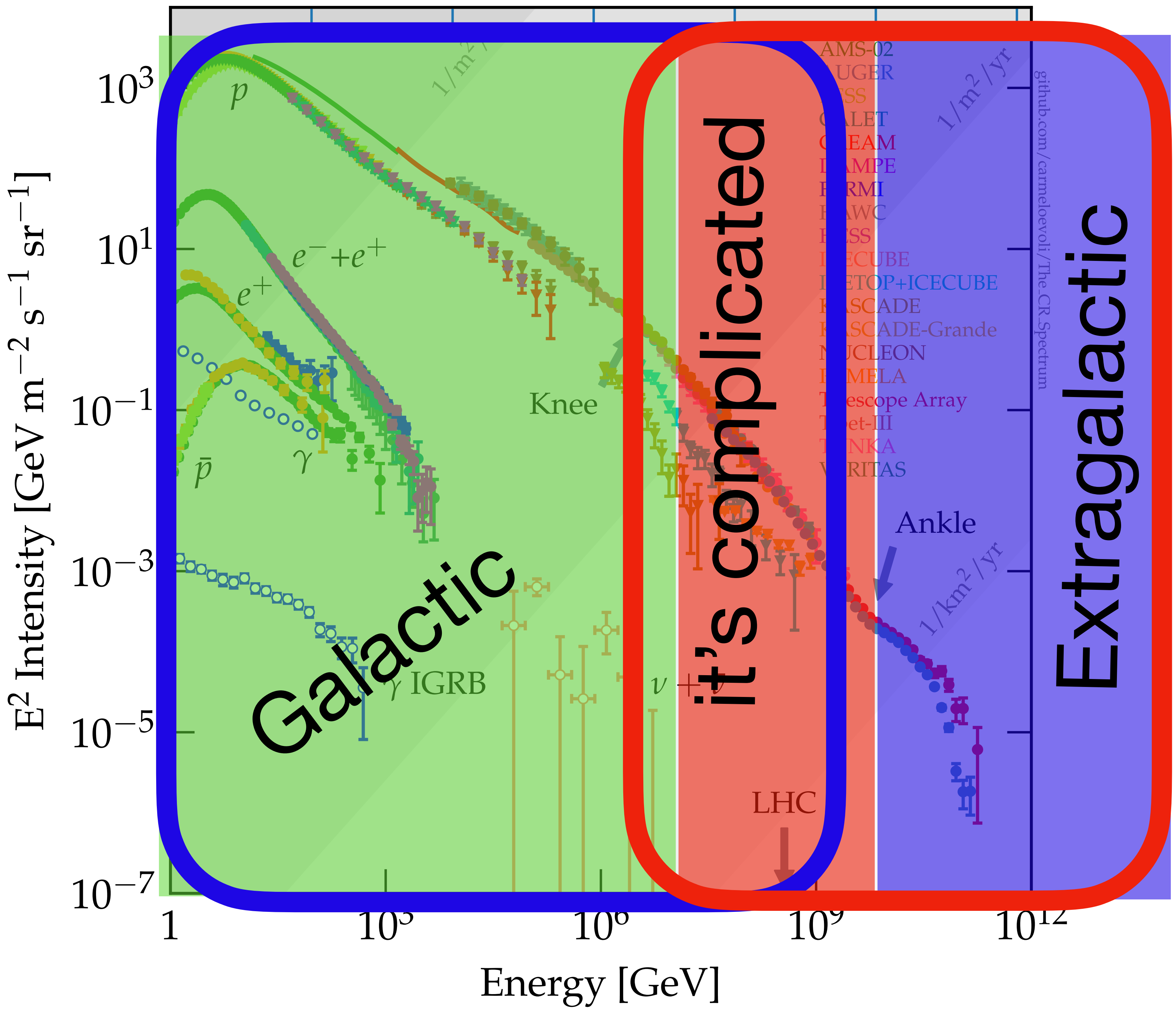
# The origin of cosmic rays (and gamma-ray astronomy)

**Pierre Cristofari**
pierre.cristofari@obspm.fr

**Journée du LUTH**
**7 Décembre 2022**

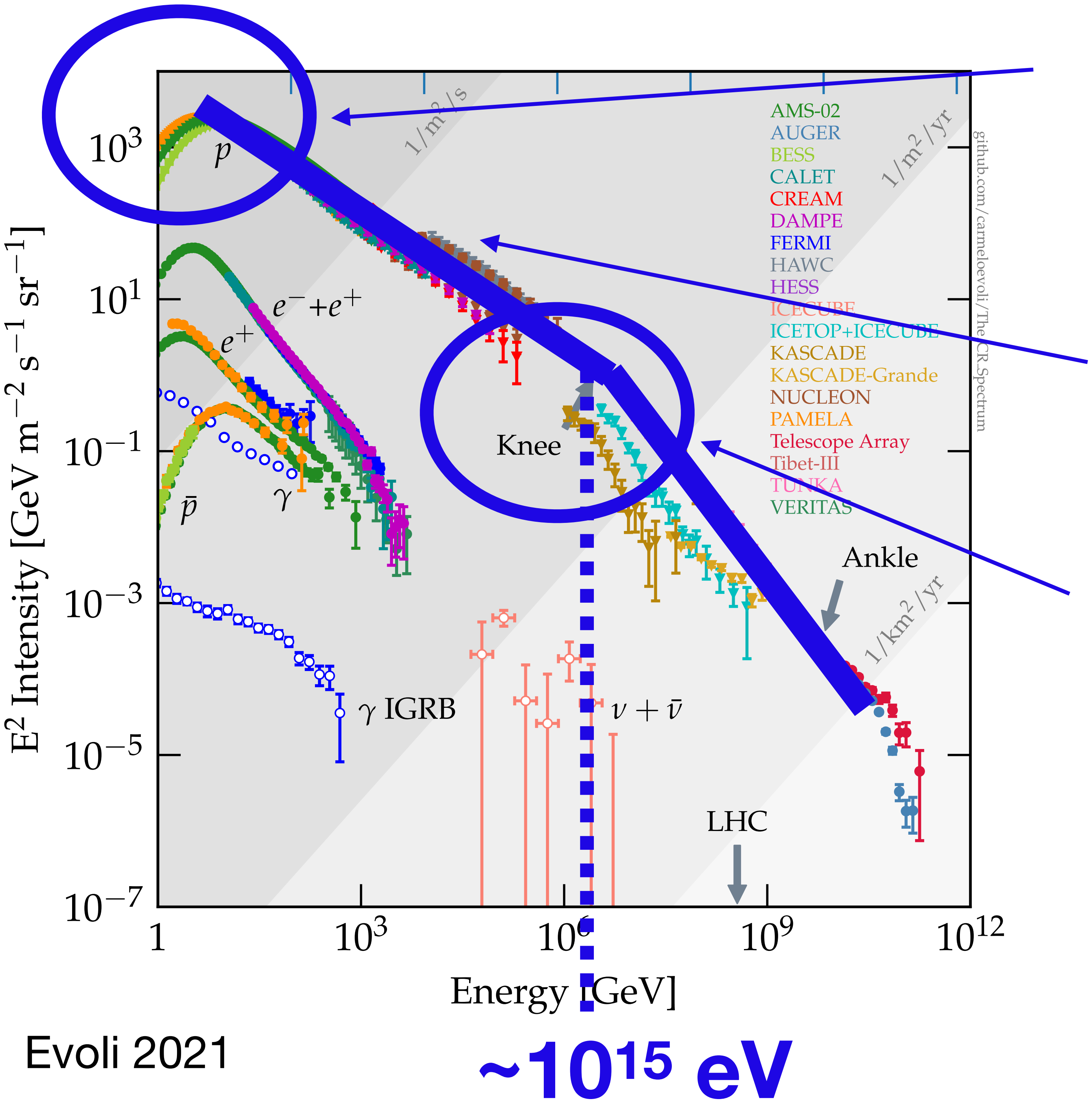
# The origin of cosmic rays




Evoli 2021

# The origin of cosmic rays

**Minimal requirements on proton sources:**




1. Sustain the total CR power ($1\ ev/cm^3$) ~ magnetic field ~thermal gas

2. Produce correct slope

3. Pevatrons (PeV= $10^{15}$ eV)

Evoli 2021

# Sources of Galactic cosmic rays



SWGO
The Southern Wide-field Gamma-ray Observatory

Key science project: the search, identification and characterization of pevatrons

