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

Stefano Gabici
APC, Paris

www.cnrs.fr

# High-energy particle acceleration in the shell of a supernova remnant

F. A. Aharonian[1], A. G. Akhperjanian[2], K.-M. Aye[3], A. R. Bazer-Bachi[4], M. Beilicke[5], W. Benbow[1], D. Berge[1], P. Berghaus[6*], K. Bernlöhr[1,7], O. Bolz[1], C. Boisson[8], C. Borgmeier[7], F. Breitling[7], A. M. Brown[3], J. Bussons Gordo[9], P. M. Chadwick[3], V. R. Chitnis[10,20*], L.-M. Chounet[11], R. Cornils[5], L. Costamante[1,20], B. Degrange[11], A. Djannati-Ataï[6], L. O'C. Drury[12], T. Ergin[7], P. Espigat[6], F. Feinstein[9], P. Fleury[11], G. Fontaine[11], S. Funk[1], Y. A. Gallant[9], B. Giebels[11], S. Gillessen[1], P. Goret[13], J. Guy[10], C. Hadjichristidis[3], M. Hauser[14], G. Heinzelmann[5], G. Henri[15], G. Hermann[1], J. A. Hinton[1], W. Hofmann[1], M. Holleran[16], D. Horns[1], O. C. de Jager[16], I. Jung[1,14*], B. Khélifi[1], Nu. Komin[7], A. Konopelko[1,7], I. J. Latham[3], R. Le Gallou[3], M. Lemoine[11], A. Lemière[6], N. Leroy[11], T. Lohse[7], A. Marcowith[4], C. Masterson[1,20], T. J. L. McComb[3], M. de Naurois[10], S. J. Nolan[3], A. Noutsos[3], K. J. Orford[3], J. L. Osborne[3], M. Ouchrif[10,20], M. Panter[1], G. Pelletier[15], S. Pita[6], M. Pohl[17*], G. Pühlhofer[1,14], M. Punch[6], B. C. Raubenheimer[16], M. Raue[5], J. Raux[10], S. M. Rayner[3], I. Redondo[11,20*], A. Reimer[17], O. Reimer[17], J. Ripken[5], M. Rivoal[10], L. Rob[18], L. Rolland[10], G. Rowell[1], V. Sahakian[2], L. Saugé[15], S. Schlenker[7], R. Schlickeiser[17], C. Schuster[17], U. Schwanke[7], M. Siewert[17], H. Sol[8], R. Steenkamp[19], C. Stegmann[7], J.-P. Tavernet[10], C. G. Théoret[6], M. Tluczykont[11,20], D. J. van der Walt[16], G. Vasileiadis[9], P. Vincent[10], B. Visser[16], H. J. Völk[1] & S. J. Wagner[14]

[1]*Max-Planck-Institut für Kernphysik, PO Box 103980, D 69029 Heidelberg, Germany*
[2]*Yerevan Physics Institute, 2 Alikhanian Brothers Street, 375036 Yerevan, Armenia*
[3]*Department of Physics, University of Durham, South Road, Durham DH1 3LE, UK*
[4]*Centre d'Etude Spatiale des Rayonnements, CNRS/UPS, 9 av. du Colonel Roche, BP 4346, F-31029 Toulouse Cedex 4, France*
[5]*Institut für Experimentalphysik, Universität Hamburg, Luruper Chaussee 149, D 22761 Hamburg, Germany*
[6]*Physique Corpusculaire et Cosmologie, IN2P3/CNRS, Collège de France, 11 Place Marcelin Berthelot, F-75231 Paris Cedex 05, France*
[7]*Institut für Physik, Humboldt-Universität zu Berlin, Newtonstrasse 15, D 12489 Berlin, Germany*
[8]*LUTH, UMR 8102 du CNRS, Observatoire de Paris, Section de Meudon, F-92195 Meudon Cedex, France*
[9]*Groupe d'Astroparticules de Montpellier, IN2P3/CNRS, Université Montpellier II, CC85, Place Eugène Bataillon, F-34095 Montpellier Cedex 5, France*
[10]*Laboratoire de Physique Nucléaire et de Hautes Energies, IN2P3/CNRS, Universités Paris VI & VII, 4 Place Jussieu, F-75231 Paris Cedex 05, France*
[11]*Laboratoire Leprince-Ringuet, IN2P3/CNRS, Ecole Polytechnique, F-91128 Palaiseau, France*
[12]*Dublin Institute for Advanced Studies, 5 Merrion Square, Dublin 2, Ireland*
[13]*Service d'Astrophysique, DAPNIA/DSM/CEA, CE Saclay, F-91191 Gif-sur-Yvette, France*
[14]*Landessternwarte, Königstuhl, D 69117 Heidelberg, Germany*
[15]*Laboratoire d'Astrophysique de Grenoble, INSU/CNRS, Université Joseph Fourier, BP 53, F-38041 Grenoble Cedex 9, France*
[16]*Unit for Space Physics, North-West University, Potchefstroom 2520, South Africa*
[17]*Institut für Theoretische Physik, Lehrstuhl IV: Wel... Ruhr-Universität Bochum, D 44780 Bochum, Germ...*
[18]*Institute of Particle and Nuclear Physics, Charles U... 180 00 Prague 8, Czech Republic*
[19]*University of Namibia, Private Bag 13301, Wind...*
[20]*European Associated Laboratory for Gamma-Ray...*

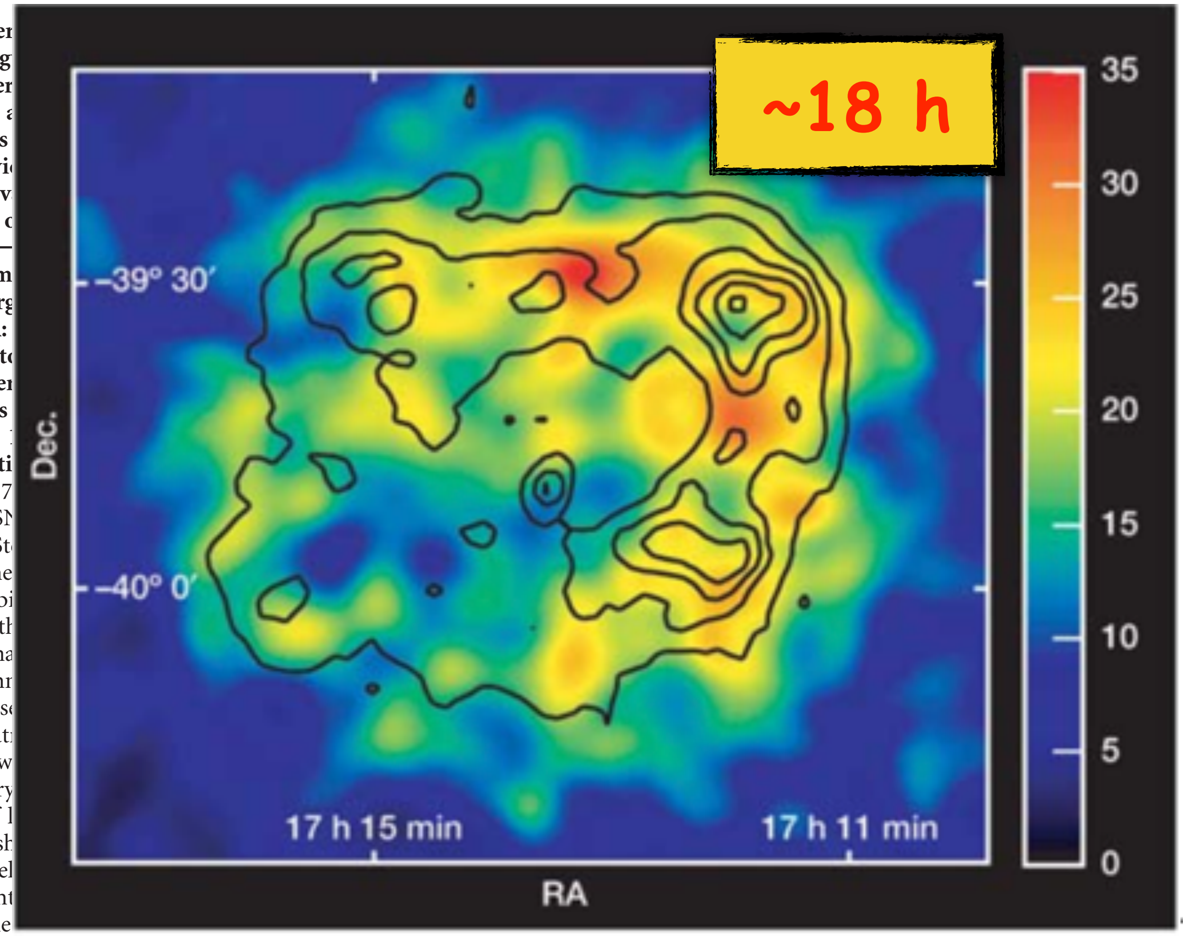
* Present addresses: Université Libre de Bruxelles, Faculté de ...s, Campus de la Plaine, CP230, Boulevard du Triomphe, 1050 Bruxelles, Belgium (P.B.); T... Fundamental Research, Homi Bhabha Road, Mumbai 400 005, India (V.R.C.); Washi... Department of Physics, 1 Brookings Drive, CB 1105, St Louis, Missouri 6...130... ...rtment of Physics and Astronomy, Iowa State University, Ames, Iowa 50011-3160... ...tment of Physics and Astronomy, University of Sheffield, The Hicks Building, H... ...heffield S3 7RH, UK (I.R.)

**A significant fraction of th... density of the interstellar medium is in the form of hi...-energy charged particles (cosmic rays)[1]. The origin of these particles remains uncertain. Although** it is gener... the energ... are super... particle a... shocks is... vocal evi... supernov... report o... (G347.3–... spectrum... TeV energ... the SNR: ... similar t... high-ene... indicates... beyond ... accelerati...

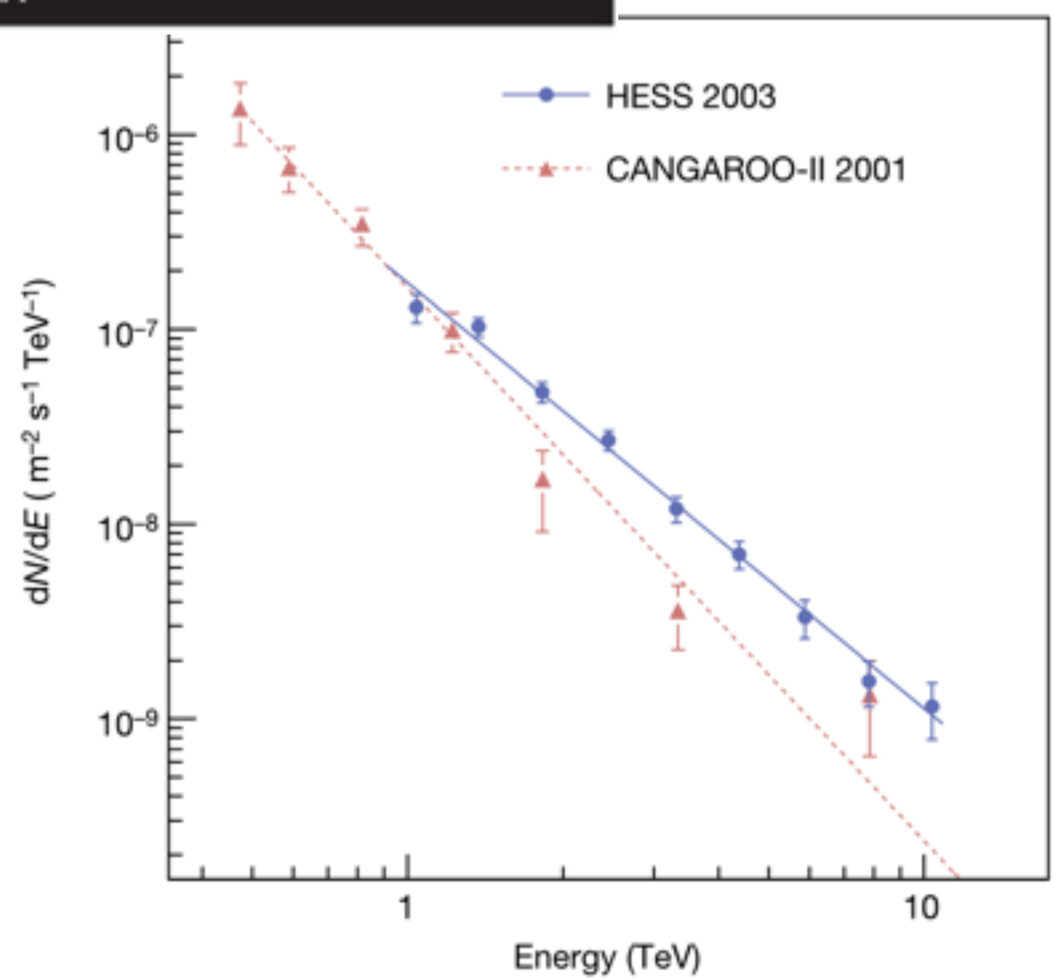
RX J17... sphere SN... Energy St... atmosphe... of Namibi... exploits th... γ-rays, na... This techn... makes us... Earth's at... actions w... secondary... speed of l... brief flash... using a tel... faint light... image the energy of the primary γ-ray. Combined with the approach o... stereoscopic imaging of the cascade using a system of telescope... as pioneered by the HEGRA collaboration[10], this yields a ver... powerful technique for imaging and obtaining energy spectra o... astronomical sources at TeV energies.

The HESS experiment is such a stereoscopic system, consisting o... four 13-m-diameter telescopes[11] spaced at the corners of a square o... side 120 m, each equipped with a 960-phototube camera[12] coverin... a large field of view of diameter 5°. Construction of the telescop... system started in 2001; the full array was completed in Decembe... 2003 with the commissioning of the fourth telescope. HESS has a... angular resolution of a few arc minutes, an effective energy rang... from 100 GeV to 10 TeV with energy resolution of 15–20% and... flux sensitivity approaching $10^{-13}$ erg cm$^{-2}$ s$^{-1}$. These characte... istics, together with its southern hemisphere location, make HES... ideally suited for spectroscopic and morphological studies o... Galactic plane sources such as RX J1713.7−3946, which is no... the first SNR shell to be confirmed as a TeV source. TeV emission ha... also been reported from the remnant of SN 1006 (ref. 13), a resu... ...to confirm wit... ...pre-collapse SN... ...northern locatio...

...X J1713.7−394... performed between May and August 2003 during two phases of th... construction and commissioning of HESS. In the first phase, tw... telescopes were operated independently, with stereoscopic even... selection done offline using GPS time stamps to identify coinciden... events. During the second phase, also using two telescopes, coinc... dent events were selected in hardware using an array level trigge... The total on-source observation time was 26 h; after run selectio... and dead time correction a data set corresponding to 18.1 live hou... was used in this analysis. At the trigger level (for observation altitu...




~18 h



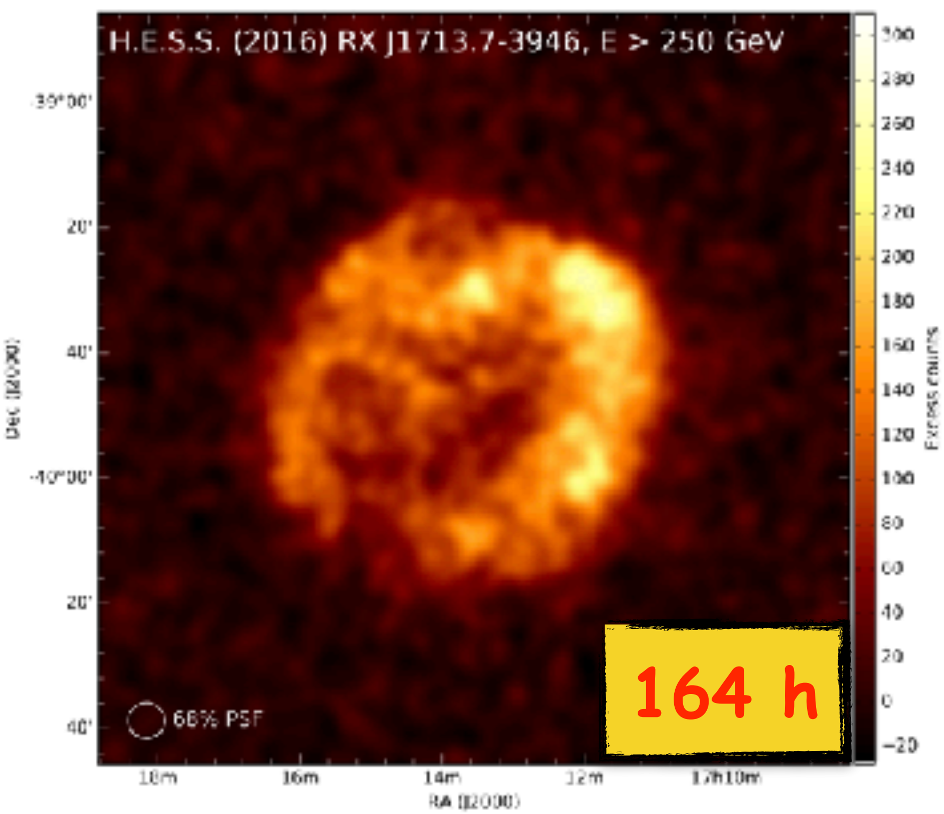

november 4th 2004

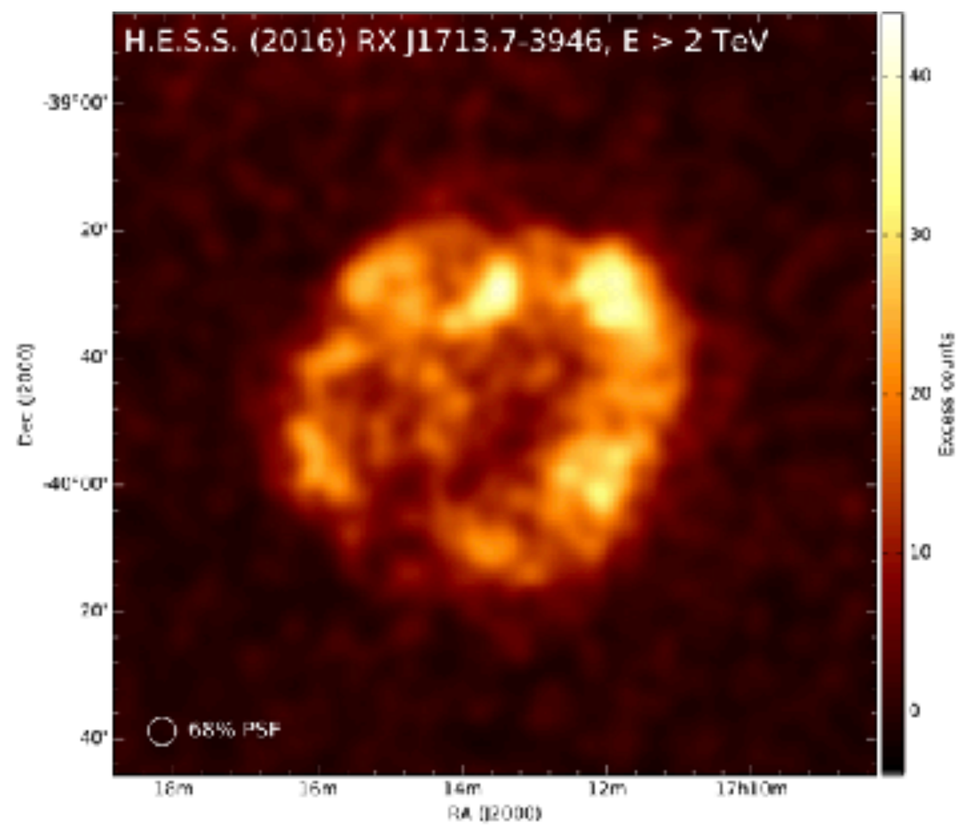
A&A 612, A6 (2018)
DOI: 10.1051/0004-6361/201629790


*H.E.S.S. phase-I observations of the plane of the Milky Way*

Astronomy & Astrophysics
Special issue

# 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★



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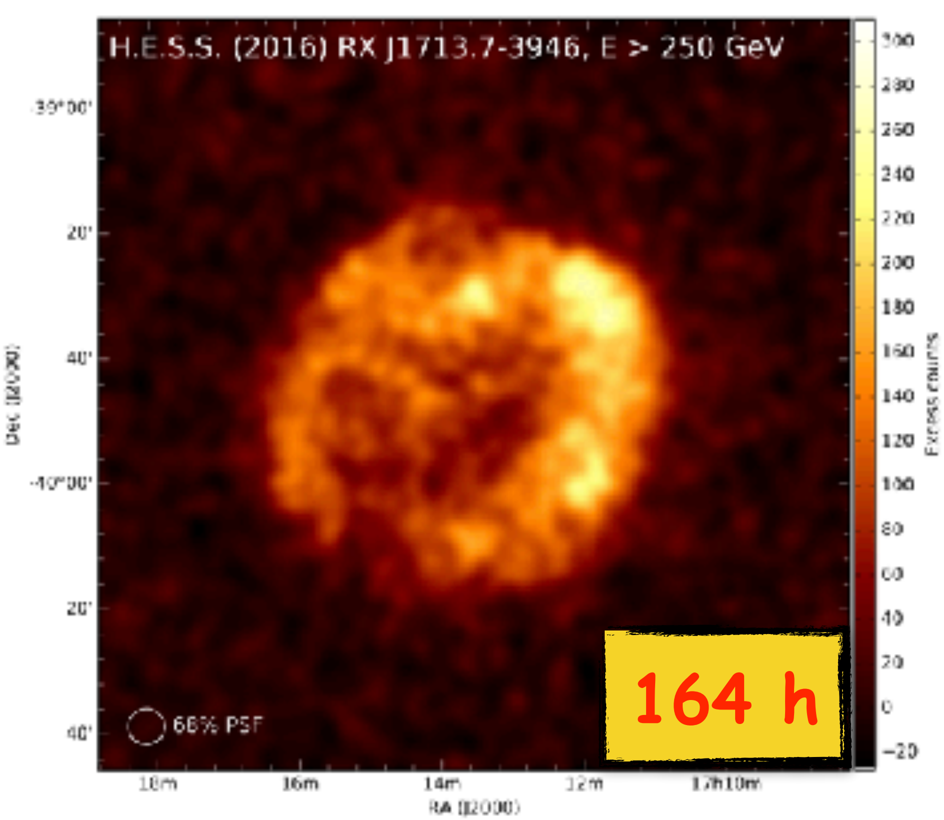
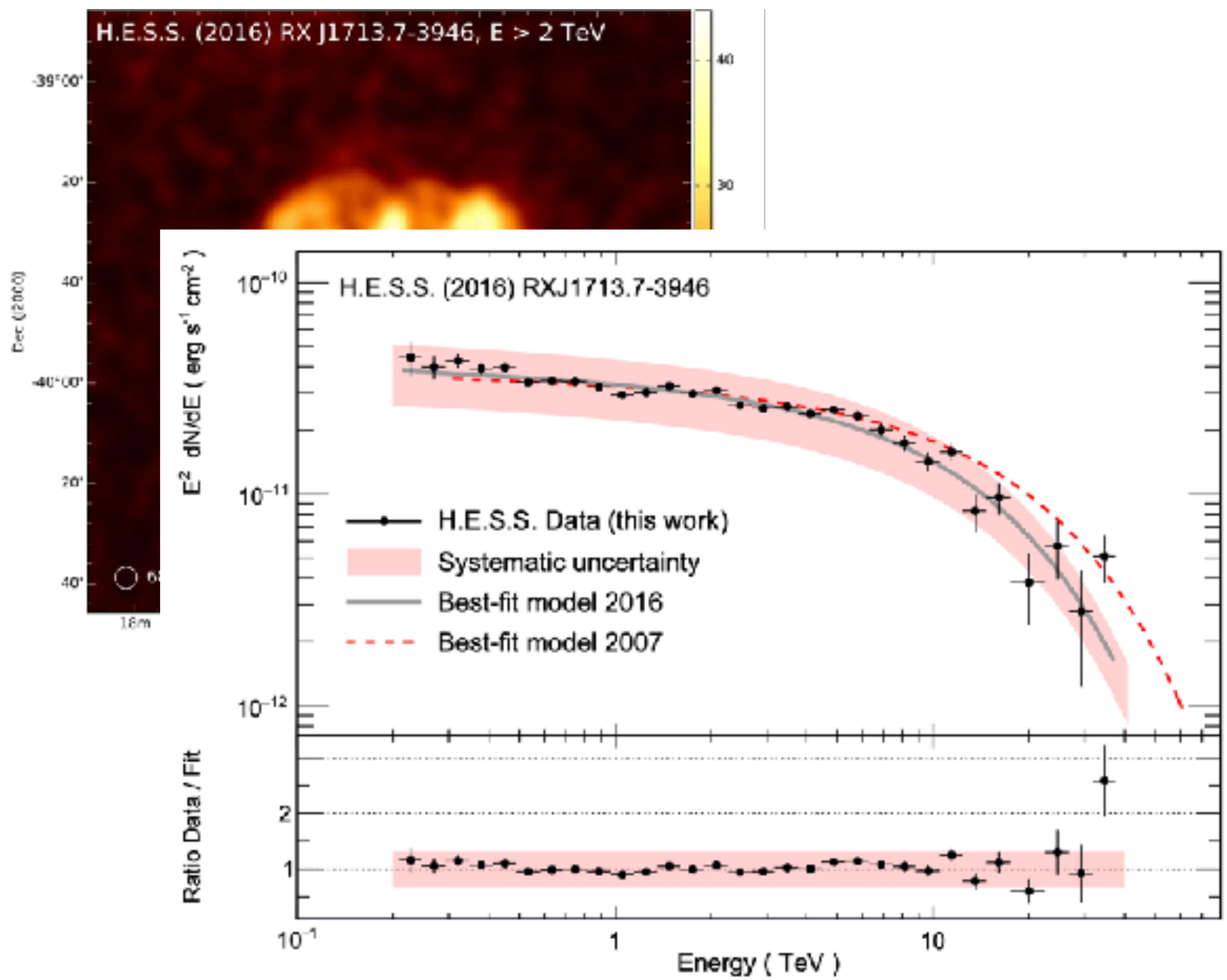


# Why do we care?

*COSMIC RAYS FROM SUPER-NOVAE*

BY W. BAADE AND F. ZWICKY

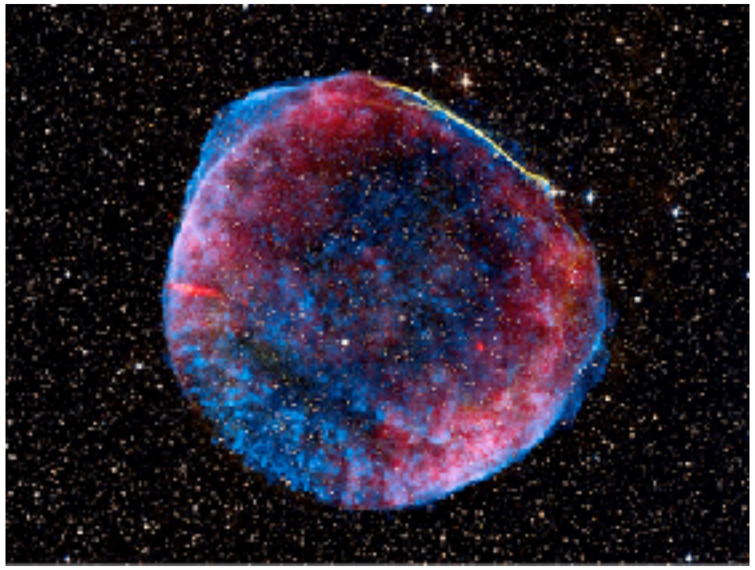
MOUNT WILSON OBSERVATORY, CARNEGIE INSTITUTION OF WASHINGTON AND CALIFORNIA INSTITUTE OF TECHNOLOGY, PASADENA

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



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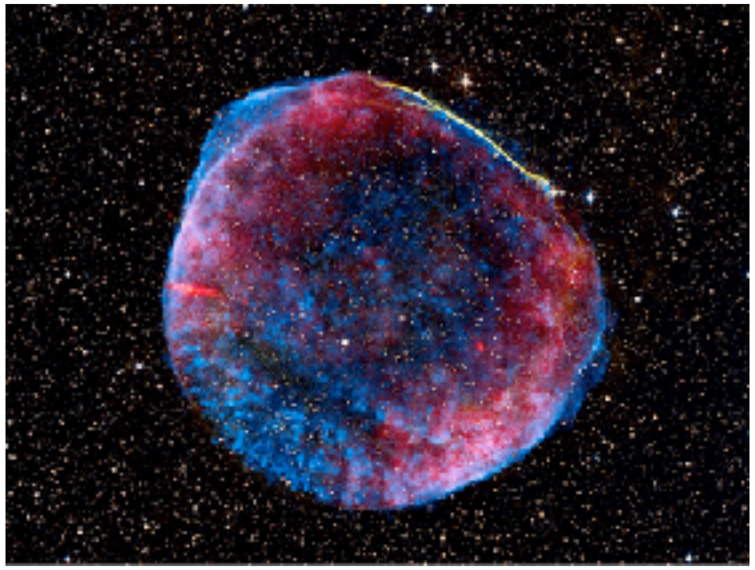

**modern formulation of the hypothesis**

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

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

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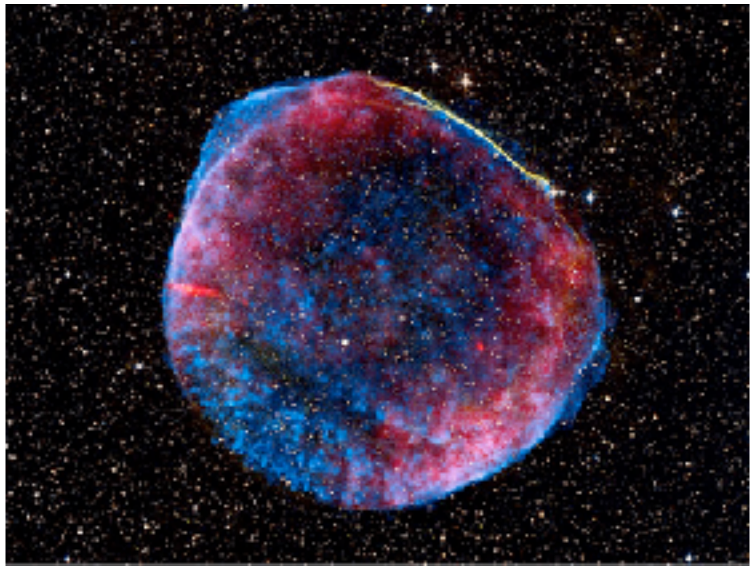

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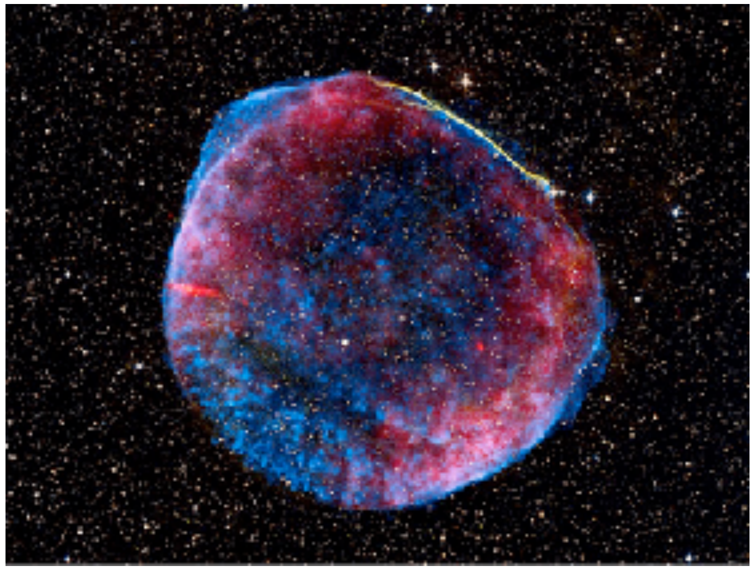

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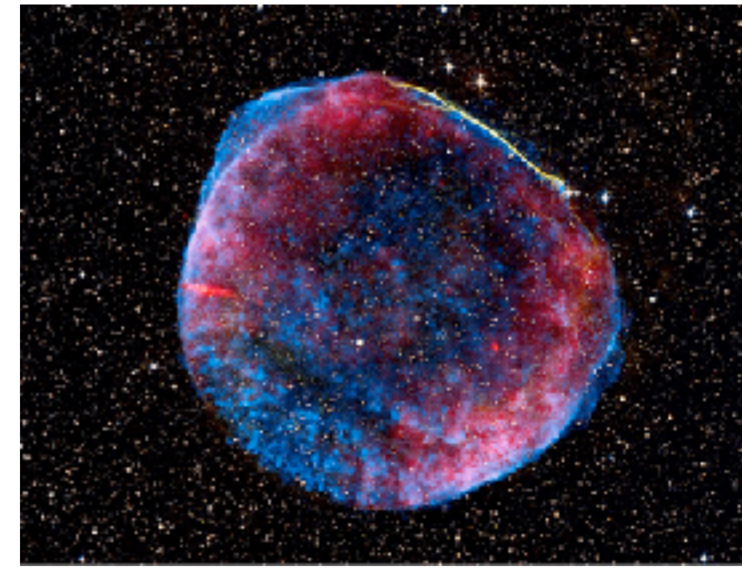

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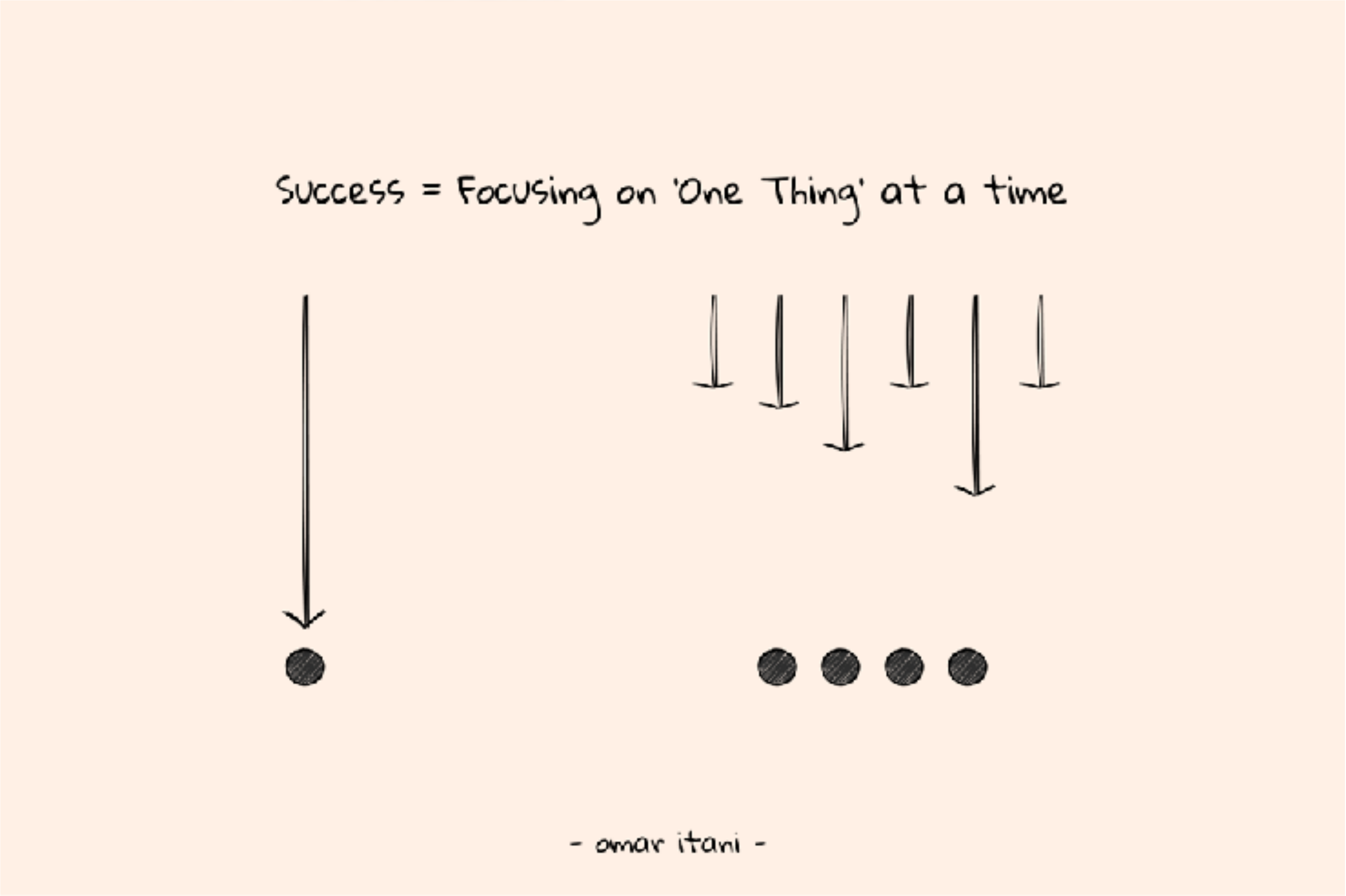
why remnants? —> radio observations —> particle acceleration at SNR shocks!

# Why just one object?

I asked google and...



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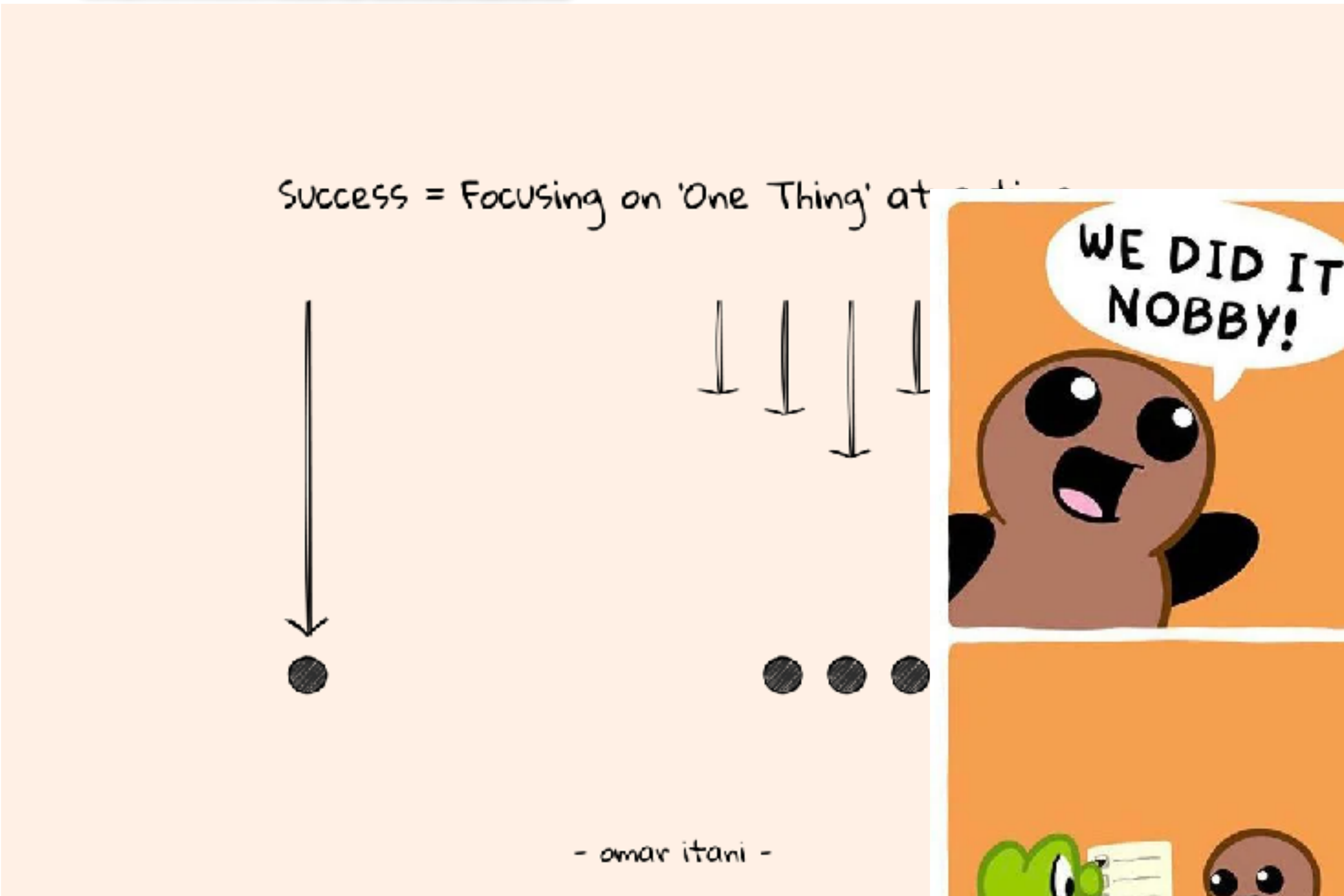


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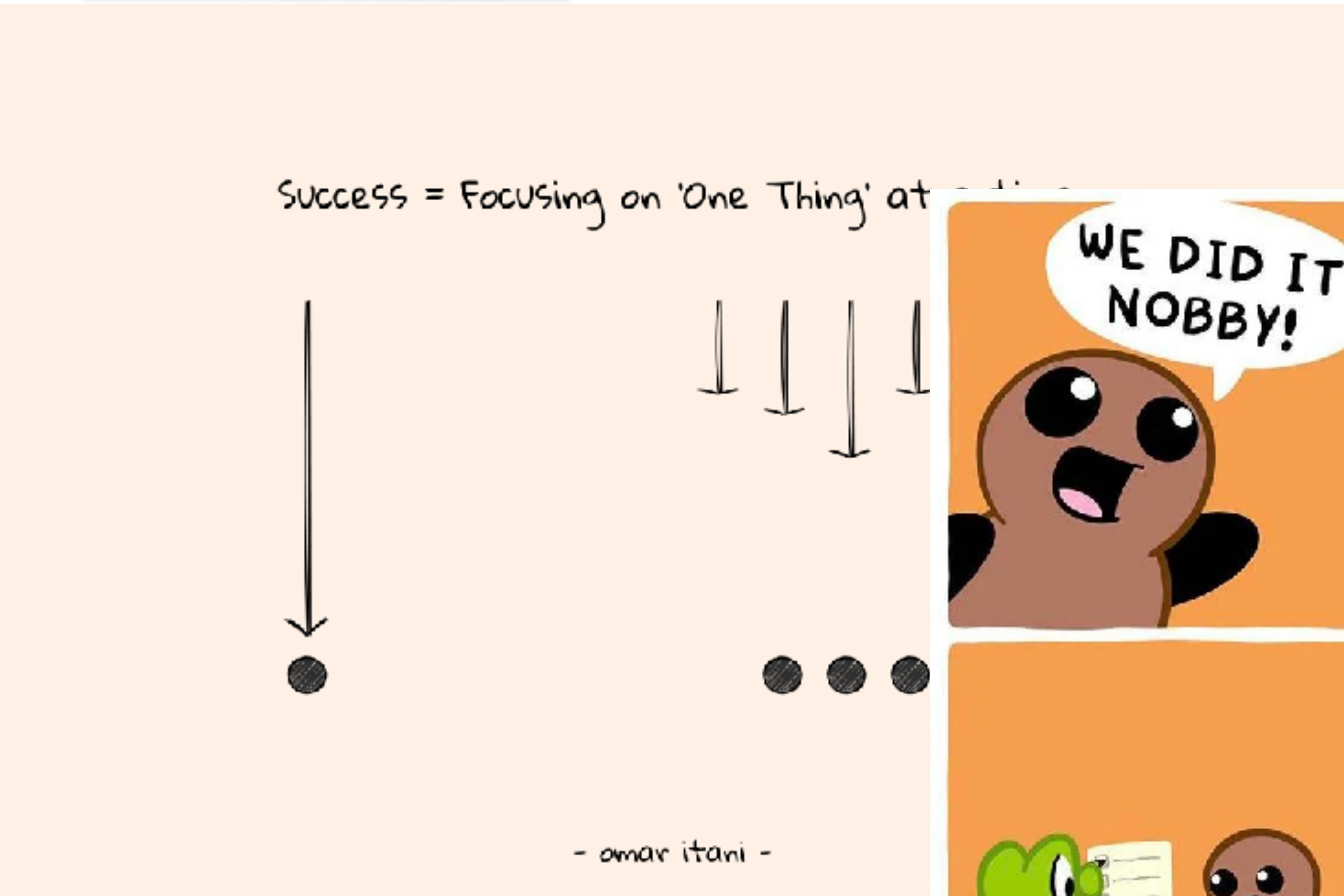



more seriously: focus on the approach rather than the details of the object under examination

Let's start from the beginning…

# The discovery of RX J1713.7-3946



## 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 $\alpha(2000) = 17^h13^m42^s$, $\delta(2000) = -39°$ 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 $4.4 \times 10^{-10}$ 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 $\sim$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 $H_\alpha$ region of 13' radius (RCW 118) and a G5IA star. A counterpart for the second source could not yet be found.

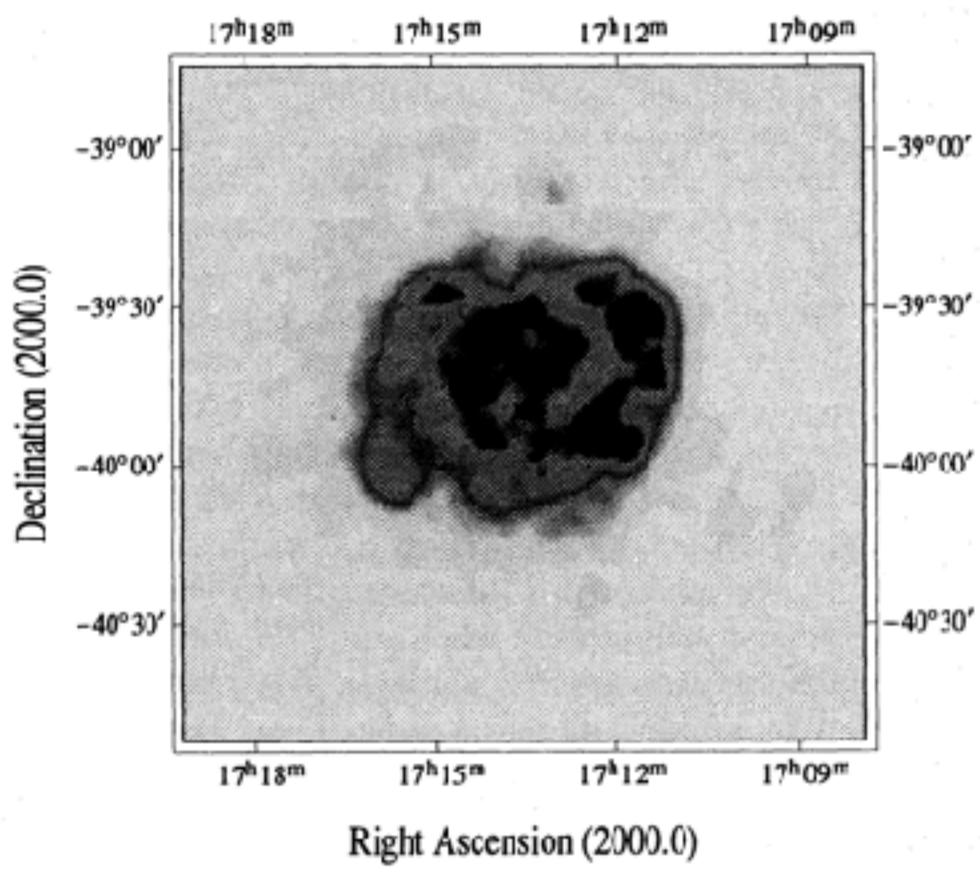


**Fig. 1.** Smoothed X-ray image of RX J1713.7-3946 in the energy range from 0.5- 2.4 keV.

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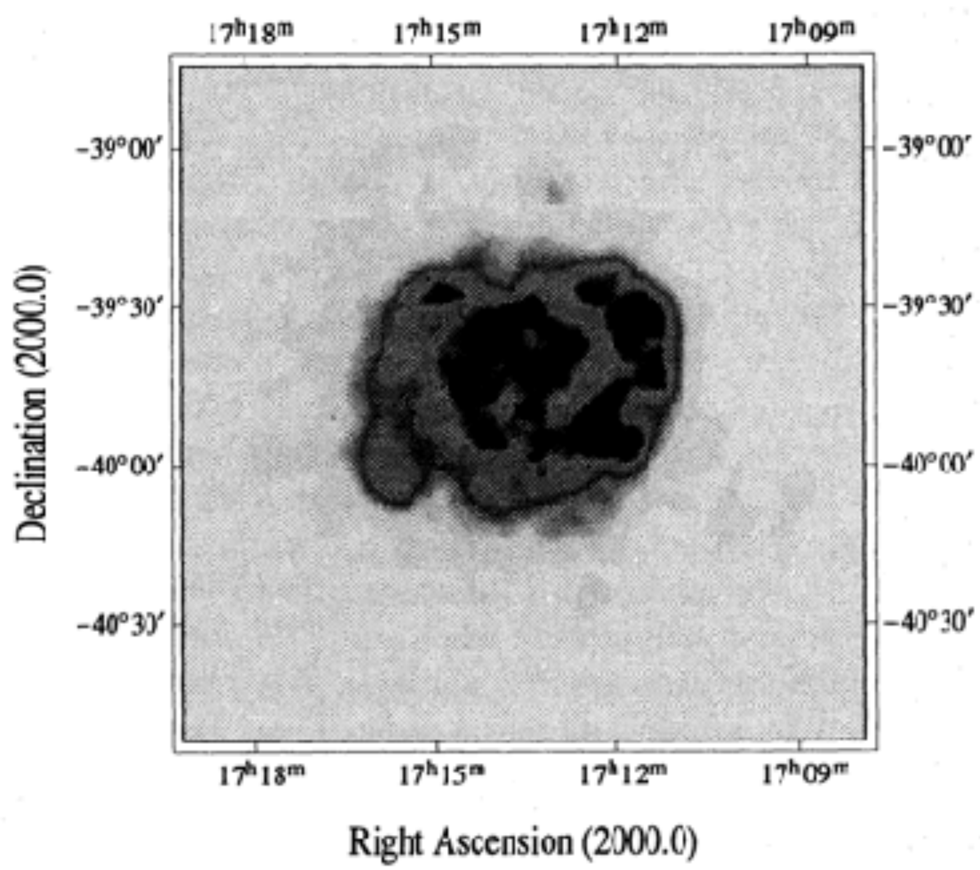


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*MPE Report 263, 1996* **267**

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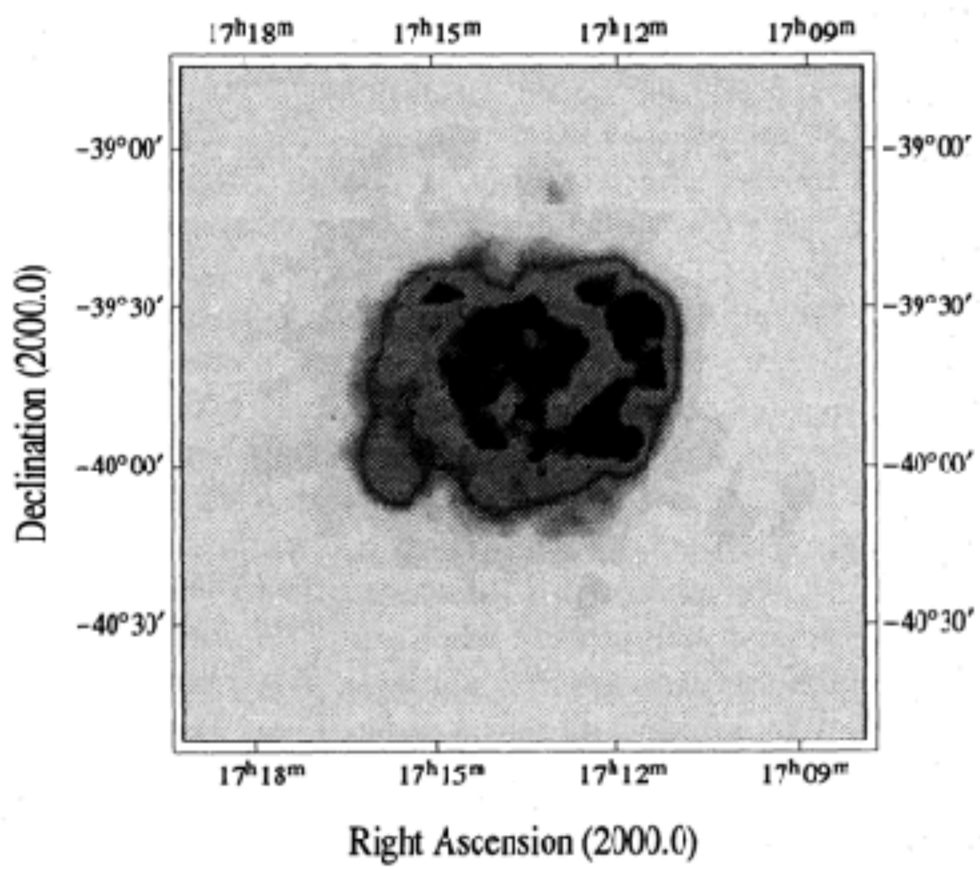


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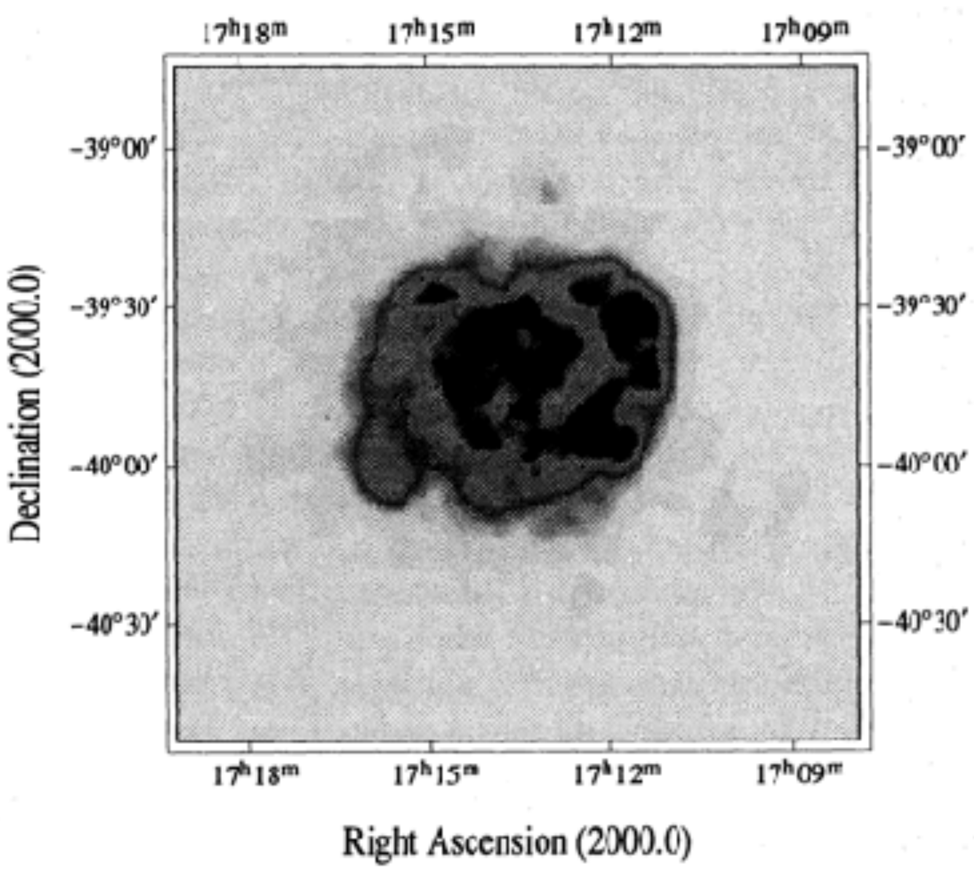


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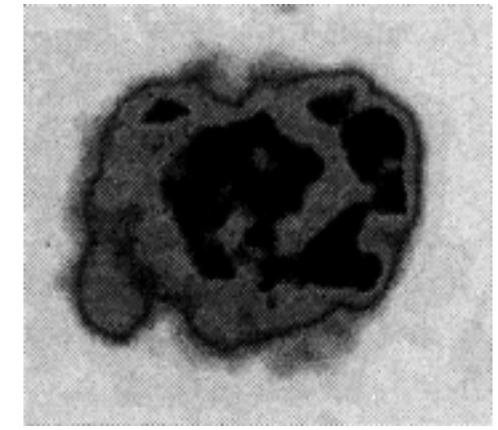
[Question 1] What is the distance to the object we want to study?

