Gamma-rays and the sources of galactic cosmic rays (with a focus on PeVatrons and galactic centre)

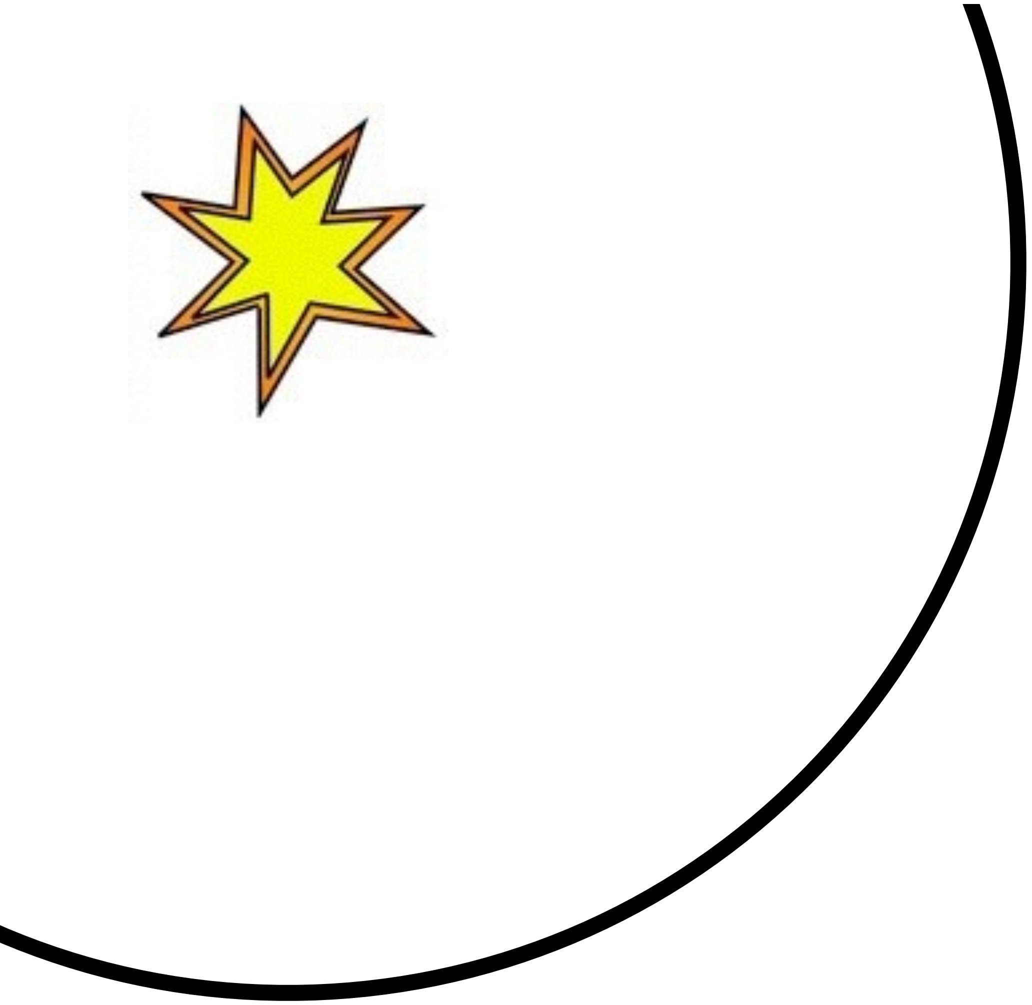
Stefano Gabici
APC, Paris

SuperNova Remnants, Cosmic Rays, γ-rays

SN explosions-> enough power to explain CRs

Baade & Zwicky 1934 (see also Ter Haar 1950)

SuperNova Remnants, Cosmic Rays, γ-rays



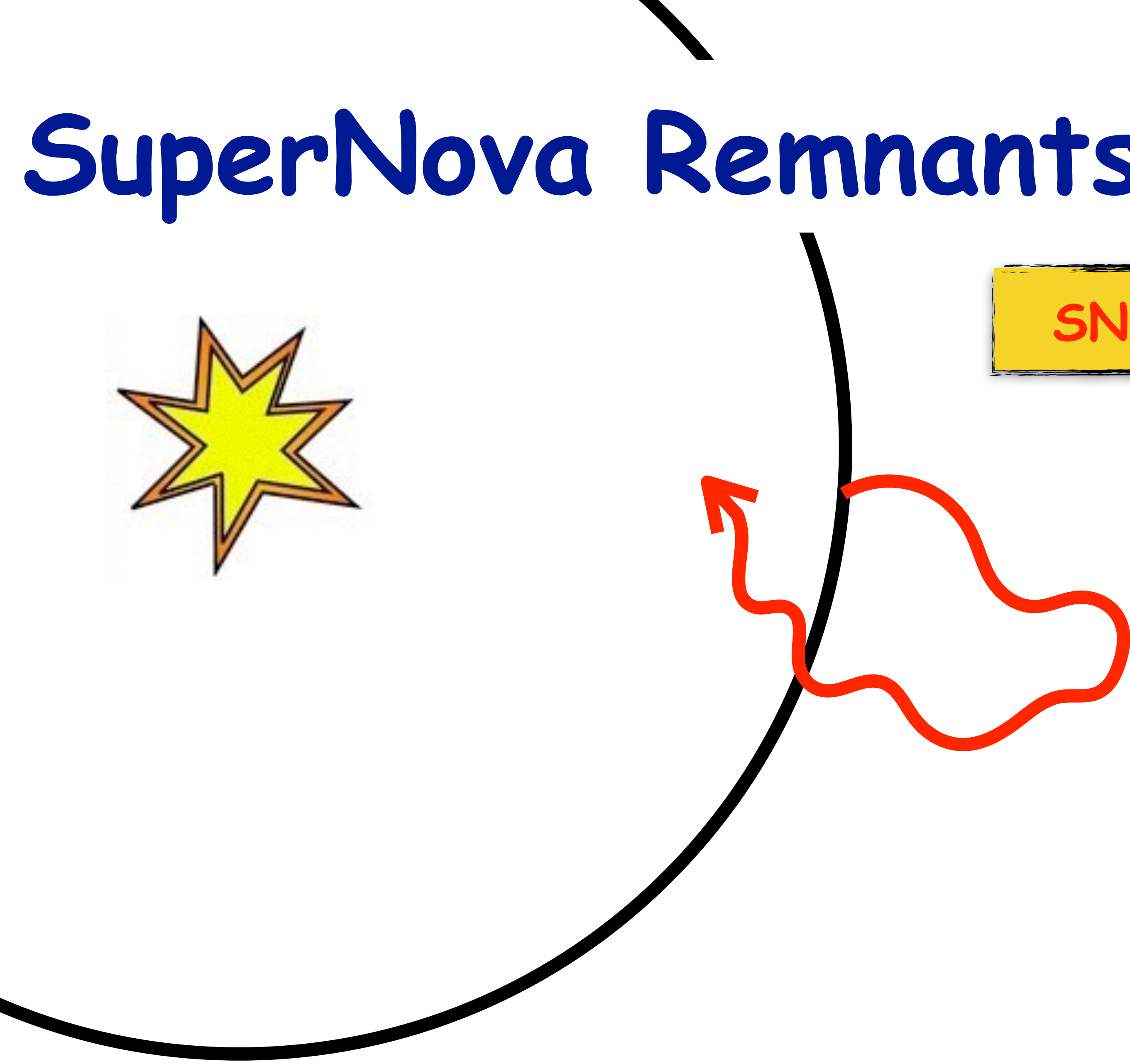
SN explosions-> enough power to explain CRs

Baade & Zwicky 1934 (see also Ter Haar 1950)

SNR shocks-> acceleration sites

Shklovsky 1954, Ginzburg & Syrovatskii 1964

SuperNova Remnants, Cosmic Rays, γ-rays



SN explosions-> enough power to explain CRs

Baade & Zwicky 1934 (see also Ter Haar 1950)

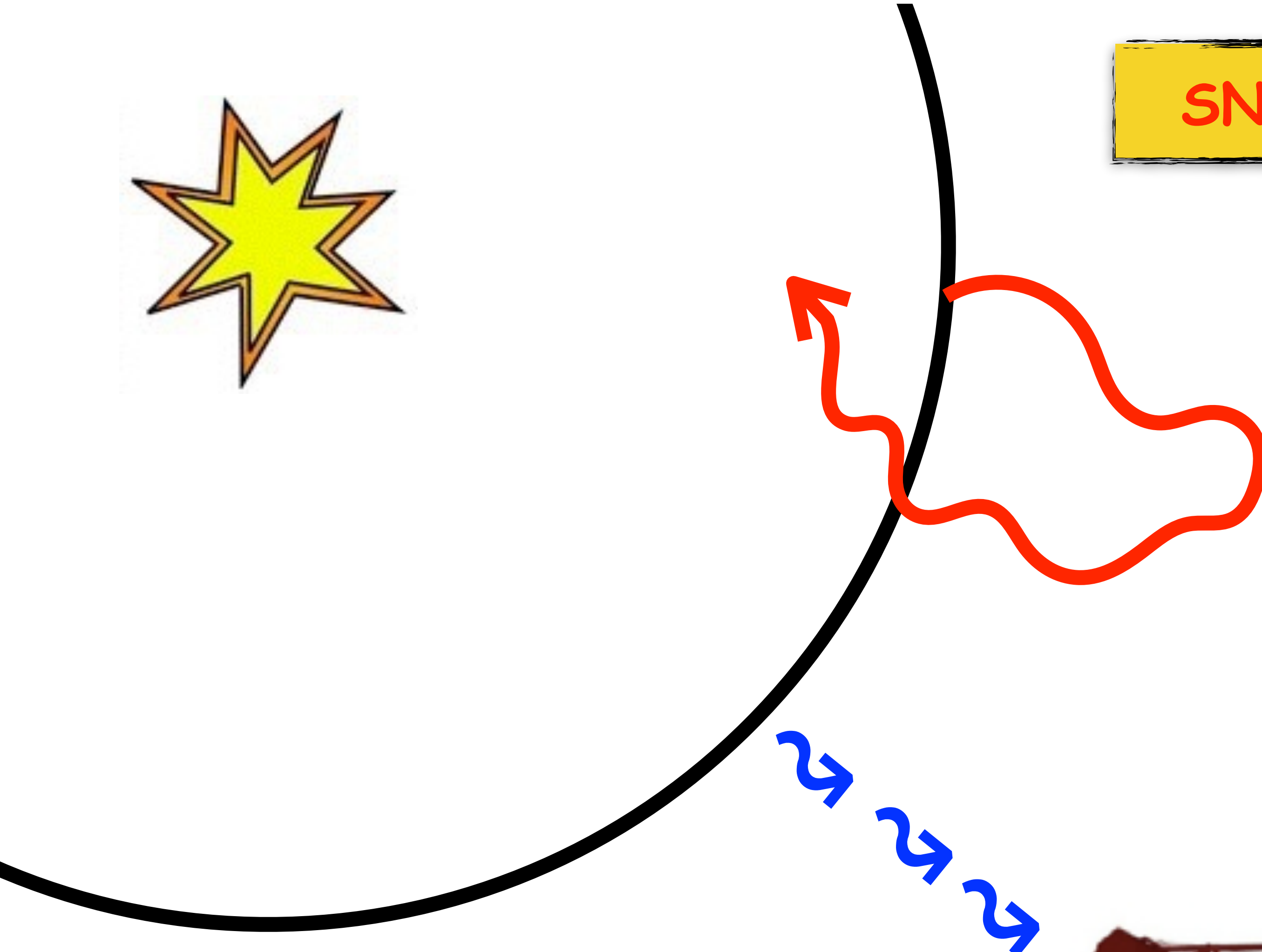
SNR shocks-> acceleration sites

Shklovsky 1954, Ginzburg & Syrovatskii 1964

Diffusive Shock Acceleration

BOBALSKy 1977-1978 (Blandford, Ostriker, Bell, Axford, Leer, Skadron, Krymskii)

SuperNova Remnants, Cosmic Rays, γ-rays



SN explosions-> enough power to explain CRs

Baade & Zwicky 1934 (see also Ter Haar 1950)

SNR shocks-> acceleration sites

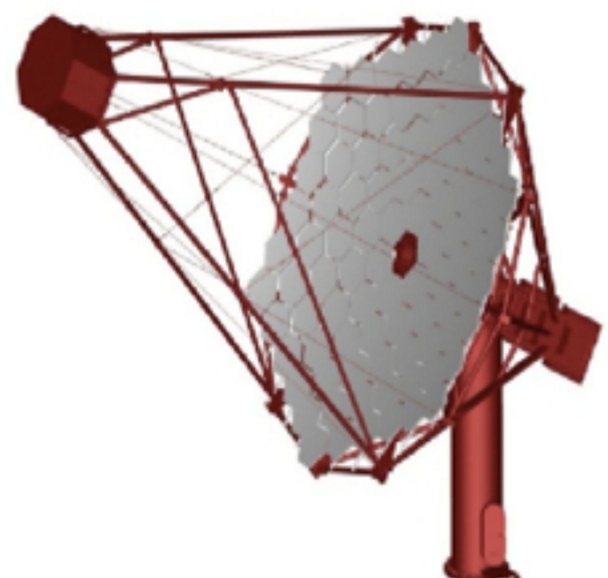
Shklovsky 1954, Ginzburg & Syrovatskii 1964

Diffusive Shock Acceleration

BOBALSKy 1977-1978 (Blandford, Ostriker, Bell, Axford, Leer, Skadron, Krymskii)

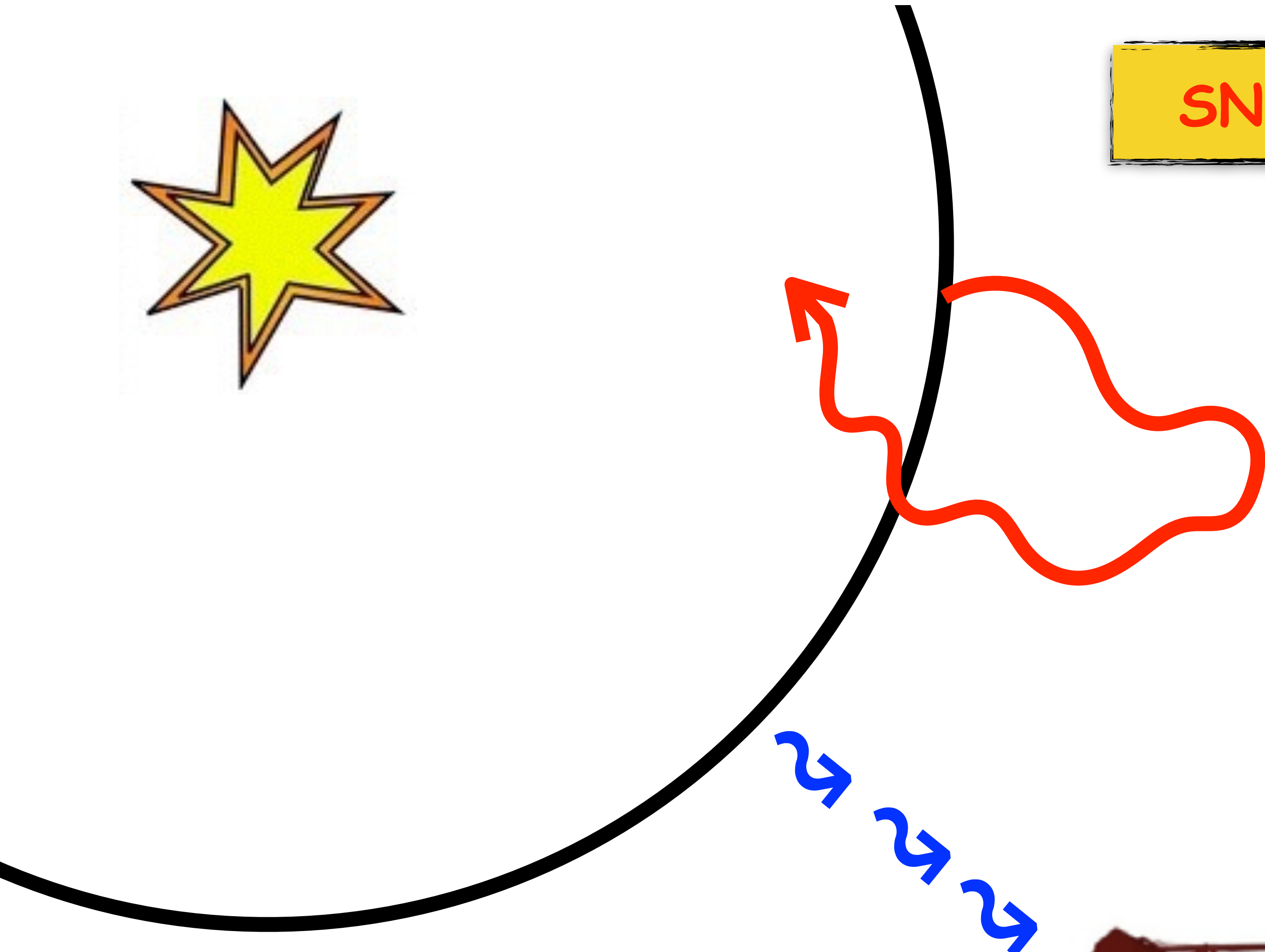
γ-rays from pp interactions

Drury, Aharonian & Völk 1994



<- Cherenkov telescope

SuperNova Remnants, Cosmic Rays, γ-rays



SN explosions-> enough power to explain CRs

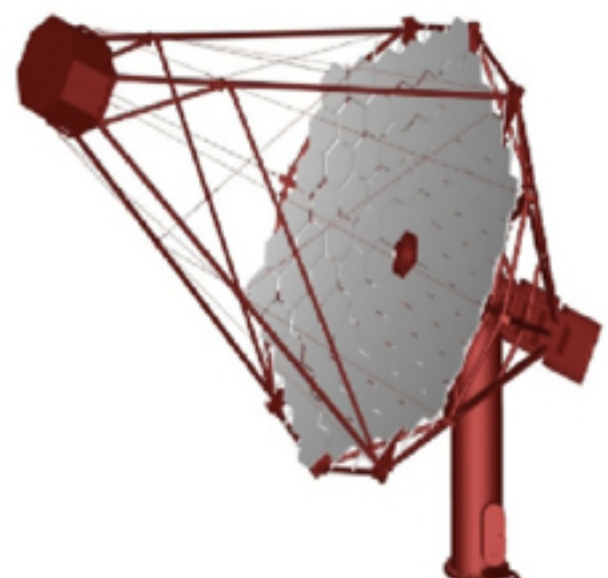
Baade & Zwicky 1934 (see also Ter Haar 1950)

SNR shocks-> acceleration sites

Shklovsky 1954, Ginzburg & Syrovatskii 1964

Diffusive Shock Acceleration

BOBALSKy 1977-1978 (Blandford, Ostriker, Bell, Axford, Leer, Skadron, Krymskii)



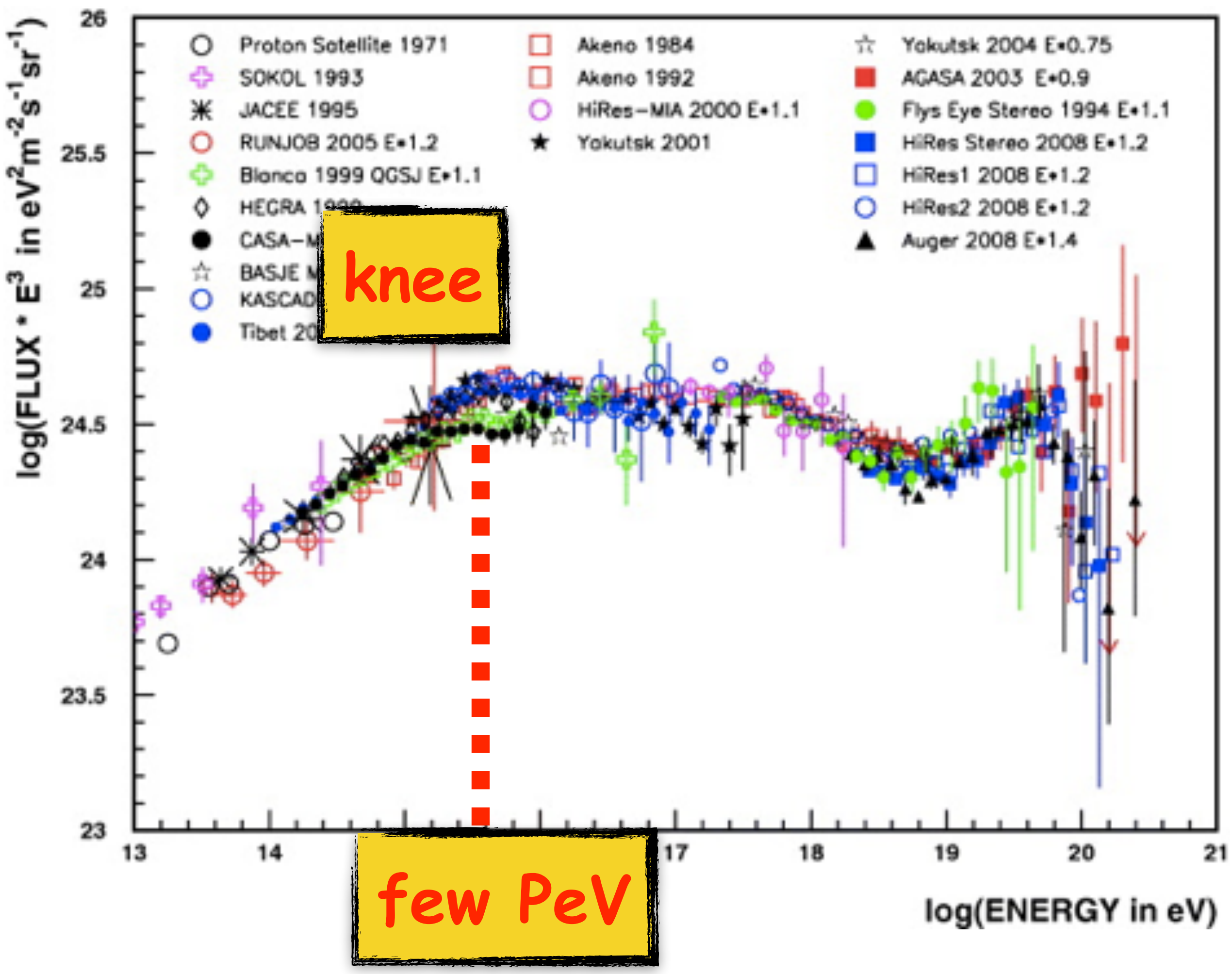
γ-rays from pp interactions

Drury, Aharonian & Völk 1994

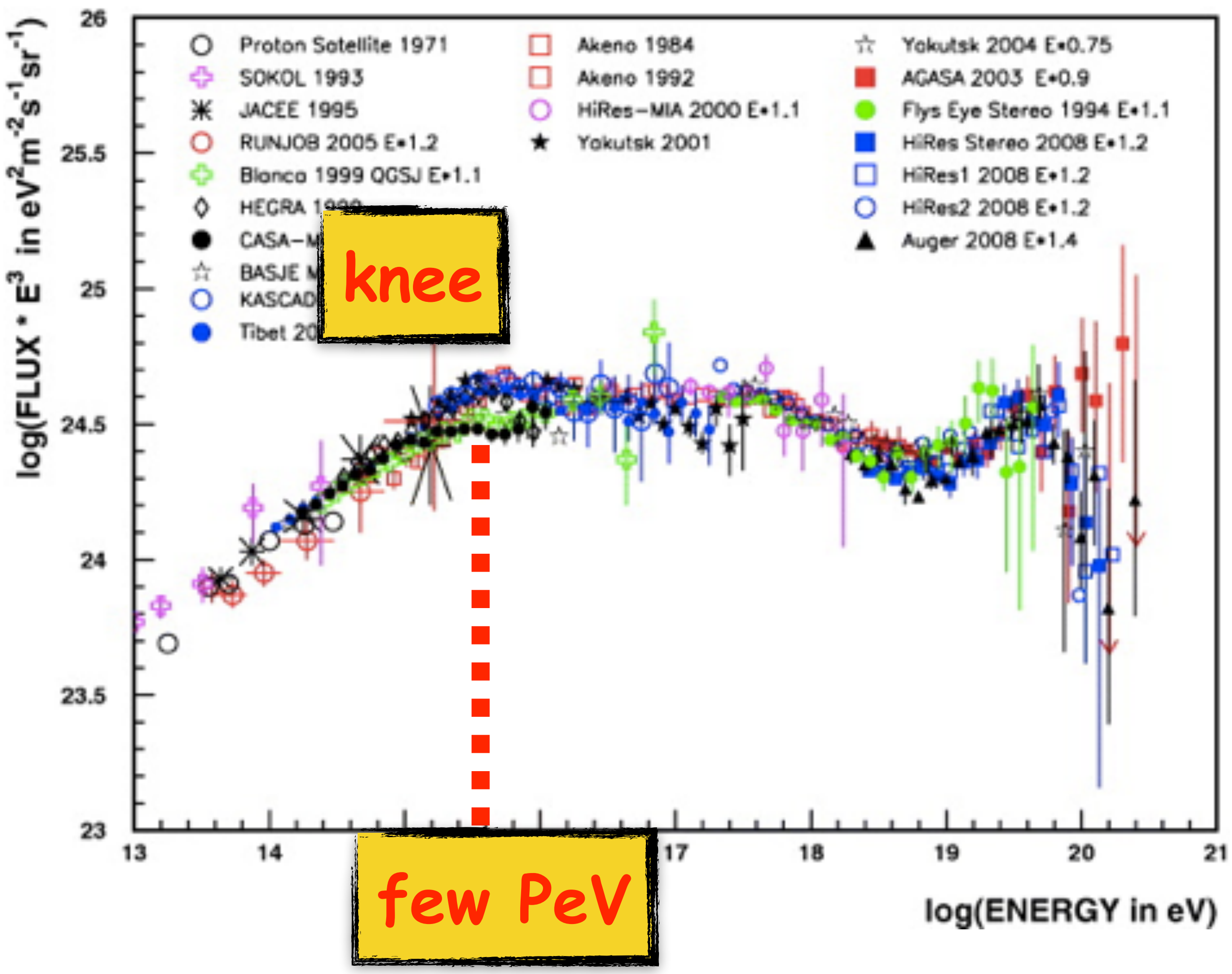
<- Cherenkov telescope

very popular but not proven (yet?)!

Are SNRs proton PeVatrons?



Are SNRs proton PeVatrons?



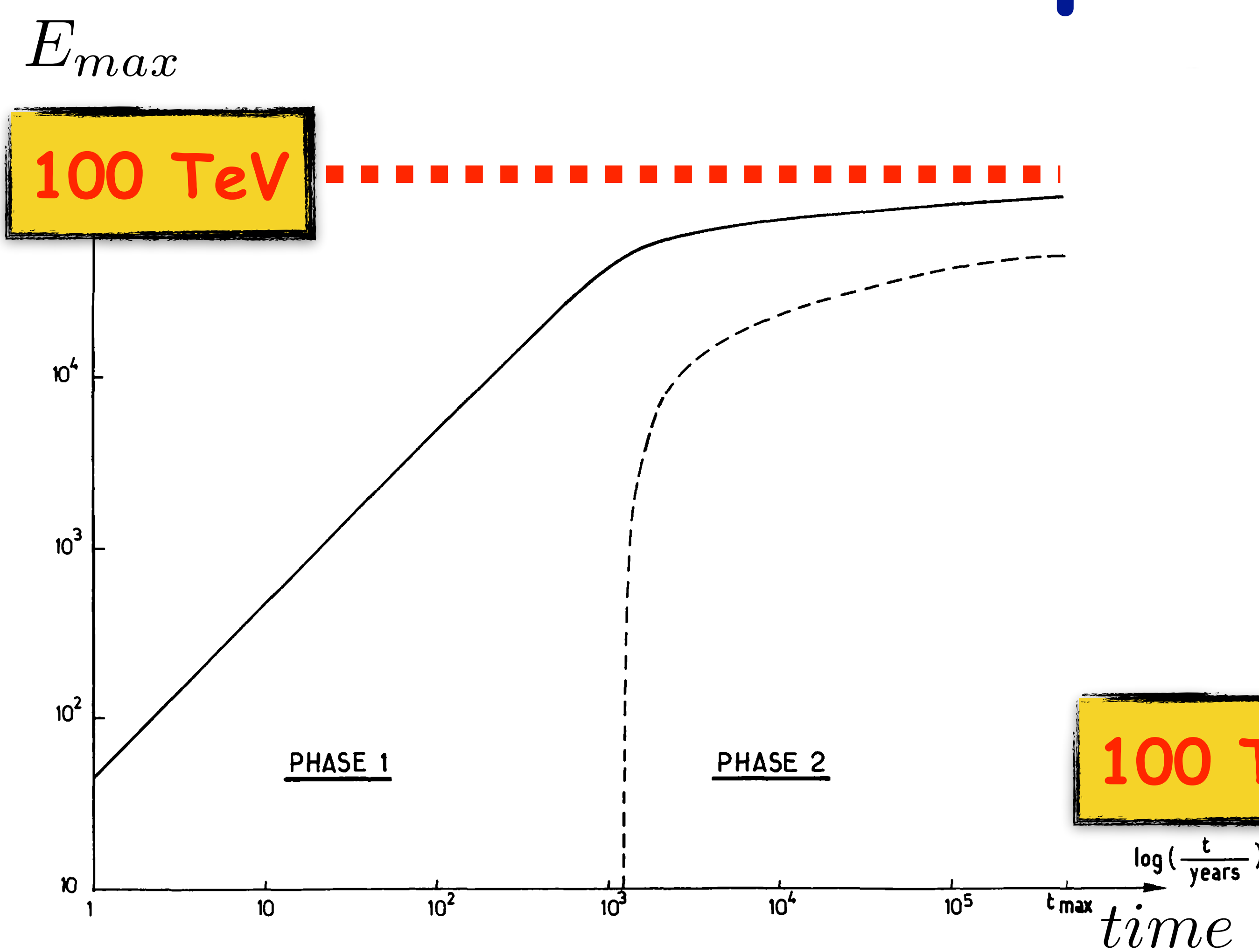
Hillas criterium

$$E_{max} \approx u \; R \; B$$

velocity → u, size → R, magnetic field → B

$$E_{max} \approx 1 \left(\frac{u}{10^3 \text{ km/s}}\right) \left(\frac{R}{\text{pc}}\right) \left(\frac{B}{\mu\text{G}}\right) \text{TeV}$$

Are SNRs proton PeVatrons?



Lagage & Cesarsky 1983

Hillas criterium

$$E_{max} \approx u \; R \; B$$

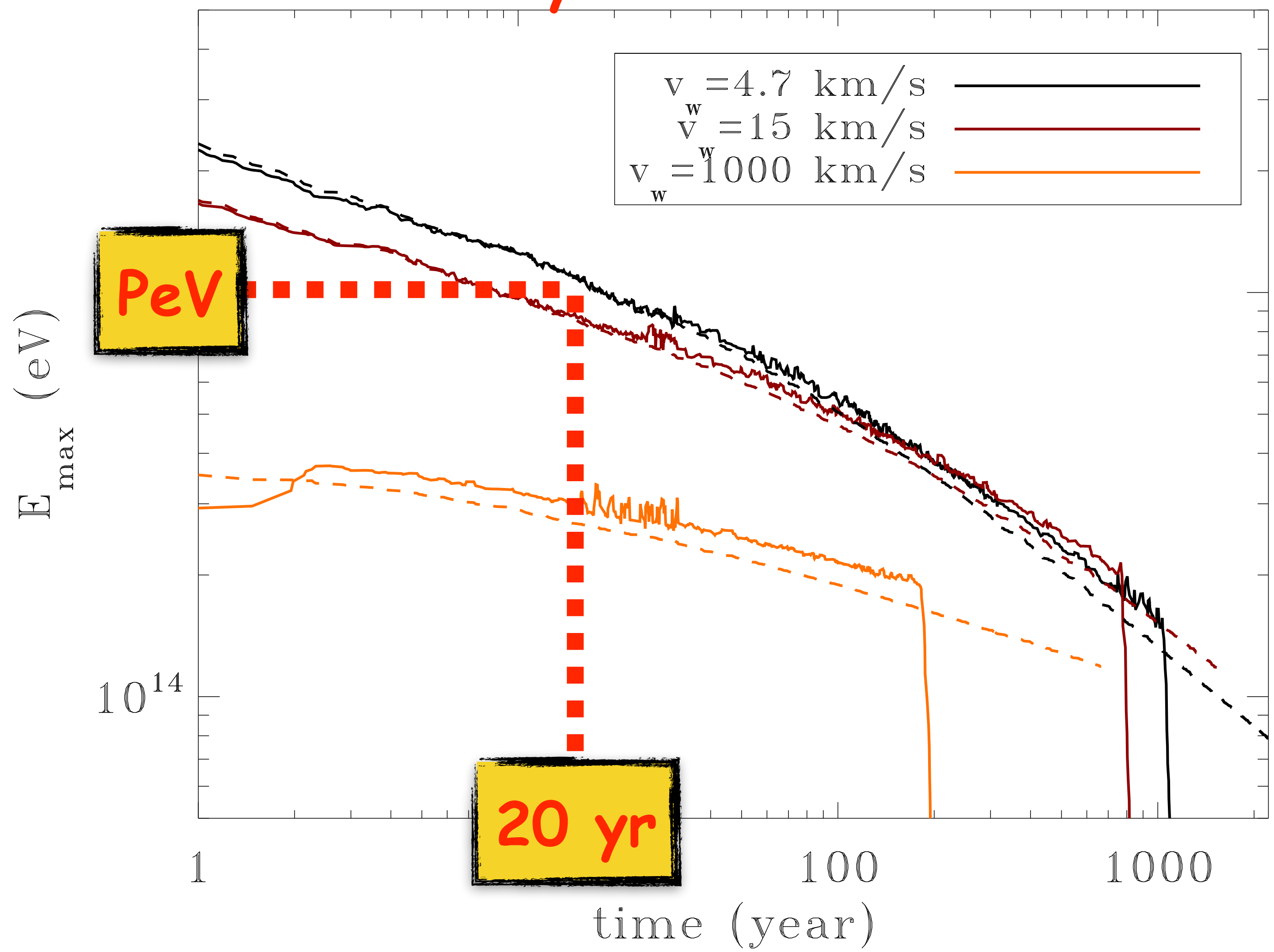
velocity (u), size (R), magnetic field (B)

$$100 \text{ TeV} \approx 1 \left(\frac{u}{10^3 \text{ km/s}} \right) \left(\frac{R}{\text{pc}} \right) \left(\frac{B}{\mu\text{G}} \right) \text{TeV}$$

~10 ~3 ~3

Are SNRs proton PeVatrons?

30 years later…



Schure & Bell 2013

Hillas criterium

$$E_{max} \approx u\ R\ B$$

velocity
size
magnetic field

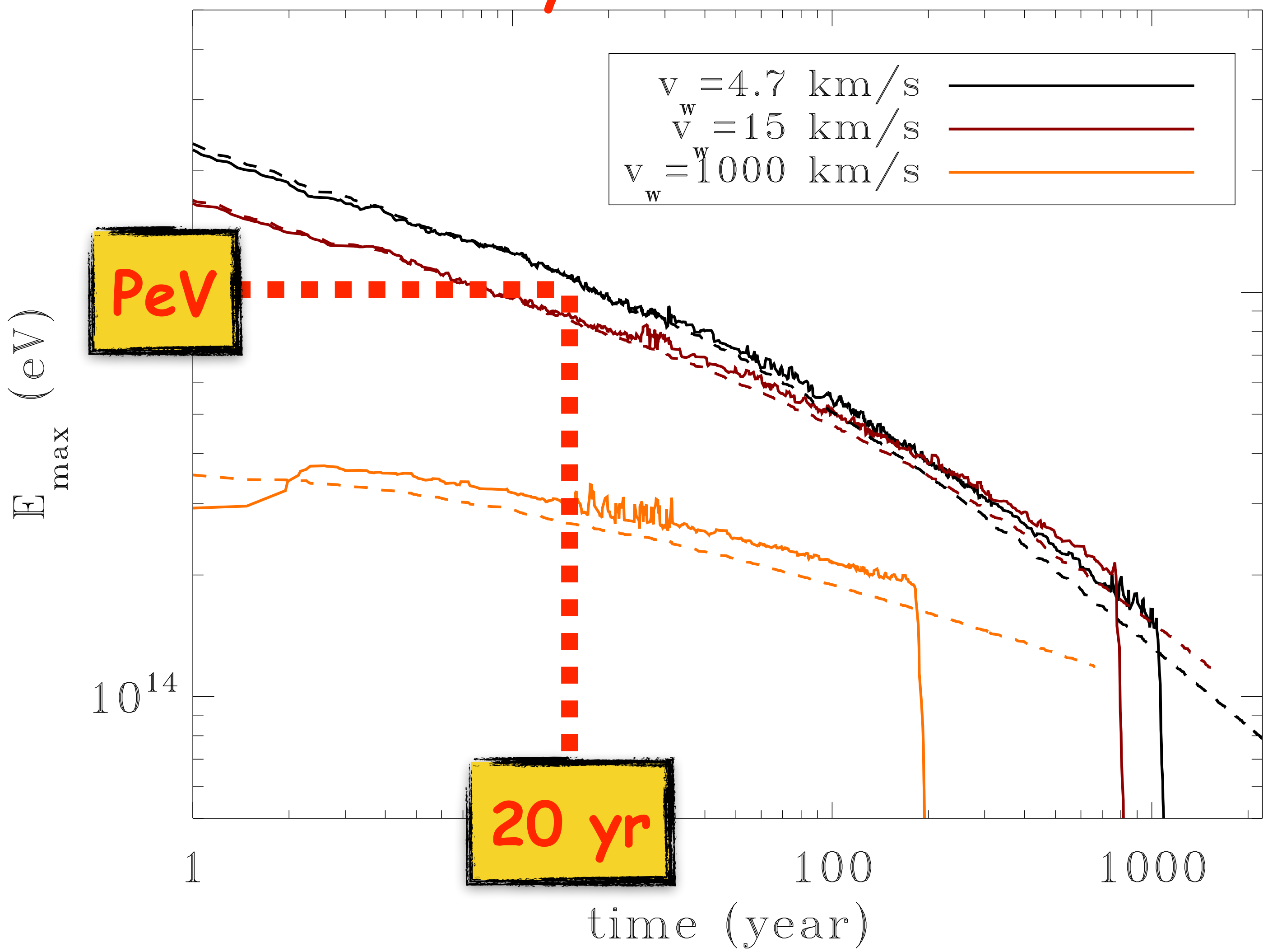
B-field amplification

$$\approx \ldots \left(\frac{B}{\mu G}\right) \text{TeV}$$

~10 ~3 ~3

Are SNRs proton PeVatrons?

30 years later…



Schure & Bell 2013

Hillas criterium

$$E_{max} \approx u \; R \; B$$

velocity

size

magnetic field

B-field amplification

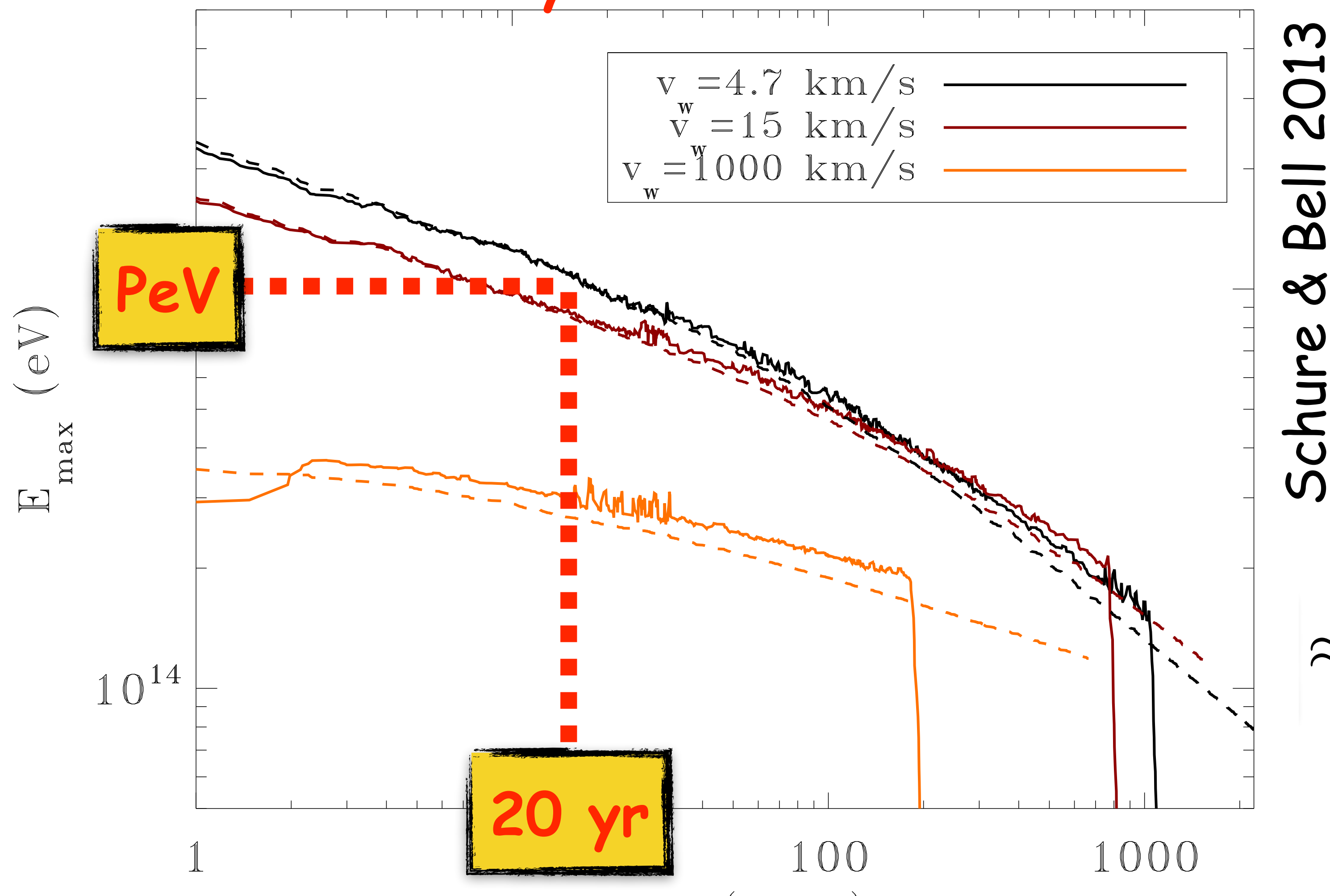
$$\approx \ldots \left(\frac{B}{\mu G}\right) \text{TeV}$$

~10 ~3 ~3

current driven, non-resonant instability (Bell 2004, 2013) -> **PeV particle acceleration possible** in the very early (tens of years) stage of a SNR evolution -> **ejecta dominated phase** -> is there **enough power** to feed the PeV CR population?

