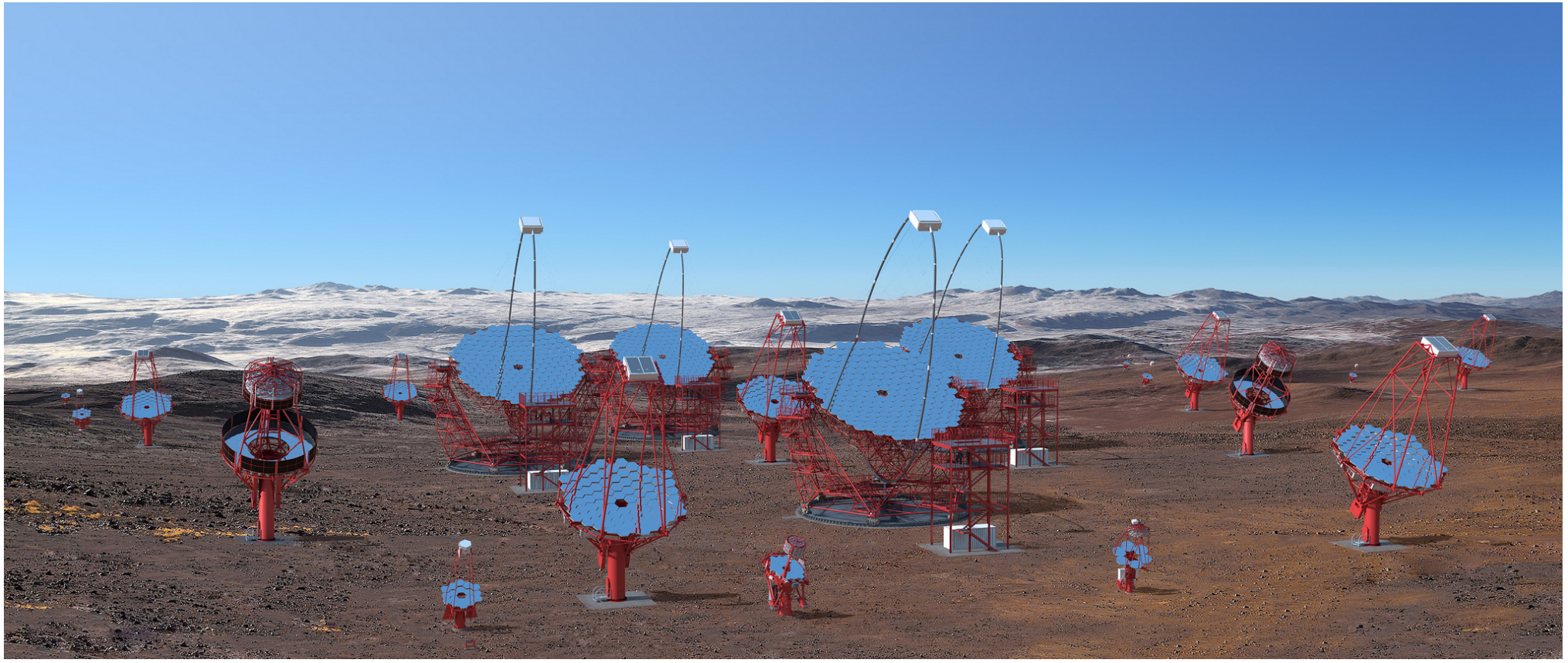
# Study of Cosmic Ray Origin and Transient Sources with CTA

## (subtext: why we need LSTs in the South)

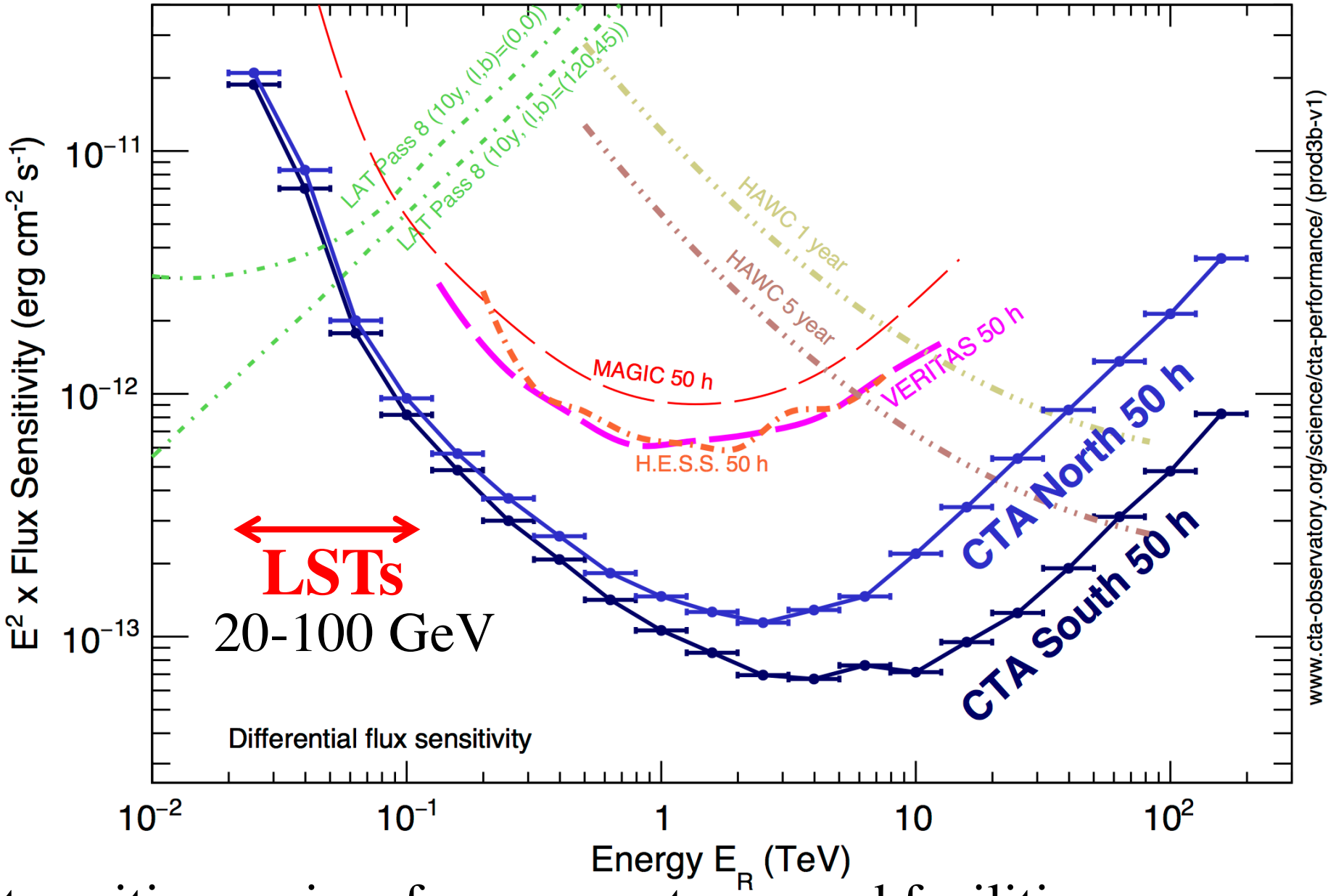
**Susumu Inoue (RIKEN)**
**on behalf of many collaborators inside/outside CTA**



# outline

1. introduction
   - CTA and LSTs
   - importance of LSTs in the South
2. cosmic ray (CR) origin
   a. Galactic CRs
   - supernova remnants (SNRs): CR acceleration and escape
   b. ultra-high-energy CRs (UHECRs)
   - active galactic nuclei (AGN) jets: role of Centaurus A
3. transient sources
   (- short gamma-ray bursts (GRBs) and gravitational waves)
   - blazar flares and neutrinos
   - radio, optical transients

