

# Galactic Science

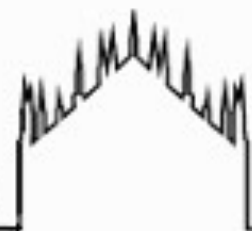
Rapporteur talk\*  
Sandro Mereghetti  
INAF, IASF Milano

INAF



ISTITUTO NAZIONALE DI ASTROFISICA  
NATIONAL INSTITUTE FOR ASTROPHYSICS

Istituto di Astrofisica Spaziale e Fisica cosmica di Milano

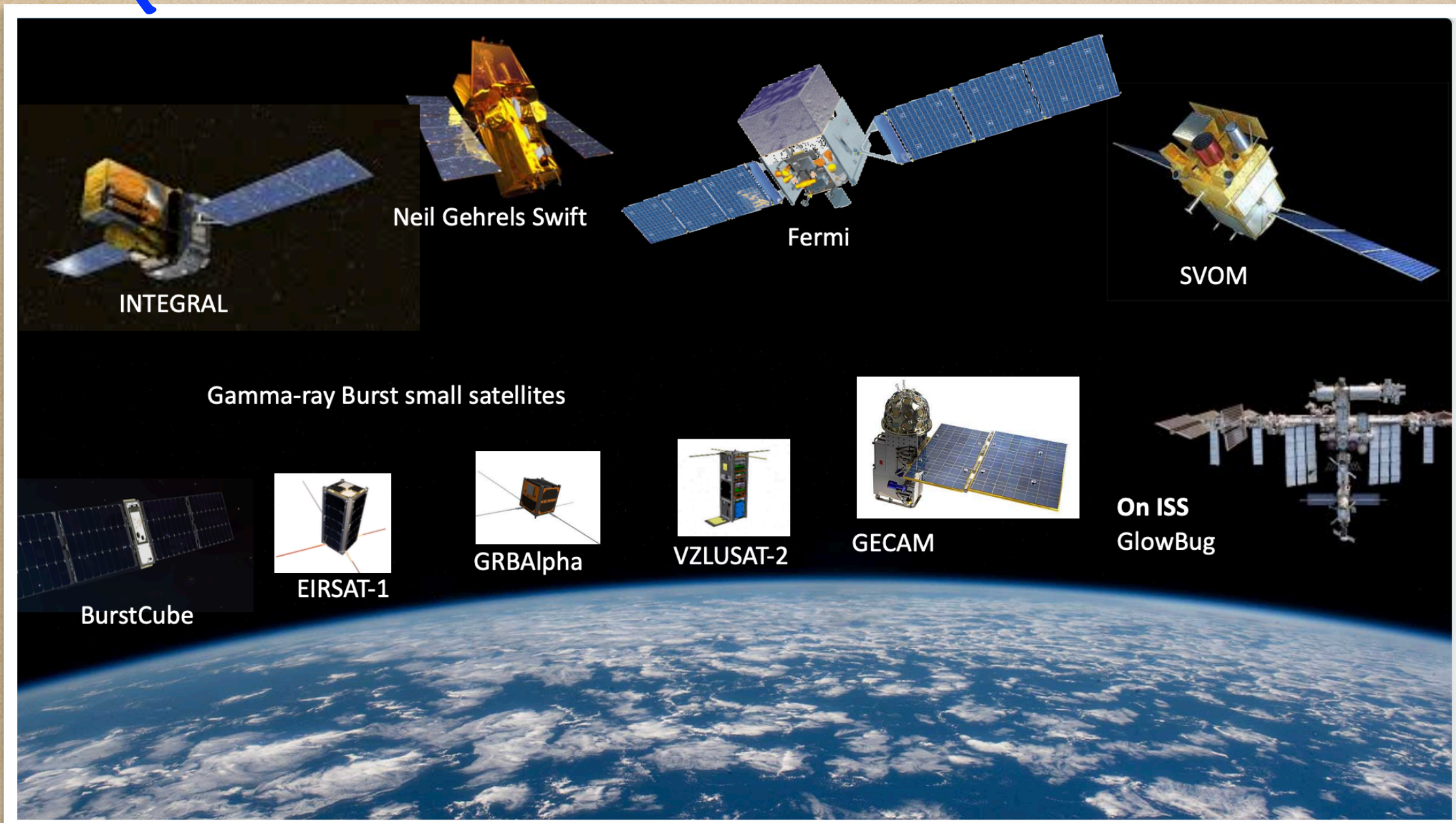


\*) My apologies for this biased and incomplete summary talk



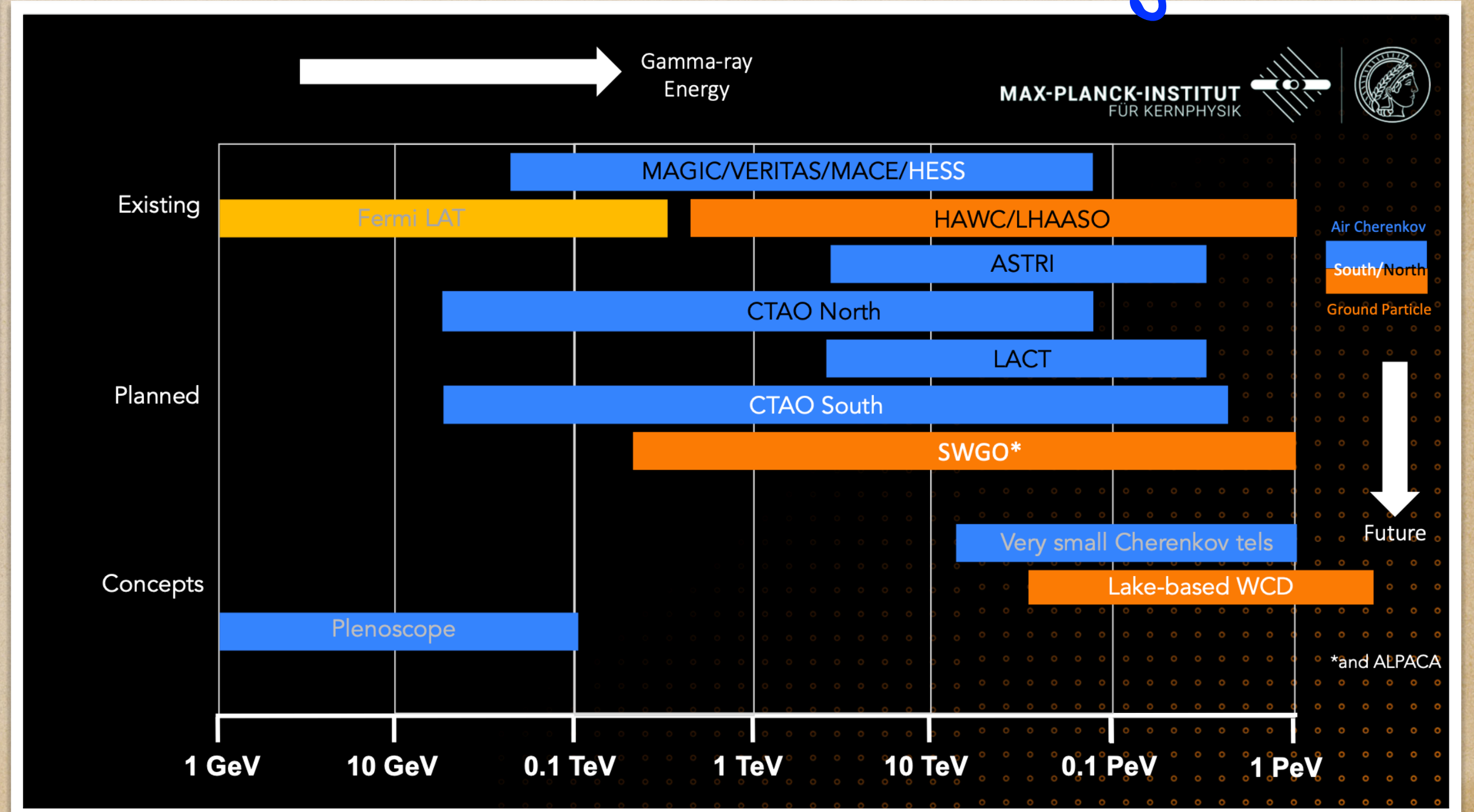
# Gamma-ray Astronomy

Hays



Space + Ground  
> 10 decades in E

Jim Hinton



Highlight talks and many other contribution on past/current/future facilities...



# VHE/UHE Gamma-ray Astronomy

from “sources-based” to classes of sources



# VHE/UHE Gamma-ray Astronomy

from “sources-based” to classes of sources

—> deeper investigations fundamental questions

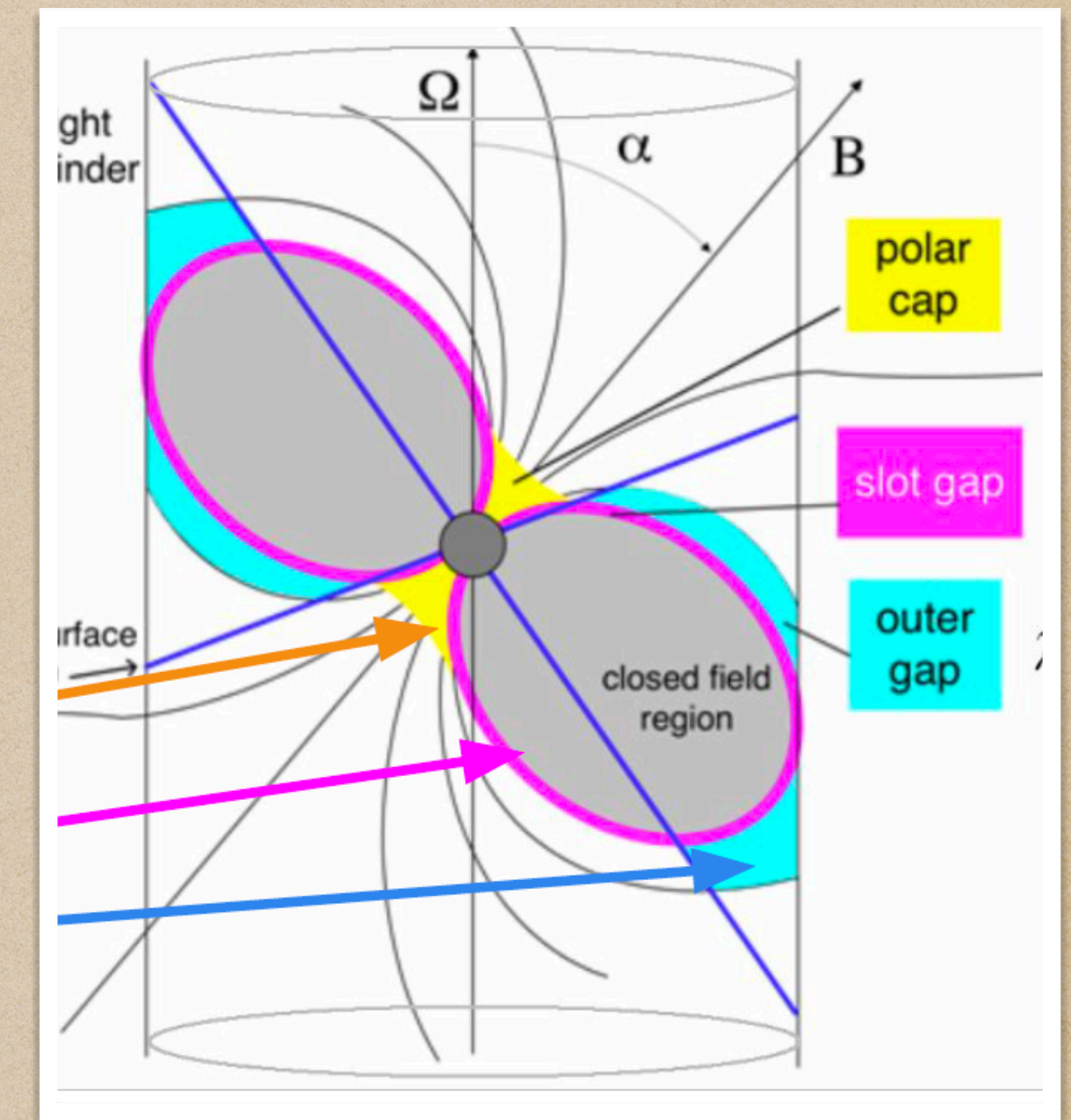
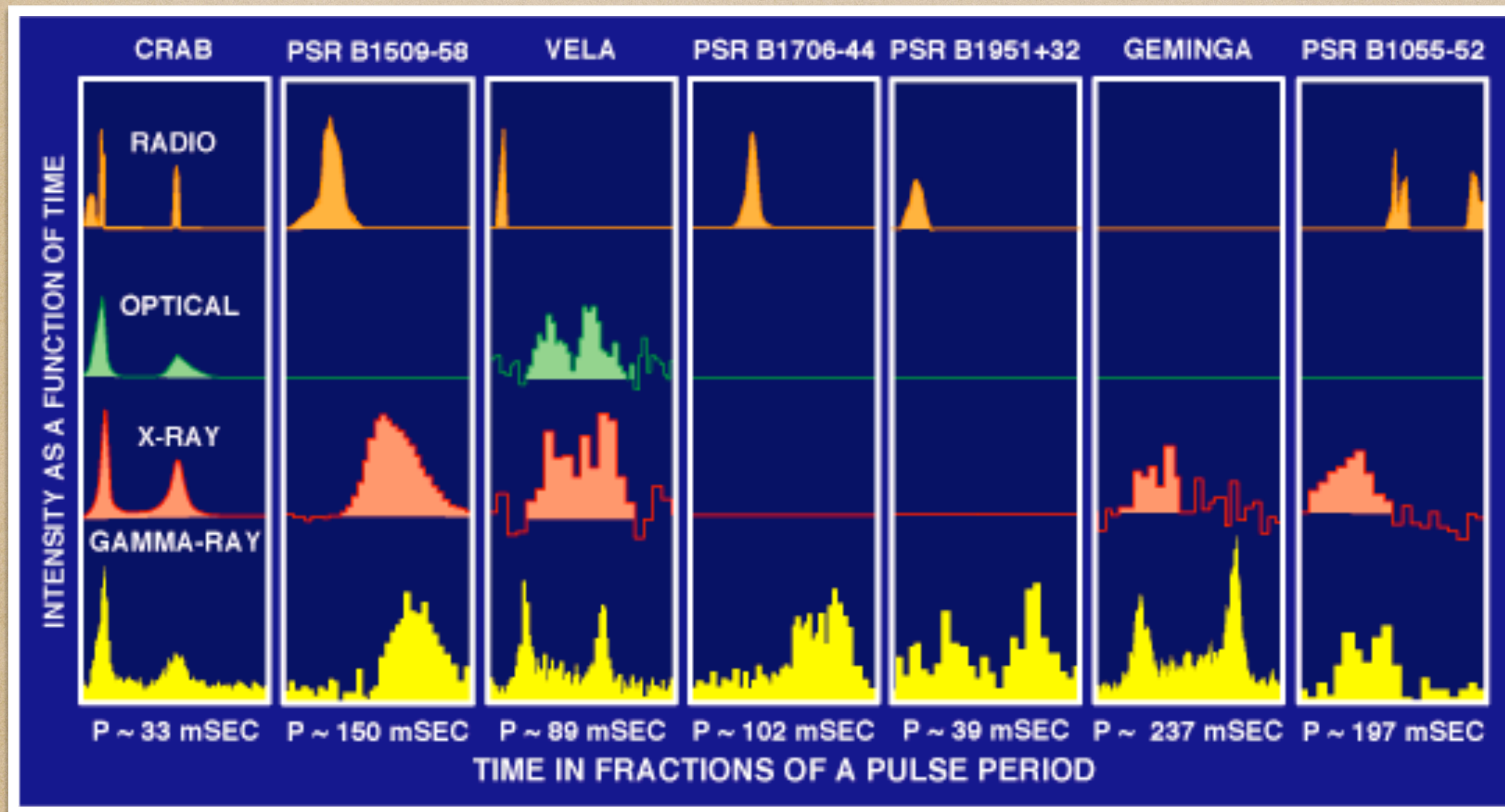
—> “prototypes” are not representative

—> from “experiment” type data management to observatory  
open to whole community



# Pulsars

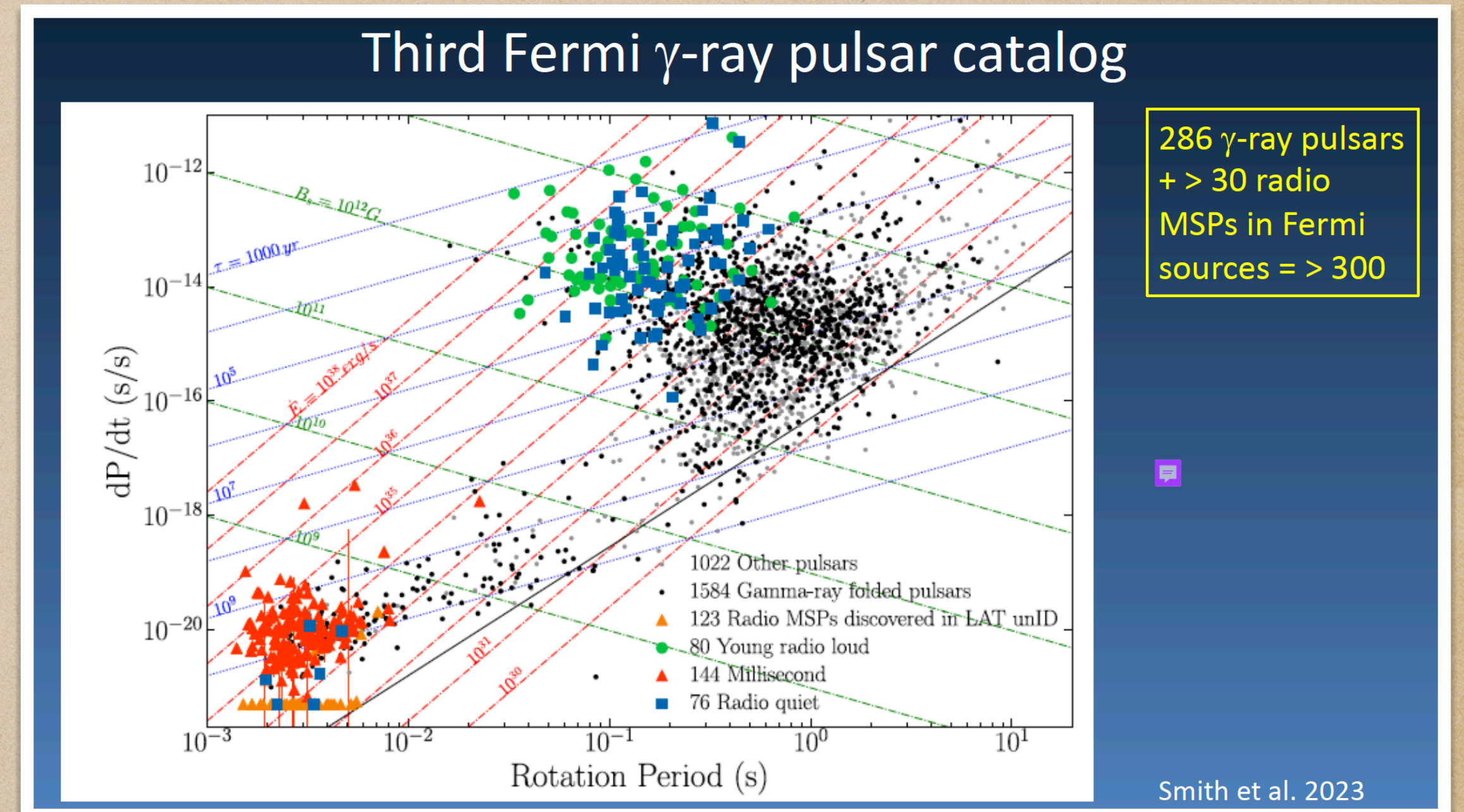
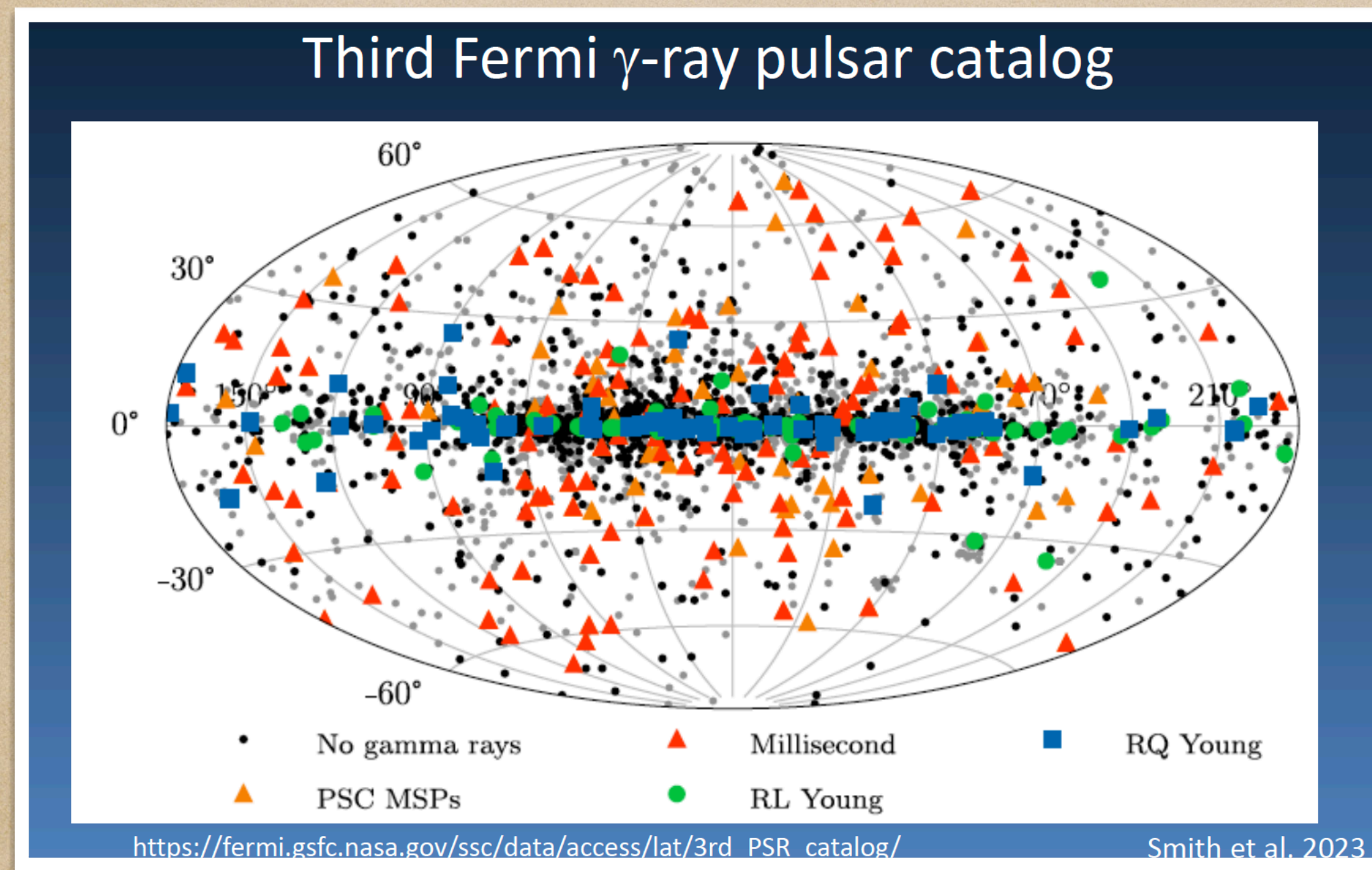
- ◆ In the "CGRO era"





# Pulsars: huge progress in observations...

Harding



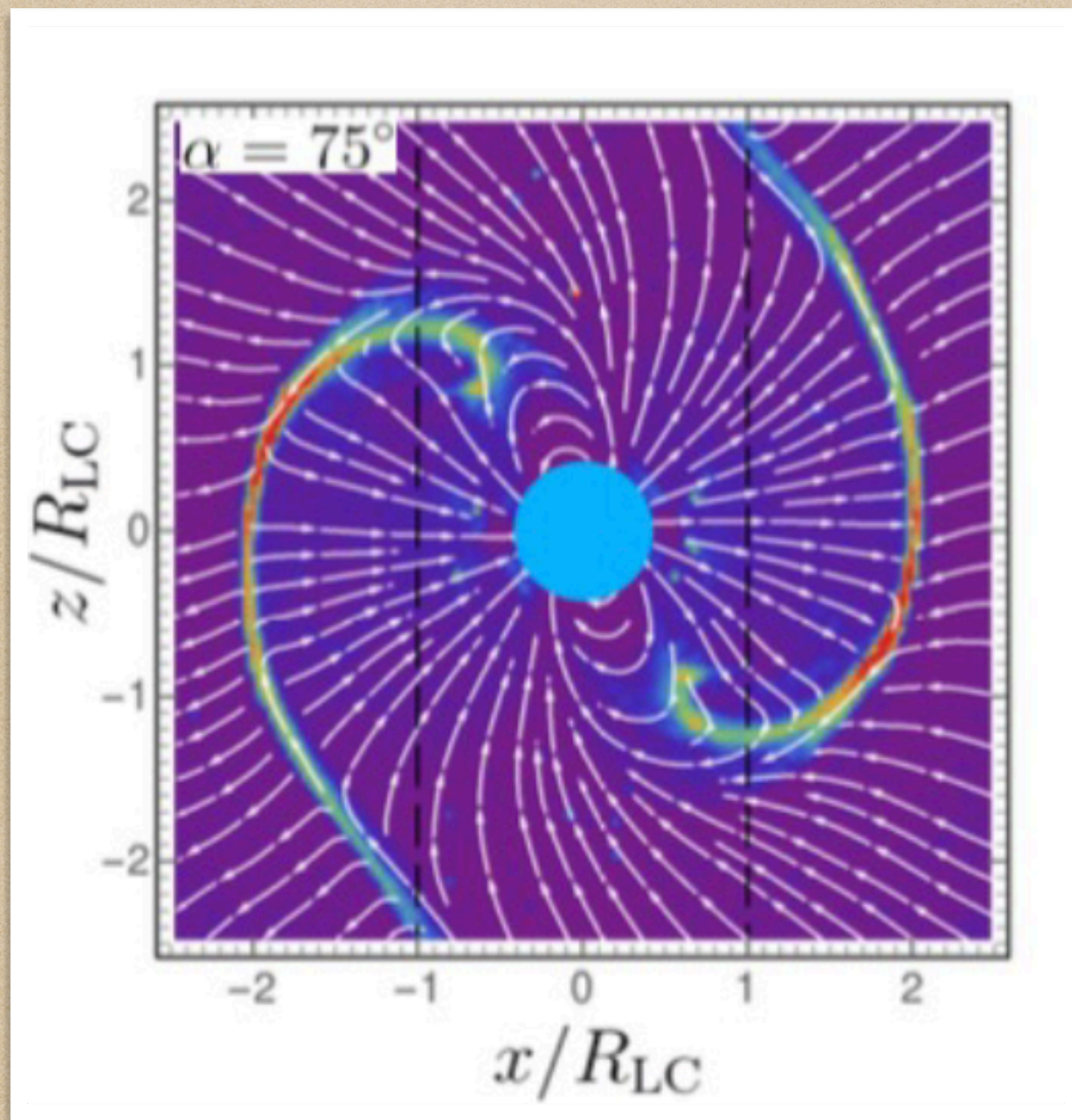
> ~300  $\gamma$ -ray PSRs

different subclasses: radio quiet / msPSR / binary / ...

