Galactic Science

Rapporteur talk*
Sandro Mereghetti
INAF, IASF Milano

*) My apologies for this biased and incomplete summary talk

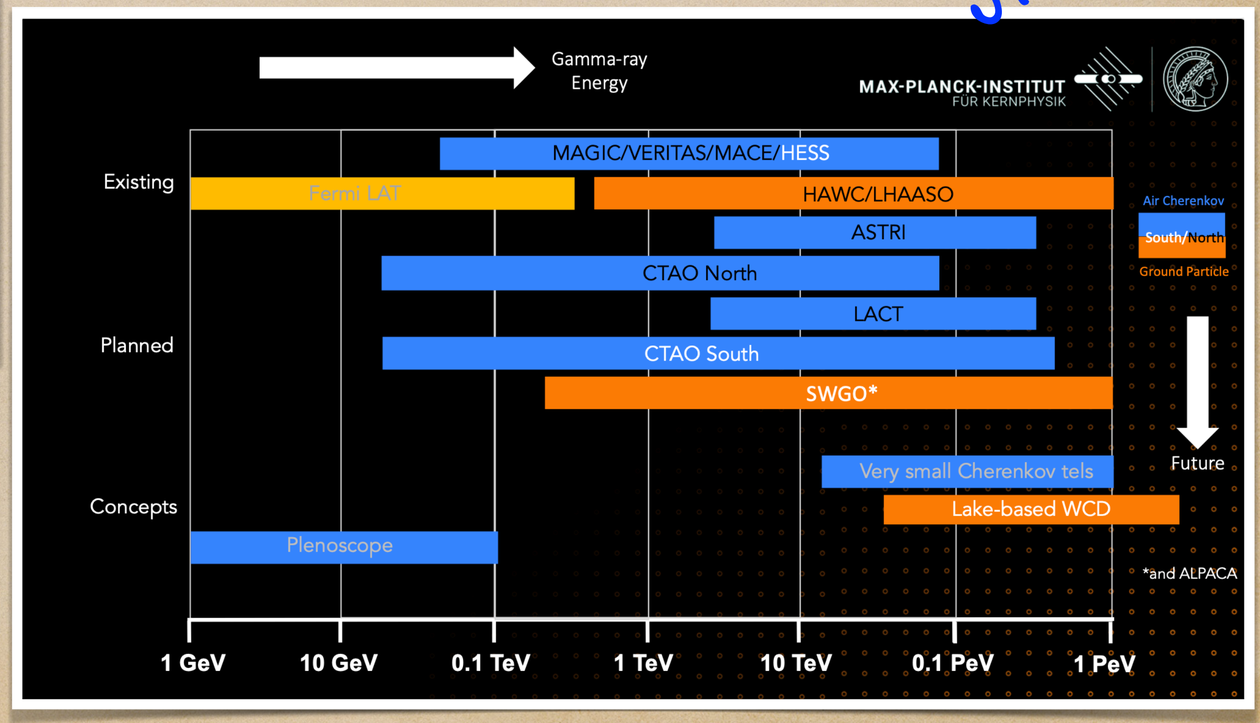
Gamma-ray Astronomy

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

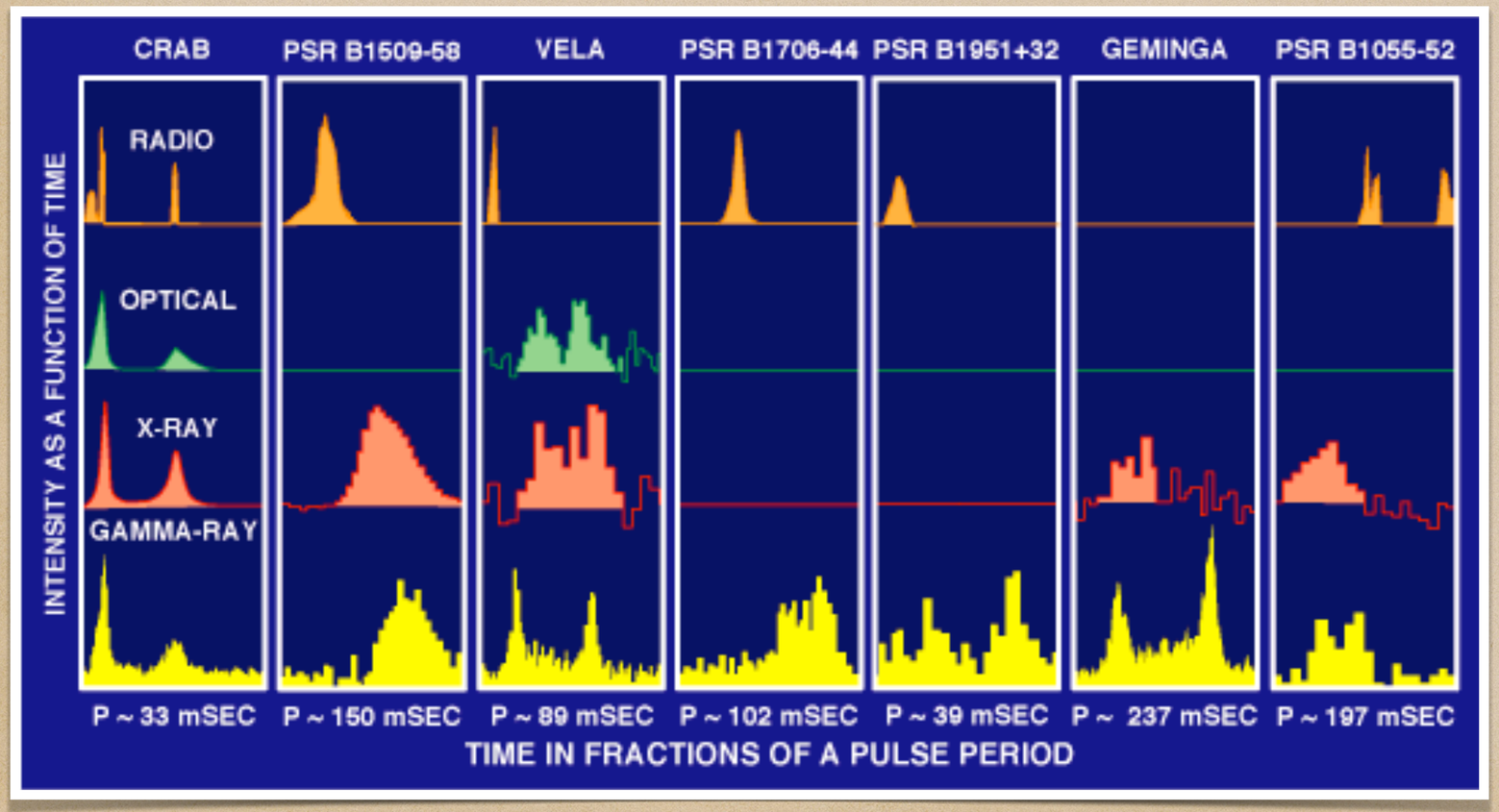
—> deeper investigations fundamental questions

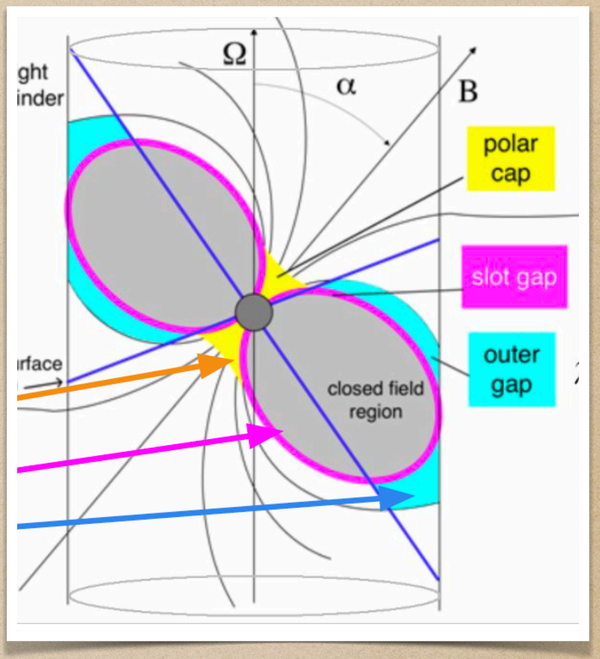
—> "prototypes" are not representative

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

Pulsars

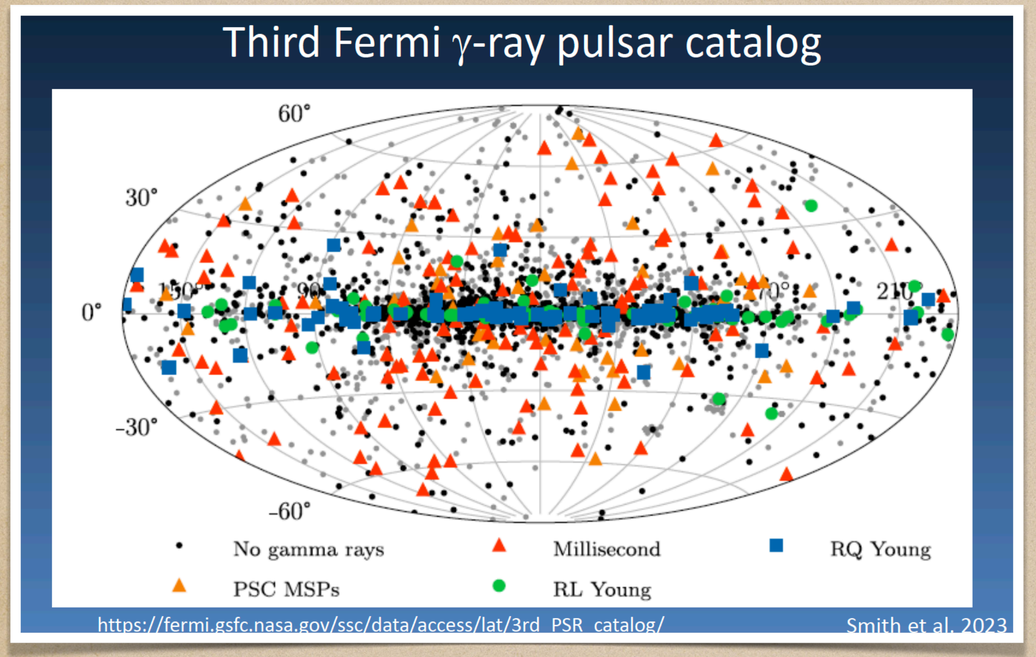
- In the "CGRO era"

