Gerd Pühlhofer,
Landessternwarte Heidelberg + IAAT Tübingen

Pulsar wind nebulae: The VHE – X-ray connection

HESS = High Energy Stereoscopic System

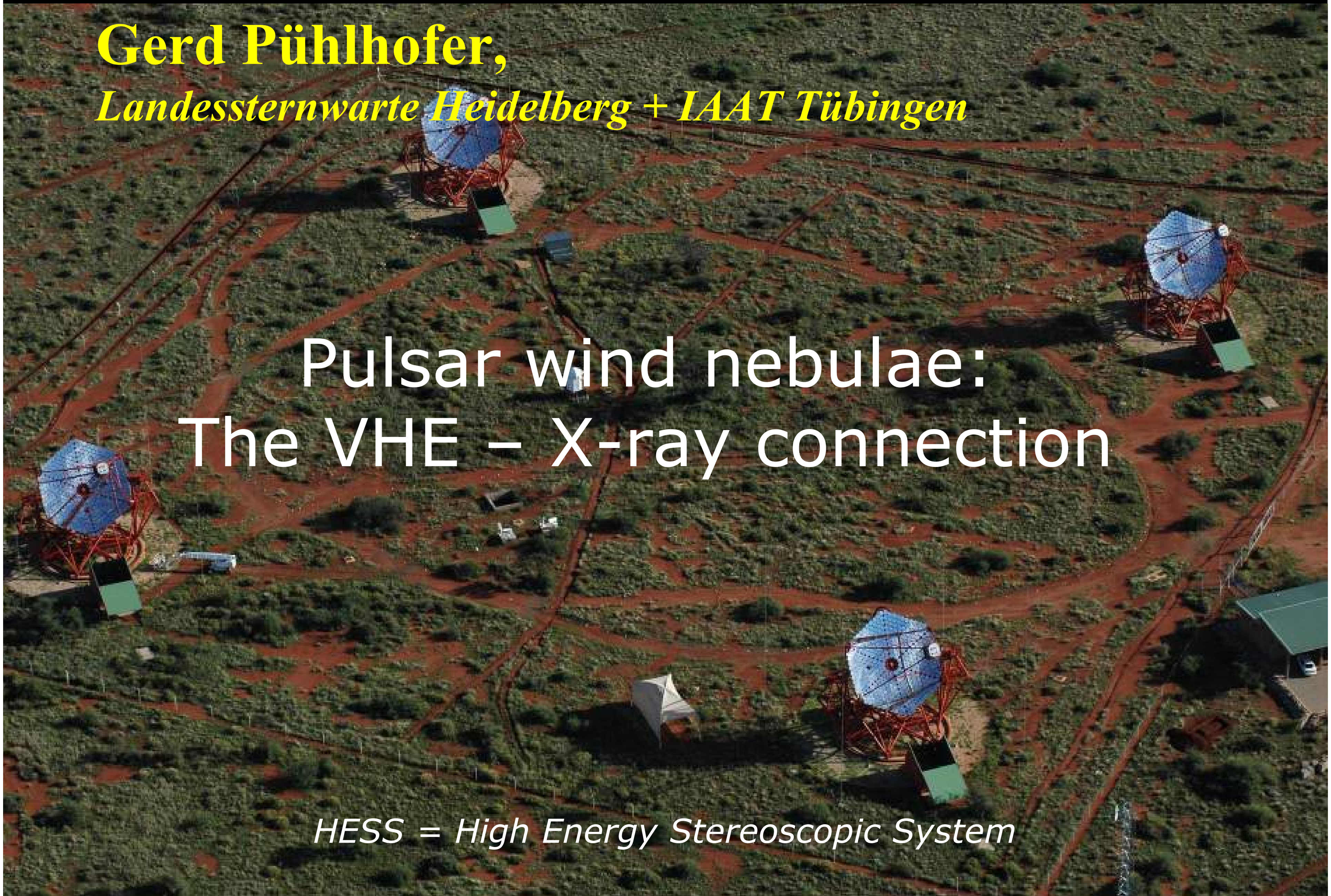
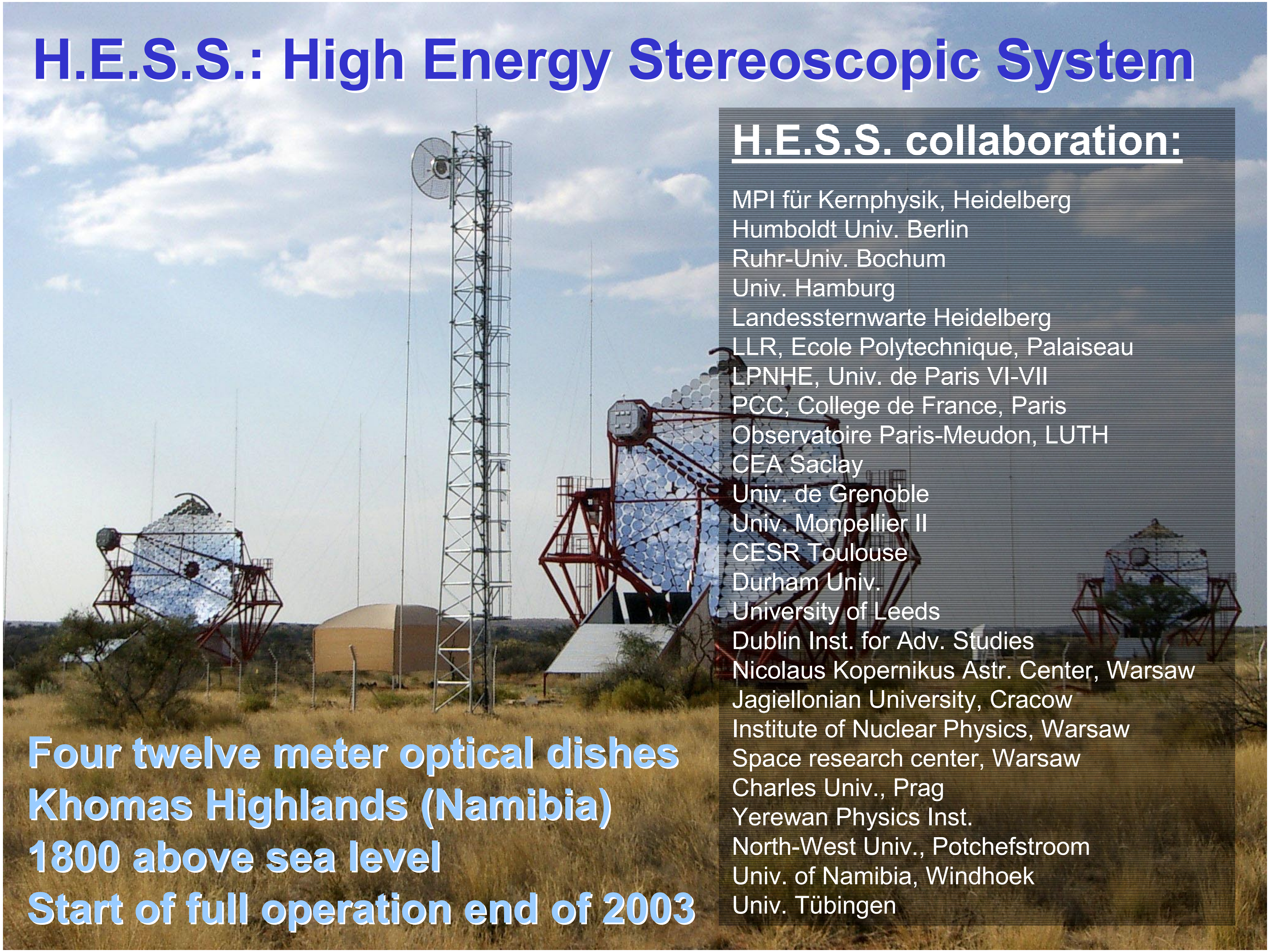


Photo: © Philippe Plailly

H.E.S.S.: High Energy Stereoscopic System



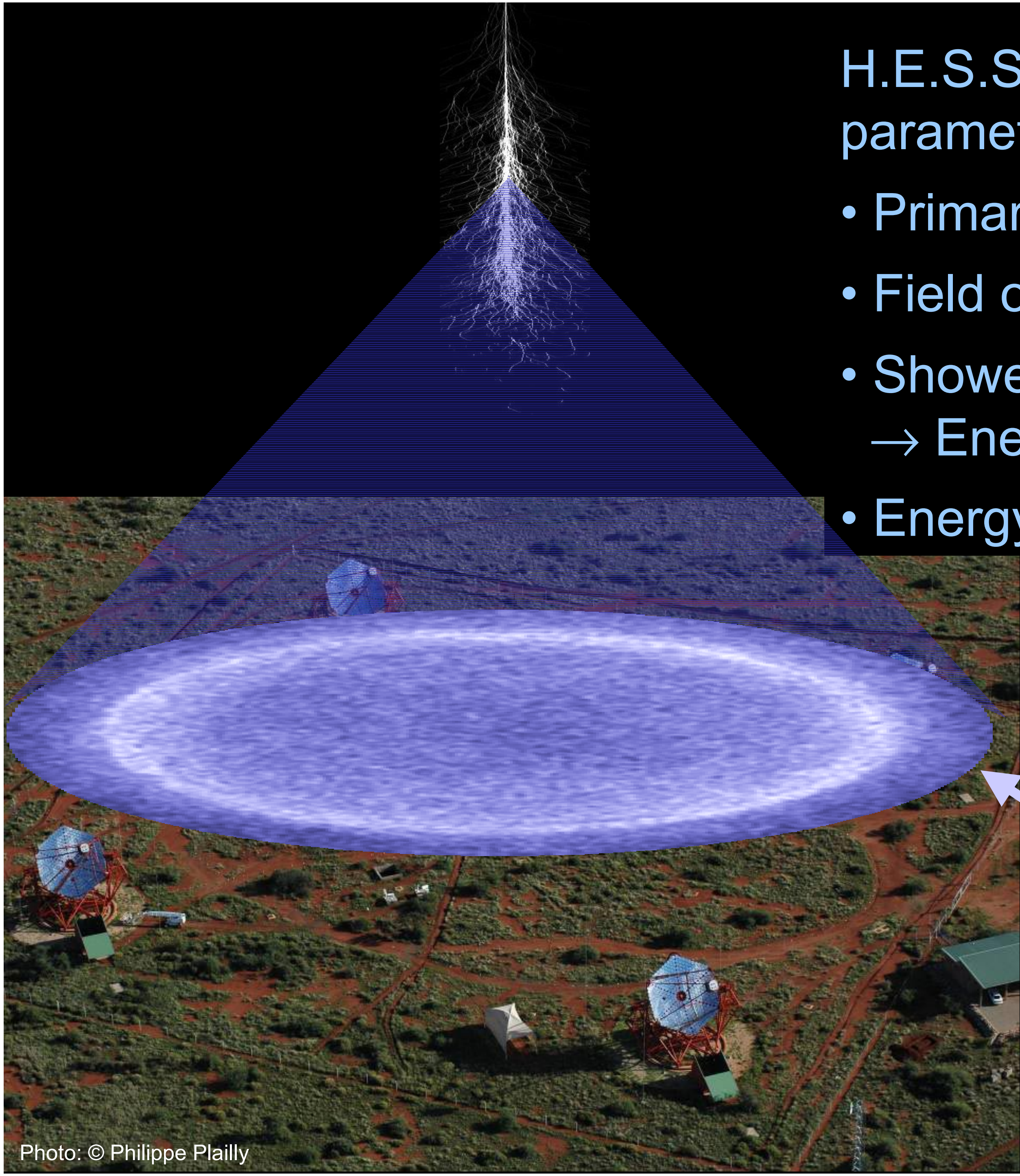
H.E.S.S. collaboration:

MPI für Kernphysik, Heidelberg
Humboldt Univ. Berlin
Ruhr-Univ. Bochum
Univ. Hamburg
Landessternwarte Heidelberg
LLR, Ecole Polytechnique, Palaiseau
LPNHE, Univ. de Paris VI-VII
PCC, College de France, Paris
Observatoire Paris-Meudon, LUTH
CEA Saclay
Univ. de Grenoble
Univ. Monpellier II
CESR Toulouse
Durham Univ.
University of Leeds
Dublin Inst. for Adv. Studies
Nicolaus Kopernikus Astr. Center, Warsaw
Jagiellonian University, Cracow
Institute of Nuclear Physics, Warsaw
Space research center, Warsaw
Charles Univ., Prag
Yerewan Physics Inst.
North-West Univ., Potchefstroom
Univ. of Namibia, Windhoek
Univ. Tübingen

Four twelve meter optical dishes
Khomas Highlands (Namibia)
1800 above sea level
Start of full operation end of 2003

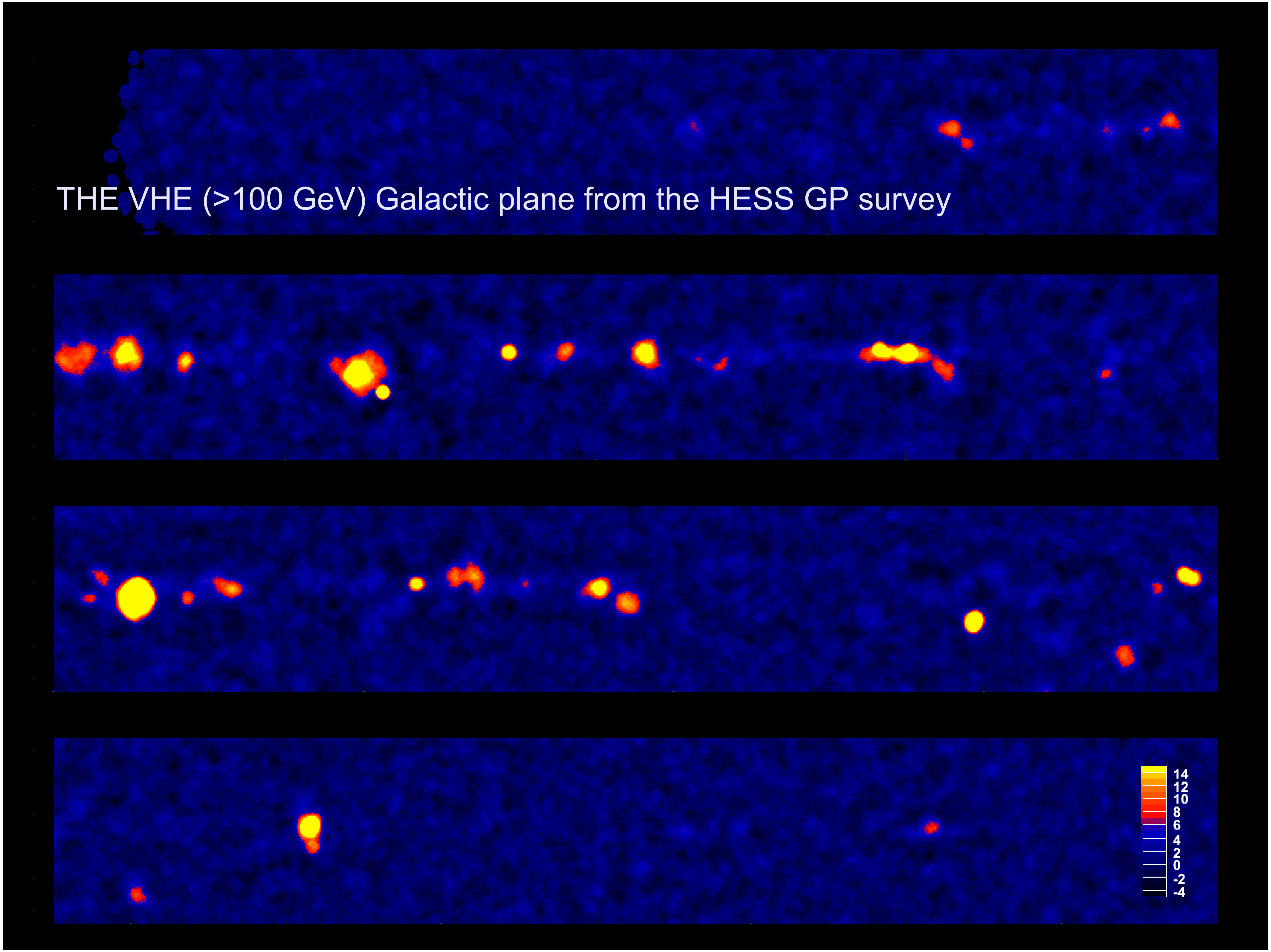
H.E.S.S. event reconstruction parameters:

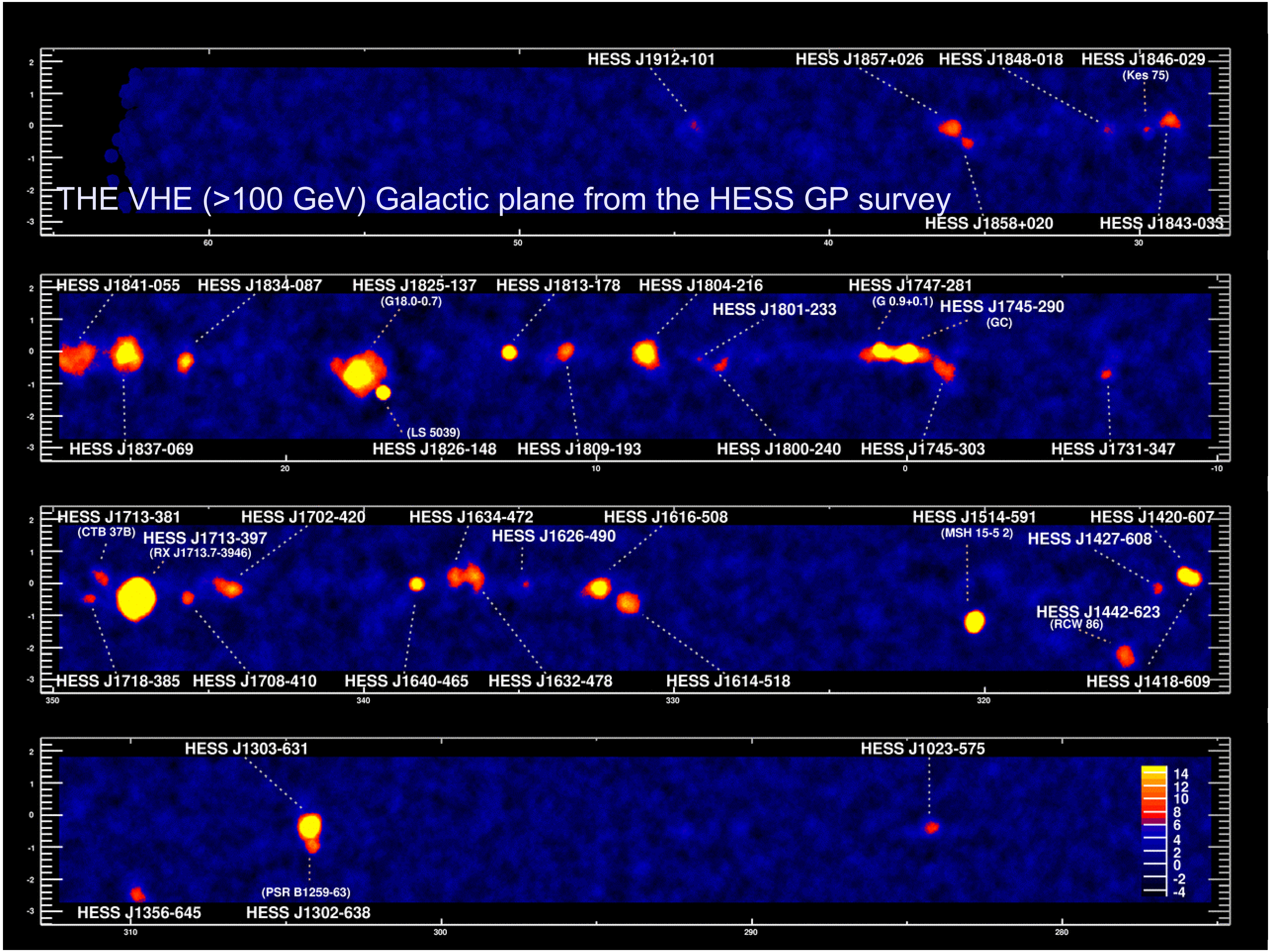
- Primary direction: < 0.1°
- Field of view: 3° FWHM
- Shower core: 10m
  → Energy resolution: 15%
- Energy range: 0.1–100 TeV



Cherenkov light from shower particles

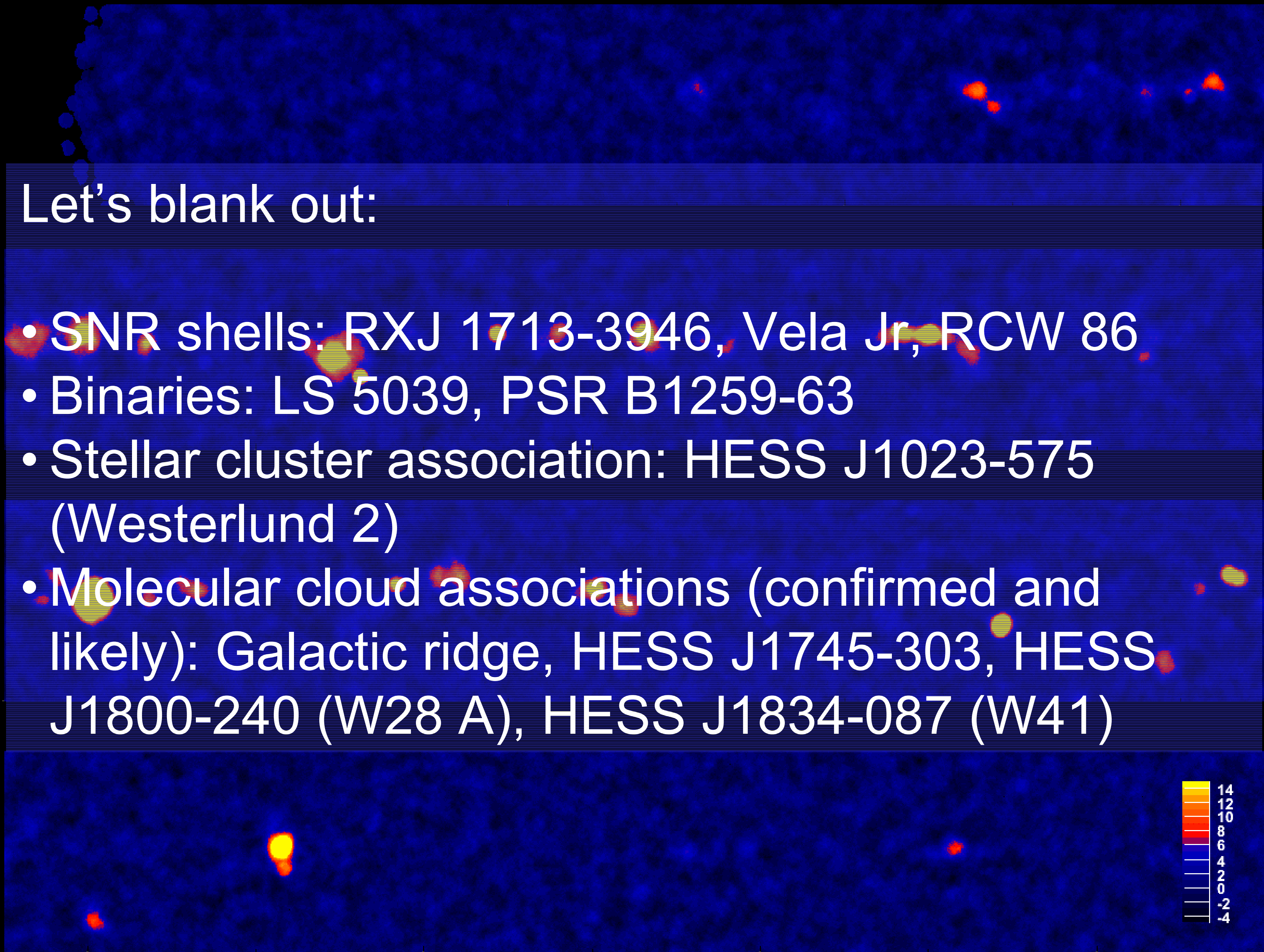
THE VHE (>100 GeV) Galactic plane from the HESS GP survey