Are SNRs proton PeVatrons?

30 years later...



Hillas criterium

$$E_{max} \approx u\ R\ B$$

velocity, size, magnetic field

≈ B-field amplification $\left(\frac{B}{\mu G}\right)$ TeV

~10 ~3 ~3

Drury instability might also play a role -> Drury,Downes 2012,2014

current driven, non-resonant instability (Bell 2004, 2013) -> **PeV particle acceleration possible** in the very early (tens of years) stage of a SNR evolution -> **ejecta dominated phase** -> is there **enough power** to feed the PeV CR population?

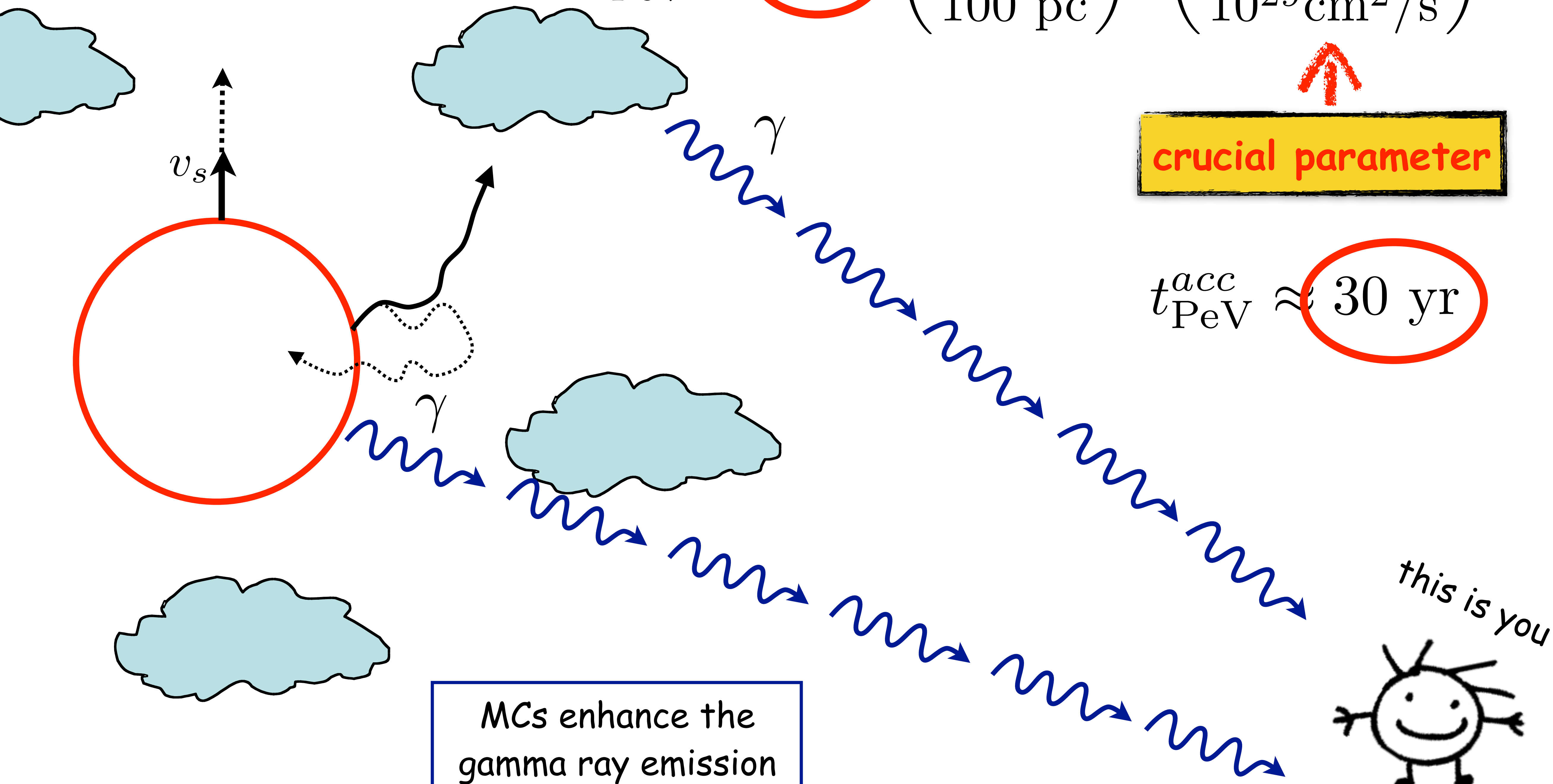
Indirect detection of PeVatrons?

$$t_{\rm PeV}^{diff} \approx 5000 \left(\frac{d}{100 \text{ pc}} \right)^2 \left(\frac{D_{PeV}}{10^{29} \text{cm}^2/\text{s}} \right)^{-1} \text{yr}$$

crucial parameter

$$t_{\rm PeV}^{acc} \approx 30 \text{ yr}$$

CRs escape the SNR

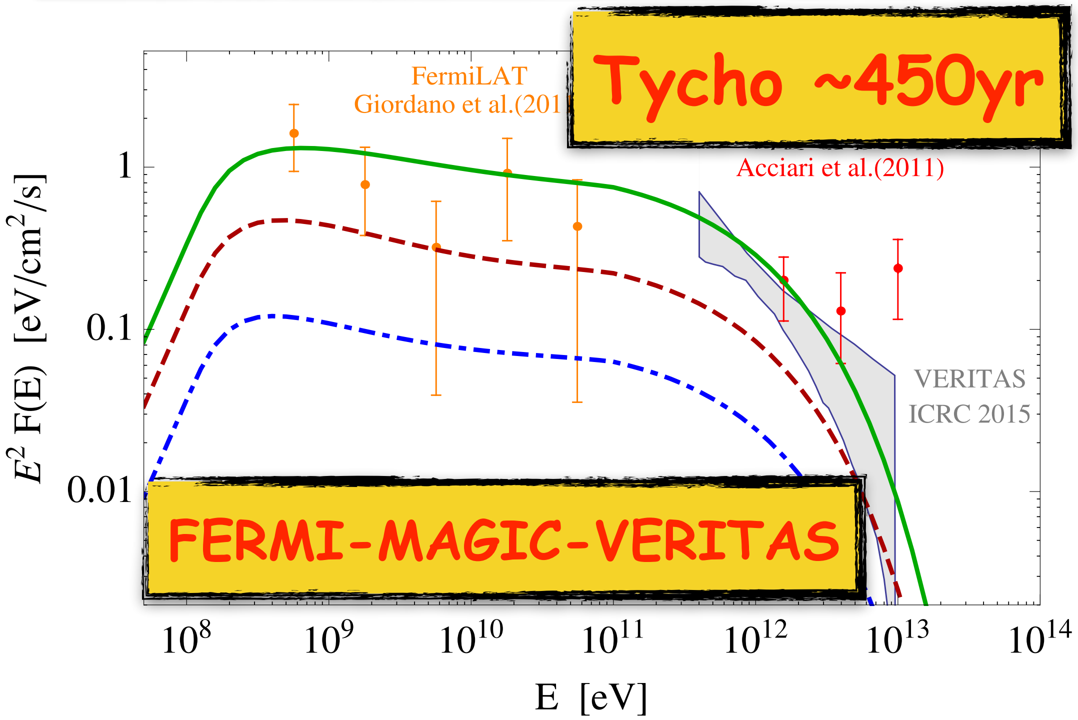


MCs enhance the gamma ray emission

SG & Aharonian 2007

SNRs in gamma rays

very young | middle aged | old



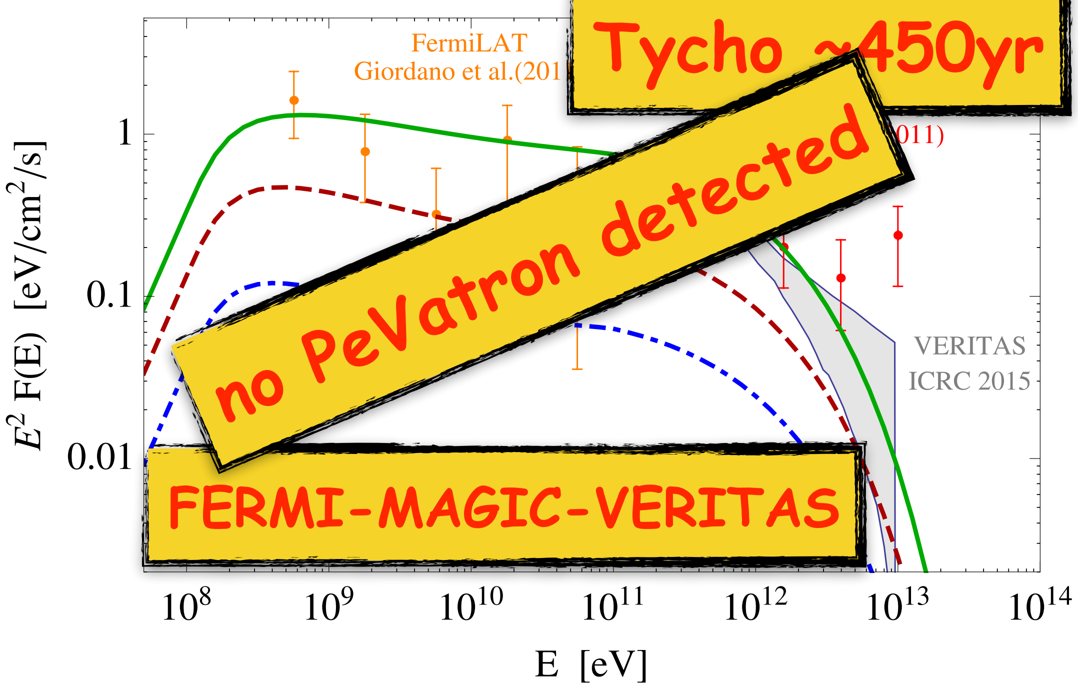
are SNRs proton PeVatrons?

hundreds of yrs | thousands of yrs | $10^4 ... 10^5$ yr

SNRs in gamma rays

very young | middle aged | old

Tycho ~450yr

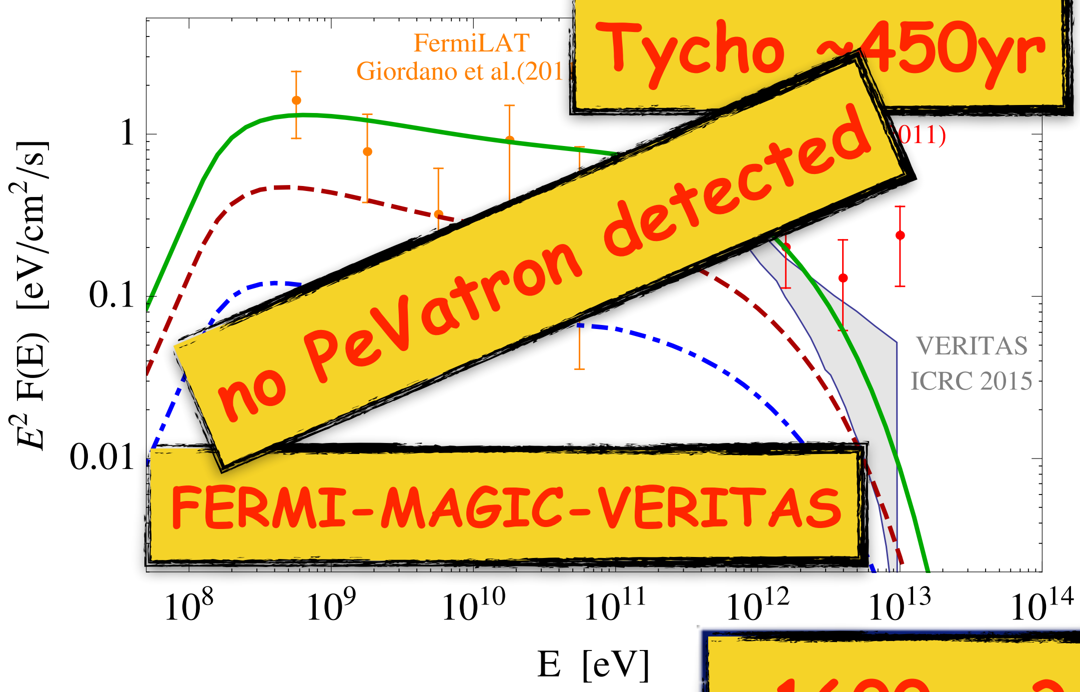


are SNRs proton PeVatrons?

hundreds of yrs | thousands of yrs | $10^4 ... 10^5$ yr

SNRs in gamma rays

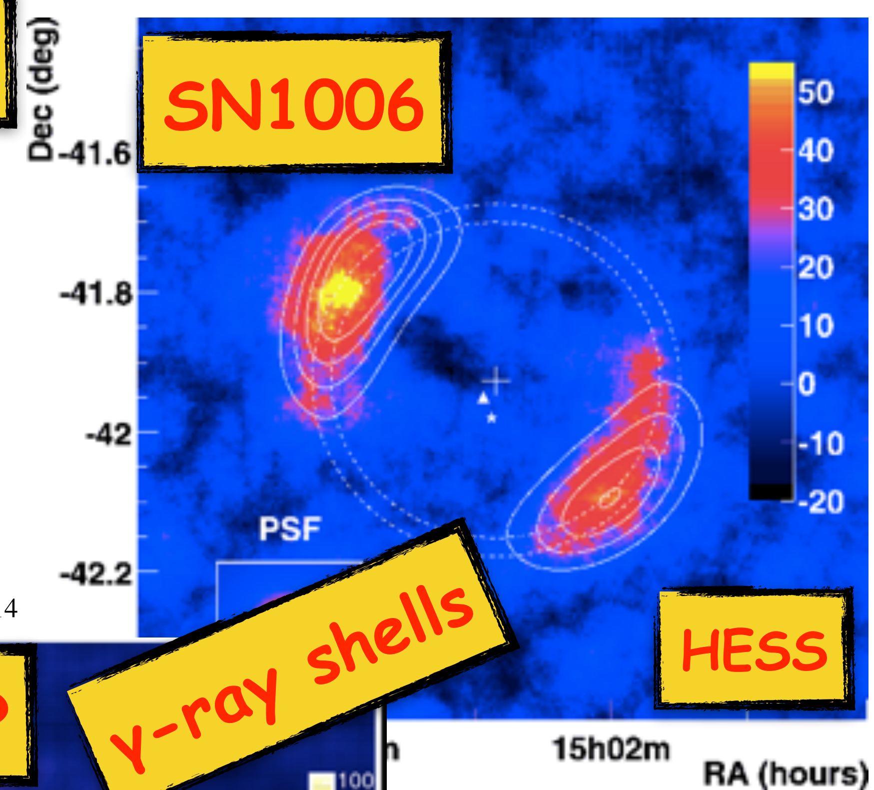
very young — middle aged — old



Tycho ~450yr

no PeVatron detected

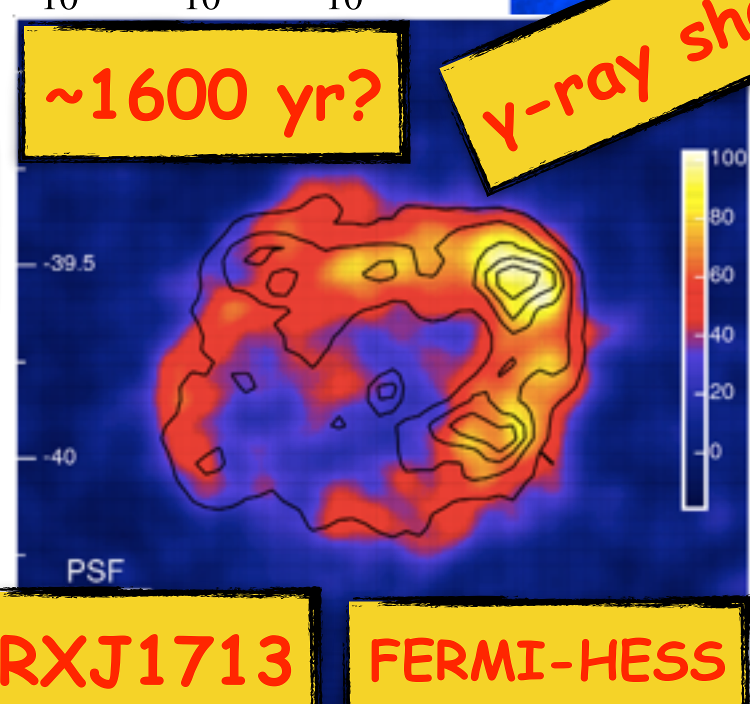
FERMI-MAGIC-VERITAS



SN1006

HESS

γ-ray shells



~1600 yr?

RXJ1713

FERMI-HESS

are SNRs proton PeVatrons?

which production spectrum?

hundreds of yrs

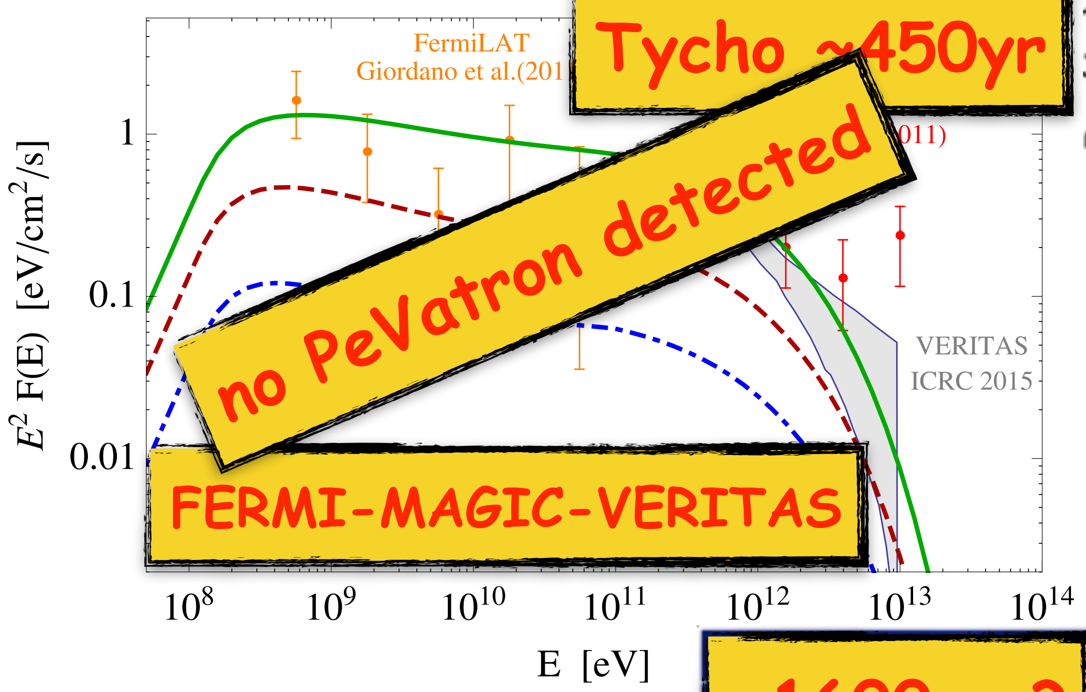
thousands of yrs

$10^4 ... 10^5$ yr

SNRs in gamma rays

very young — middle aged — old

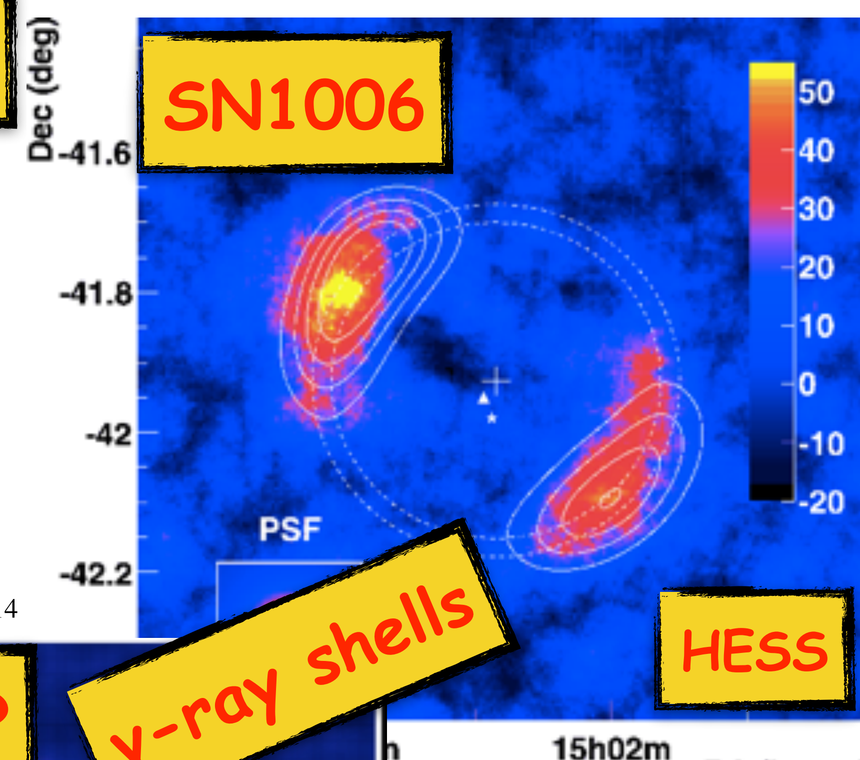
Tycho ~450yr



no PeVatron detected

FERMI-MAGIC-VERITAS

SN1006

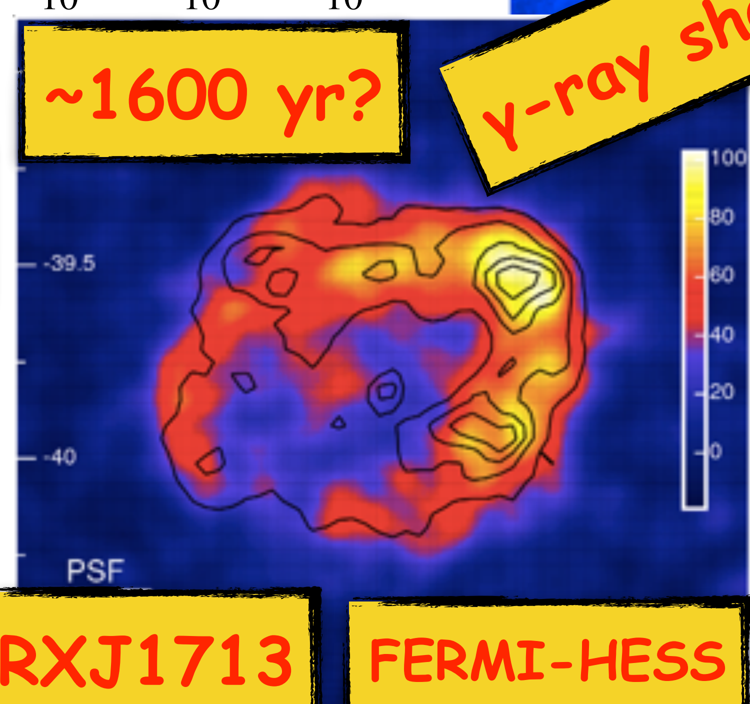


γ-ray shells

HESS

effect of interactions with ISM?

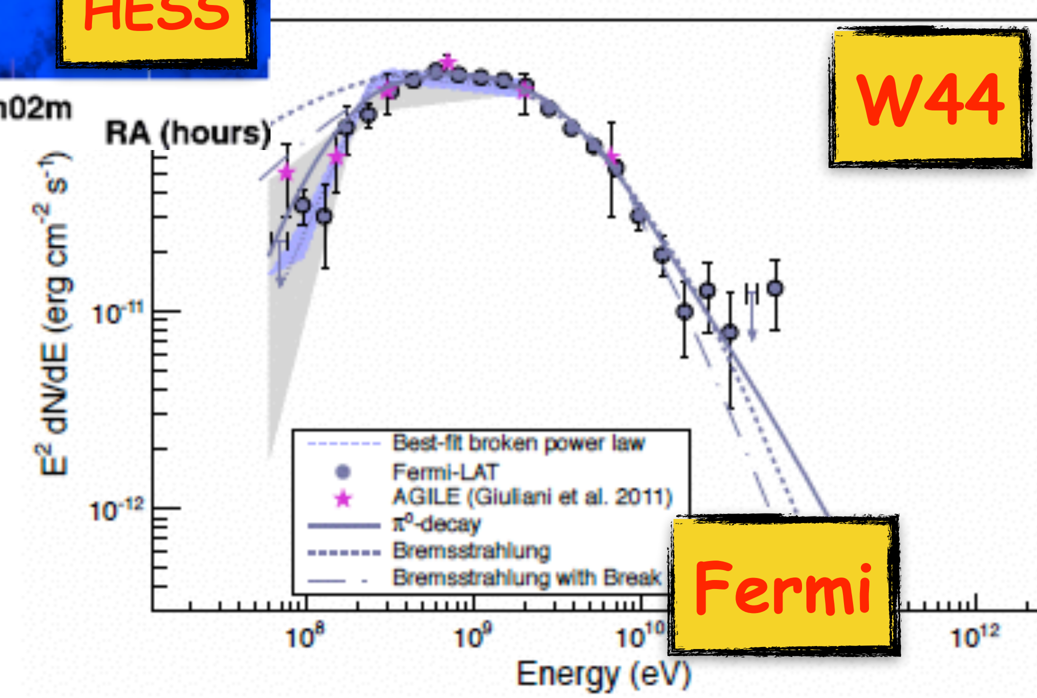
~1600 yr?



RXJ1713

FERMI-HESS

W44



Fermi

are SNRs proton PeVatrons?

which production spectrum?

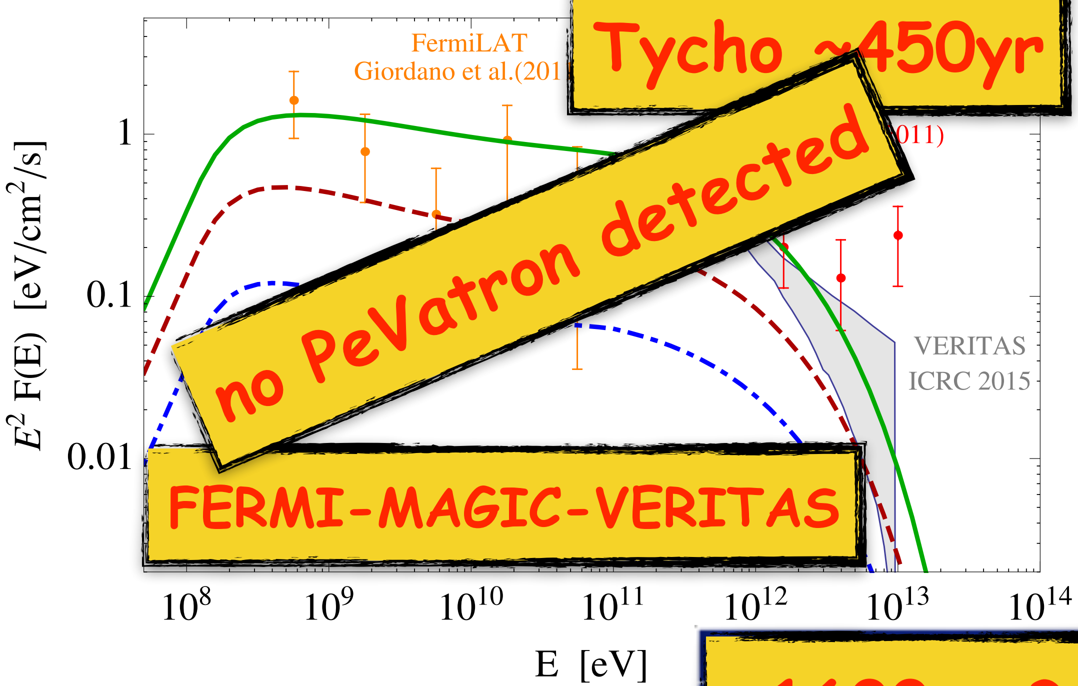
hundreds of yrs

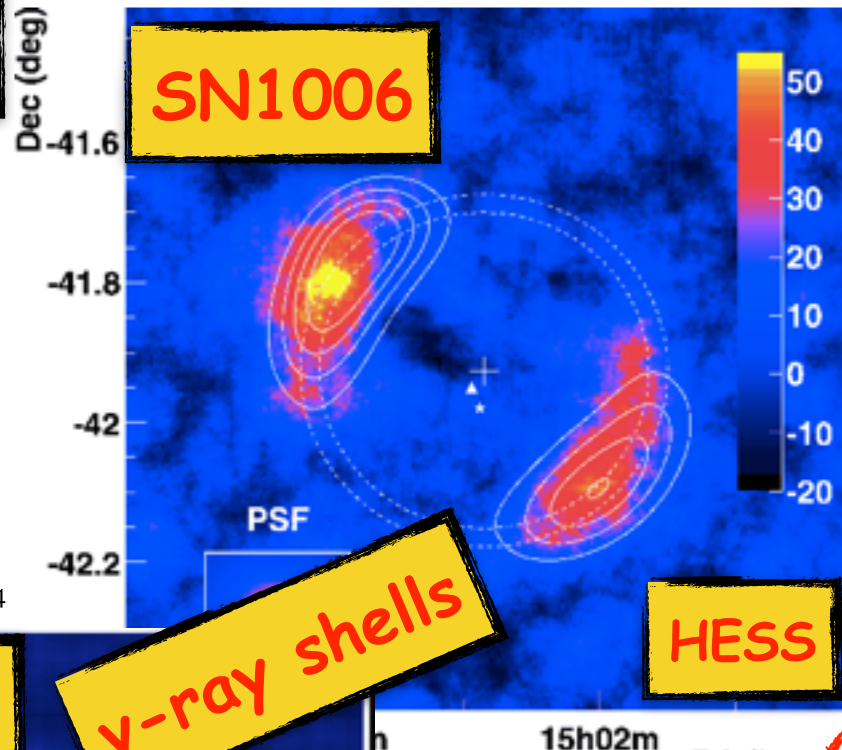
thousands of yrs

$10^4 \ldots 10^5$ yr

SNRs in gamma rays

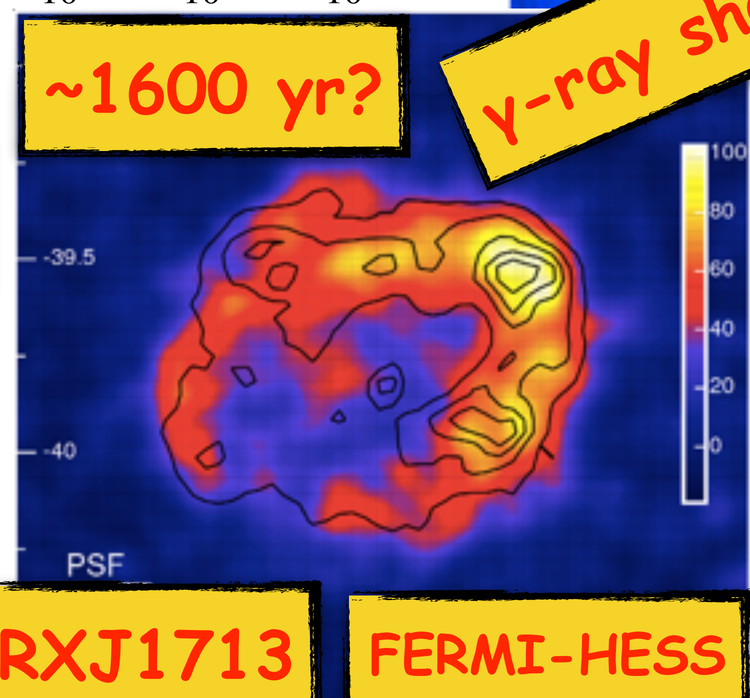
very young — middle aged — old

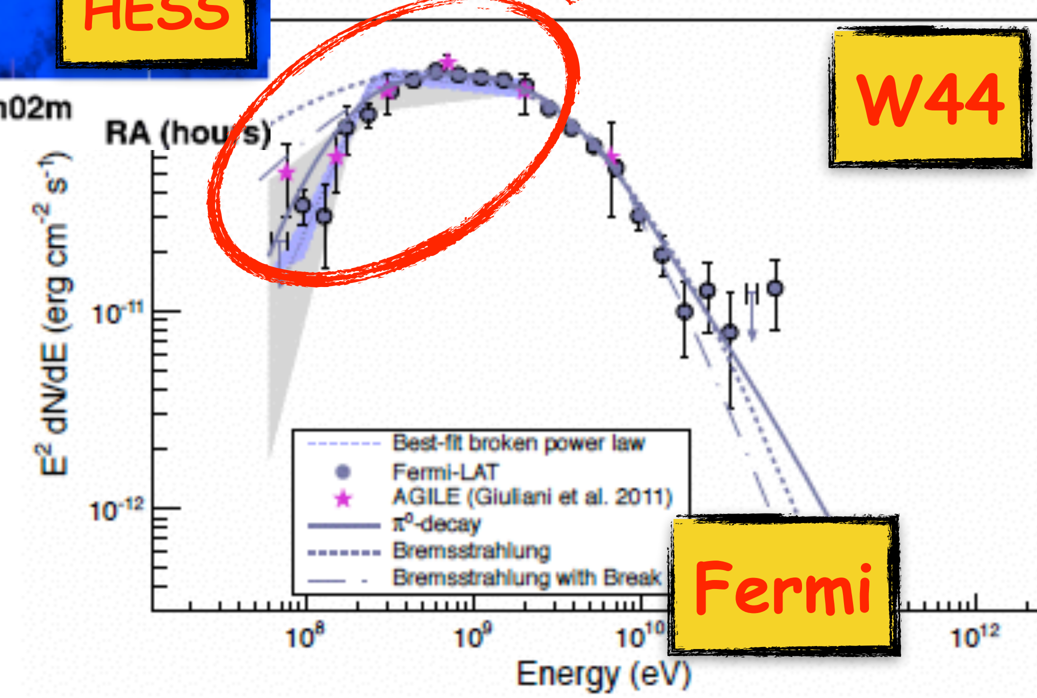




effect of interactions with ISM?

pion decay->hadronic





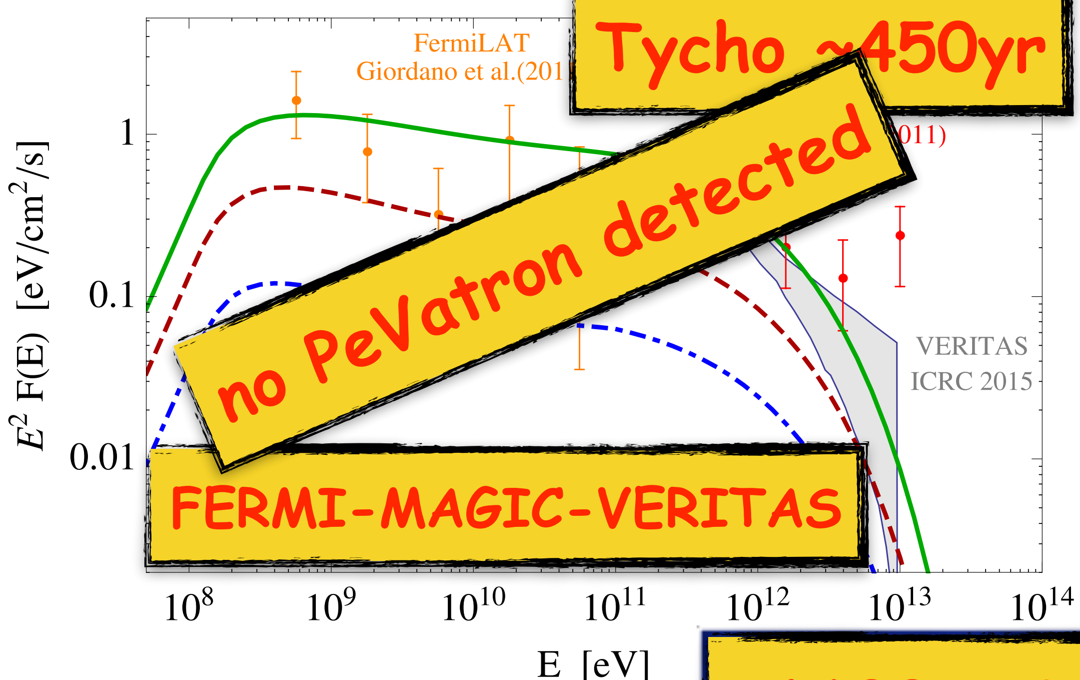
are SNRs proton PeVatrons?

which production spectrum?

hundreds of yrs — thousands of yrs — $10^4 … 10^5$ yr

SNRs in gamma rays

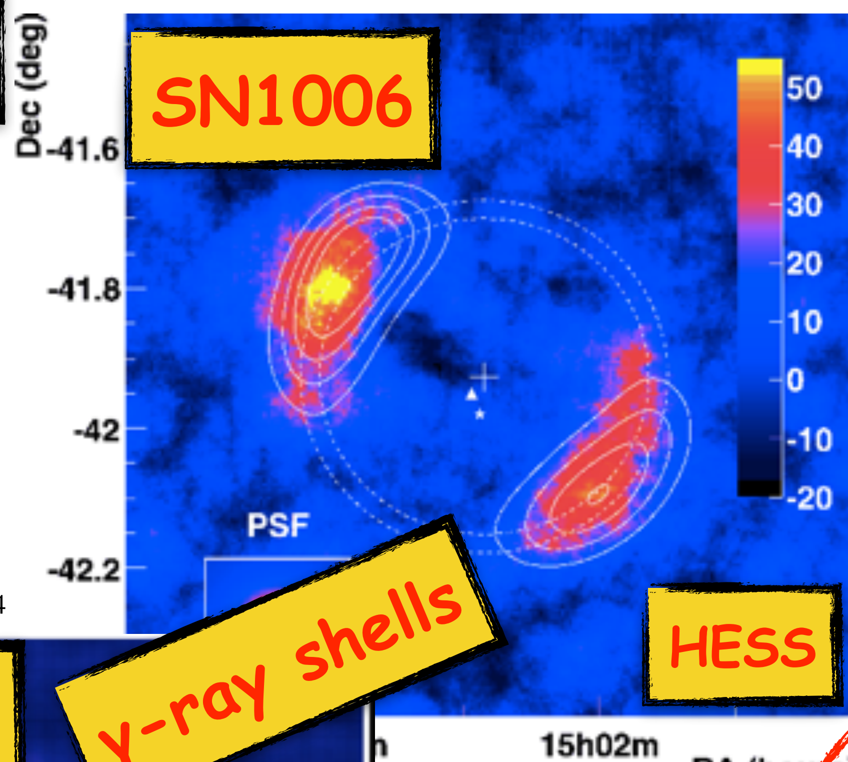
very young | middle aged | old



Tycho ~450yr

no PeVatron detected

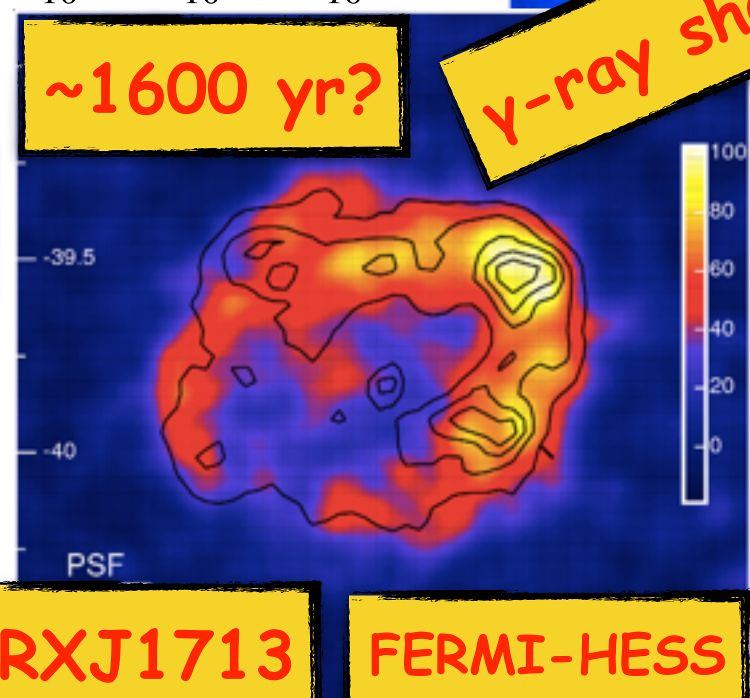
FERMI-MAGIC-VERITAS



SN1006

HESS

γ-ray shells



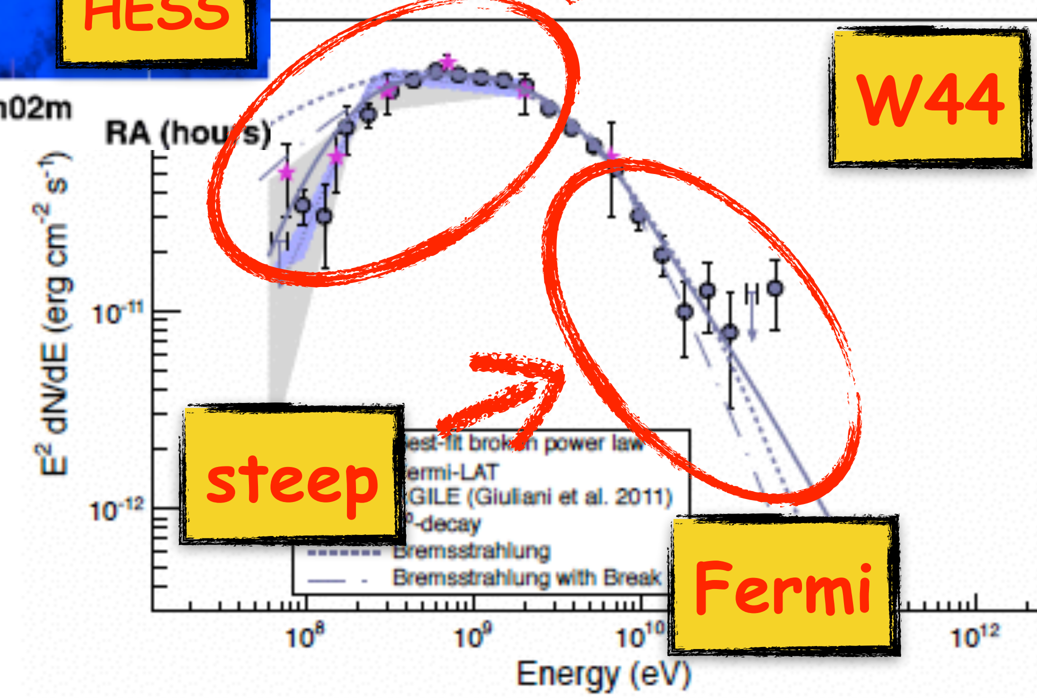
~1600 yr?