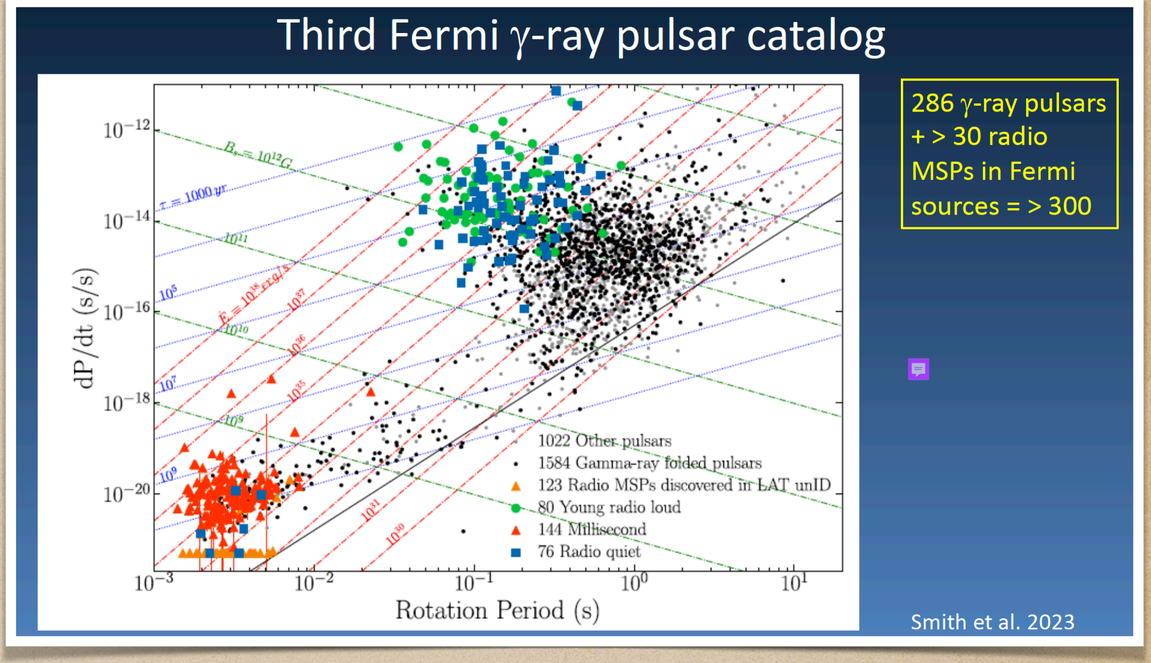




Pulsars: huge progress in observations…

Harding

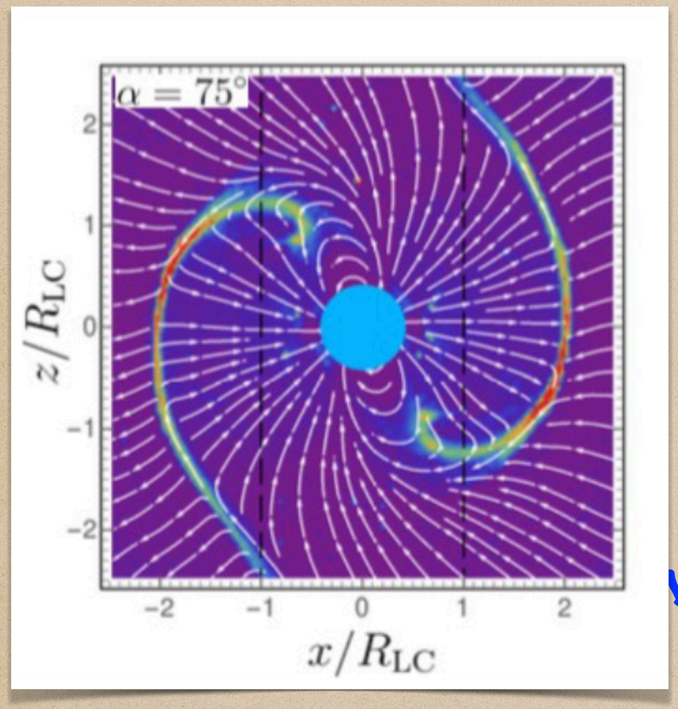




>~300 γ-ray PSRs

different subclasses: radio quiet / msPSR / binary /…

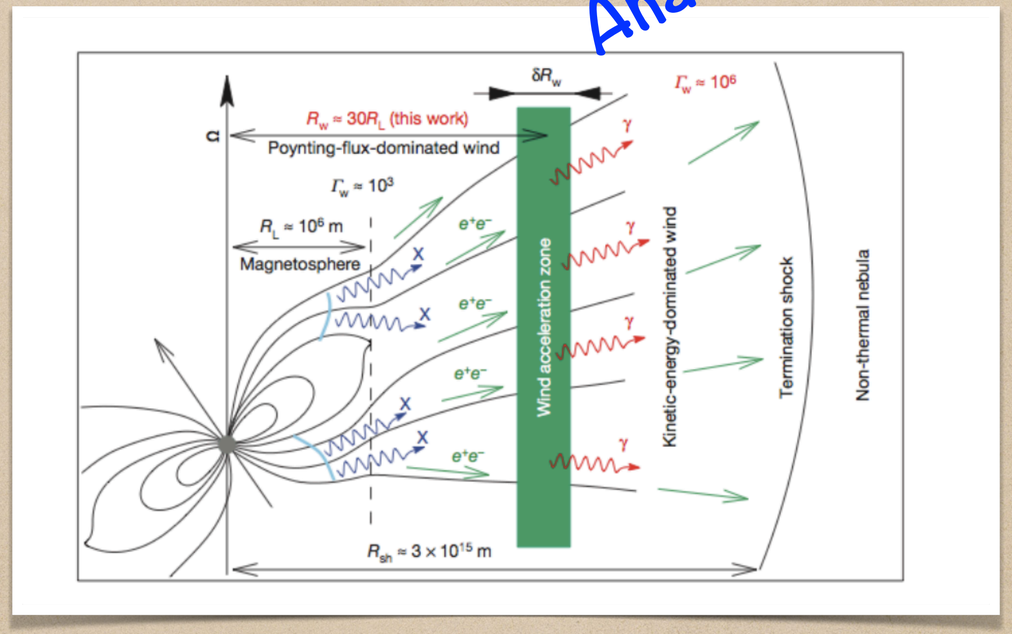
… and in theory



Harding

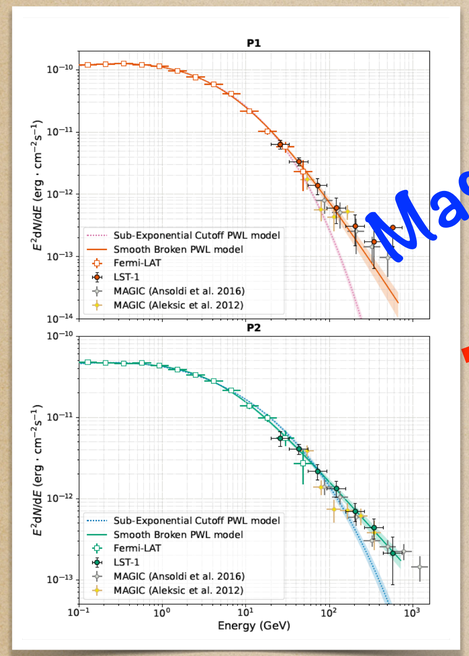
- Global PIC models —> most particle acceleration in current sheet

Aharonian

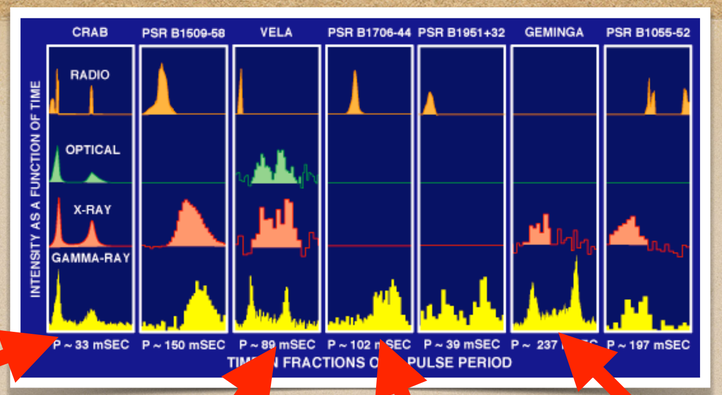


- Comptonization of cold wind e+/- on pulsed X/opt radiation (but difficult to go above ~1 TeV)

Pulsars: VHE

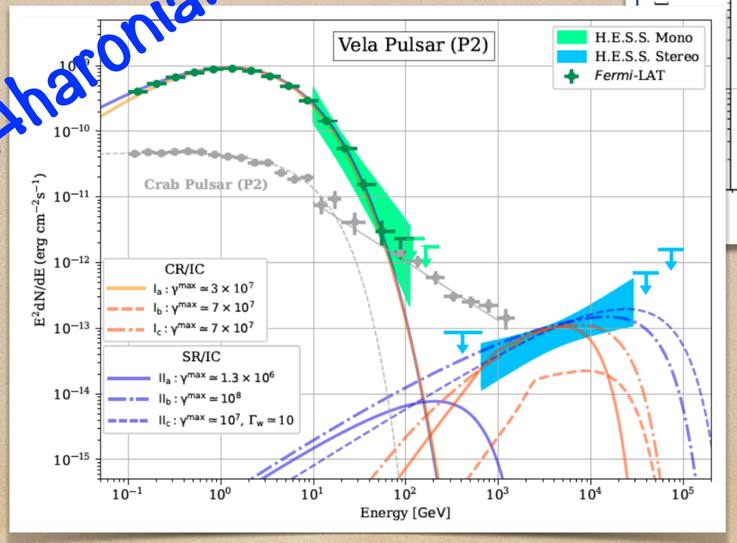


Mas-Aguilar

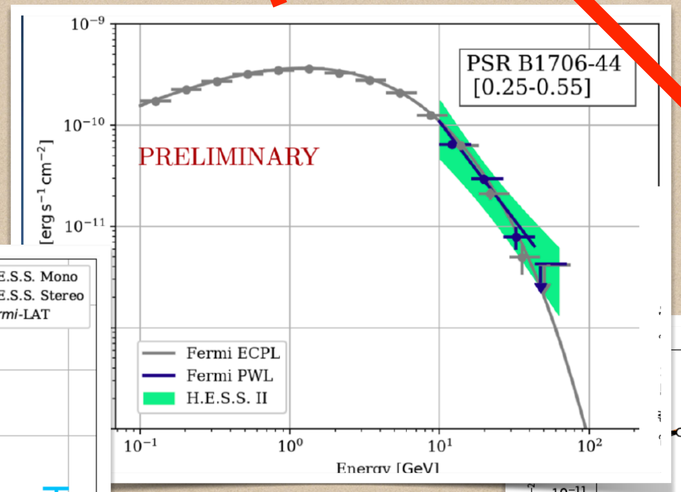


Crab up to ~1 TeV
(1st TeV PSR MAGIC)
VERITAS - LST-1

Aharonian



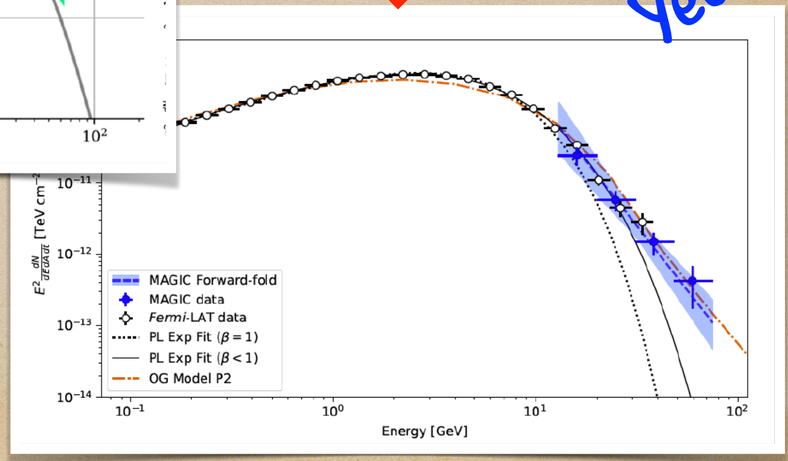
Vela P2 up
to ~30 TeV
HESS



PSR 1706-44
HESS

Geminga
MAGIC LST-1

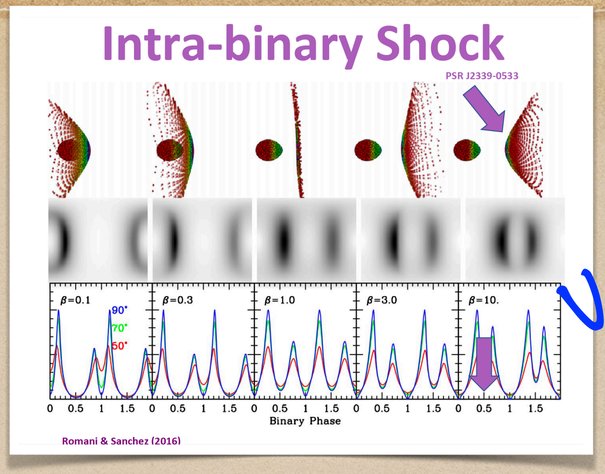
Yeung



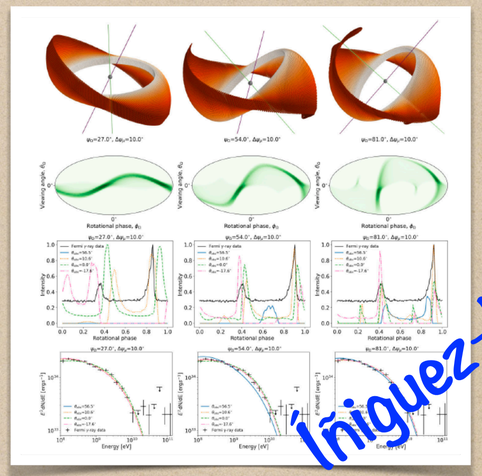
Pulsars

- "Spiders" (MSP devouring companion stars) as unique multiwavelength laboratories

- Detailed models of synchro-curvature radiation → pulse profiles and spectra



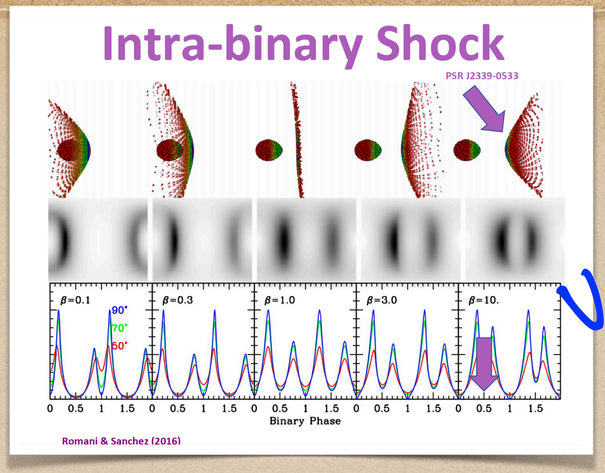
Venter



Íñiguez-Pascual

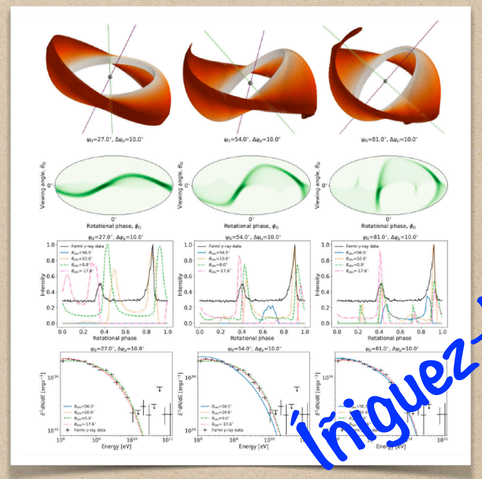
Pulsars

- "Spiders" (MSP devouring companion stars) as unique multiwavelength laboratories