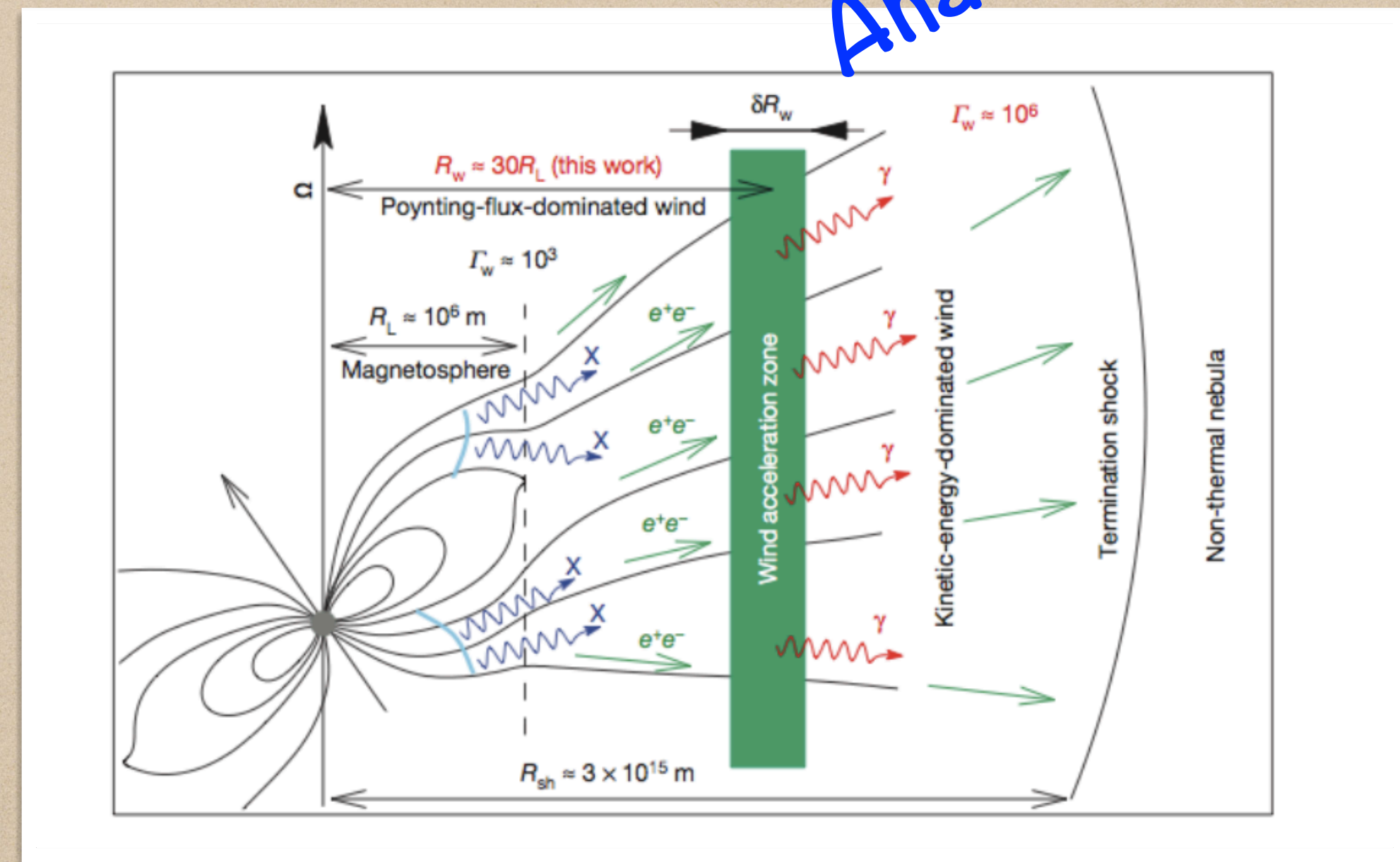


# ... and in theory

Aharonian



Harding

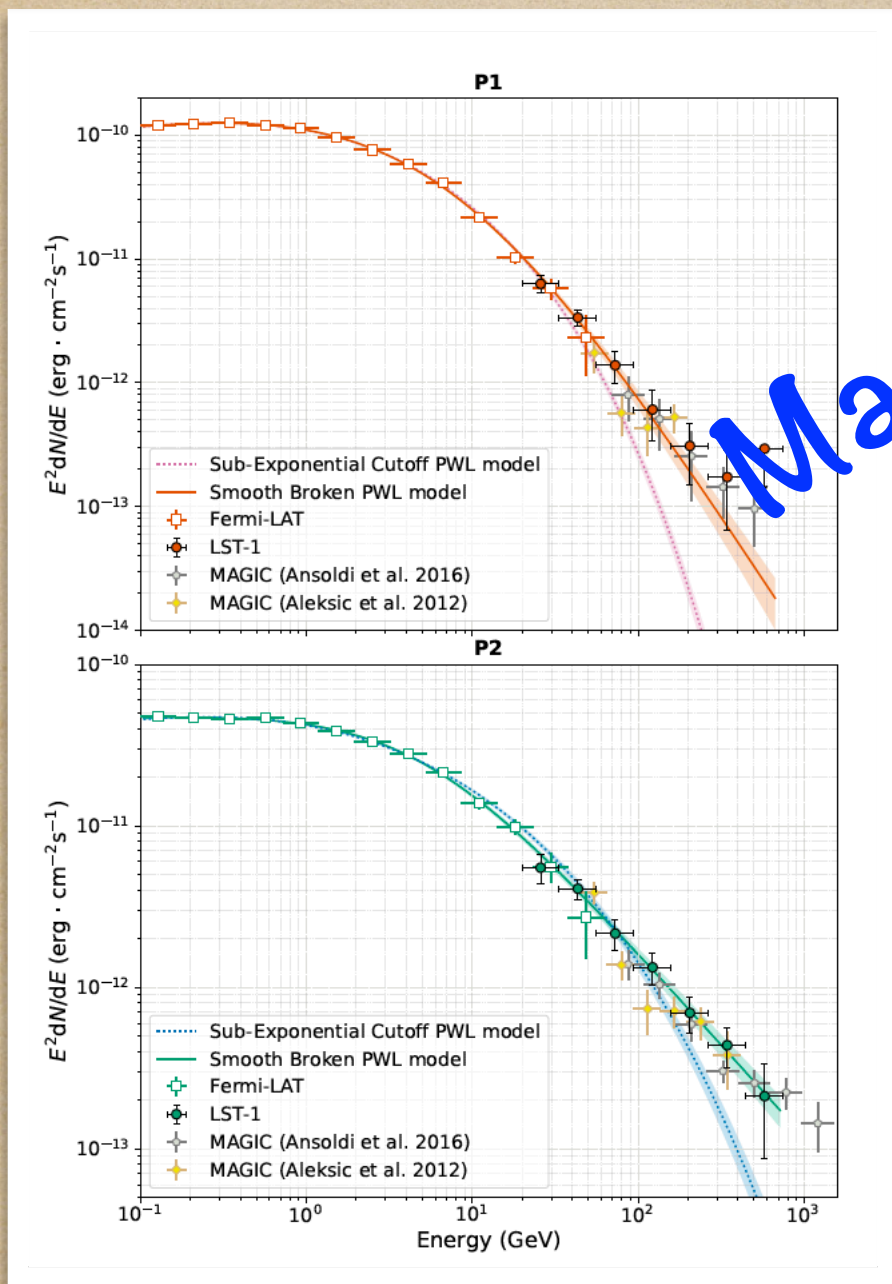


- Global PIC models  $\rightarrow$  most particle acceleration in current sheet

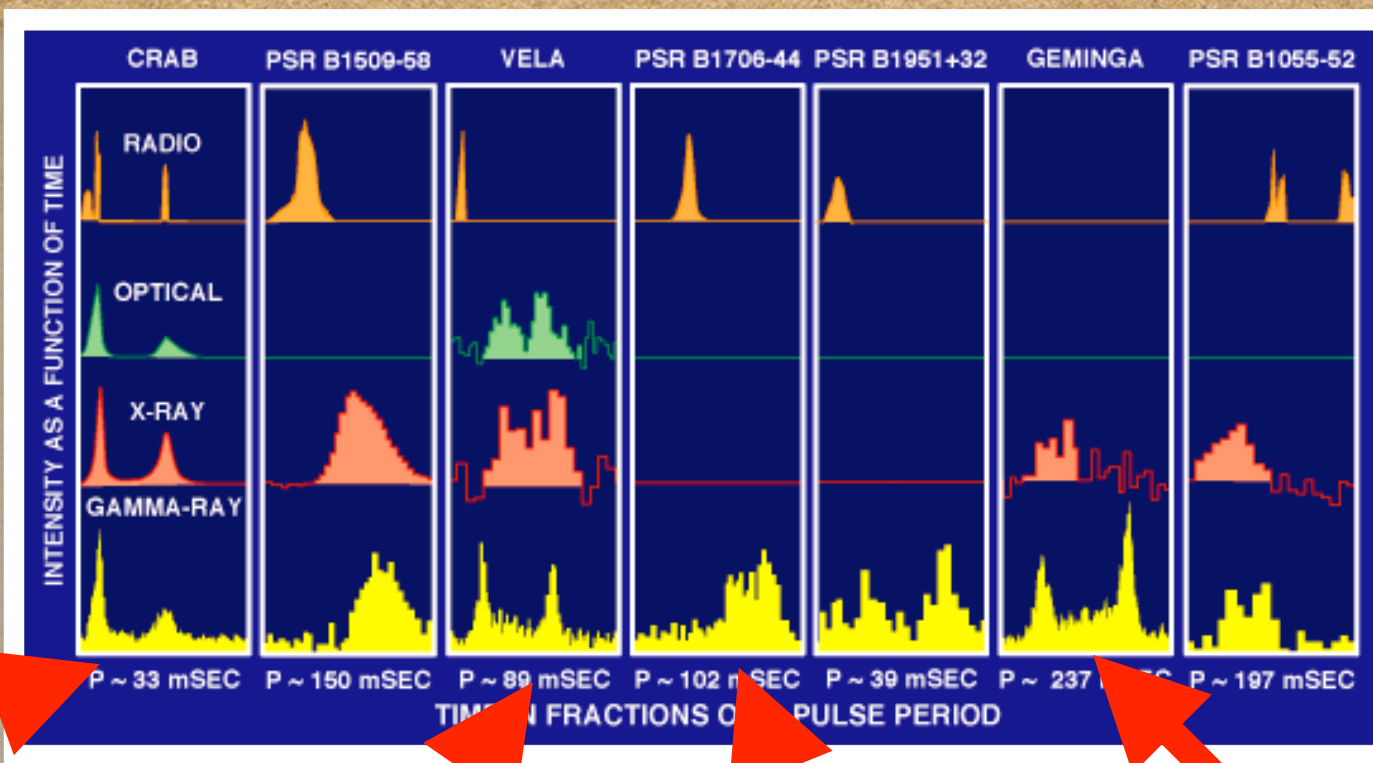
- Comptonization of cold wind  $e+/-$  on pulsed X/opt radiation (but difficult to go above  $\sim 1$  TeV)



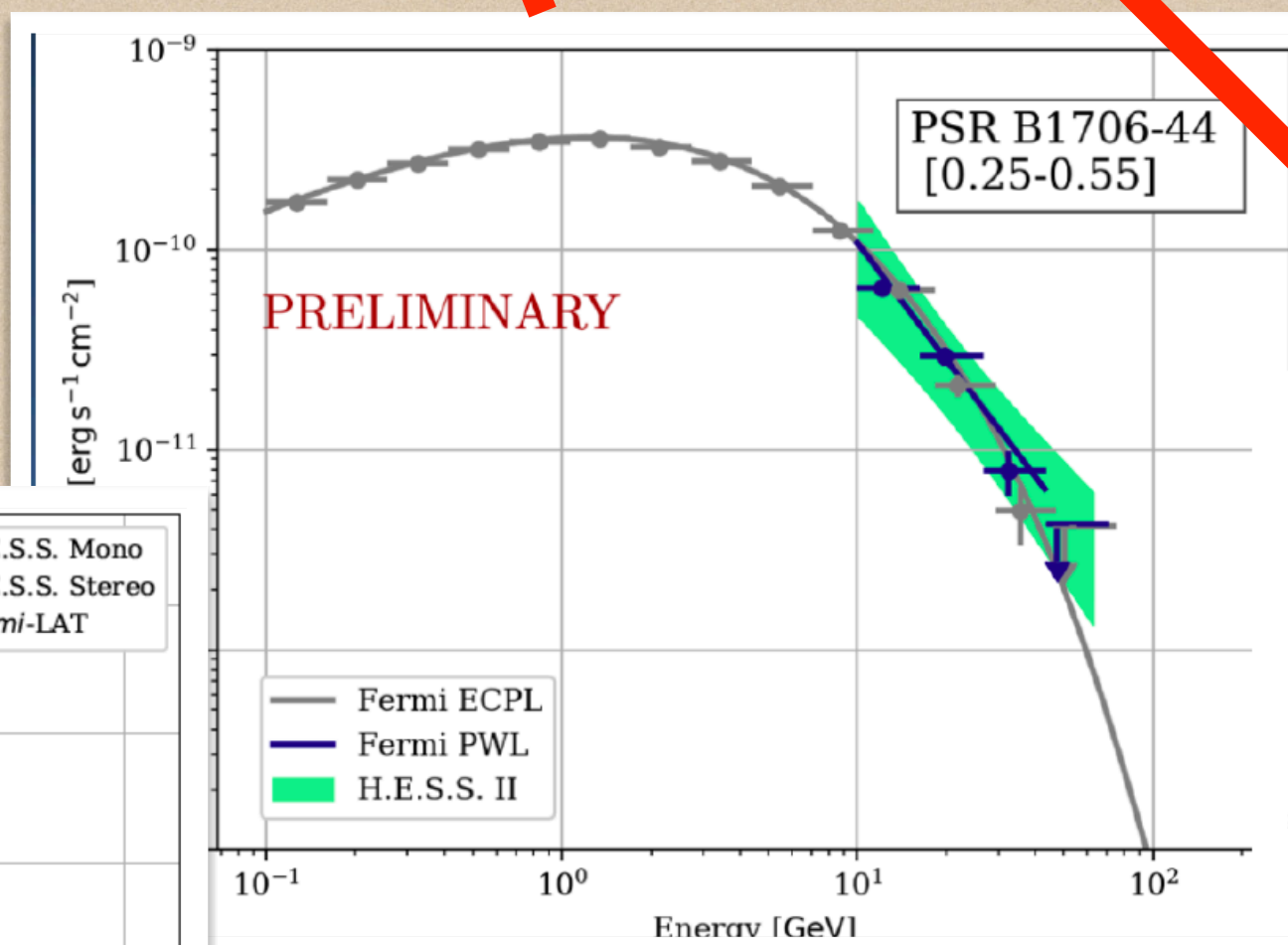
# Pulsars: VHE



Mas-Aguilar



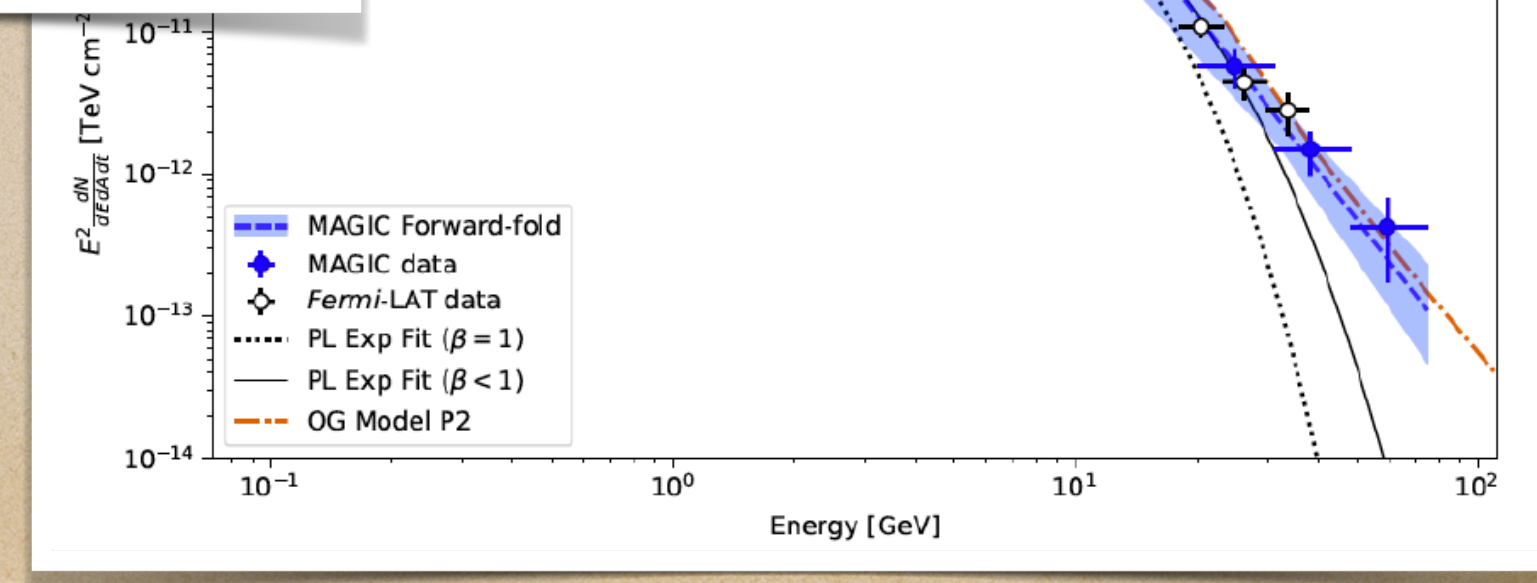
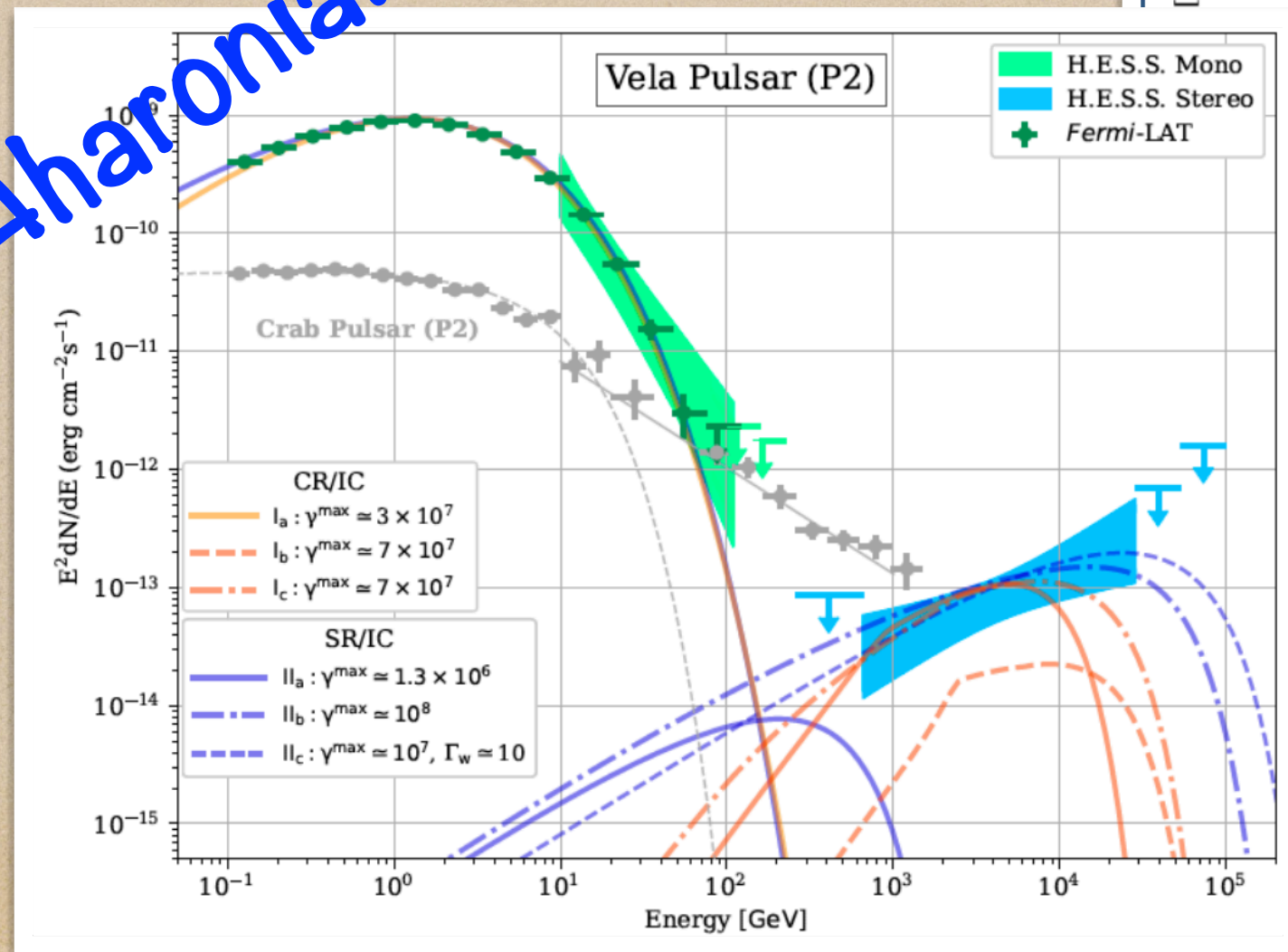
Aharonian



PSR 1706-44  
HESS

Geminga  
MAGIC LST-1

Yeung



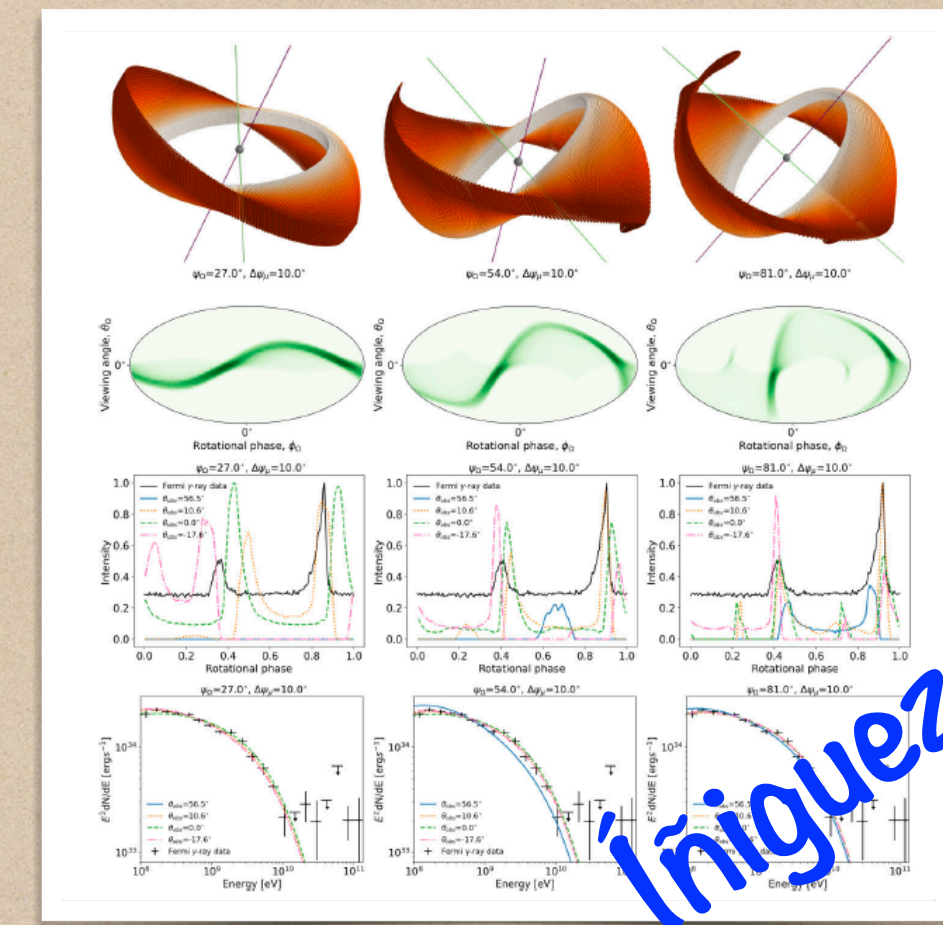
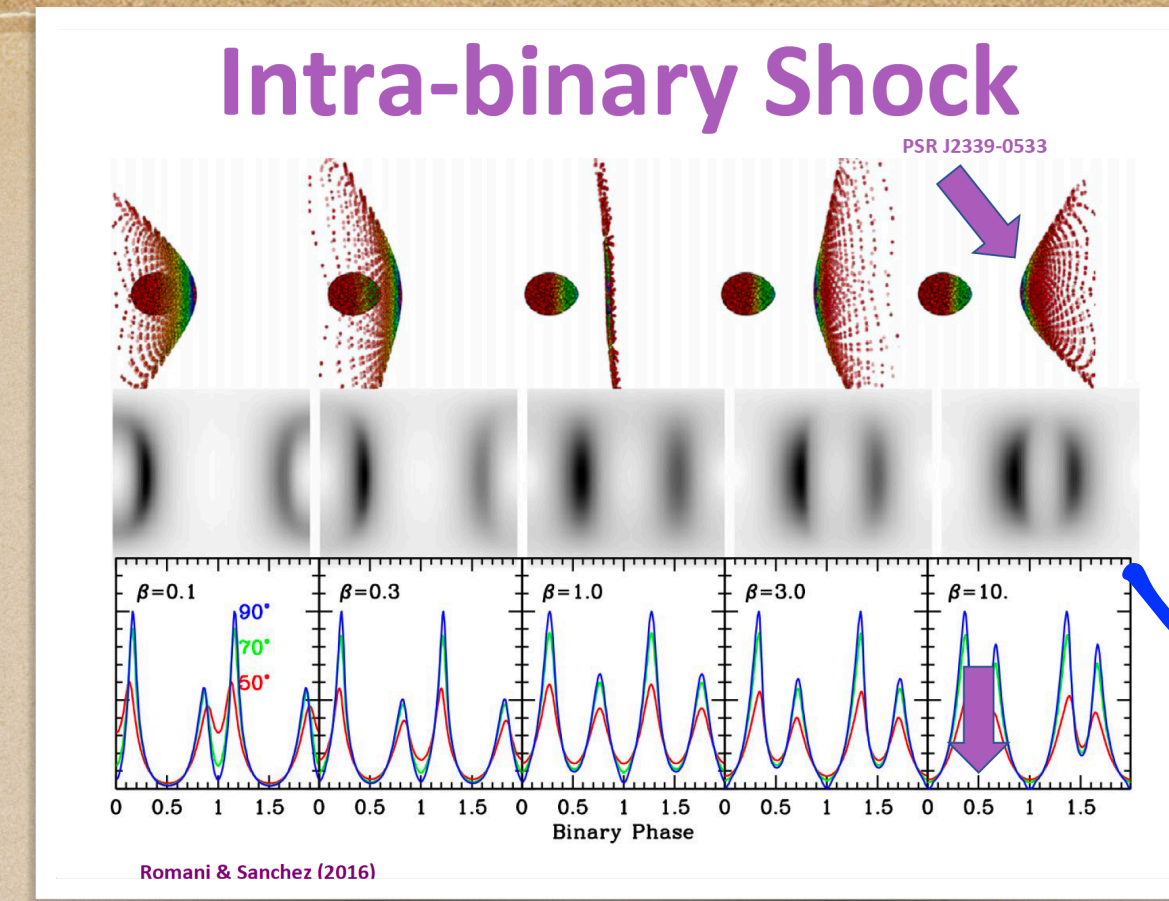
Crab up to ~1 TeV  
(1st TeV PSR MAGIC)  
VERITAS - LST-1