CR ISM

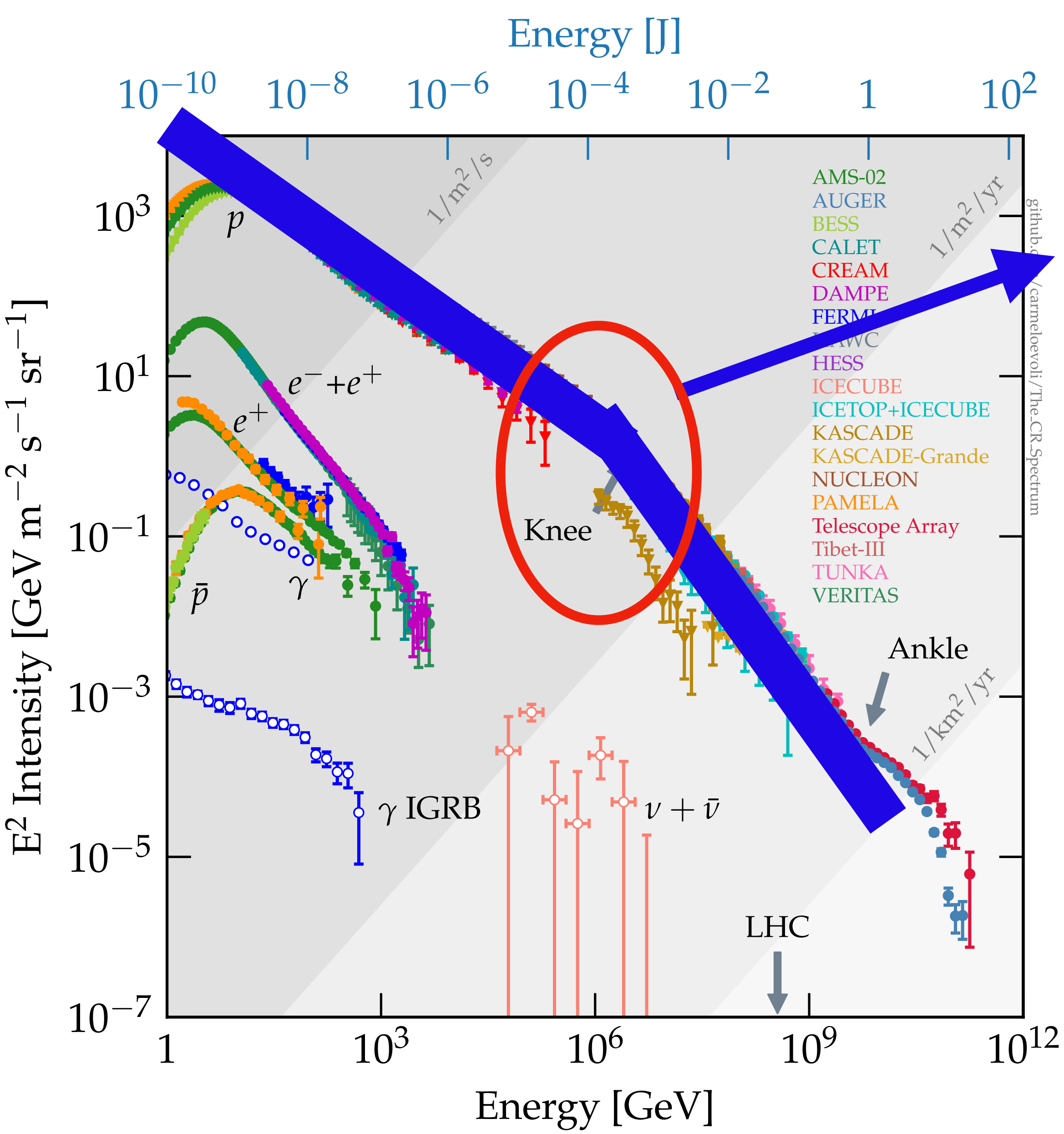
$$p + p \to p + p + \pi^0$$

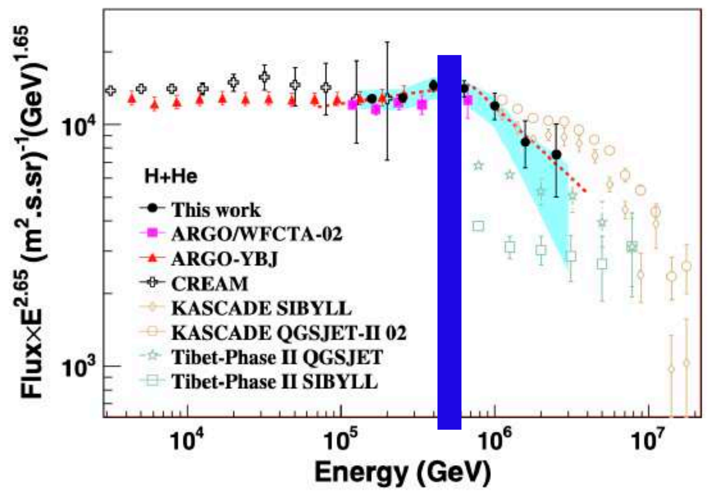
$$\pi^0 \to \gamma + \gamma$$

$$E_\gamma \sim \frac{E_p}{10}$$

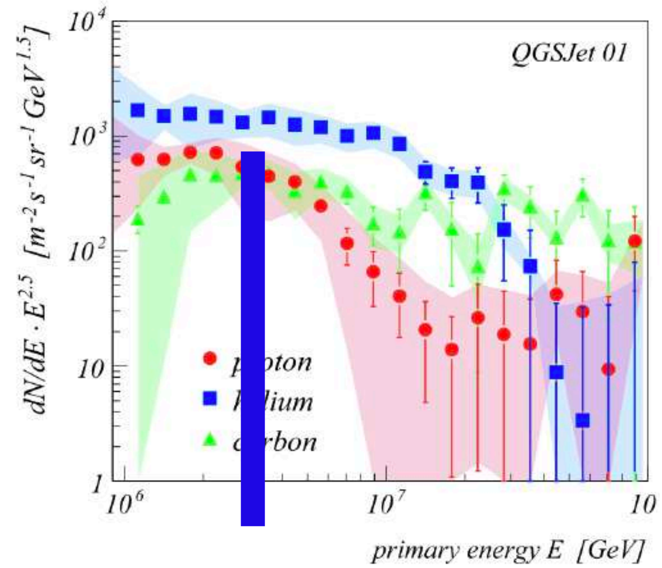
$$E_\gamma = 100 \text{ TeV} \to E_p = 1 \text{ PeV}$$

# Pevatrons




ARGO-YBJ
~700 TeV
Bartoli et al. 2015




KASCADE
~3-4 PeV
Antoni et al. 2005

**Source of Galactic CRs must accelerate protons up to the knee!**

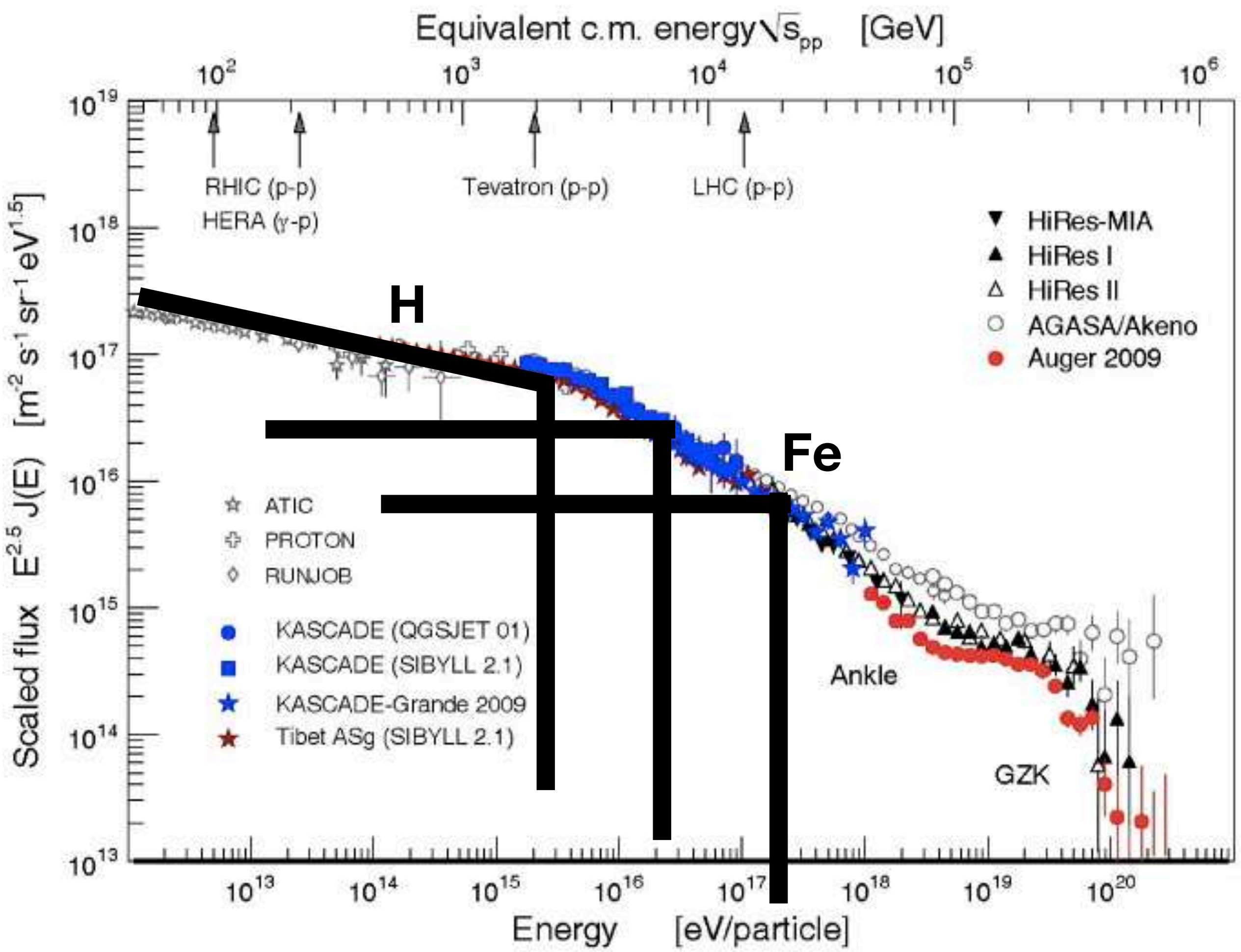
+ Z dependent knee

# Pevatrons

**MORE PRECISELY**

**Source of Galactic CRs must accelerate up to AT LEAST the knee!**

**~100 PeV**



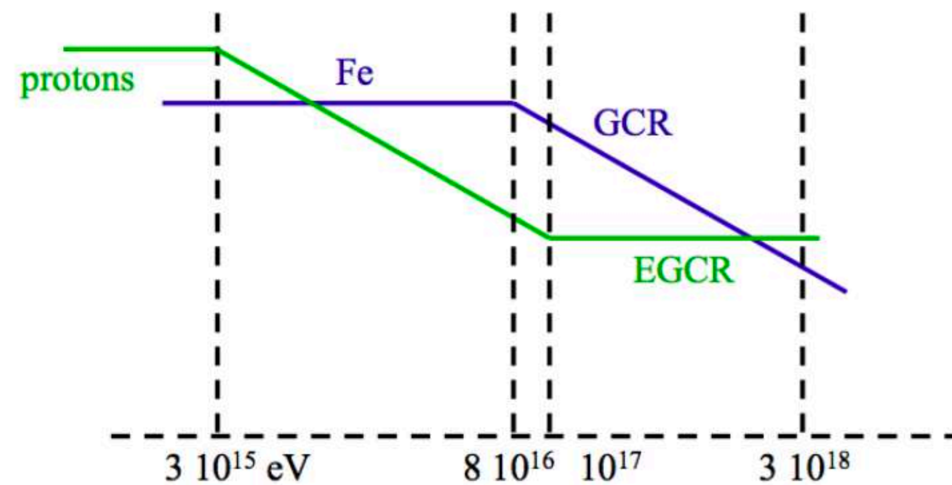




Figure 4: Sketch of the GCR/EGCR transition, with the proton and Fe components indicated (respectively in green and in blue on the color version of the figure). In ordinate, the CR flux is multiplied by $E^x$, where $x$ is the logarithmic slope of the CR spectrum below the knee. (See also Fig. 3).