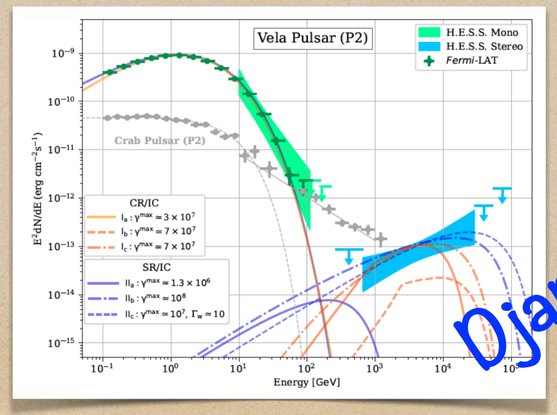
Venter

- Detailed models of synchro-curvature radiation → pulse profiles and spectra



Íñiguez-Pascual

- HESS discovery of a distinct emission component 0.5-12 TeV in PSR J1509-5850 similar to Vela, but much higher L_{TeV}/L_{GeV}



Djannati-Atai

Pulsars

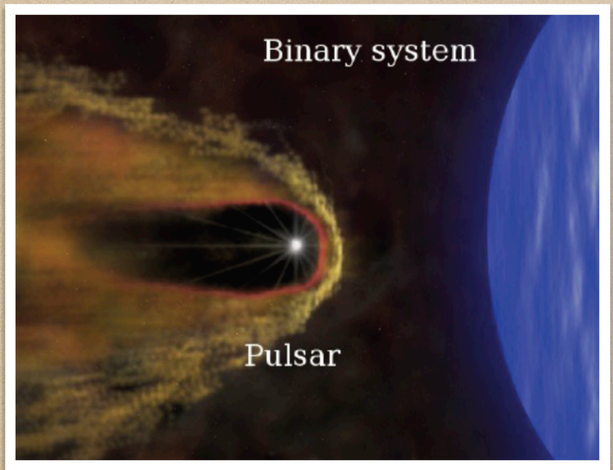
- Reasonably well established location of particle acceleration and HE emission but origin of HE/VHE emission still open
  Parallel E field ?
  Reconnection ?

- 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 !

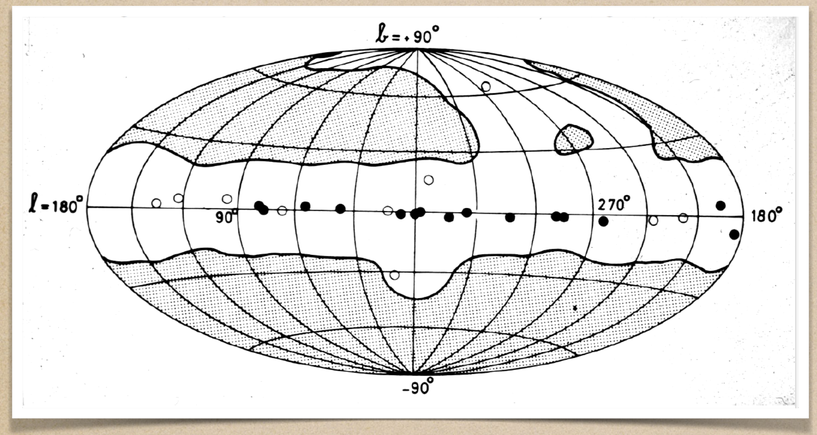


System	HE	VHE	Star	CO	P_{orbit}
LS 5039	Y	Y	ON6.5 V	?	3.9 d
LMC P3	Y	Y	O5 III	?	10.3 d
4FGL J1405.1-6119	Y	-	O6.5 III	?	13.7 d
1FGL J1018.6-5856	Y	Y	O6 V	?	16.5 d
HESS J1832-093	Y	Y	O6 V	?	86.3 d
LS I +61 303	Y	Y	B0 Ve	PSR (269 ms)	26.5 d
HESS J0632+057	Y	Y	B0 Vpe	?	317 d
PSR B1259-63	Y	Y	O9.5 Ve	PSR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

Ribó

Gamma-ray binaries

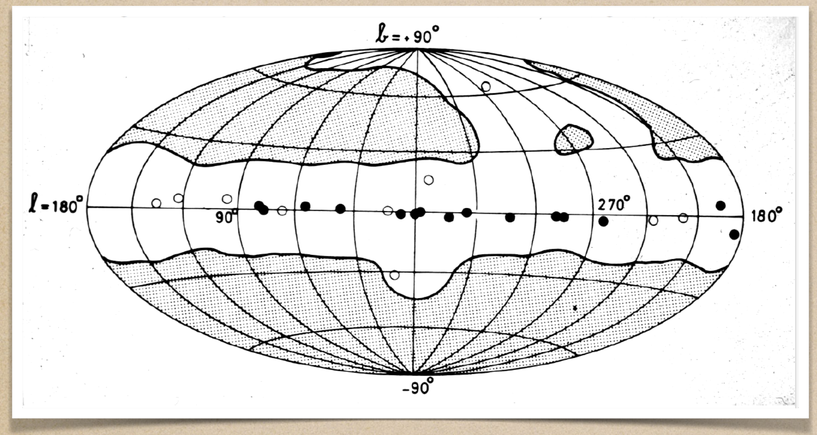
LS I +61 303 = CG 135+01



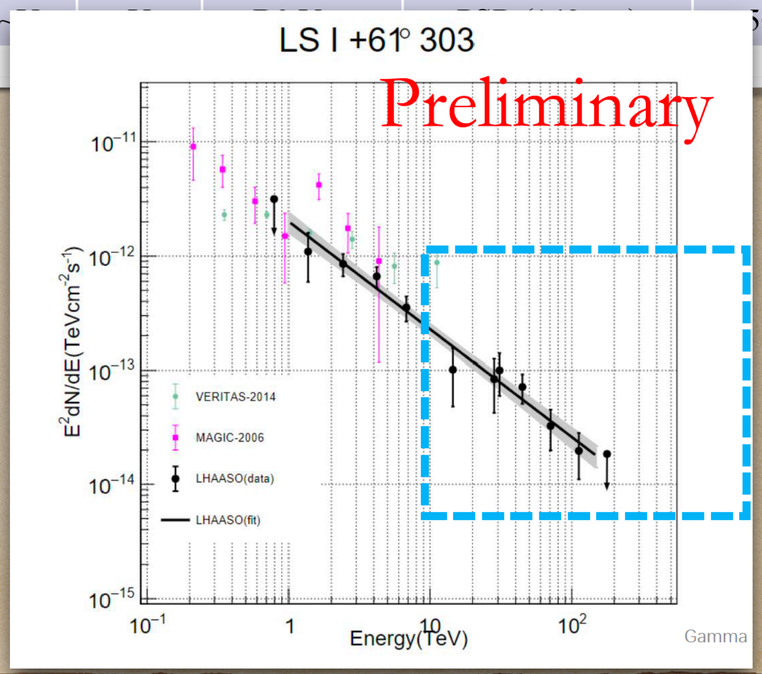
System	HE	VHE	Star	CO	P_{orbit}
LS 5039	Y	Y	ON6.5 V	?	3.9 d
LMC P3	Y	Y	O5 III	?	10.3 d
4FGL J1405.1-6119	Y	-	O6.5 III	?	13.7 d
1FGL J1018.6-5856	Y	Y	O6 V	?	16.5 d
HESS J1832-093	Y	Y	O6 V	?	86.3 d
LS I +61 303	Y	Y	B0 Ve	PSR (269 ms)	26.5 d
HESS J0632+057	Y	Y	B0 Vpe	?	317 d
PSR B1259-63	Y	Y	O9.5 Ve	PSR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

Gamma-ray binaries

LS I +61 303 = CG 135+01



System	HE	VHE	Star	CO	P_{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					50 yr

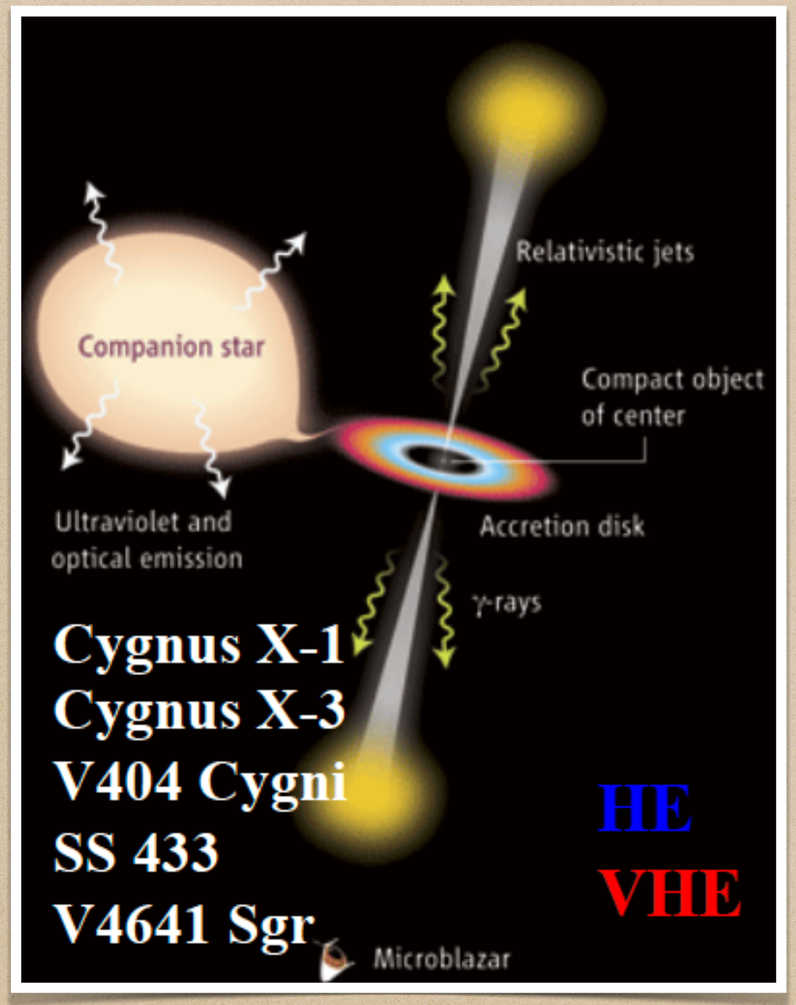


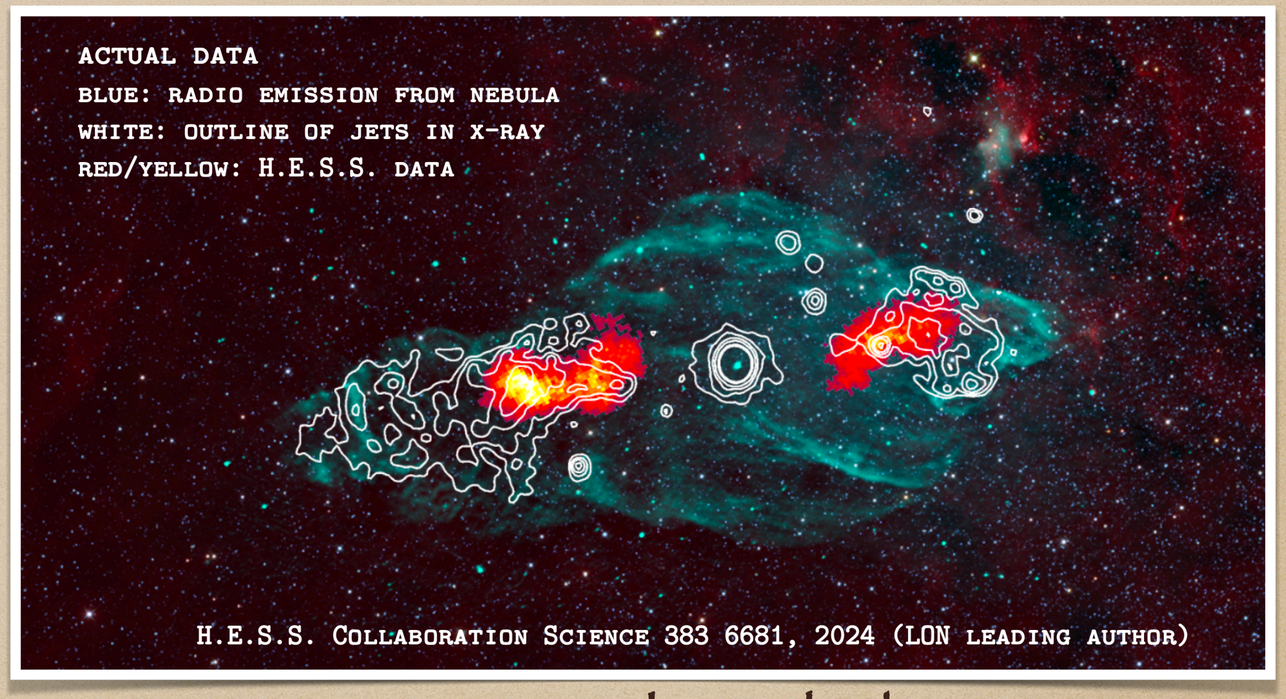
- LHAASO detection of up to 100 TeV with no break in PL