Vela P2 up to ~30 TeV  
HESS



# Pulsars

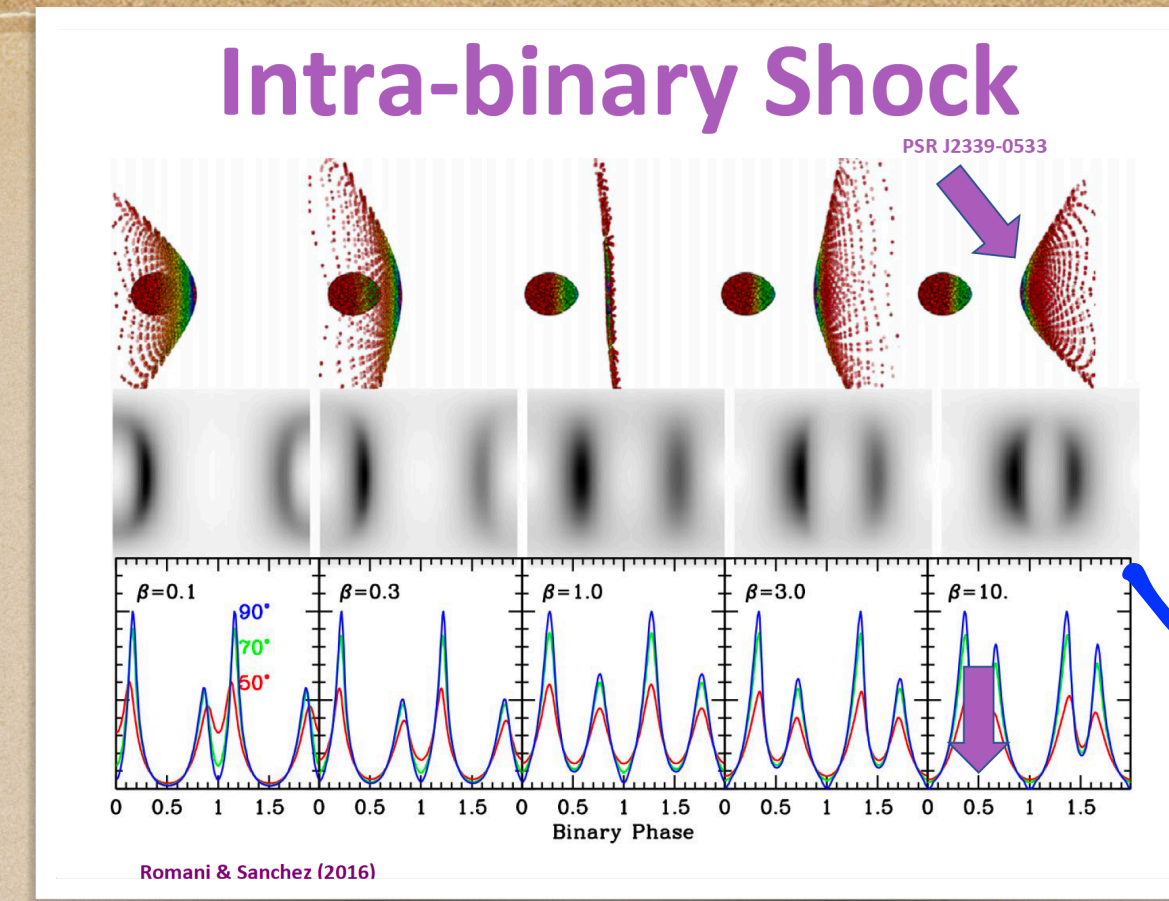
- ◆ “Spiders” (MSP devouring companion stars) as unique multiwavelength laboratories
- ◆ Detailed models of synchro-curvature radiation → pulse profiles and spectra



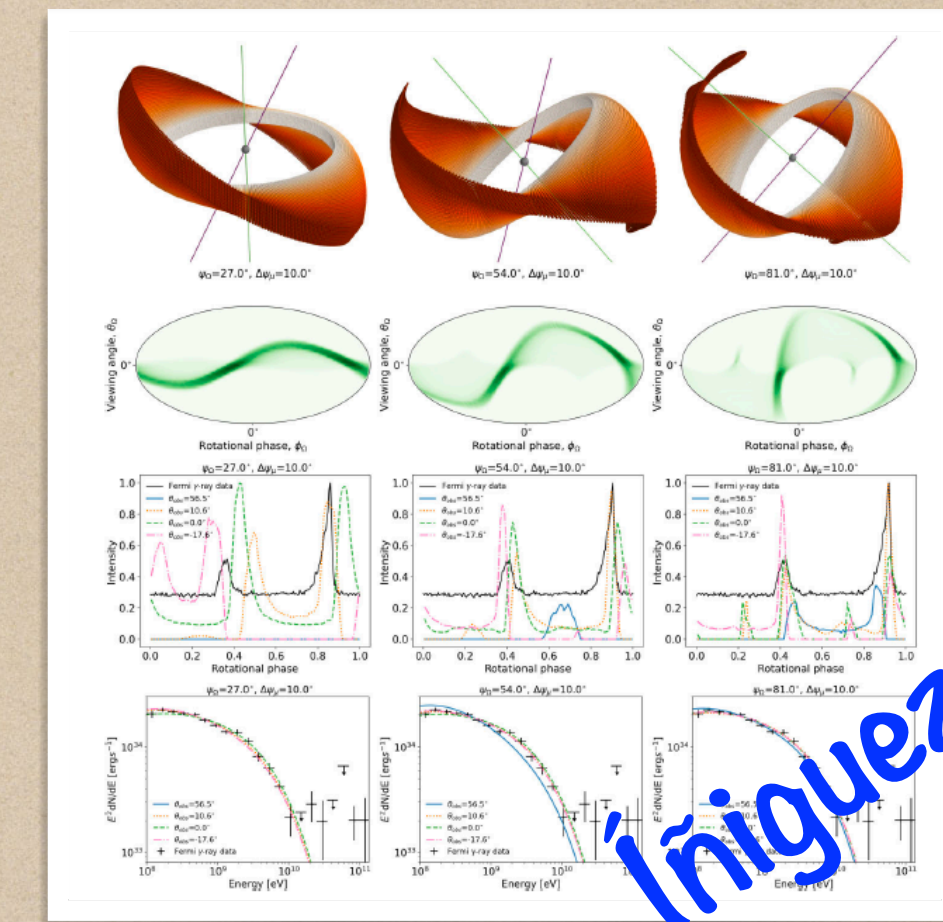


# Pulsars

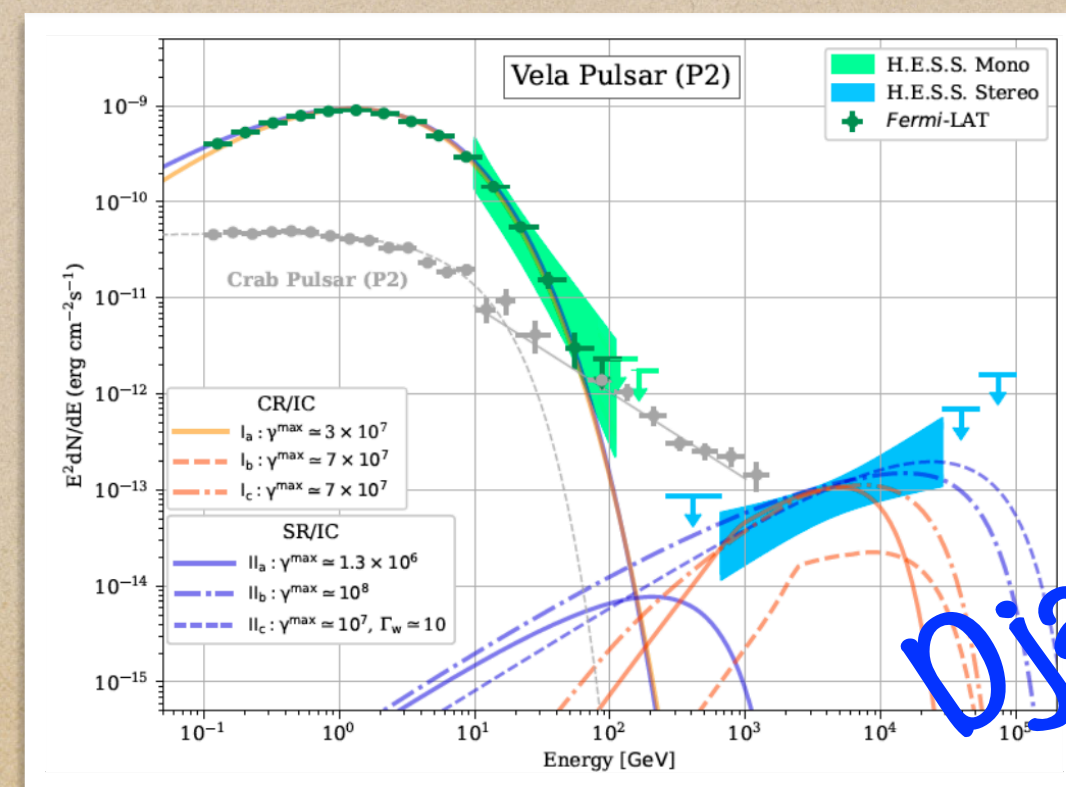
- ◆ “Spiders” (MSP devouring companion stars) as unique multiwavelength laboratories
- ◆ Detailed models of synchro-curvature radiation → pulse profiles and spectra
- ◆ HESS discovery of a distinct emission component similar to Vela, but much higher  $L_{\text{TeV}}/L_{\text{GeV}}$



Venter



Iniguez-Pascual



Djannati-Atai



# Pulsars

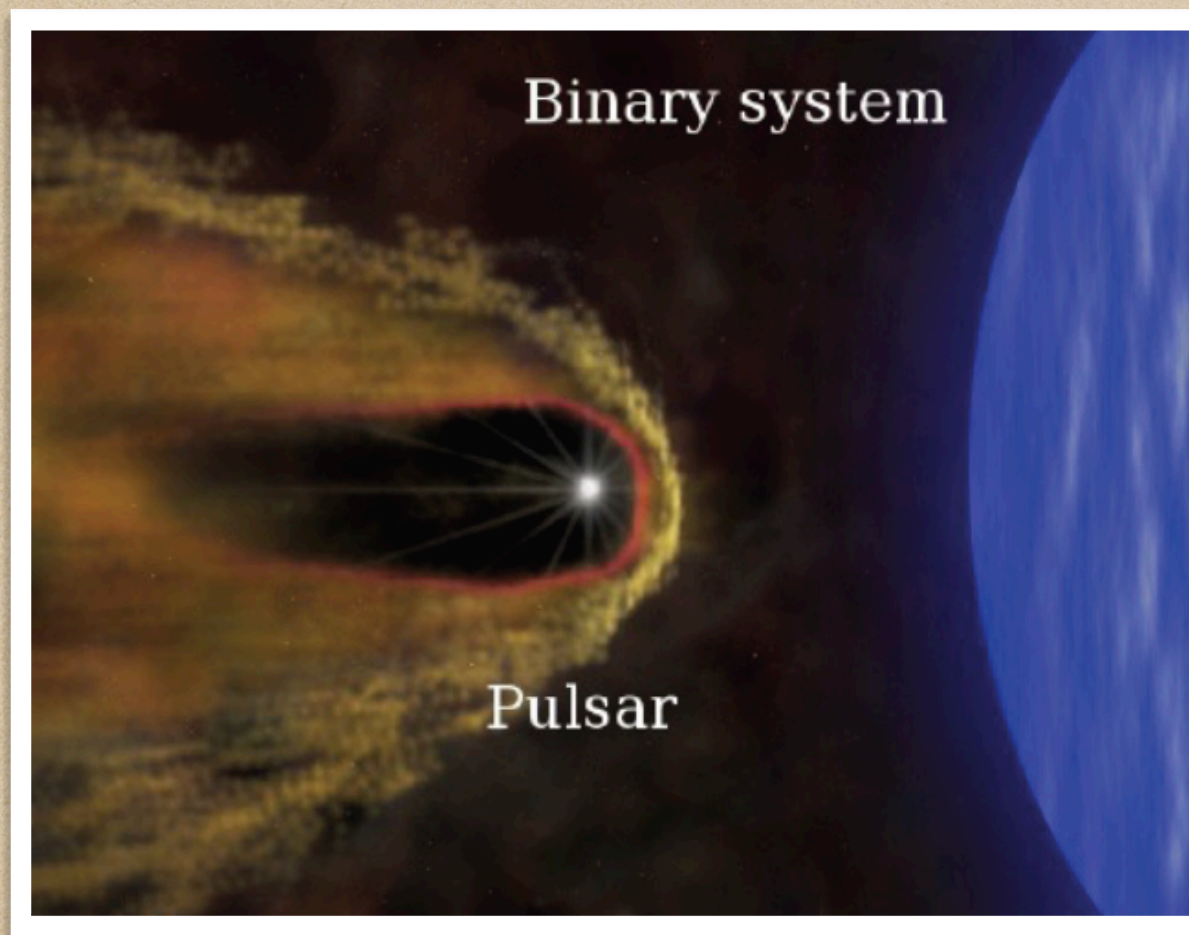
- ◆ Reasonably well established location of particle acceleration and HE emission but origin of HE/VHE emission still open  
Parallel E field ?  
Reconnection ?
- ◆ Is there a cut-off in the VHE spectra ? At which E?  
(PL fits are OK up to now)  
Only in Vela evidence for a completely different spectral component  
(but peak phase is the same of HE P2)



# Gamma-ray binaries

- ◆ SED peaks at GeV/TeV in only 9 systems  
(cfr hundreds of X-ray binaries with SED peak at keV)

Non-accreting!



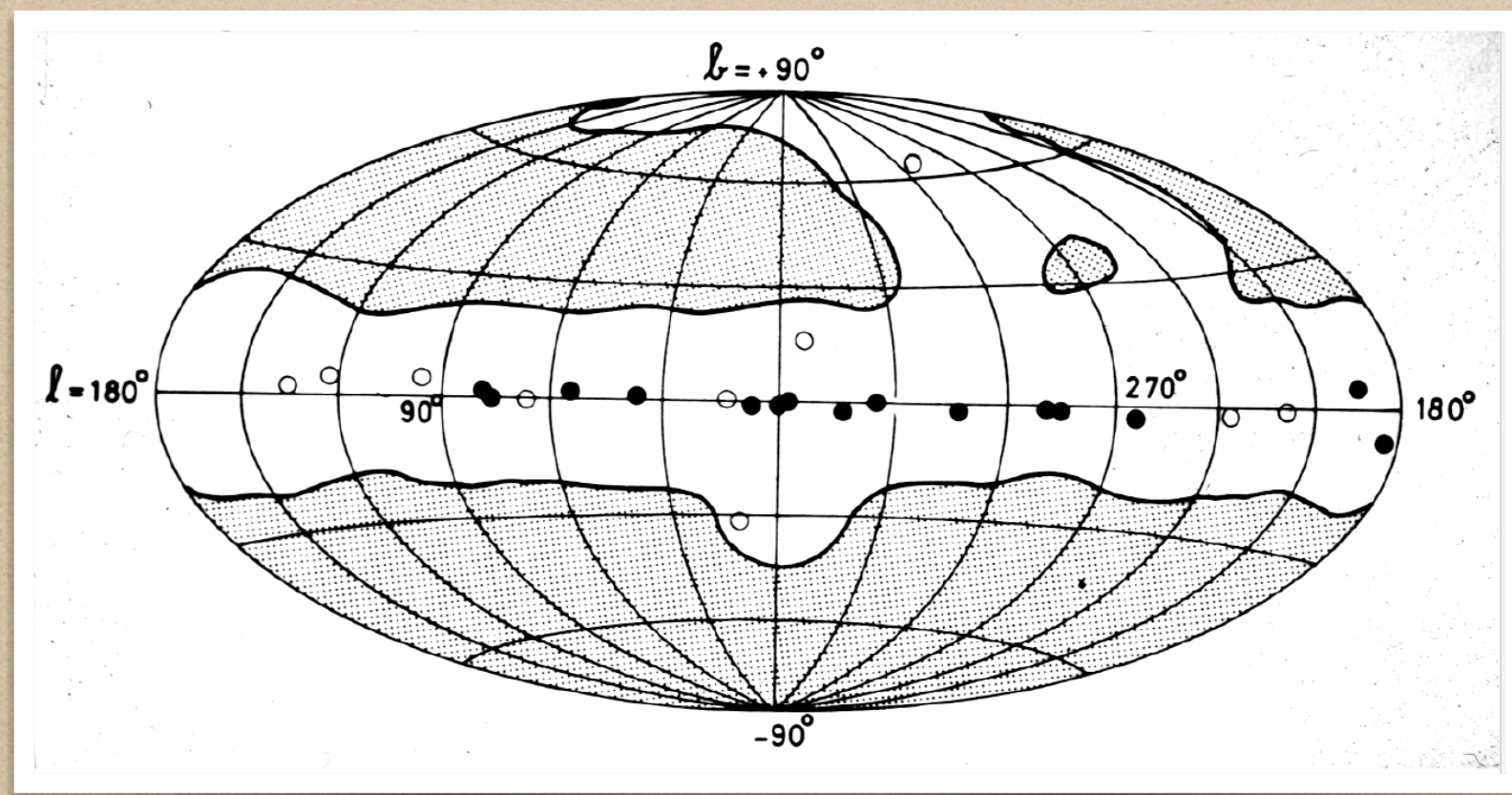
System	HE	VHE	Star	CO	$P_{\text{orbit}}$
LS 5039	Y	Y	ON6.5 V	?	3.9 d
LMC P3	Y	Y	O5 III	?	10.3 d
4FGL J1405.1-6119	Y	-	O6.5 III	?	13.7 d
1FGL J1018.6-5856	Y	Y	O6 V	?	16.5 d
HESS J1832-093	Y	Y	O6 V	?	86.3 d
LS I +61 303	Y	Y	B0 Ve	PSR (269 ms)	26.5 d
HESS J0632+057	Y	Y	B0 Vpe	?	317 d
PSR B1259-63	Y	Y	O9.5 Ve	PSR (47.7 ms)	~3.4 yr
PSR J2032+4127	~Y	Y	B0 Vpe	PSR (143 ms)	~50 yr

Ribó



# Gamma-ray binaries

LS I +61 303 = CG 135+01

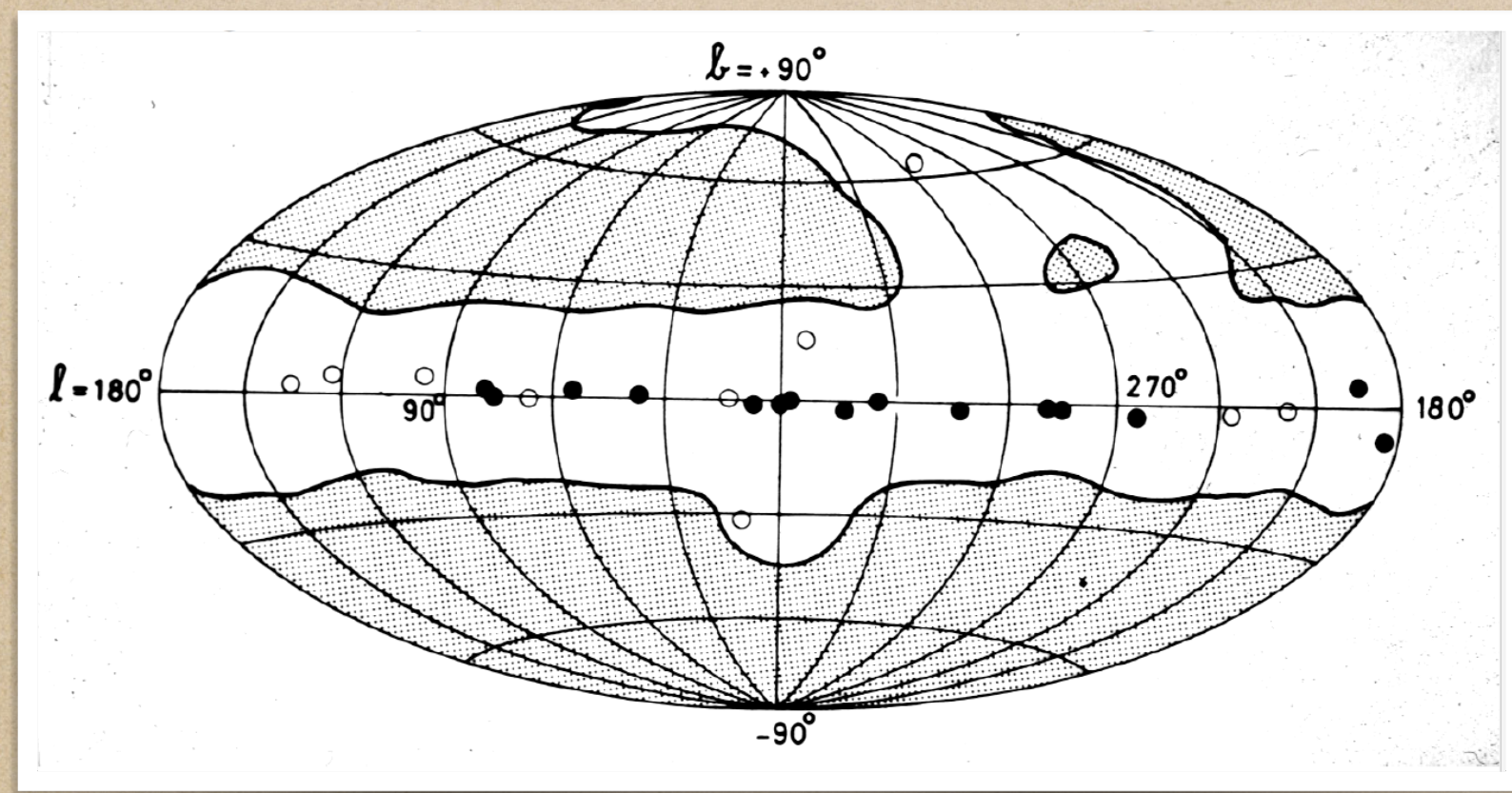


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# Gamma-ray binaries

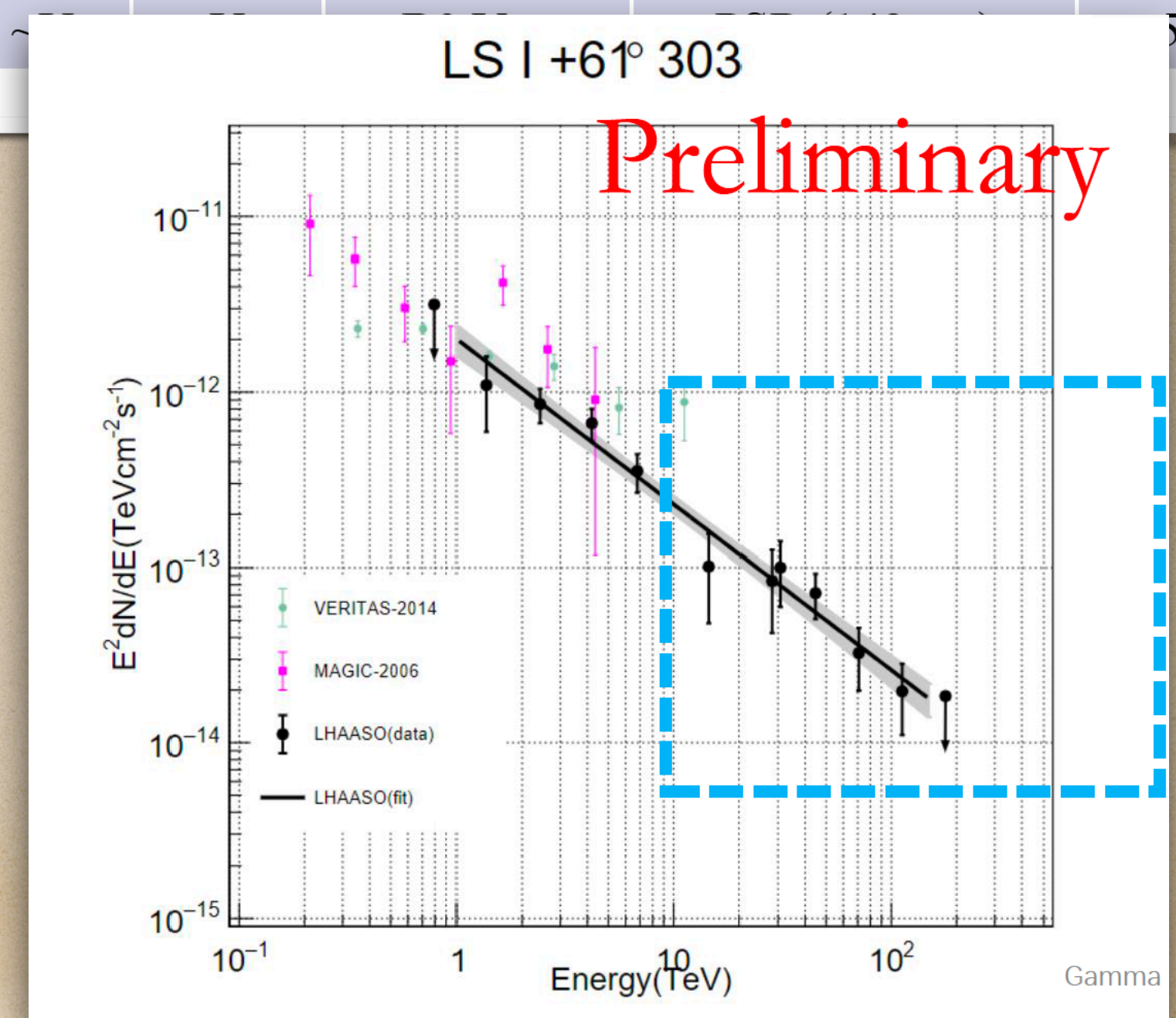
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- ◆ LHAASO detection of up to 100 TeV with no break in PL