Z dependent knee ⟷ DSA depends on rigidity

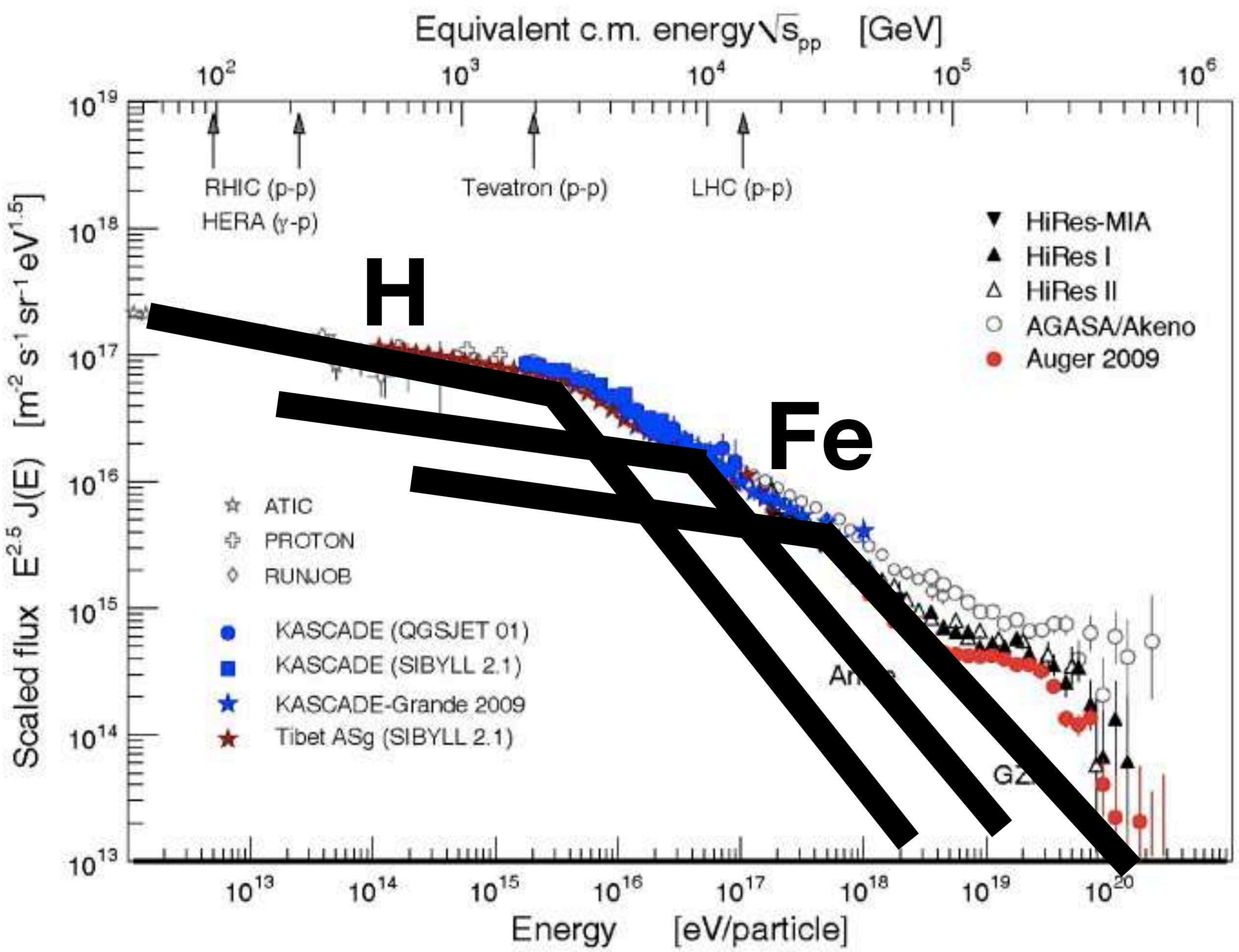
Hillas 2006, Parizot 2014

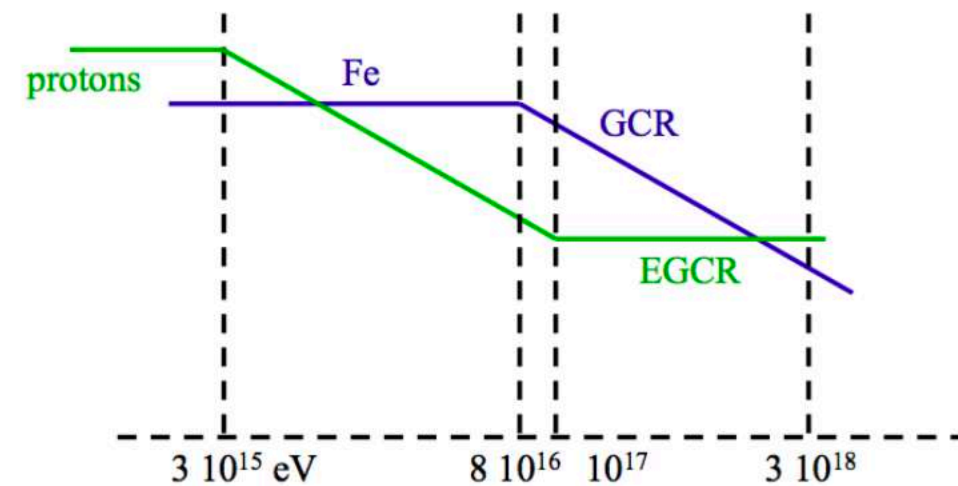
# Pevatrons

## MORE PRECISELY

**Source of Galactic CRs must accelerate up to AT LEAST the knee!**

**~100 PeV**

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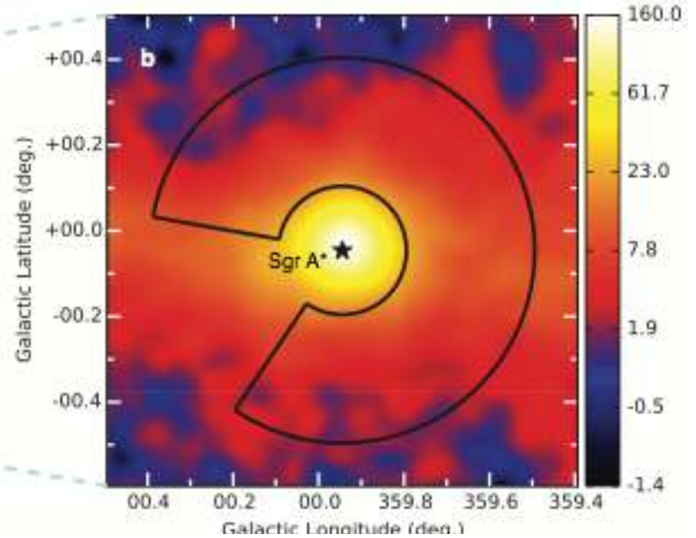
**Smooth transition from Galactic to extraGalactic**

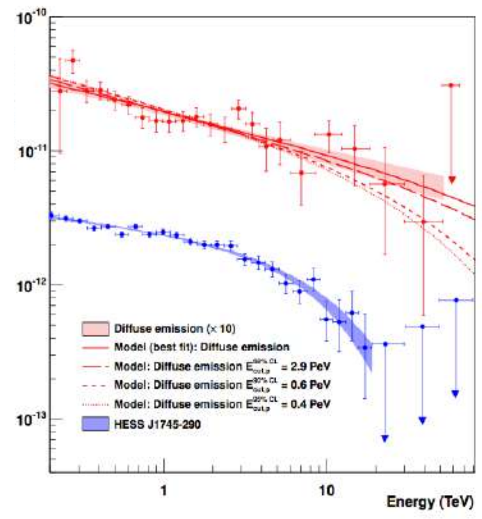
Hillas 2006, Parizot 2014

# What sources can be (proton) pevatrons?

- ★ Sufficient amount of PeV protons?
- ★ « Hard-enough » spectra above $10^{15}$ eV?
- ★ What sources can be (super)pevatrons? $10^{16}$ $10^{17}$ eV

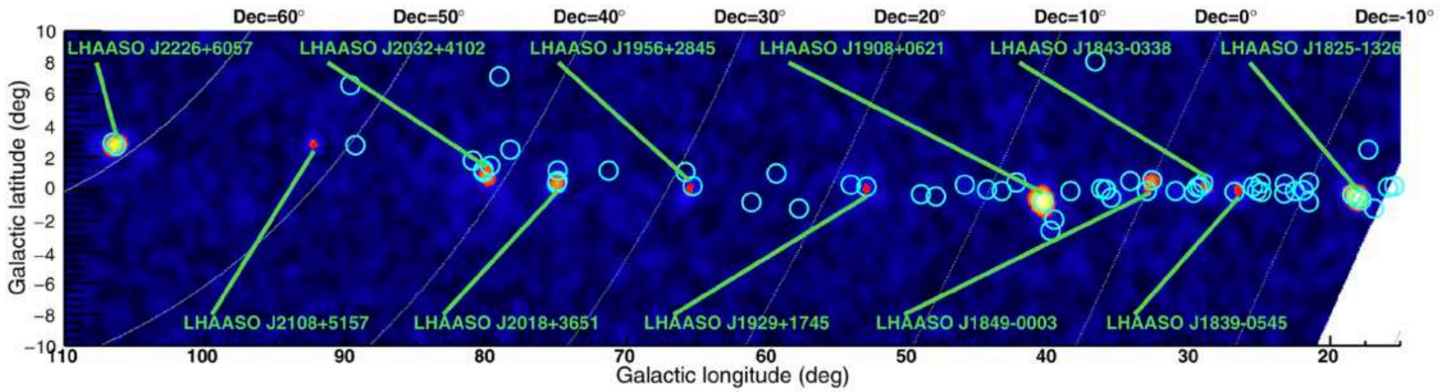
## HESS J1745-290




HESS collab. 2016

## LHAASO 12 Galactic pevatrons



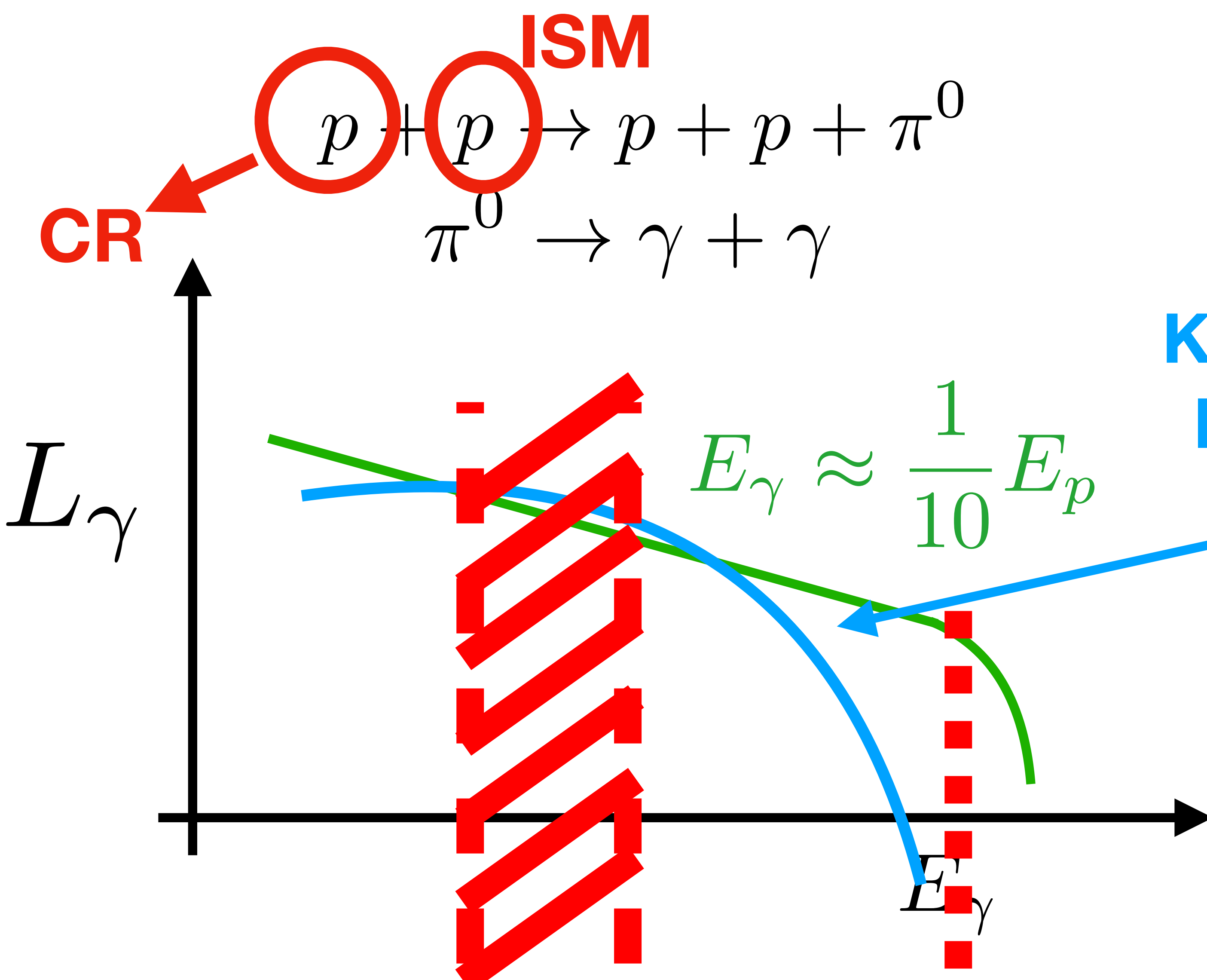

Cao et al. 2021

**Not clear if hadronic or leptonic (probably leptonic for most sources)**

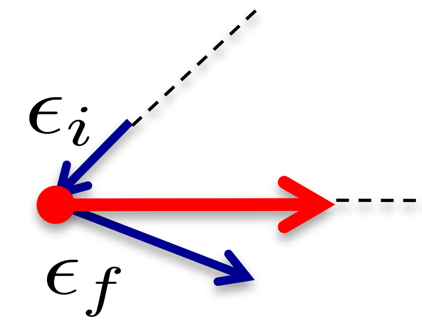
De Ona Whilhelmi et al. (2022)

# What sources can be (proton) pevatrons?

**Hadronic interactions :**
**Pion decay**




**Leptonic interactions :**
**Inverse Compton scattering**




**Klein-Nishina suppression:**
**Inefficient above >50 TeV**

**100 TeV gamma rays probe the acceleration of PeV protons (hadronic)**

De Ona Whilhelmi et al. (2022)

