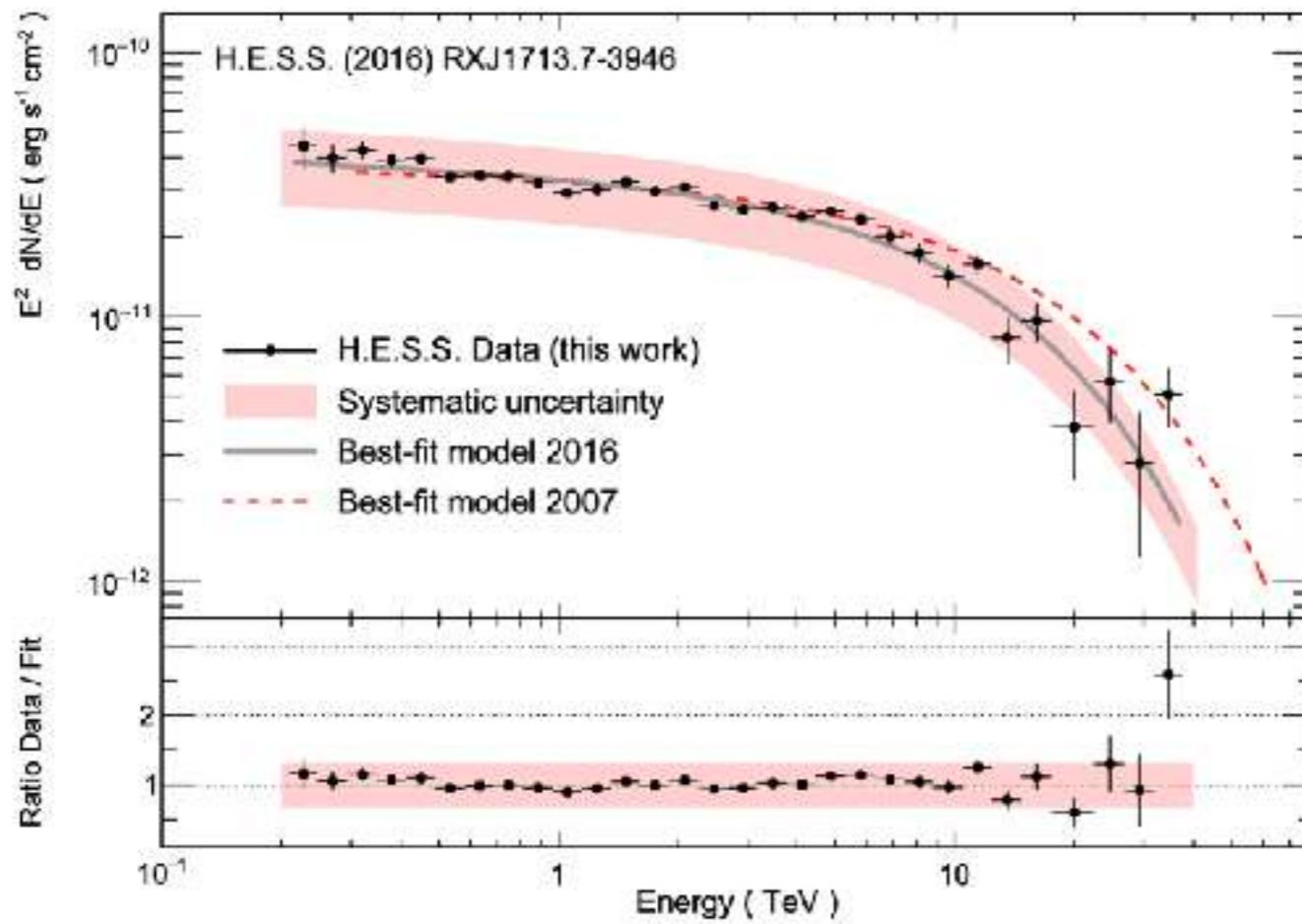
$$E_\gamma \sim \frac{4}{3} \gamma^2 \epsilon_{CMB}$$



$$E_e \sim 20 \left(\frac{E_\gamma}{\text{TeV}} \right)^{1/2} \text{ TeV}$$

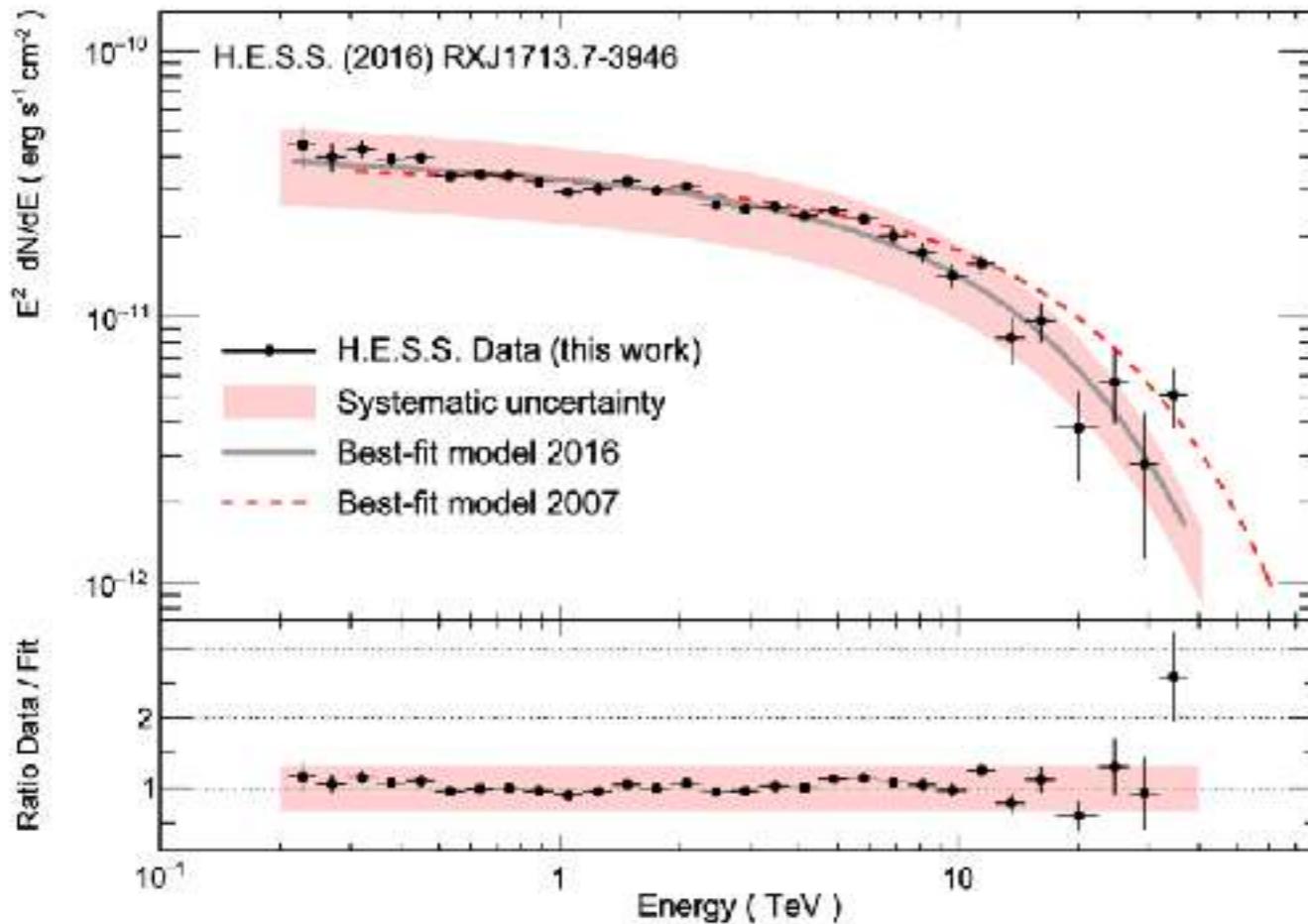


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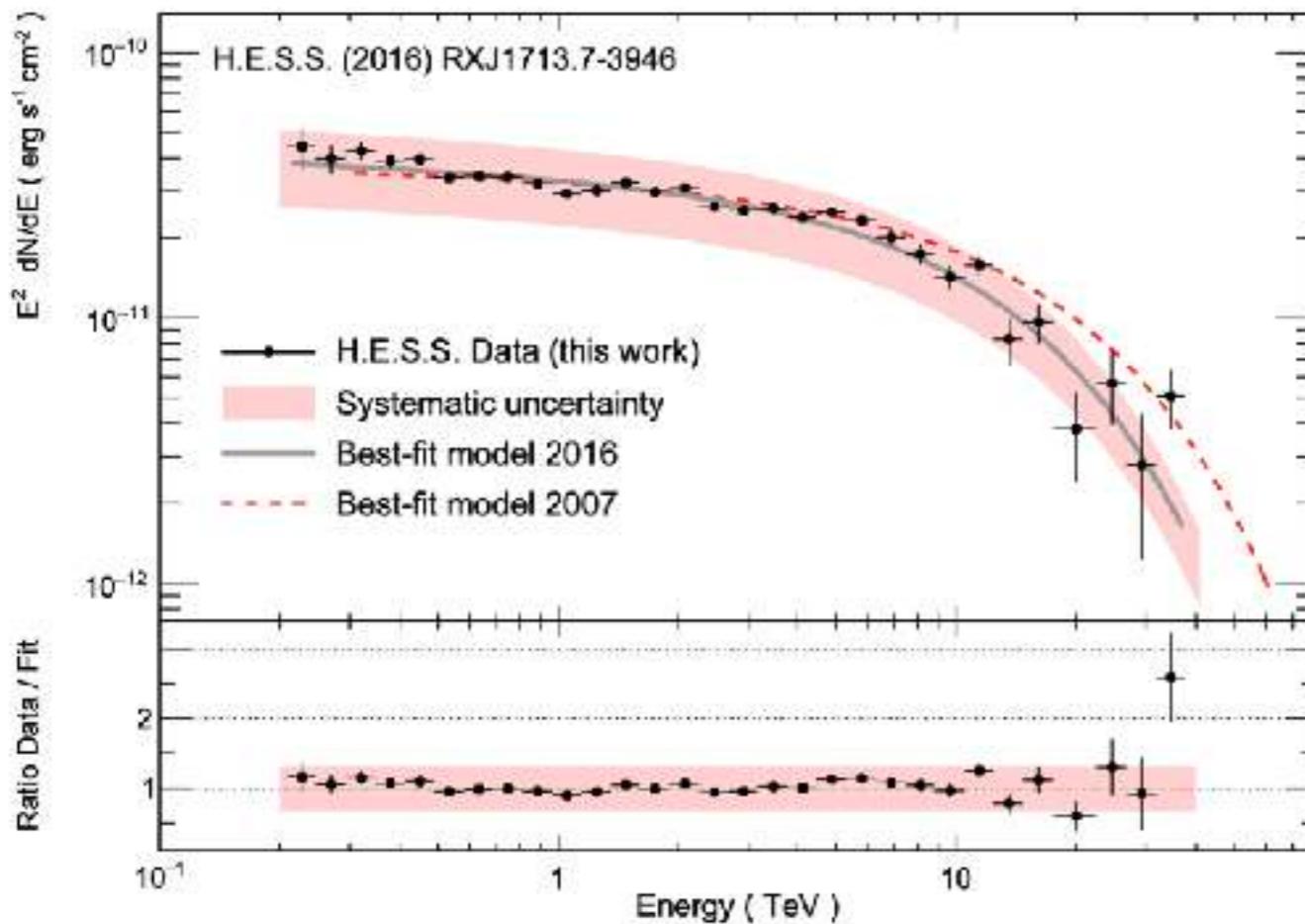
Hadronic or leptonic? This is the question

if leptonic \rightarrow electrons also emit synchrotron photons!



Hadronic or leptonic? This is the question

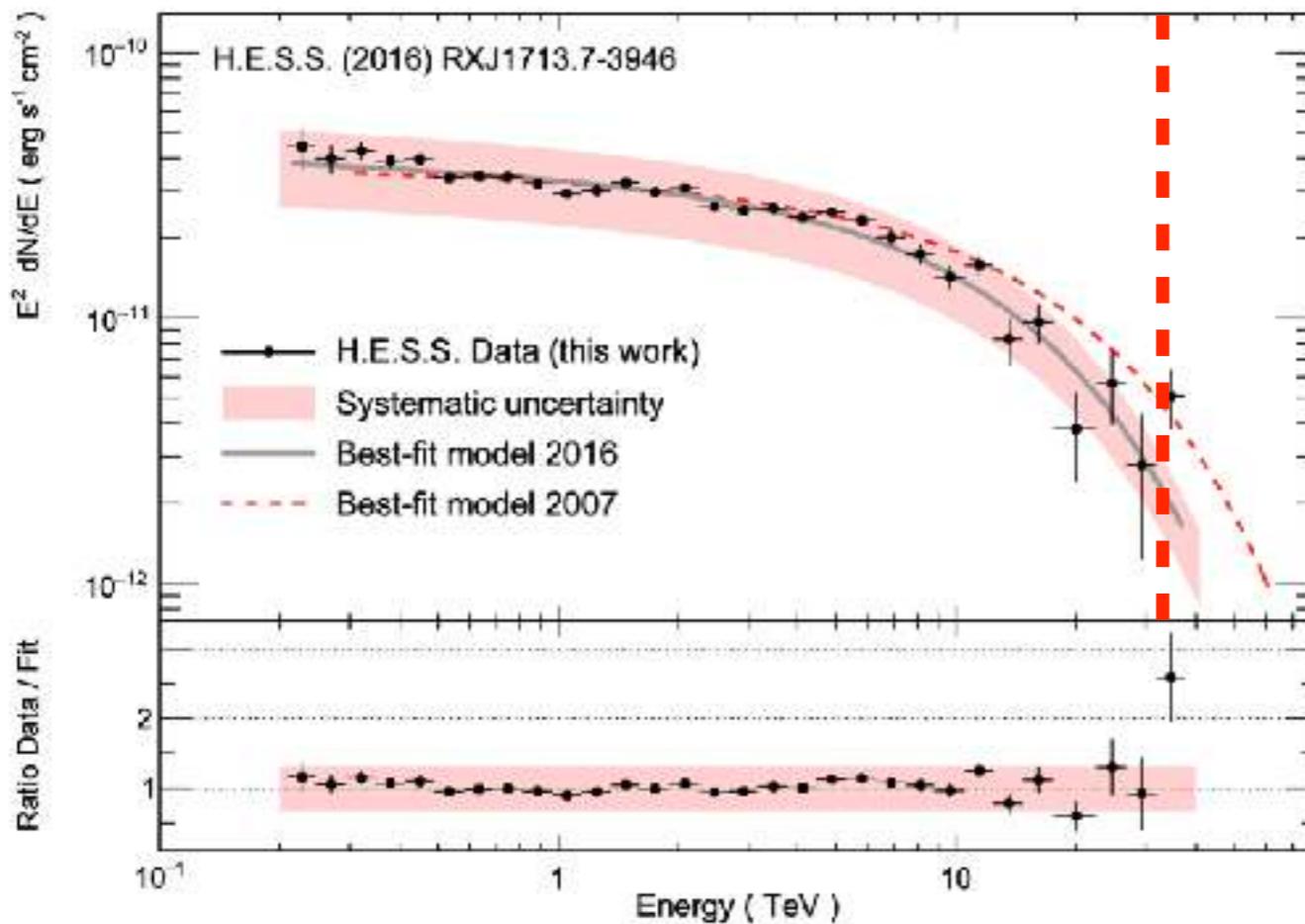
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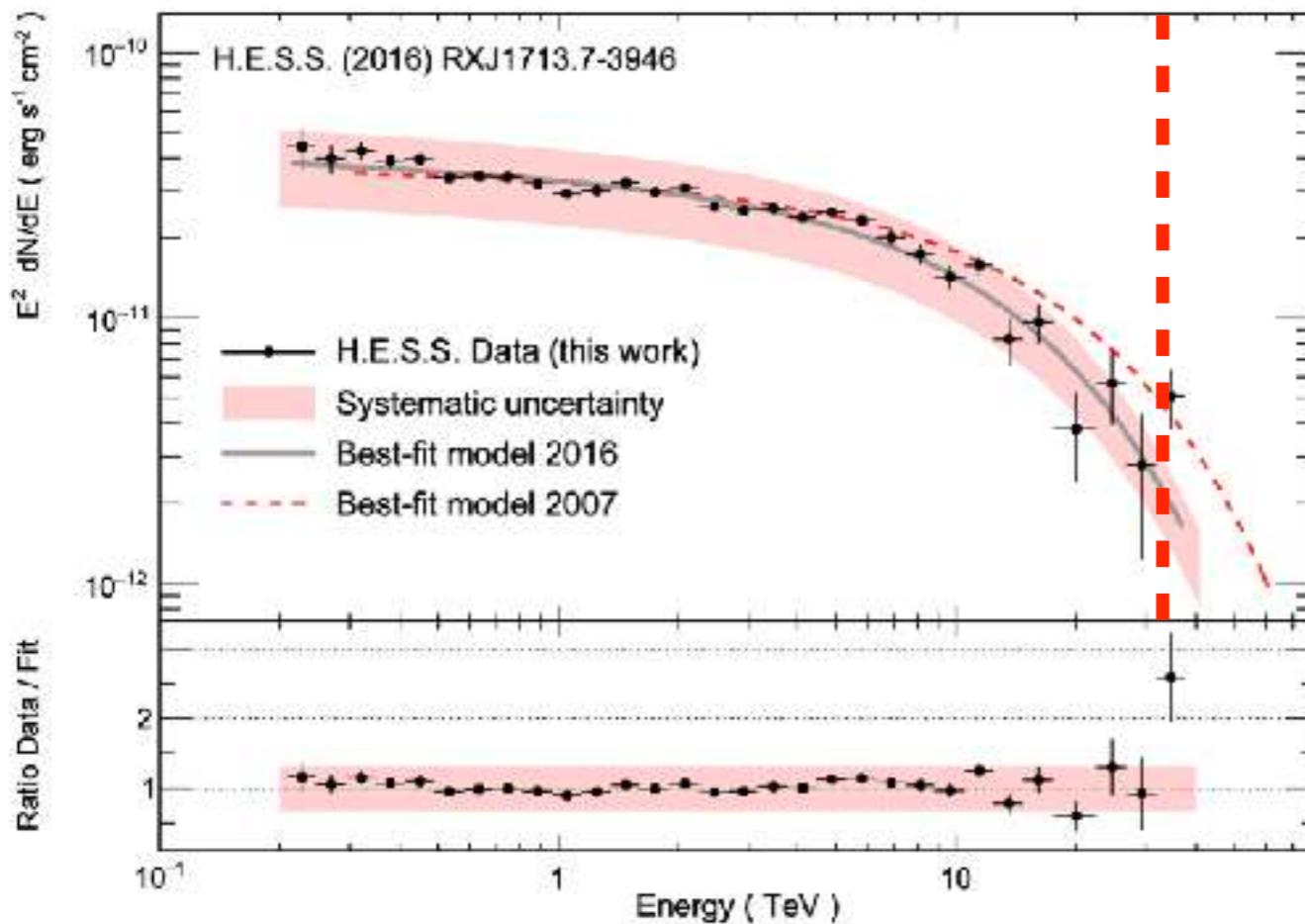
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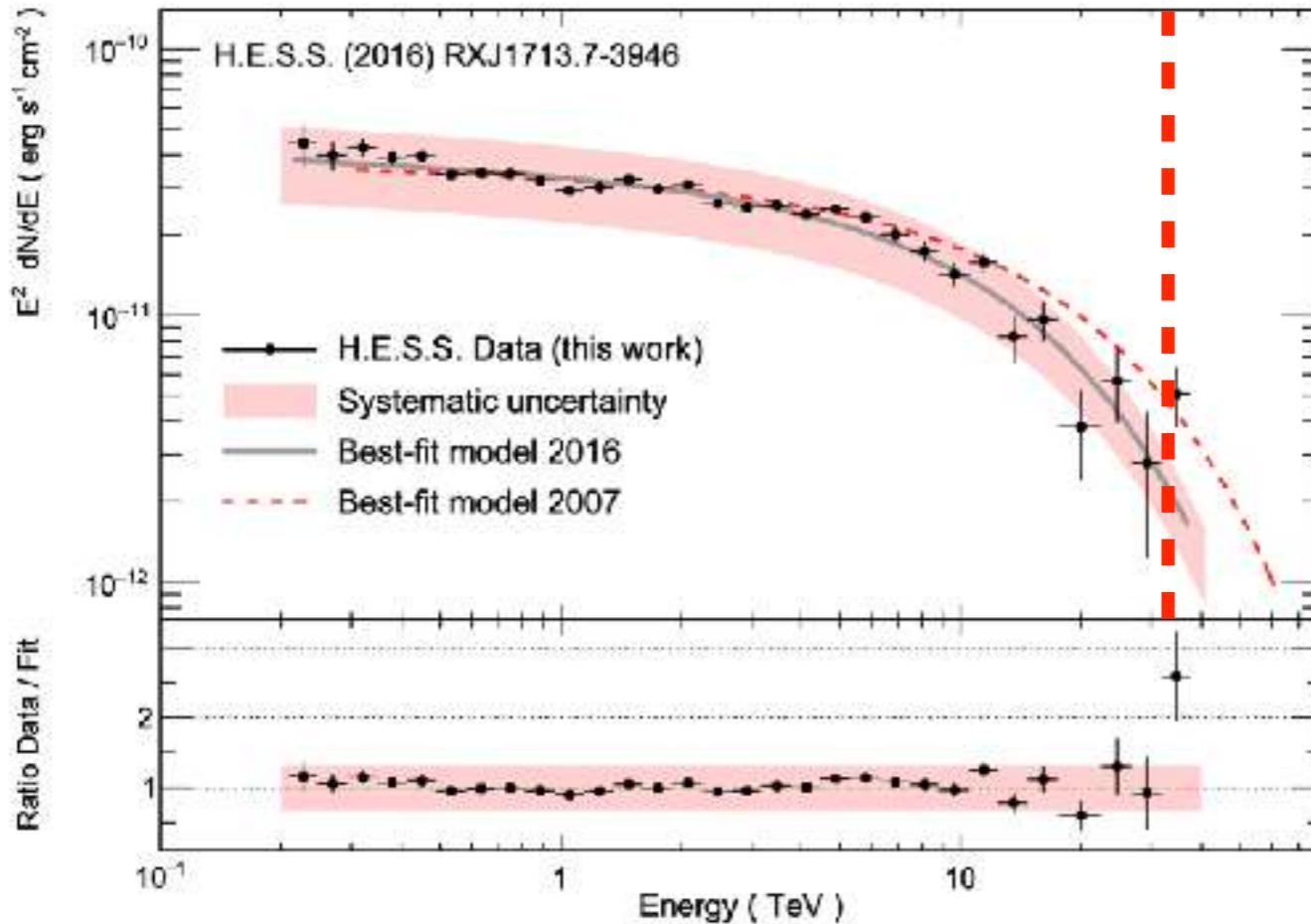
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$$E_e^{up} \approx 100 \text{ TeV} \longrightarrow E_{syn} \propto E_e^2 B \approx 1 \left(\frac{B}{10 \mu\text{G}} \right) \text{ keV}$$

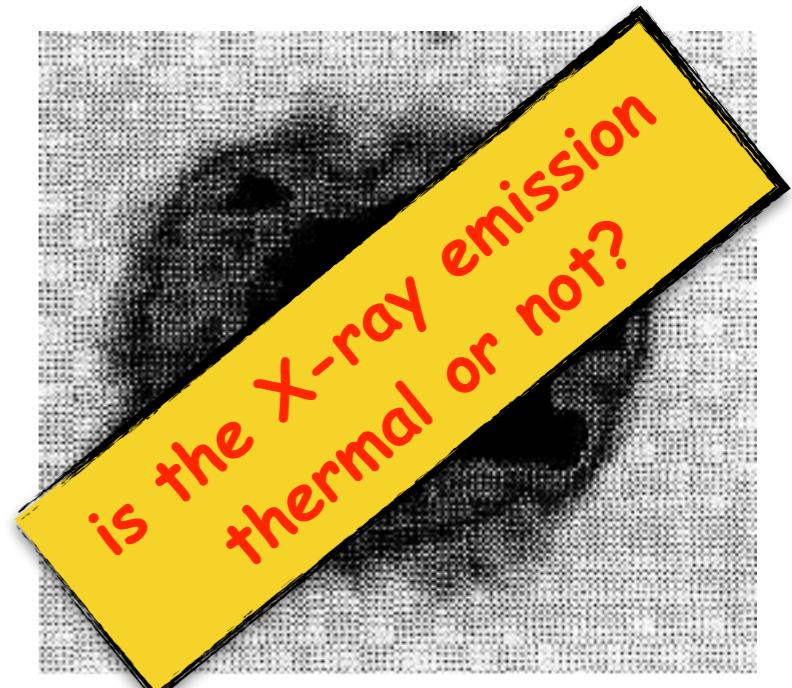
→ X-rays !

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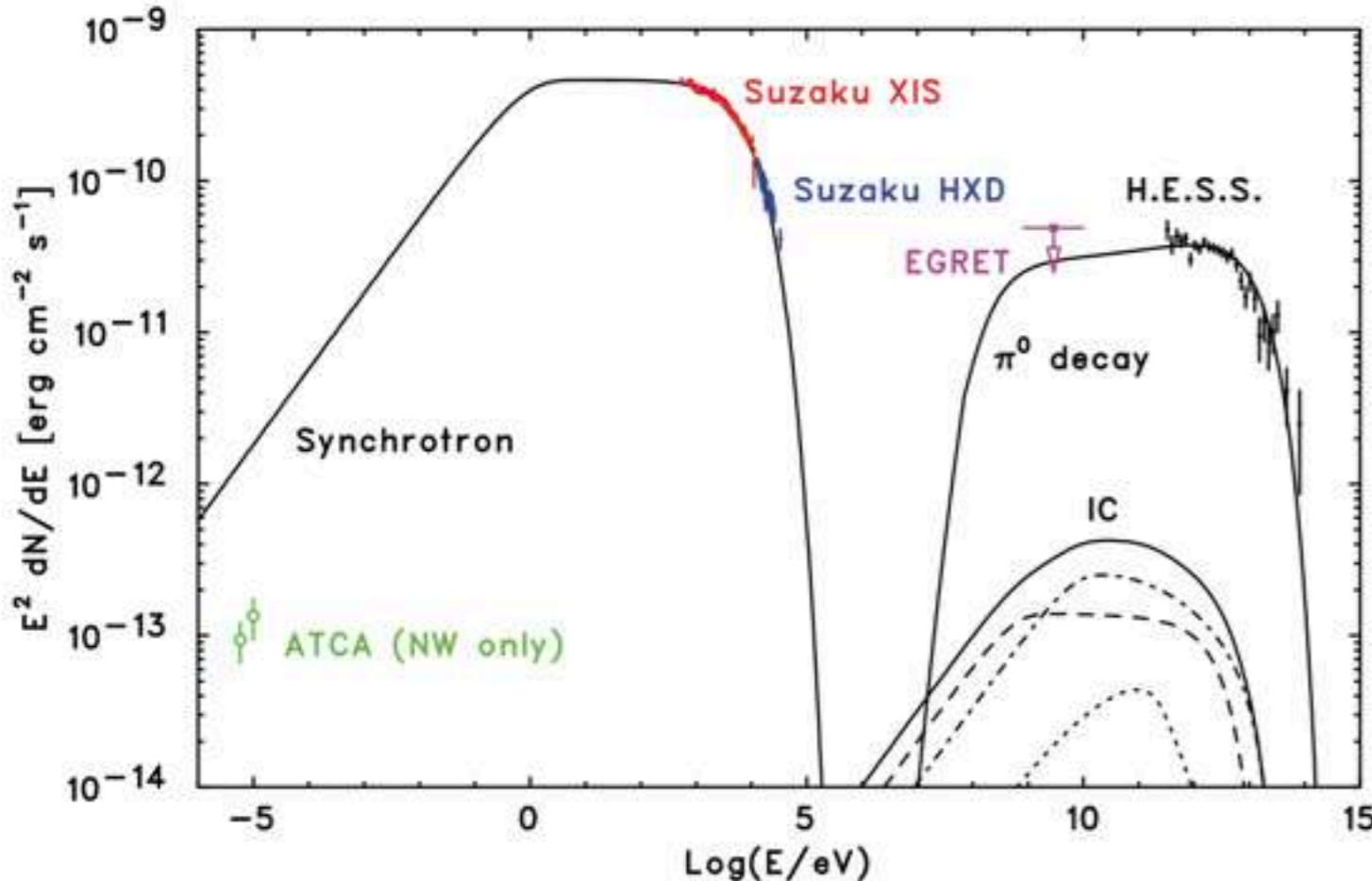
Synchrotron X-rays from RX J1713

Koyama+ 97 → no line emission in X-ray spectrum (ASCA) → non-thermal !

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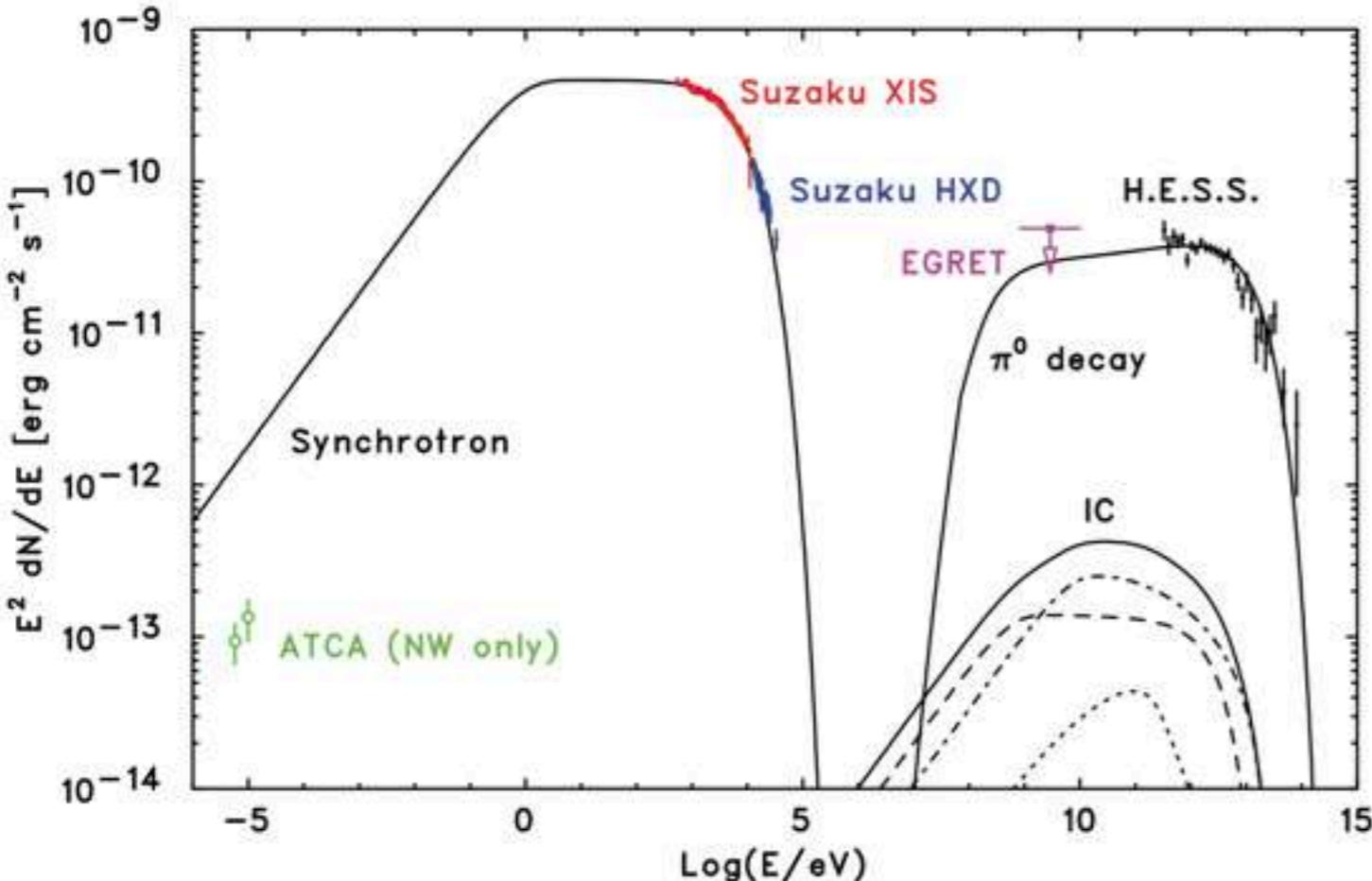
Tanaka+ 2008 (SUZAKU)