# How far is RX J1713.7-3946 ?

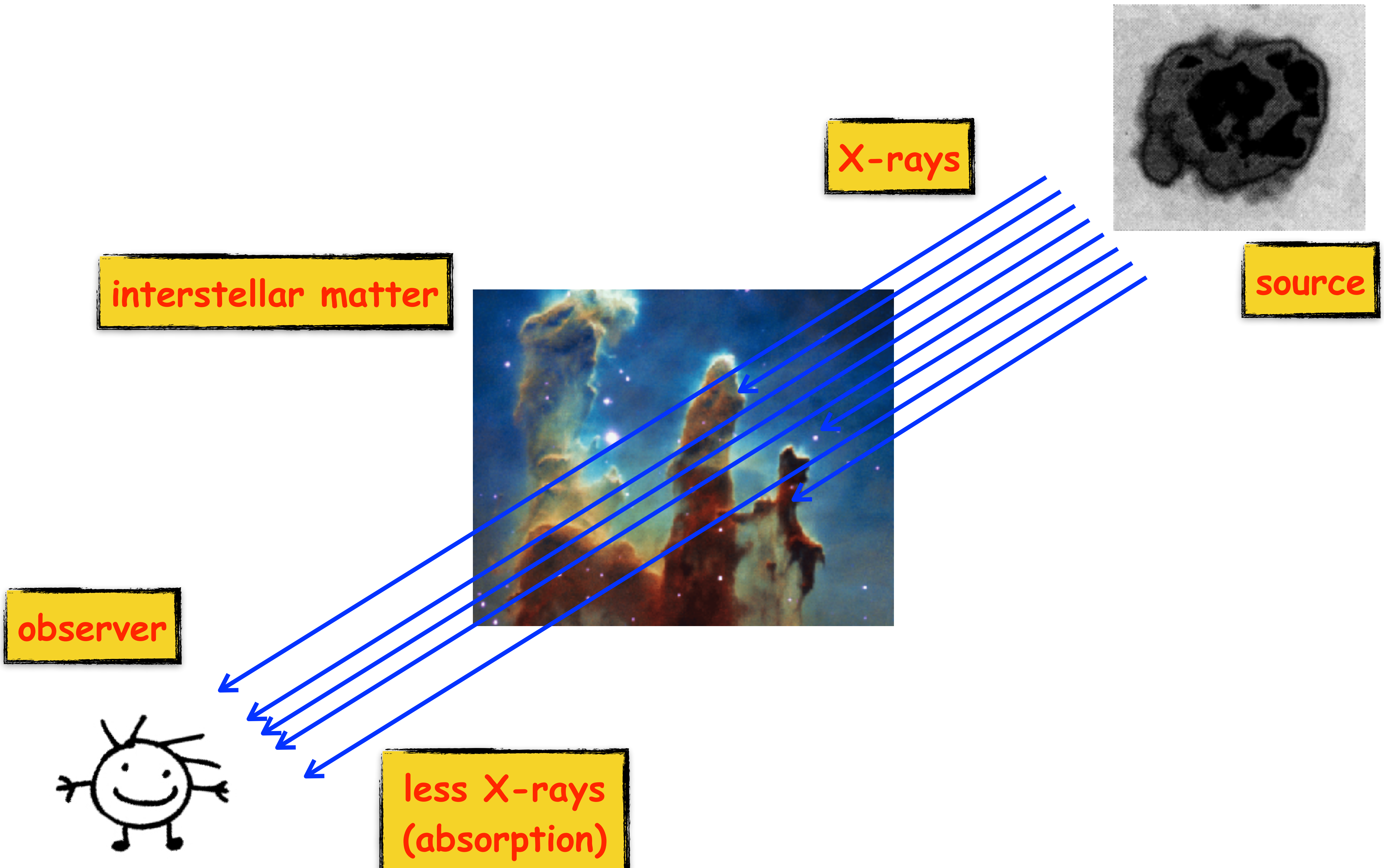
X-rays



source

observer

# How far is RX J1713.7-3946 ?



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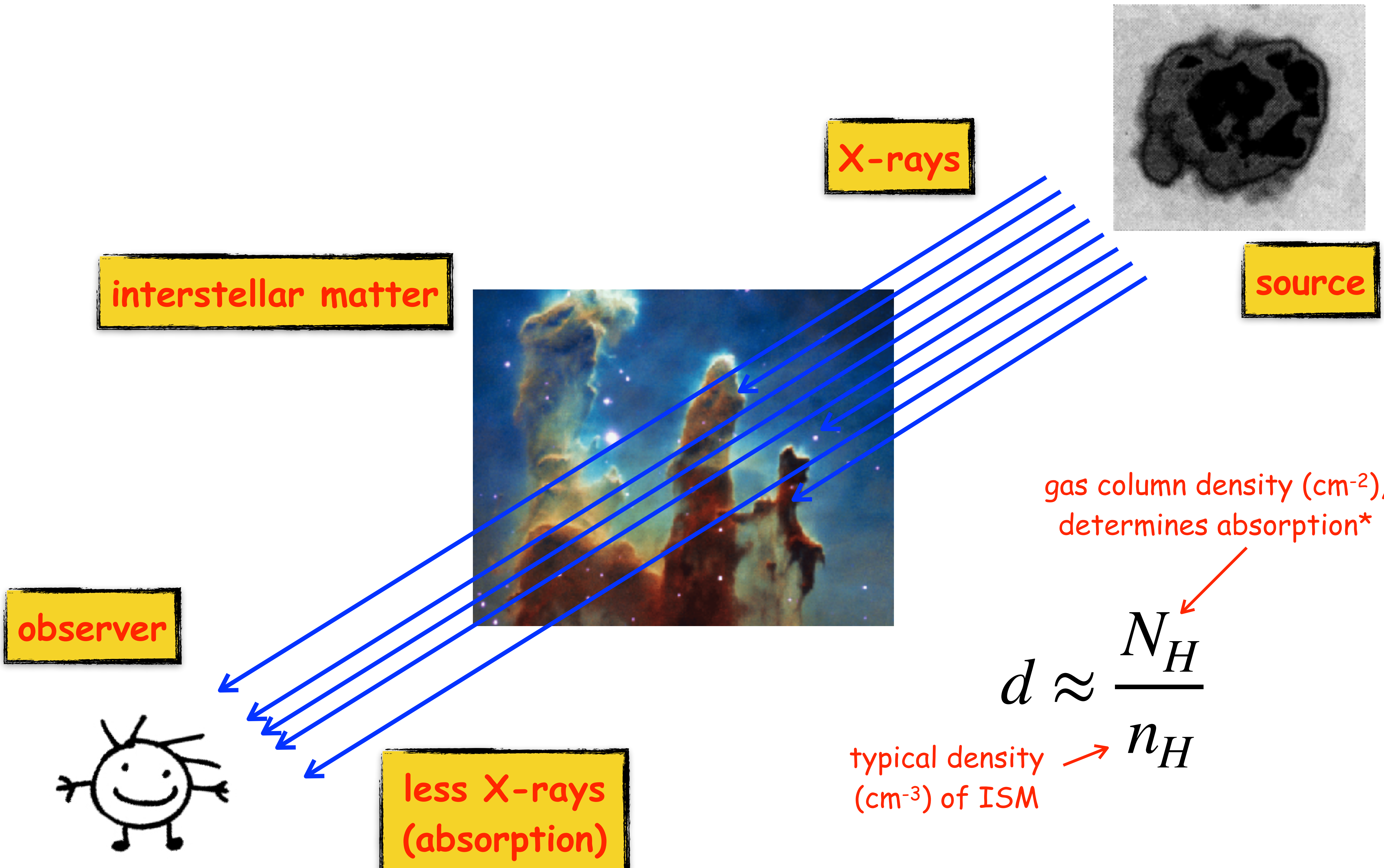



gas column density ($cm^{-2}$), determines absorption*

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

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

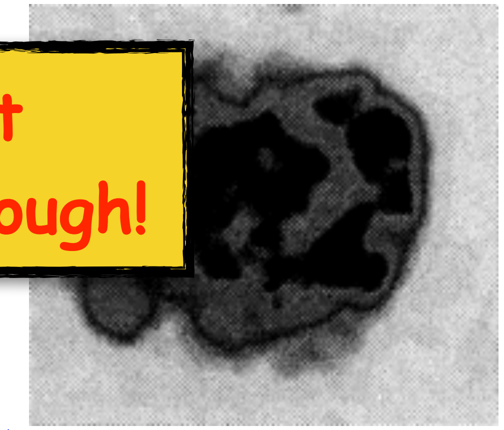
* also internal absorption should be taken into account…

# How far is RX J1713.7-3946 ?

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

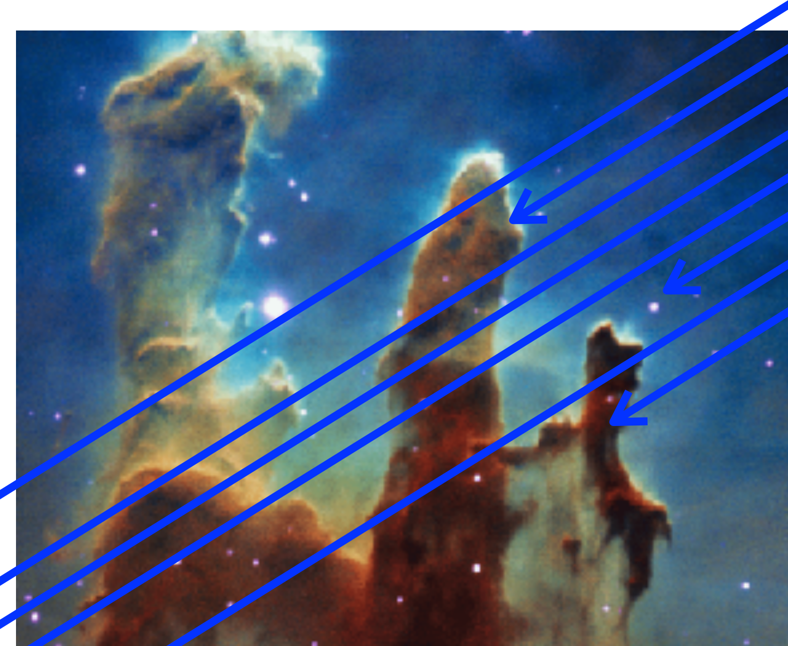
extremely rough, but measuring distances is tough!

X-rays



source

interstellar matter



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

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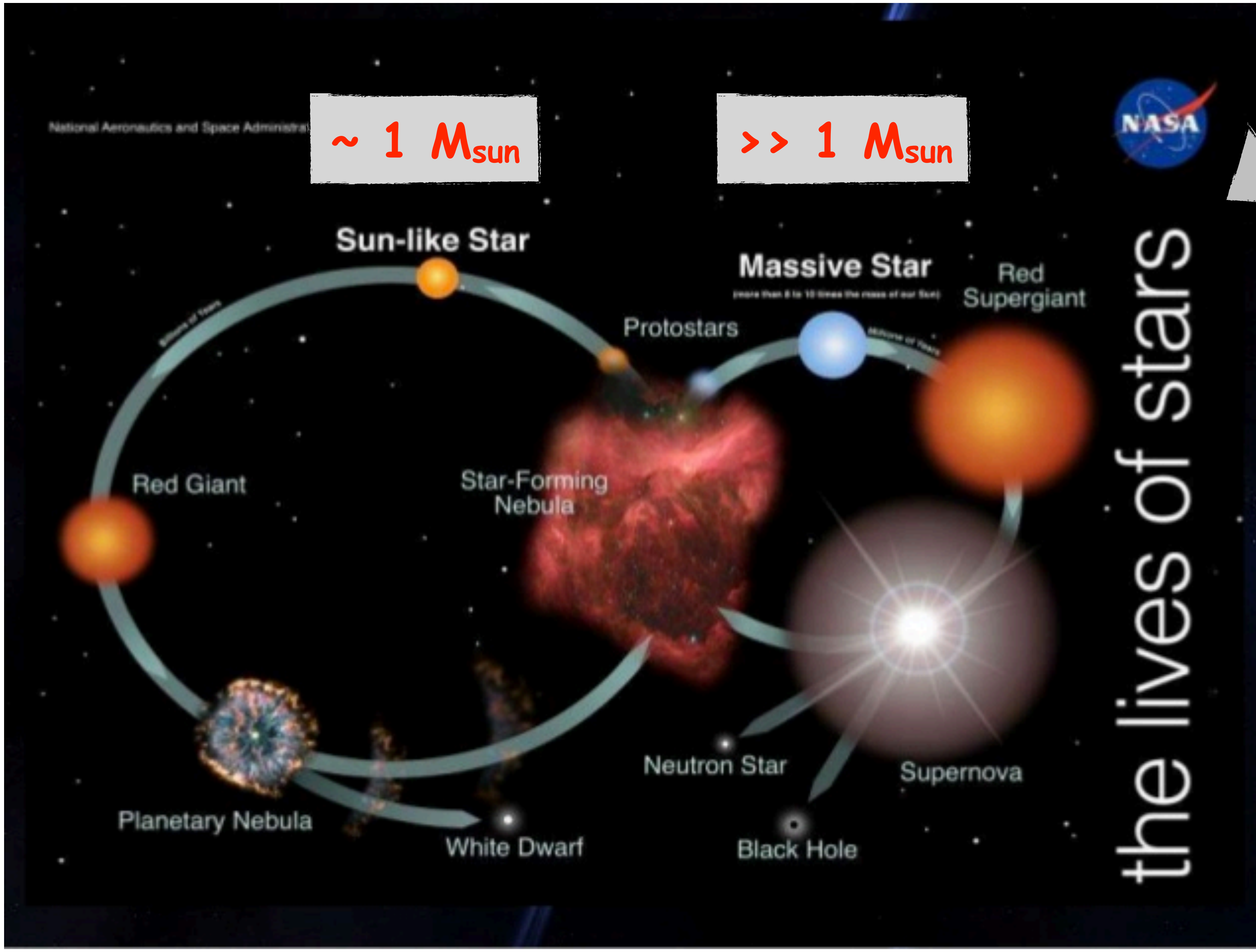
[Question 2] How old is the object we want to study?

# [Inset 1] The life of a supernova remnant

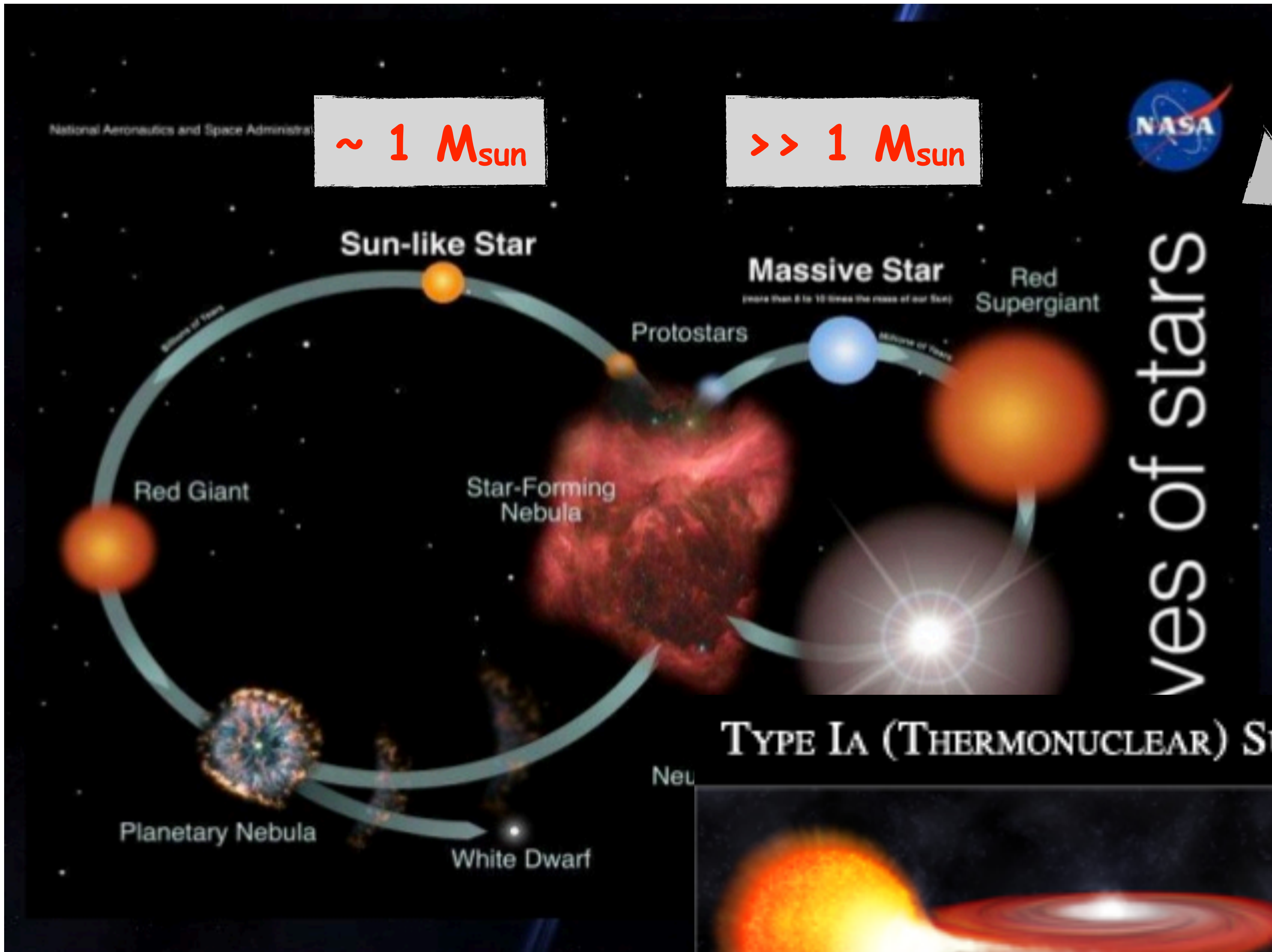
# Thermonuclear & core-collapse supernovae




core-collapse

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

# Thermonuclear & core-collapse supernovae

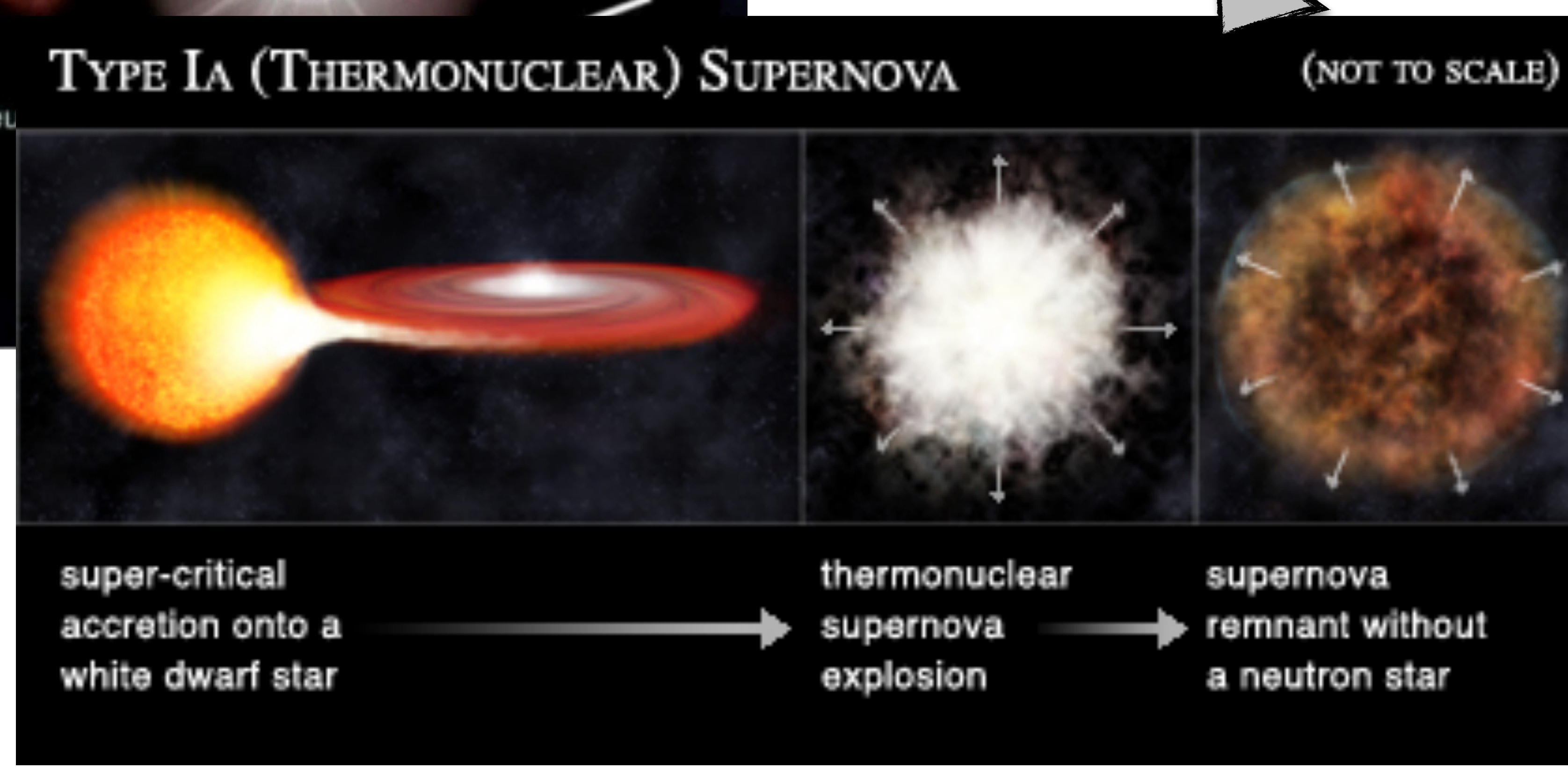



core-collapse

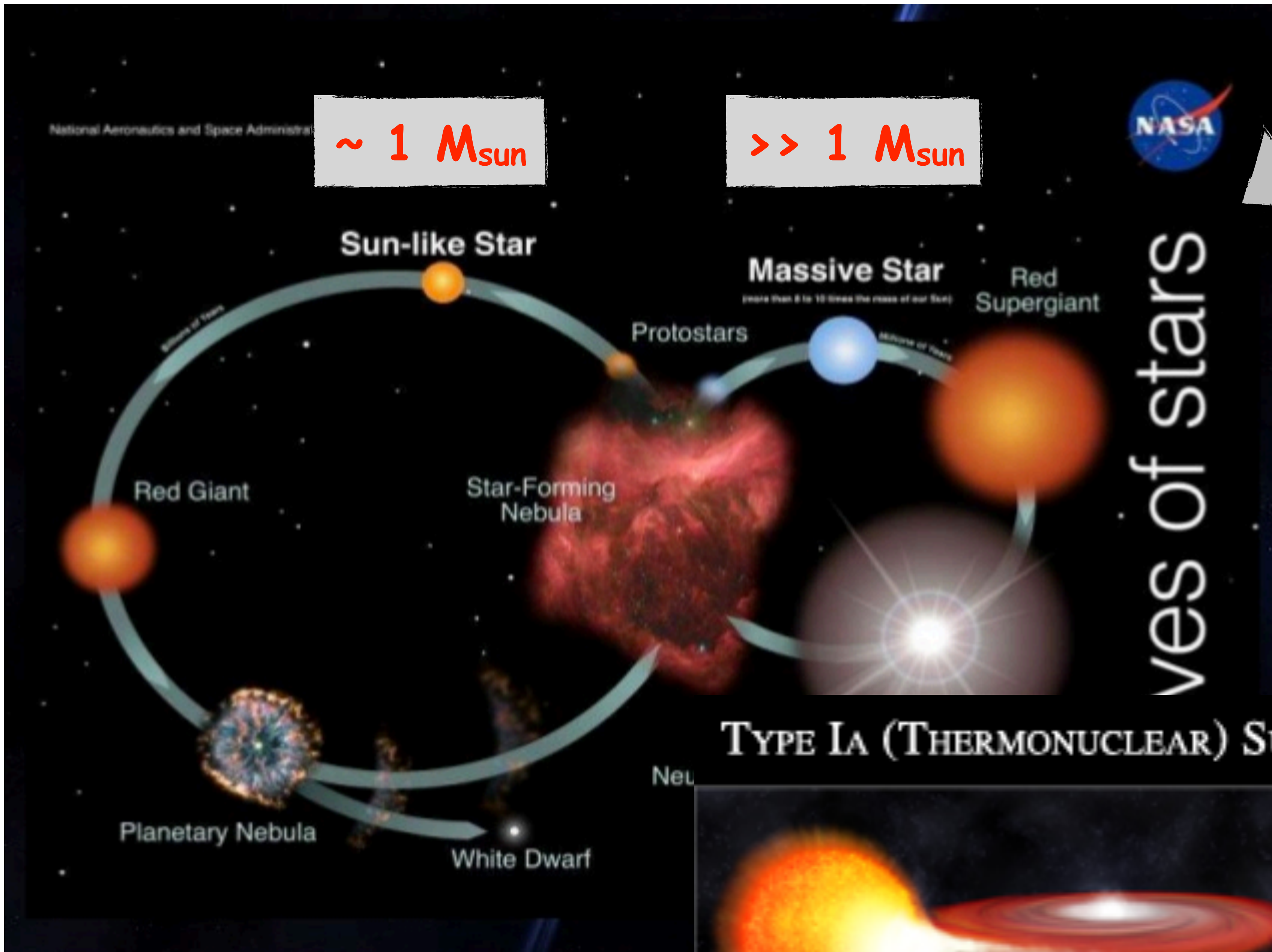
$$M_{ej} \sim \text{several } M_\odot$$

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

thermonuclear



# Thermonuclear & core-collapse supernovae

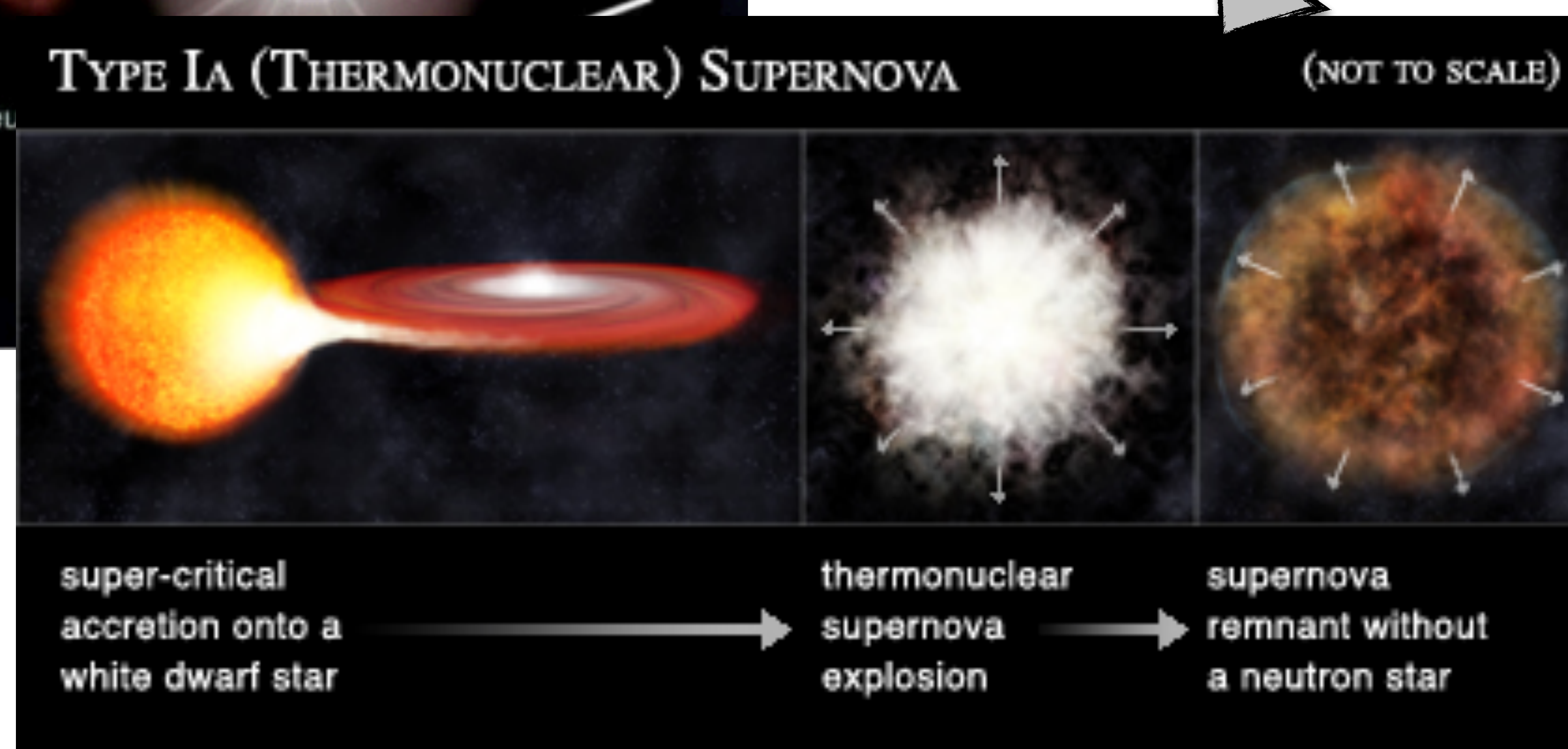



core-collapse

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

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

thermonuclear




explosion energy

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

# Astrophysical explosions

interstellar medium

pressure

$P$

density

$\varrho$

massive star

# Astrophysical explosions

interstellar medium

mass of the ejecta $M_{ej}$

explosion energy $E_{SN}$

$P$ $\varrho$


supernova

# Astrophysical explosions

interstellar medium

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

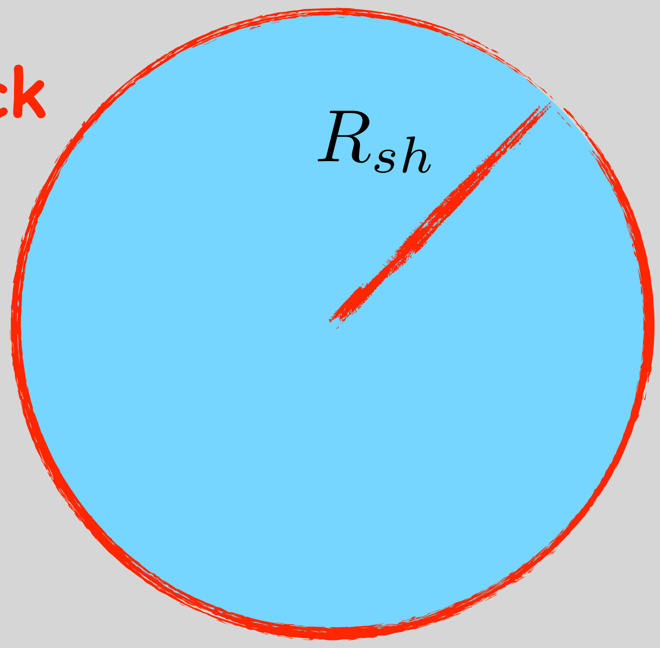
# Astrophysical explosions

interstellar medium

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

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

shock



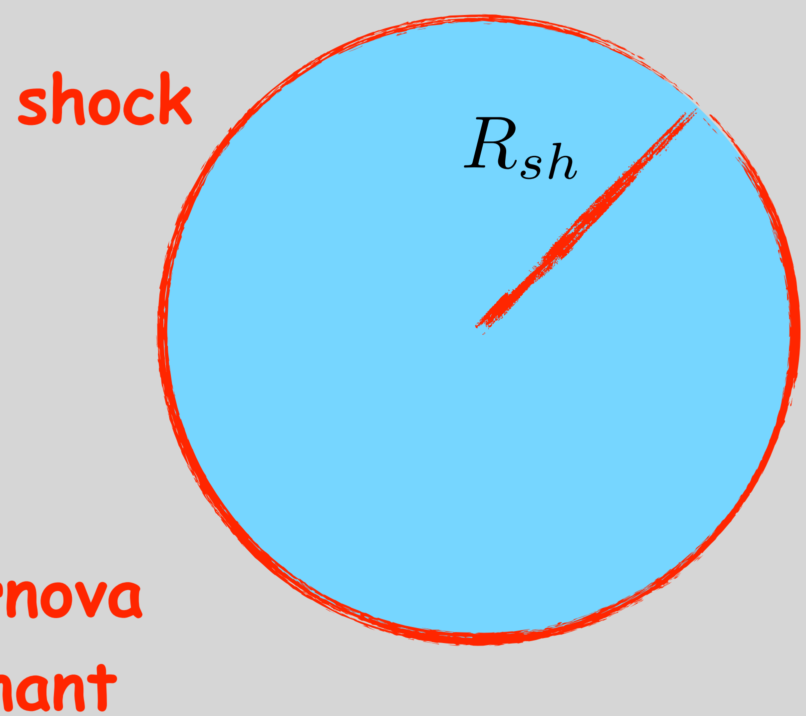

supernova remnant

# Astrophysical explosions

interstellar medium

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

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



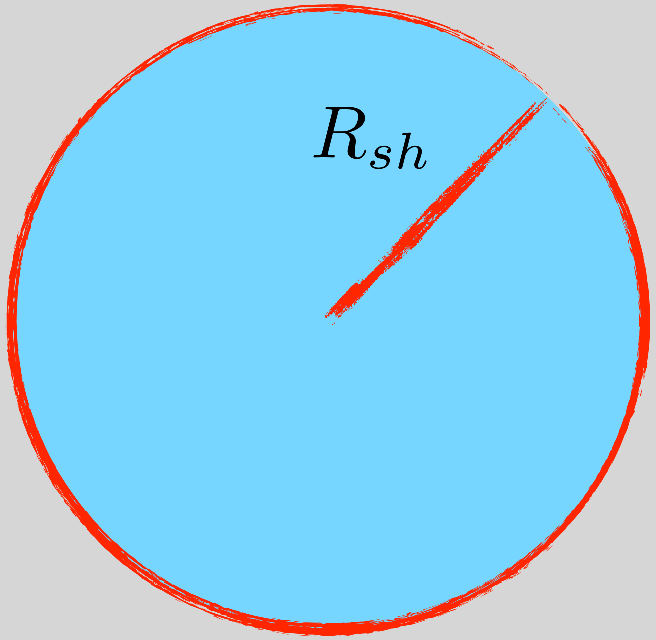
# Astrophysical explosions

interstellar medium

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

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

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



# Astrophysical explosions

interstellar medium

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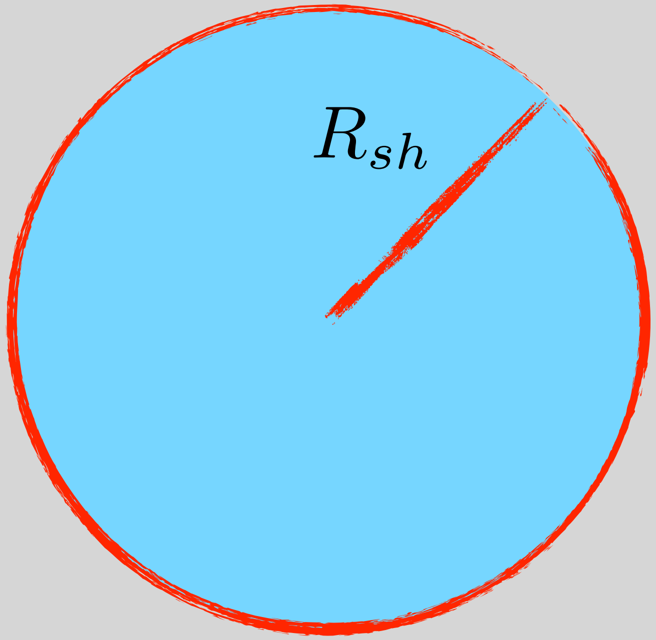

# Astrophysical explosions

interstellar medium

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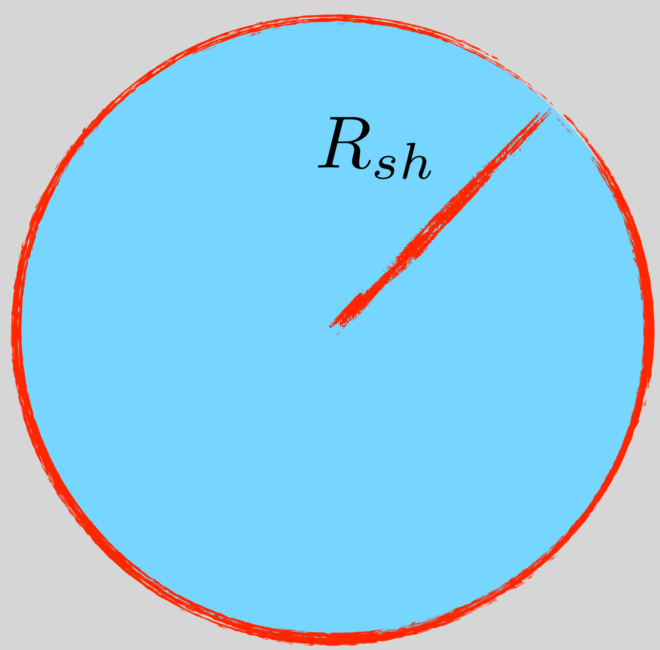


free expansion
(constant speed)

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

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

# Astrophysical explosions

interstellar medium

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

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

free expansion (constant speed)

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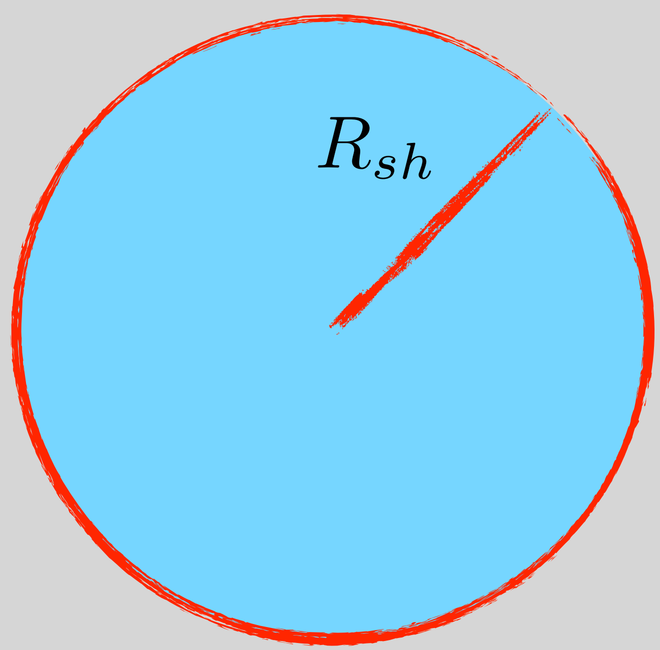


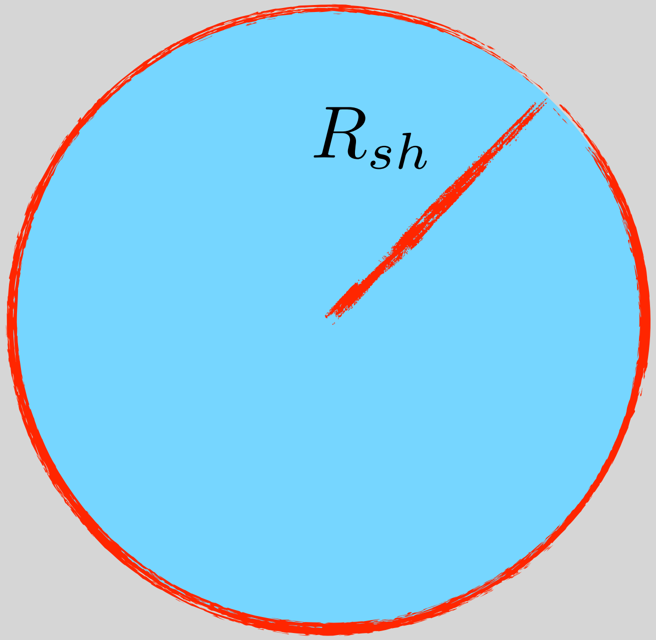

$$E_{SN} = \frac{1}{2} M_{ej} v_{sh}^2 \longrightarrow v_{sh} = \sqrt{\frac{2E_{SN}}{M_{ej}}} \sim 10000 \left( \frac{M_{ej}}{M_\odot} \right)^{-1/2} \mathrm{km/s}$$

# Astrophysical explosions

**interstellar medium**

$$\boxed{M_{ej} = M_{sw}}$$

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

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# Astrophysical explosions

interstellar medium

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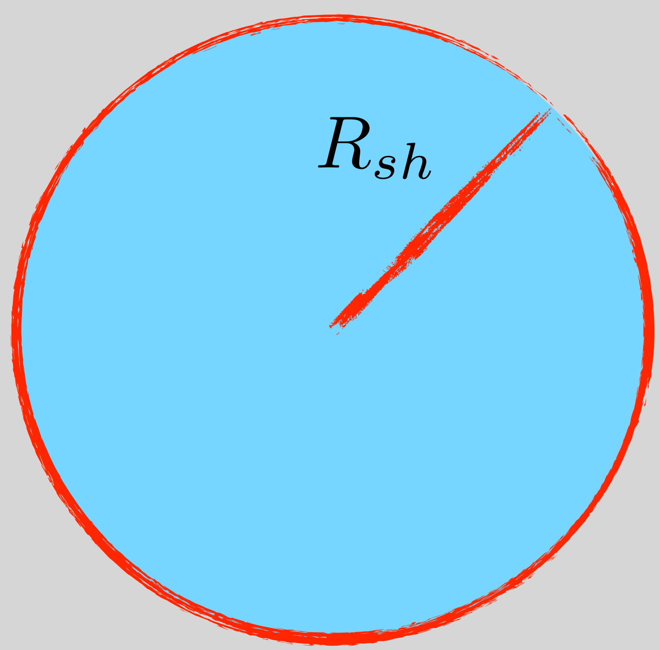



$$R_* = \left(\frac{3M_{ej}}{4\pi\varrho}\right)^{1/3} \sim 2\left(\frac{M_{ej}}{M_\odot}\right)^{1/3}\left(\frac{n}{\mathrm{cm}^{-3}}\right)^{-1/3} \mathrm{pc}$$

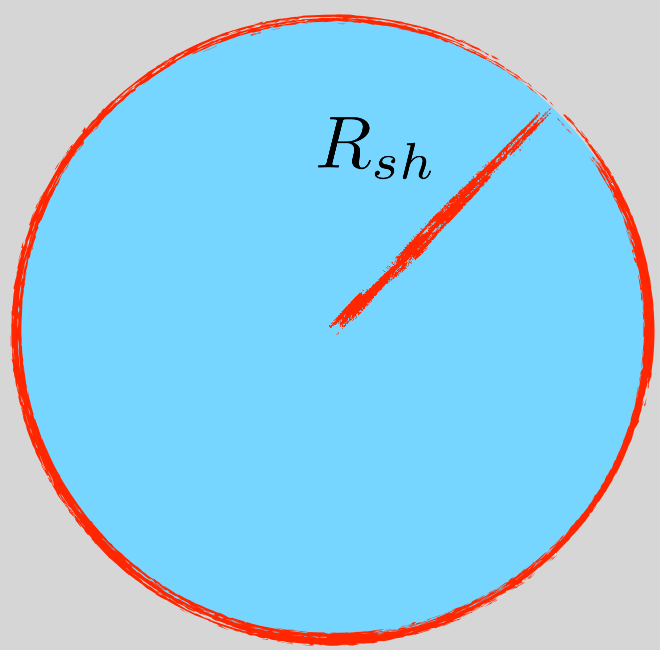
# Astrophysical explosions

interstellar medium

$$\boxed{M_{ej} = M_{sw}}$$

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

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




it takes few centuries
to reach this moment

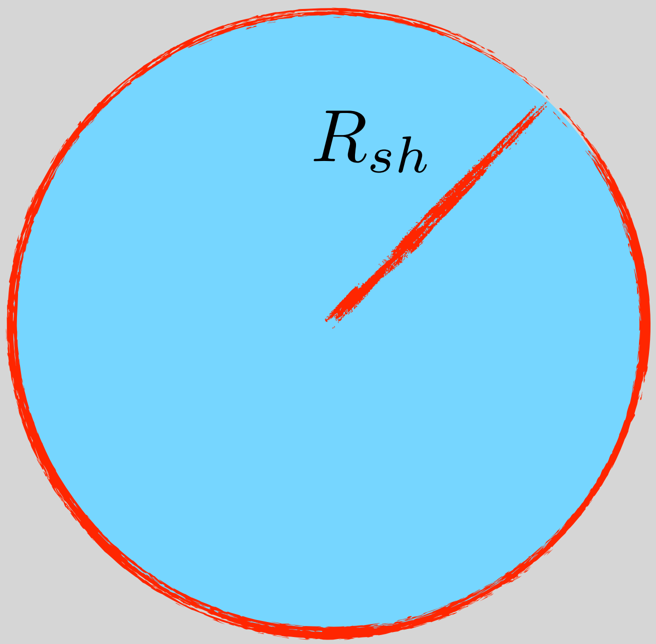
$$R_* = \left( \frac{3M_{ej}}{4\pi\varrho} \right)^{1/3} \sim 2 \left( \frac{M_{ej}}{M_\odot} \right)^{1/3} \left( \frac{n}{\mathrm{cm}^{-3}} \right)^{-1/3} \mathrm{pc}$$

# Astrophysical explosions

interstellar medium

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

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

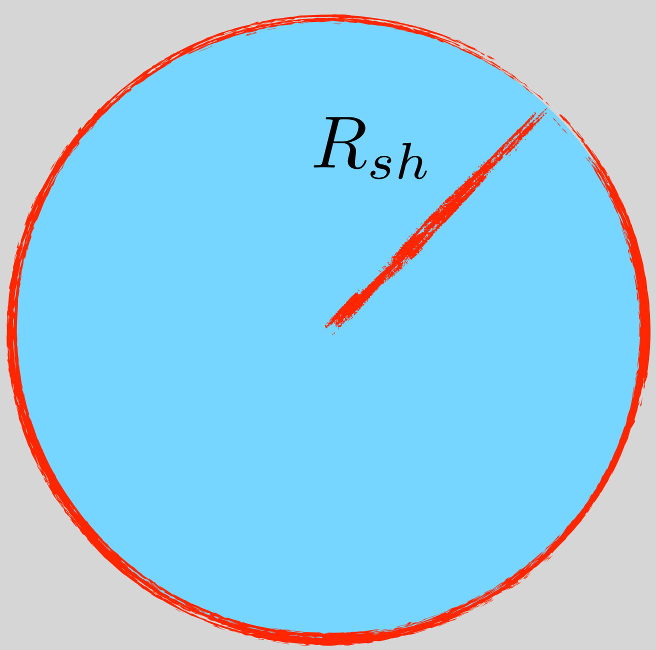


# Astrophysical explosions

interstellar medium

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

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




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

# Astrophysical explosions

interstellar medium

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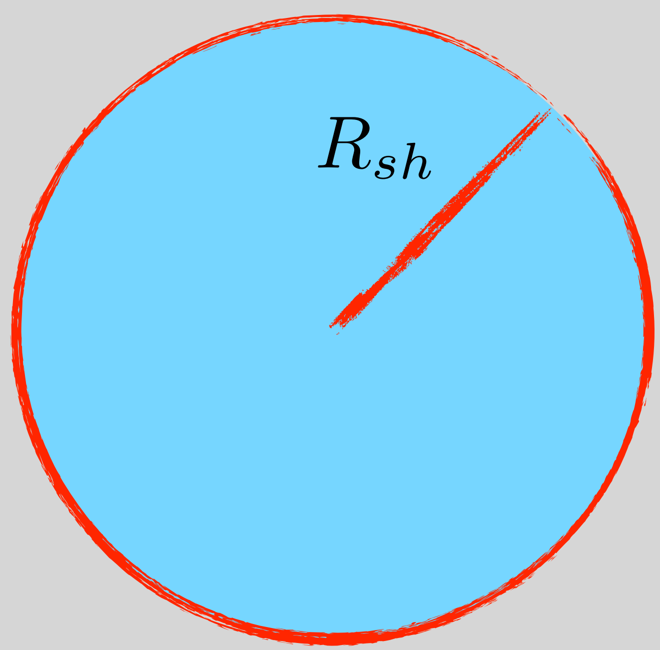
$\cancel{M_{ej}}$ $E_{SN}$ $P$ $\varrho$

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# Astrophysical explosions

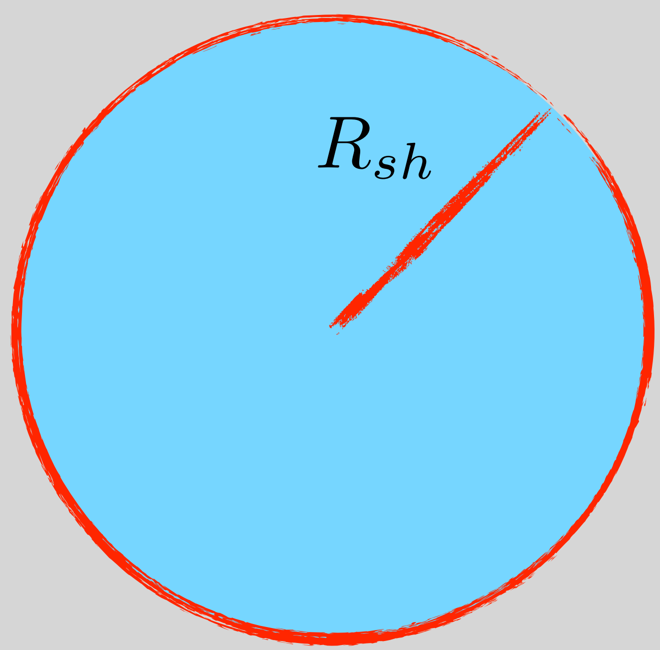
interstellar medium

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

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

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

strong shock

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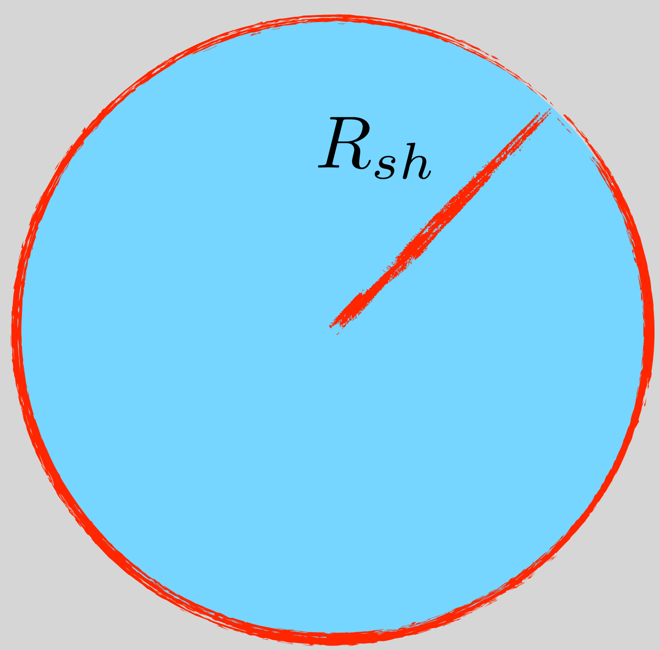


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# Astrophysical explosions

interstellar medium

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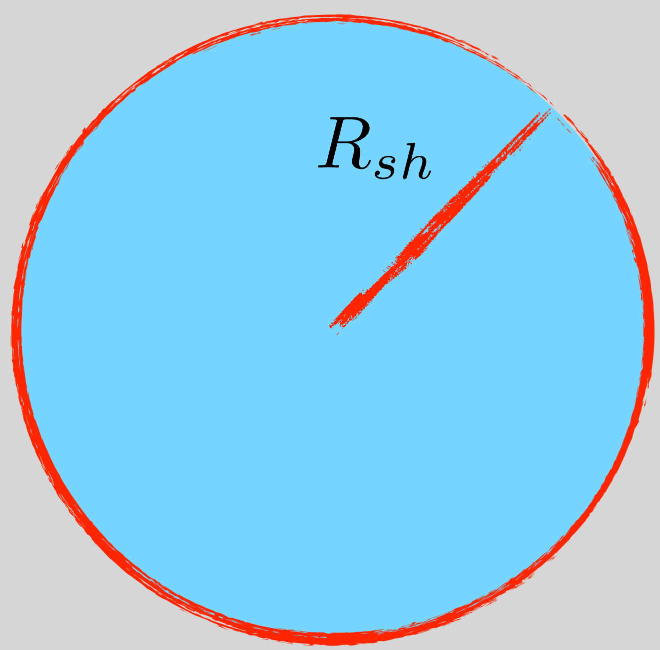


the shock begins to feel the presence of the ambient gas and decelerates

strong shock

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

# Astrophysical explosions

interstellar medium

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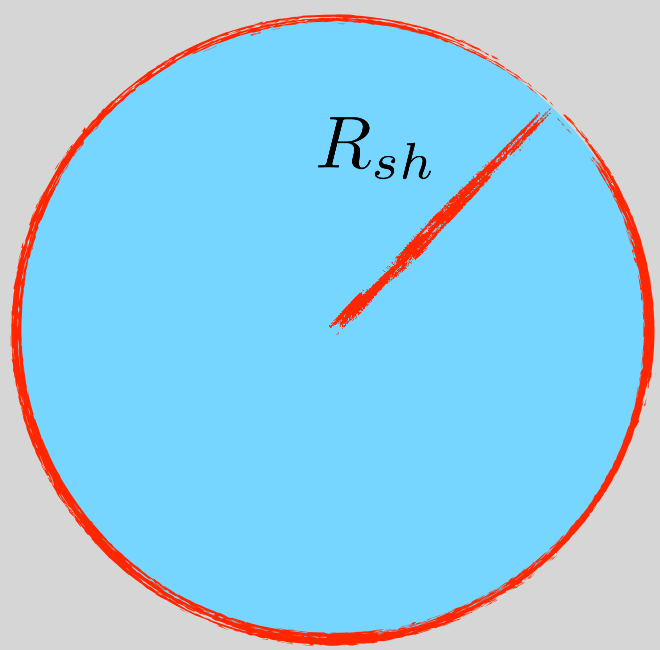
$c_s \approx 10 \text{ km/s}$

**strong shock**




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

order unity

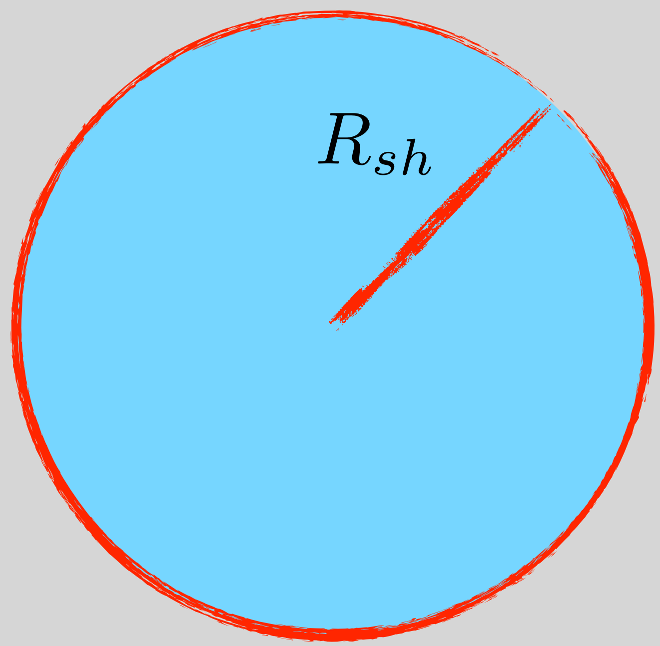
non-dimensional quantity: $a = \dfrac{\varrho\, R_{sh}^5}{E_{SN}\, t^2} \longrightarrow R_{sh} = a \left(\dfrac{E_{SN}}{\varrho}\right)^{1/5} t^{2/5}$

# Astrophysical explosions

interstellar medium

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

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




**Sedov-Taylor solution**

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

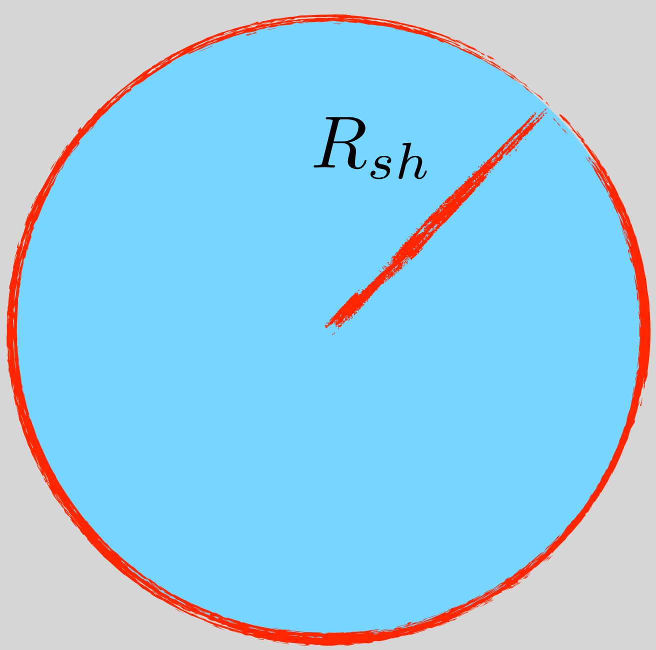
$$u_{sh} = \frac{2}{5} \frac{R_{sh}}{t} \propto t^{-3/5}$$

# Astrophysical explosions

interstellar medium

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

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




Sedov-Taylor solution

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

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

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

# SNR shocks in one slide


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

early times —> $\boxed{M_{ej} \gg M_{sw}}$ mass of the ISM swept up by the shock

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

late times —> $\boxed{M_{ej} \ll M_{sw}}$

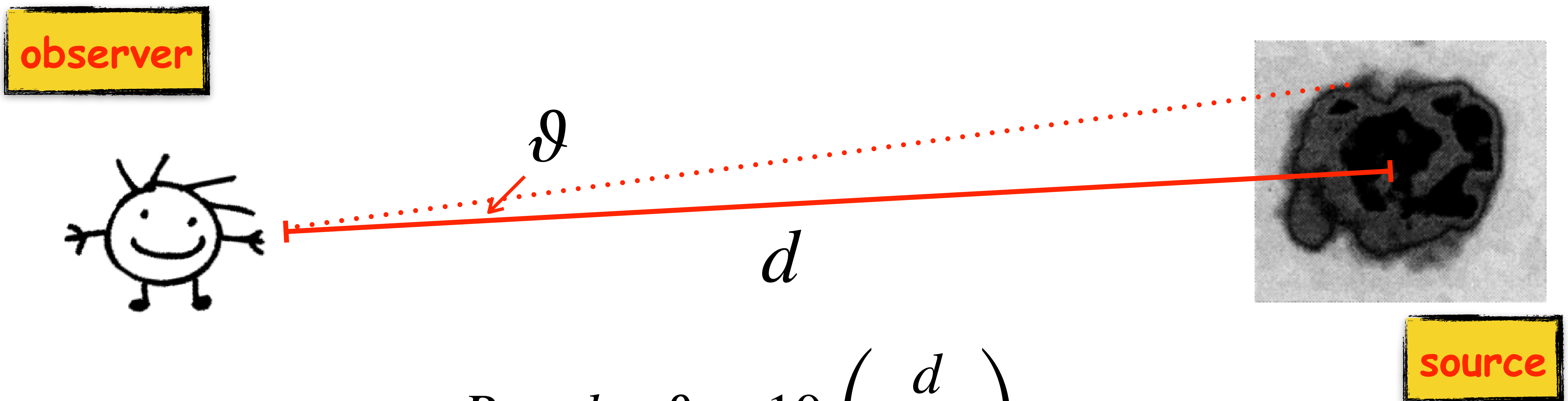
solution must depend on ρ (ISM density) and not $M_{ej}$!