# What sources can be (proton) pevatrons?

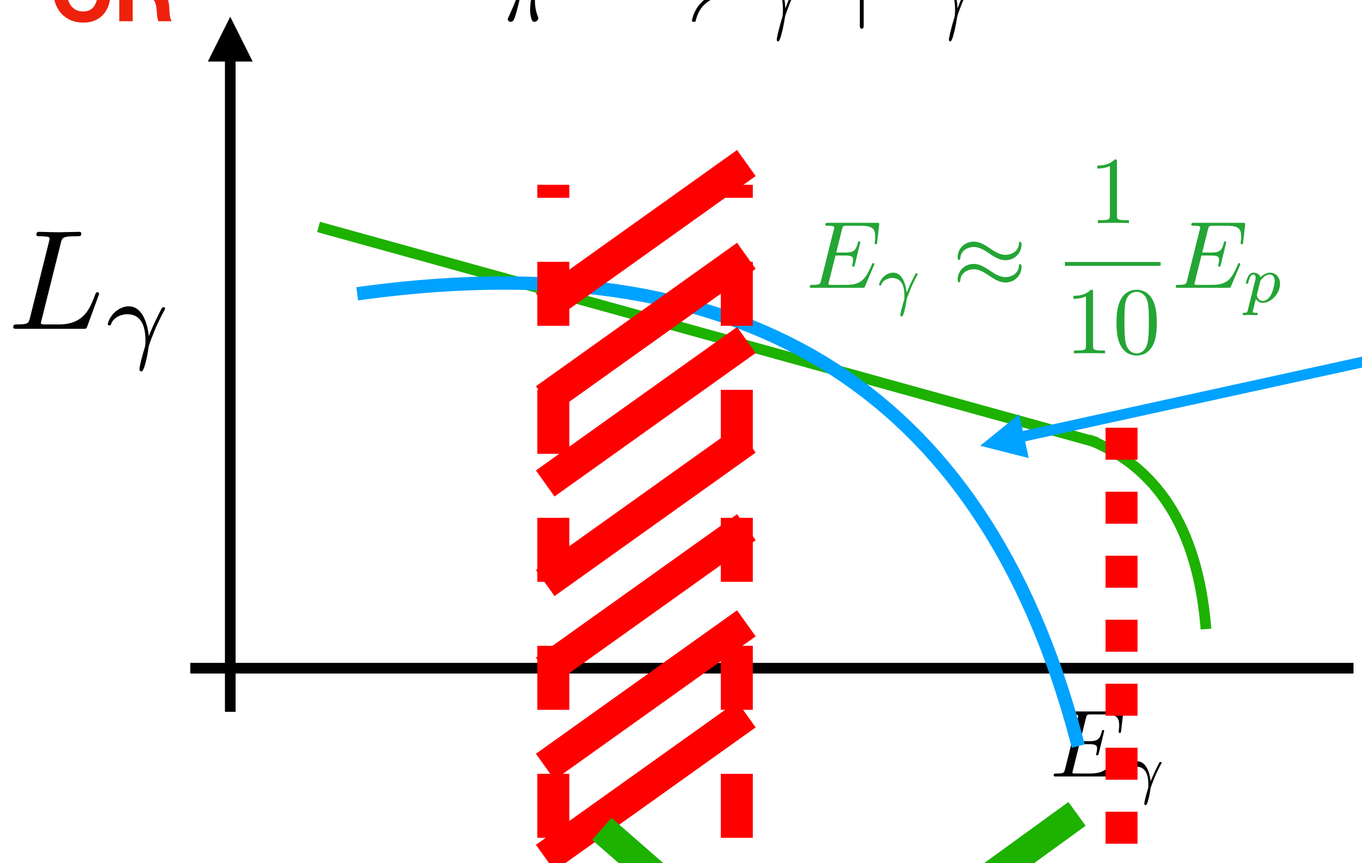
## Hadronic interactions : Pion decay

ISM

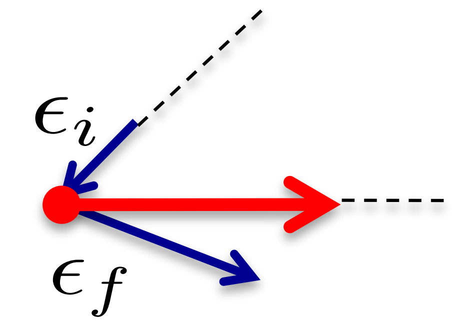
CR

$$p + p \rightarrow p + p + \pi^0$$

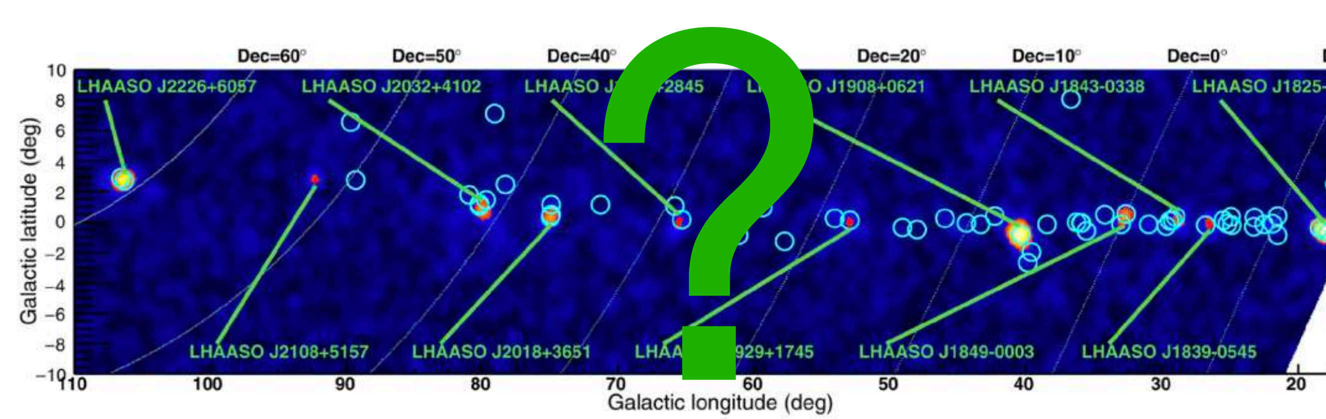
$$\pi^0 \rightarrow \gamma + \gamma$$




## Leptonic interactions : Inverse Compton scattering




**Klein-Nishina suppression: Inefficient above >50 TeV**

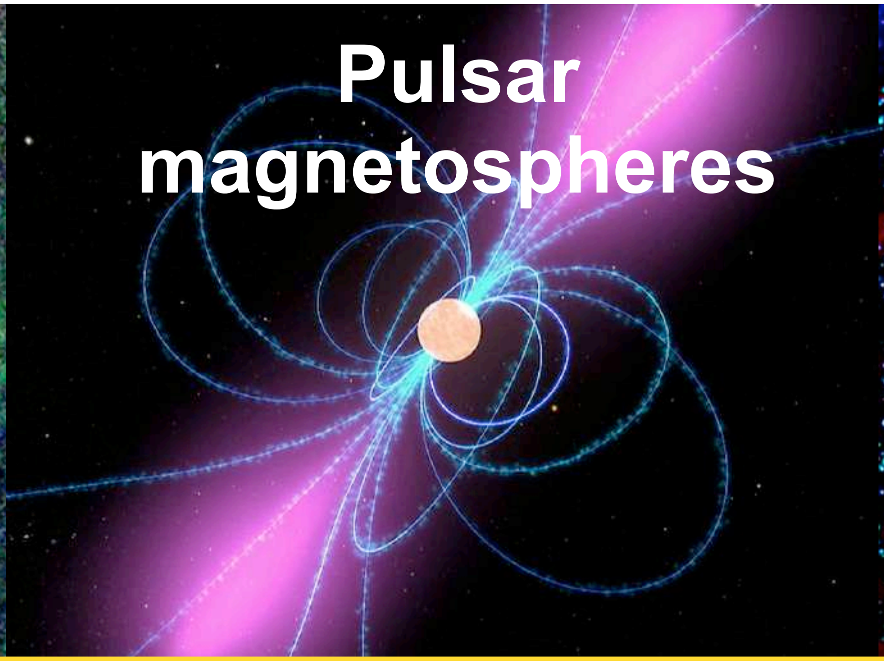



**100 TeV gamma rays probe the acceleration of PeV protons (hadronic)**

Vannoni et al. (2007), Brehaus et al. (2021)

De Ona Whilhelmi et al. (2022)

# What sources can be (proton) pevatrons?



022)
021)

Strong shocks: Diffusive shock acceleration, acceleration up to very high energy

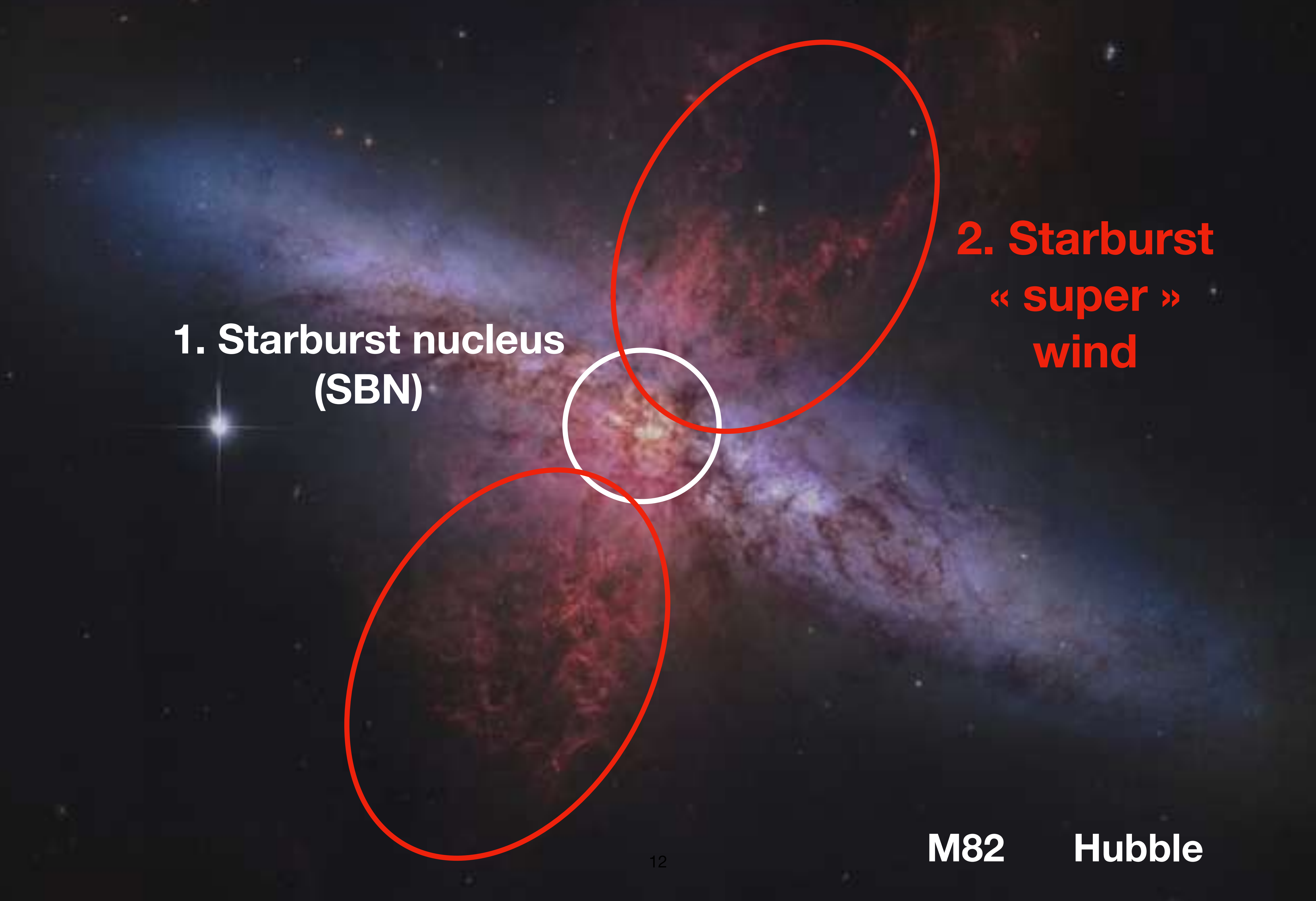
Cristofari 2021 « The hunt for pevatrons: the case of supernova remnants »


Zirakashvili et al. (2008)
Bykov et al. (2018)