Synchrotron X-rays from RX J1713

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Tanaka+ 2008 (SUZAKU)



leptonic scenario

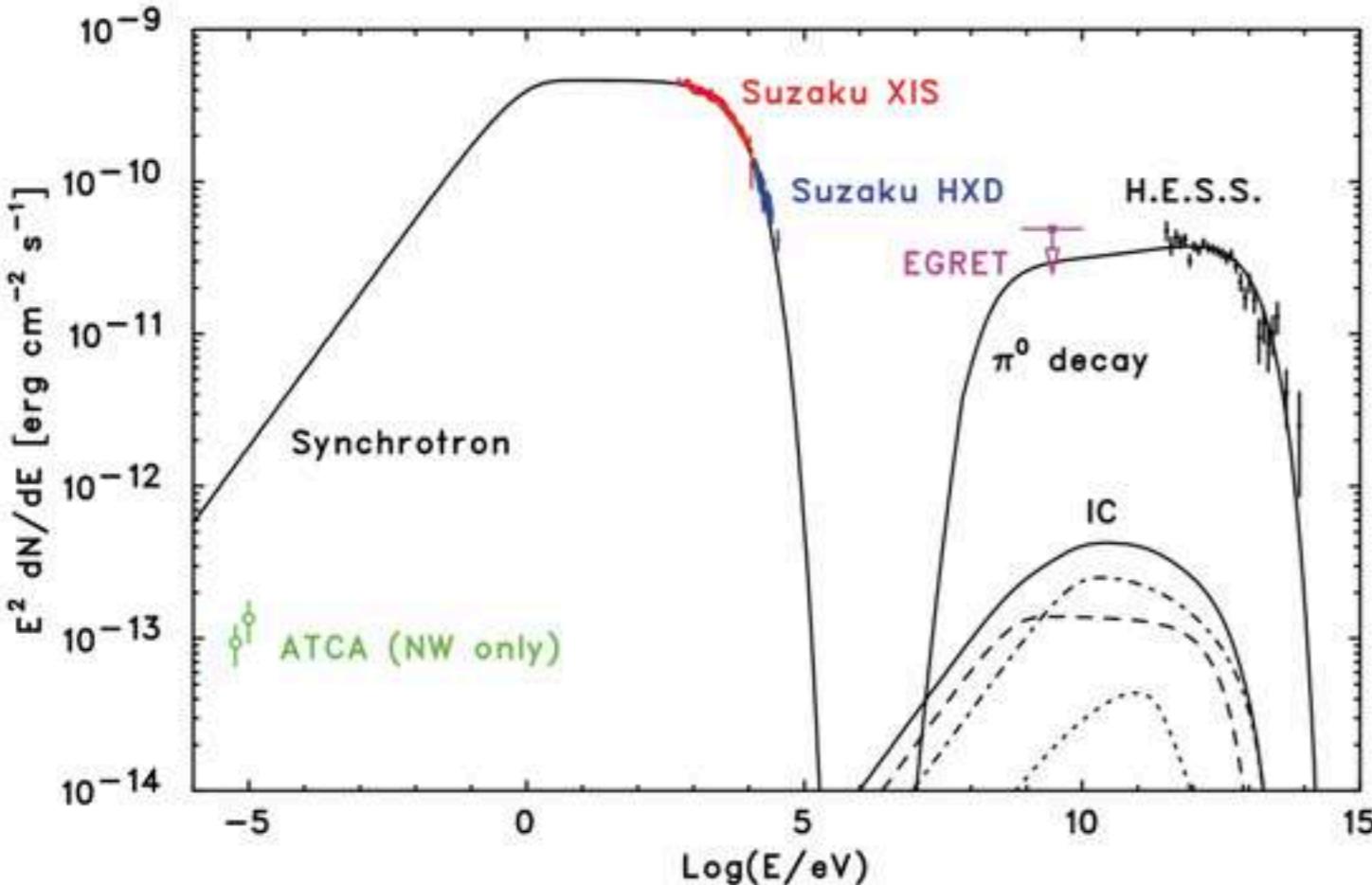
$$F_\gamma \propto E^{-2} \rightarrow N_e \propto E^{-3}$$

we need a E^{-3} spectrum

Synchrotron X-rays from RX J1713

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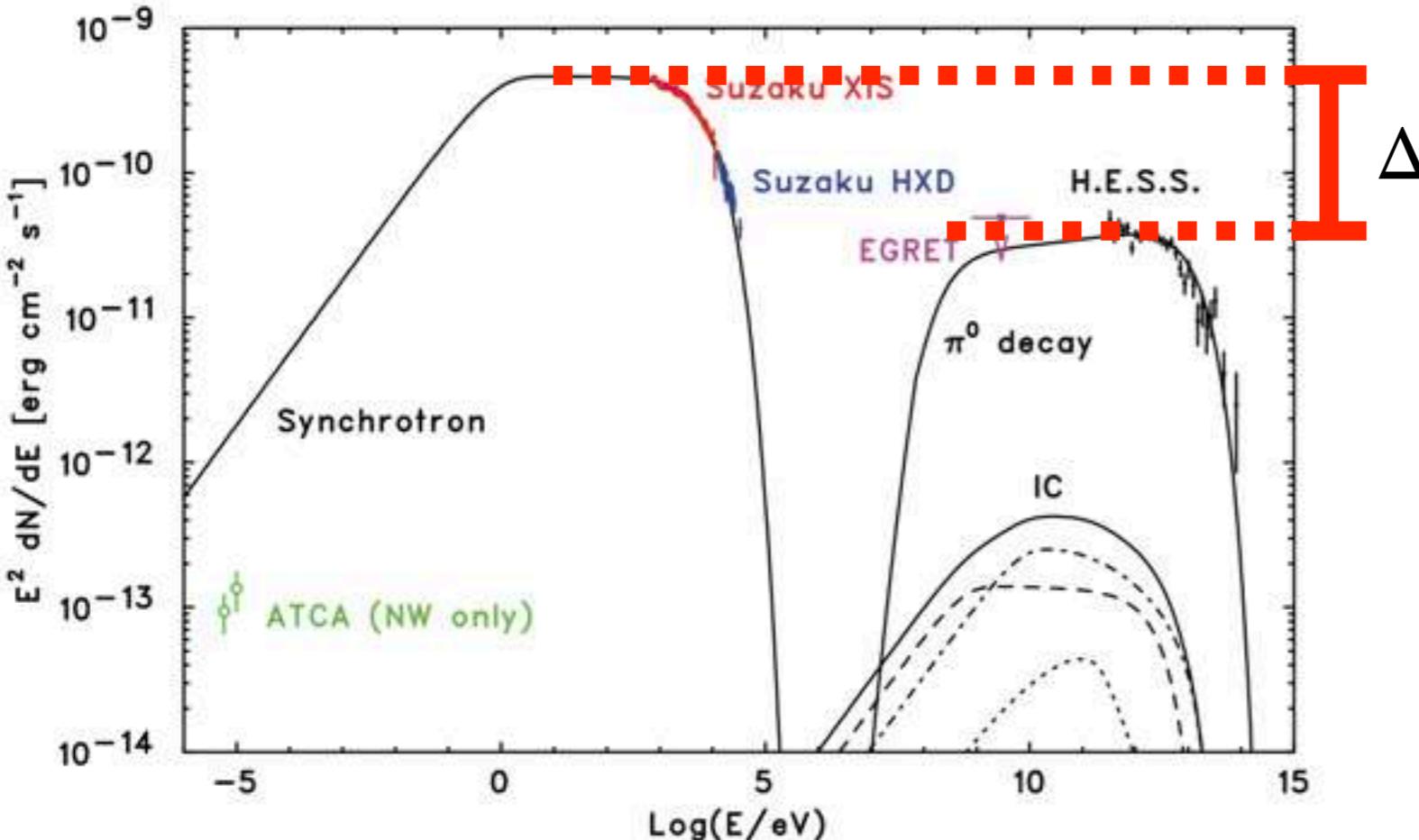
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we need a E^{-3} spectrum

Synchrotron X-rays from RX J1713

Koyama+ 97 → no line emission in X-ray spectrum (ASCA) → non-thermal !

Tanaka+ 2008 (SUZAKU)



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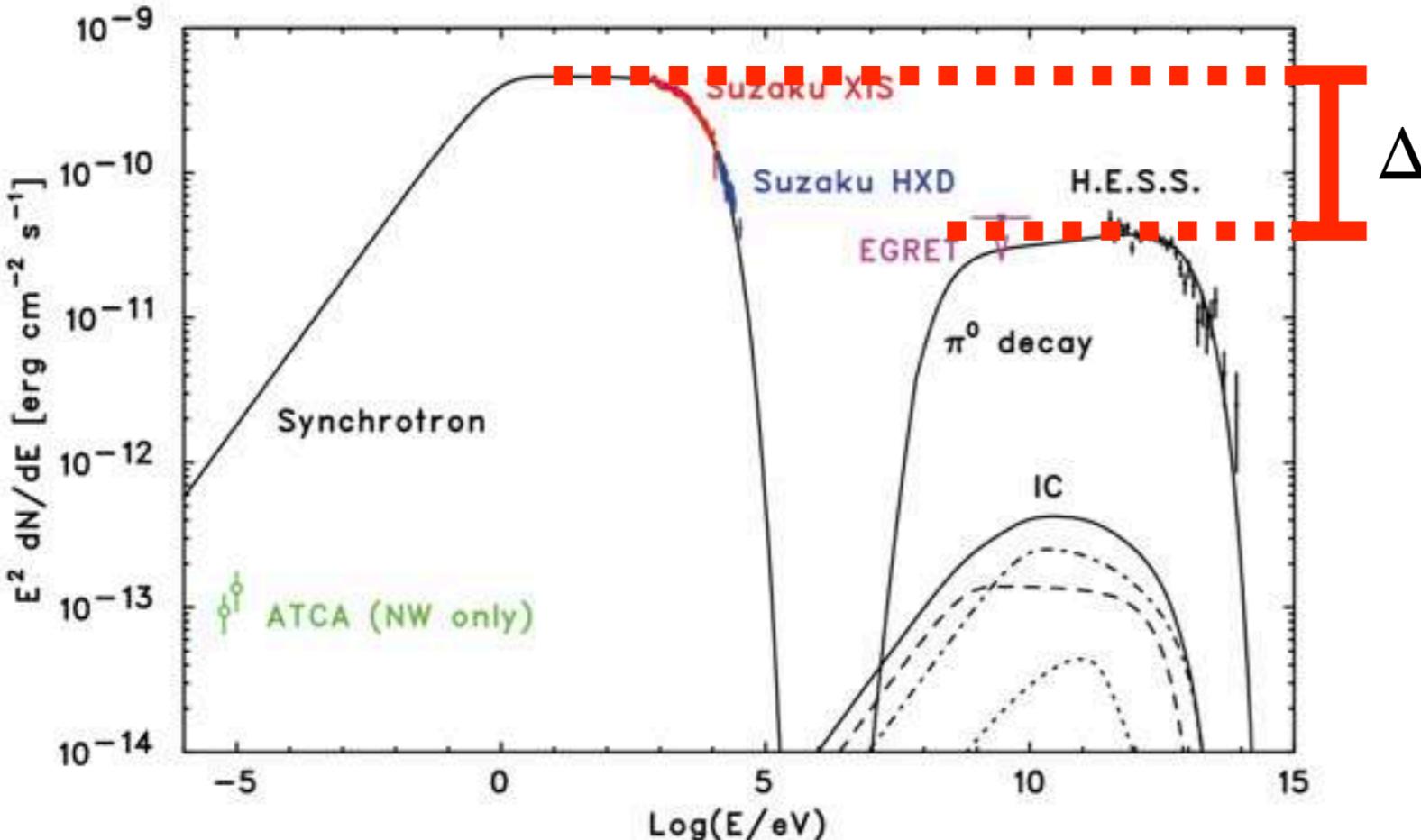
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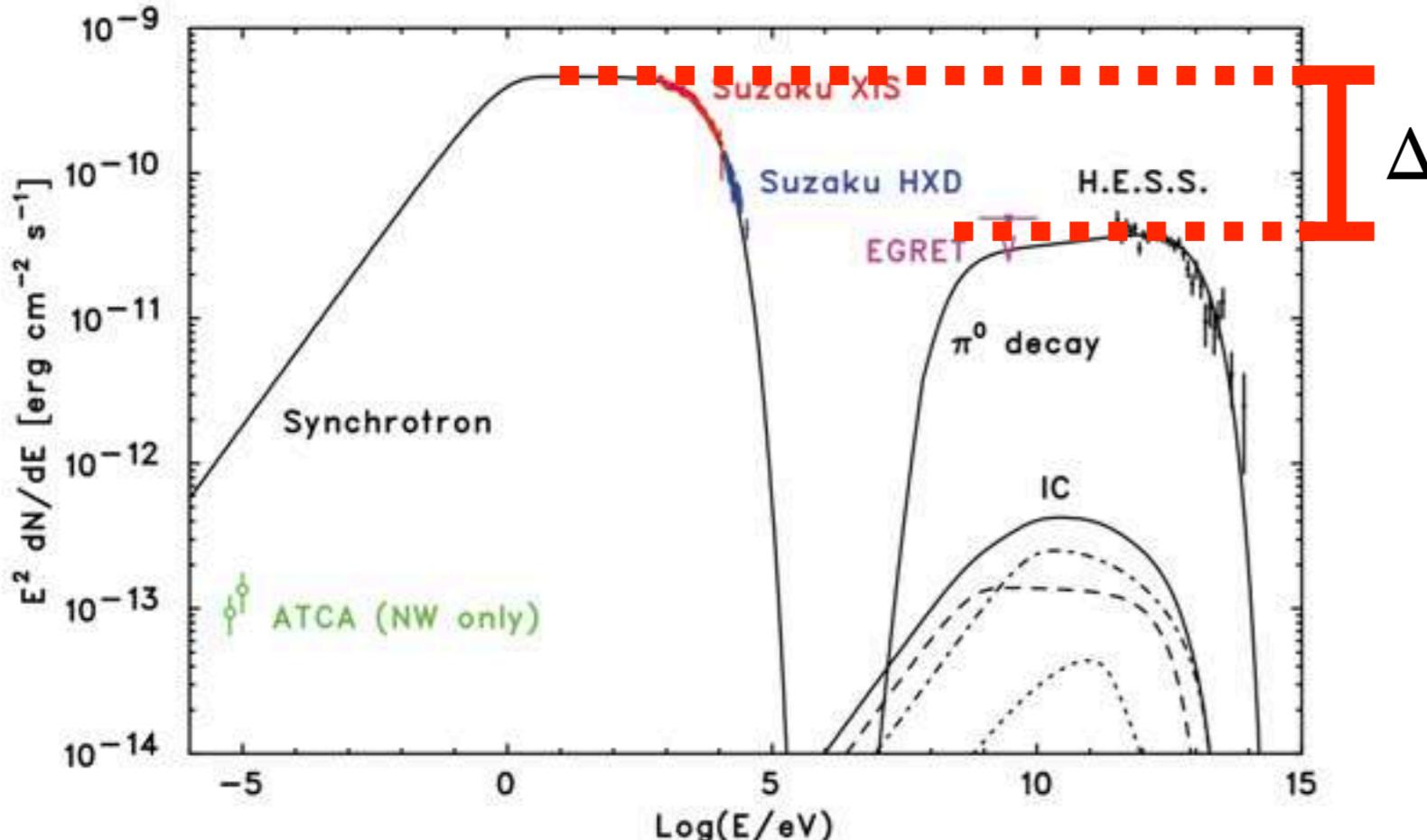
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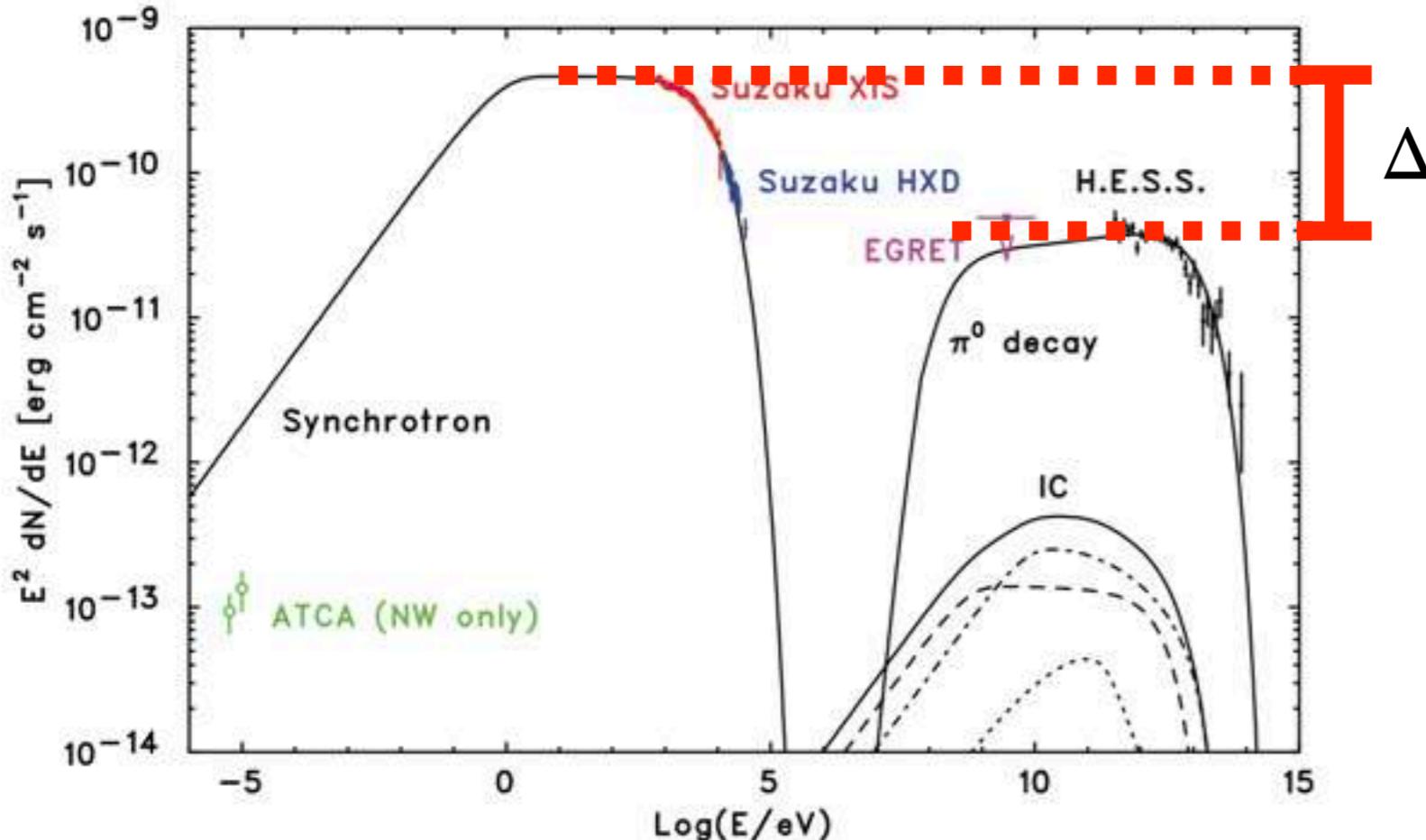
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↓ ratio

$$\Delta = \frac{\omega_B}{\omega_{CMB}} \approx 10 \rightarrow B \approx 10 \mu\text{G}$$

Synchrotron X-rays from RX J1713: checking assumptions

synchro/ICS losses steepen the spectrum by 1 power

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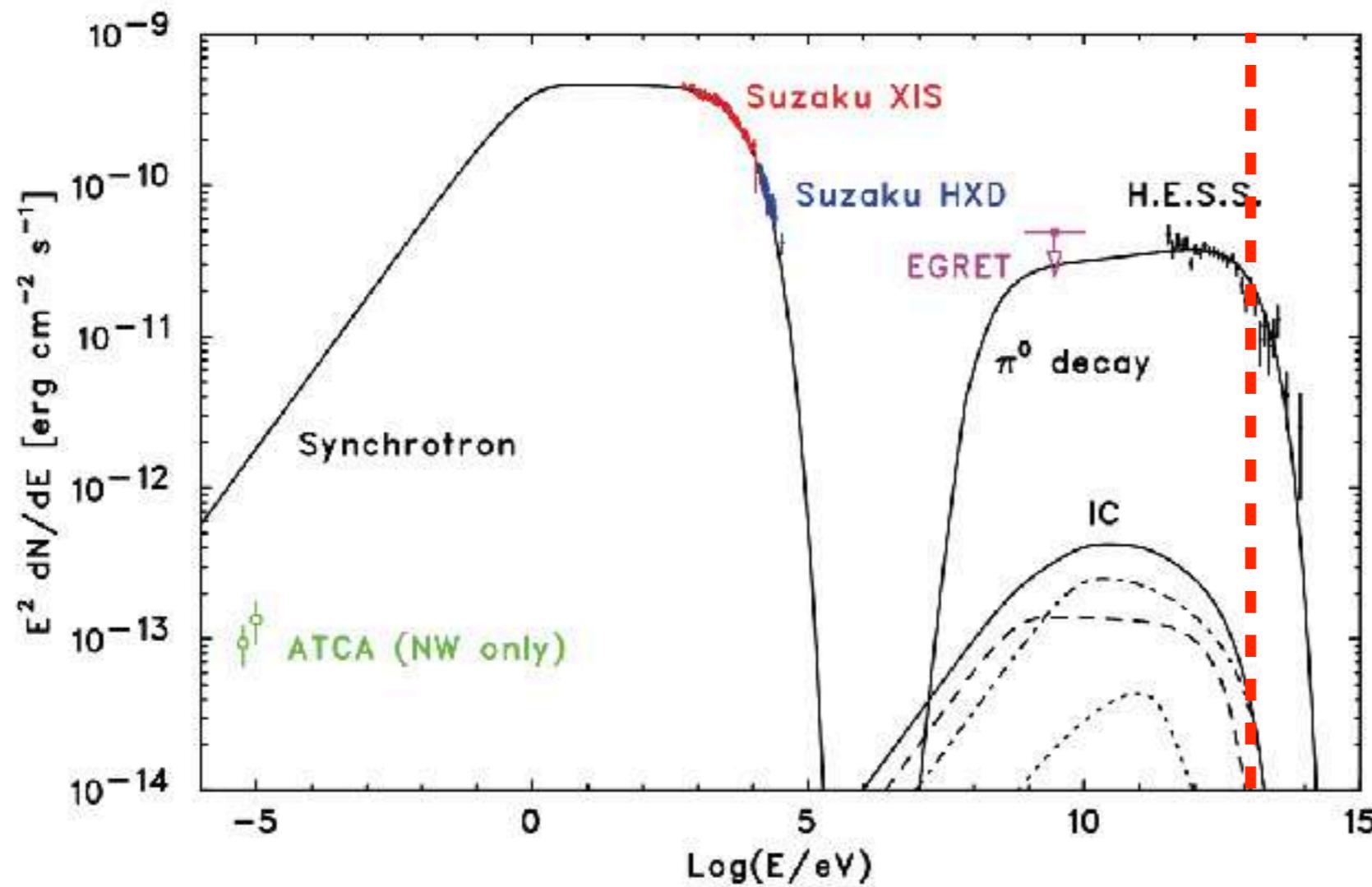
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$$E_e \sim 20 \left(\frac{E_\gamma}{\text{TeV}} \right)^{1/2} \text{ TeV} \longrightarrow E_\gamma^{\text{cool}} \approx 10 \text{ TeV}$$

in gammas, the spectrum
is cooled above 10 TeV

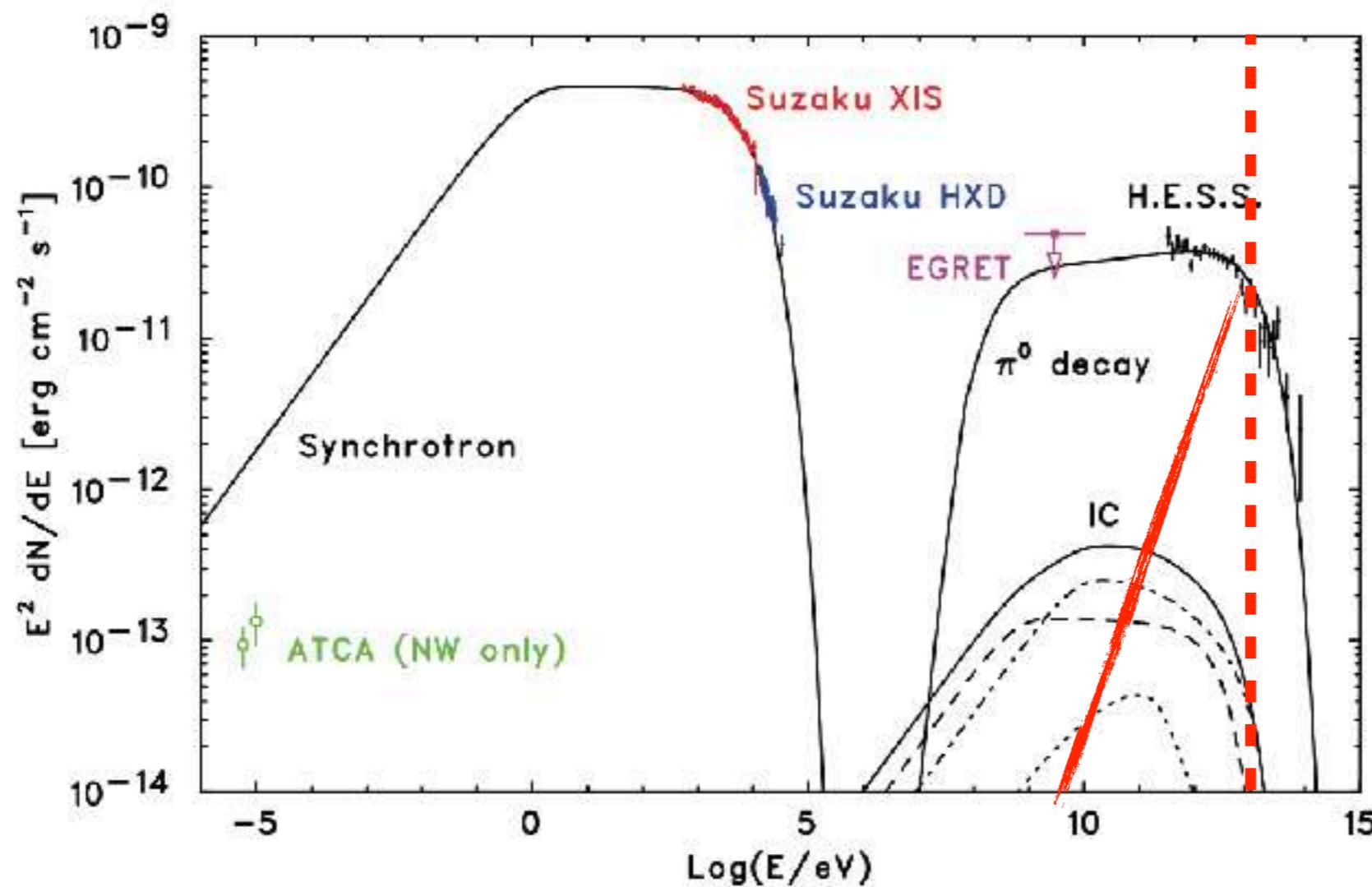
Predicted leptonic gamma-ray spectrum



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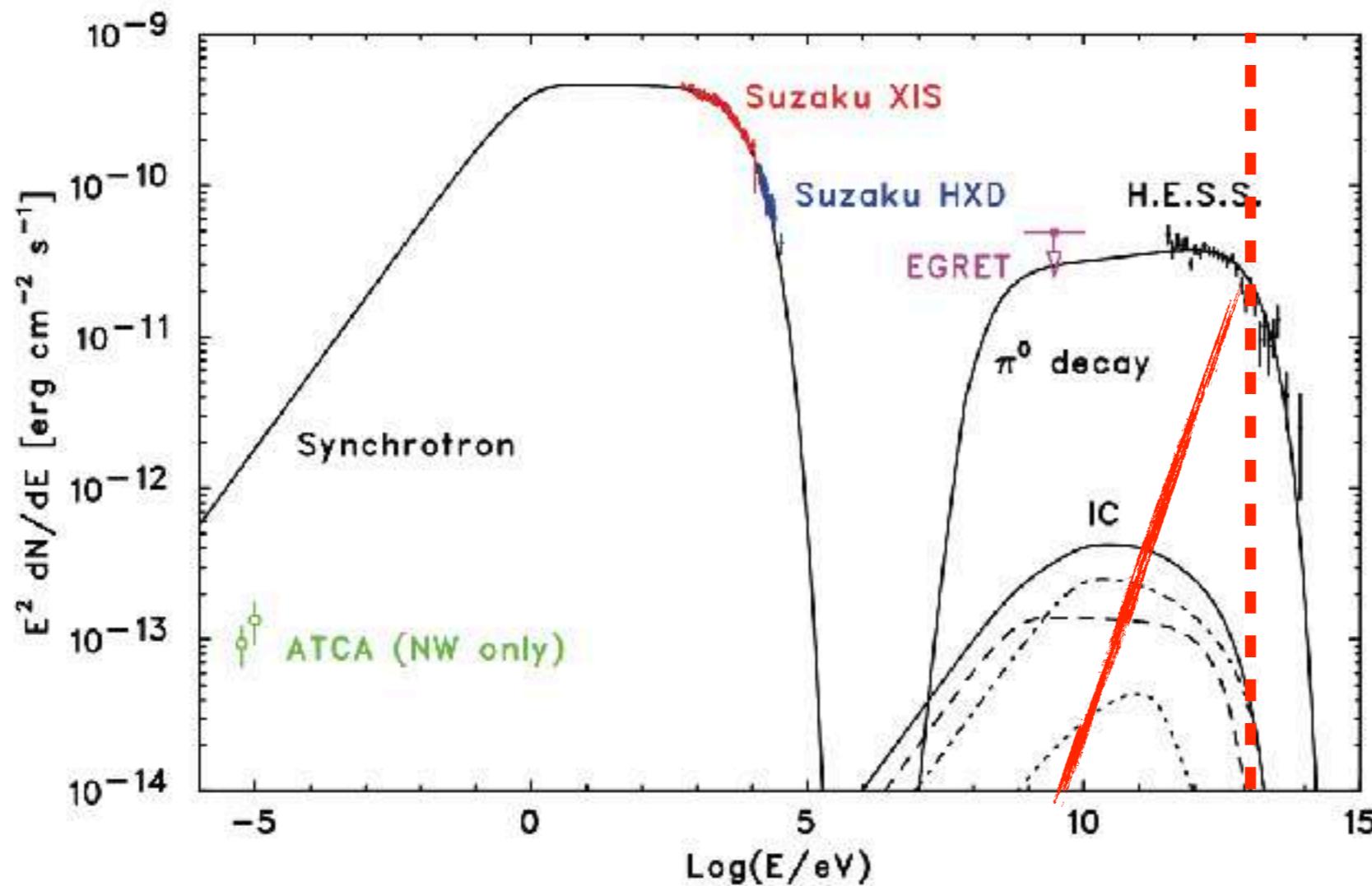
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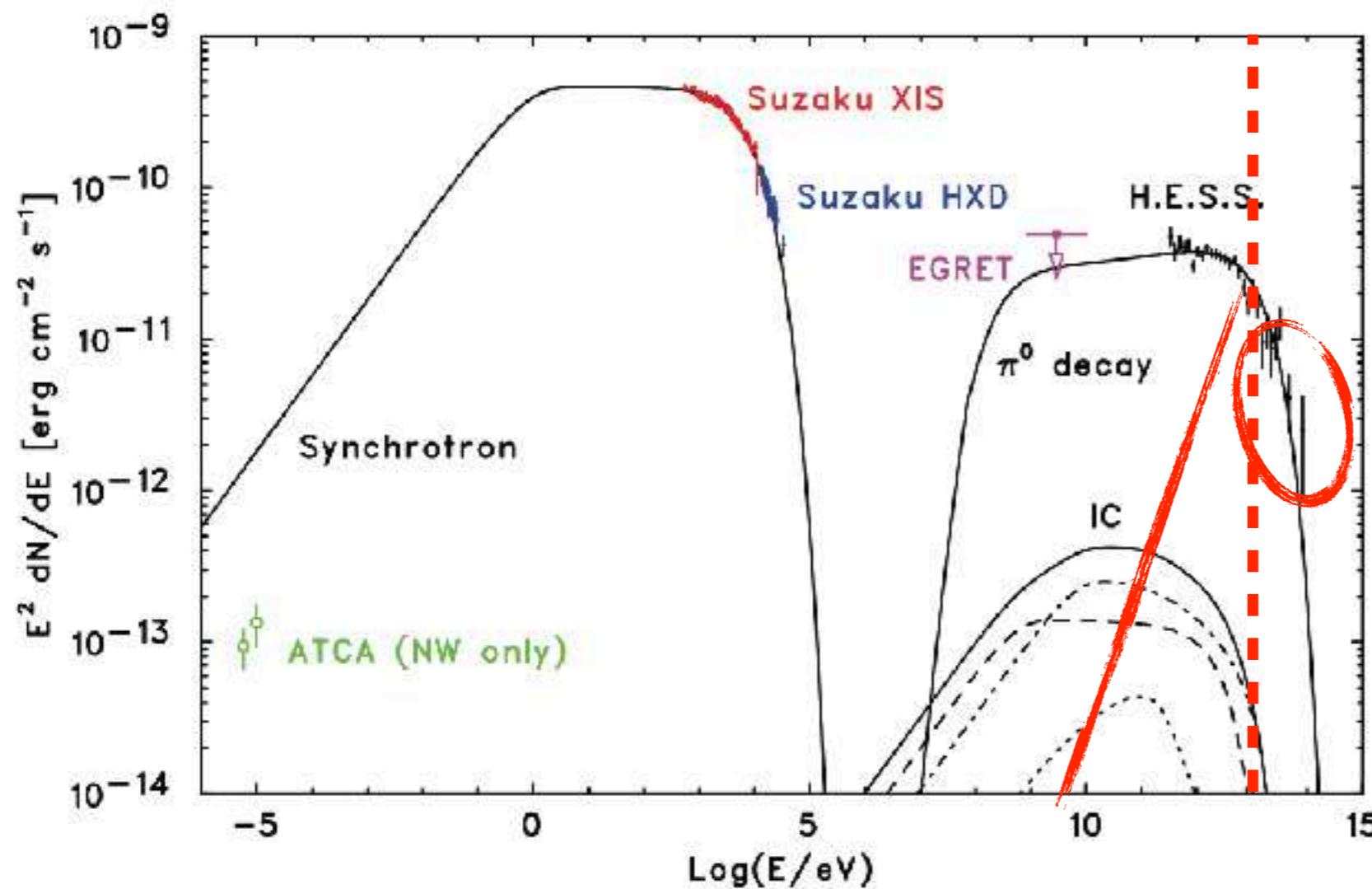
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cutoff \rightarrow maximum energy
of accelerated particles...