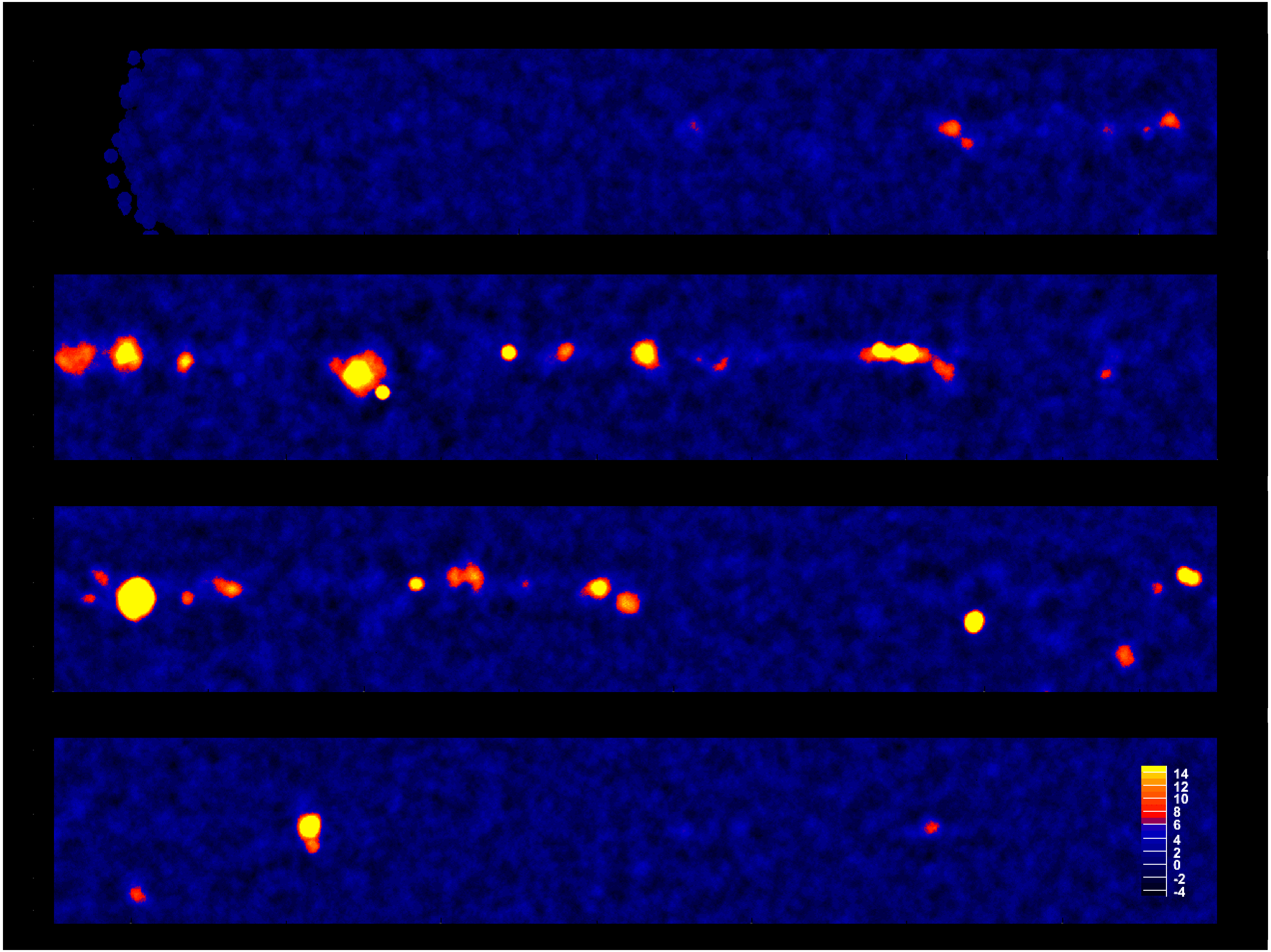



THE VHE (>100 GeV) Galactic plane from the HESS GP survey
HESS J1912+101
HESS J1857+026
HESS J1848-018
HESS J1846-029
(Kes 75)
HESS J1858+020
HESS J1843-033
HESS J1841-055
HESS J1834-087
HESS J1825-137
(G18.0-0.7)
HESS J1813-178
HESS J1804-216
HESS J1747-281
(G 0.9+0.1)
HESS J1801-233
HESS J1745-290
(GC)
(LS 5039)
HESS J1837-069
HESS J1826-148
HESS J1809-193
HESS J1800-240
HESS J1745-303
HESS J1731-347
HESS J1713-381
(CTB 37B)
HESS J1713-397
(RX J1713.7-3946)
HESS J1702-420
HESS J1634-472
HESS J1626-490
HESS J1616-508
HESS J1514-591
(MSH 15-5 2)
HESS J1427-608
HESS J1420-607
HESS J1442-623
(RCW 86)
HESS J1718-385
HESS J1708-410
HESS J1640-465
HESS J1632-478
HESS J1614-518
HESS J1418-609
HESS J1303-631
HESS J1023-575
(PSR B1259-63)
HESS J1356-645
HESS J1302-638
14
12
10
8
6
4
2
0
-2
-4

Let’s blank out:

- SNR shells: RXJ 1713-3946, Vela Jr, RCW 86
- Binaries: LS 5039, PSR B1259-63
- Stellar cluster association: HESS J1023-575 (Westerlund 2)
- Molecular cloud associations (confirmed and likely): Galactic ridge, HESS J1745-303, HESS J1800-240 (W28 A), HESS J1834-087 (W41)

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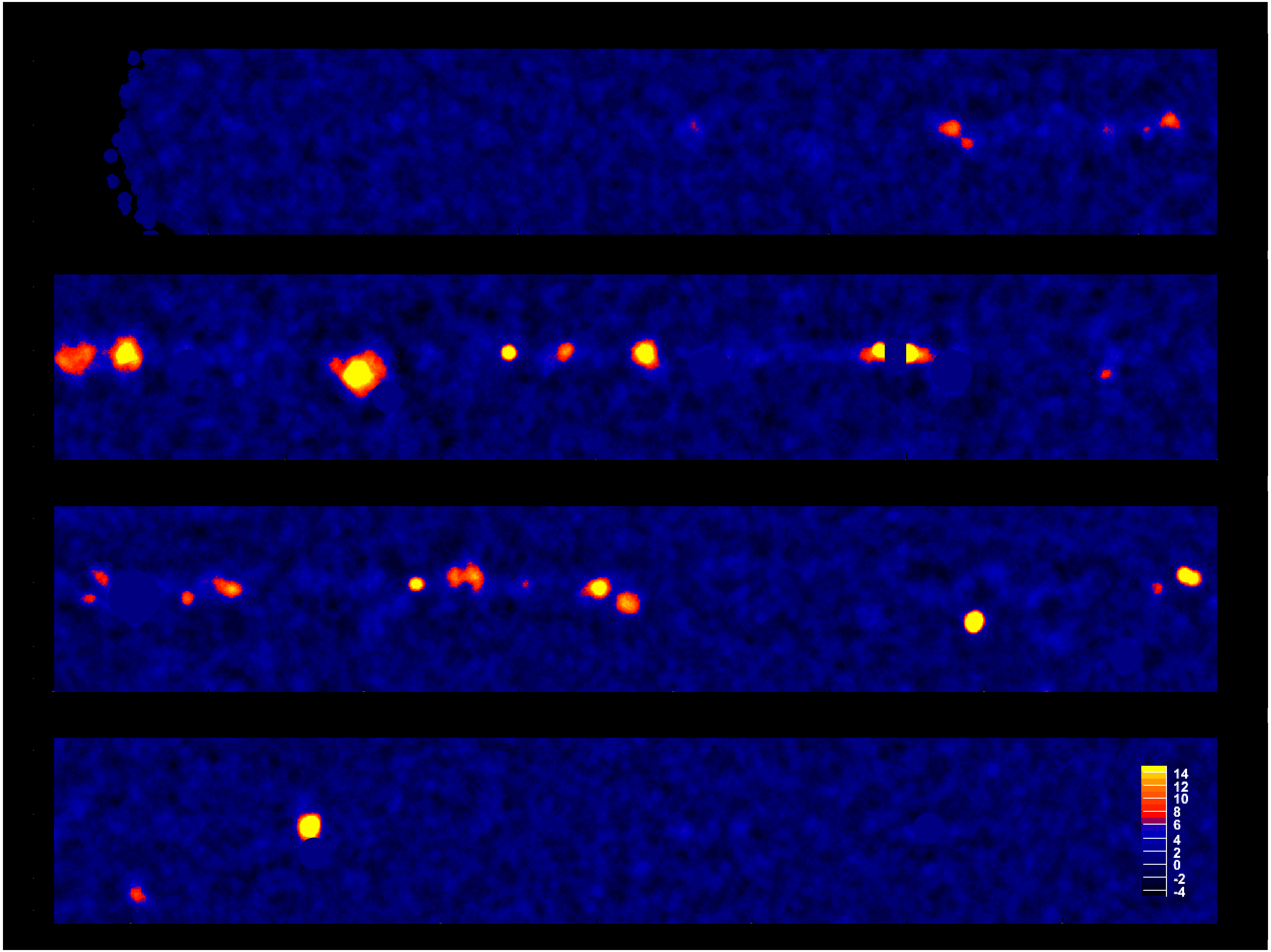

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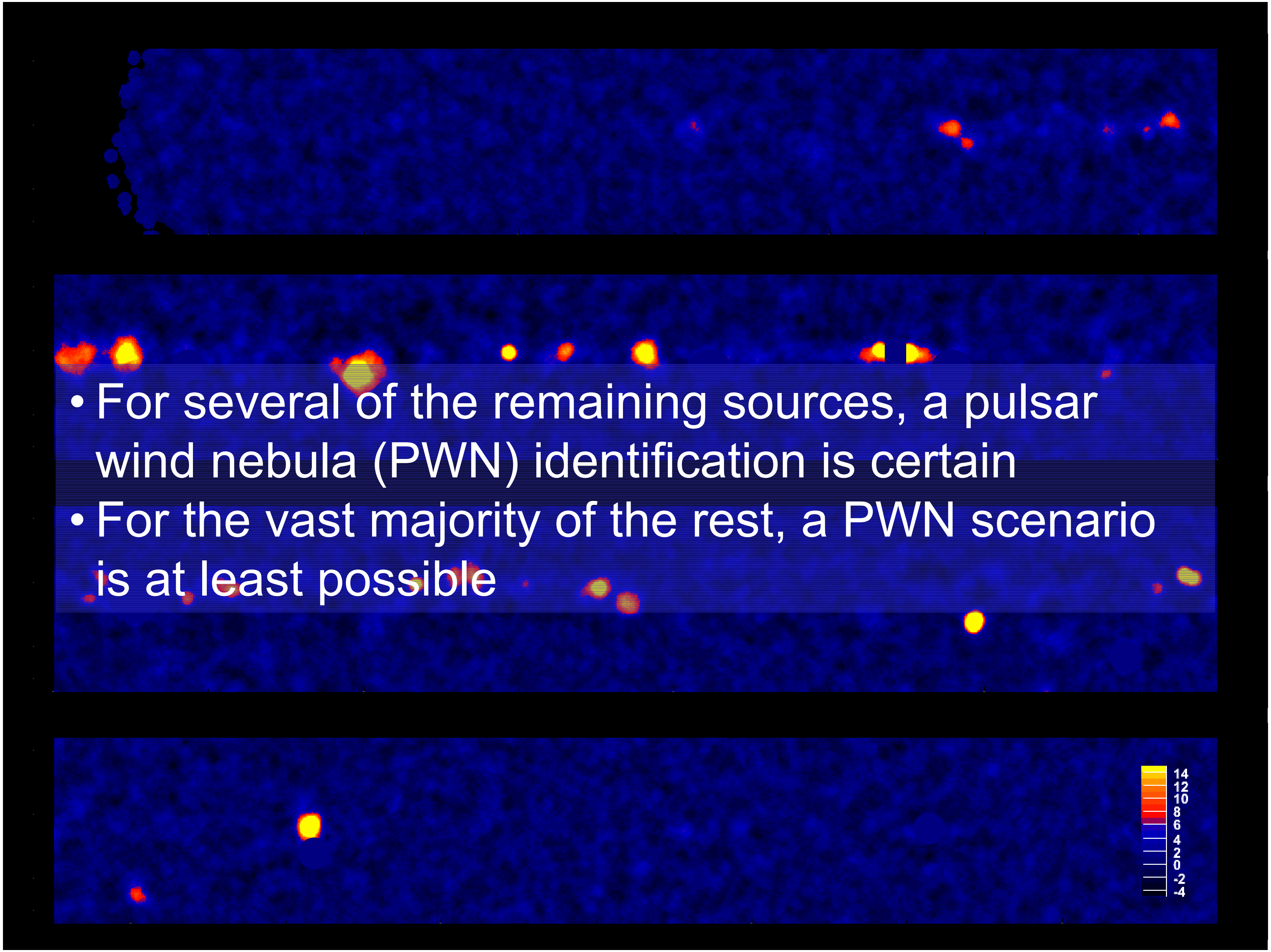


- For several of the remaining sources, a pulsar wind nebula (PWN) identification is certain
- For the vast majority of the rest, a PWN scenario is at least possible

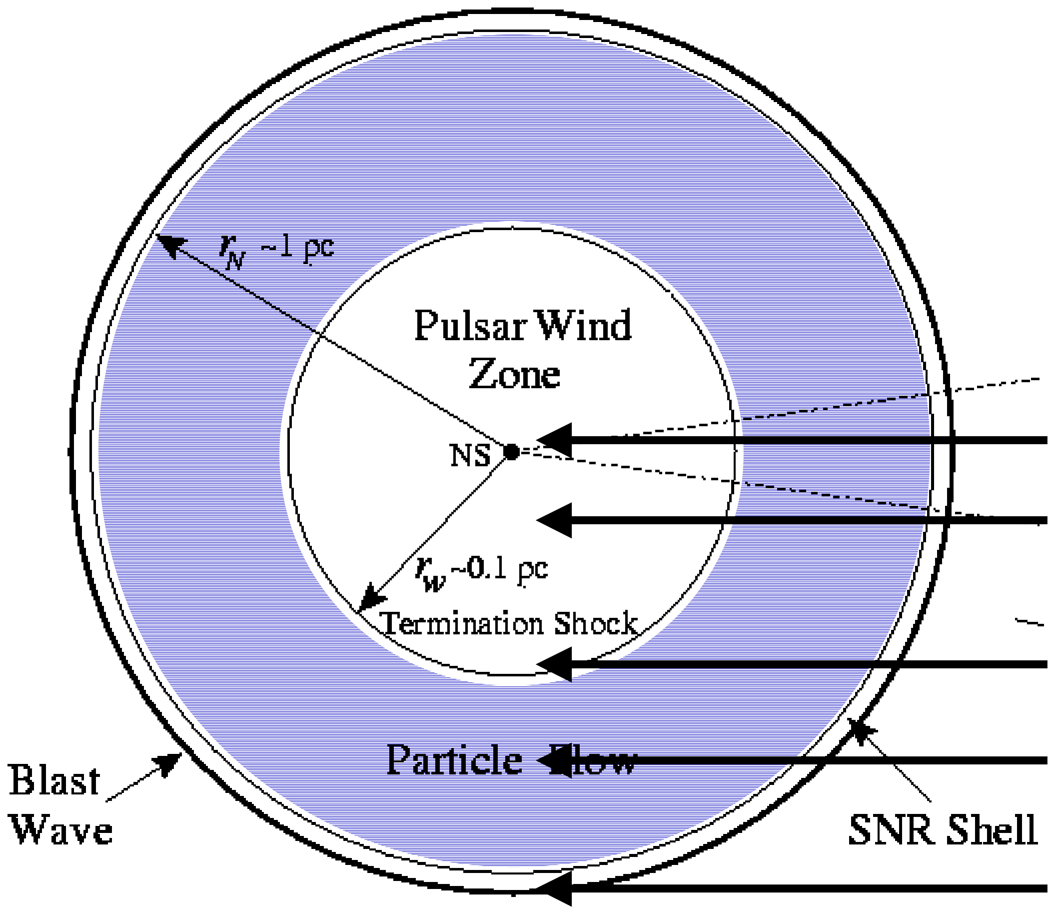
Overview

- Some general statements about the relation between X-ray and VHE pulsar wind nebulae
- Young vs. middle-aged and relic PWN
- Pevatrons and INTEGRAL
- Identification problem of large-offset VHE PWN
- Underluminous X-ray PWN and associated issues

Warning: totally biased towards VHE-detected PWN

Geometry of a pulsar wind (nebula)

Sketch by Slane



Neutron star

Cold, non-emitting flow

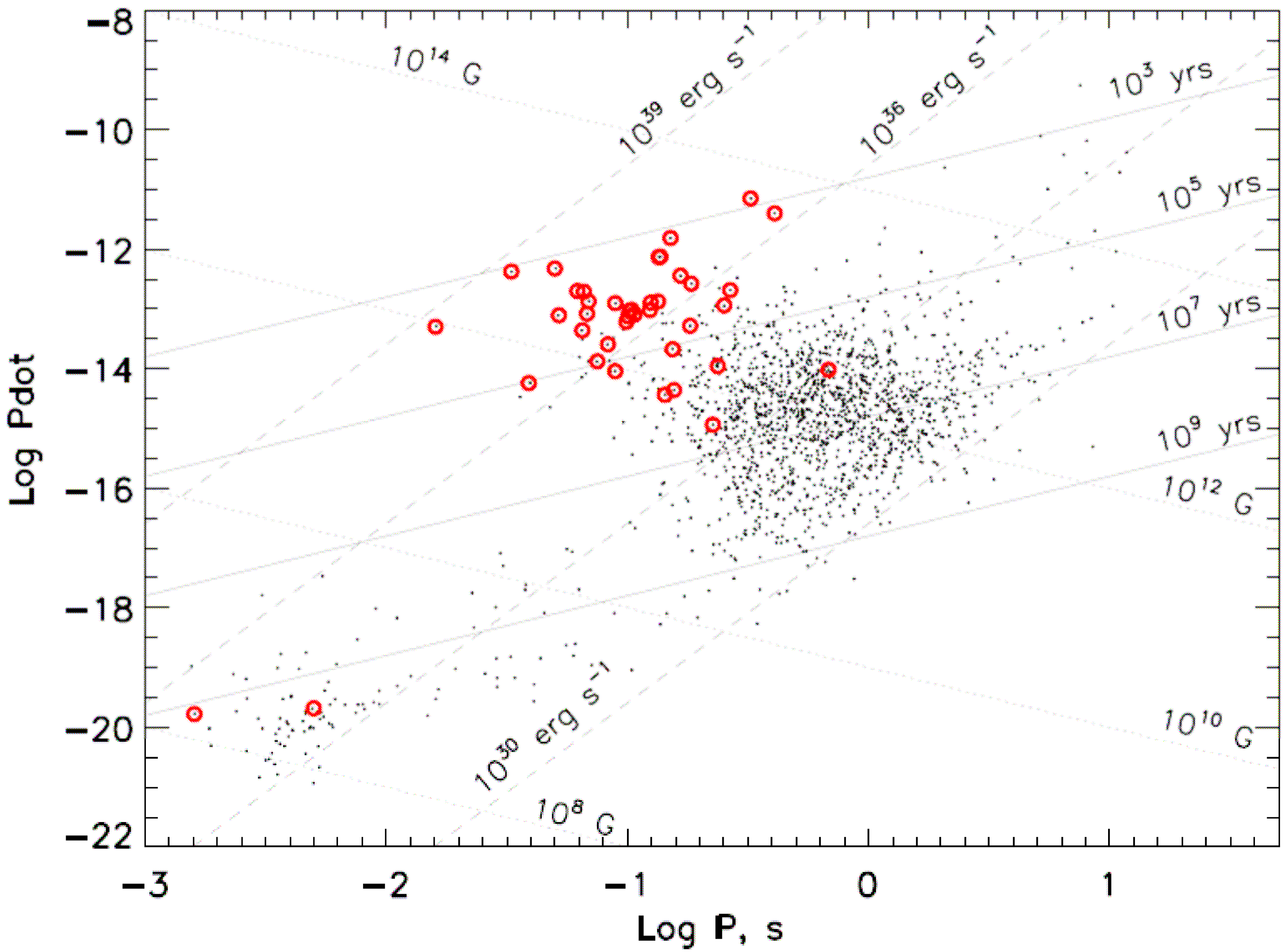
Acceleration of particles at termination shock

Visible (i.e. emitting) pulsar wind nebula

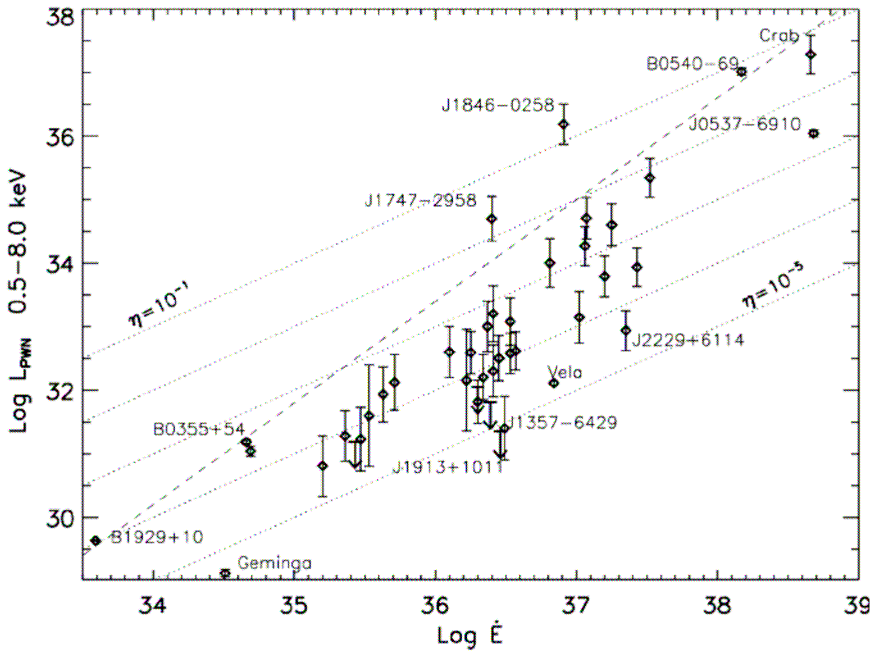
Possibly interaction with surrounding SNR (e.g. reverse shock)

X-ray emitting PWN: sample study

Chandra PWN review, Kargaltsev & Pavlov, astro-ph/0801.2602



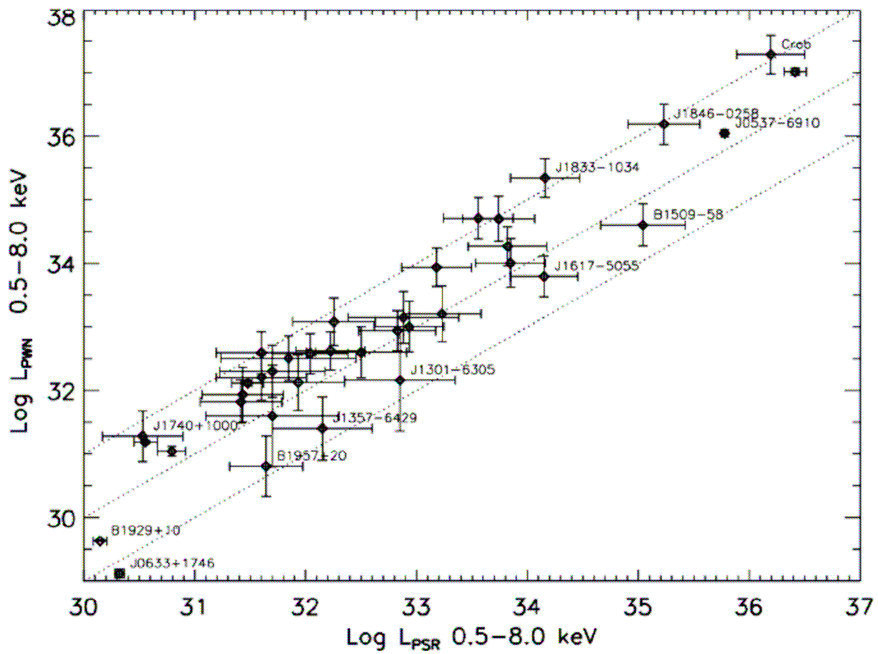
X-ray emitting PWN: sample study



ε or η:
Efficiency of current pulsar energy loss into given observation band

Large scatter of X-ray synchrotron efficiencies

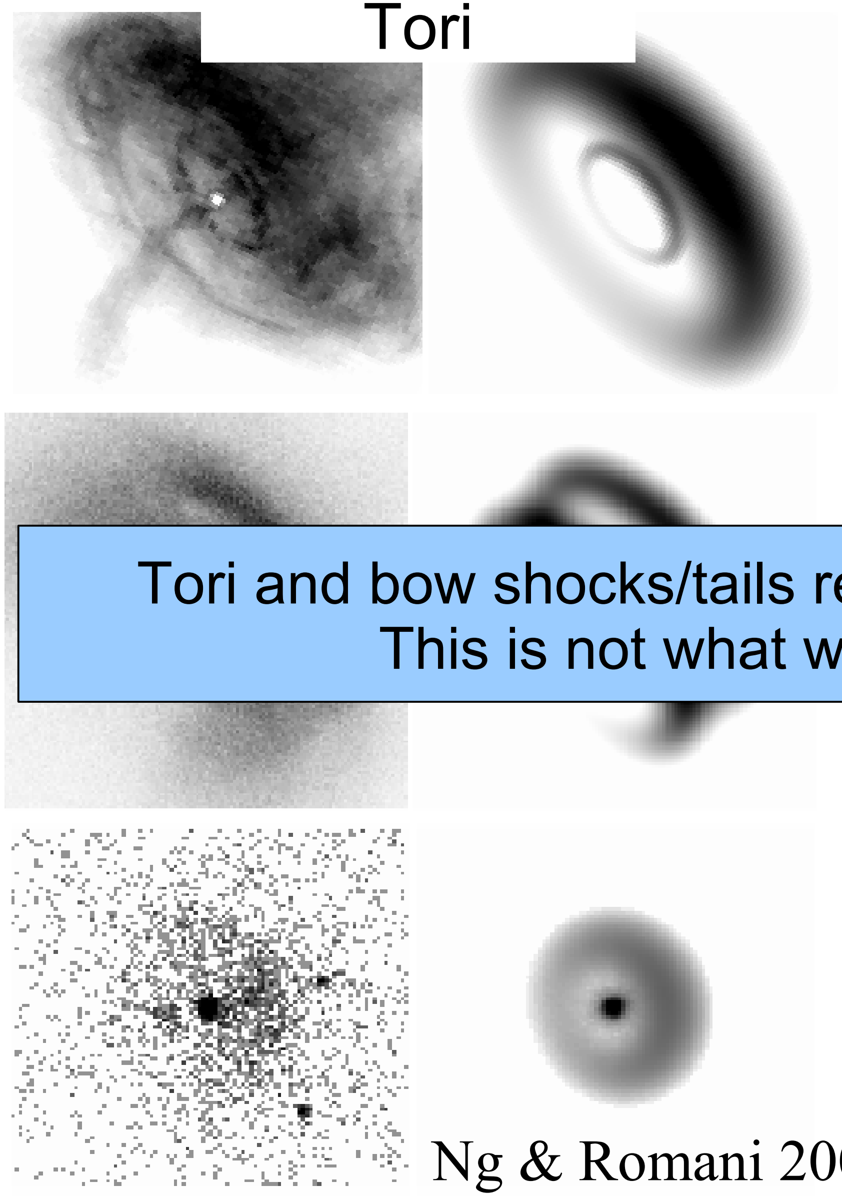
But fairly good correlation between nonthermal magnetospheric and PWN emission