Cong Li

microQSOs

Stellar mass BH accreting from companion stars



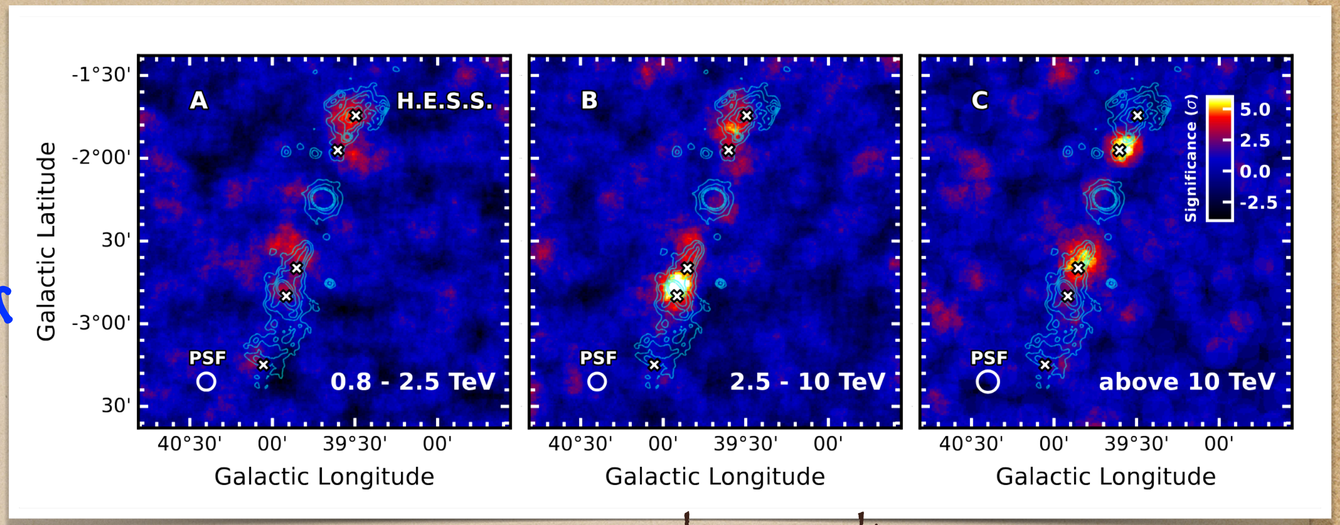


SS 433 in W50 radio nebula

microQSOs

- Energy-dependent morphology of SS433

Wagner

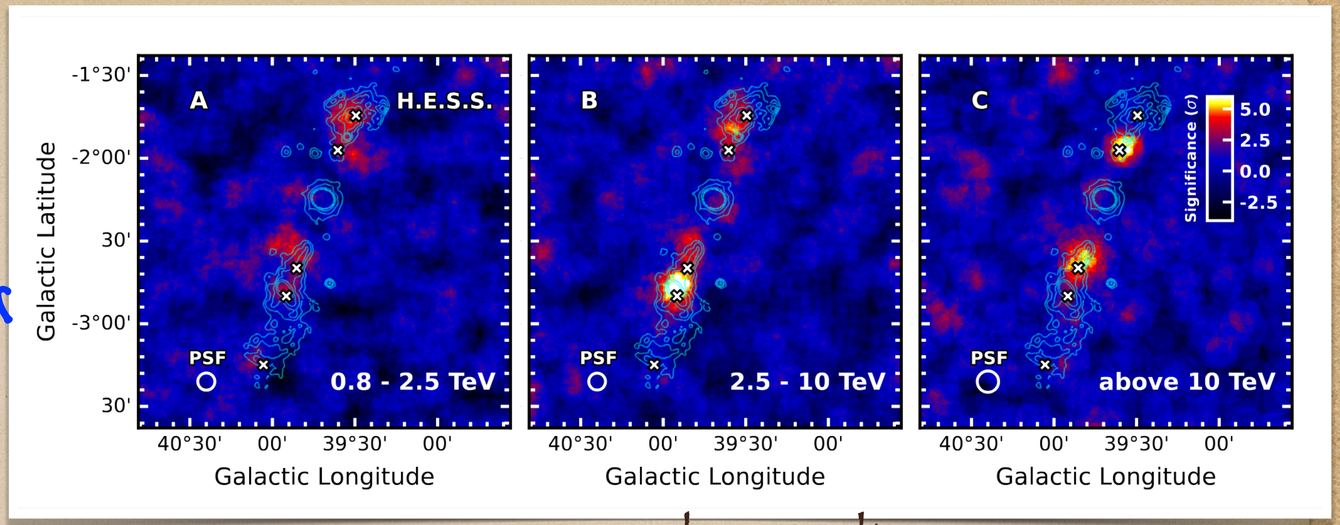


Lower E at larger distances

microQSOs

- Energy-dependent morphology of SS433

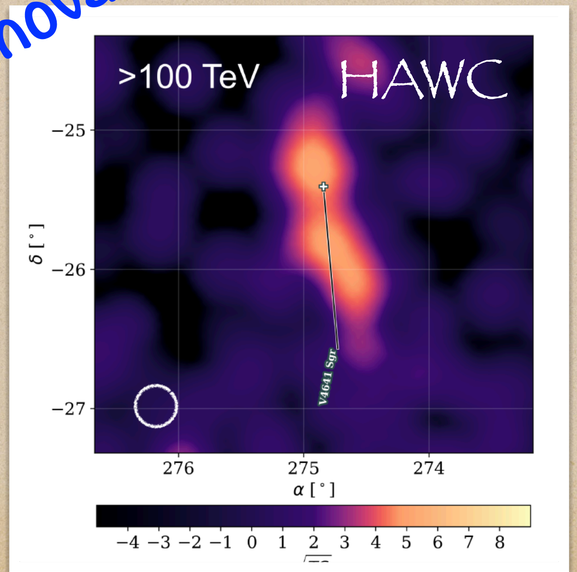
Wagner



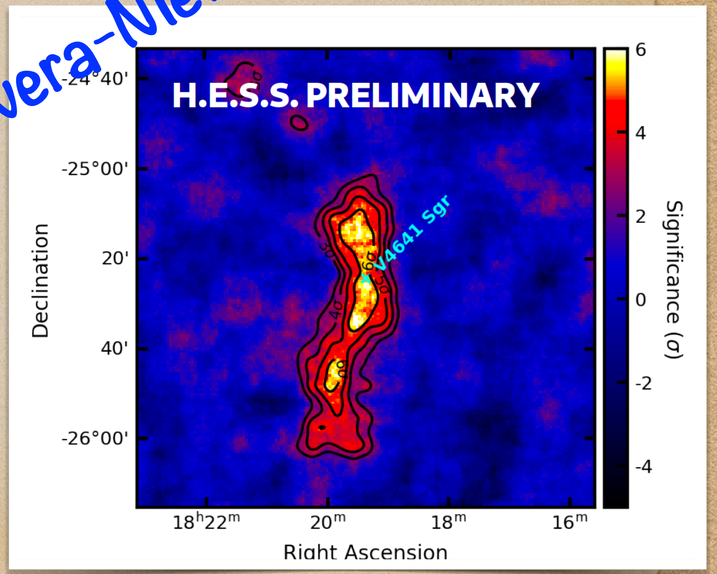
Lower E at larger distances

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

Casanova



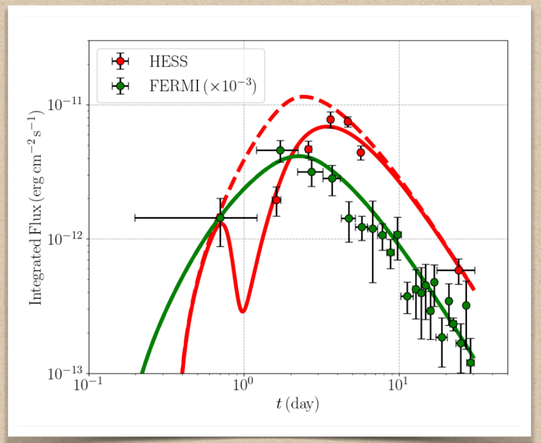
Olivera-Nieto



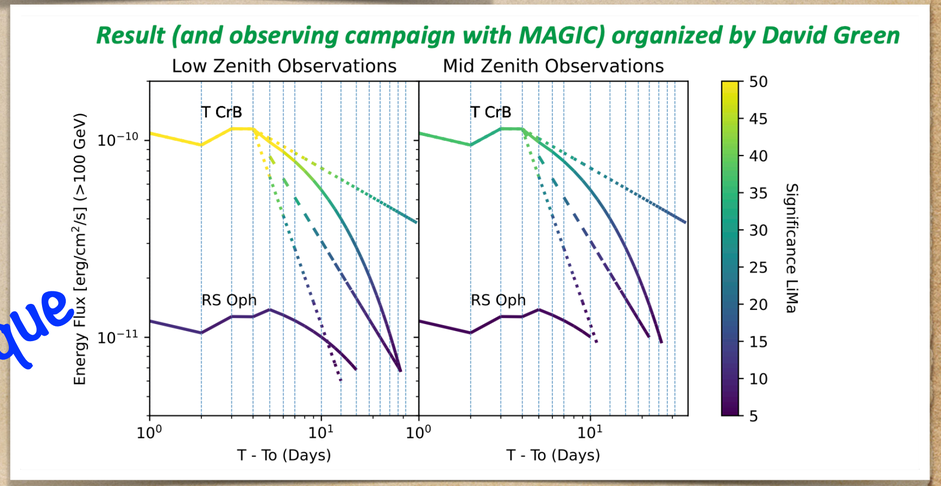
WD binaries (Novae)

- 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

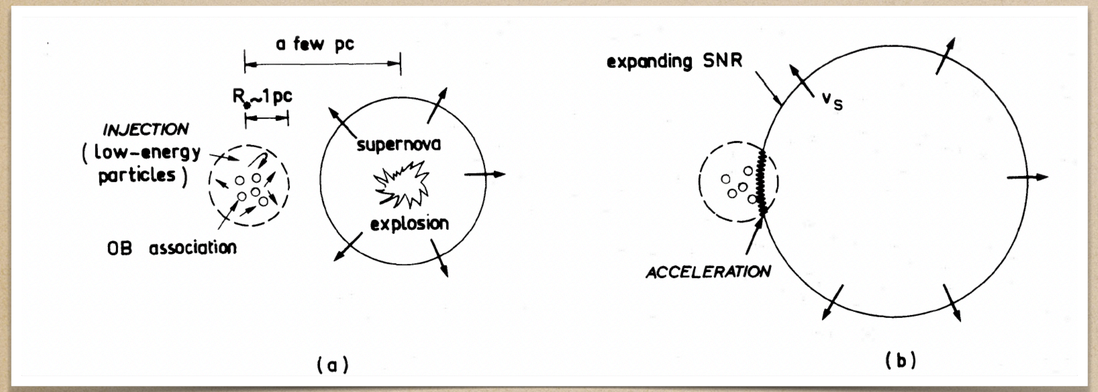
Massive Star Clusters

- An old idea… "SNOBs"

(=SNR + OB assoc or HII region)

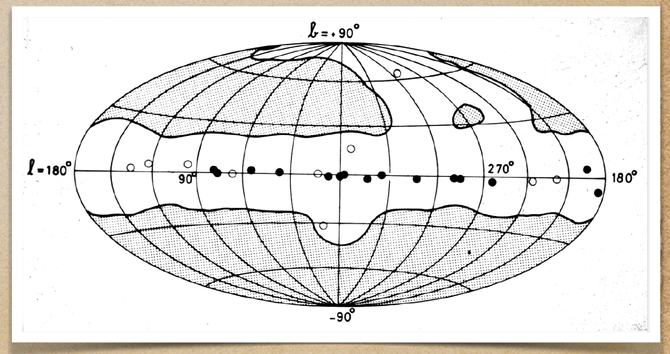
ON GAMMA-RAY SOURCES, SUPERNOVA REMNANTS, OB ASSOCIATIONS, AND THE ORIGIN OF COSMIC RAYS

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 γ-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