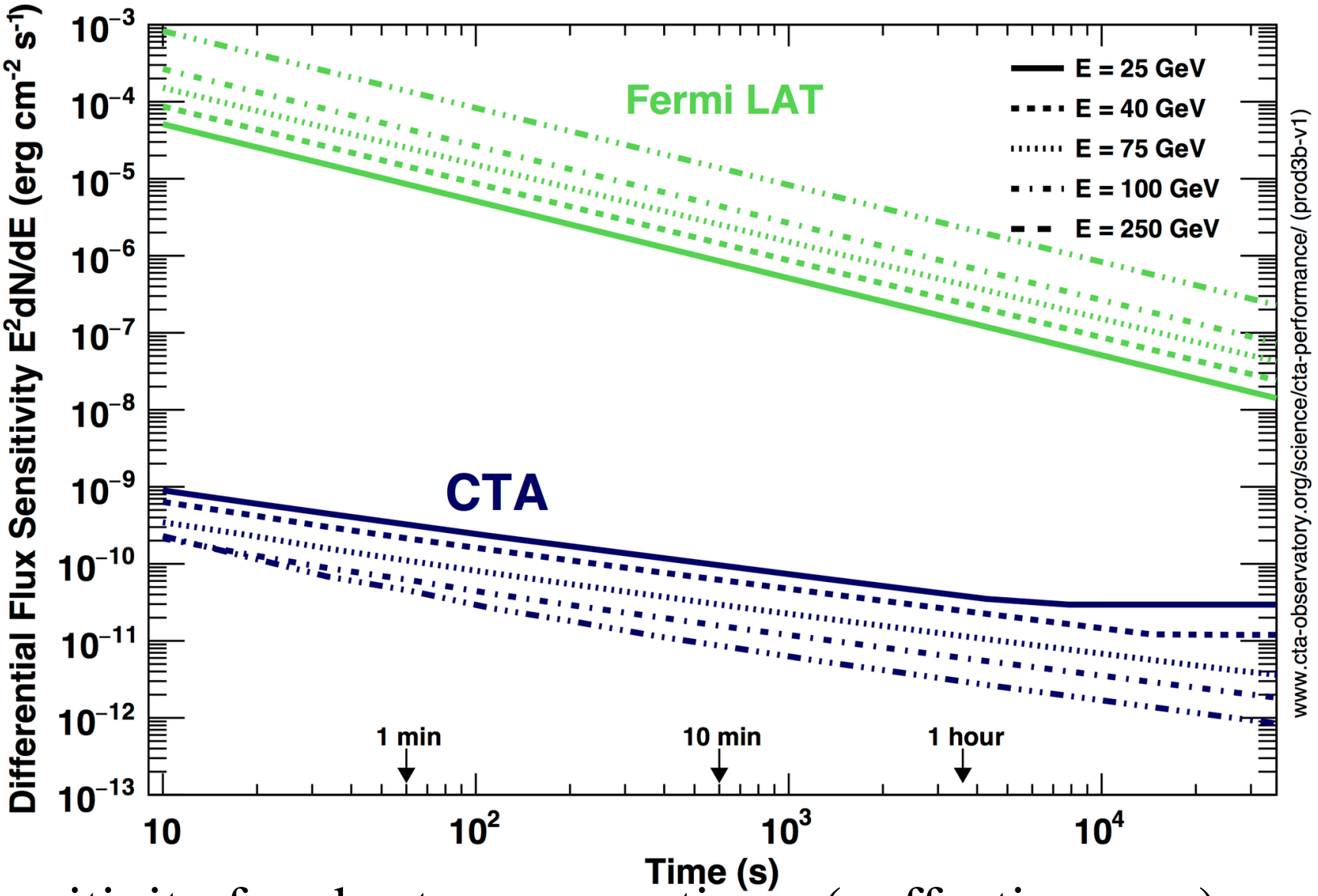
# CTA sensitivity (steady sources)




transition regime from space to ground facilities

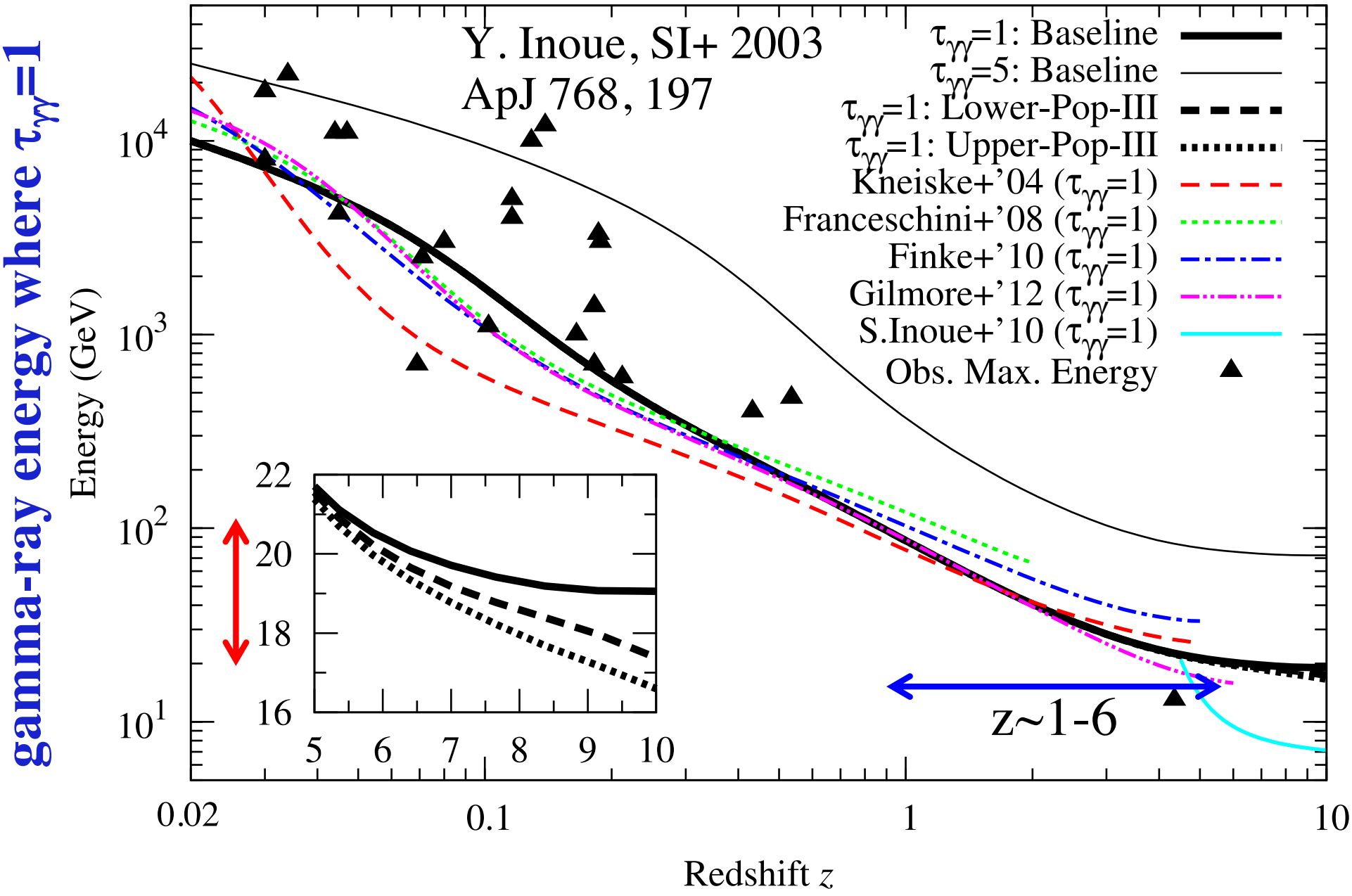
-> currently some sensitivity gap

# CTA vs Fermi-LAT for transient/variable sources




- sensitivity for short exposure times (~effective area) greater than satellites by several orders of magnitude
- rapid slewing for LSTs (180 deg in 20 sec)