Chandra PWN review, Kargaltsev & Pavlov, astro-ph/0801.2602

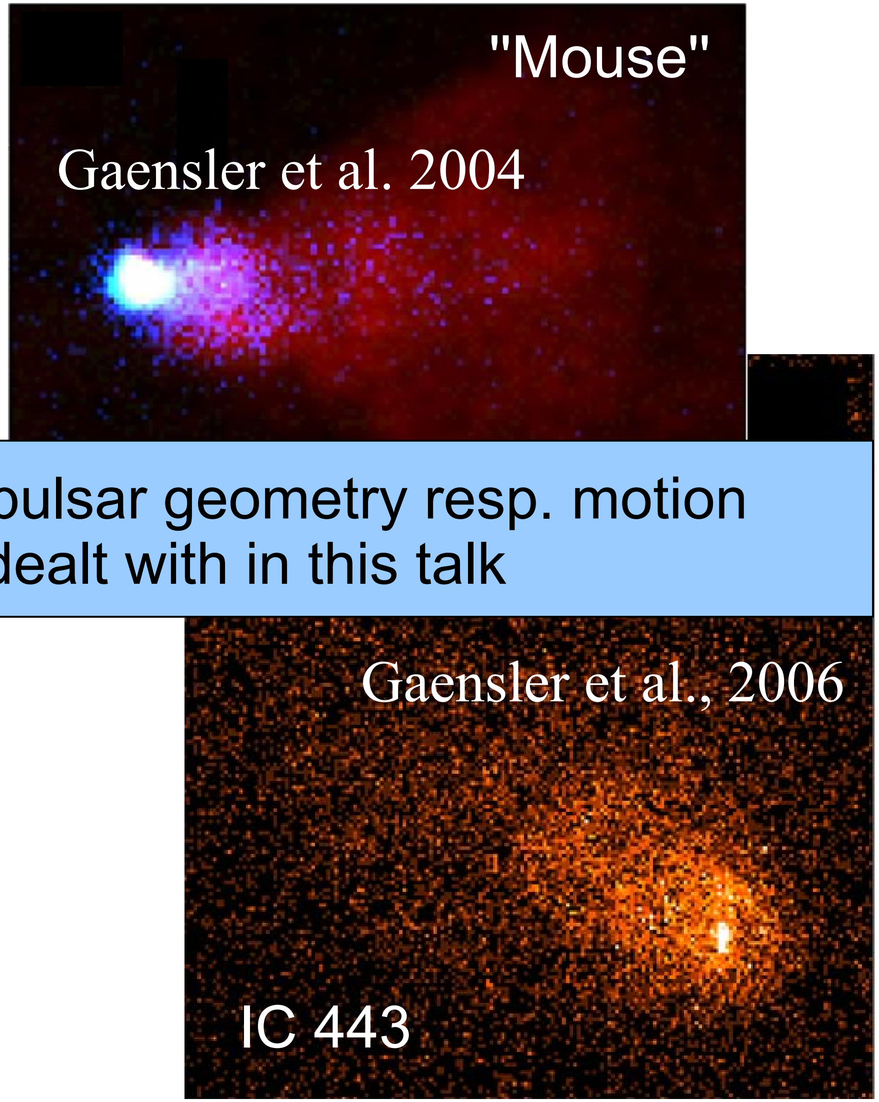
“Usual” X-ray PWN seen with Chandra

Tori



Ng & Romani 2003

Bow shocks and wakes



Tori and bow shocks/tails reflect pulsar geometry resp. motion
This is not what will be dealt with in this talk

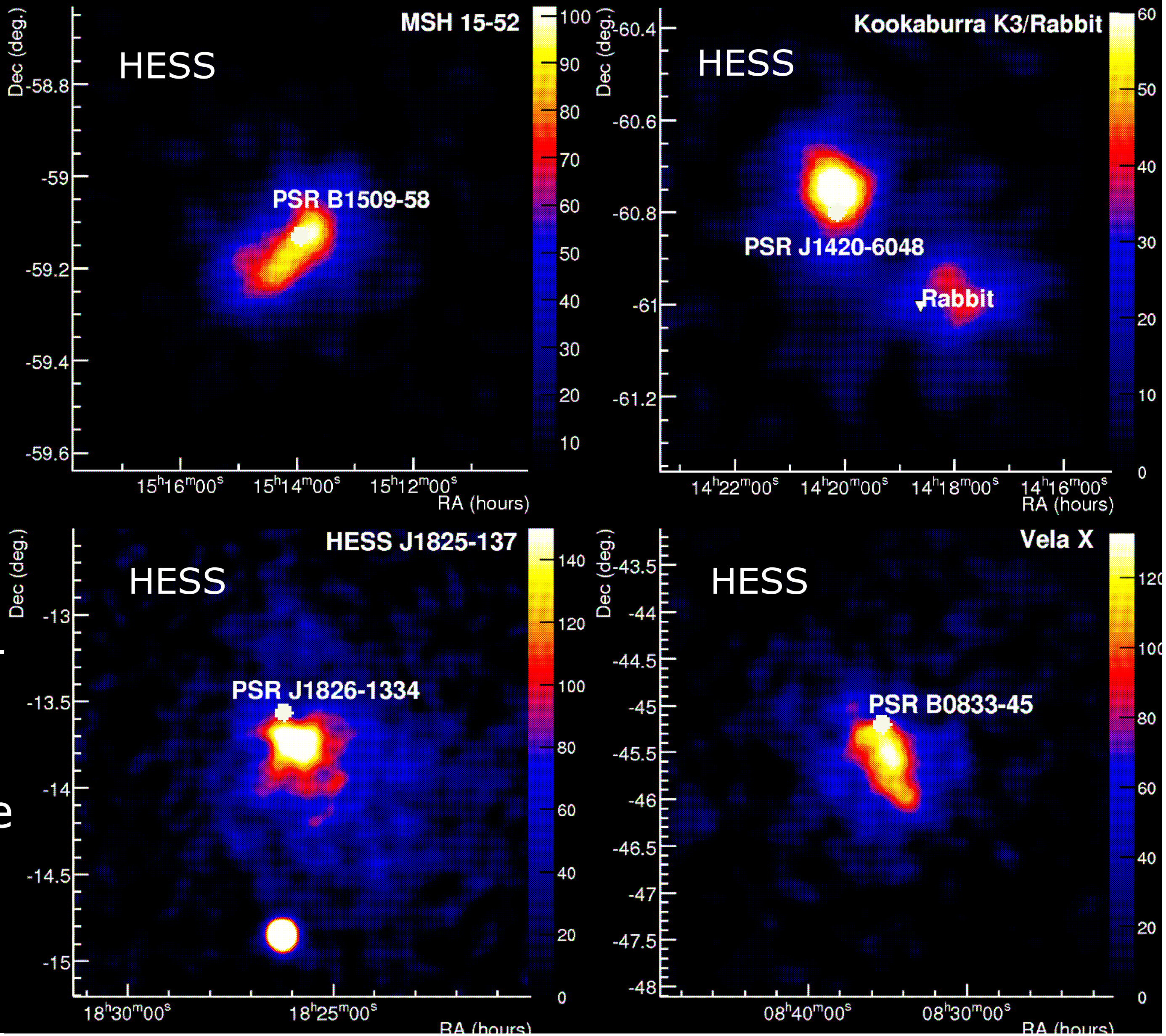
PWN: the largest identified Galactic VHE population

Several firmly identified VHE pulsar wind Nebulae (PWN)

Many VHE PWN candidates

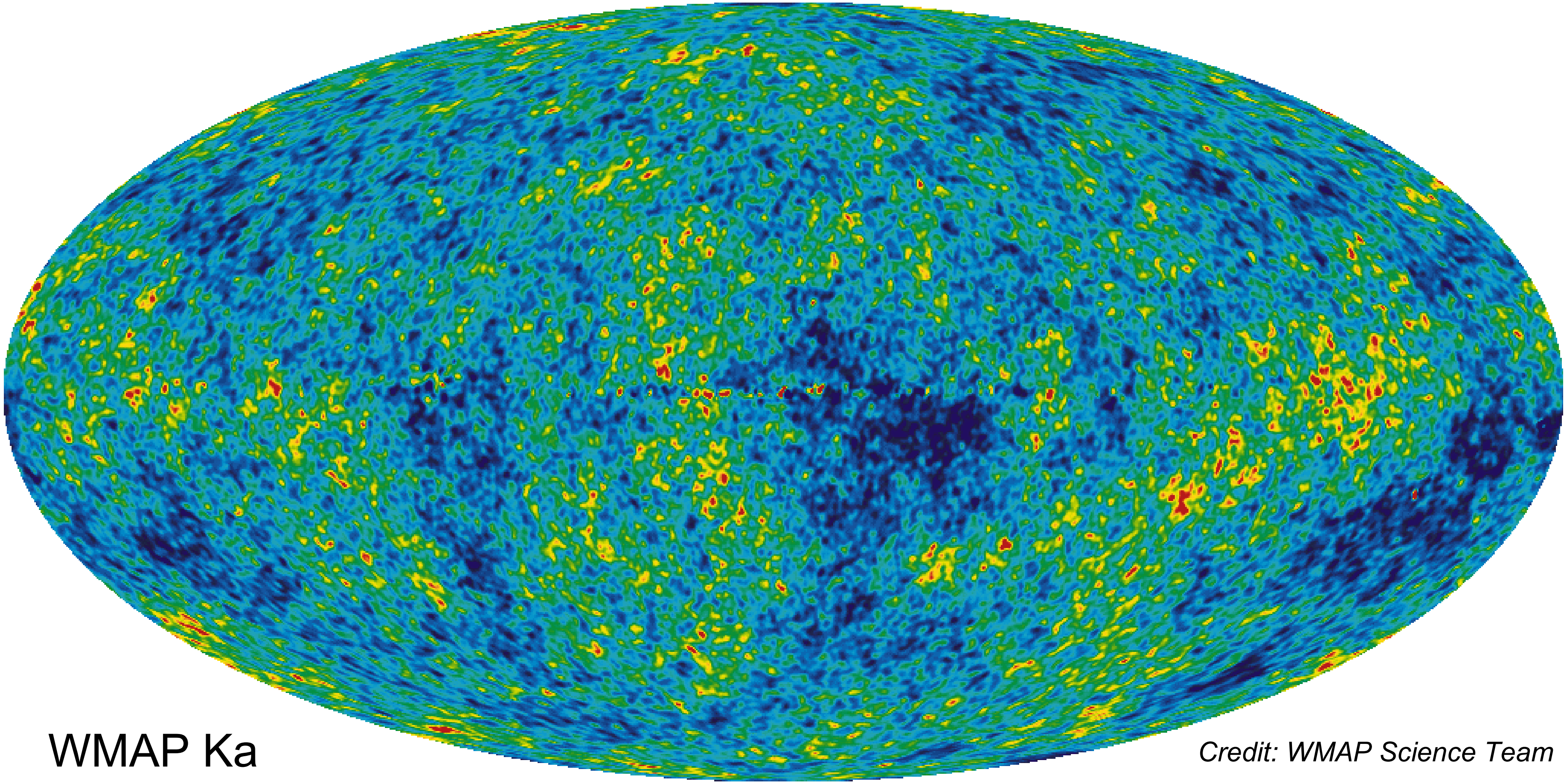
Why identified:
- known pulsar
- morphology matches with X-ray PWN

Most VHE PWN are
- extended
- displaced from the pulsar



Cosmic microwave background …

… serves as homogeneous target for Inverse compton scattering of electrons

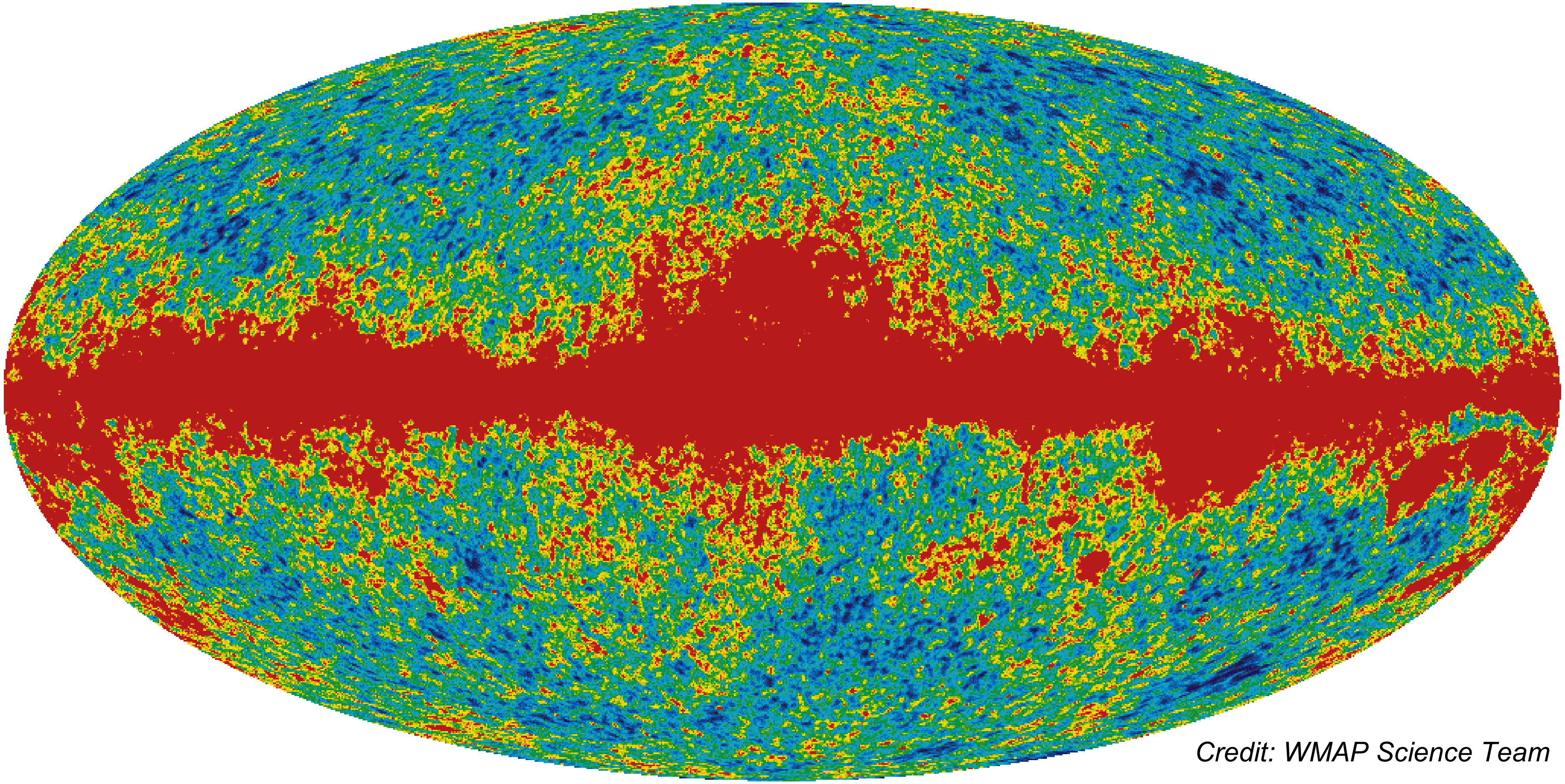


WMAP Ka

Credit: WMAP Science Team

CMB + Galactic "foreground"

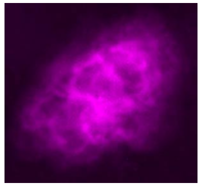
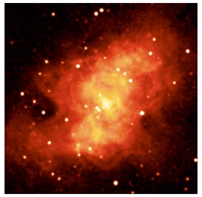
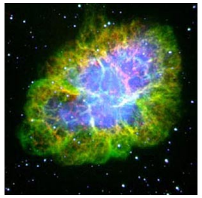
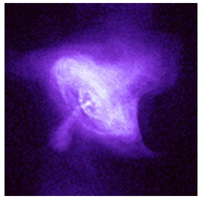
In addition, stellar and dust radiation fields can boost IC emission

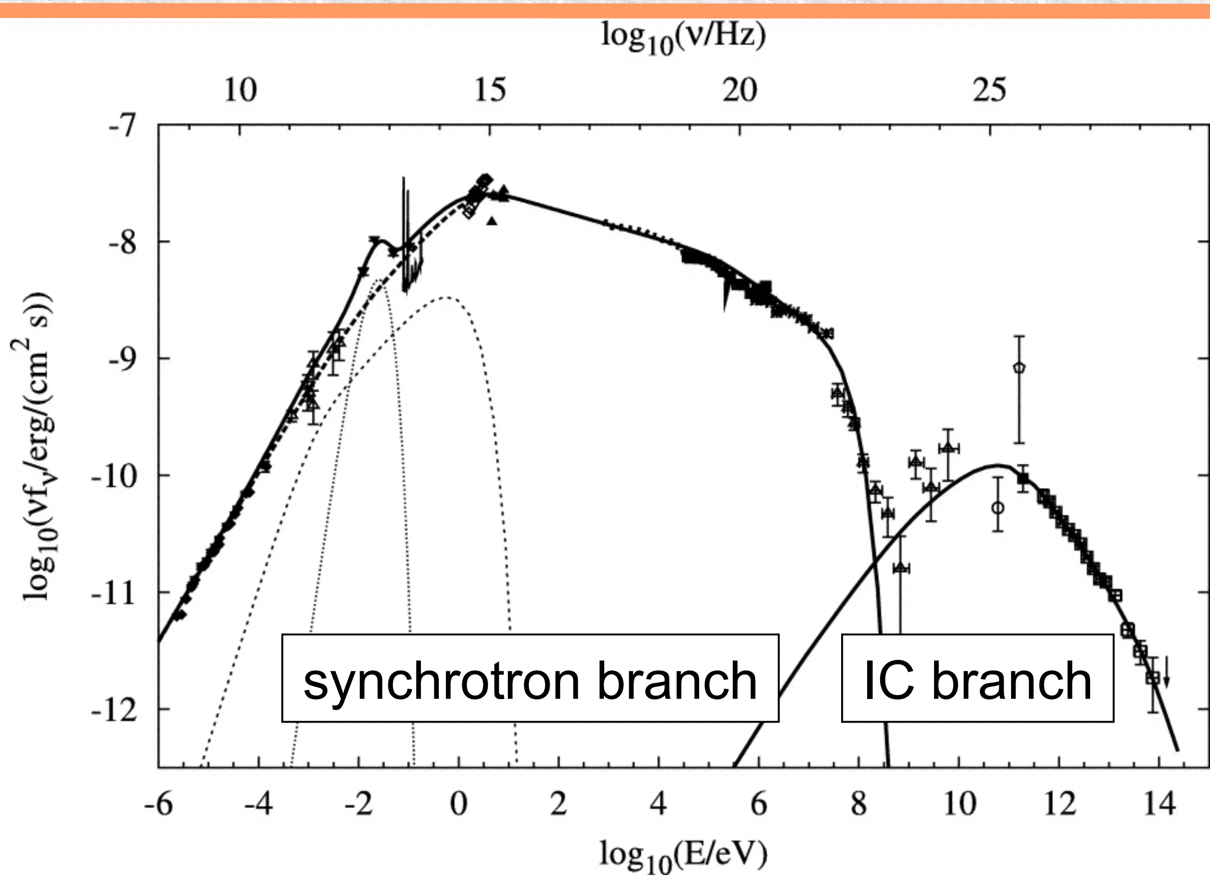


Credit: WMAP Science Team

WMAP Ka (Thermal and nonthermal)
Stellar and dust photon fields are hard to access (esp. 3-D)

The young Crab Nebula (1000 years)

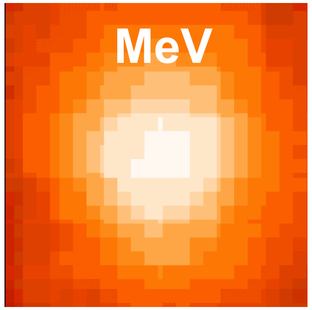


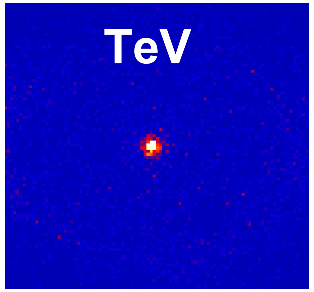
HEGRA collaboration, ApJ 2004, 614, 897

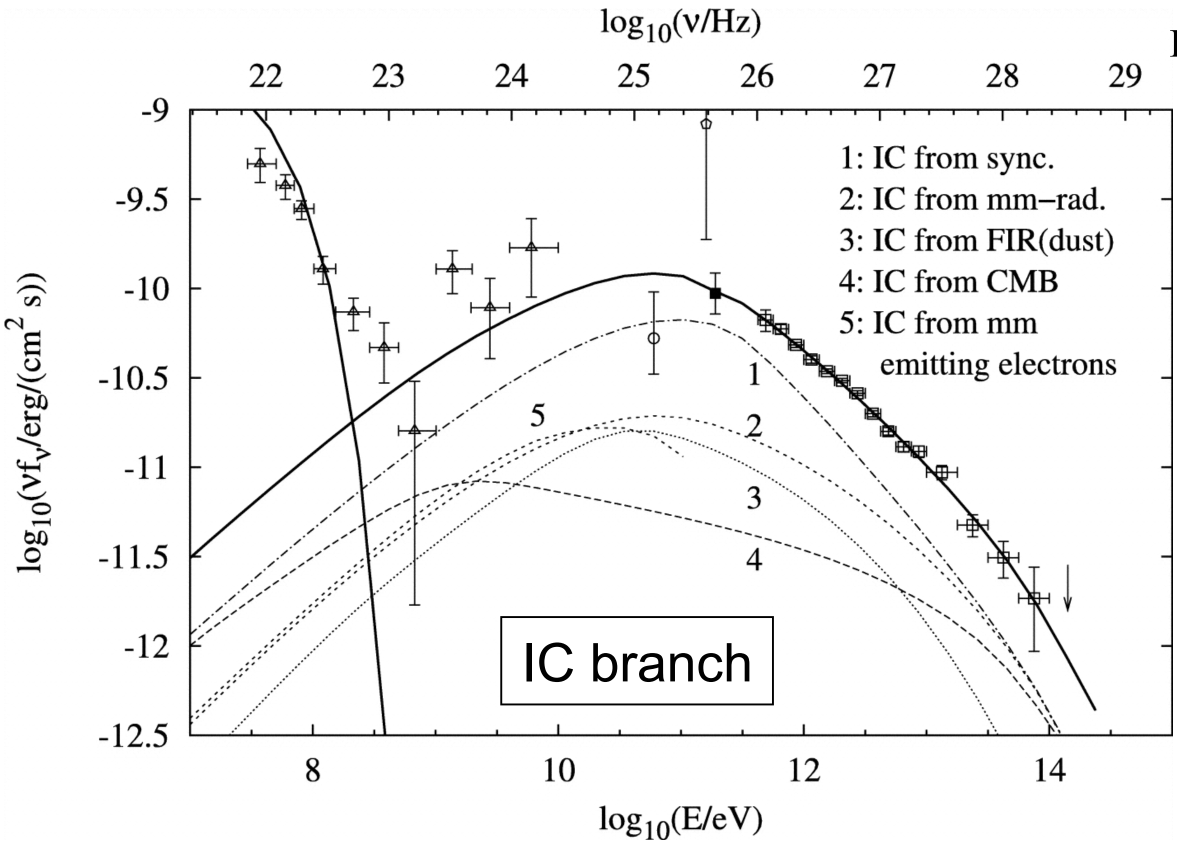
(Northern Hemisphere source)

compact source, high B-field (160 µG) →
- high synchrotron efficiency, IC emission comparatively low
- synchrotron photons produce relevant target field for IC (“SSC”)
  → IC coupled to B-field again