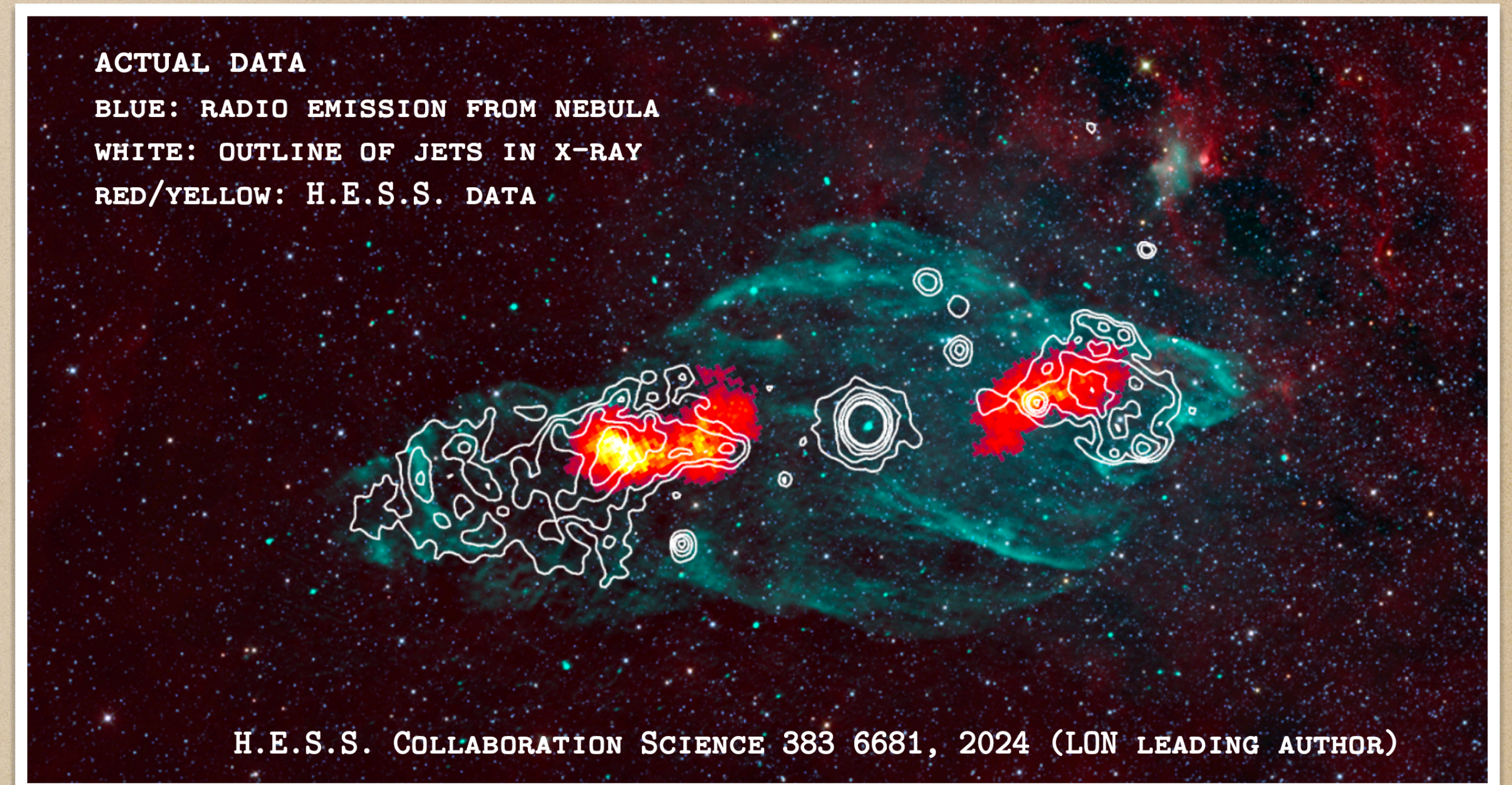
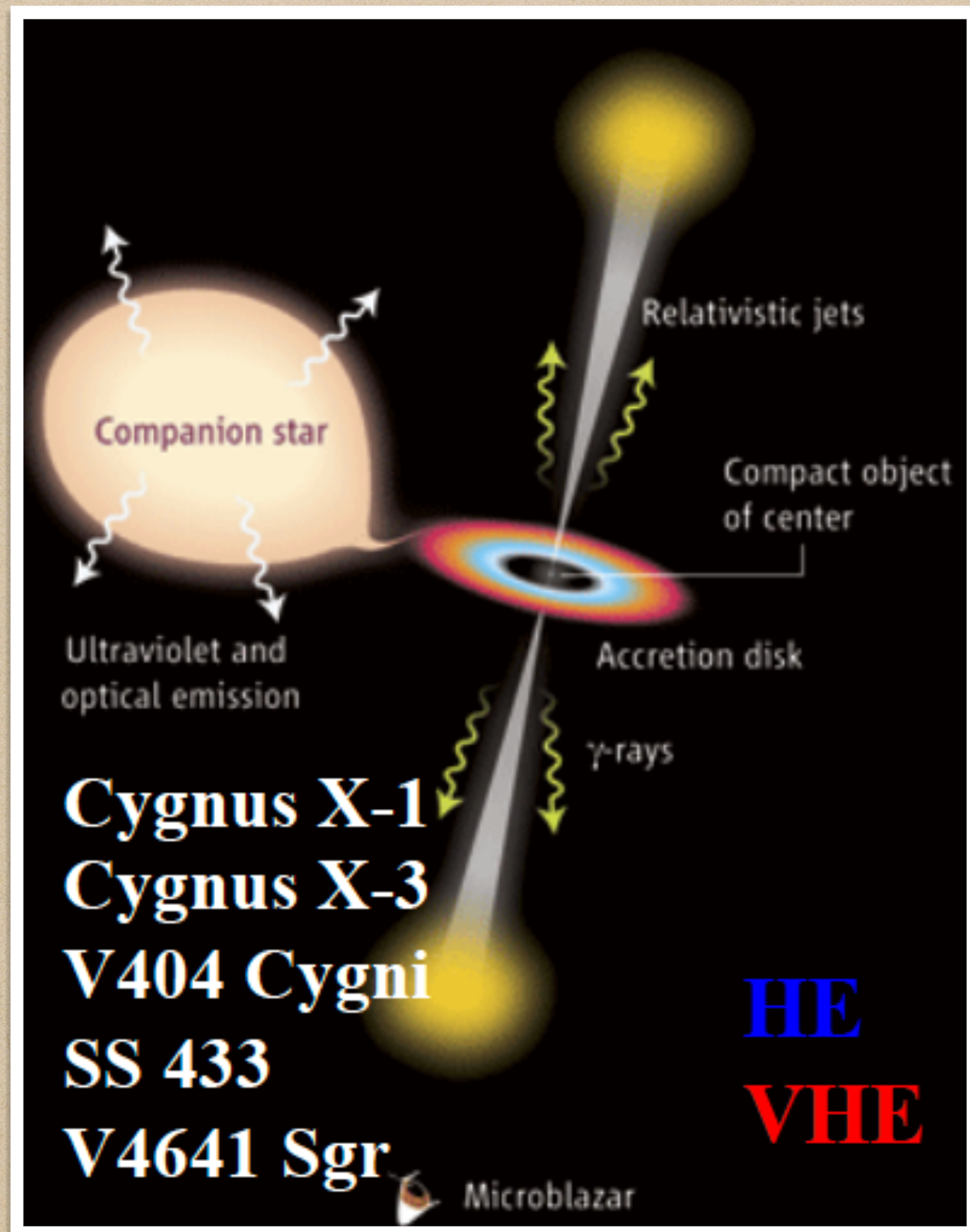
Cong Li





# microQSOs

Stellar mass BH accreting from  
companion stars



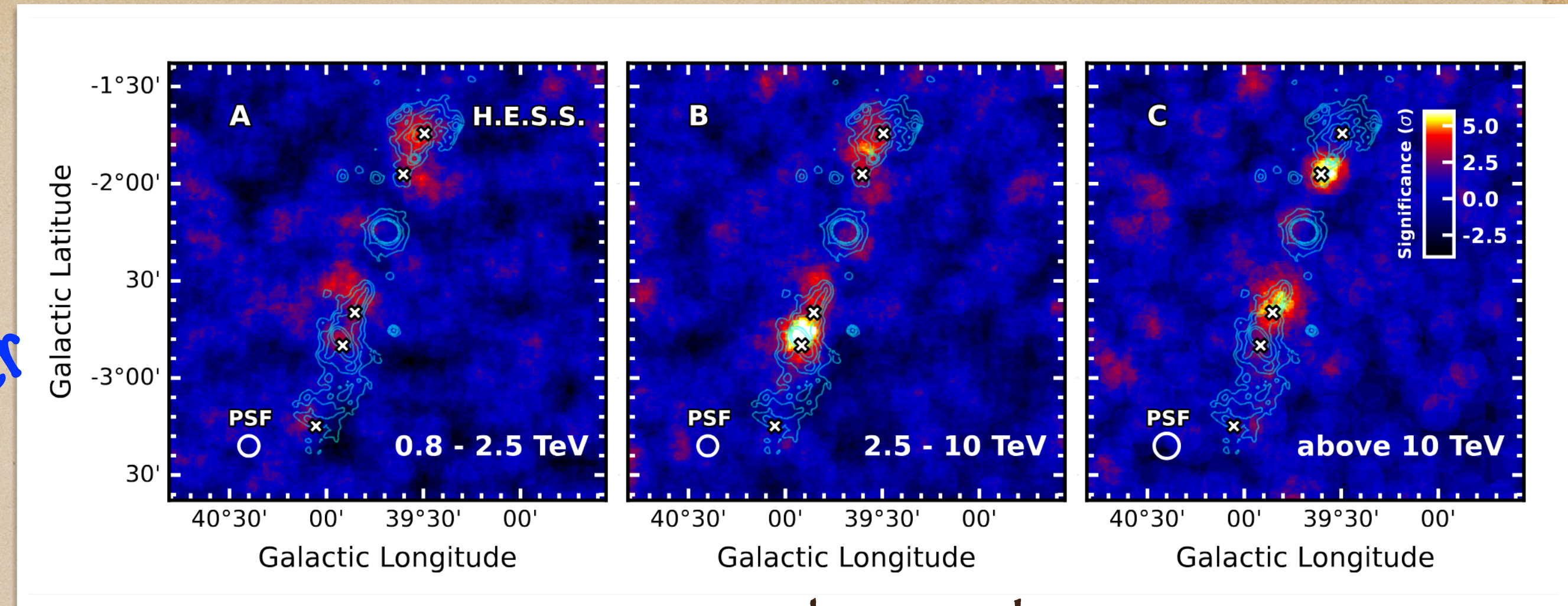
SS 433 in W50 radio nebula



# microQSOs

- ◆ Energy-dependent morphology of SS433

Wagner



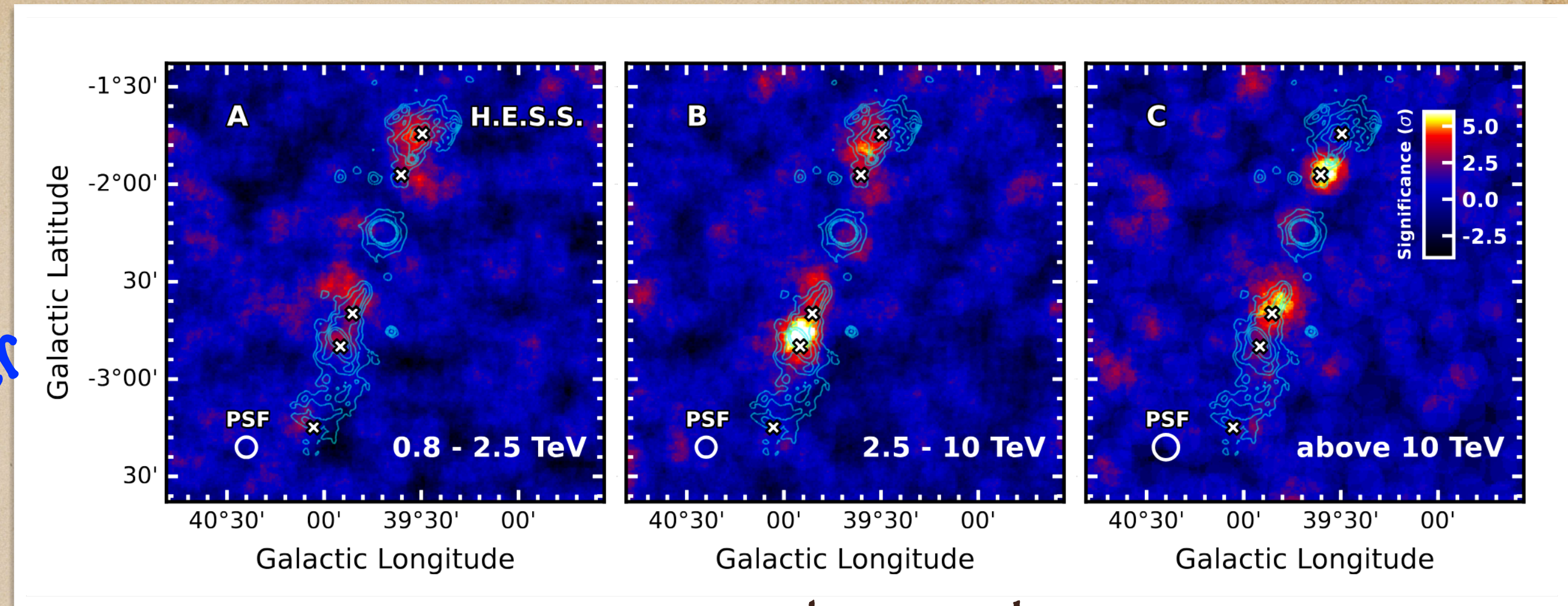
Lower  $E$  at larger distances



# microQSOs

- ◆ Energy-dependent morphology of SS433

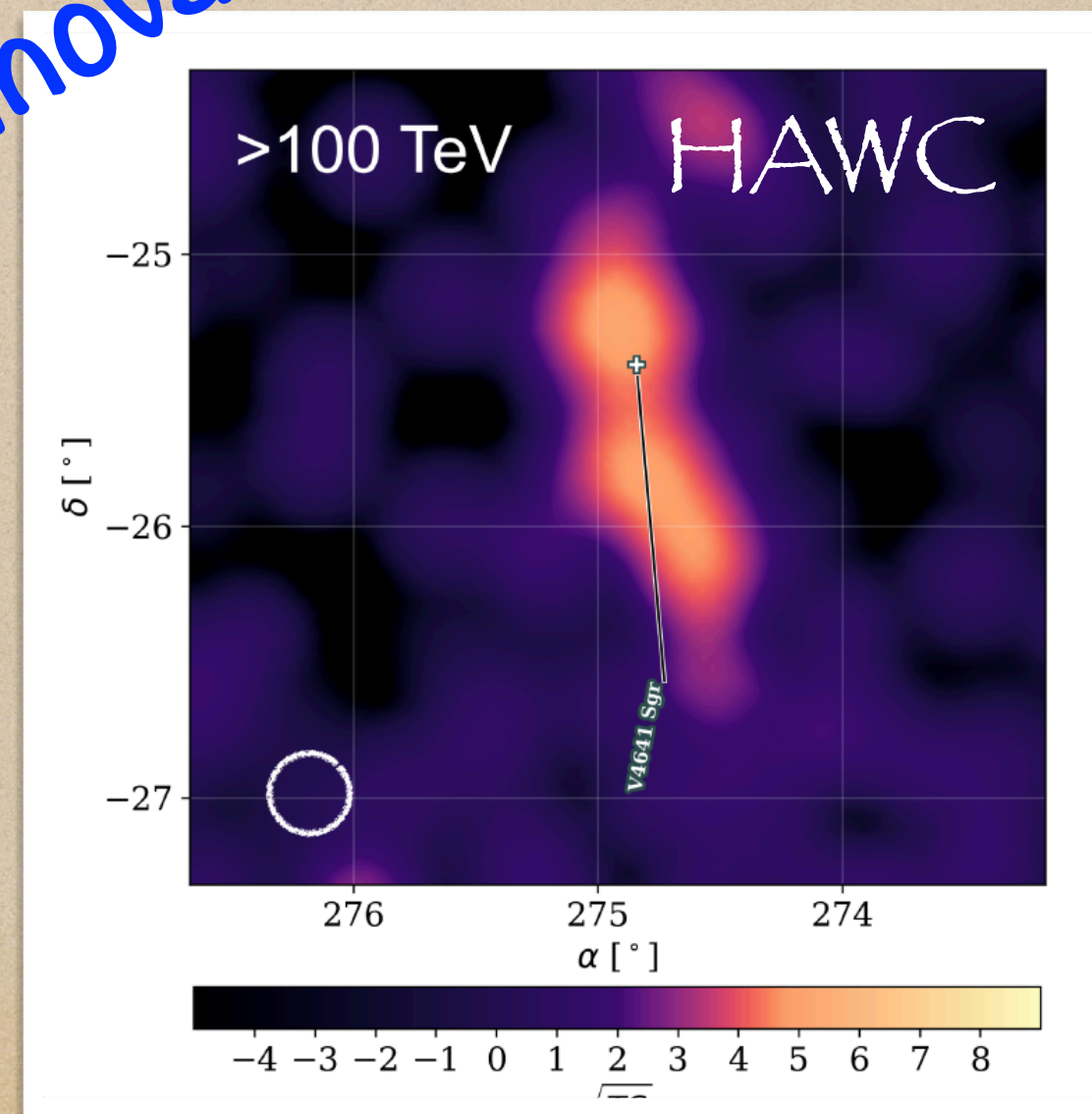
Wagner



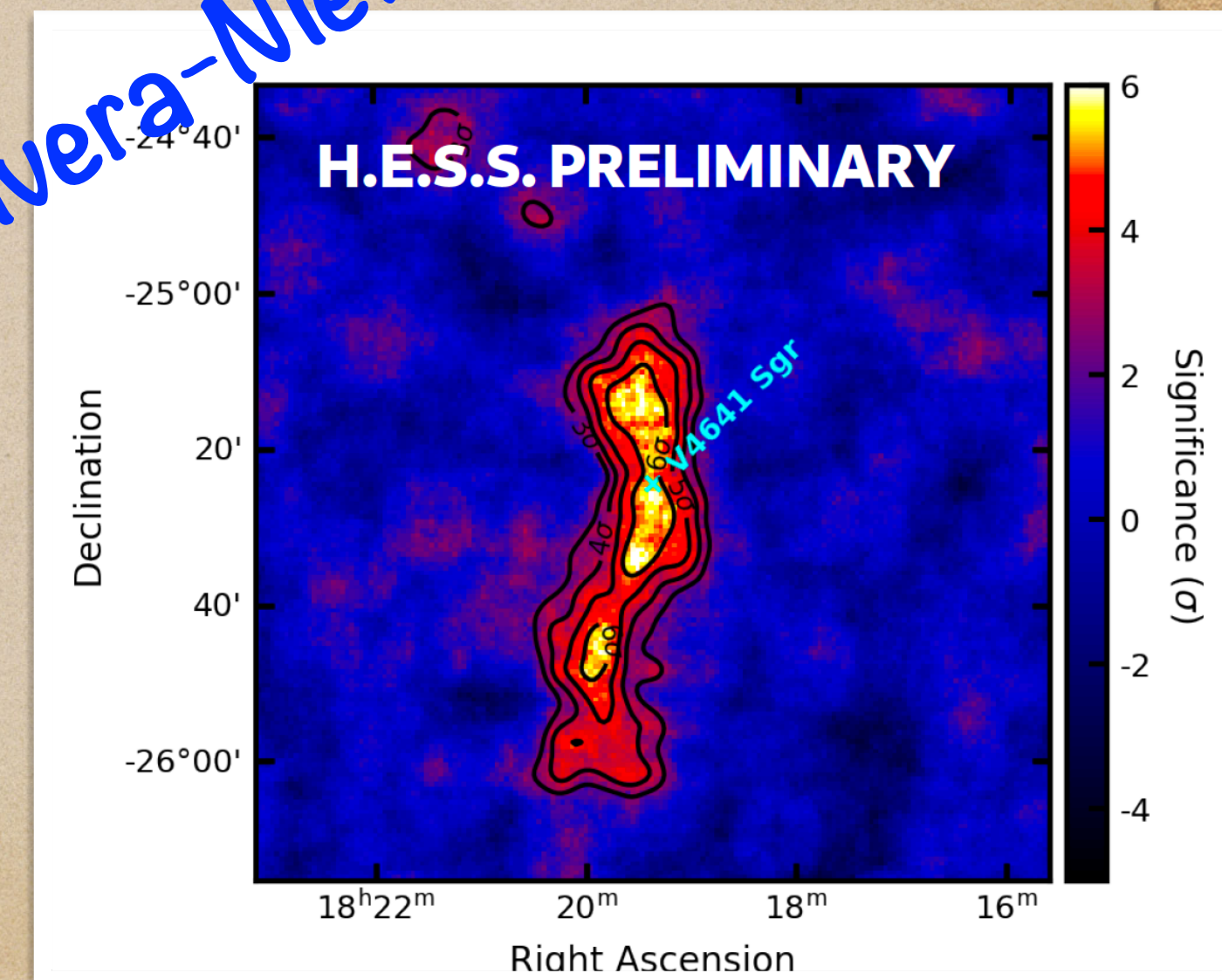
Lower E at larger distances

- ◆ Large scale (~100 pc) elongated structure around V4641 Sgr

Casanova



Olivera-Nieto

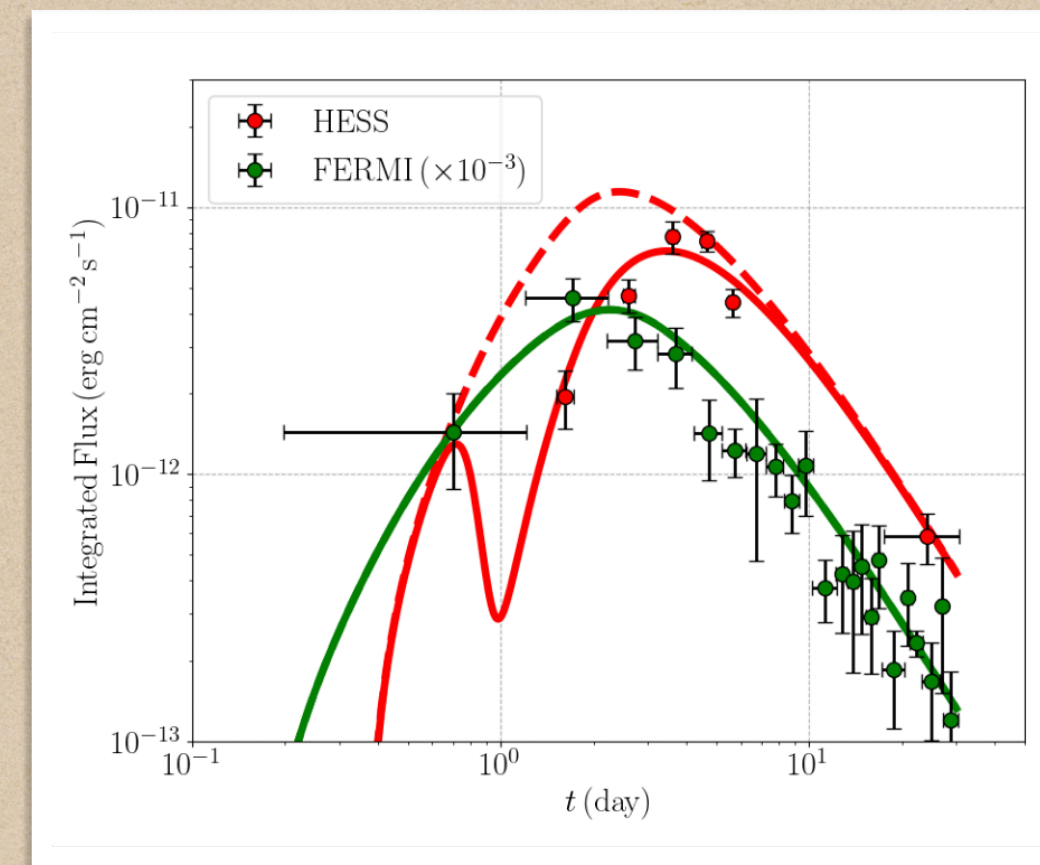




# WD binaries (Novae)

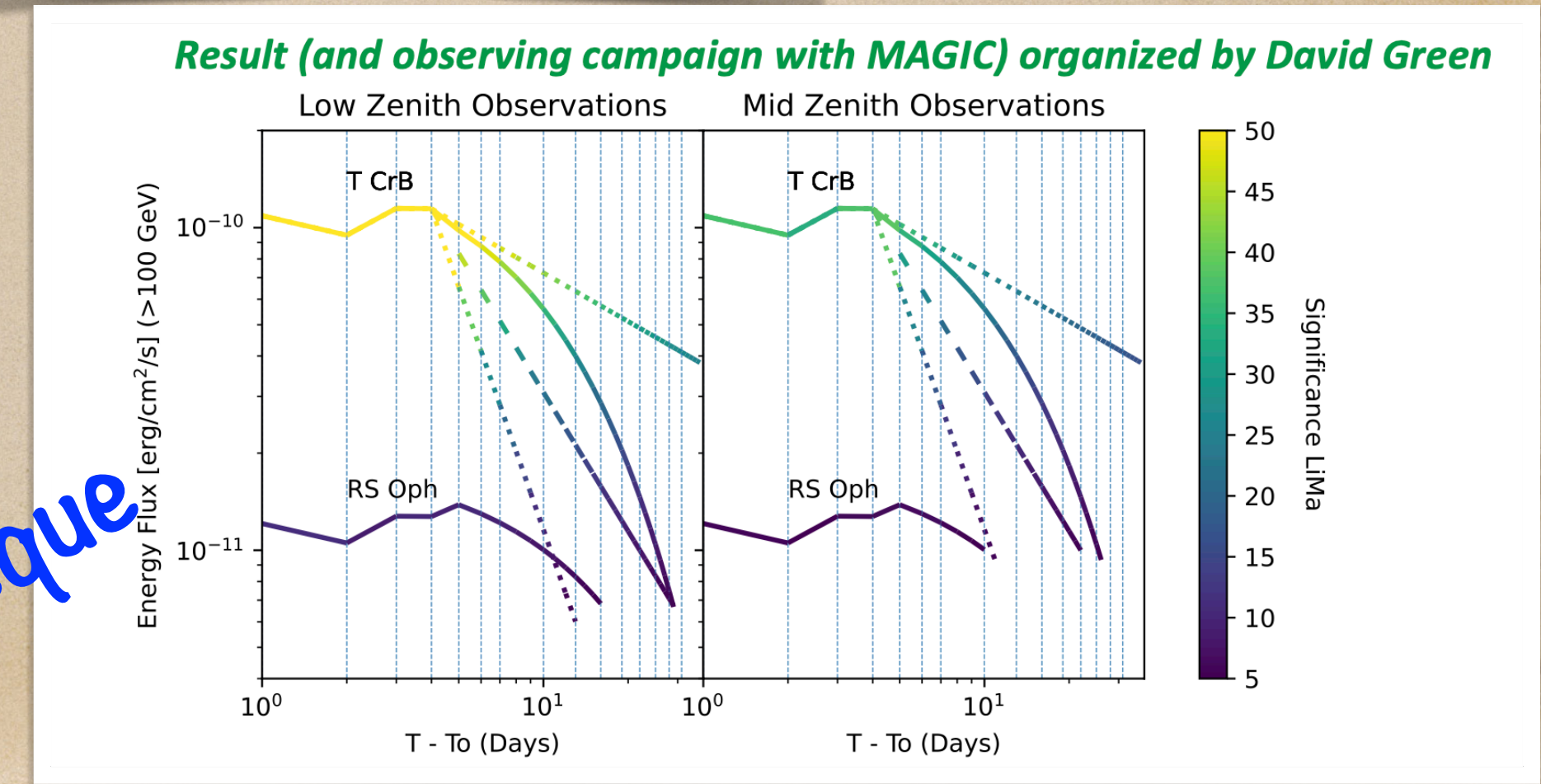
- ◆ Several Novae detected by Fermi/LAT (none at TeV yet...)
- ◆ RS Oph (WD + red SG) - absorption by optical photons can explain TeV-GeV delay in light curve
- ◆ Great expectations for the predicted (2024?) outburst of T CrB: ~80 yr recurrent Nova