# extragalactic gamma-ray horizon vs redshift

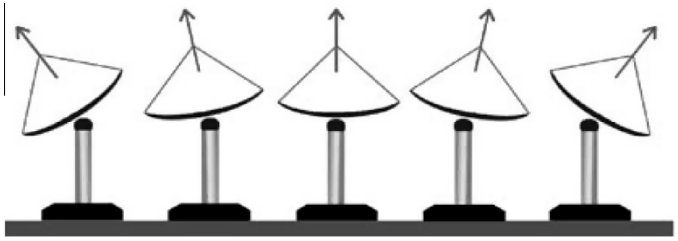



LSTs crucial for high-z extragalactic transients

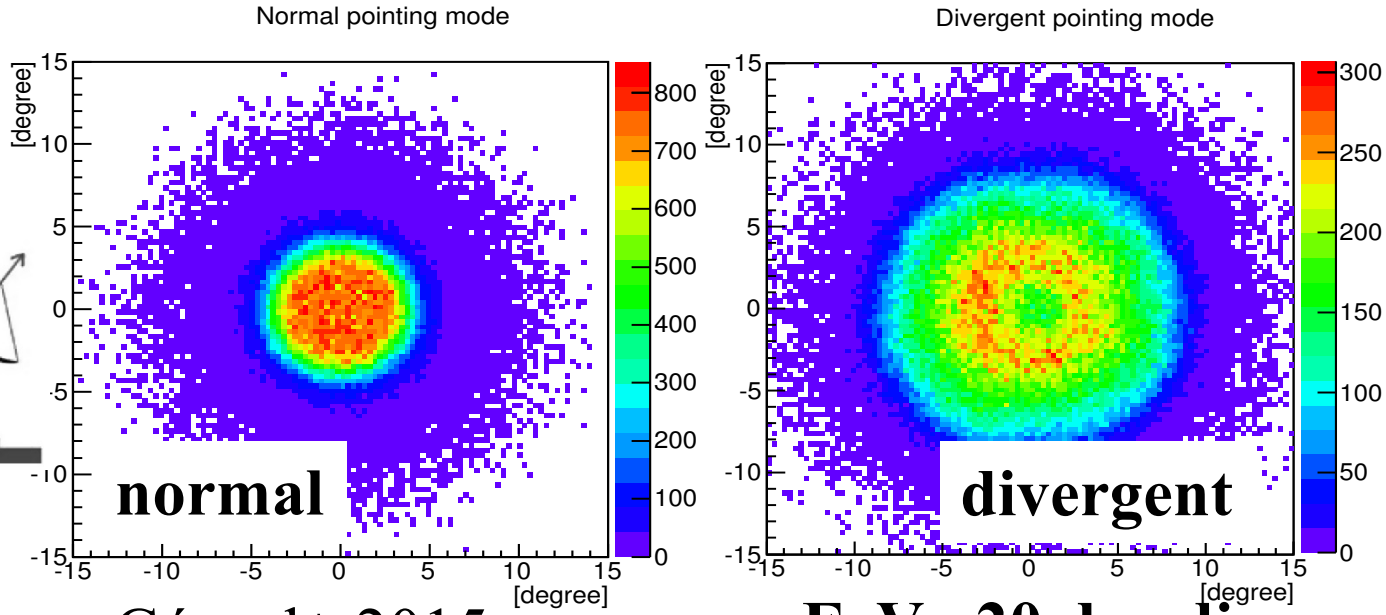
# CTA vs current Cherenkov telescopes for transients

- all-sky coverage with North and South sites
- versatile pointing (sub-arrays, divergent pointing)
- real-time analysis (alerts issued in ~30 sec)

divergent pointing for MSTs/SSTs



Szanecki+ 2015




Gérard+ 2015

**FoV ~20 deg dia.**

wider FoV at expense of angular/energy resolution

- fast scanning of large regions, e.g. GW follow-up
- transient survey?

# importance of Southern sky / all-sky coverage

unique targets in Southern sky

- Galactic Center
- inner Galactic plane (majority of Galactic objects )
- Magellanic Clouds
- Centaurus A (nearest active galaxy + radio galaxy)

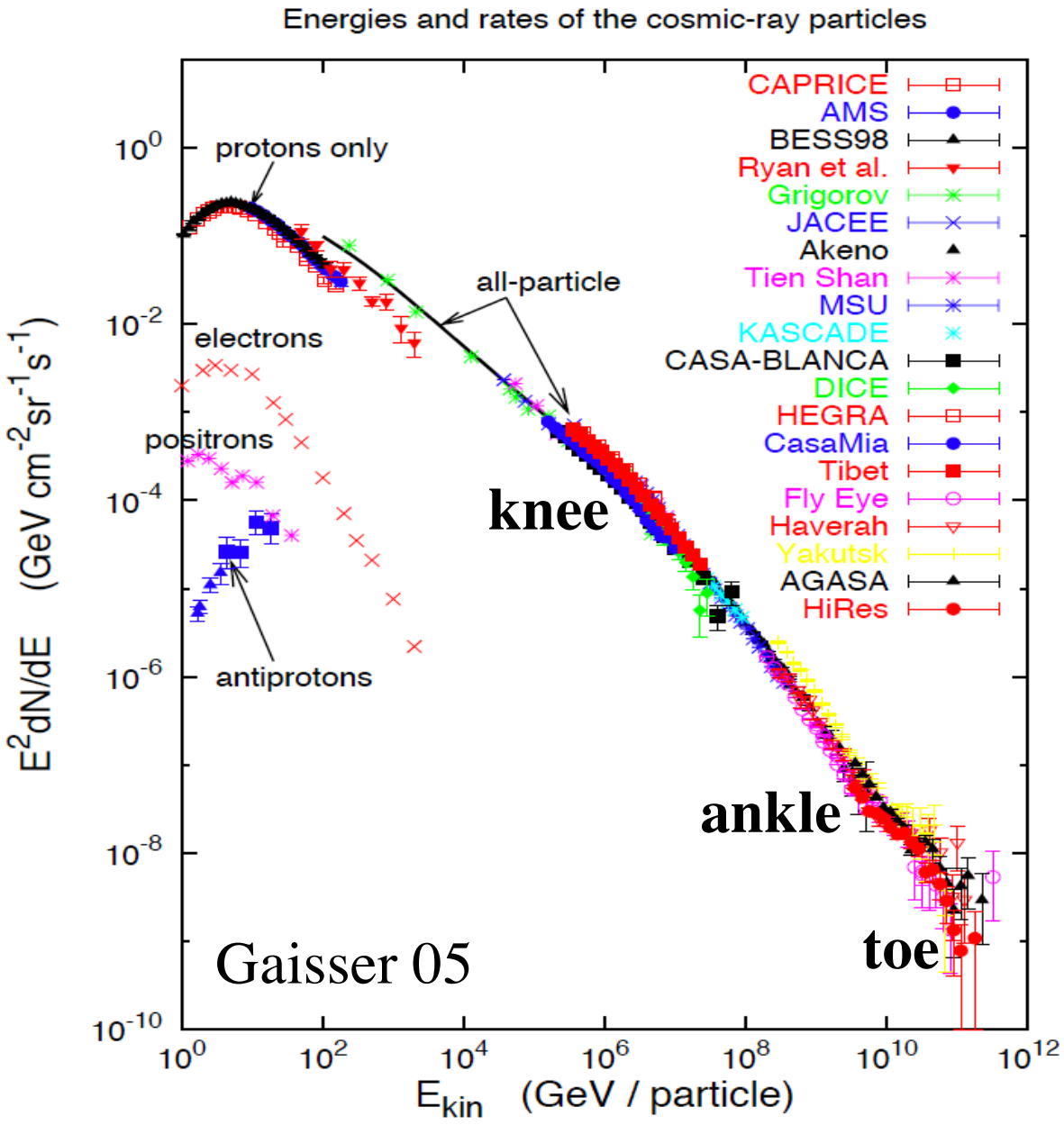
unique facilities (transient factories) in Southern hemisphere

- radio: SKA and its pathfinders (ASKAP, MWA, MeerKAT...)
- optical: LSST
- neutrinos at extremely high energy: IceCube

all sky coverage

- potentially unique transients (“Rosetta Stone” events)
  c.f. SN 1987A, GW170817...

# 2. cosmic ray origin
# observed spectrum of cosmic rays




**up to knee ($<10^{15\text{-}16}$ eV)**

Galactic SNRs?

likely, but not yet definitive

**knee-ankle** ($10^{15\text{-}16}$-$10^{18}$ eV)

Galactic? no new source?