The young Crab Nebula (1000 years)

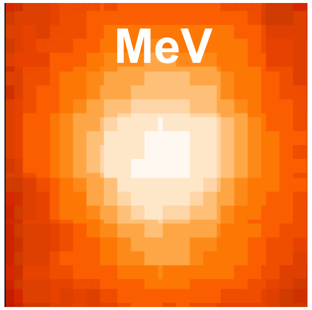


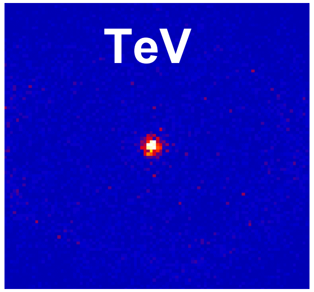


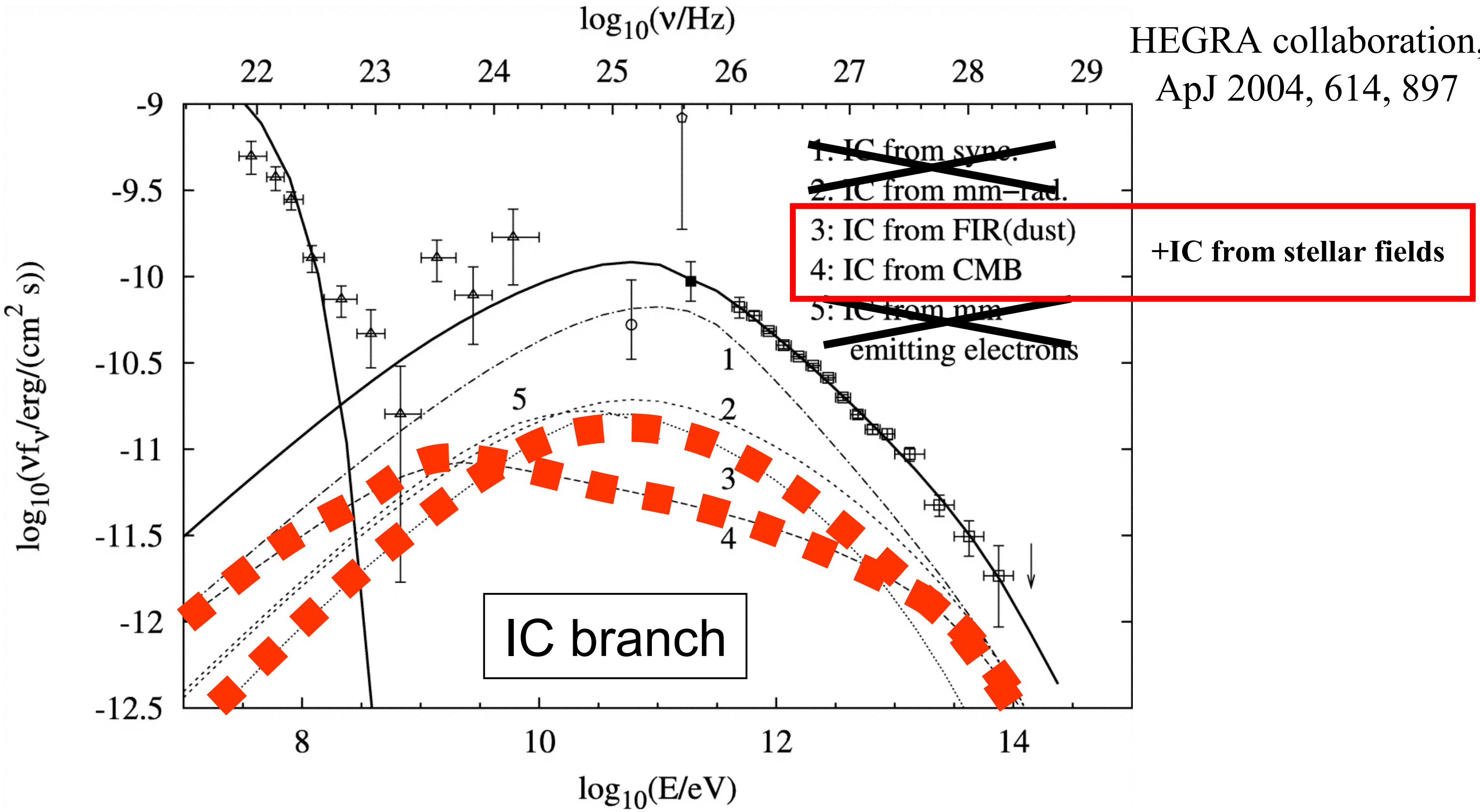


HEGRA collaboration, ApJ 2004, 614, 897

The young Crab Nebula (1000 years)







HEGRA collaboration, ApJ 2004, 614, 897

Extended pulsar wind nebulae from middle-aged pulsars

- **are simpler because IC scattering off external, in principle well known target photon fields**
- **are much more common…**

F_X / F_{VHE} …

… or F_{VHE} / F_X: a widely used diagnostic tool useful for investigating VHE – X-ray source associations

from Kargaltsev et al., ApJ 670, 2007

Name	Type	f_γ/f_X	Extended in TeV?	X-Ray Counterpart
LSI +61 303	HMXB/μ-quasar	0.8	No	Yes
LS 5039	HMXB/μ-quasar	0.7	No	Yes
PSR B1259–63	HMXB/pulsar	0.4	No	Yes
HESS J1634–472	HMXB/NS?	0.03–125	Yes?	IGR J16358–4726?
HESS J1632–478	HMXB?	0.2	Yes?	IGR J16320–4751
1ES 1218+30.4	BL Lac	0.3	No	Yes
Mrk 421	BL Lac	2.0	No	Yes
RX J1713.7–3946	SNR	0.075	Yes	G347.3–0.5
G266.6–1.2	SNR	0.6	Yes	Vela Junior
Crab	PWN	0.008	No	Crab PWN
HESS J1825–137	PWN	3.4	Yes	B1823–13 PWN
MSH 15–52	PWN	0.27	Yes	Yes
Vela X	PWN	0.6	Yes	Yes
G0.9+0.1	PWN?	0.1	No?	Yes
HESS J1804/B1800–21[d]	PWN	100	Yes	Yes
HESS J1804/Ch1[e]	PWN?	30	Yes	Yes
HESS J1804/Ch2[f]	PWN?	50	Yes	Yes
HESS J1804/Diff.[g]	SNR?	$\gtrsim$4	Yes	Yes

Lifetime of VHE-emitting electrons

from Aharonian et al., A&A 460, 2006

$$\tau_{VHE} \approx 3.1 \times 10^5 \, (w_r/\text{eV cm}^{-3})^{-1} \, (E/1\ \text{TeV})^{-1} \ \text{years}$$

$$w_r = \eta w_{ph} + 0.025 \ \text{eV cm}^{-3} \, (B/\mu G)^2$$

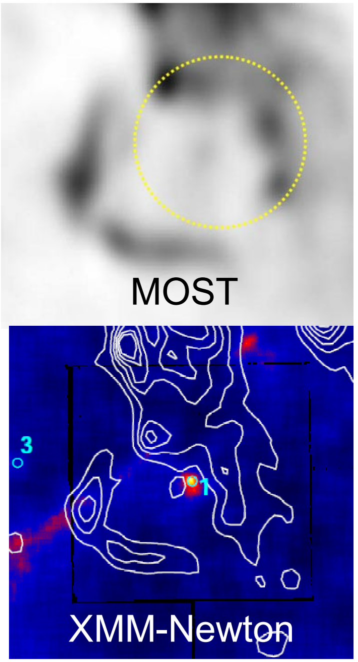
η normalisation factor due to KN suppression

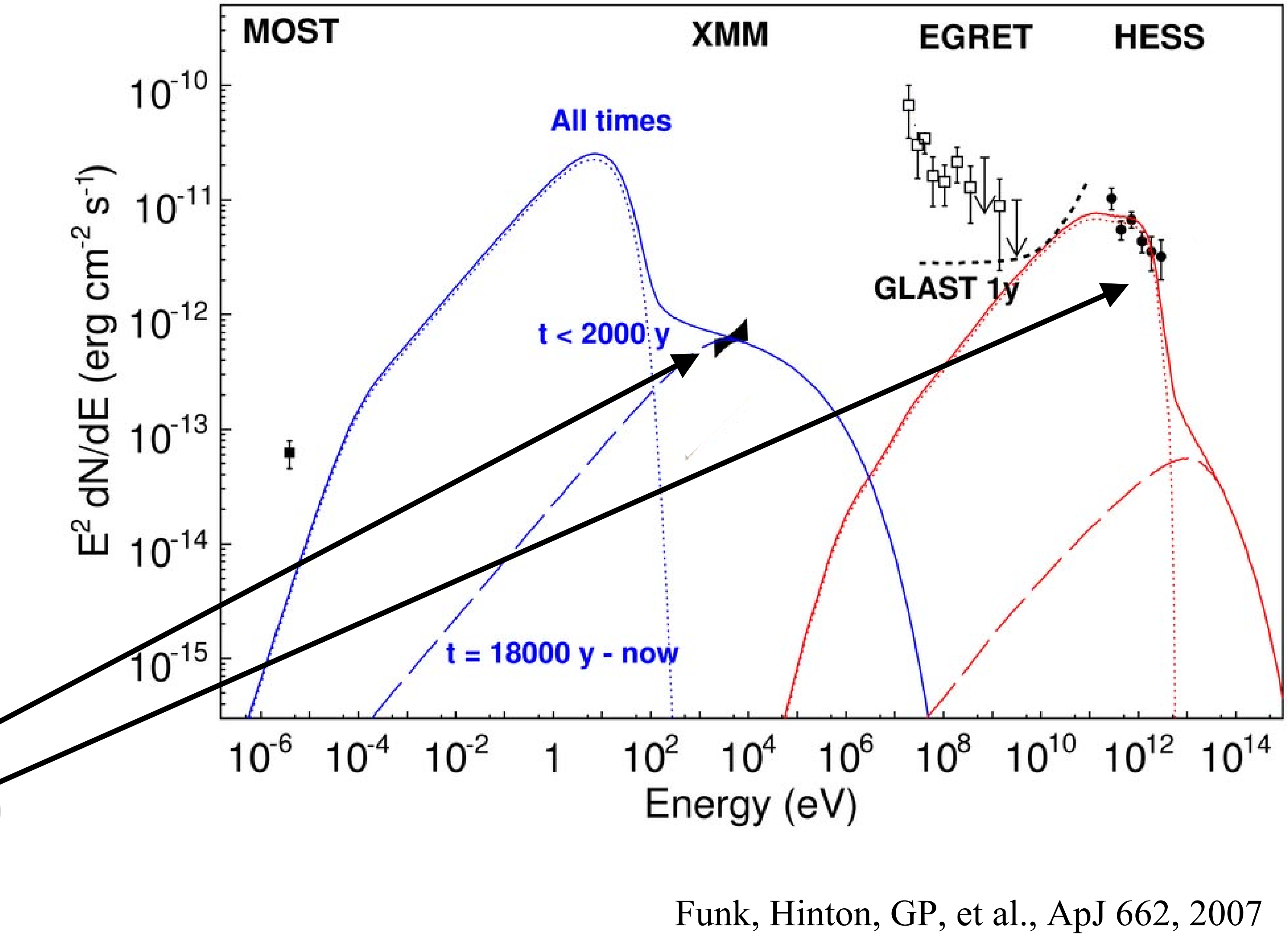
W_{ph} energy density in photon fields (CMB, IR, starlight)

→ For low B-fields, the lifetime of VHE-emitting electrons can greatly exceed the lifetime of the X-ray - synchrotron emitting (higher-energy) electrons

→ The VHE PWN reflects the injection evolution of the pulsar

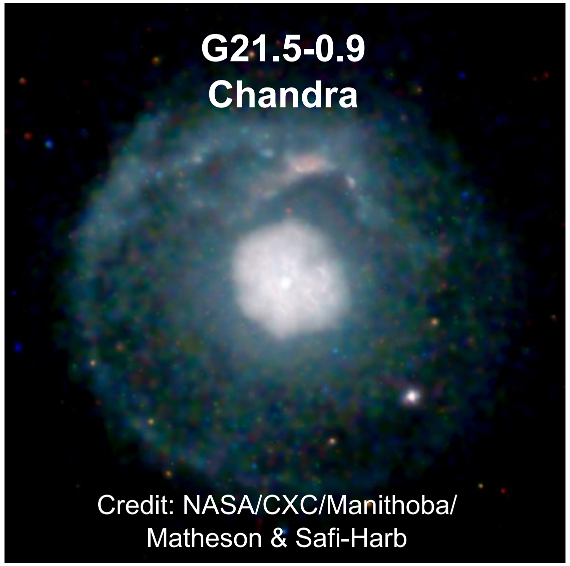
HESS J1640-465: a “relic” PWN scenario





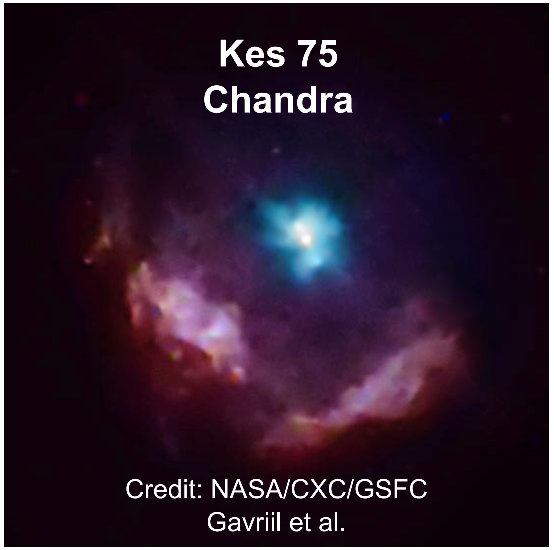
Funk, Hinton, GP, et al., ApJ 662, 2007

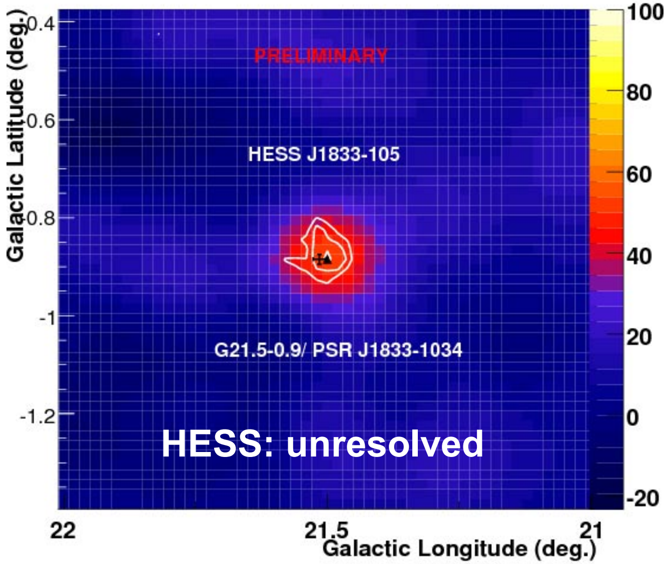
G21.5-0.9, Kes 75: Crab companions?



Edot = 3.3×10^{37} erg s^{-1}
t ~ 1000 years (« t_c)
Camilo et al., ApJ 637, 2006

Edot = 8×10^{36} erg s^{-1}
t ~ 800 years (≈ t_c)
Magnetar-like behaviour
Gotthelf et al., ApJ 542, 2000
Ng et al., astro-ph/0804.3384



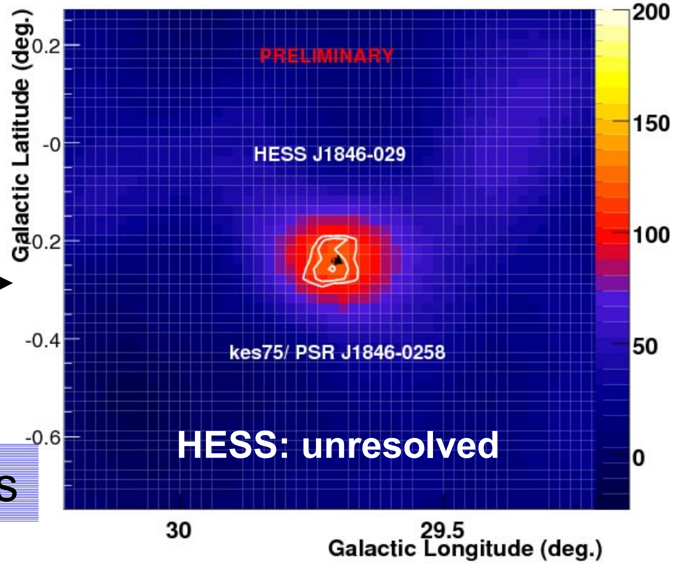


HESS coll., Djannati-Atai et al. astro-ph/0710.2247

F_X / F_{VHE} ~ 30
→ B ~ 15μG

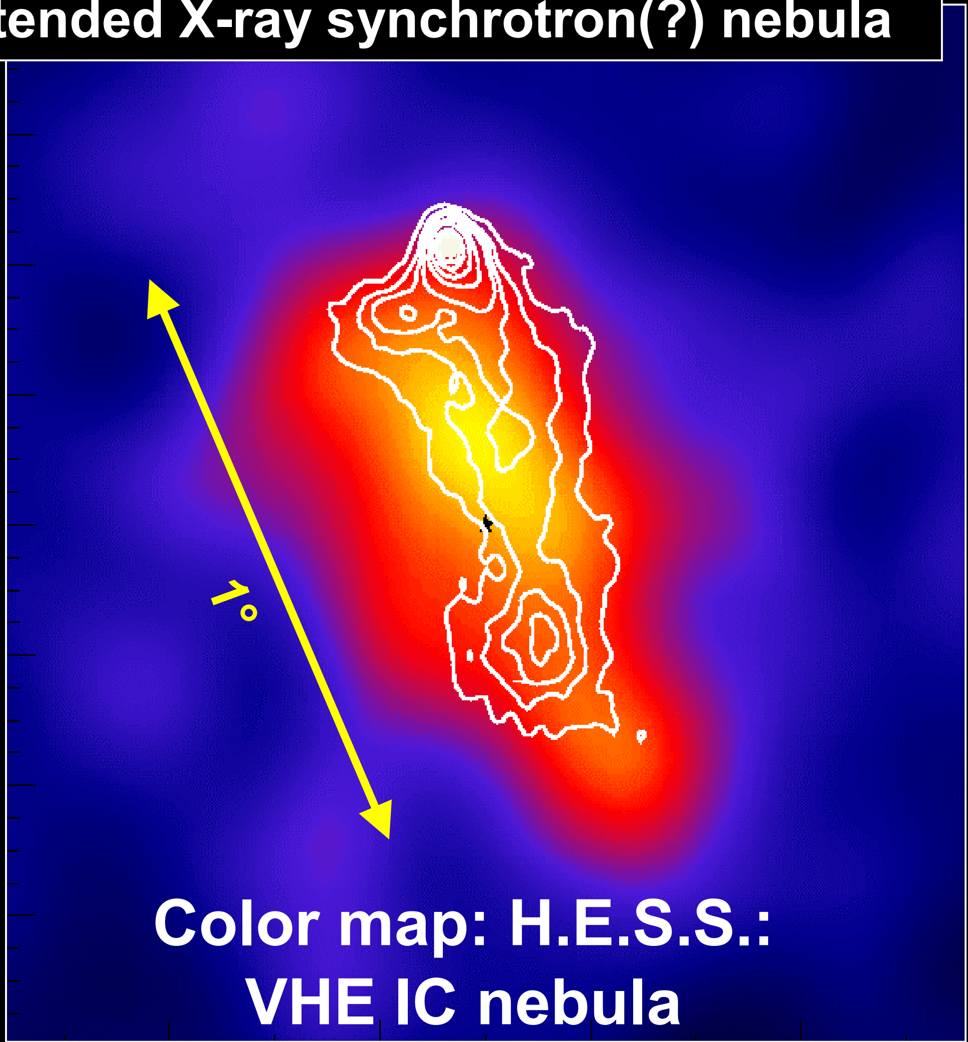
F_X / F_{VHE} ~ 10
→ B ~ 10μG

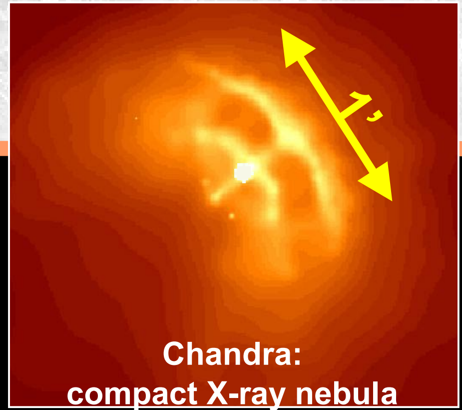
Below equipartition B-fields



Vela-X: a middle-aged PWN

ROSAT contours:
extended X-ray synchrotron(?) nebula

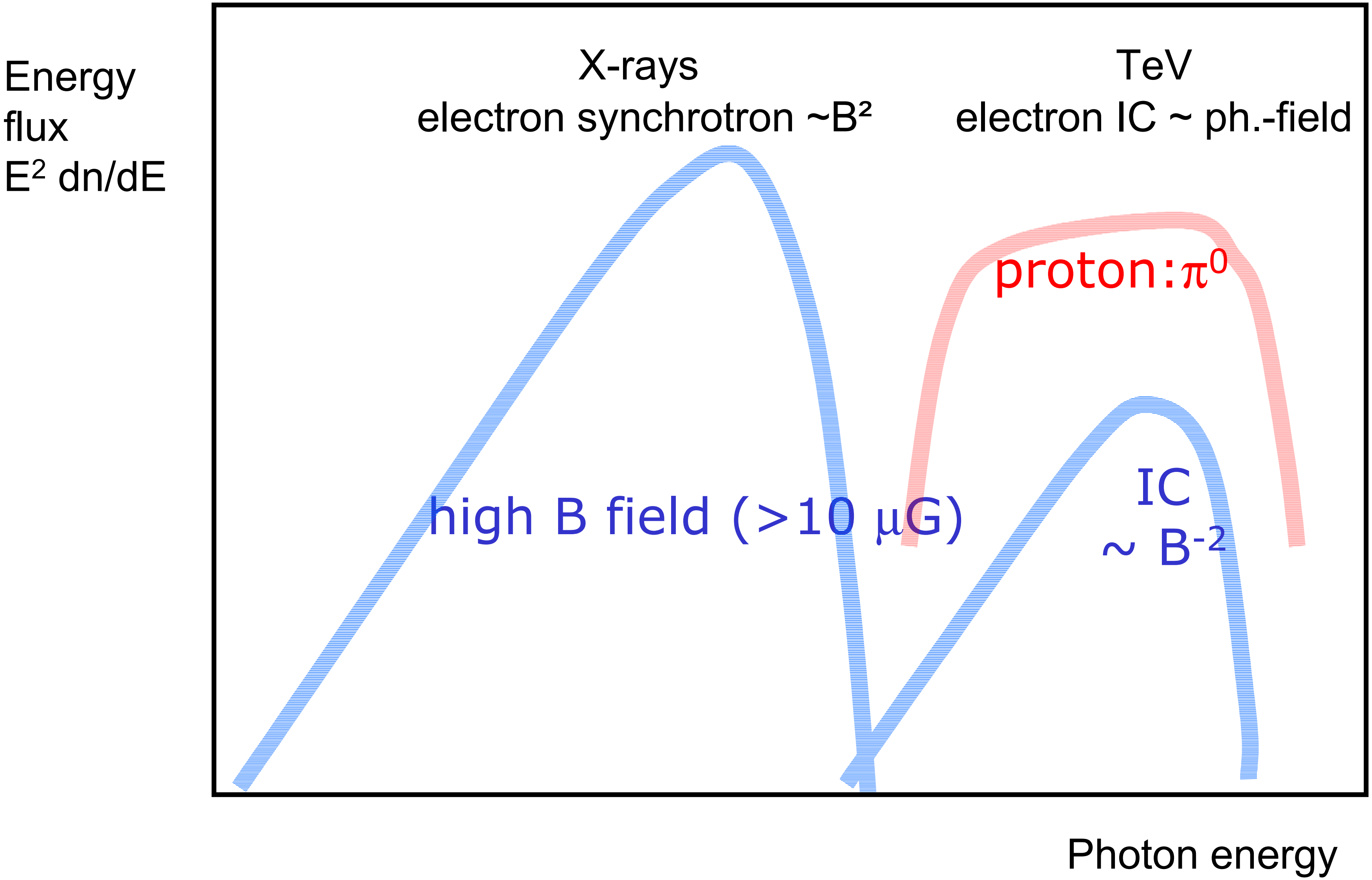




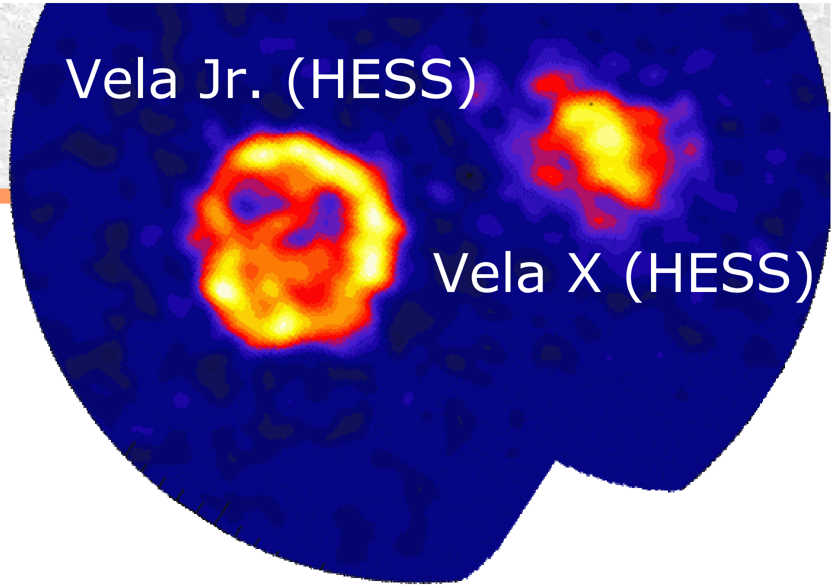
VHE spectrum (peak!) interpreted as IC scattering
→ $E_{nonth} \sim 2 \times 10^{45}$ erg