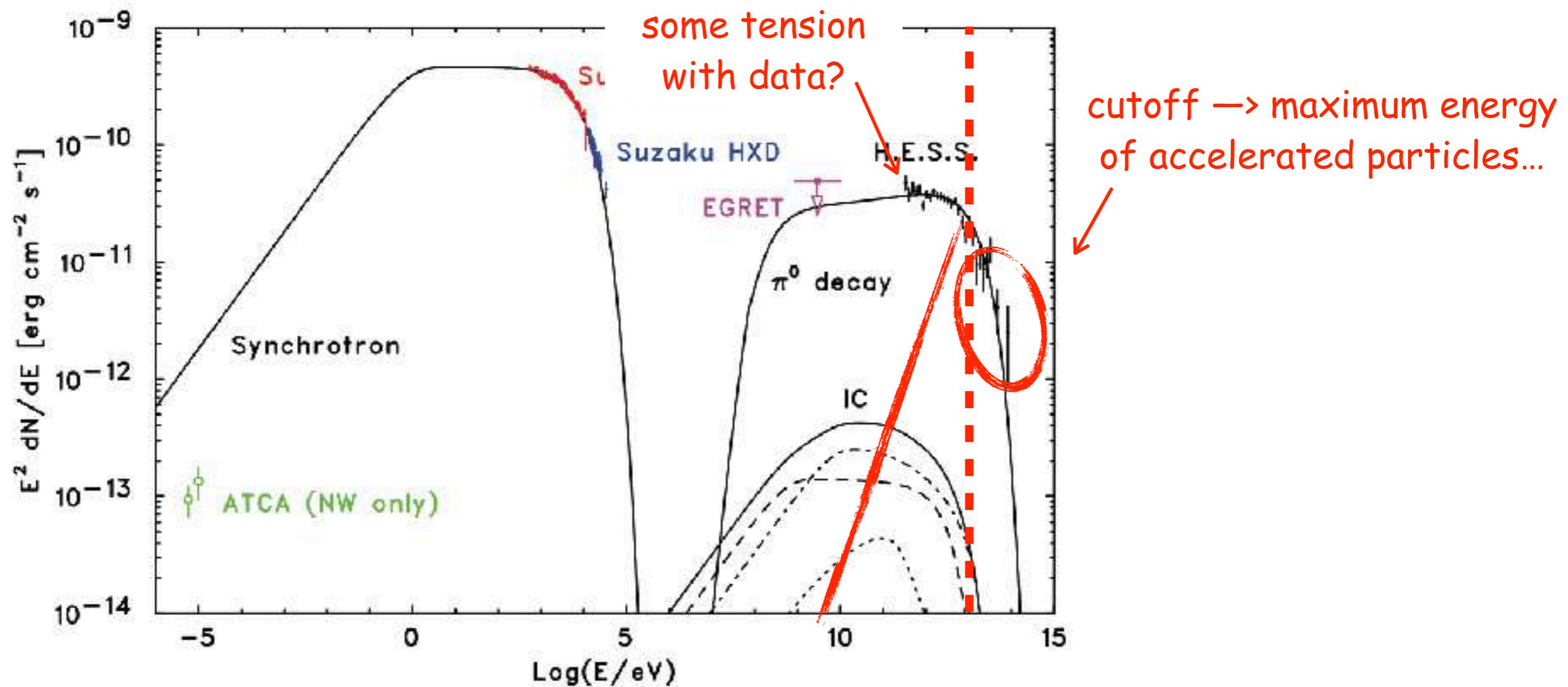
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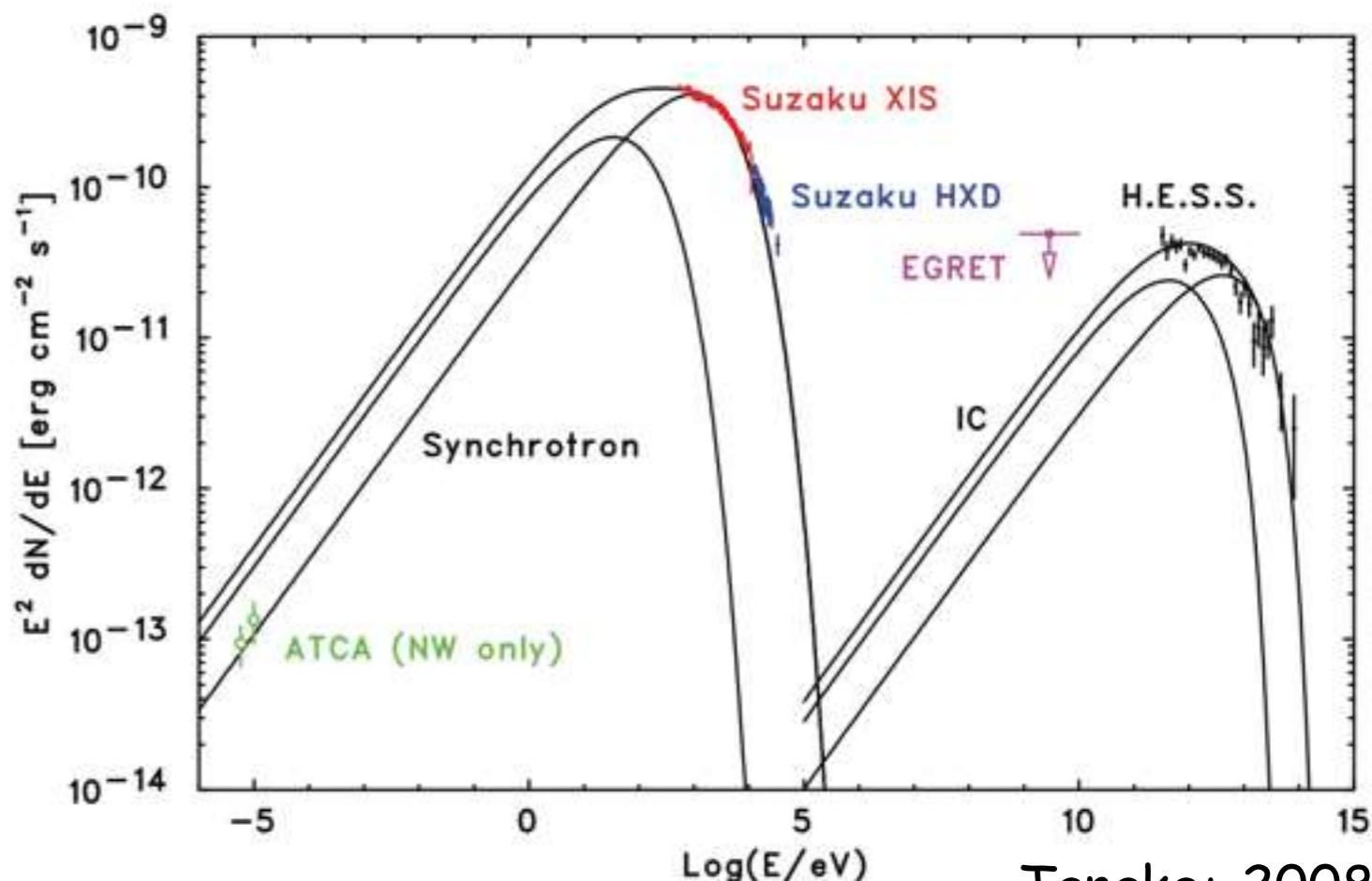
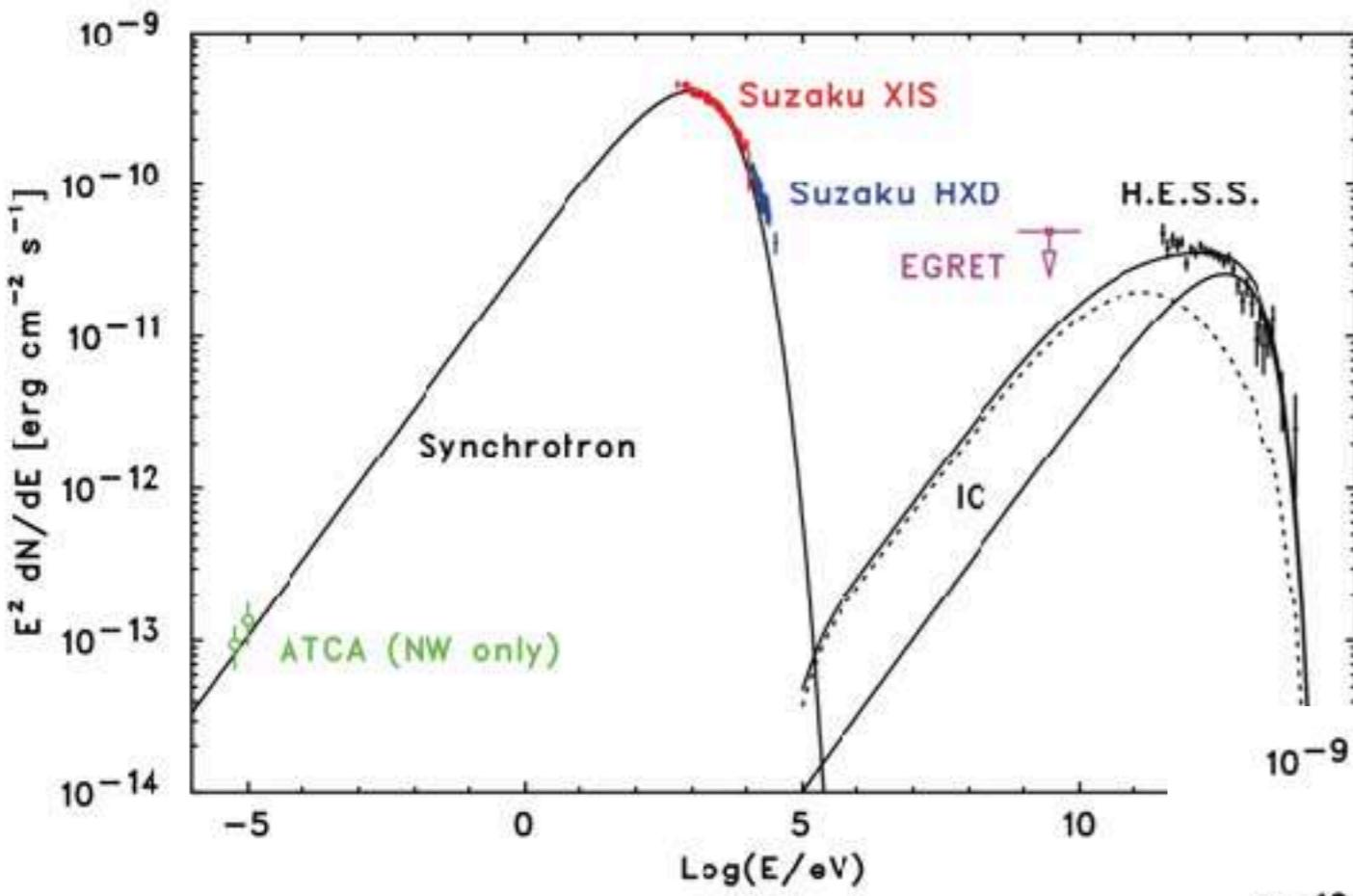
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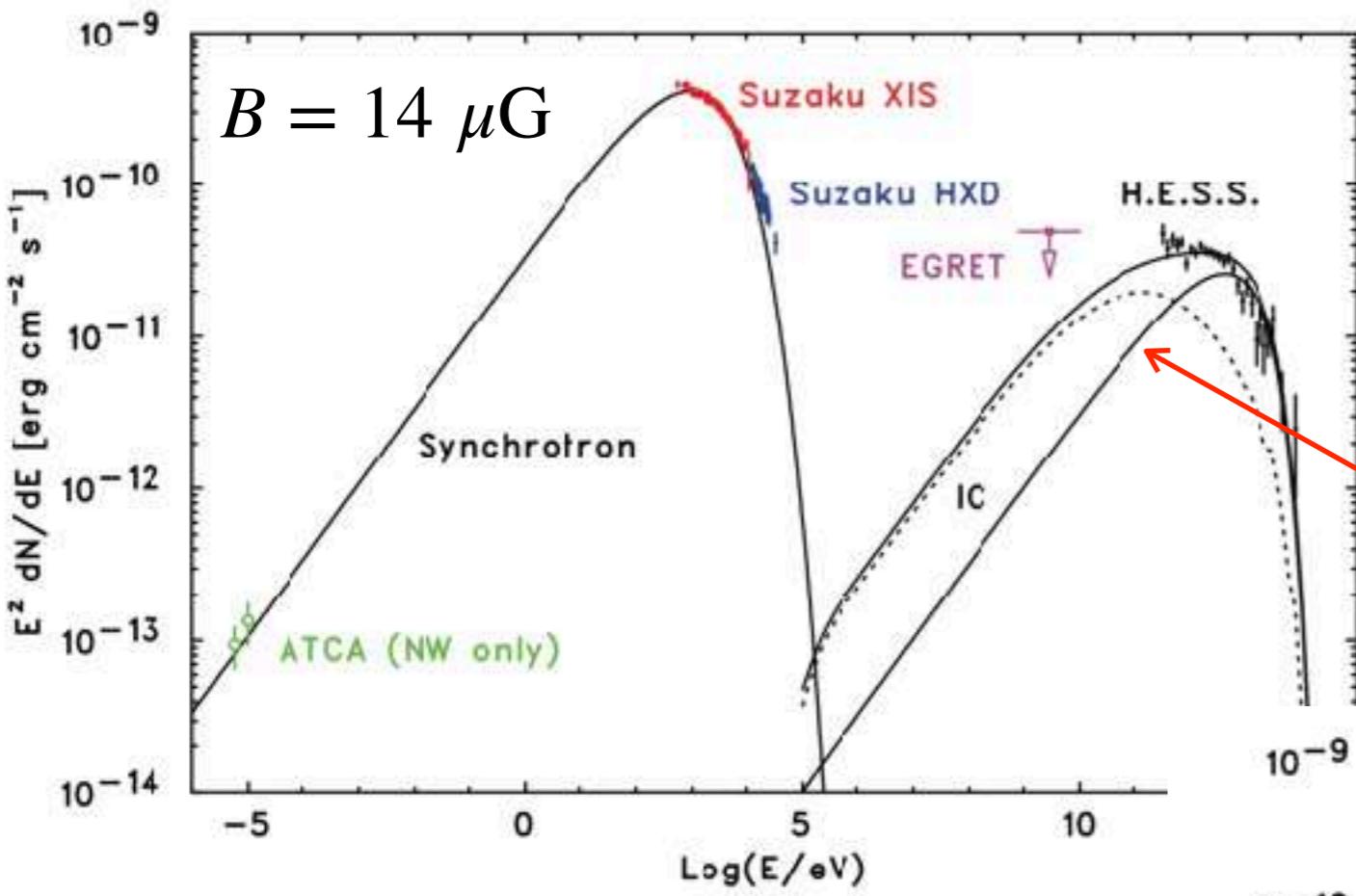
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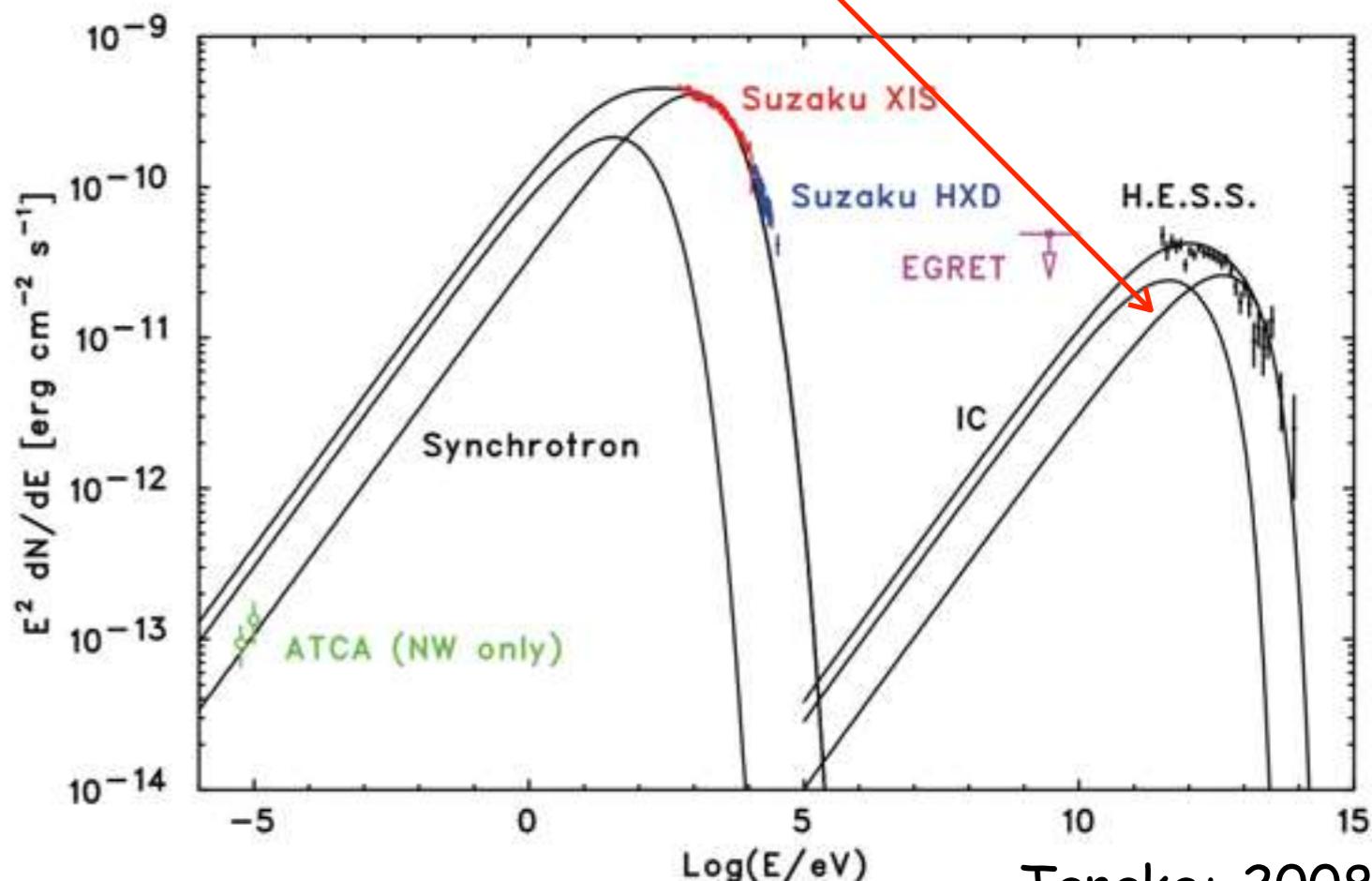
Saving the leptonic model



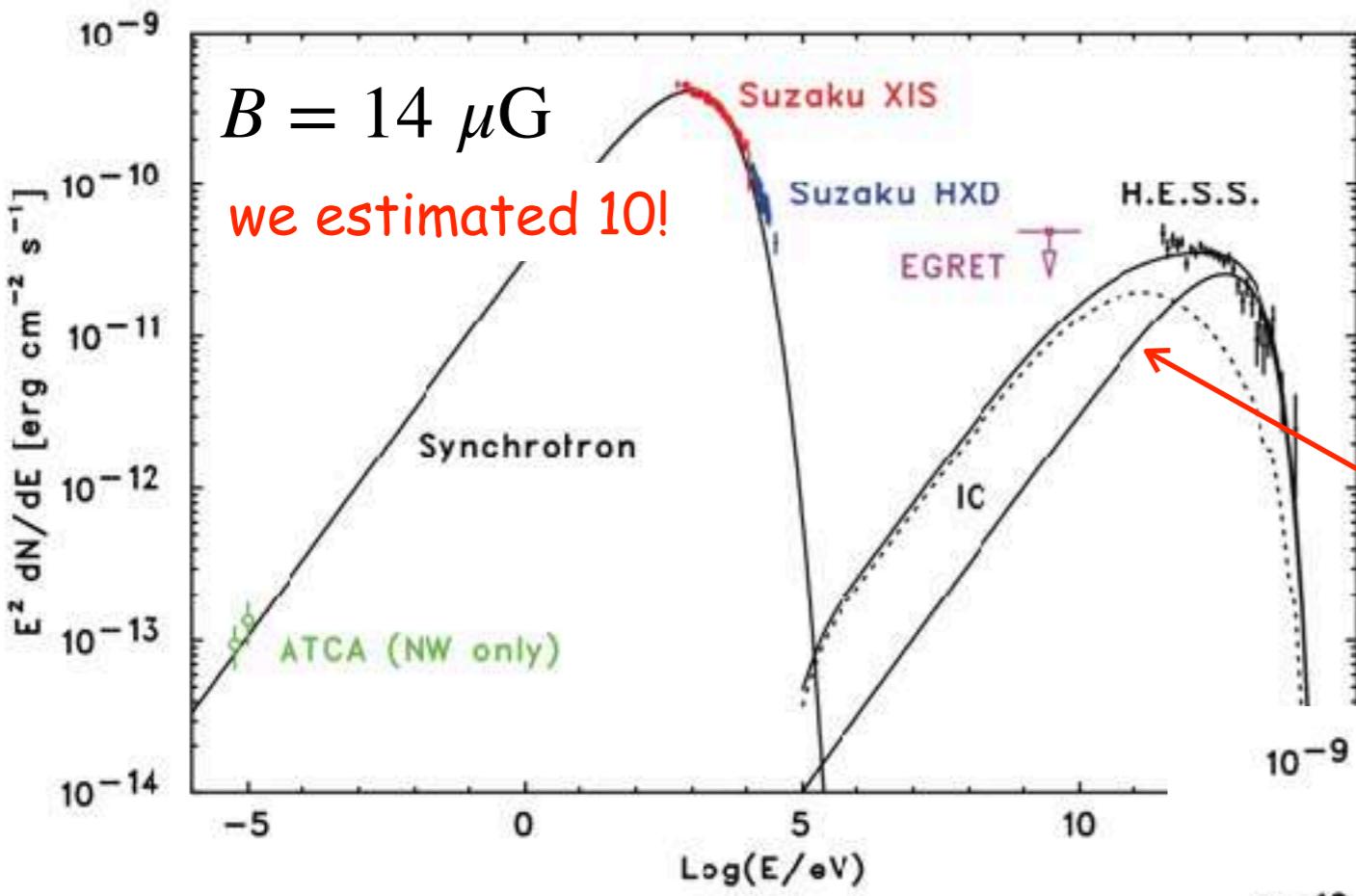
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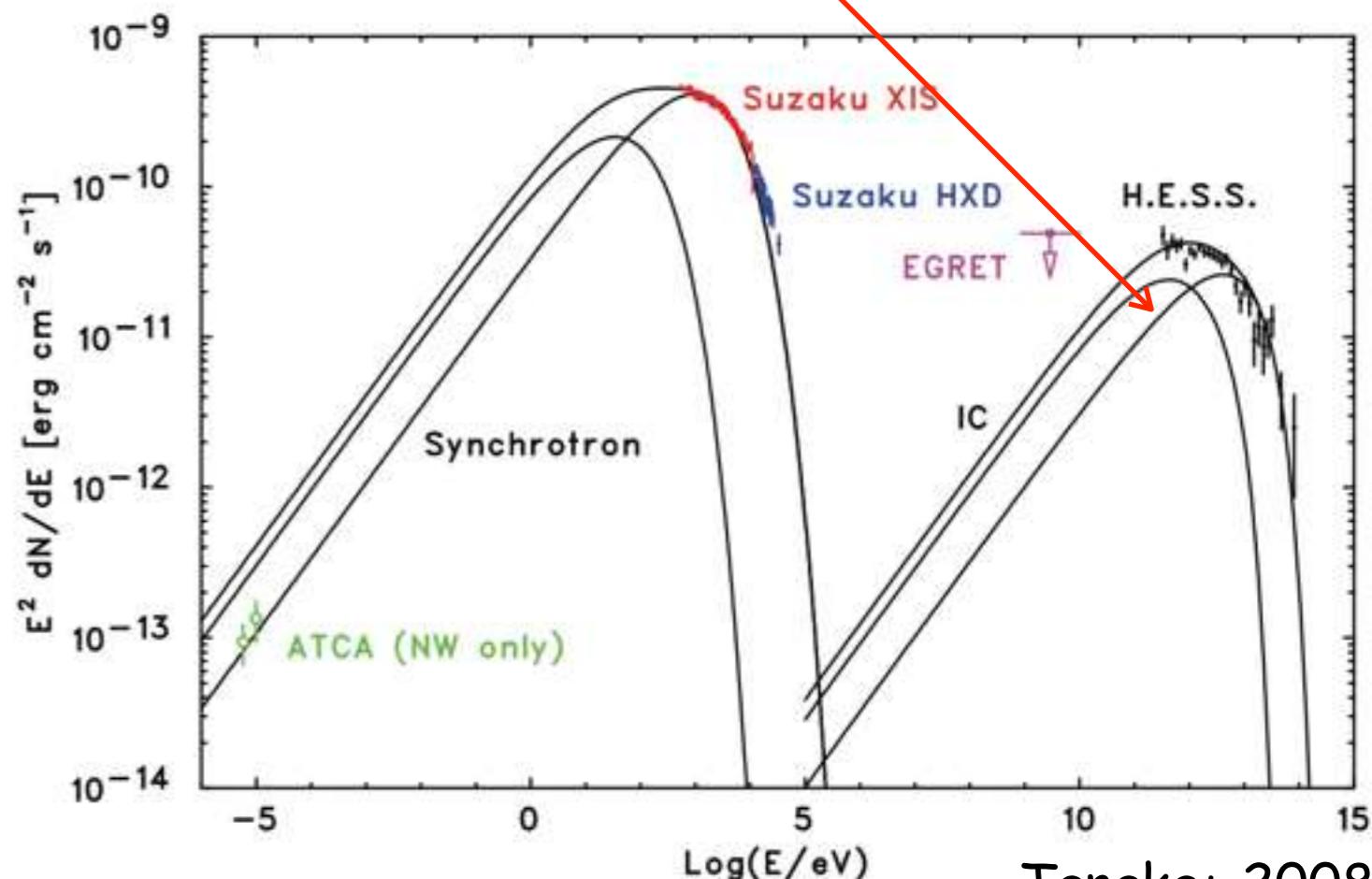
consistent with our
rough estimate!



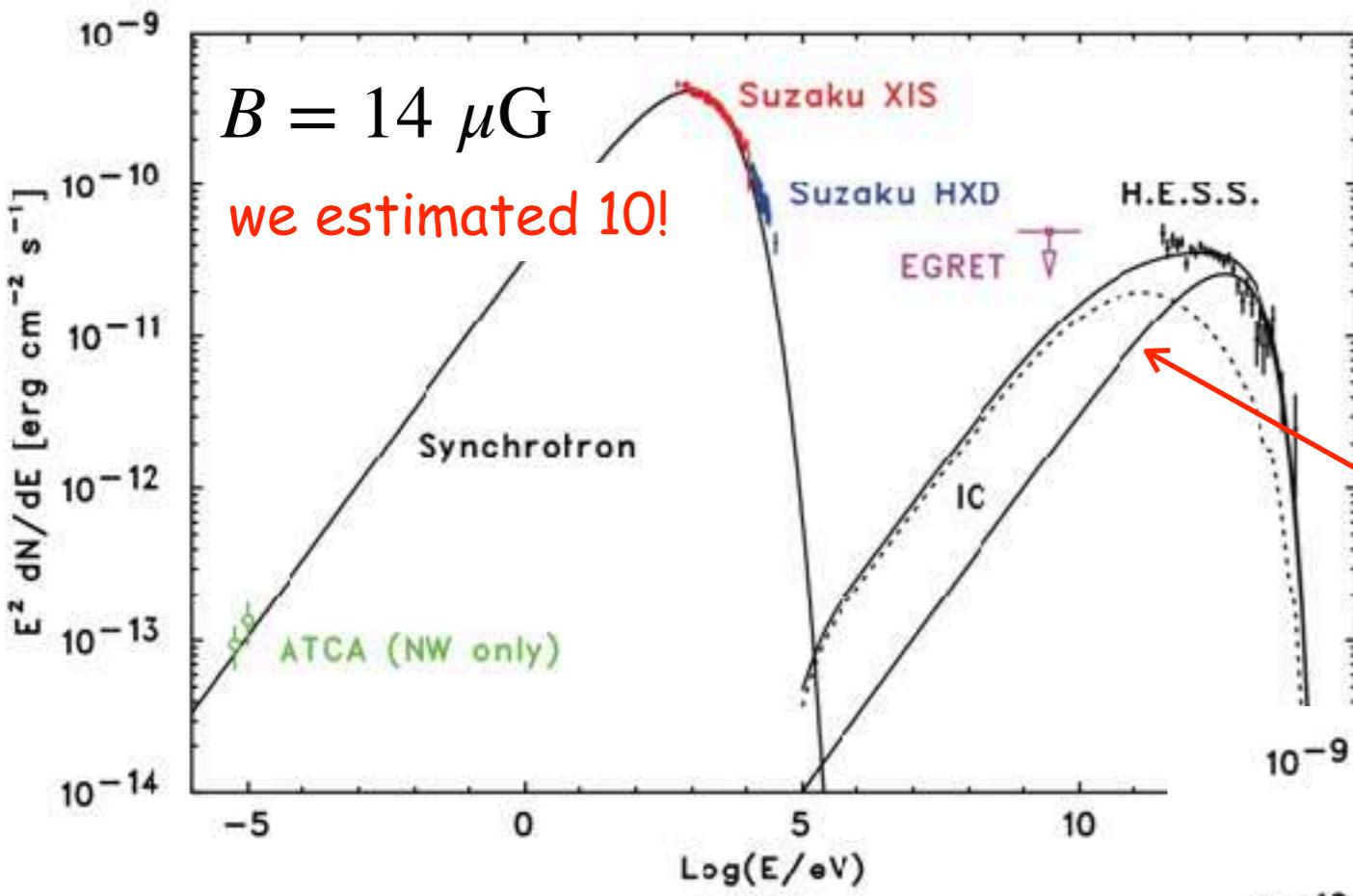
Saving the leptonic model



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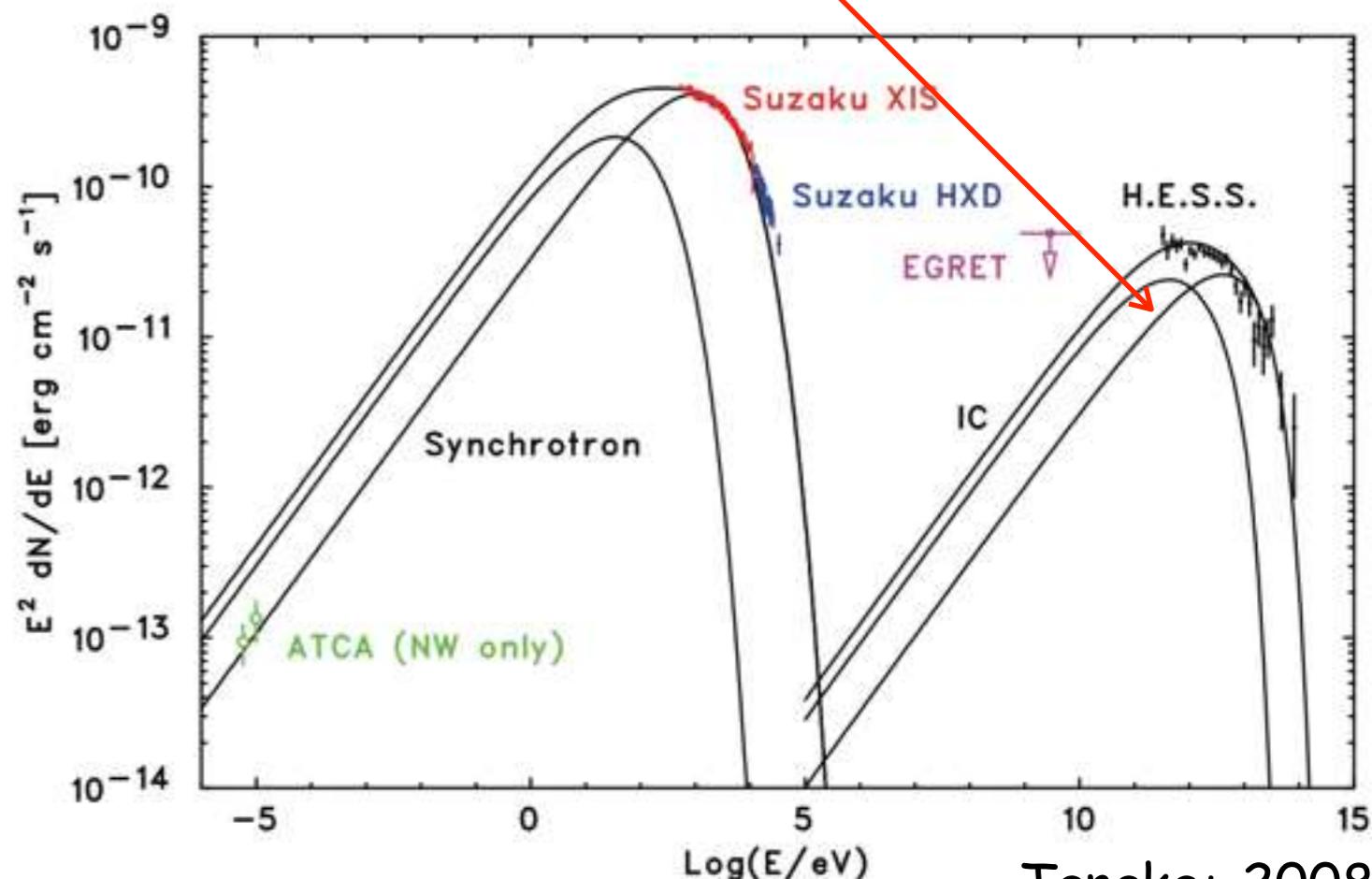
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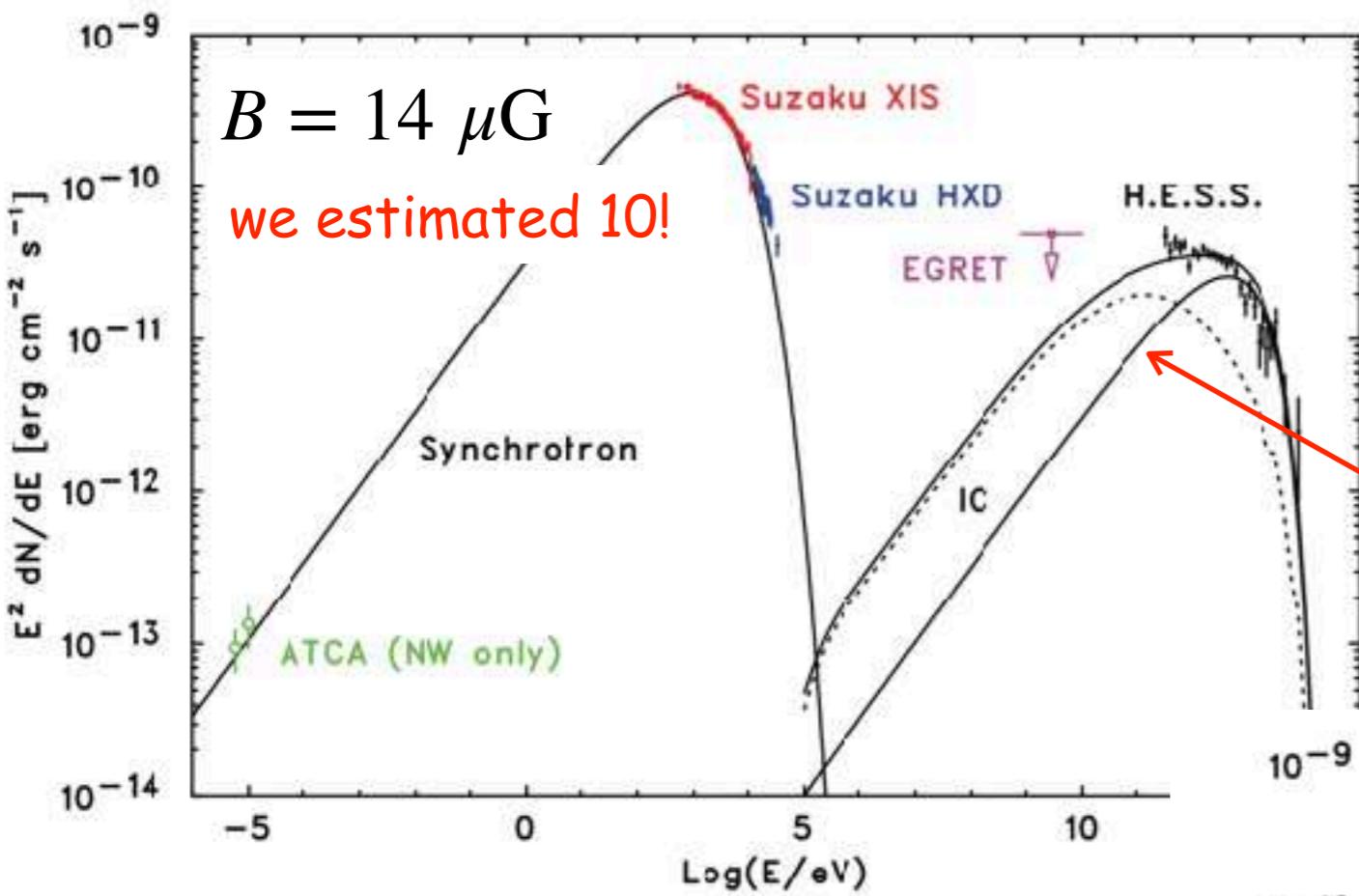
$$W_e \sim 1.4 \times 10^{47} \text{ erg}$$

small!