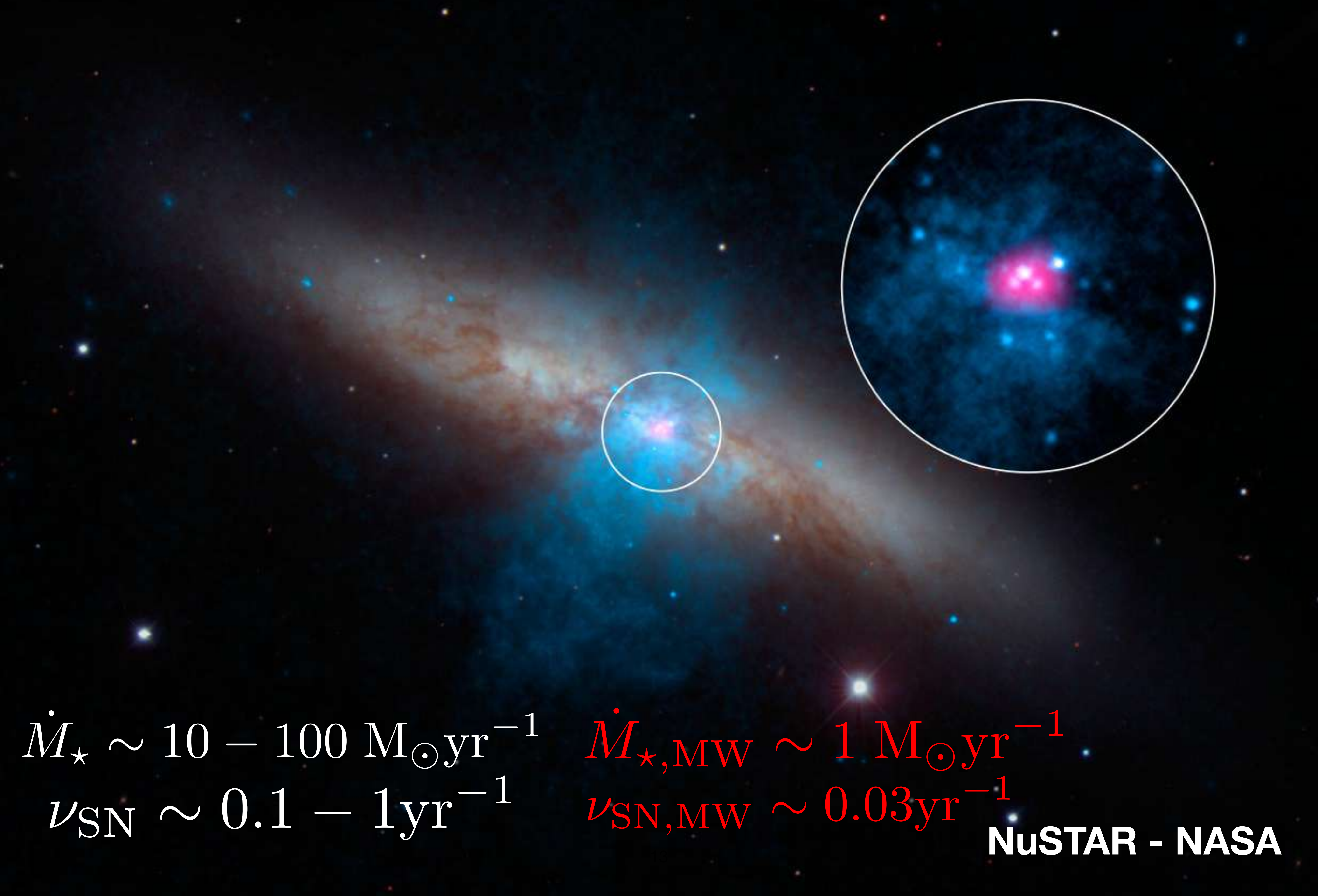
Bykov et al. (2022)


Bell et al. (2004, 2014)

# Science with CTA: Starburst galaxies



# Science with CTA: Starburst galaxies

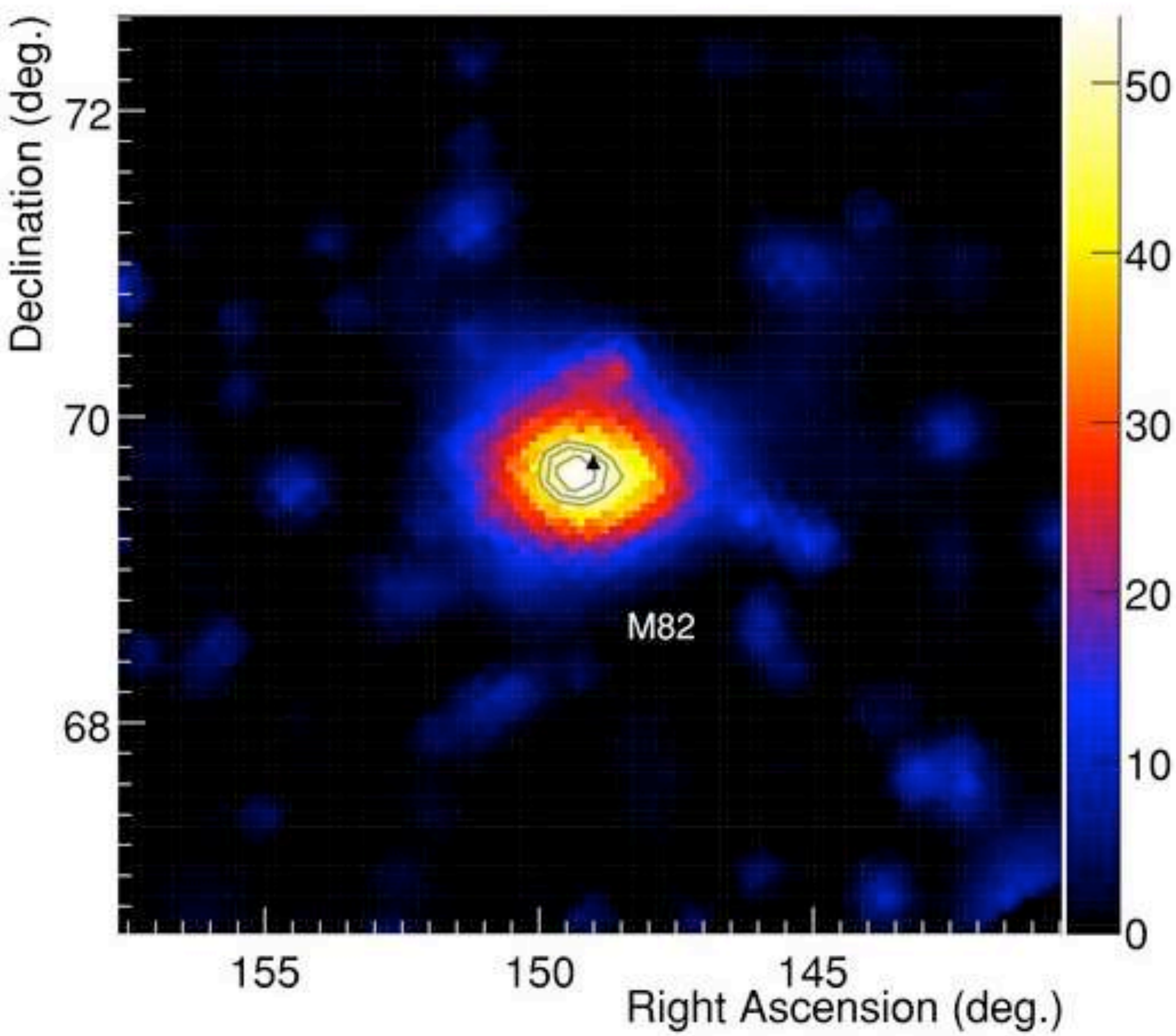


$\dot{M}_\star \sim 10 - 100 \ \mathrm{M_\odot yr^{-1}}$ $\quad$ $\dot{M}_{\star,\mathrm{MW}} \sim 1 \ \mathrm{M_\odot yr^{-1}}$

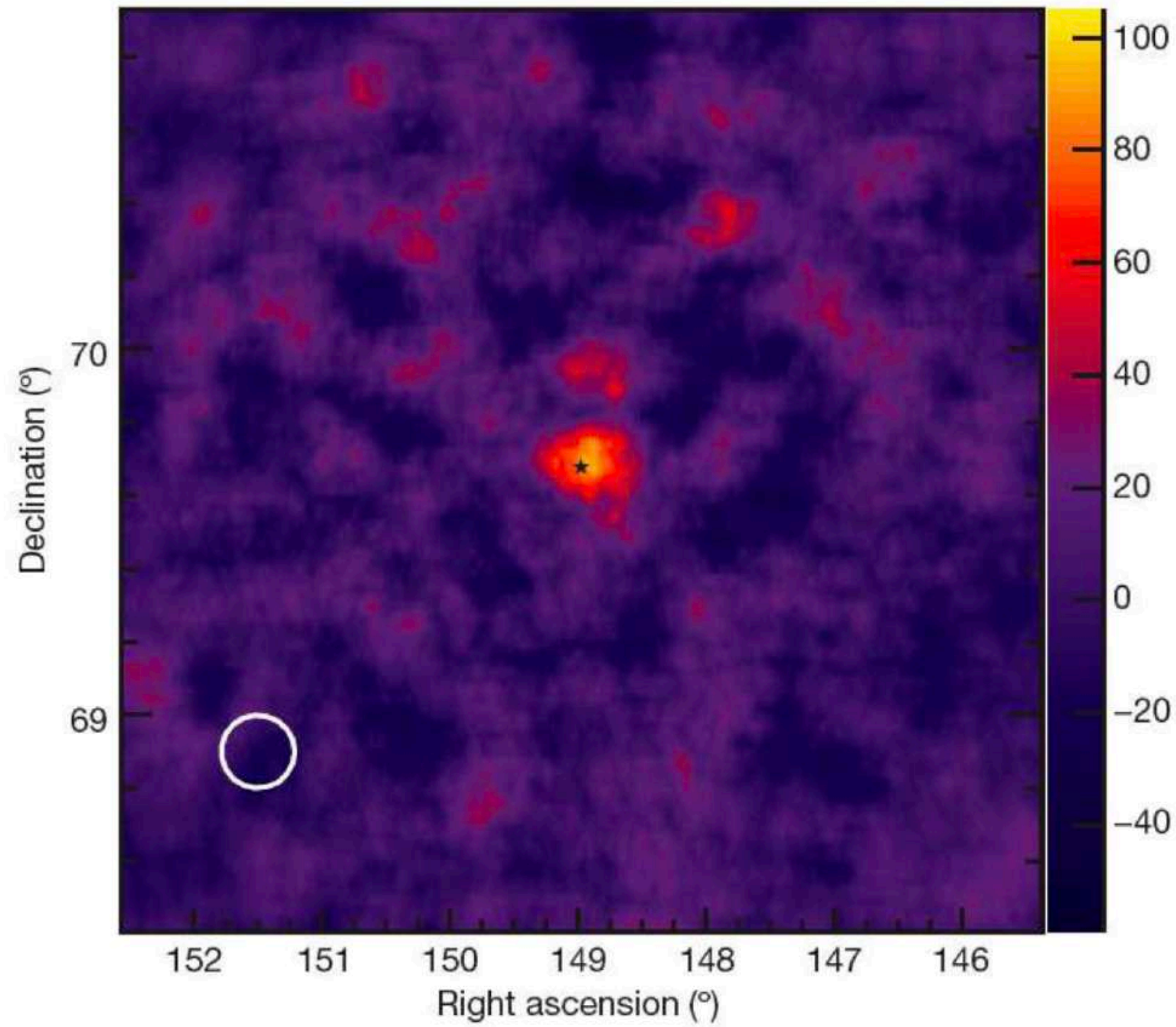
$\nu_{\mathrm{SN}} \sim 0.1 - 1 \mathrm{yr^{-1}}$ $\quad$ $\nu_{\mathrm{SN,MW}} \sim 0.03 \mathrm{yr^{-1}}$

NuSTAR - NASA

# Gamma rays from M82




Fermi-LAT(2009)