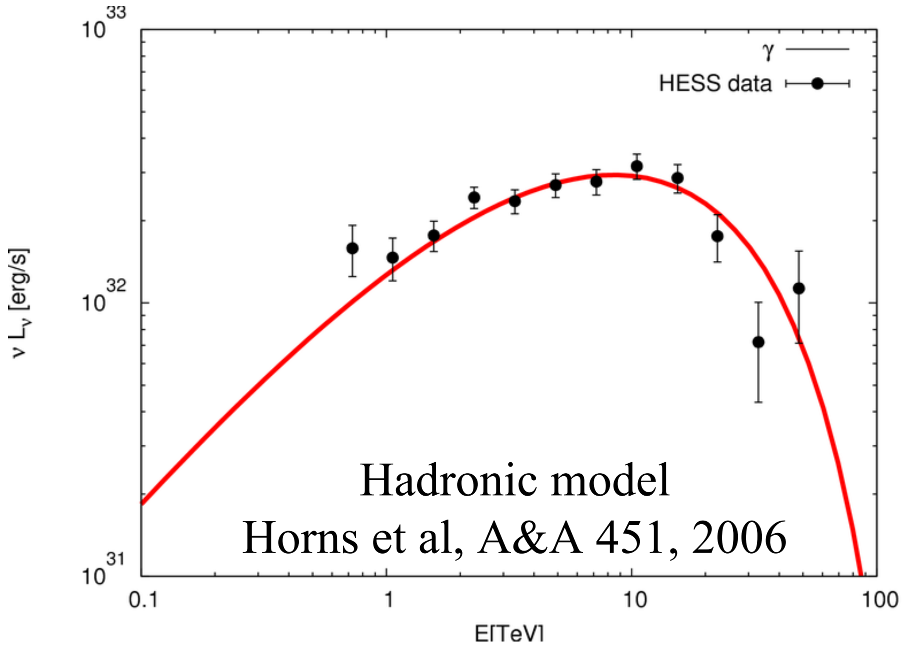
Caveat:
→ this isn't the entire PWN (as seen in radio)
→ sensitivity limited?

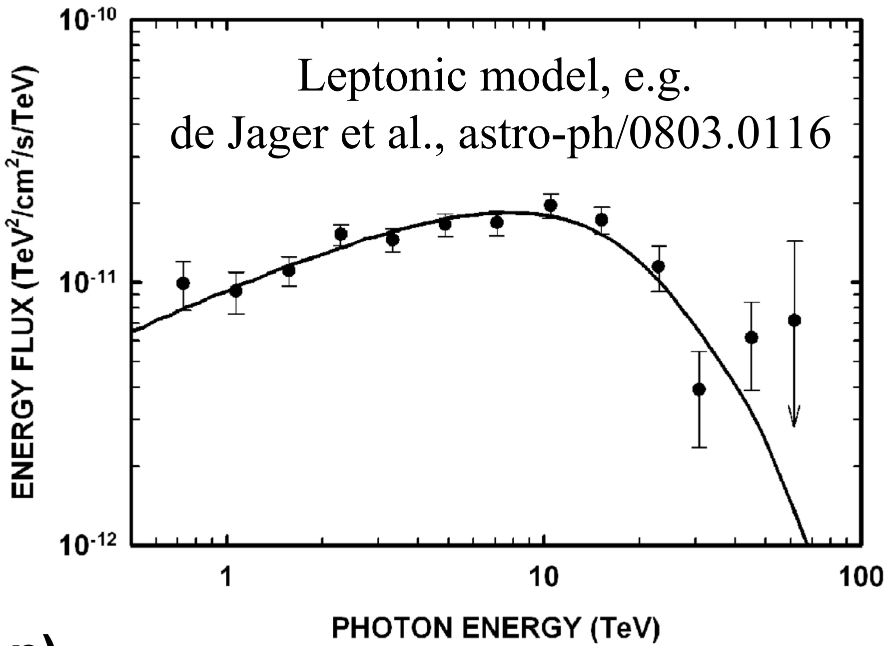
VHE + X-rays in case of a hadronic source



Vela X: nucleonic PWN?



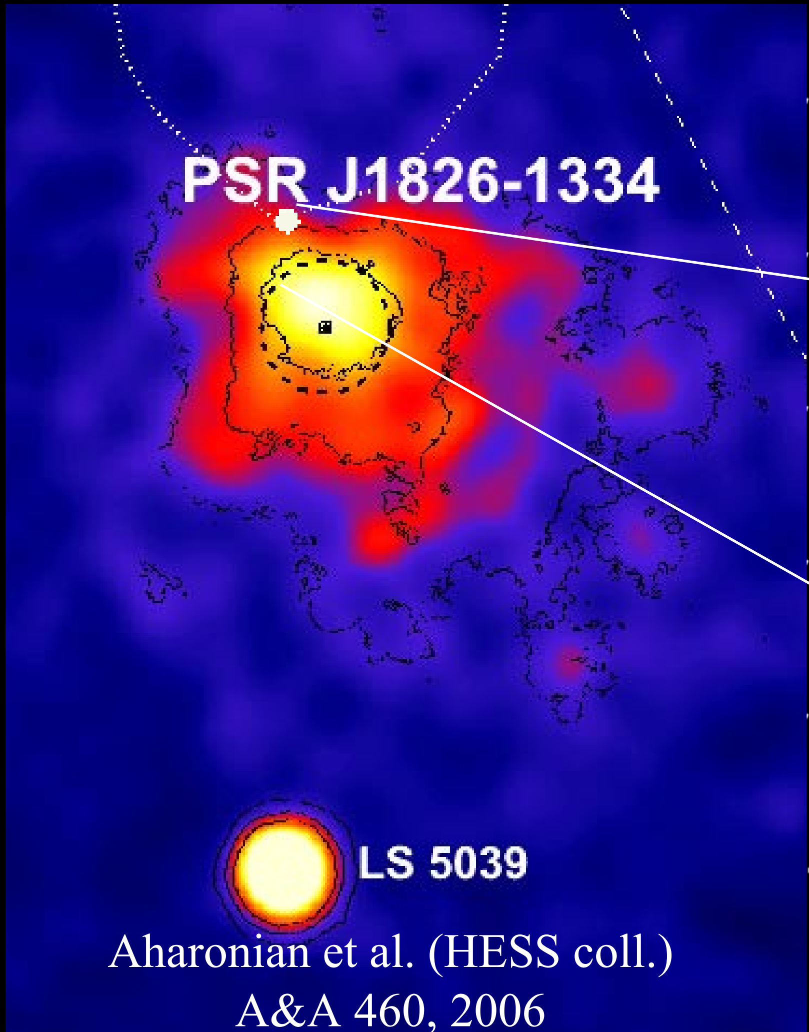


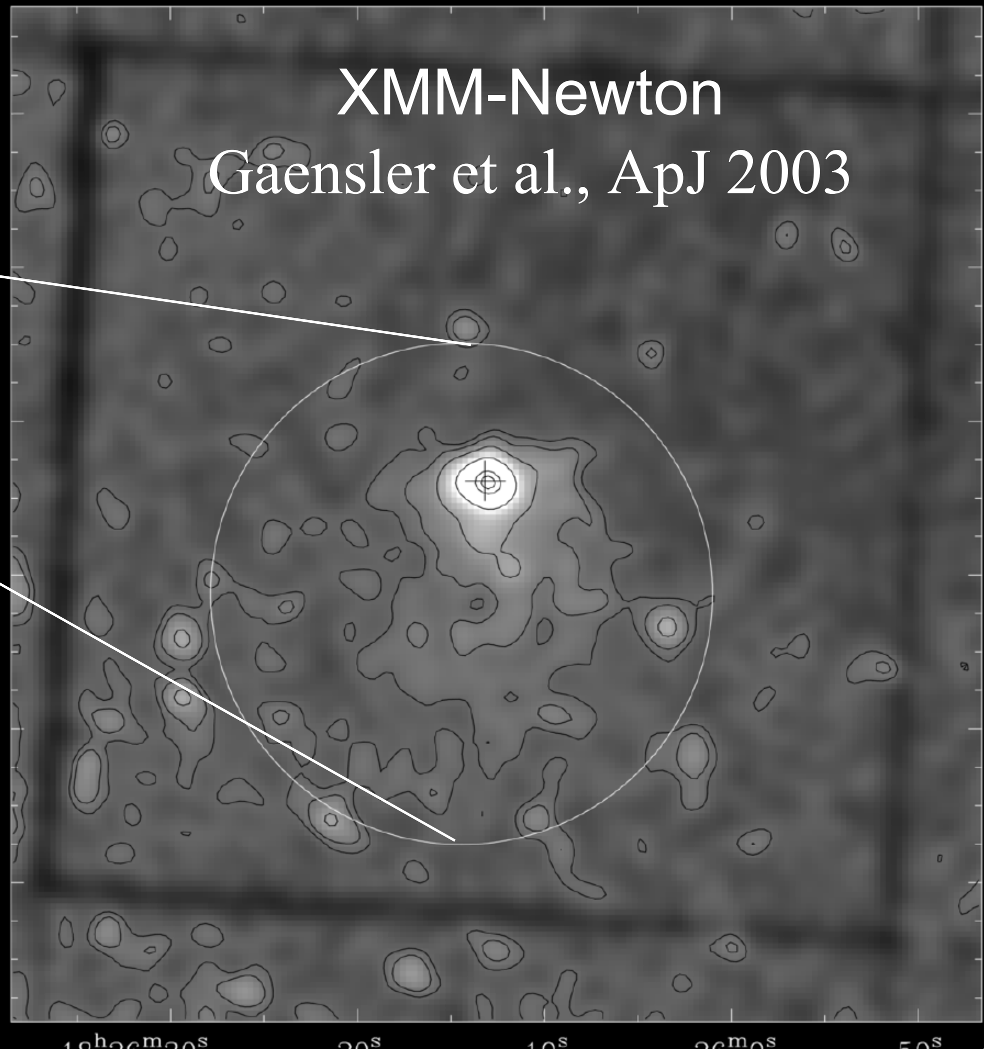


- **Debate still somewhat open**
- **Some criticism on the hadronic scenario**
- **In this talk, the standard view of leptonically-dominated PWN is adopted**
- **(hadronically mediated acceleration)**

“Relic” pulsar wind nebulae

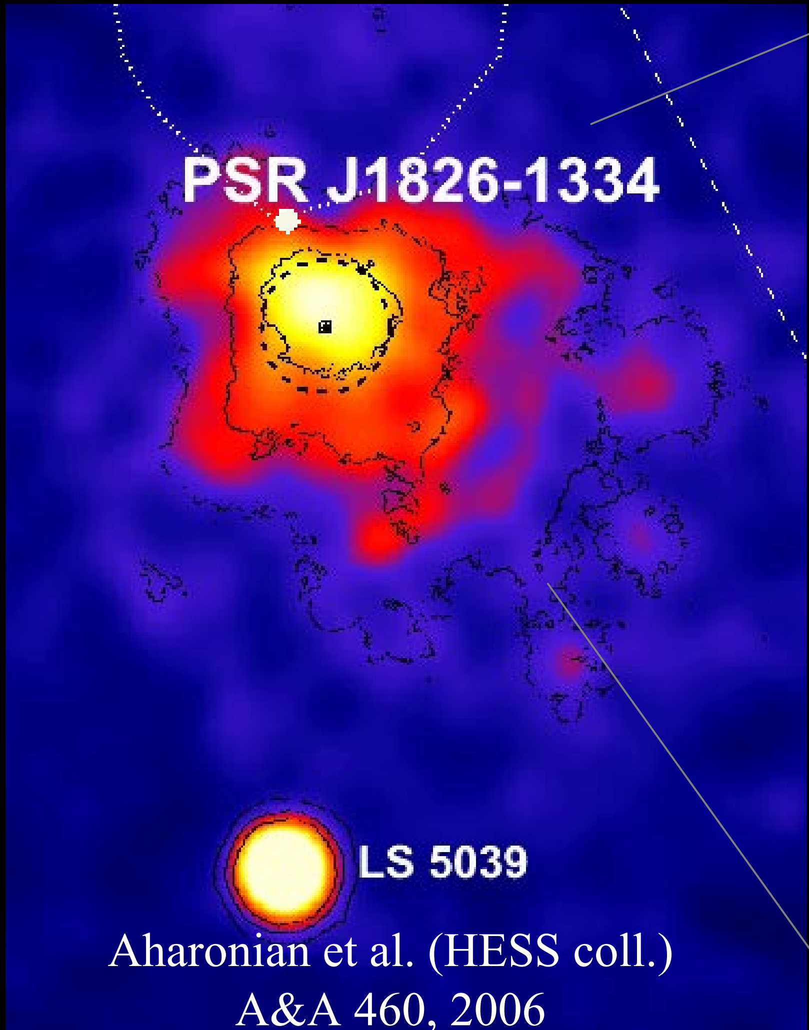
HESS J1825-137:
Identification with X-ray PWN G 18.0-0.7

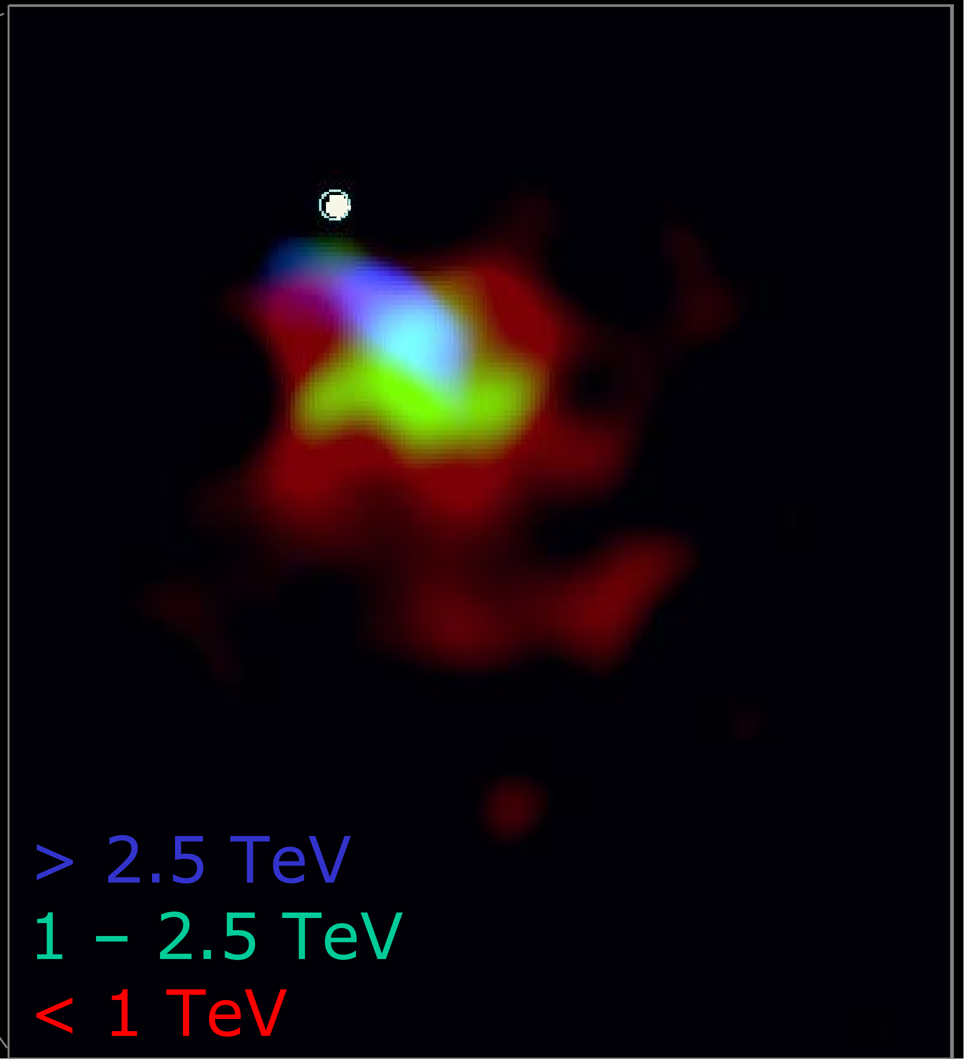




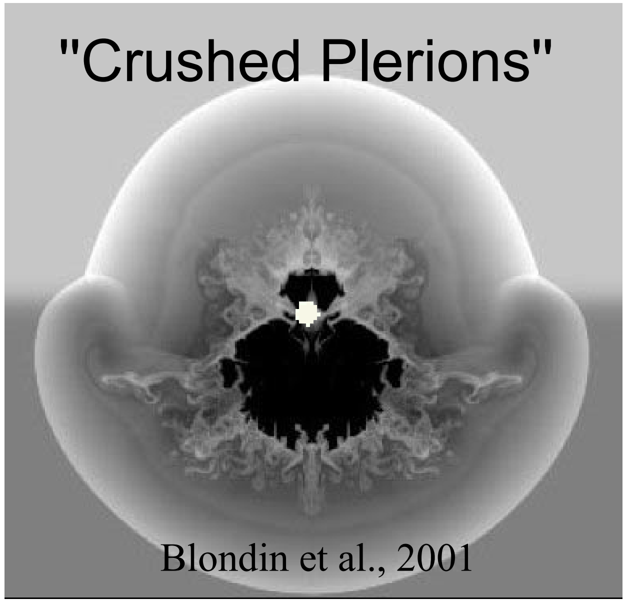
Archetype for a TeV – X-ray PWN association

HESS J1825-137:
Identification (mainly) by TeV spectral imaging

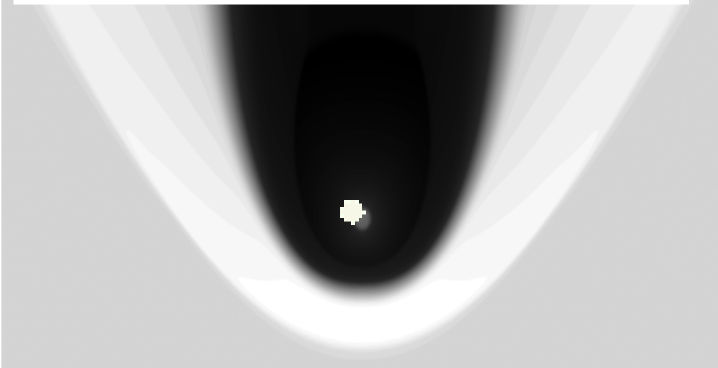




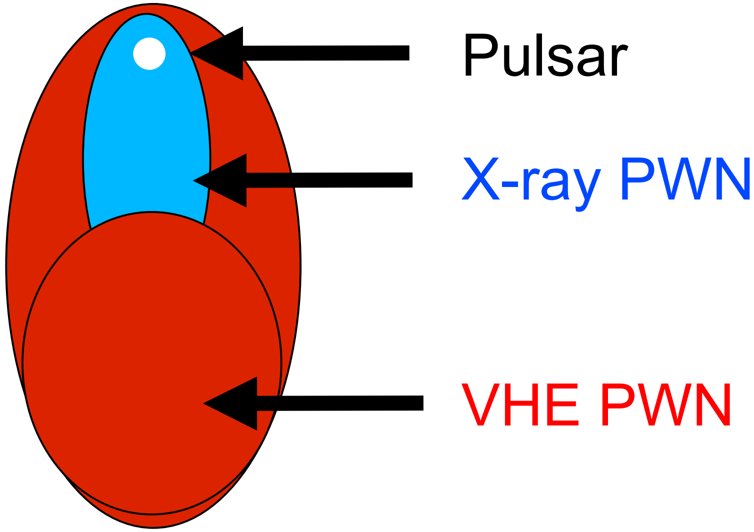
Asymmetric VHE Pulsar Wind Nebulae



Or pulsar proper motion/
ram pressure?