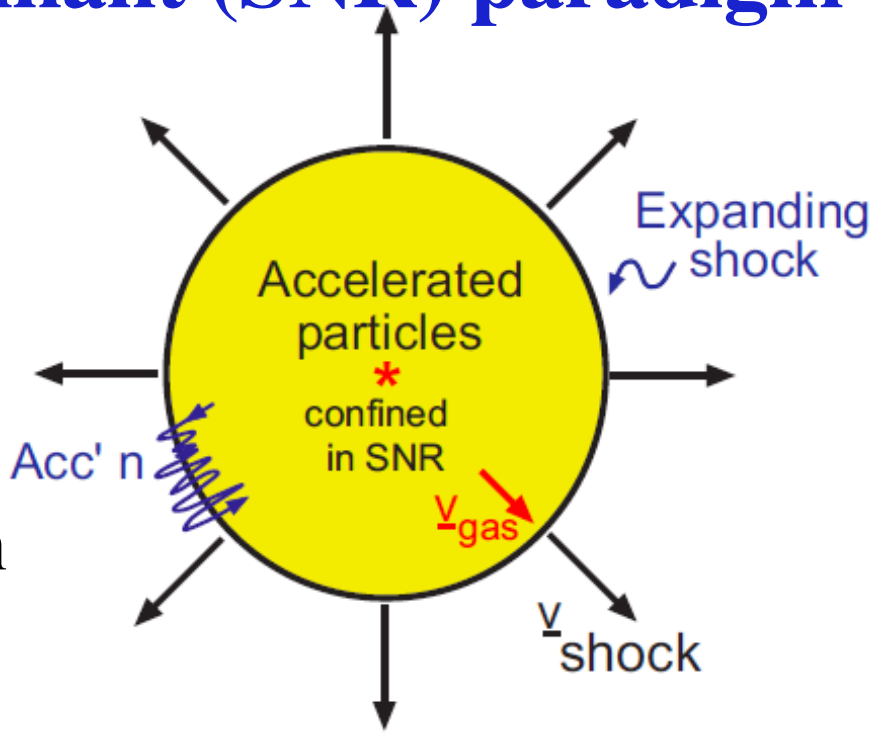
**above ankle ($>10^{18}$ eV)**

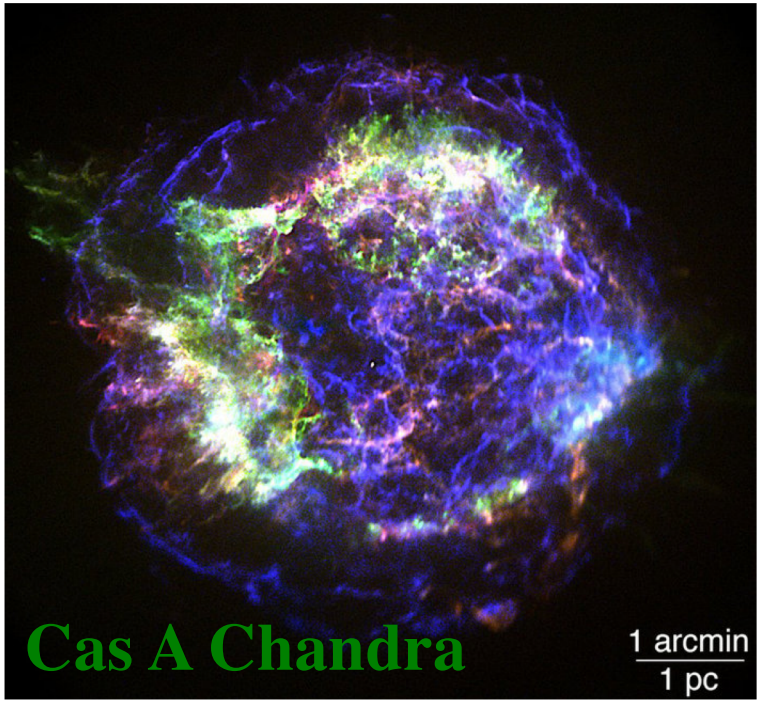
extragalactic: AGNs?

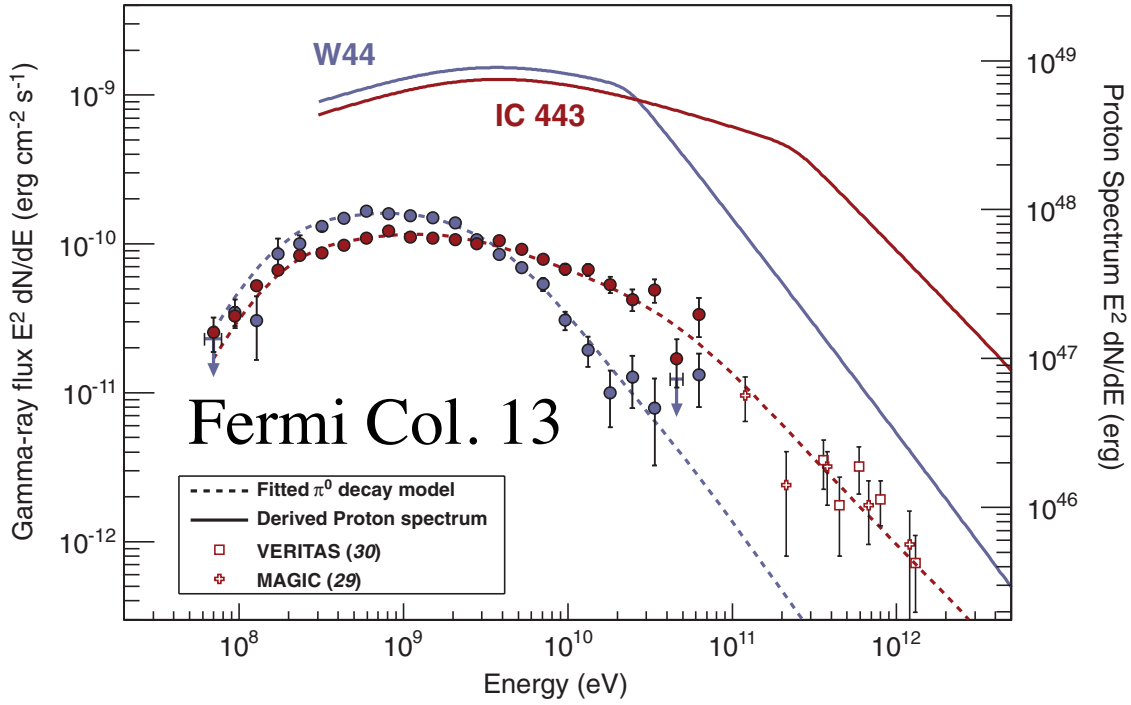
GRBs?

# Galactic CRs: supernova remnant (SNR) paradigm

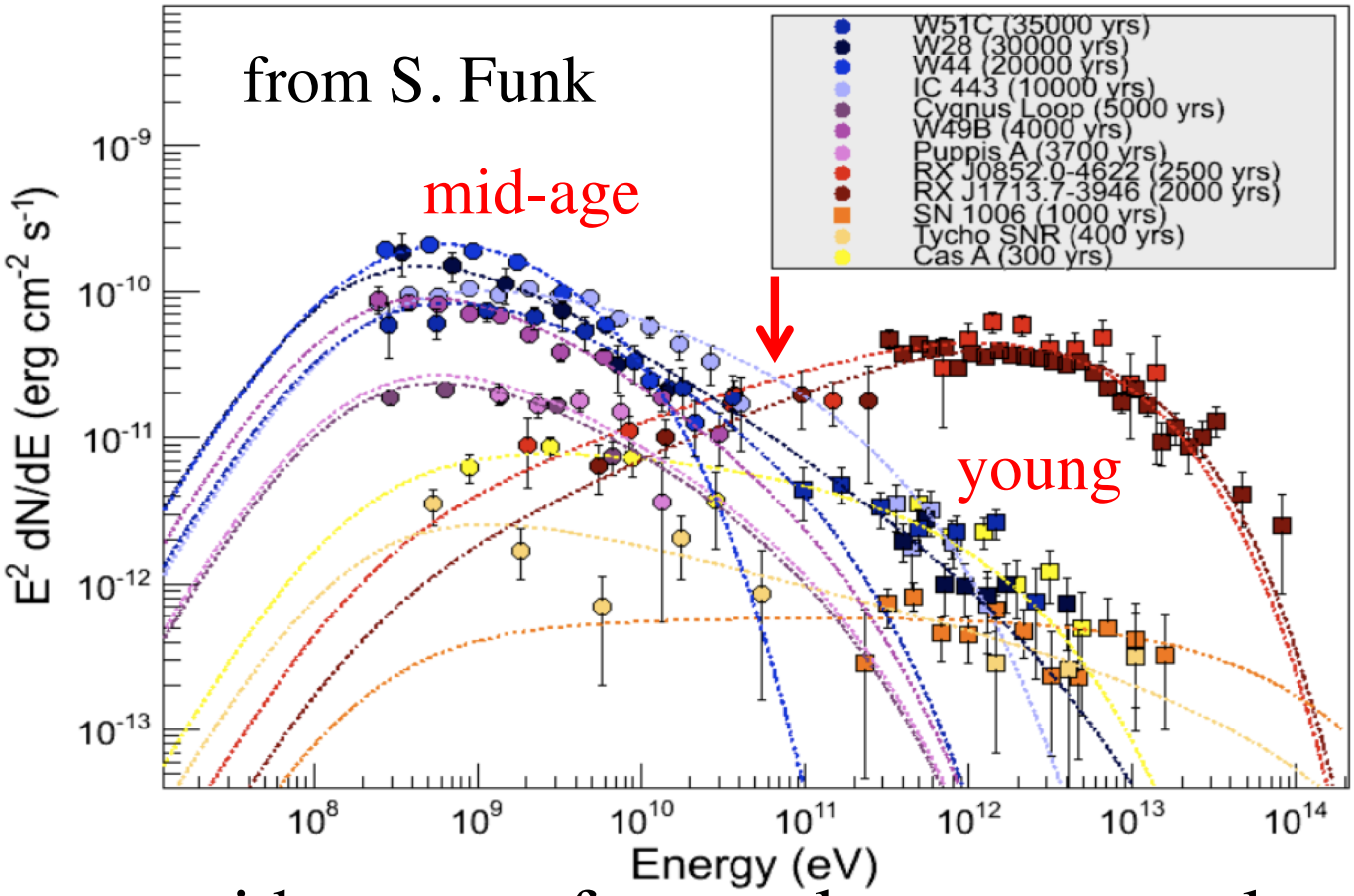
- consistent energetics
  $L_{GCR} \sim 10^{41}$ erg/s~0.1x$E_{SN}/t_{SN}$
- plausible theory of
  diffusive shock acceleration
- observational evidence
  radio+X-ray: electron acceleration
  GeV(-TeV): proton acceleration