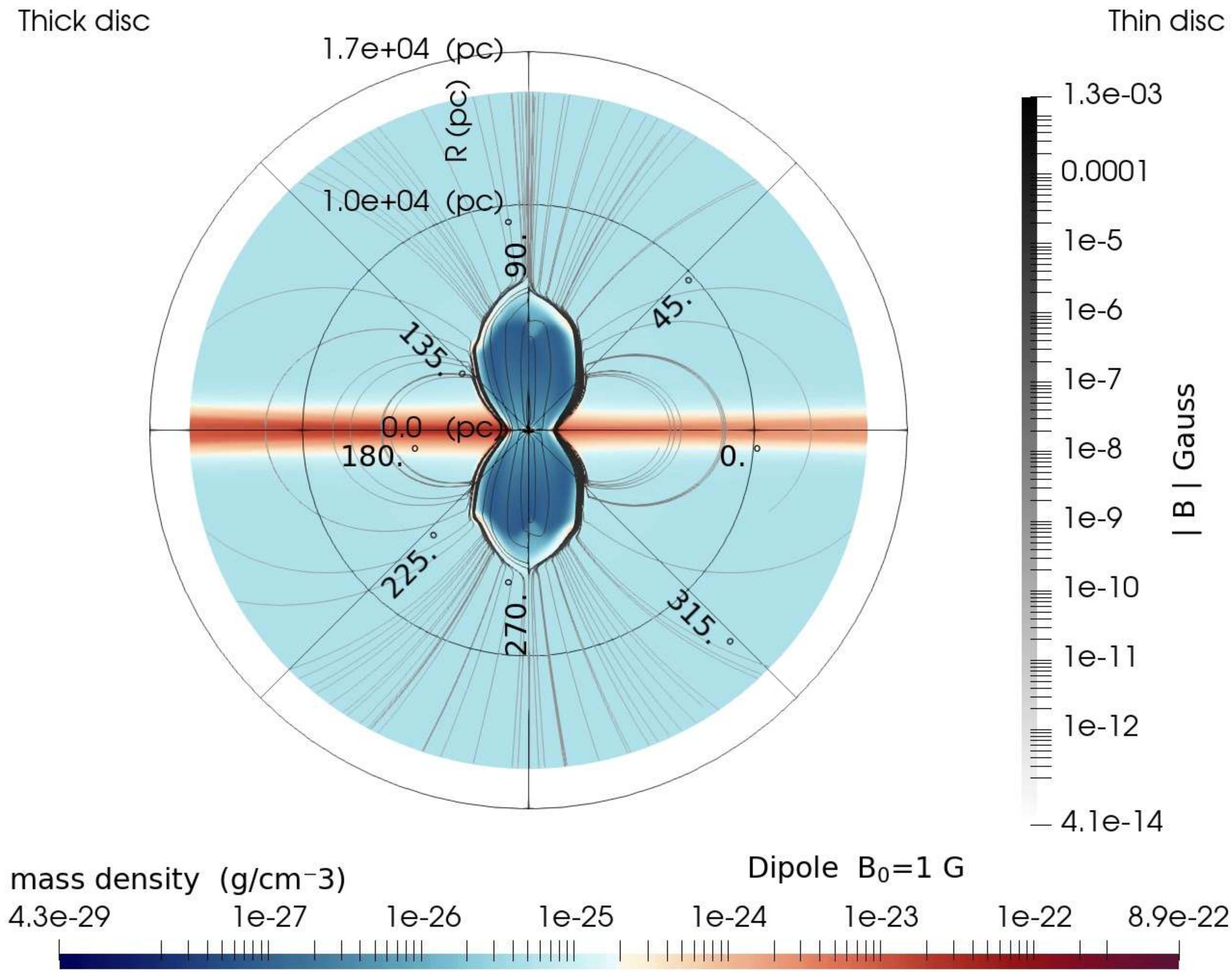



Veritas (2009)

Paglione et al. 1996, Torres et al. 2004, Persic et al. 2008, Rephaeli et al 2010, Lacki & Thompson 2013, Peretti et al. 2018,2020, 2021, Kornecki et al. 2021

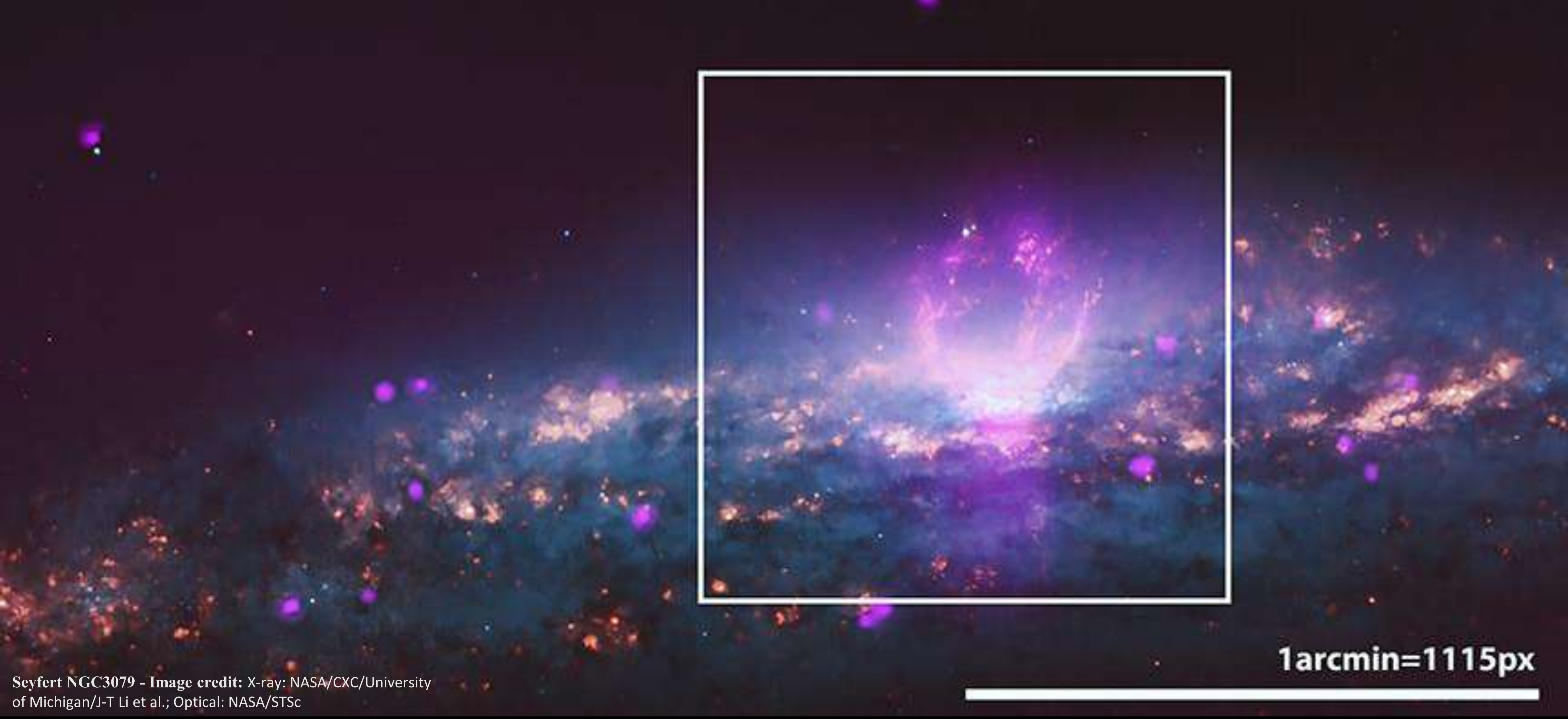
**Not resolved yet, could be with CTA!**

# Large scale structures of starburst galaxies

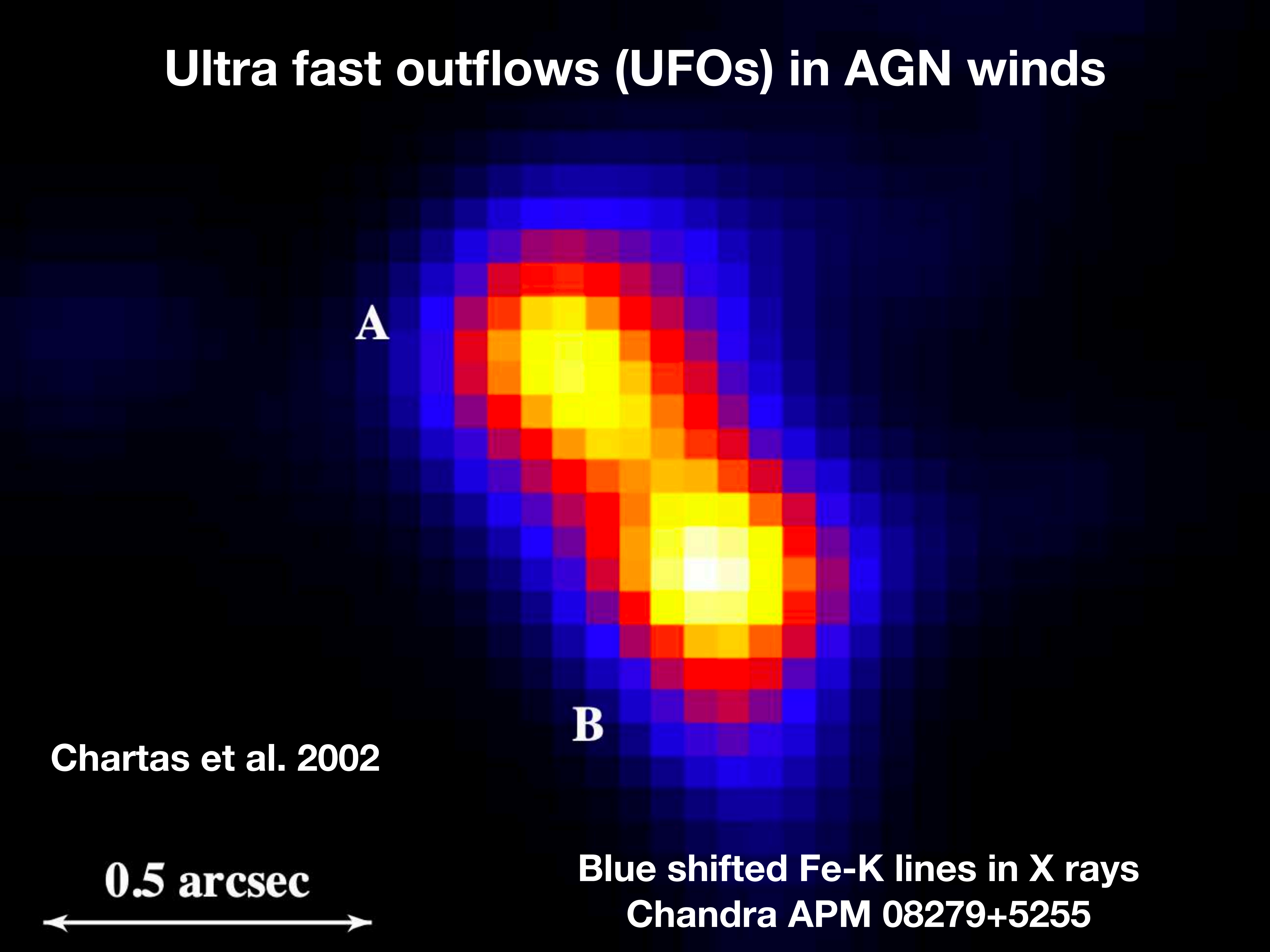



MHD ARMVAC Zakaria Meliani, PC et al.