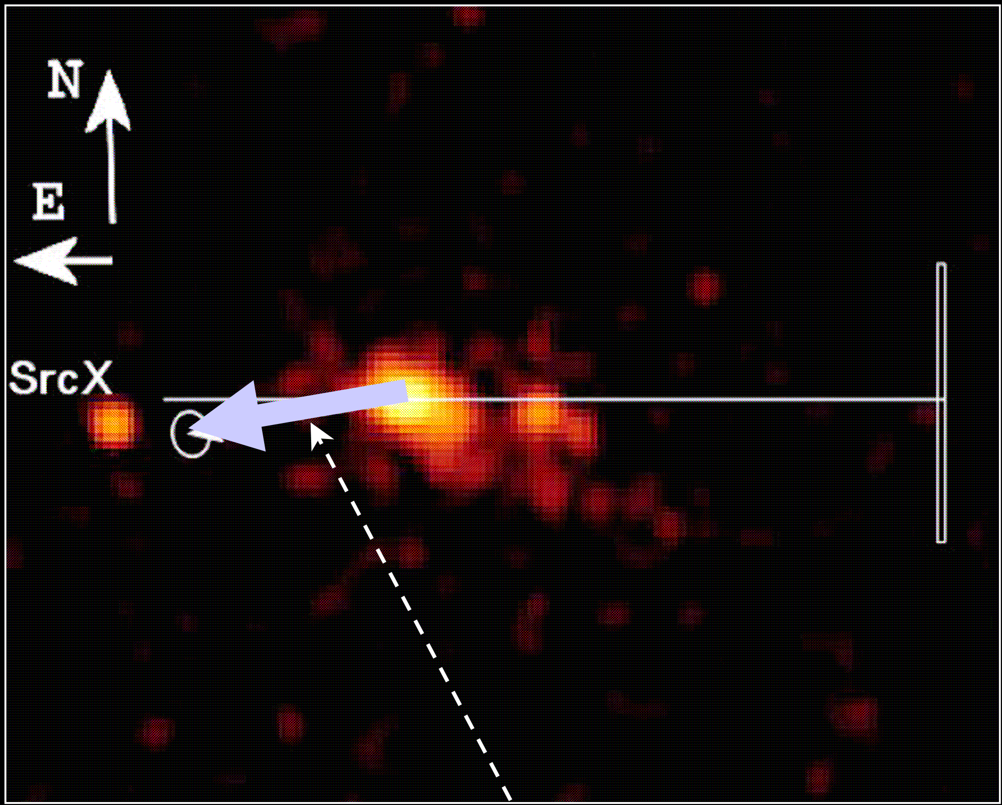


Offset VHE PWN



+ IC electron lifetime larger than synchrotron lifetime
+ larger particle injection efficiency in the past

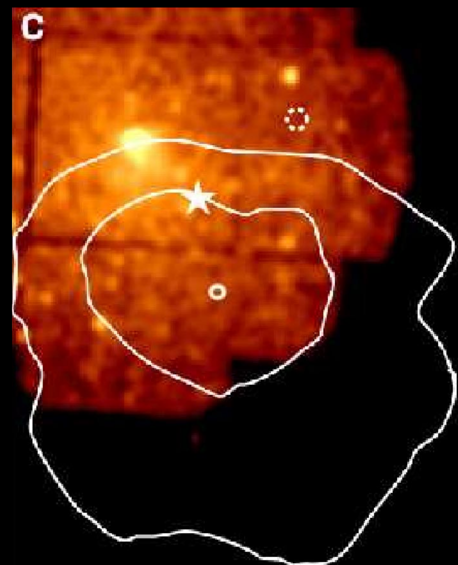
Confirmation of the crushed PWN scenario …



… in the HESS J1825-137 / G 18.0-0.7 system

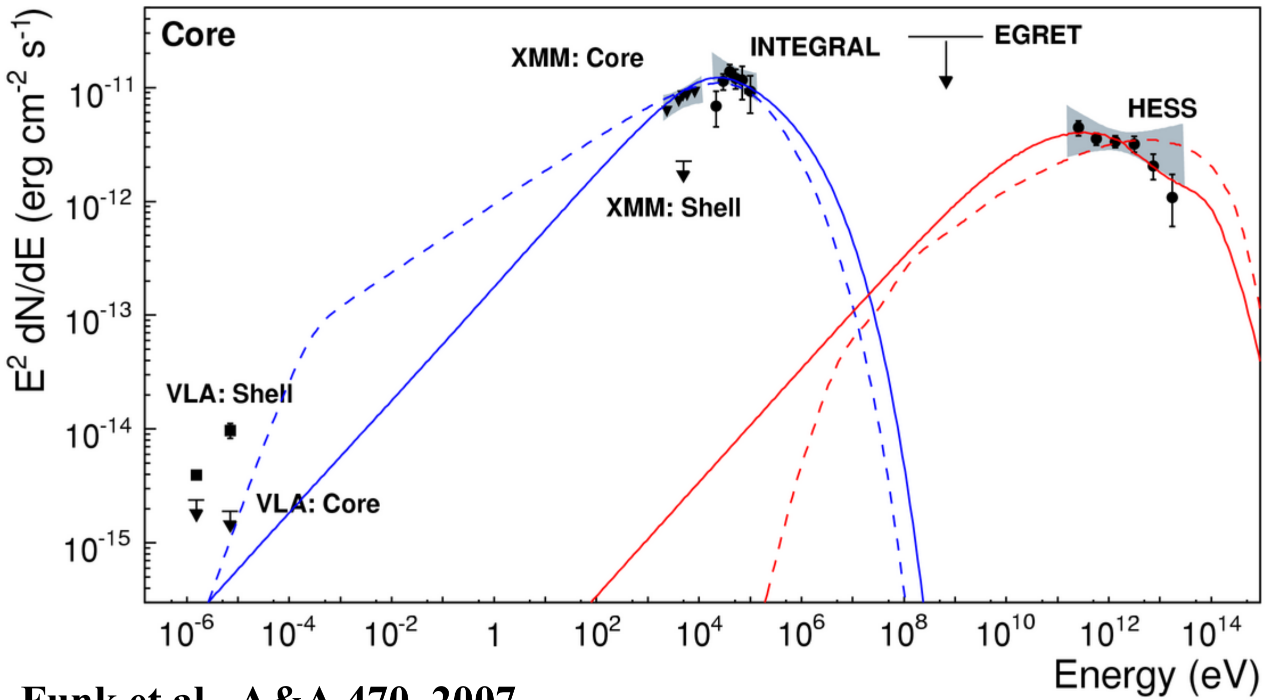
Pavlov et al., ApJ 675, 2008

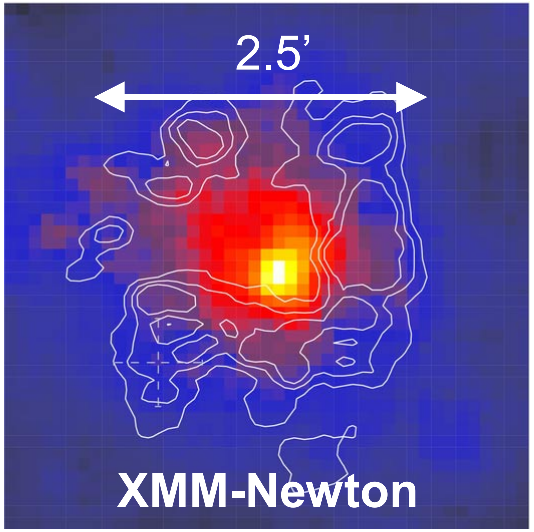
pulsar proper motion (VLA) perpendicular to relic PWN direction



XMM EPIC MOS1+2

HESS J1813-178: Identification with X-ray PWN?





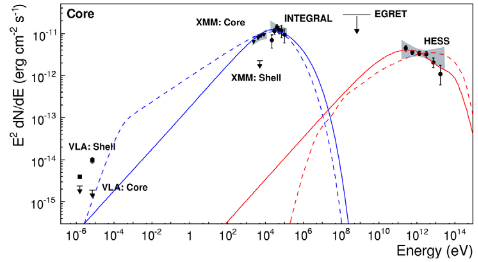
Funk et al., A&A 470, 2007

If INTEGRAL source can be identified with X-ray (synchrotron) nebula
→ Object is a “Pevatron”

HESS J1813-178: „Pevatron“ hypothesis

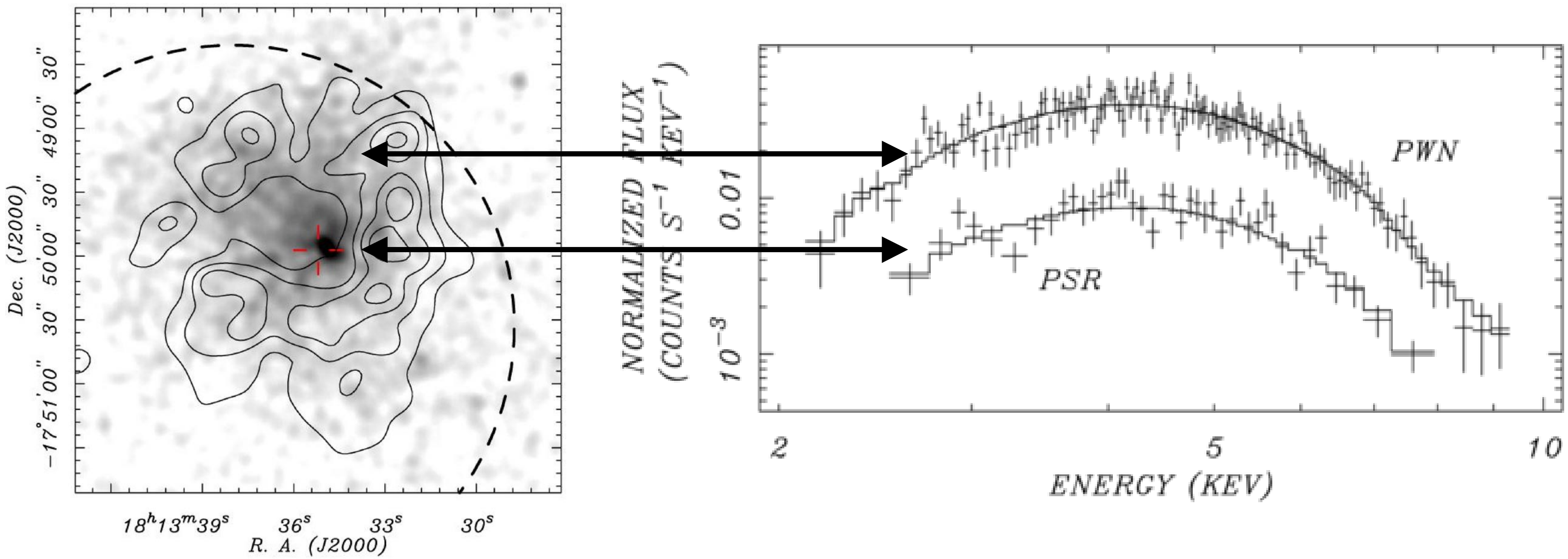
Chandra:

- Compact source: identified as pulsar
- PWN dominates up to ~10 keV



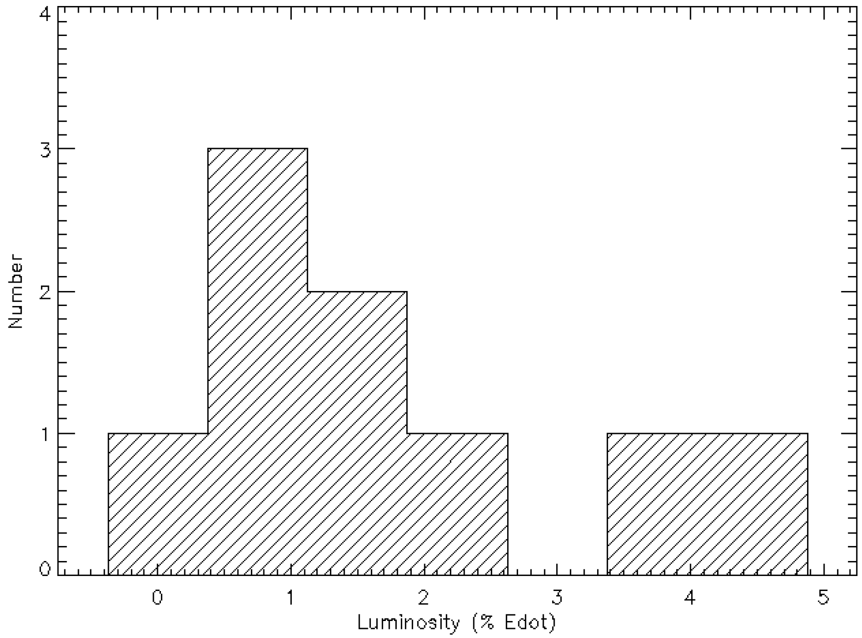
→ INTEGRAL association with PWN not unplausible

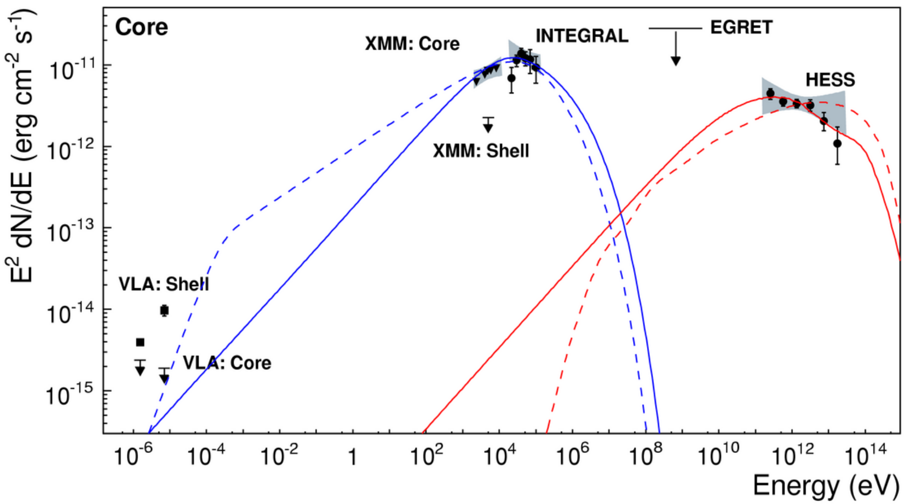
Helfand et al., ApJ 665, 2007



HESS J1813-178: Identification with X-ray PWN?

INTEGRAL pulsars with known Edot





Dean & Hill (astro-ph/0804.3420, RN):

→ Extreme pulsar properties

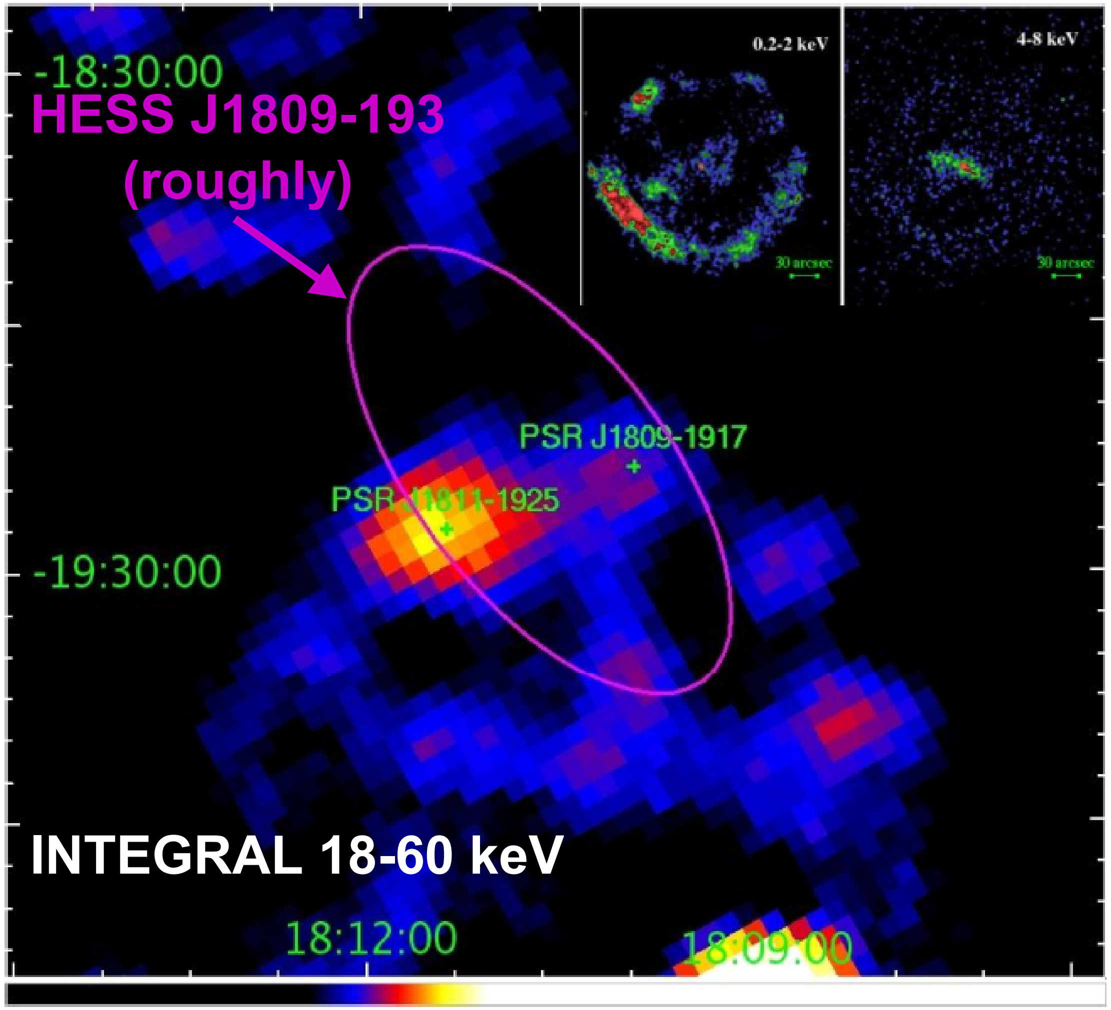
- **Either underluminous in INTEGRAL band (ε=0.01)**
- **Or spin-down age decoupled from SNR age (cf. e.g. G11.2-0.3)**

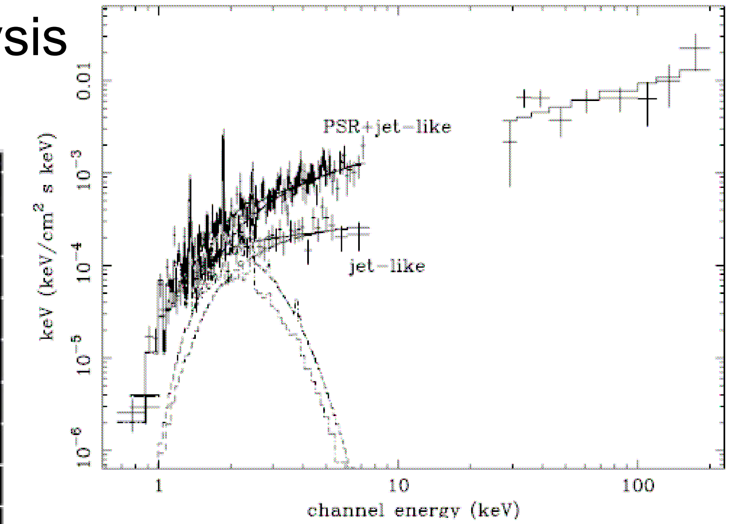
HESS J1809-193: two PSR counterparts

Dean et al., MNRAS 384, 2008

INTEGRAL

+ Chandra reanalysis of G11.2-0.3

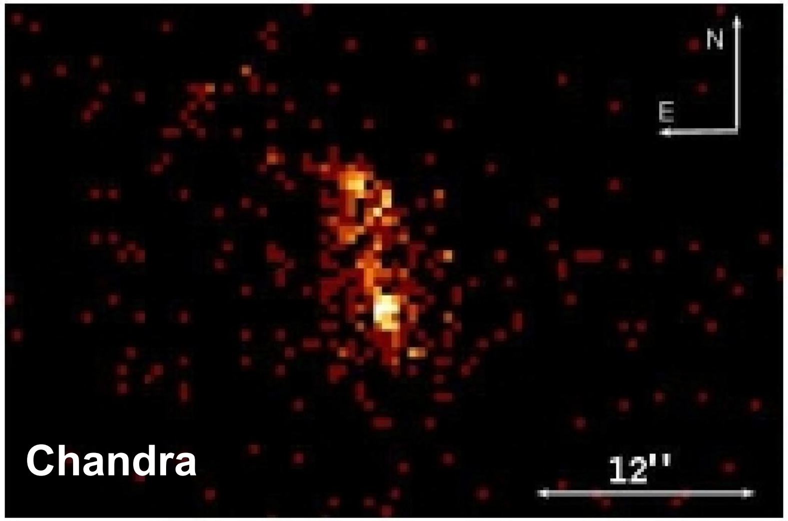




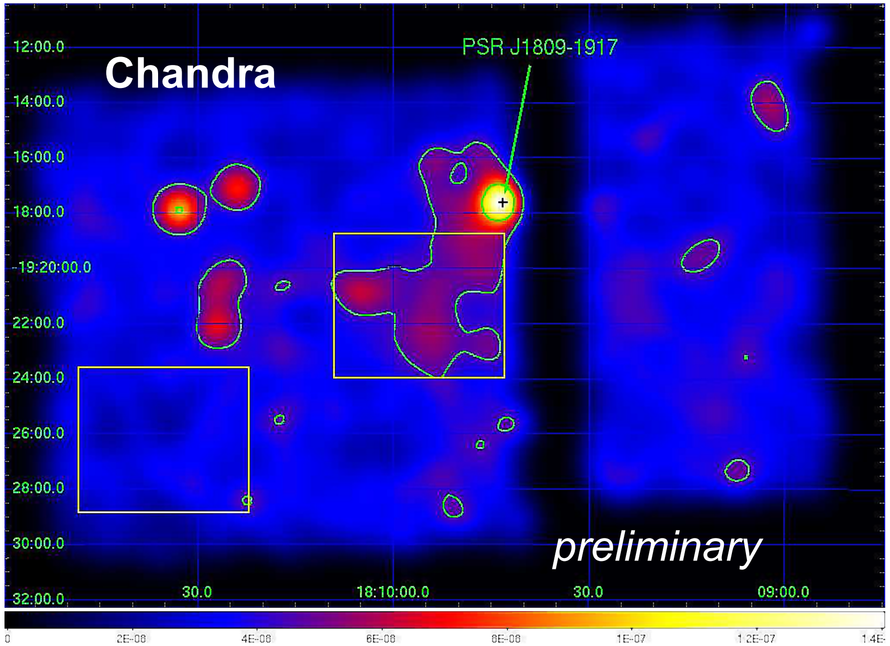
50% of the 20-100 keV flux from PSR J1811-1925 is from the PWN

But no evidence for a morphological connection to the VHE source

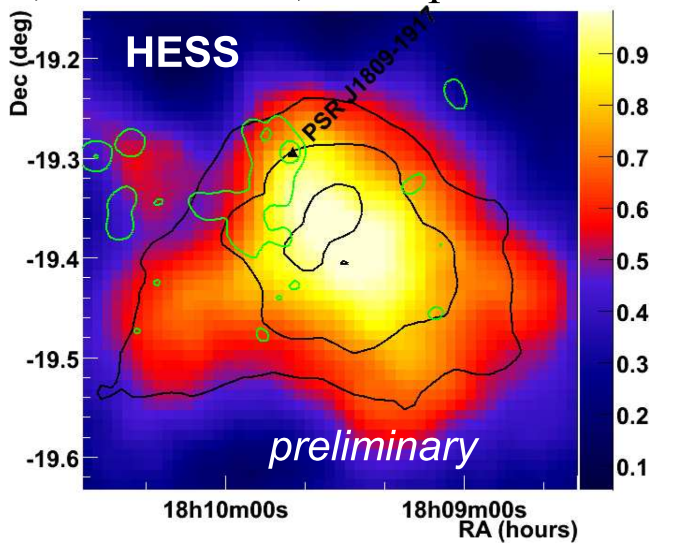
The PWN around PSR J1809-1917



Kargaltsev & Pavlov, ApJ 670, 2007

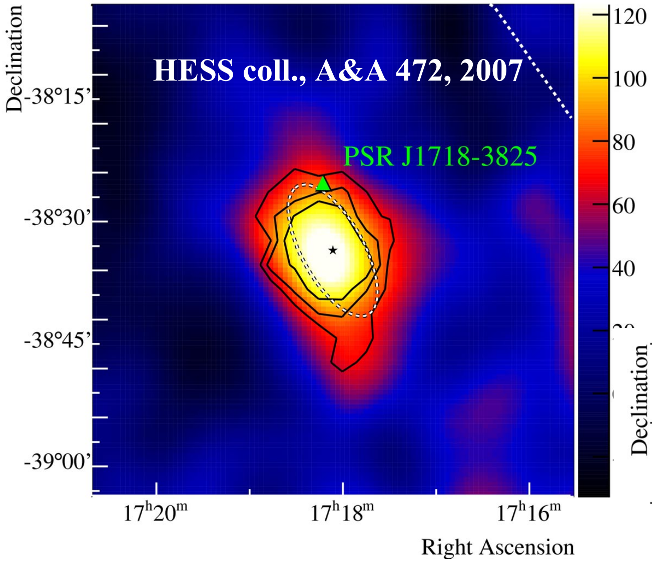


HESS coll., Komin et al., astro-ph/0709.2432

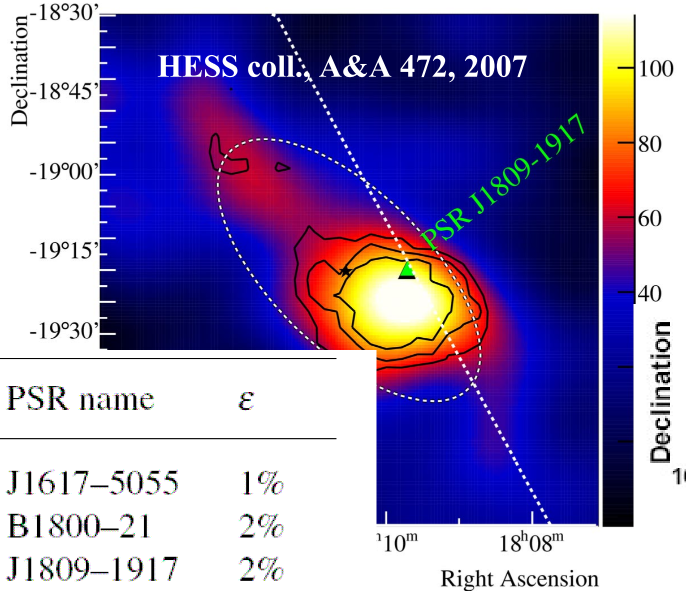


- → **The PWN around PSR J1809-1917 is very likely contributing to HESS J1809-193**
- → **Especially in this case, multiple components in the VHE source cannot be excluded**

VHE PWN candidates

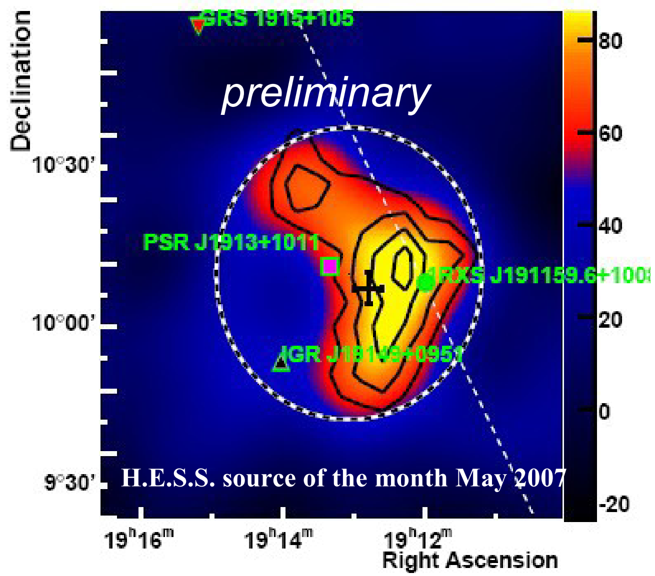


- Classification because of association with powerful pulsar
- no X-ray PWN required for this classification
- Large ε-values are in principle possible (decoupling from Edot)