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

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

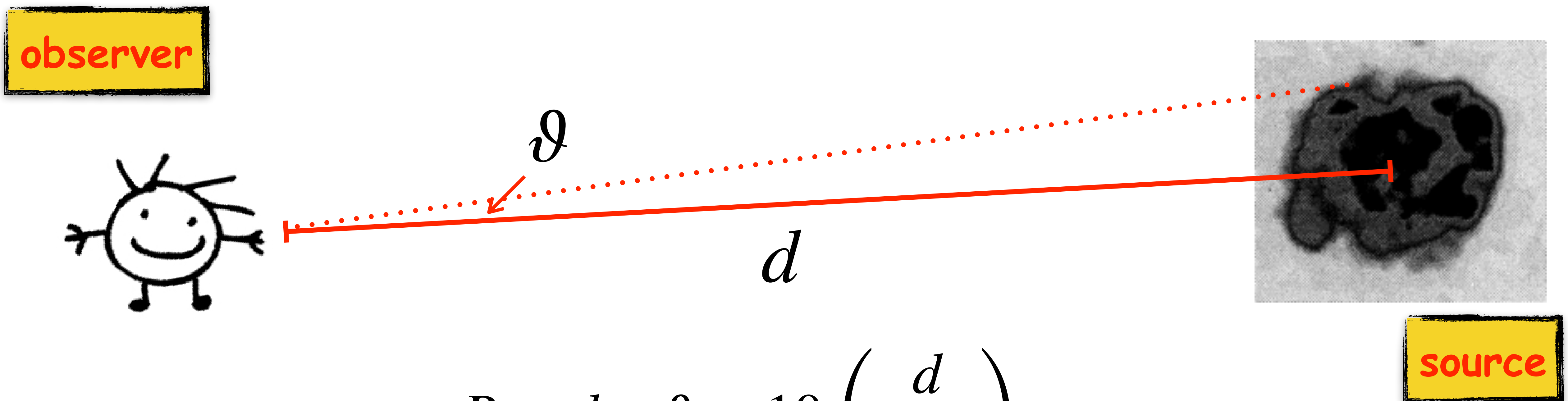
[End of Inset 1]

# How old is RX J1713.7-3946 ?




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

# How old is RX J1713.7-3946 ?




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

$$R \sim \left( \frac{E_{SN}}{\varrho} \right)^{1/5} t^{2/5} \longrightarrow t \sim \left( \frac{\varrho}{E_{SN}} \right)^{1/2} R^{5/2} \propto d^{5/2}$$

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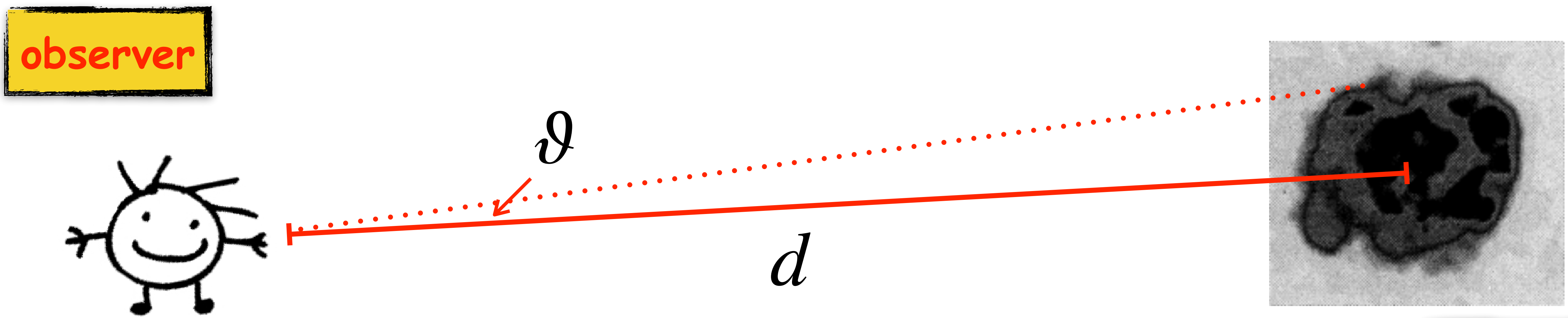


$$R \sim d \times \vartheta \sim 10 \left( \frac{d}{\mathrm{kpc}} \right) \ \mathrm{pc}$$

uncertainty on d is catastrophic!

$$R \sim \left( \frac{E_{SN}}{\varrho} \right)^{1/5} t^{2/5} \longrightarrow t \sim \left( \frac{\varrho}{E_{SN}} \right)^{1/2} R^{5/2} \propto d^{5/2}$$

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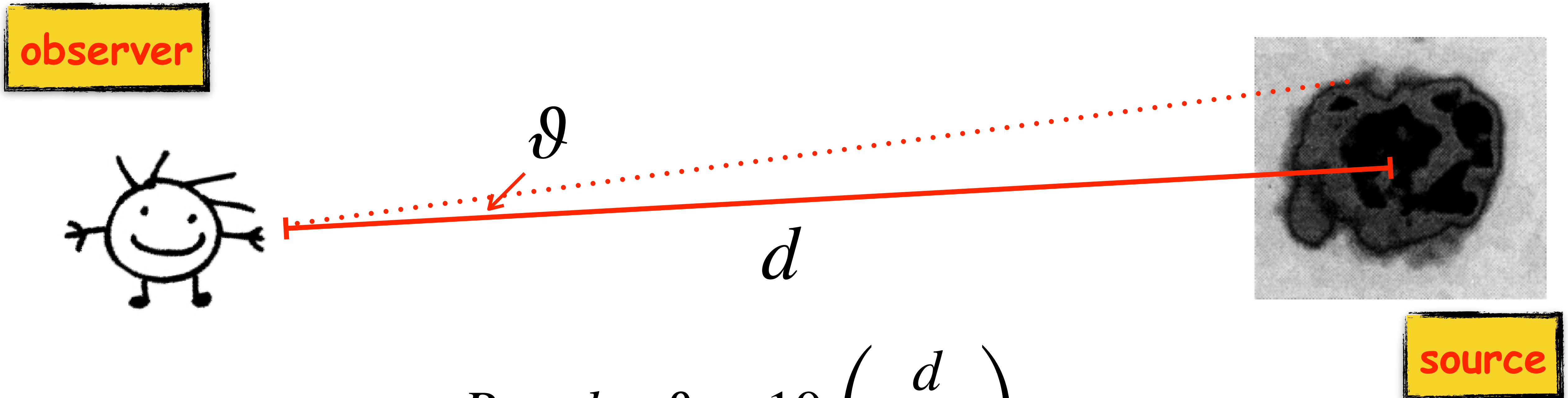


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$t \sim 2 \ \mathrm{kyr} \rightarrow d \sim 1 \ \mathrm{kpc}$ —> early Sedov phase

$t \sim 10^4 \ \mathrm{yr} \rightarrow d \sim 2 \ \mathrm{kpc}$ —> late Sedov phase

# Multiwavelenght

# ~~Multi-wavelenght~~

~~Multiwavelenght~~

Multimessenger

~~Multiwavelenght~~

~~Multimessenger~~

~~Multiwavelenght~~

~~Multimessenger~~

Multi-alphabet astronomy

~~Mult elenght~~

~~Multin enger~~

# Multi-alphabet astronomy


之幷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
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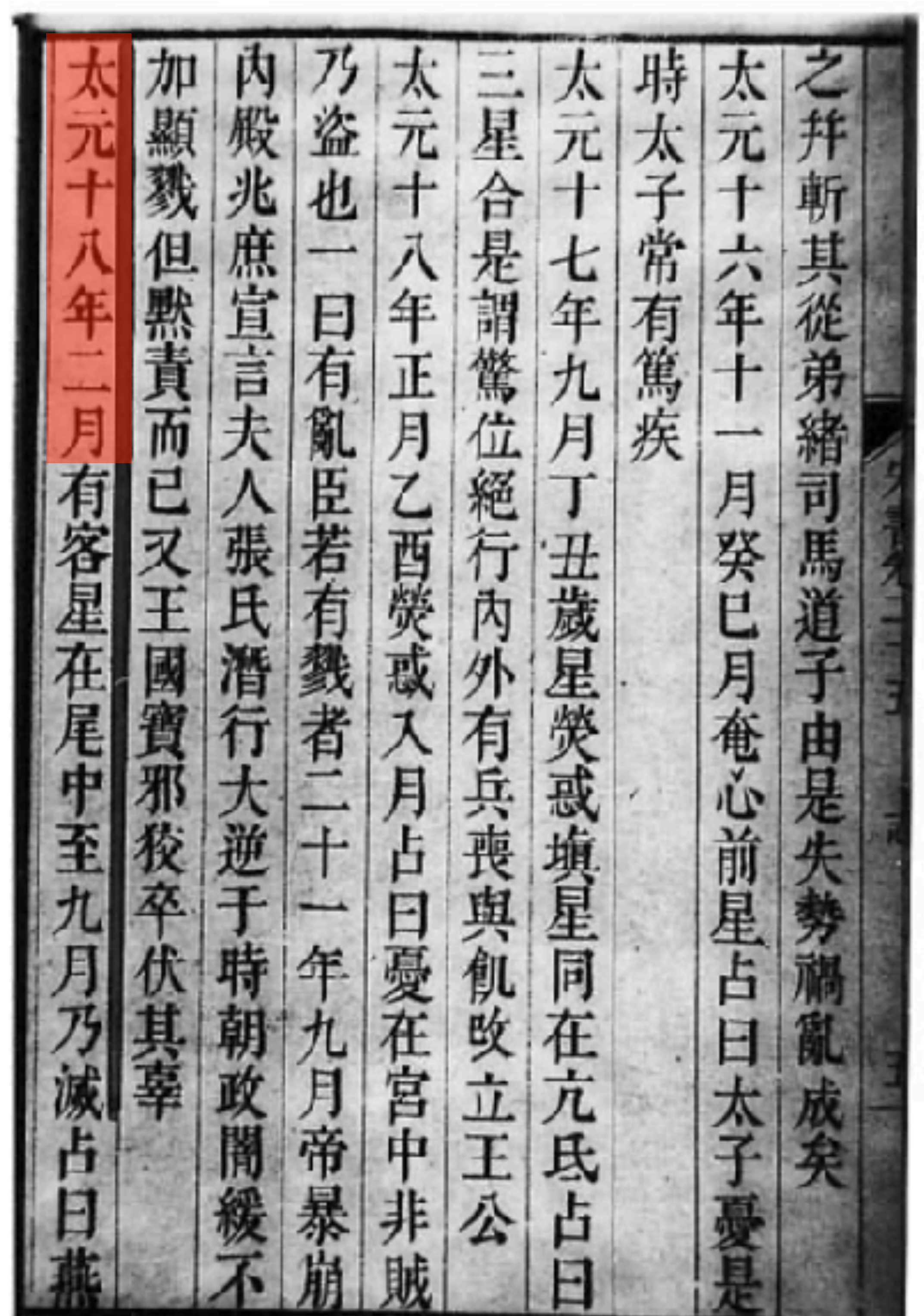
Wang+ 1997

~~Multi-wavelenght~~

# Multi-alphabet astronomy

~~Multimessenger~~

“Tài yuán shíbā nián èr yuè”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Wang+ 1997

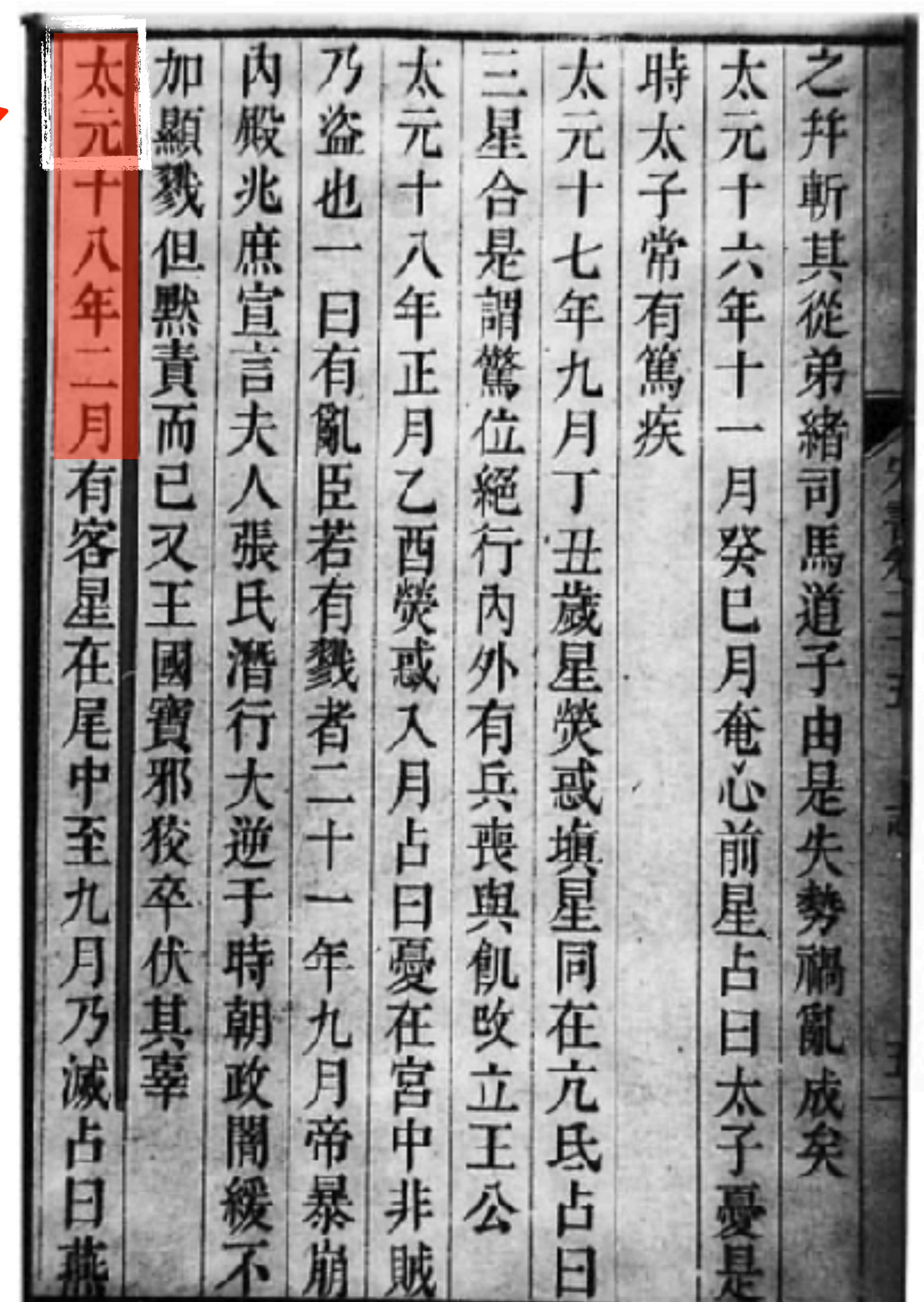
~~Mult elenght~~

~~Multin enger~~

# Multi-alphabet astronomy

"Tài yuán shíbā nián èr yuè"

Tai Yuan reign period



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Wang+ 1997

# ~~Mult elenght~~

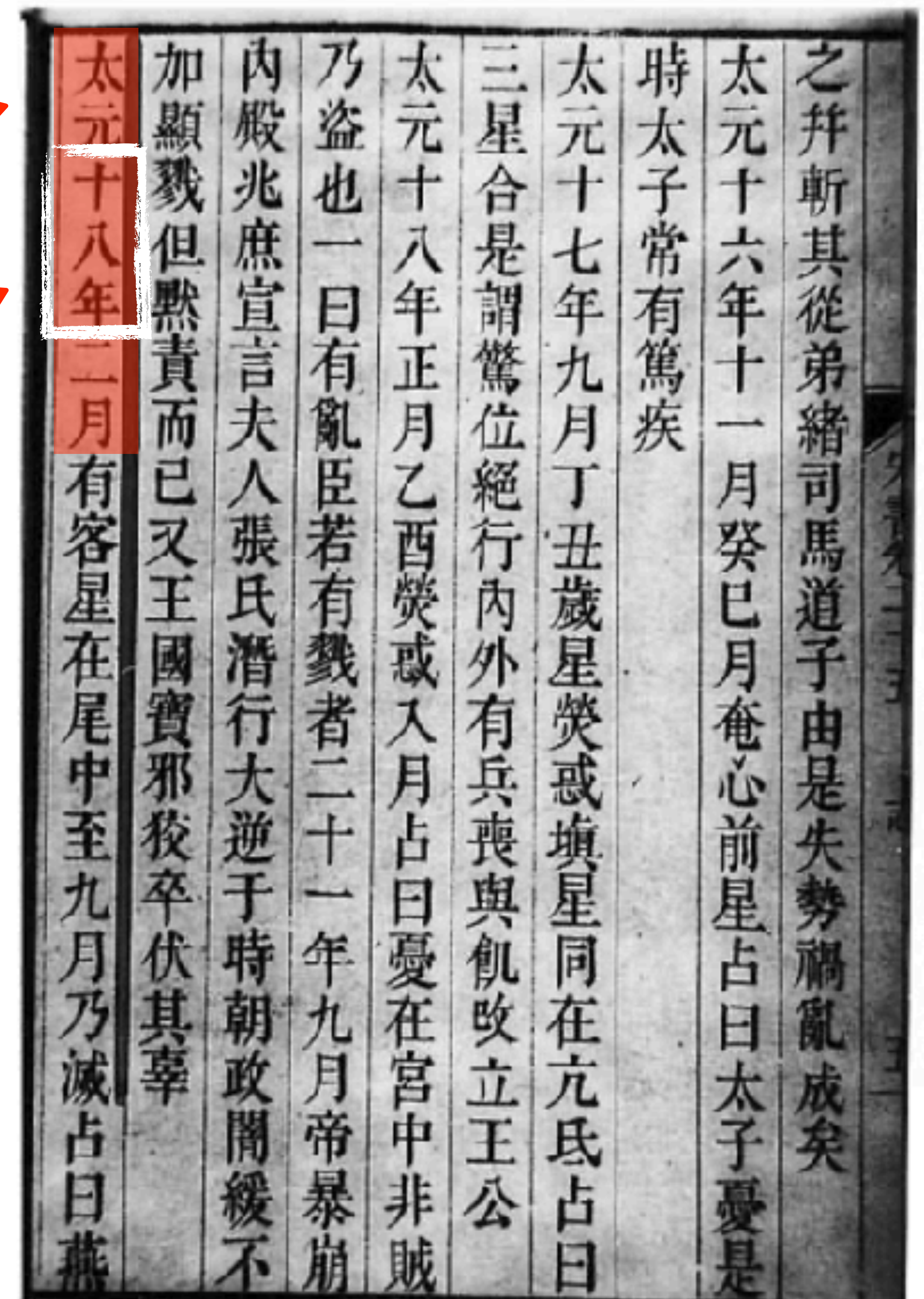
# Multi-alphabet astronomy

# ~~Multin enger~~

"Tài yuán shíbā nián èr yuè"

Tai Yuan reign period

18th year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Wang+ 1997

# ~~Multi-wavelenght~~

# Multi-alphabet astronomy

# ~~Multi-messenger~~

“Tài yuán shíbā nián èr yuè”

Tai Yuan reign period

18th year

2nd (lunar) month


之并斬其從弟緒司馬道子由是失勢禍亂成矣
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Wang+ 1997

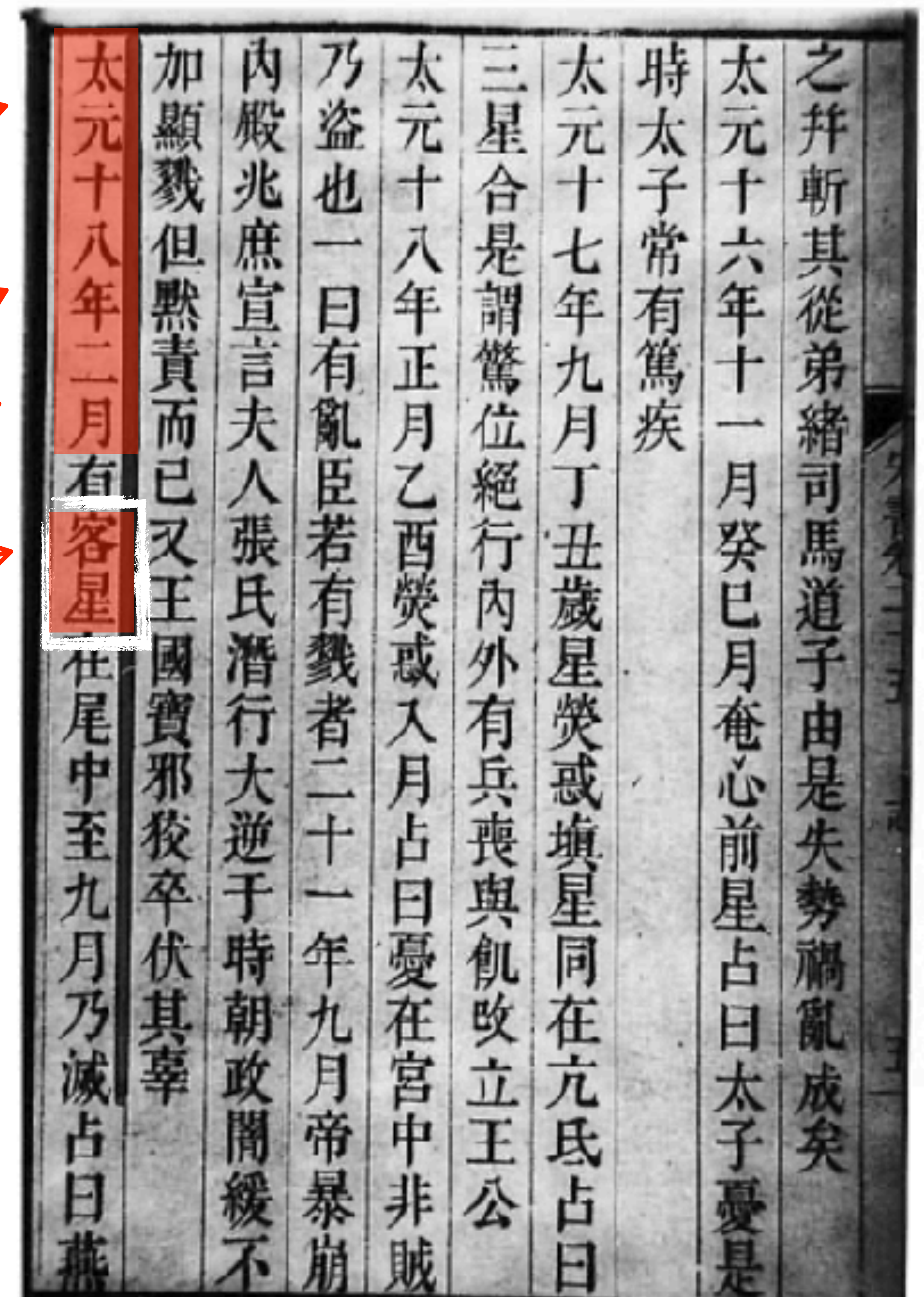
~~Multiwavelenght~~

~~Multimessenger~~

# Multi-alphabet astronomy

"Tài yuán shíbā nián èr yuè"

"Kè xīng"

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太元十八年二月有客星在尾中至九月乃滅占曰燕

Wang+ 1997

# ~~Mult elenght~~

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# Multi-alphabet astronomy

"Tài yuán shíbā nián èr yuè"

Tai Yuan reign period

18th year

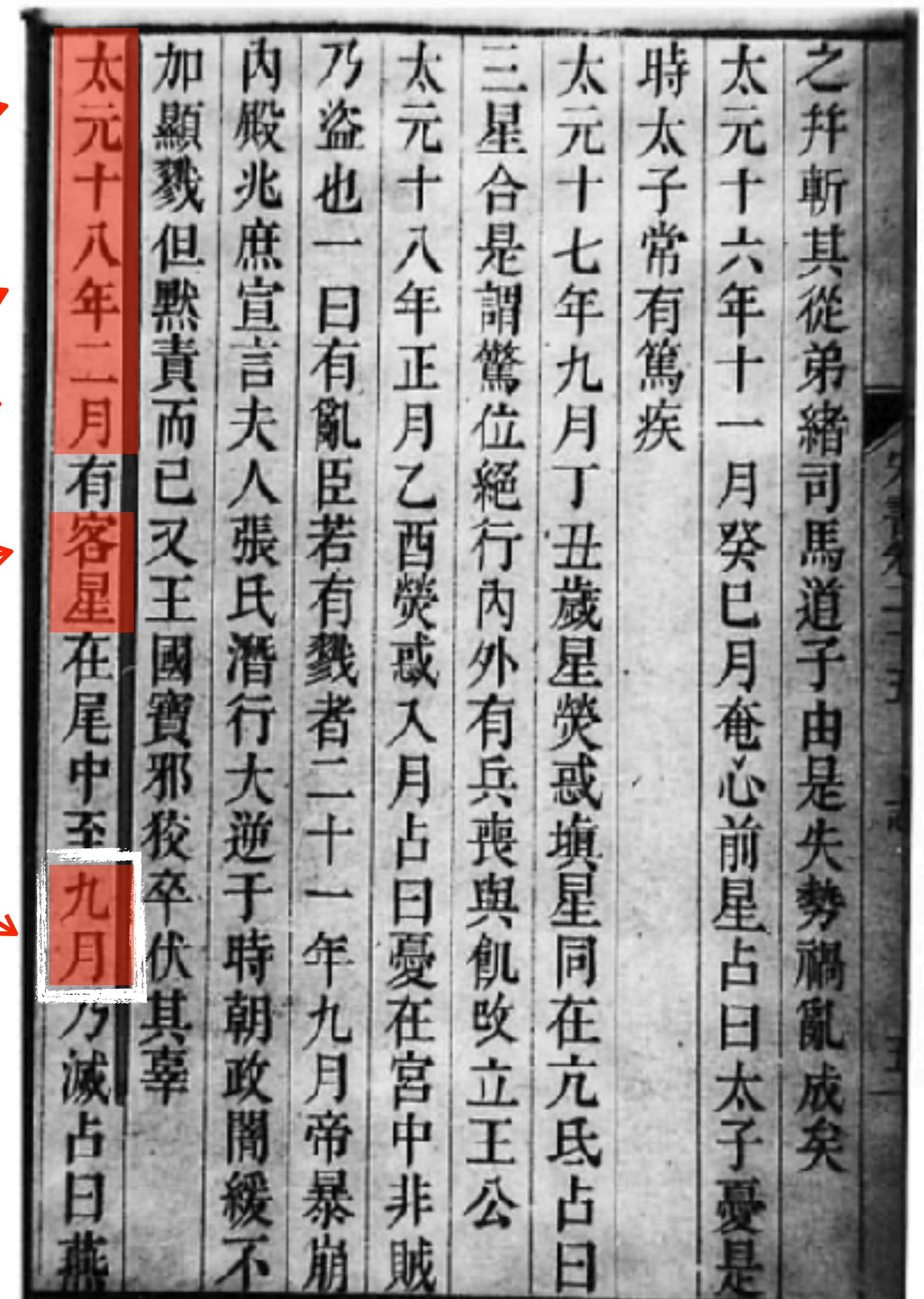
2nd (lunar) month

"Kè xīng"

guest star

"jiǔ yuè"

9th month


之幷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
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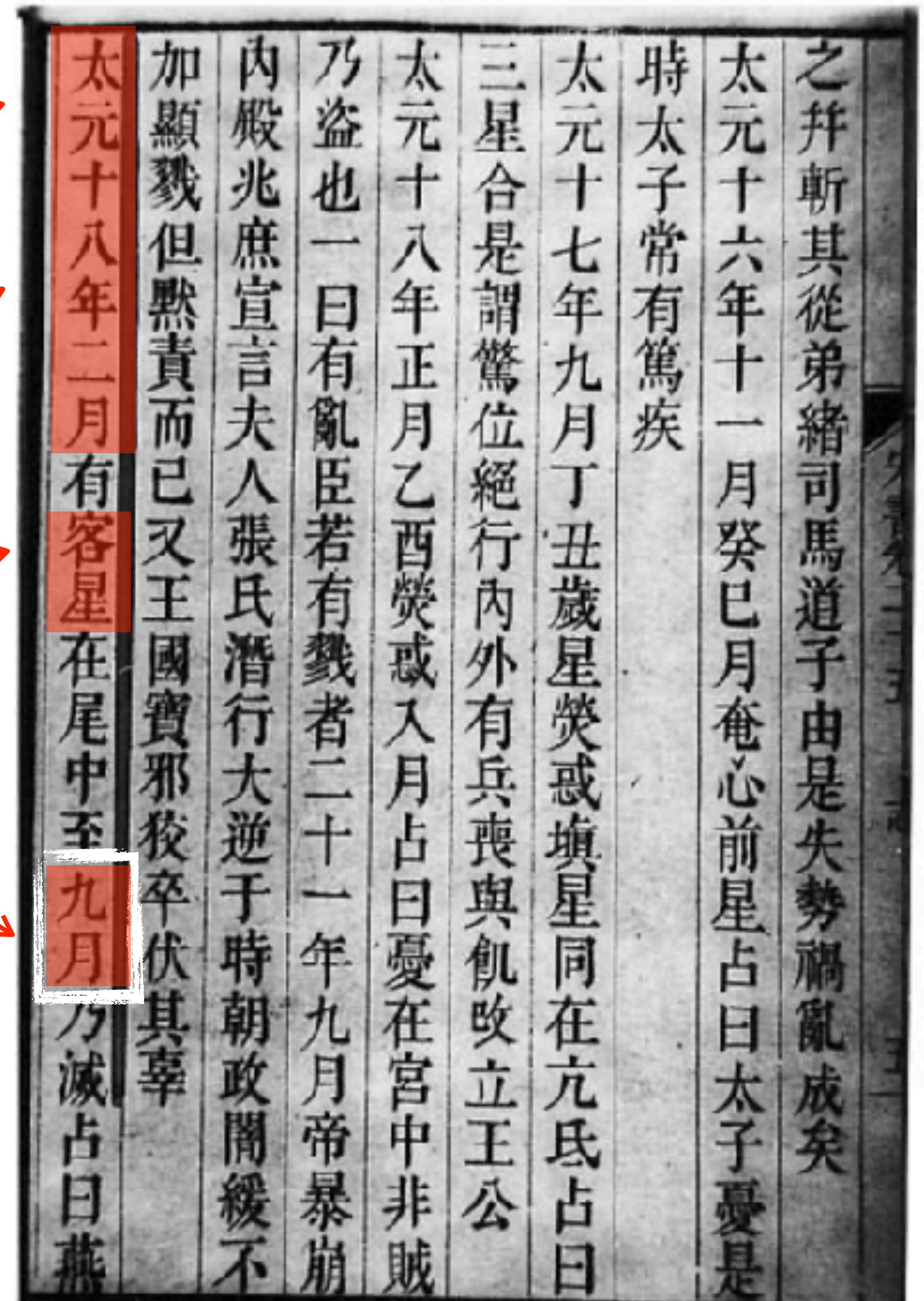

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**this corresponds to year 393, and the position in the sky also seems to match!**

Wang+ 1997

# 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 >> $10^4$ yr!

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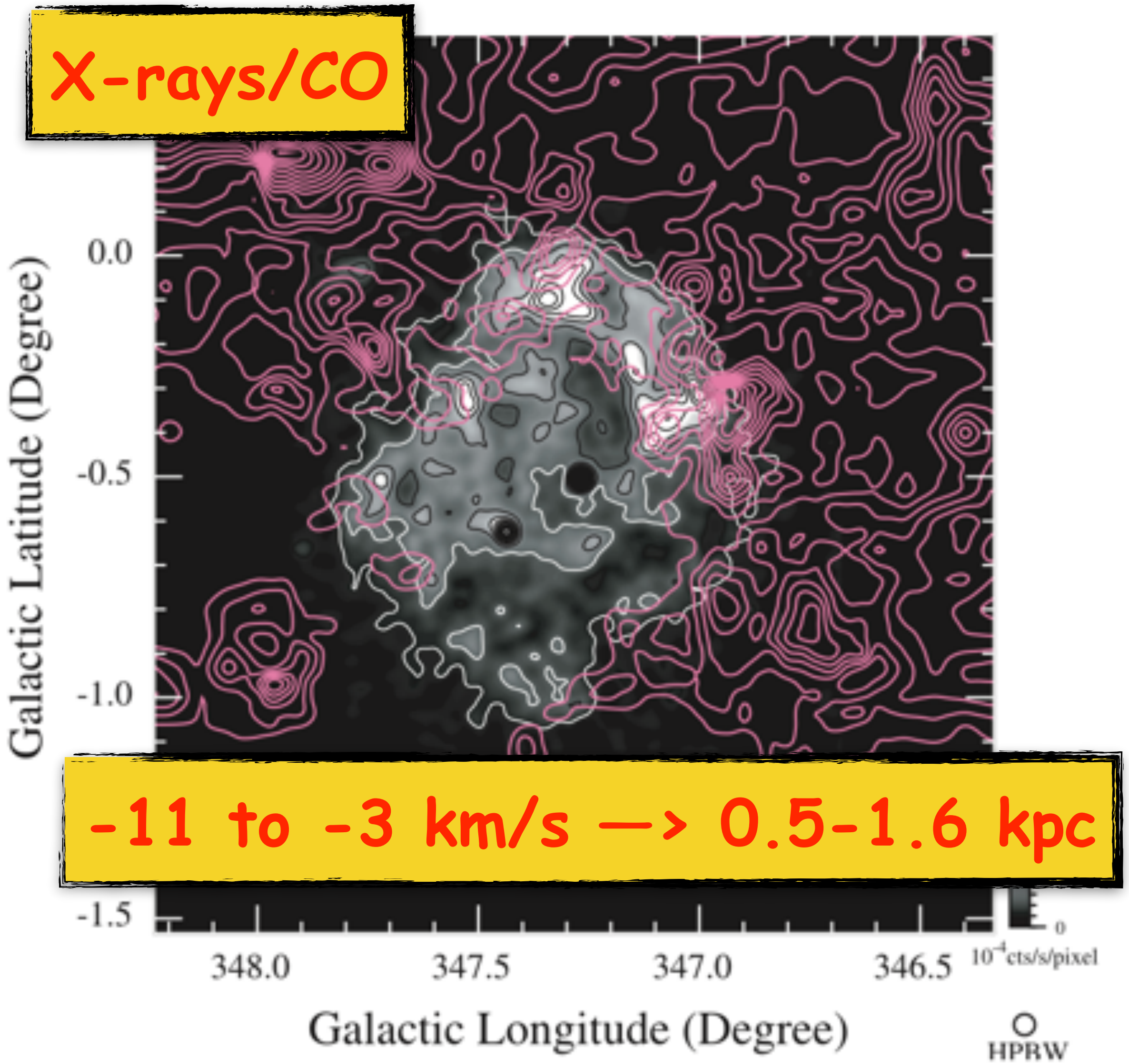


-11 to -3 km/s —> 0.5-1.6 kpc

Fukui+ 2003

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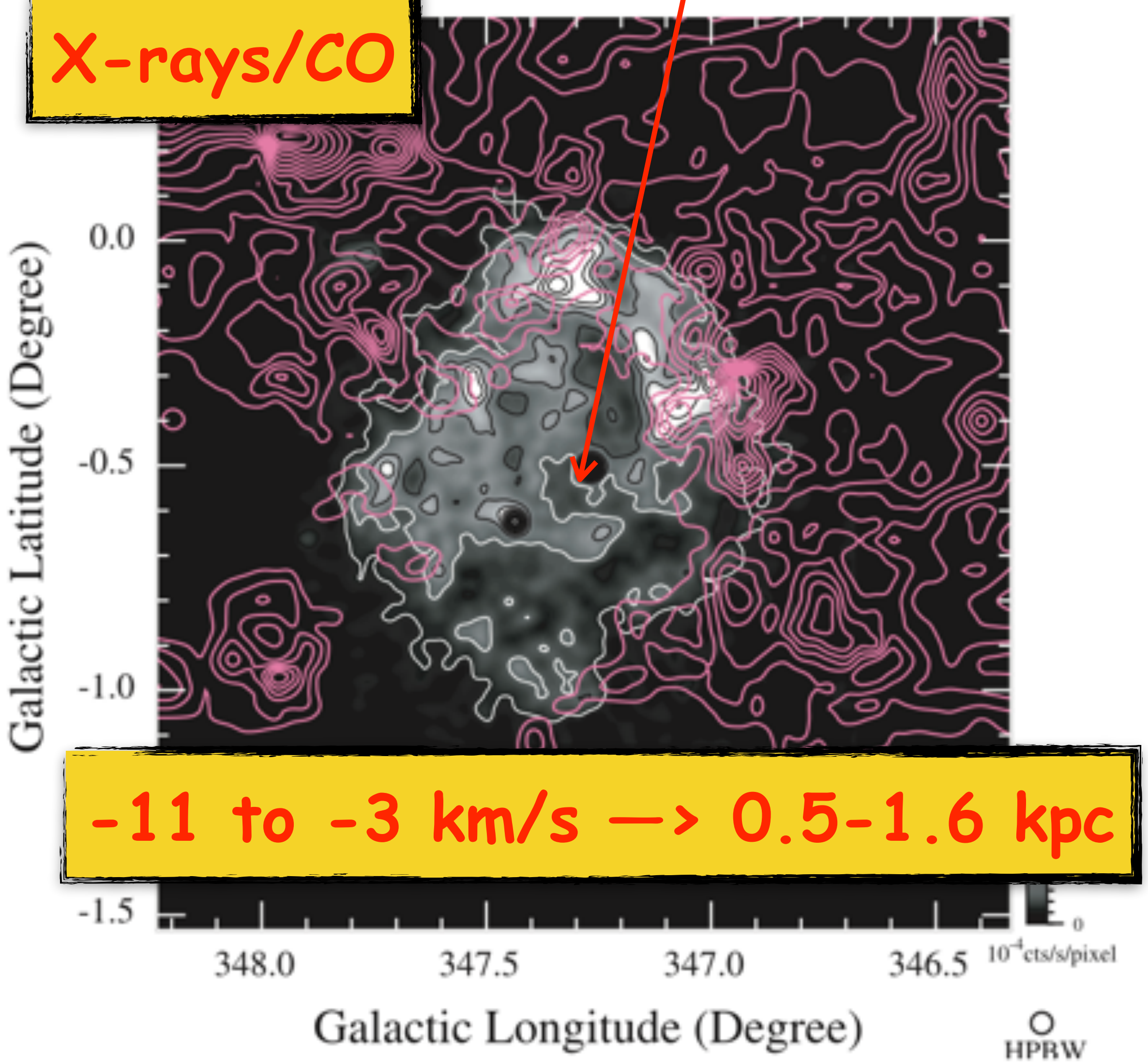


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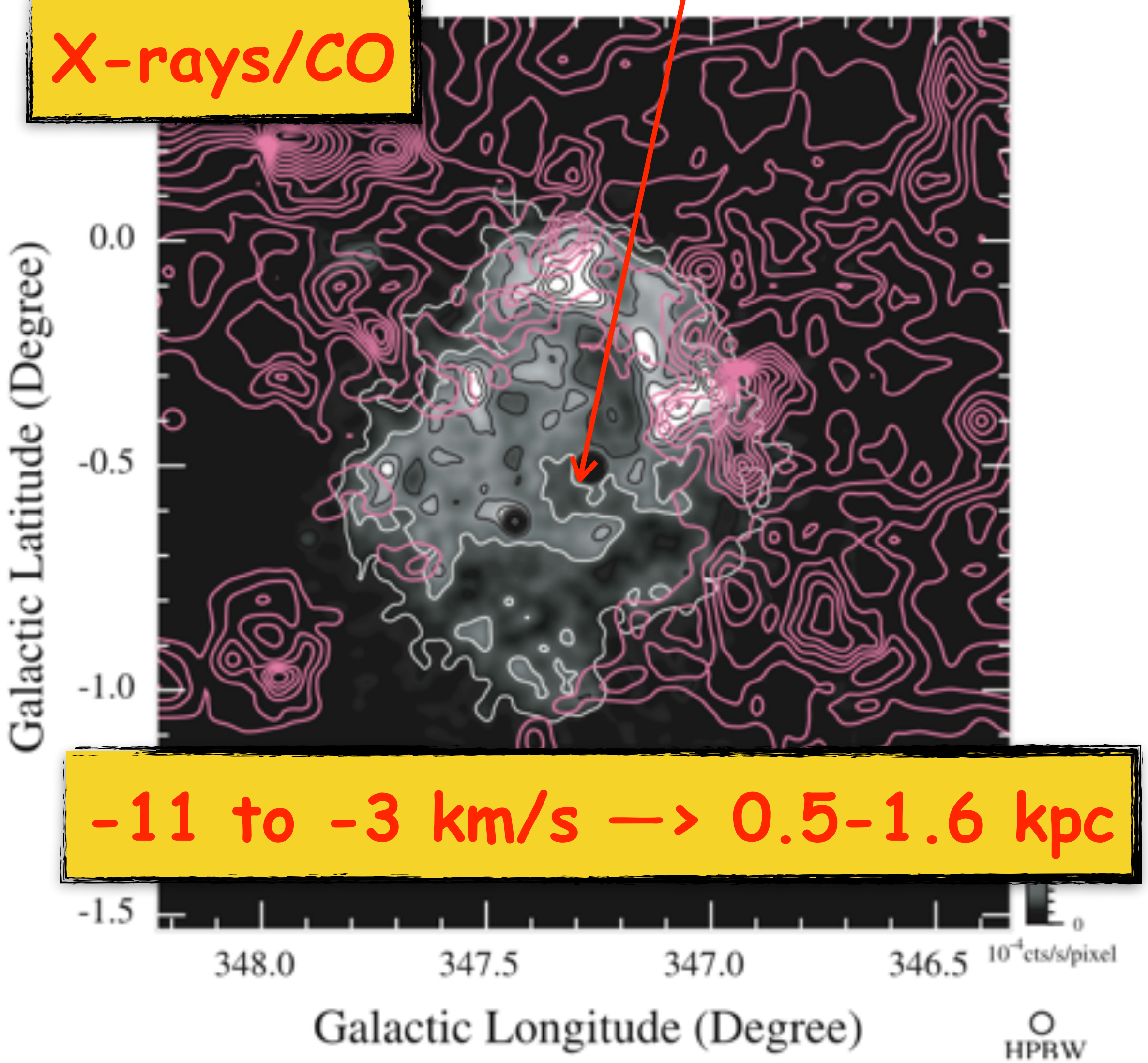


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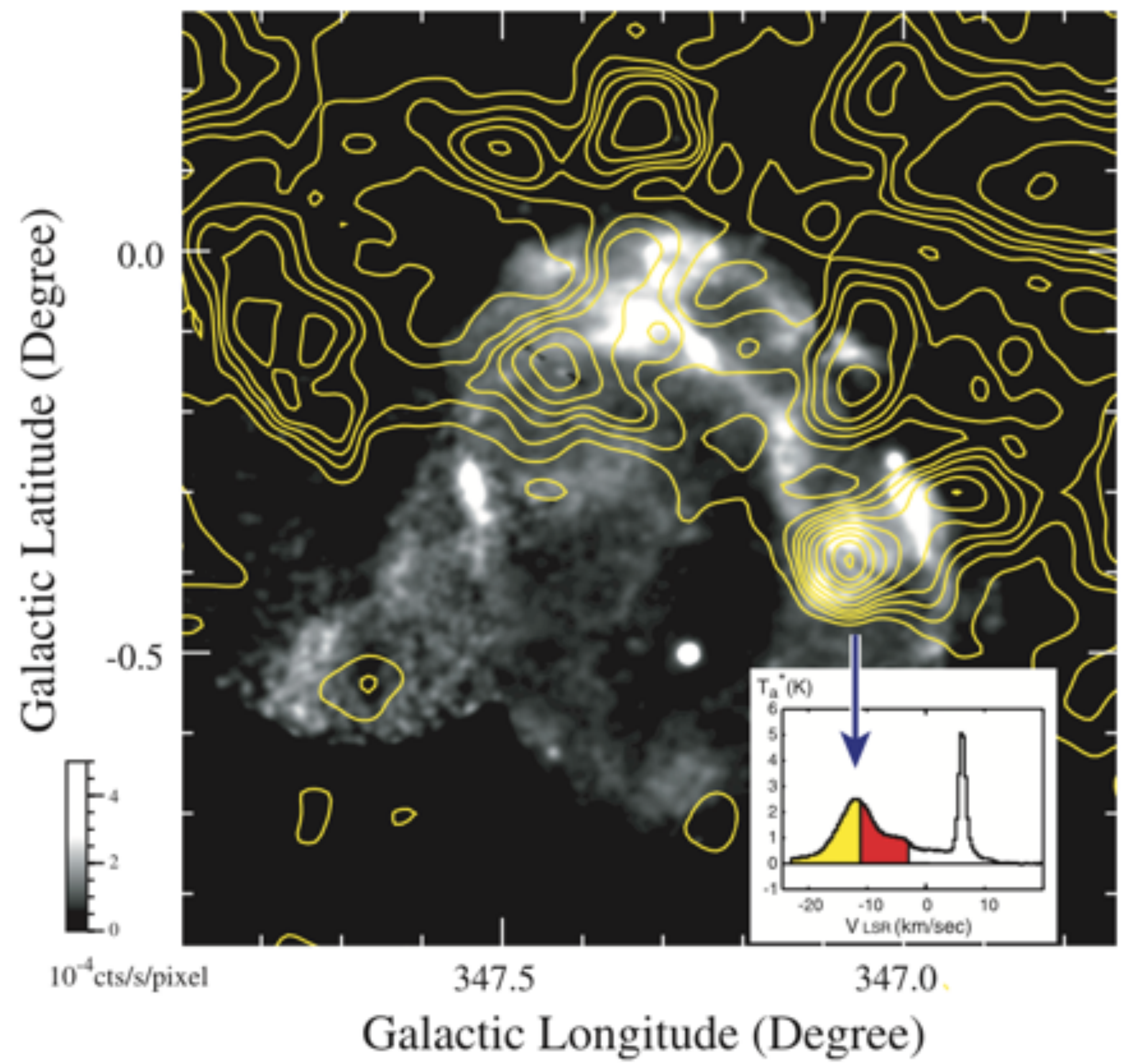


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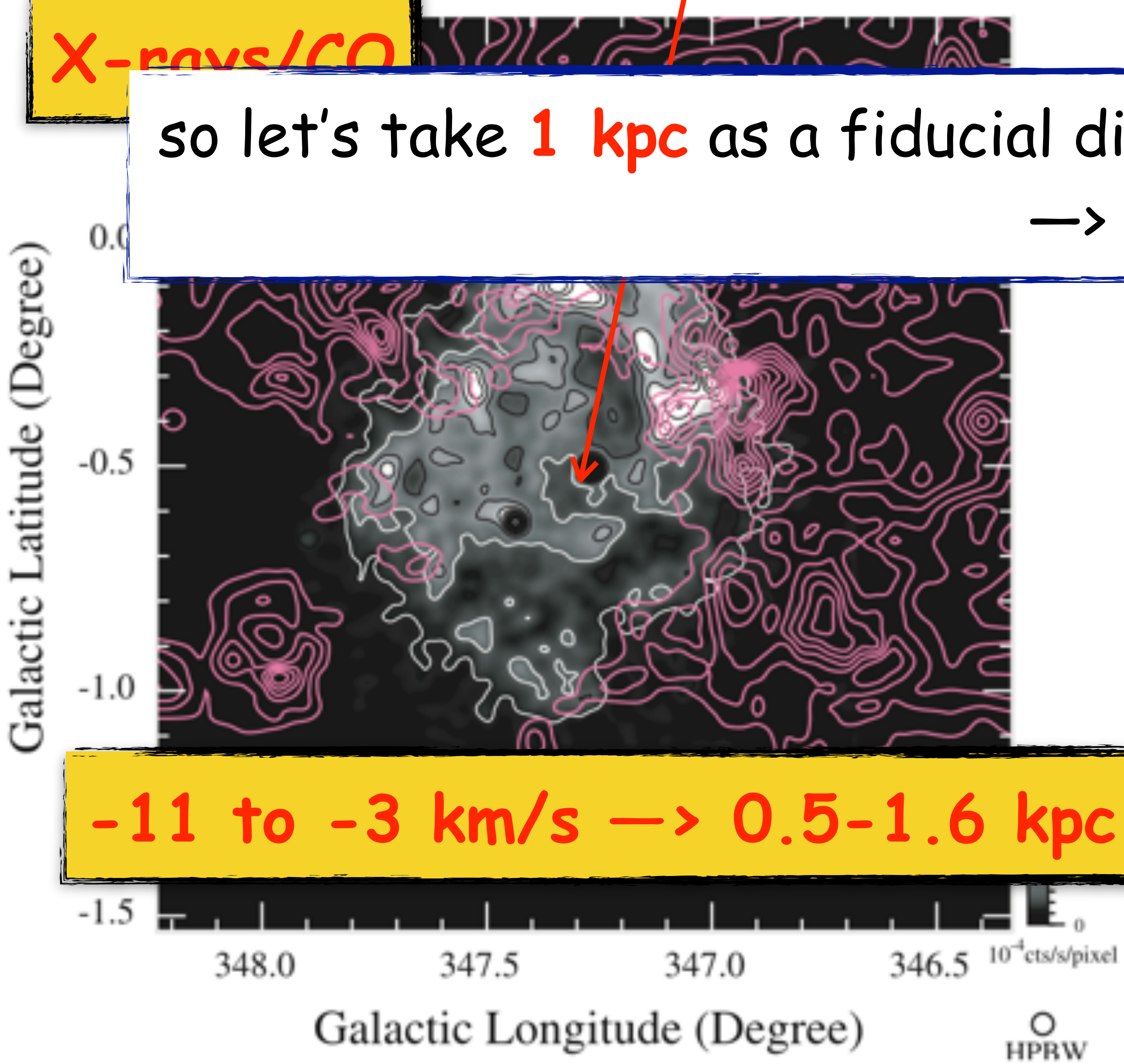
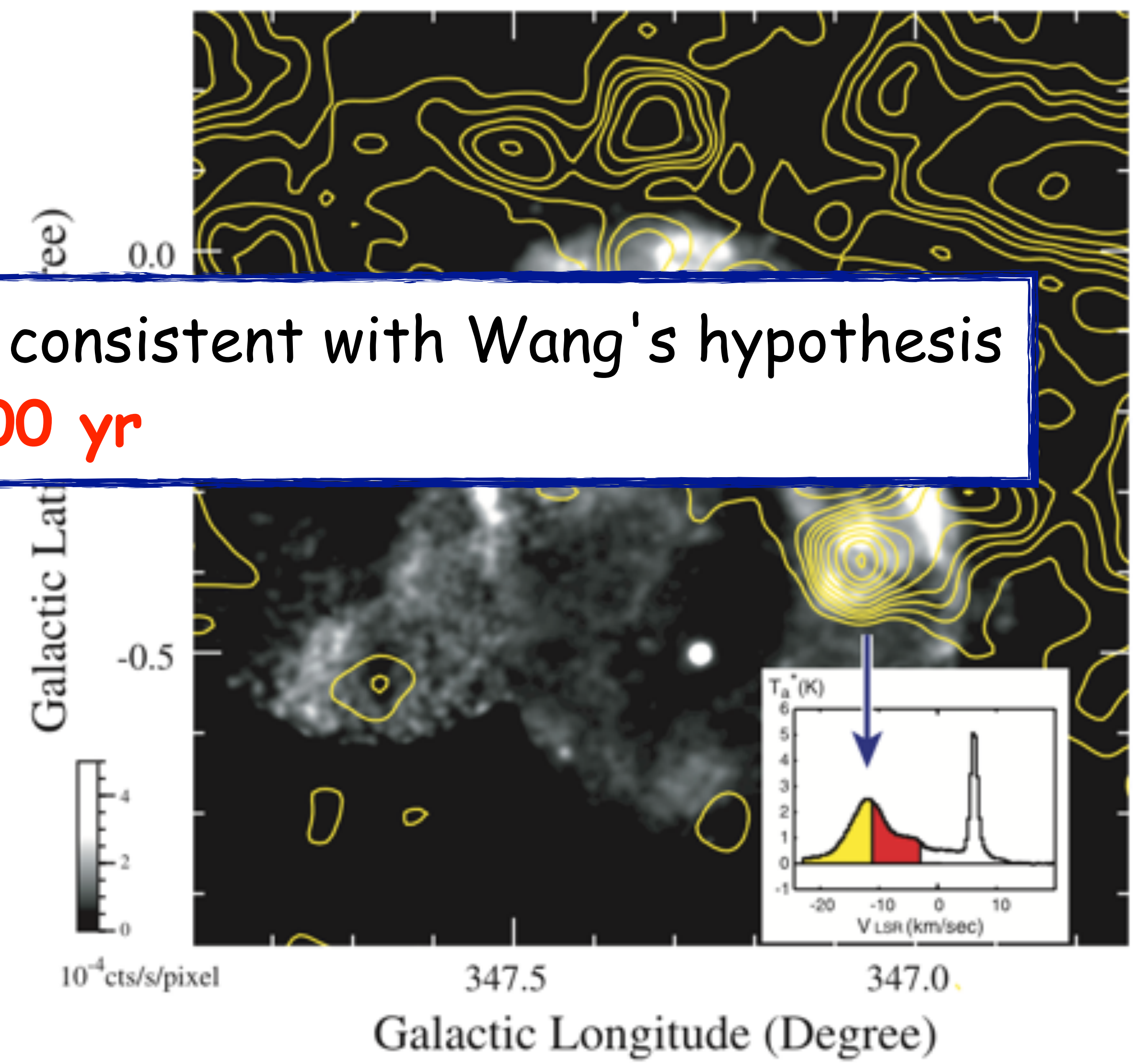



so let's take **1 kpc** as a fiducial distance, consistent with Wang's hypothesis —> **t ~ 1600 yr**

**-11 to -3 km/s —> 0.5-1.6 kpc**

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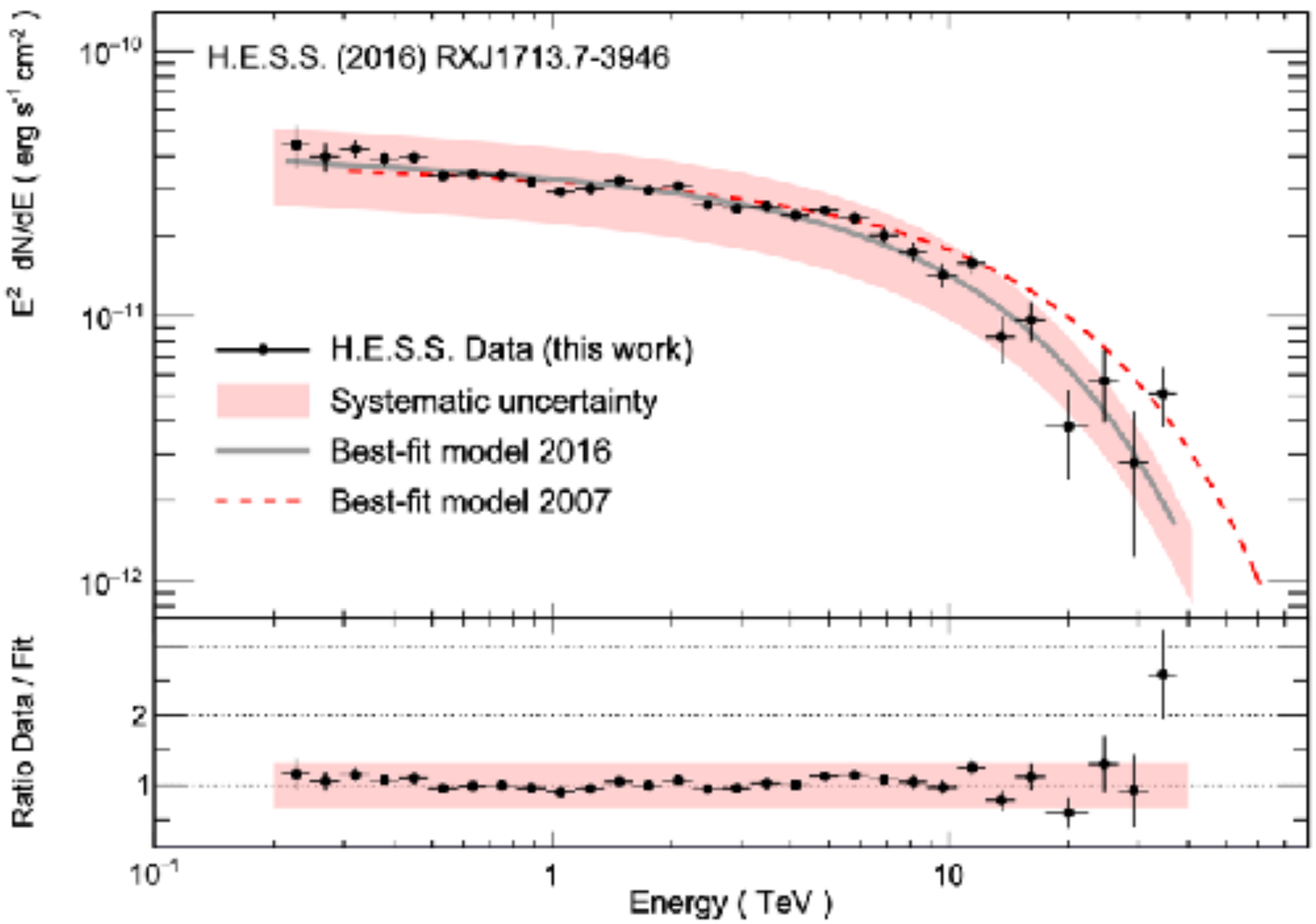
# VHE gamma ray luminosity



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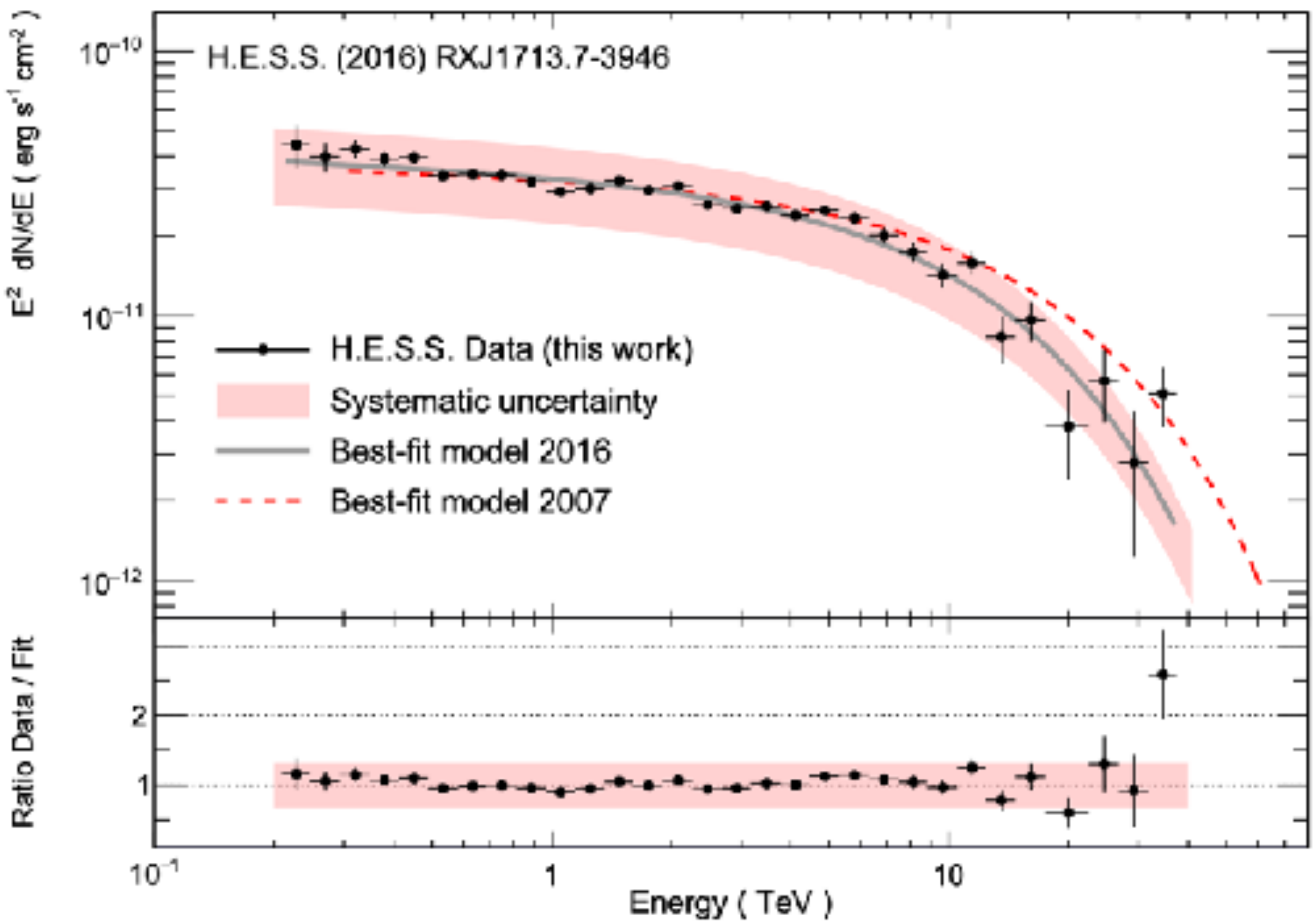


$$F(E) = F_0 E^{-\Gamma} e^{-\left(\frac{E}{E_{cut}}\right)}$$

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

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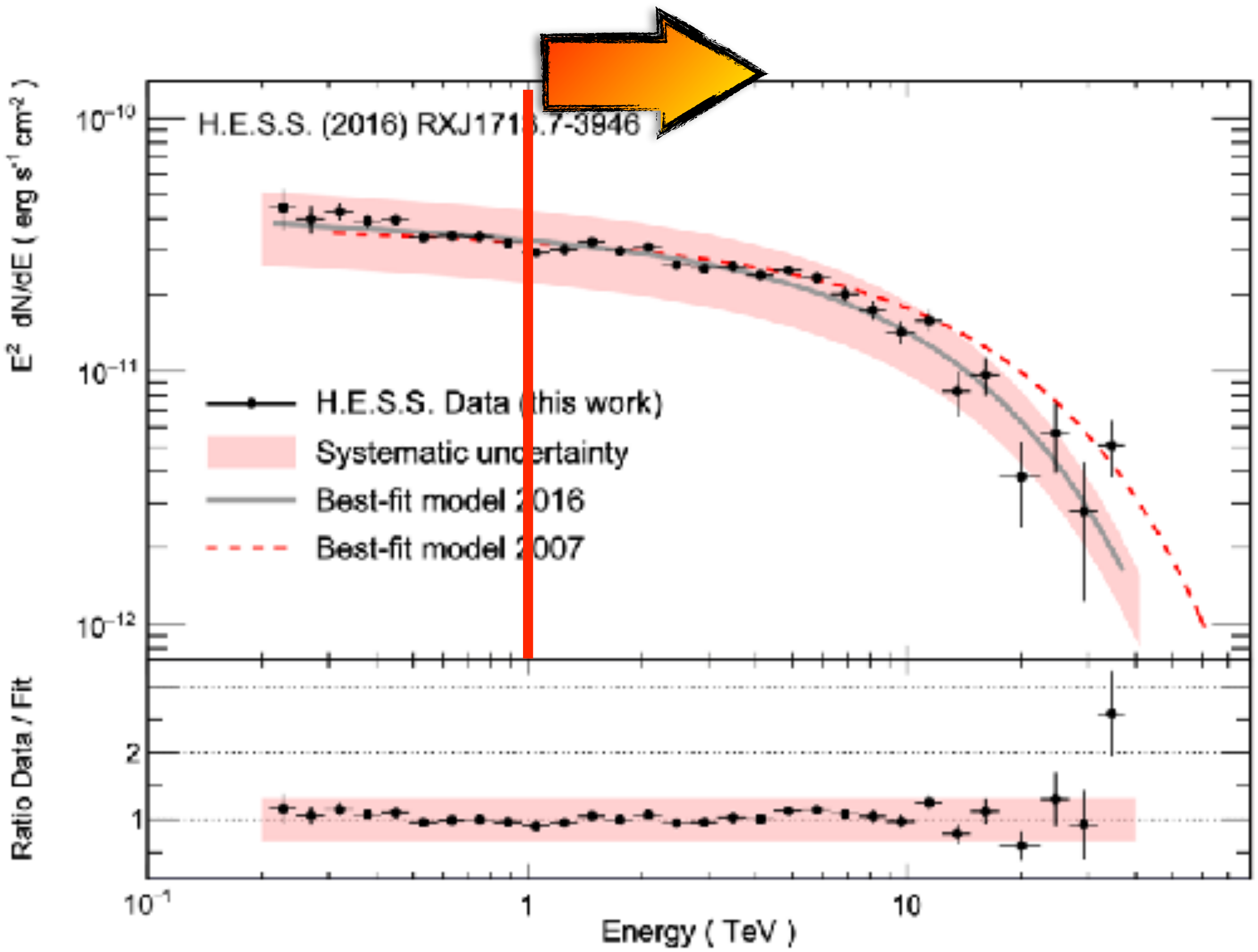