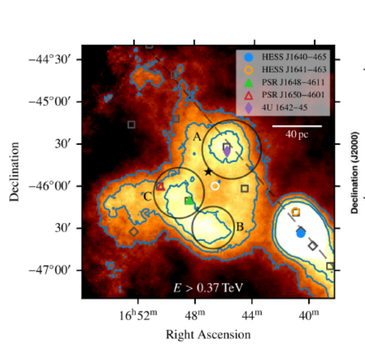
Kinetic luminosity 10^35-36 erg/s

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

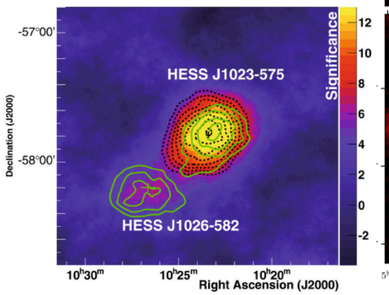
Young OB associations are γ-ray sources, but SNe contribution dominant for CR production

Massive Star Clusters

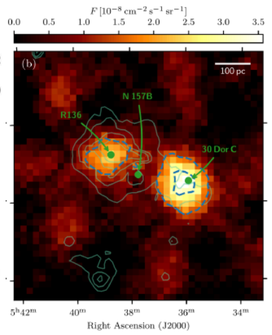
- Several young MSC detected at VHE/UHE in MW (and LMC!): potential contributors of 1-100 PeV CRs



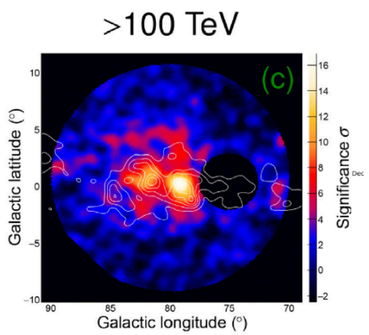
Westerlund 1
H.E.S.S. 2023



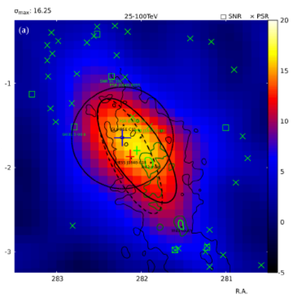
Westerlund 2
H.E.S.S. 2011



R136, 30 Dor C
H.E.S.S. 2024



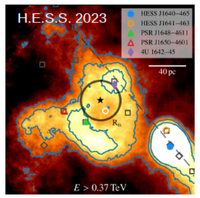
Cygnus X
LHAASO 2024

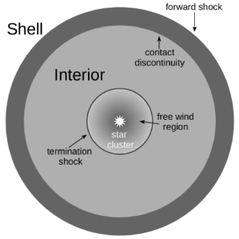


W43
LHAASO 2024

Cygnus Cocoon(GeV-TeV)[Fermi 2012, HAWC2022]
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 1[Sun et.al 2020]
Carina nebular [Ge et.al 2022]
M17 [Liu et.al 2022]

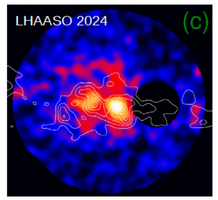
Westerlund 1

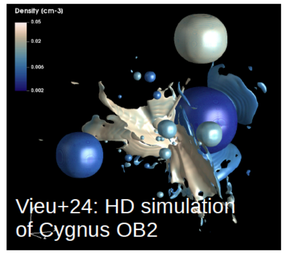




compact cluster
→ *has a cluster wind termination shock*

Cygnus OB2





loose cluster/association

Härer

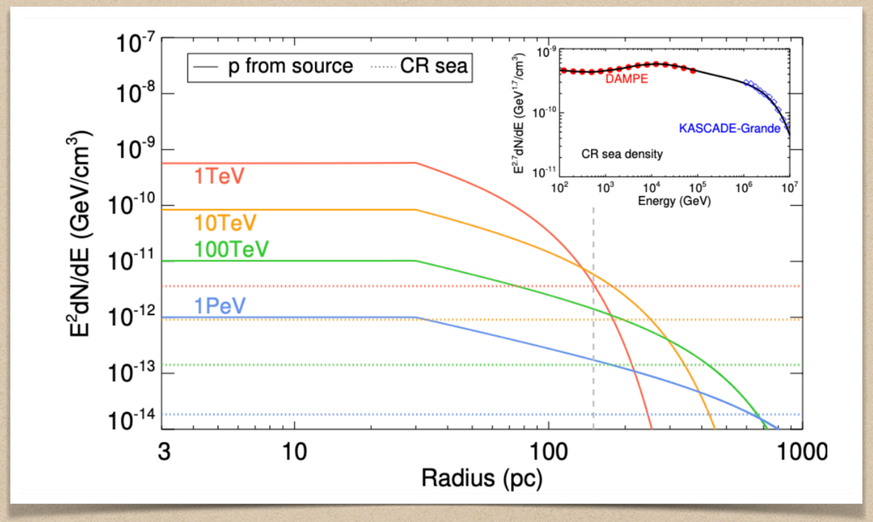
A variety of cases

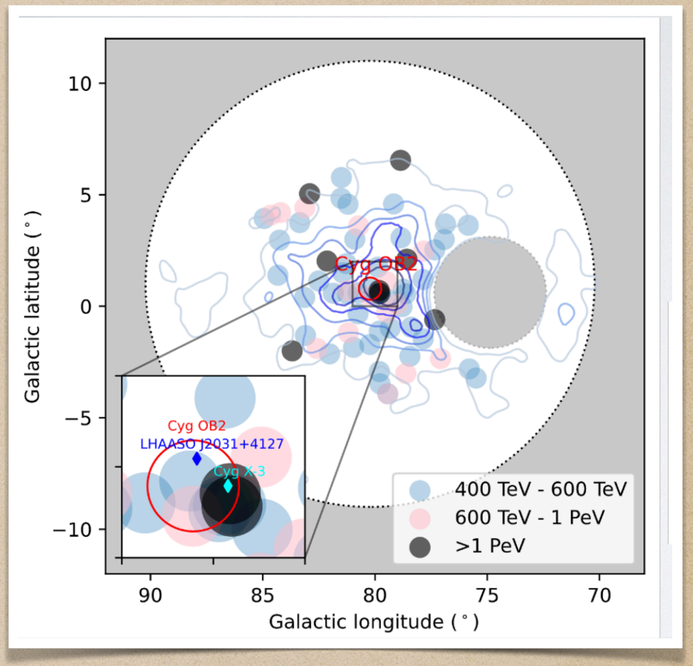
Massive Star Clusters

Ruizhi Yang

- LHAASO results on Cyg OB2

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



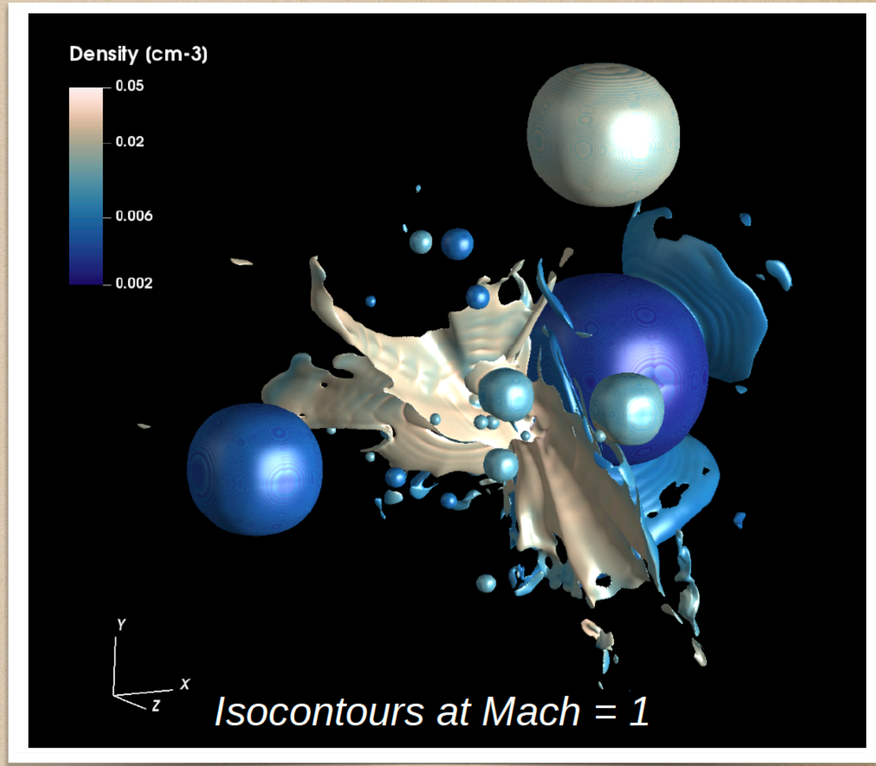


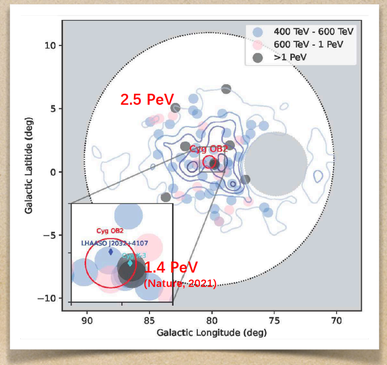
Central concentration of highest E photons

Massive Star Clusters

Vieu

- 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)



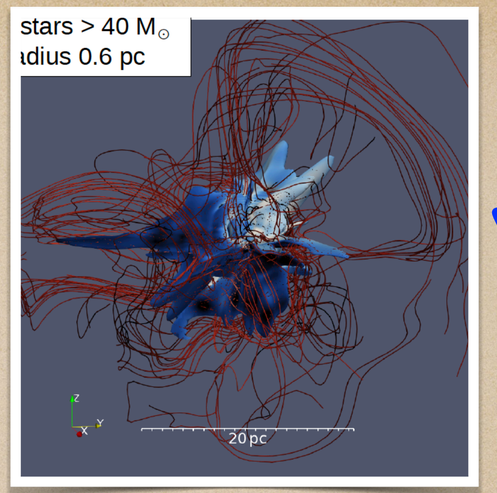


Massive Star Clusters

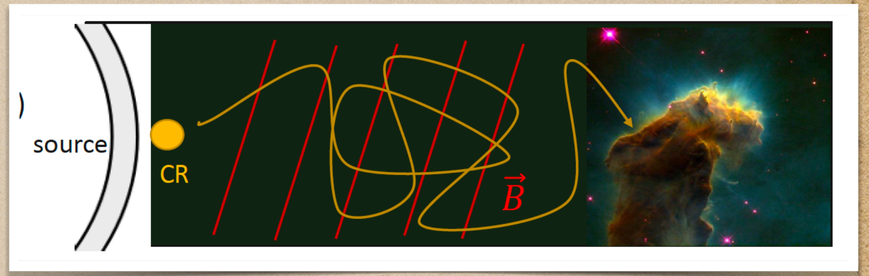
- 3D MHD simulations →importance of complex B field morphology and and interaction between individual winds

- Model of escape and transport of CR between young MSC and MC, and compute expected γ-rays

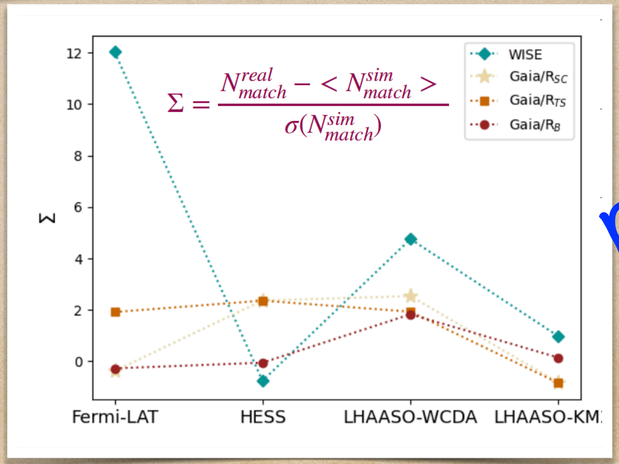
- Significant correlation between GeV sources and young clusters embedded in dense MC



Härer



Inventar



Peron

- Several other interesting talks on MSC:

  contribution to diffuse emission (Menchiari)

  prospects for future facilities (Bonollo, D'Aì,..)