RXJ1713

FERMI-HESS

effect of interactions with ISM?

pion decay->hadronic



W44

steep

Fermi

are SNRs proton PeVatrons?

which production spectrum?

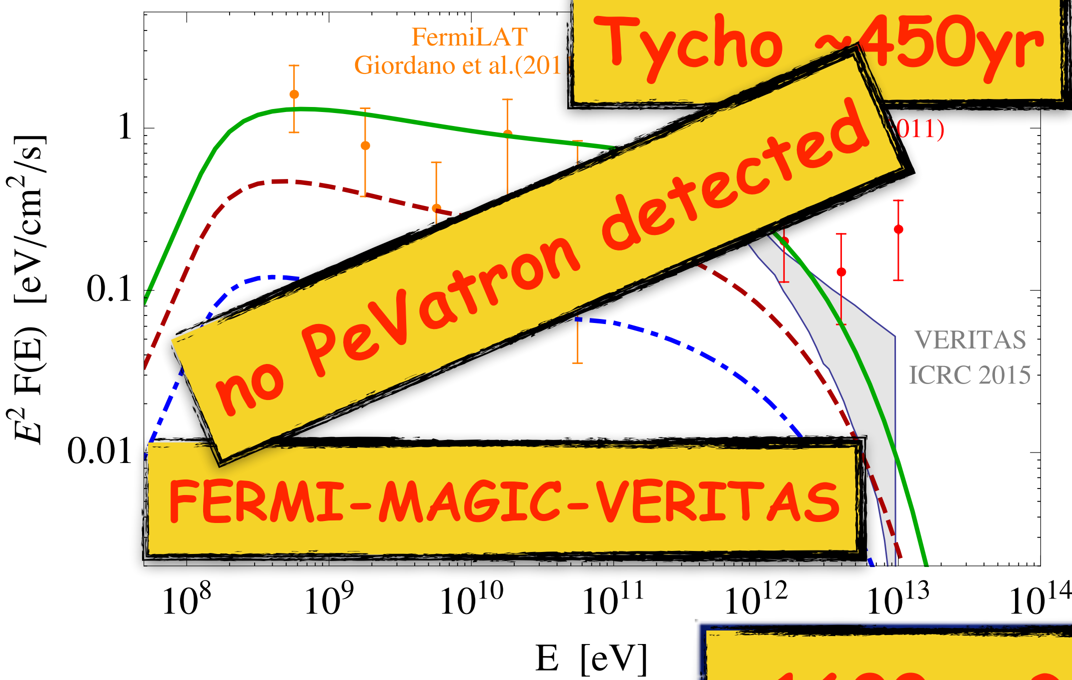
hundreds of yrs

thousands of yrs

$10^4...10^5$ yr

SNRs in gamma rays

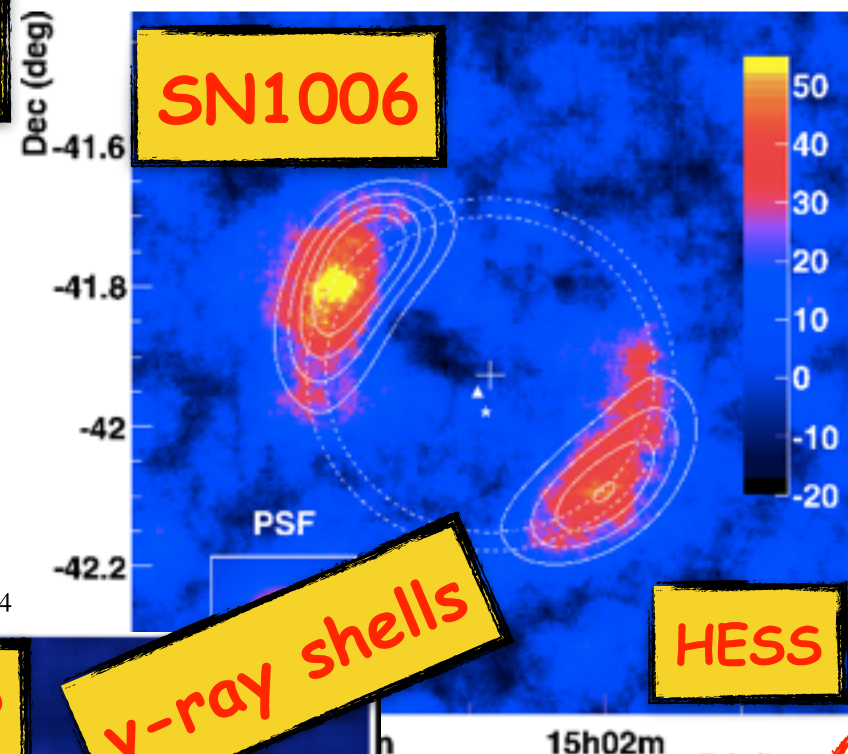
very young — middle aged — old



Tycho ~450yr

no PeVatron detected

FERMI-MAGIC-VERITAS



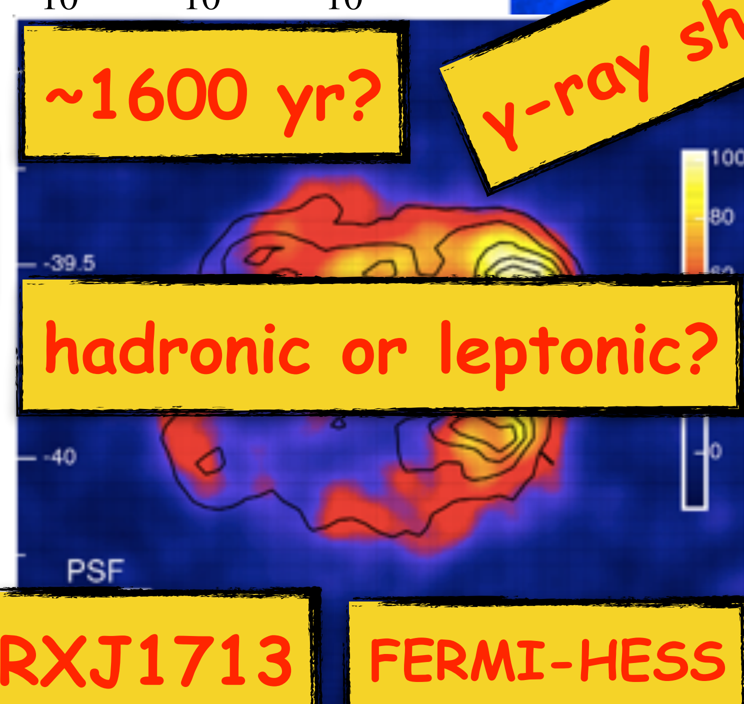
SN1006

HESS

γ-ray shells

effect of interactions with ISM?

pion decay->hadronic

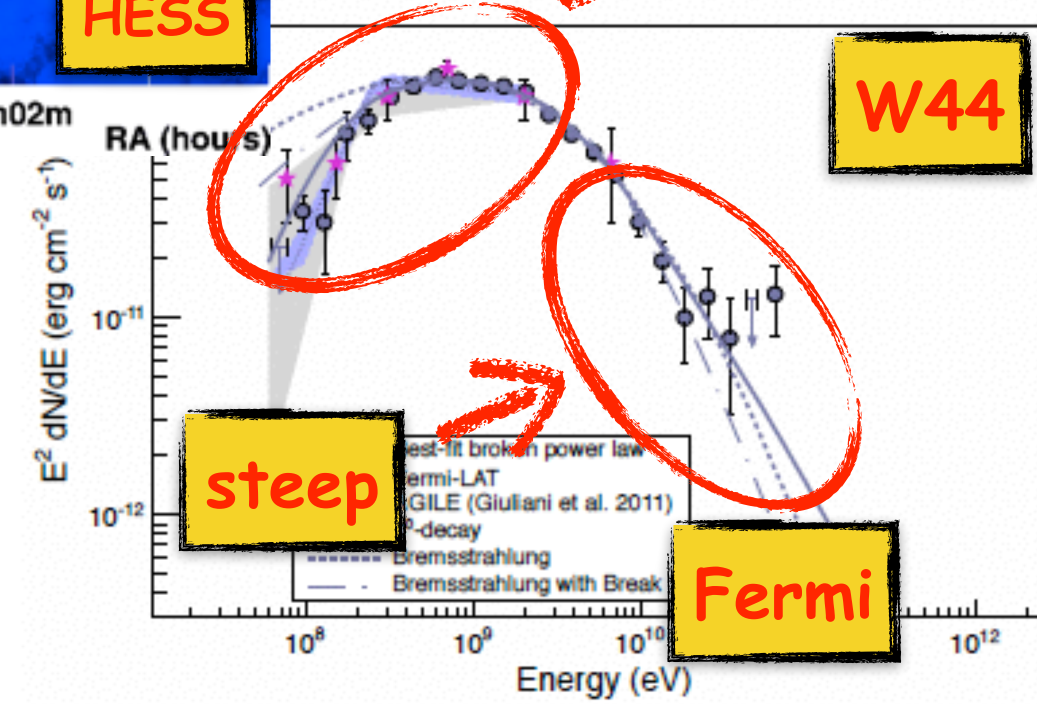


~1600 yr?

hadronic or leptonic?

RXJ1713

FERMI-HESS



W44

steep

Fermi

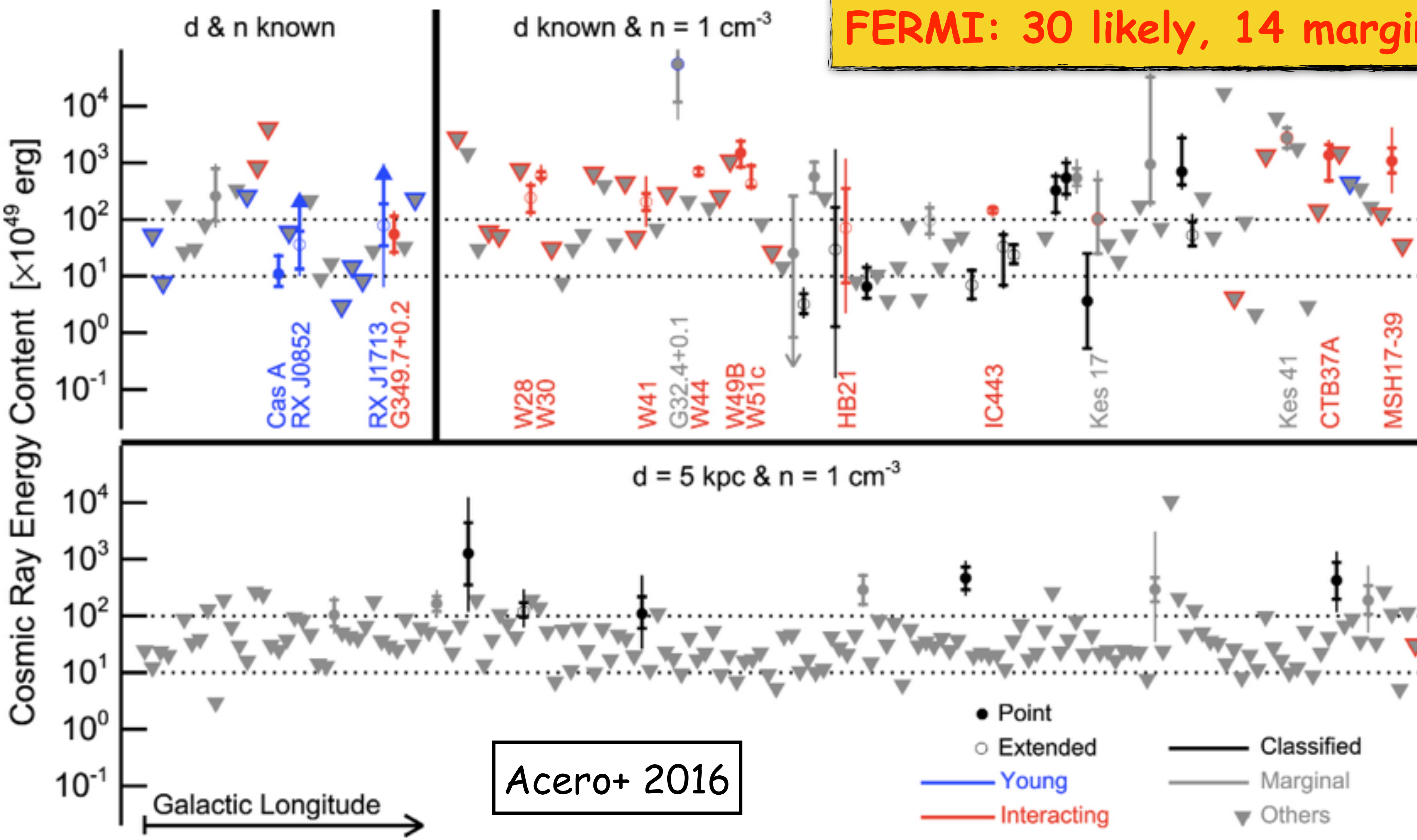
are SNRs proton PeVatrons?

which production spectrum?

hundreds of yrs — thousands of yrs — $10^4 ... 10^5$ yr

GeV domain

Is the paradigm consistent with γ-ray data? Tests for CR origin



FERMI: 30 likely, 14 marginal, 245 u.l.

10-100% E_{SN} converted into CRs

TeV domain

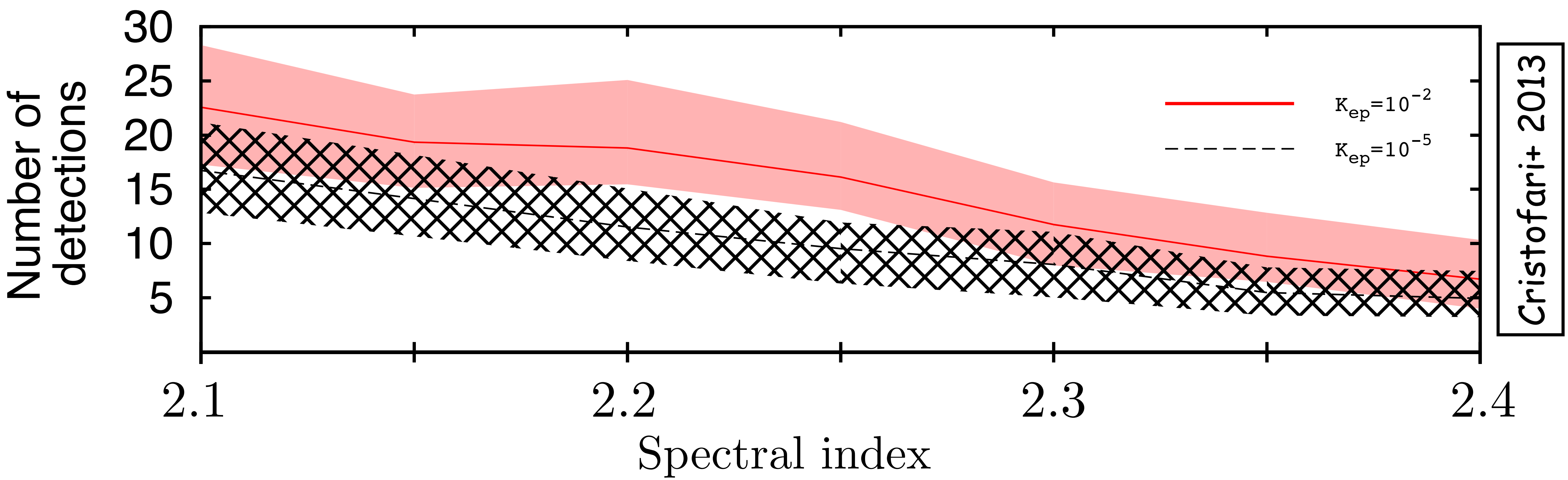
Is the paradigm consistent with γ-ray data? Tests for CR origin

How many SNRs should we detect in the HESS galactic plane survey?

Is the paradigm consistent with γ-ray data? Tests for CR origin

How many SNRs should we detect in the HESS galactic plane survey?

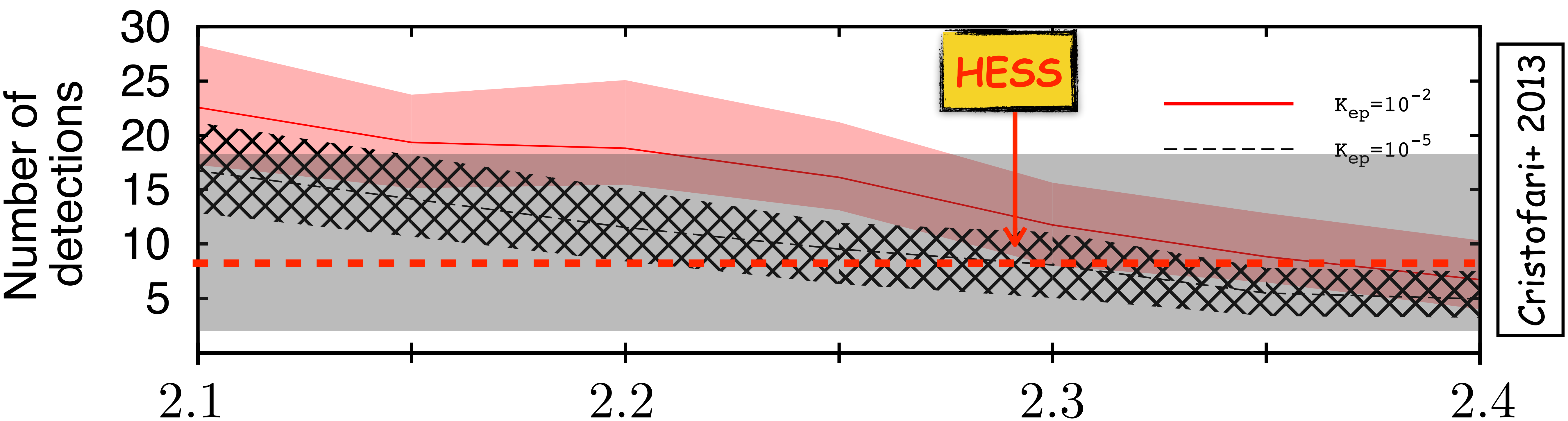
RED and BLACK regions -> with or without Inverse Compton contribution



Is the paradigm consistent with γ-ray data? Tests for CR origin

How many SNRs should we detect in the HESS galactic plane survey?

RED and BLACK regions -> with or without Inverse Compton contribution



<- too many too few ->

allowed range of spectral slopes from CR propagation studies!

A proton PeVatron in the galactic centre

Observational signature

p-p interactions -> $E^{p}_{max} \approx 1 \text{ PeV} \longrightarrow E^{\gamma}_{max} \approx 100 \text{ TeV}$

inverse Compton-> suppressed in the multi-TeV domain (Klein-Nishina effect)

A proton PeVatron in the galactic centre

Observational signature

unattenuated γ-ray spectrum extending to the multi-TeV domain

p-p interactions -> $E^p_{max} \approx 1 \text{ PeV} \longrightarrow E^\gamma_{max} \approx 100 \text{ TeV}$

inverse Compton-> suppressed in the multi-TeV domain (Klein-Nishina effect)

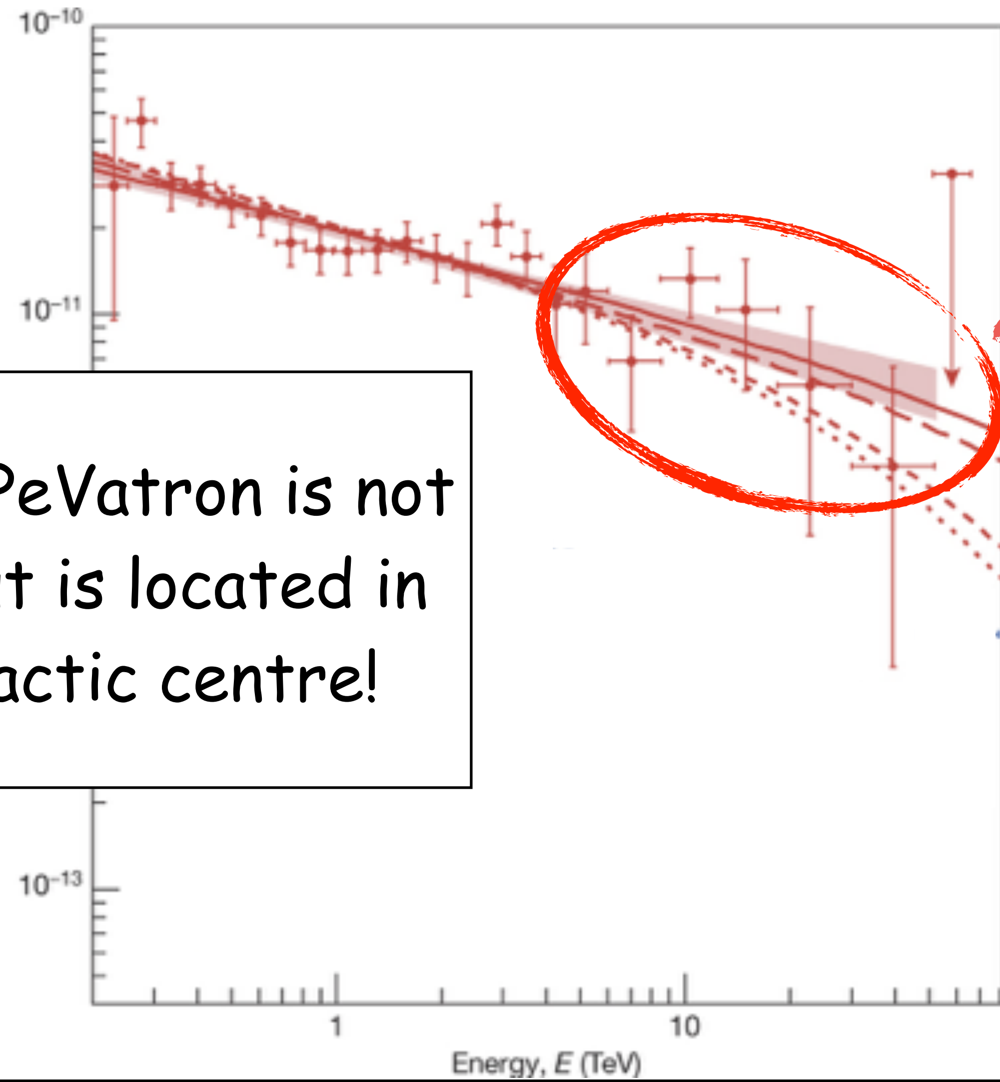
A proton PeVatron in the galactic centre

Observational signature

unattenuated γ-ray spectrum extending to the multi-TeV domain

p-p interactions -> $E^{p}_{max} \approx 1\ \mathrm{PeV} \longrightarrow E^{\gamma}_{max} \approx 100\ \mathrm{TeV}$

inverse Compton-> suppressed in the multi-TeV domain (Klein-Nishina effect)



diffuse emission from the GC

no cutoff!

the first PeVatron is not a SNR but is located in the Galactic centre!

H.E.S.S. Coll. 2016

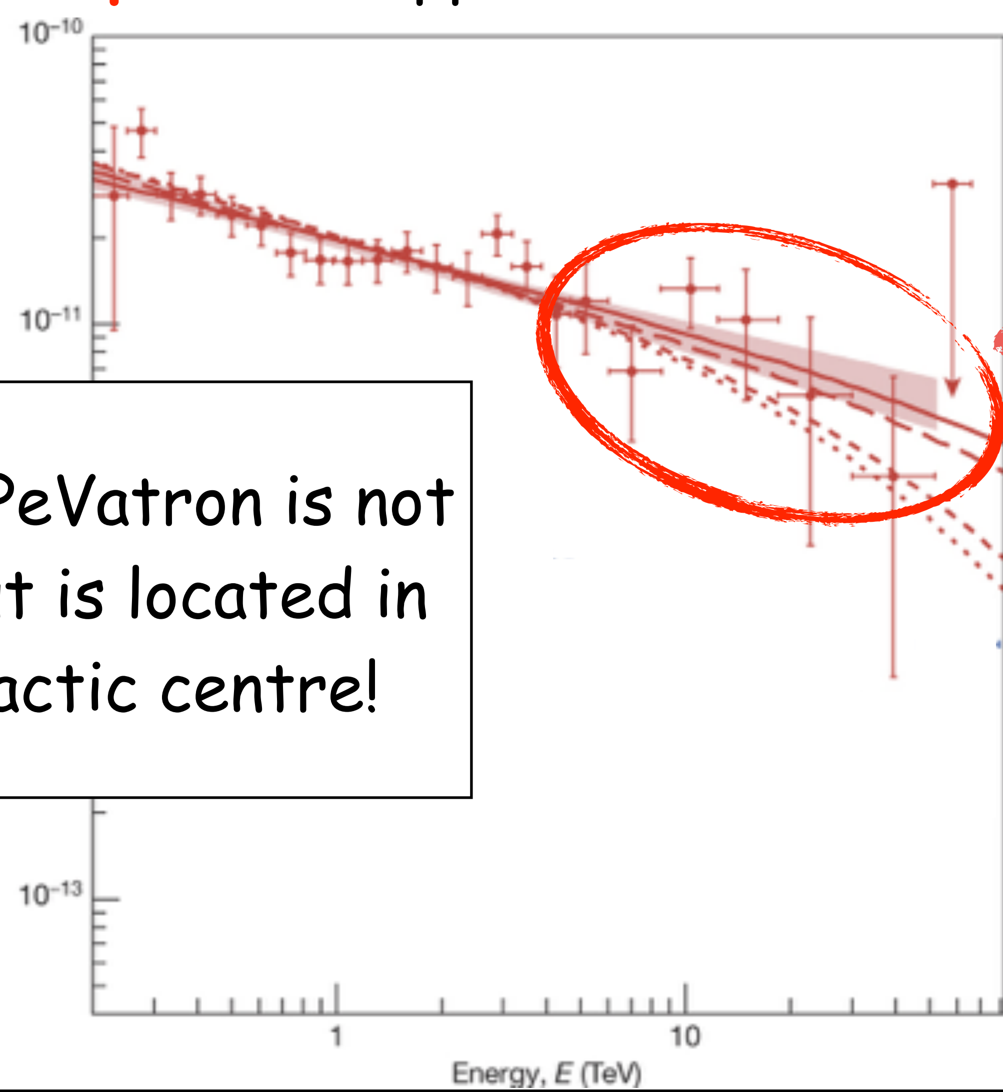
A proton PeVatron in the galactic centre

Observational signature

unattenuated γ-ray spectrum extending to the multi-TeV domain

p-p interactions -> $E^{p}_{max} \approx 1 \text{ PeV} \longrightarrow E^{\gamma}_{max} \approx 100 \text{ TeV}$

inverse Compton-> suppressed in the multi-TeV domain (Klein-Nishina effect)



the first PeVatron is not a SNR but is located in the Galactic centre!

diffuse emission from the GC

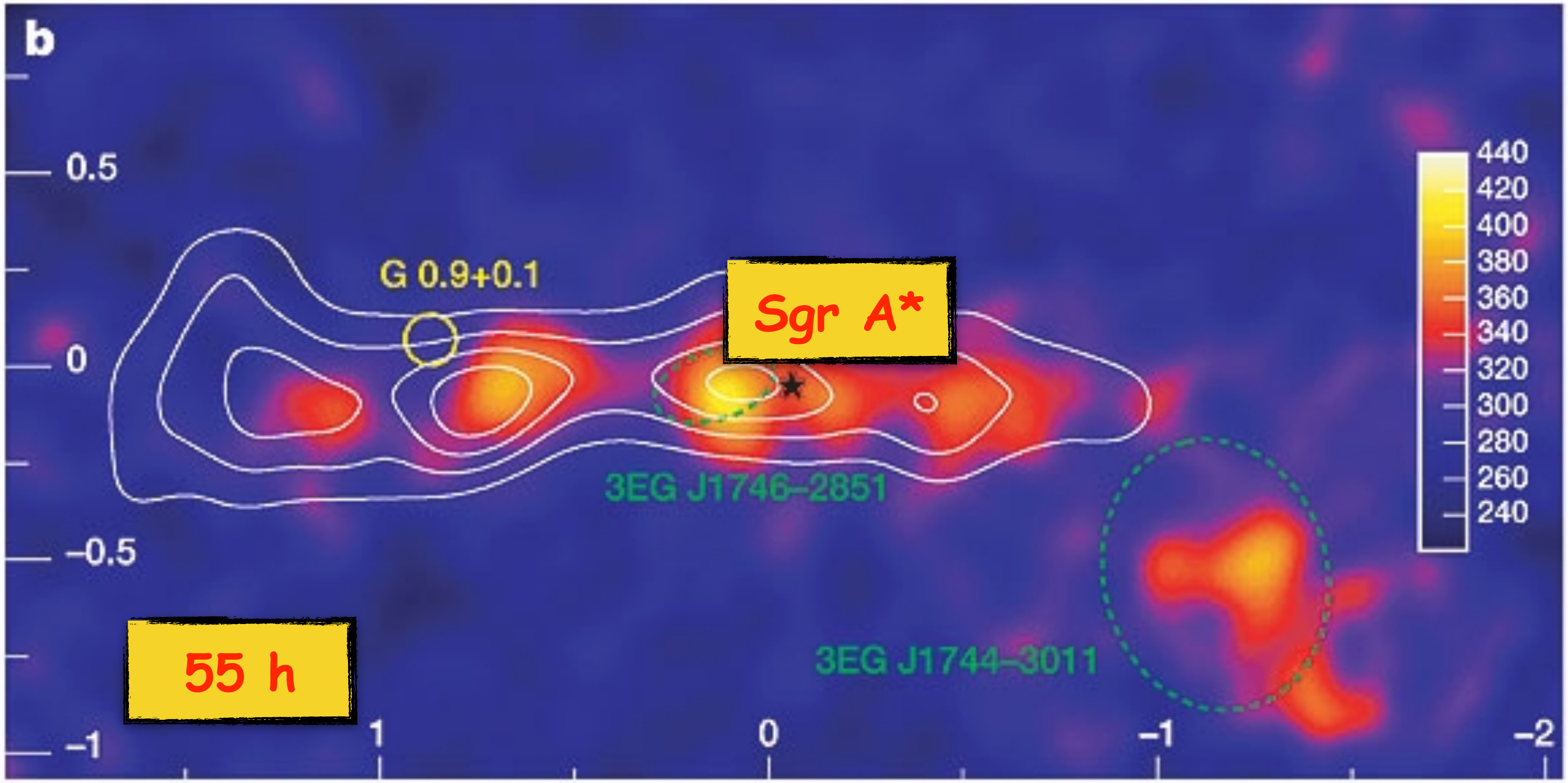
no cutoff!

a cutoff @ …	deviates from data @
2.9 PeV	68%
0.6 PeV	90%
0.4 PeV	95%

H.E.S.S. Coll. 2016

The GC ridge as seen 10 years ago

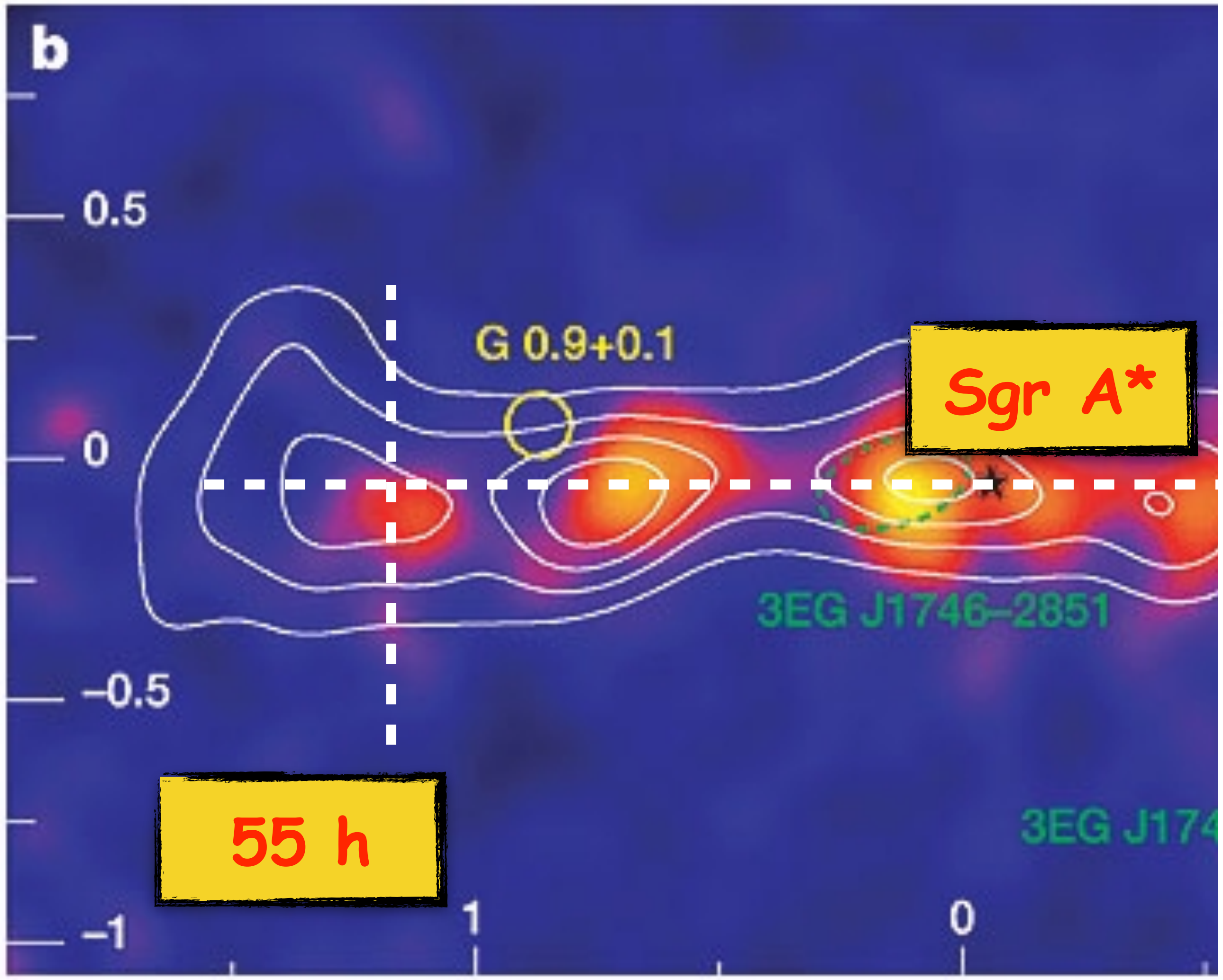
H.E.S.S. Coll. 2006

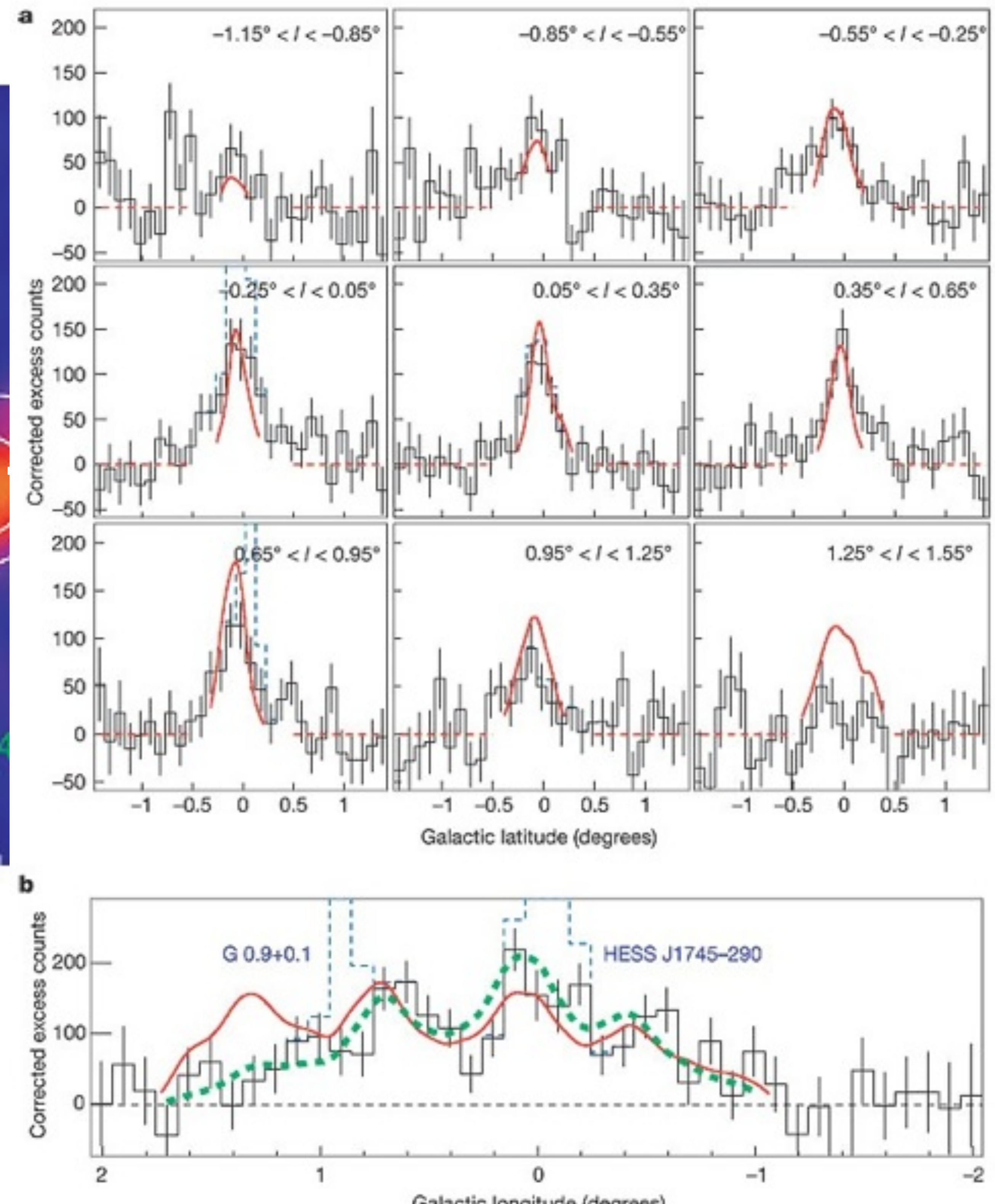


color scale -> γ-rays
contours -> gas (CS)