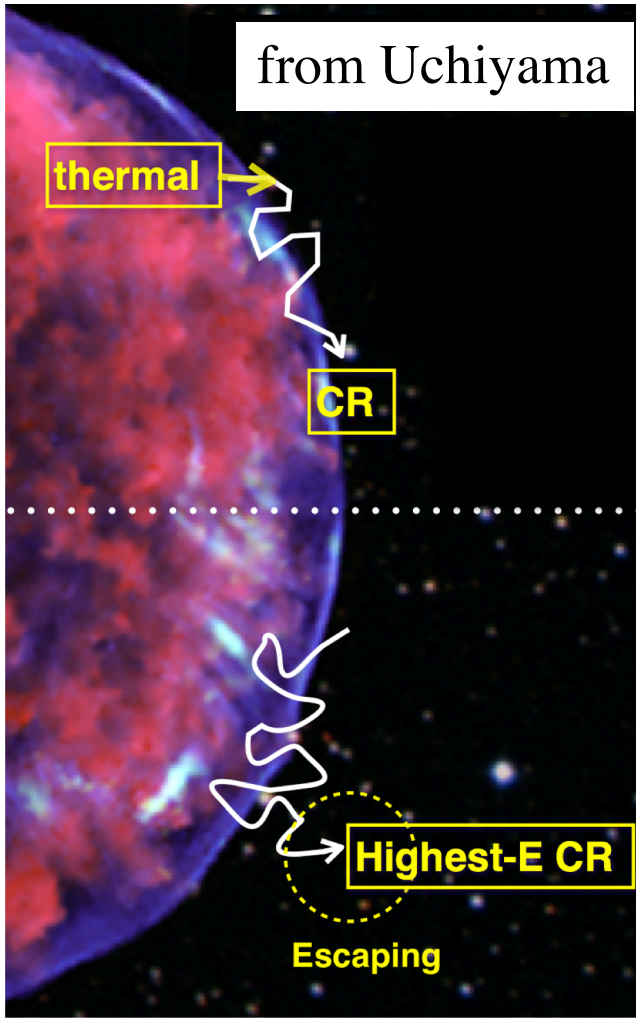


# issues for the SNR paradigm: acceleration to PeV, CR escape

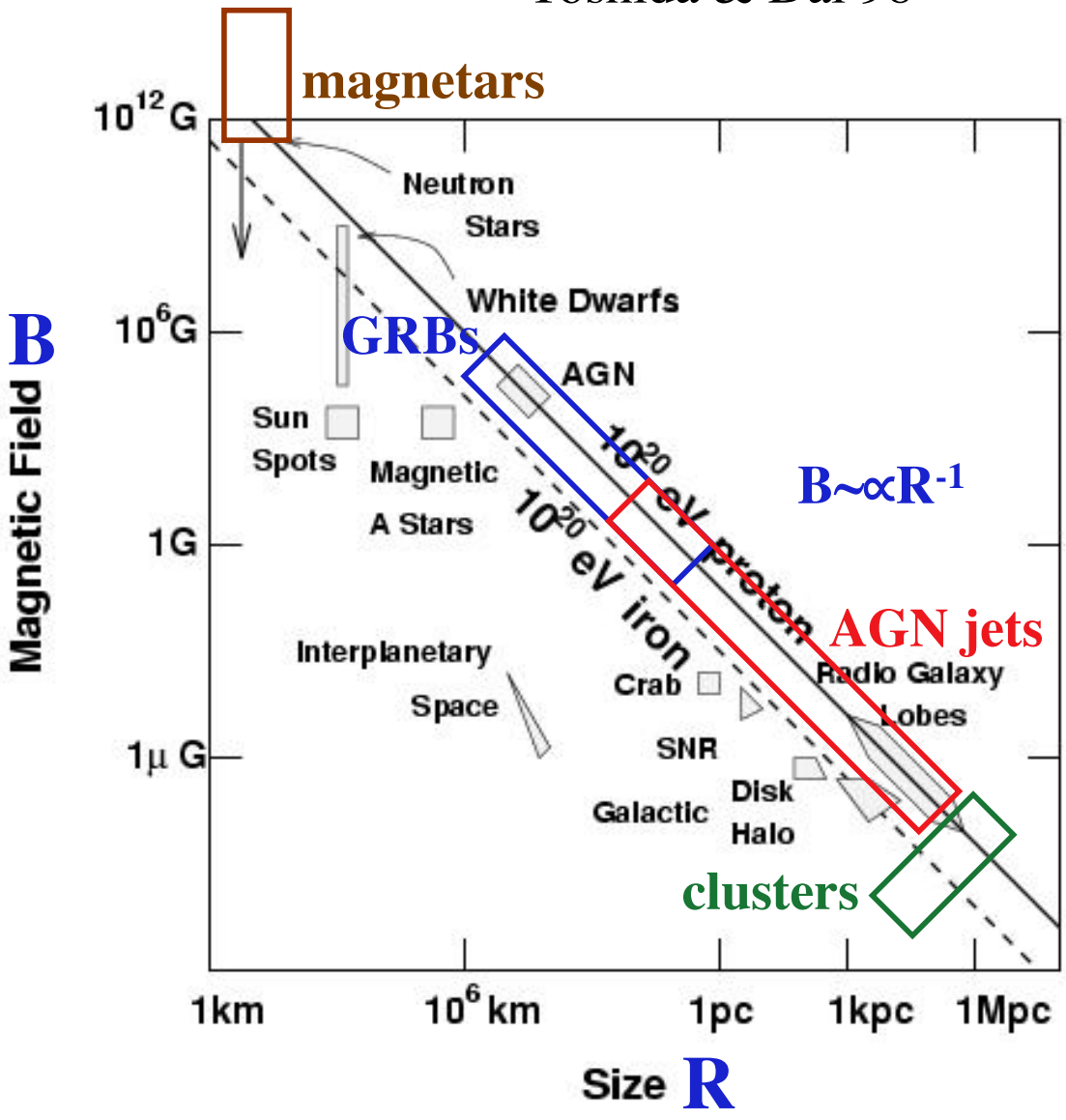



- no evidence yet for accelerators up to knee energy (Pevatrons) non-SNR sources (black holes, pulsars, ...)?
  -> search featuring SSTs
- potential evidence for time- and energy-dependent CR escape
  -> clarify including South LSTs