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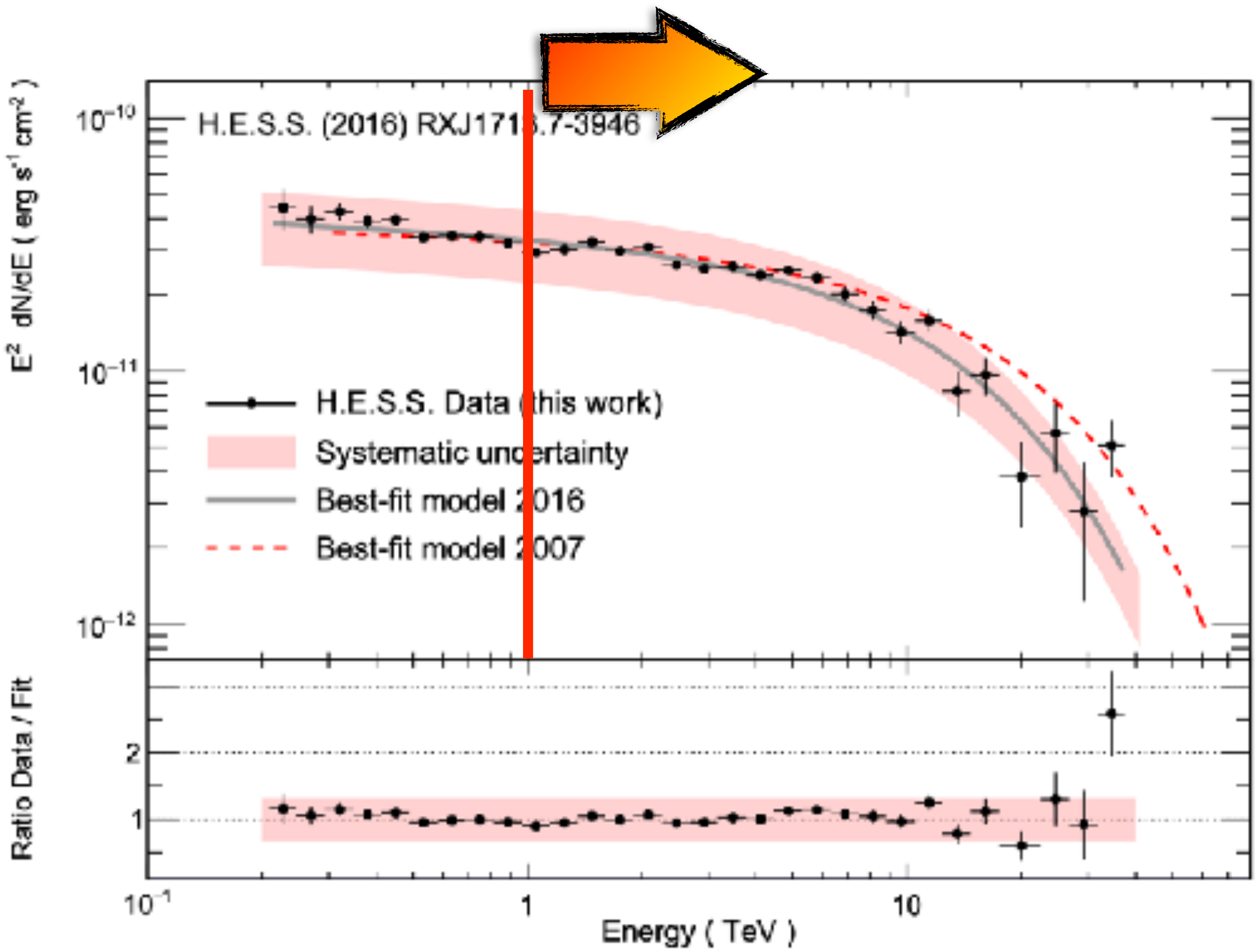


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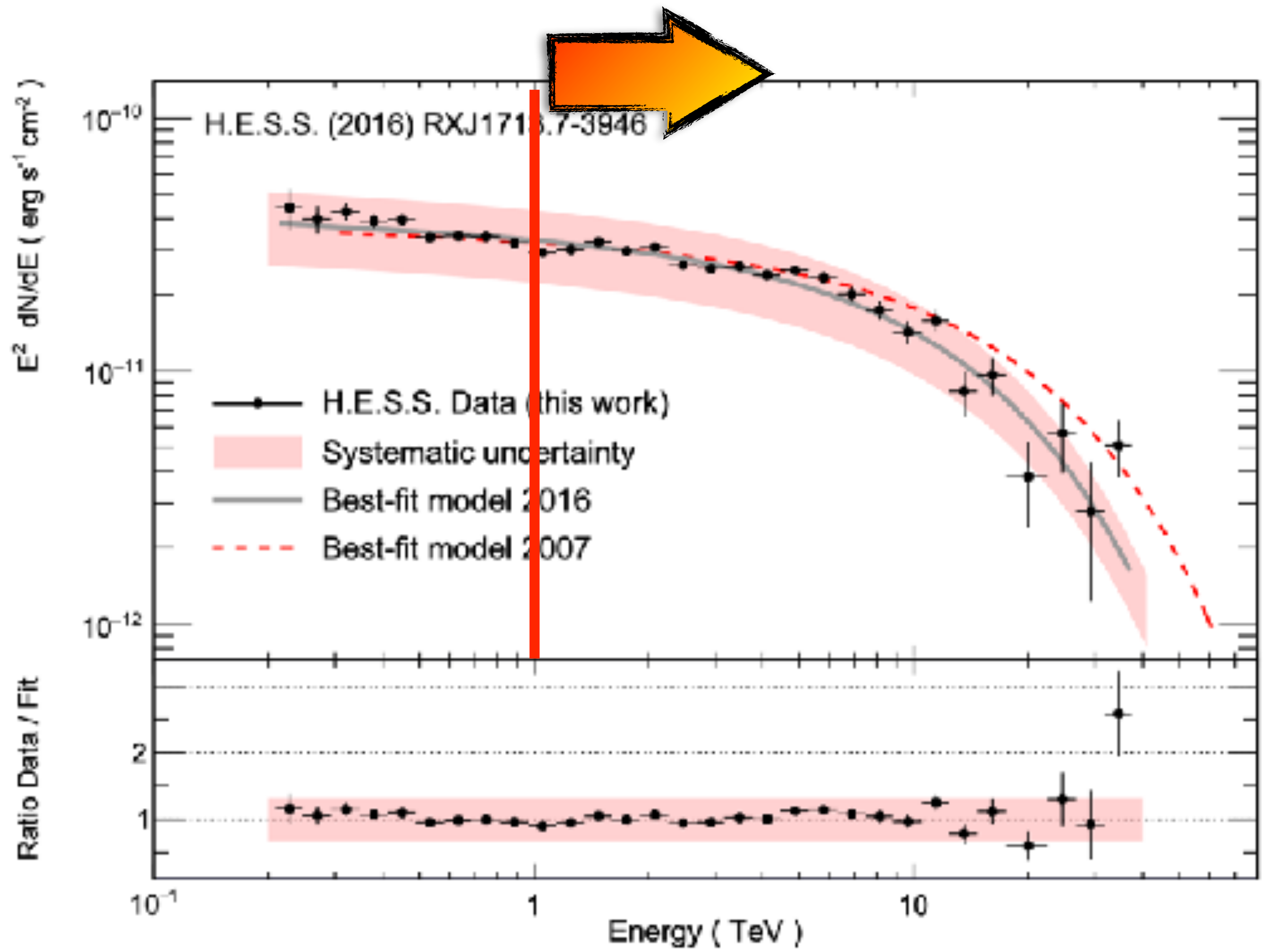


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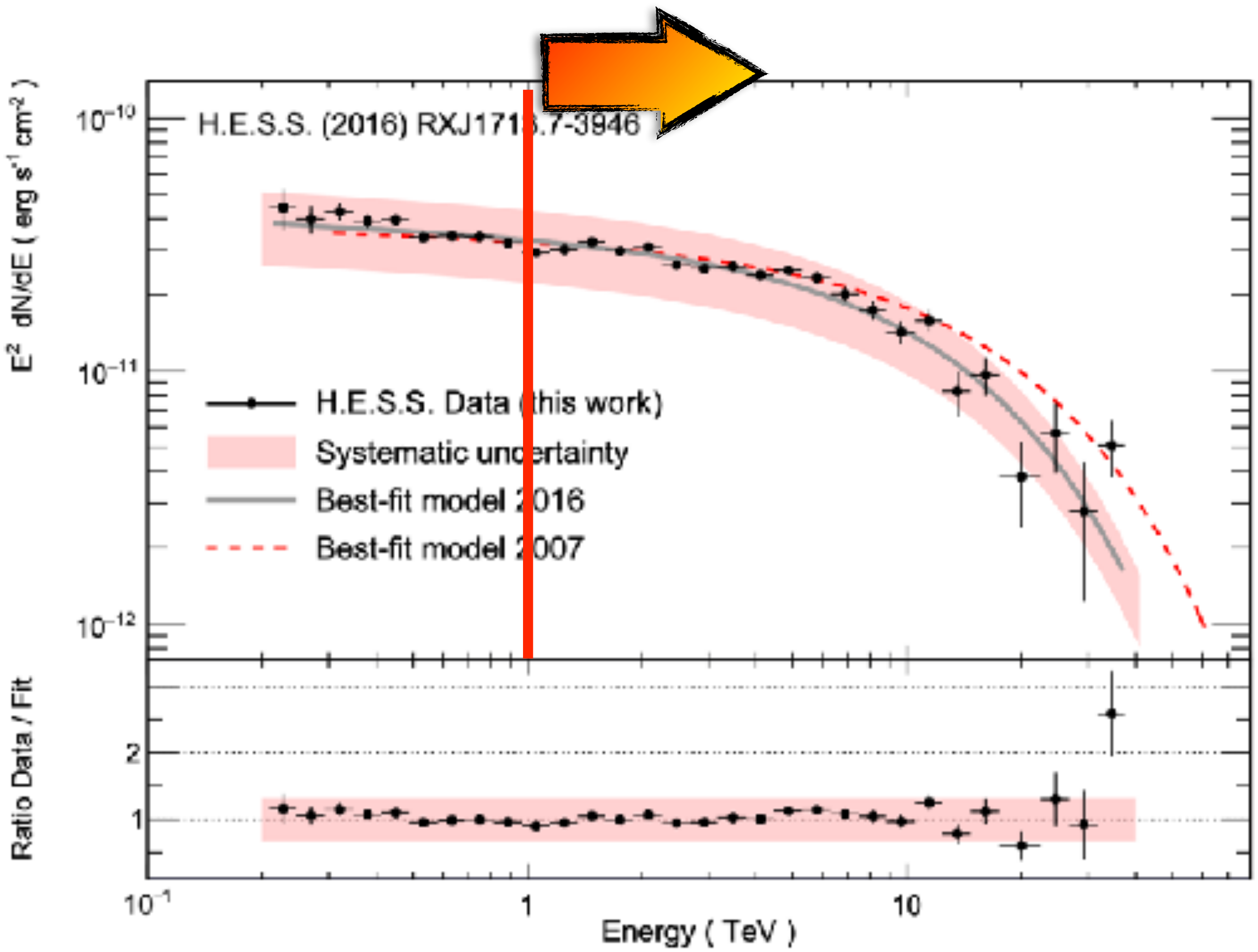


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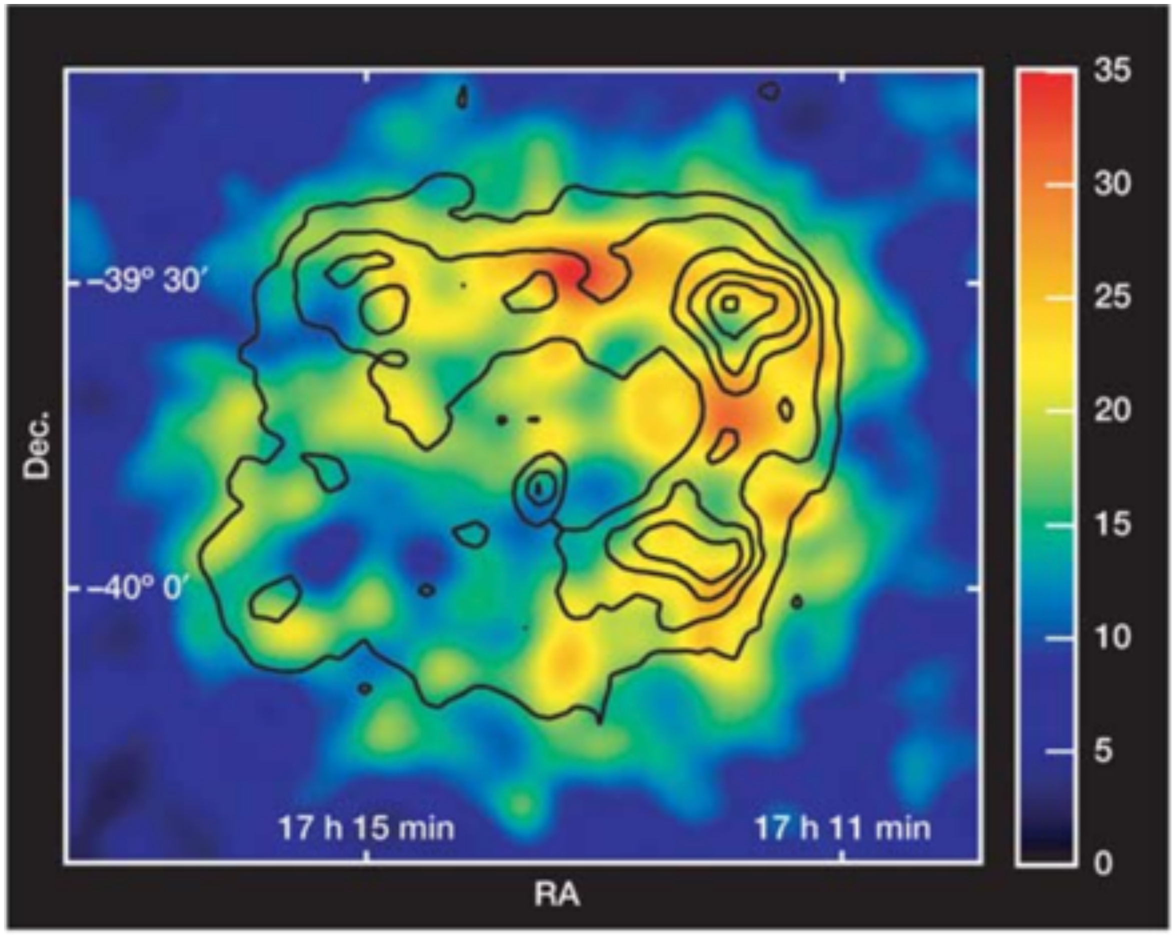
[Question 3] How much energy we need to explain the TeV emission?

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

# Hadronic or leptonic? This is the question



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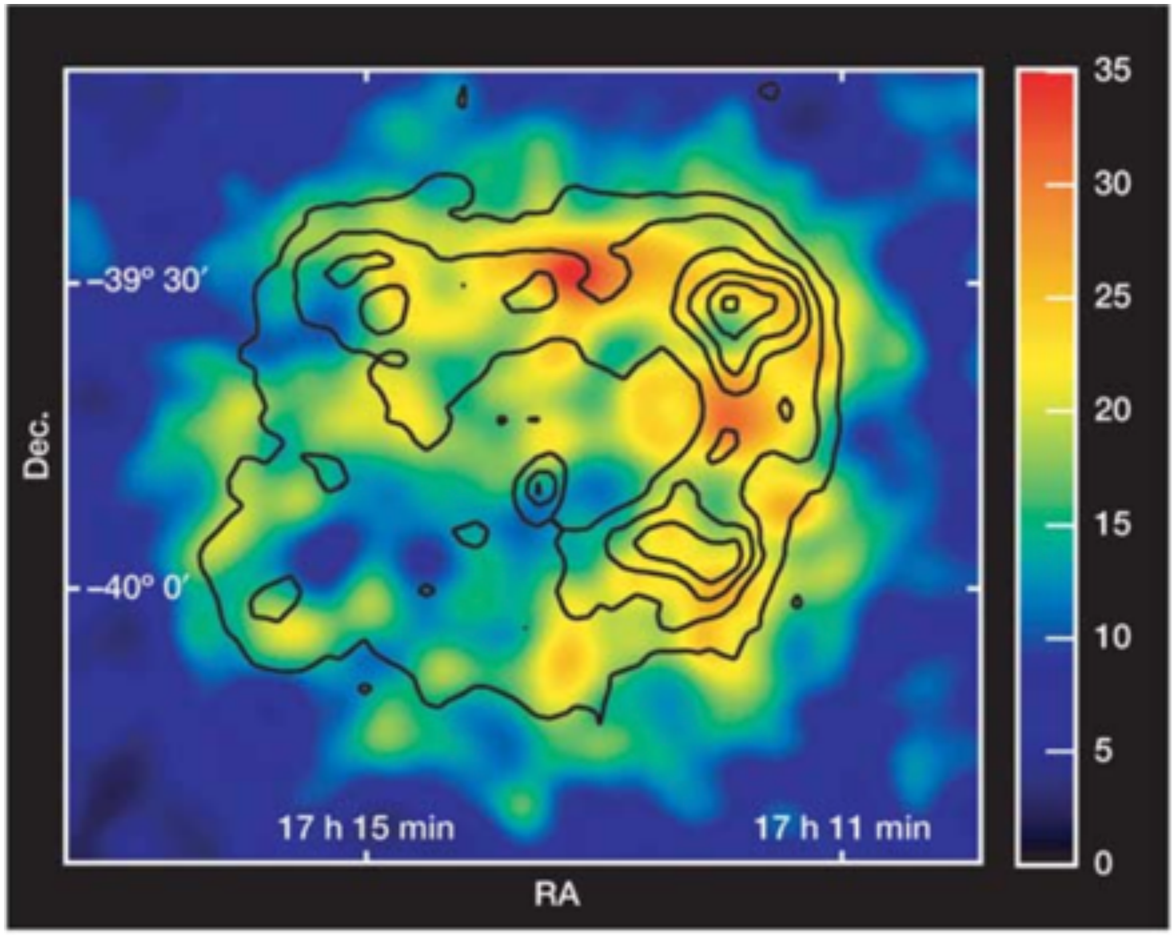
p-p interactions

target: ambient gas



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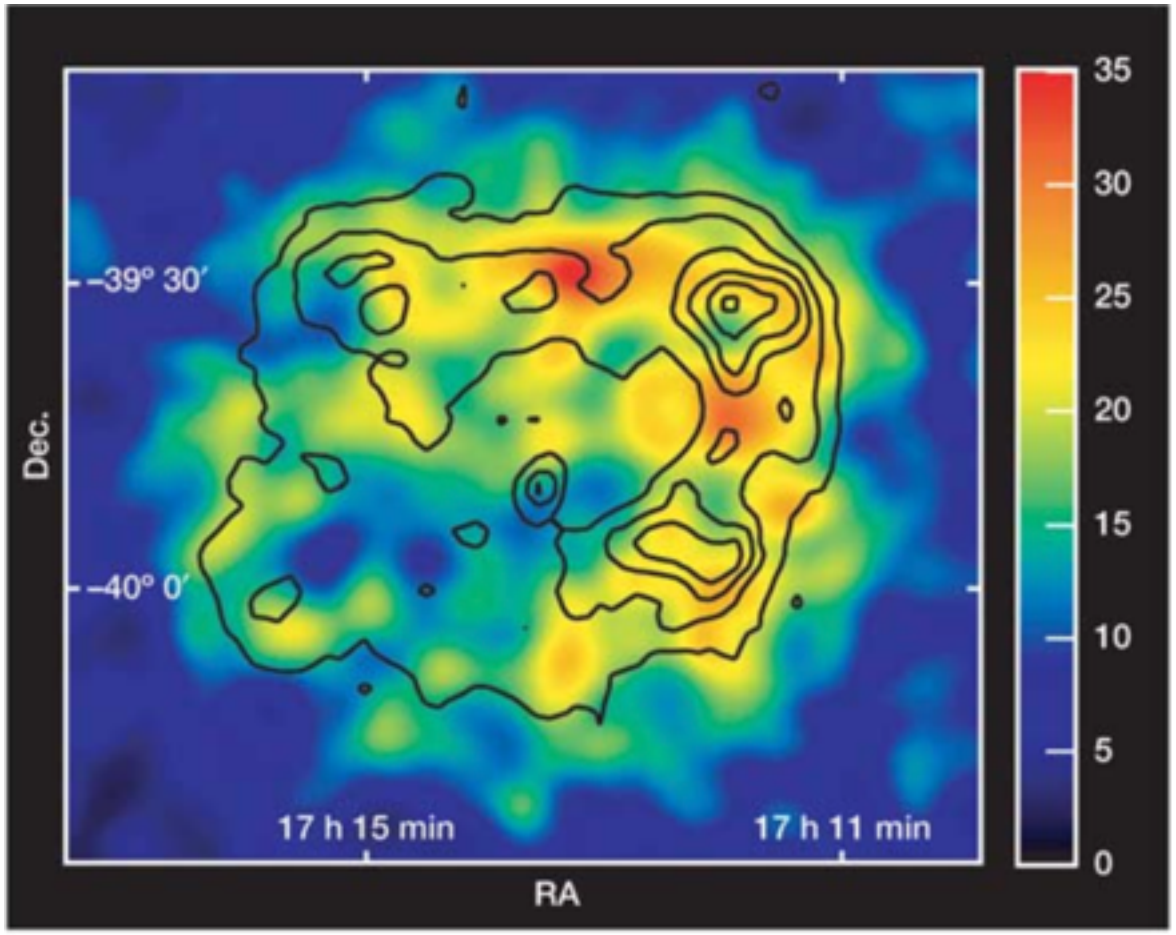


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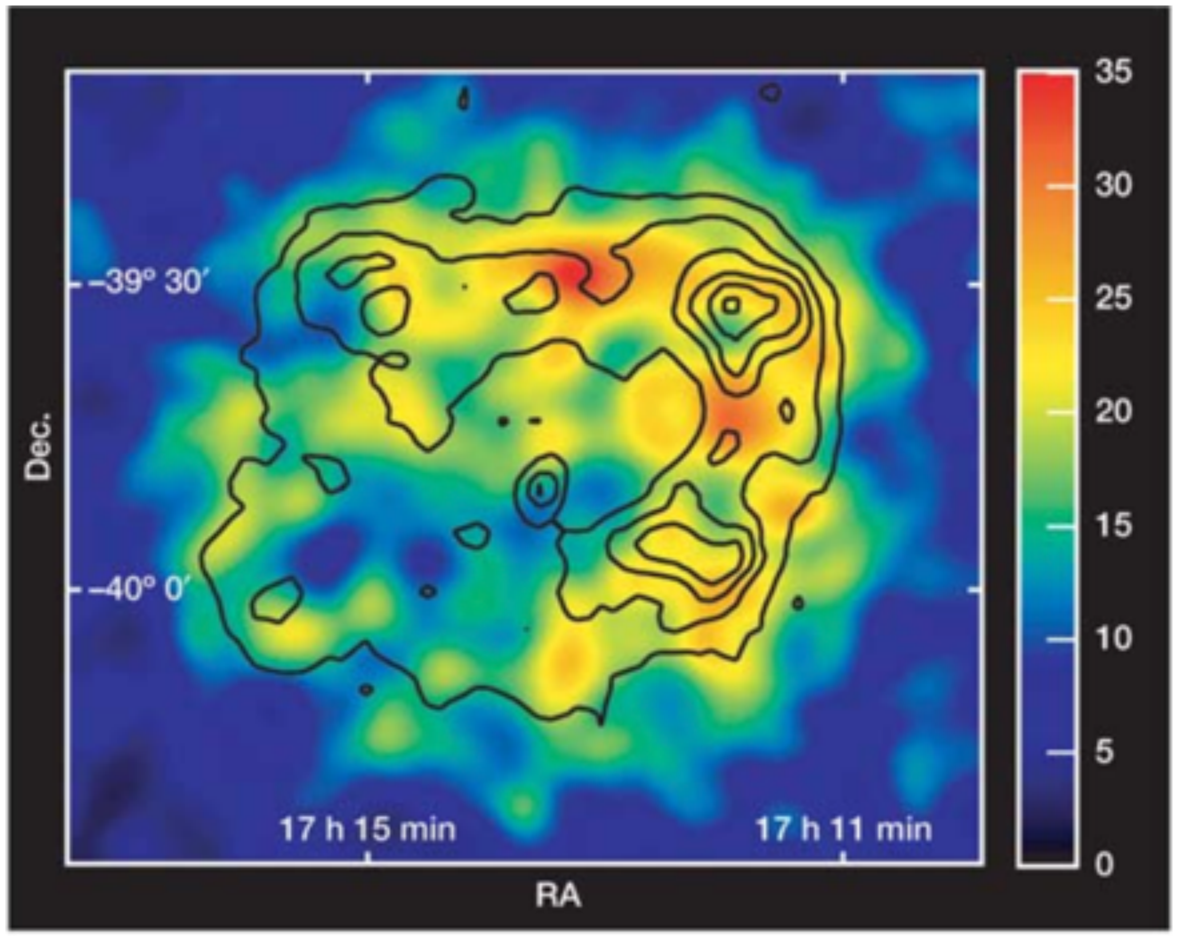


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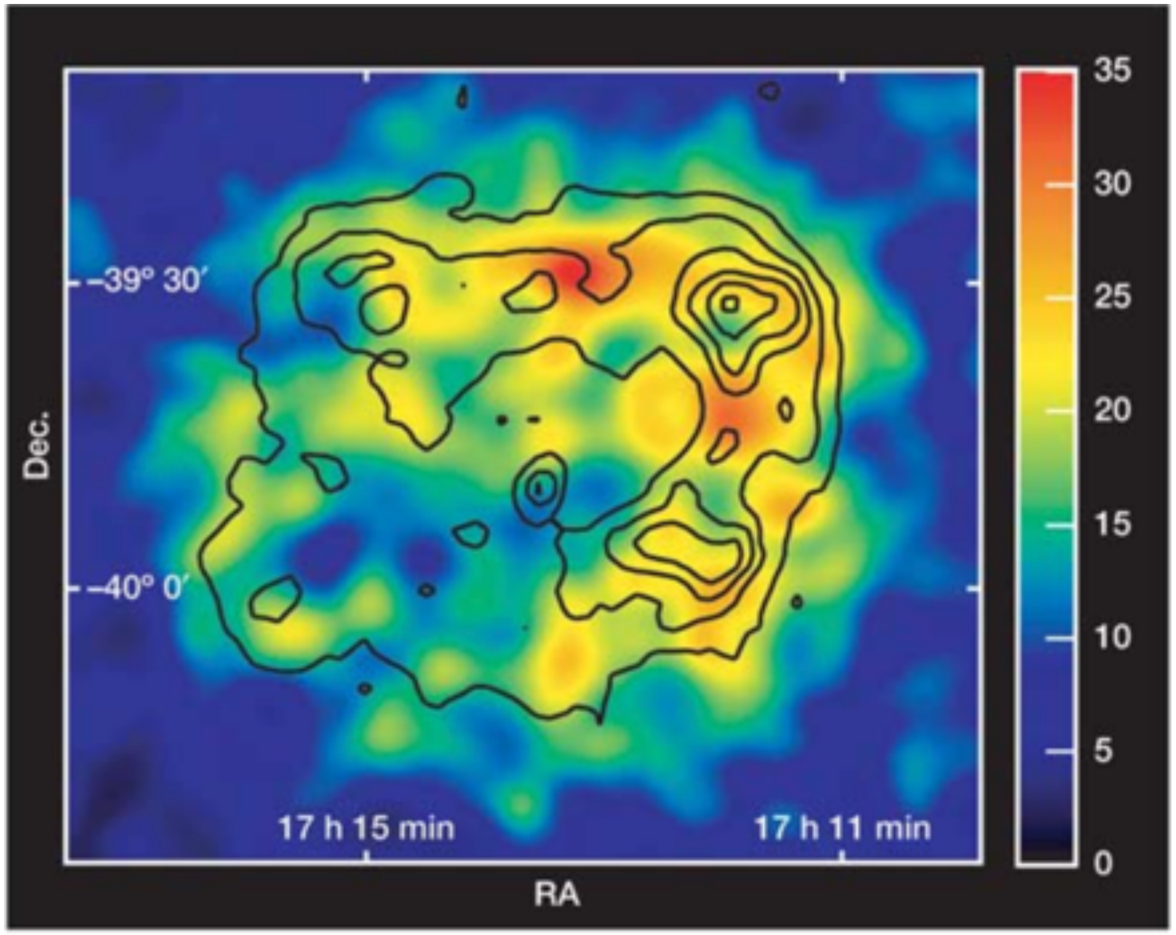


**inverse Compton**

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

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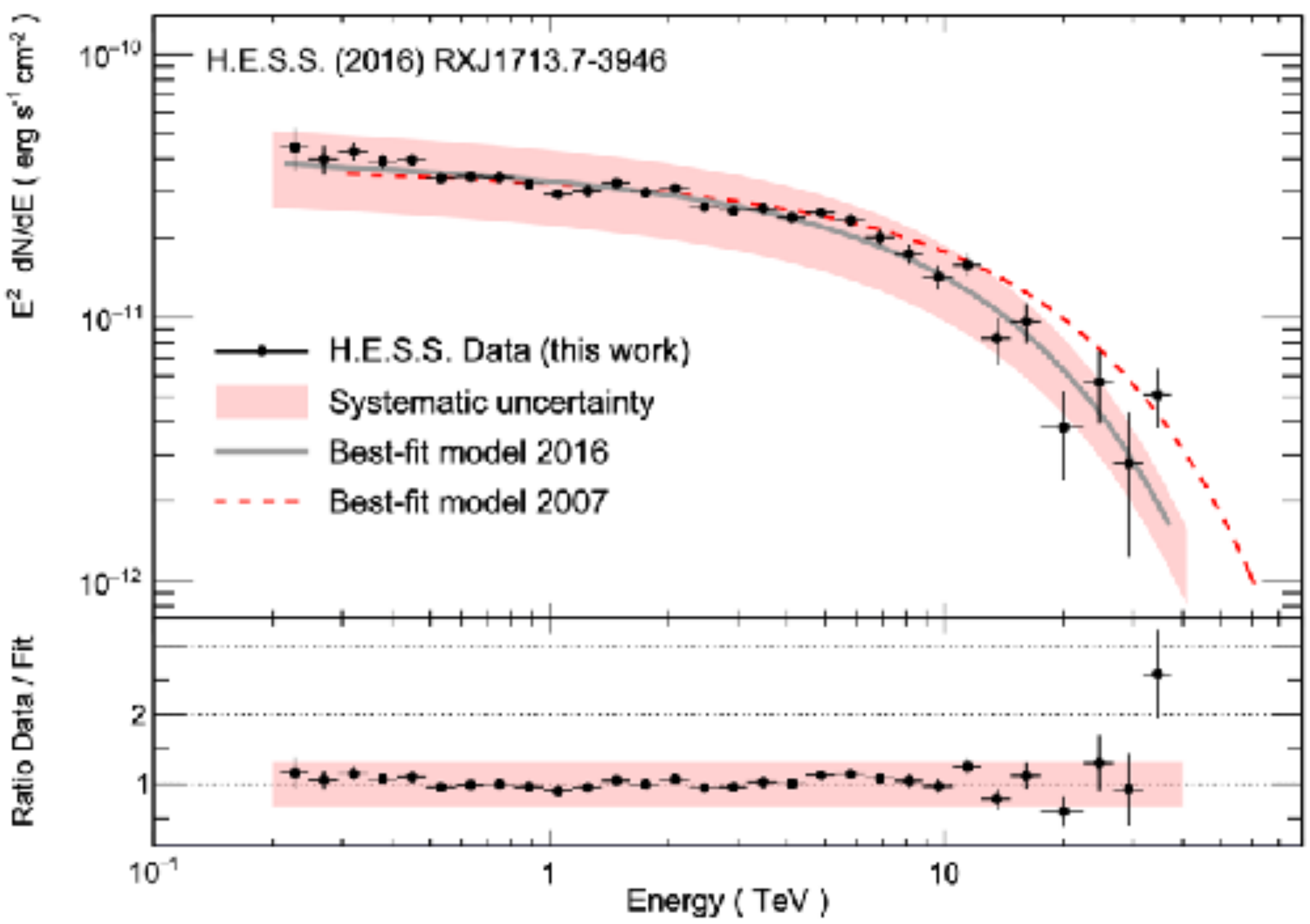

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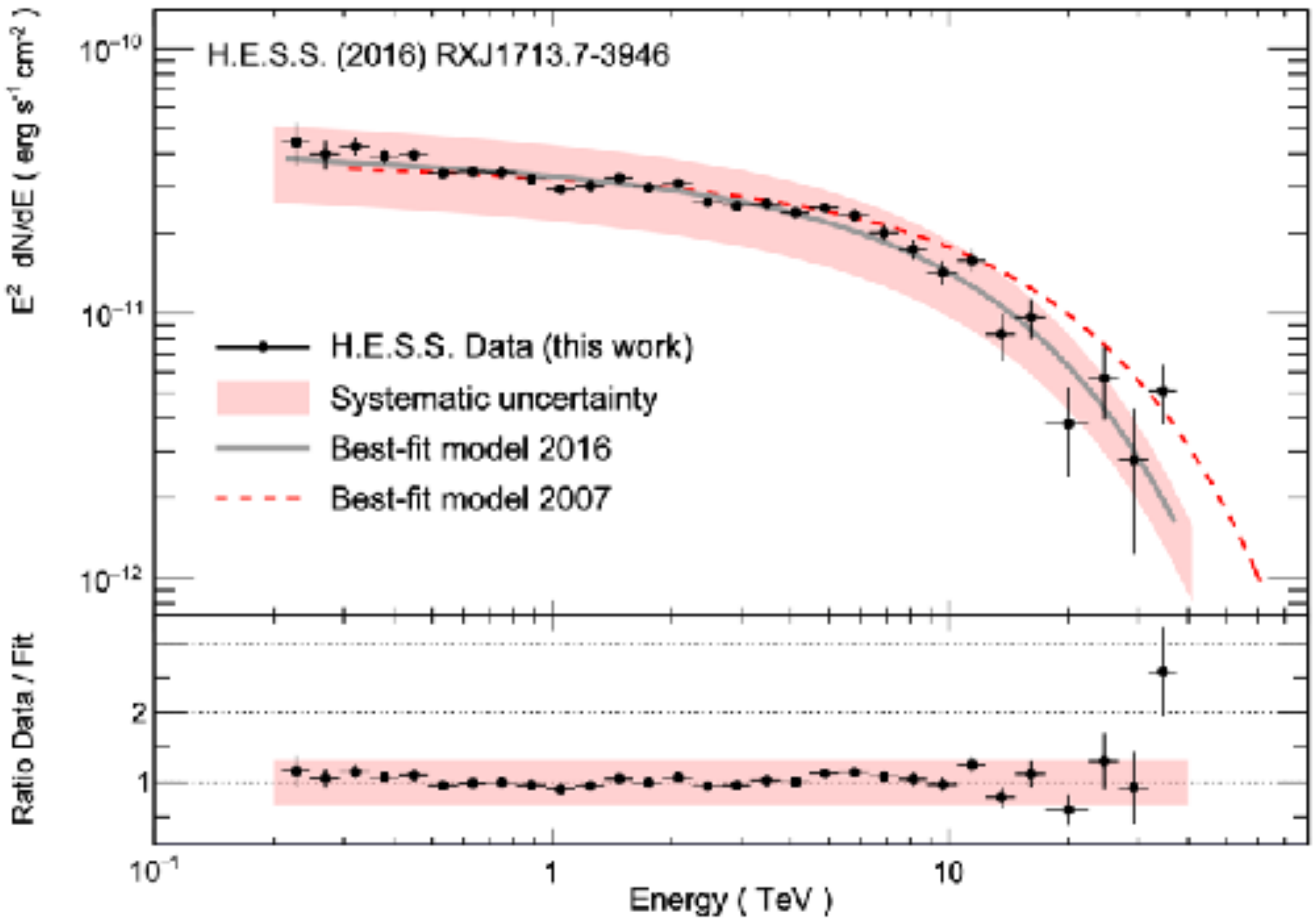

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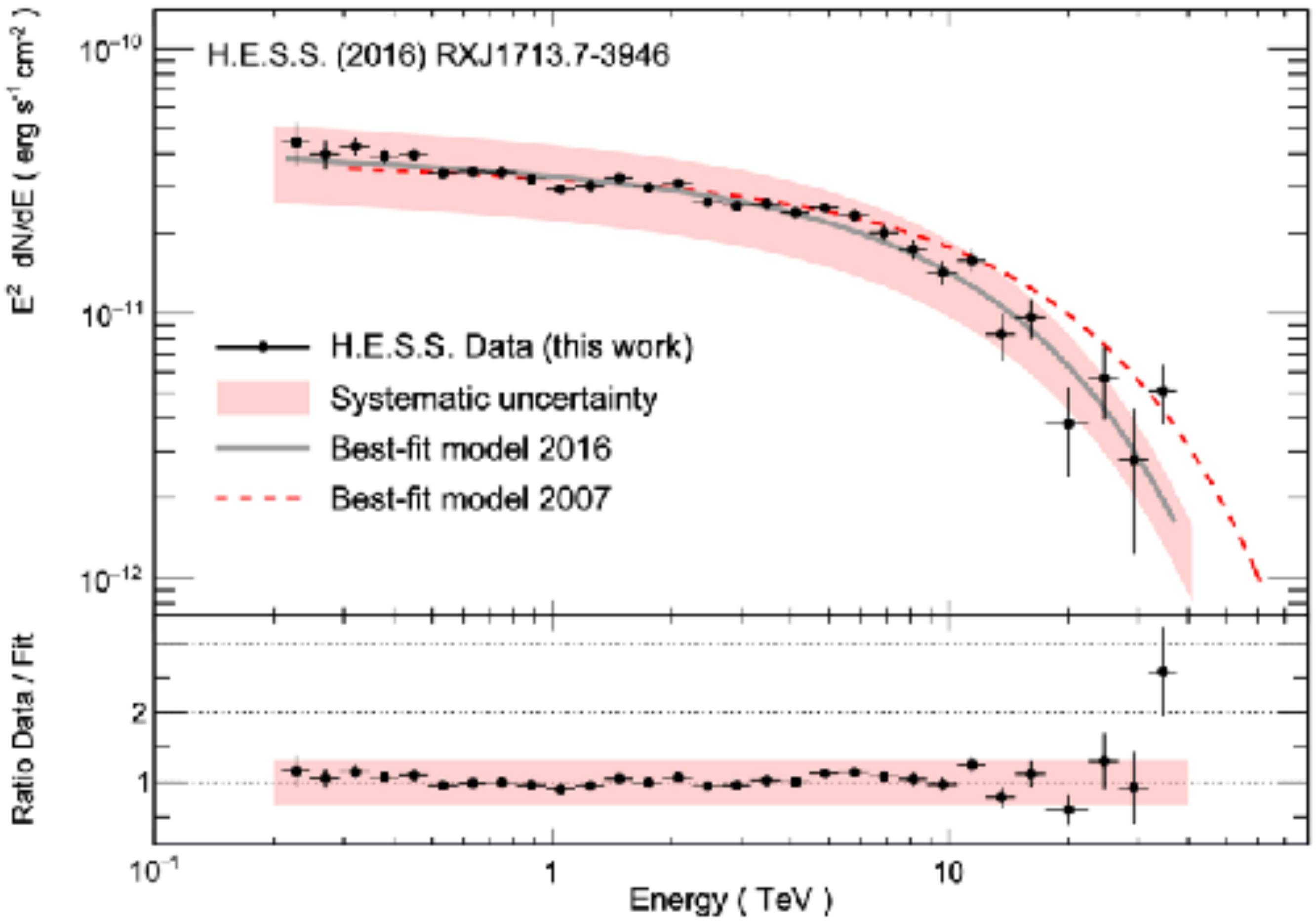


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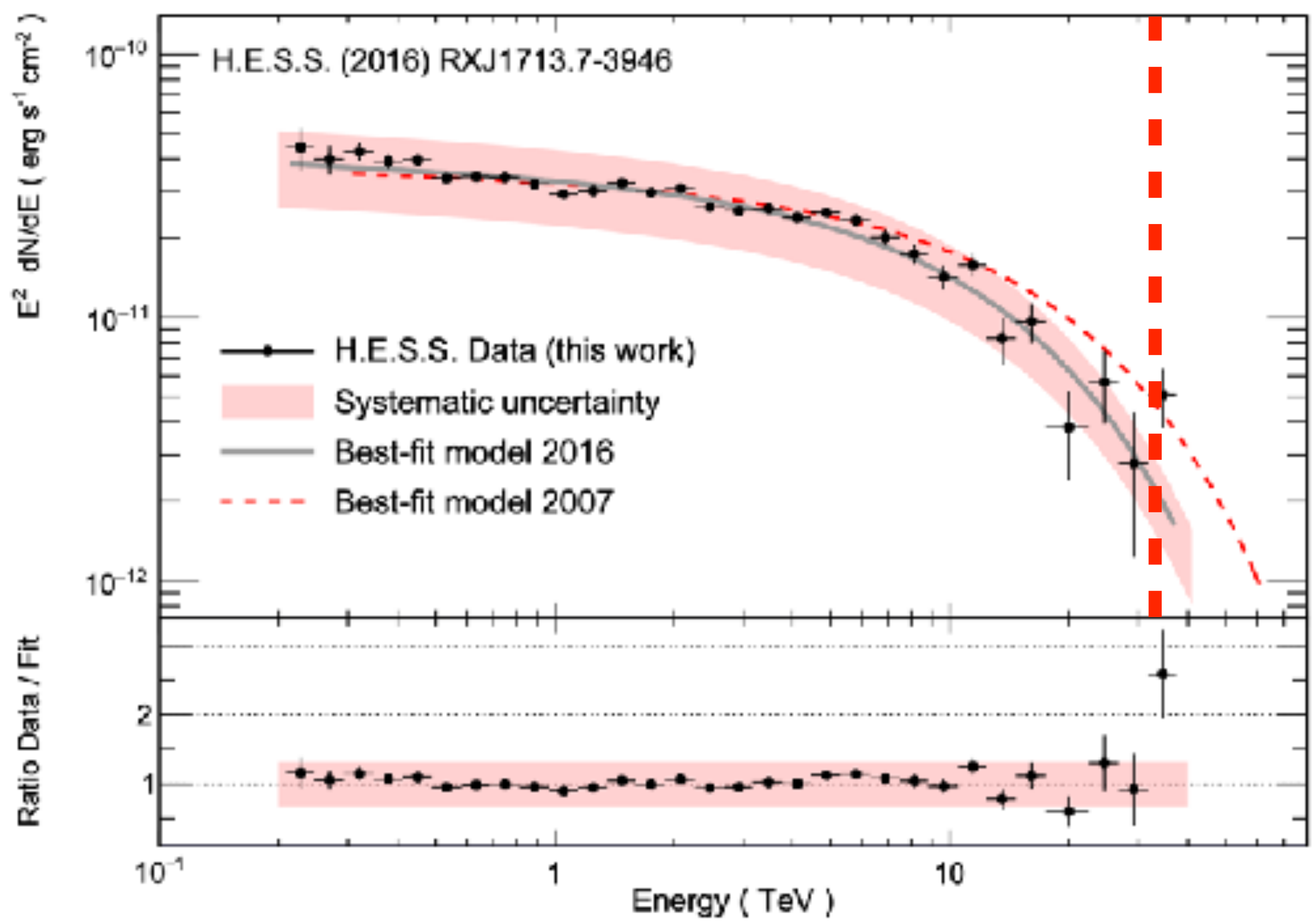


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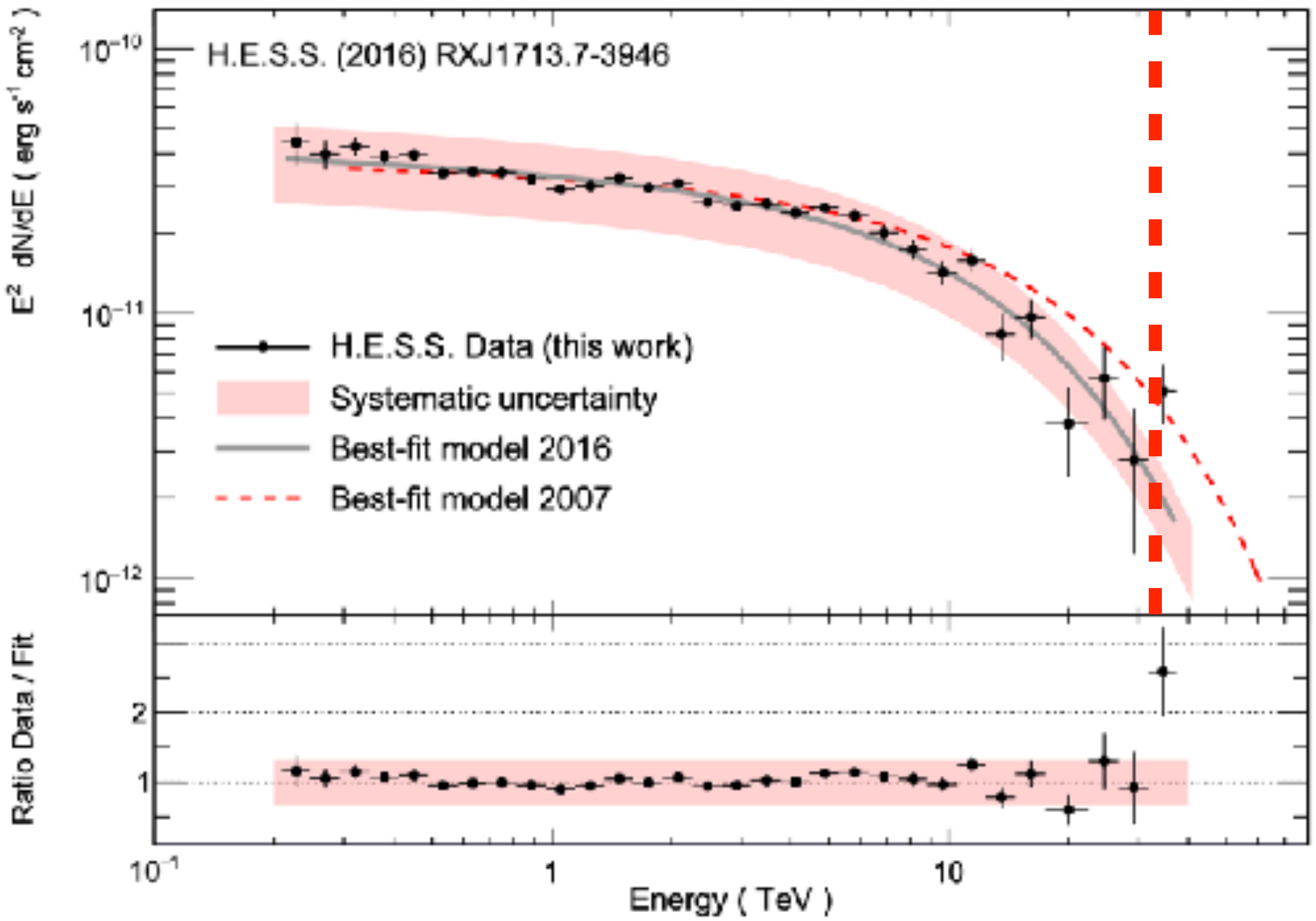


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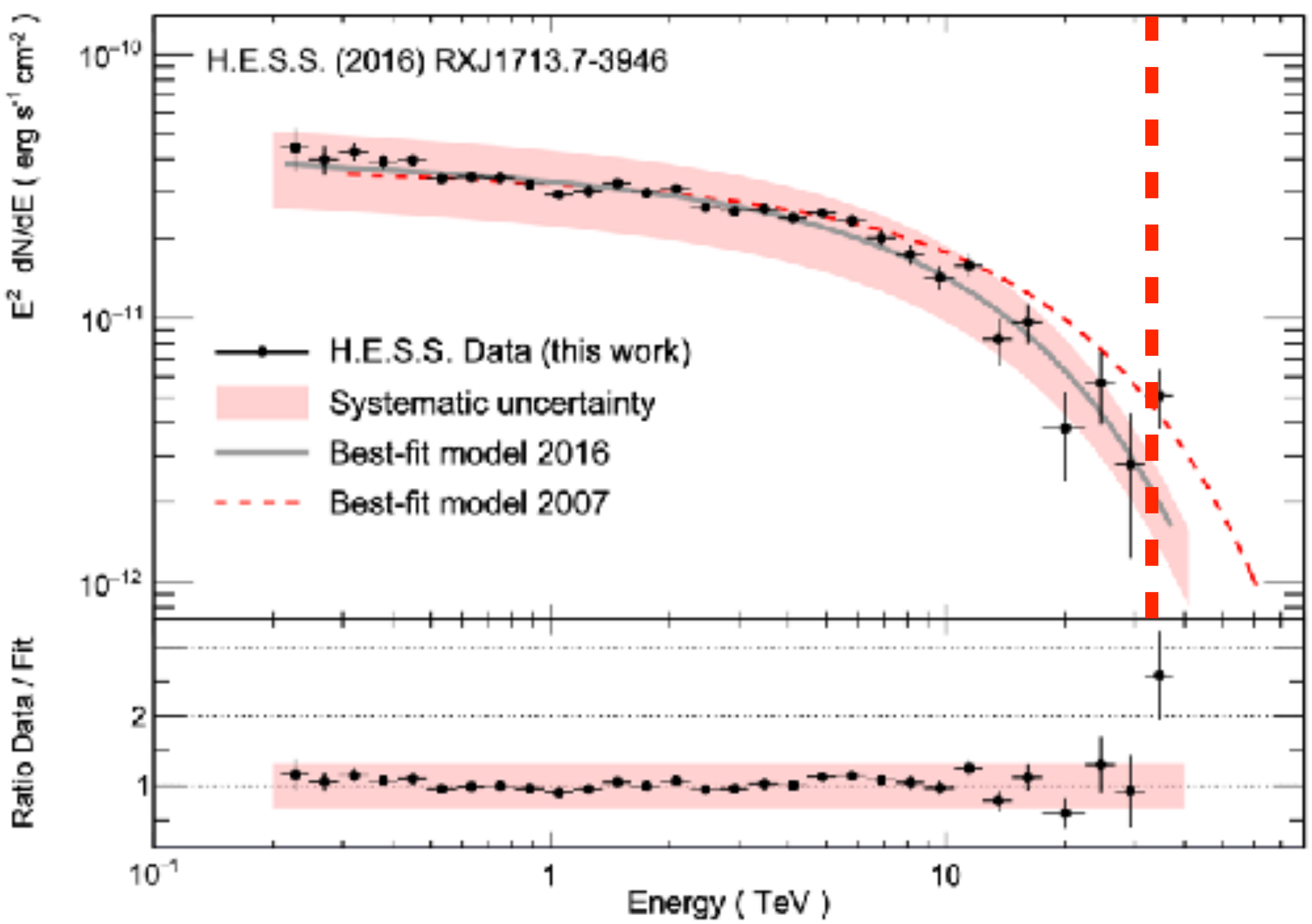


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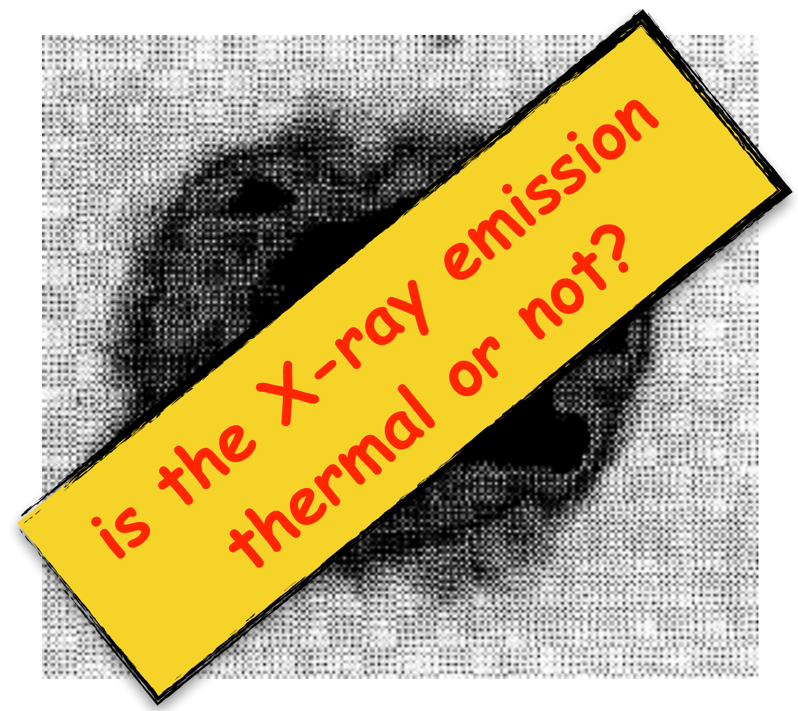


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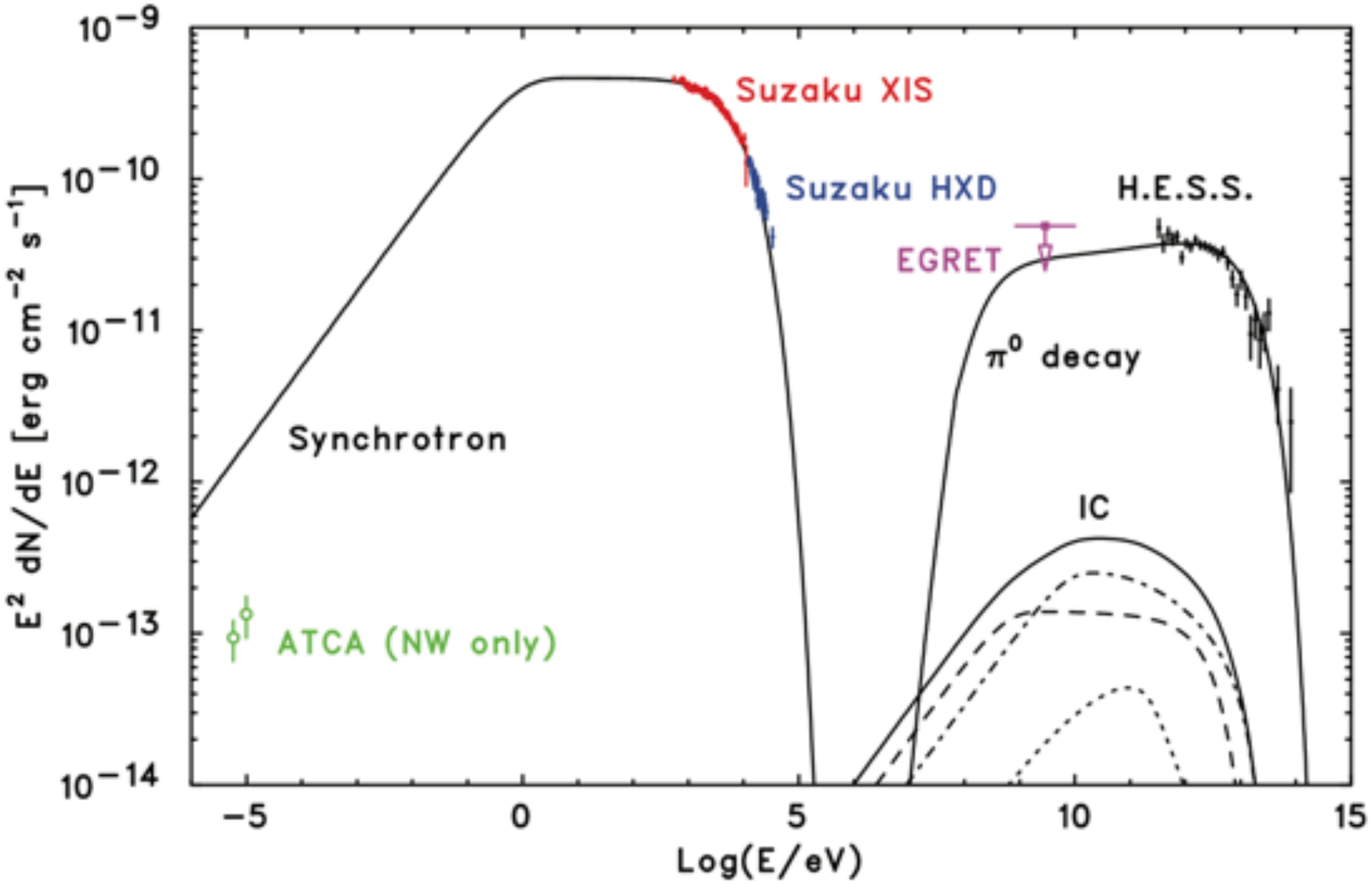