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Saving the leptonic model

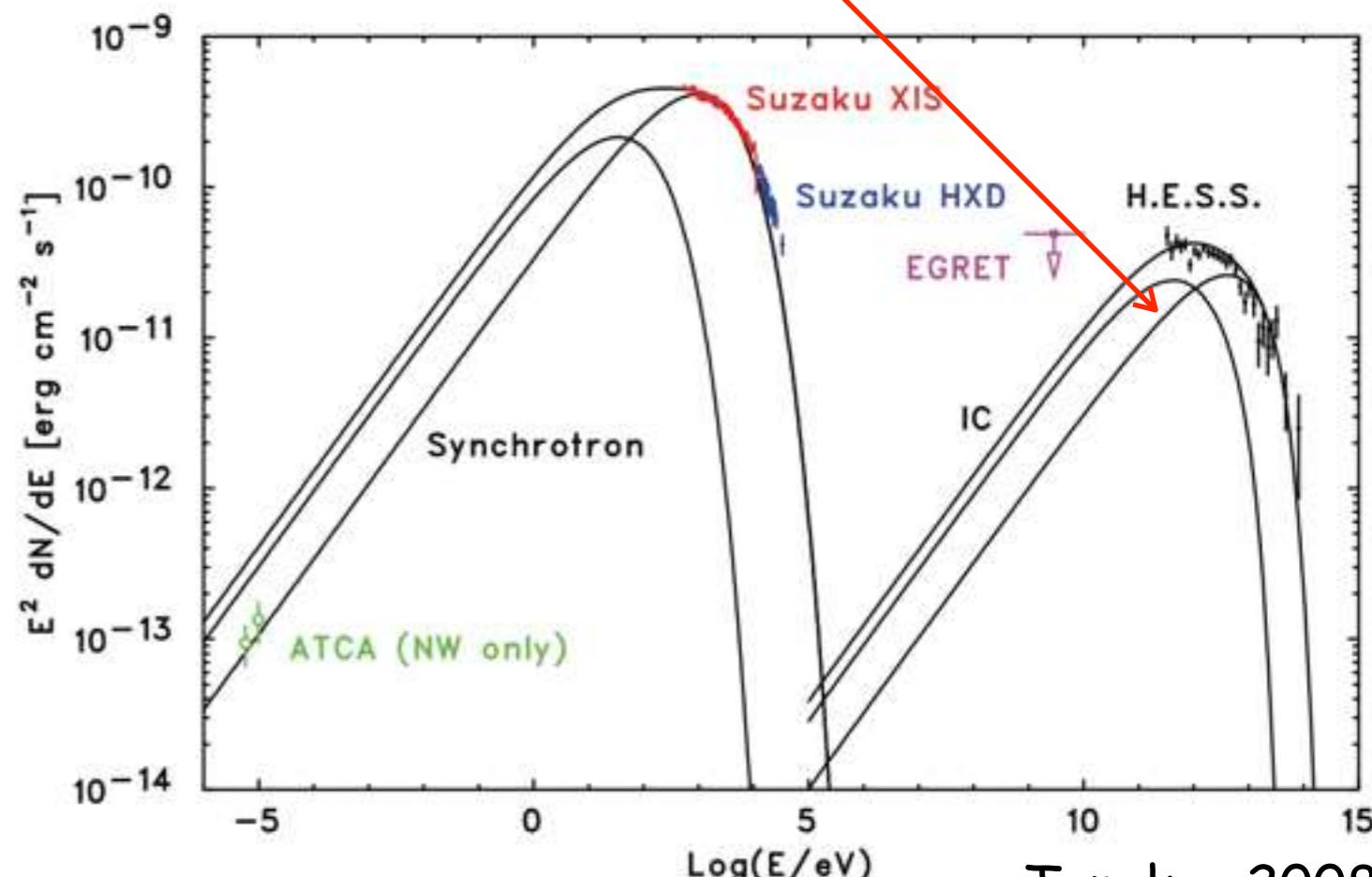


← add (optical) radiation field

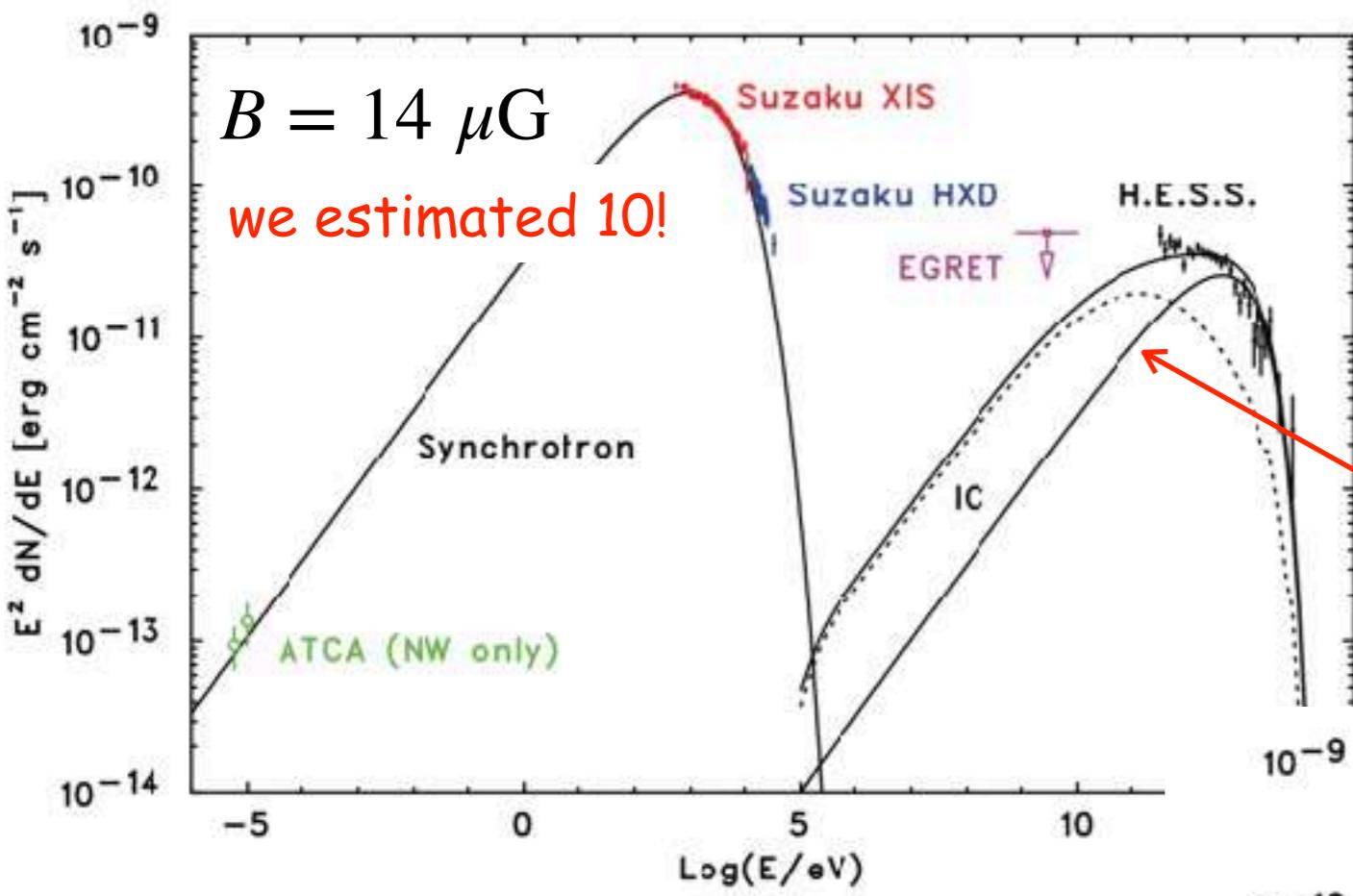
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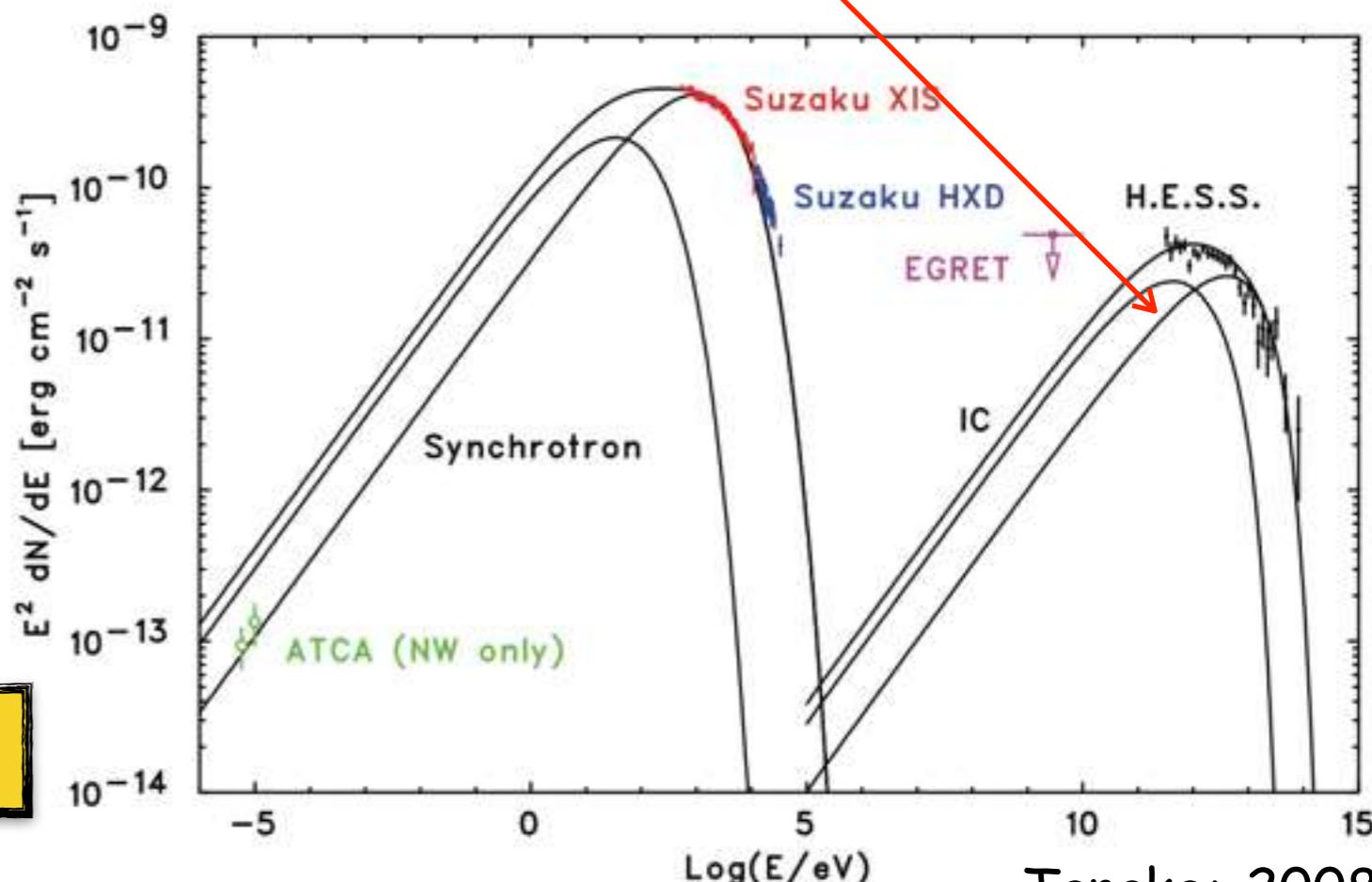
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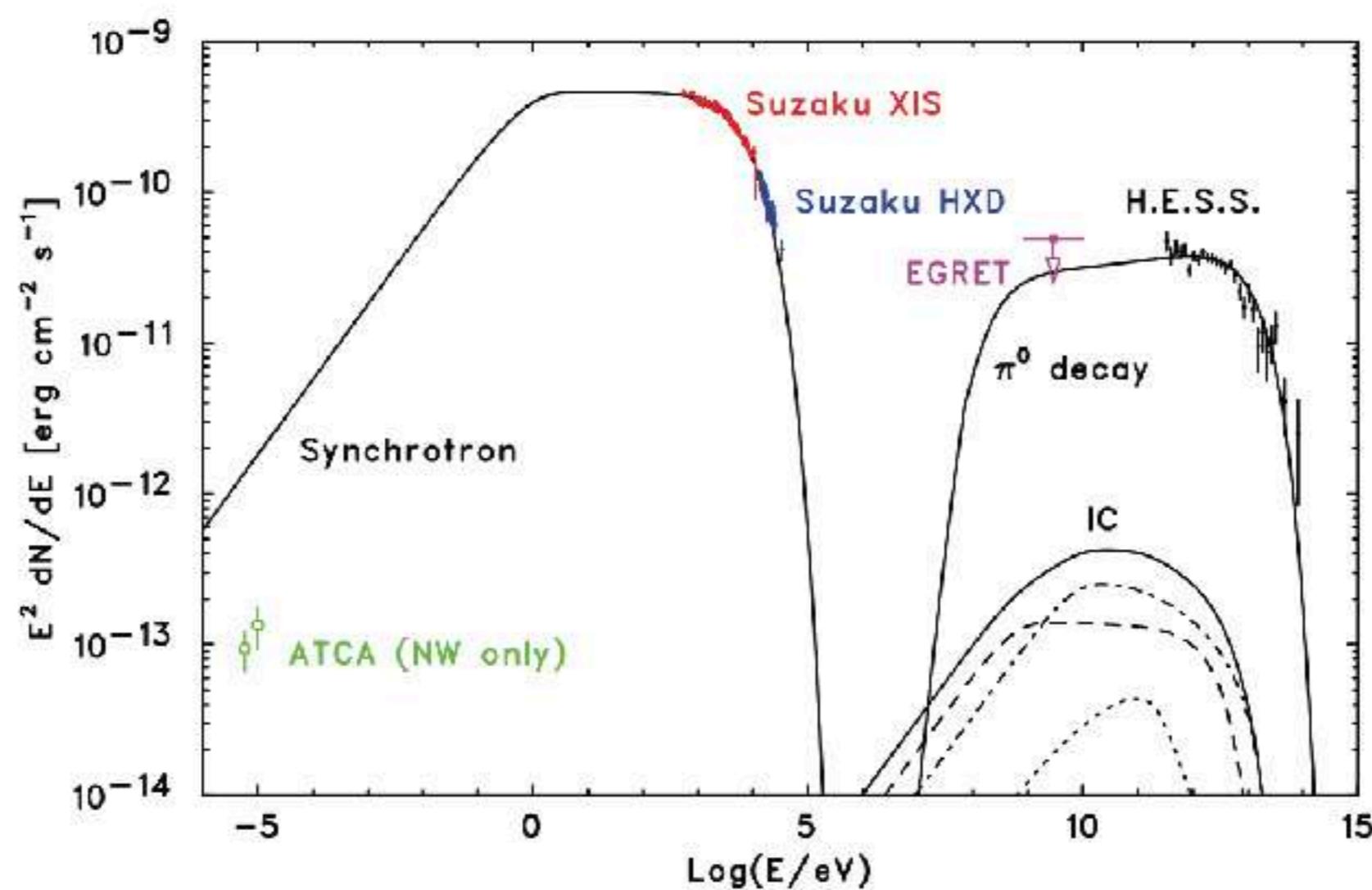
$$W_e \sim 3.4 \times 10^{47} \text{ erg}$$

small!

add another population →



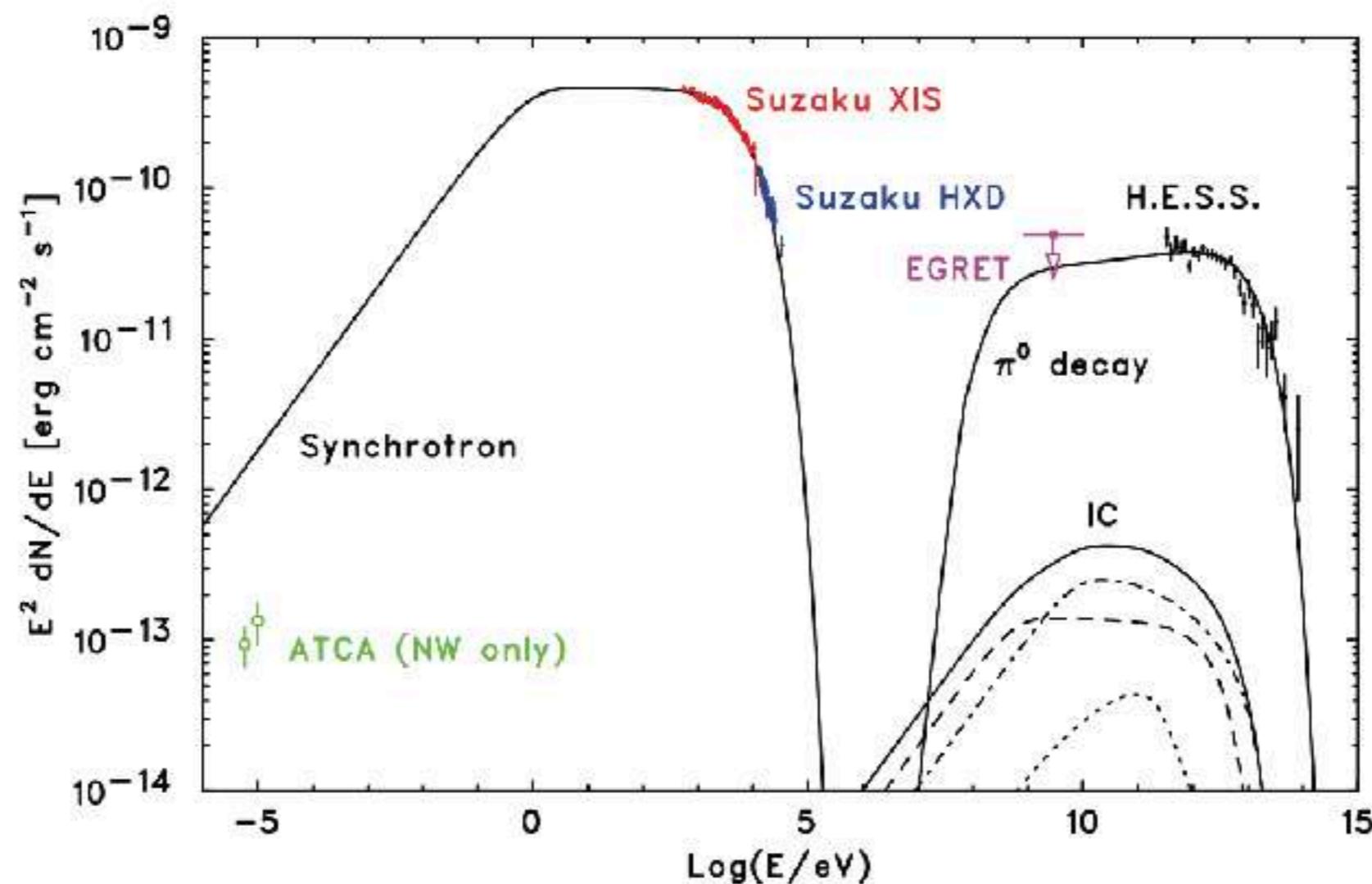
Hadronic model



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CR protons do not cool ! \rightarrow

$$Q_p \propto E^{-2} \rightarrow N_p \sim Q_p \times \tau_{age} \propto E^{-2} \rightarrow F_\gamma \propto E^{-2}$$



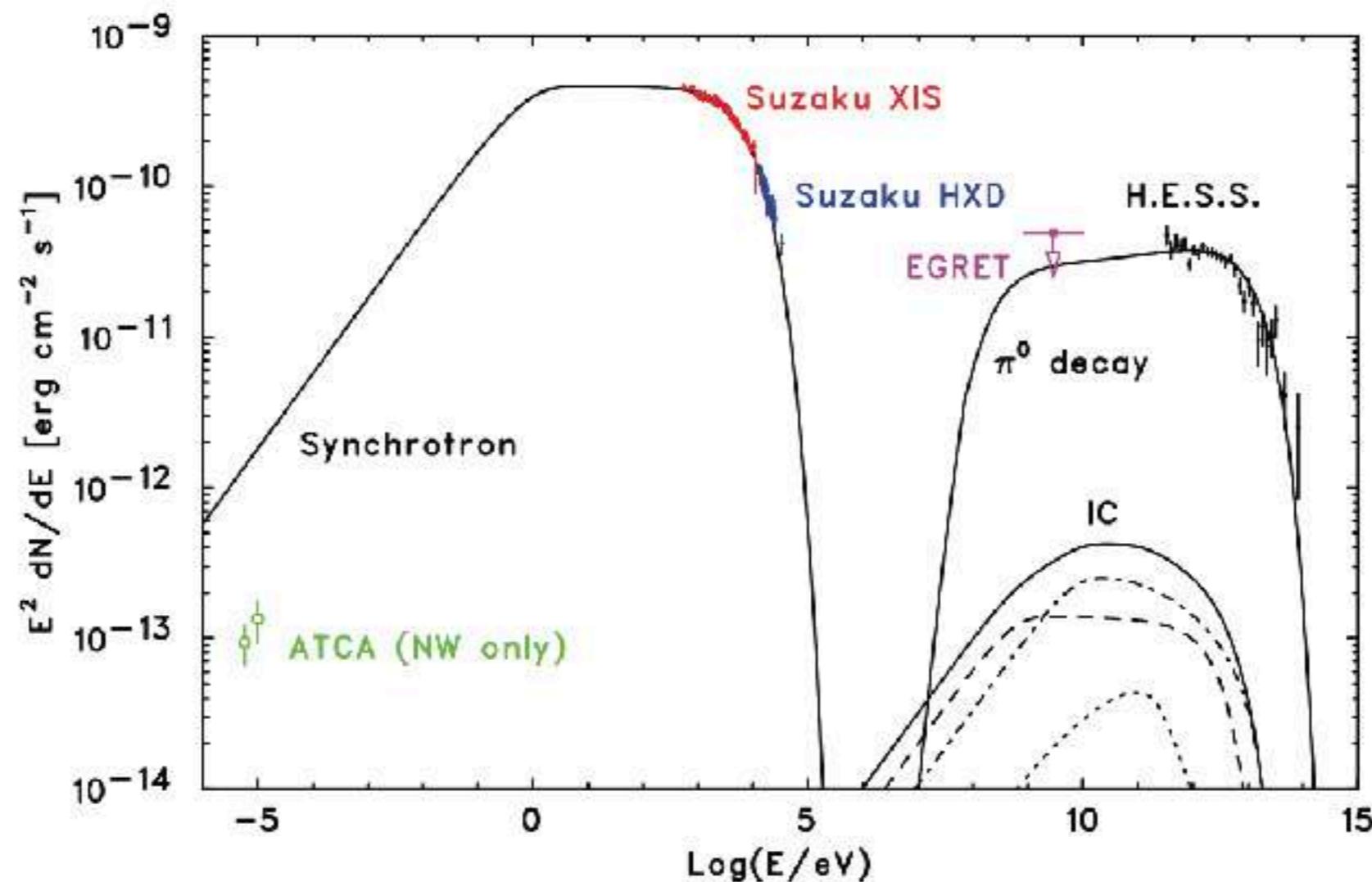
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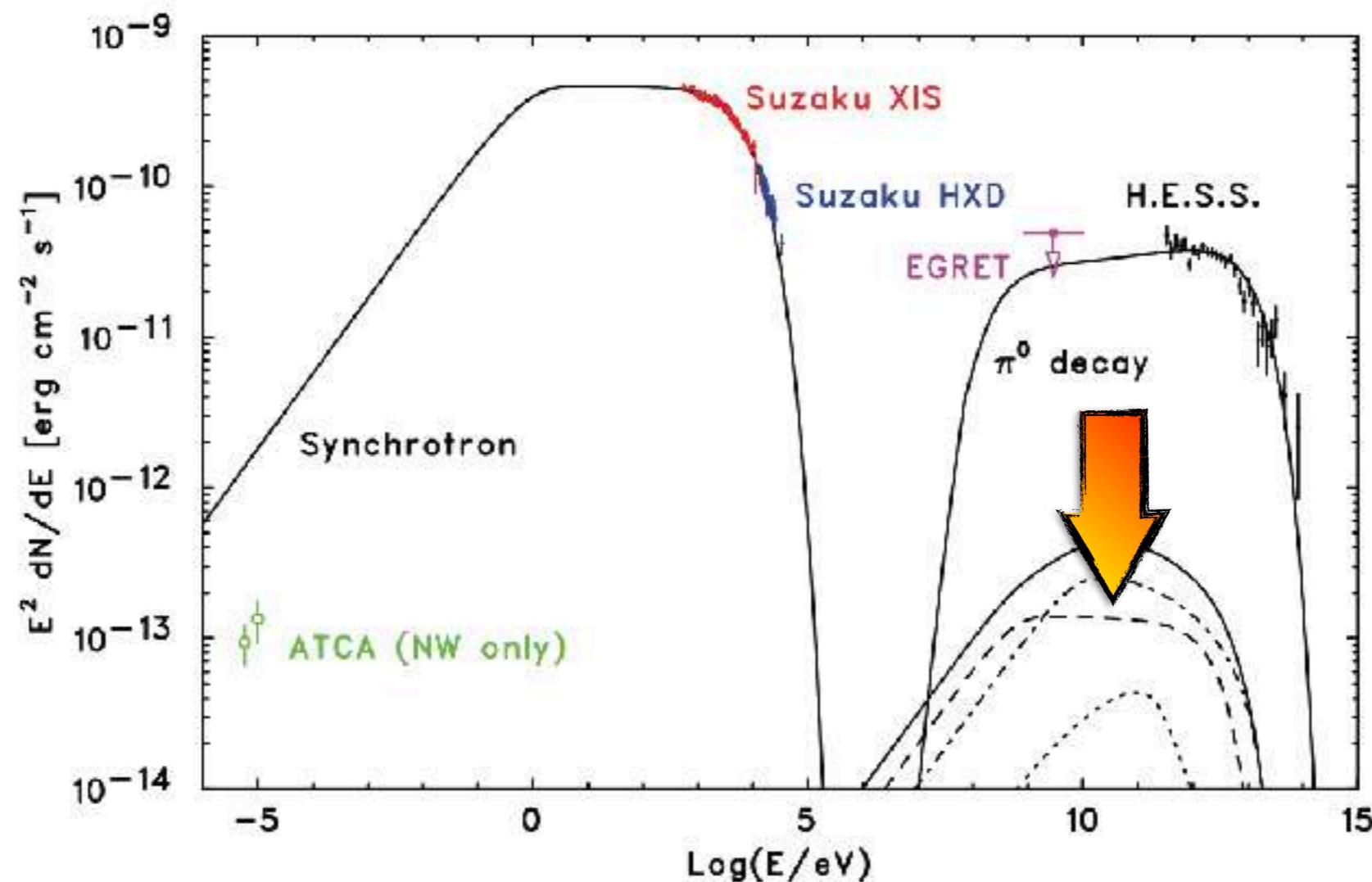
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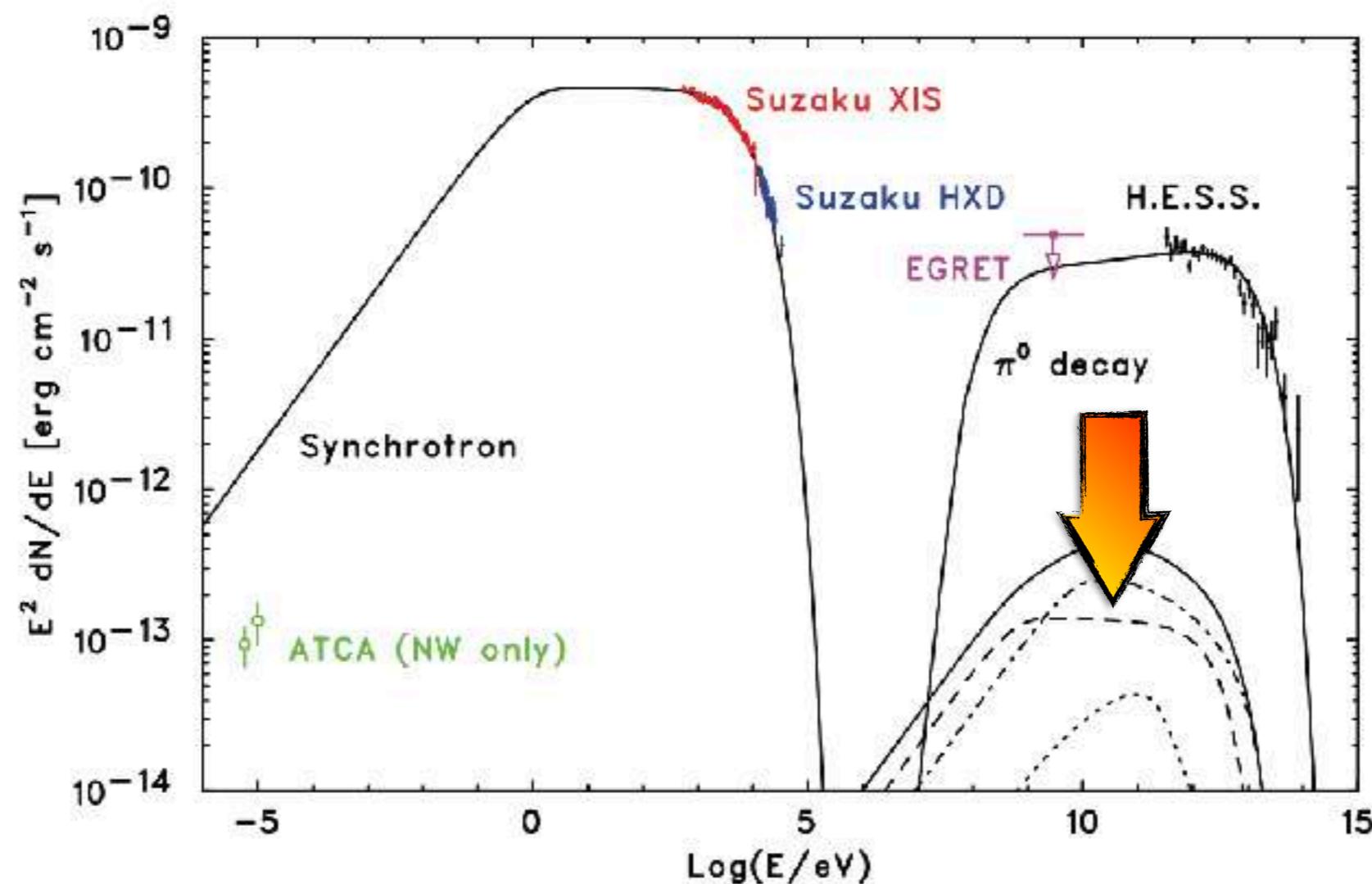
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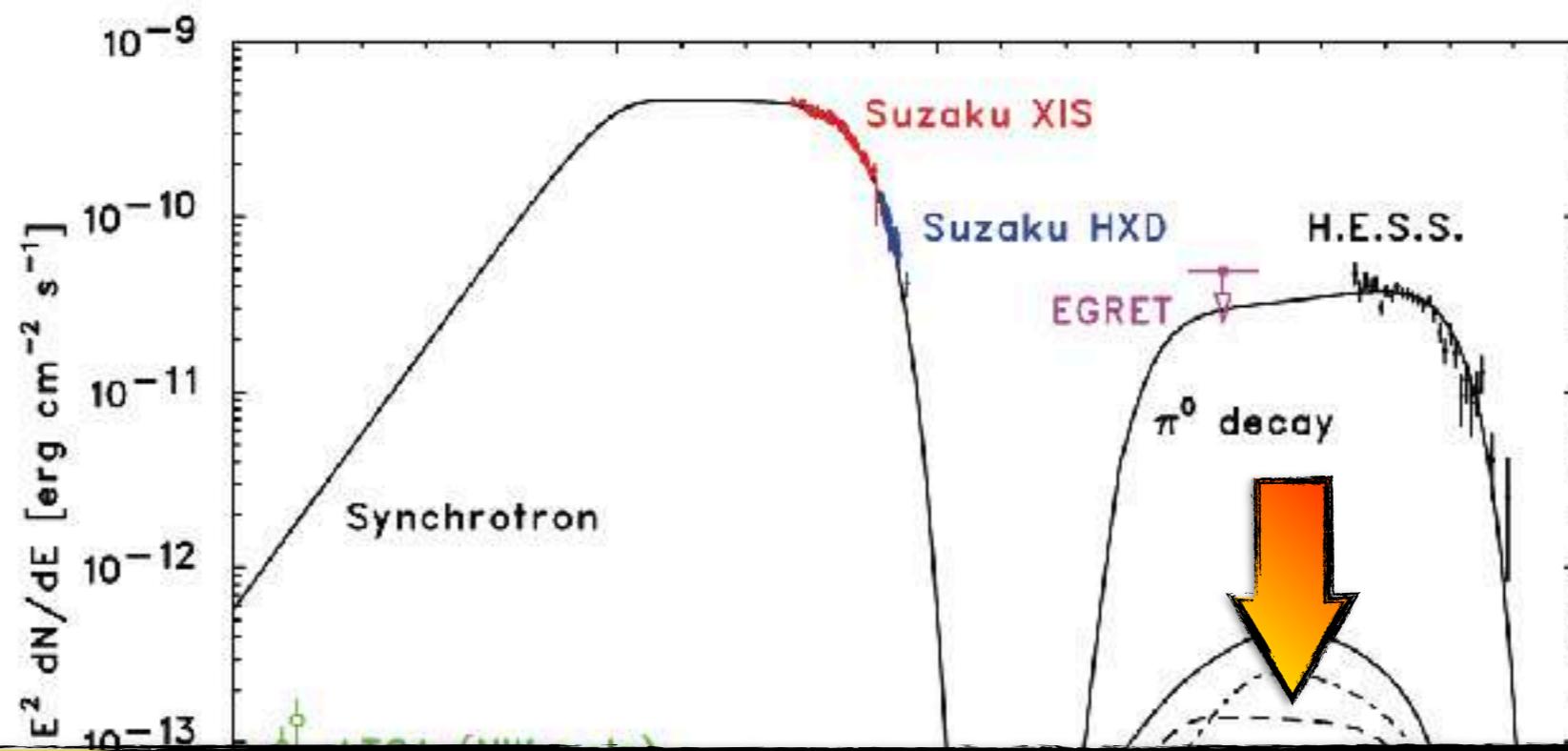
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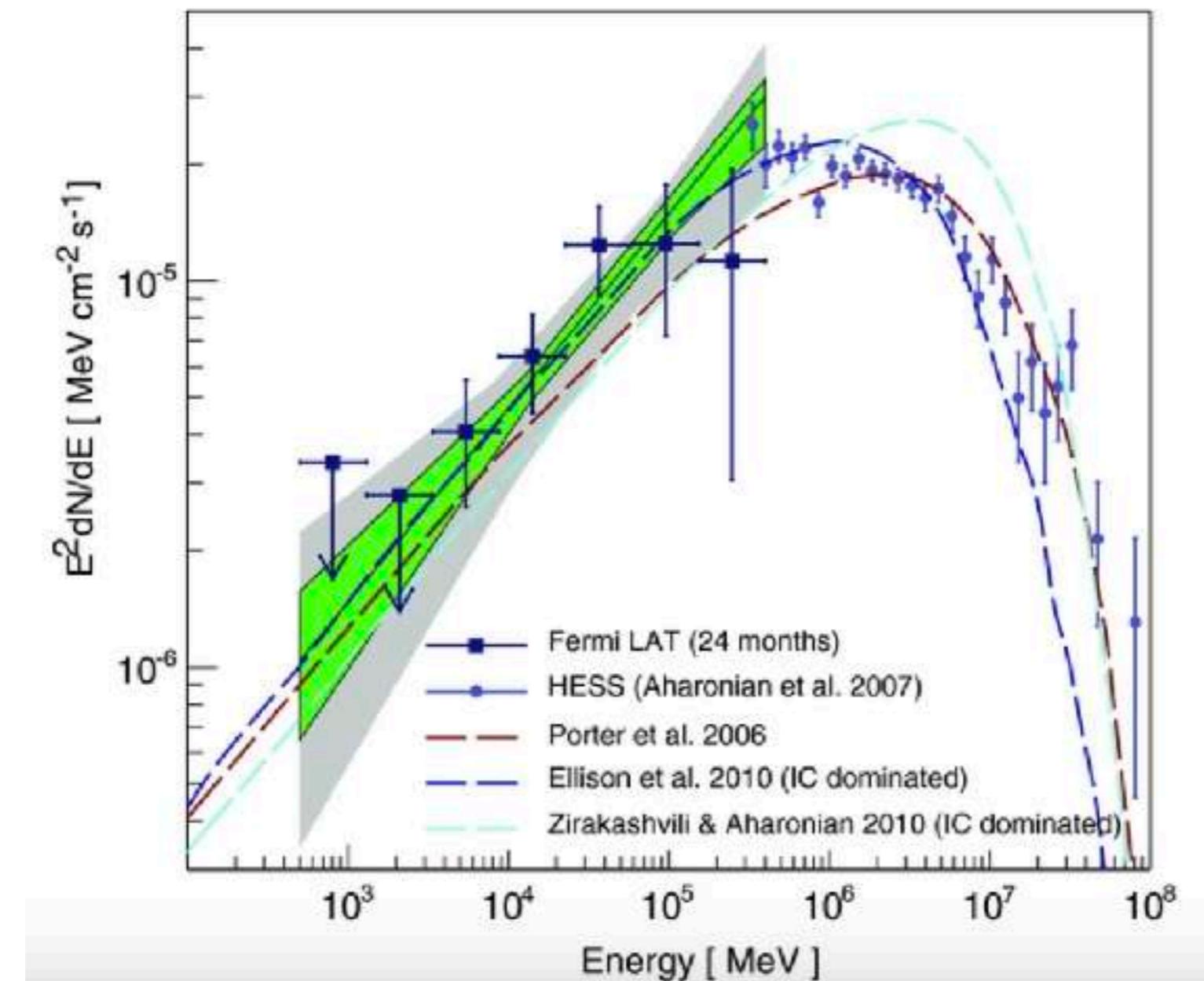