Fauverge



Phan

Paneque





# Massive Star Clusters

- ◆ An old idea... "SNOBs"

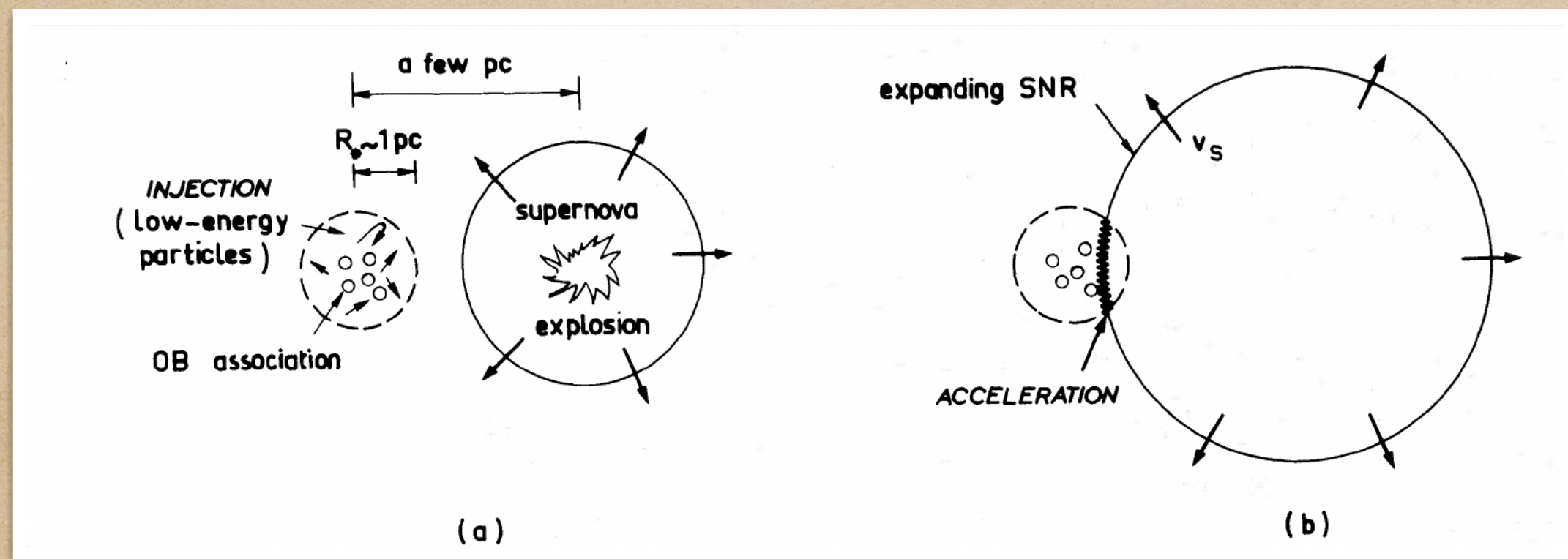
( $\approx$ SNR + OB assoc or HII region)

ON GAMMA-RAY SOURCES, SUPERNOVA REMNANTS, OB ASSOCIATIONS,  
AND THE ORIGIN OF COSMIC RAYS

THIERRY MONTMERLE

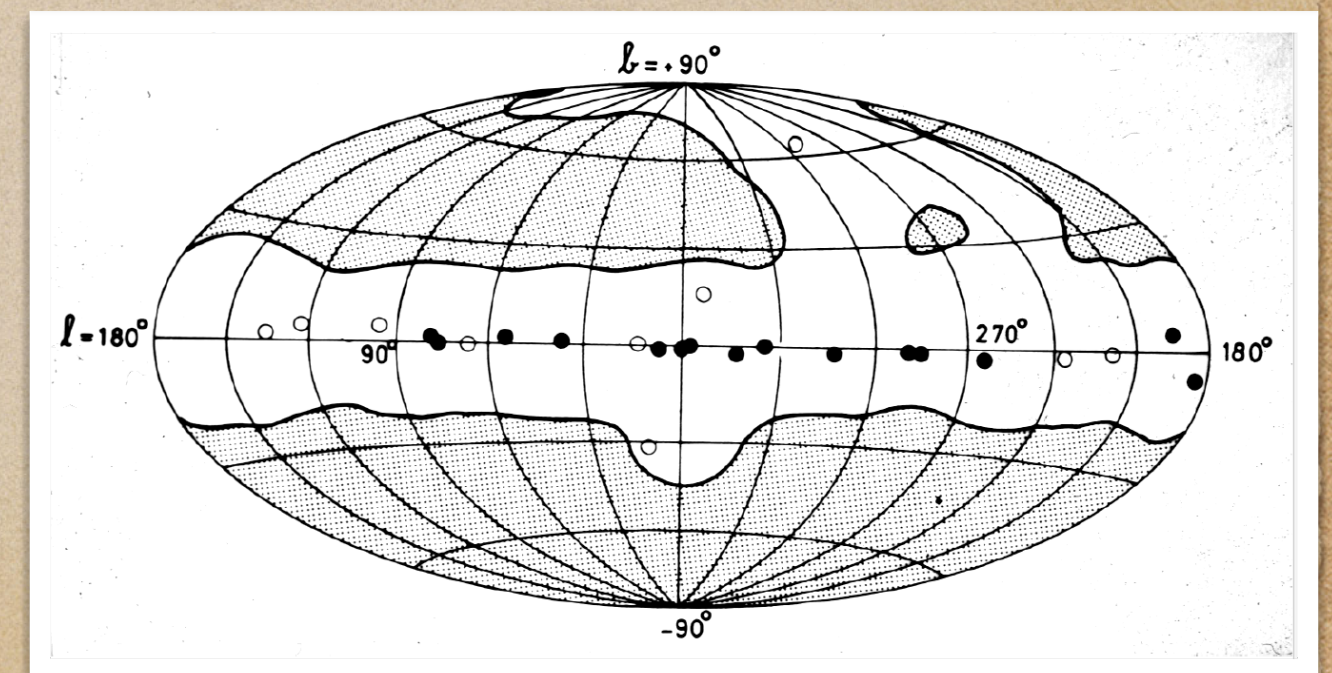
Section d'Astrophysique, Centre d'Etudes Nucléaires de Saclay, France

Received 1978 July 26; accepted 1979 January 5



Injection of non-thermal particles from OB stars and subsequent acceleration in SNR shocks

SNR as a class not strong  $\gamma$ -ray emitters among COS-B sources...  
only the SNOBs





# Massive Star Clusters

- ◆ An old idea...  
role of stellar winds

**GAMMA RAYS FROM ACTIVE REGIONS IN THE GALAXY:  
THE POSSIBLE CONTRIBUTION OF STELLAR WINDS\***

CATHERINE J. CESARSKY and THIERRY MONTMERLE

*Service d'Astrophysique, Centre d'Etudes Nucléaires de Saclay, 91191 Gif-sur-Yvette Cedex, France*

1983

Kinetic luminosity  $10^{35-36}$  erg/s

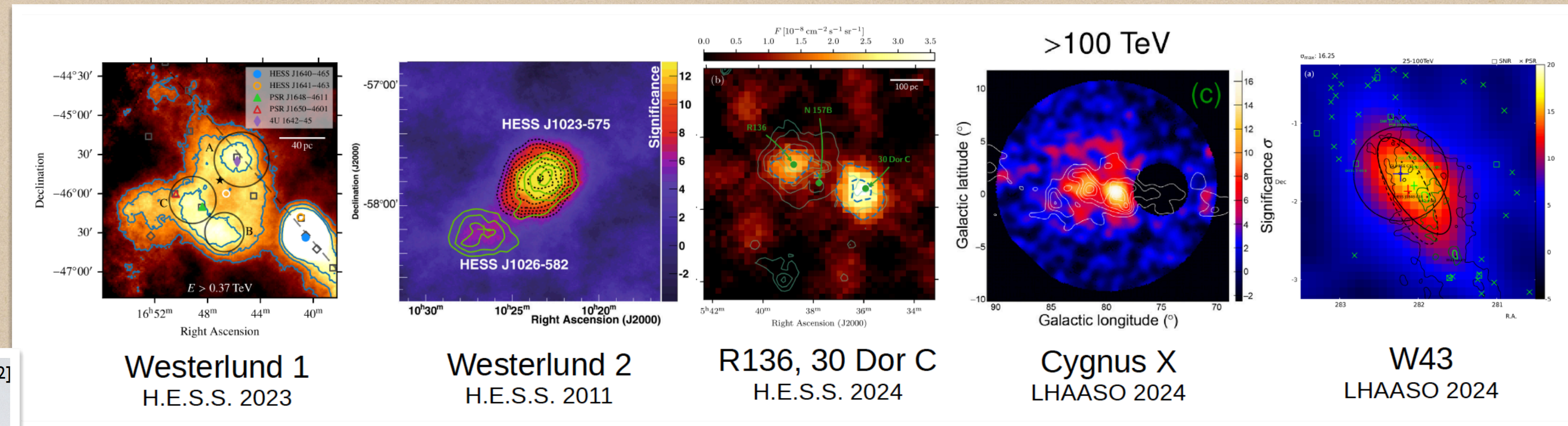
Integrated over few million yrs lifetime becomes comparable to that of SNe

Young OB associations are  $\gamma$ -ray sources, but SNe contribution dominant for CR production

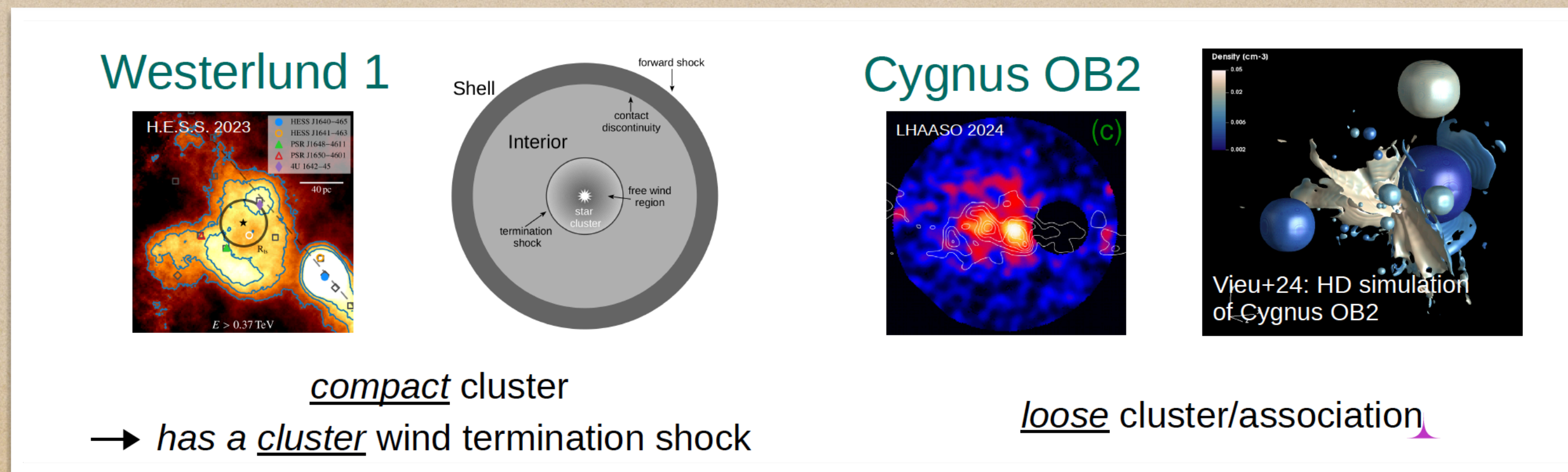


# Massive Star Clusters

- Several young MSC detected at VHE/UHE in MW (and LMC!): potential contributors of 1-100 PeV CRs



Cygnus Cocoon (GeV-TeV) [Fermi 2012, HAWC 2022]  
 Westerlund 1 (TeV) [HESS collaboration 2012]  
 Westerlund 2 (GeV, TeV?) [Yang et.al 2018]  
 NGC 3603 (GeV, TeV) [Yang et.al 2017]  
 W43 (GeV, TeV?) [Yang et.al 2020]  
 W40 (GeV) [Sun et.al 2019]  
 G25/RSGC I [Sun et.al 2020]  
 Carina nebular [Ge et.al 2022]  
 M17 [Liu et.al 2022]



Härer

A variety of cases

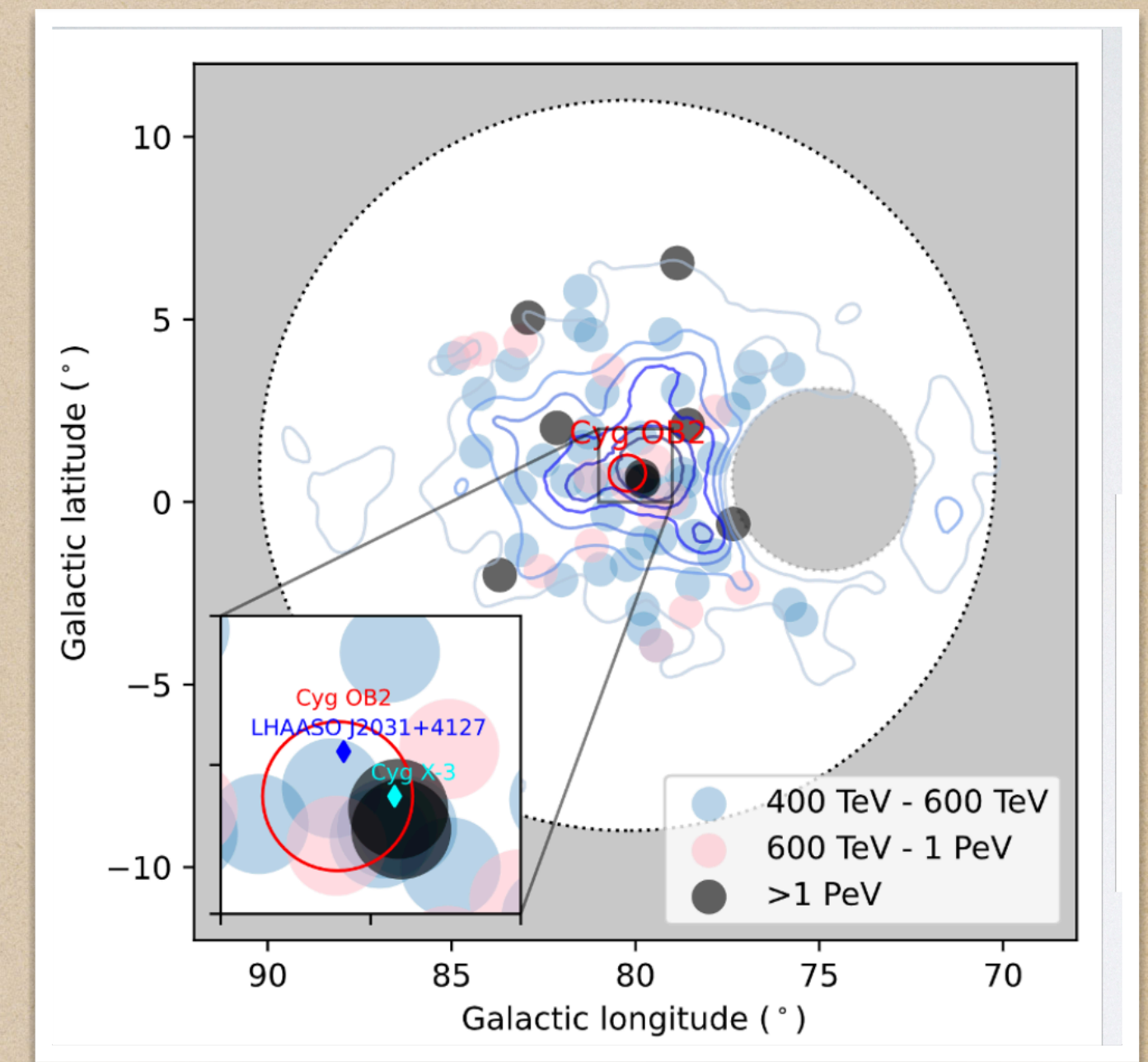
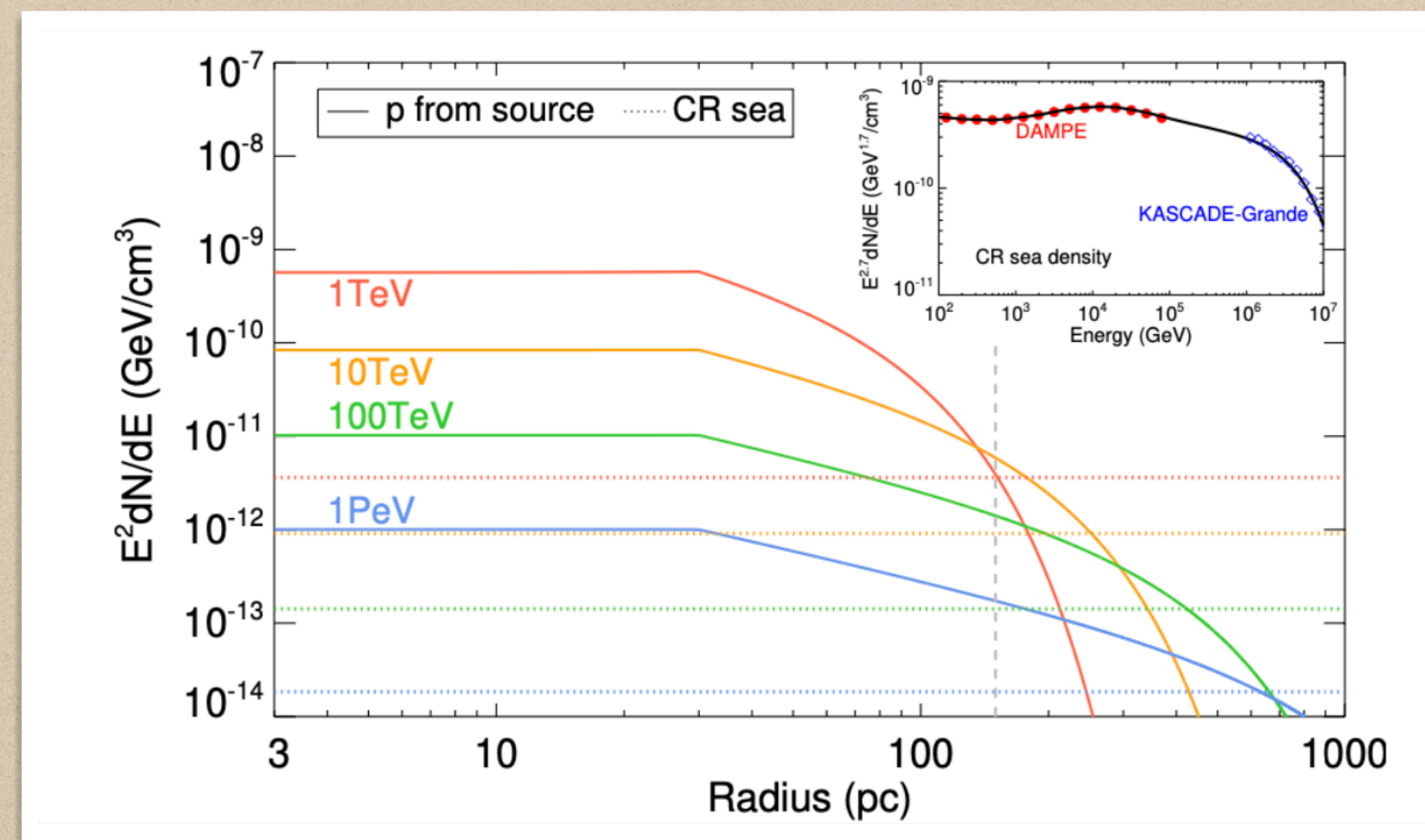


Ruizhi Yang

# Massive Star Clusters

## ◆ LHAASO results on Cyg OB2

Energy density of high E protons much higher than CR sea up to large radial distances



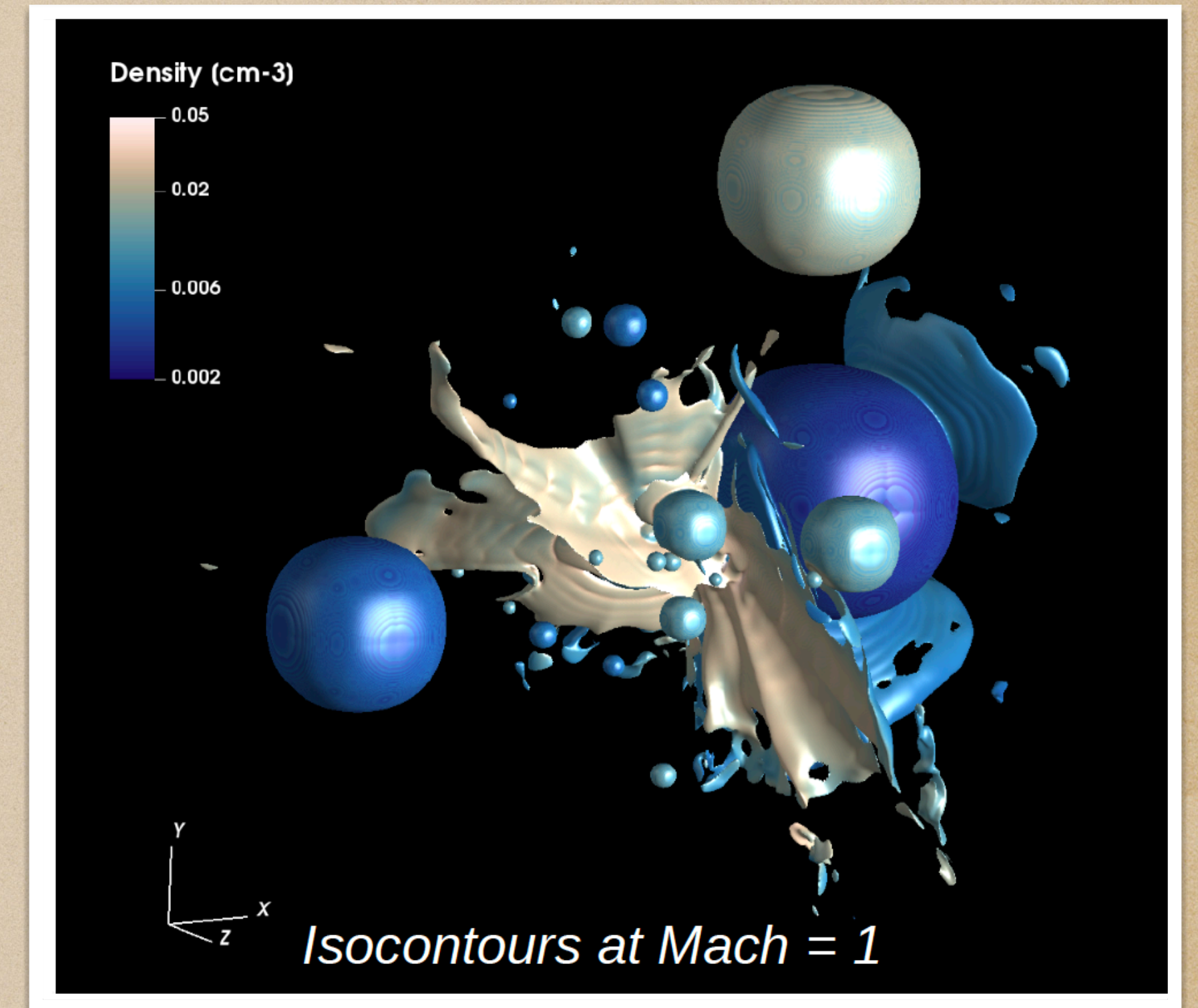
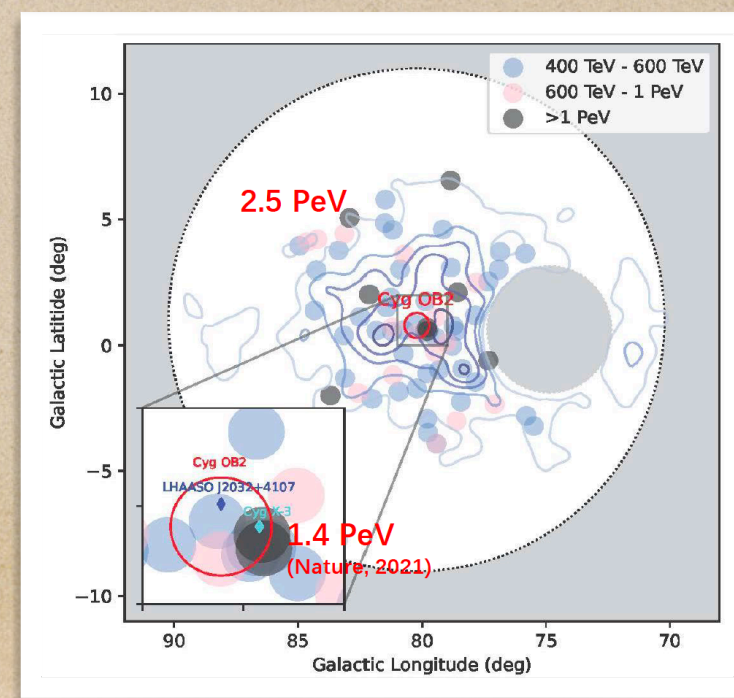
Central concentration of highest E photons