- ..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)

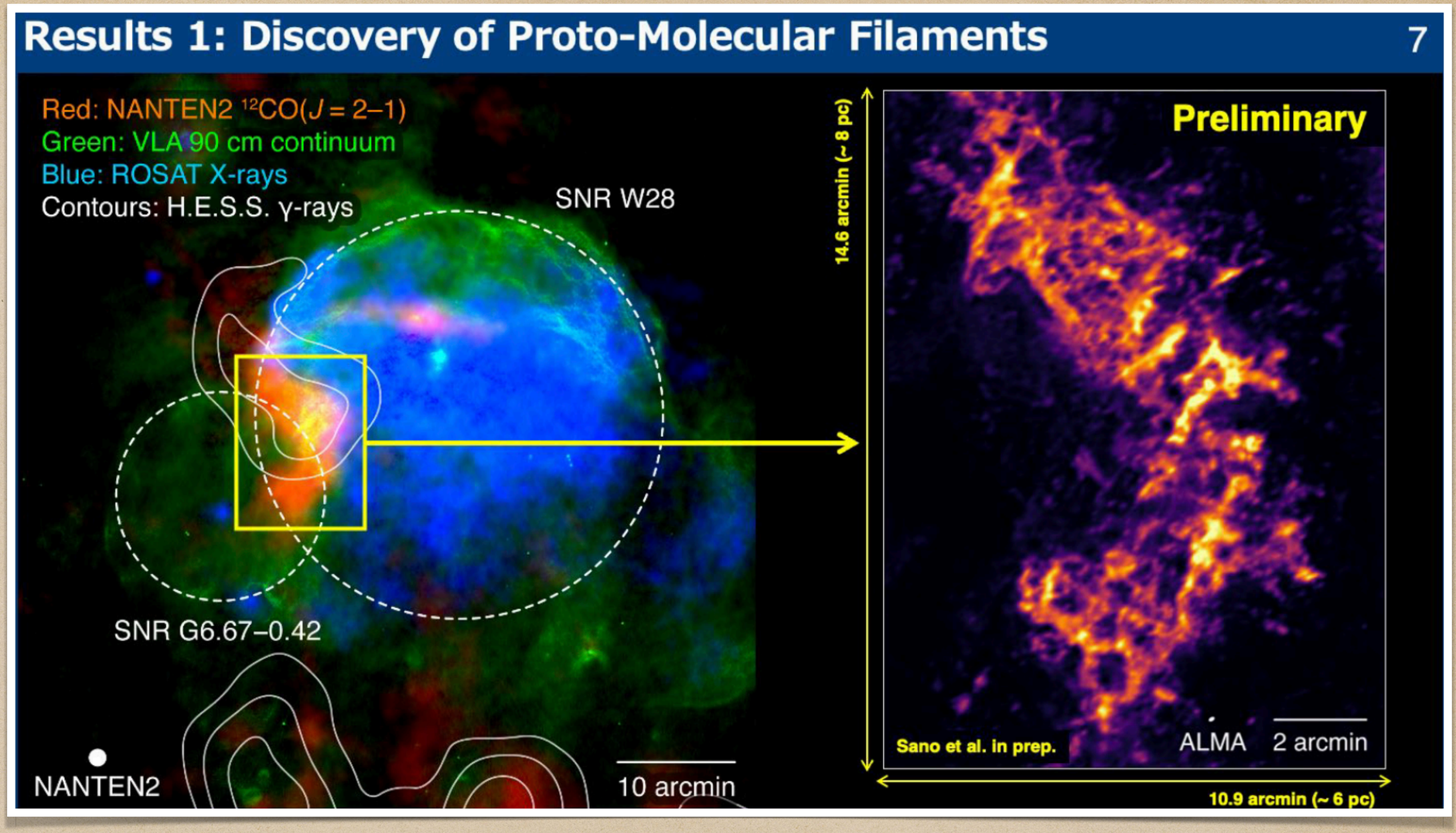
  correlations btw MC illuminated by SNRs and unid. LHAASO srcs (Mitchell)

  Vela X region (Sei)

  Fermi/LAT u.l. on nearby SN 2023ixf —> $\varepsilon < 1\%$ (Martí-Devesa)

Importance of multi wavelength

Hidetoshi Sano



Cosmic Rays

Felix Aharonian

In the 1960s, the pioneers of the field recognized the great potential of γ-ray astronomy to solve the "50-year-old puzzle" of CR …

…yet we keep talking about the potential of γ-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…

Brian Reville

WHERE THERE'S SMOKE THERE'S FIRE….

CR Acceleration & Propagation

Two excellent invited talks:

- Critical review on Acceleration issues:

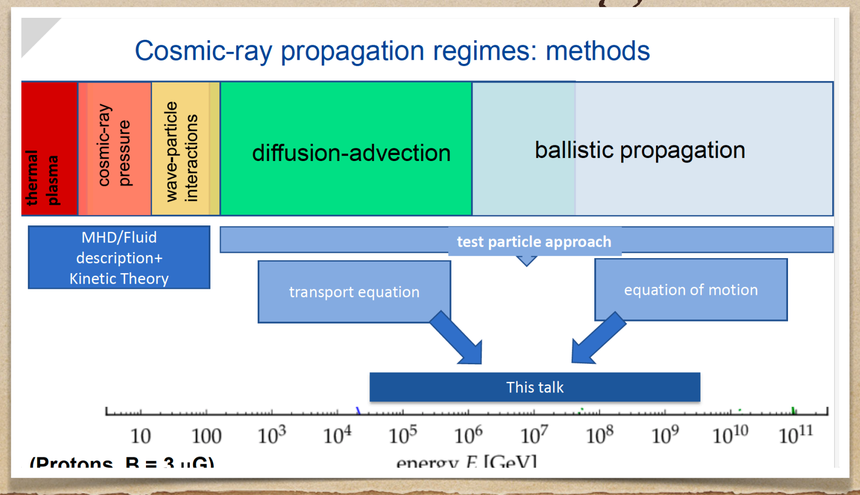
  SNRs still set the standards, but more work needed…

Brian Reville

WHERE THERE'S SMOKE THERE'S FIRE….

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

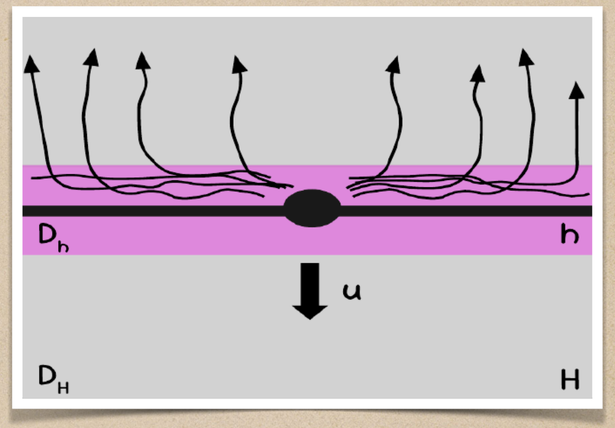
Julia Tjus



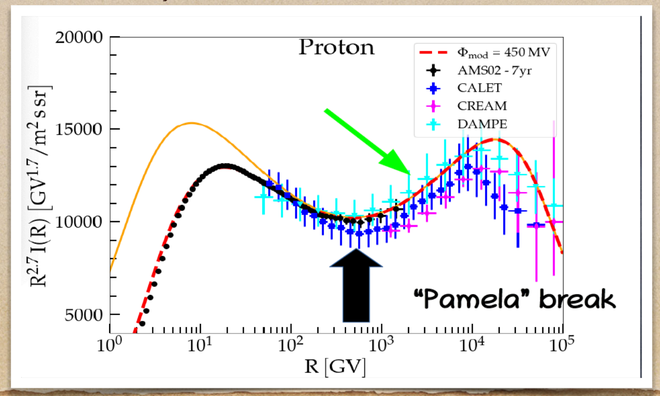
- Physically motivated scenario to explain several features in CR spectrum / composition based on two ideas:

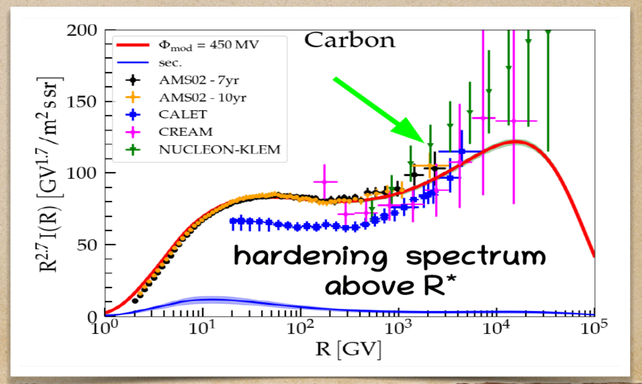
a) inefficient scattering in gal disk where B parallel to plane.
CR transported to halo by B field random walk induced by turbulence

Recchia



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



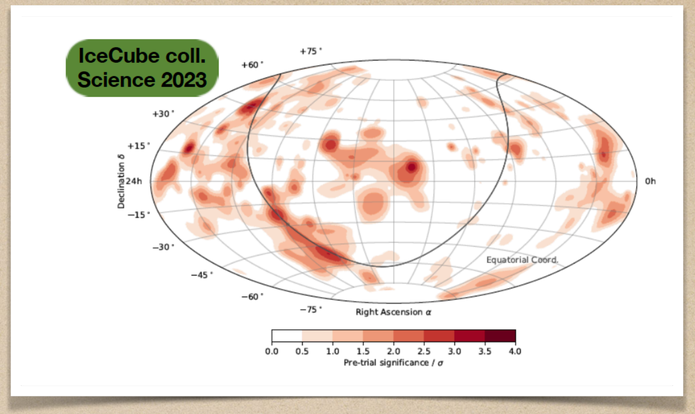


- Recently discovered flux of neutrinos from Galactic plane is above the expectations based on homogeneous diffusion can be explained by models with harder CR spectrum in inner Galaxy

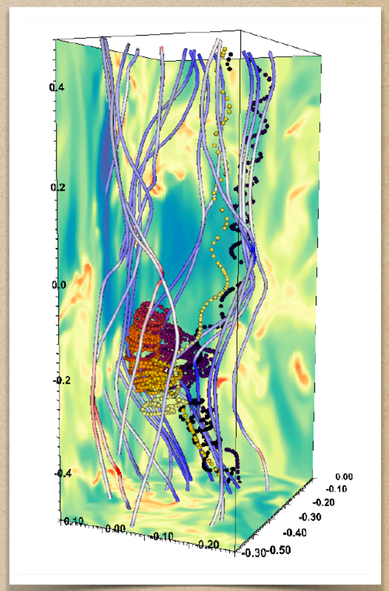
- Importance of mirror diffusion —> low diffusion coefficient around sources as required for TeV halos

- anisotropic propagation with CRs injected at discrete transient sources in the disc —> clumpy diffuse emission at >100 TeV ≠ smoother emission ~ GeV energies.