if hadronic, O(10%) of the SN energy goes to CRs,
as required to explain all of them!

[End of Inset 2]

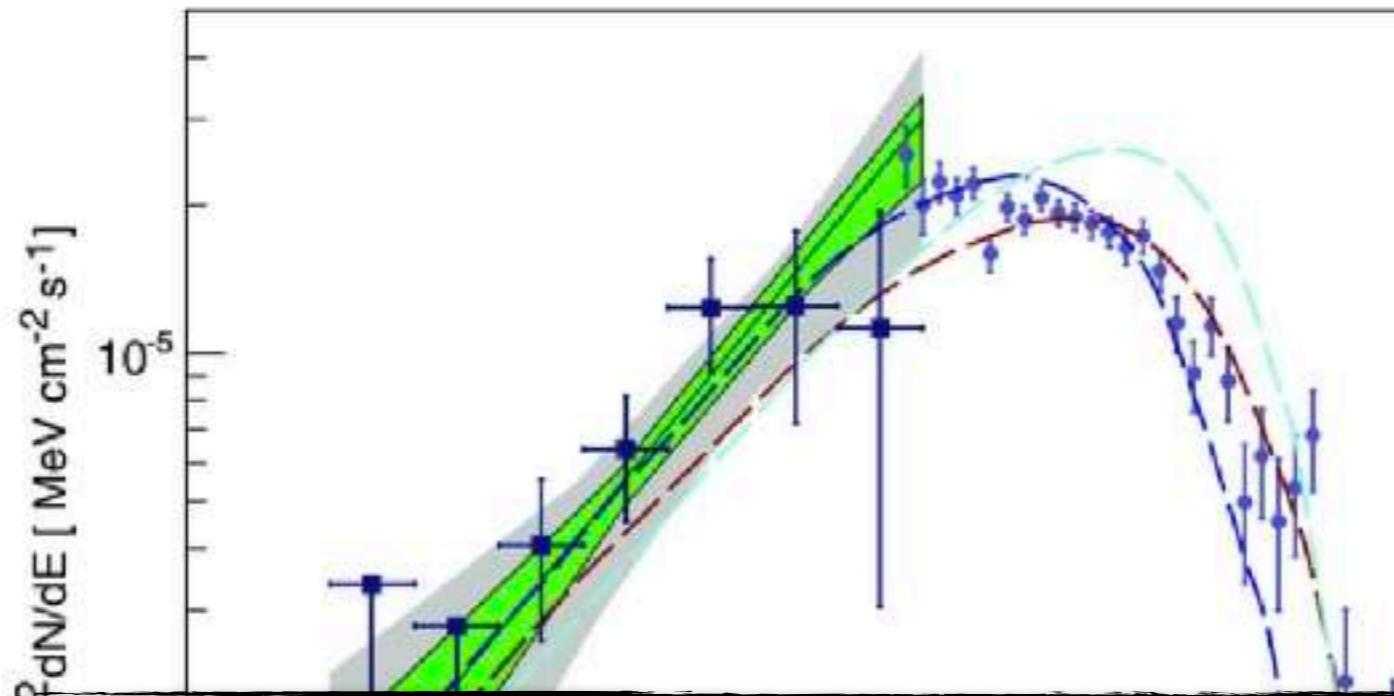
Fermi spectrum

Fermi data are more consistent with leptonic models

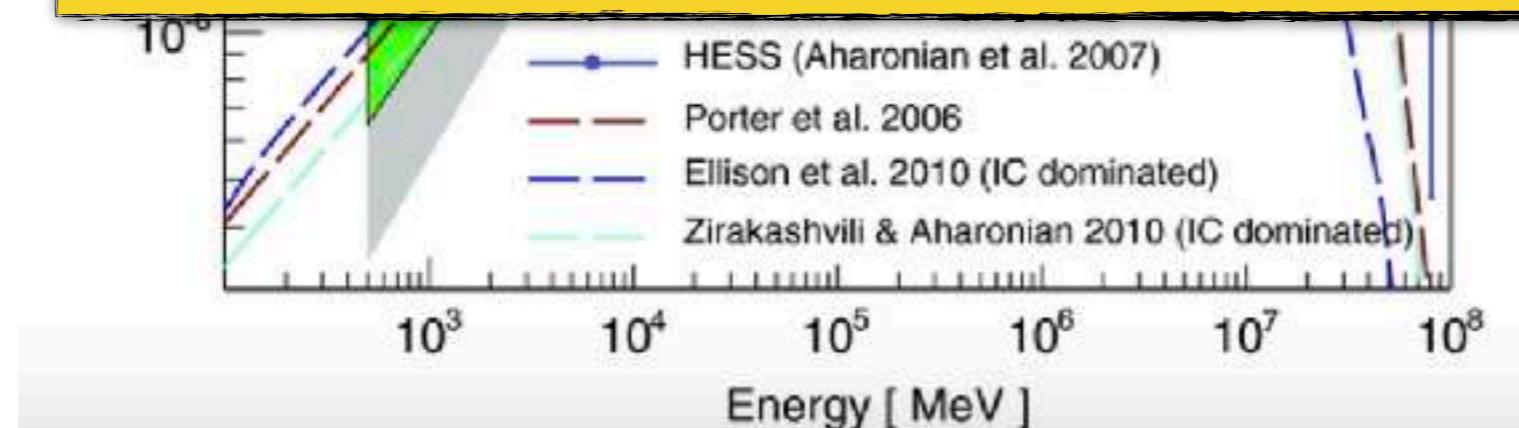


Why do we see a cutoff?

what can we learn from the position off the cutoff?



how is the maximum energy of particles determined?



$$E_{cut} = 12.9 \pm 1.1 \text{ TeV} \rightarrow E_{max}^p \sim 130 \text{ TeV}$$

$$\rightarrow E_{max}^e \sim 70 \text{ TeV}$$

[Inset 3] What is the maximum possible energy particles can get an a given source?

The Hillas criterion

Charged particles and electromagnetic fields

cosmic rays are charged particles → they are affected by electromagnetic fields

$$\vec{E}(\vec{r}, t)$$

$$\vec{B}(\vec{r}, t)$$

Charged particles and electromagnetic fields

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$$\vec{E} \quad (\text{X})$$

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Simplifying assumption → consider only constant fields

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Simplifying assumption → consider only constant fields

A particle of charge q moving at a velocity \mathbf{u} will experience a force:

$$\vec{F} = \frac{d\vec{p}}{dt} = q \left(\vec{E} + \frac{\vec{u}}{c} \times \vec{B} \right)$$

relativistic momentum $\vec{p} = \gamma m \vec{u}$

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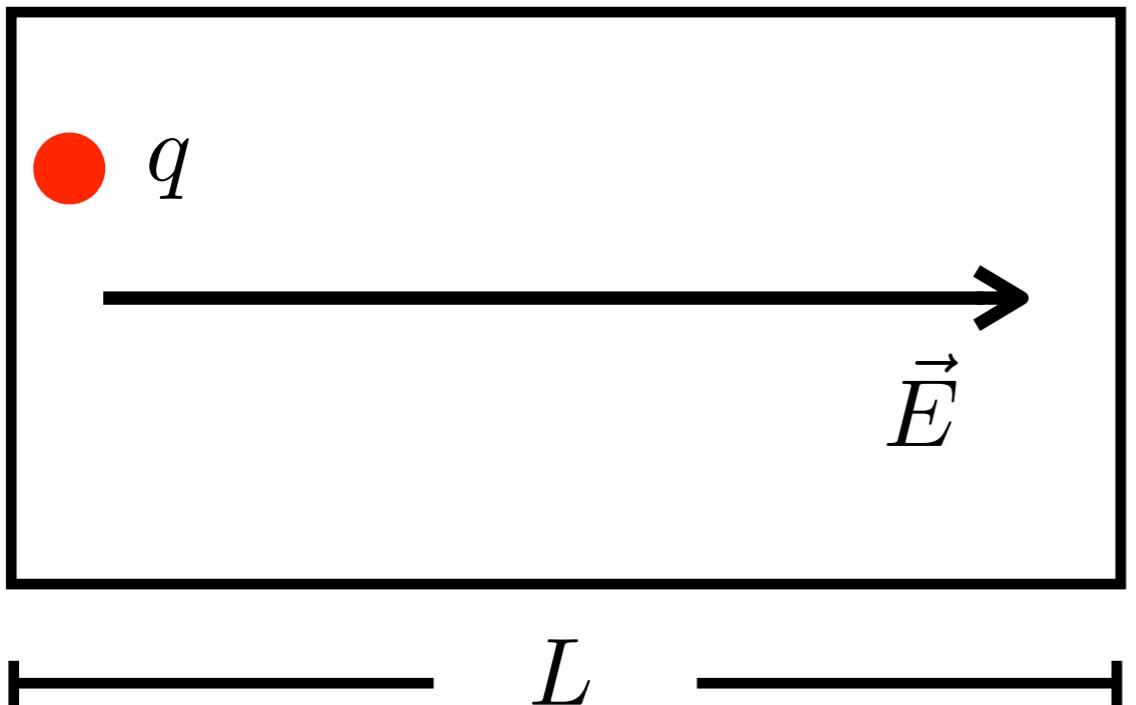
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Lorentz force
⊥ to velocity →
doesn't change
the particle energy!

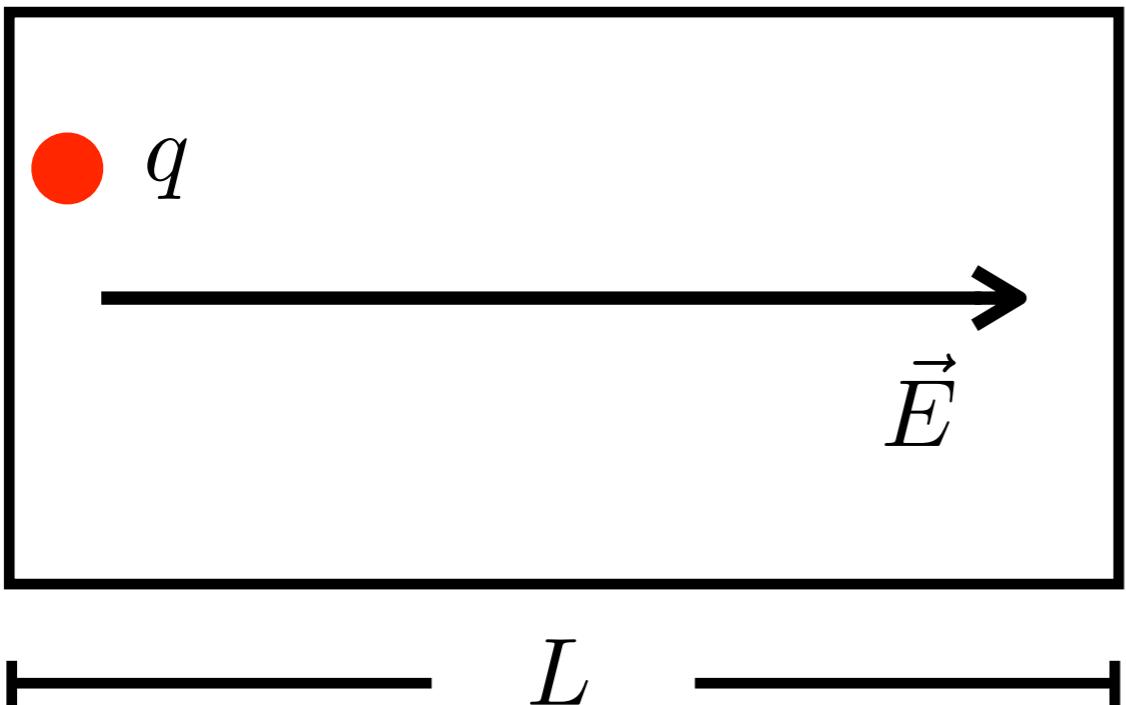
Maximum energy

this is an accelerator



Maximum energy

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$$E_t^{max} = qEtc = qEL$$

large
accelerator

large charge

strong E field

Can we keep a static and uniform electric field in an astrophysical plasma?

unfortunately, that's quite difficult...

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unfortunately, that's quite difficult...

An excess of electrical charge is needed to maintain a static electric field. However we should remember...

"...a basic property of plasma, its tendency towards electrical neutrality. If over a large volume the number of electrons per cubic centimeter deviates appreciably from the corresponding number of positive ions, the electrostatic forces resulting yield a potential energy per particle that is enormously greater than the mean thermal energy. Unless very special mechanisms are involved to support such large potentials, the charged particles will rapidly move in such a way as to reduce these potential difference, i.e., to restore electrical neutrality."

(Lyman Spitzer "Physics of fully ionised gases")

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So, the answer is no...

Way-out: time varying B

We DO need electric fields to accelerate particles!

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Maxwell equations

$$\nabla \vec{E} = 4\pi \varrho$$

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

$$\nabla \vec{B} = 0$$

$$\nabla \times \vec{B} = \frac{4\pi}{c} \vec{j} + \frac{1}{c} \frac{\partial \vec{E}}{\partial t}$$

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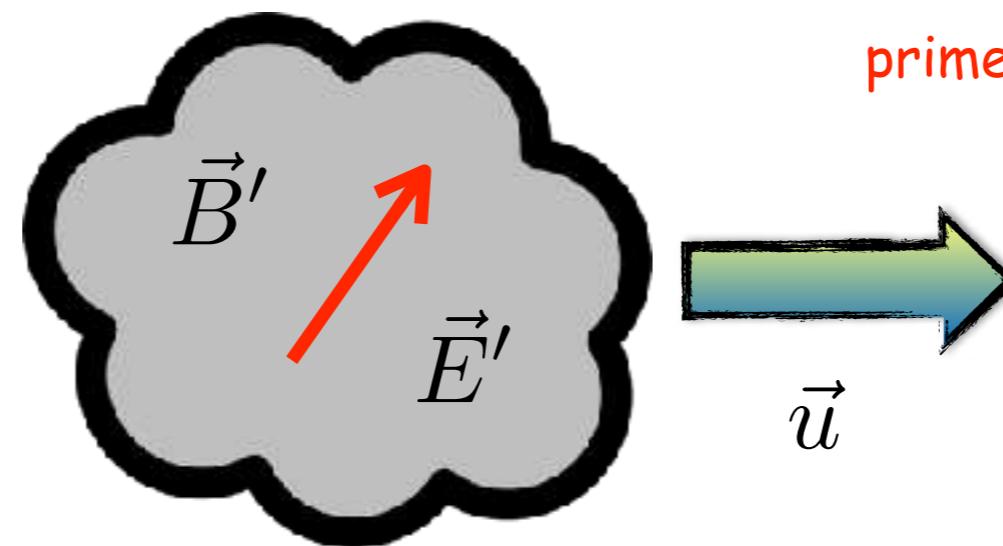
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A time varying magnetic field
acts as a source of electric field!

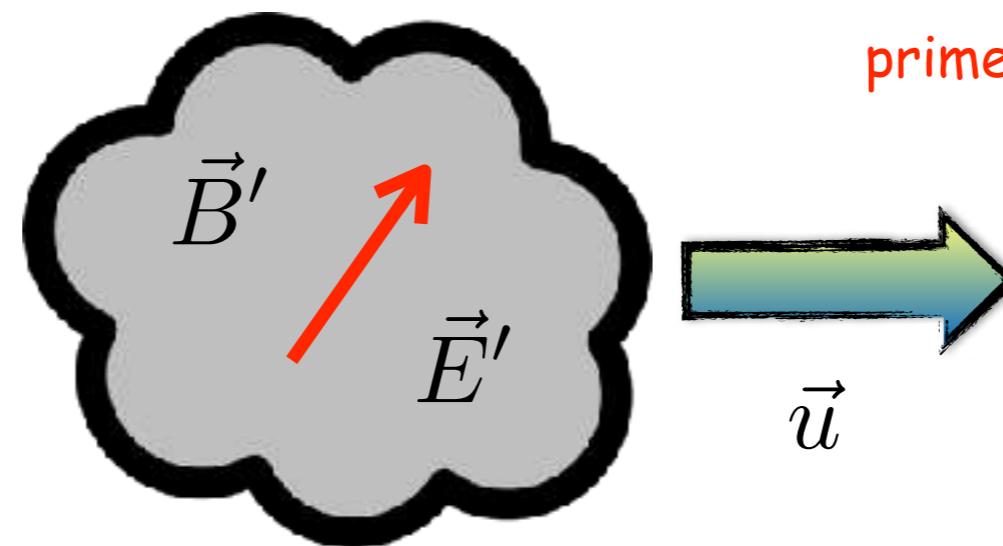
An equivalent way: change rest frame

Consider a magnetised cloud of plasma moving at a (non relativistic) velocity \mathbf{u}



An equivalent way: change rest frame

Consider a magnetised cloud of plasma moving at a (non relativistic) velocity \mathbf{u}



primed quantities → cloud frame

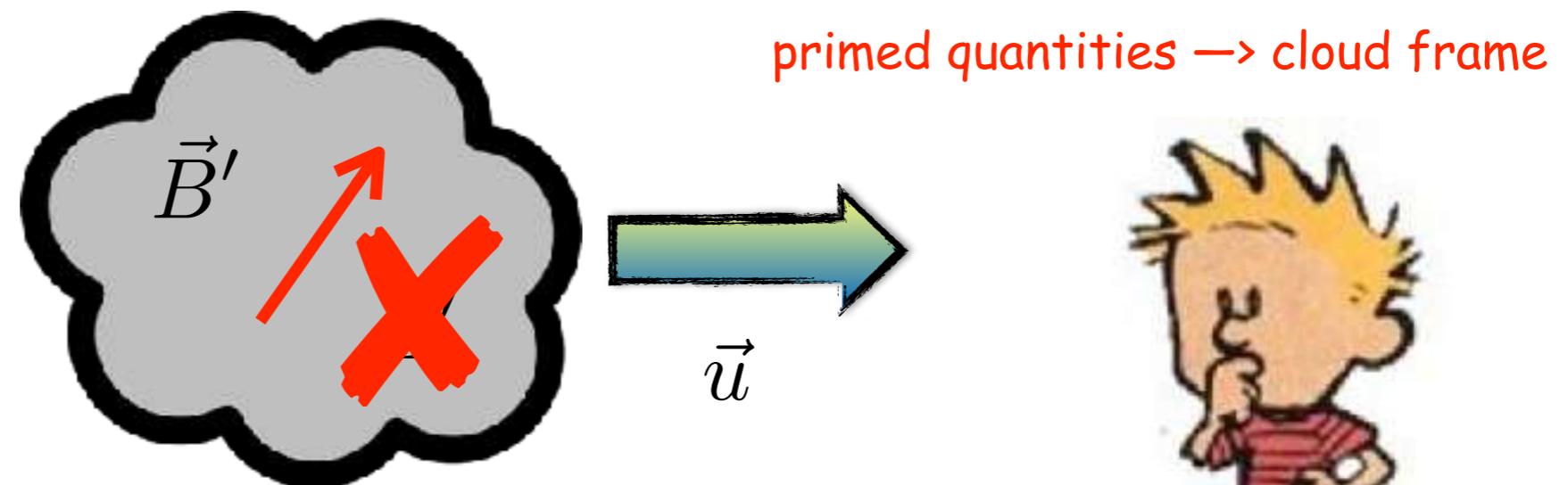


Lorentz transformation

$$\vec{E}' = \vec{E} + \frac{\vec{u}}{c} \times \vec{B}$$

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Lorentz transformation

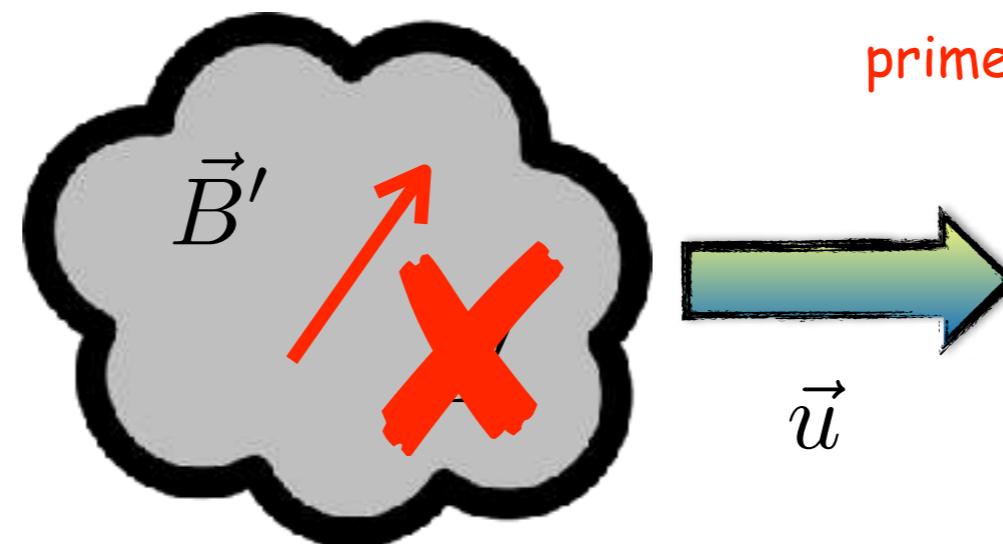
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$$0 = \vec{E} + \frac{\vec{u}}{c} \times \vec{B} \longrightarrow \vec{E} = -\frac{\vec{u}}{c} \times \vec{B}$$

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an observer in the lab frame sees an electric field!

Order of magnitude estimates of the induced electric field

time-varying B-field

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

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characteristic length

$$\nabla \times \rightarrow \frac{1}{L}$$

$$\frac{\partial}{\partial t} \rightarrow \frac{1}{T}$$

characteristic time

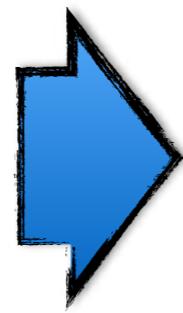
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characteristic length

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$$\frac{\partial}{\partial t} \rightarrow \frac{1}{T}$$

characteristic time

$$E \approx \frac{L}{T} \frac{B}{c} \approx \frac{U}{c} B$$

characteristic velocity

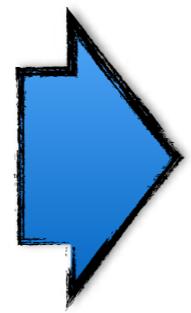
Order of magnitude estimates of the induced electric field

time-varying B-field

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

characteristic length

$$\nabla \times \rightarrow \frac{1}{L}$$



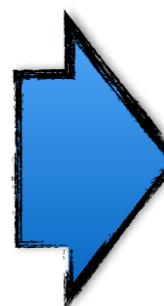
$$E \approx \frac{L}{T} \frac{B}{c} \approx \frac{U}{c} B$$

characteristic velocity

characteristic time

Lorentz
transformation

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



$$E \approx \frac{U}{c} B$$



Hillas criterion

Let's go back to the results obtained for the electrostatic accelerator

$$E_t^{max} = qEL$$

$$E \approx \frac{U}{c}B$$

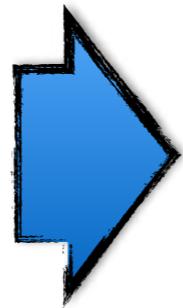


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$$E_t^{max} \approx \left(\frac{q}{c}\right) B U L$$

Diagram illustrating the components of the Hillas criterion formula:

- electric charge**: Points to the term $\frac{q}{c}$.
- velocity**: Points to the term U .
- size**: Points to the term L .
- B-field**: Points to the term B .

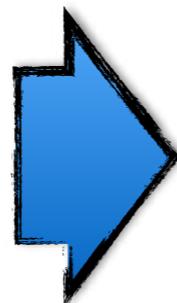


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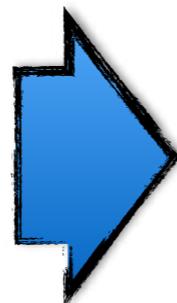


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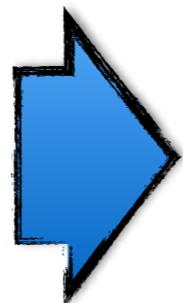


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Diagram illustrating the components of the Hillas criterion formula:

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1

acceleration region
(5-10% of R_s)

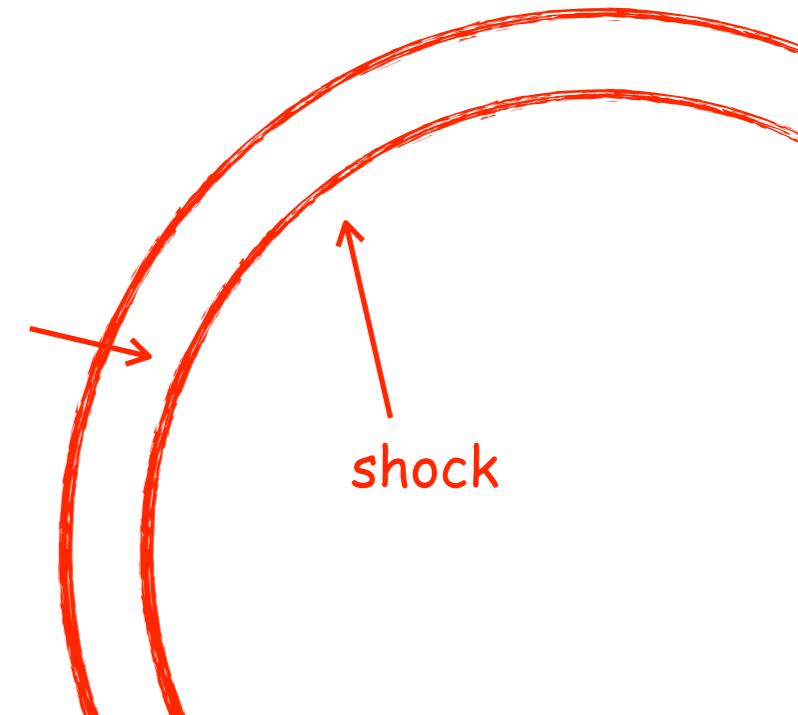
shock

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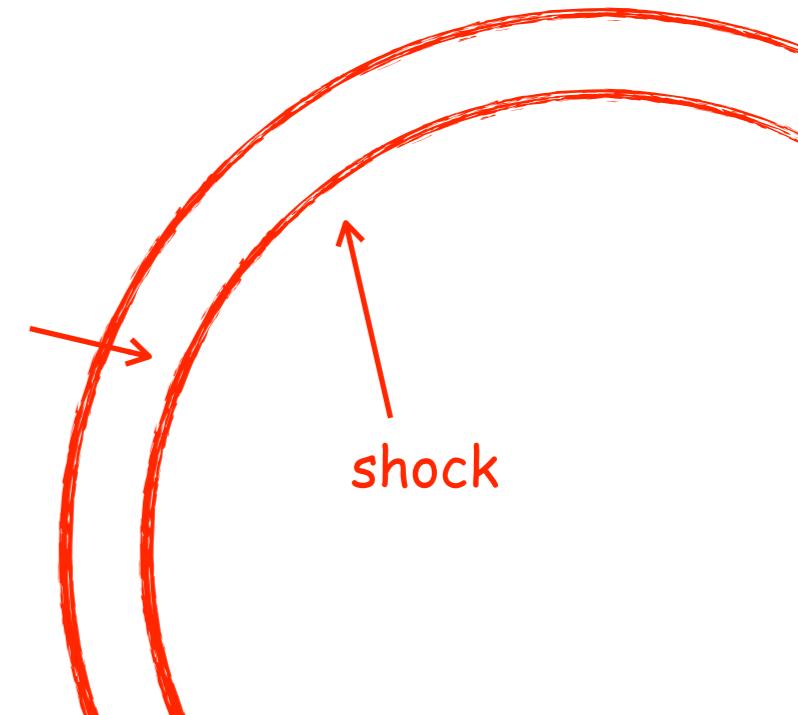
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(Hilla 2005)

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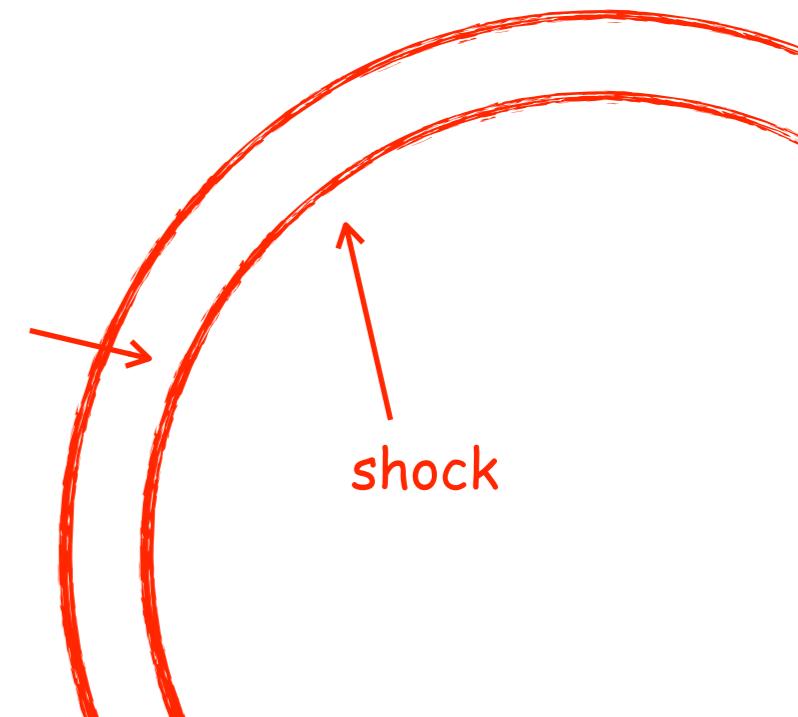
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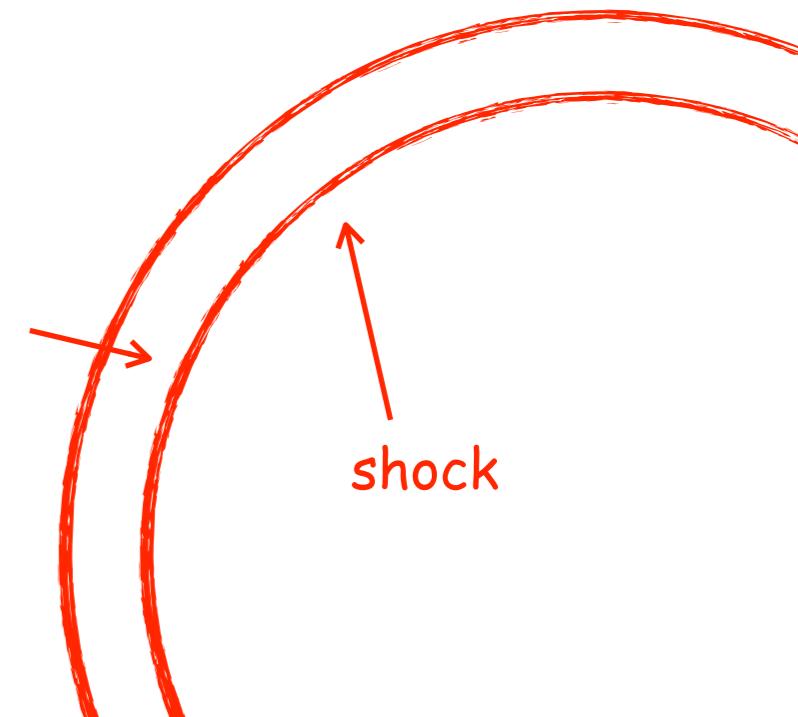
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$$E_{max} = 100 \left(\frac{B_{up}}{20 \mu G} \right) \text{ TeV}$$

this is the upstream field!

acceleration region
(5-10% of R_s)



Summarising...

this applies to protons only! (we ignored energy losses...)