# UHECR sources: acceleration

**"Hillas plot"** adapted from Yoshida & Dai 98




**E ≦ Ze B R (v/c)**

confinement

**$E_{max}$** acceleration vs:
escape
source lifetime
adiab. expansion loss
radiative loss

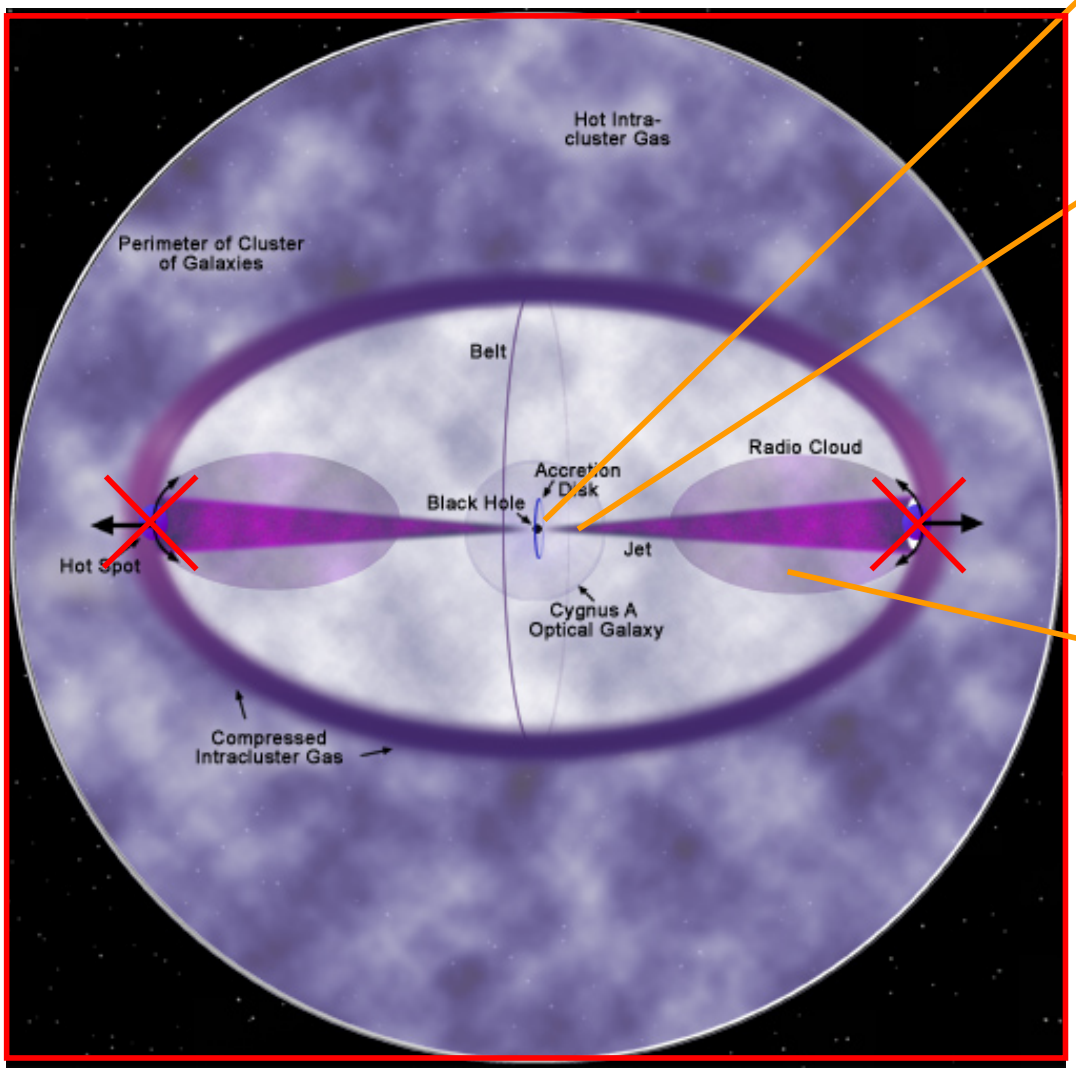
**old favorite: AGN jets**

**leading contender: GRBs**

**dark horse: magnetars**
**clusters, etc.**

# AGN: acceleration sites

## low power (FR 1) radio galaxy




from Chandra webpage

**near-nucleus**

**highest E not expected**

e.g. Szabo & Protheroe 94

**inner jet (blazar)**

**$E_{max} \sim E_{pg} \sim < 10^{20}$eV**

**accel./escape nontrivial**

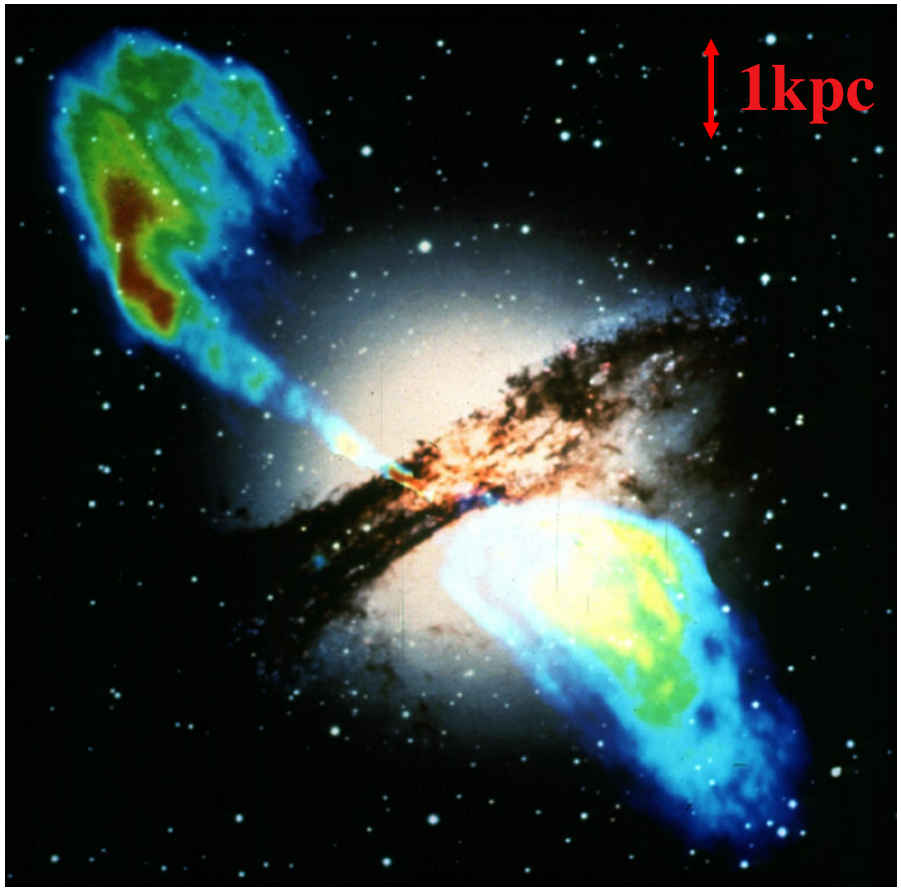