The GC ridge as seen 10 years ago

H.E.S.S. Coll. 2006

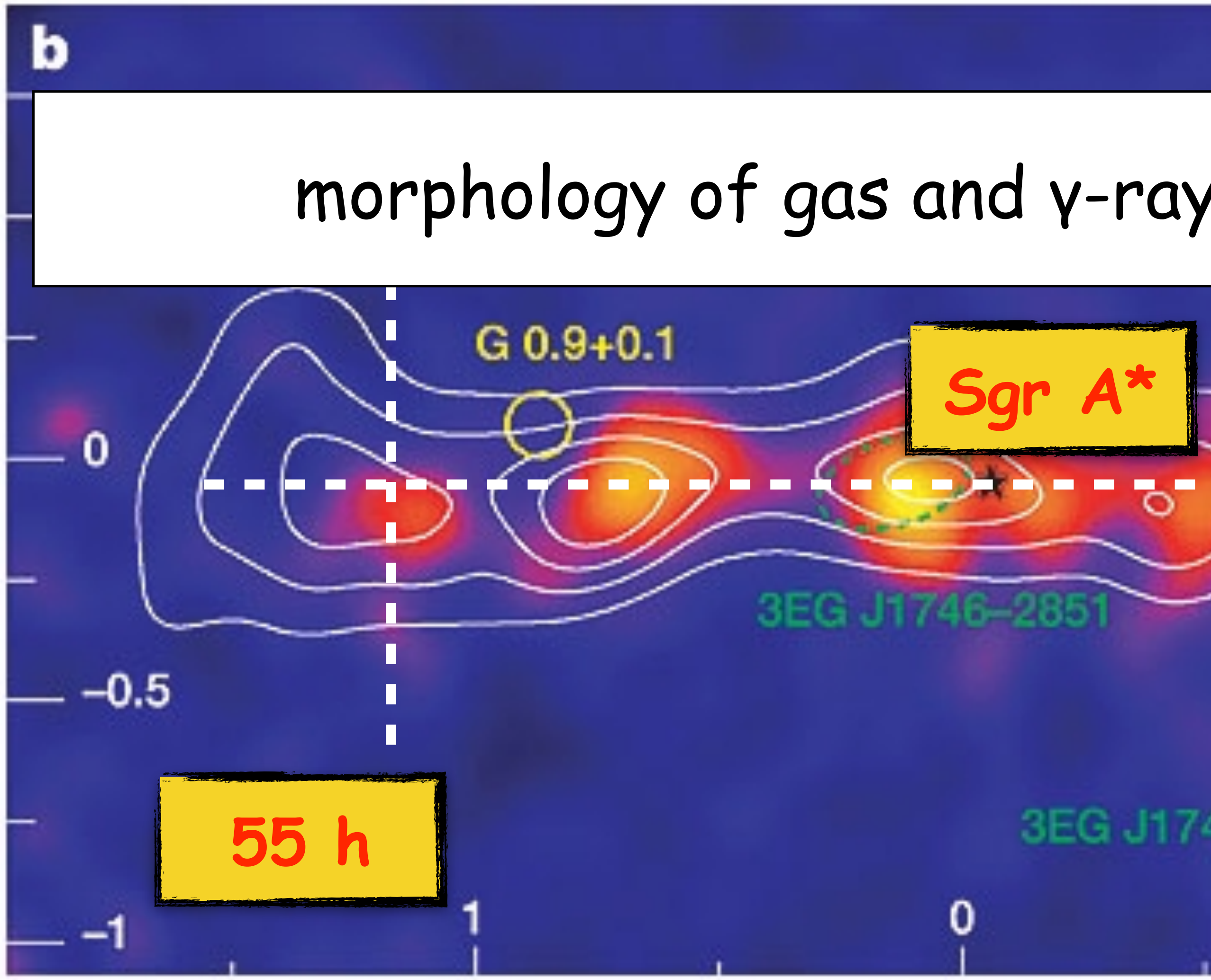


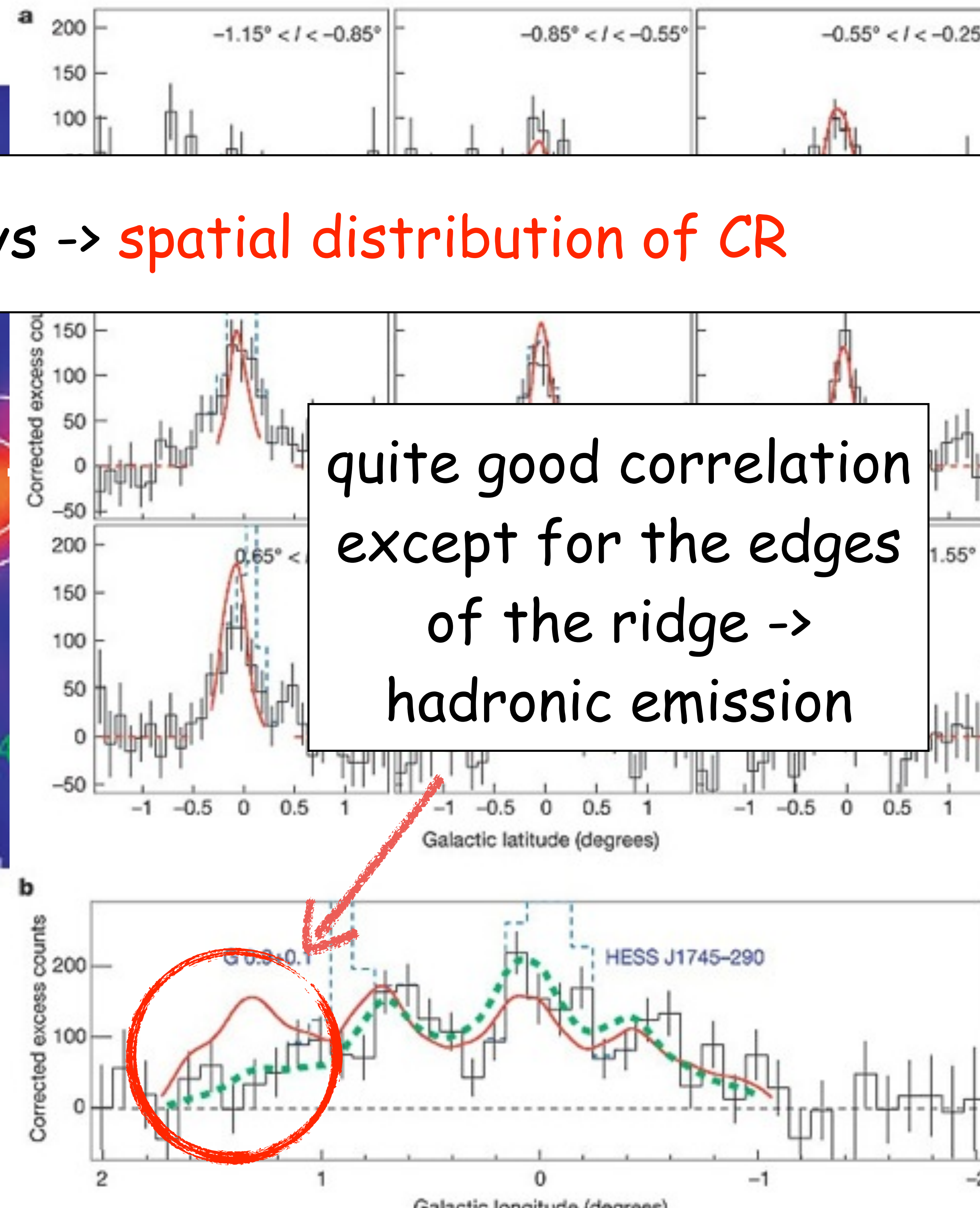


histogram -> γ-rays
red -> gas (CS)

The GC ridge as seen 10 years ago

H.E.S.S. Coll. 2006





morphology of gas and γ-rays -> spatial distribution of CR

Sgr A*

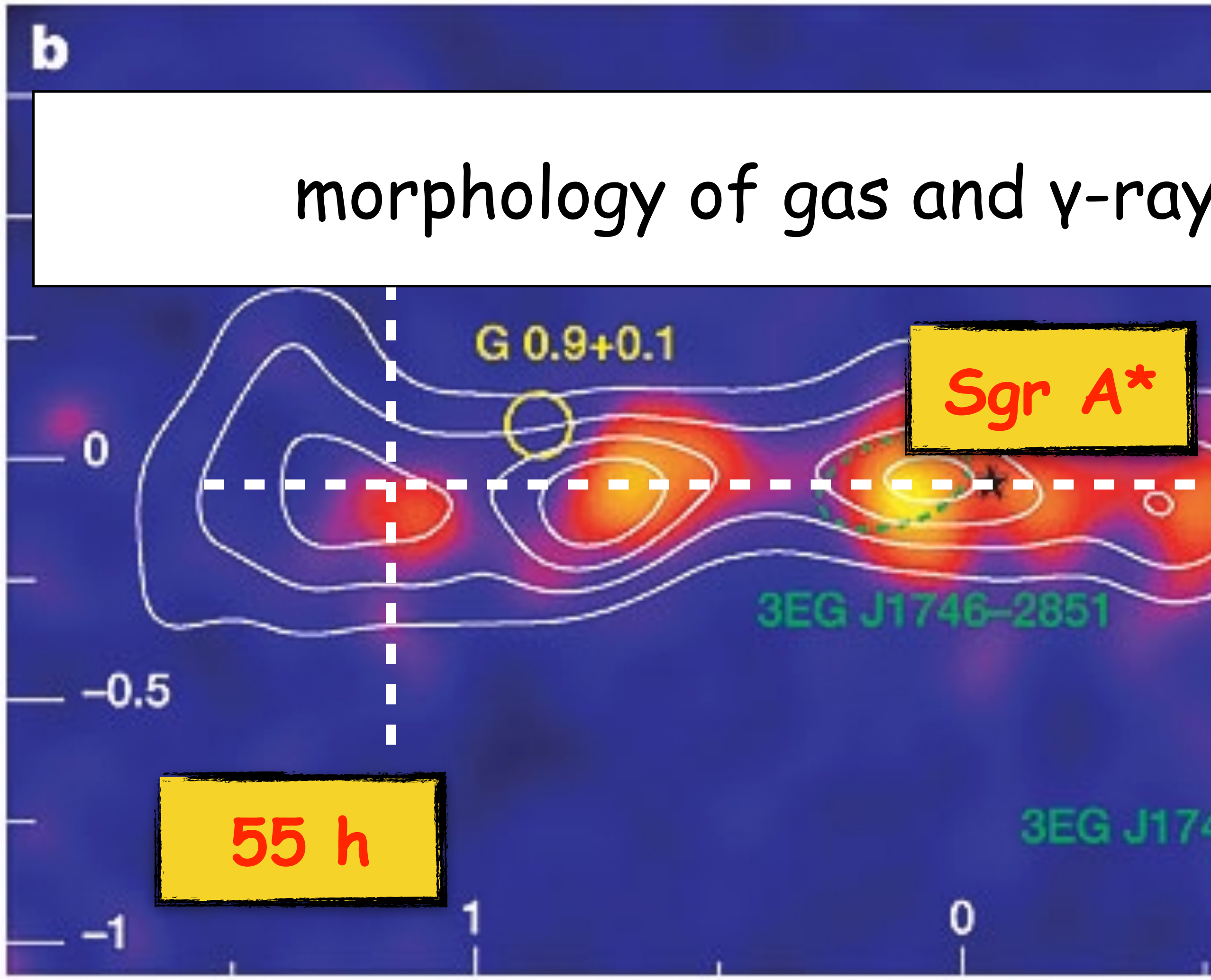
55 h

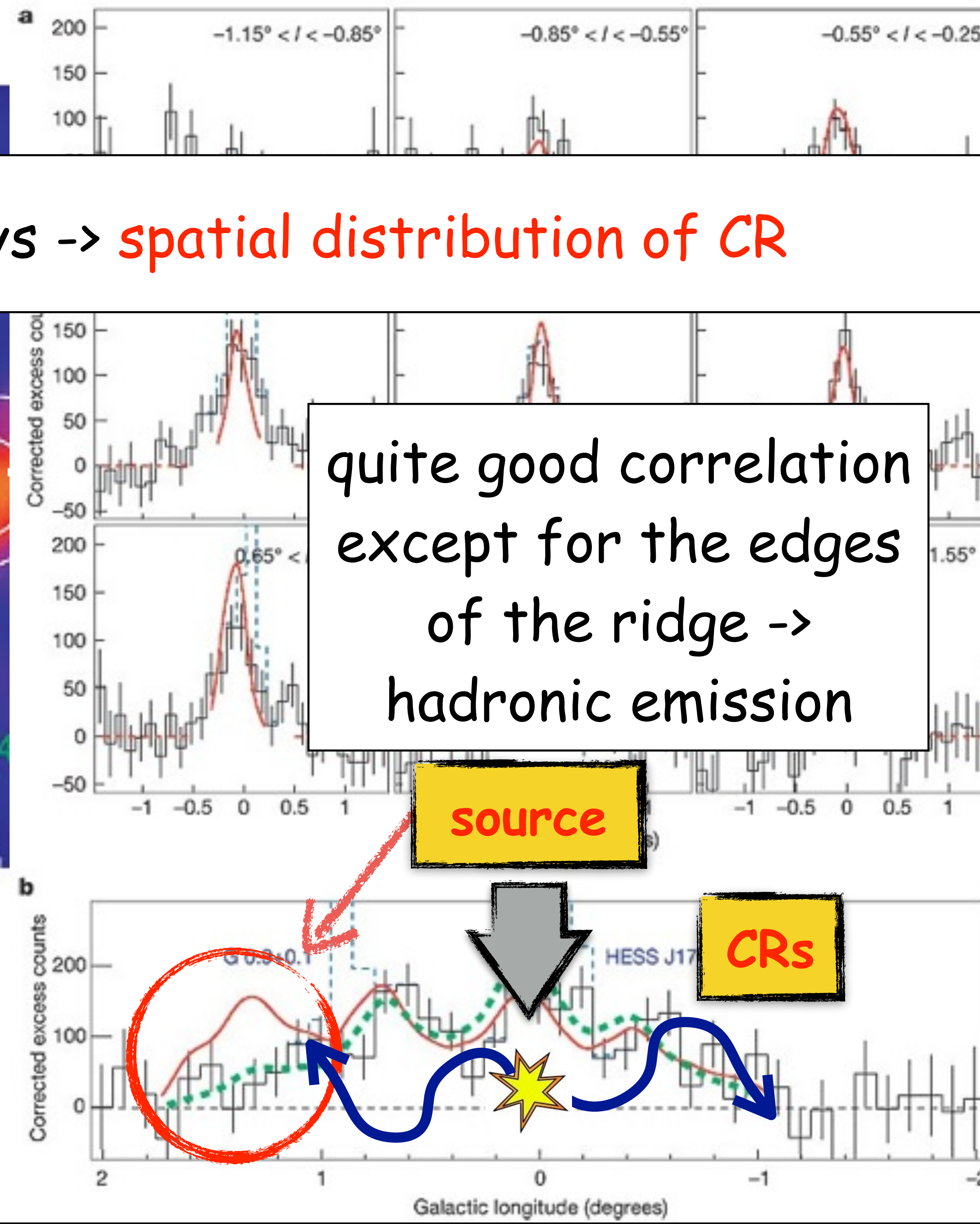
quite good correlation except for the edges of the ridge -> hadronic emission

histogram -> γ-rays
red -> gas (CS)

The GC ridge as seen 10 years ago

H.E.S.S. Coll. 2006





morphology of gas and γ-rays -> spatial distribution of CR

quite good correlation except for the edges of the ridge -> hadronic emission

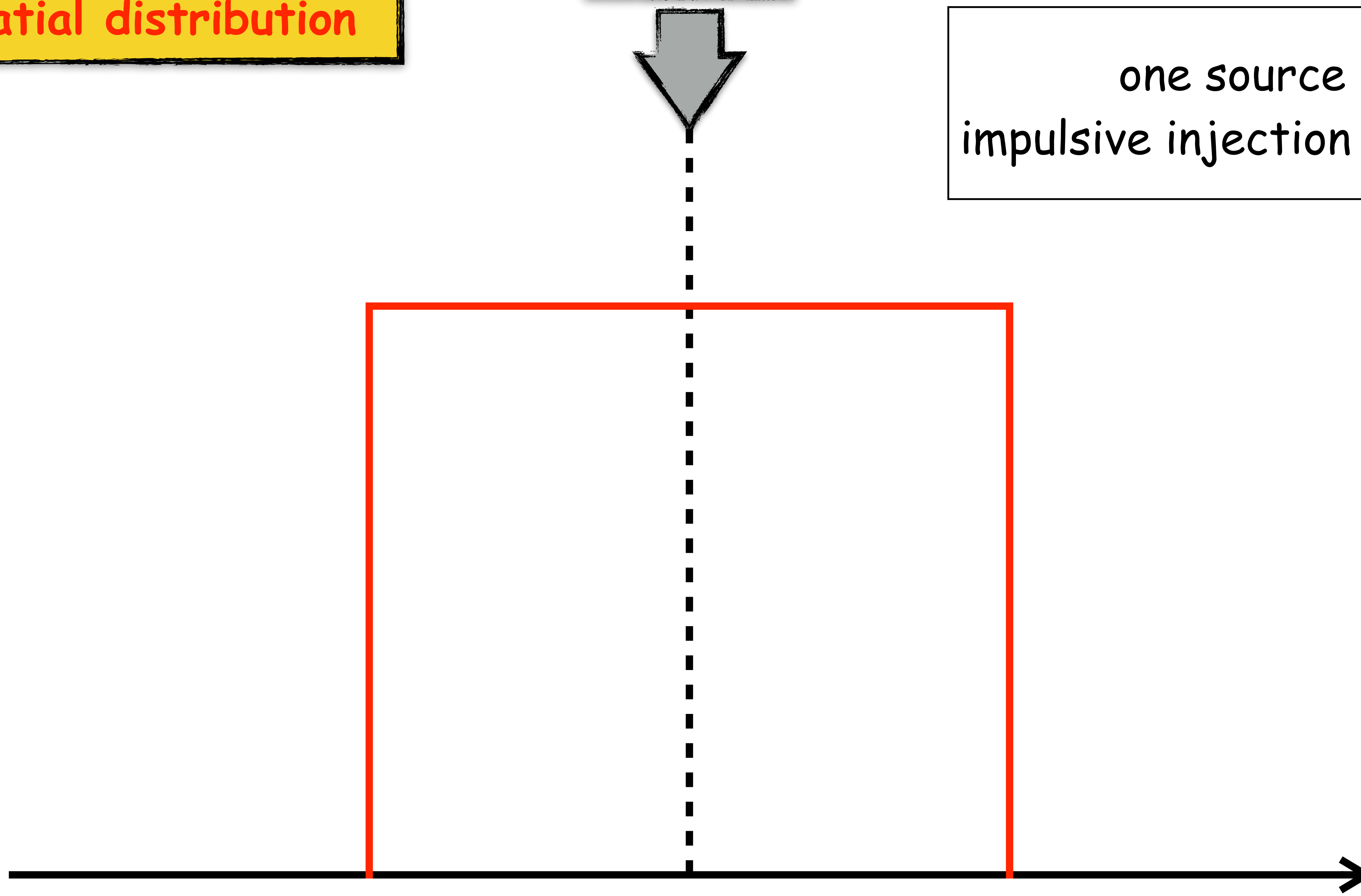
histogram -> γ-rays

red -> gas (CS)

Where is the source?

CR spatial distribution

Sgr A*



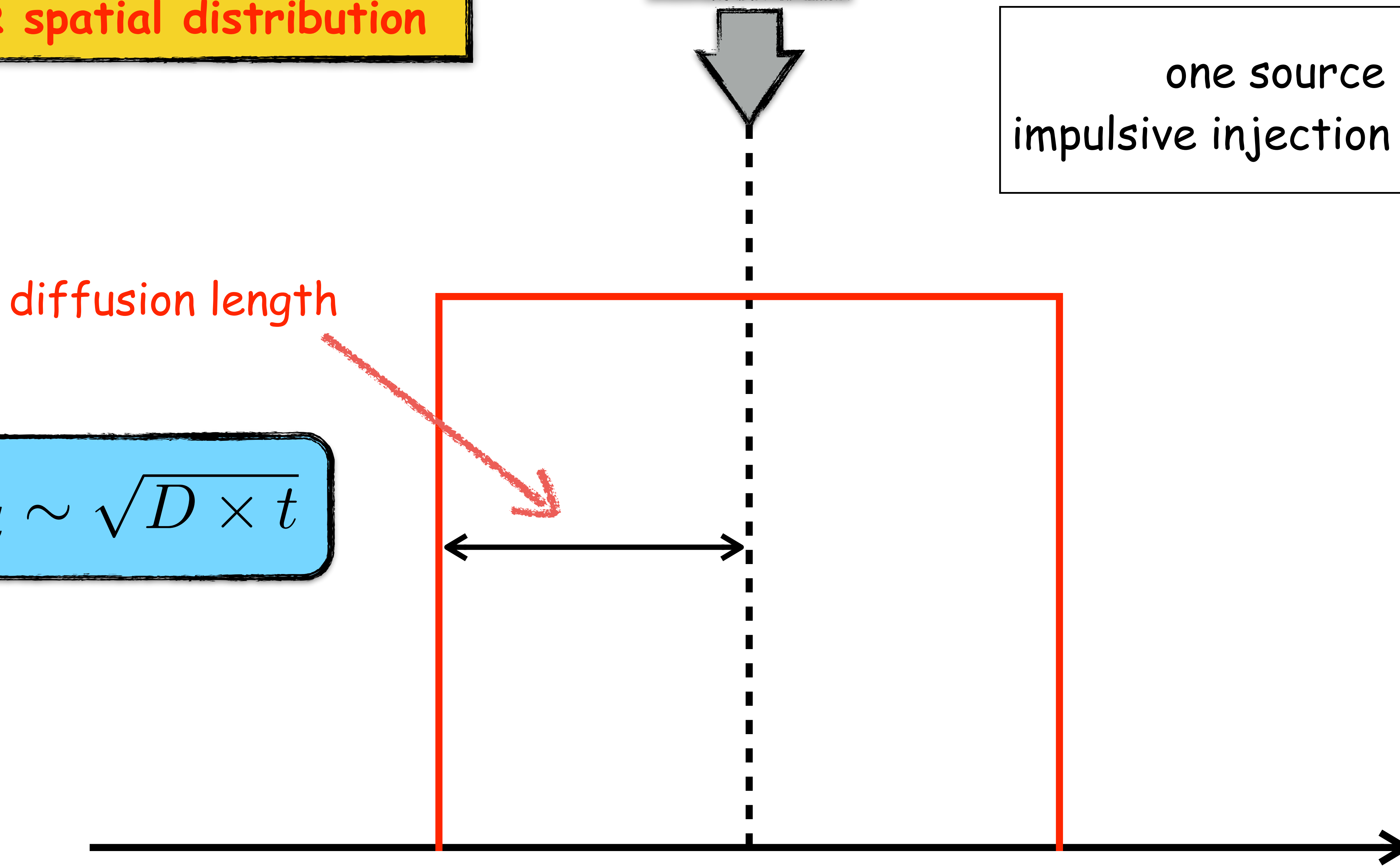
one source
impulsive injection of CRs

Where is the source?

Sgr A*

CR spatial distribution

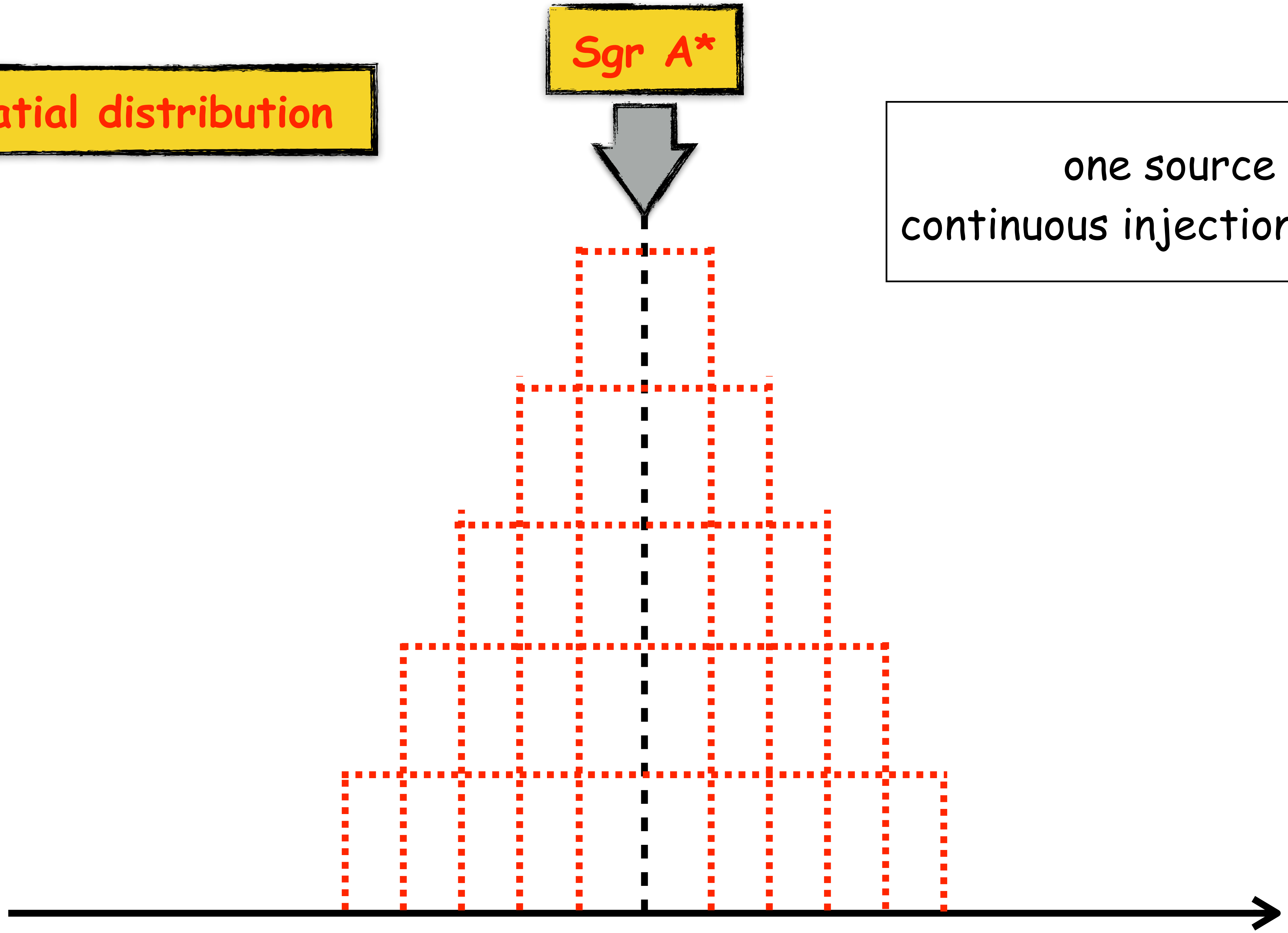
one source
impulsive injection of CRs



$$l_d \sim \sqrt{D \times t}$$

Where is the source?

CR spatial distribution



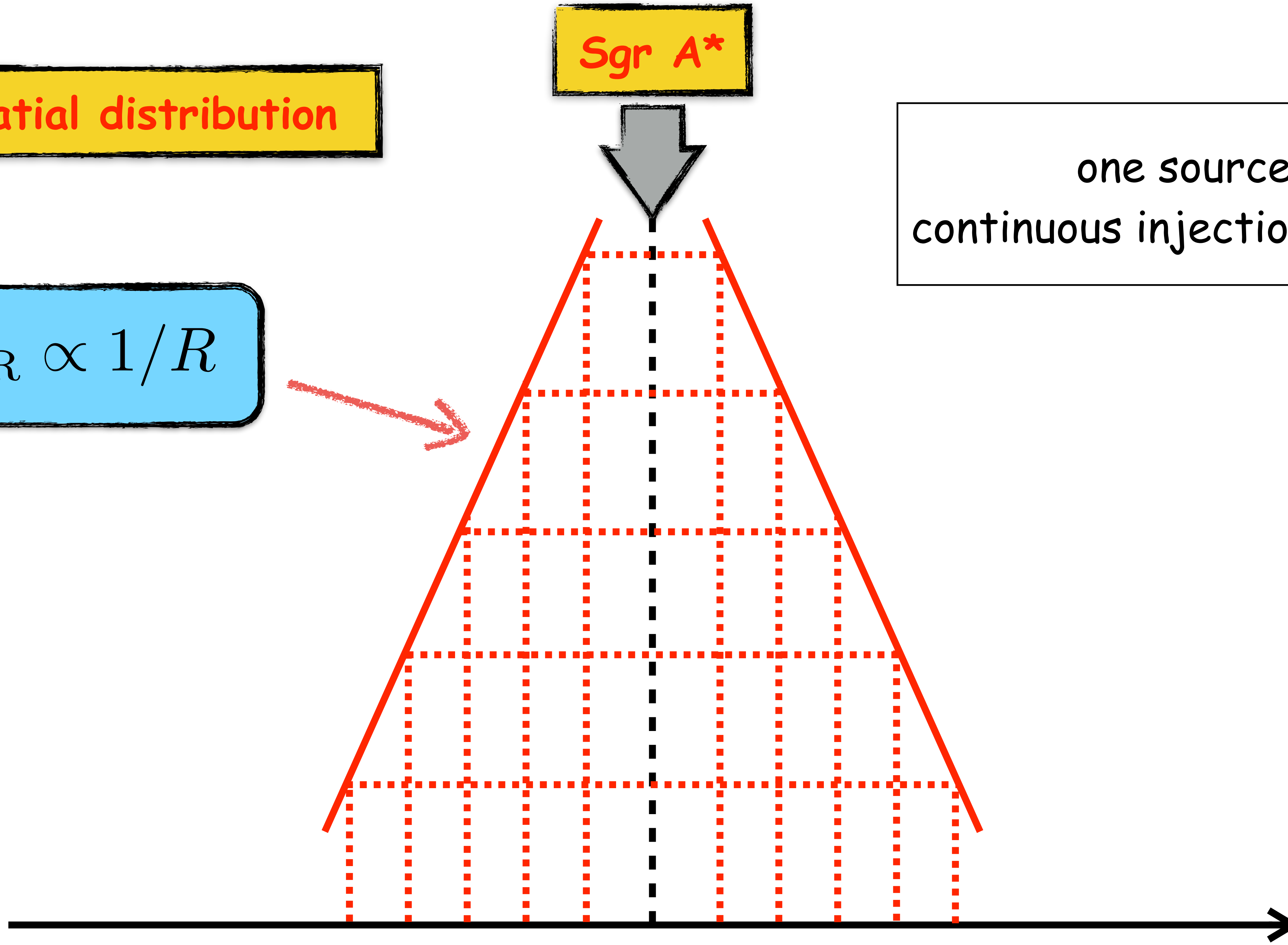
one source

continuous injection of CRs

Where is the source?

CR spatial distribution

$$n_{\rm CR} \propto 1/R$$

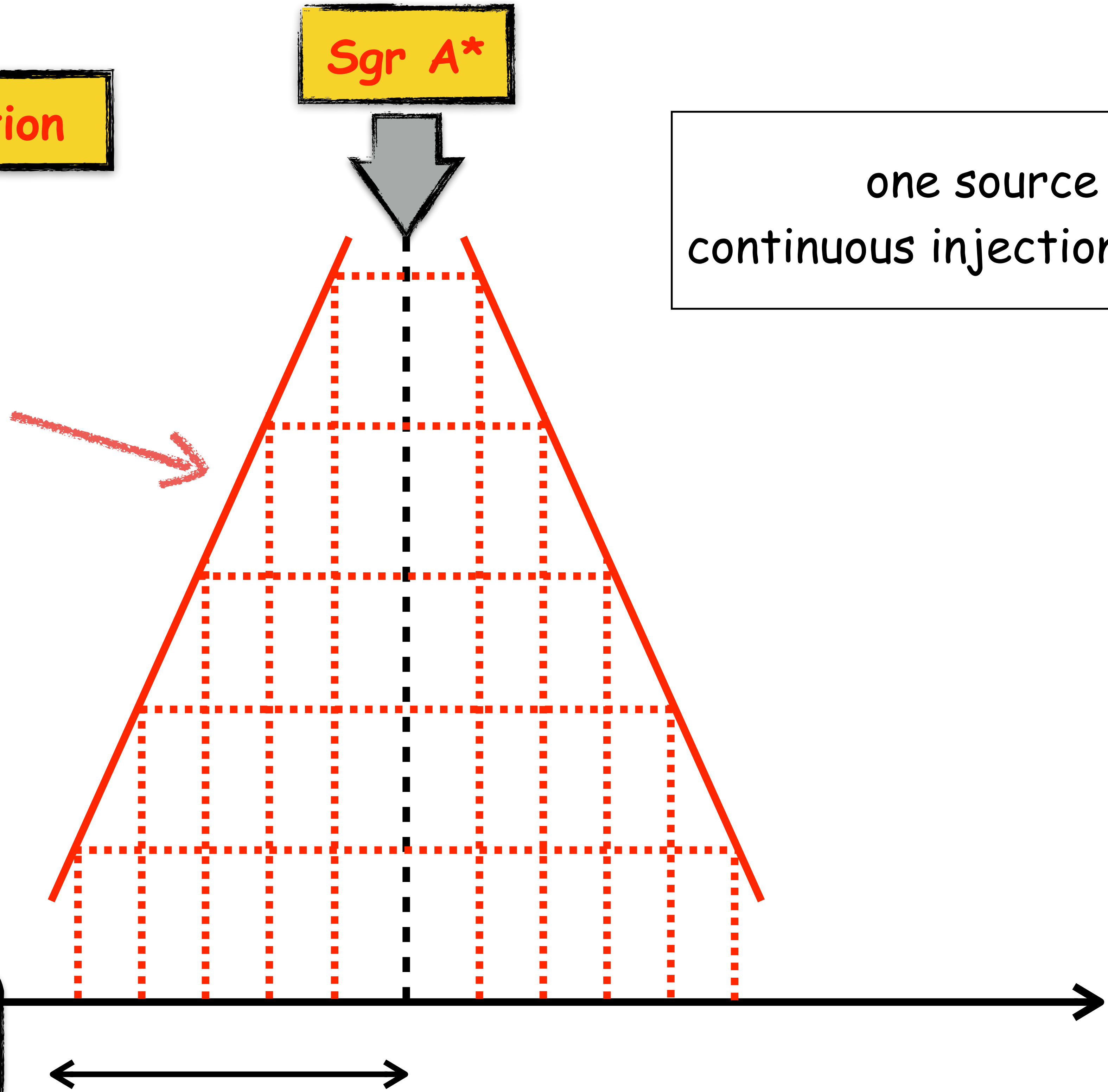


one source
continuous injection of CRs

Where is the source?

CR spatial distribution

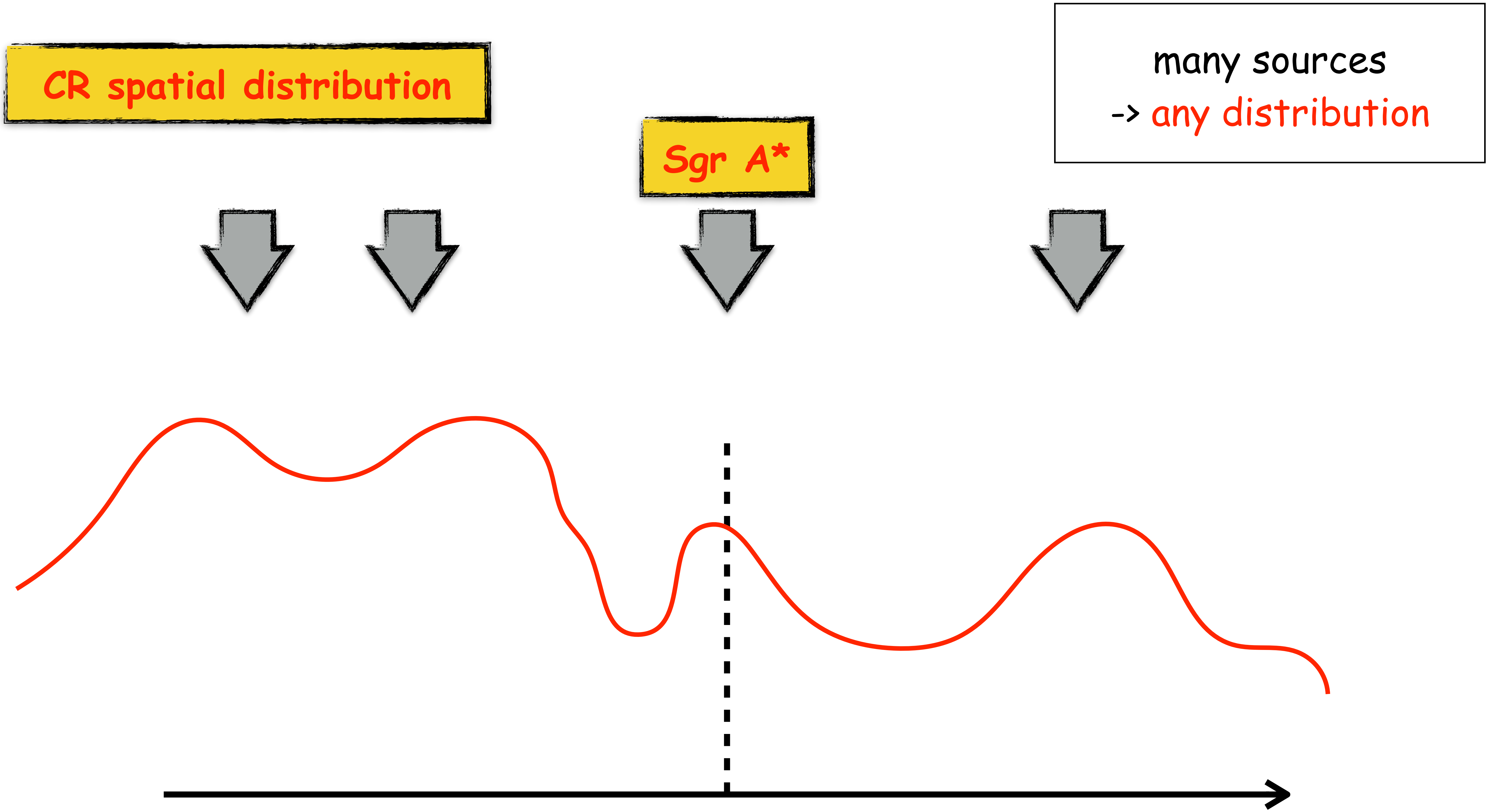
$n_{\rm CR} \propto 1/R$



one source
continuous injection of CRs

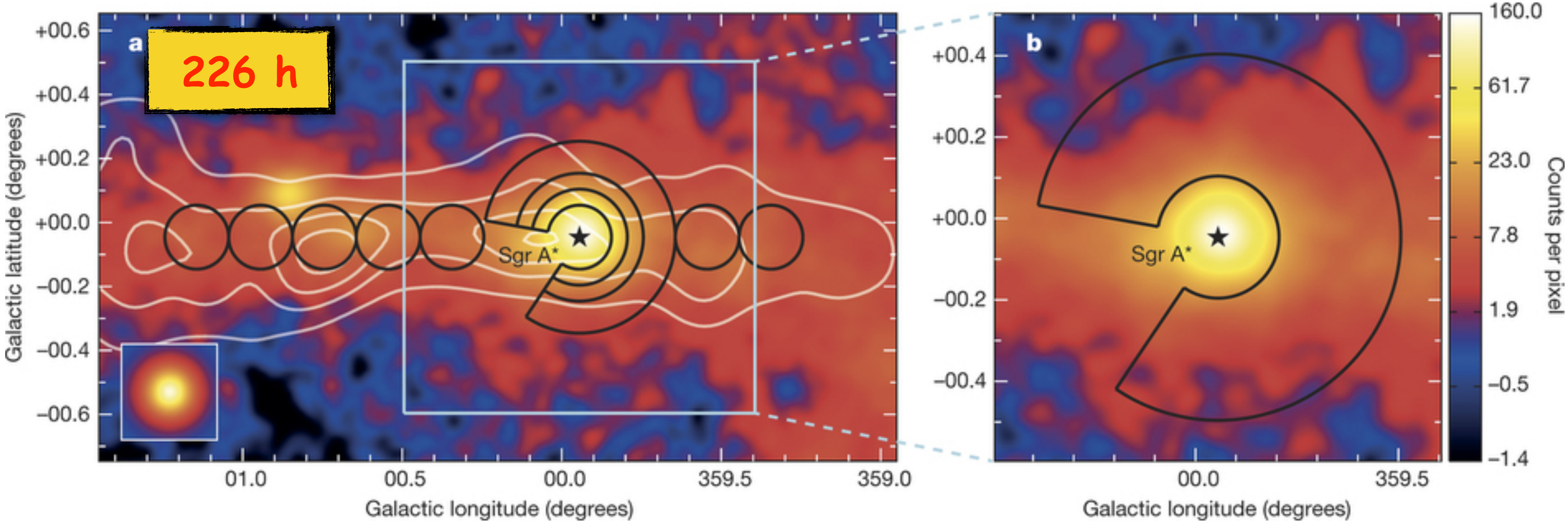
$l_d \sim \sqrt{D \times t}$

Where is the source?