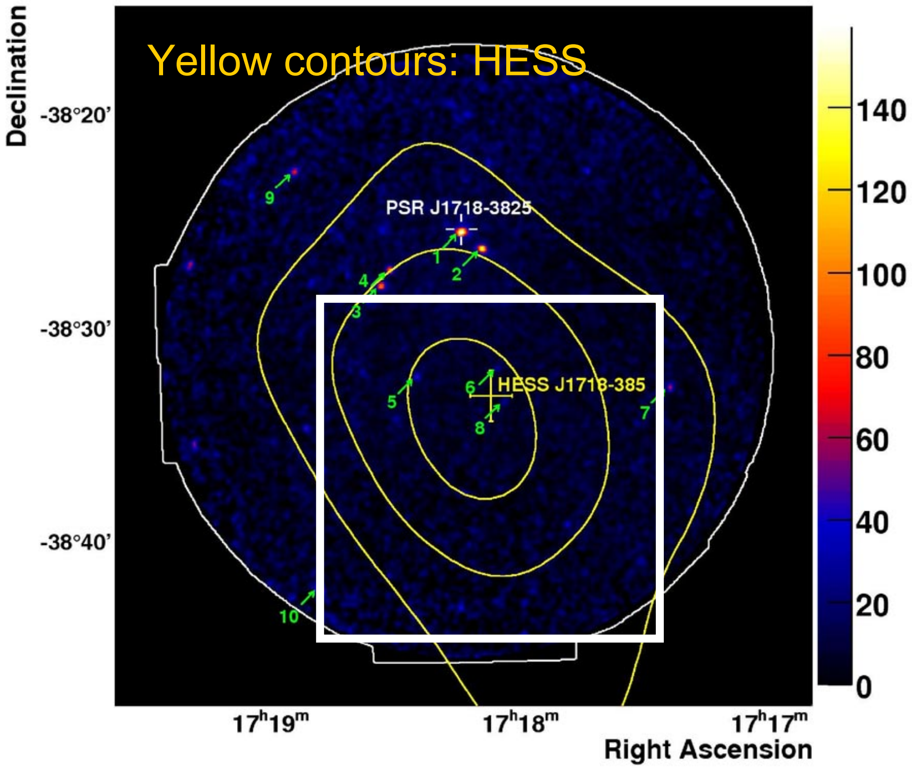
VHE source	$F_{0.3-30}$*	PSR name	ε
HESS J1616–508	3.7×10^{-11}	J1617–5055	1%
HESS J1804–216	2.9×10^{-11}	B1800–21	2%
HESS J1809–193	2.8×10^{-11}	J1809–1917	2%
HESS J1912+101	1.8×10^{-11}	J1913+1011	2%
HESS J1718–385	4.3×10^{-12}	J1718–3825	0.5%
HESS J1303–631	2.3×10^{-11}	J1301–6305	7%
HESS J1702–420	1.4×10^{-11}	J1702–4128	11%

* in units of erg cm^{-2} s^{-1} **HESS coll., Gallant et al., AIP 978, 2008**

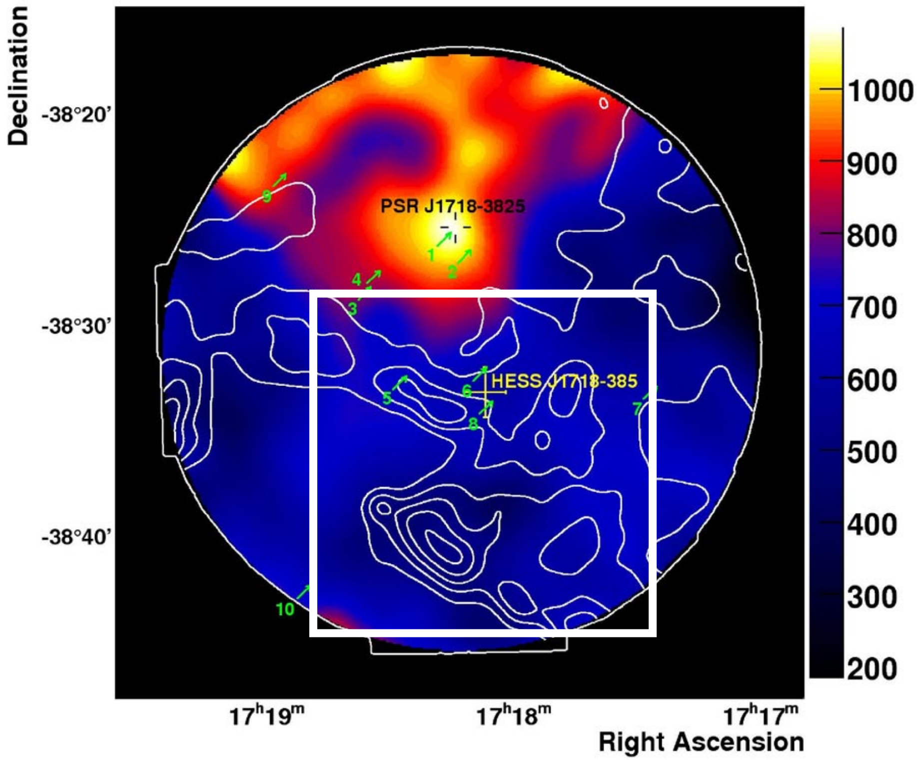


HESS J1718-385: a VHE PWN candidate

XMM, 0.5-10 keV



XMM, point sources subtracted



Hinton et al., A&A 476, 2007

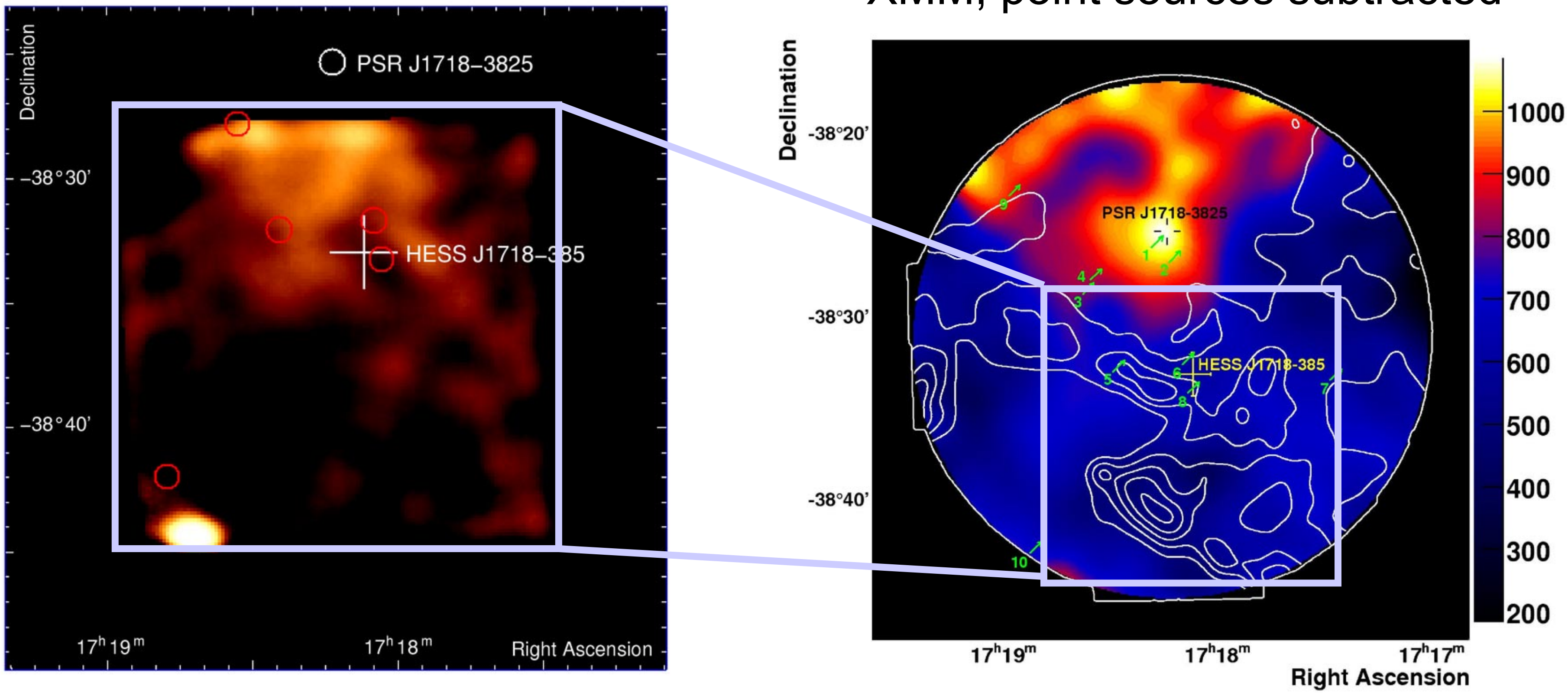
compact but still extended X-ray emission around PSR J1718-3825
→ likely the compact X-ray PWN, but no clear link to the HESS source

+ Suzaku pointing to search for weak diffuse emission

HESS J1718-385: a VHE PWN candidate

Suzaku, 0.5-7 keV

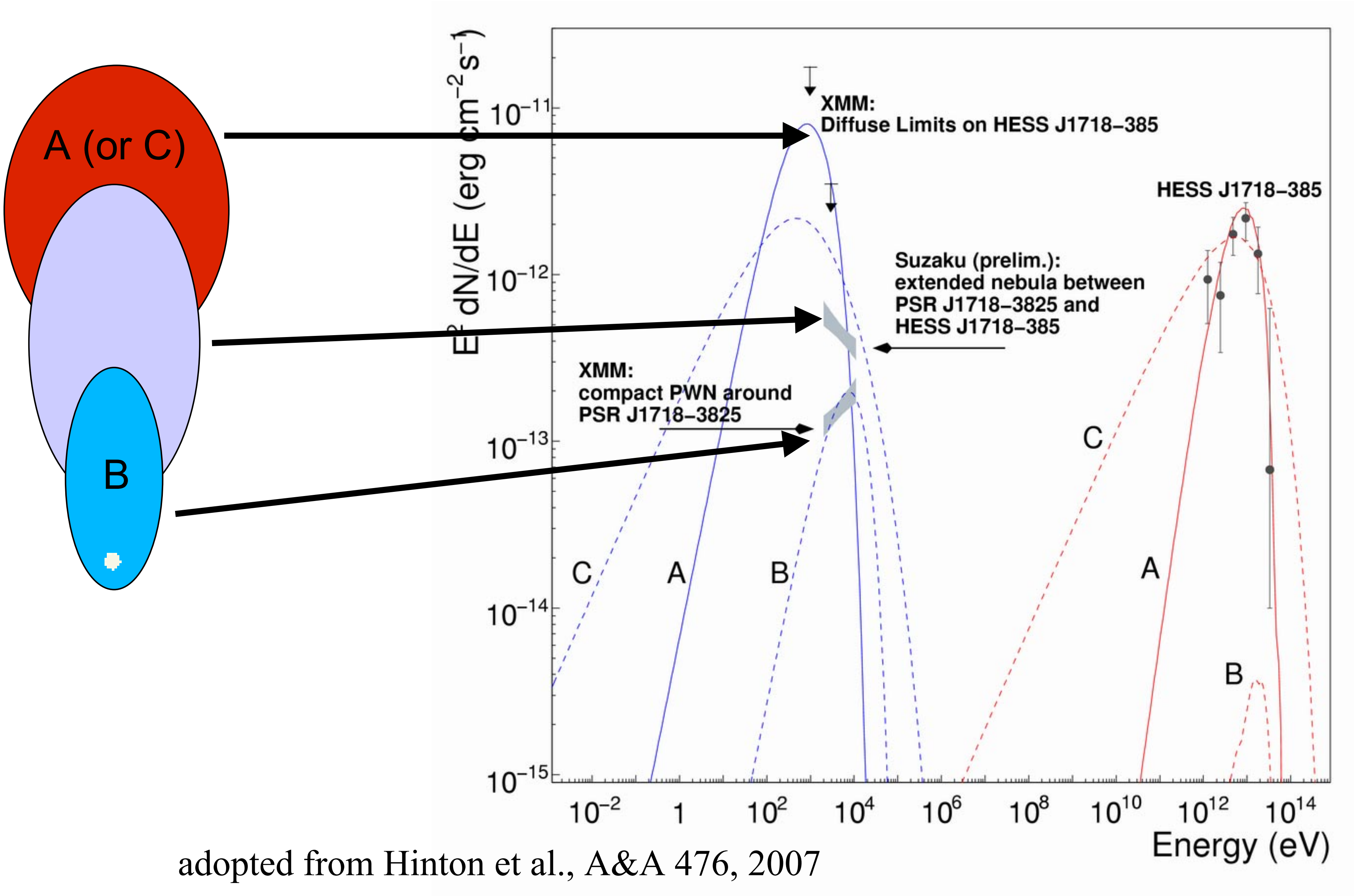
XMM, point sources subtracted



GP et al. 2007 (Suzaku conf.):

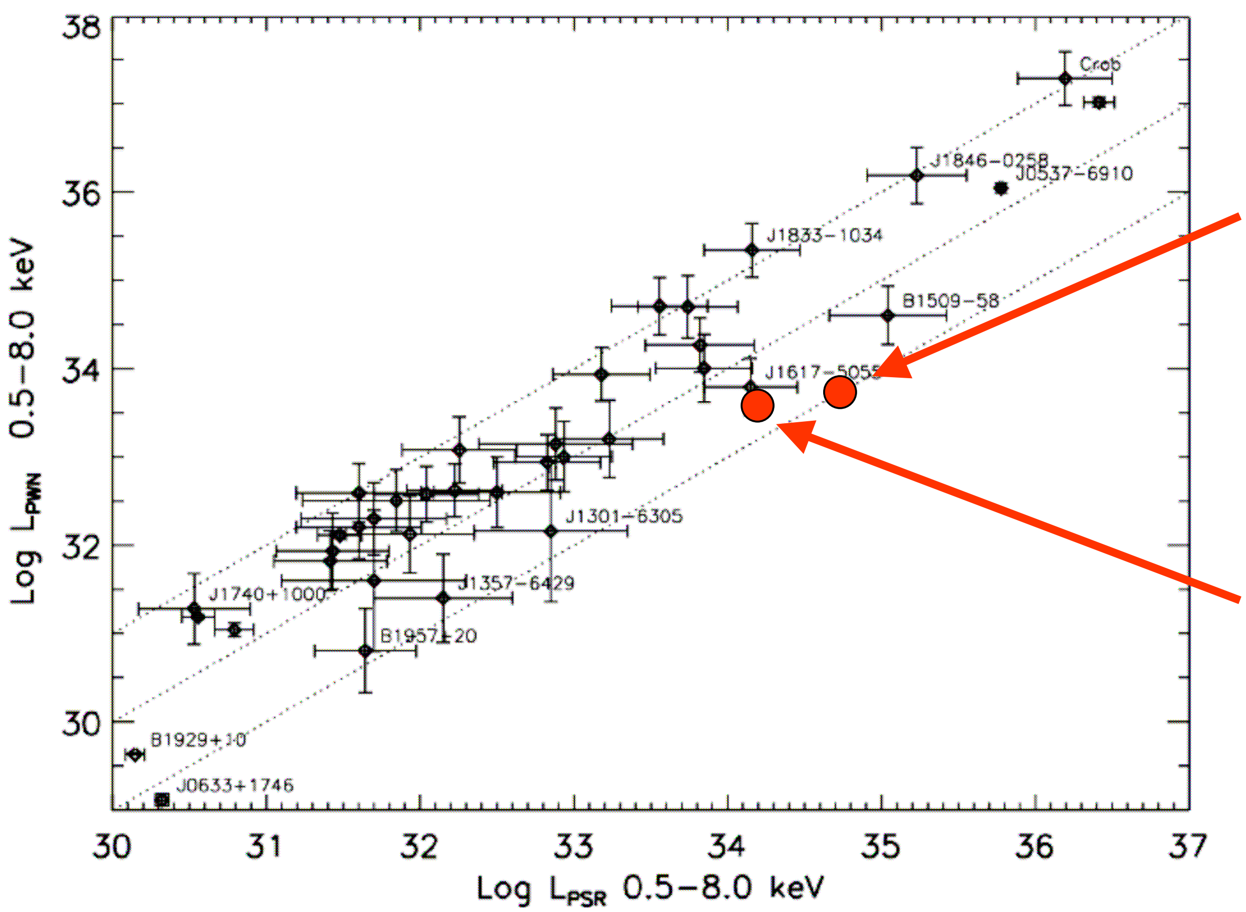
diffuse emission could morphologically connect XMM PWN with HESS source

HESS J1718-385: a VHE PWN candidate



adopted from Hinton et al., A&A 476, 2007

“Underluminous” PWN



Chandra PWN review, Kargaltsev & Pavlov, astro-ph/0801.2602

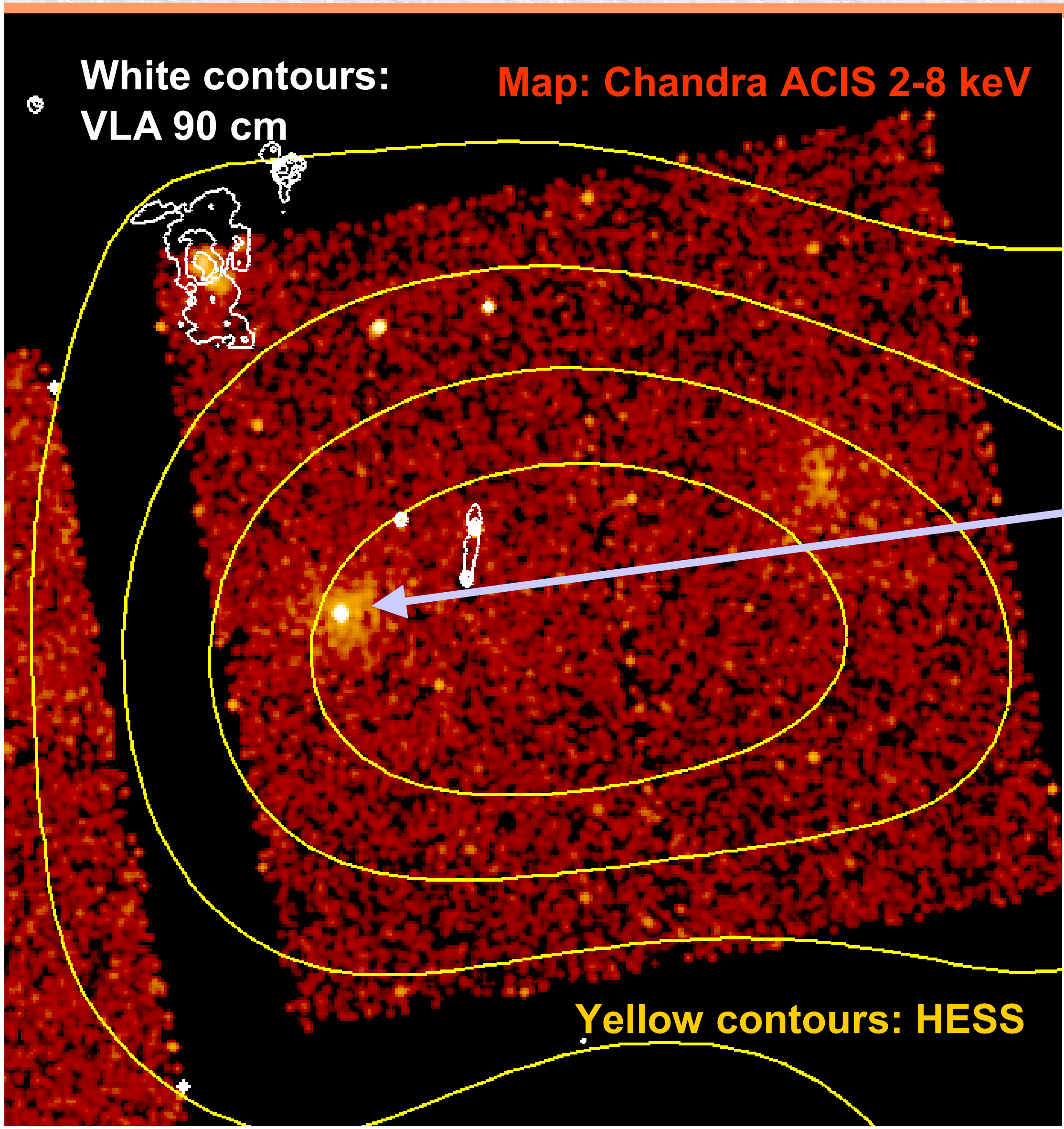
PSR J1838-0655 (X-ray pulsar discovered using XTE)

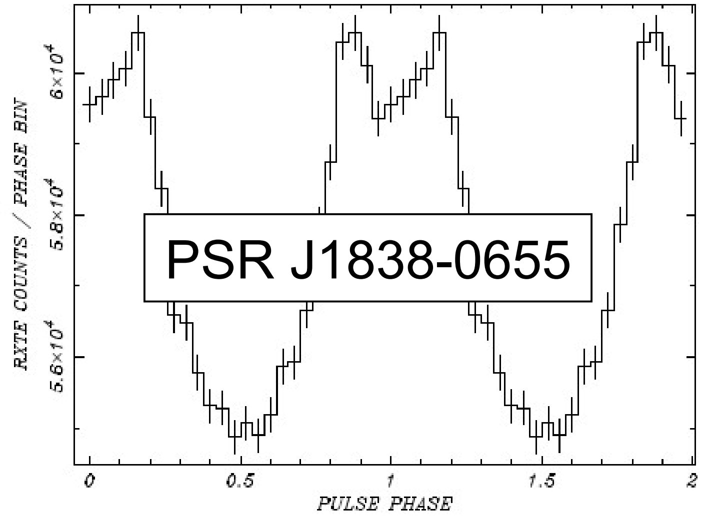
Gotthelf & Halpern, astro-ph/0803.1361

Detection of PWN around PSR J1617-505 with Chandra, but association with HESS J1616-508 inconclusive

Kargaltsev et al., astro-ph/0805.1041

HESS J1837-069: Chandra + RXTE





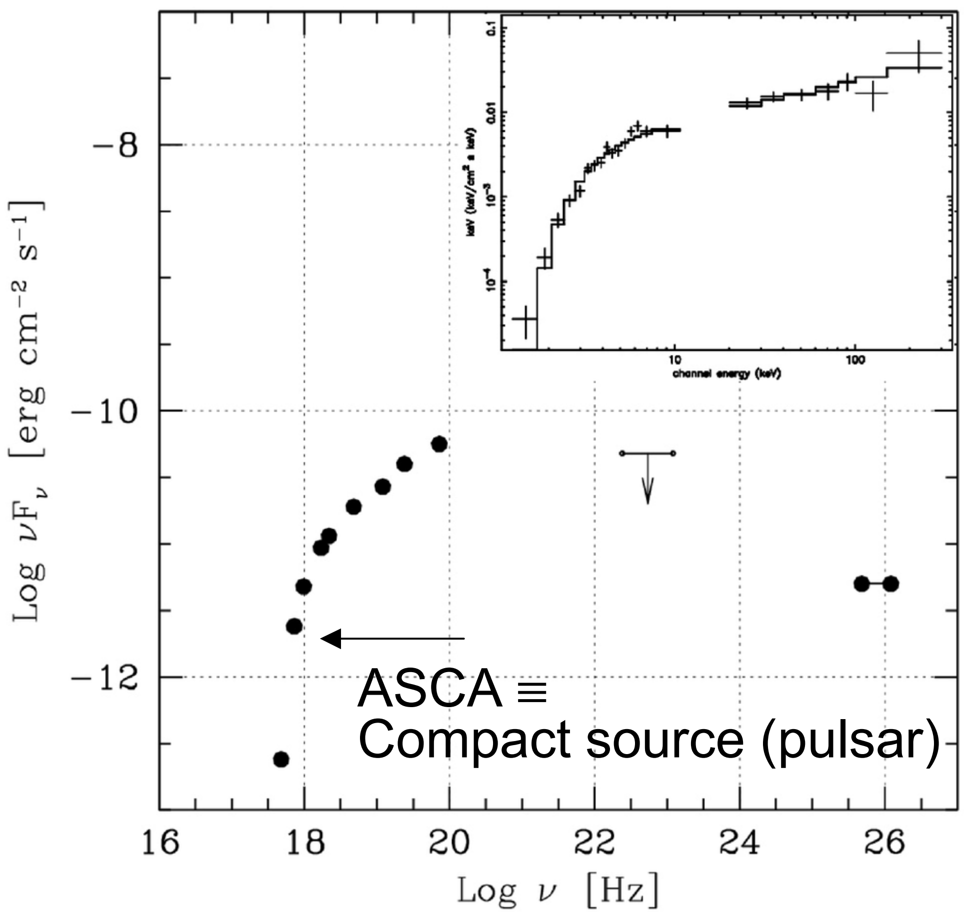
Gotthelf & Halpern, astro-ph/0803.1361

- Edot = 5.5×10^{36} erg s^{-1}
- $\eta_{PWN,X} = 10^{-3}$
- age = 23 kyr

→ Good counterpart to HESS source

→ But some interesting / open issues

AX J1838.0-0655: Compact source dominates

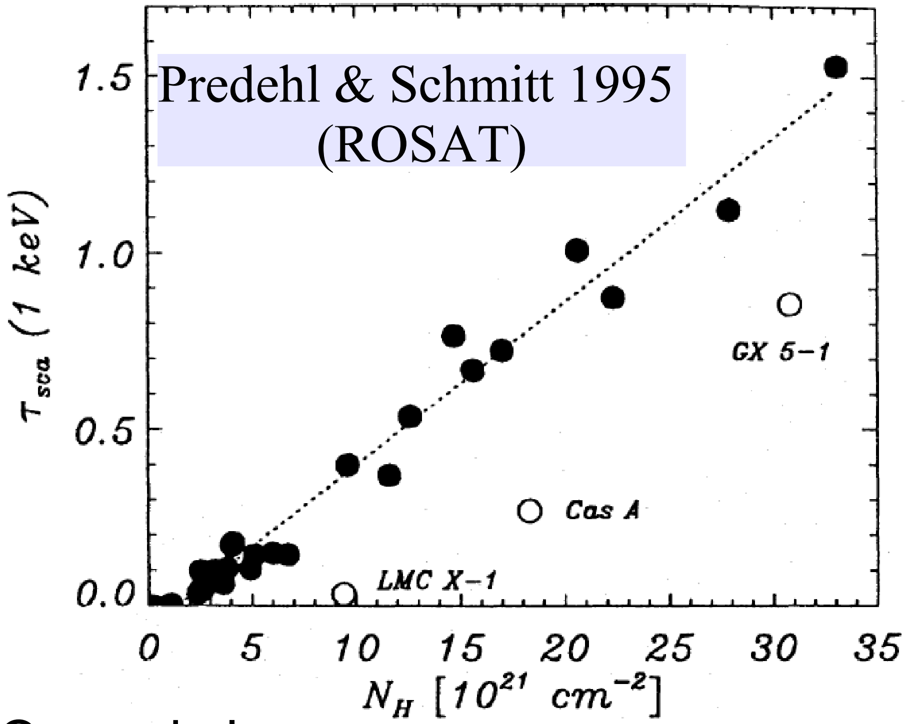


INTEGRAL source (Malizia et al. 2006, Lutovinov et al. 2005):

Possible hard X-ray – VHE connection

→ INTEGRAL source is presumably not the extended PWN (cf. HESS J1813-178)

Reflexion halo around AX J1838.0-0655?