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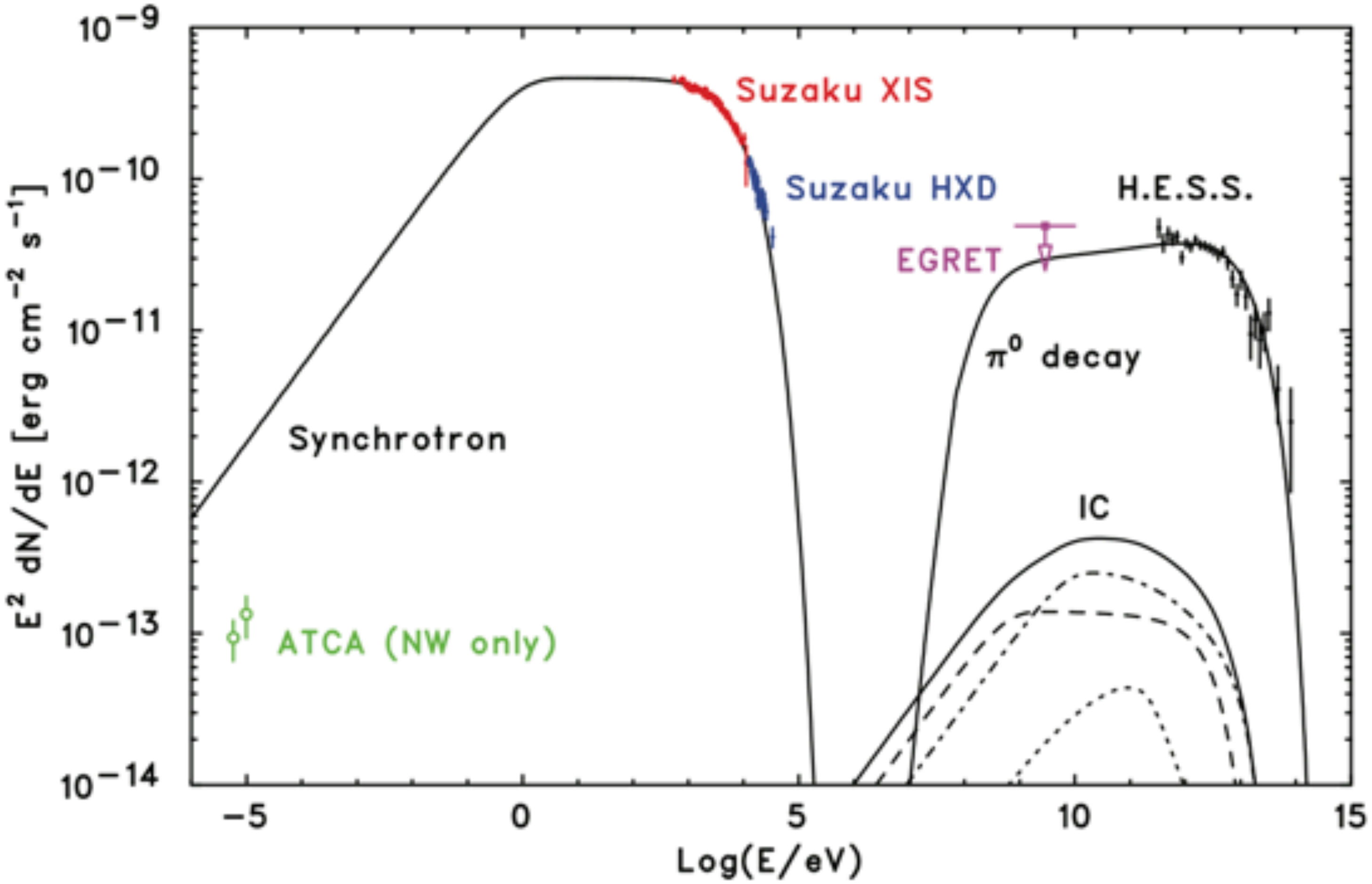


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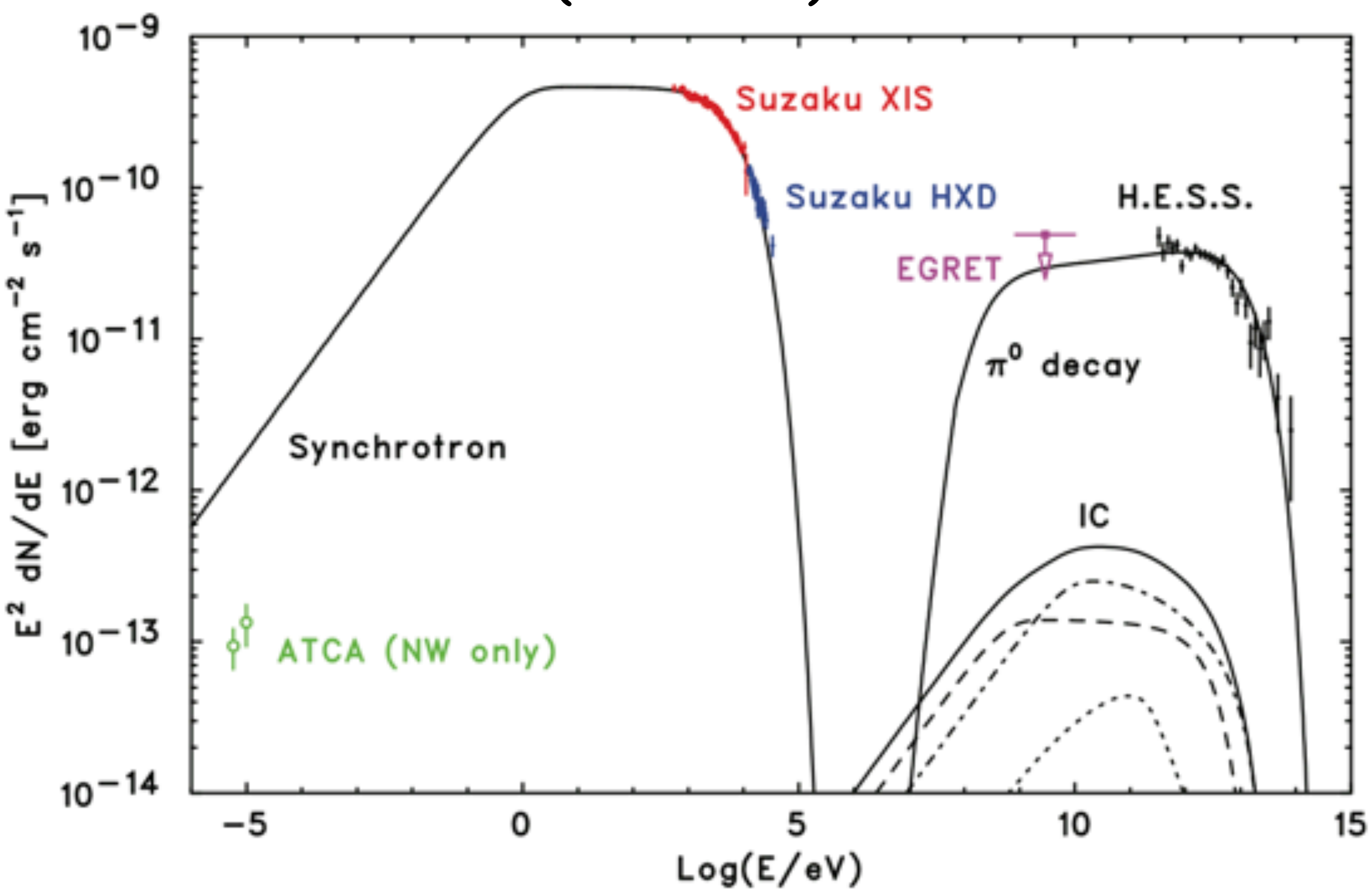


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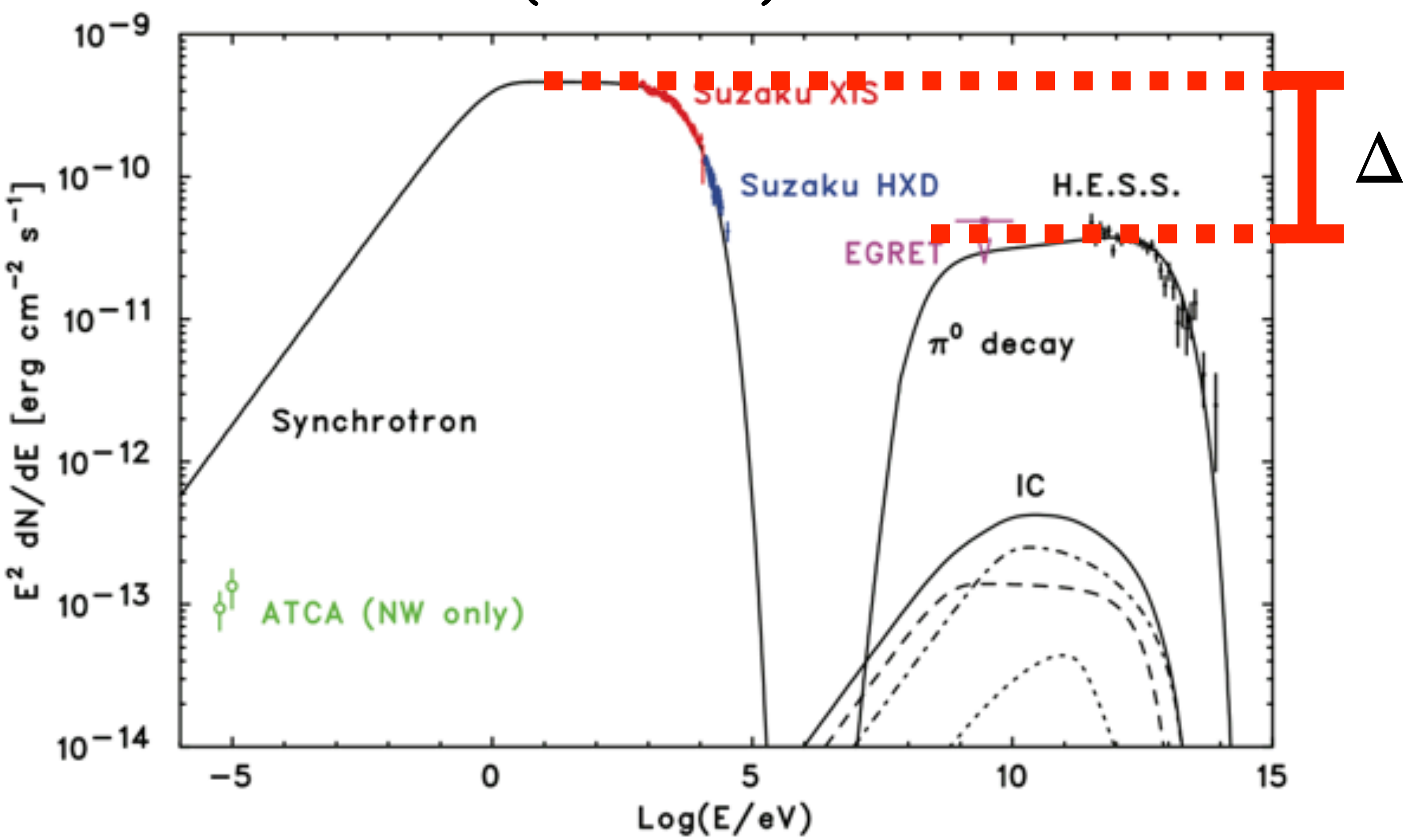


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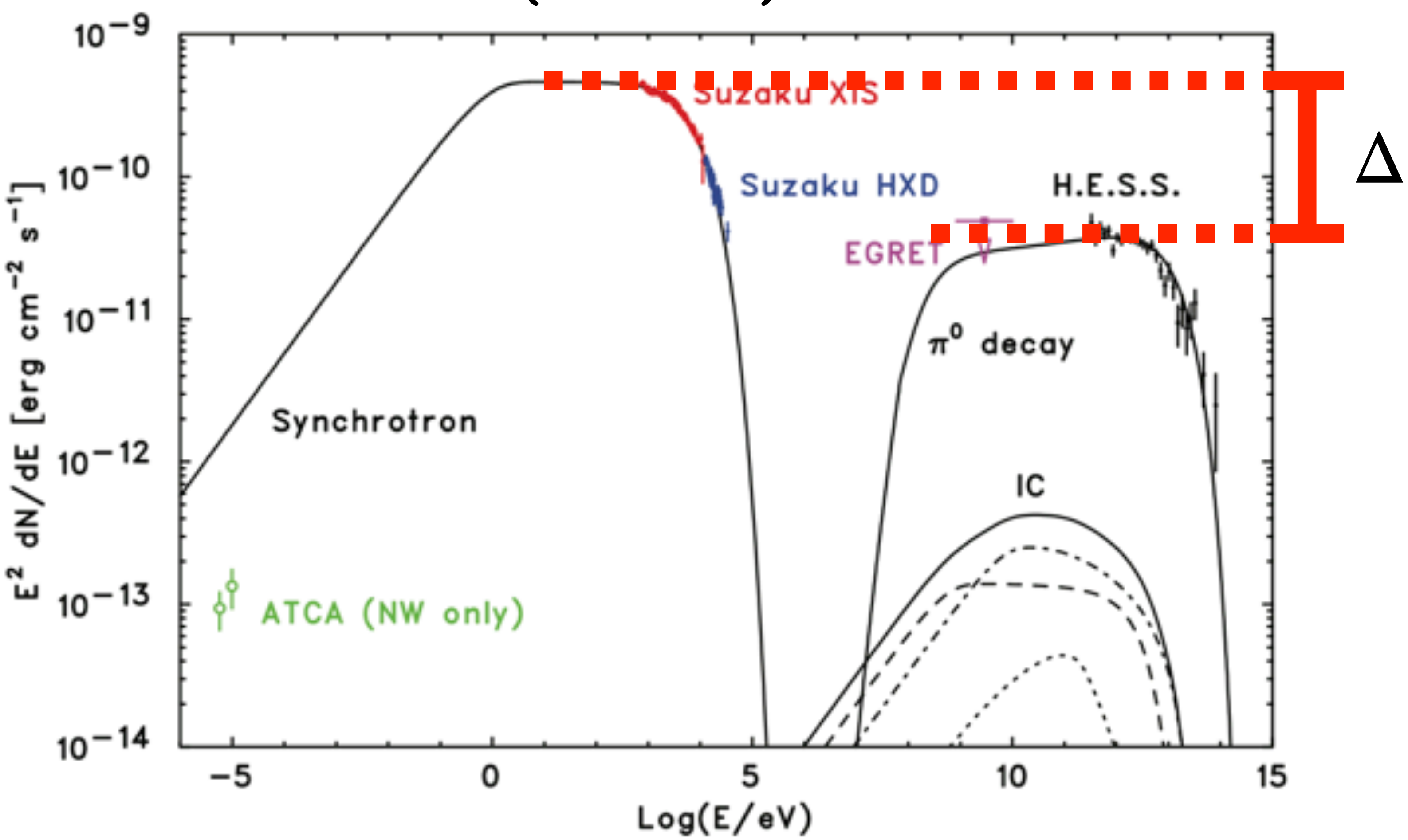


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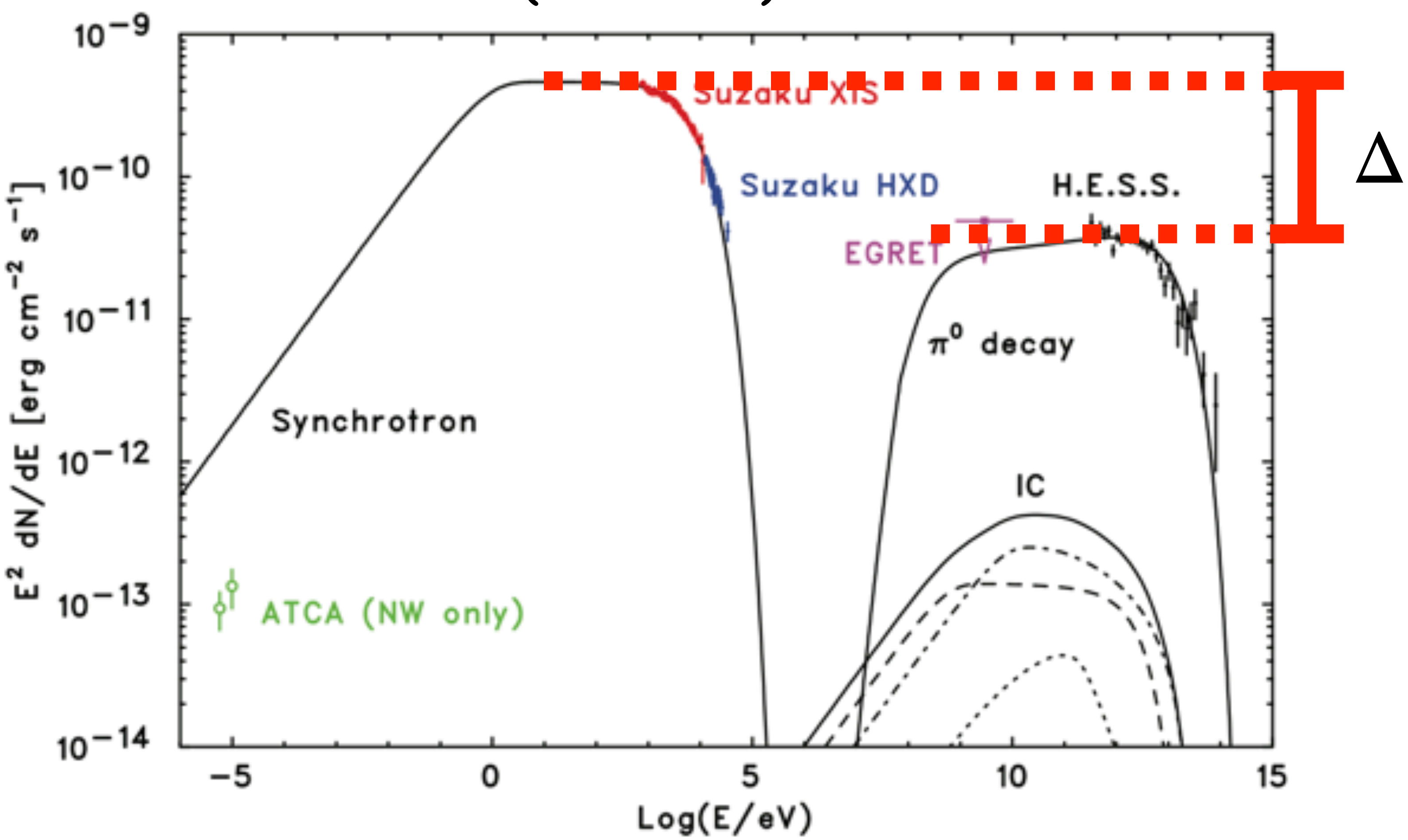


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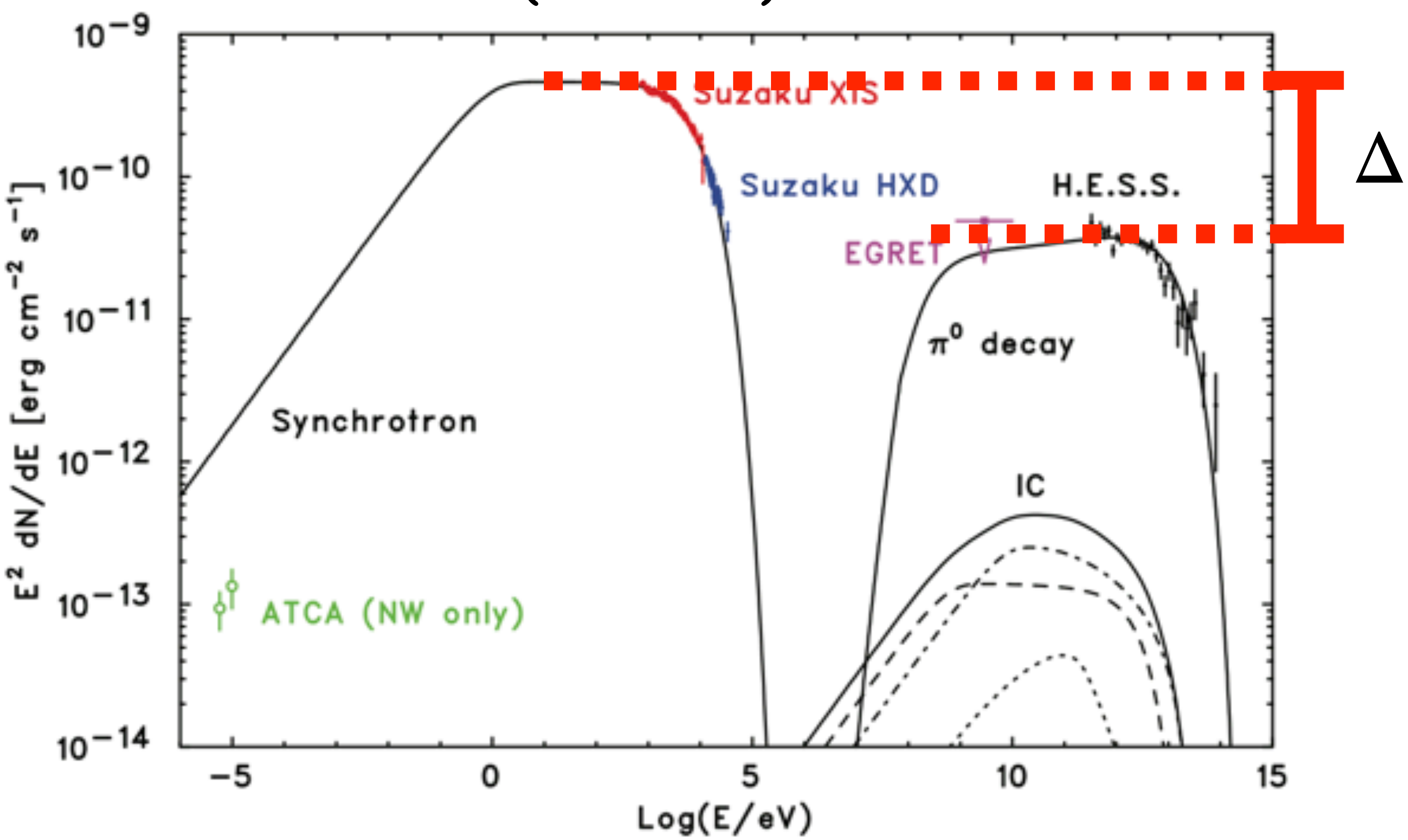


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synchro/ICS losses steepen the spectrum by 1 power

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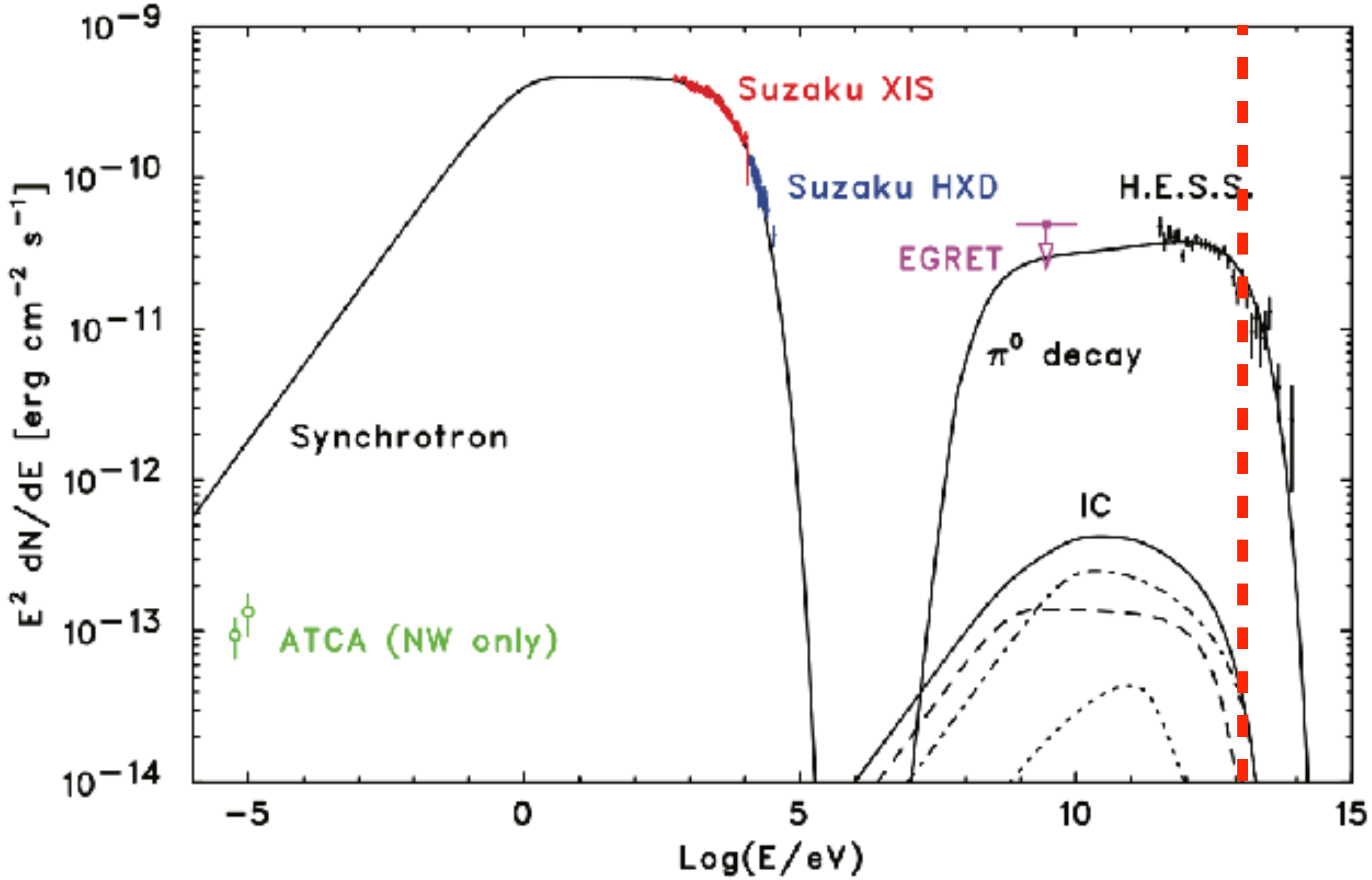
$$E_e \sim 20 \left( \frac{E_\gamma}{TeV} \right)^{1/2} \text{TeV} \longrightarrow \text{E}_\gamma^{\text{cool}} \approx 10 \text{ TeV}$$

in gammas, the spectrum is cooled above 10 TeV

# Predicted leptonic gamma-ray spectrum



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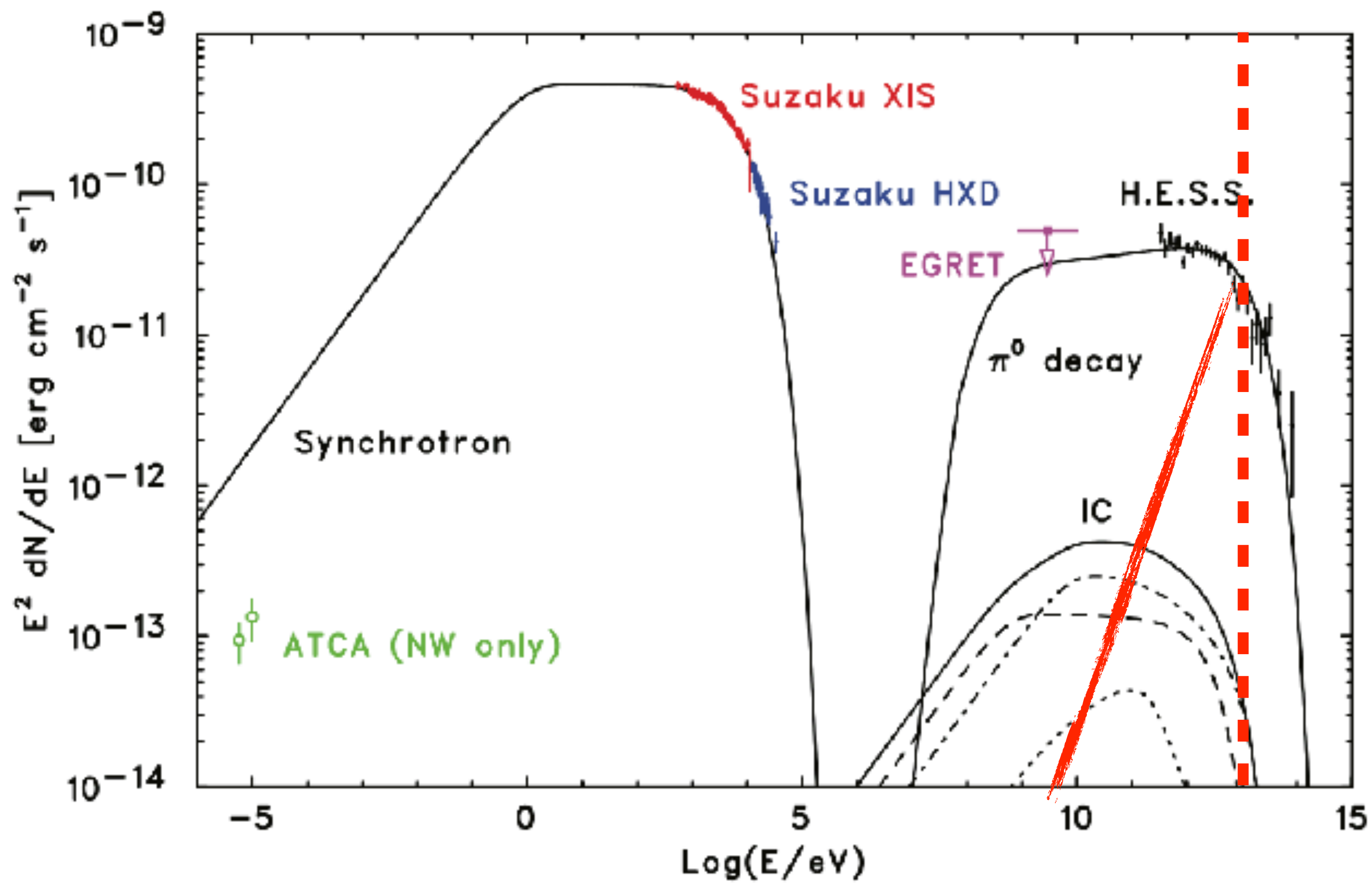

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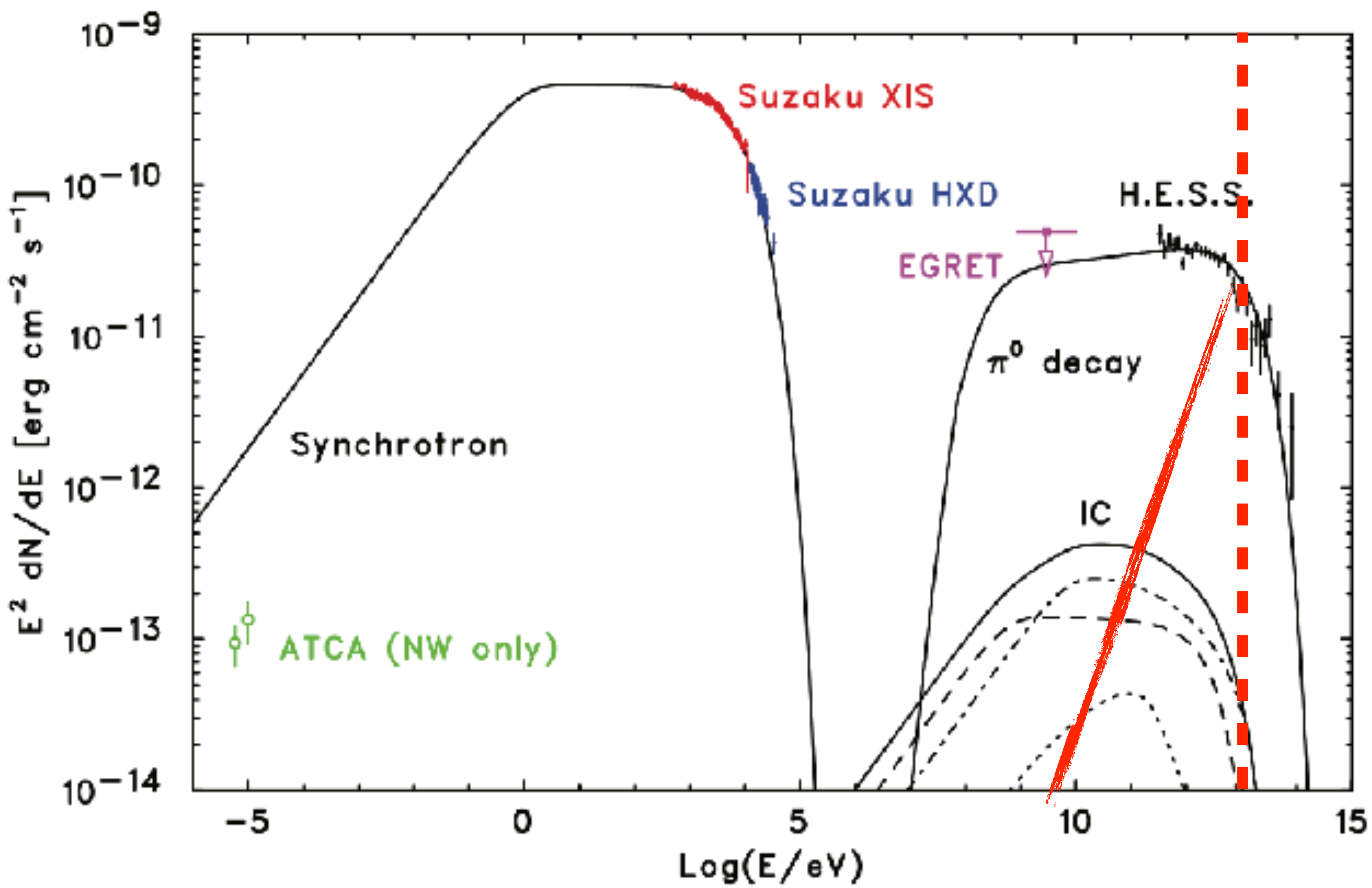

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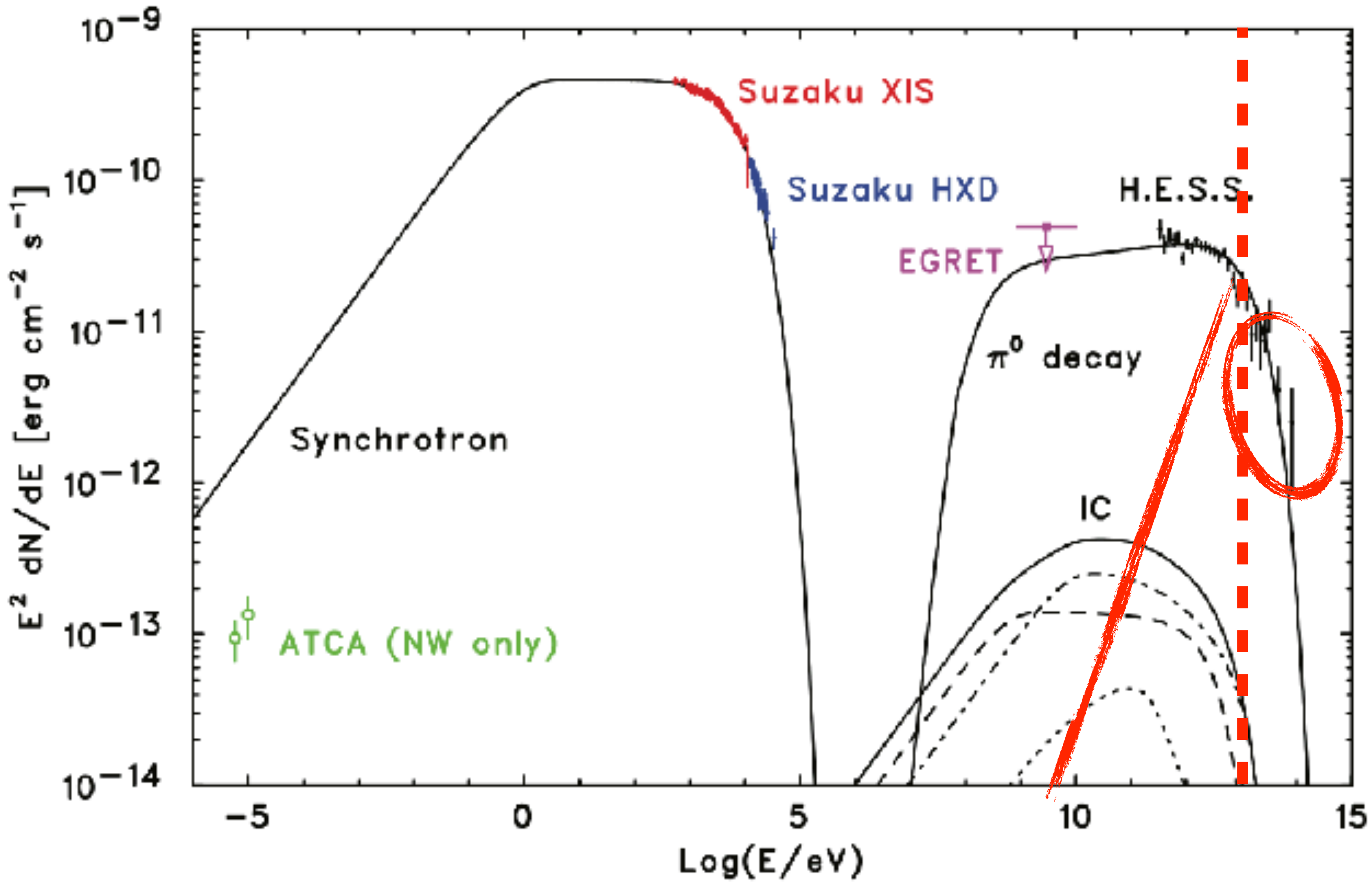


cutoff —> maximum energy of accelerated particles…

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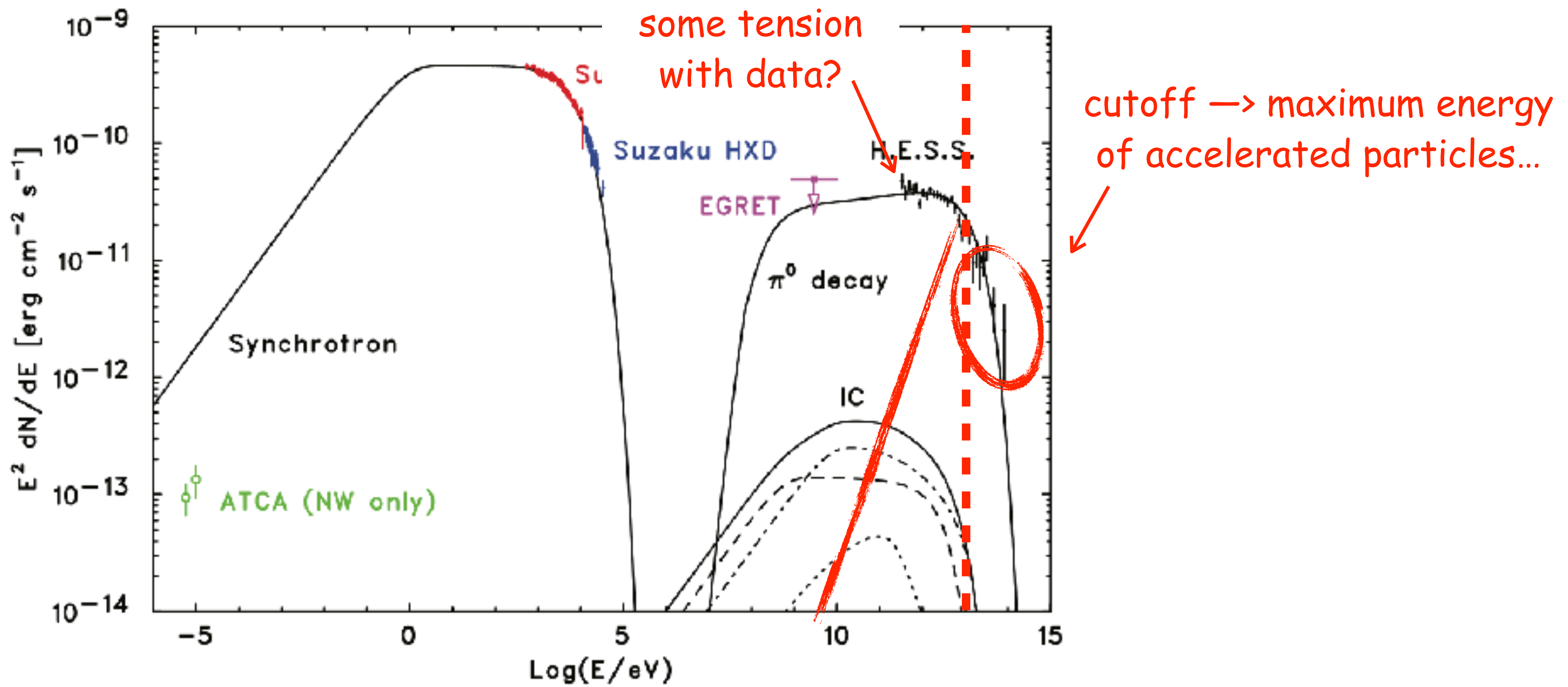
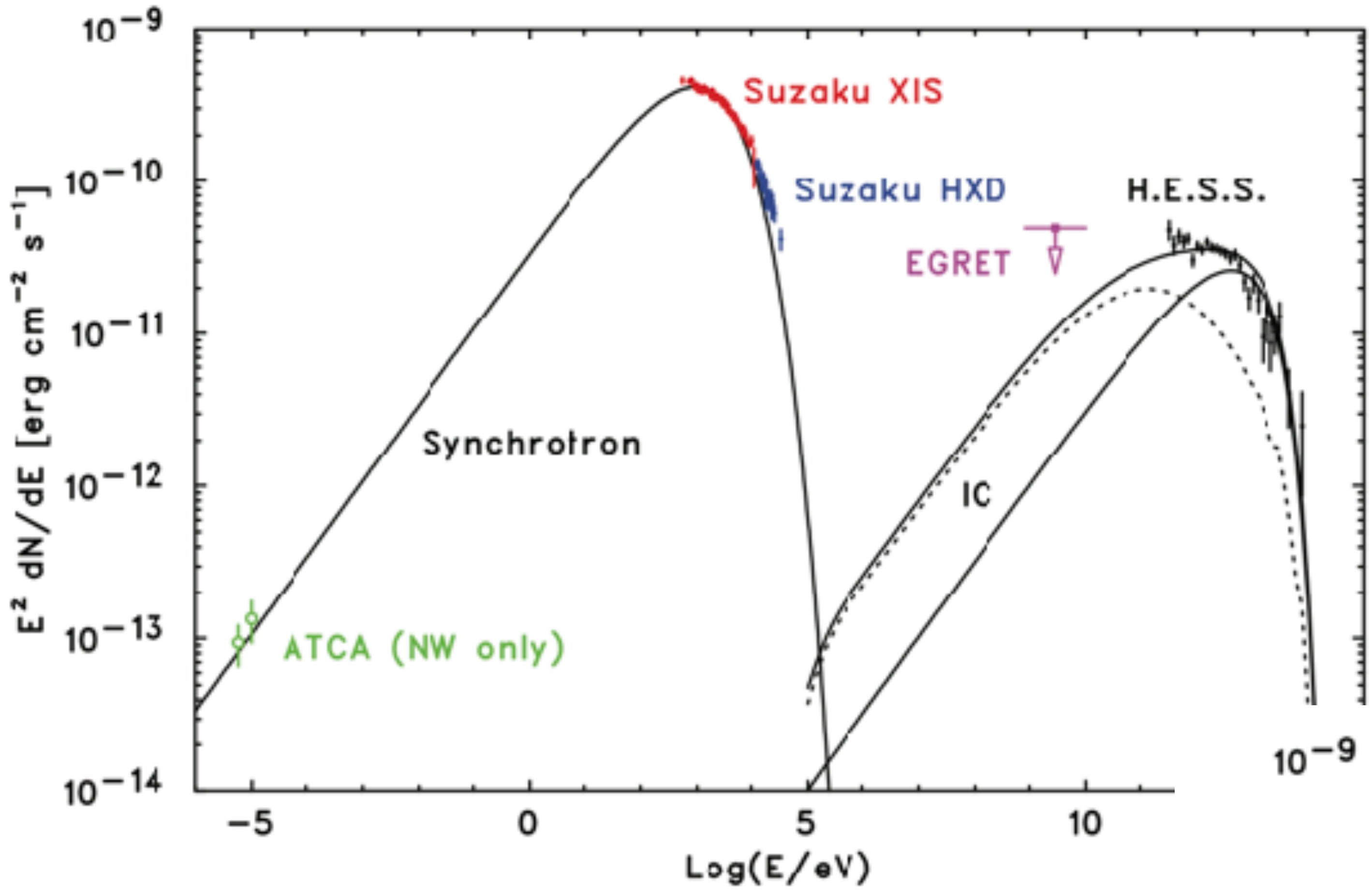
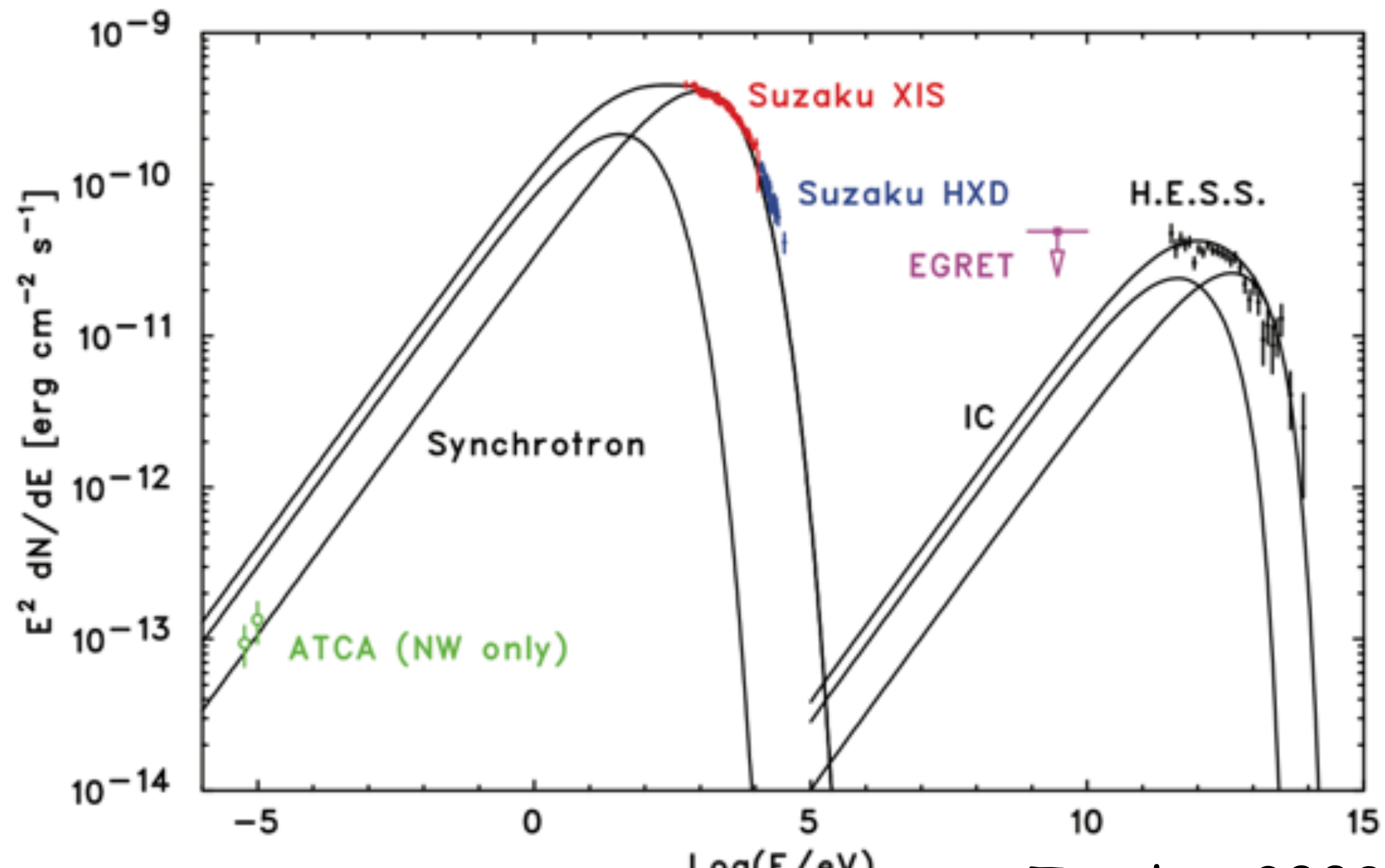


# Saving the leptonic model

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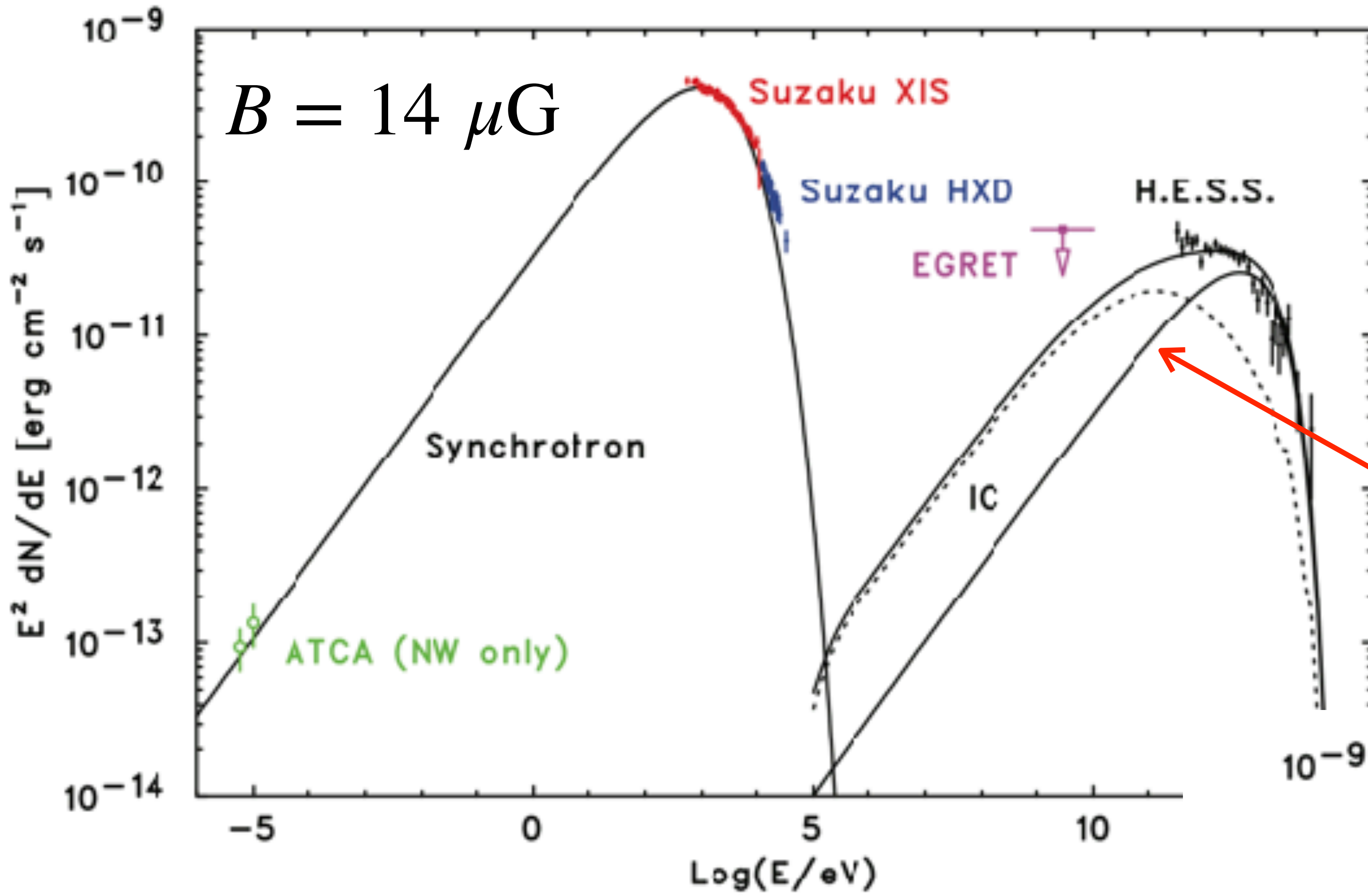
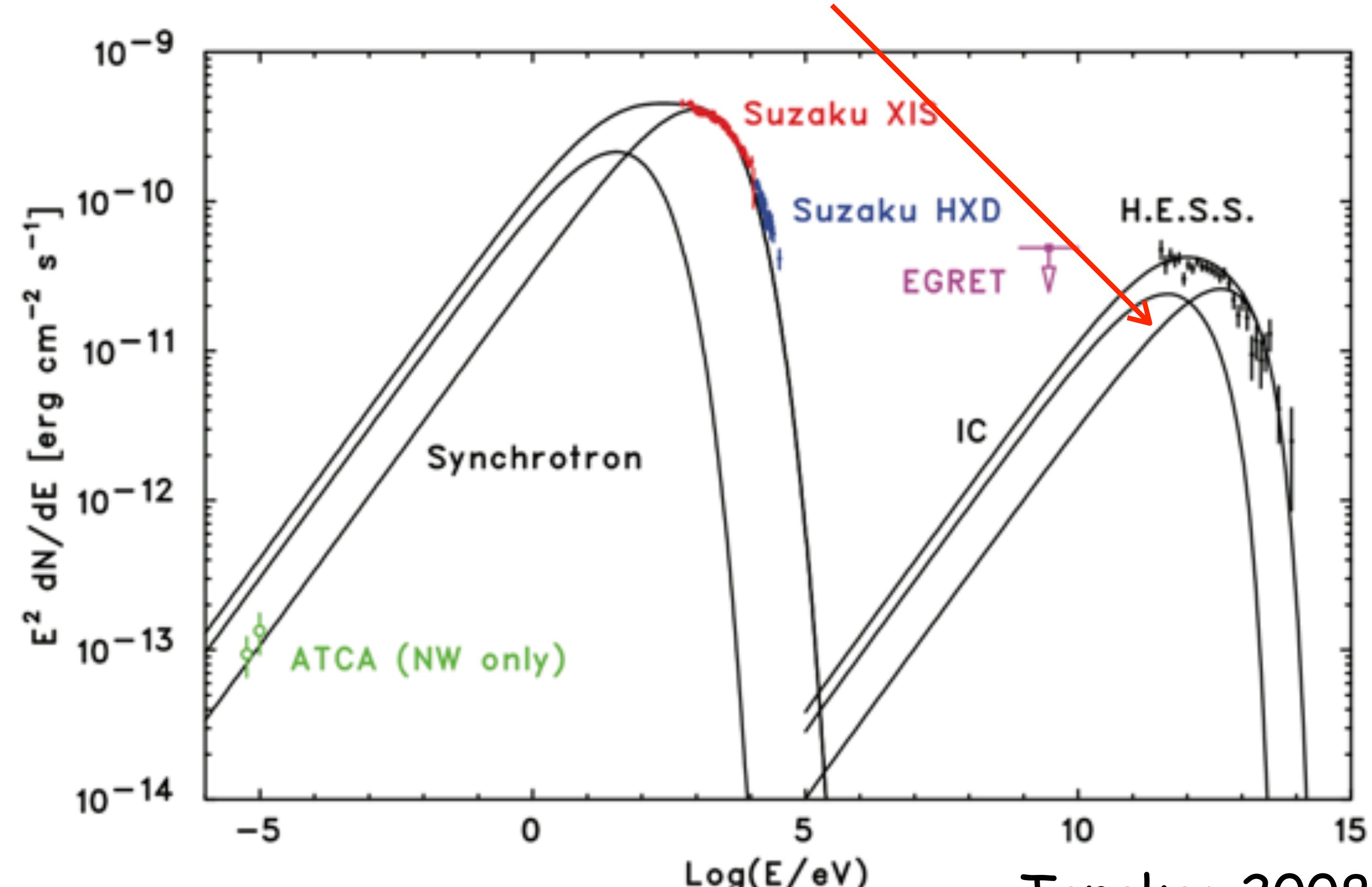



consistent with our rough estimate!