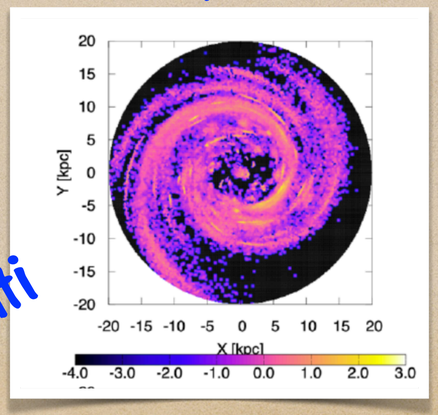
Gaggero



Barreto-Mota



Giacinti

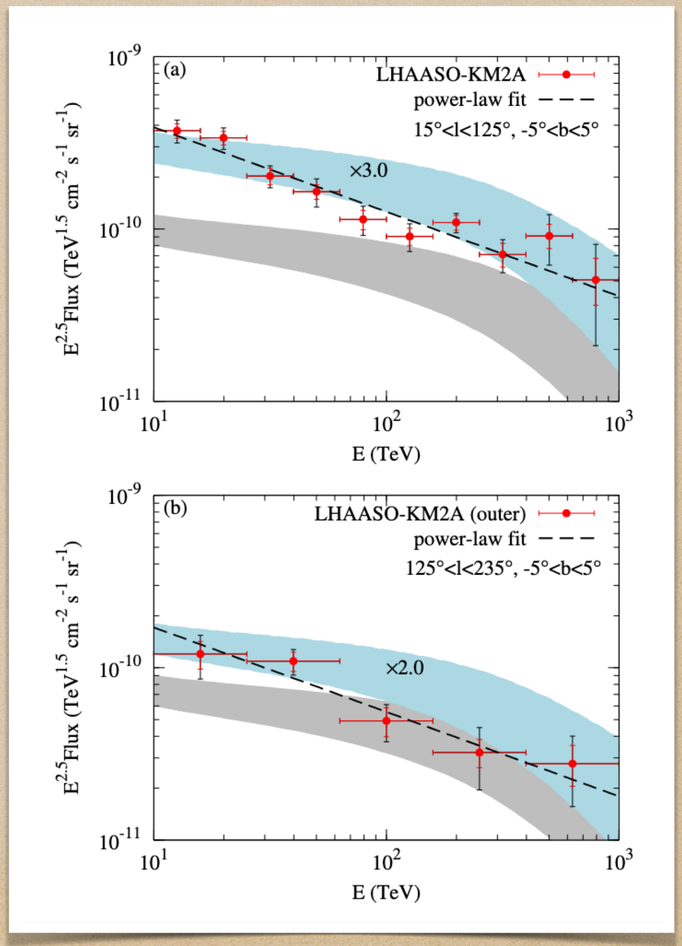


TeV to PeV Galactic diffuse emission

- Flux 2-3 x higher than expected

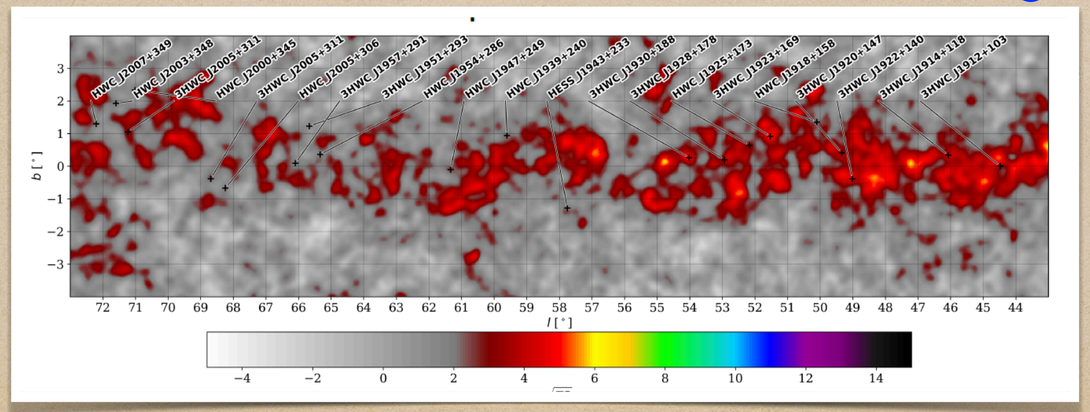
Zhen Cao

LHAASO



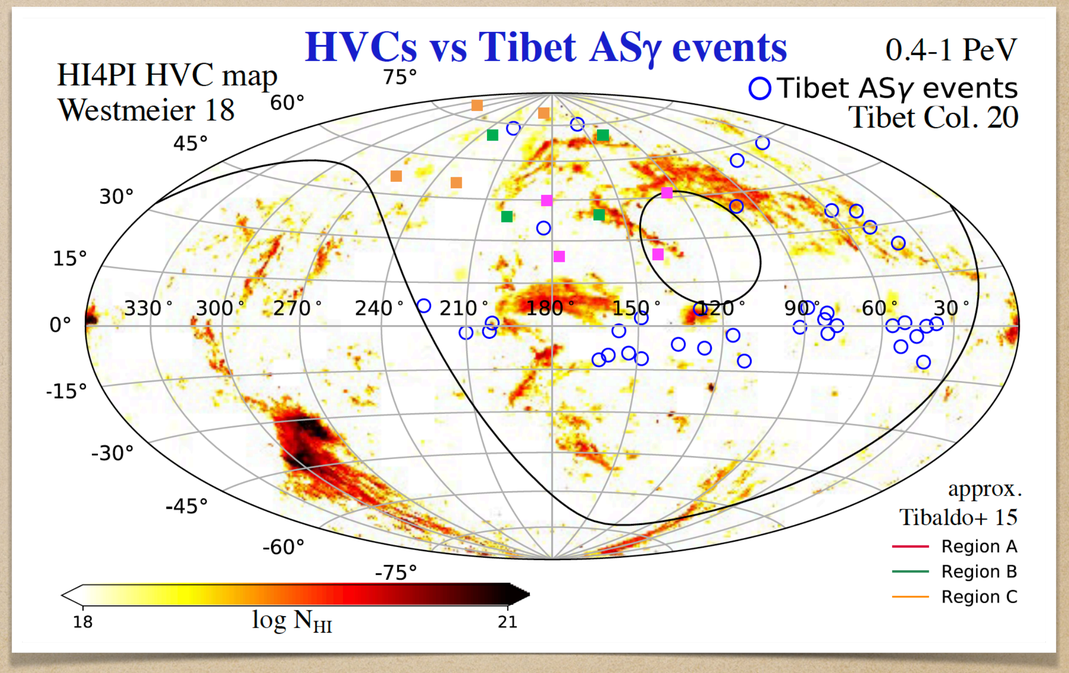
Casanova

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

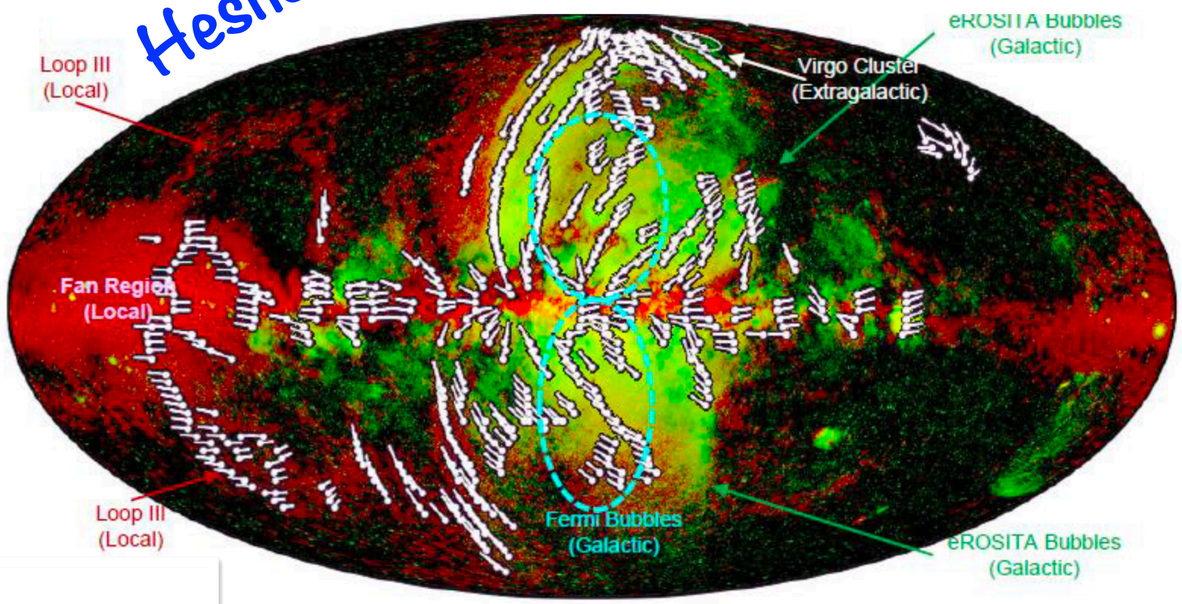
Susumu Inoue



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

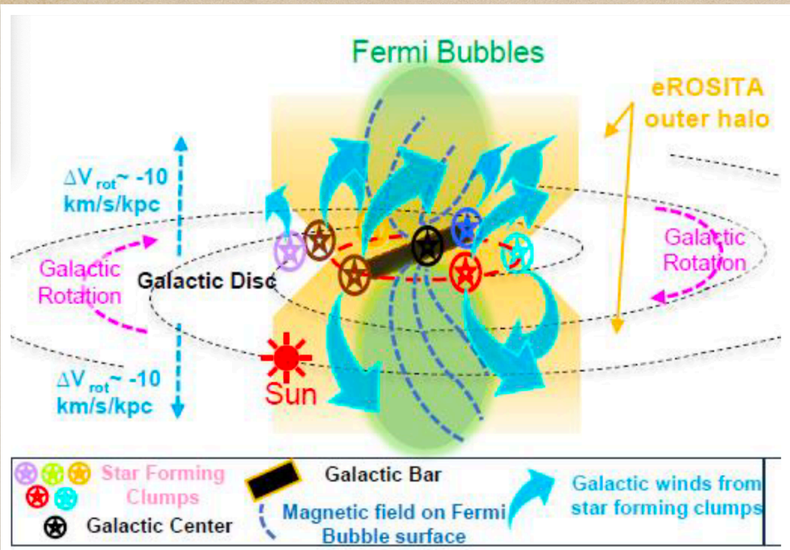
Heshou Zhang

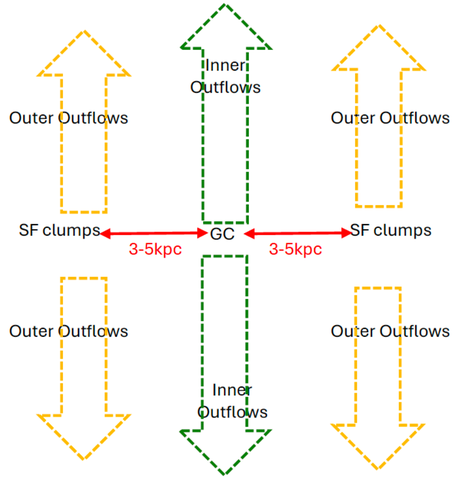


arXiv: **2408.06312**

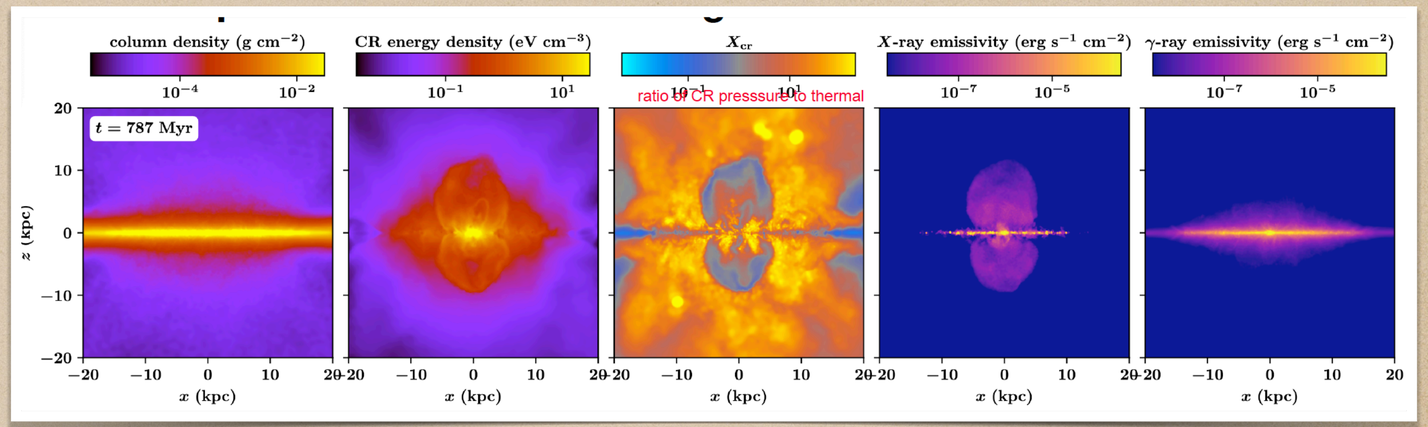
White bars: magnetic field (23 GHz)
Green: 0.6-1.0 keV X-ray

Within Local Spiral Arm, or beyond the Galactic Disc?





- Detailed MHD simulations —> Outflows launched by CRs from entire disk of Milky Way



Kjellgren

- AGN jet-shock can explain X-ray, γ, microwave observations of the Fermi bubbles —> powerful jets from SgrA* SMBH 5 Myr ago. + TDE jet model for the origin of the SgrA lobes

Fulai Guo

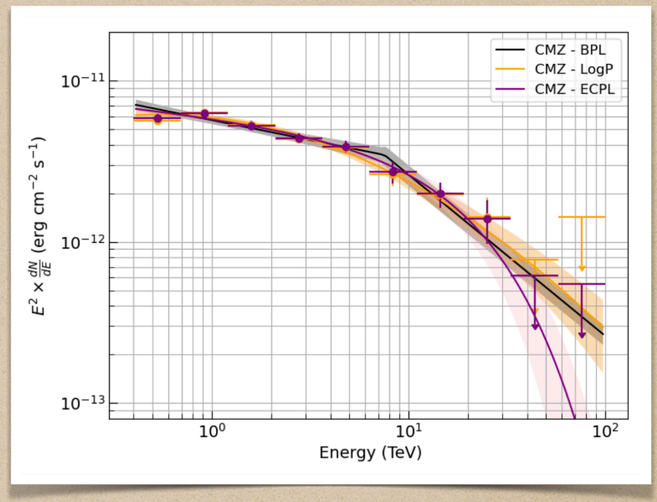
- Prospects for CTAO detection

Xotta

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 —> continuous injection
- First evidence for curvature in CMZ spectrum
- Spectral cut-off in SNR G0.9+0.1