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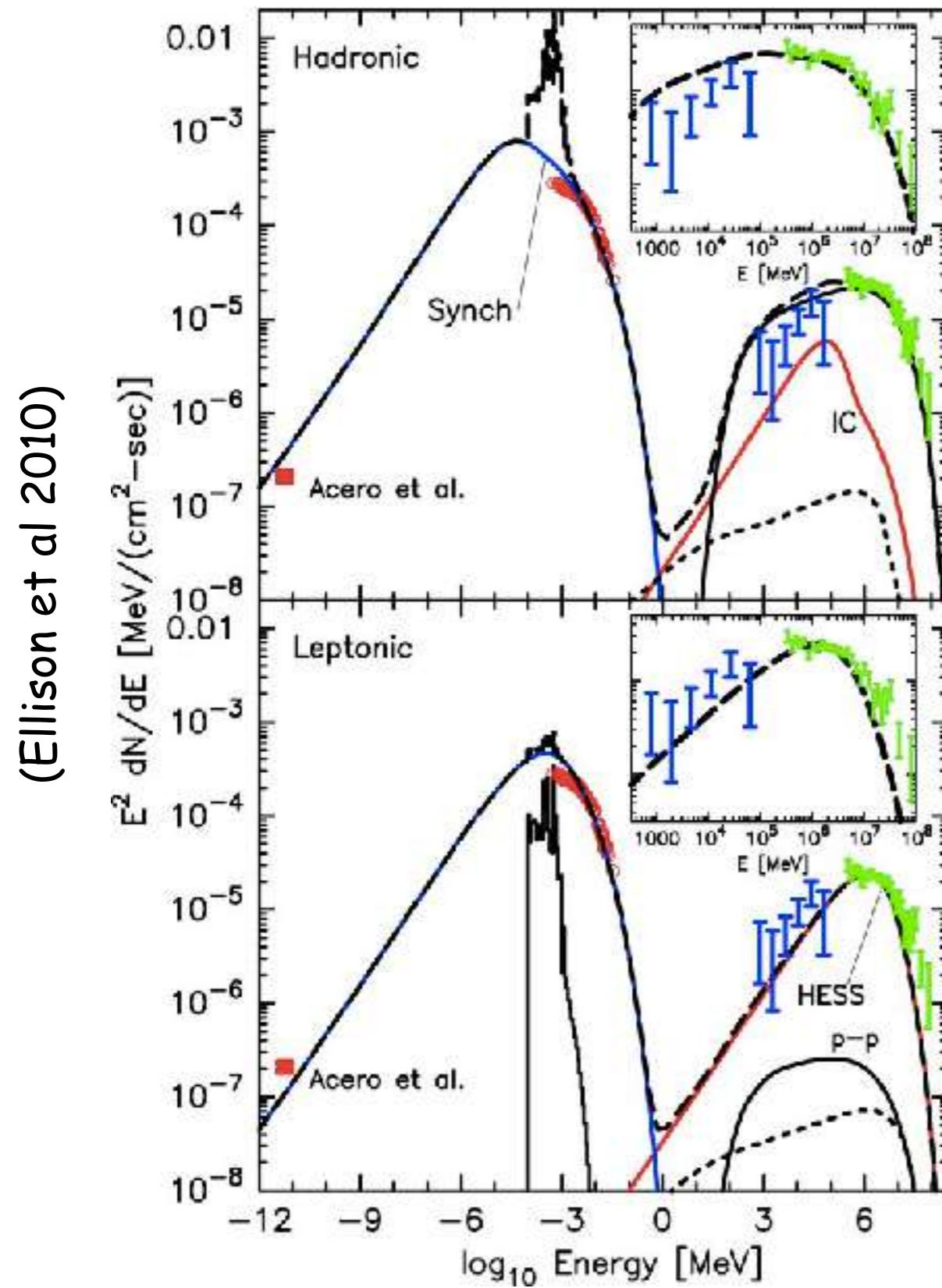
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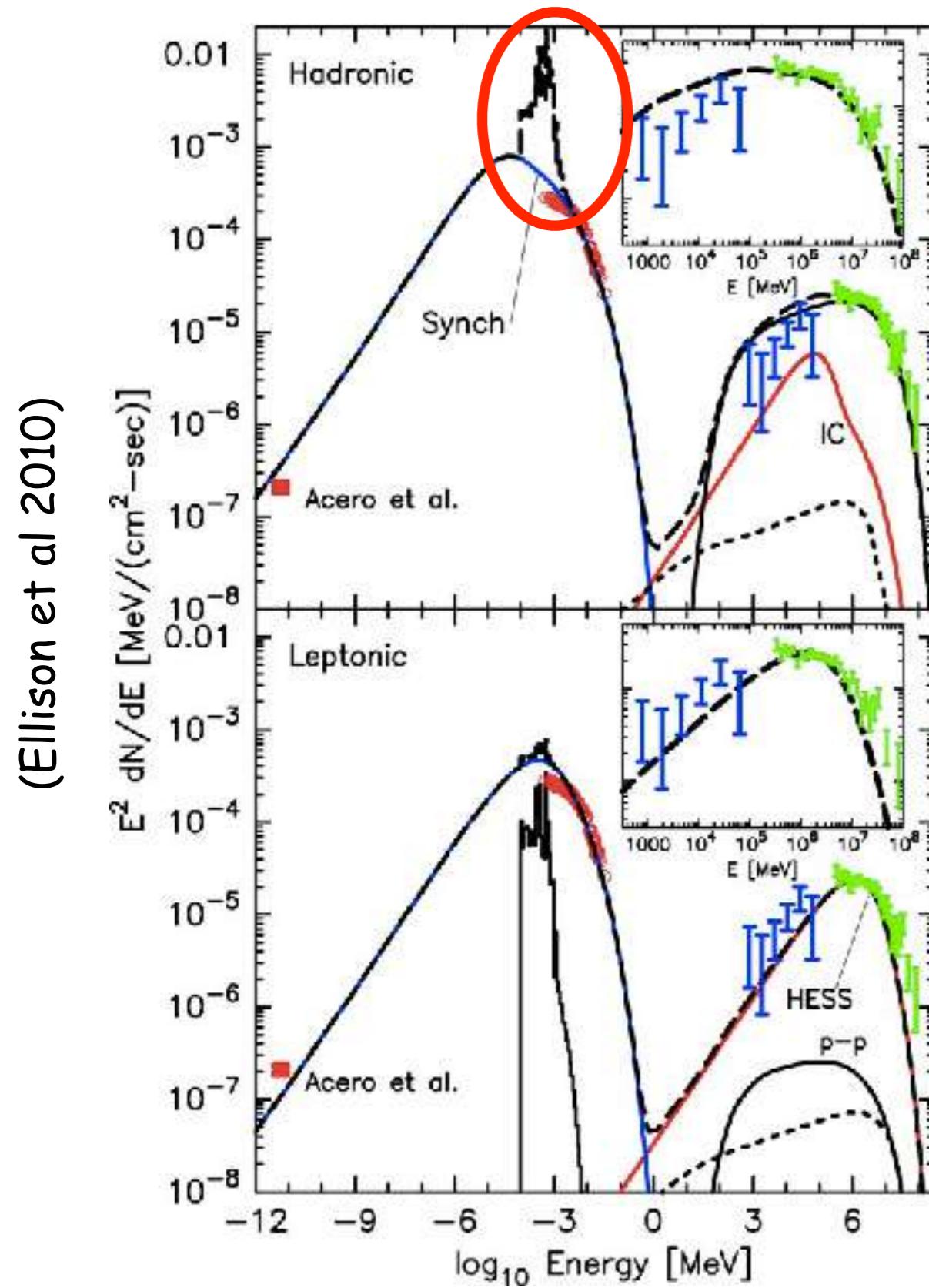
on the other hand, one needs a slightly smaller E_{max} , which helps a bit...

[End of Inset 3]

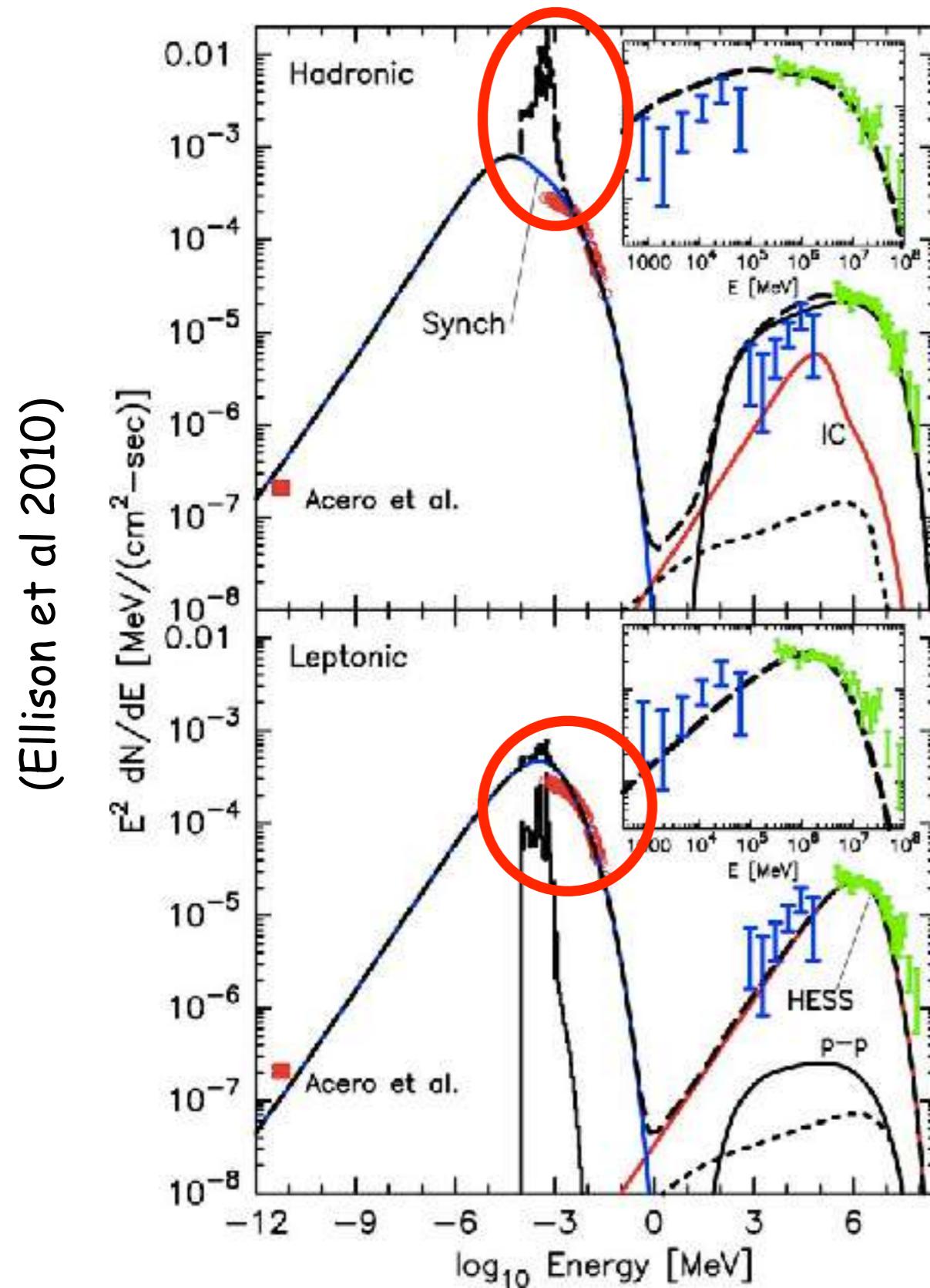
Finally, RXJ1713 is hadronic or leptonic?



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hadronic

high gas density + shock heating
→ bright X-ray thermal emission (lines)
→ NOT OBSERVED

(see also Katz&Waxman2008)

leptonic

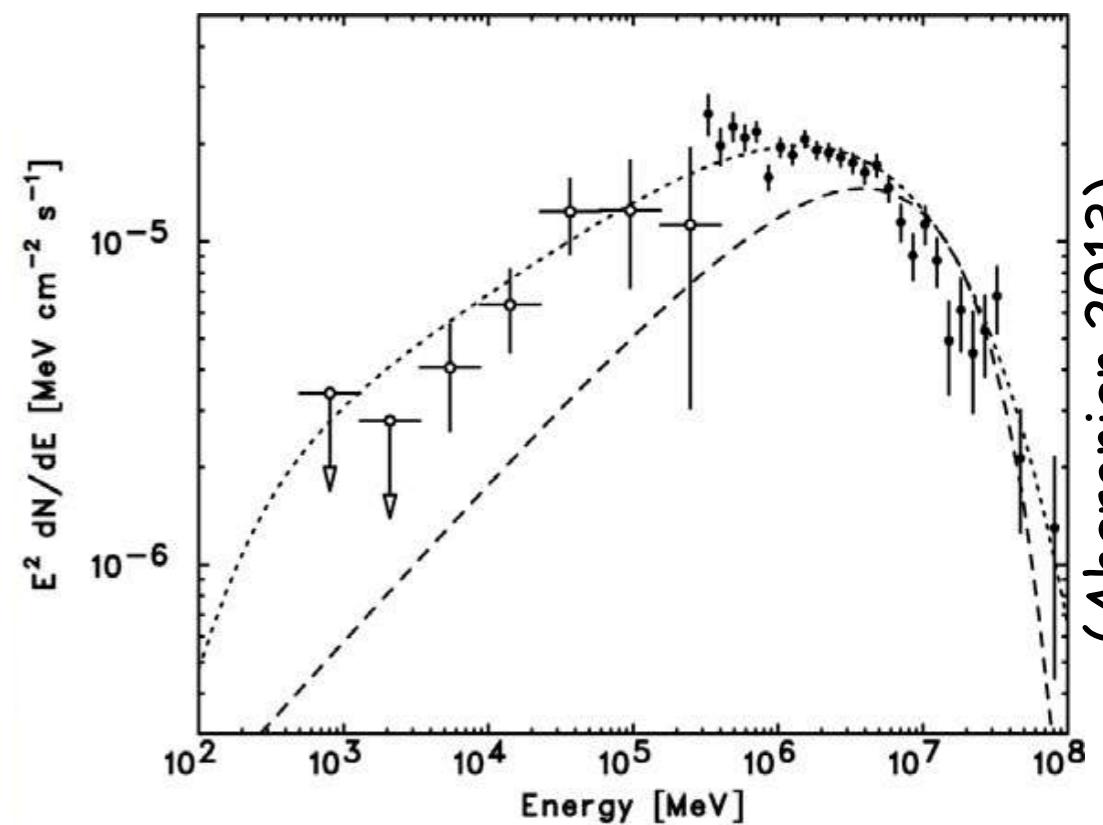
gas density is not a crucial parameter so
one can tune it not to violate X-ray
constraints

RXJ1713: difficulties of one-zone leptonic models

two features in the electron spectrum:

acceleration time = synchrotron loss time \rightarrow acceleration cutoff at E_{\max}

SNR age = synchrotron loss time \rightarrow cooling break at E_{cool}

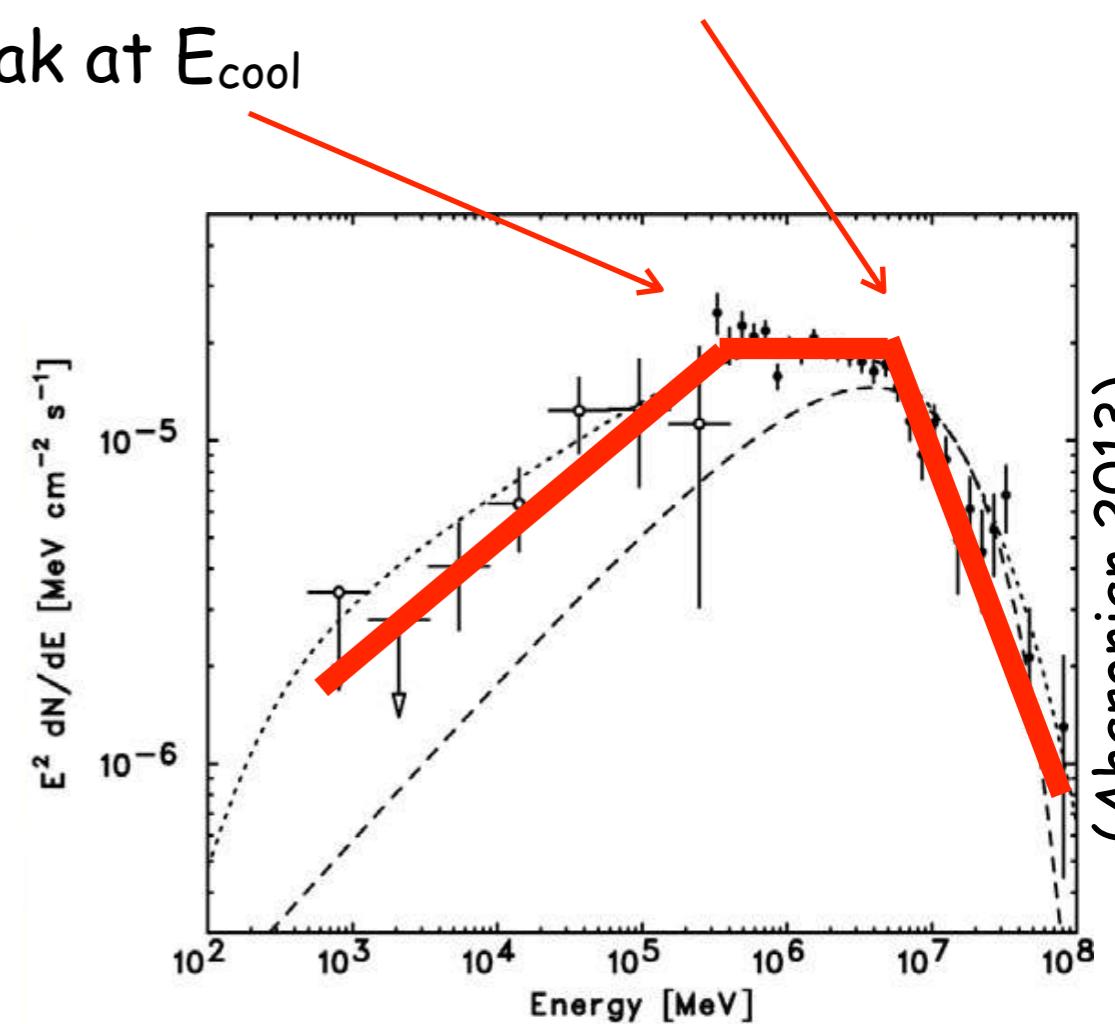


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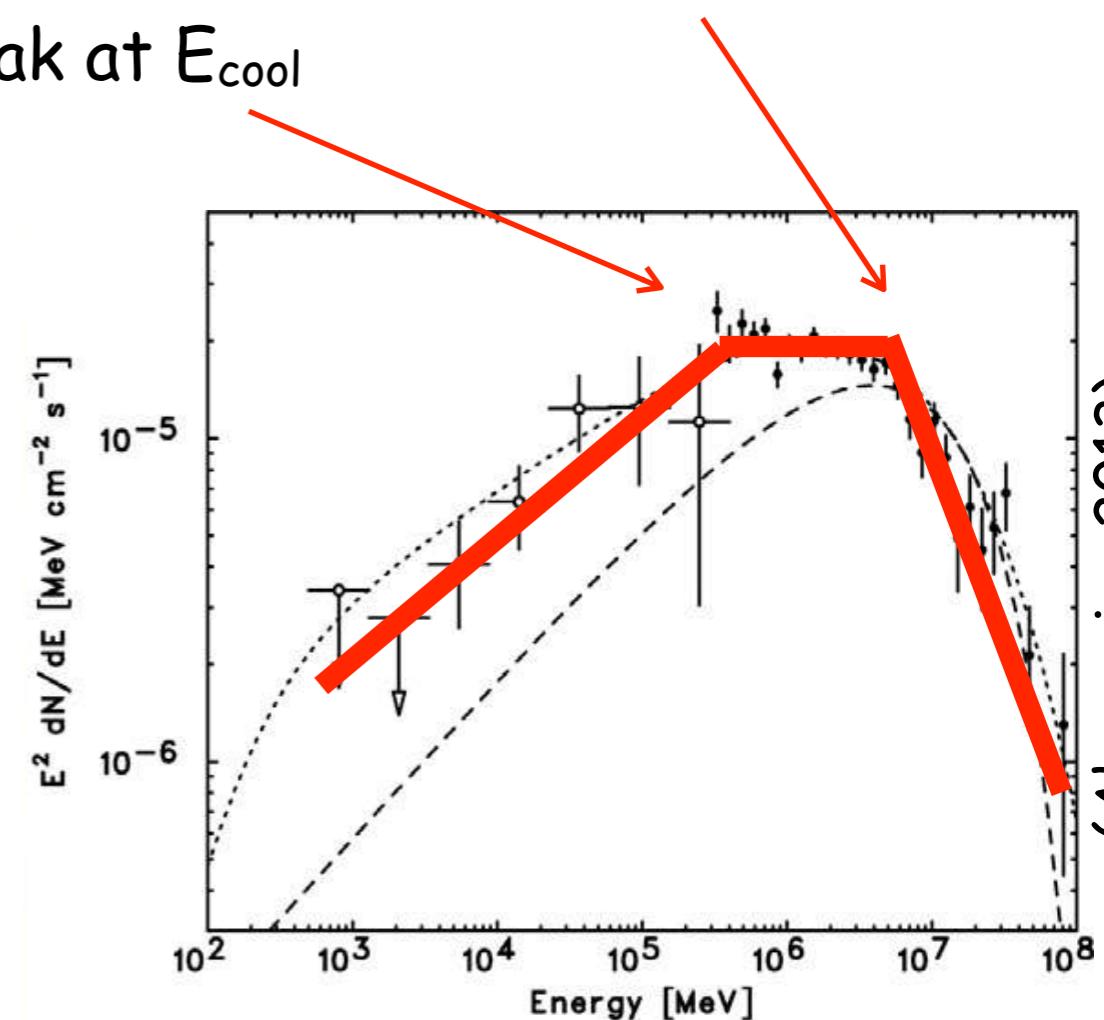
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to fit simultaneously X and gamma rays
with electrons the magnetic field MUST
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(Aharonian 2013)

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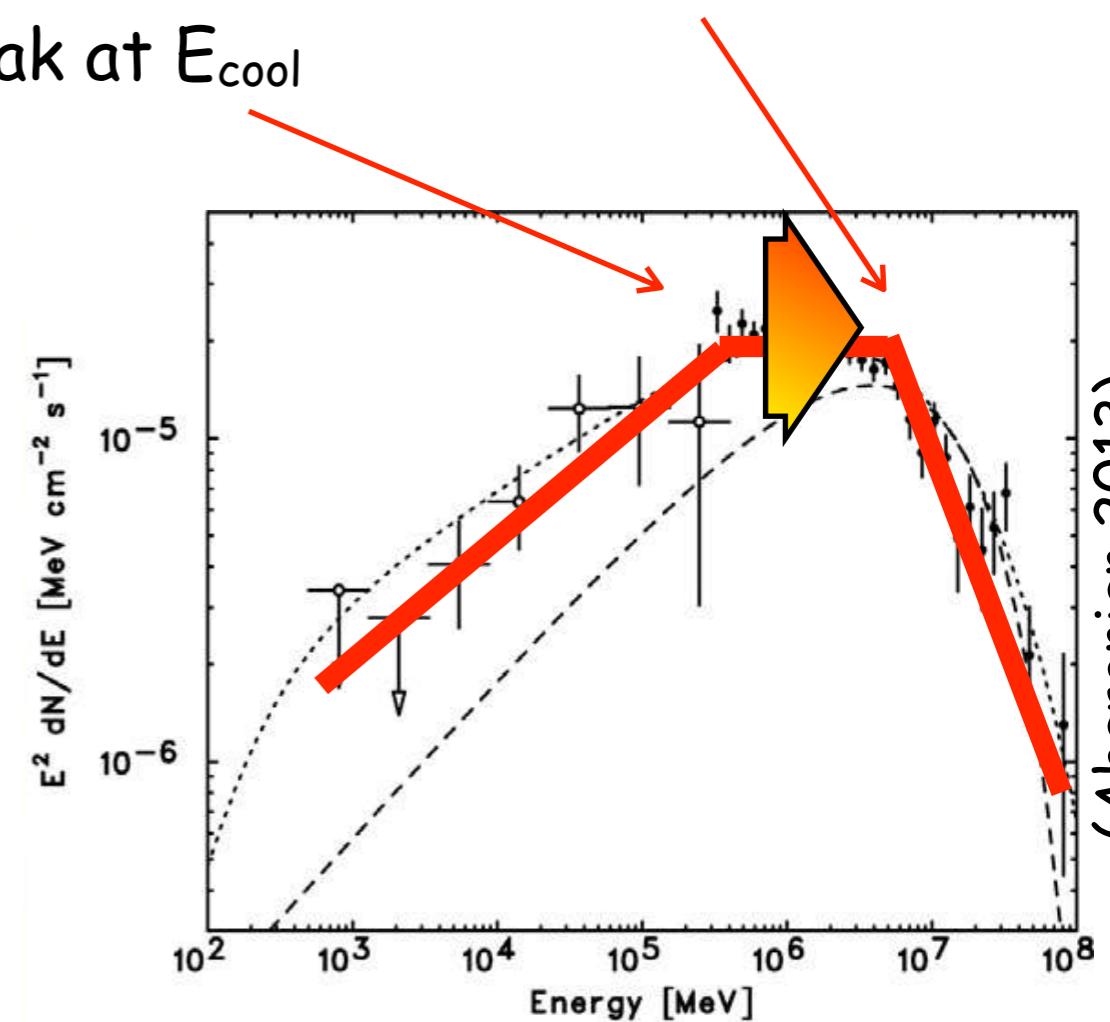
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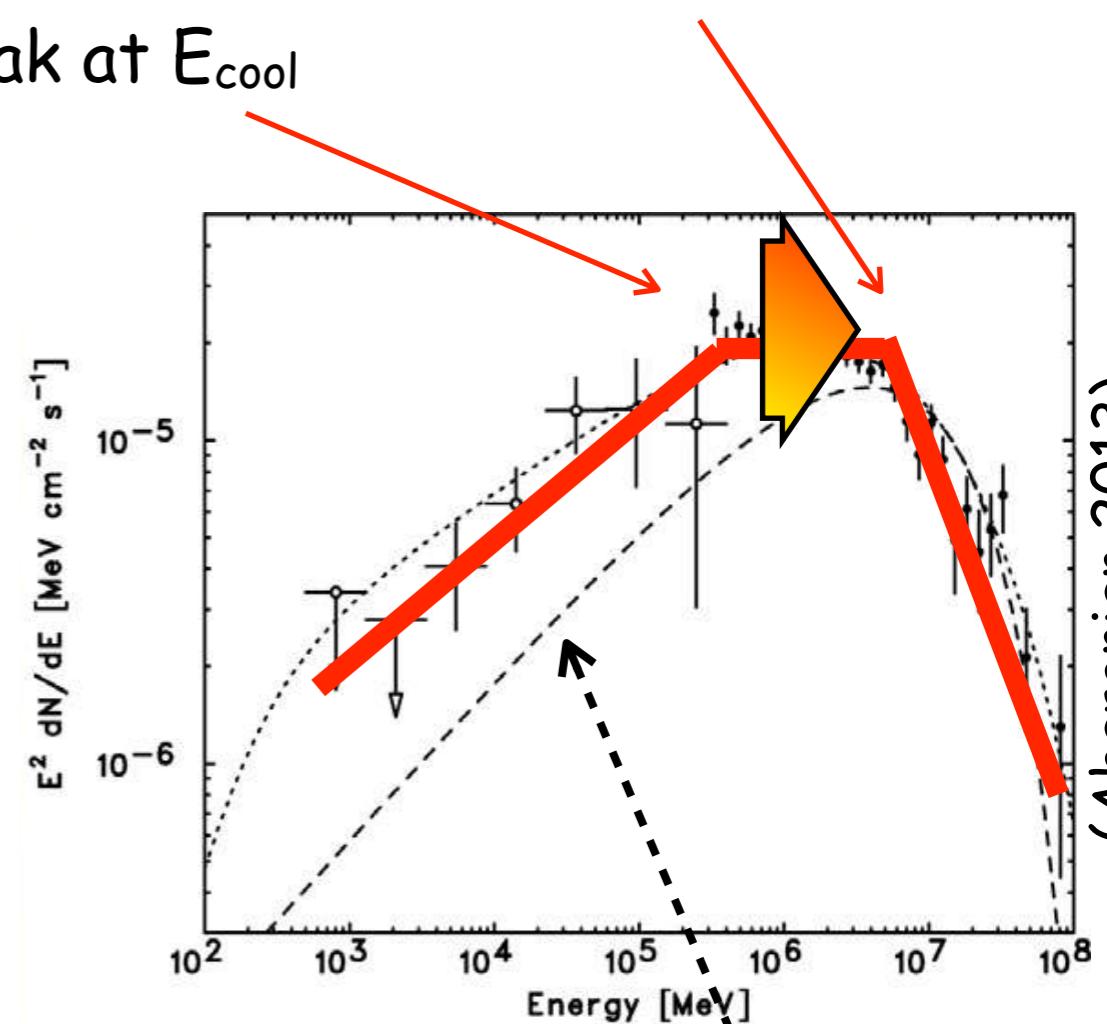
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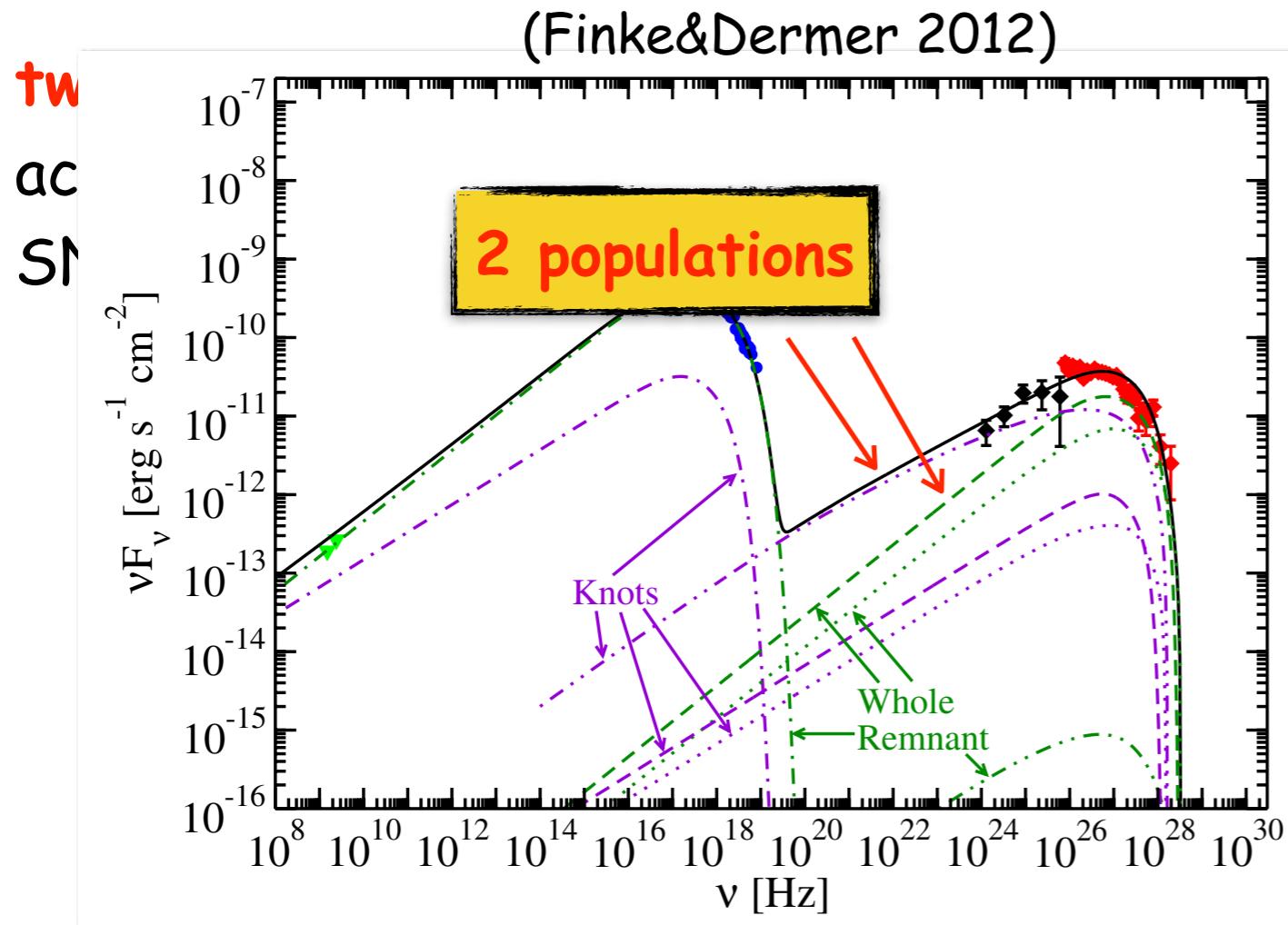
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one-zone IC model