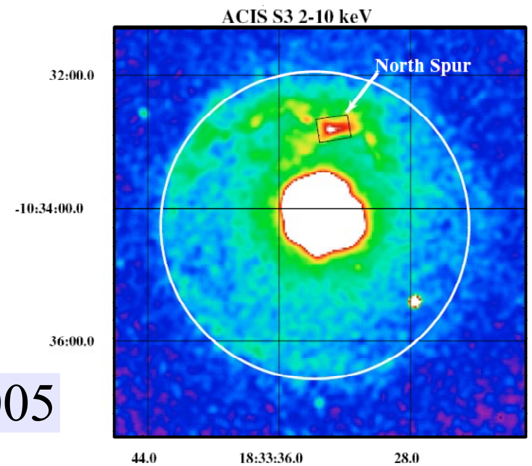


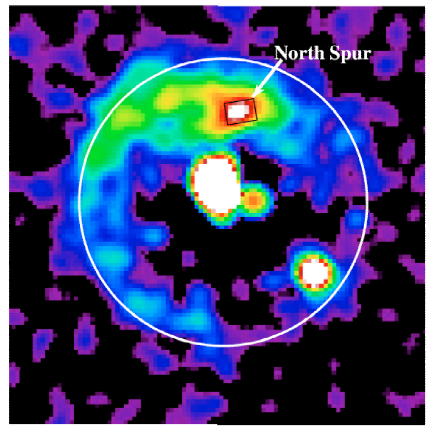
Predehl & Schmitt 1995 (ROSAT)

AX J1838.0-0655:

$N_H \sim 5 \times 10^{22}$ cm^{-2}
$\rightarrow \tau_{sca}$ (1keV) = 2.5 !!!

Open circles:
additional intrinsic
absorption





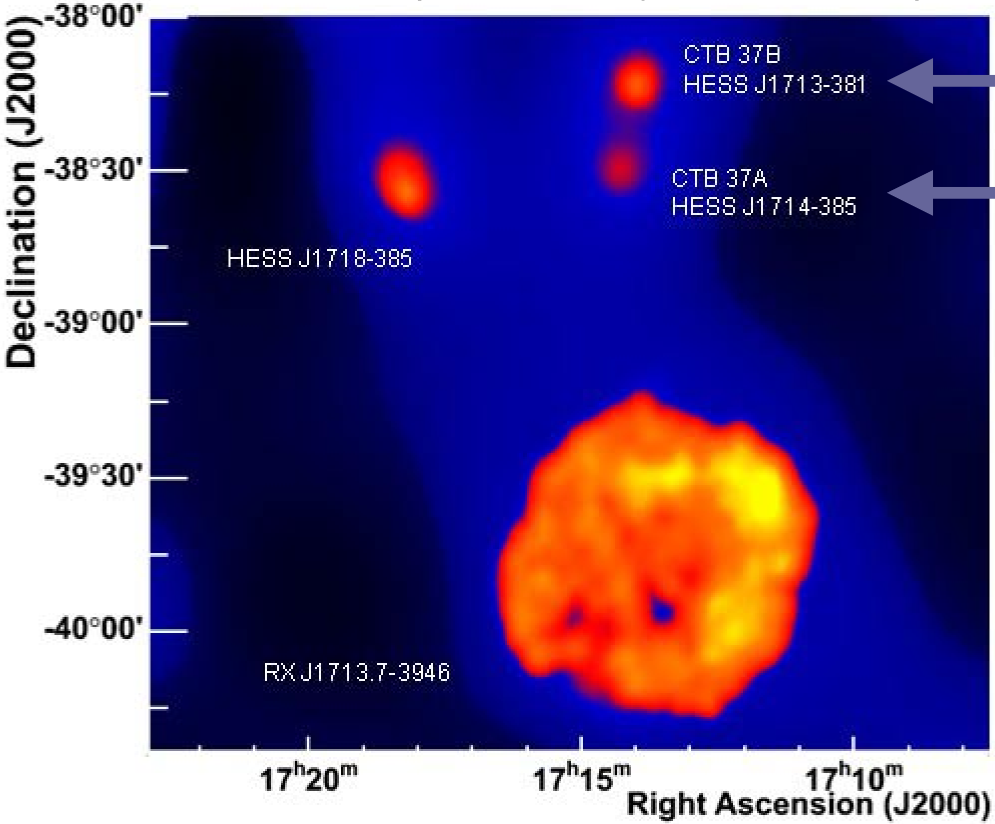
Cf. G21.5-0.9, Bocchino et al. 2005

Summary

- VHE astronomy provides a new window to PWN physics
- Efficient way to detect (relic) PWN because of the ubiquitous target photon fields for IC (CMB, + dust and starlight), independent of B-field
- Combination of X-ray and VHE allows e.g. determination of B-field (with caveats)
- Currently, for identification of VHE PWN mostly morphological arguments and efficiency into VHE flux is used
- X-rays reflect mostly current spin-down power (short synchrotron lifetime), whereas VHE, similar to radio, should allow to access the entire deposited pulsar energy budget (for moderately low B-fields)
- Cf., e.g., to R_{PWN} / R_{shock} – “radius method” by Swaluw & Wu (ApJ 555, 2001) based on radio-PWN to infer the initial spin rates

At the sensitivity limit of current VHE instruments

H.E.S.S. (adaptively smoothed)



HESS source of the month April 2008

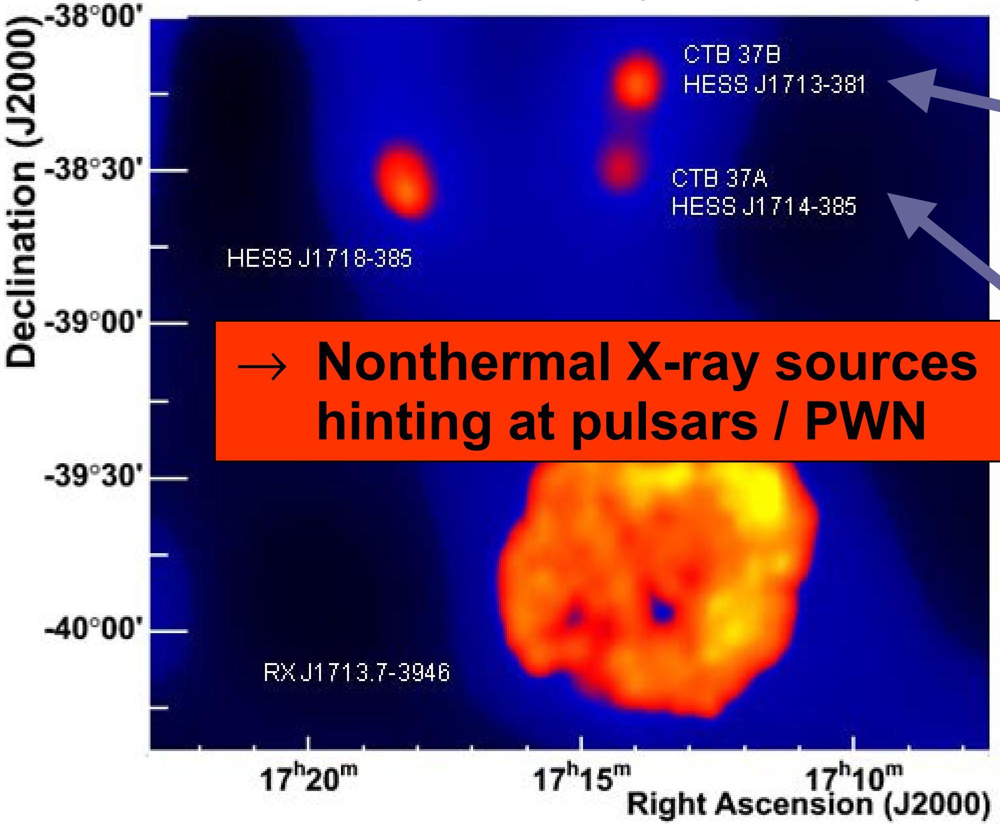
Two shell-type supernova remnants

Plausible hadronic emission scenarios exist for both sources

HESS collaboration,
astro-ph/0803.0682 & astro-ph/0803.0702

At the sensitivity limit of current VHE instruments

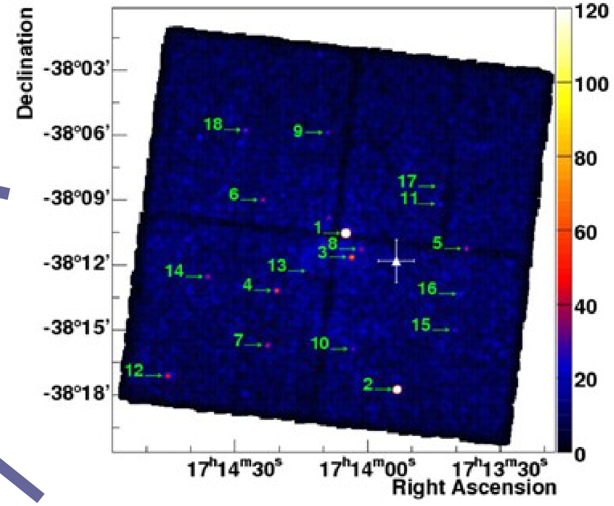
H.E.S.S. (adaptively smoothed)

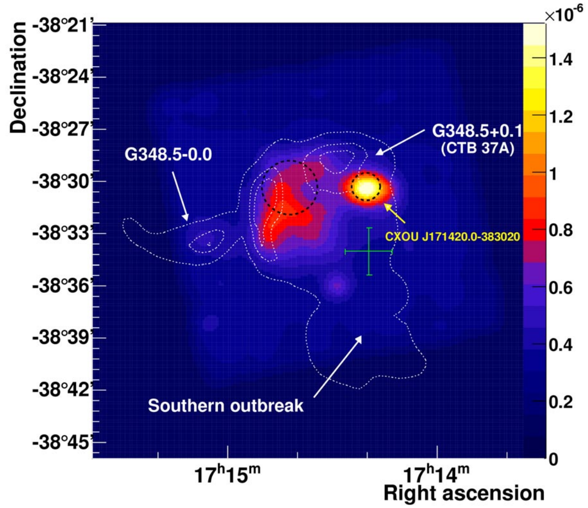


→ **Nonthermal X-ray sources hinting at pulsars / PWN**

HESS source of the month April 2008

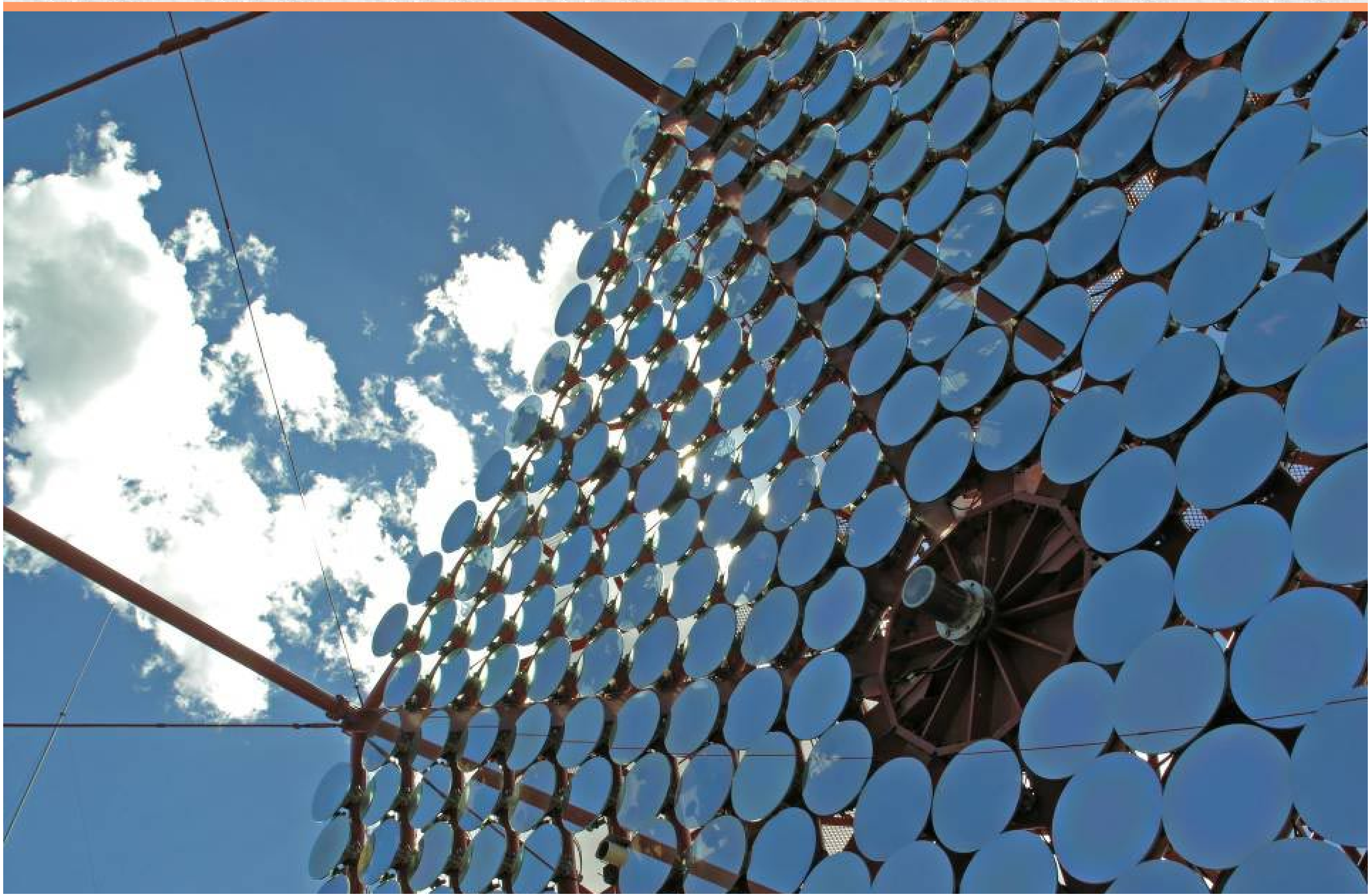
Chandra



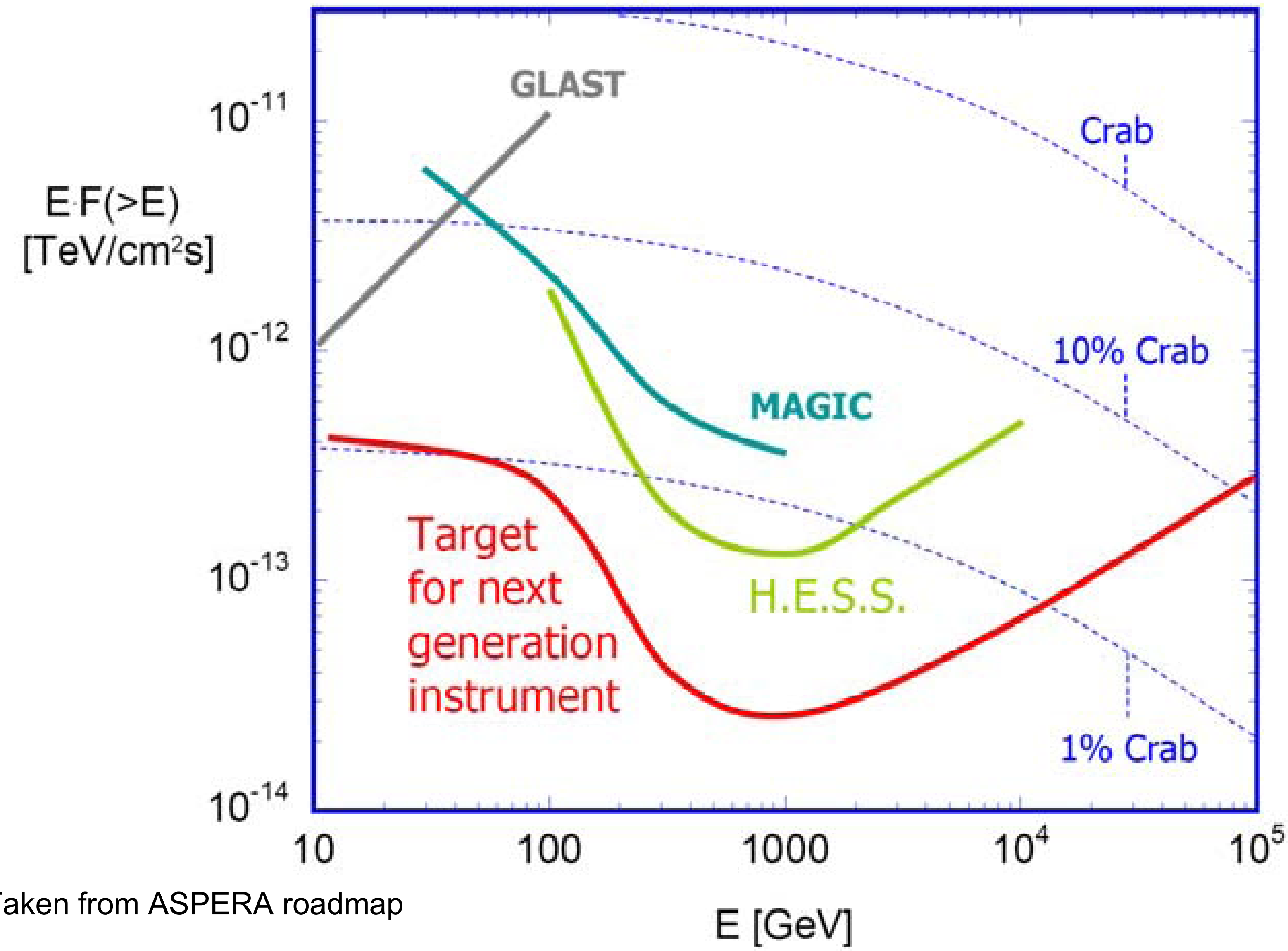


HESS collaboration,
astro-ph/0803.0682 & astro-ph/0803.0702

CTA: The Cherenkov Telescope Array



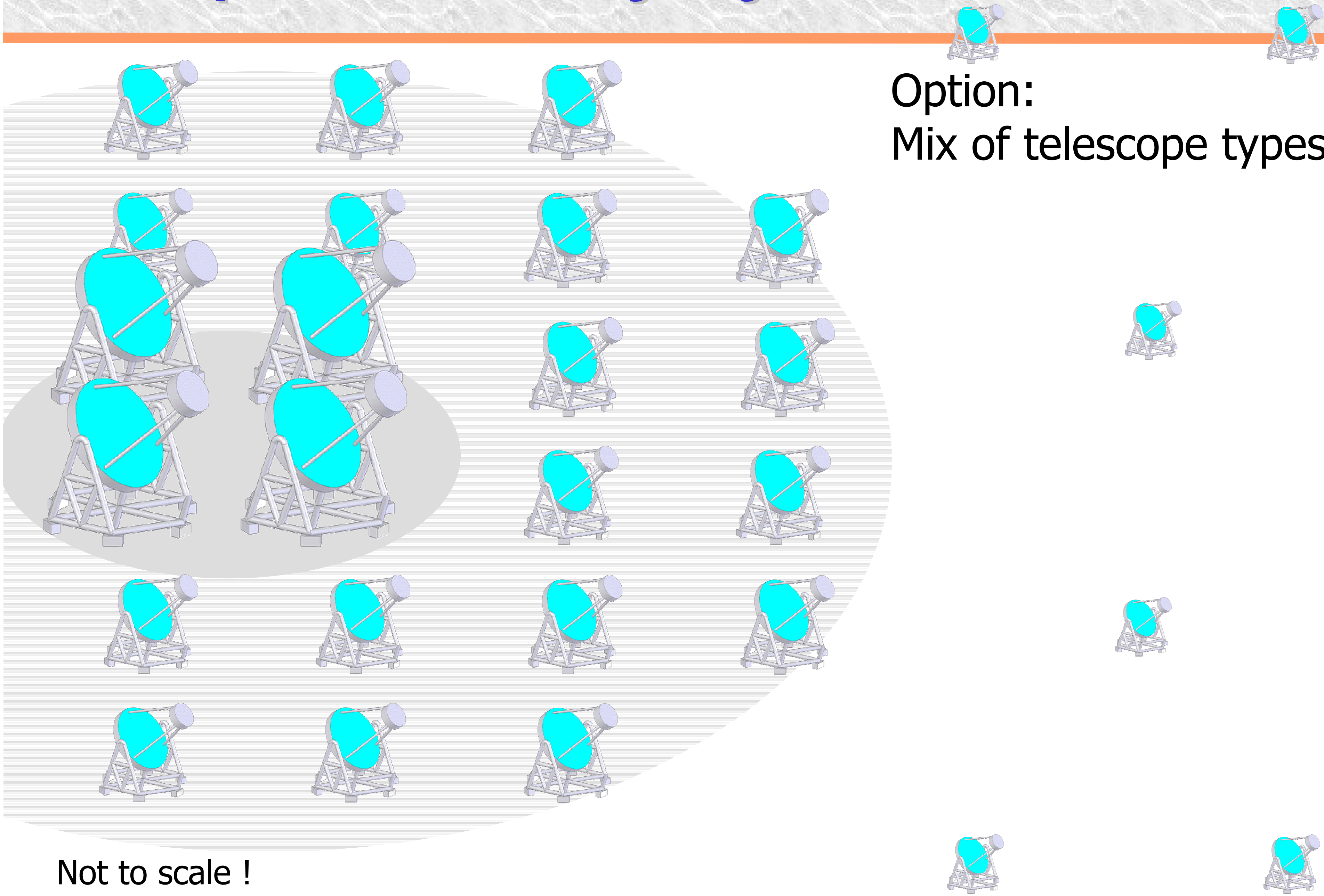
CTA (Cherenkov Telescope Array): target sensitivity



Taken from ASPERA roadmap

CTA: possible array layout

Option:
Mix of telescope types



Not to scale !

CTA: The Cherenkov Telescope Array

- Consortium is currently being formed
- Mostly European, recent statement for Japanese commitment

- Currently under design study
- “Call for proposals” for science requirements

CTA: The Cherenkov Telescope Array