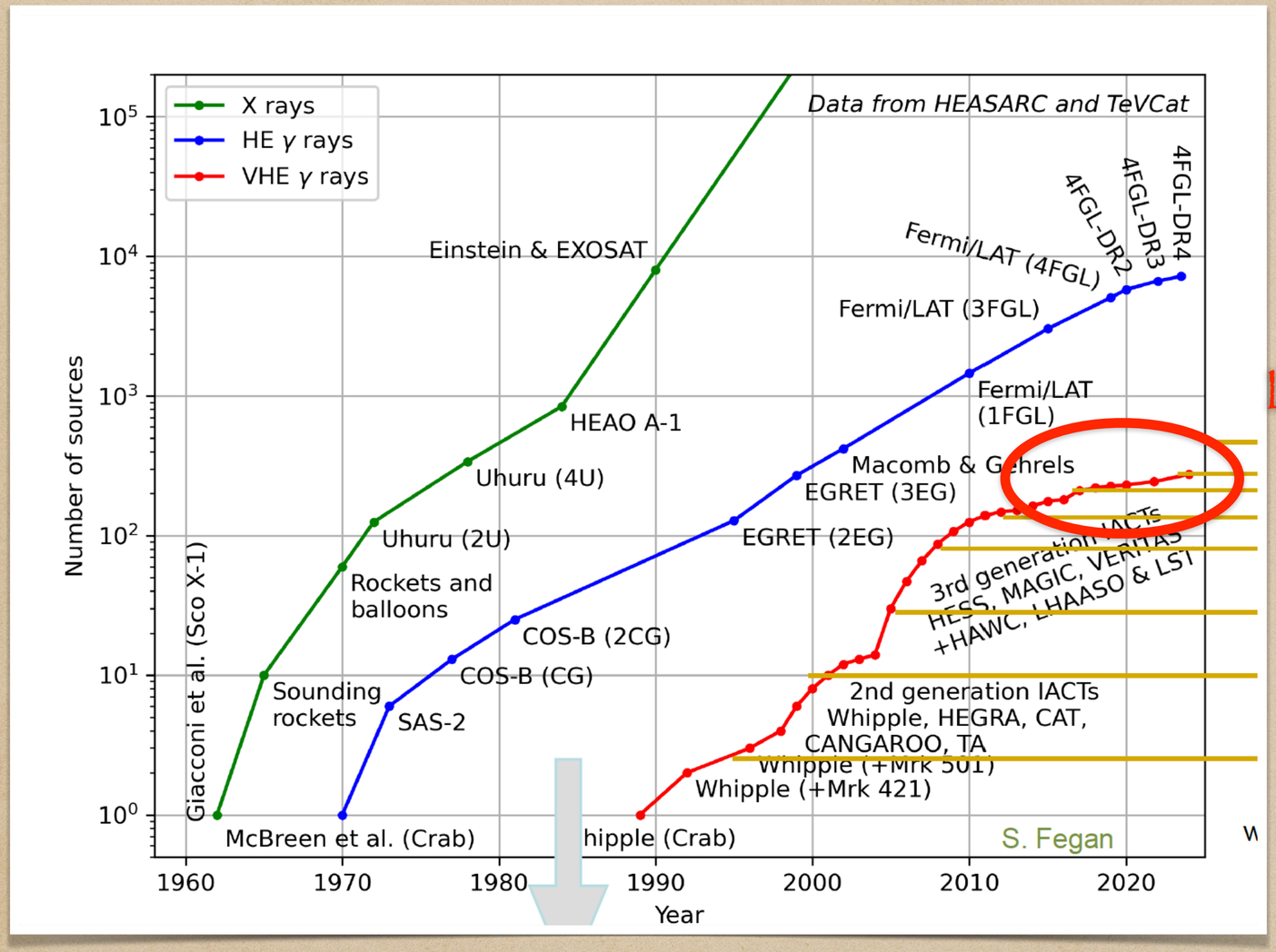
Devin



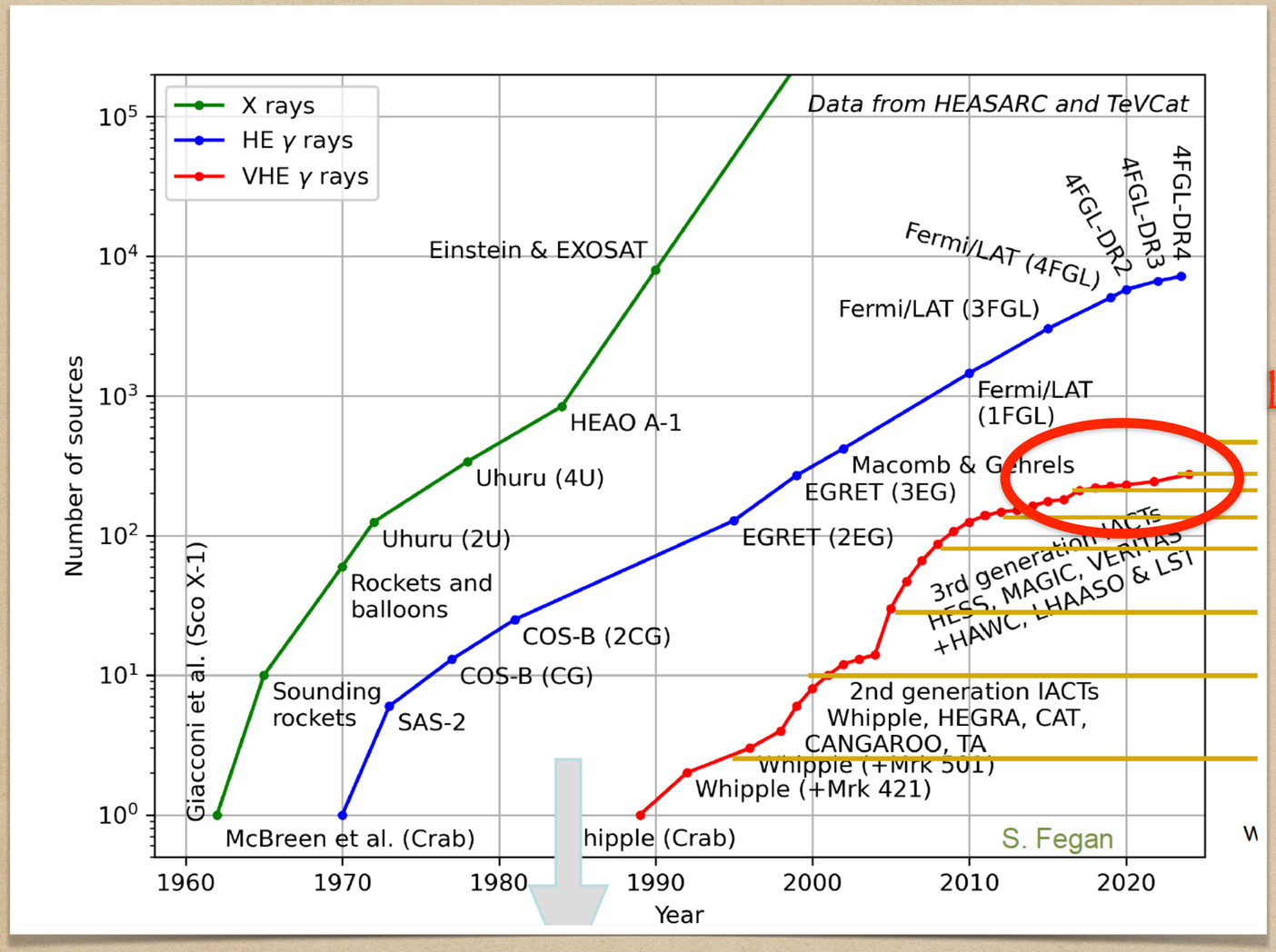
Final remarks

- Lot of progress…. but also many open questions

  → Motivation from new, more powerful facilities

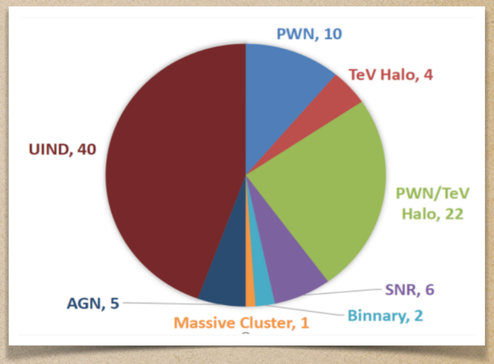


Low derivative



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

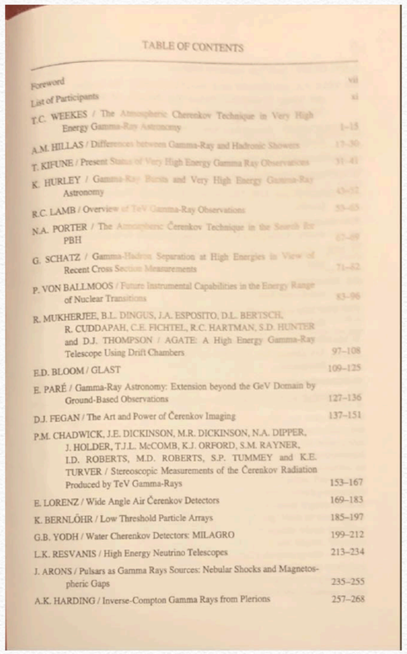
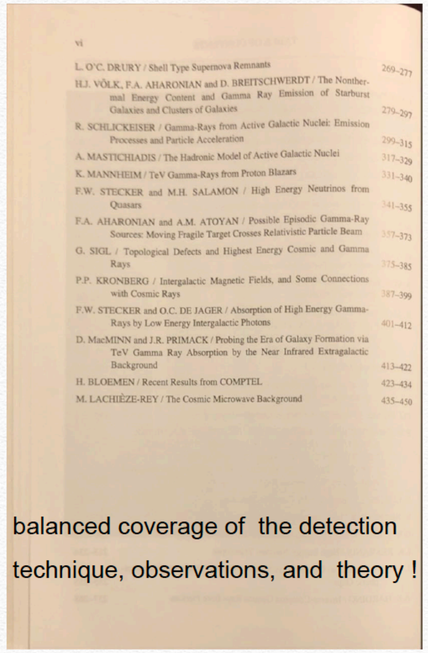


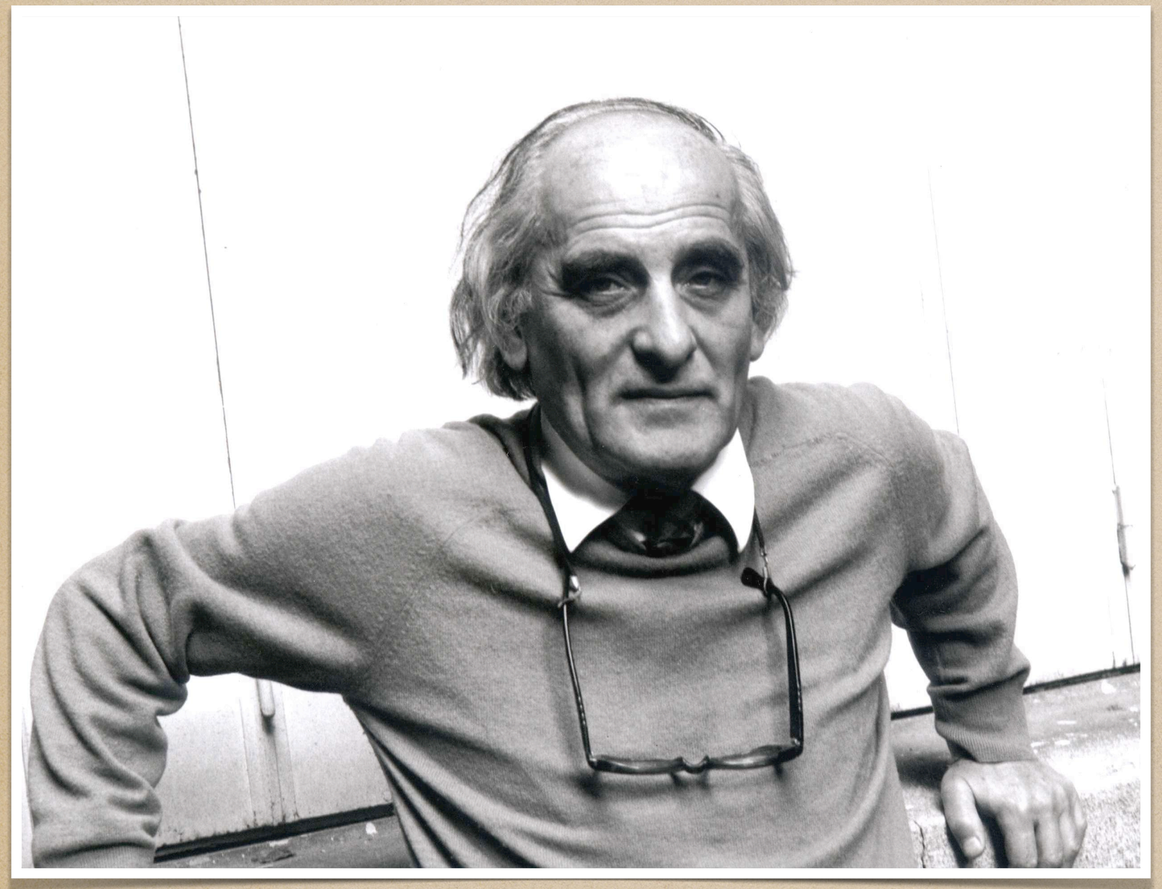
TABLE OF CONTENTS



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

No Italians !

Thank you Beppo !!



Thank you Nanni !!