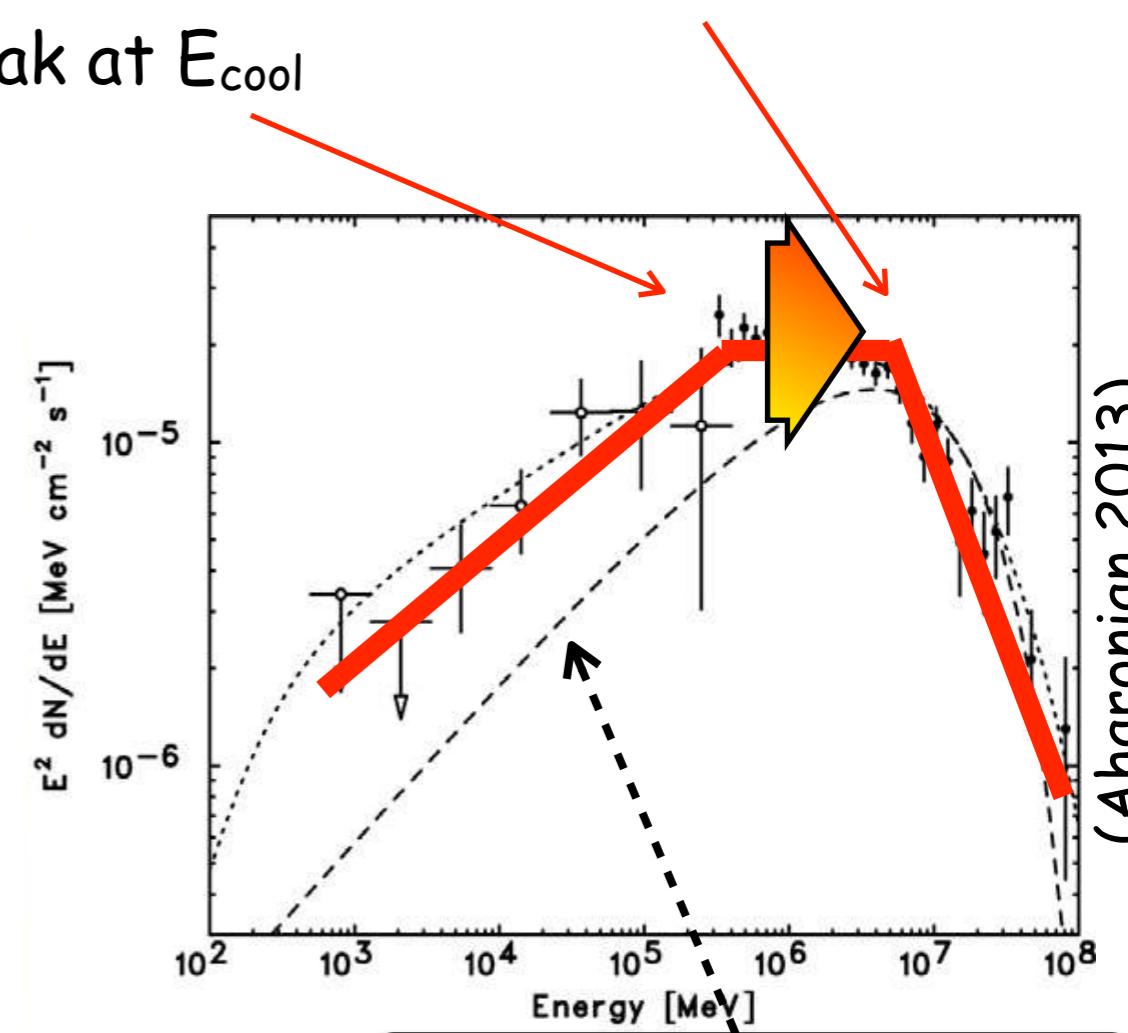
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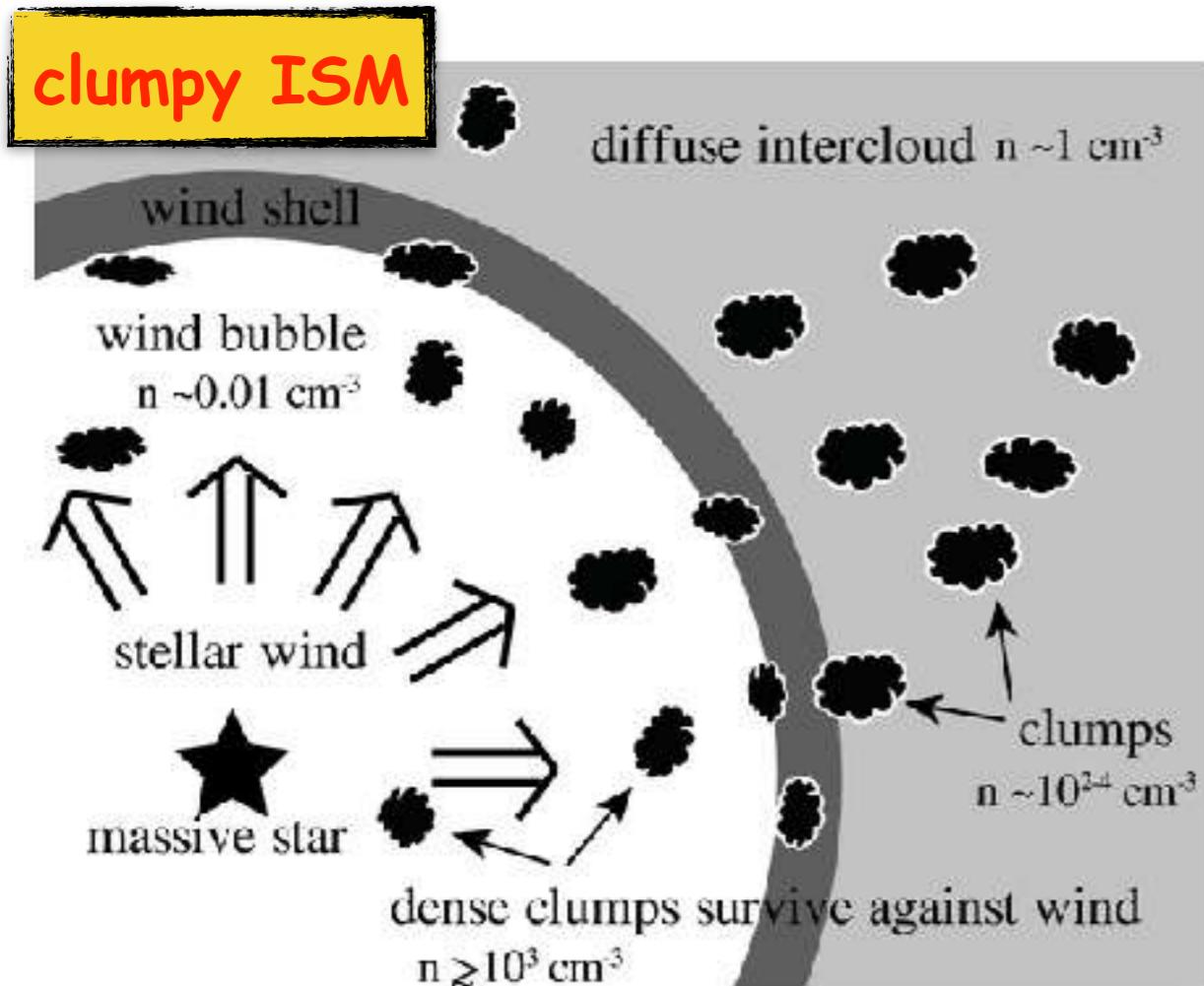
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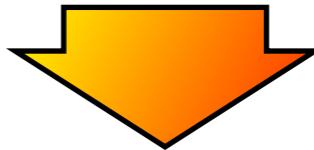
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Hadronic RXJ1713: a SNR inside a MC?

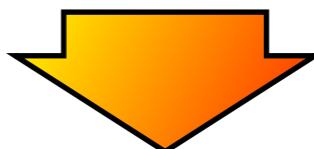
Zirakashvili & Aharonian 2010, Fukui+ 2012, Inoue+ 2012, Gabici & Aharonian 2014



stellar wind sweeps the gas and creates a cavity



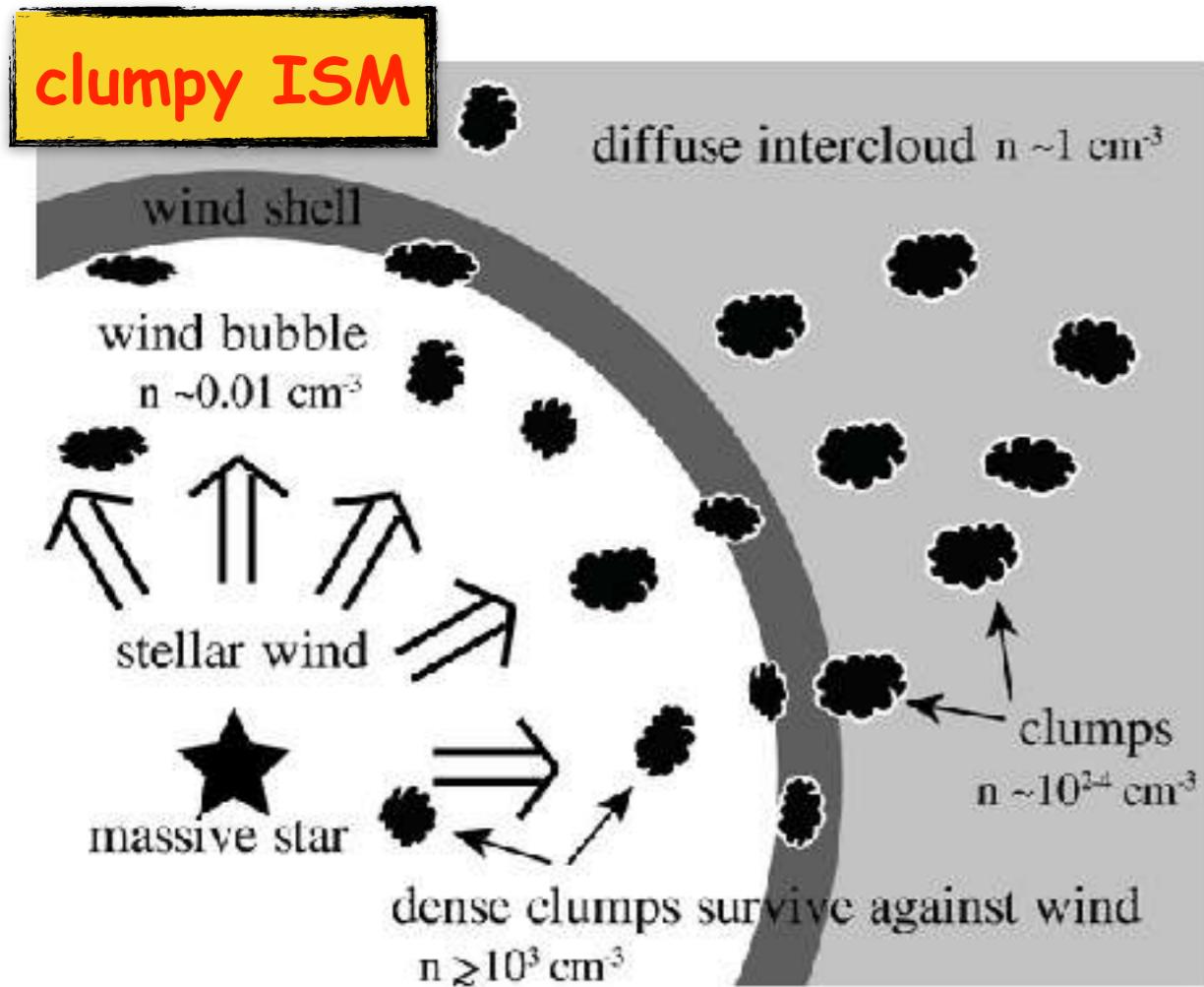
dense clumps survive (unshocked) both the stellar wind and the SNR shock



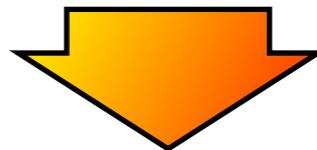
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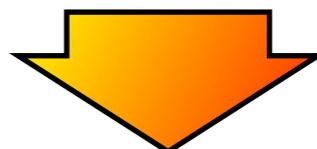
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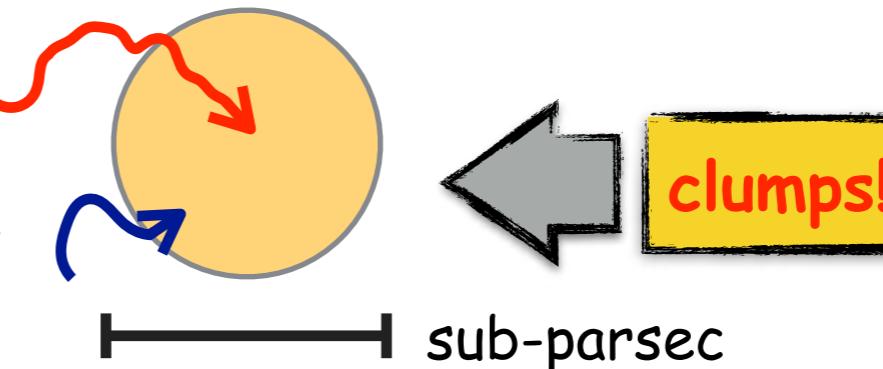
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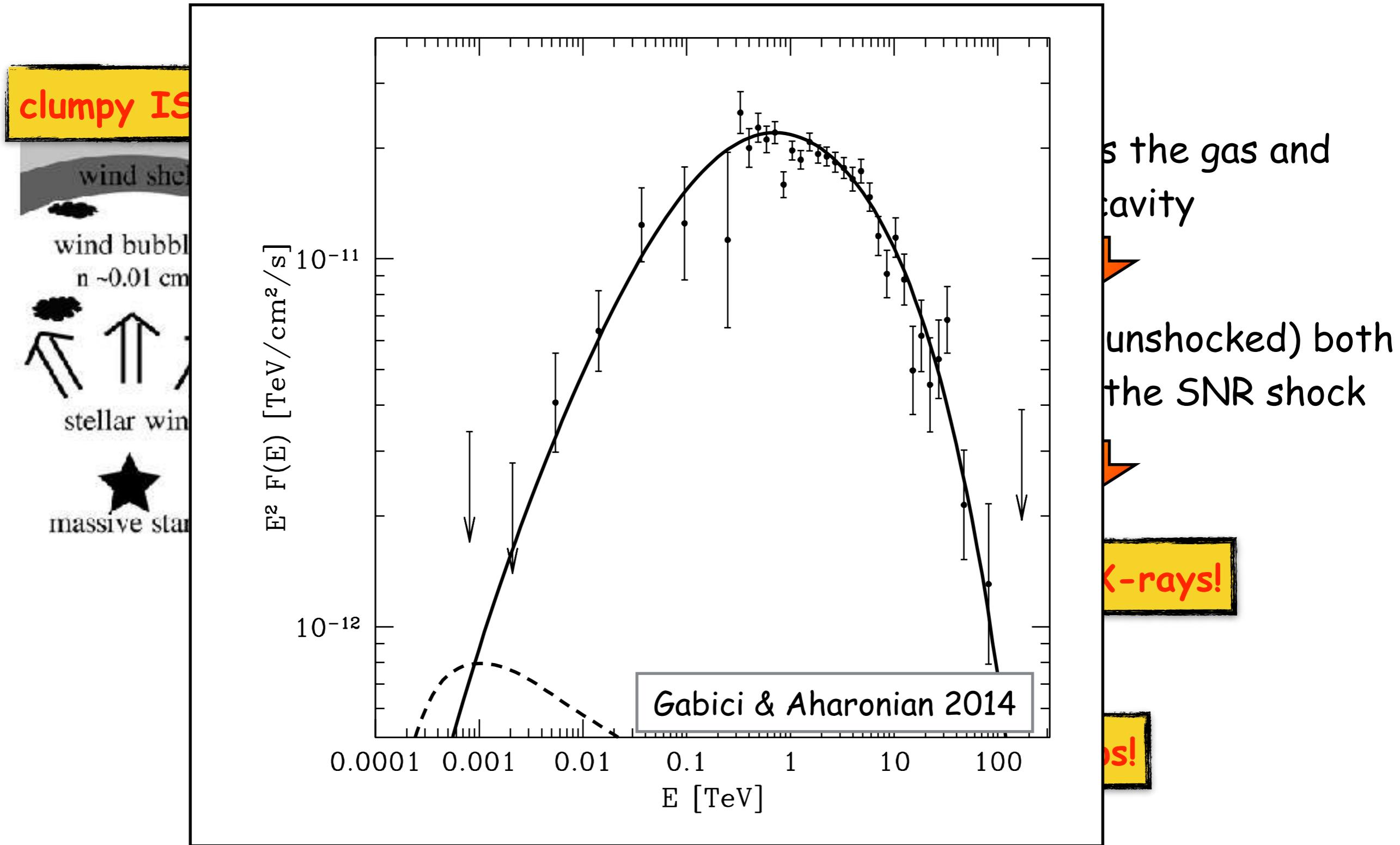
high energy CRs penetrate

low energy CRs don't



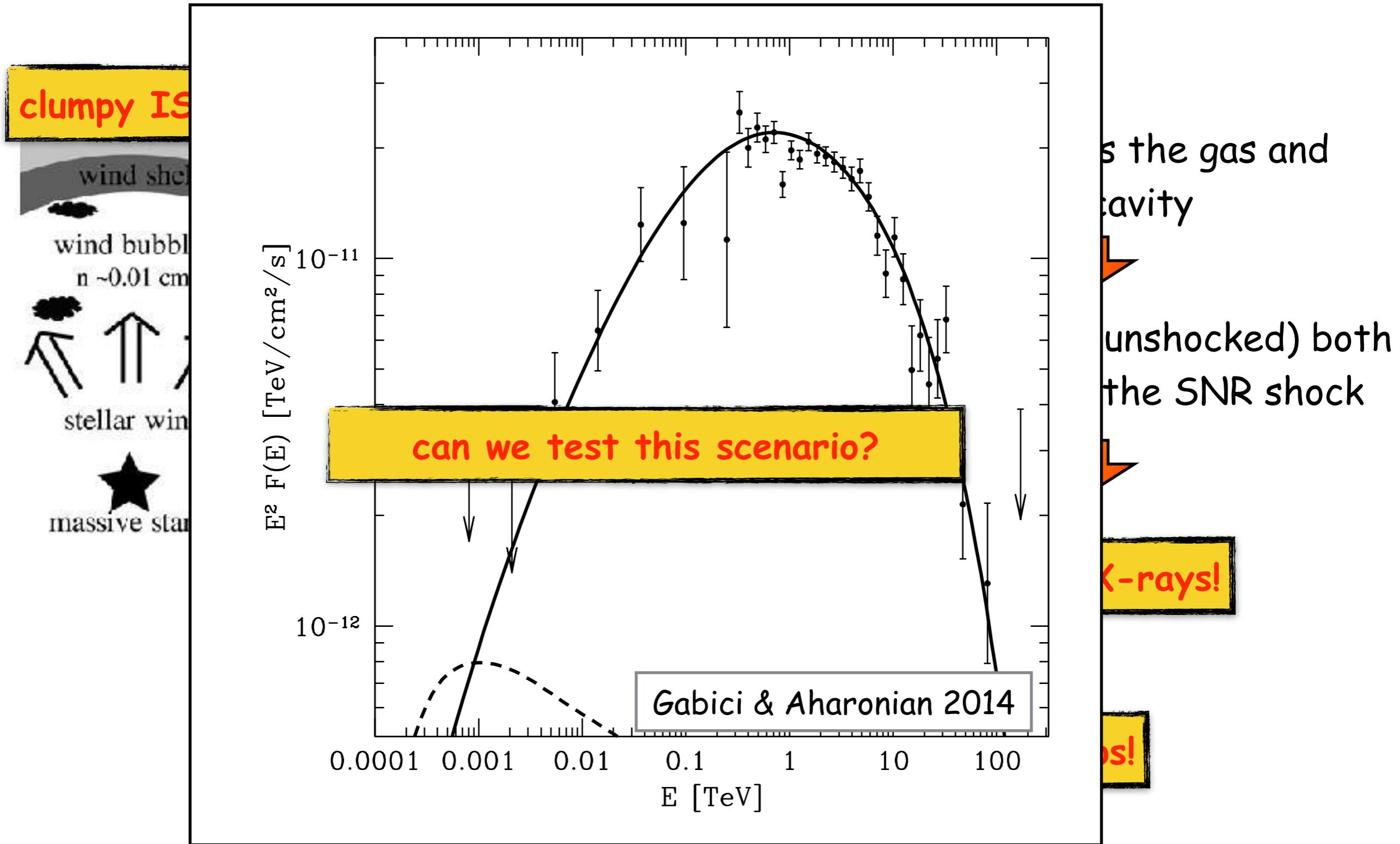
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$$M_{cl}^{tot} \sim 50 - 500 M_{\odot}$$

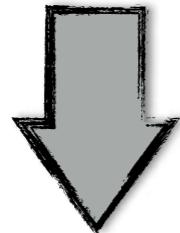
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$n_{cl} \sim 10^3 \text{ cm}^{-3}$

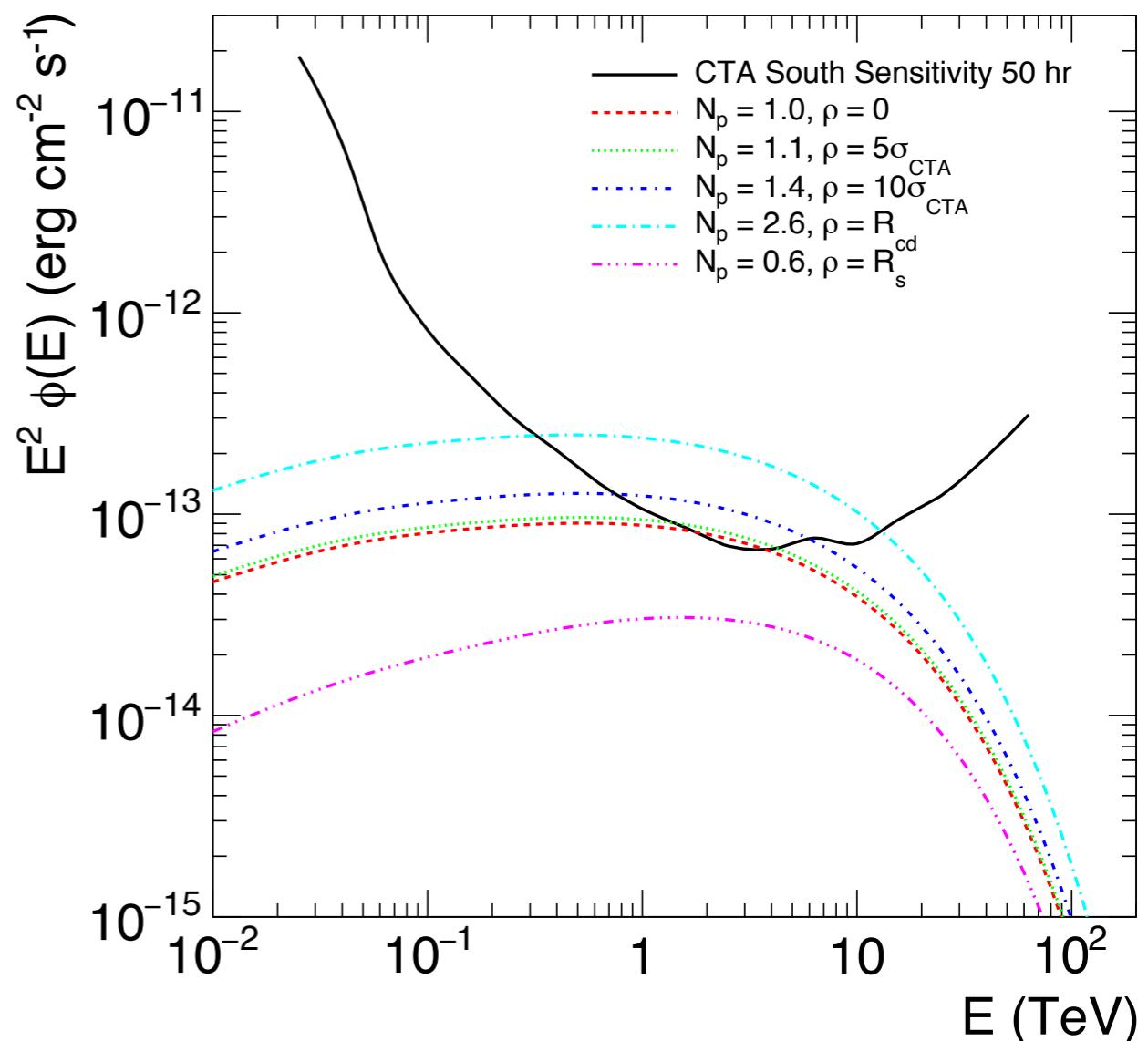
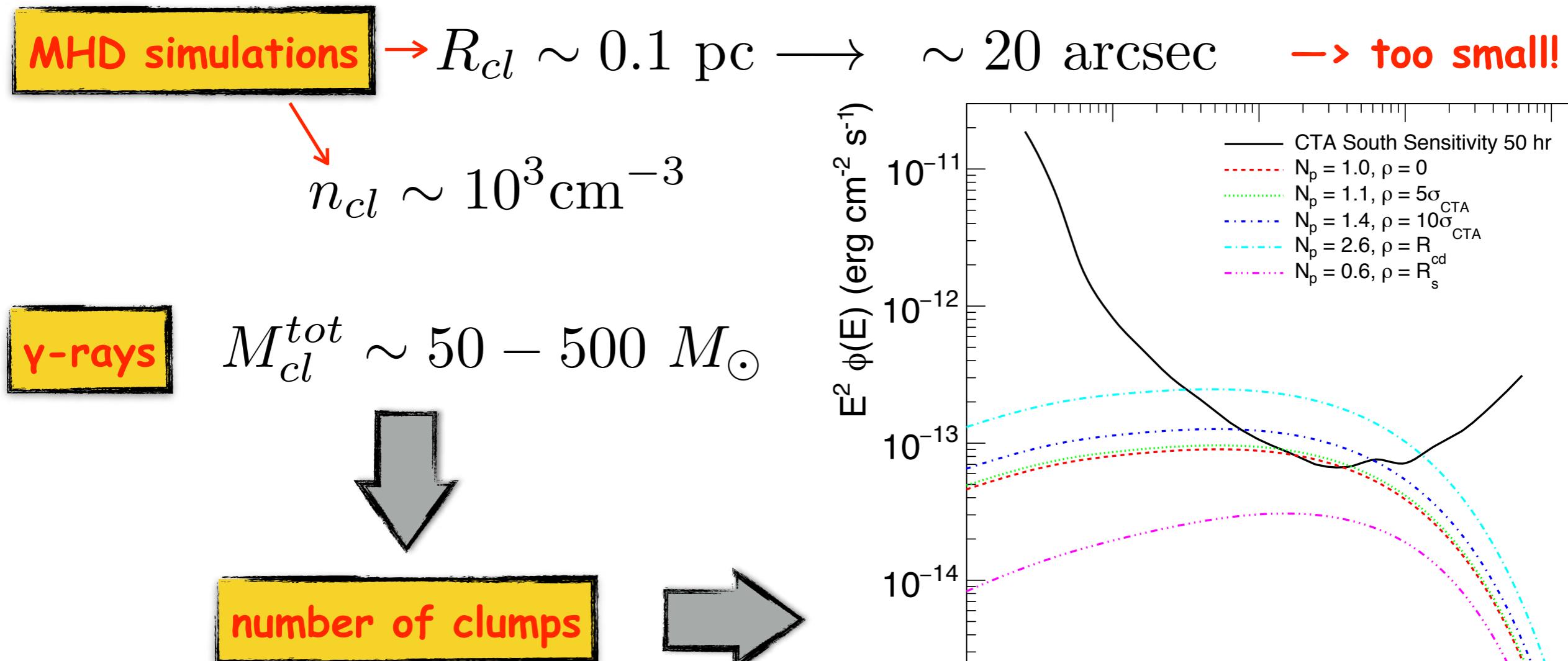
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number of clumps

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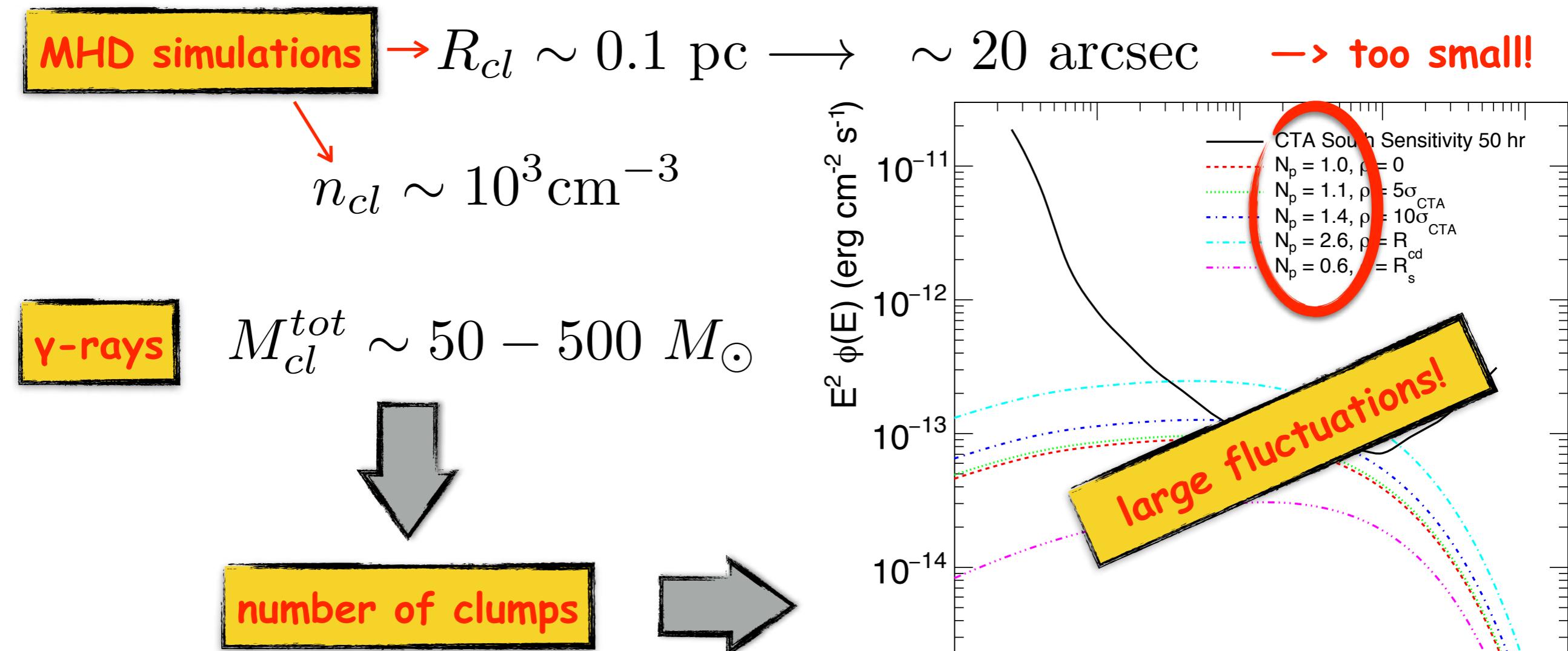
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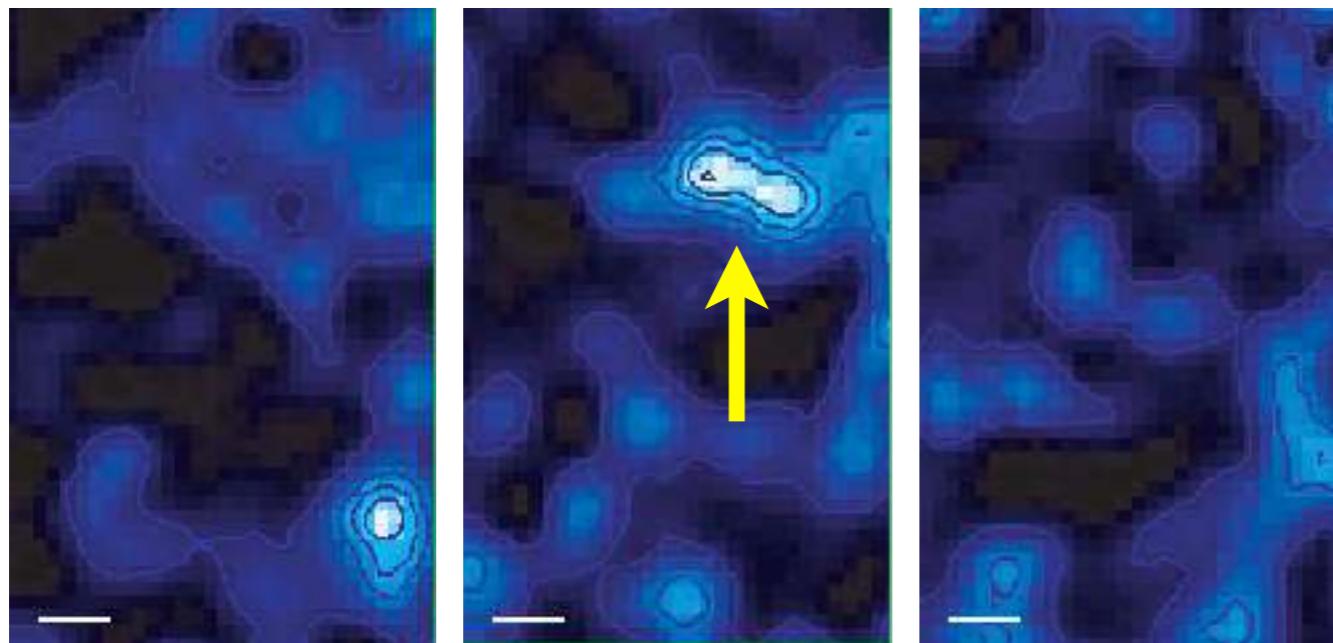


...and X-ray telescopes

RXJ1713 (Uchiyama+ 2007), Cas A (Uchiyama & Aharonian 2008)

fast X-ray variability

RX J1713



- Requires amplified magnetic field
- Size of the emission ~20 arcsec

YEARS

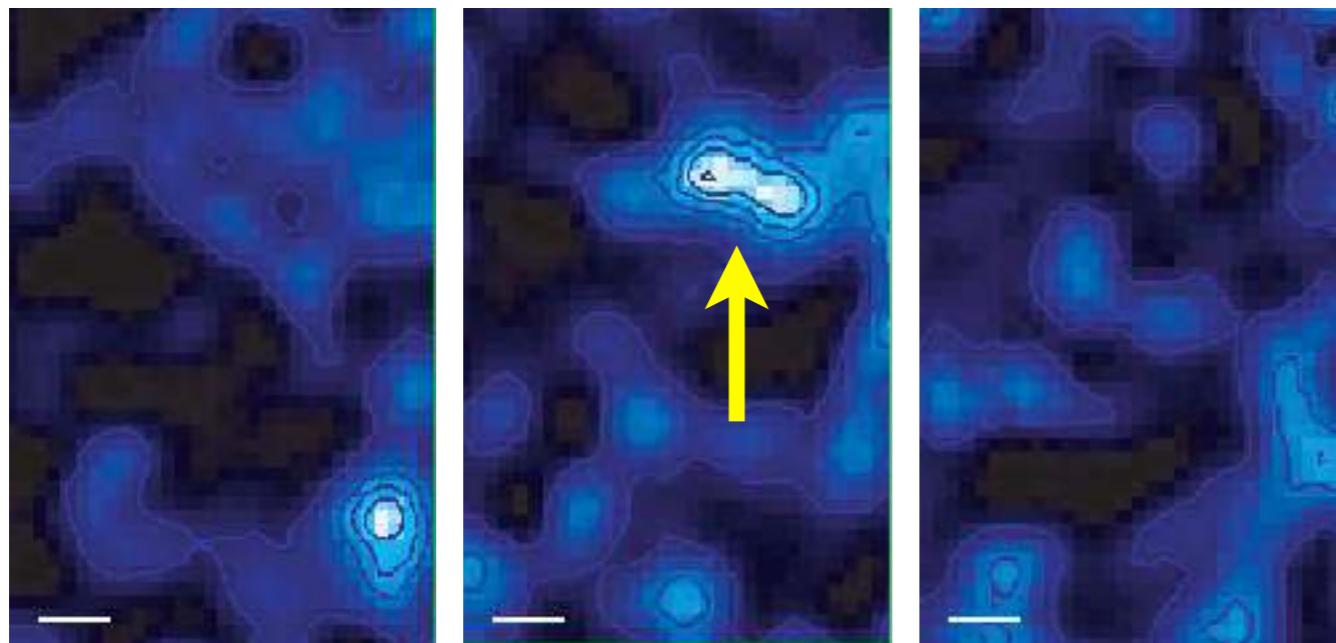
exercise: estimate B !