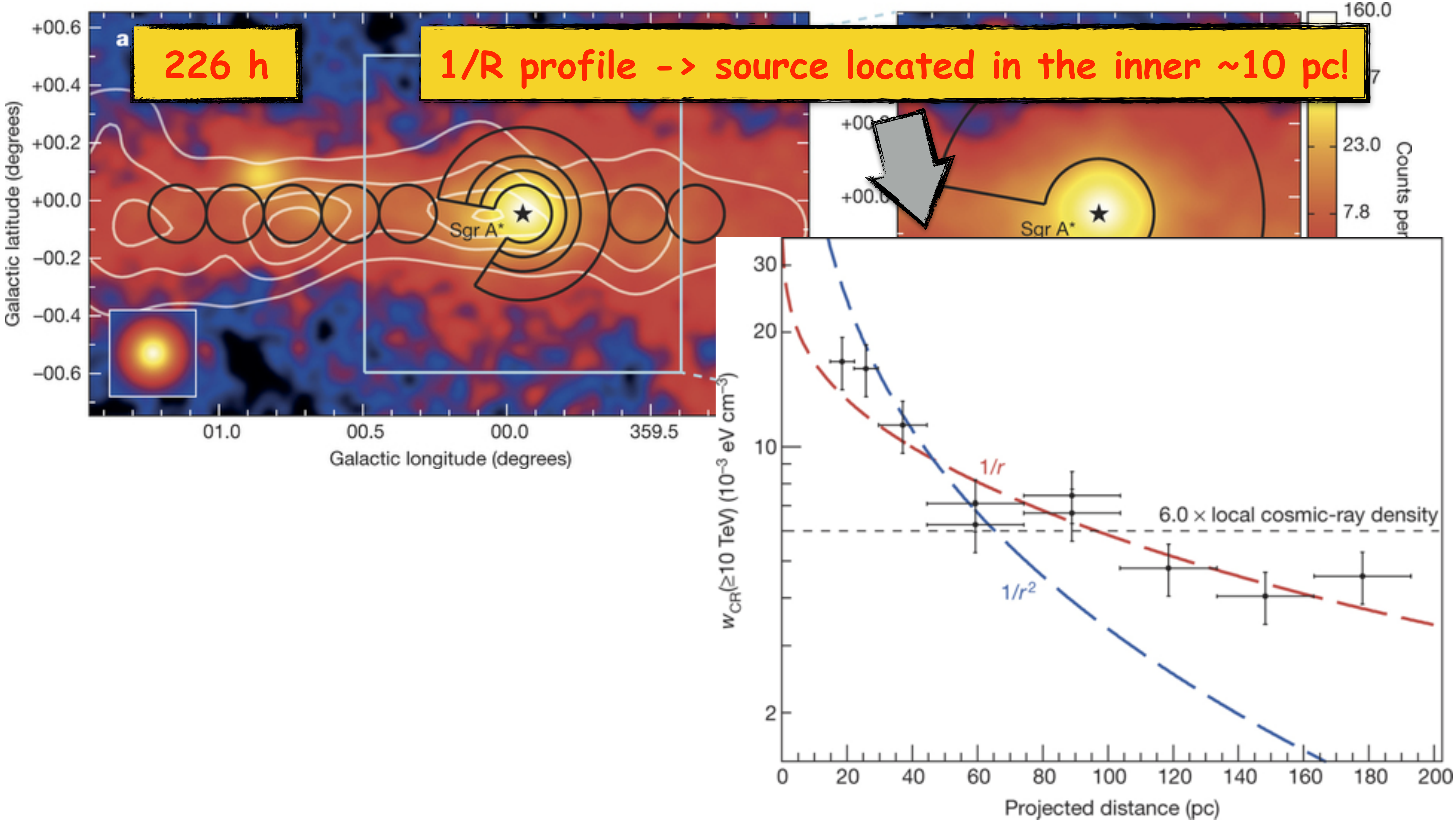
The source is at the GC

H.E.S.S. Coll. 2016



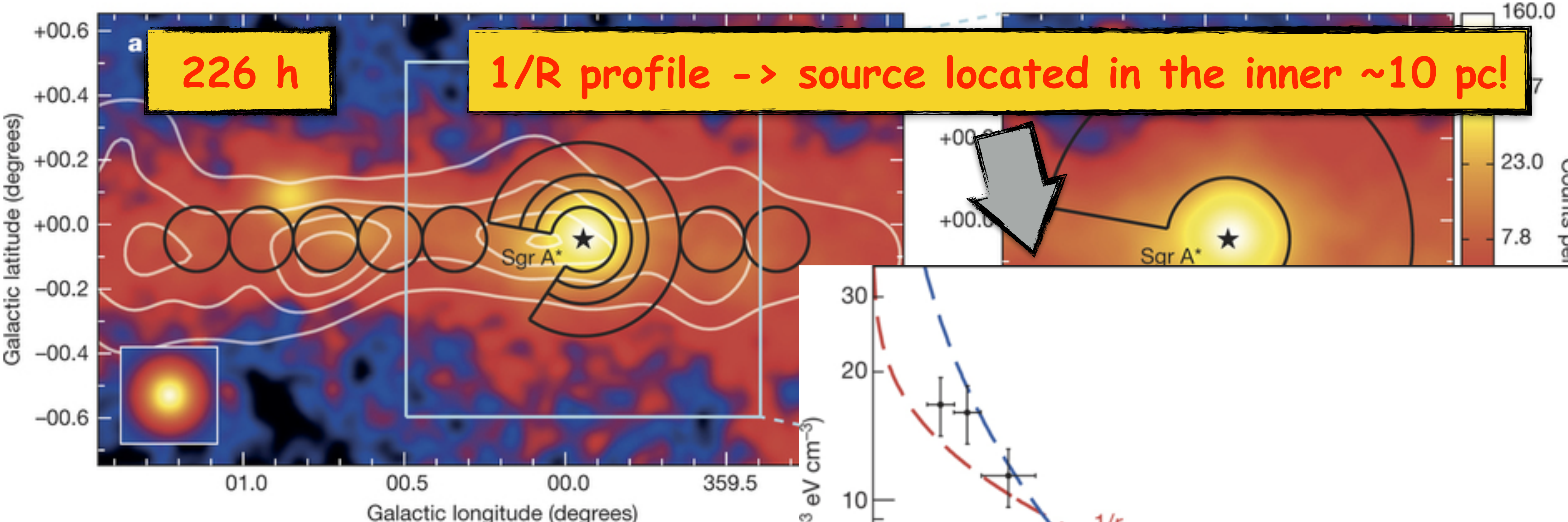
The source is at the GC

H.E.S.S. Coll. 2016



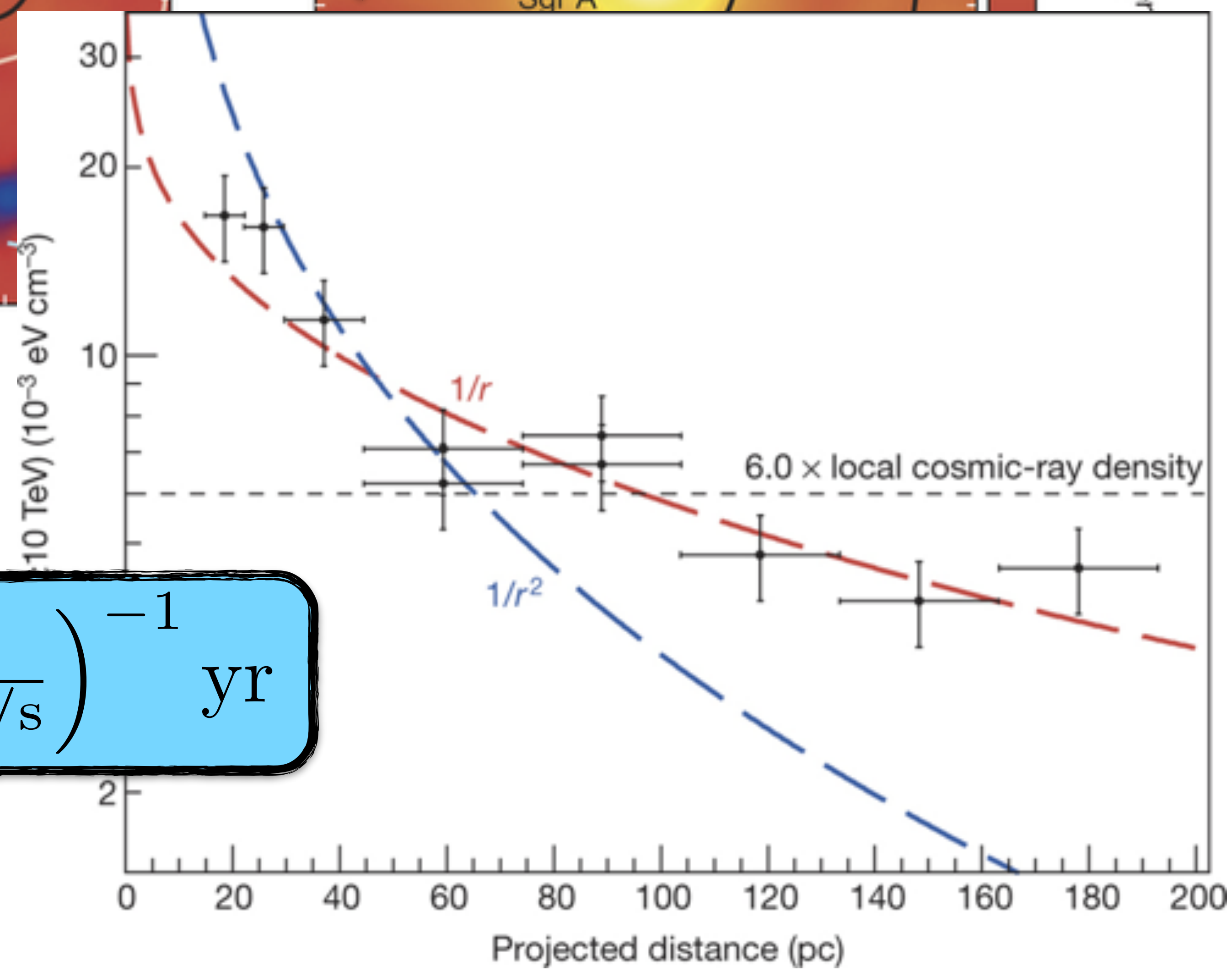
The source is at the GC

H.E.S.S. Coll. 2016



226 h

1/R profile -> source located in the inner ~10 pc!

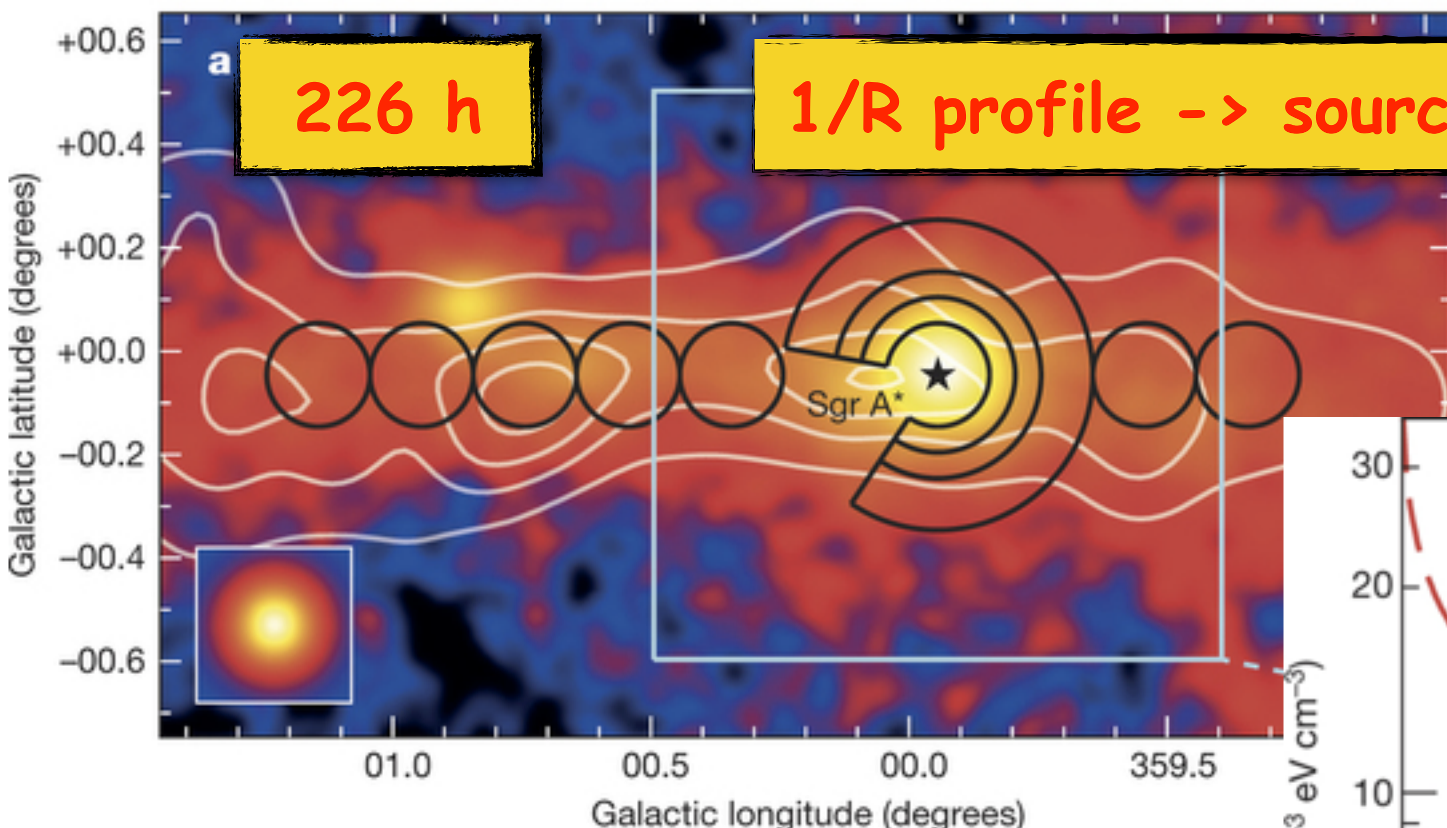


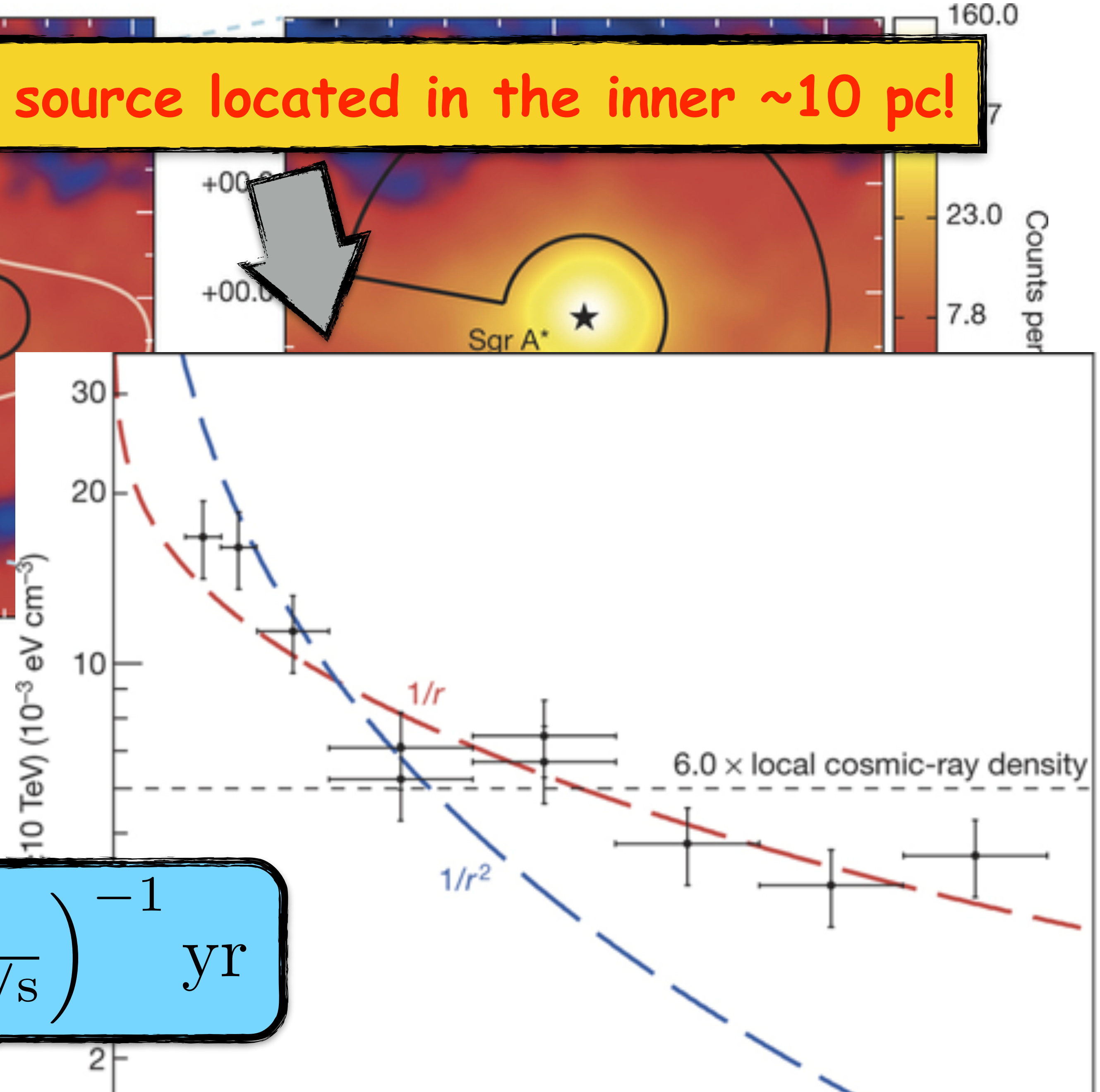
accelerator must be active for:

$$\Delta t > \frac{R^2}{6 \times D} \sim 2 \times 10^3 \left(\frac{D}{10^{30} \mathrm{cm}^2/\mathrm{s}} \right)^{-1} \mathrm{yr}$$

The source is at the GC

H.E.S.S. Coll. 2016





226 h

1/R profile -> source located in the inner ~10 pc!

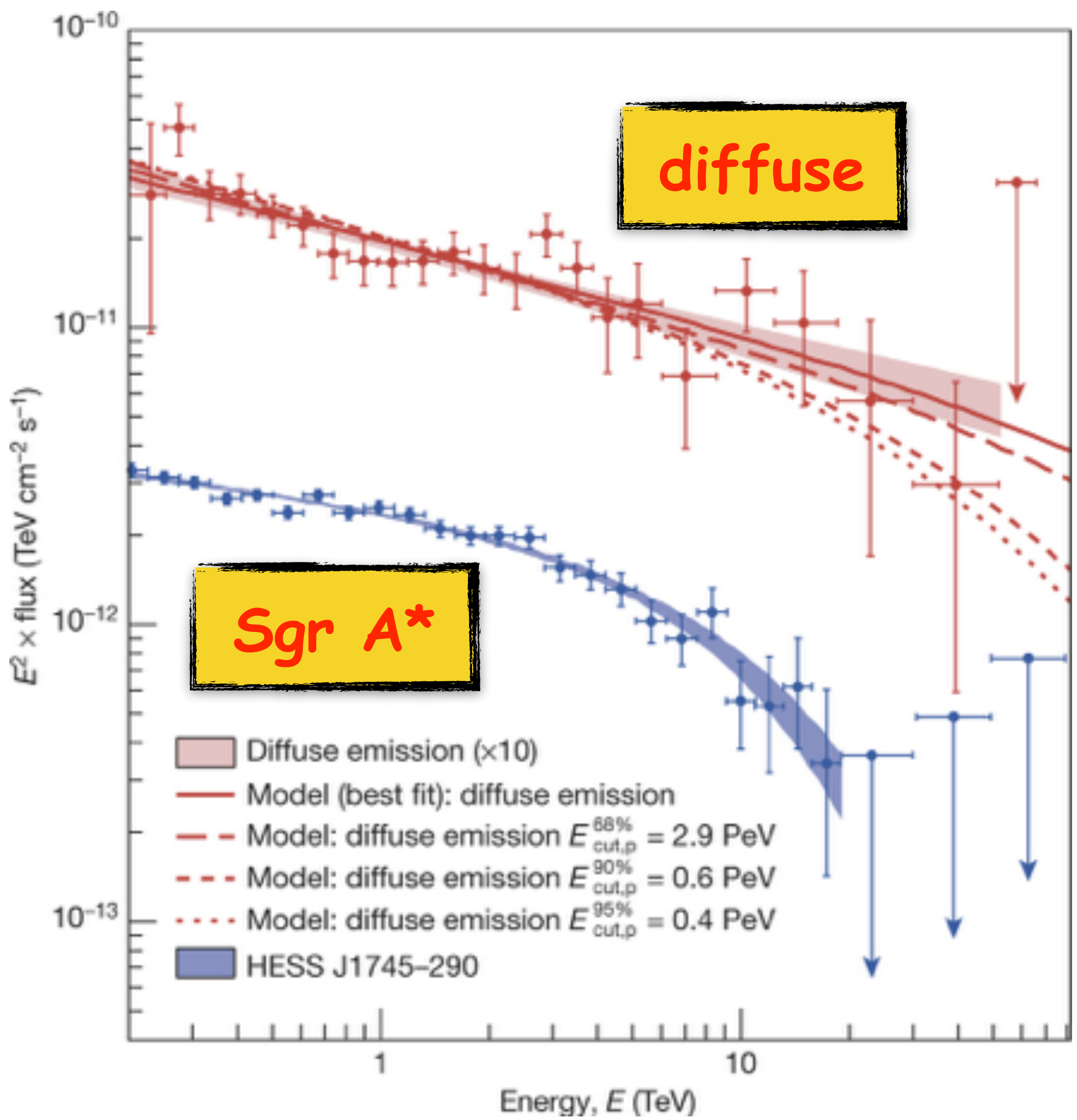
accelerator must be active for:

$$\Delta t > \frac{R^2}{6 \times D} \sim 2 \times 10^3 \left(\frac{D}{10^{30} \mathrm{cm}^2/\mathrm{s}} \right)^{-1} \mathrm{yr}$$

multi-source scenarios require excessive fine-tuning/unrealistic number of sources

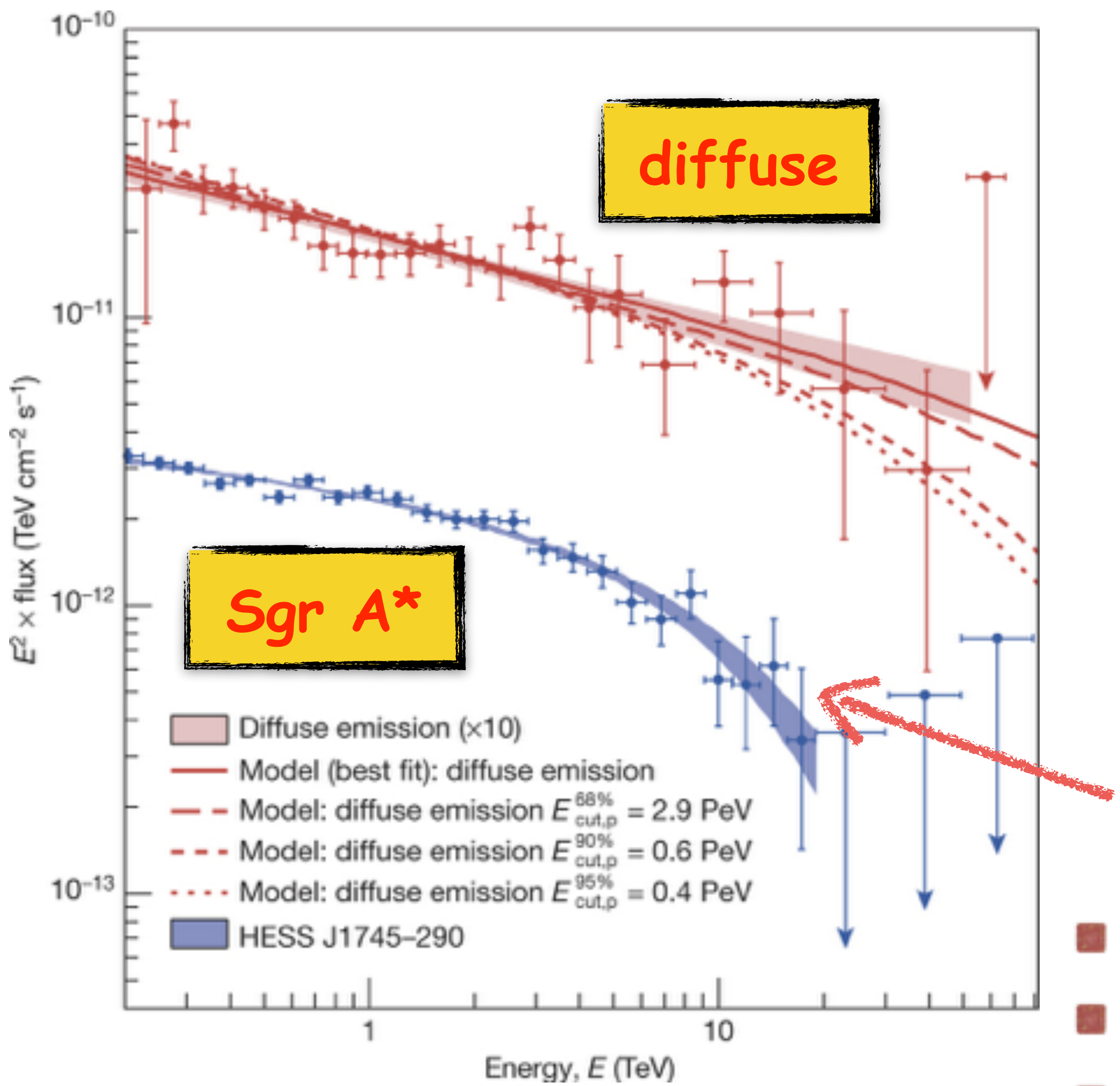
Supermassive black hole as a PeVatron

is Sgr A* as the source of PeV cosmic rays?



Supermassive black hole as a PeVatron

is Sgr A* as the source of PeV cosmic rays?

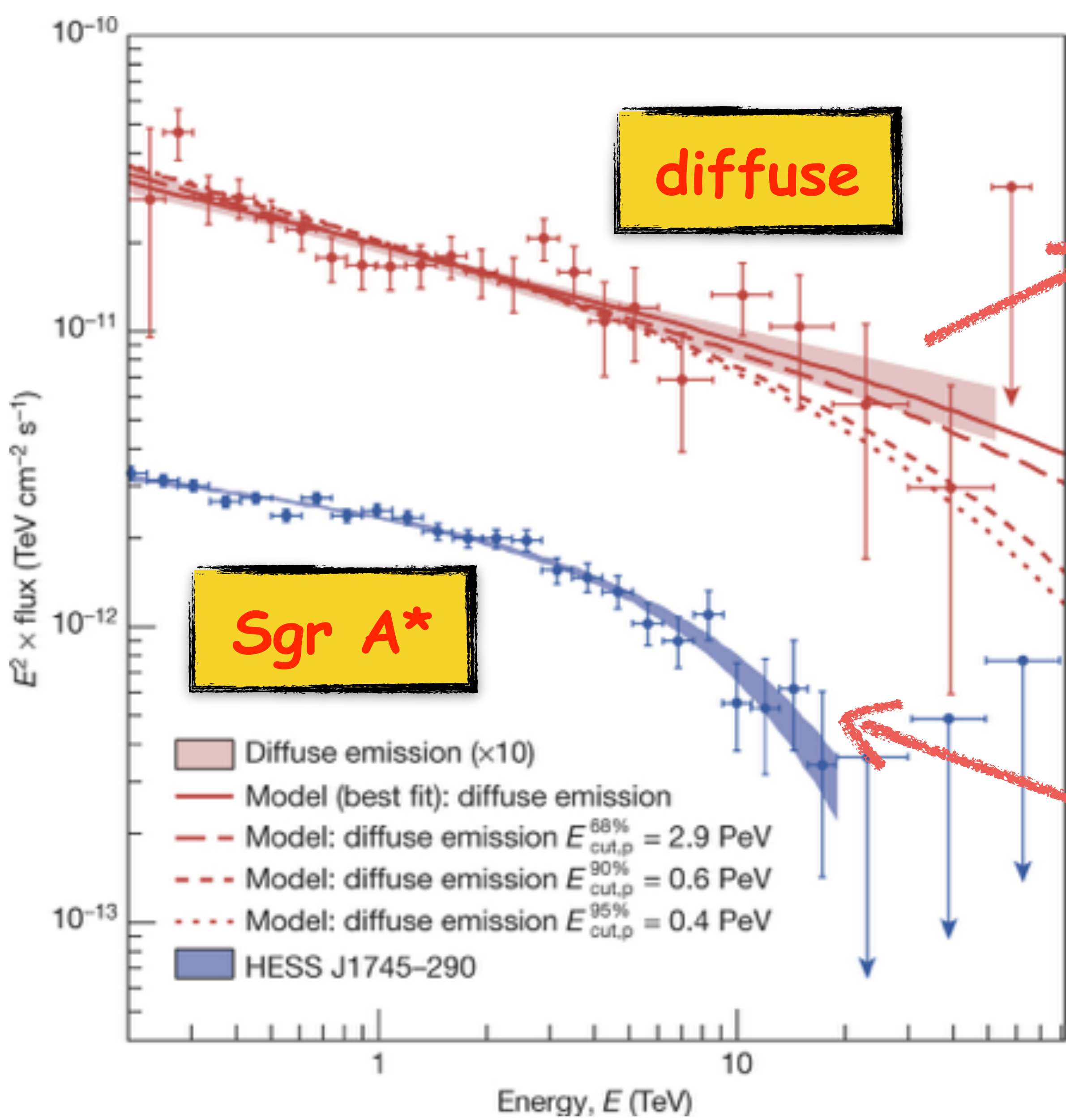


~10 TeV cutoff -> inconsistency? no...

- emission could be unrelated
- time dependent effect
- γγ-absorption w. IR photons? (Celli+ 2016)

Supermassive black hole as a PeVatron

is Sgr A* as the source of PeV cosmic rays?



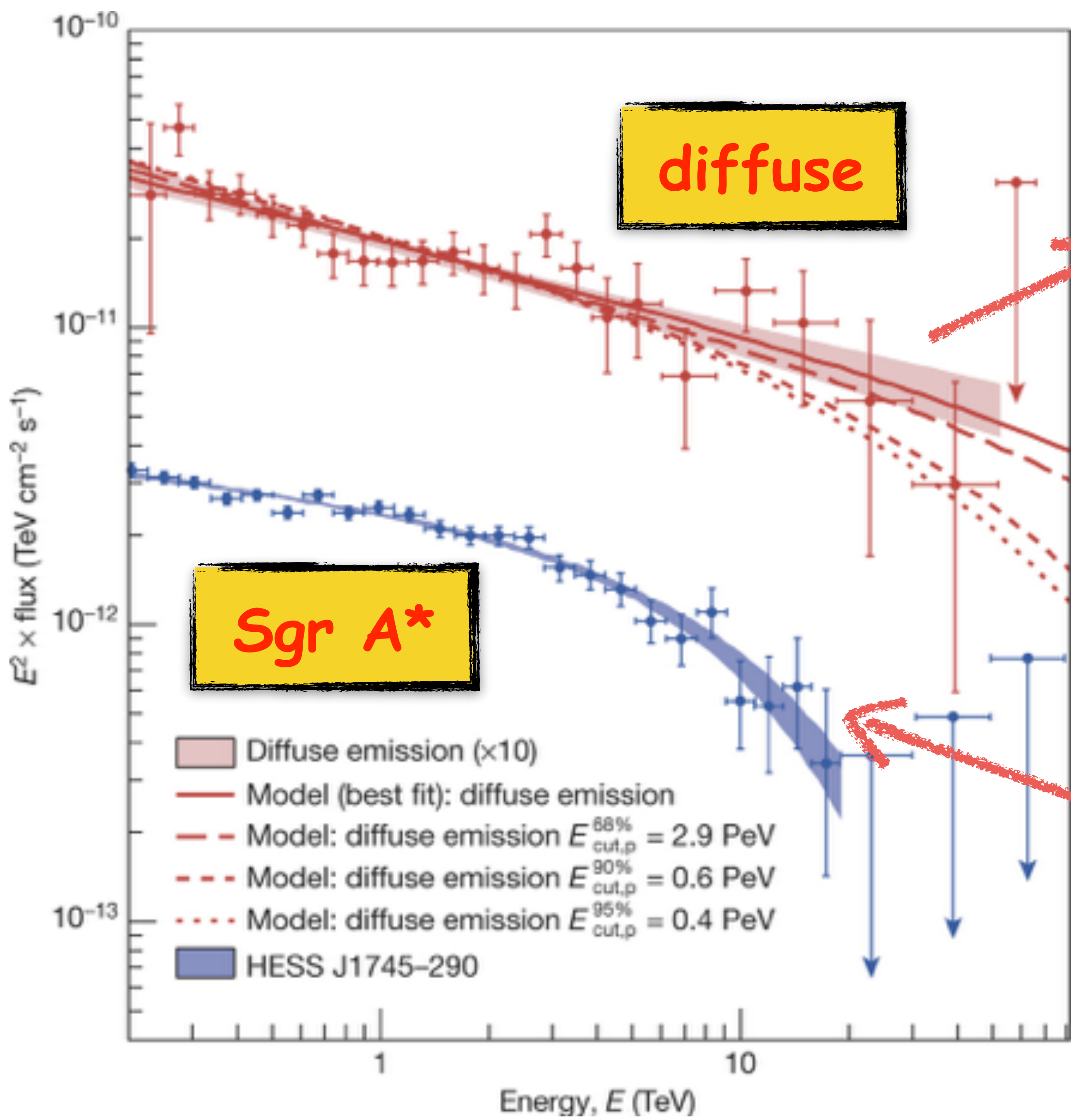
gas mass → $W_p \sim 10^{49}$erg

~10 TeV cutoff -> inconsistency? no...

- emission could be unrelated
- time dependent effect
- γγ-absorption w. IR photons? (Celli+ 2016)

Supermassive black hole as a PeVatron

is Sgr A* as the source of PeV cosmic rays?



gas mass

$$W_p \sim 10^{49} \mathrm{erg}$$

1/R profile

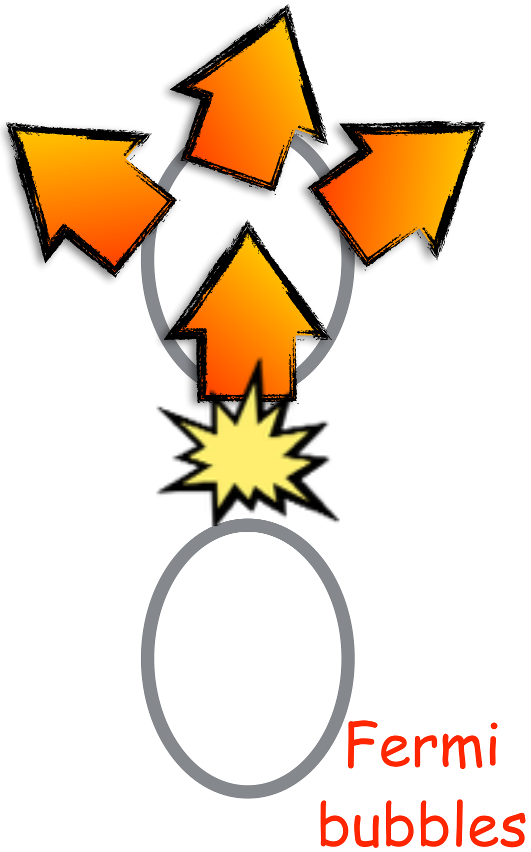
$$\dot{Q}_p \sim 4 \times 10^{37} \left(\frac{D}{10^{30} \mathrm{cm}^2/\mathrm{s}} \right) \mathrm{erg/s}$$

~10 TeV cutoff -> inconsistency? no...

- emission could be unrelated
- time dependent effect
- γγ-absorption w. IR photons? (Celli+ 2016)

speculations

BH activity, cosmic rays, neutrinos



the GC activity highly variable (Ponti+2013) -> what if the CR acceleration efficiency was larger in the past?

speculations

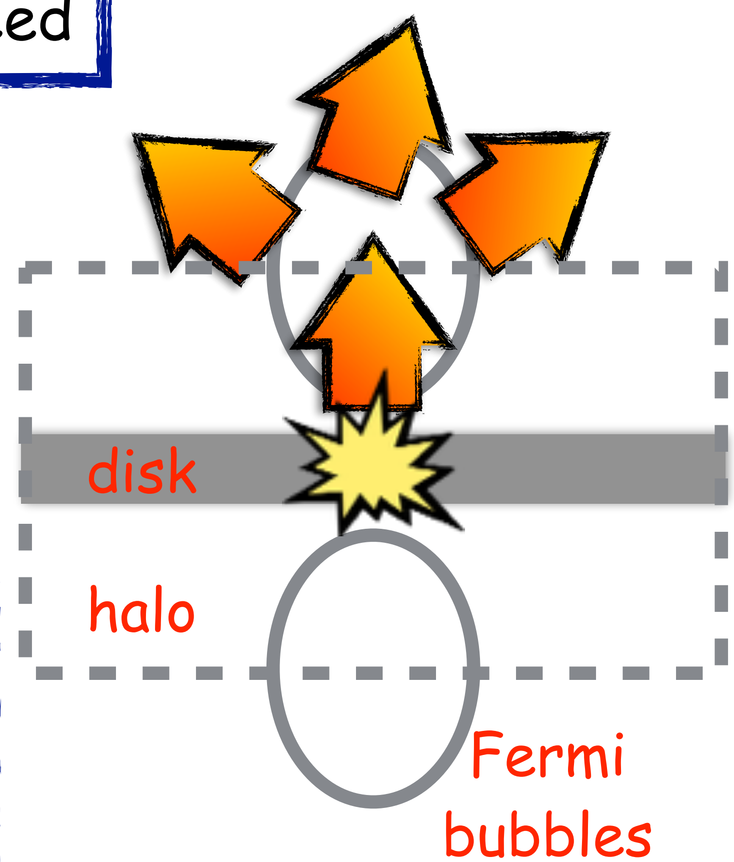
BH activity, cosmic rays, neutrinos

to explain **all** CRs >10 TeV we need

$$L_{CR} \approx 10^{39} \text{ erg/s}$$

for ~10^6-10^7 yrs

the GC activity highly variable (Ponti+2013) -> what if the CR acceleration efficiency was larger in the past?



speculations

BH activity, cosmic rays, neutrinos

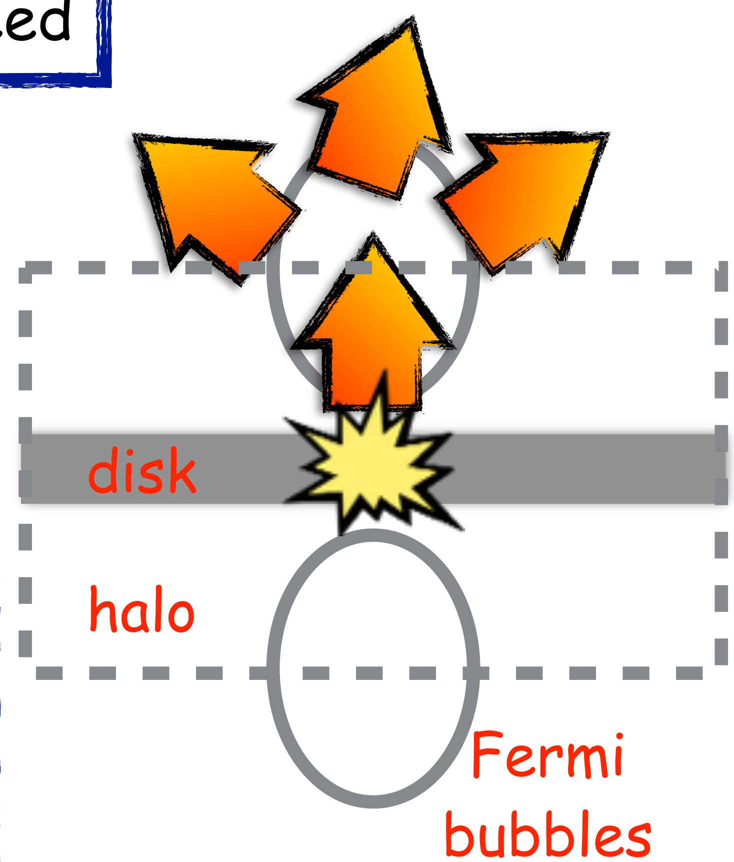
~200 kpc

to explain **all** CRs >10 TeV we need

$$L_{CR} \approx 10^{39} \ \mathrm{erg/s}$$

for ~10^6-10^7 yrs

the GC activity highly variable (Ponti+2013) -> what if the CR acceleration efficiency was larger in the past?



evidence for a huge reservoir of ionized gas (> 10^{10} M_{sun}) in the halo from X-ray observations (Gupta+ 2012)

speculations

BH activity, cosmic rays, neutrinos

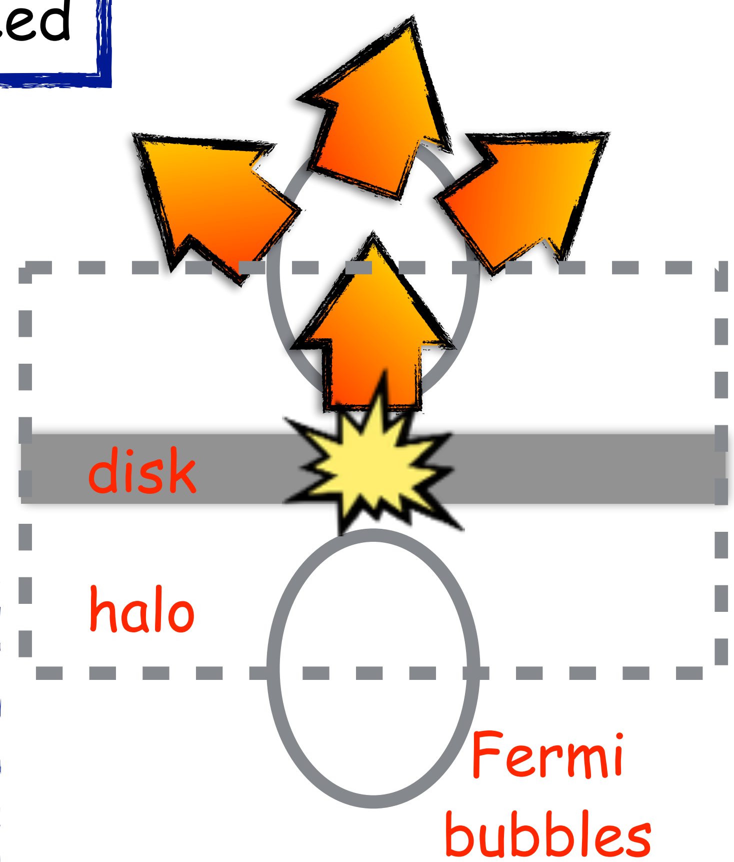
~200 kpc

to explain **all** CRs >10 TeV we need

$$L_{CR} \approx 10^{39} \text{ erg/s}$$

for ~10^6-10^7 yrs

the GC activity highly variable (Ponti+2013) -> what if the CR acceleration efficiency was larger in the past?



evidence for a huge reservoir of ionized gas (> 10^{10} M_{sun}) in the halo from X-ray observations (Gupta+ 2012)

IceCube neutrinos

Taylor, SG, Aharonian 2014

speculations

BH activity, cosmic rays, neutrinos

~200 kpc

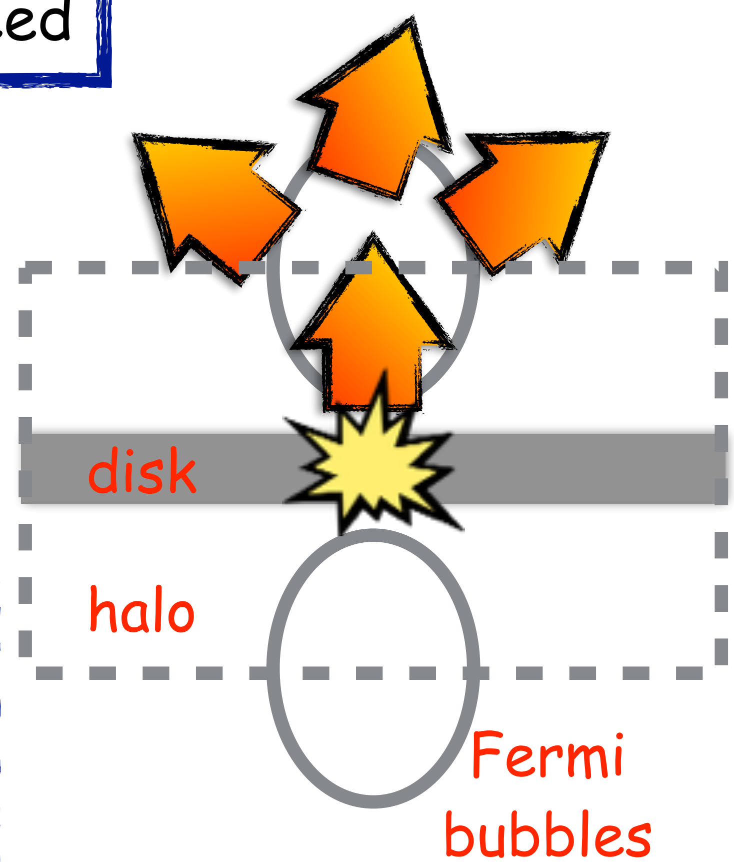
to explain **all** CRs >10 TeV we need

$$L_{CR} \approx 10^{39} \ \mathrm{erg/s}$$

for ~10^6-10^7 yrs

the GC activity highly variable (Ponti+2013) -> what if the CR acceleration efficiency was larger in the past?

evidence for a huge reservoir of ionized gas (> 10^{10} M_{sun}) in the halo from X-ray observations (Gupta+ 2012)



CR bursts from GC
Ptuskin & Khazan (1981)
see also Fujita+ 2016
CR in Gal. breeze
Taylor & Giacinti 2016