# Massive Star Clusters

View

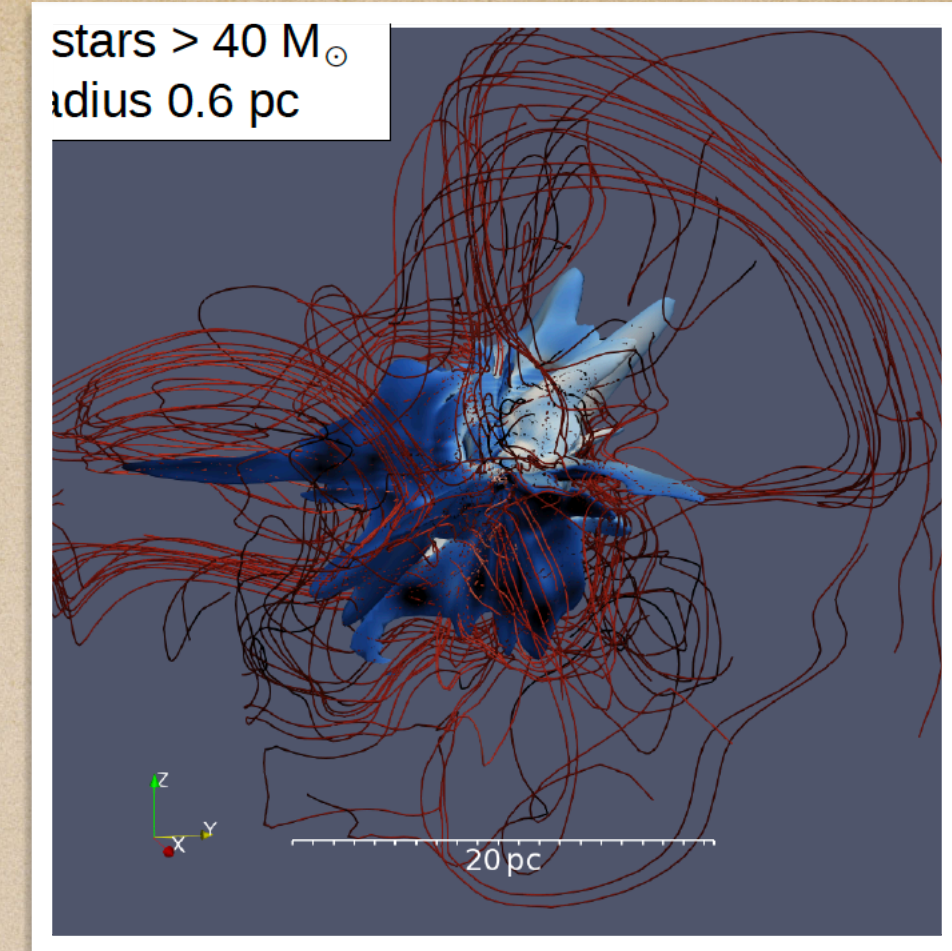
- ◆ large-scale hydrodynamic simulations of Cyg OB2, resolving individual massive star winds and their interactions
- ◆ Leptonic origin for GeV emission (no target gas close to powerful stars)
- ◆ A past powerful SN needed to account for PeV emission  
(plausible for cluster age of 3-5 Myr)



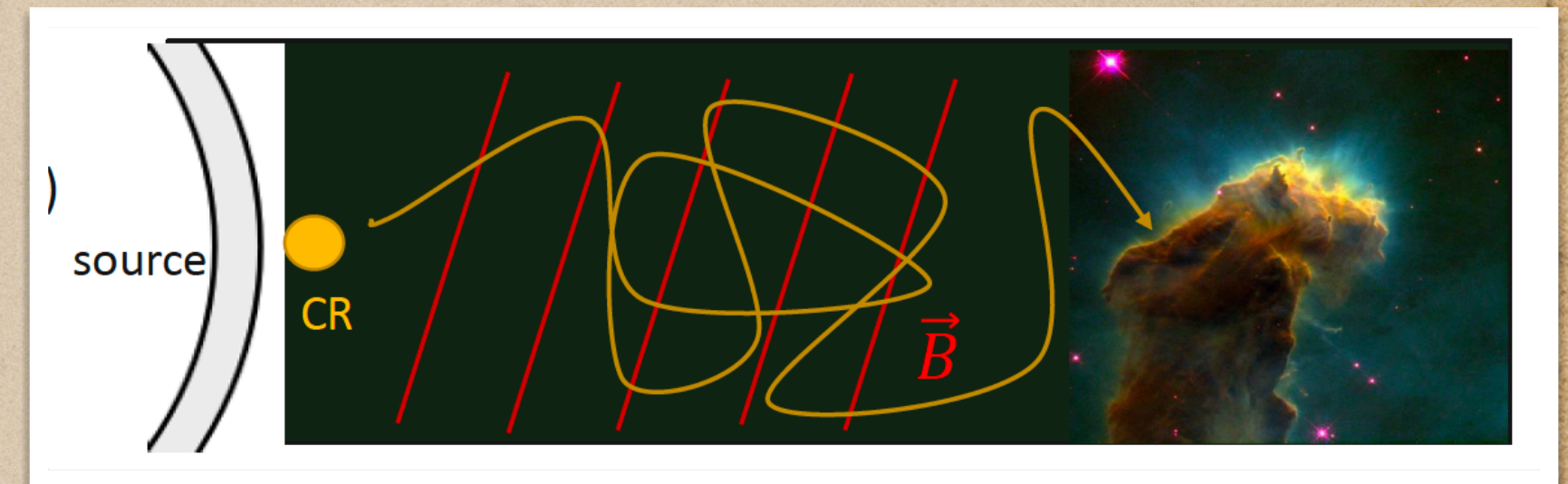


# Massive Star Clusters

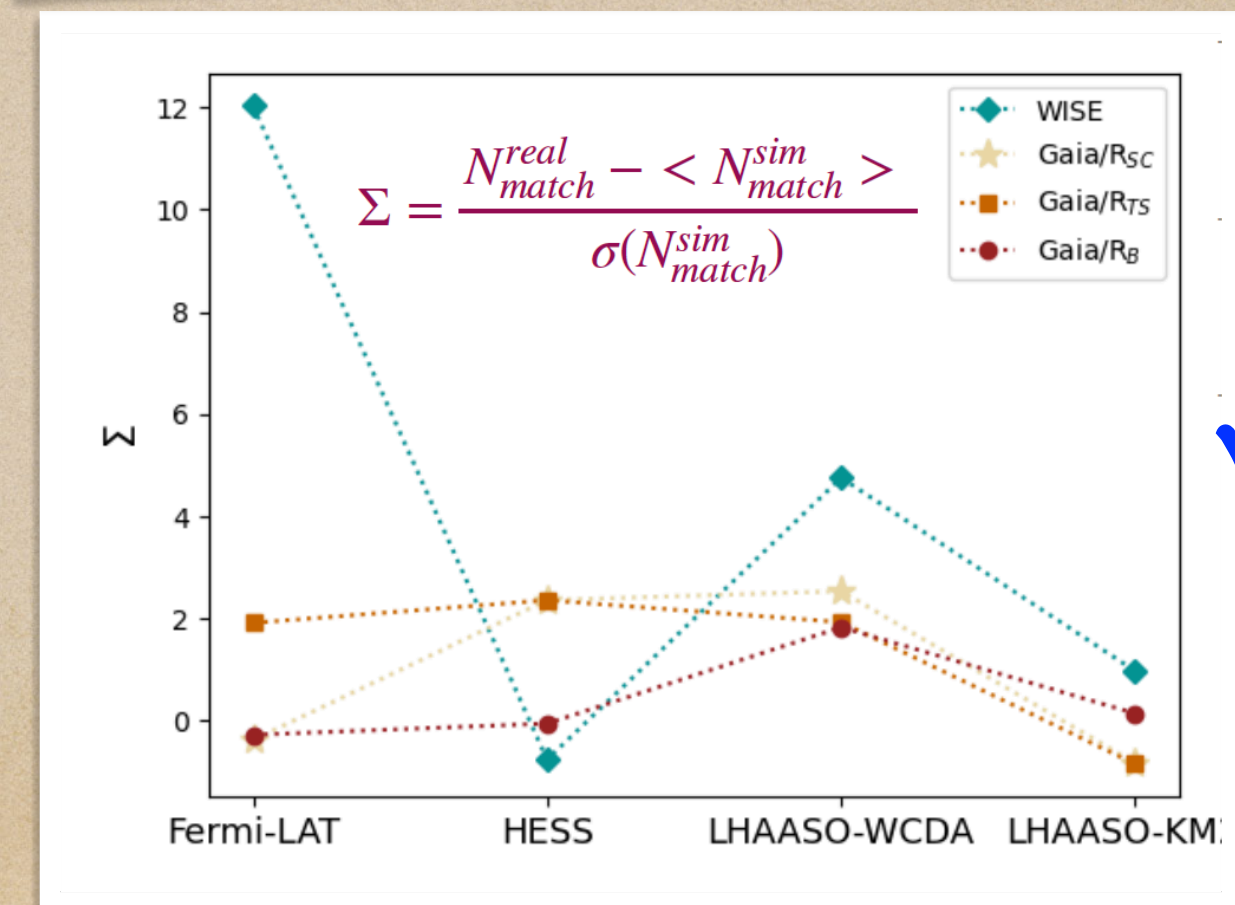
- ◆ 3D MHD simulations → importance of complex B field morphology and interaction between individual winds
- ◆ Model of escape and transport of CR between young MSC and MC, and compute expected  $\gamma$ -rays
- ◆ Significant correlation between GeV sources and young clusters embedded in dense MC



Härer



Inventar



Peron



◆ Several other interesting talks on MSC:

contribution to diffuse emission (**Menchiari**)

prospects for future facilities (**Bonollo, D'Ai,...**)

◆ ..and on SNRs/PWNs

SN 1006 (**Tao**) ; SNR G69.7+1.0 (**Rigoselli**) ; G106.3+2.7 (**Emery**)

possible association of G284.3-1.8 and g-ray binary 1FGL J1018 (**Tanaka**)

correlations btw MC illuminated by SNRs and unid. LHAASO srcs (**Mitchell**)

Vela X region (**Sei**)

Fermi/LAT u.l. on nearby SN 2023ixf  $\rightarrow \epsilon < 1\%$  (**Martí-Devesa**)

Importance of multi wavelength

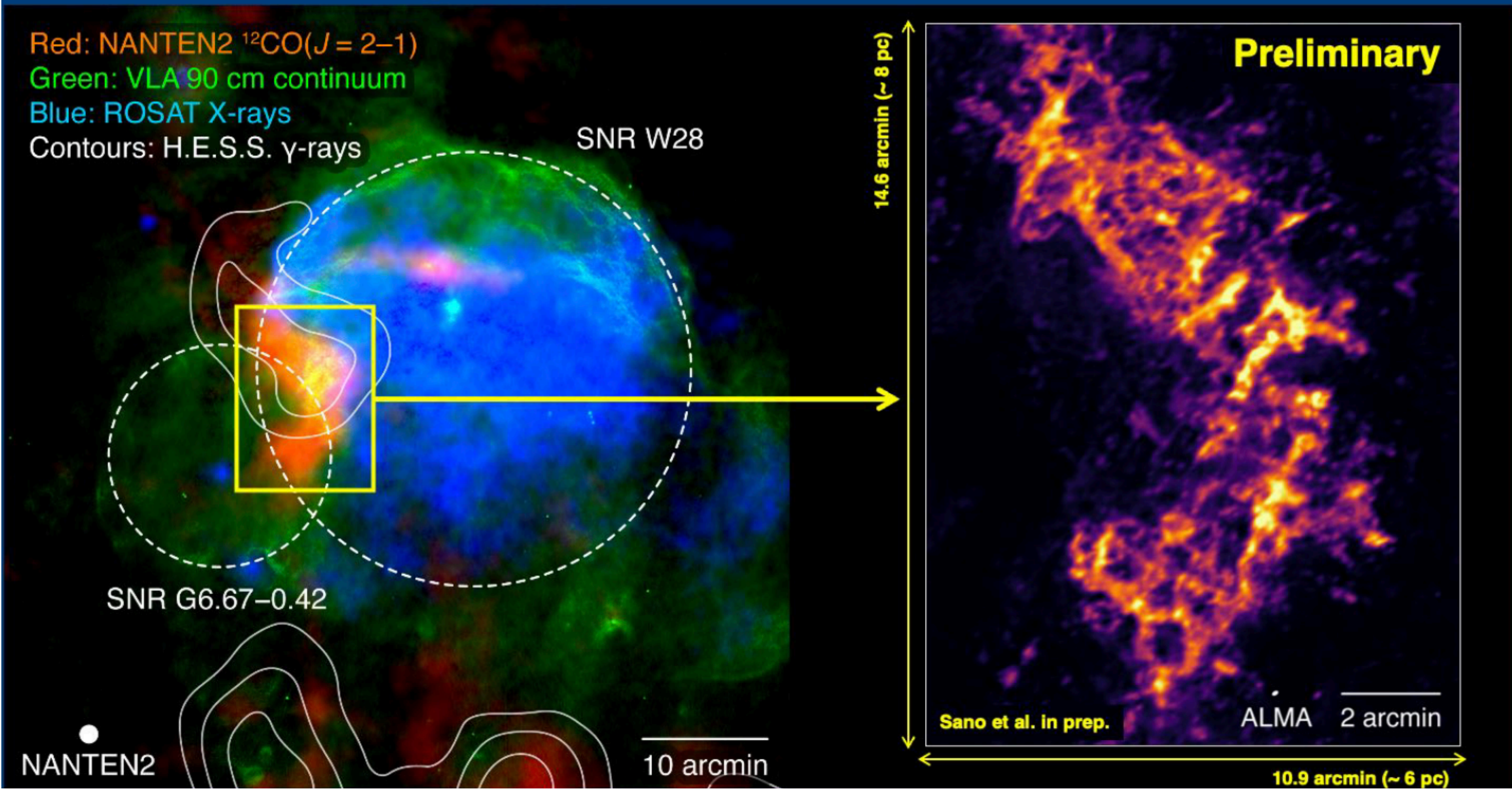


Hidetoshi Sano

# Results 1: Discovery of Proto-Molecular Filaments

7

Red: NANTEN2  $^{12}\text{CO}(J = 2-1)$   
Green: VLA 90 cm continuum  
Blue: ROSAT X-rays  
Contours: H.E.S.S.  $\gamma$ -rays





# Cosmic Rays

Felix Aharonian

In the 1960s, the pioneers of the field recognized the great potential of  $\gamma$ -ray astronomy to solve the “50-year-old puzzle” of CR ...

...yet we keep talking about the potential of  $\gamma$ -ray astronomy to solve this “110+ years old puzzle”

Hundreds of TeV sources: important laboratories of particle accelerators



# CR Acceleration & Propagation

Two excellent invited talks:

- Critical review on Acceleration issues:

SNRs still set the standards, but more work needed...

**WHERE THERE'S SMOKE THERE'S FIRE....**

*Brian Reville*



# CR Acceleration & Propagation

Two excellent invited talks:

- Critical review on Acceleration issues:

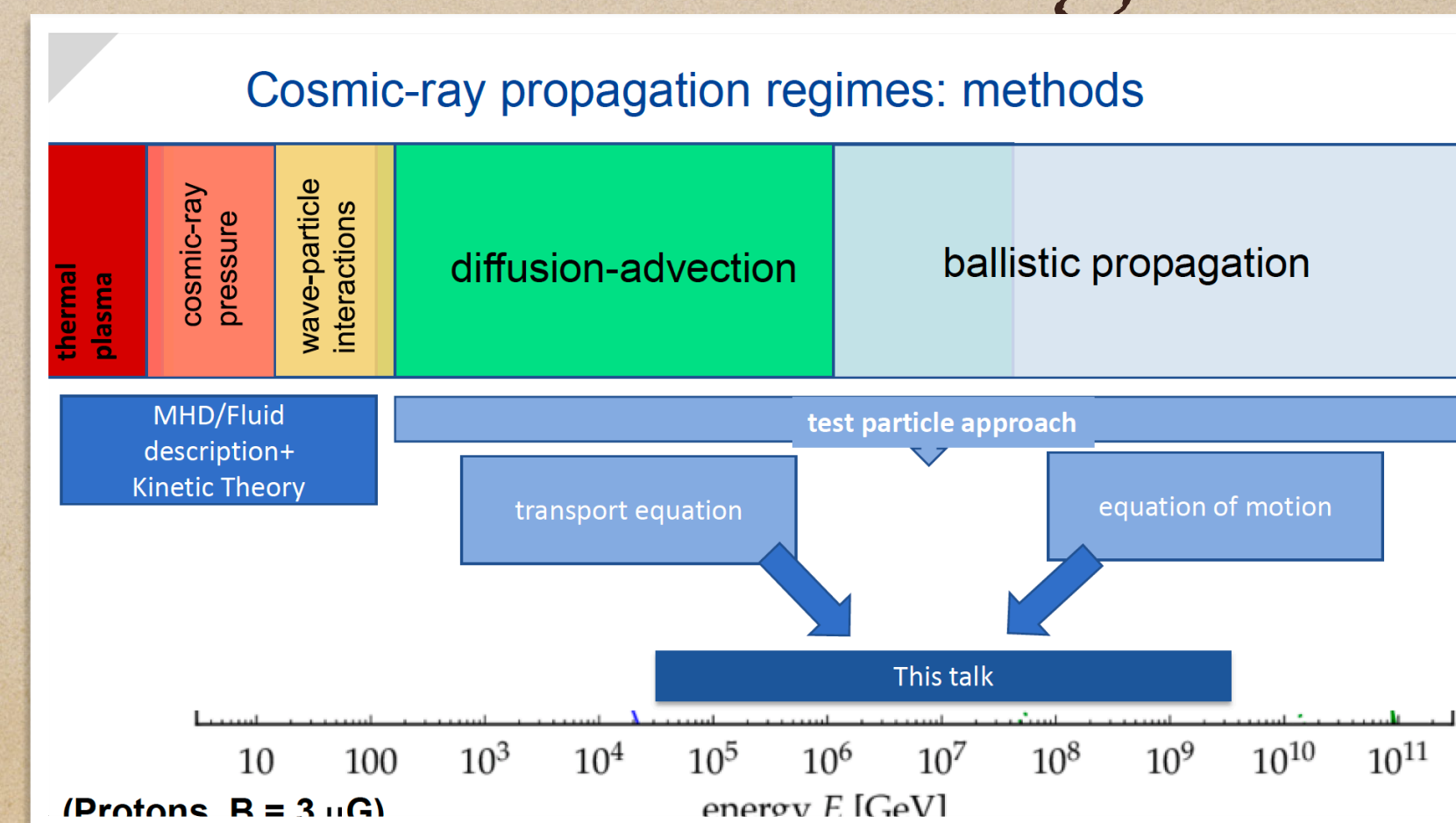
SNRs still set the standards, but more work needed...

Brian Reville

**WHERE THERE'S SMOKE THERE'S FIRE....**

- Propagation - State of the art framework for modelling CR propagation in different regimes