# AGN-driven wind bubbles (UFOs)




**Seyfert NGC3079 - Image credit:** X-ray: NASA/CXC/University of Michigan/J-T Li et al.; Optical: NASA/STSc



Ultra fast outflows (UFOs) in AGN winds
A
B
Chartas et al. 2002
0.5 arcsec
Blue shifted Fe-K lines in X rays
Chandra APM 08279+5255

# Ultra fast outflows (UFOs) in AGN winds

$$\dot{M} = 10^{-3} - 10\ M_\odot/\mathrm{yr}$$

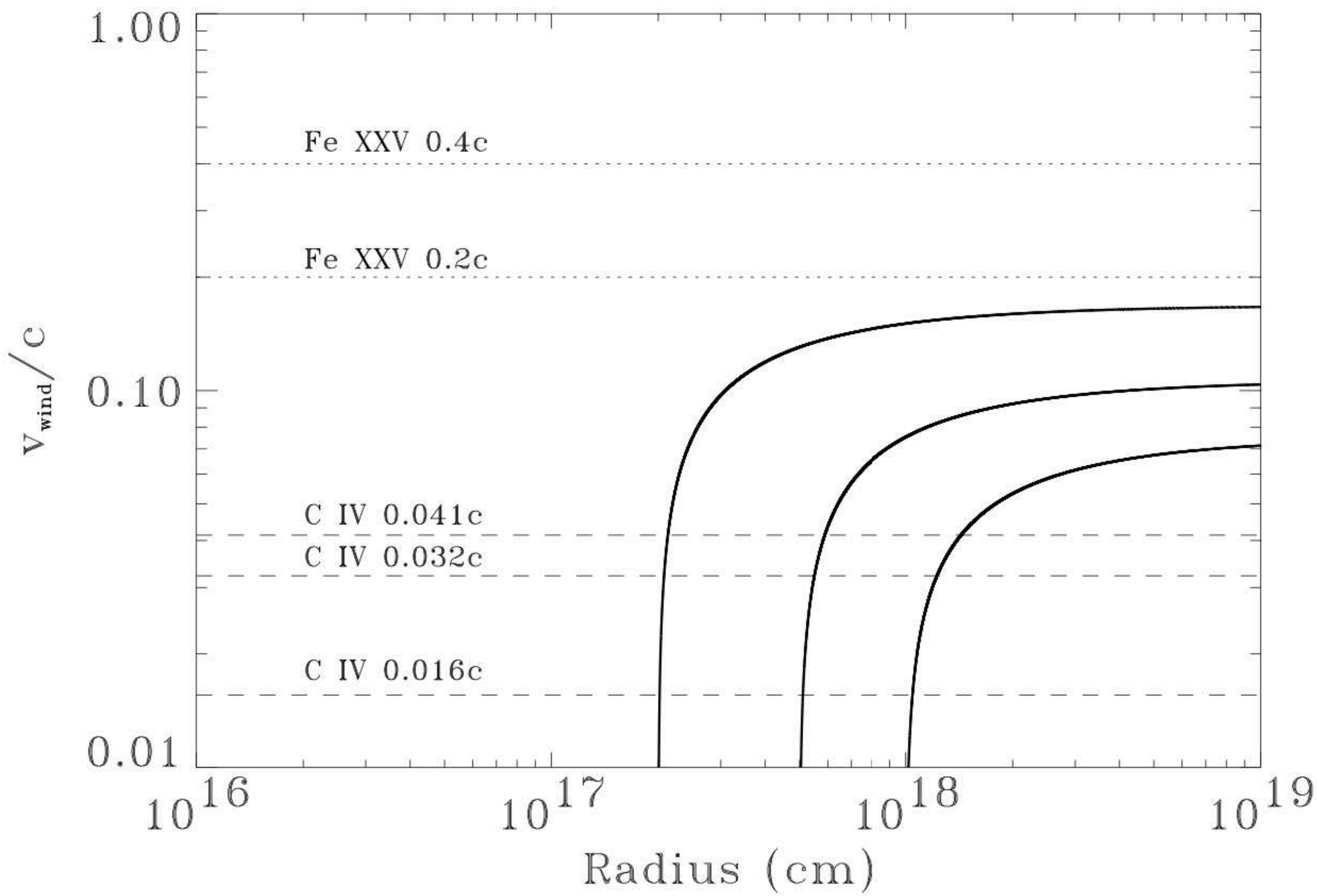



FIG. 3.— Wind velocity as a function of radius from the central source for a radiation pressure driven wind. For a qualitative comparison we have estimated the wind velocities for launching radii of $2 \times 10^{17}$ cm, $5 \times 10^{17}$ cm, and $1 \times 10^{18}$ cm. We have over-plotted the observed C IV BAL (dashed lines) and Fe XXV BAL (dotted lines) velocities.

Cha

0

ys

Chandra AP M1082791 5299

# Ultra fast outflows (UFOs) in AGN winds

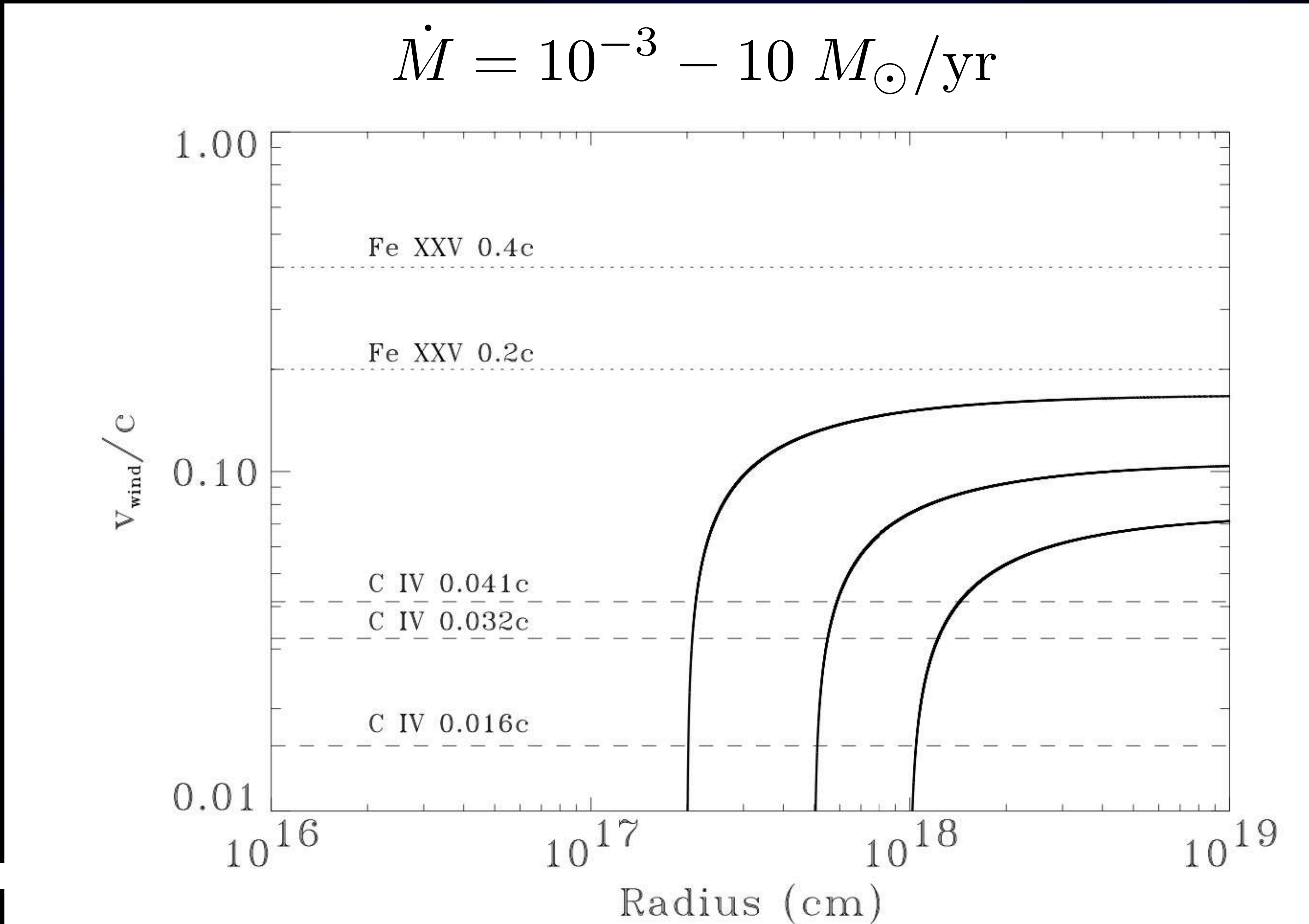



FIG. 3.— Wind veloci… e comparison we have estimated the wind vel… ne observed C IV BAL (dashed lines) and Fe X…

Char…

0… …ys

…2794-5295

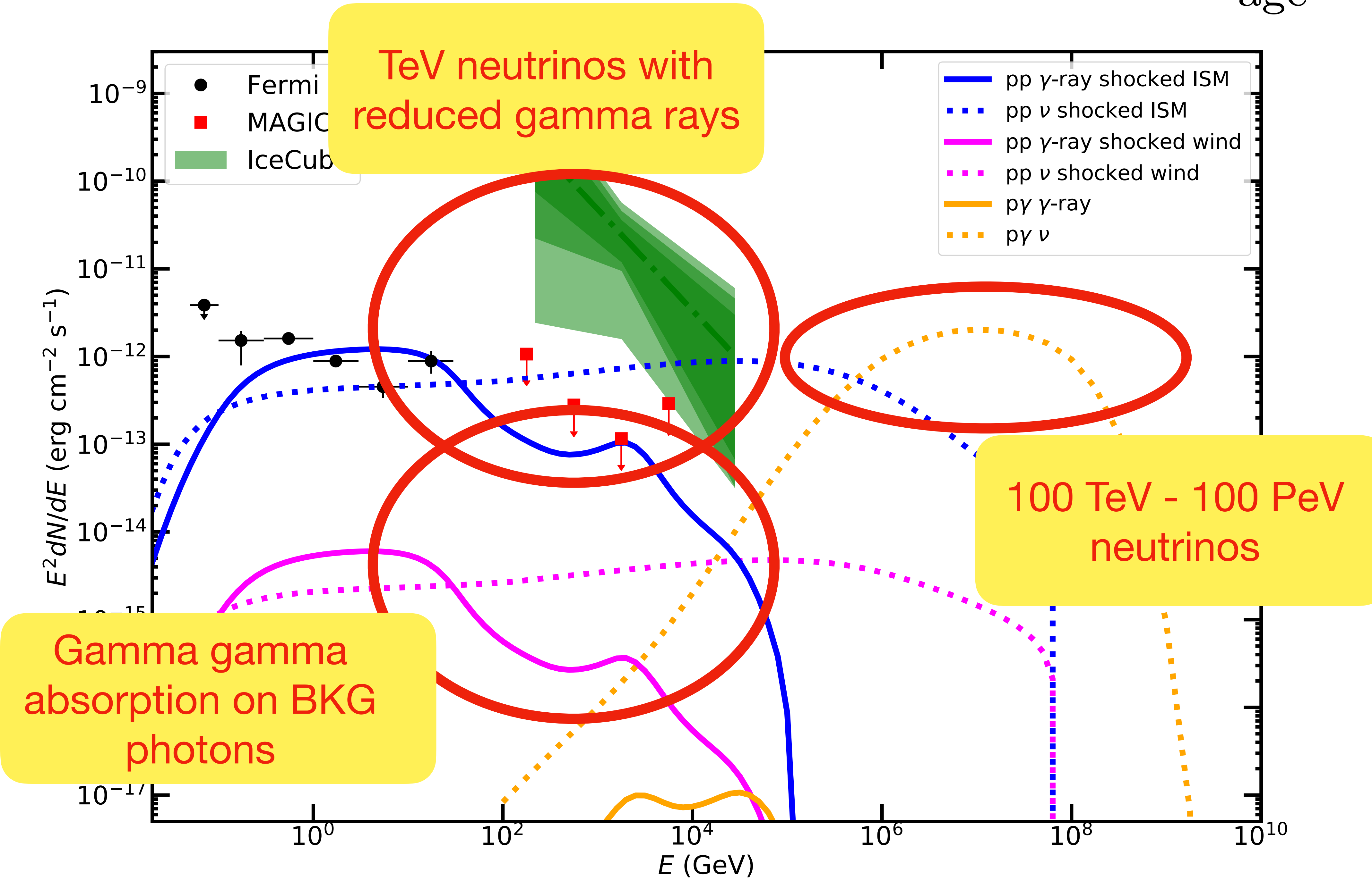
**Launching mechanism?**
**Accretion activity on the SMBH?**
**(Review Laha et al. 2021)**