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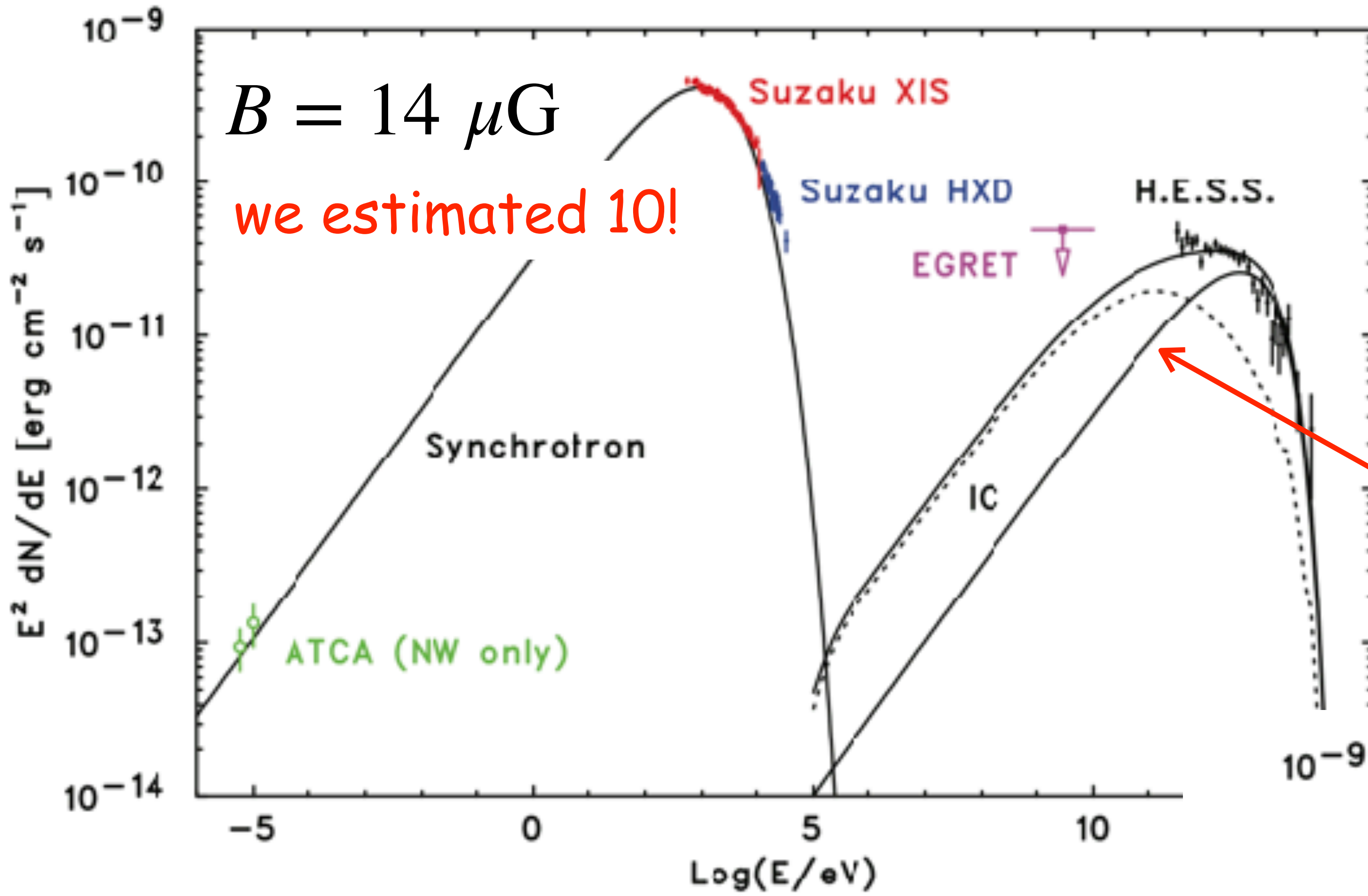


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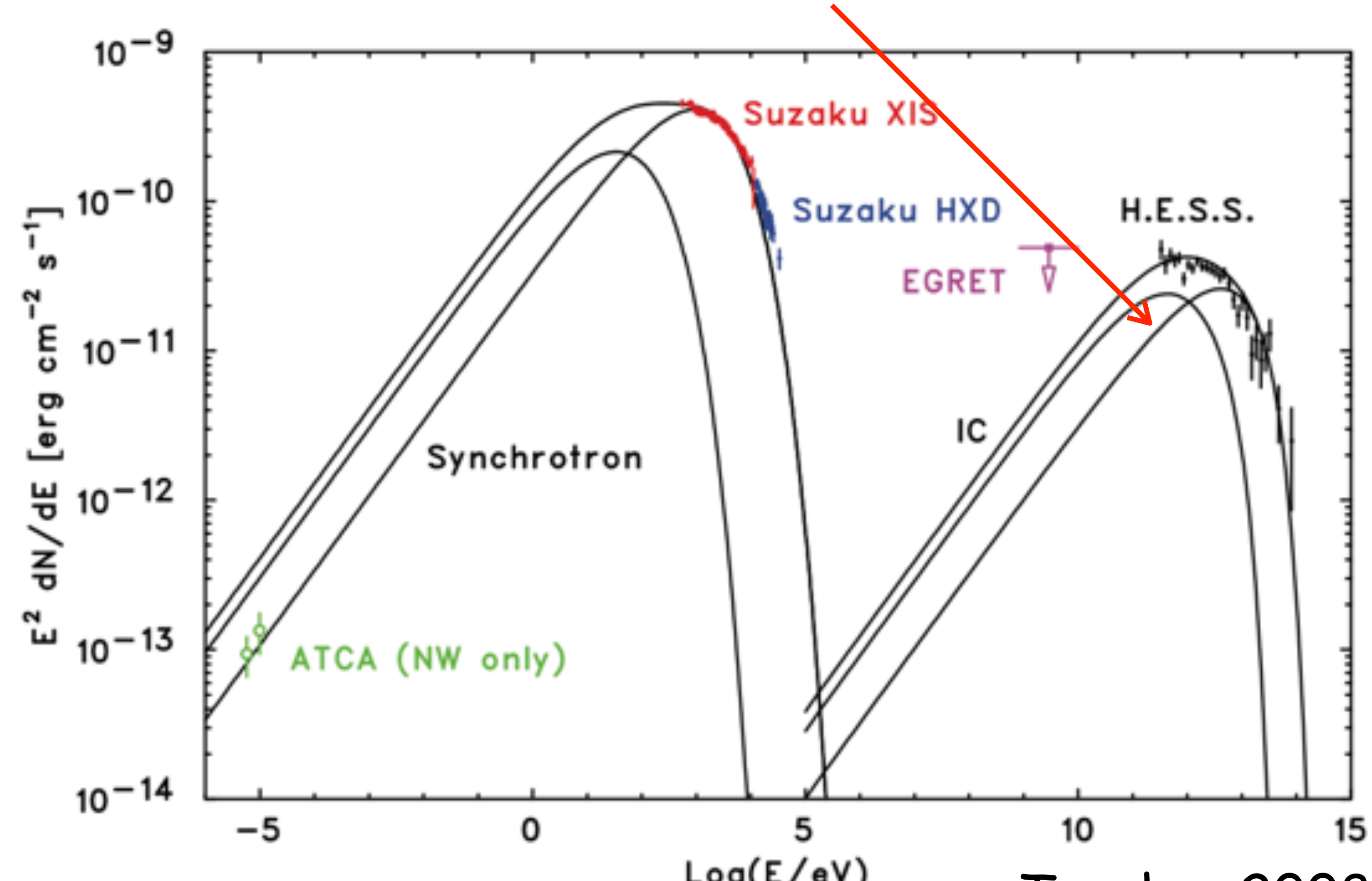


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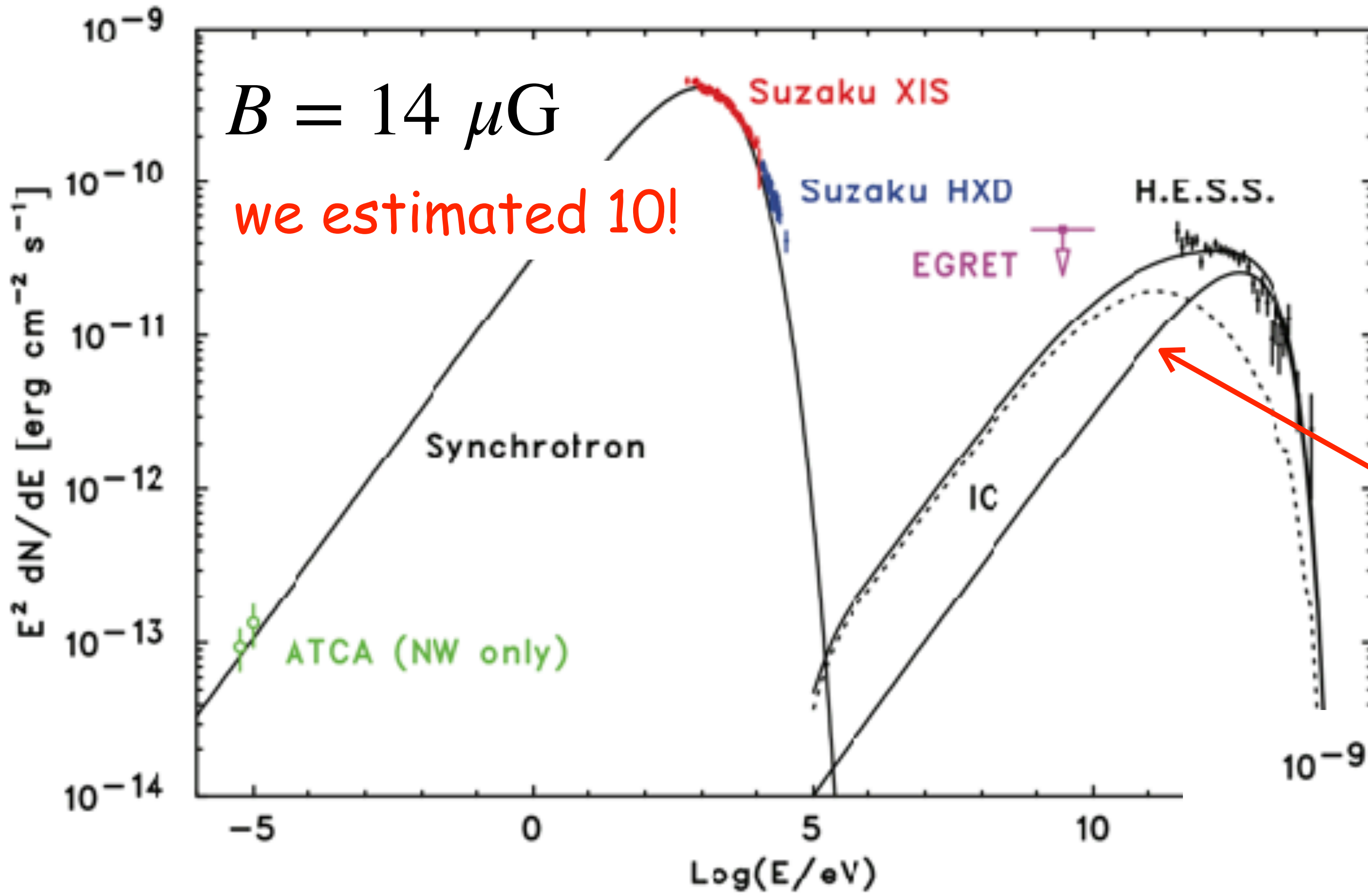
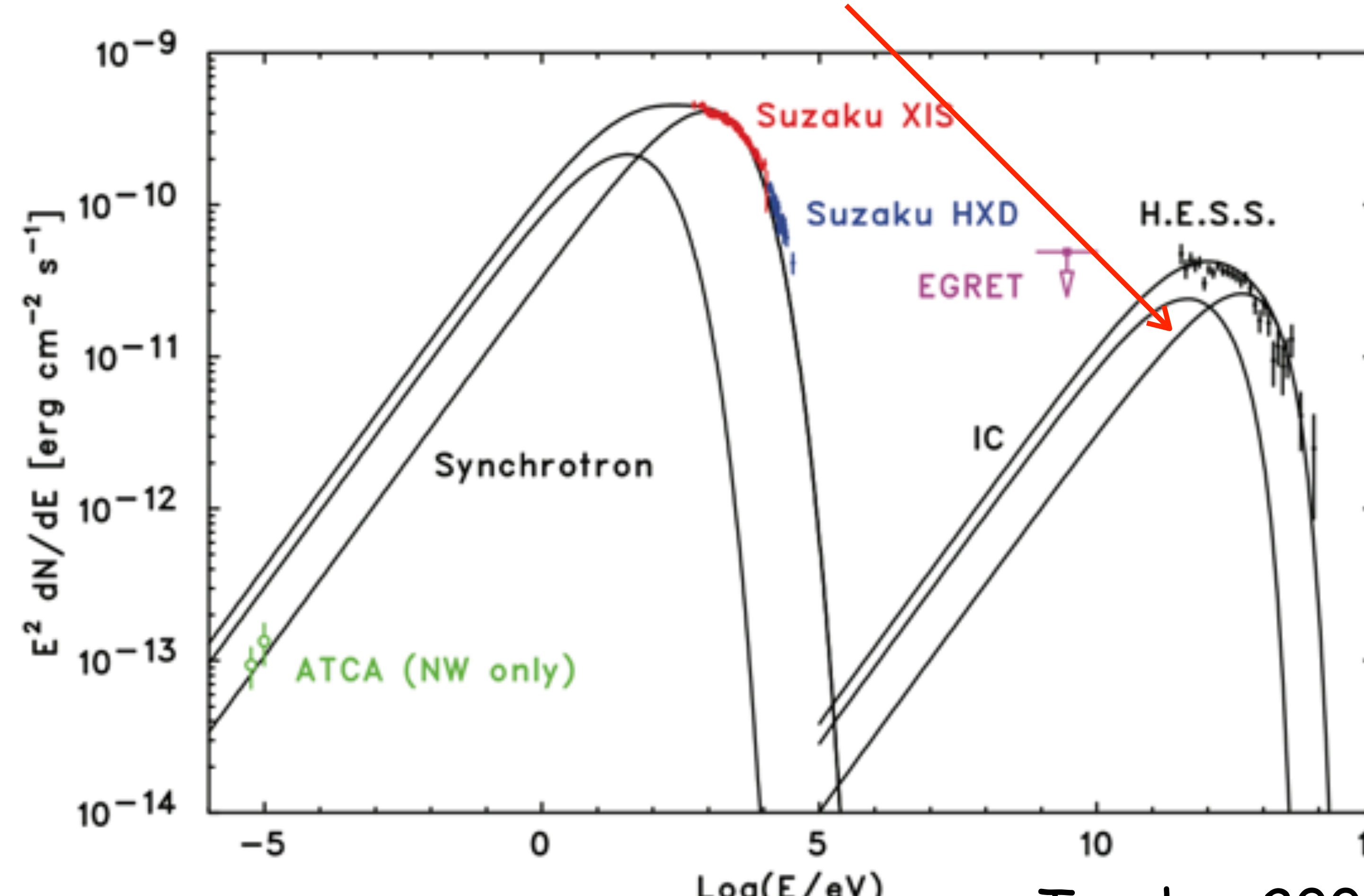



$$W_e \sim 1.4 \times 10^{47}\mathrm{erg}$$

small !

consistent with our rough estimate!

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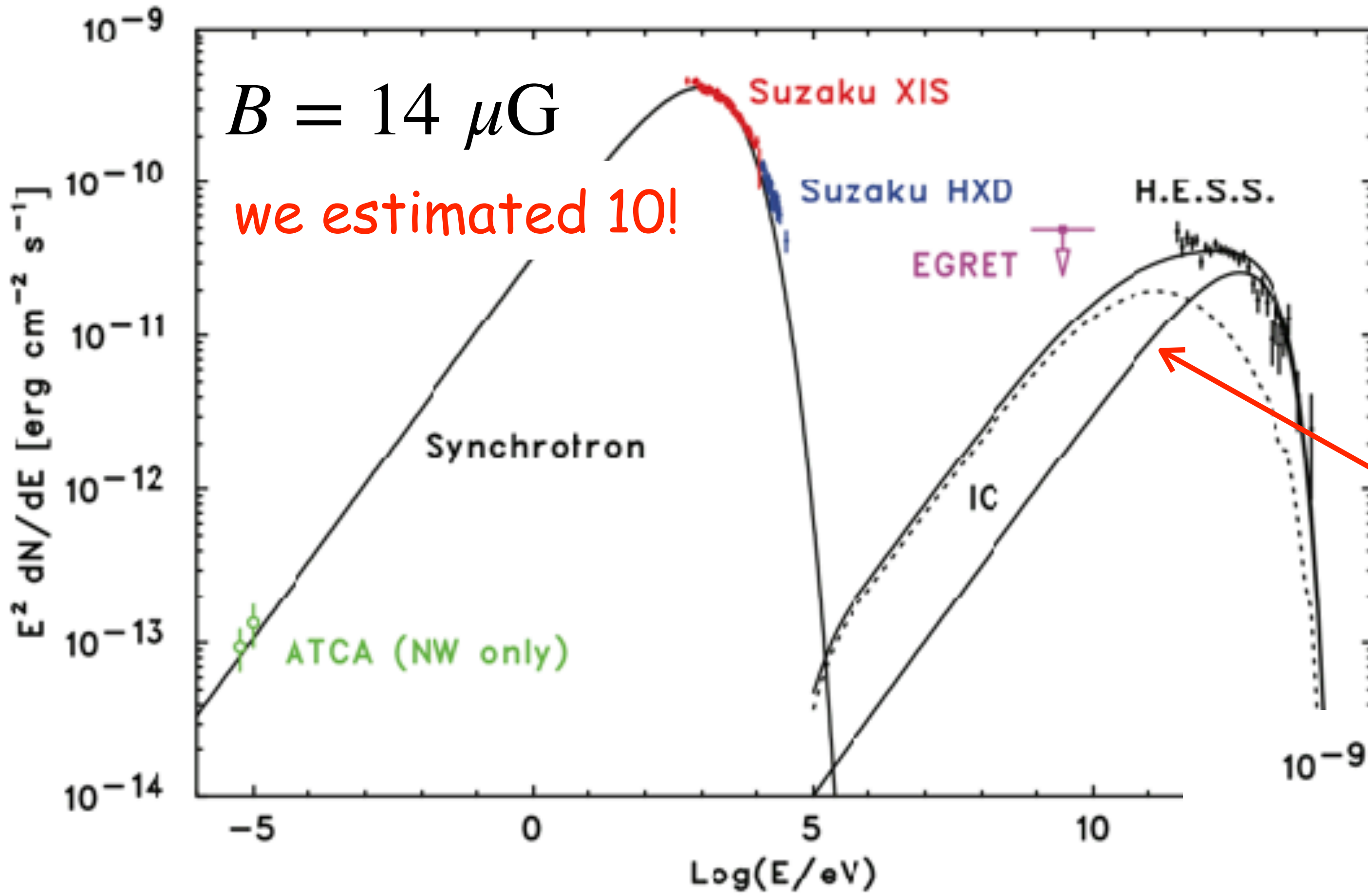


<- add (optical) radiation field

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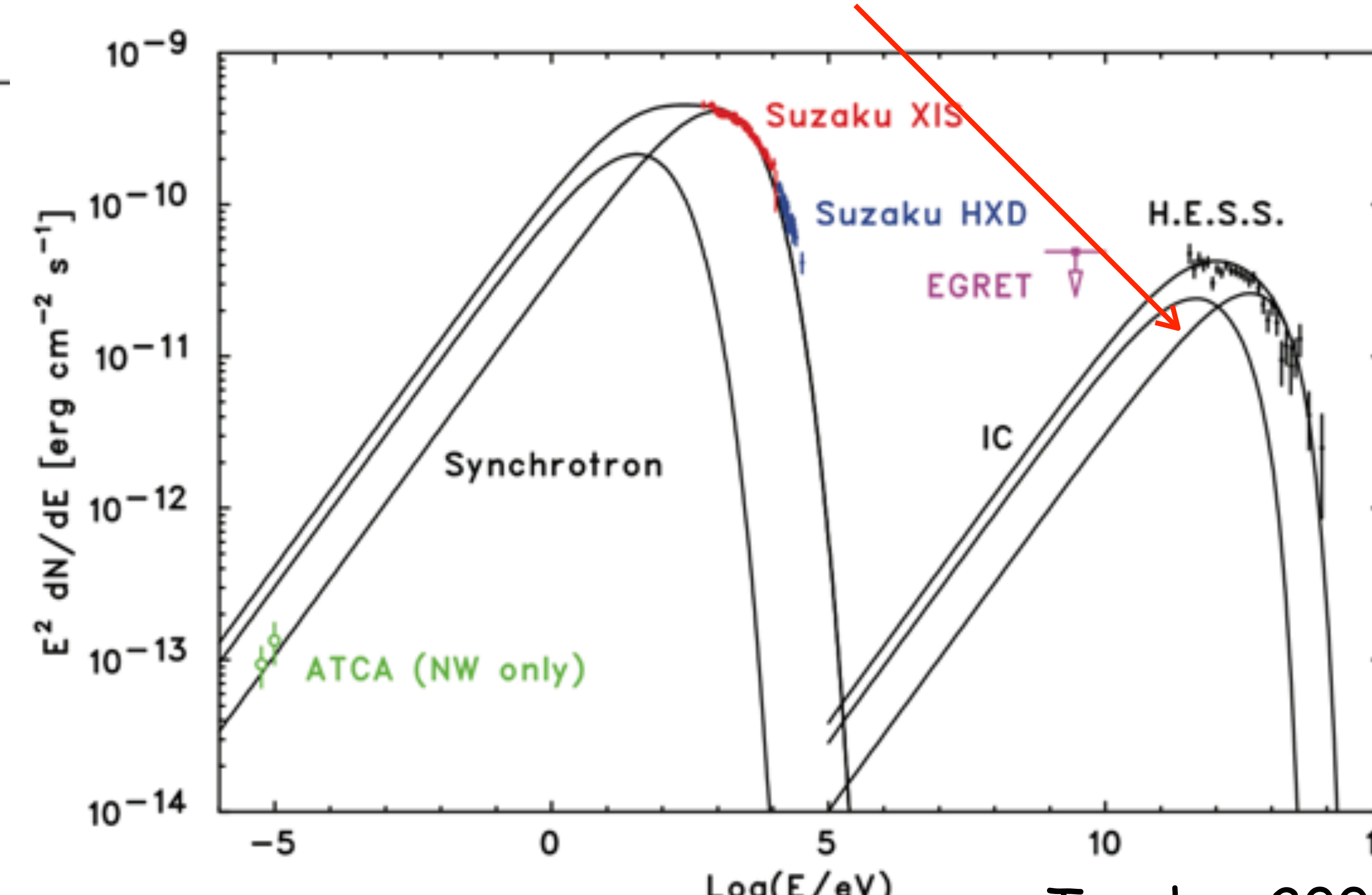


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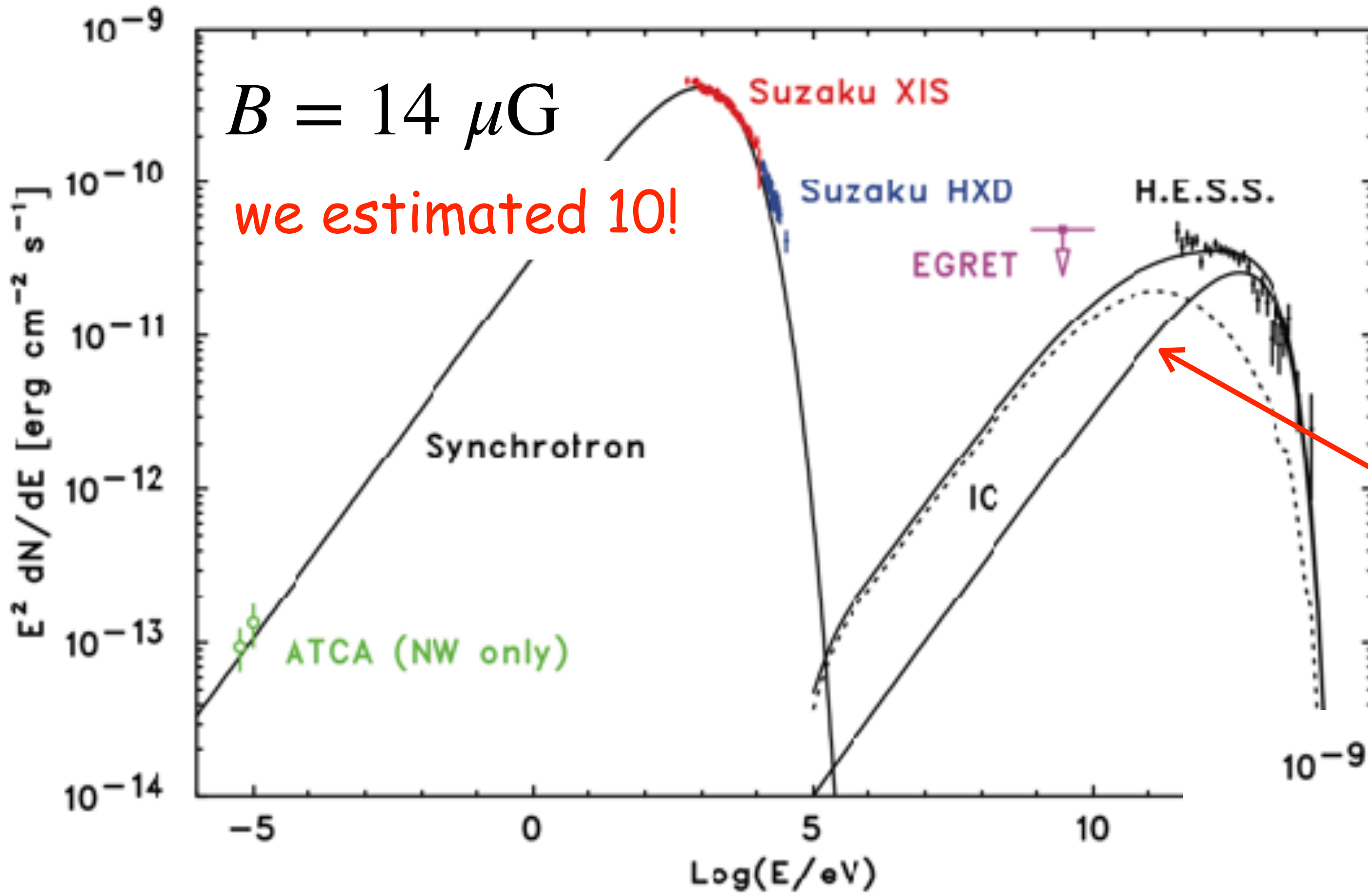



we estimated 10!

<— add (optical) radiation field

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

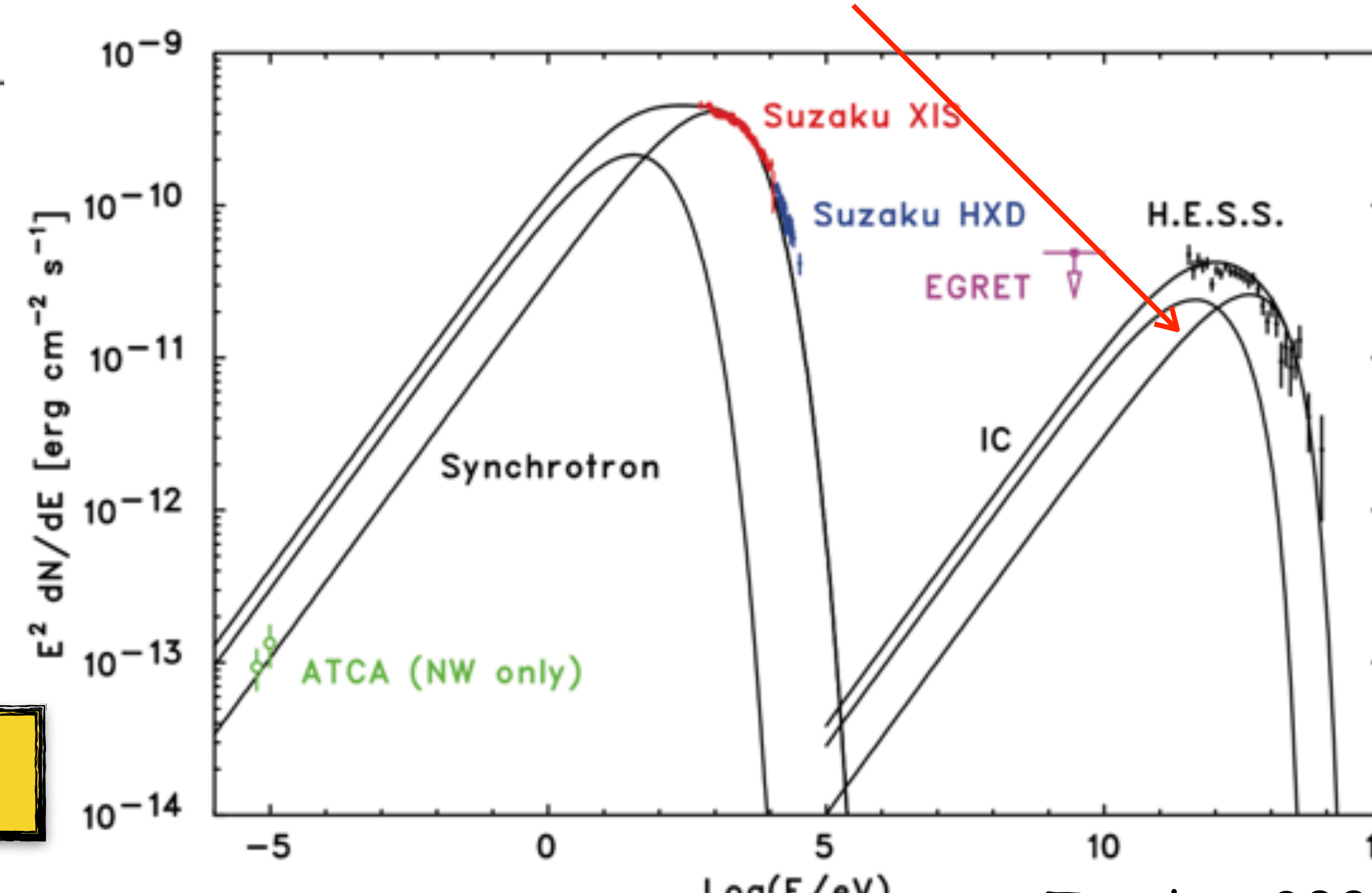
small !

consistent with our rough estimate!

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

small !

add another population —>

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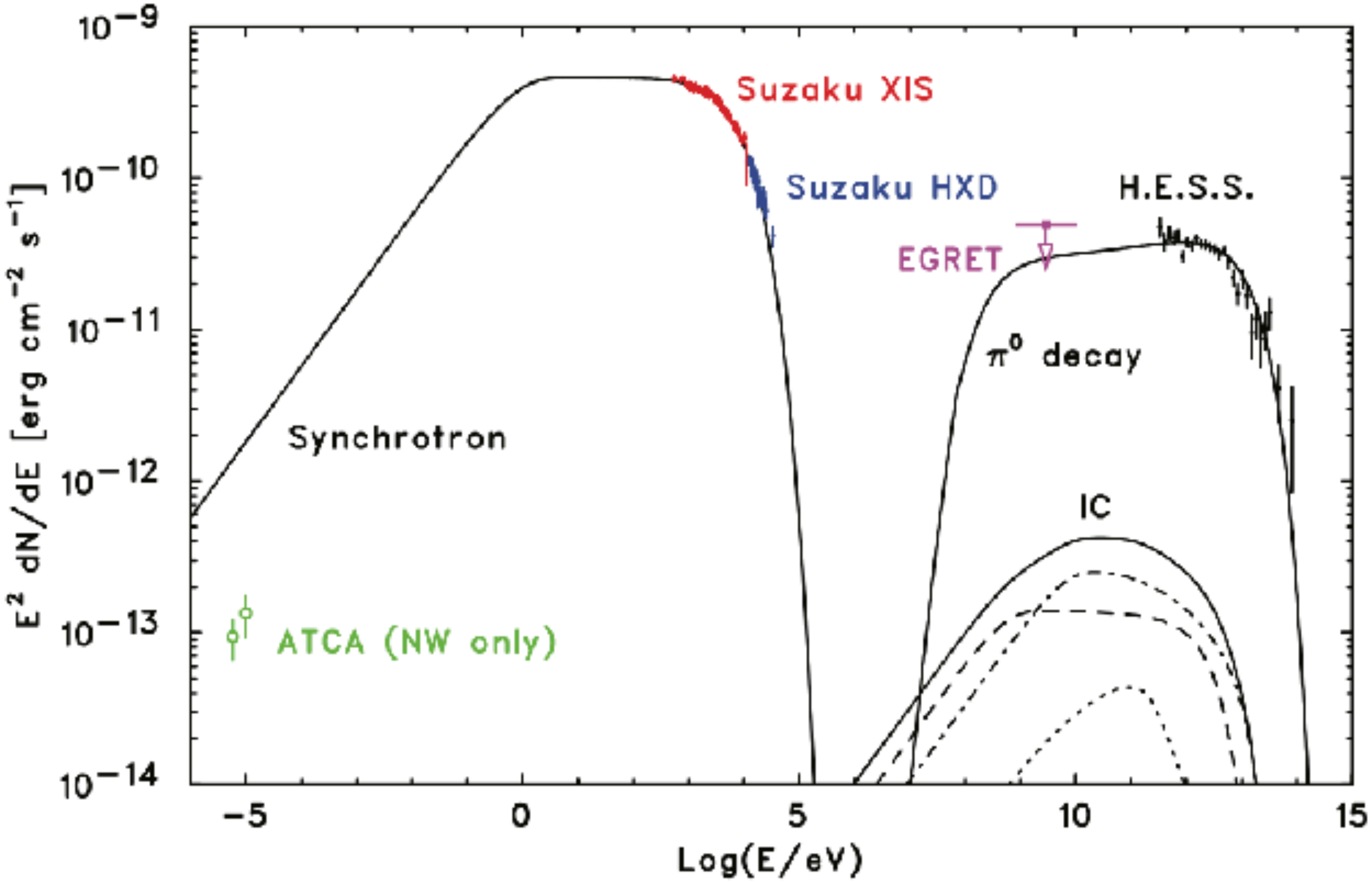
# Hadronic model




Tanaka+ 2008

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CR protons do not cool ! —>

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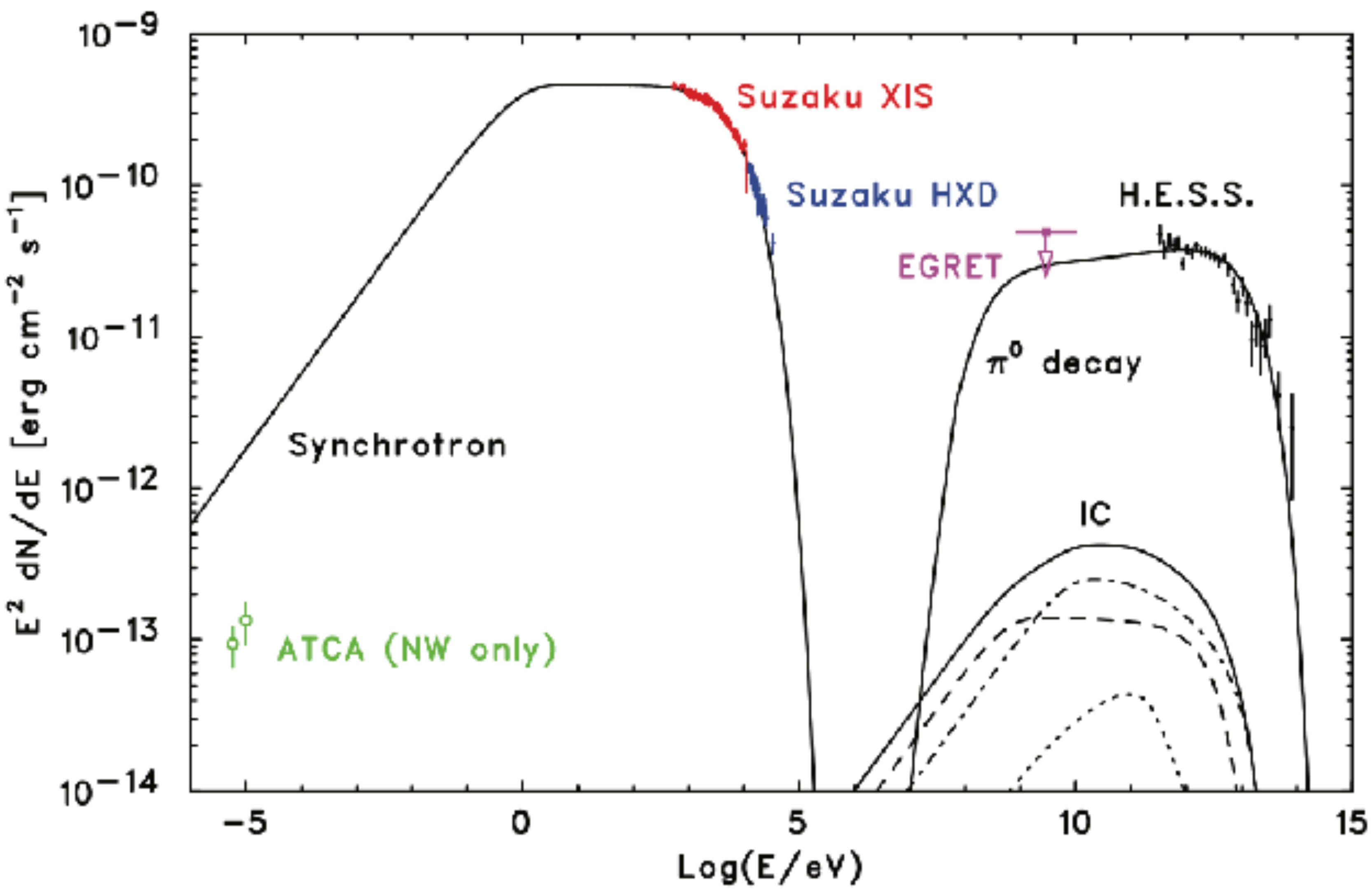


Tanaka+ 2008

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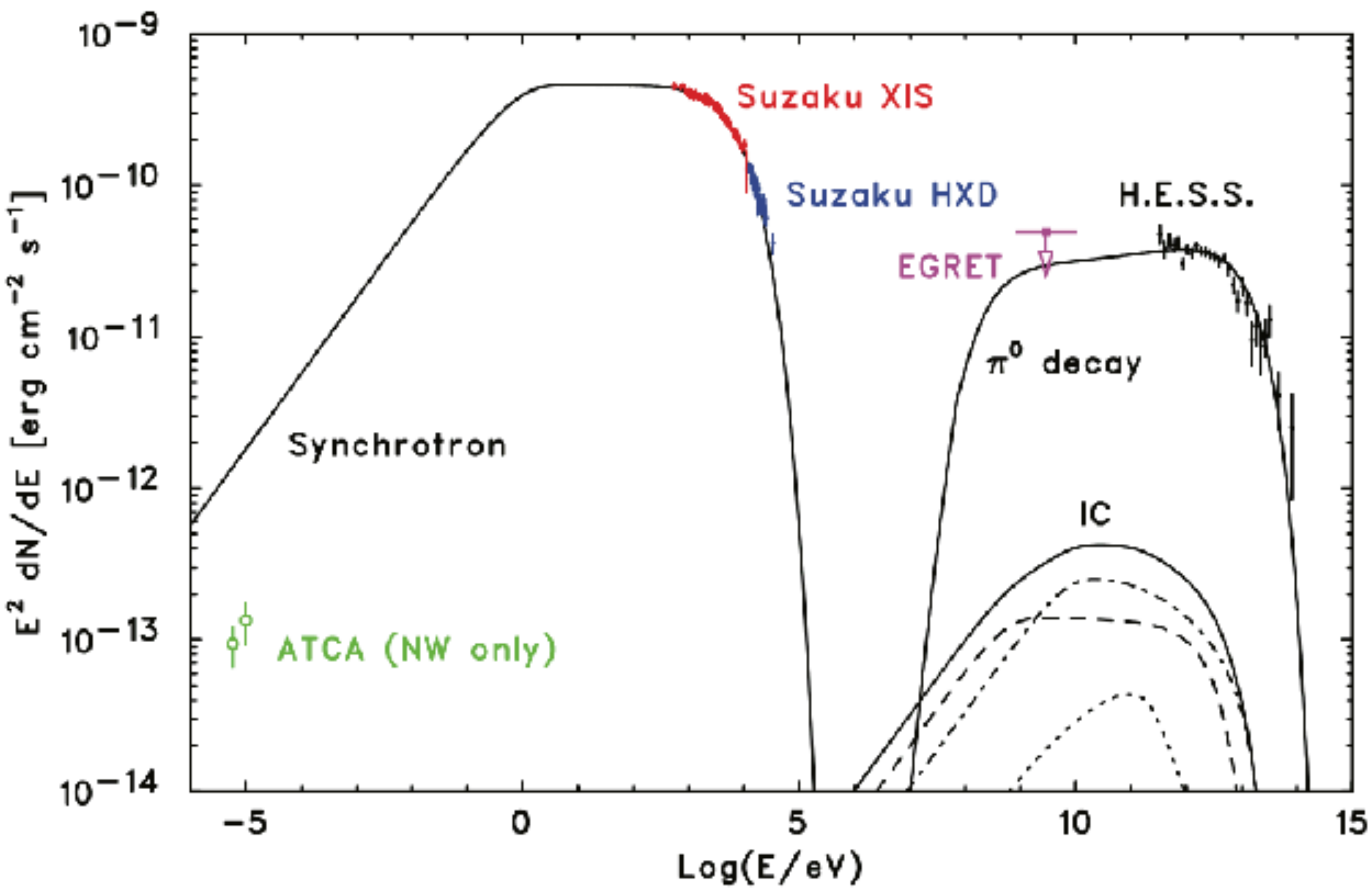


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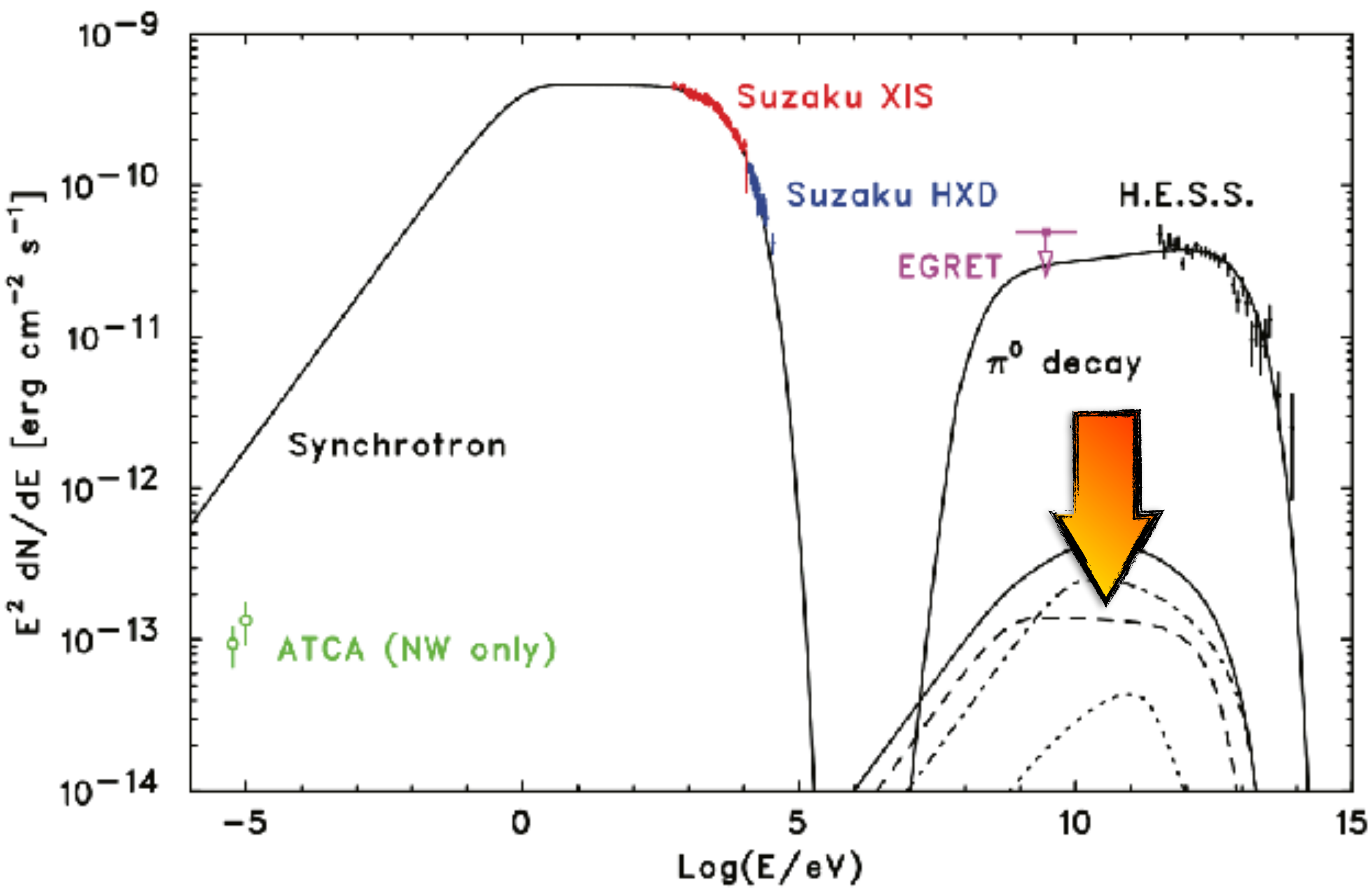
to kill inverse Compton!




Tanaka+ 2008

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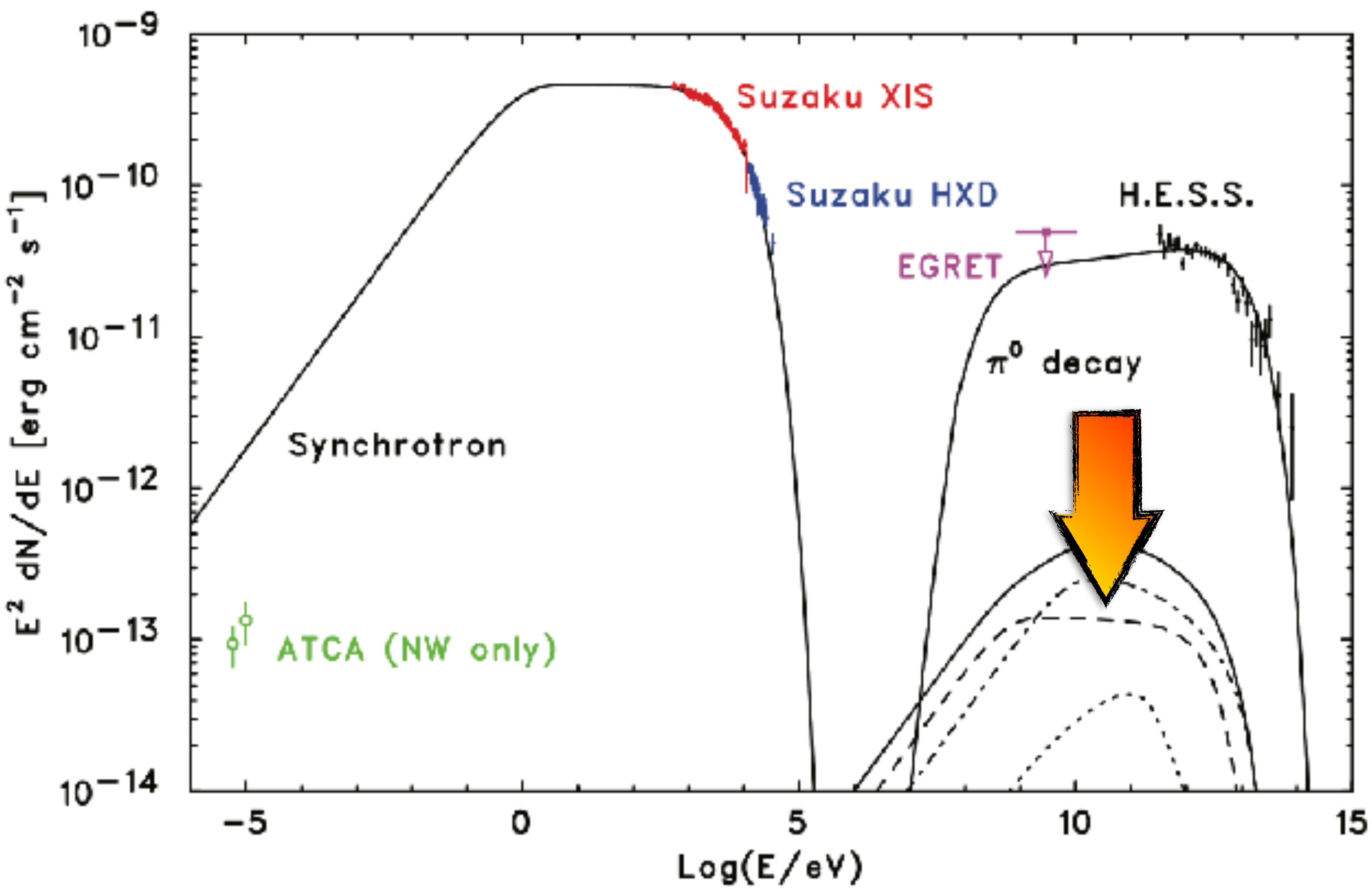


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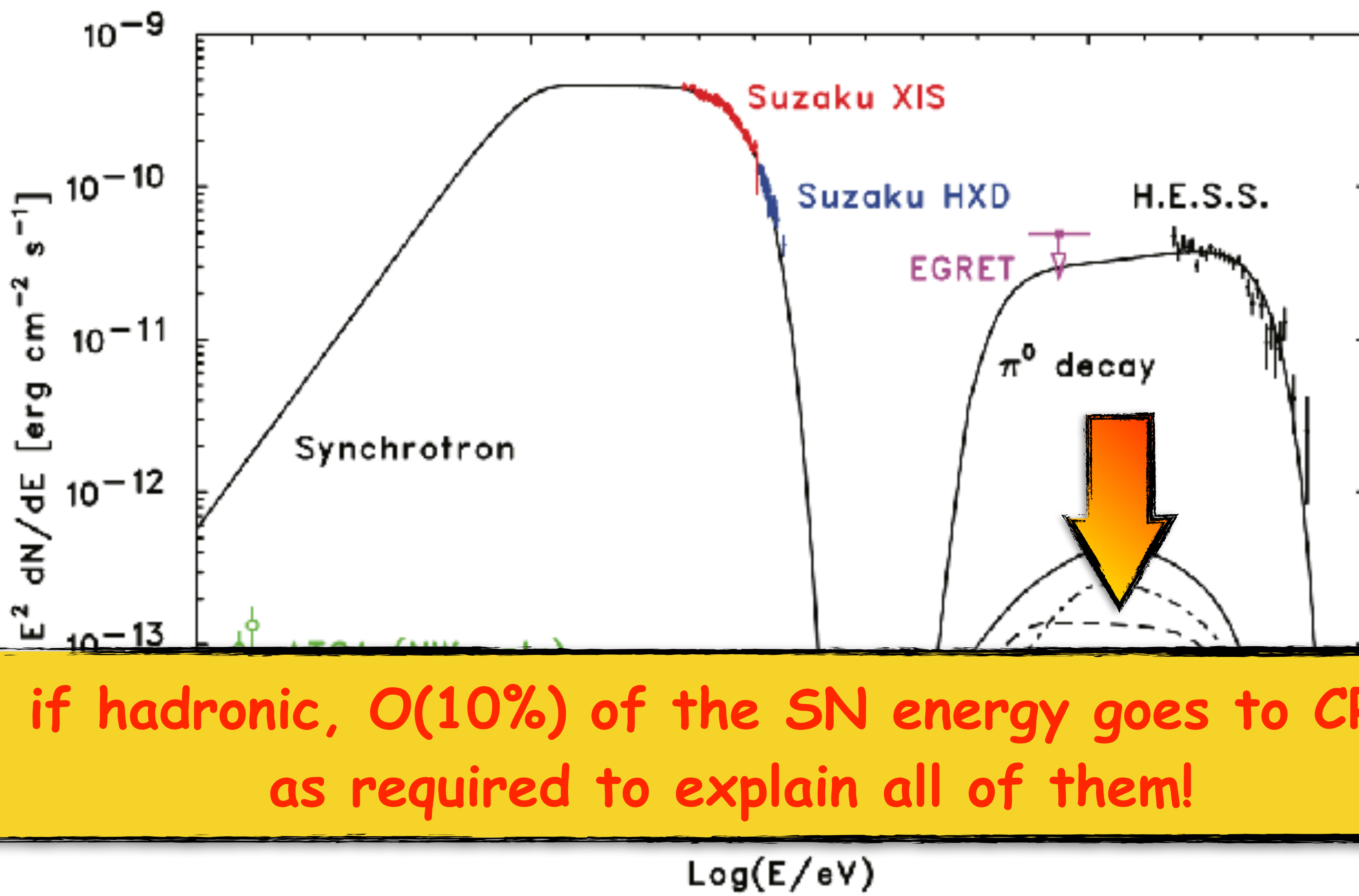


if hadronic, O(10%) of the SN energy goes to CRs, as required to explain all of them!

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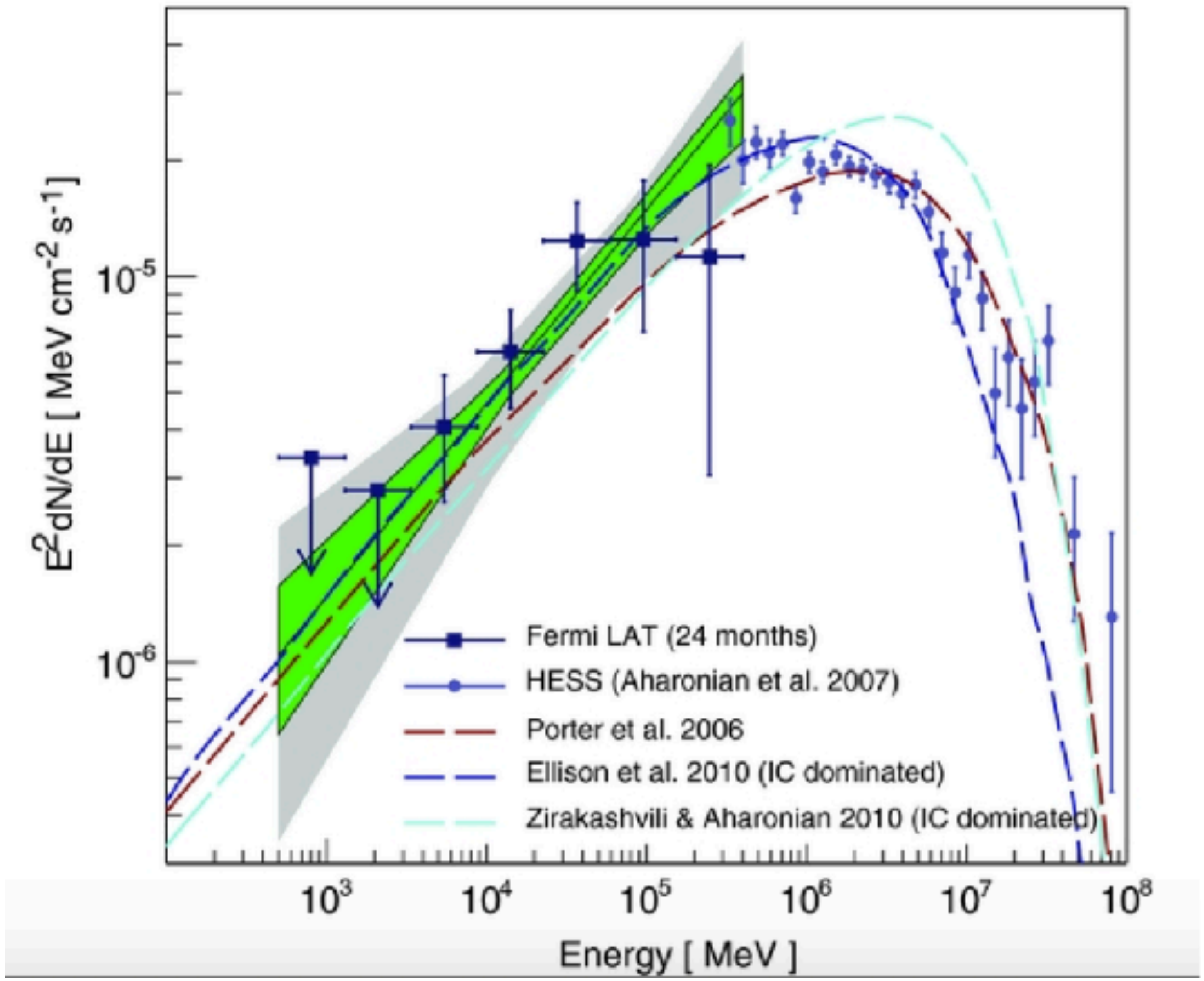
[End of Inset 2]

# Fermi spectrum

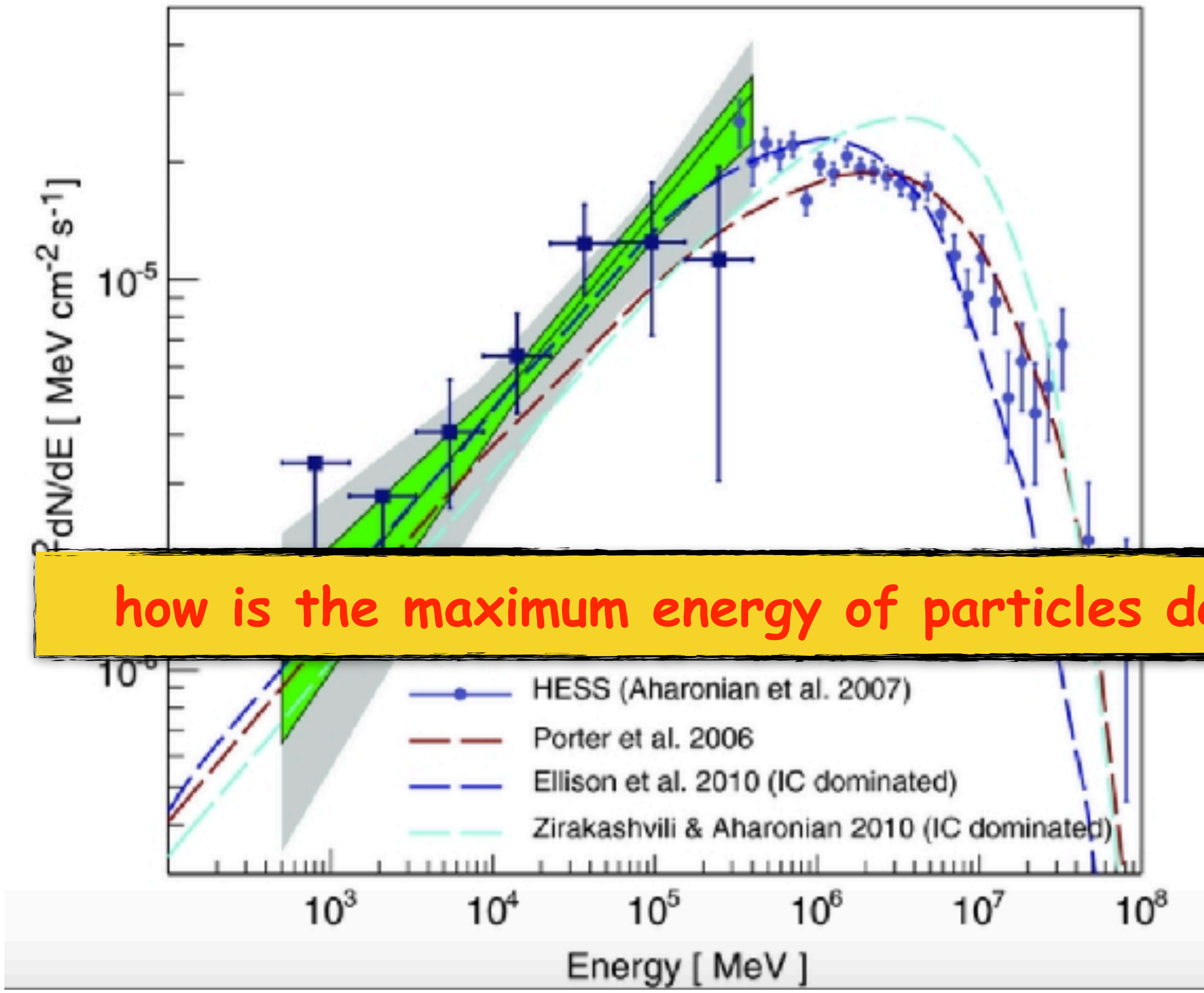
Fermi data are more consistent with leptonic models




Abdo+ 2011

# Why do we see a cutoff?

what can we learn from the position off the cutoff?




how is the maximum energy of particles determined?

$$E_{cut} = 12.9 \pm 1.1 \text{ TeV} \quad \longrightarrow E^p_{max} \sim 130 \text{ TeV}$$

$$\longrightarrow E^e_{max} \sim 70 \text{ TeV}$$

[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

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

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A particle of charge q moving at a velocity u fill experience a force:

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

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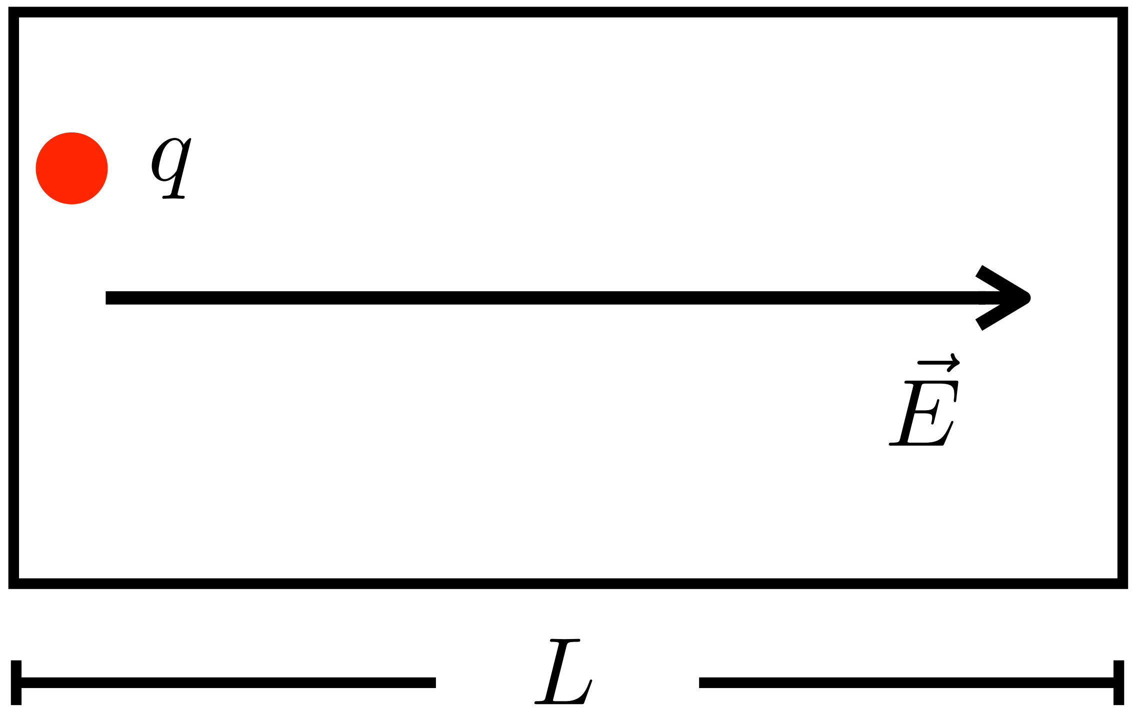
Lorentz force
$\perp$ to velocity —>
doesn't change
the particle energy!