IceCube neutrinos

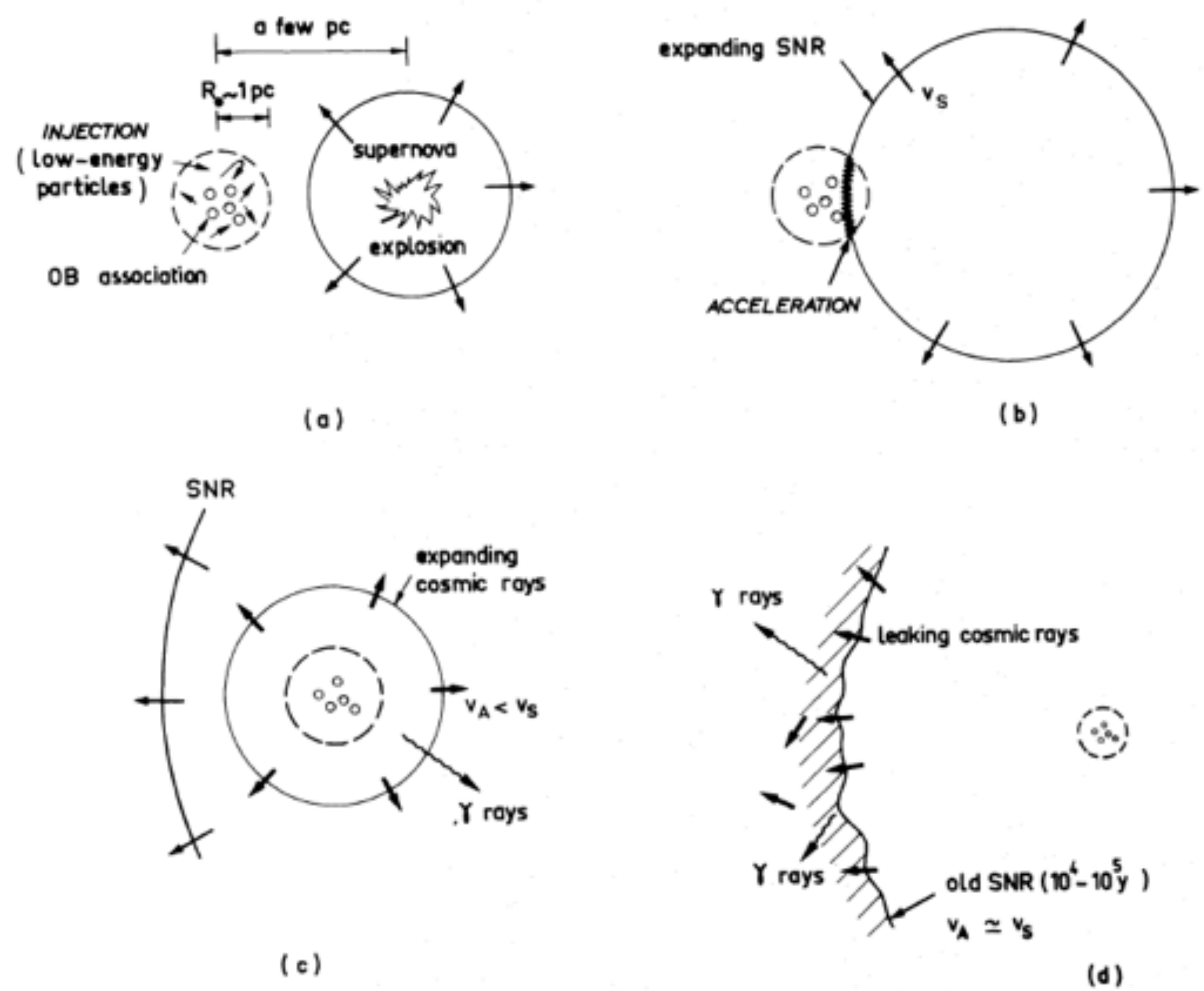
Taylor, SG, Aharonian 2014

The importance of being a SNOB

Montmerle 1979

SuperNovae OB associations

tentative spatial association between SNOBs and COS B hot spots



The importance of being a SNOB

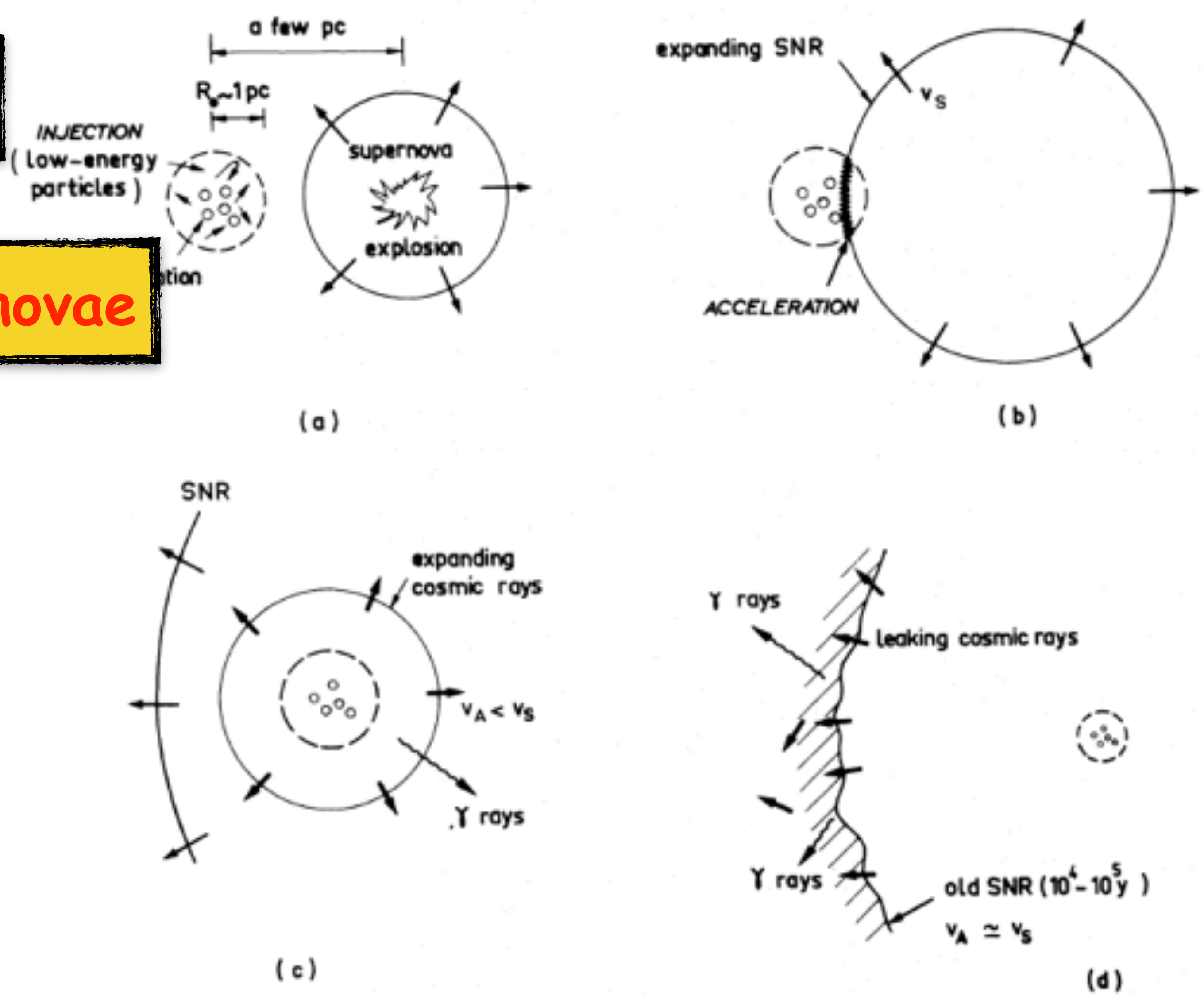
SuperNovae → SN, OB associations → OB

Montmerle 1979

tentative spatial association between SNOBs and COS B hot spots

OB stars

supernovae



The importance of being a SNOB

Montmerle 1979

SuperNovae → SN; OB associations → OB

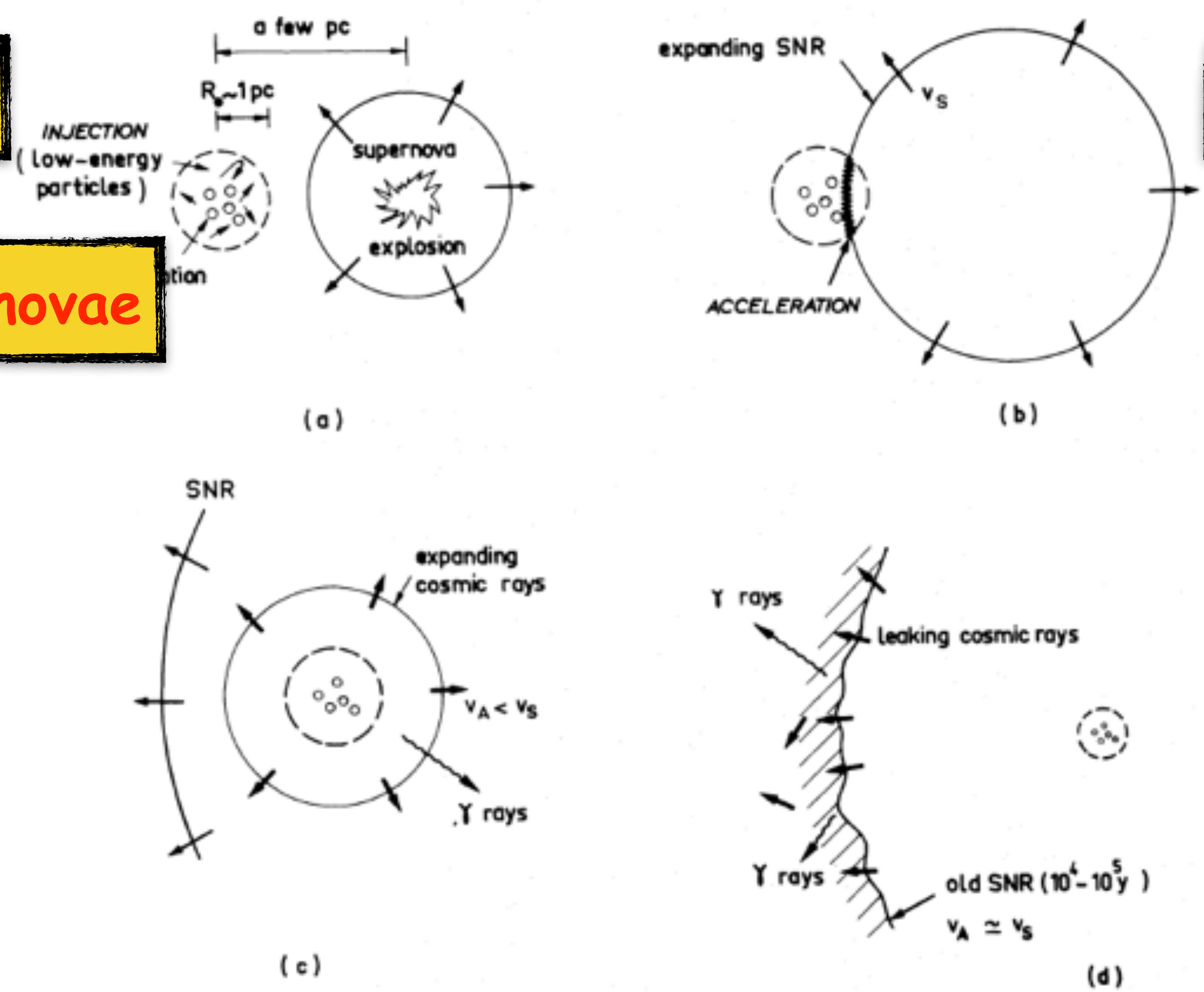
tentative spatial association between SNOBs and COS B hot spots

OB stars

supernovae

SNRs

CR acceleration



The importance of being a SNOB

SuperNovae — OB associations

Montmerle 1979

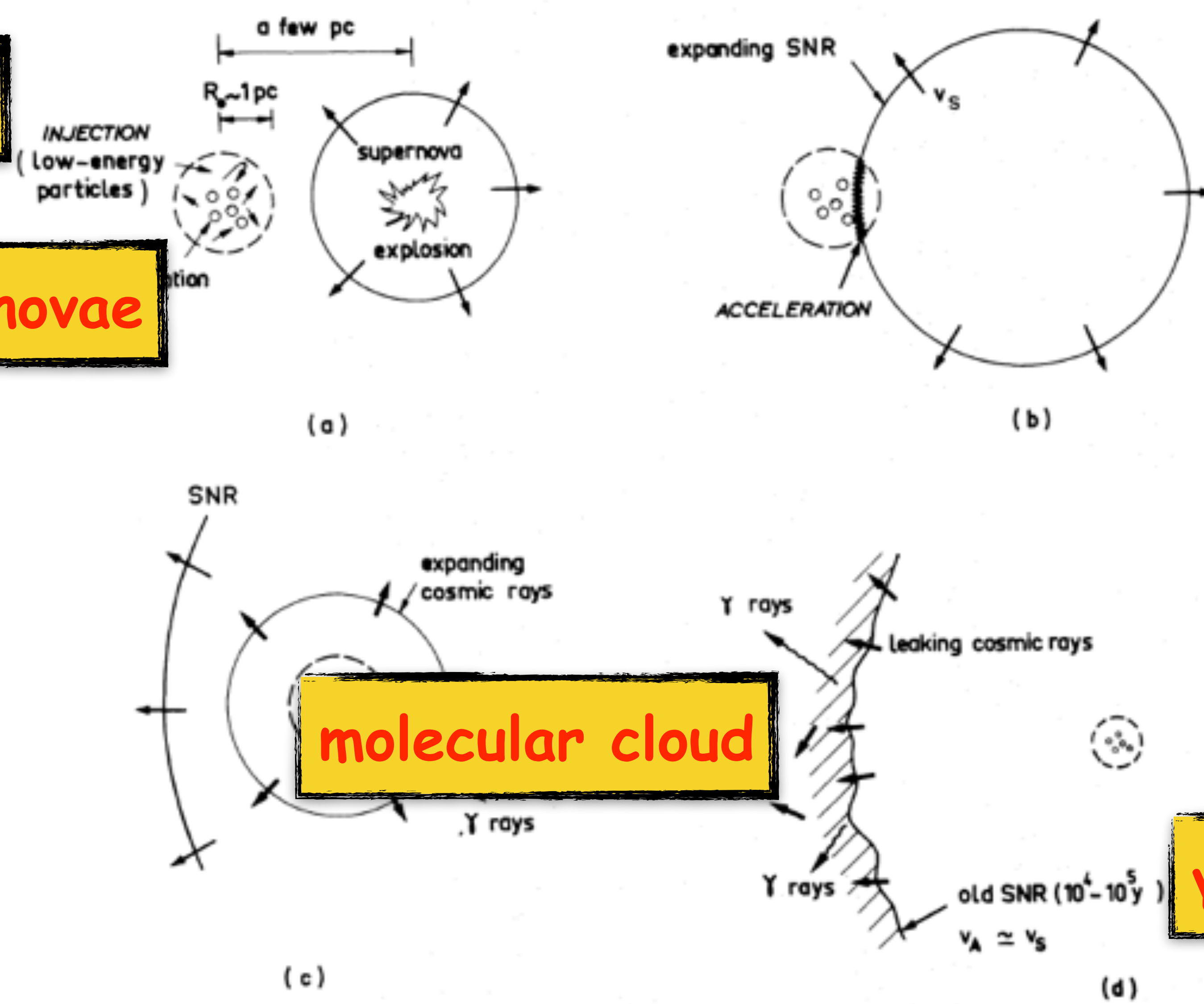
tentative spatial association between SNOBs and COS B hot spots

OB stars

supernovae

SNRs

CR acceleration



molecular cloud

γ-rays

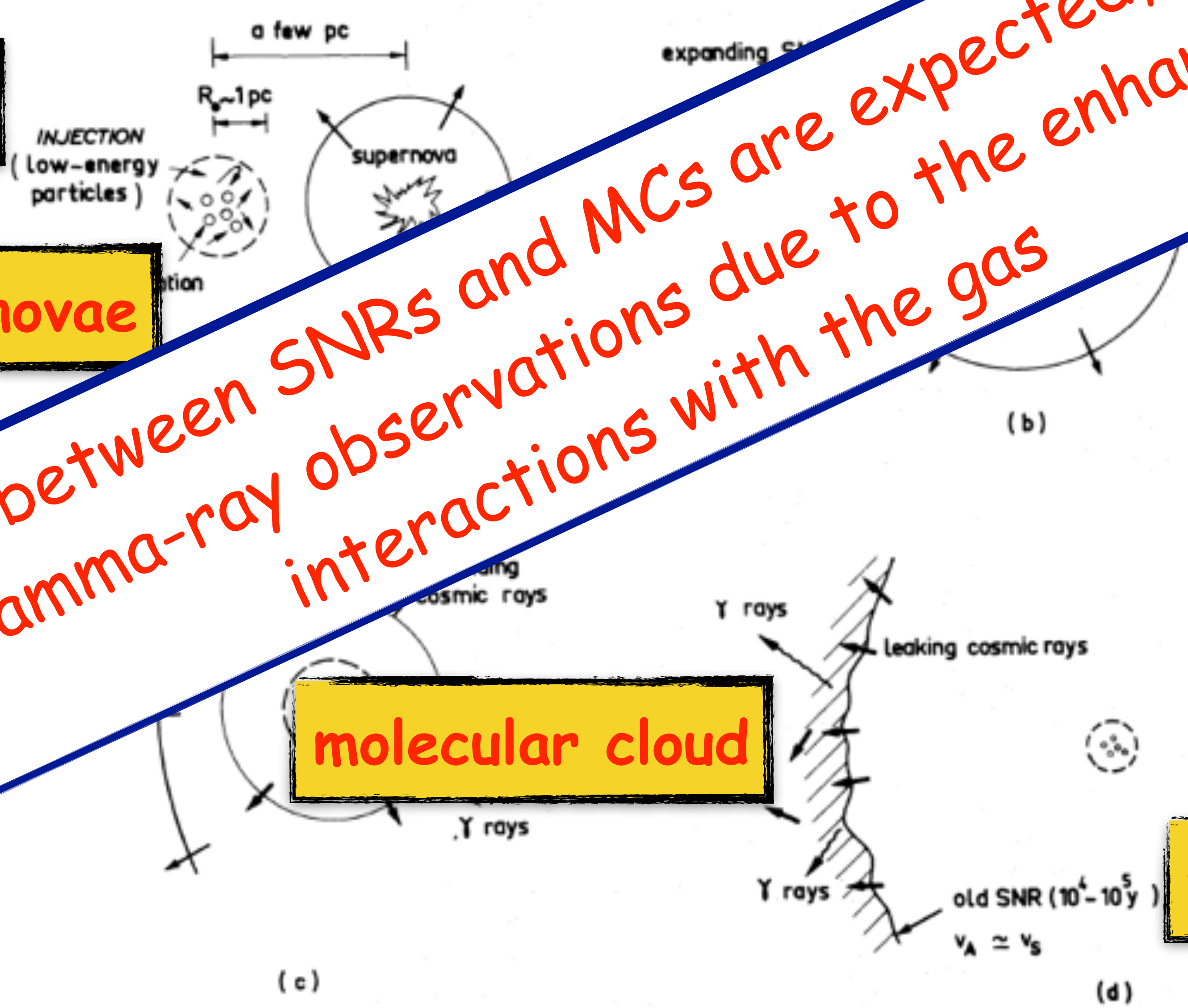
Black & Fazio 1973

The importance of being a SNOB

Montmerle 1979

SuperNovae OB ...ations

tentative spatial association between SNOBs and ...



OB stars

supernovae

CR acceleration

molecular cloud

γ-rays

Black & Fazio 1973

associations between SNRs and MCs are expected, and are ideal targets for gamma-ray observations due to the enhanced rate of CR interactions with the gas

Another scenario: SNOBs, superbubbles…

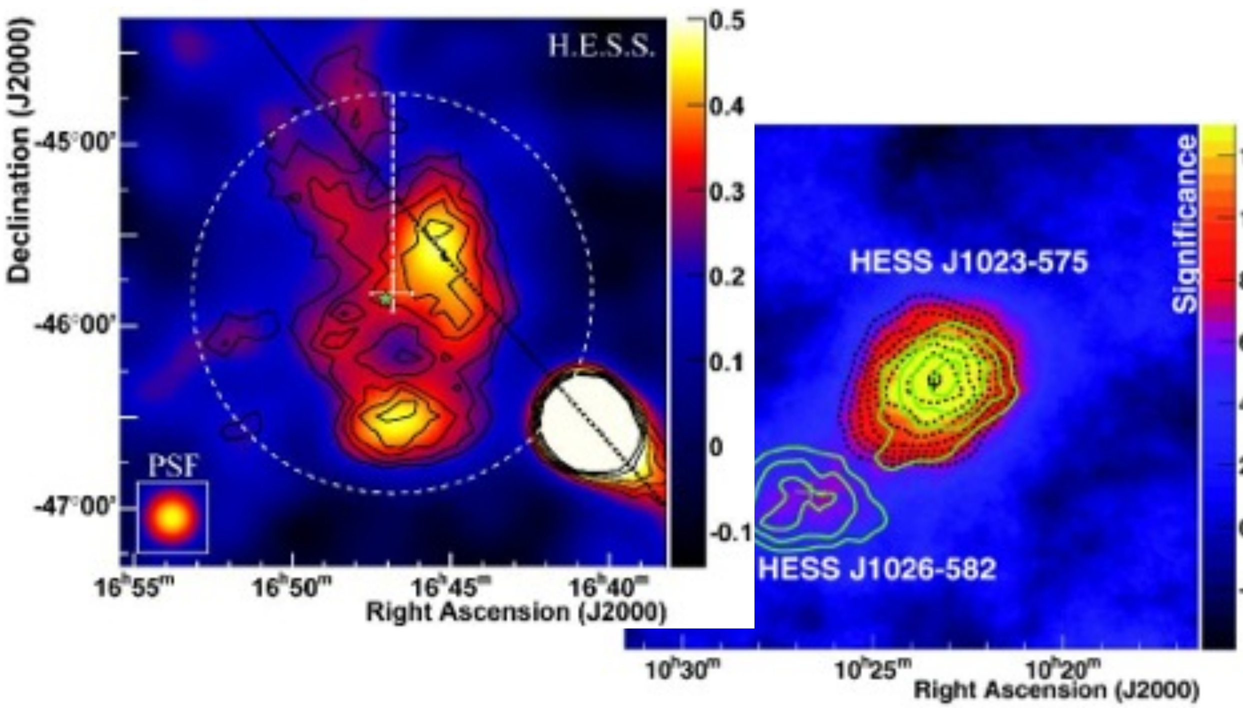
- chemical composition -> CRs originate in a source which is a mixture ~20% stellar outflow/SN ejecta and ~80% interstellar medium (Murphy+ 2016 and references)
- stars form in clusters -> SN explosions -> SNOBs and superbubbles

Another scenario: SNOBs, superbubbles...

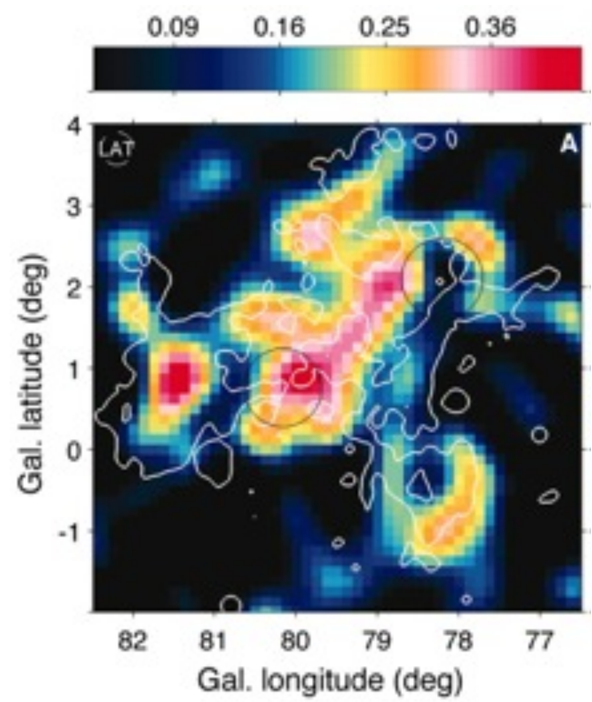
- chemical composition -> CRs originate in a source which is a mixture ~20% stellar outflow/SN ejecta and ~80% interstellar medium (Murphy+ 2016 and references)
- stars form in clusters -> SN explosions -> SNOBs and superbubbles

star clusters in γ-rays

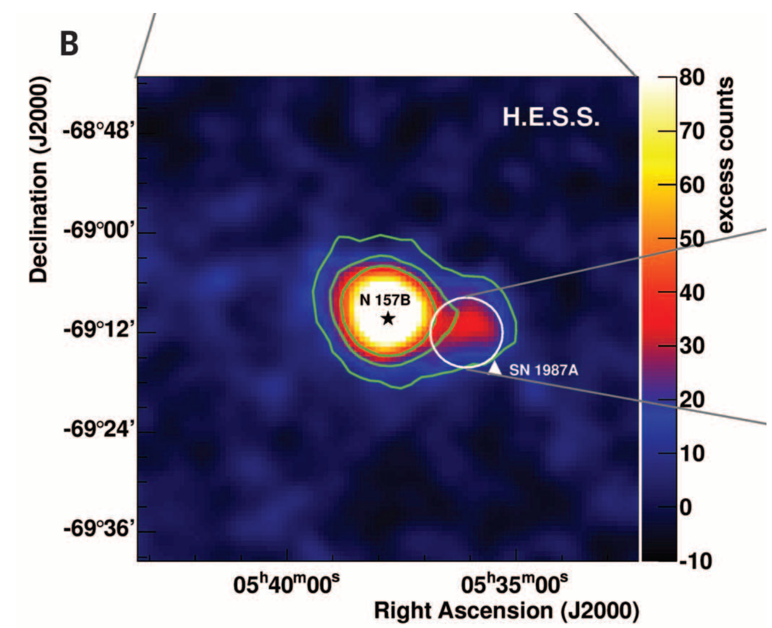
superbubbles in γ-rays



westerlund 1 and 2, HESS



Cygnus, Fermi



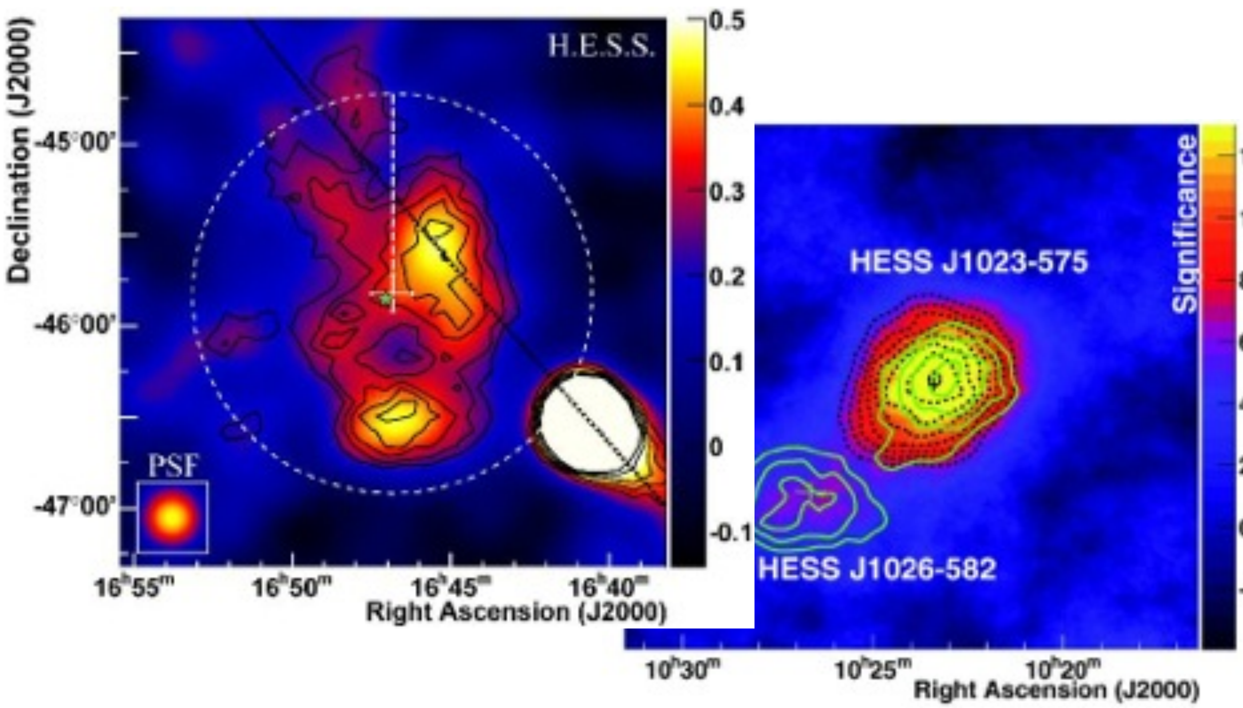
30 Dor C, LMC, HESS

Another scenario: SNOBs, superbubbles...

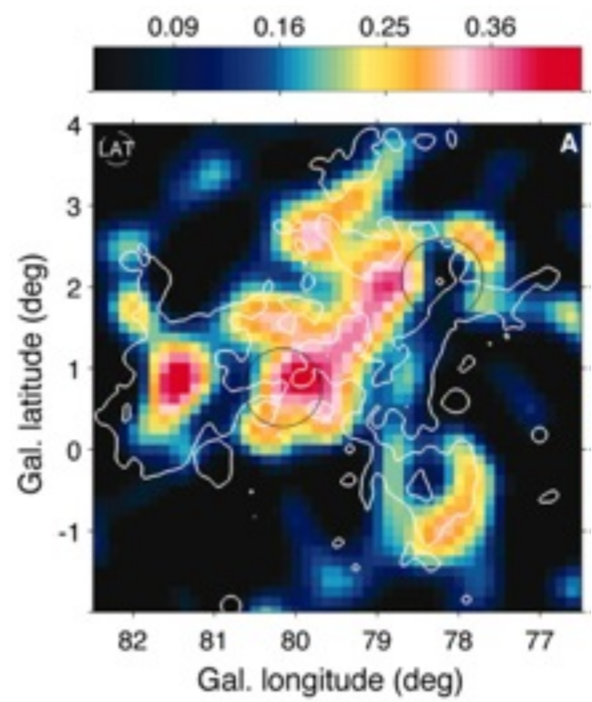
- chemical composition -> CRs originate in a source which is a mixture ~20% stellar outflow/SN ejecta and ~80% interstellar medium (Murphy+ 2016 and references)
- stars form in clusters -> SN explosions -> SNOBs and superbubbles

star clusters in γ-rays

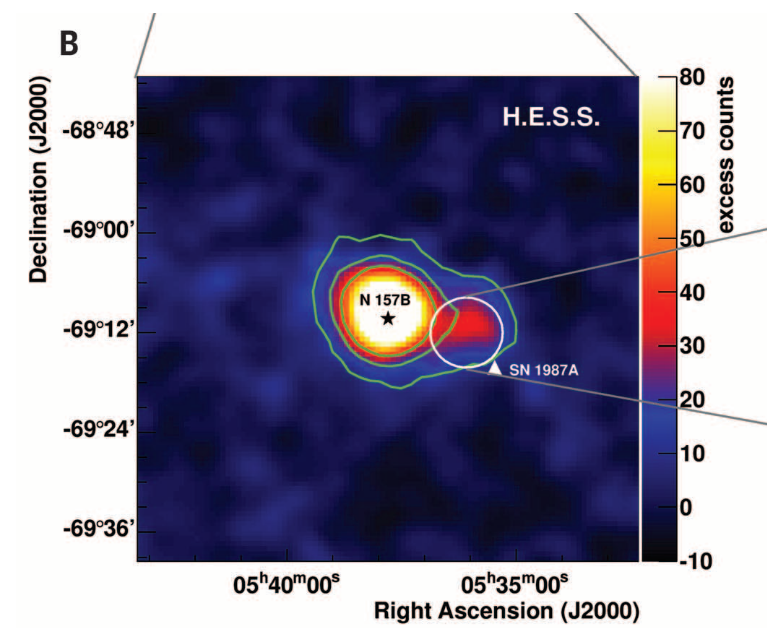
superbubbles in γ-rays



westerlund 1 and 2, HESS



Cygnus, Fermi



30 Dor C, LMC, HESS

- the acceleration mechanism might be completely different (Bykov&Fleishman92)
- particle spectrum not universal, large E_{max} (large size!)

Conclusions

The SNR hypothesis for the origin of galactic CRs is widely accepted

...but it is not proven!

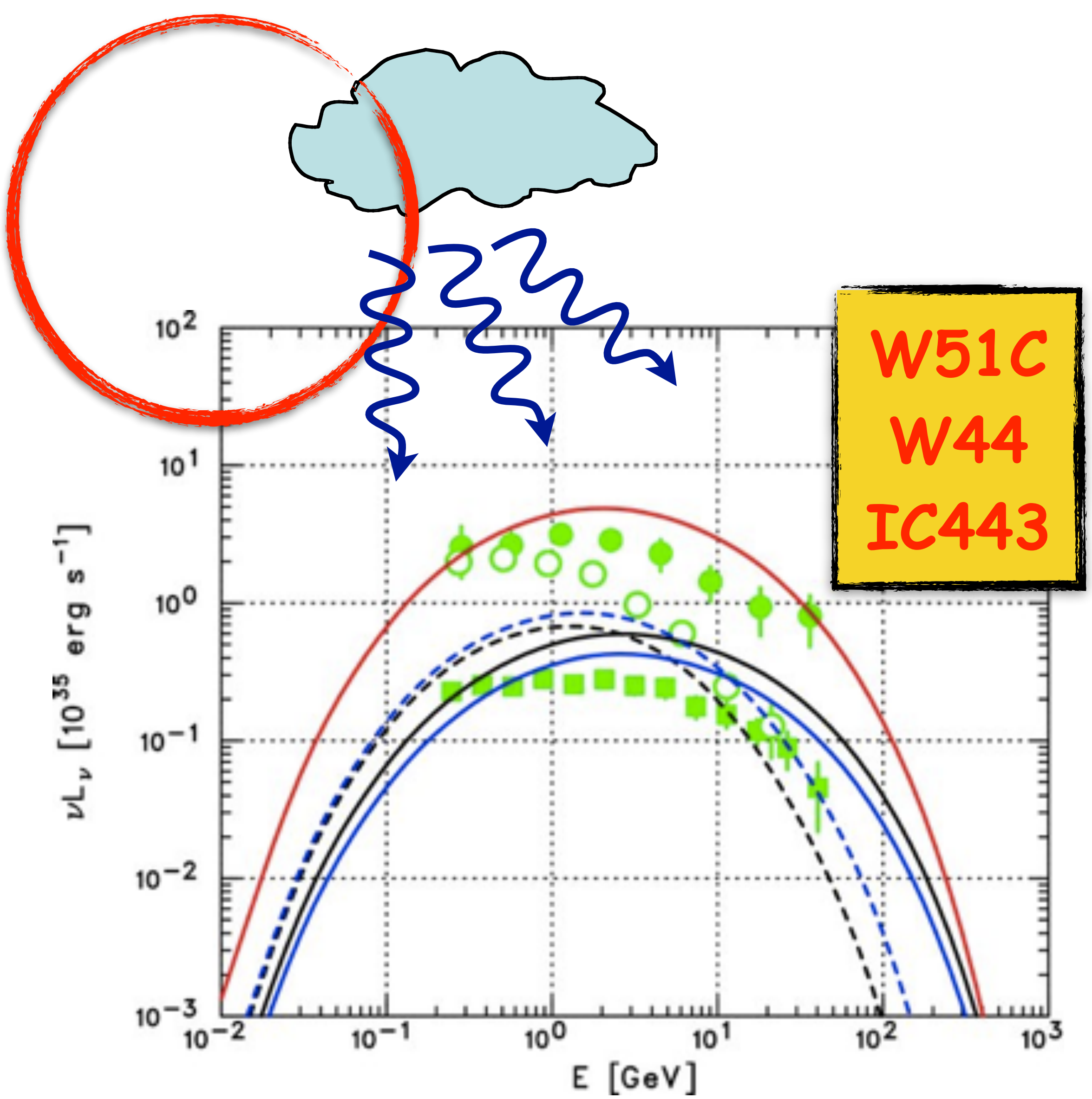
- tested against Fermi and HESS observations -> OK
- one crucial question is: where are PeVatrons?
- the only known proton PeVatron in the MW is the galactic centre!
- SNOBs/superbubbles are gainign some observational support
- needs to explore alternative scenarios to the standard SNR hypothesis

Backup slides

Molecular Clouds: boosting γ-ray emission

Blandford&Cowie 1982, Aharonian+ 1994, Bykov+ 2000, Uchiyama+ 2010

shock/MC interaction



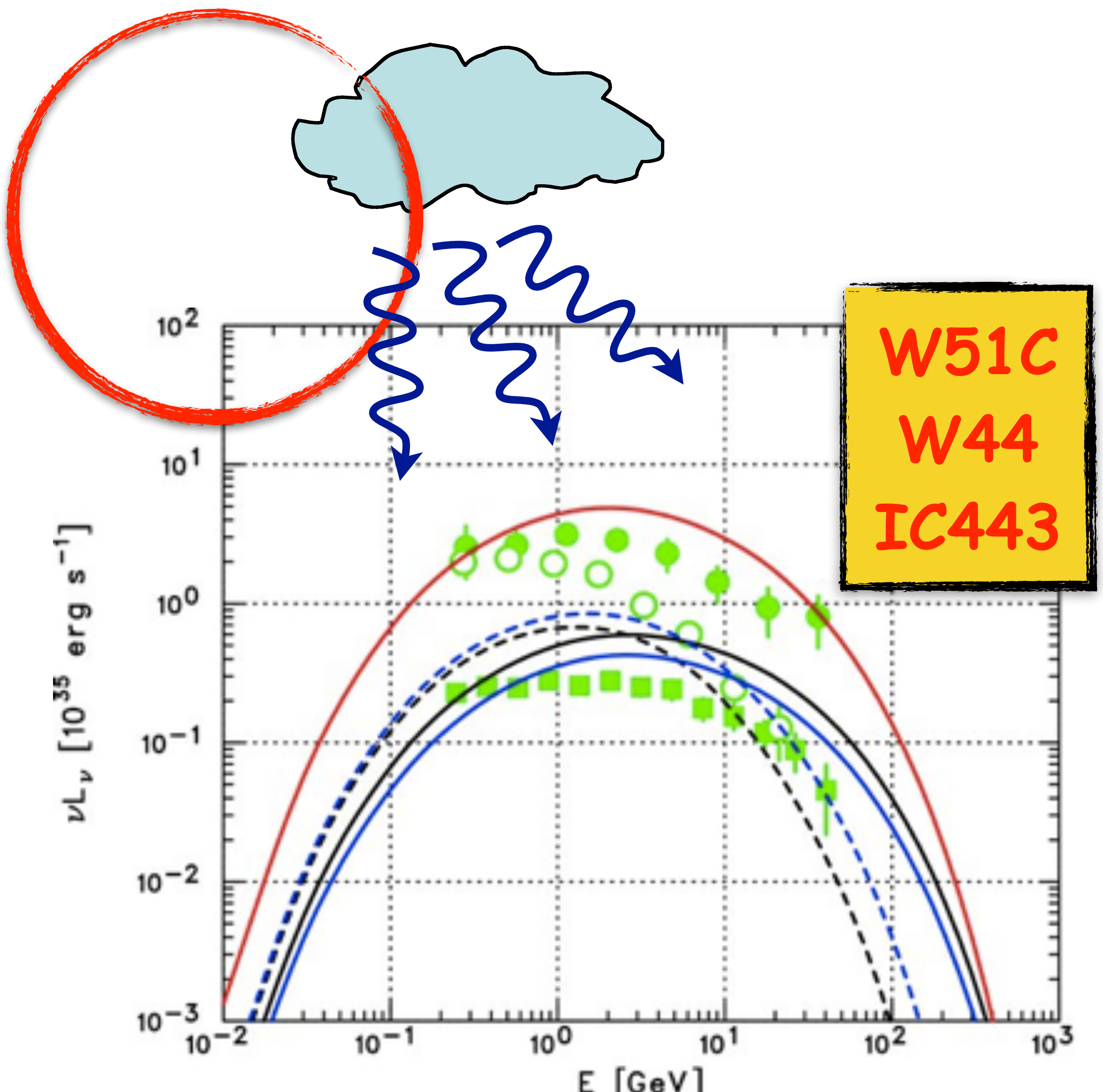
W51C
W44
IC443

see L. Nava's talk

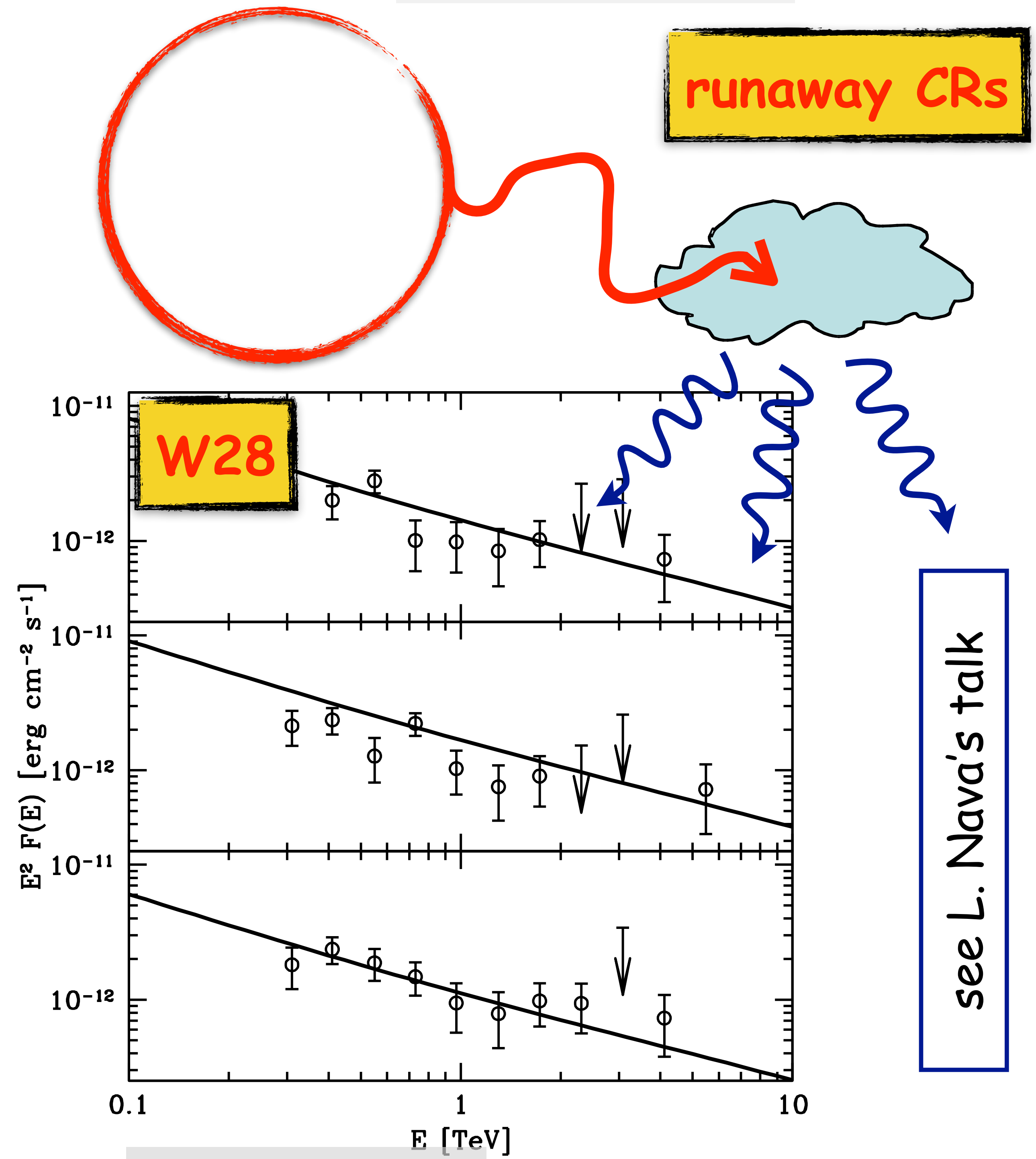
Molecular Clouds:boosting γ-ray emission