e.g. Mannheim 93

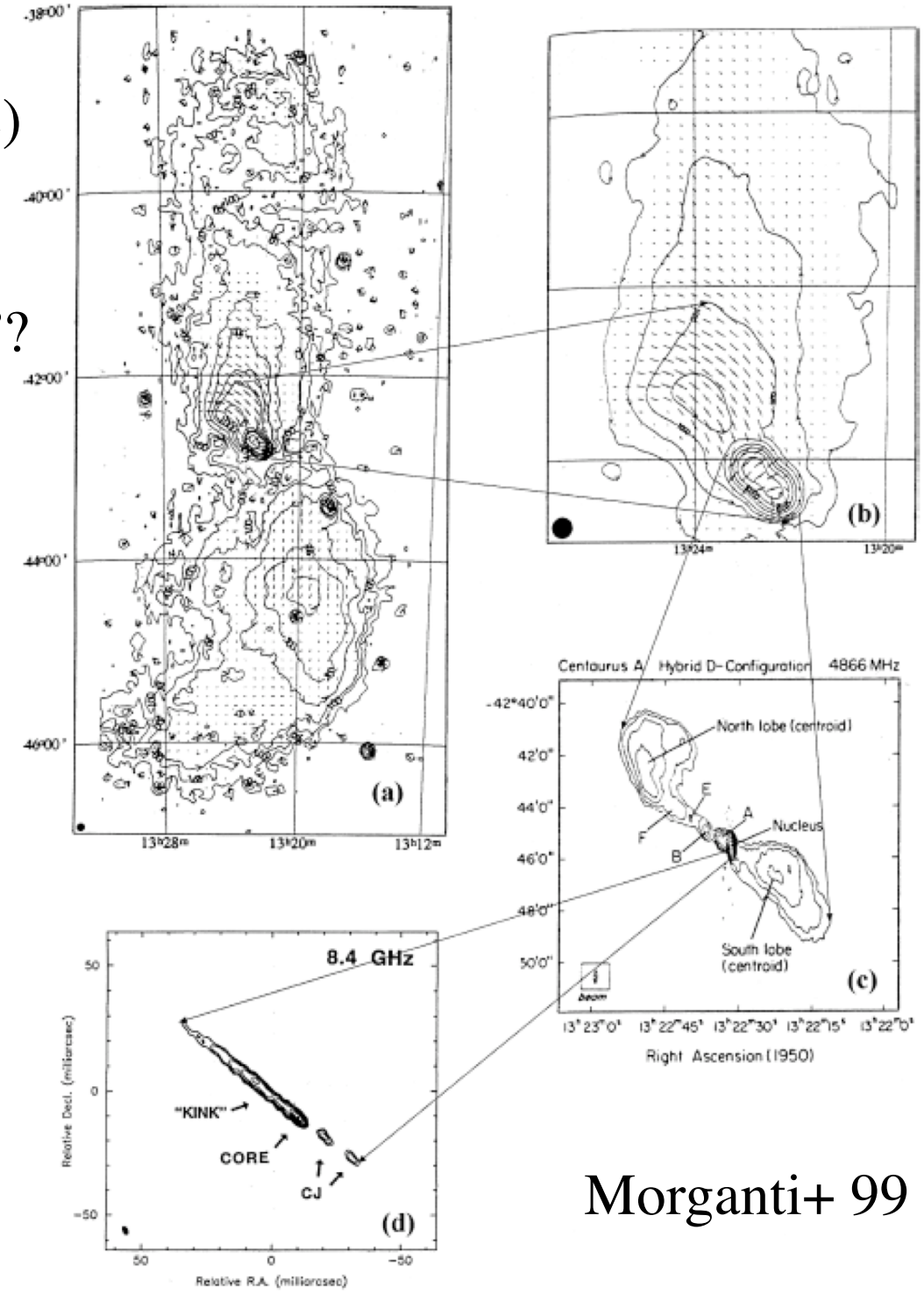
**diffuse lobe?**

**c.f. diffuse GeV from**
**Cen A, Fermi bubble**

# Centaurus A

- nearest AGN by far (D~3-5 Mpc)
- low power ($P_{2.7}$~2x$10^{24}$ W/Hz)
- inner lobes (~10 kpc); active
- outer lobes (650 kpc); “inactive”?

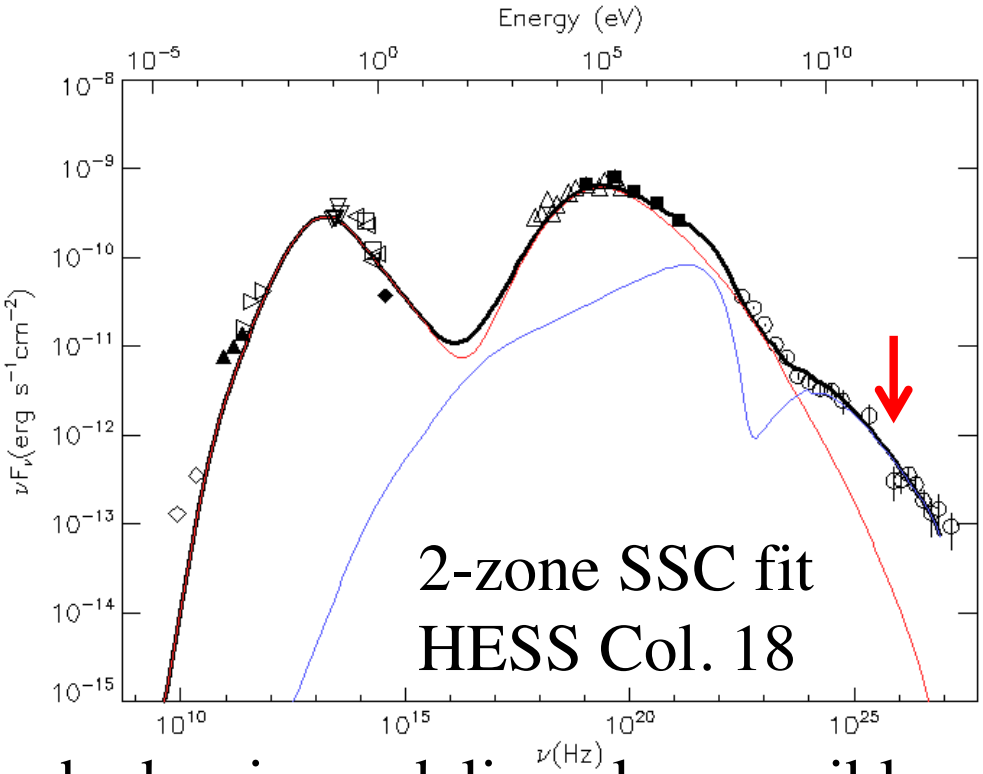


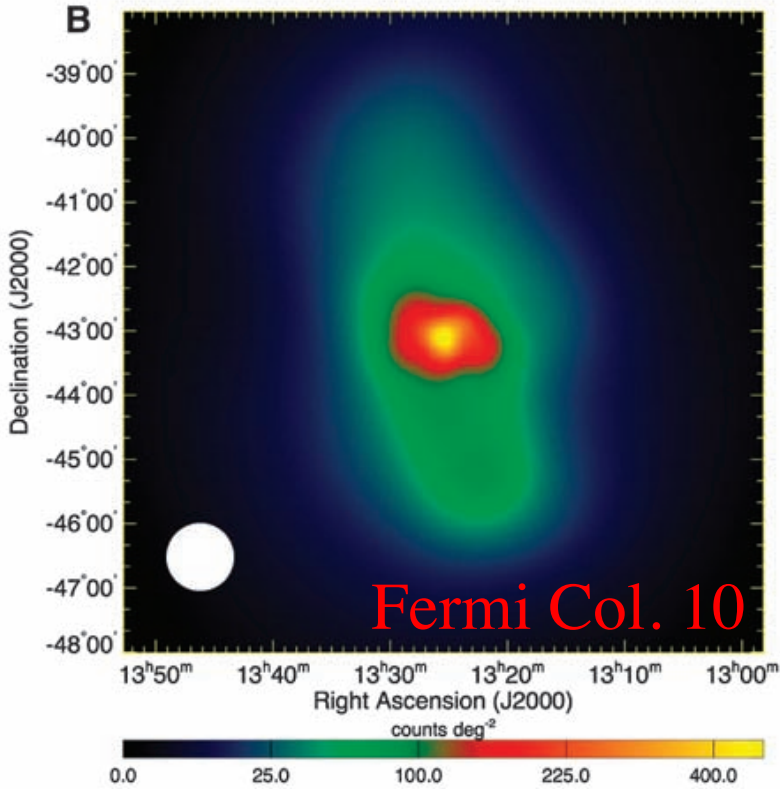

Morganti+ 99

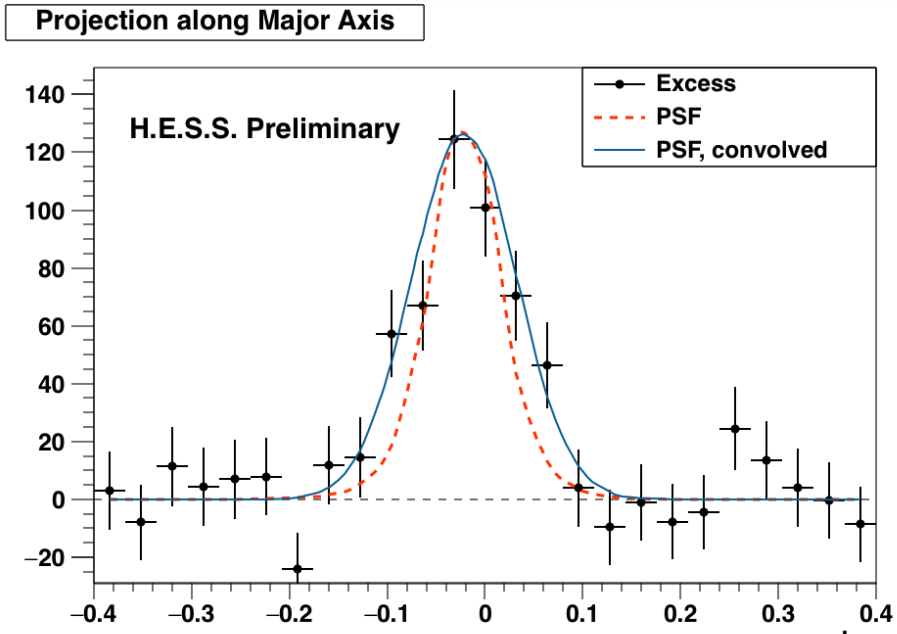
# Cen A in gamma-rays

- diffuse GeV associated with outer lobe
- 2 component GeV+TeV associated with "core" (includes inner lobe)
- spatial extension of "core" TeV along jet direction?
  -> need South LSTs