# Maximum energy

this is an accelerator



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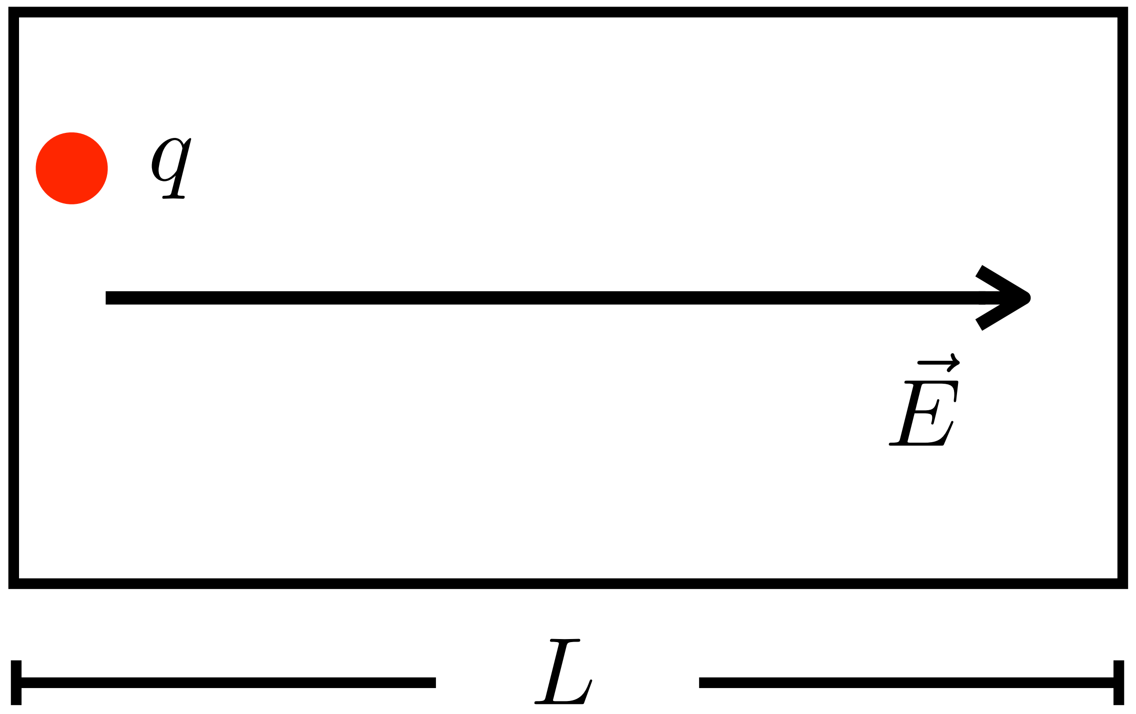


$$E_t^{max} = qEtc = qEL$$

large accelerator

large charge

strong E field

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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."

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**So, the answer is no…**

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

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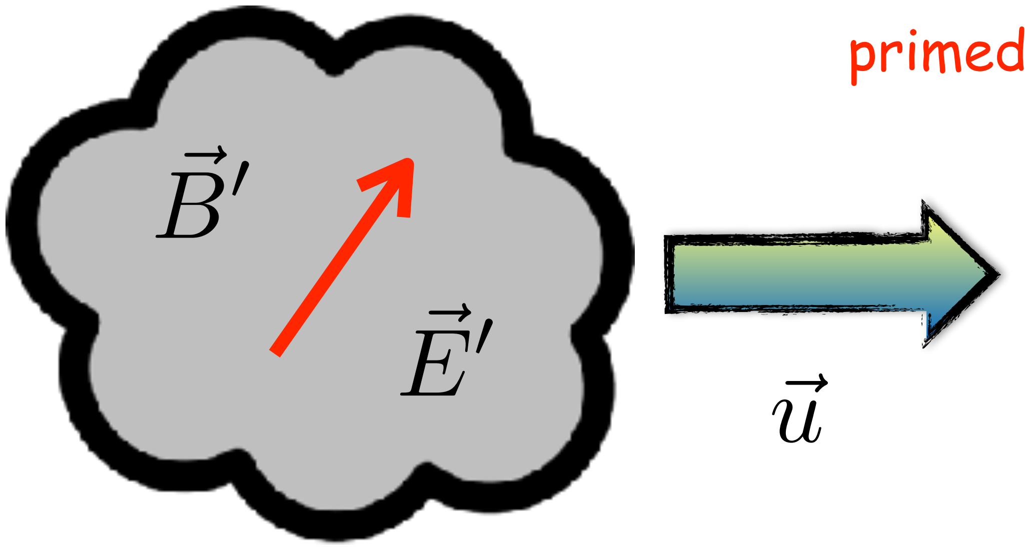
A time varying magnetic field acts as a source of electric field!

# An equivalent way: change rest frame

**Consider a magnetised cloud of plasma moving at a (non relativistic) velocity u**

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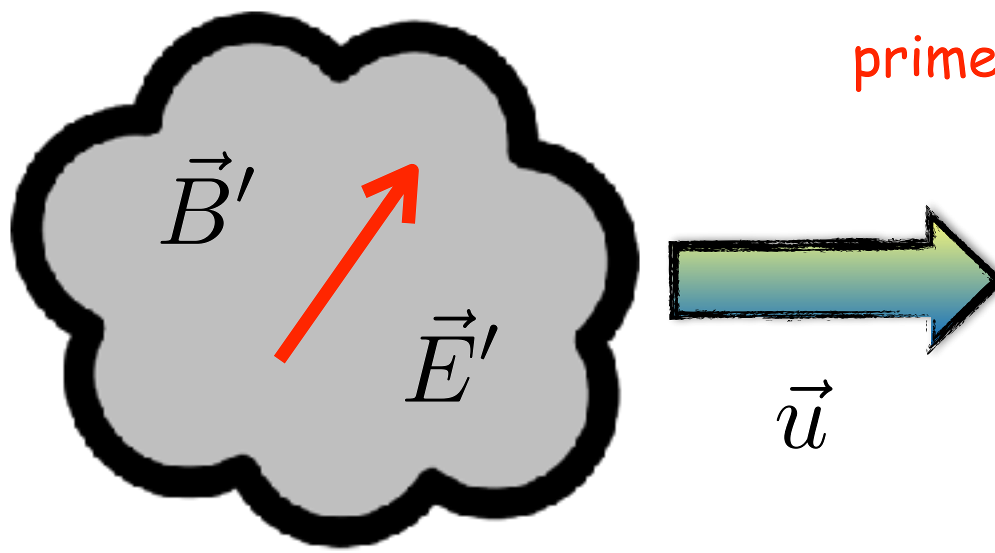


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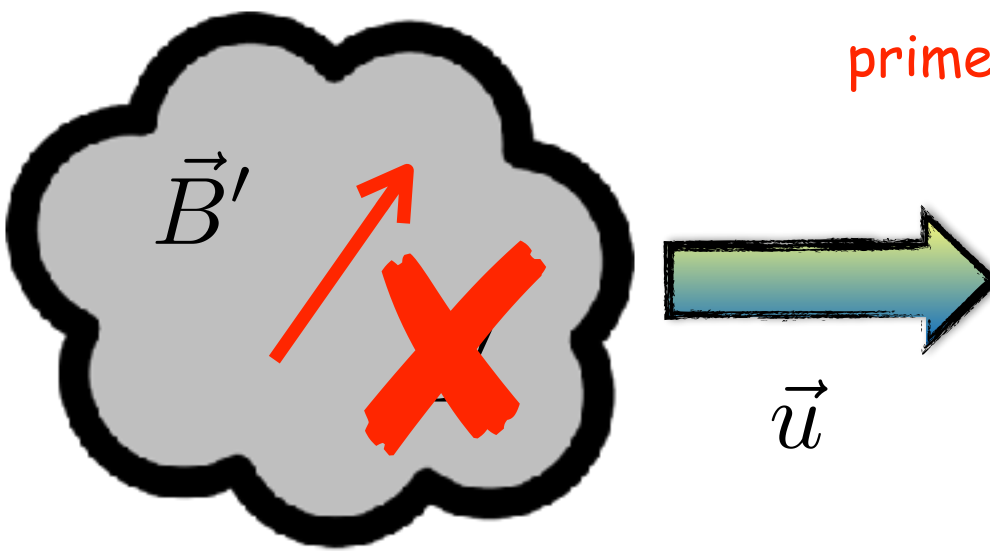


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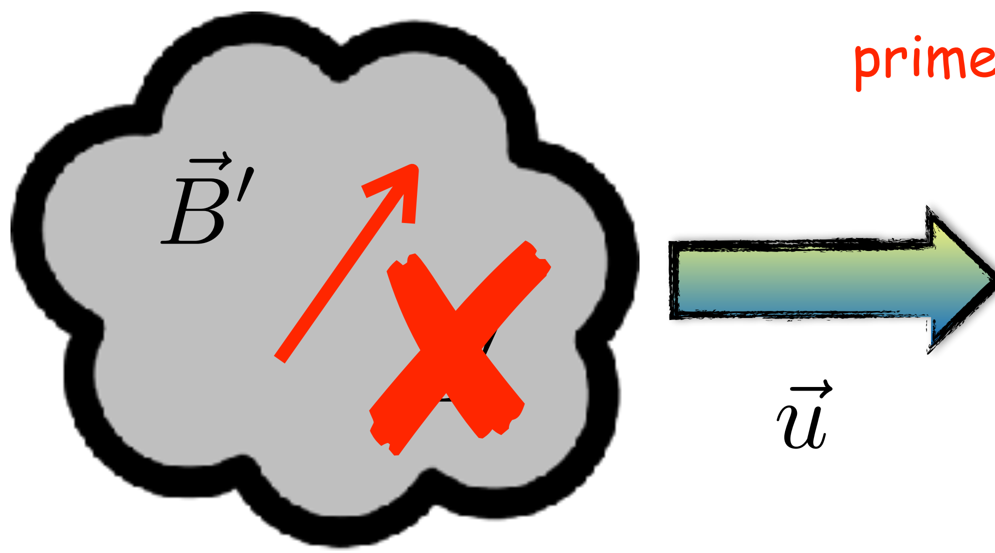


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an observer in the lab frame sees an electric field!

# Order of magnitude estimates of the induced electric field

time-varying B-field

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characteristic length

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

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

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

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size

B-field

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B-field  size

$$\boxed{E_t^{max} \approx 3 \times 10^{12} Z \left(\frac{B}{\mu\mathrm{G}}\right) \left(\frac{U}{1000\ \mathrm{km/s}}\right) \left(\frac{L}{\mathrm{pc}}\right) \ \mathrm{eV}}$$

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**very general, we didn't assume anything about the nature of the accelerator!**

# Hillas criterion for RX J1713

$$E_t^{max} \approx 3 \times 10^{12} Z \left(\frac{B}{\mu\mathrm{G}}\right) \left(\frac{U}{1000\ \mathrm{km/s}}\right) \left(\frac{L}{\mathrm{pc}}\right)\ \mathrm{eV}$$

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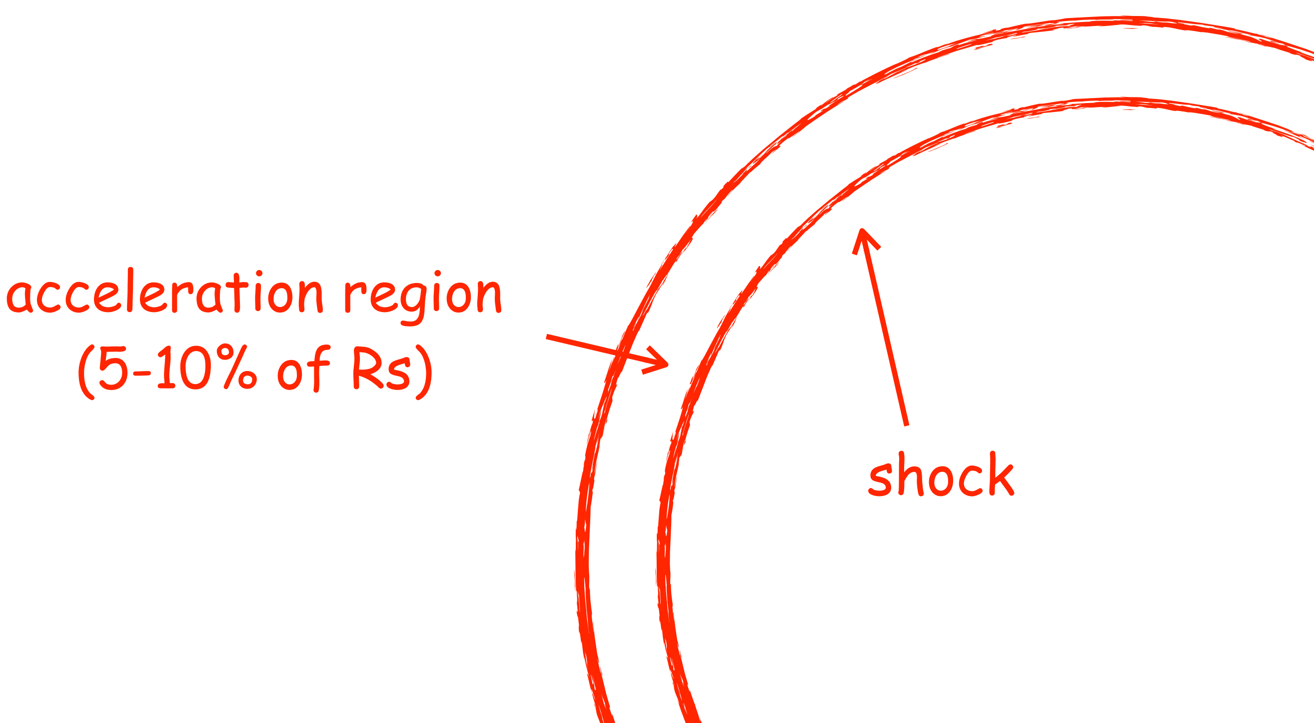

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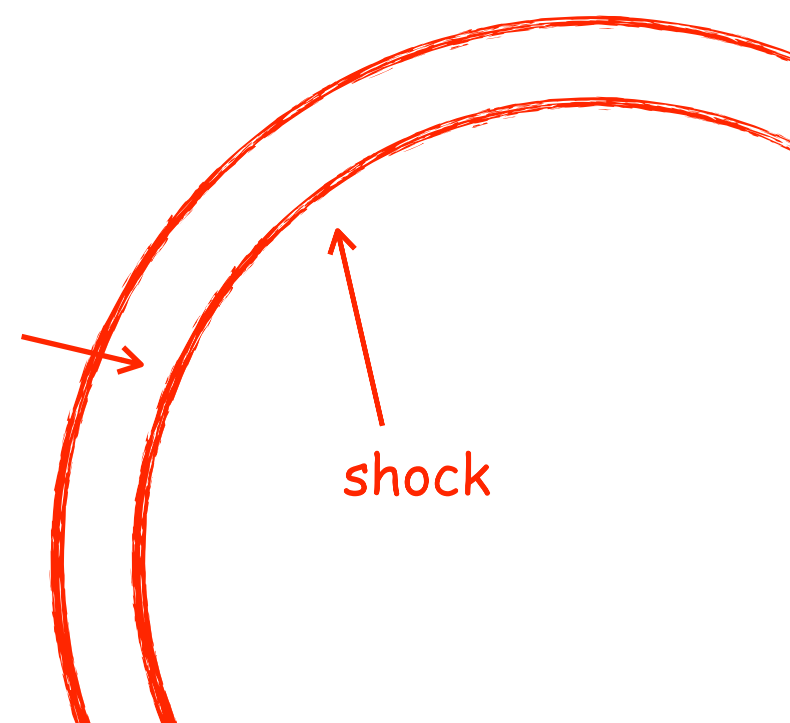

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1/2 correction for
spherical geometry
(Hilla 2005)

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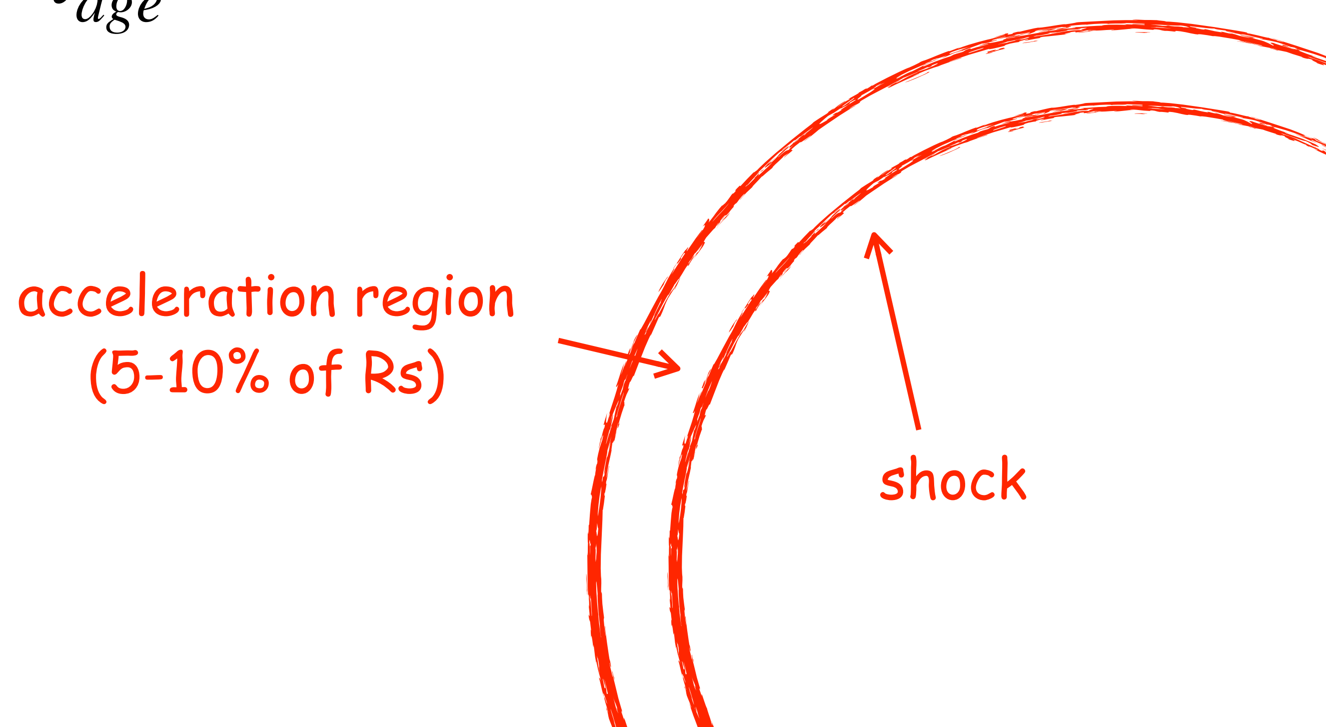

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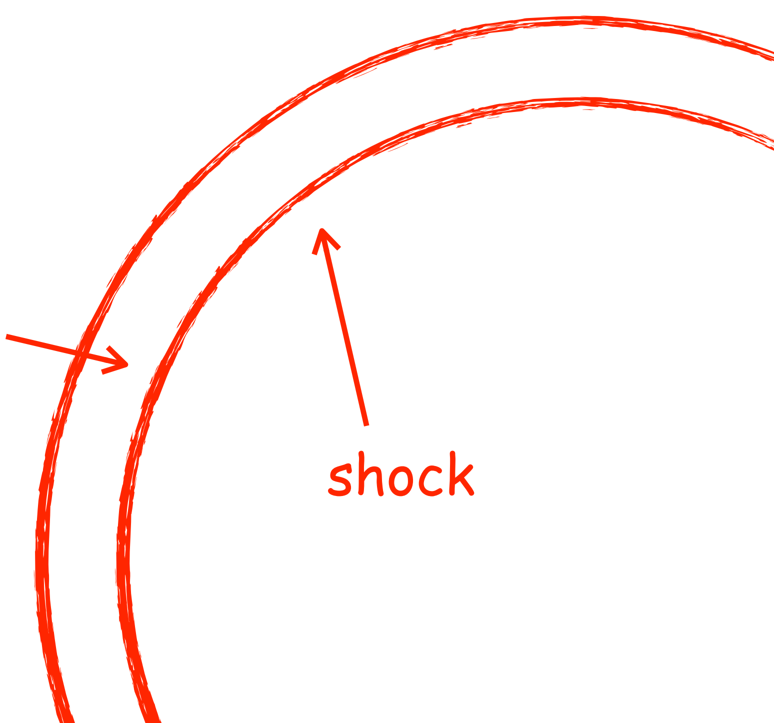
acceleration region
(5-10% of Rs)



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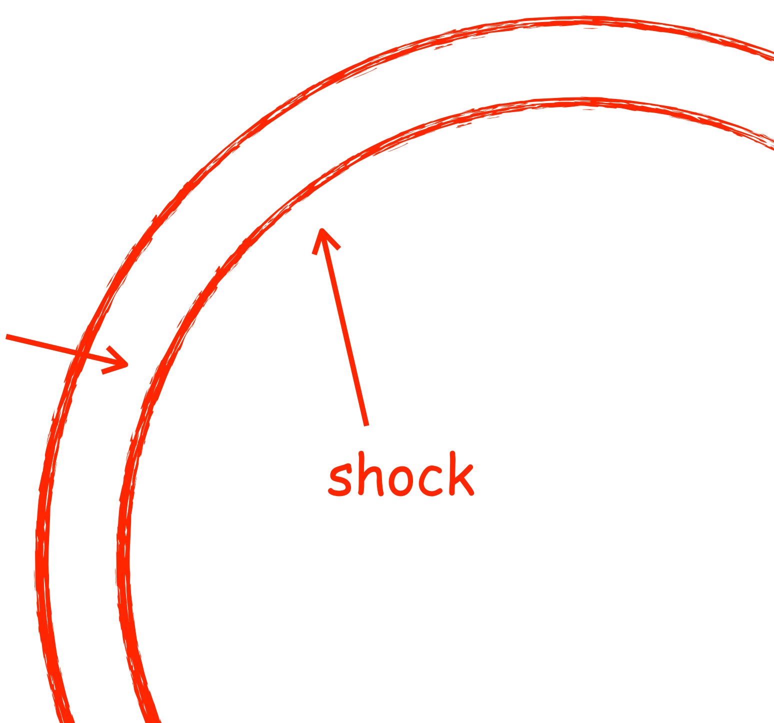


this is the upstream field!

# Summarising...

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

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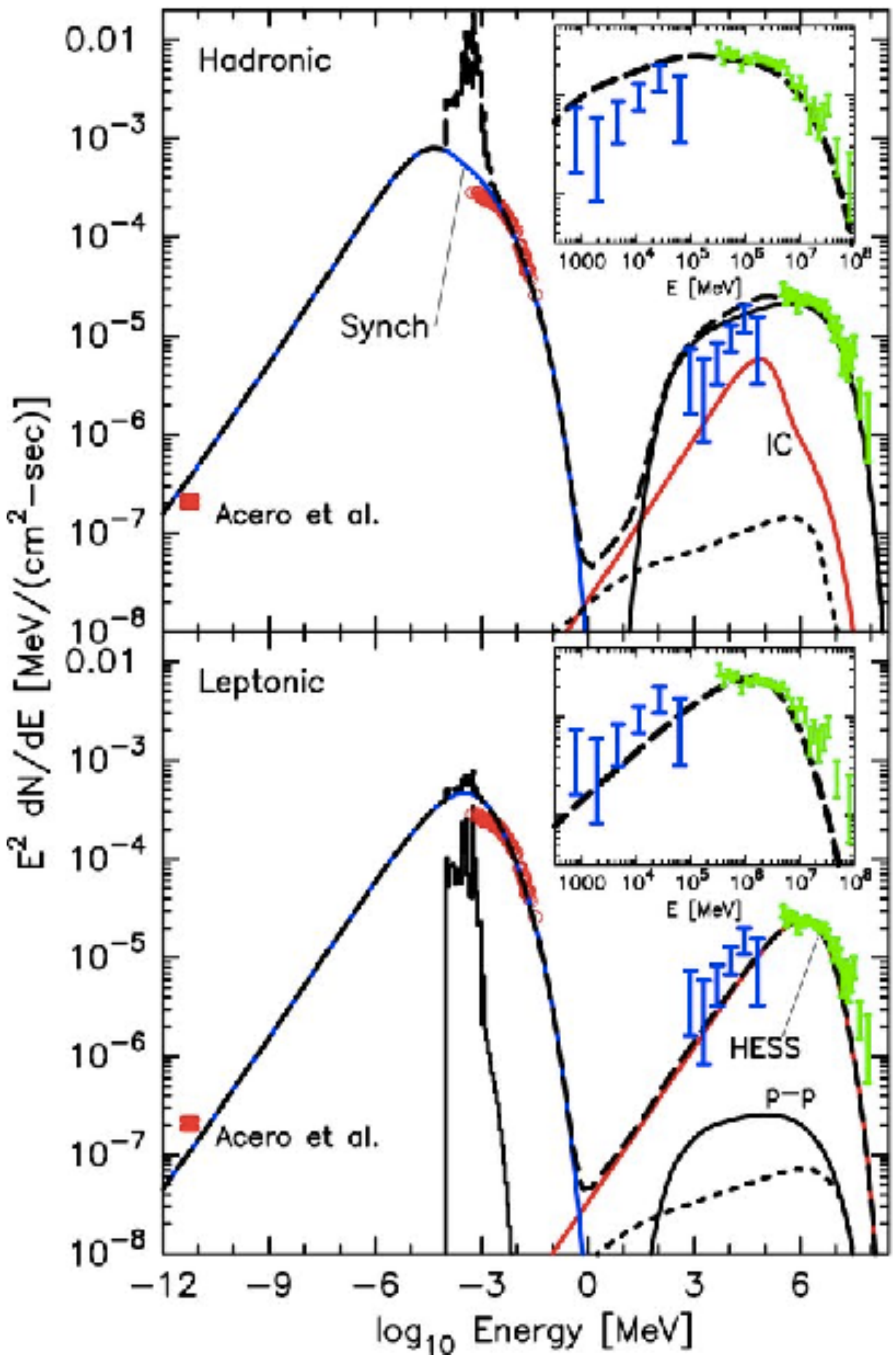
on the other hand, one needs a slightly smaller Emax, which helps a bit...

[End of Inset 3]

# Finally,RXJ1713 is hadronic or leptonic?

(Ellison et al 2010)



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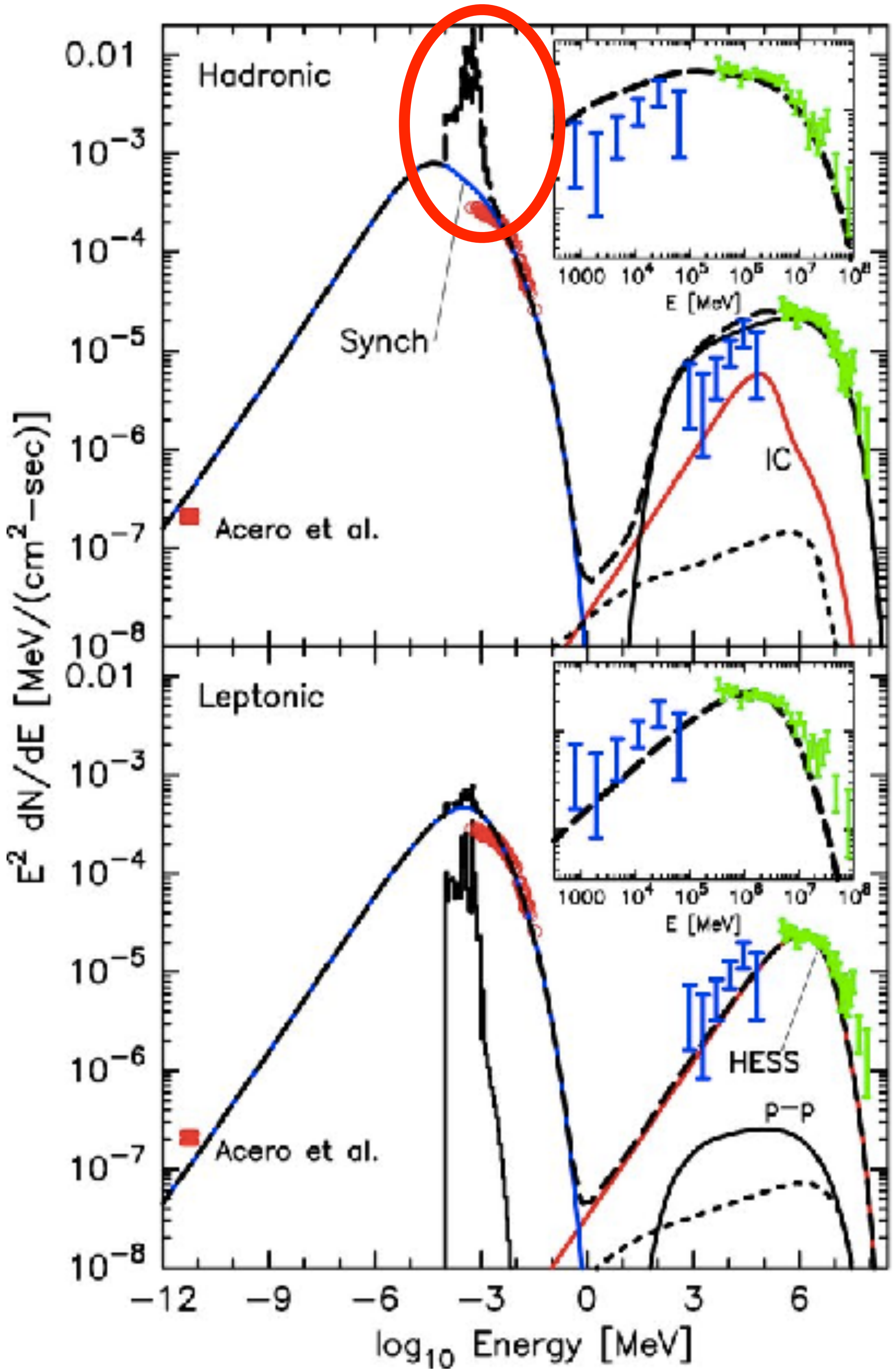


**hadronic**

high gas density + shock heating

-> bright X-ray thermal emission (lines)

**-> NOT OBSERVED**

(see also Katz&Waxman2008)

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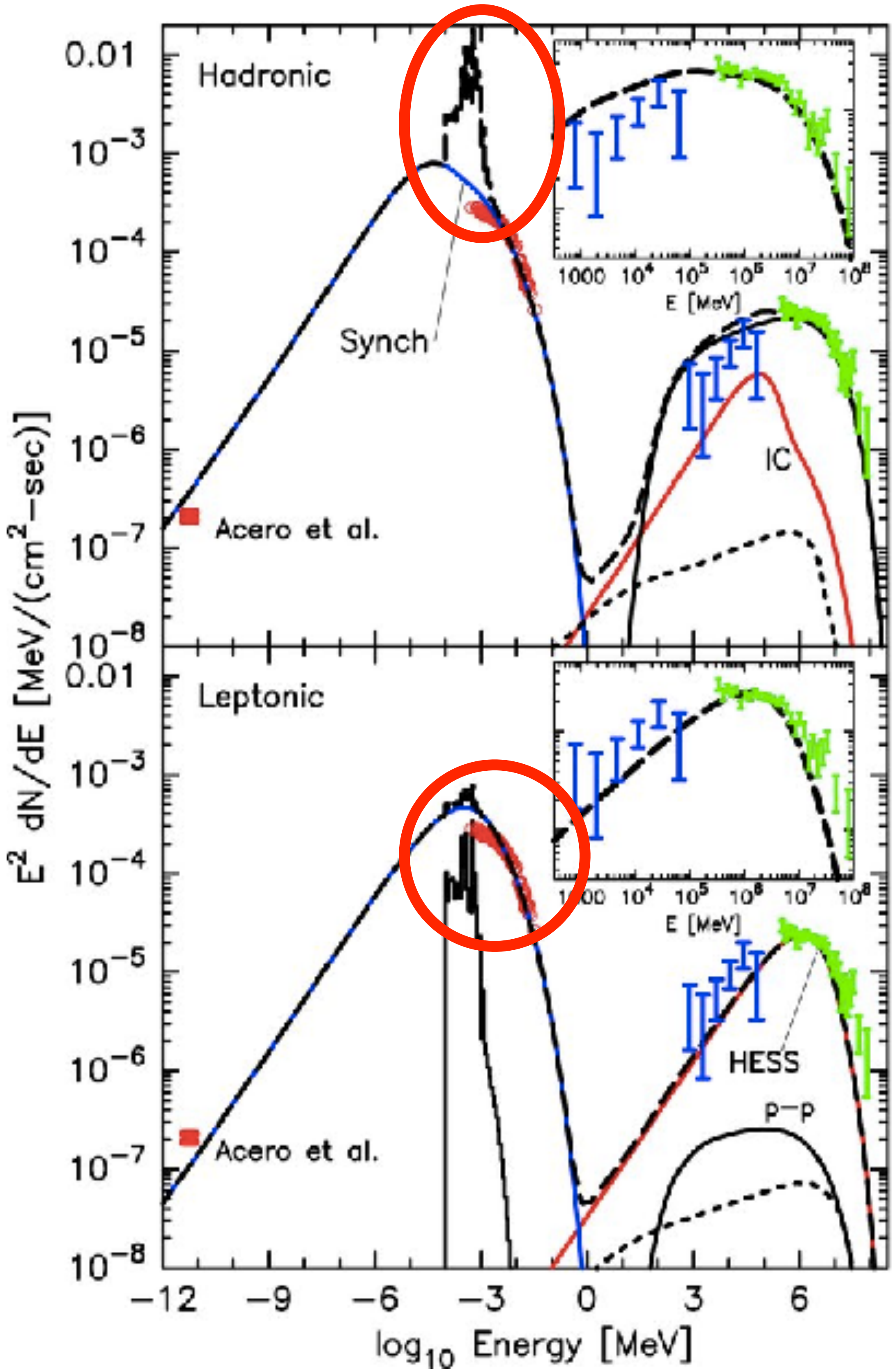


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-> bright X-ray thermal emission (lines)
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(see also Katz&Waxman2008)

**leptonic**

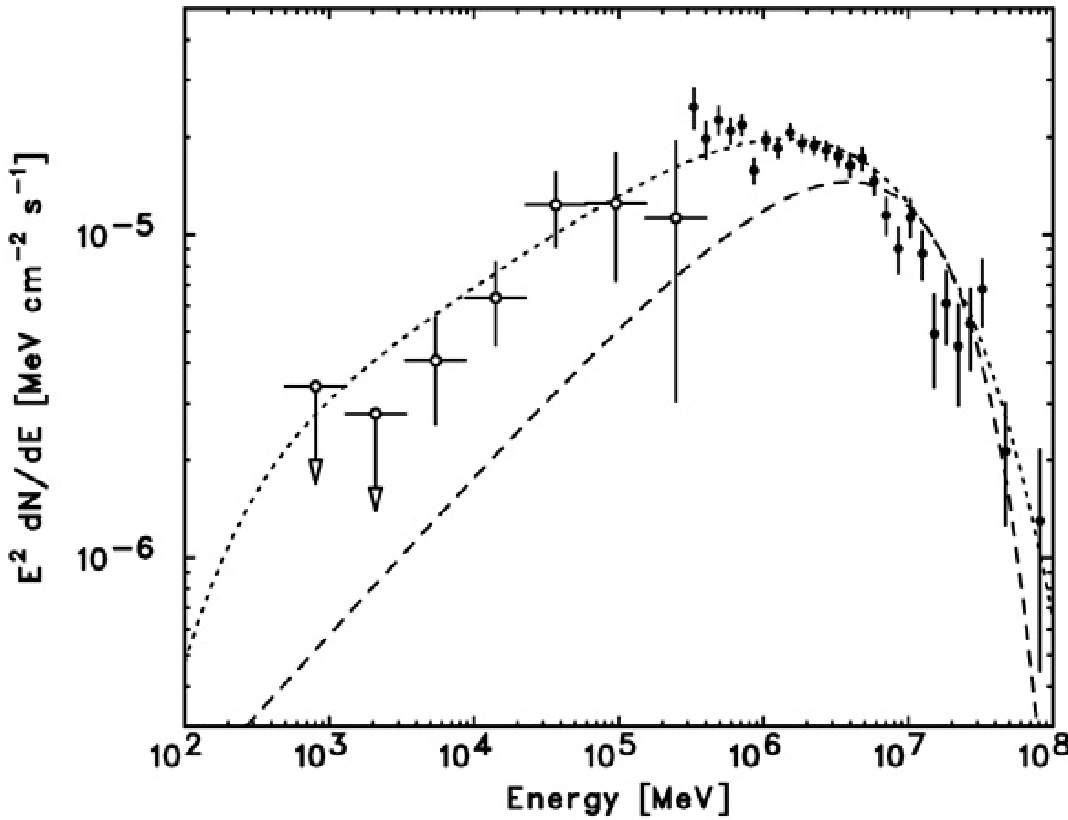
gas density is not a crucial parameter so one can tune it not to violate X-ray constraints

# RXJ1713: difficulties of one-zone leptonic models

**two features in the electron spectrum:**

acceleration time = synchrotron loss time -> acceleration cutoff at $E_{max}$

SNR age = synchrotron loss time -> cooling break at $E_{cool}$

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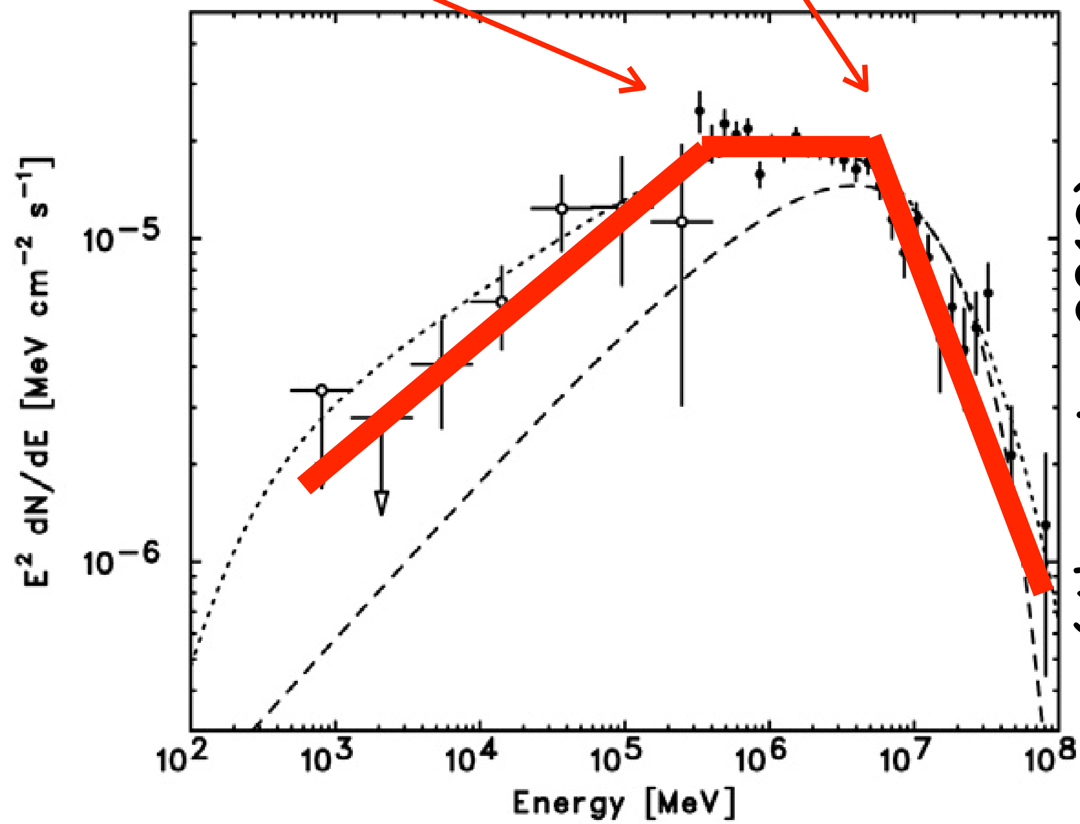


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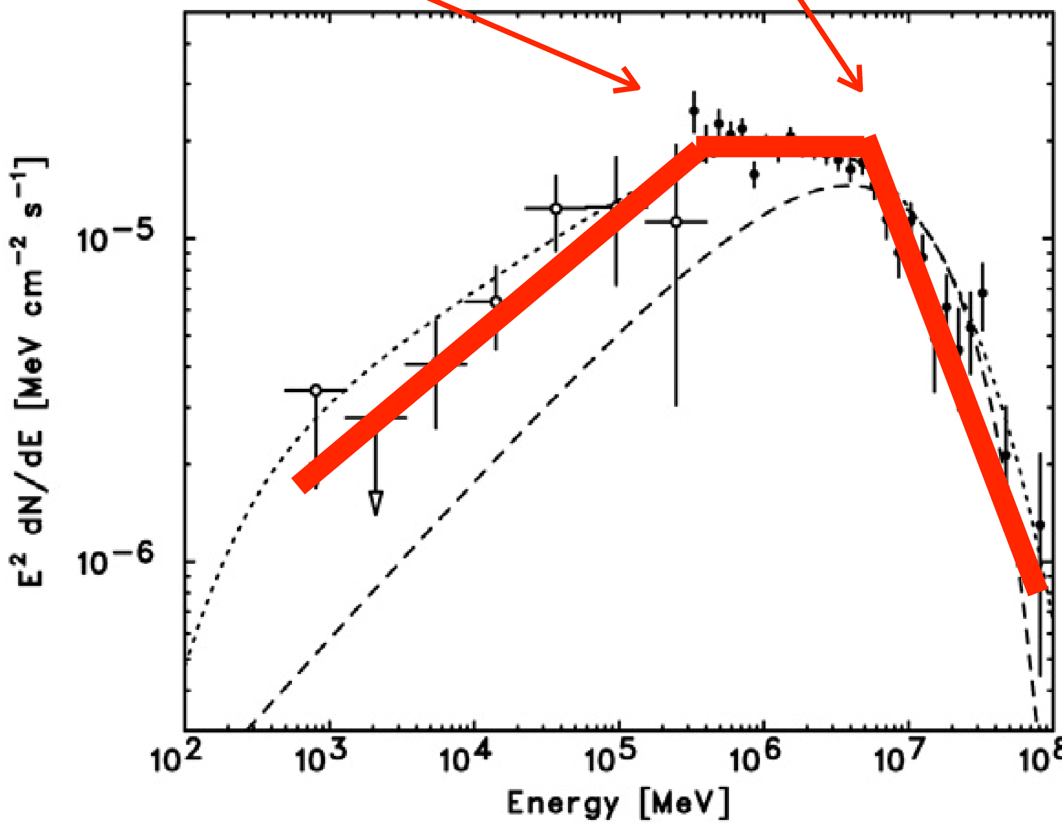
to fit simultaneously X and gamma rays with electrons the magnetic field MUST be **at most ~10 microGauss**

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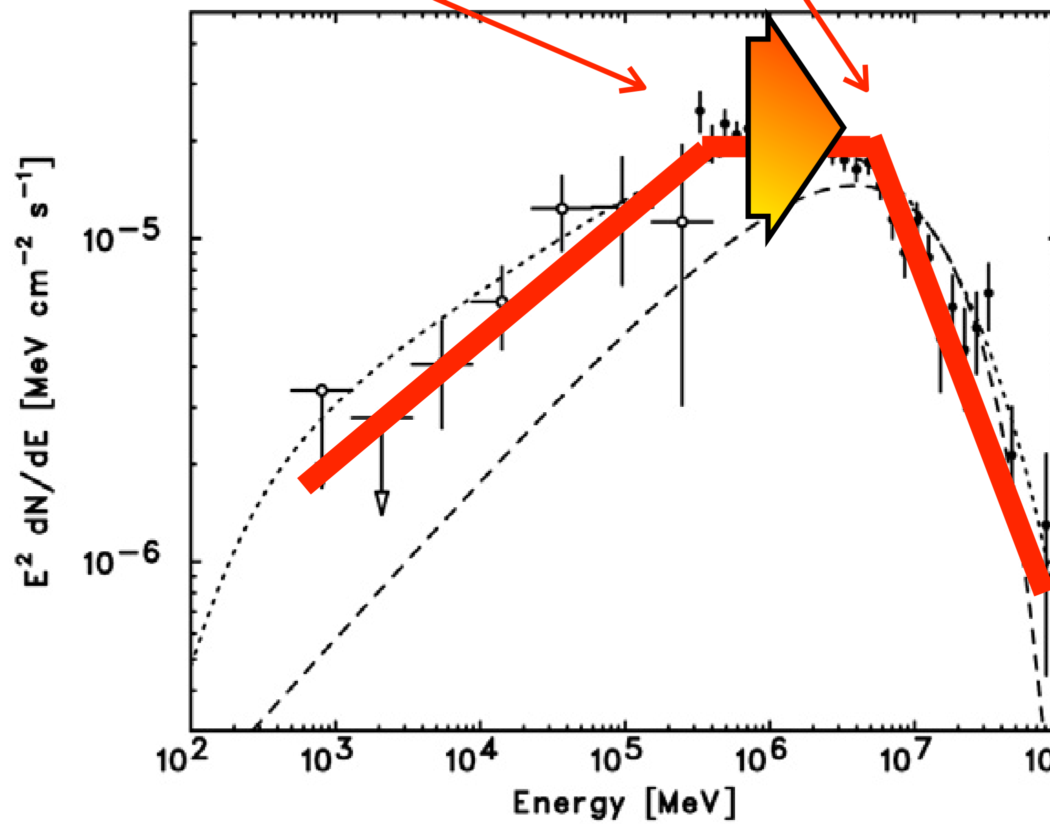


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**no cooling break** is expected...

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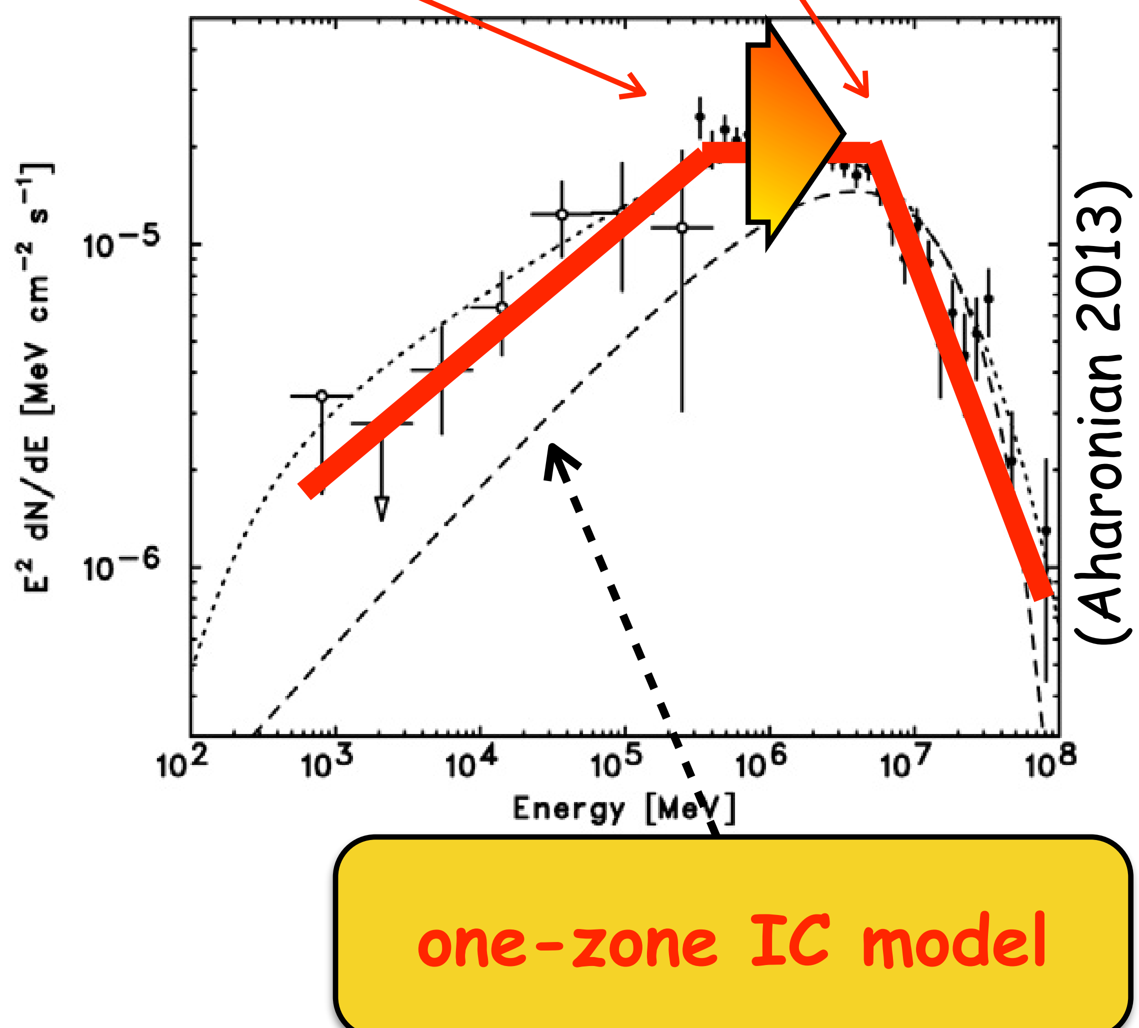


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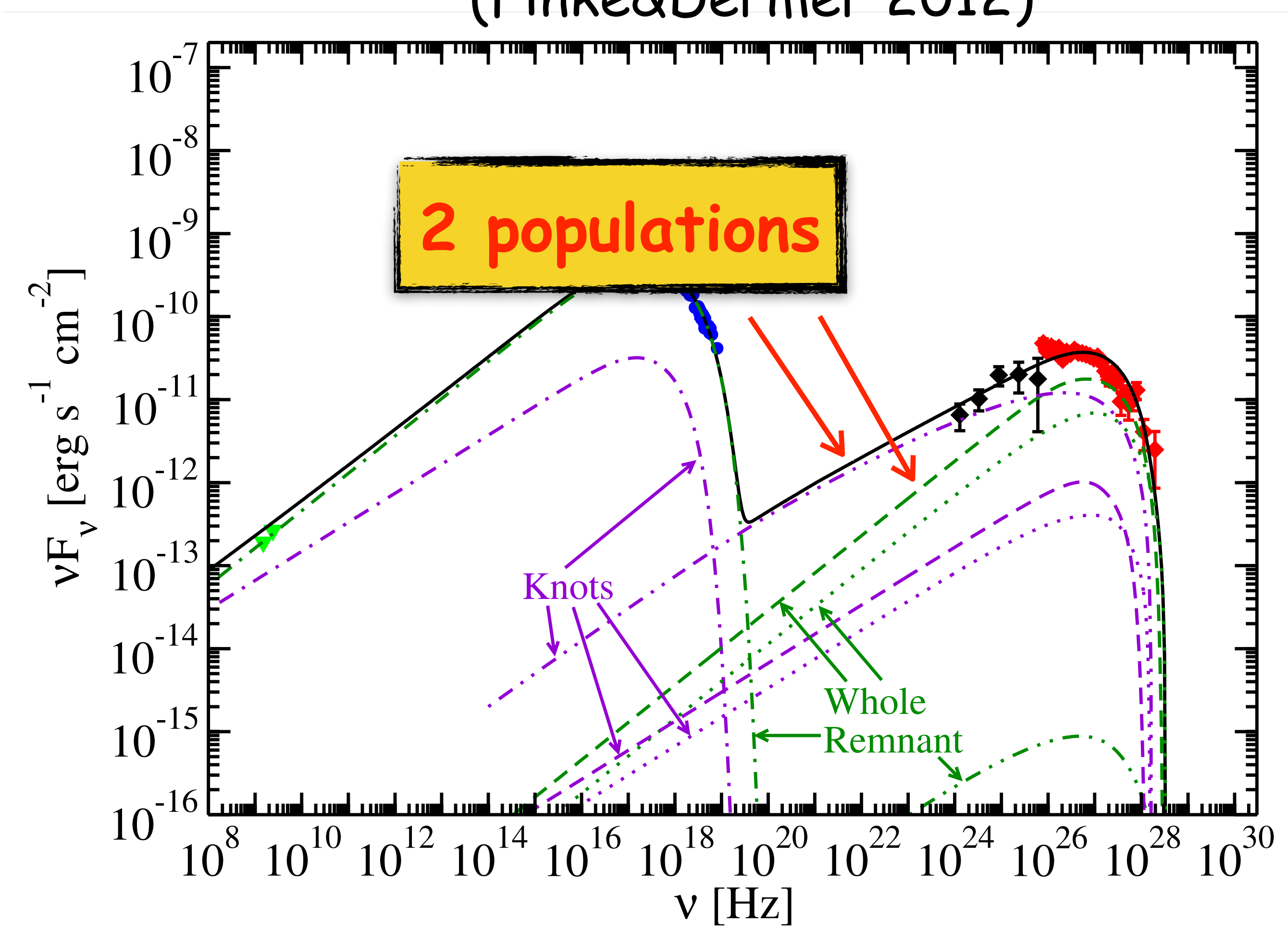
# RXJ1713: difficulties of one-zone leptonic models

(Finke&Dermer 2012)

tw

ac

SN




acceleration cutoff at $E_{max}$

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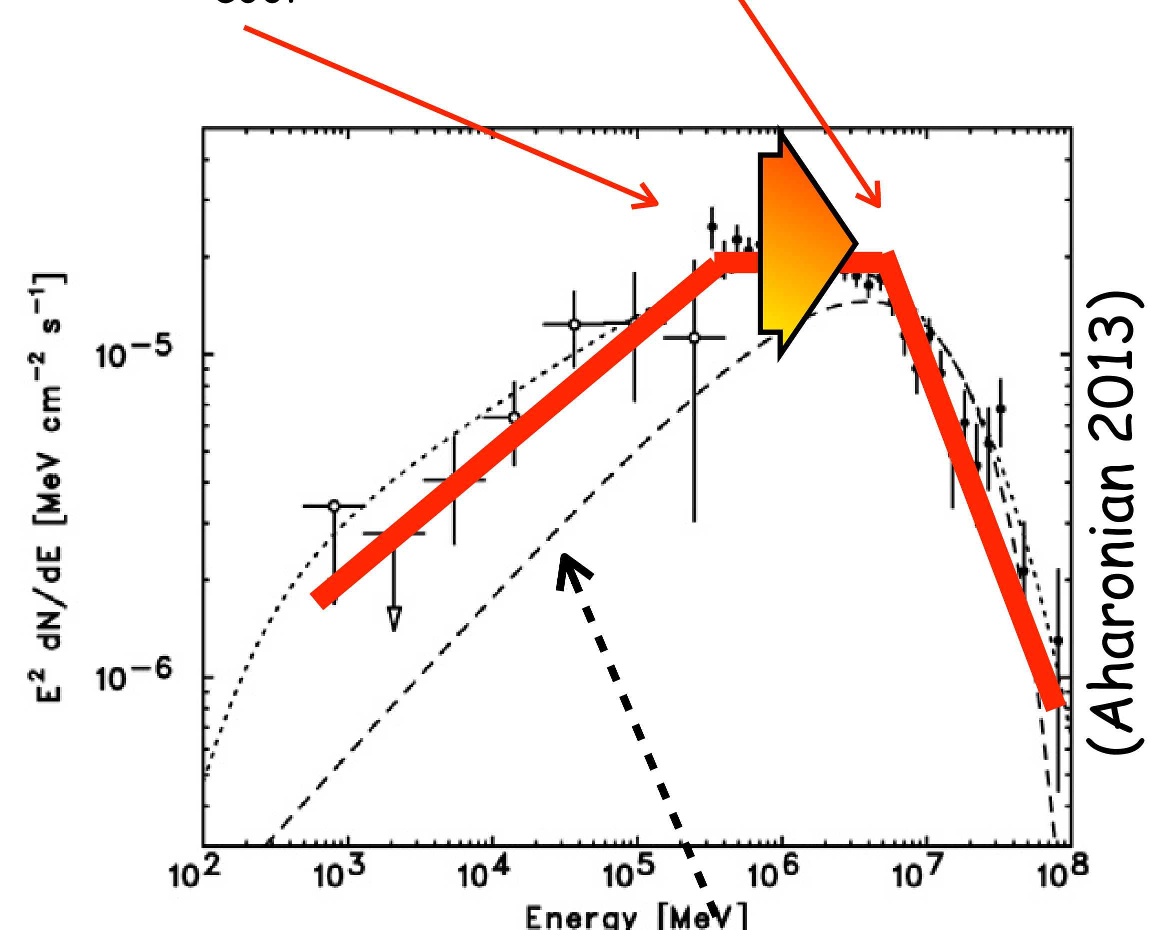