Blandford&Cowie 1982, Aharonian+ 1994, Bykov+ 2000, Uchiyama+ 2010

shock/MC interaction



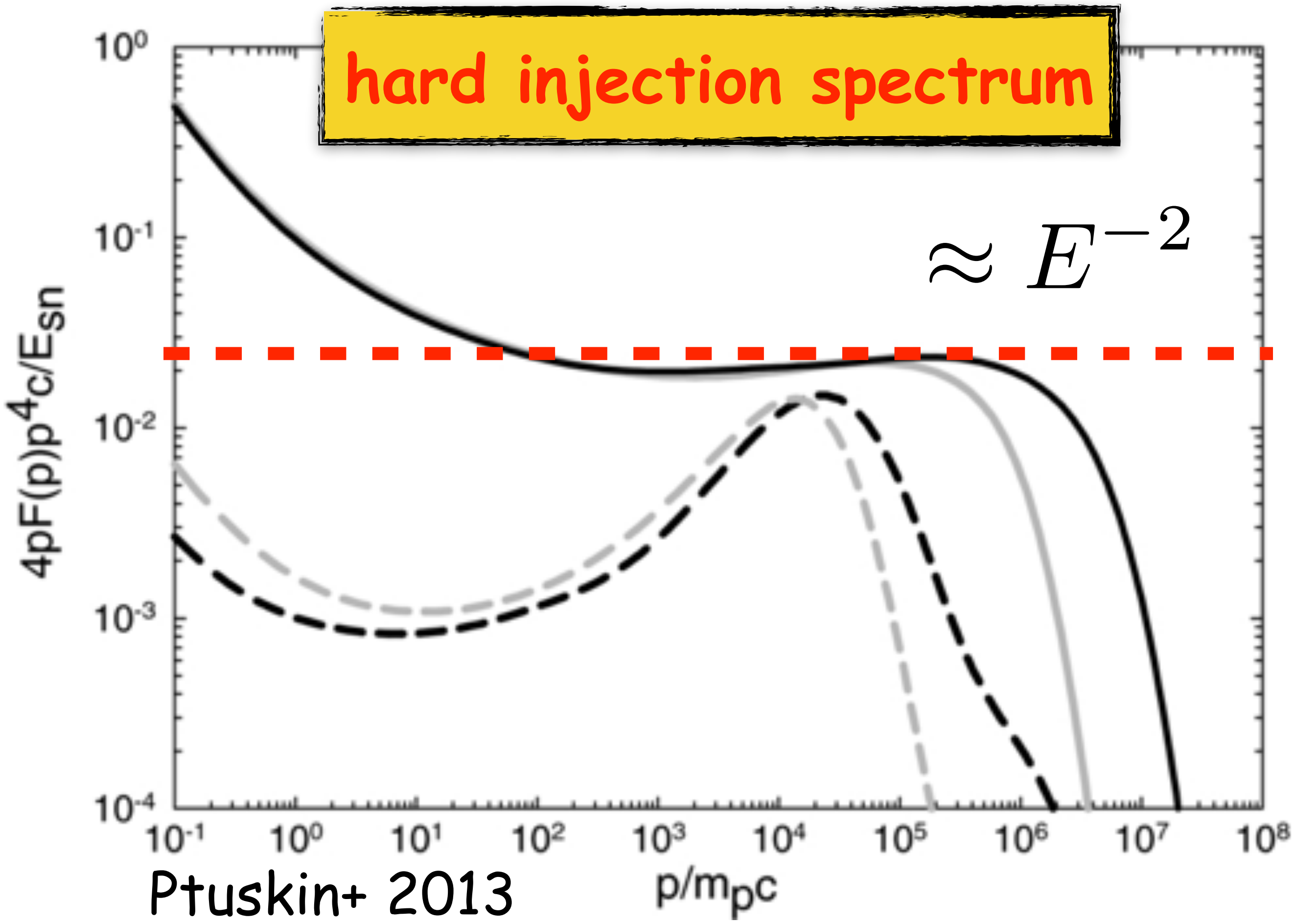
runaway CRs

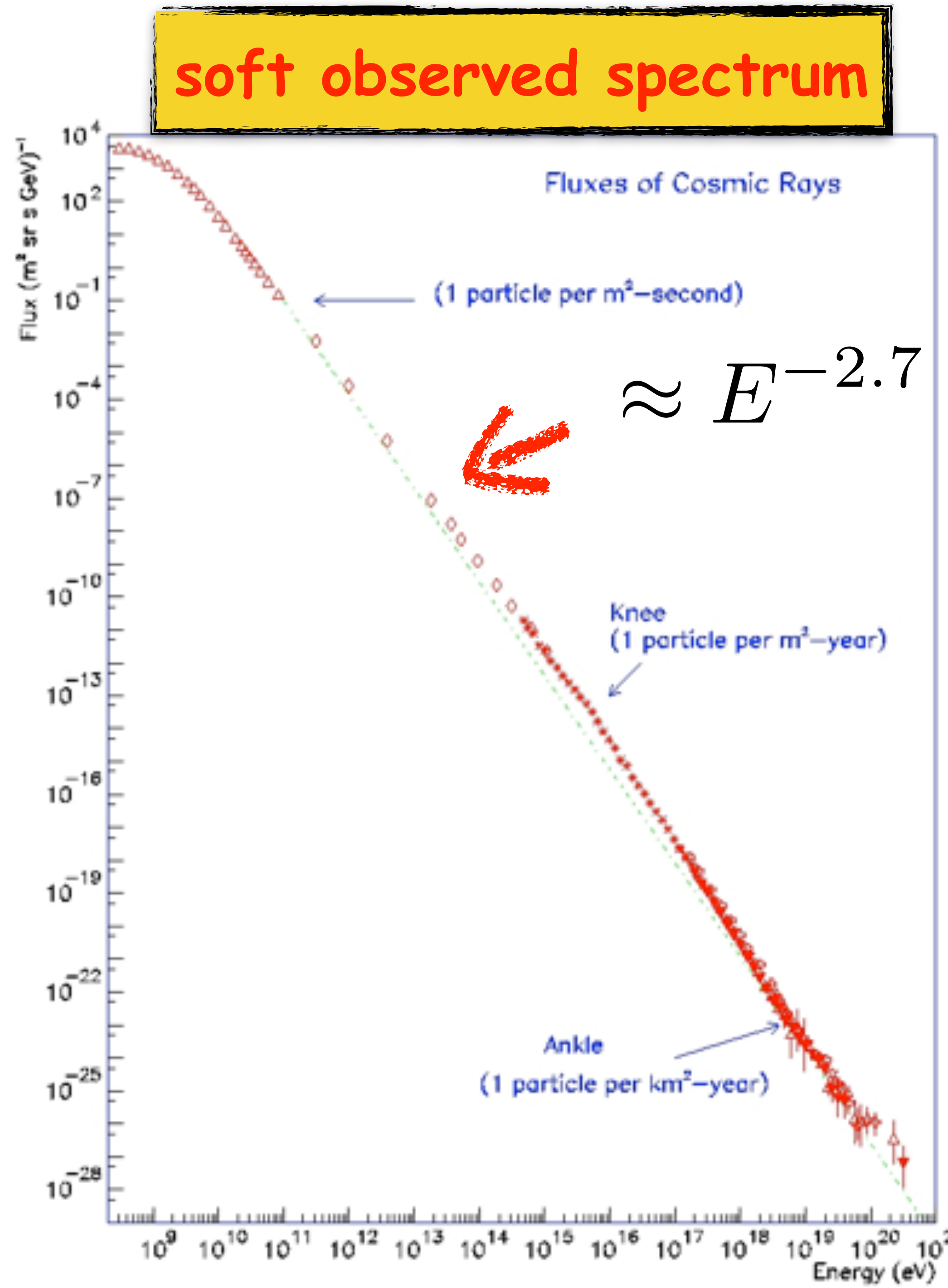


see L. Nava's talk

Aharonian&Atoyan 1996, SG&Aharonian 2007, SG+ 2009,2010, Nava&SG 2013

From SNRs to the galactic pool

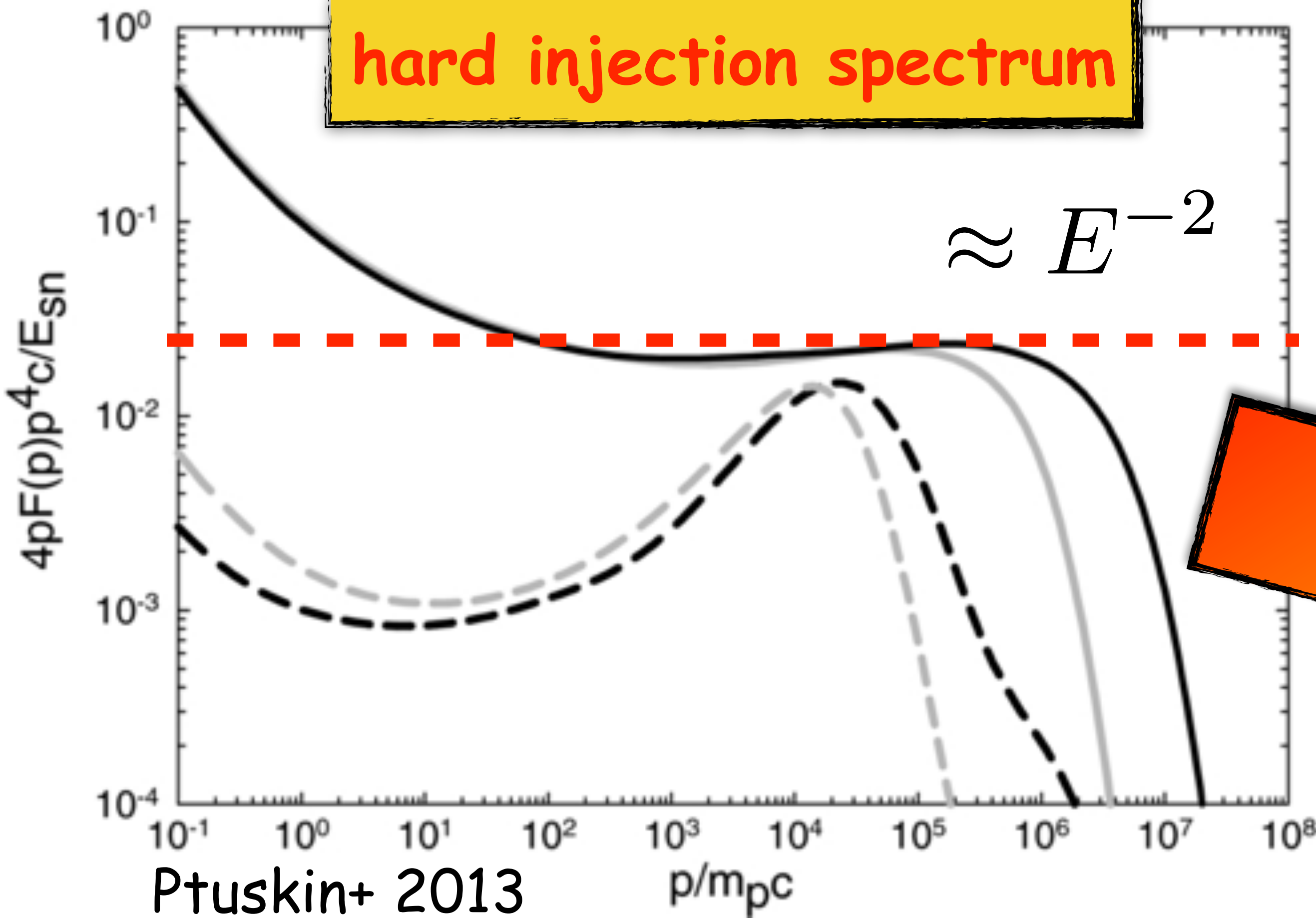




From SNRs to the galactic pool

hard injection spectrum

$\approx E^{-2}$

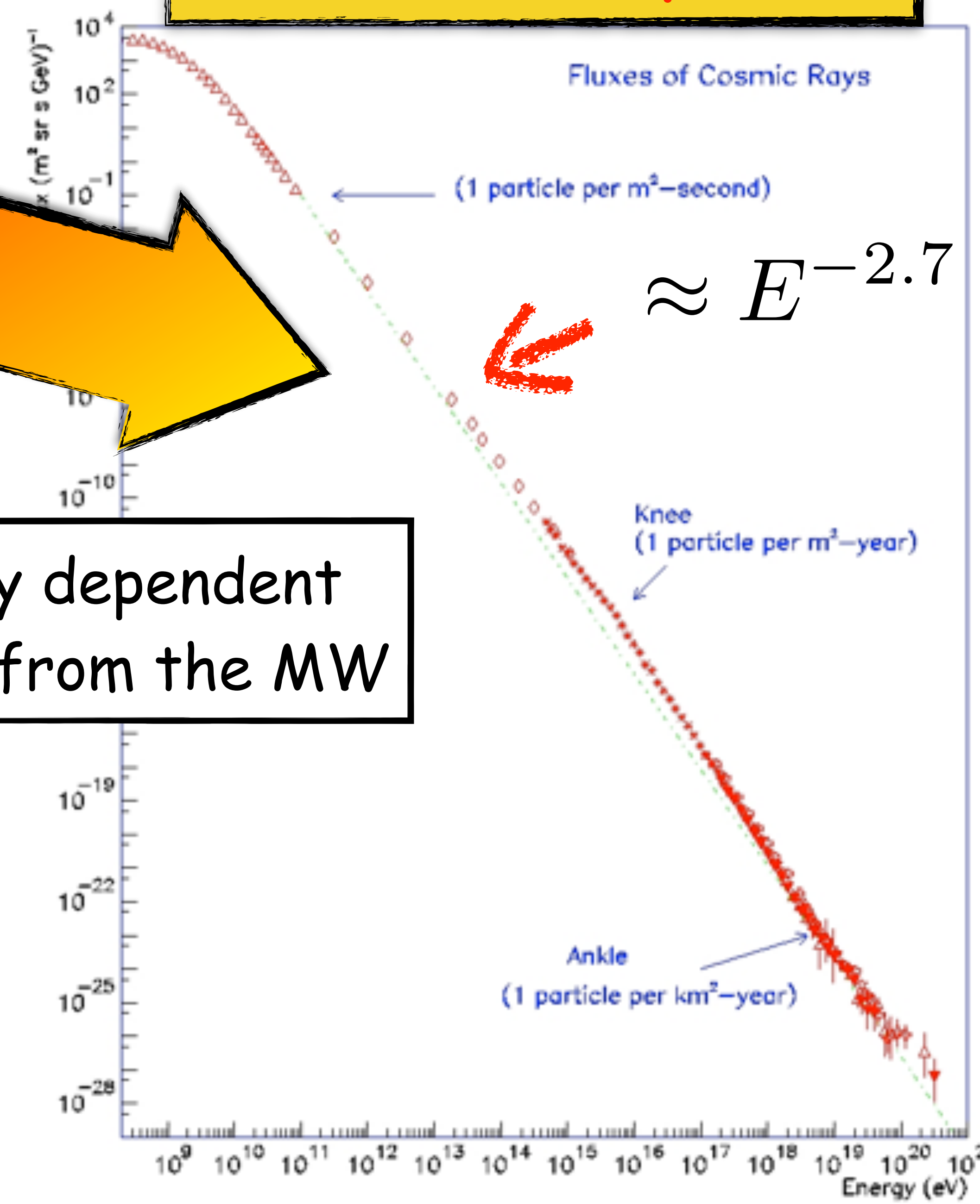


Ptuskin+ 2013

energy dependent escape from the MW

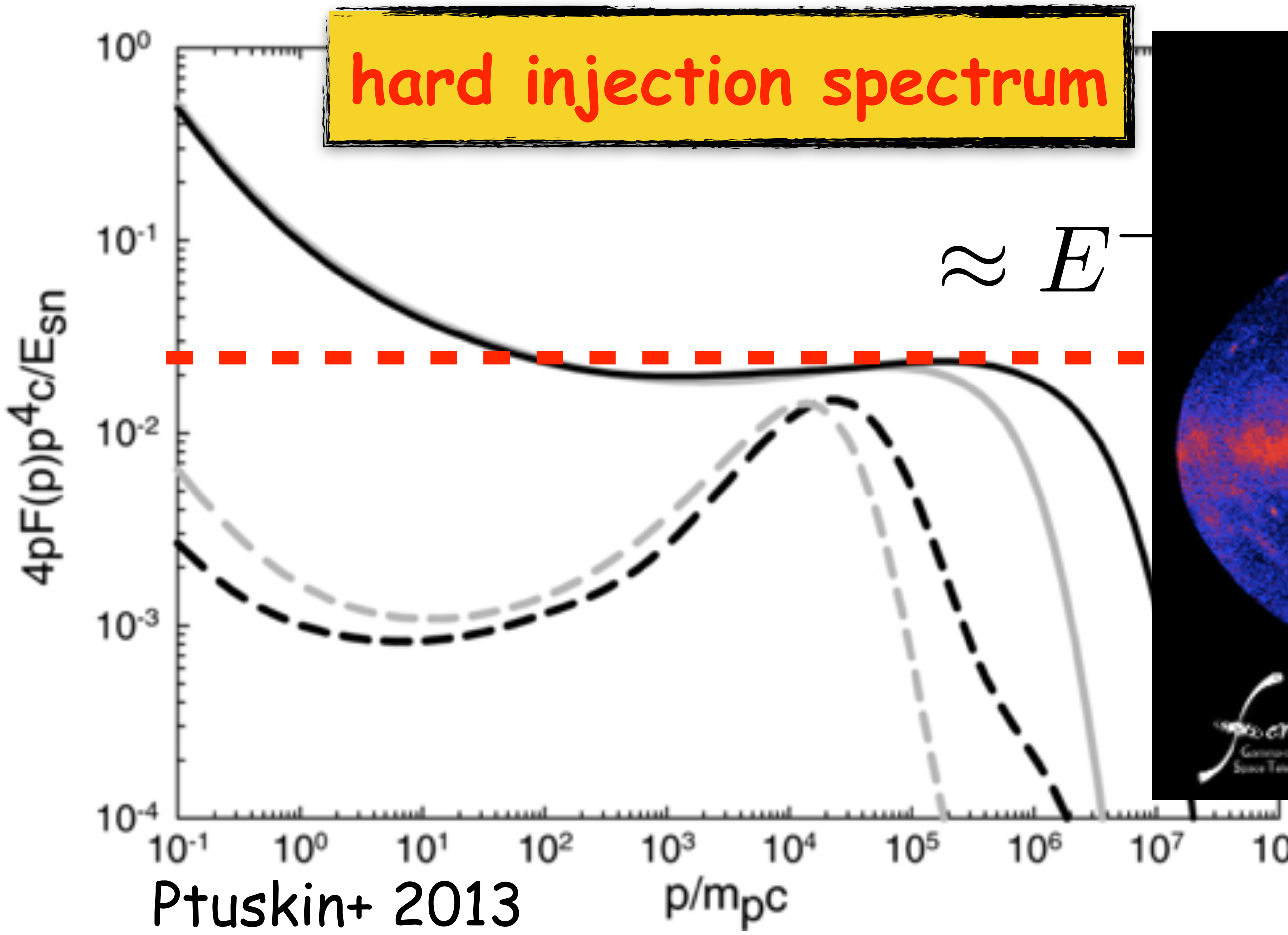
soft observed spectrum

$\approx E^{-2.7}$



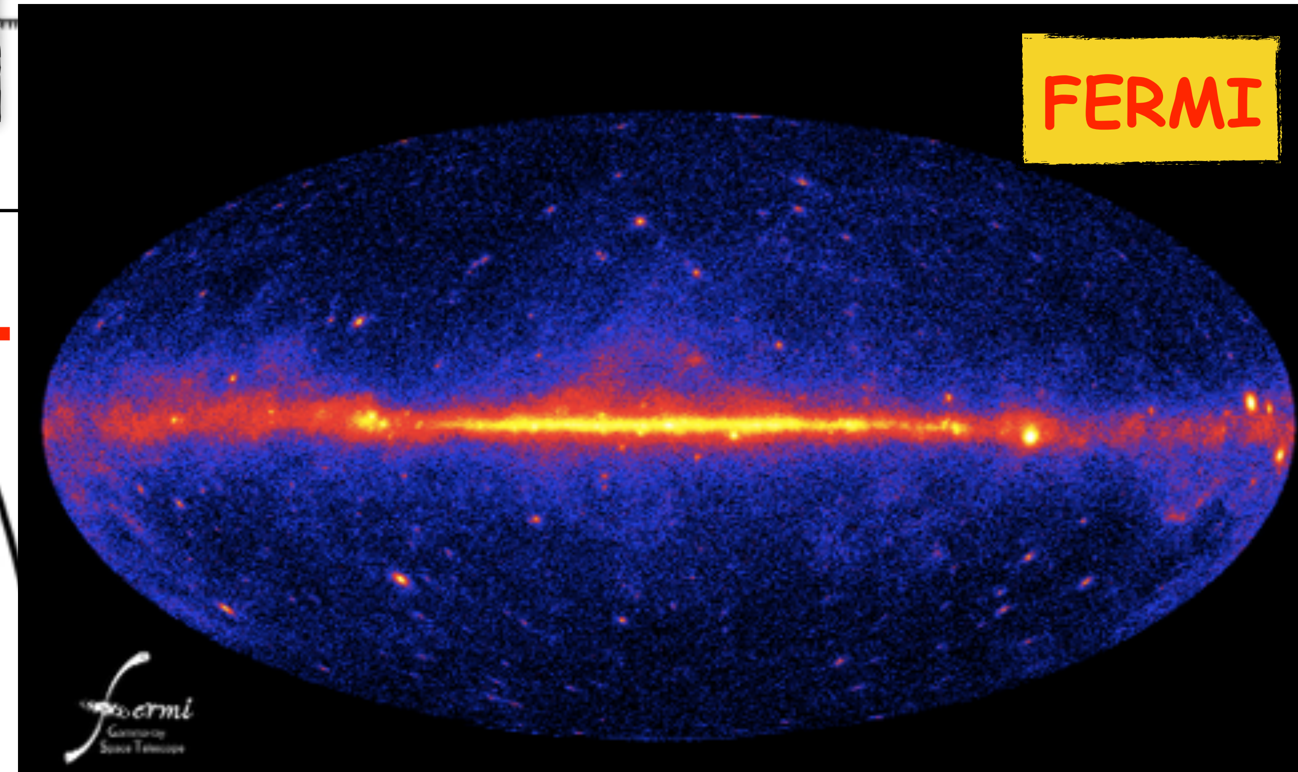
From SNRs to the galactic pool

hard injection spectrum



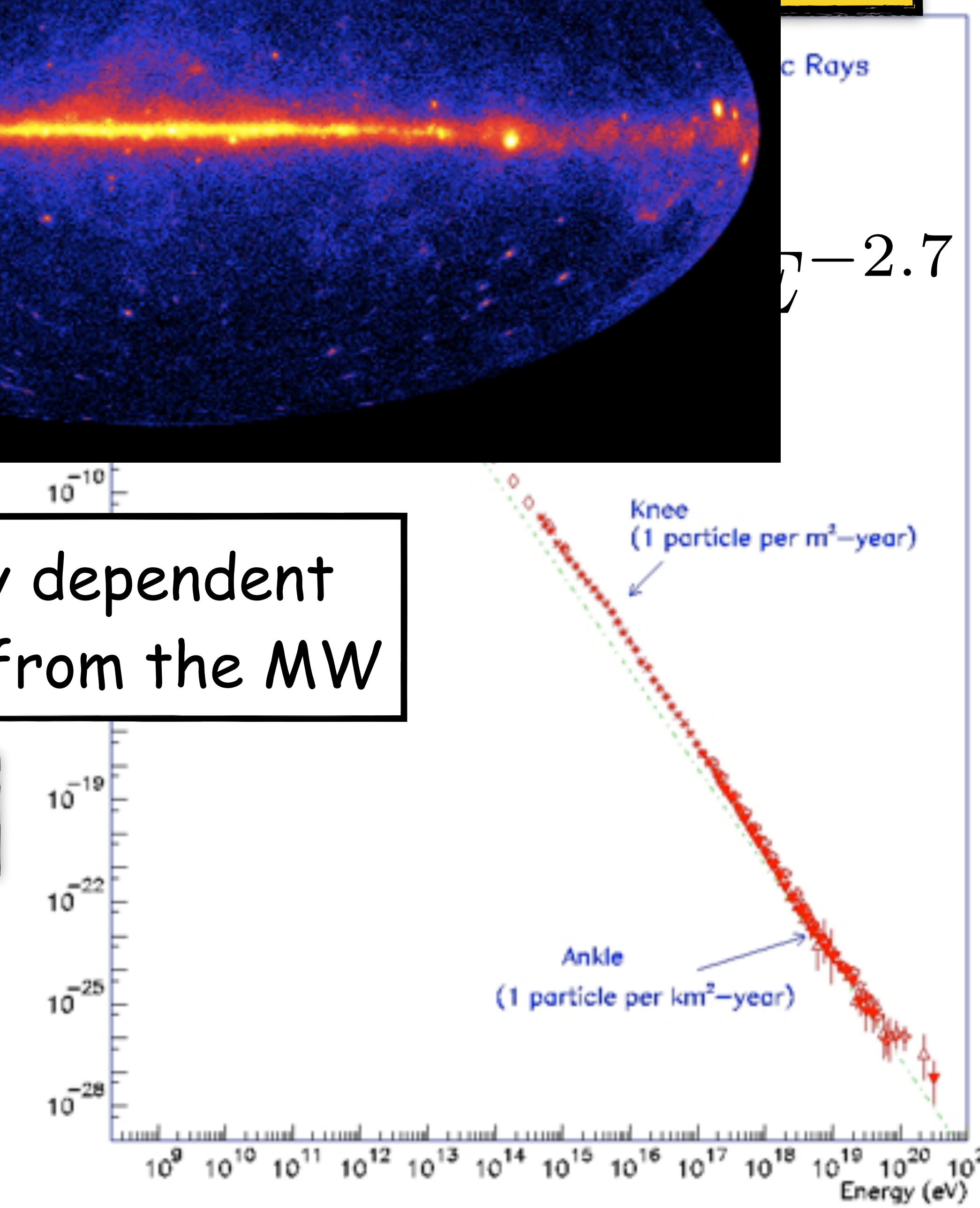
Ptuskin+ 2013

$\approx E^{-}$



rum

$^{-2.7}$



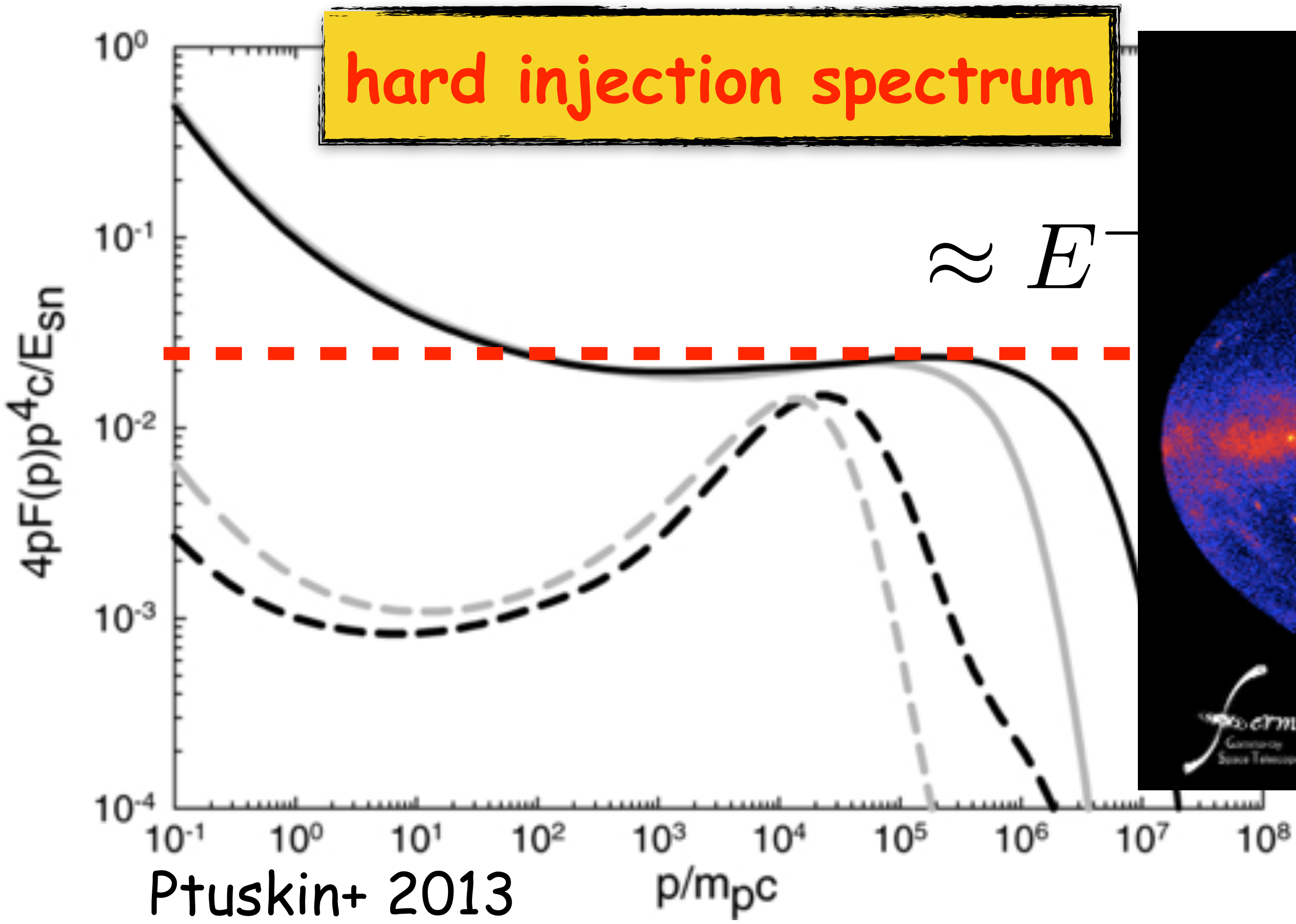
energy dependent
escape from the MW

production of stable secondary particles

γ-rays, nuclei (-> B/C), e^+, e^-, $\bar{p}$, ...

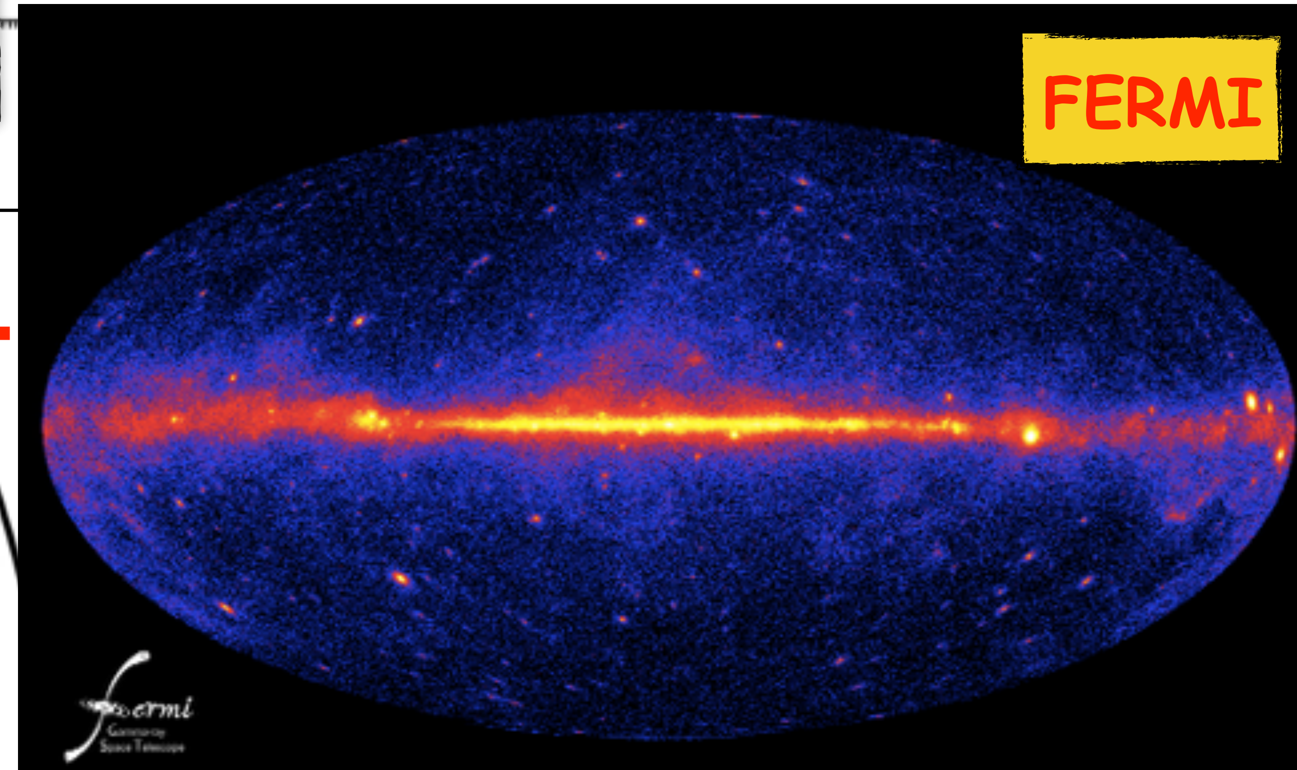
From SNRs to the galactic pool

hard injection spectrum

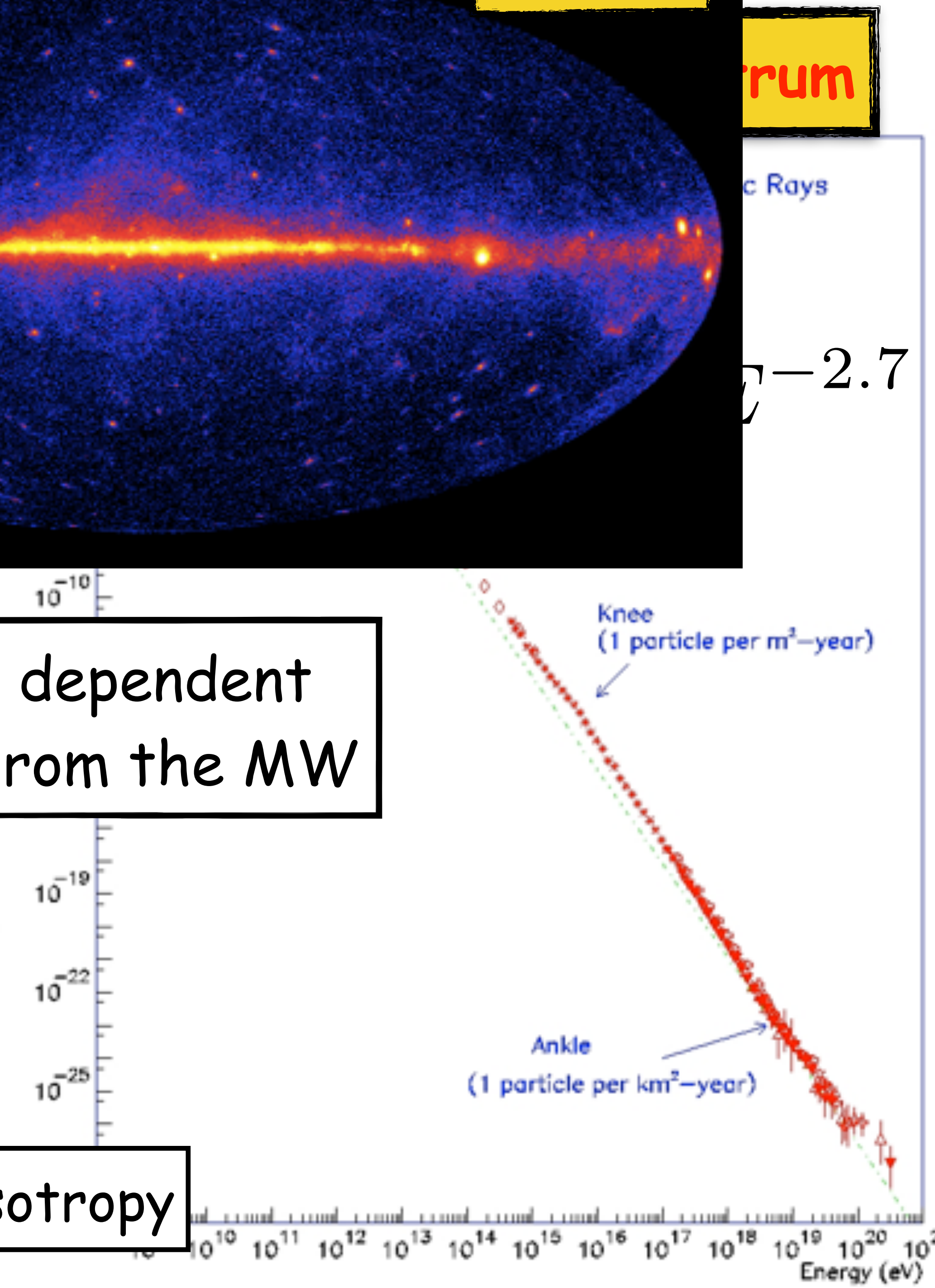


Ptuskin+ 2013

$\approx E^{-}$



rum



$E^{-2.7}$

energy dependent escape from the MW

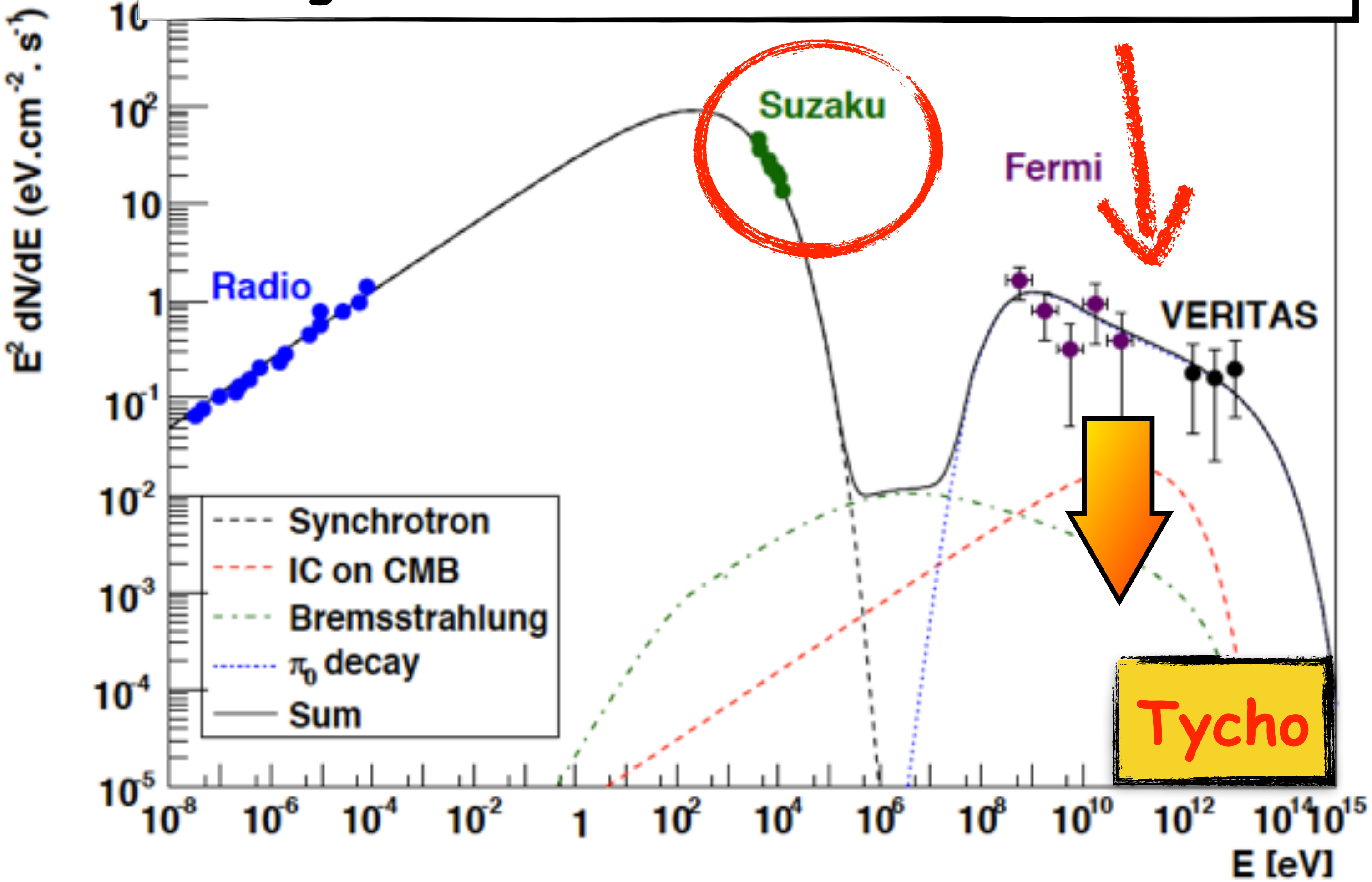
production of stable secondary particles

γ-rays, nuclei (-> B/C), e⁺, e⁻, p̄, ...

additional constraints from chemical composition & anisotropy

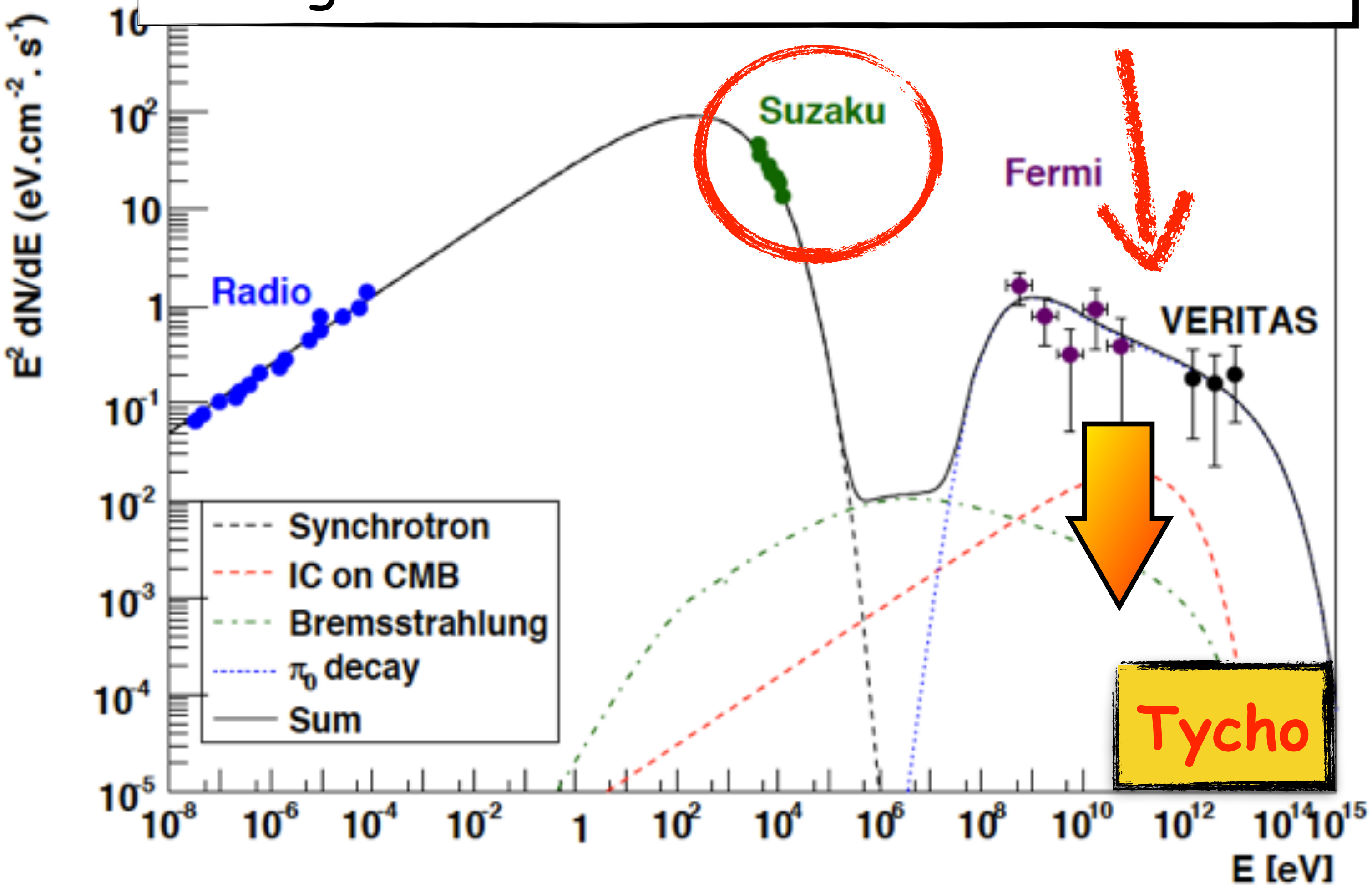
Young/mid aged SNRs: hadronic or leptonic?