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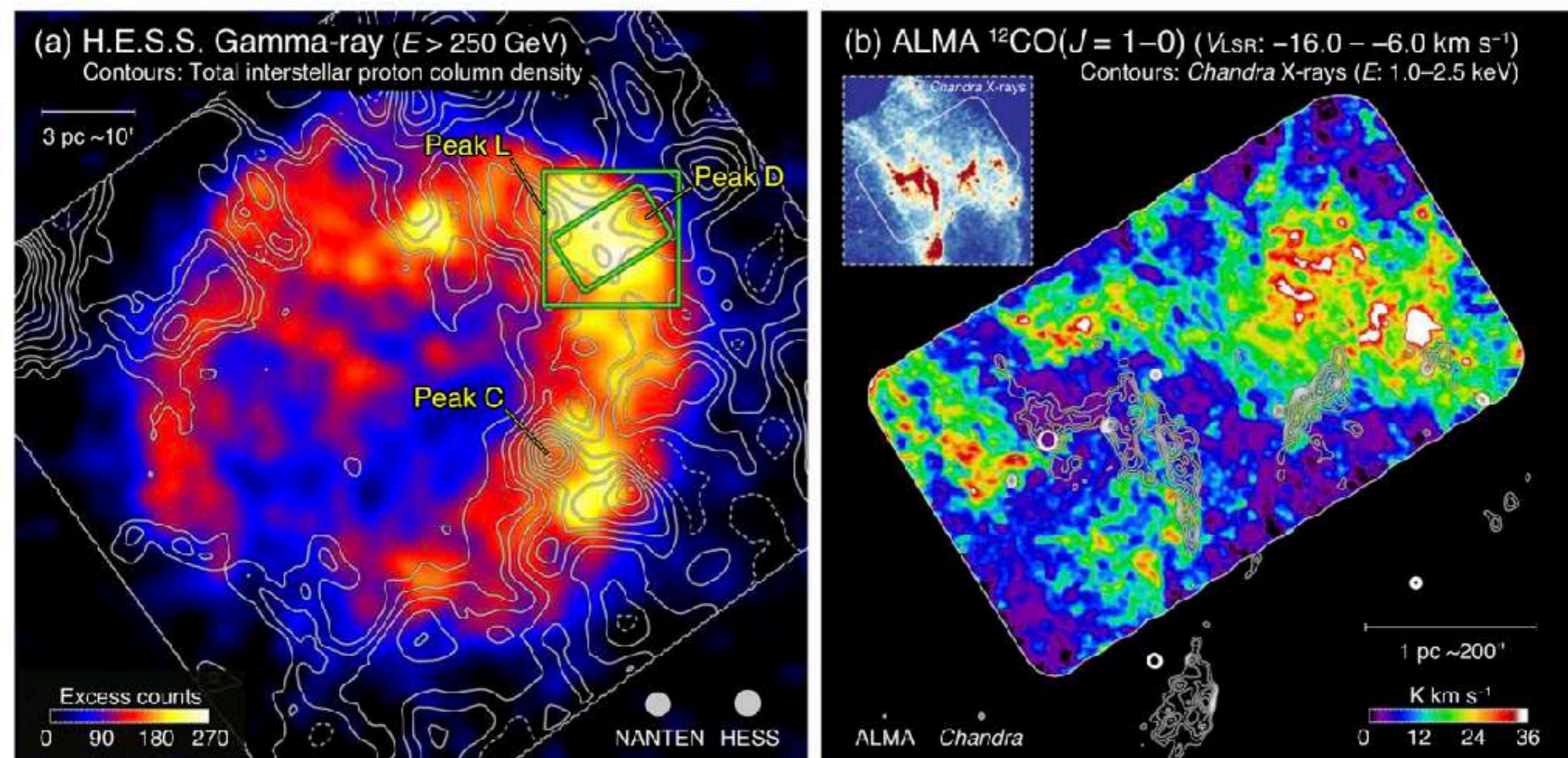
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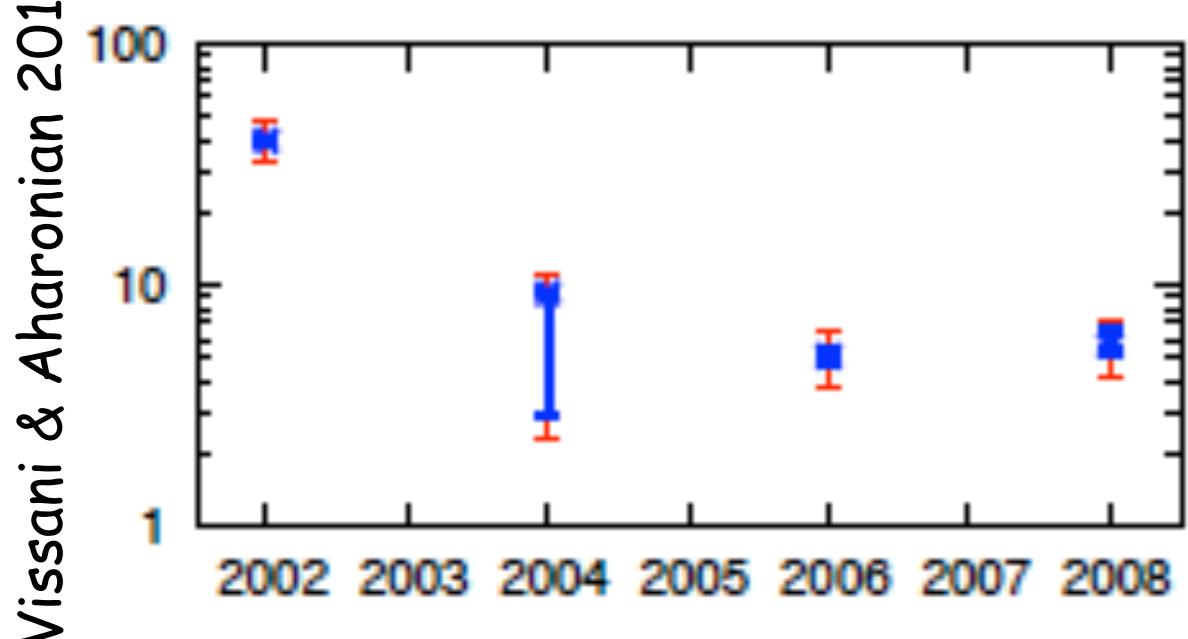
$$\tau_{syn/IC} \sim \frac{E}{dE/dt} \approx 1 \left(\frac{\omega_{TOT}}{0.25 \text{ eV/cm}^3} \right)^{-1} \left(\frac{E}{\text{TeV}} \right)^{-1} \text{Myr}$$

Small clumps are there!



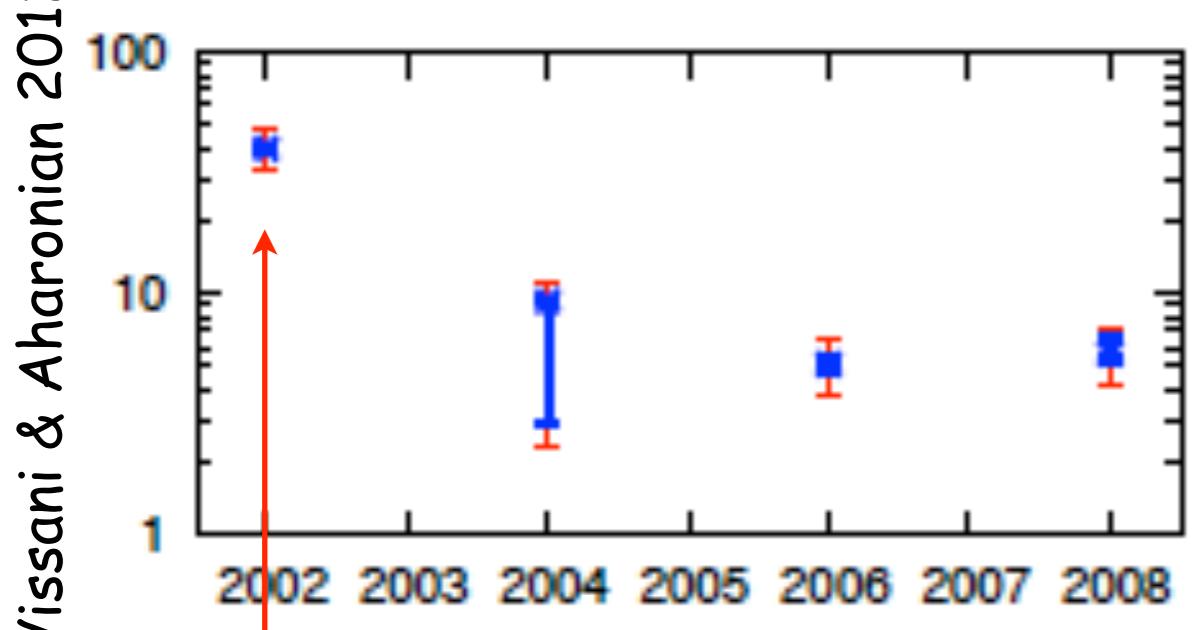
Neutrinos

predictions of the neutrino flux (> 50 GeV)
per ($\text{km}^2 \times \text{yr}$) from RX J1713 as a fct of time



Neutrinos

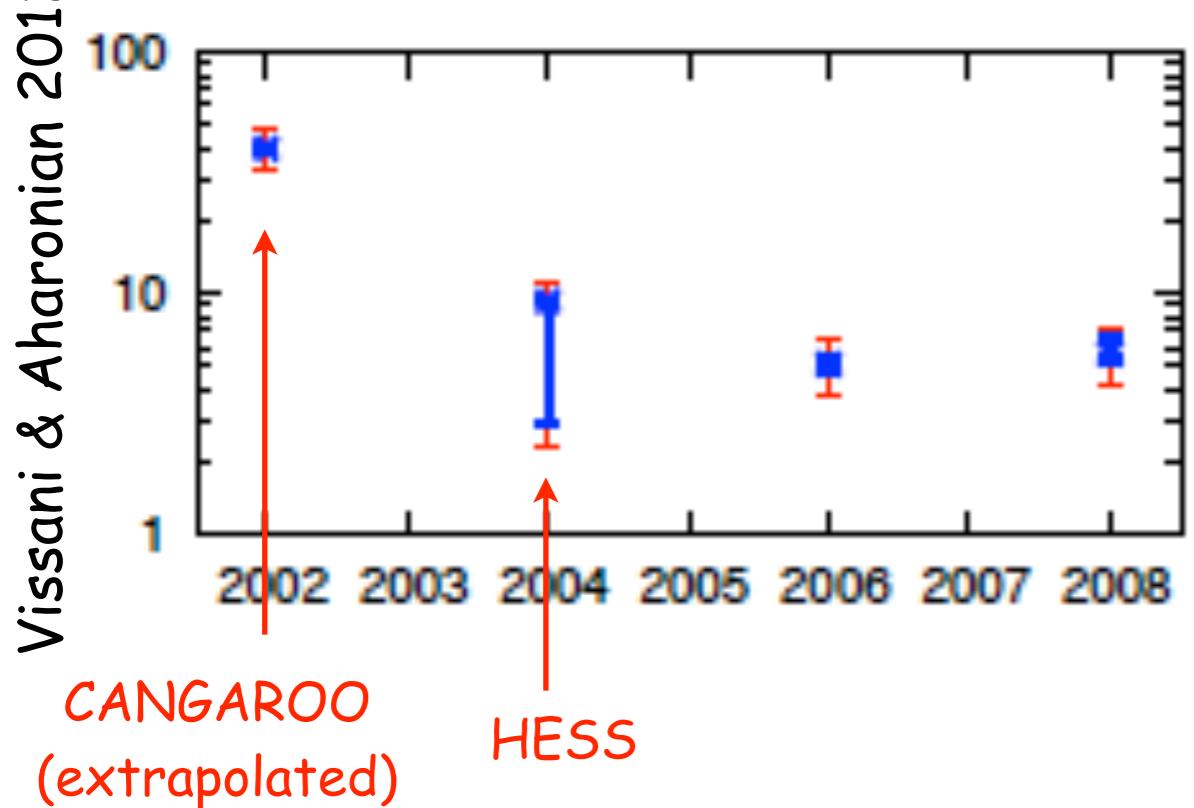
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CANGAROO
(extrapolated)

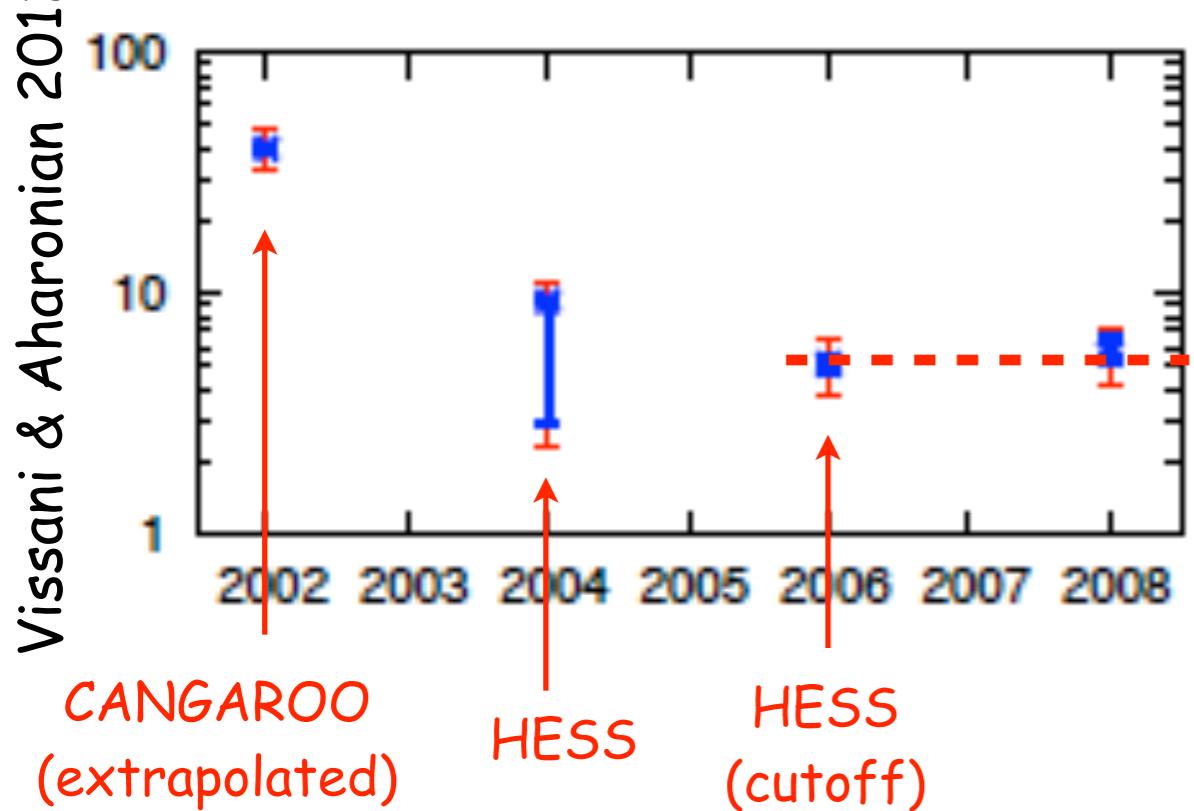
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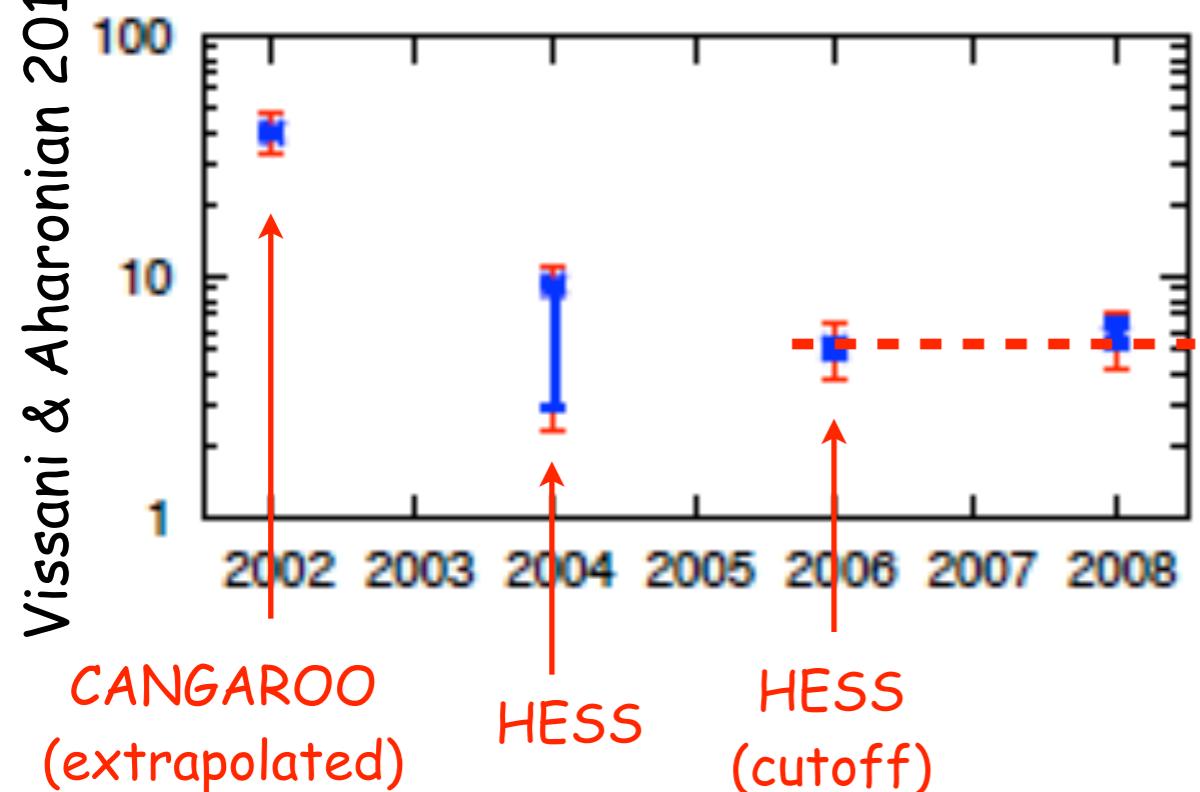
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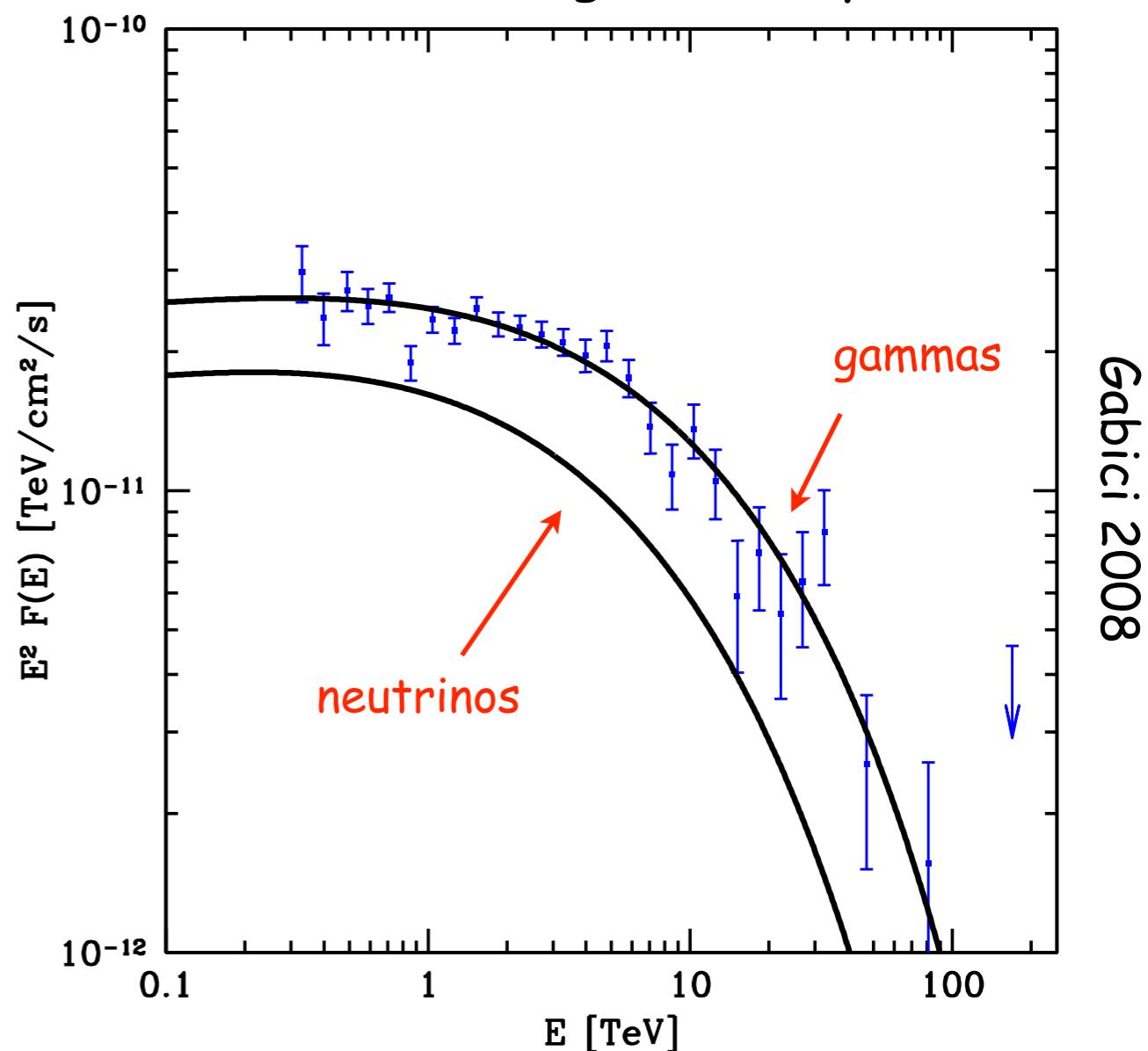
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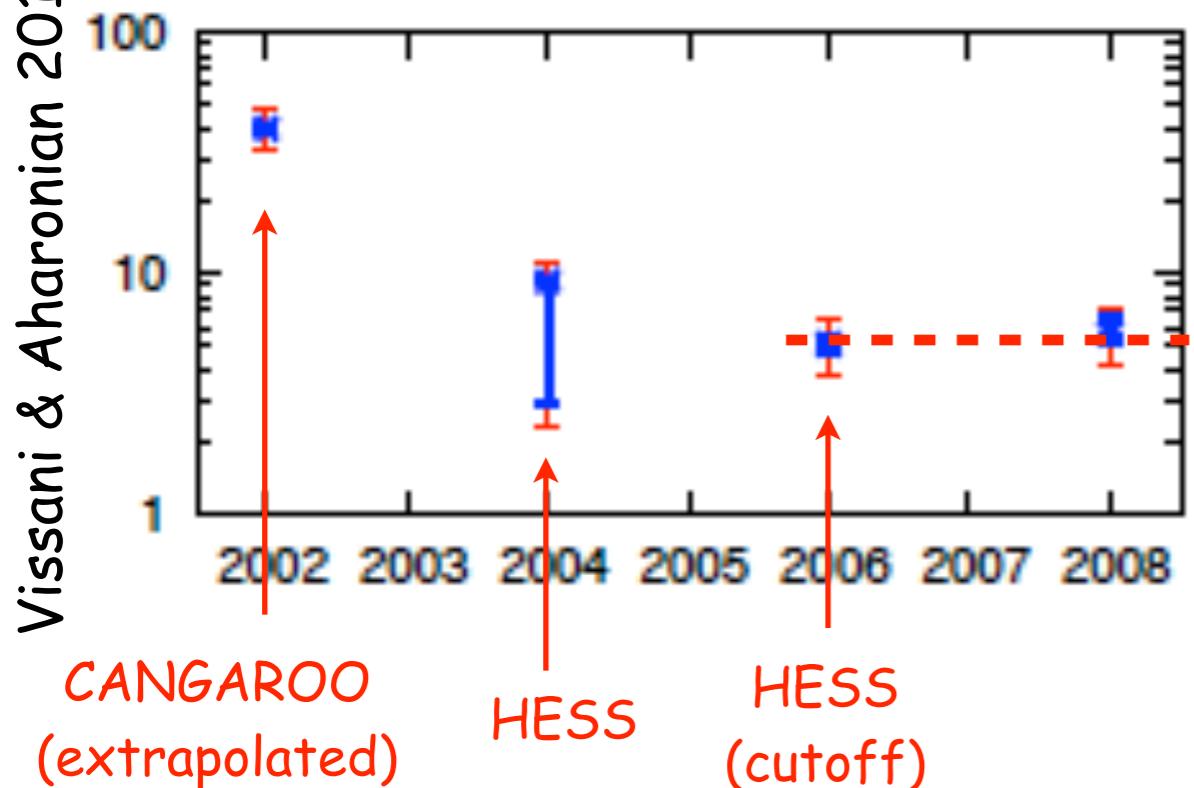
totally model independent

(SNRs are transparent
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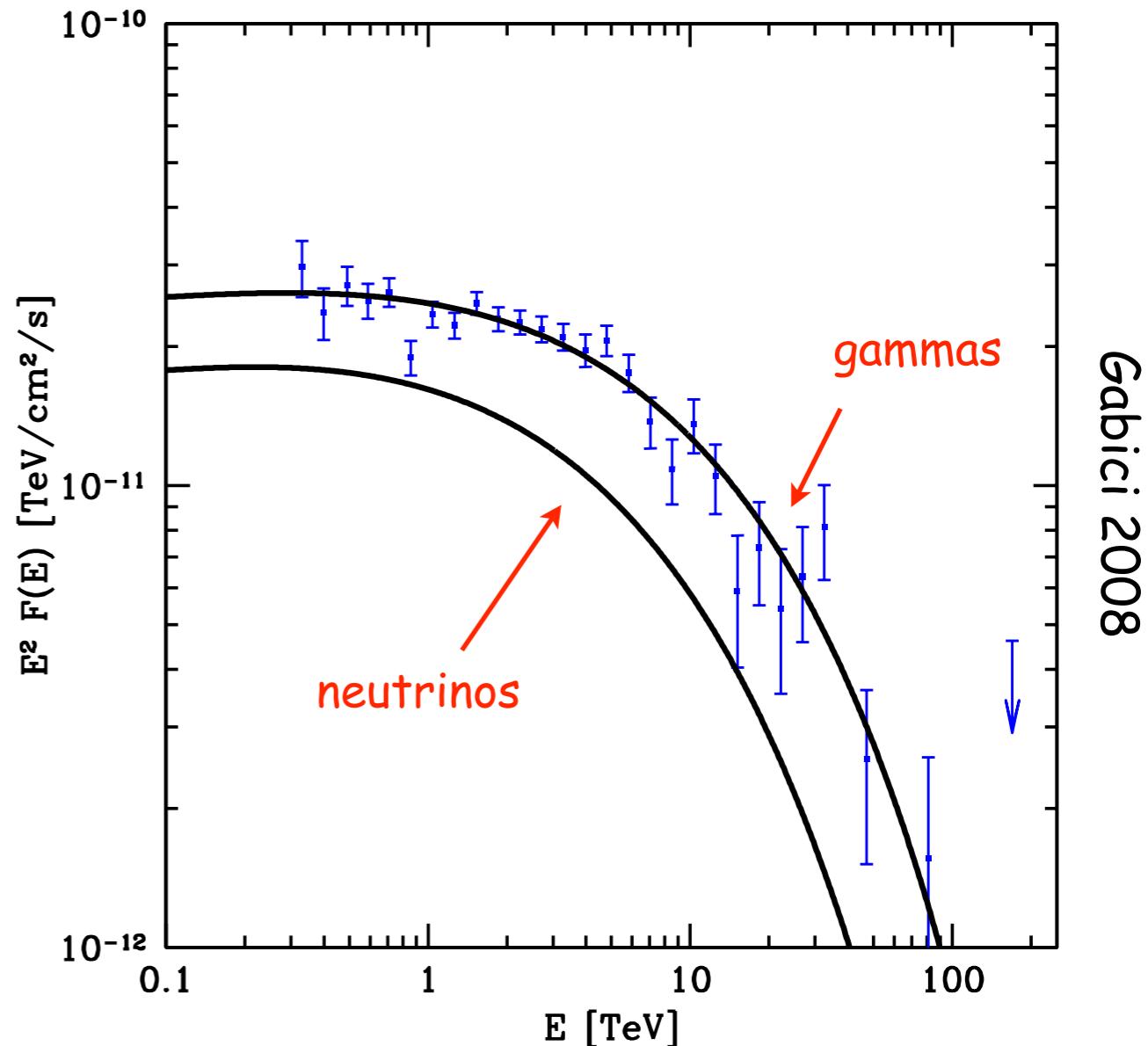
upper limit on nu emission
(gammas 100% hadronic)

$$F_\nu(> 1 \text{ TeV}) = 2.4 \nu / (\text{km}^2 \text{ yr})$$

Villante & Vissani 2008

totally model independent

(SNRs are transparent
sources of gamma-rays)



Gabici 2008

Conclusions

- Most of the history of astronomy can be probably described as an ethereal struggle to measure distances of far away bodies → first question for any problem si: how distant is this phenomenon taking place?
- Use photons of all possible wavelengths, particles of any possible kind, and also read old stuff in any language!
- You will invariably end up with more solutions for a given problem → Always ask "how much it costs?" (in terms of energy)
- Most important: NEVER do sophisticated calculations before having guessed the solution with simple order of magnitude estimates