$$u = 0.28c$$

# The case of NGC1068

$$\dot{M} = 0.05 M_{\odot}/\mathrm{yr}$$

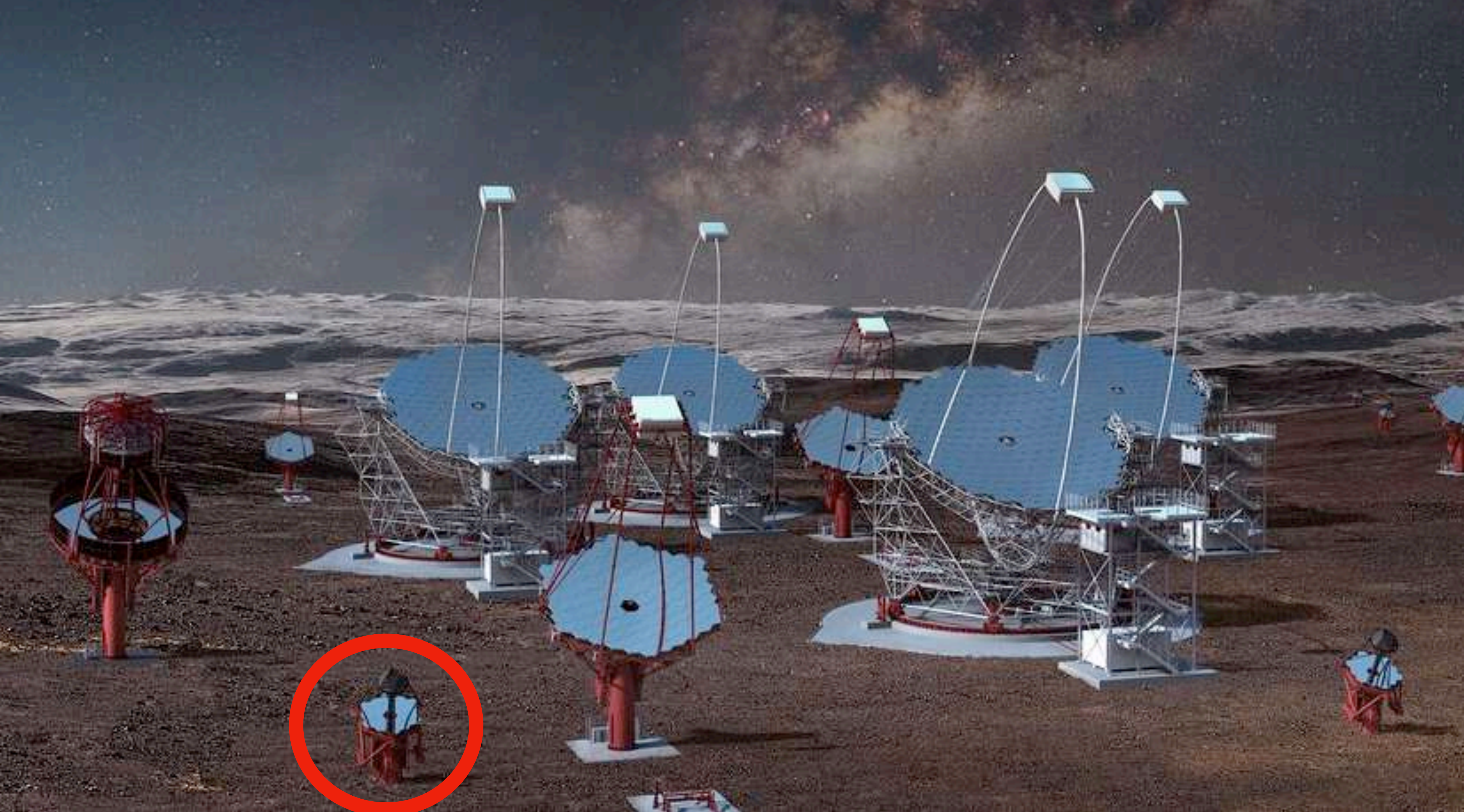
$$t_{\mathrm{age}} = 1000\mathrm{yr}$$

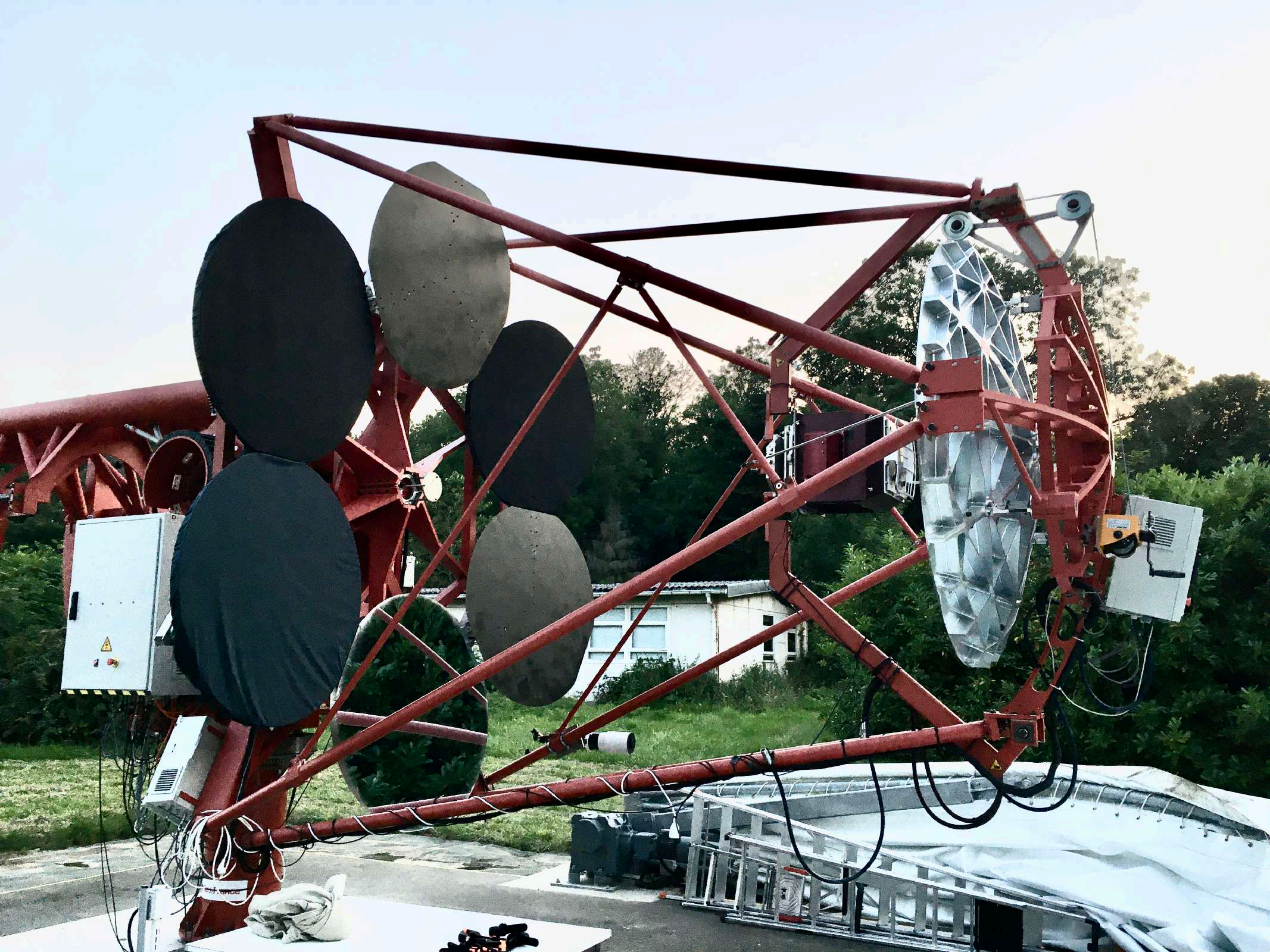


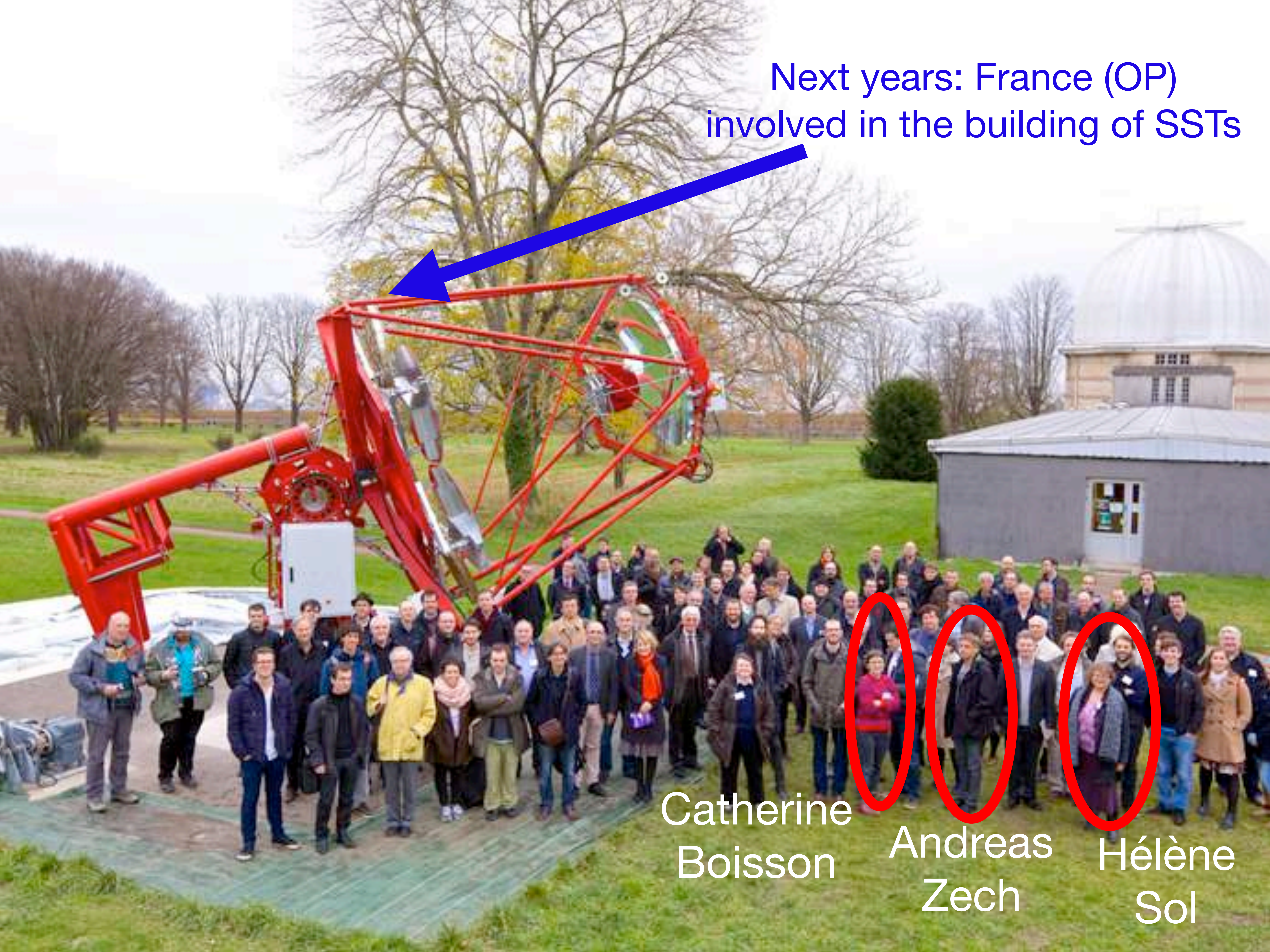

**Peretti, Lamastra, Saturni, Ahlers, Blasi, Morlino, PC in prep. 2022**

# Cherenkov Telescope Array (CTA)

France (INSU, IN2P3, CEA), Observatoire de Paris, LUTH involved on many levels






Next years: France (OP)
involved in the building of SSTs
Catherine
Boisson
Andreas
Zech
Hélène
Sol

# « Data » in CTA

FAIR = Findable, Accessible, Interoperable, Reusable

1. Portal to access data
2. Archive
3. Provenance
4. Data lake (all data, proposals, etc.)
5. Gammapy (tool for gamma-ray astronomy)

**Catherine Boisson, Mathieu Servillat, Paula Kornecki, PC**

# Goal: understanding particle acceleration at strong collisionless shocks shocks (SNRs, SNe, Superbulles, Starbursts, AGN winds)