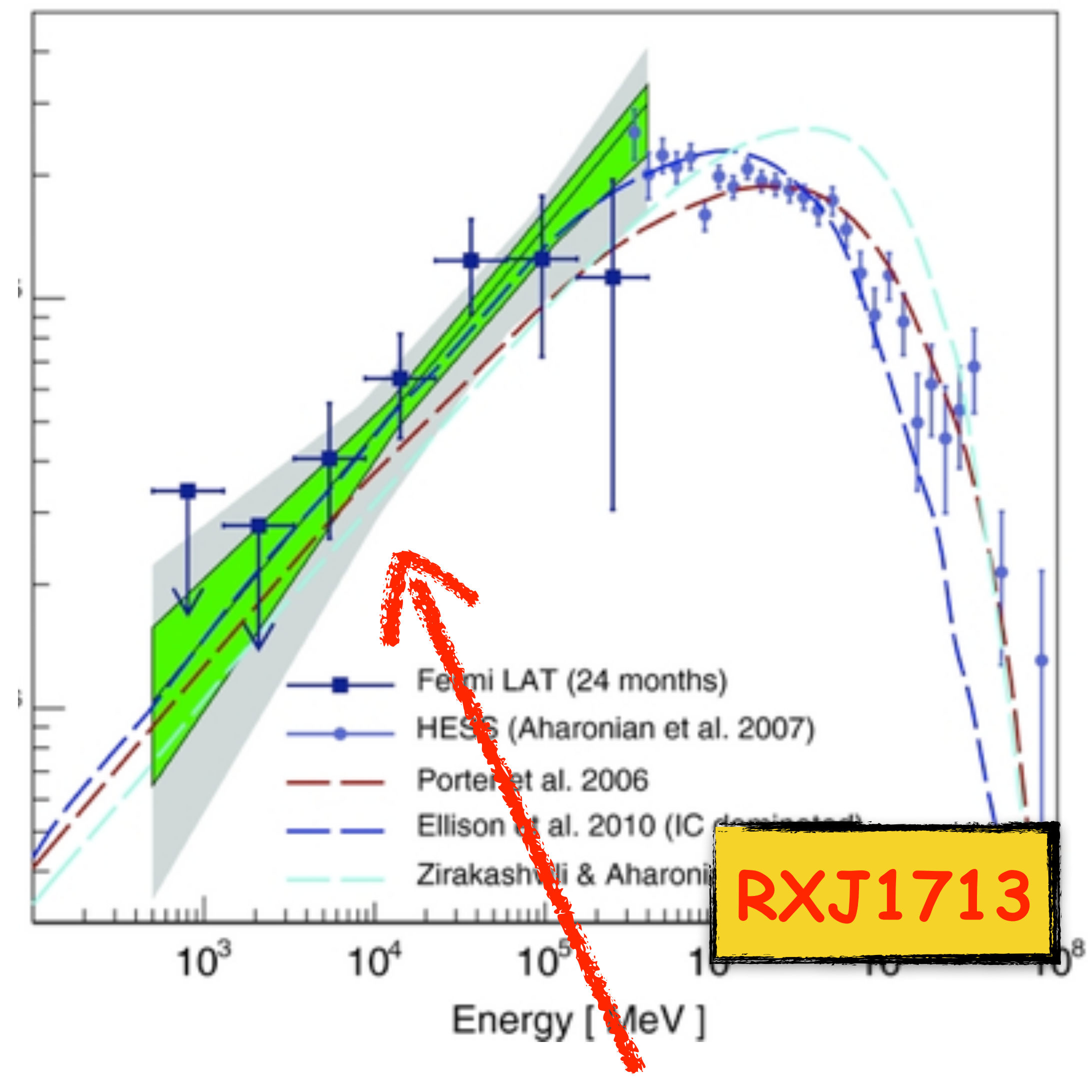
strong B-field -> low ICS -> soft hadronic



Young/mid aged SNRs: hadronic or leptonic?

strong B-field -> low ICS -> **soft hadronic**





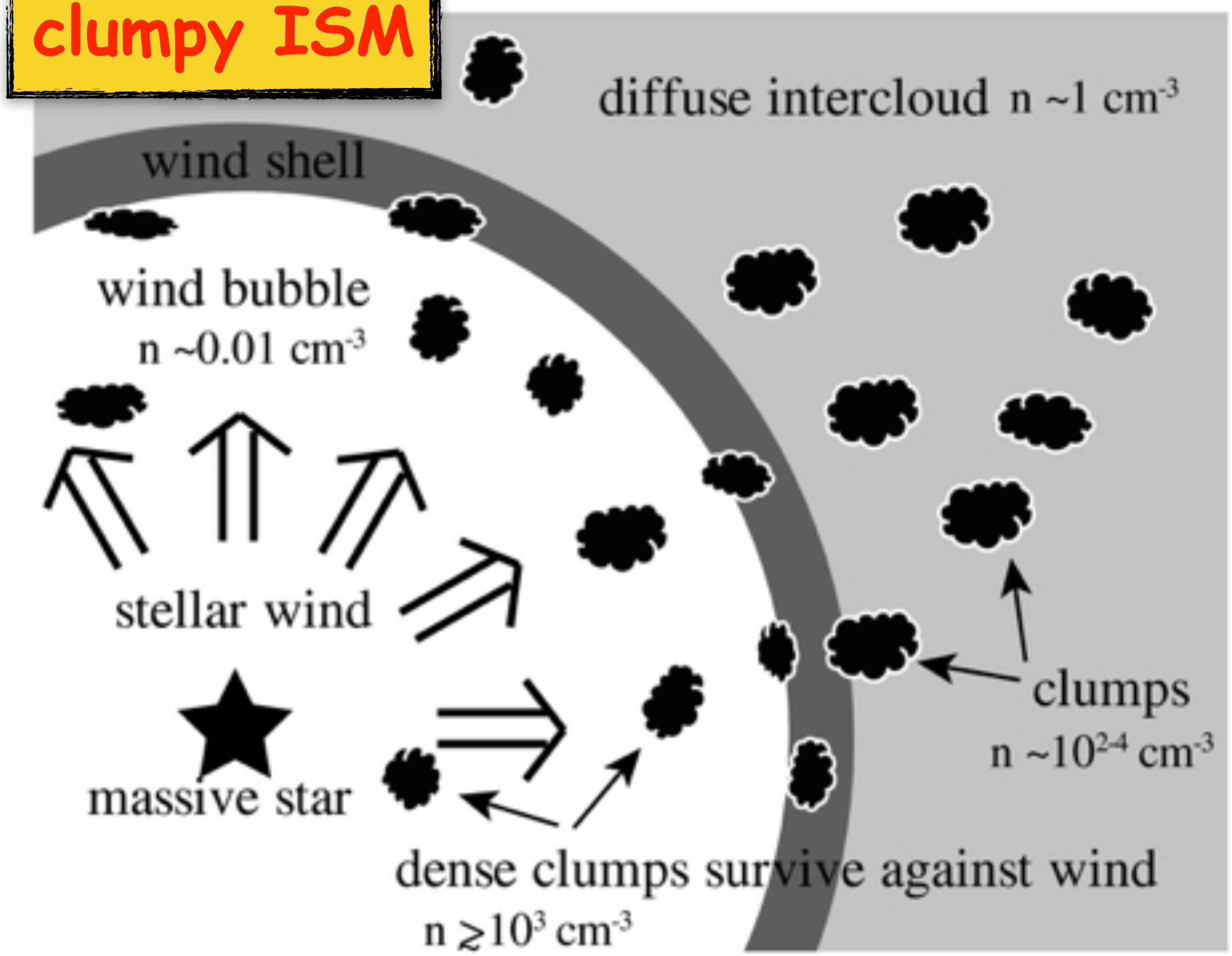
weak B-field -> uncooled e$^-$ spectrum -> **hard leptonic***

* very low level of thermal X-rays from RXJ1713 -> leptonic? (Ellison+ 2010)

Soft/hadronic & hard/leptonic?

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

clumpy ISM



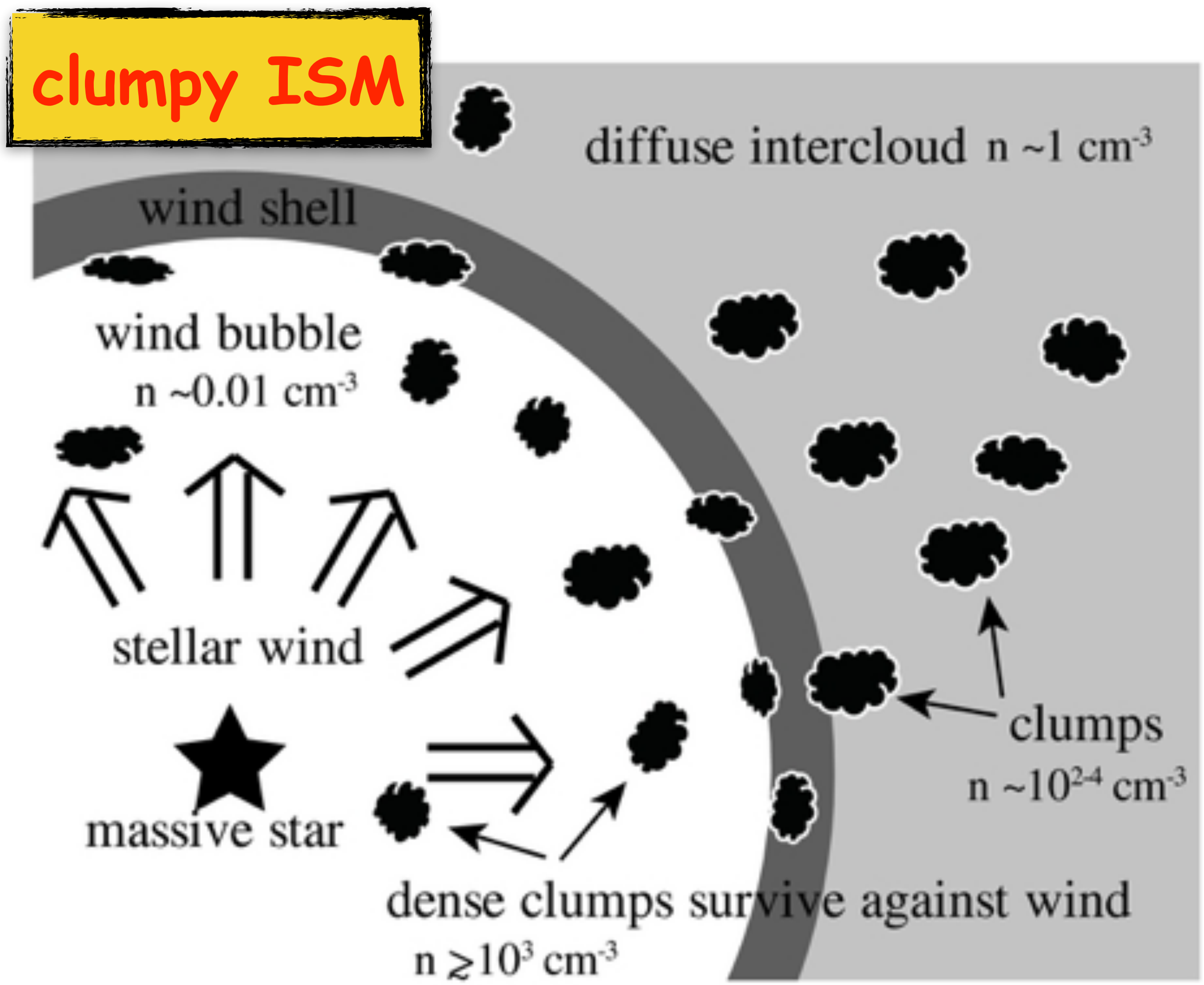
stellar wind sweeps the gas and creates a cavity

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

no thermal X-rays!

Soft/hadronic & hard/leptonic?

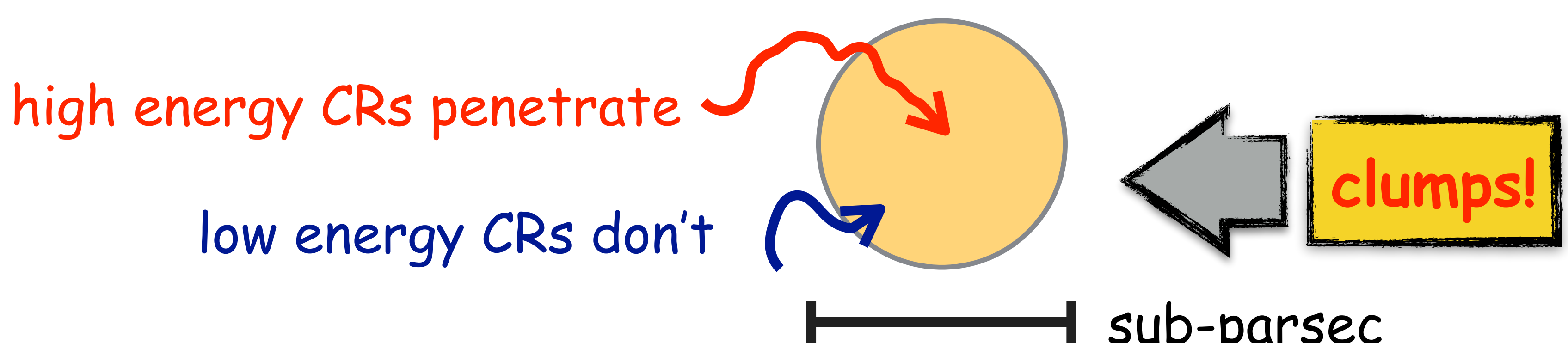
Zirakashvili & Aharonian 2010, Fukui+ 2012, Inoue+ 2012, Gabici & Aharonian 2014



stellar wind sweeps the gas and creates a cavity

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

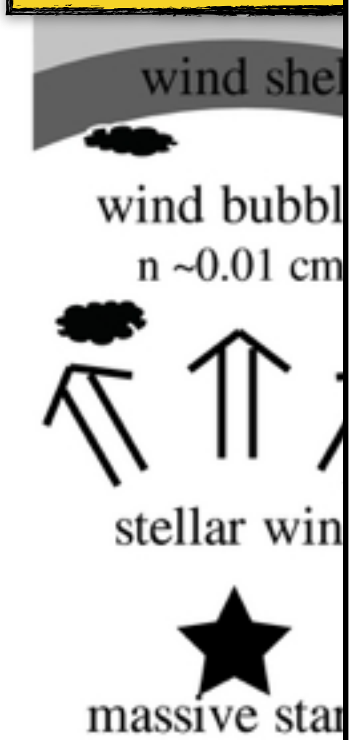
no thermal X-rays!

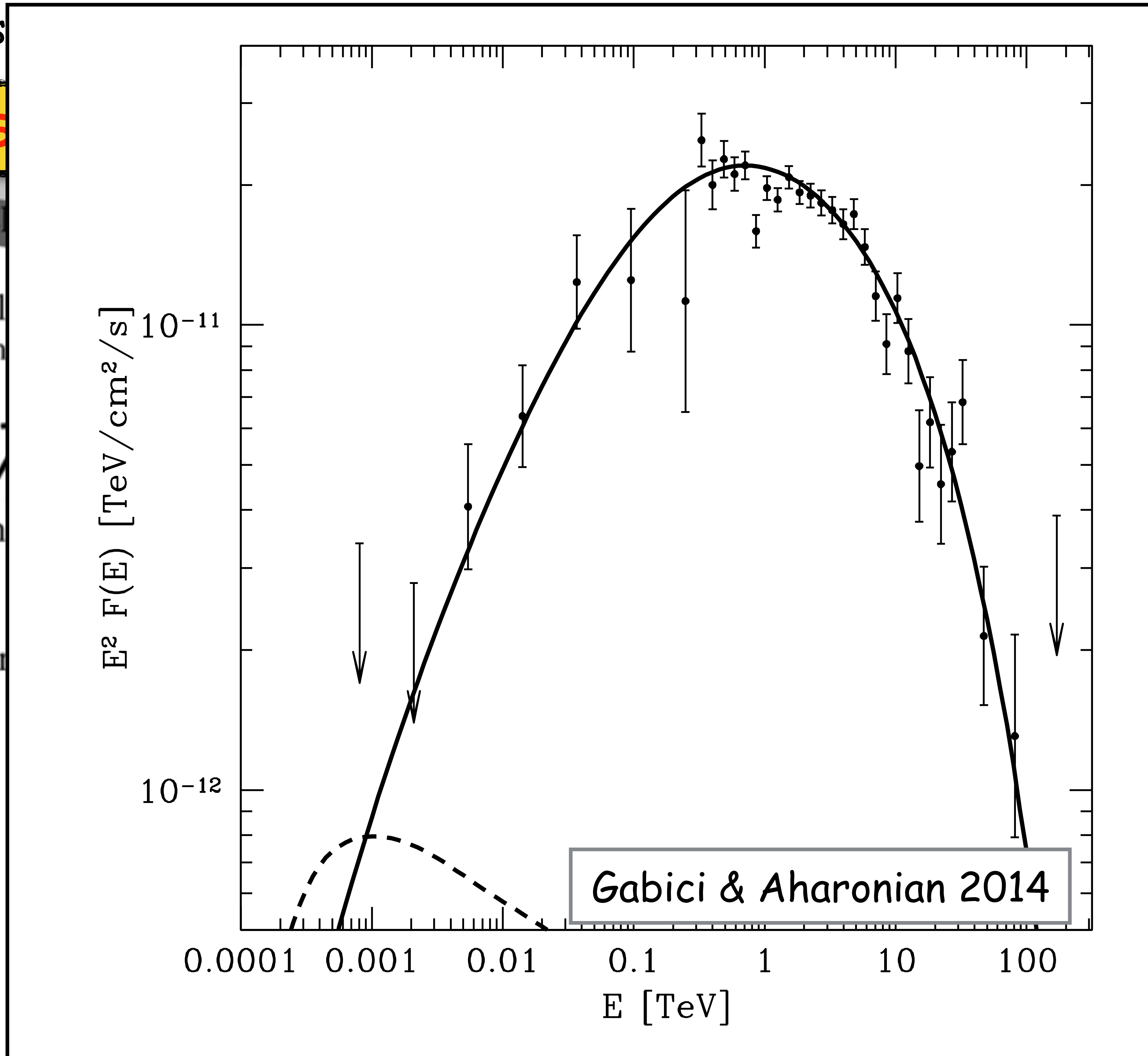


Soft/hadronic & hard/leptonic?

Zirakas ... aronian 2014

clumpy IS





s the gas and
cavity

unshocked) both
the SNR shock

X-rays!

os!

Soft/hadronic & hard/leptonic?

Zirakas

clumpy IS

wind shel

wind bubbl
n ~0.01 cm

stellar win

massive sta

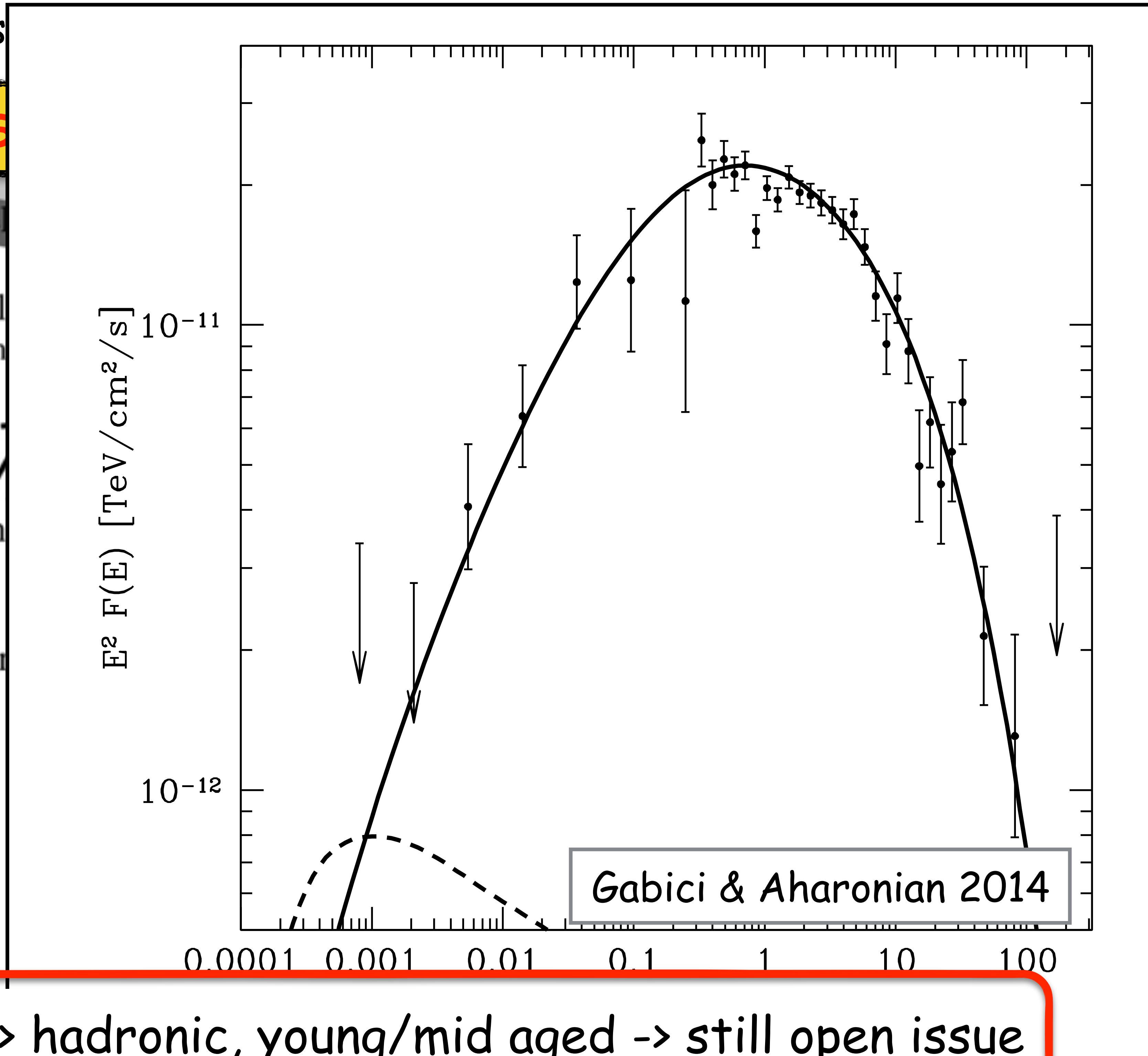
aronian 2014

s the gas and
avity

unshocked) both
the SNR shock

X-rays!

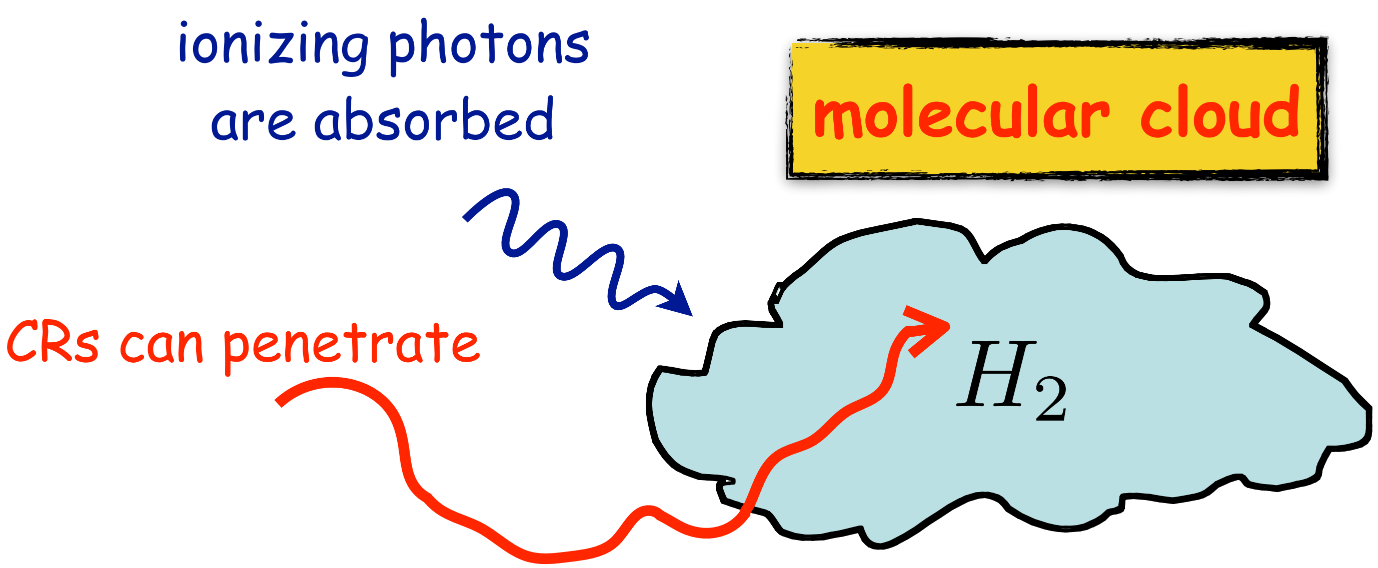
s!



old SNRs -> hadronic, young/mid aged -> still open issue

The MeV domain: CR ionization

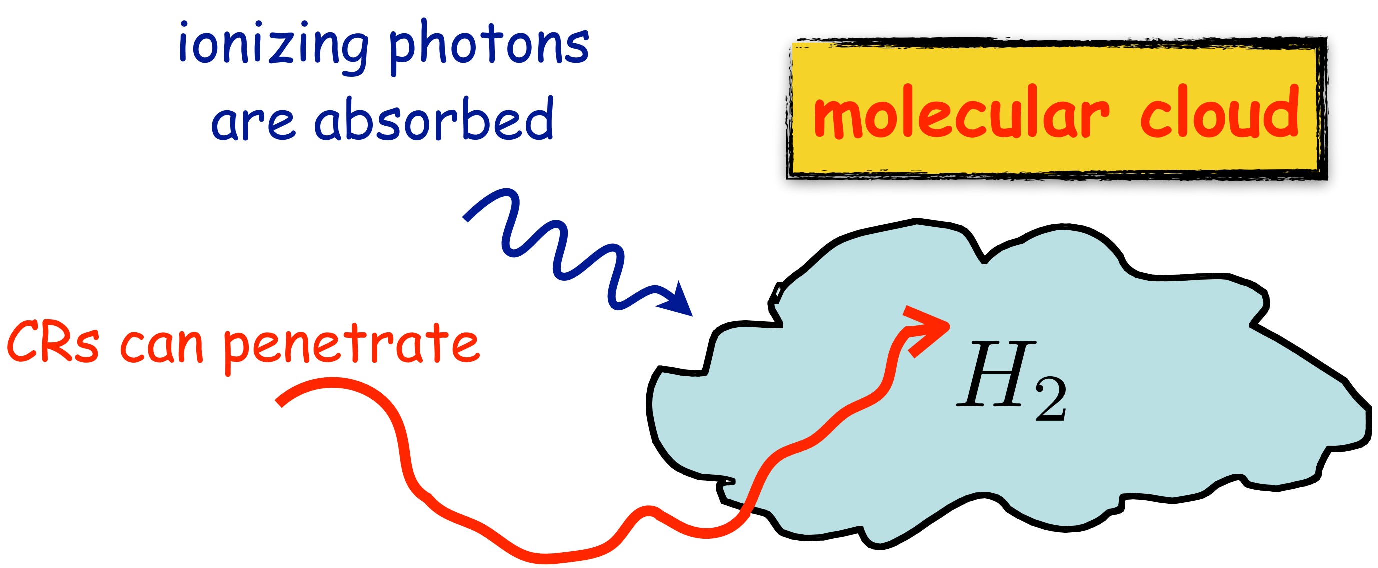
(see SG & Montmerle 2015, Padovani+ 2009 for recent reviews)



$$H_2 + CR \longrightarrow H_2^+ + e^-$$

The MeV domain: CR ionization

(see SG & Montmerle 2015, Padovani+ 2009 for recent reviews)



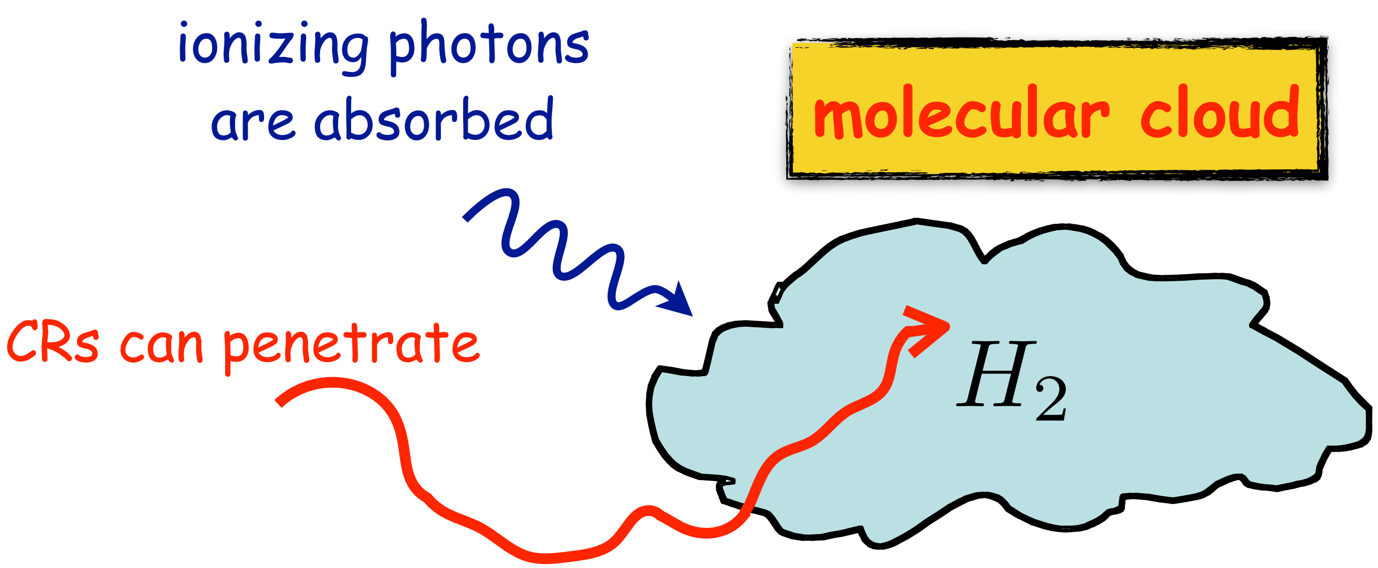
$$H_2 + CR \longrightarrow H_2^+ + e^-$$

chemistry

$$H_3^+, HCO^+, DCO^+ \ldots$$

The MeV domain: CR ionization

(see SG & Montmerle 2015, Padovani+ 2009 for recent reviews)



$$H_2 + CR \longrightarrow H_2^+ + e^-$$

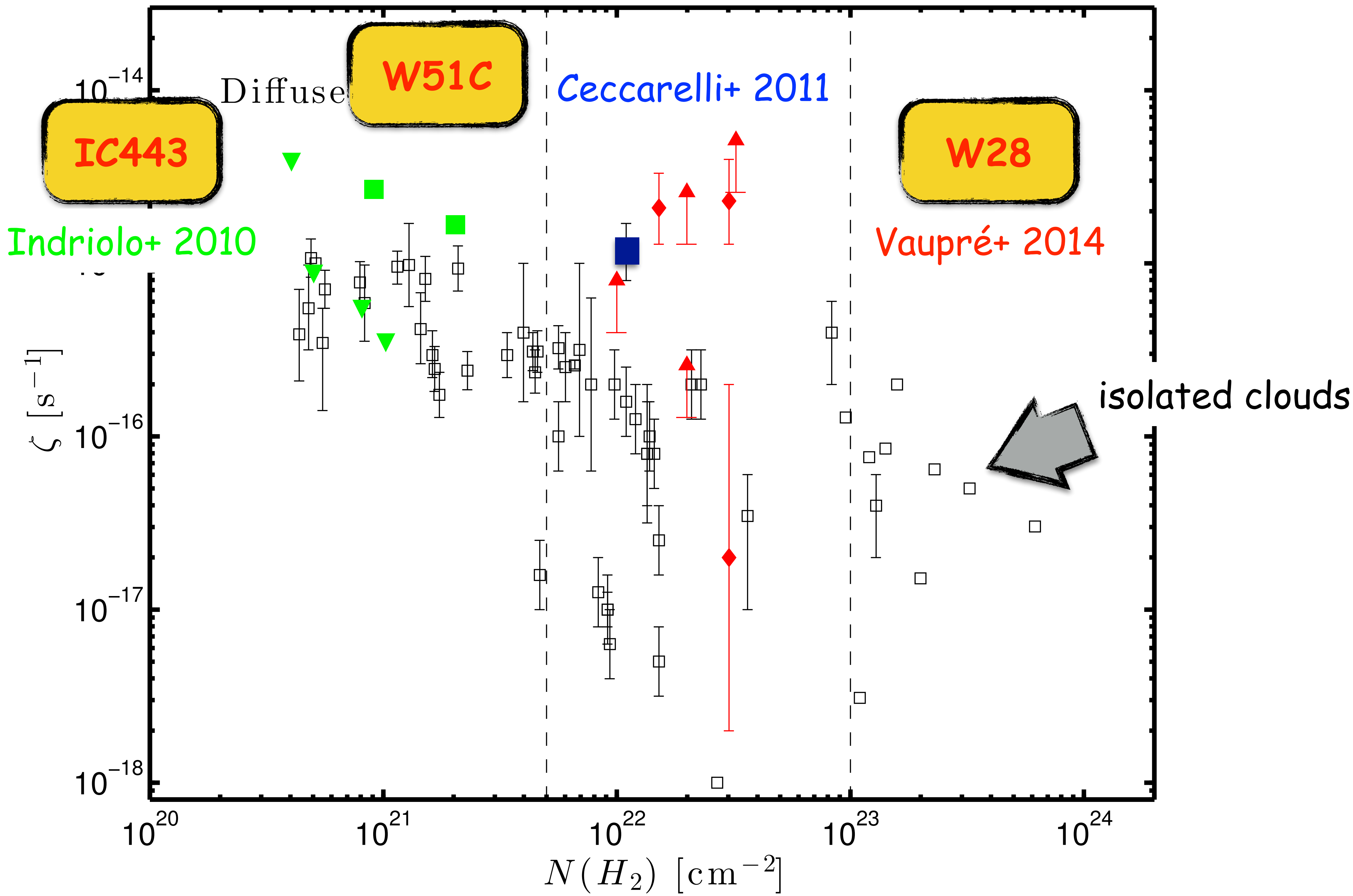
chemistry

$$H_3^+, HCO^+, DCO^+ \ldots$$

see e.g. McCall+, Indriolo+, Ceccarelli+, Vaupré+ ...

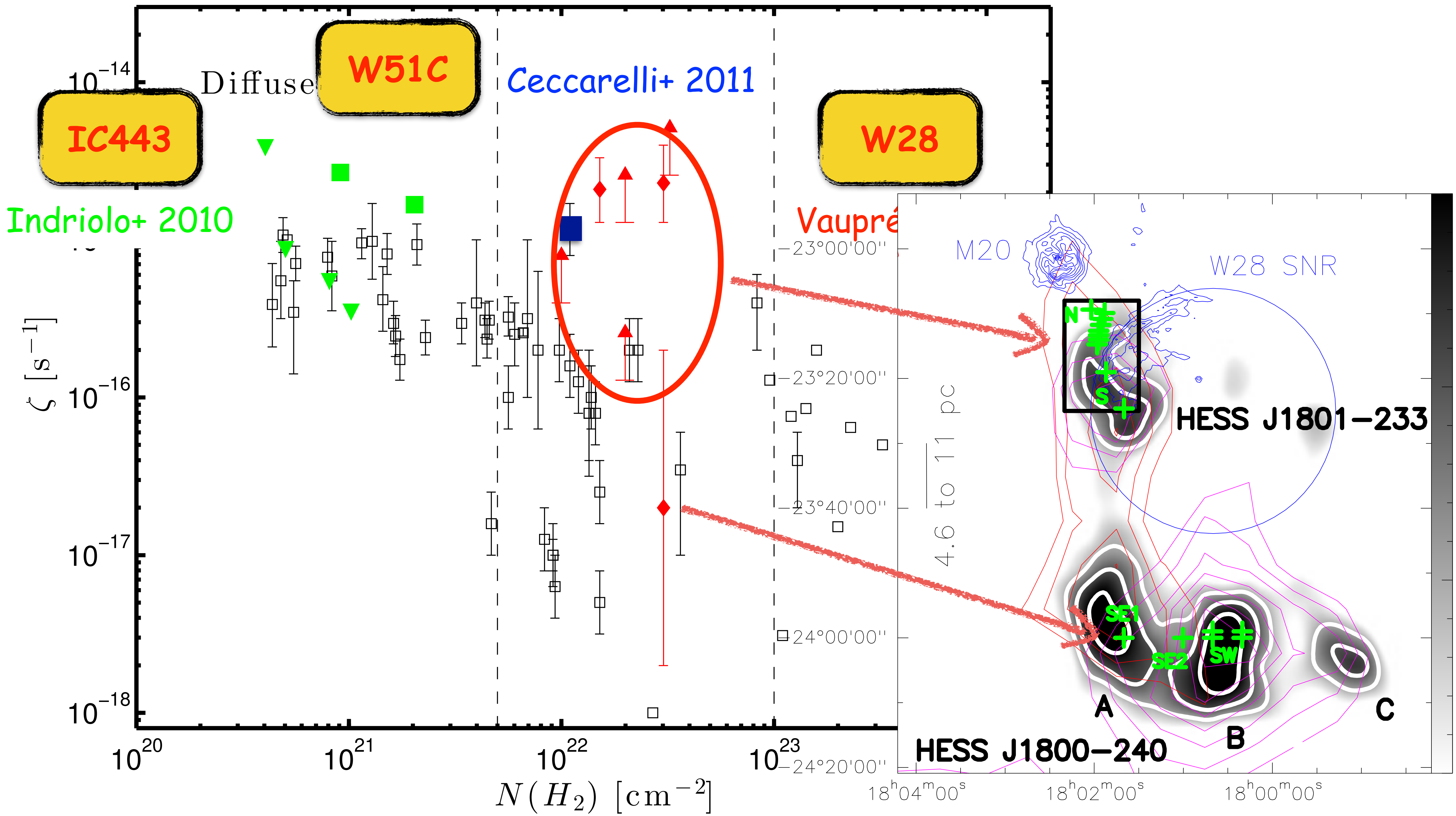
SuperNova Remnants & MeV cosmic rays

(for a review see SG & Montmerle 2015)



SuperNova Remnants & MeV cosmic rays

(for a review see SG & Montmerle 2015)



Intro | SNRs | Gal Centre | SNRs? | Conclusions

SuperNova Remnants & MeV cosmic rays