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one-zone IC model

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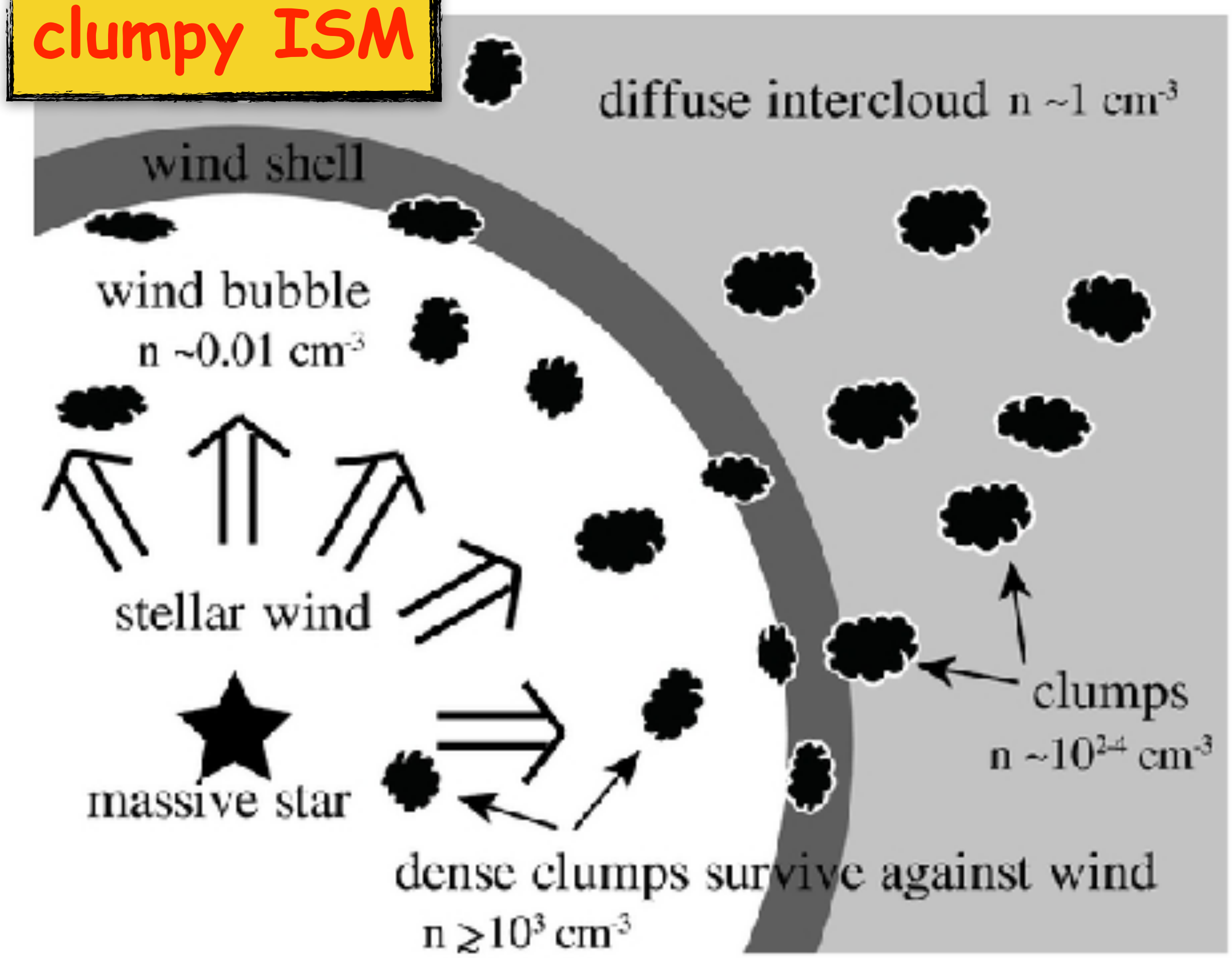
clumpy ISM

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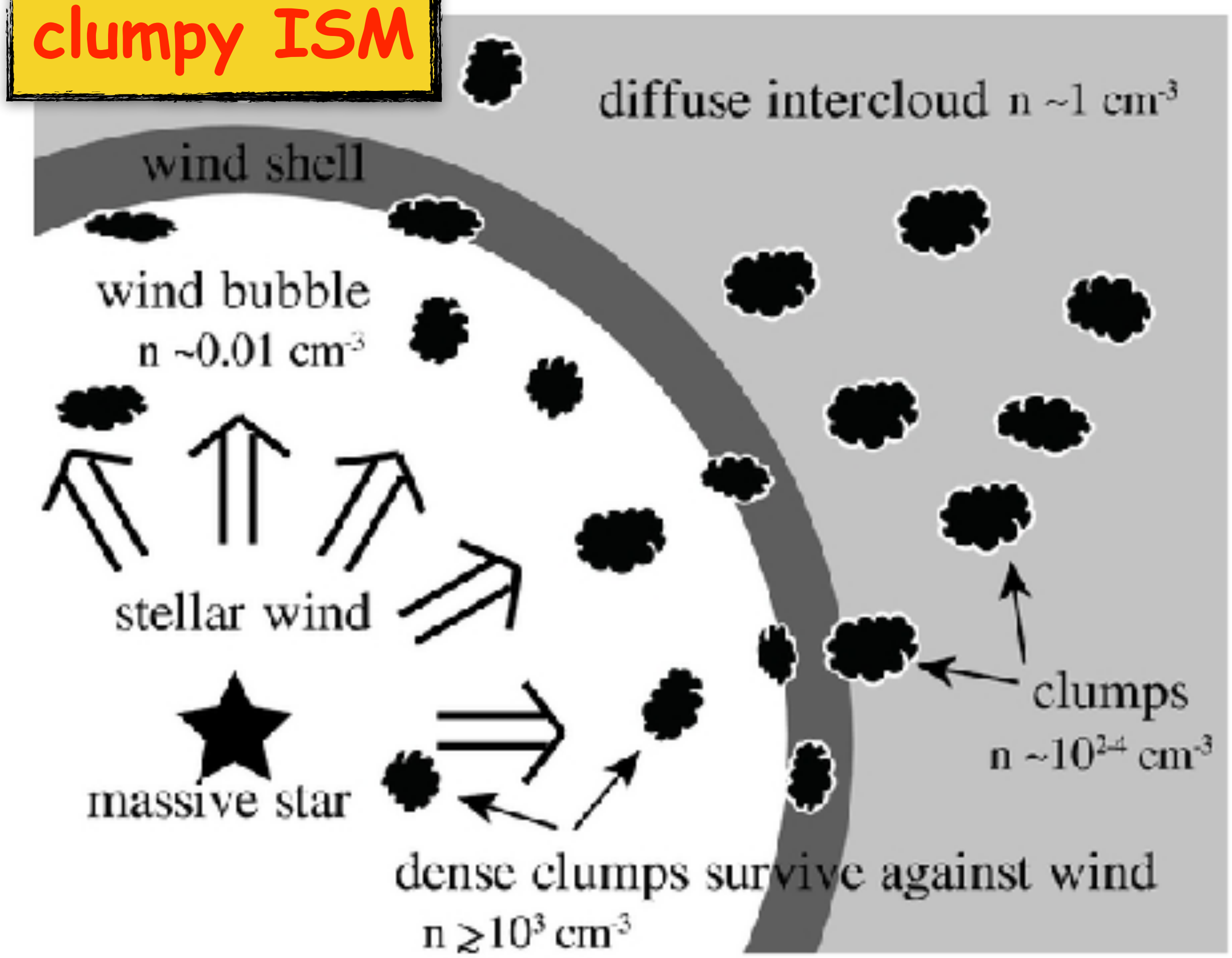


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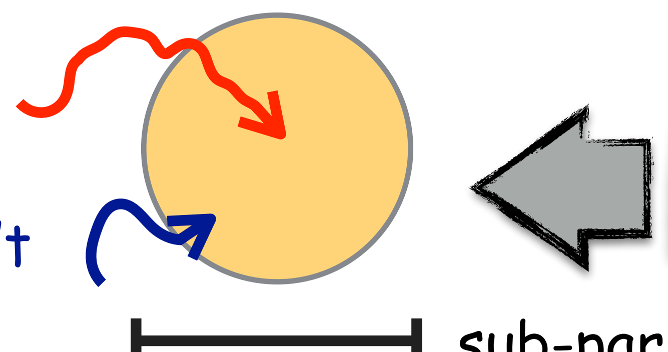
high energy CRs penetrate

low energy CRs don't



clumps!

sub-parsec

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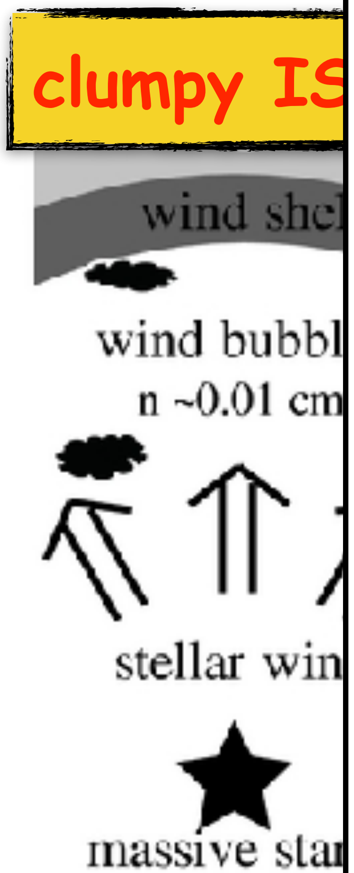


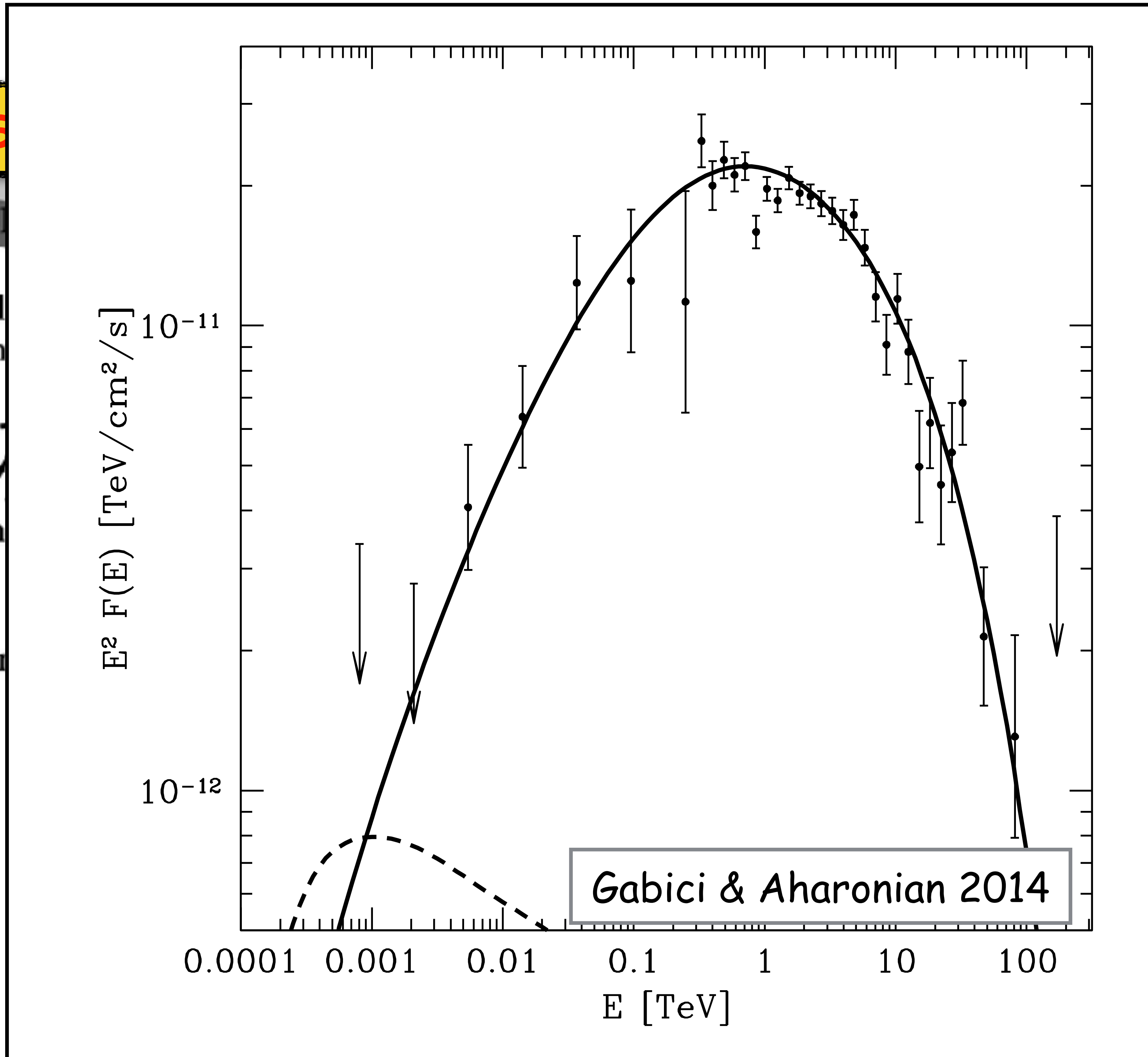


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ps!

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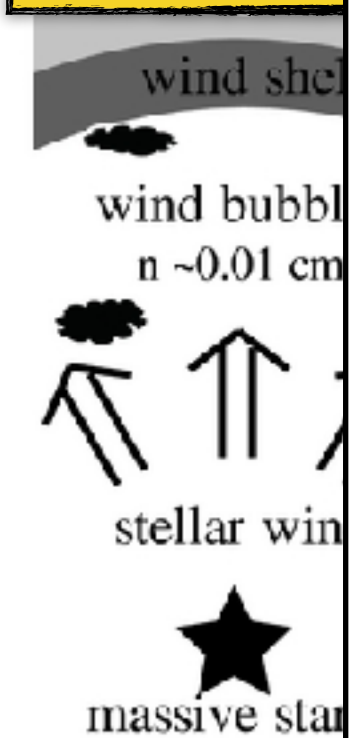


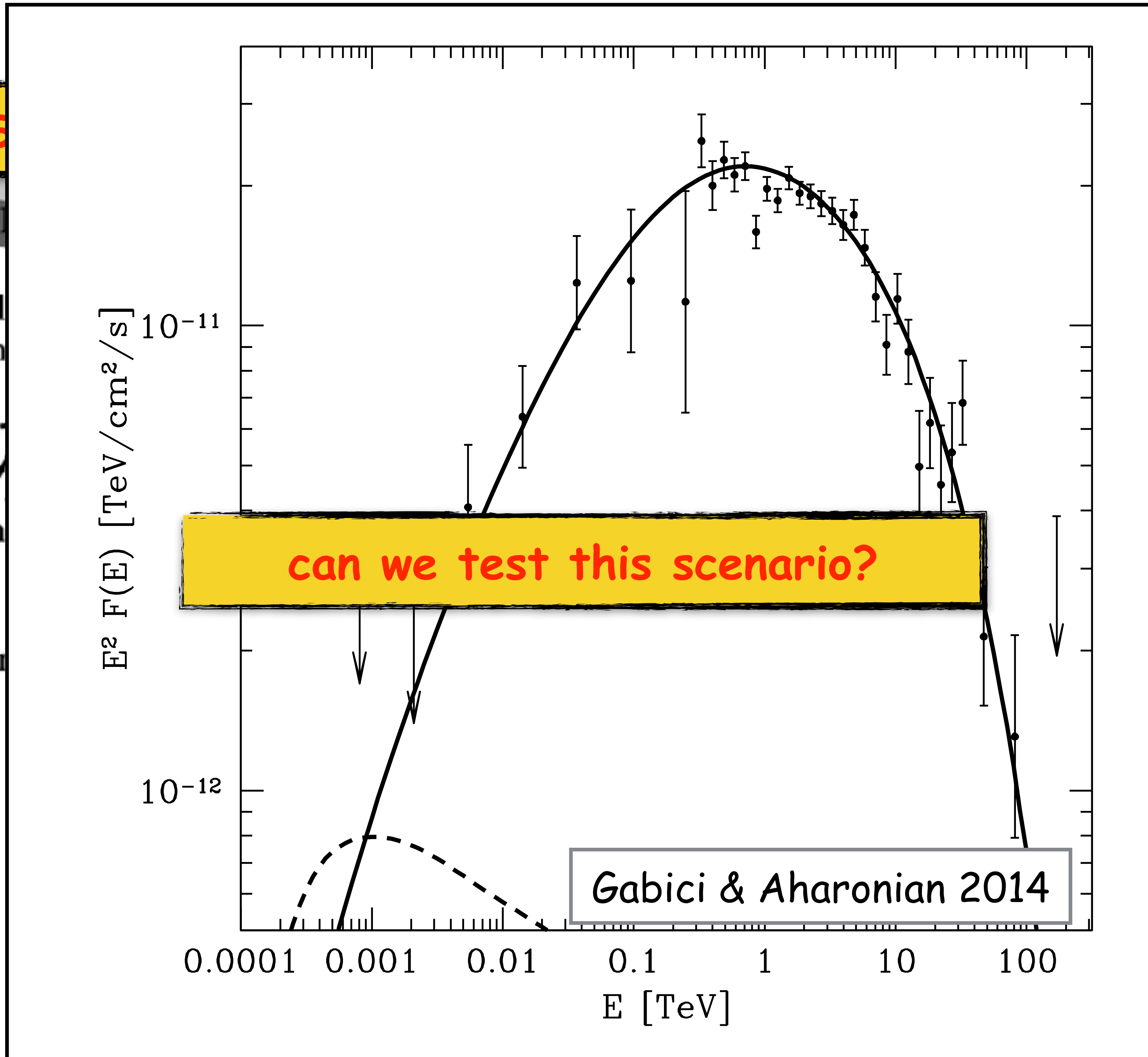


can we test this scenario?

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avity

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-rays!

s!

# CTA superior angular resolution -> morphological studies

different morphology in hadronic and leptonic scenarios! —> Acero et al. 2017, Celli et al. 2018

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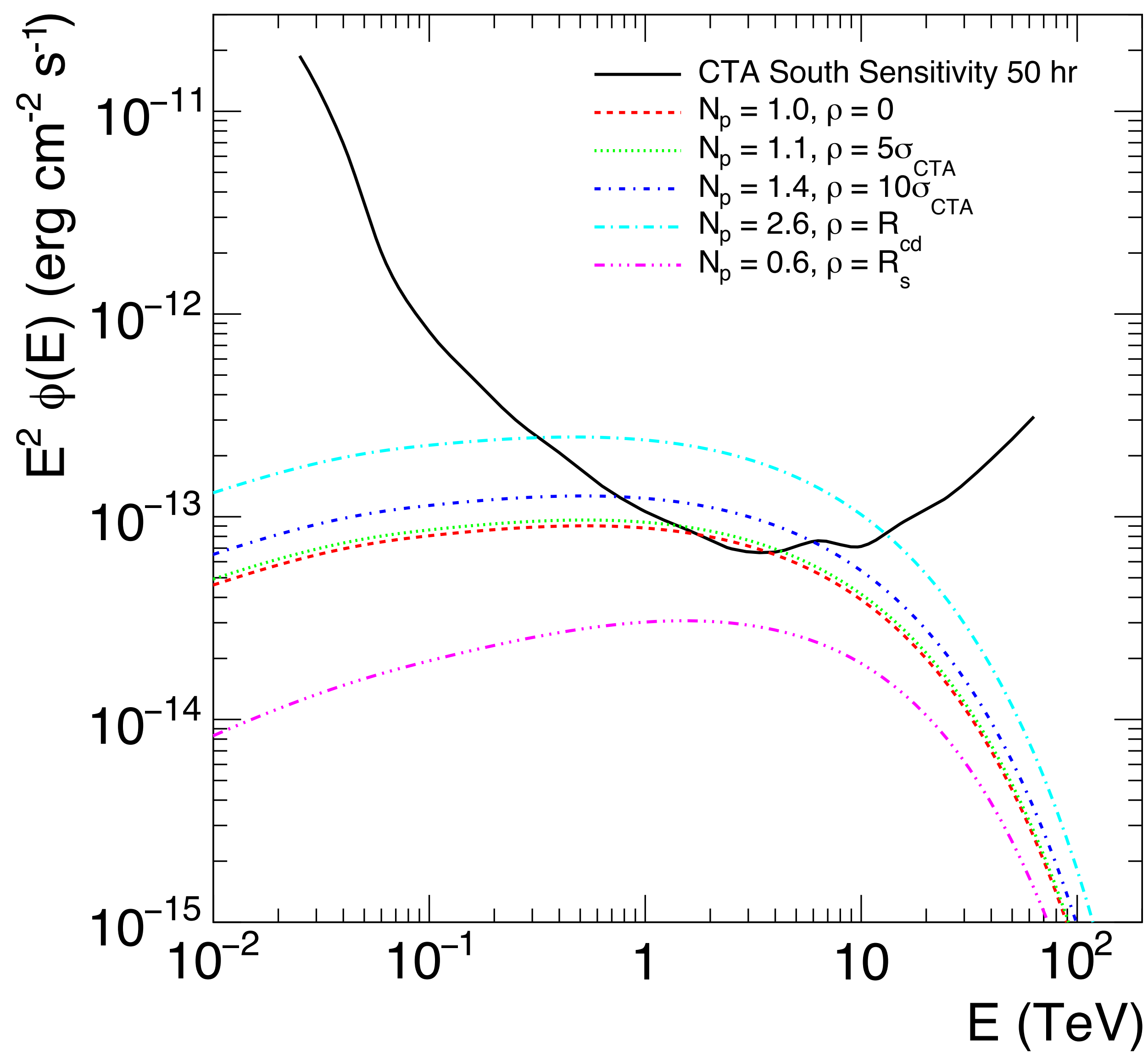


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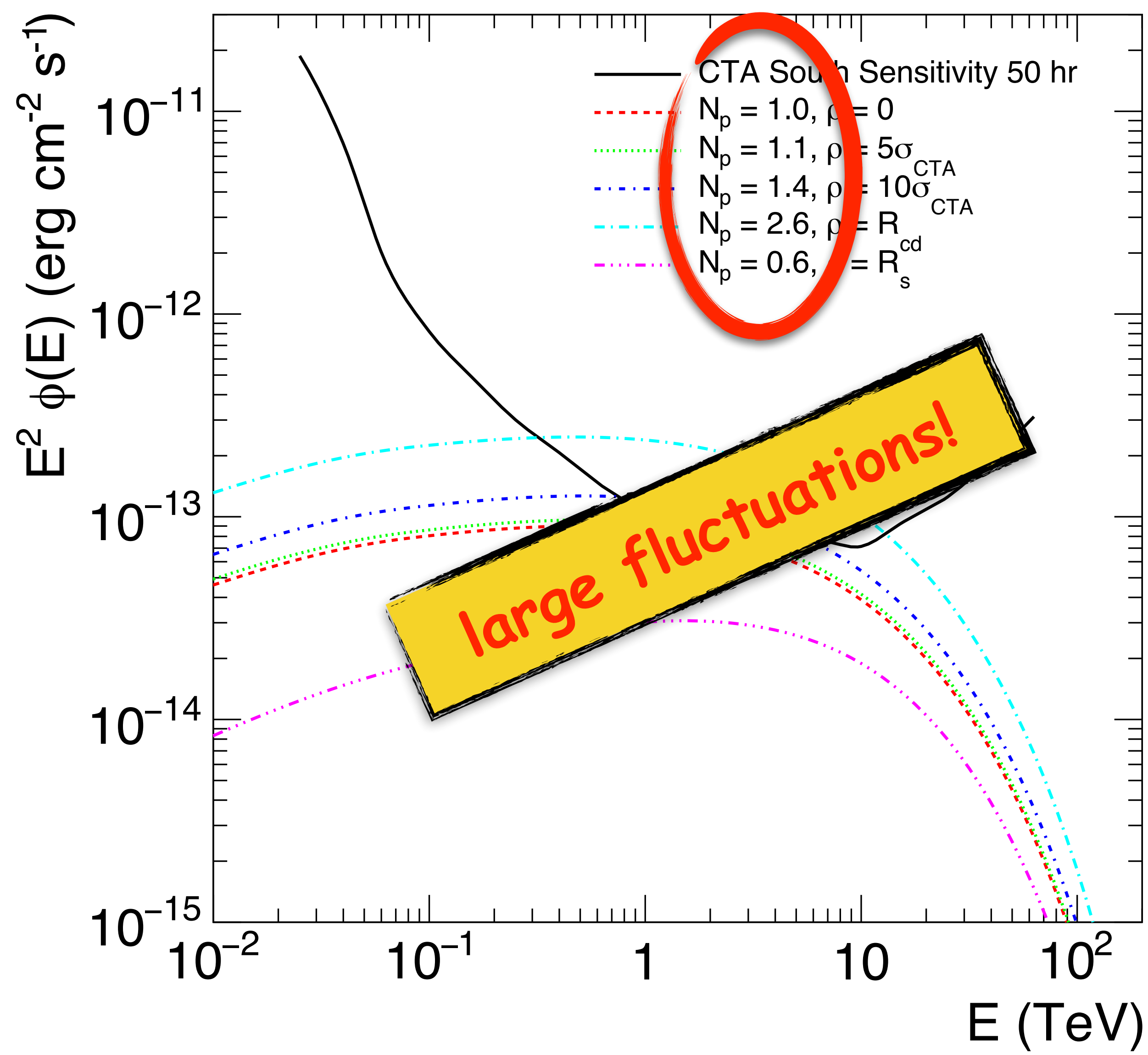


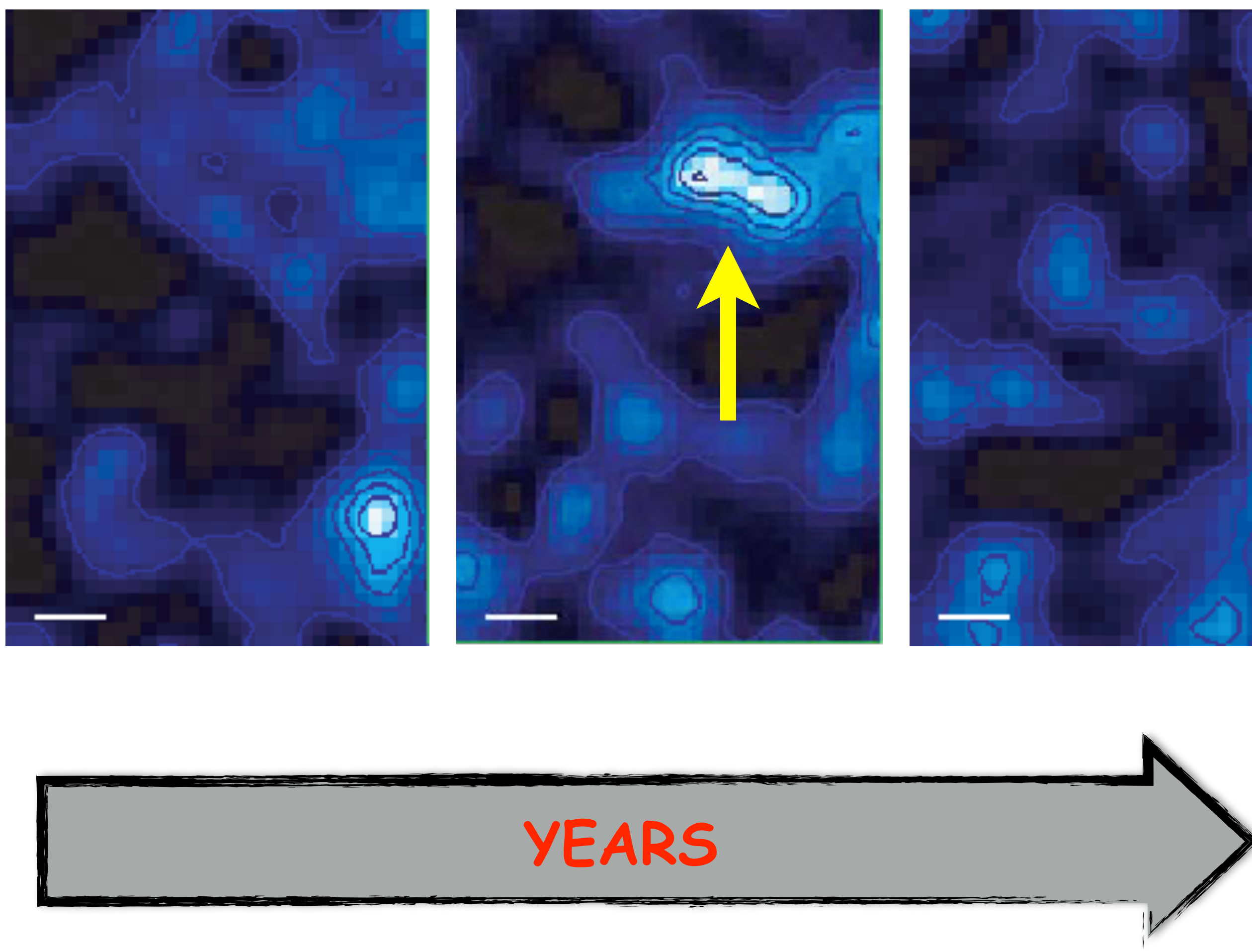

Celli et al. 2018

# ...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

exercise: estimate B !

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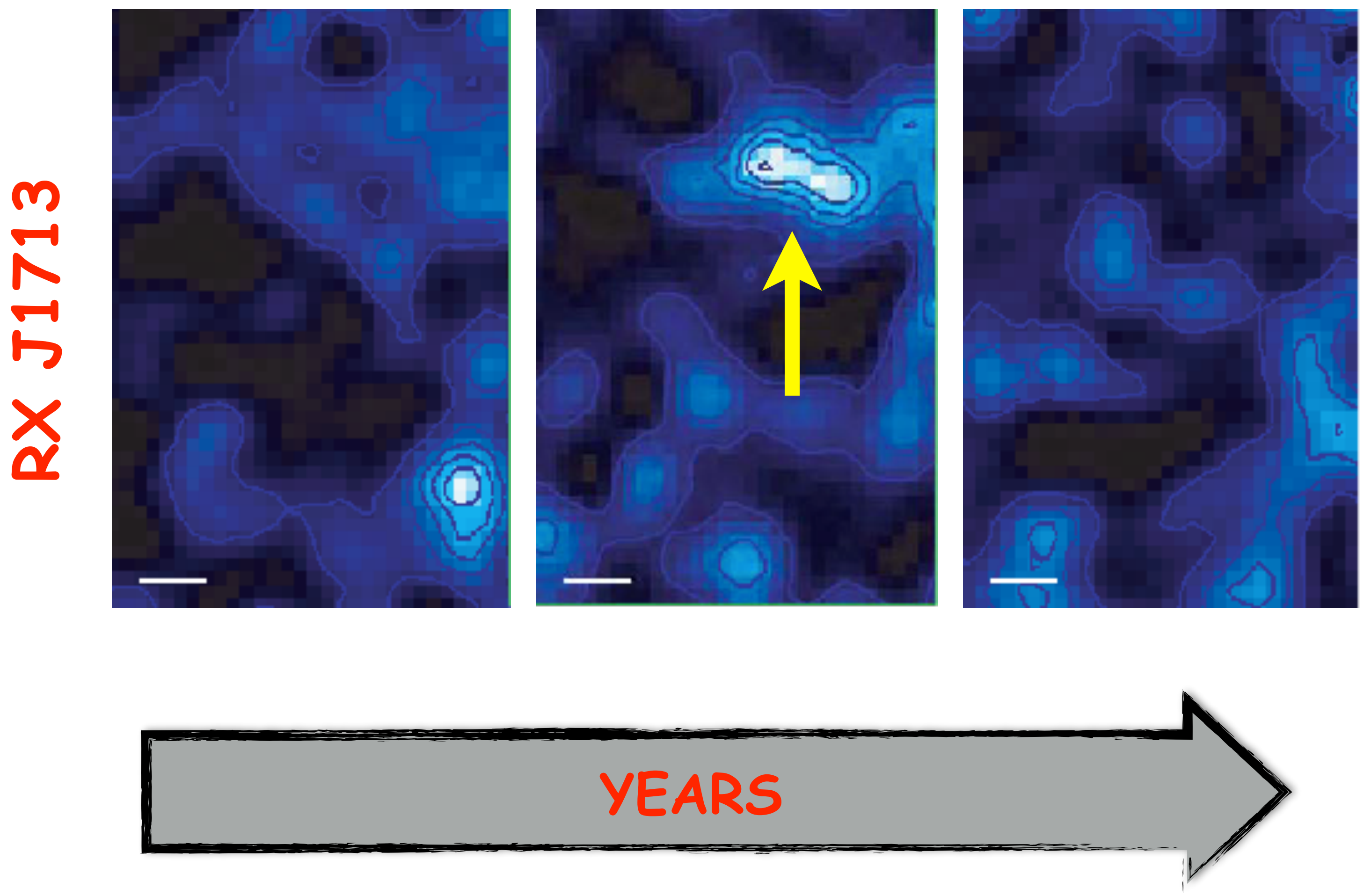


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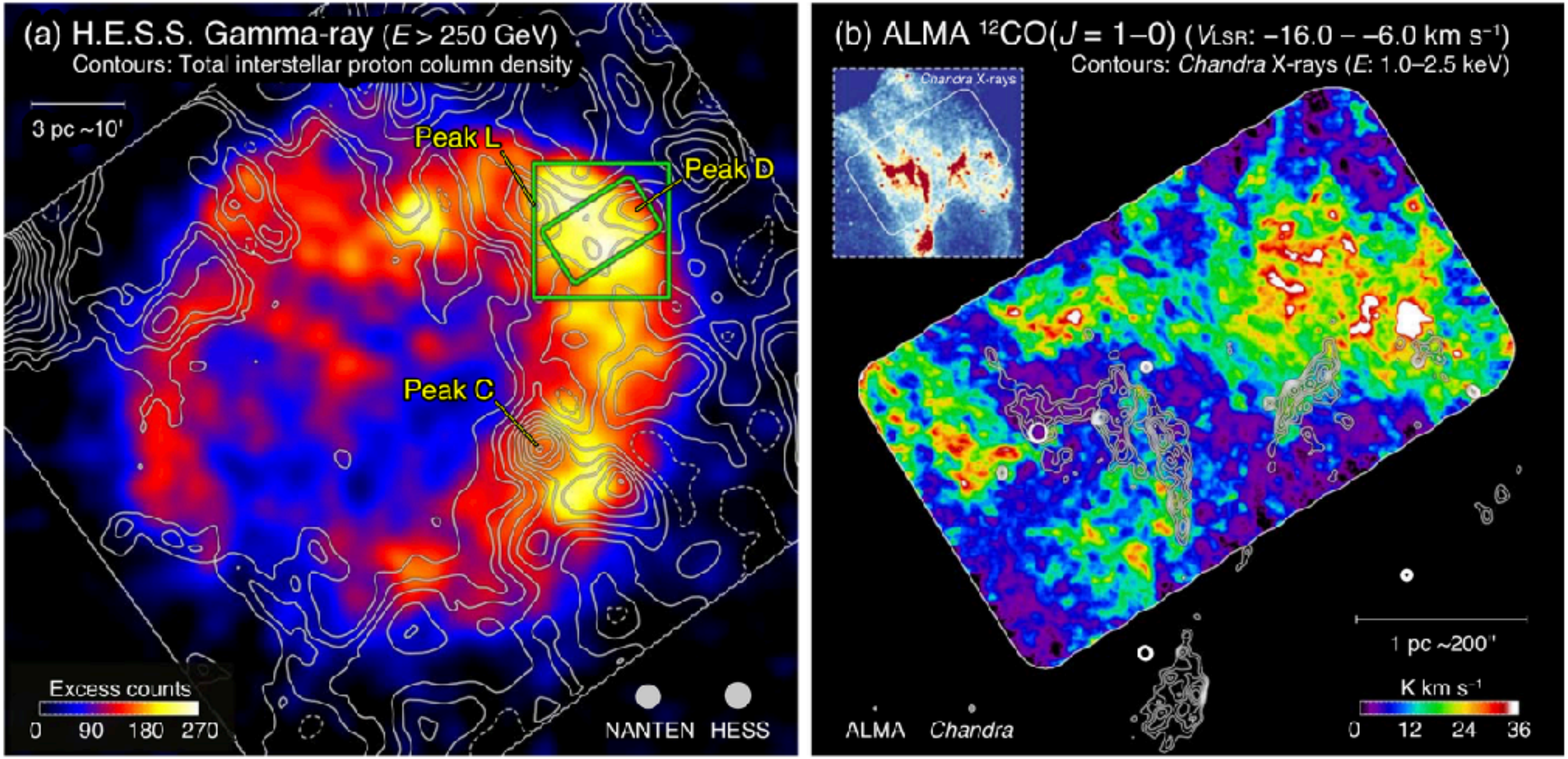
$$\tau_{syn/IC} \sim \frac{E}{\mathrm{d}E/\mathrm{d}t} \approx 1 \left(\frac{\omega_{TOT}}{0.25\ \mathrm{eV/cm^3}}\right)^{-1} \left(\frac{E}{\mathrm{TeV}}\right)^{-1} \ \mathrm{Myr}$$

# Small clumps are there!

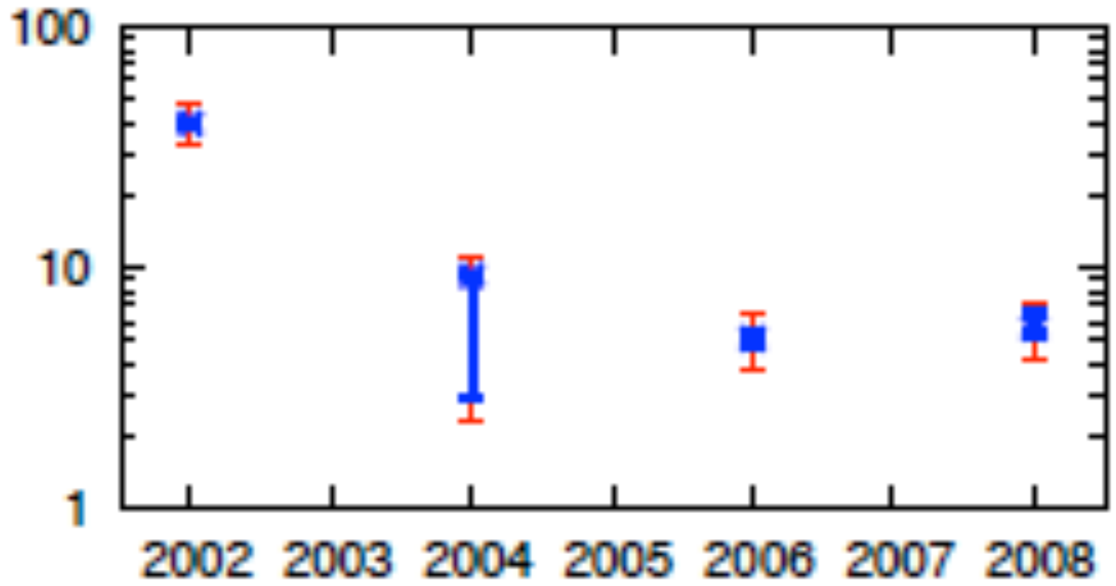



Sano+ 2020

# Neutrinos

predictions of the neutrino flux (> 50 GeV)
per (km$^2$ x yr) from RX J1713 as a fct of time

Vissani & Aharonian 2012



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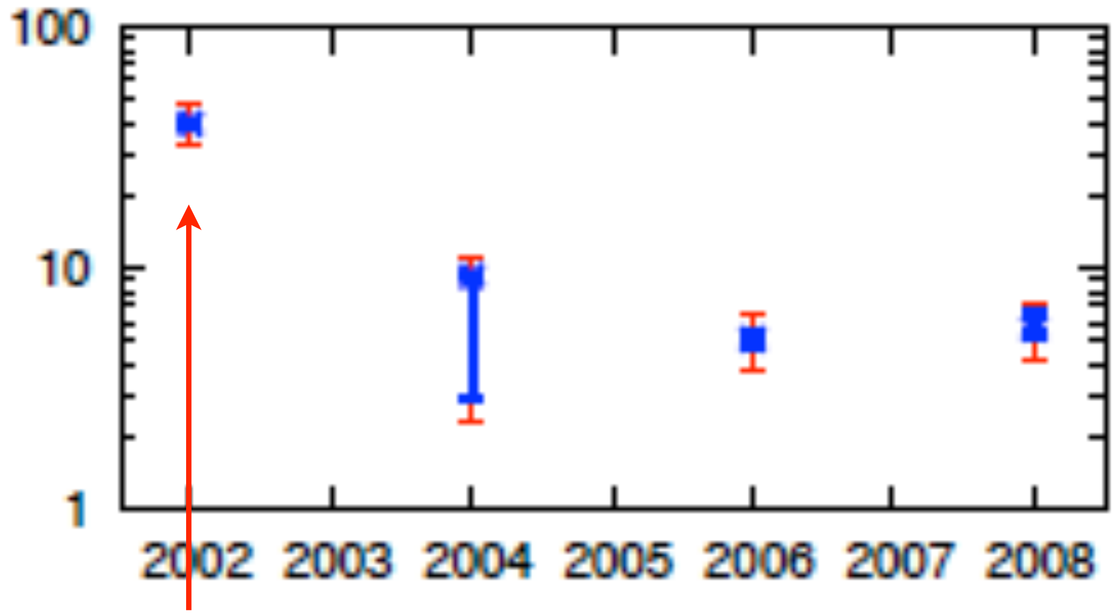


CANGAROO
(extrapolated)

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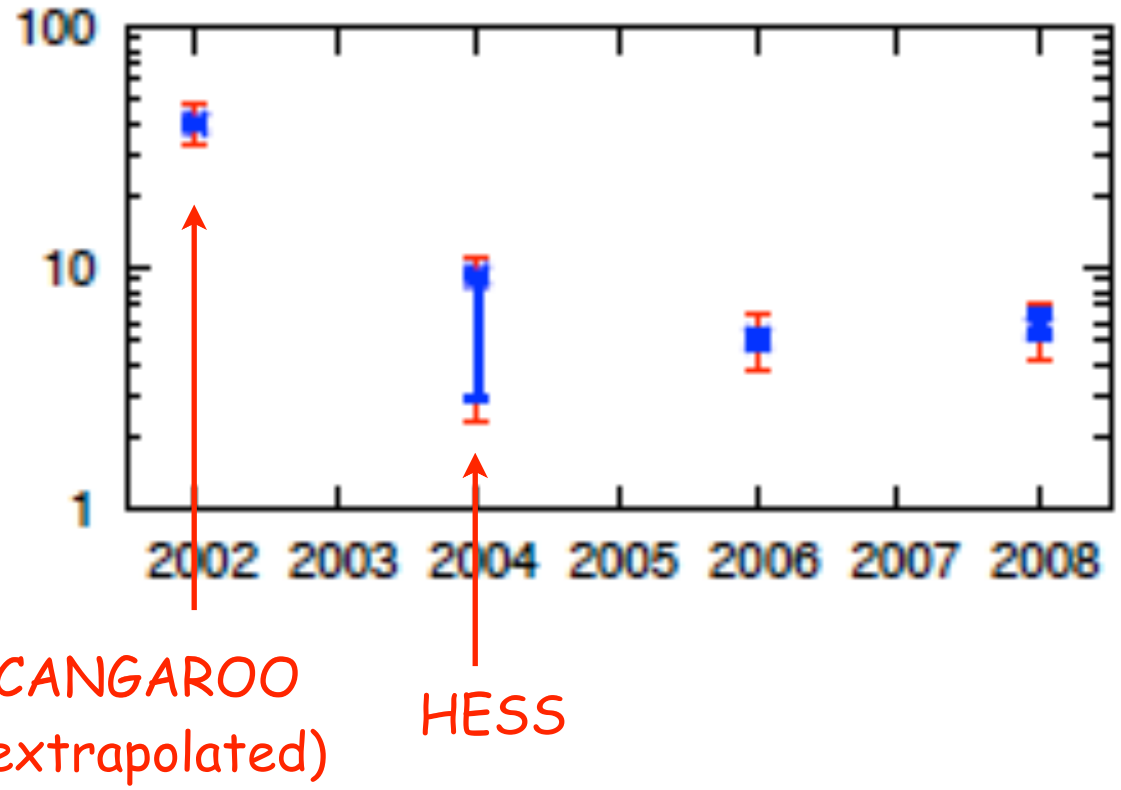

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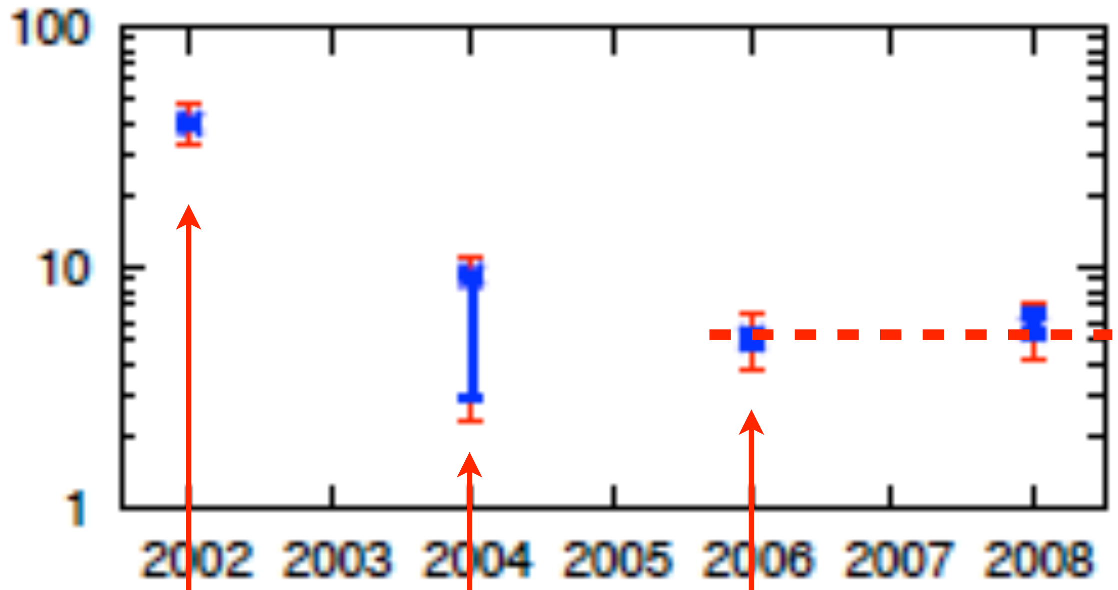


Vissani & Aharonian 2012

CANGAROO (extrapolated)

HESS

HESS (cutoff)

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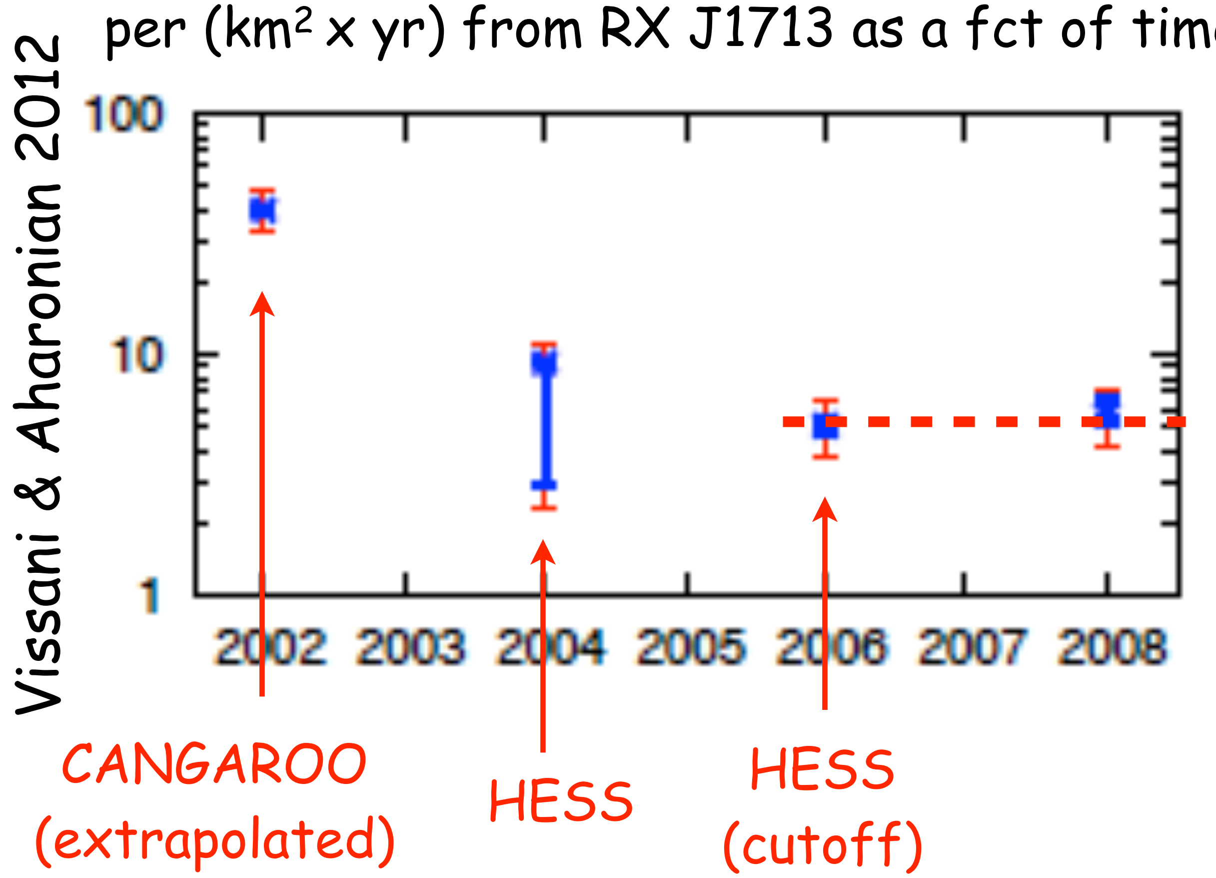
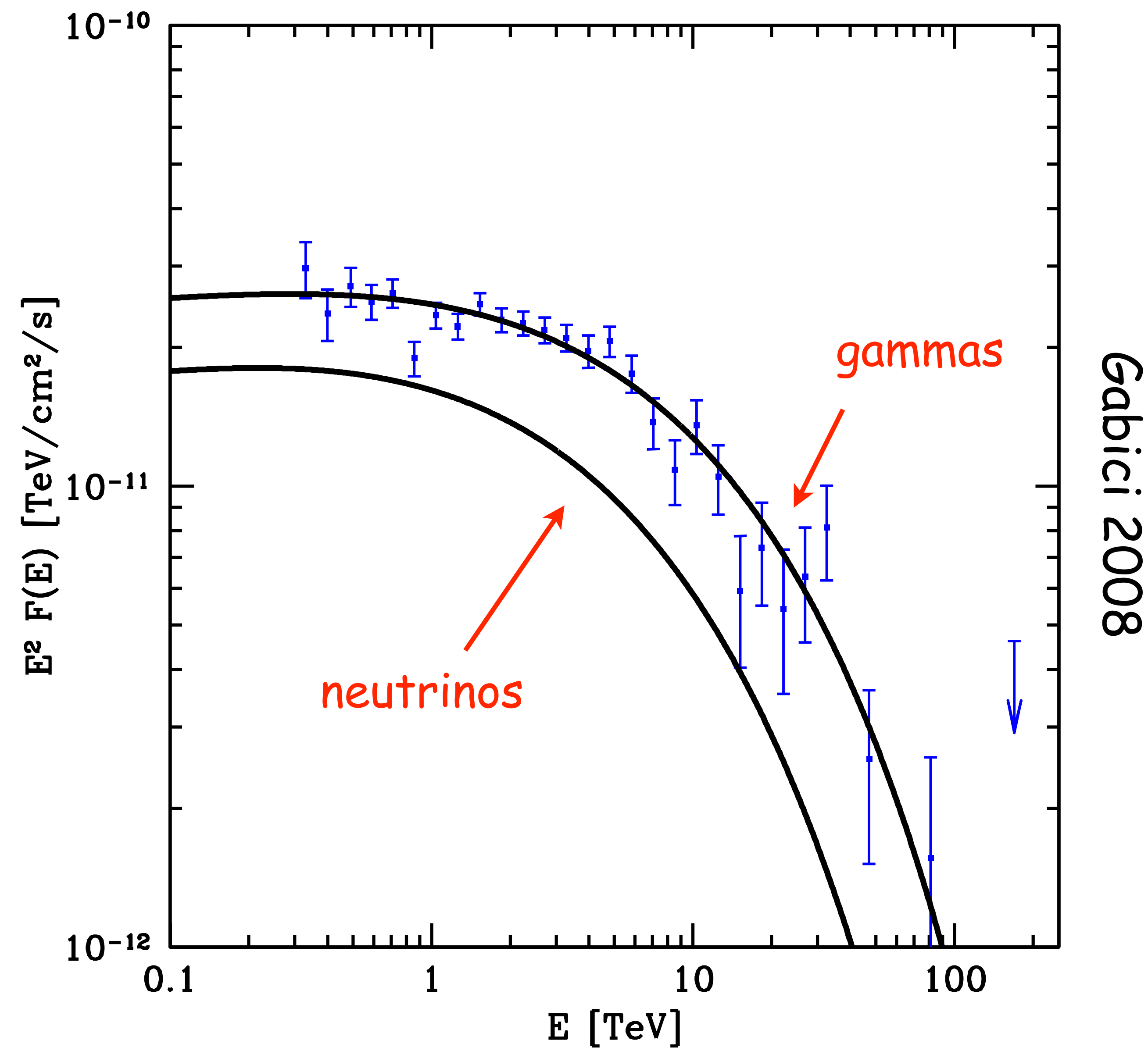



**totally model independent**

(SNRs are transparent
sources of gamma-rays)



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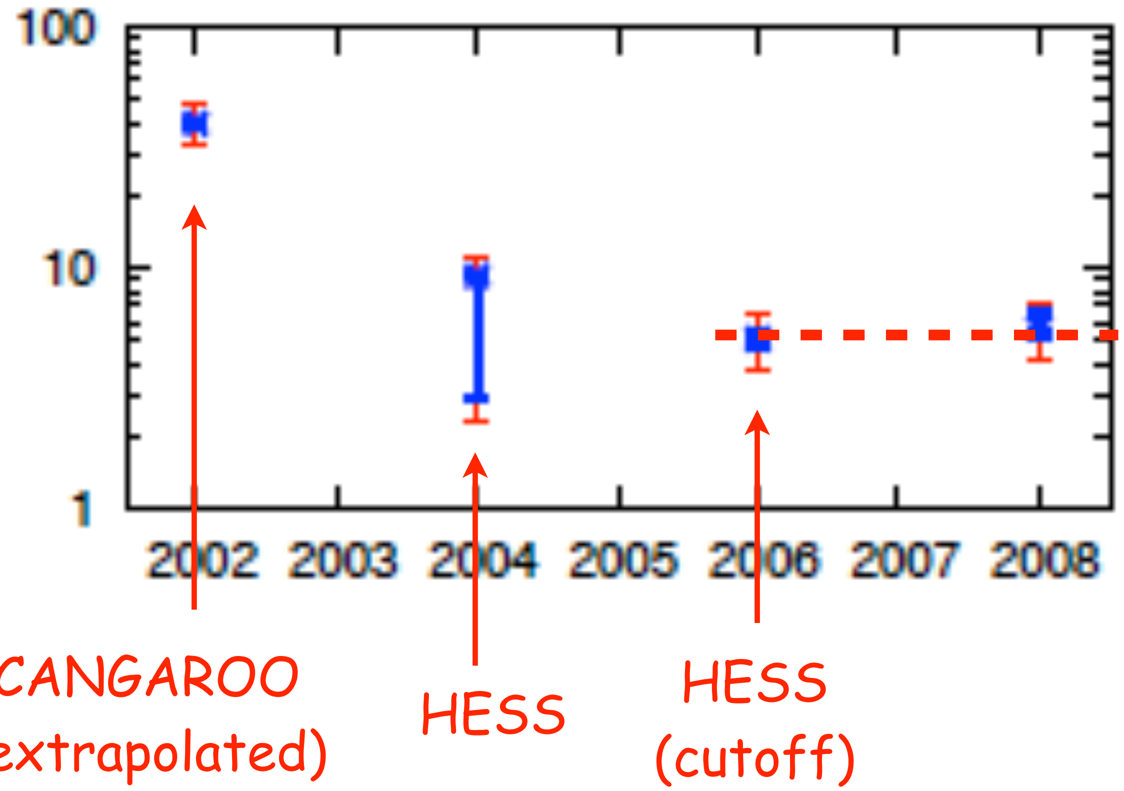


upper limit on nu emission

(gammas 100% hadronic)

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

Villante & Vissani 2008

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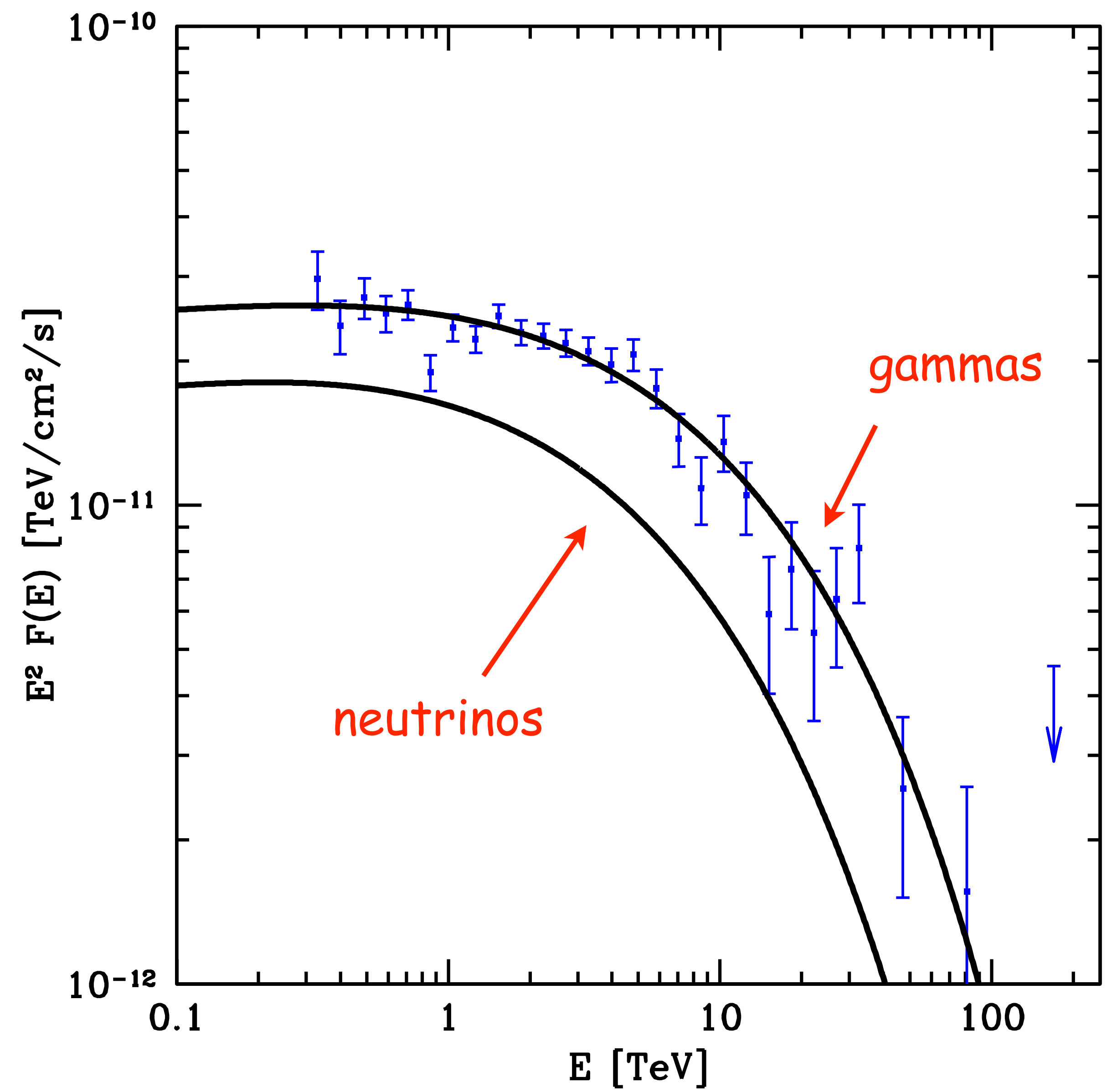


Gabici 2008

# 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