Julia Tjus

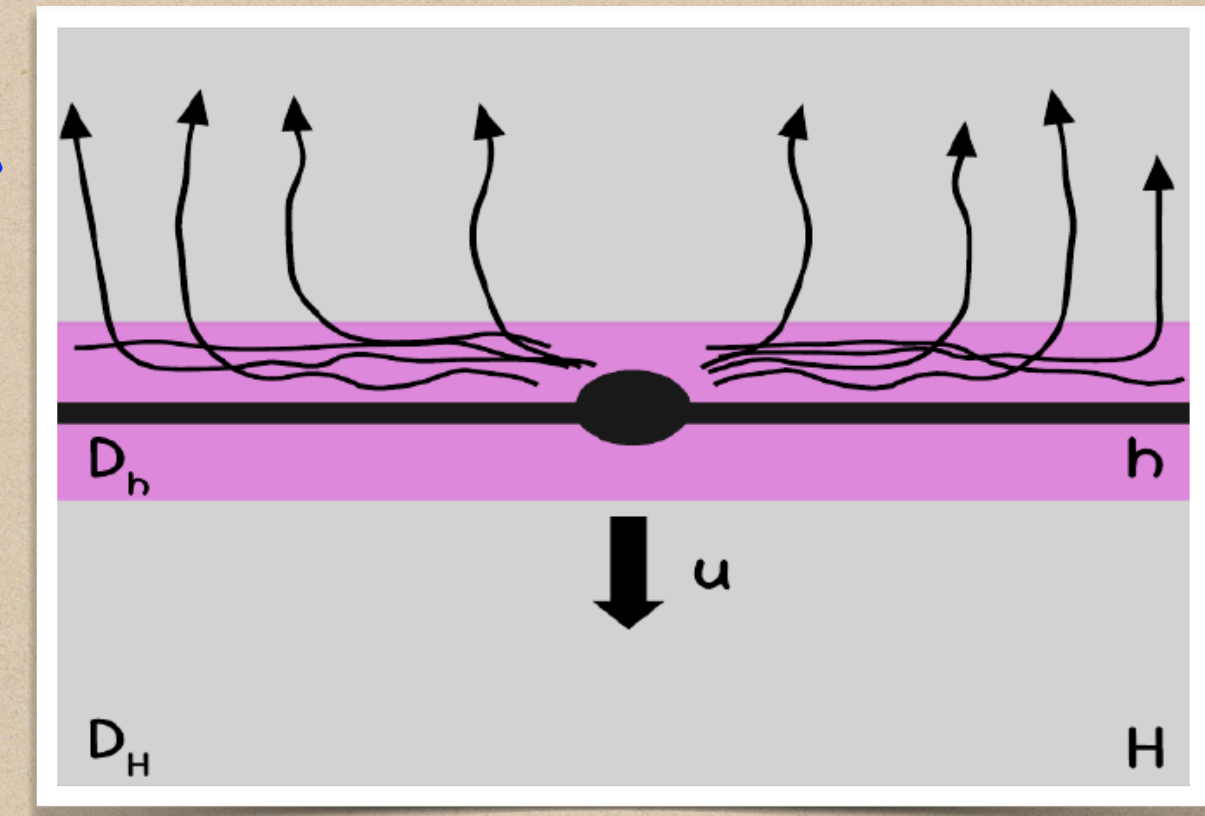




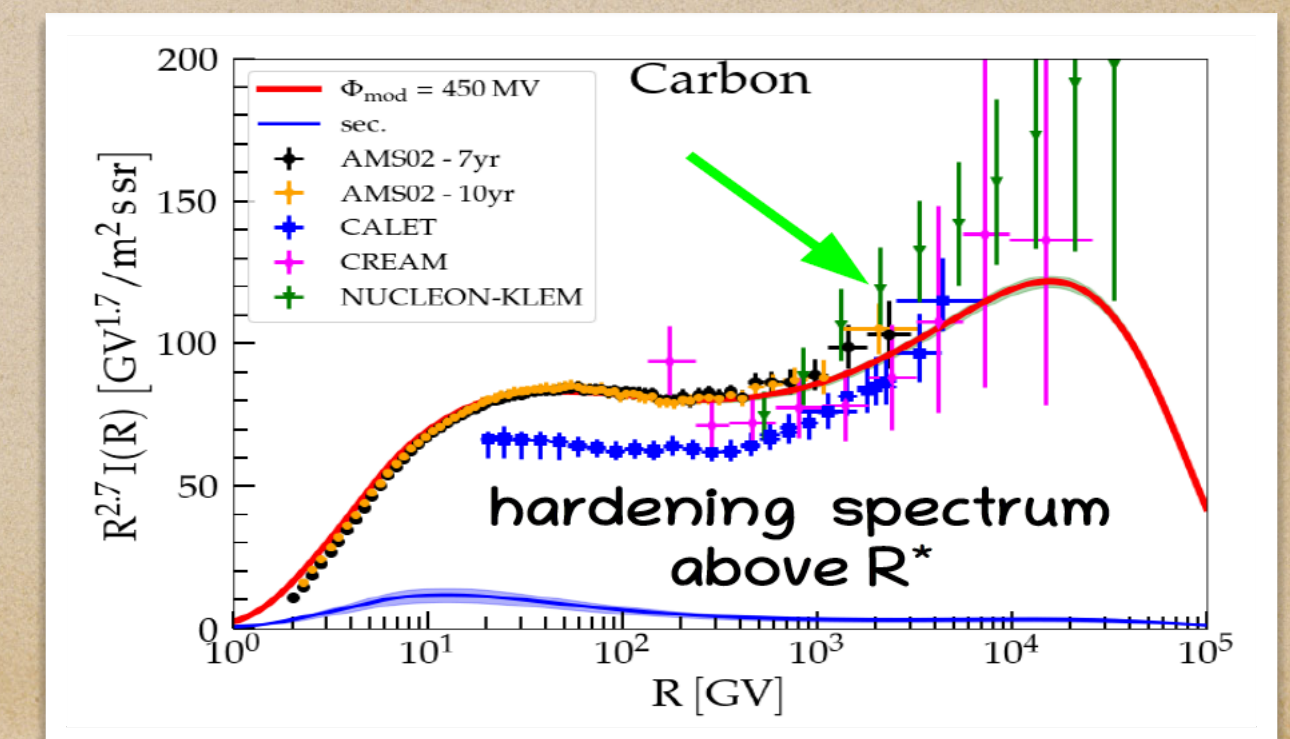
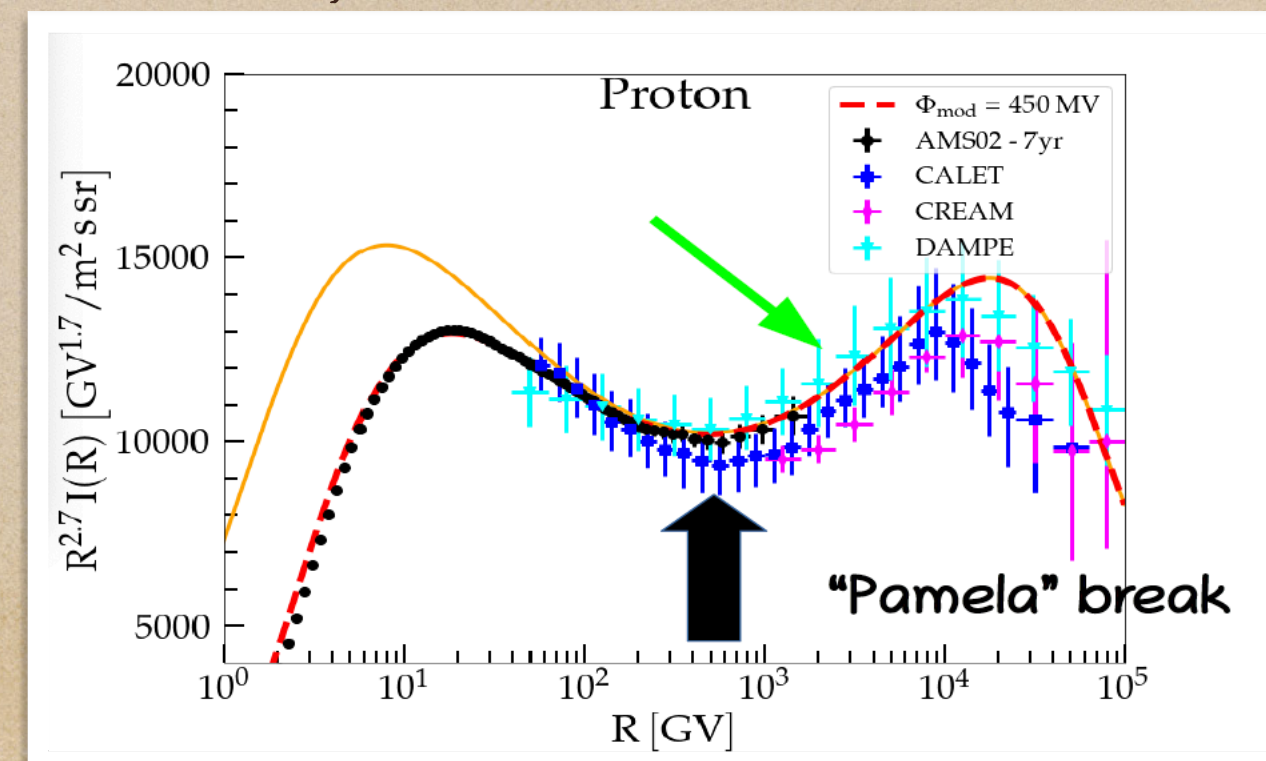
◆ Physically motivated scenario to explain several features in CR spectrum / composition based on two ideas:

*Recchia*

a) inefficient scattering in gal disk where  $B$  parallel to plane.  
CR transported to halo by  $B$  field random walk induced by turbulence



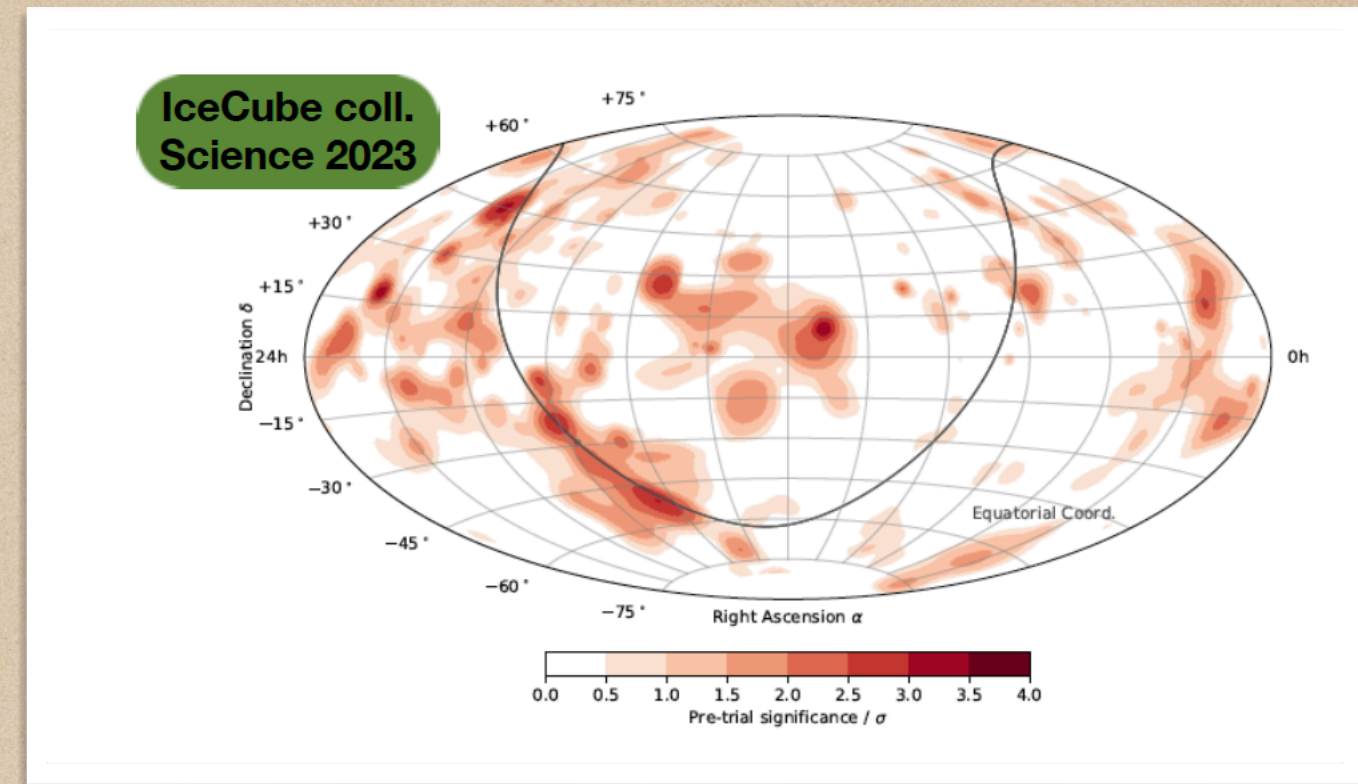
b) spectral steepening at  $\sim 15$  TV is maximum rigidity reached acceleration by the majority of SNR (only a fraction of sources, contributing to  $\sim 10 - 20\%$  of the CR population, can accelerate up to  $\sim PV$ )



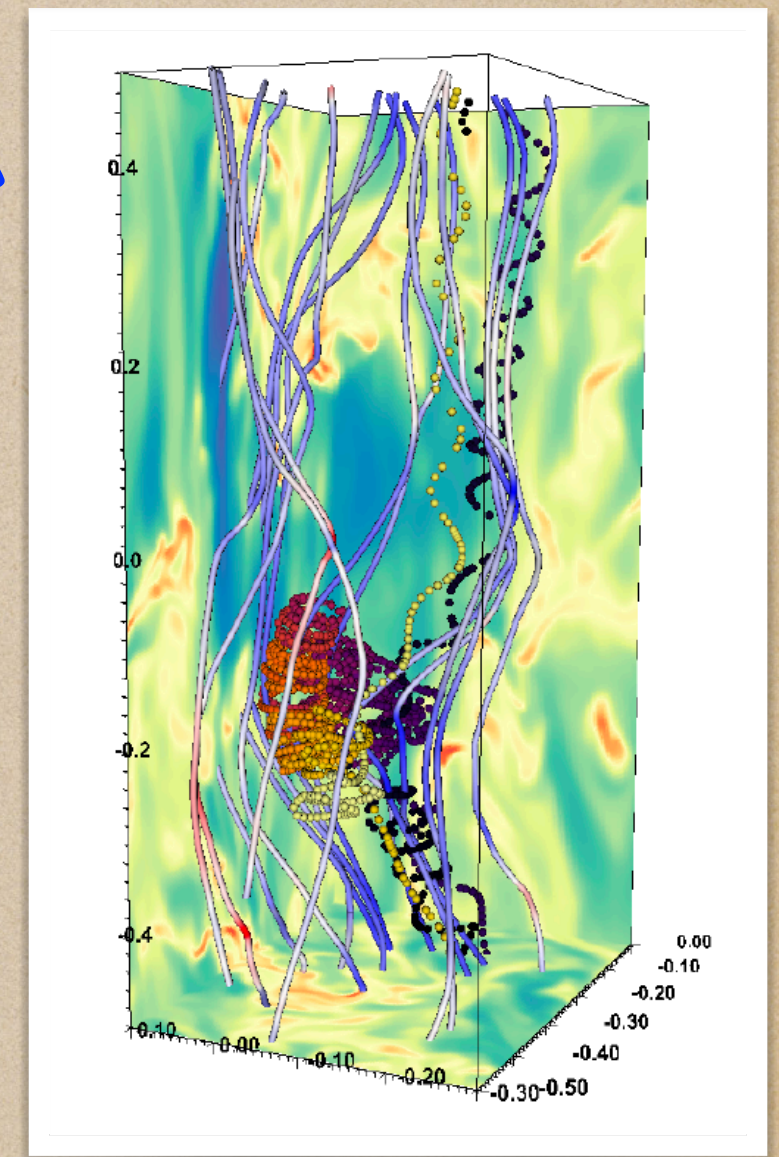


- ◆ Recently discovered flux of neutrinos from Galactic plane is above the expectations based on homogeneous diffusion can be explained by models with harder CR spectrum in inner Galaxy
- ◆ Importance of mirror diffusion  $\rightarrow$  low diffusion coefficient around sources as required for TeV halos
- ◆ anisotropic propagation with CRs injected at discrete transient sources in the disc  $\rightarrow$  clumpy diffuse emission at  $>100$  TeV  $\neq$  smoother emission  $\sim$  GeV energies.

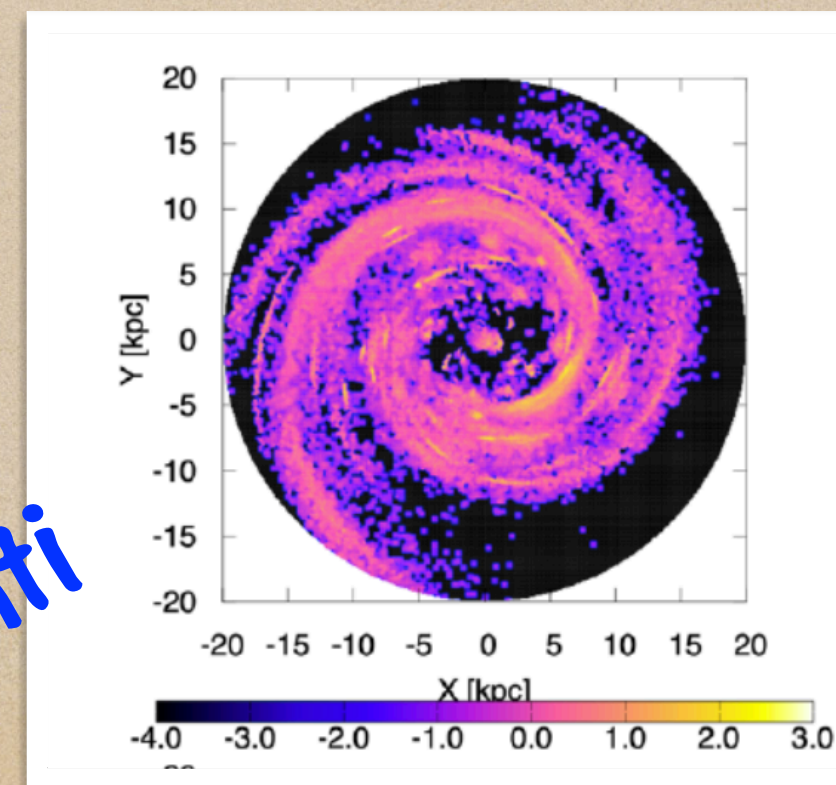
Gaggero



Barreto-Mota



Giacinti



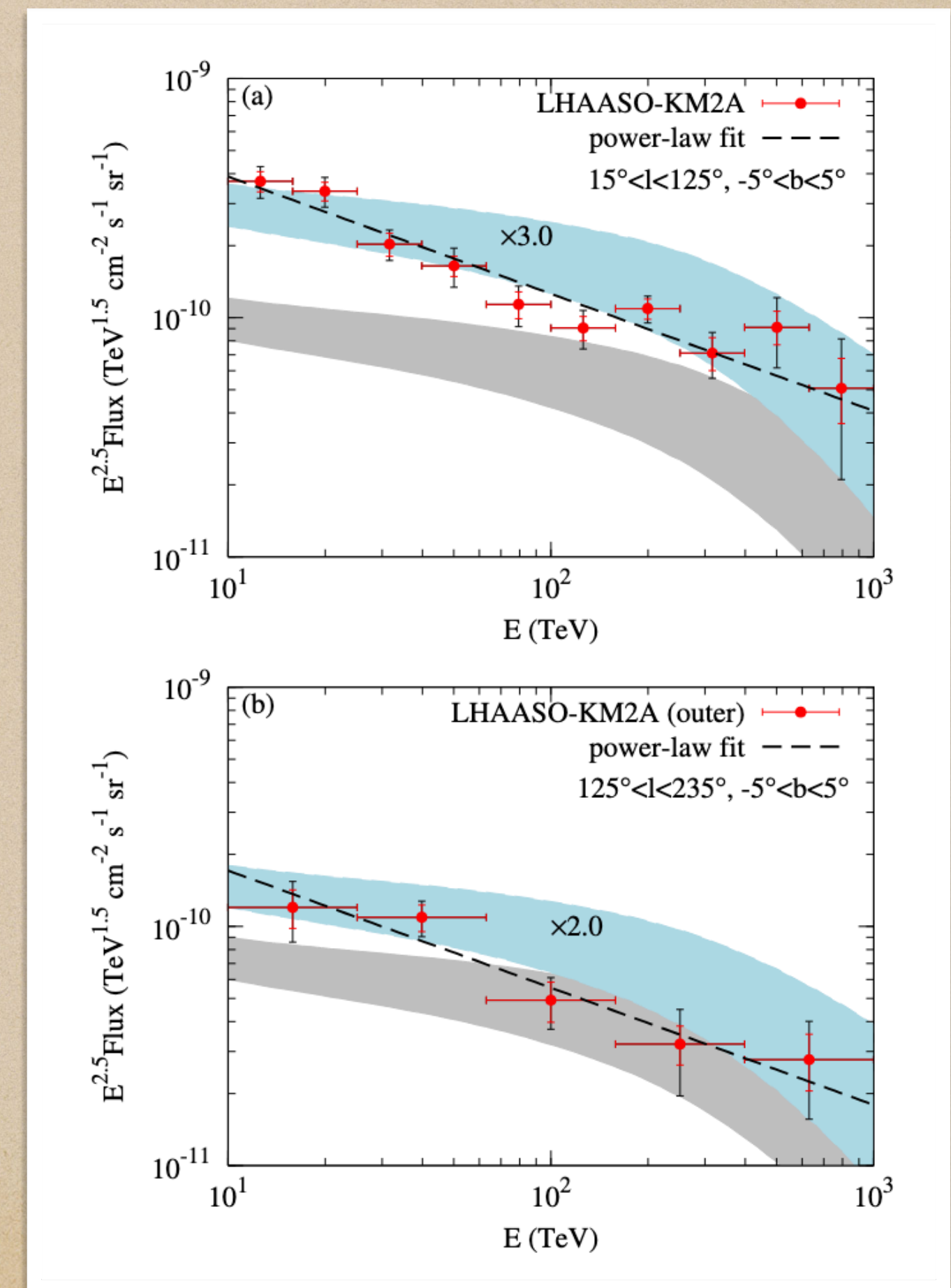


# TeV to PeV Galactic diffuse emission

Zhen Cao

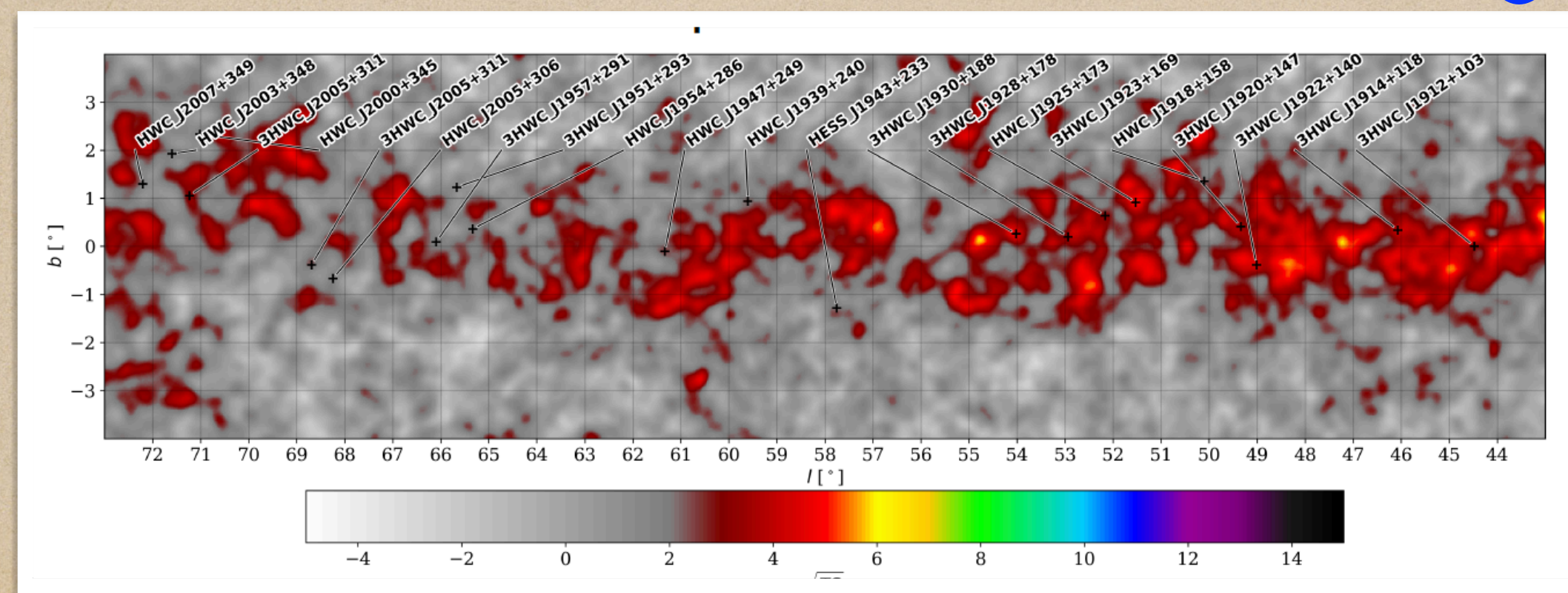
- ◆ Flux 2-3 x higher than expected

LHAASO



Casanova

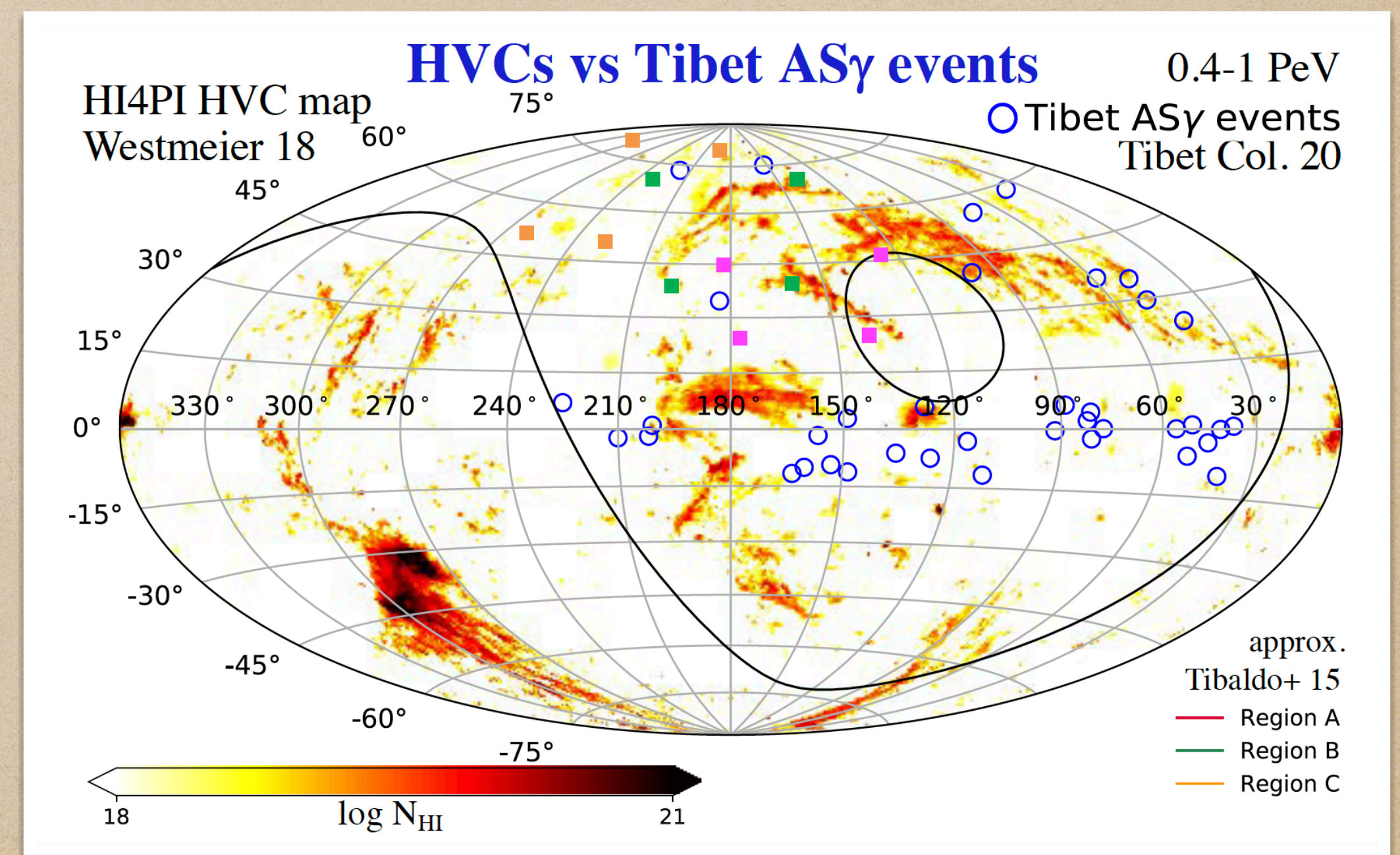
HAWC





- ◆ Observations at GeV-PeV can probe circumgalactic CR, which play important thermal and dynamical roles for the formation and evolution of the MW, but no evidence in Tibet AS-gamma data for signals associated with intermediate and high velocity clouds seen in HI

Susumu Inoue

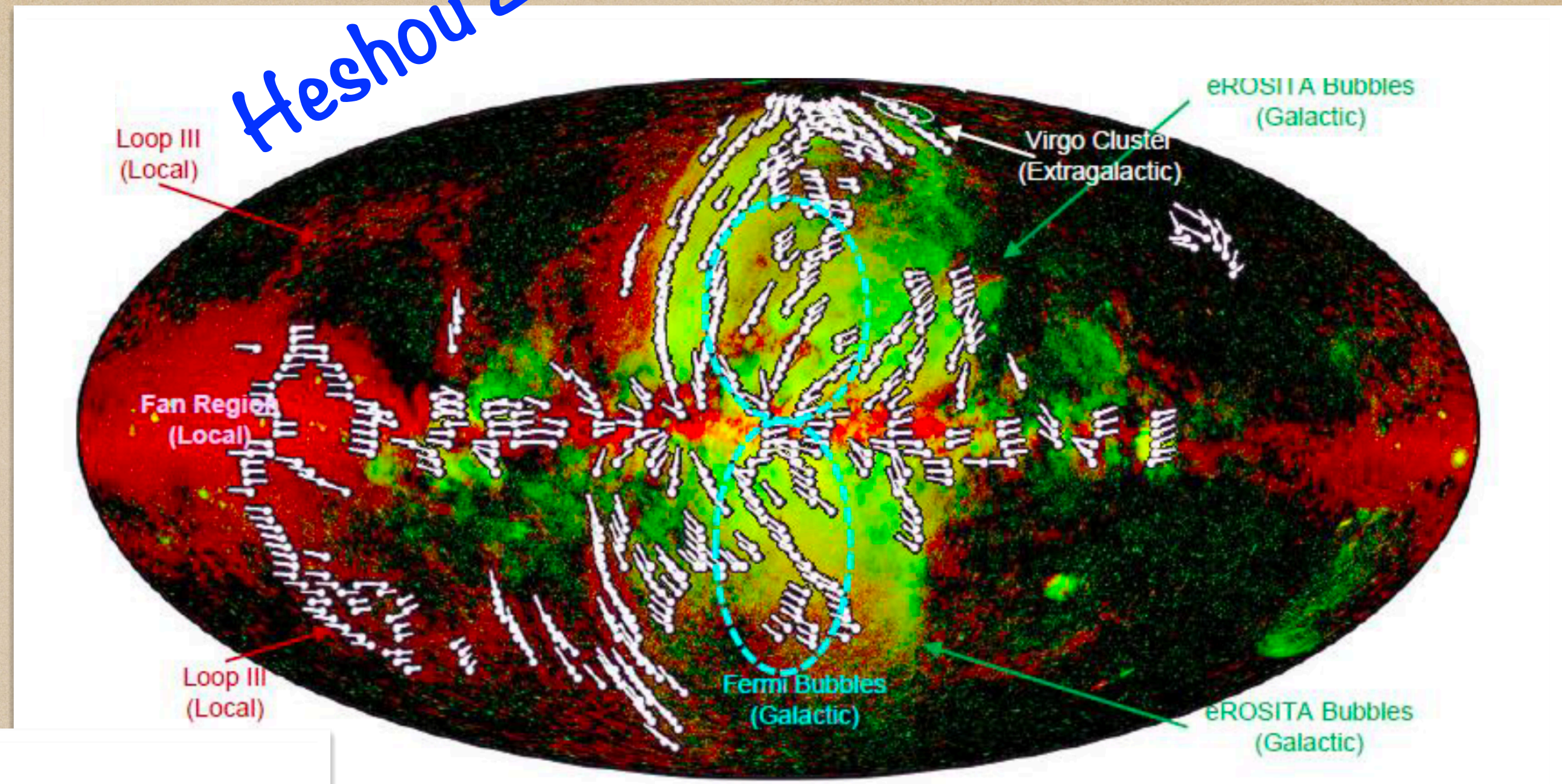




Heshou Zhang

# Fermi & eROSITA bubbles

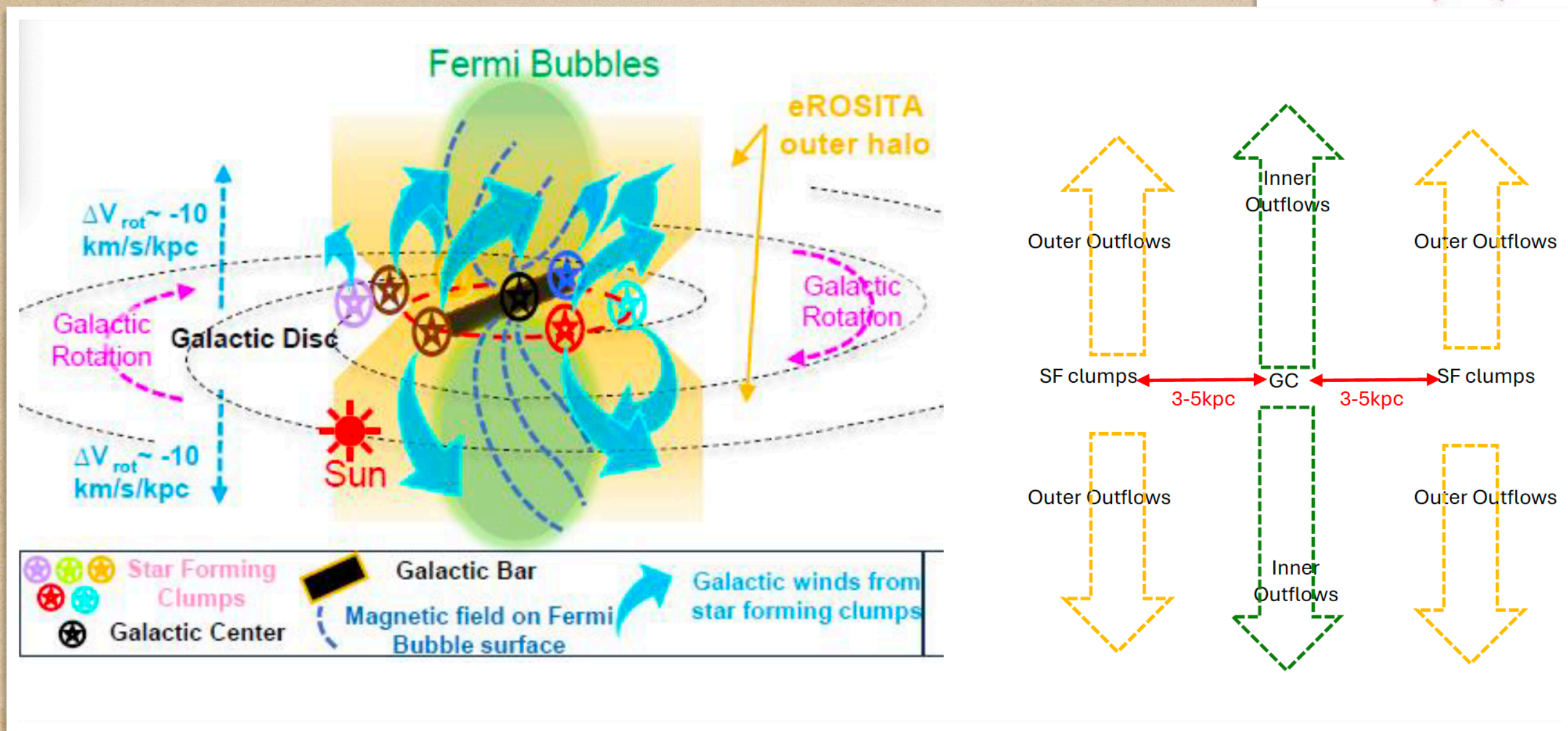
- gamma-rays and polarized radio emission  
 → kpc-scale magnetised structures in the Galactic magnetic halo which trace the Galactic outflows powered by 3-5 kpc star forming ring



iv: 2408.06312

White bars: magnetic field (23 GHz)  
 Green: 0.6-1.0 keV X-ray

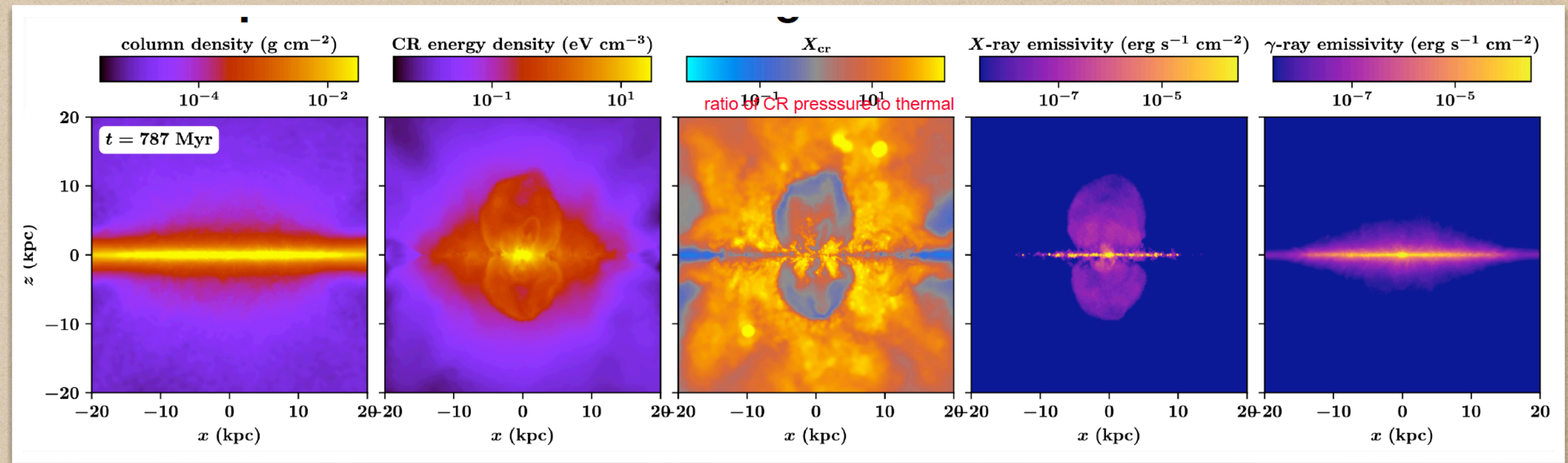
*Within Local Spiral Arm, or beyond the Galactic Disc?*





- ◆ Detailed MHD simulations  $\rightarrow$  Outflows launched by CRs from entire disk of Milky Way

Kjellgren



- ◆ AGN jet-shock can explain X-ray,  $\gamma$ , microwave observations of the Fermi bubbles  $\rightarrow$  powerful jets from SgrA\* SMBH 5 Myr ago. + TDE jet model for the origin of the SgrA lobes

Fulai Guo

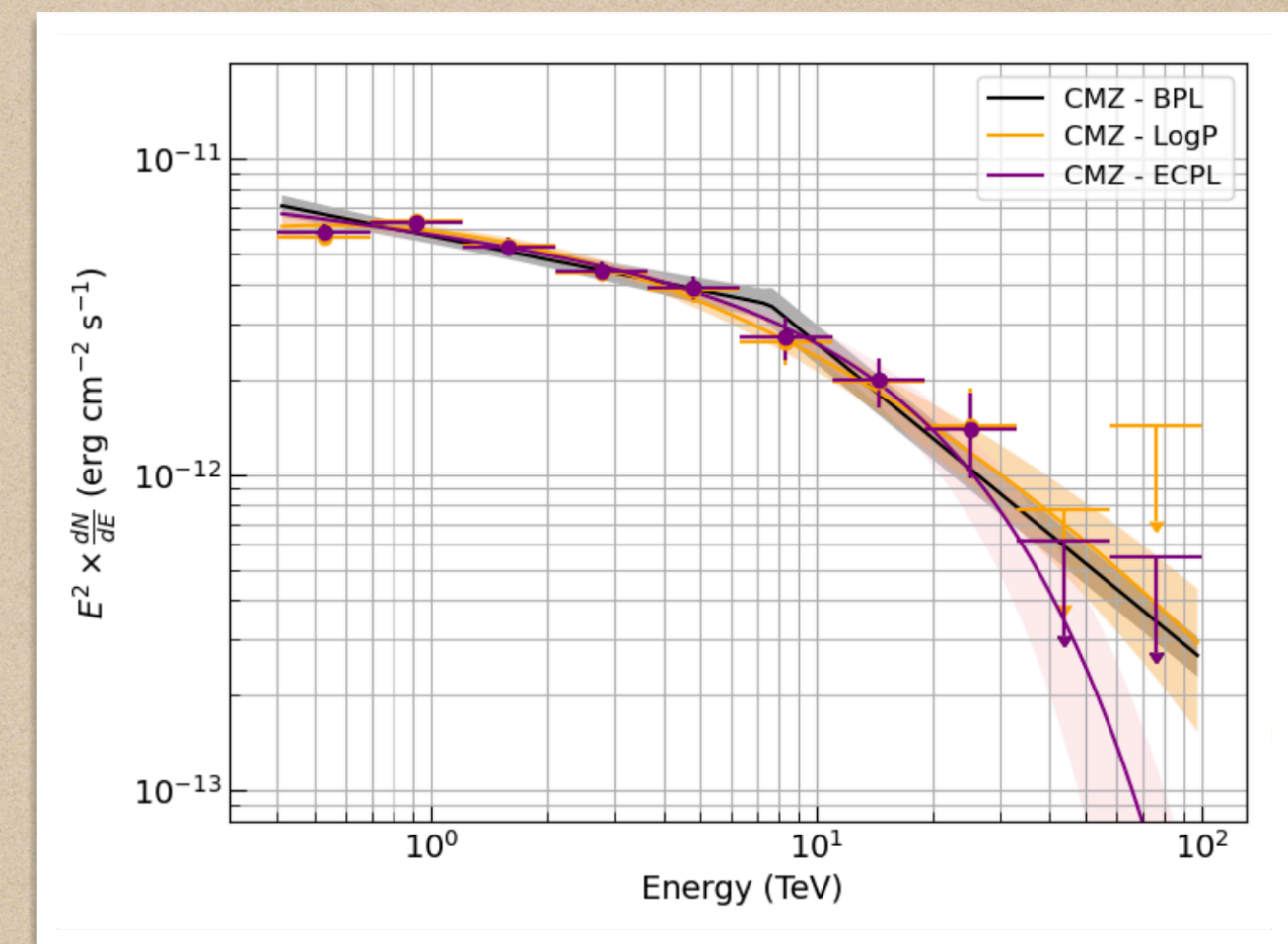
- ◆ Prospects for CTAO detection *Lotta*



# Gal Center Pevatron?

- ◆ New analysis with much more HESS data, new 3-D max.lik. and new 3-D gas template
- ◆ Confirms  $1/r$  radial profile and no spectral variations in CMZ  $\rightarrow$  continuous injection
- ◆ First evidence for curvature in CMZ spectrum
- ◆ Spectral cut-off in SNR  $G0.9+0.1$

Devin





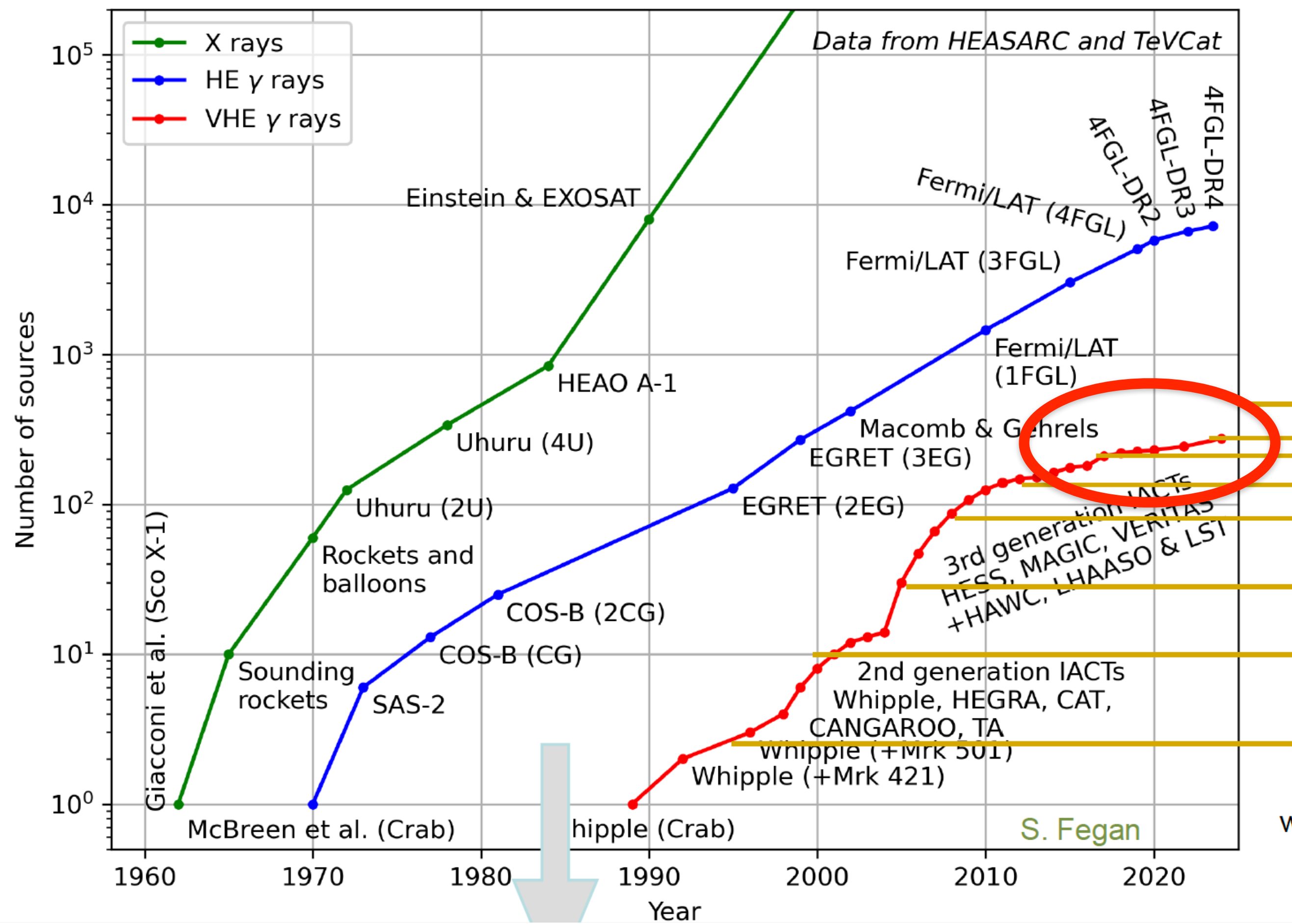
# Final remarks

- ◆ Lot of progress.... but also many open questions
  - Motivation from new, more powerful facilities



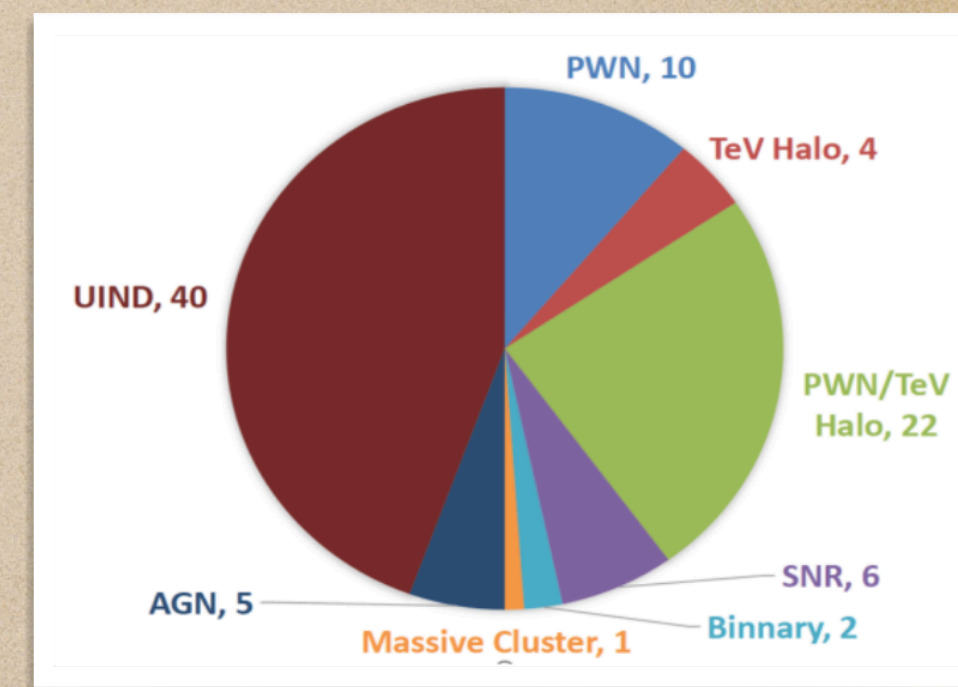






Low derivative

LHAASO



But the real game-changer will be CTAO



# Final remarks

- ◆ Lot of progress.... but also many open questions
  - Motivation from new, more powerful facilities
- ◆ Increasing involvement with other communities - multi-wavelength, multi-messenger
- ◆ A bright future ahead!

My apologies for this biased and incomplete summary talk



# Final remarks

First Heidelberg Gamma Ray Astrophysics Symposium (workshop) - Oct 3-7, 1994  
*Theory and Observations*

30 yrs ago

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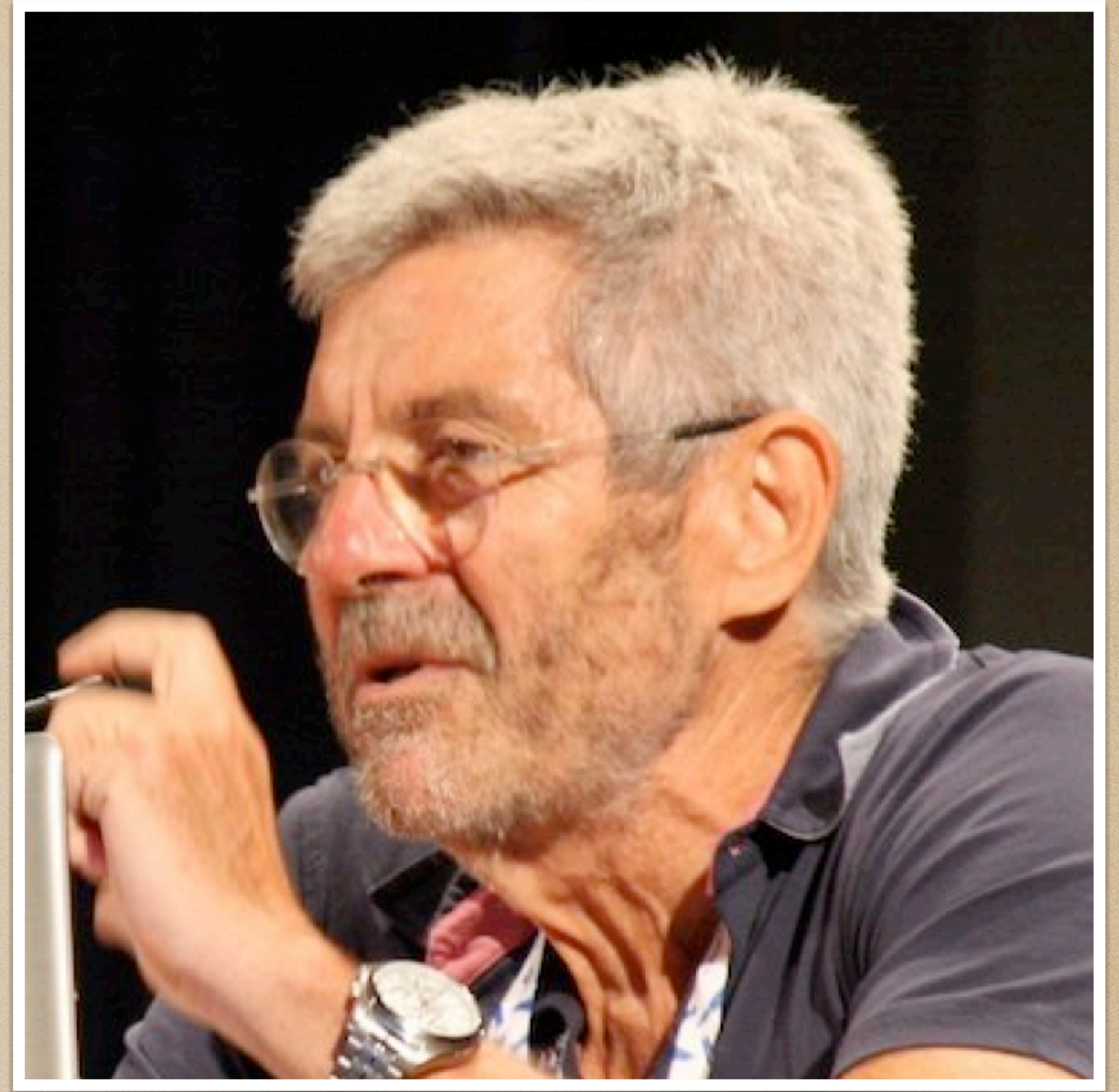
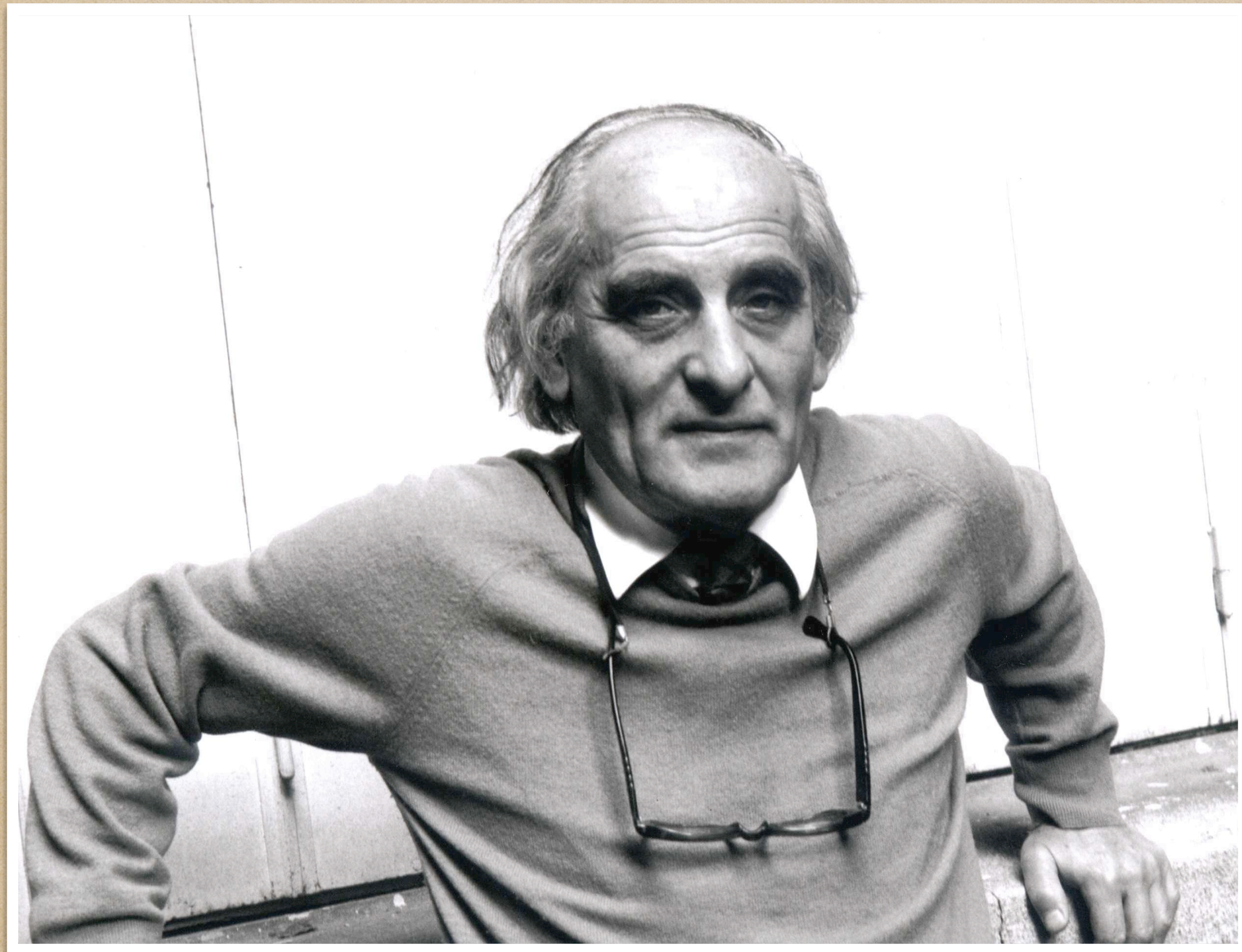
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balanced coverage of the detection technique, observations, and theory !

← No Italians !



Thank you Beppo !!



Thank you Nanni !!