hadronic modeling also possible
Cerruti+ 1610.00255



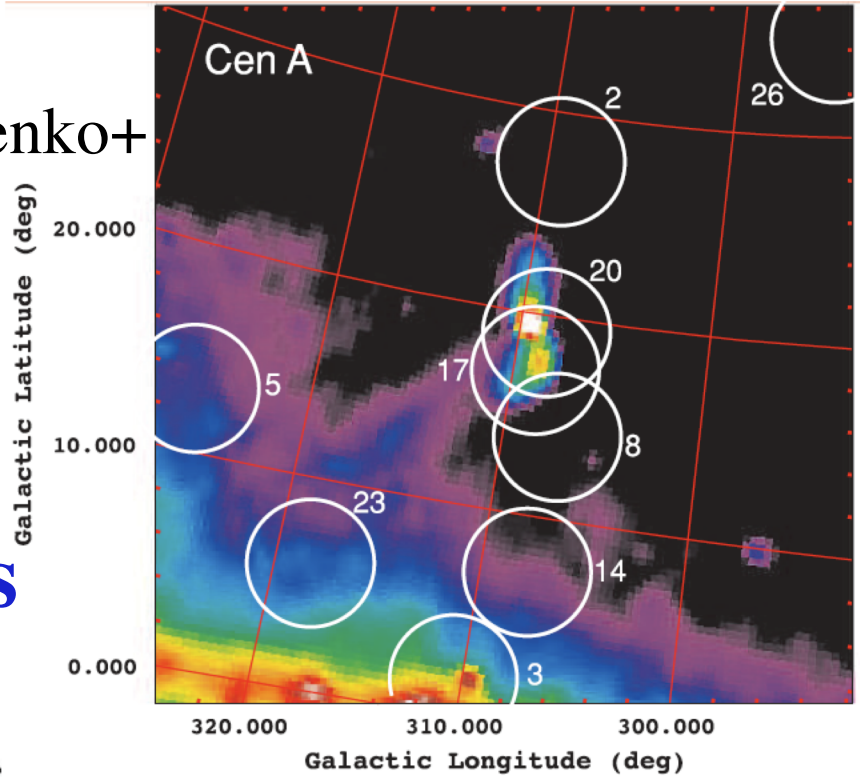




Sanchez+ (HESS), TeVPA 2018

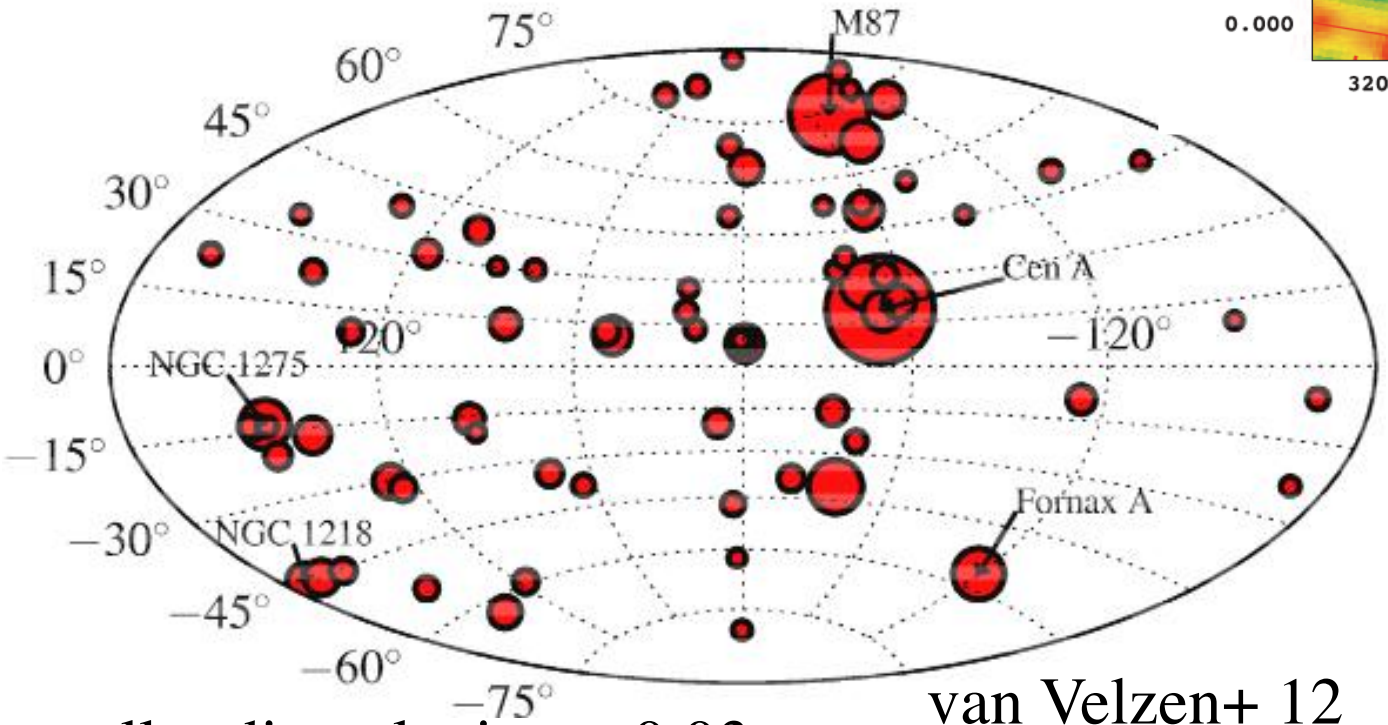
# Cen A in UHECRs?

- potential correlation with Auger "warm" spot

Moskalenko+ 09




# vs other nearby radio galaxies




van Velzen+ 12

all radio galaxies z<0.03
circle area proportional to radio flux

| name | D[Mpc] |
|---|---|
| **Cen A** | **3.6** |
| M87 | 18 |
| For A | 21 |
| UGC 7360 | 32 |
| NGC 4696 | 42 |
| NGC 5090 | 47 |
| I 4296 | 51 |
| NGC 6328 | 59 |
| NGC 11294 | 67 |
| 2MASX | 69 |

# 3. Transient Sources: Gamma-Ray Bursts

Most luminous explosions
in the Universe,
largely unexplored at VHE

via VHE observations:

**Clarify physics of GRBs**

- mechanisms of prompt and early afterglow radiation, particle acceleration, jet formation

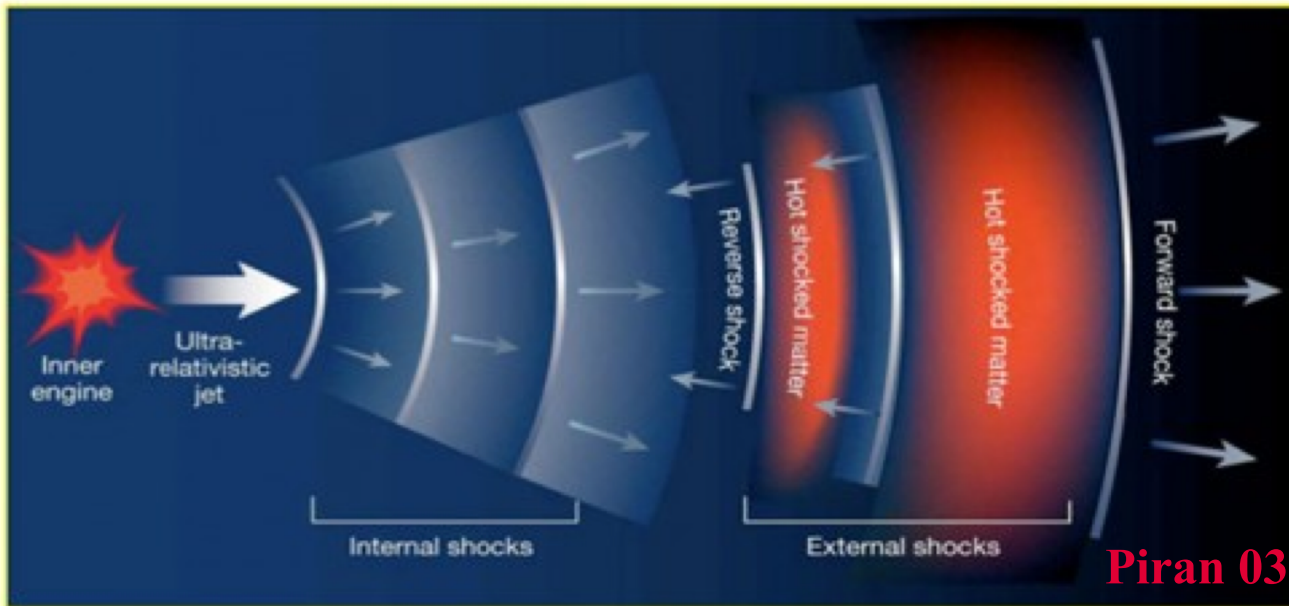
**Probe the Universe**

- extragalactic background light (deeper than AGN)
- intergalactic magnetic fields

**Test UHECR origin, fundamental physics**

search for signatures of:

- accelerated hadrons
- Lorentz invariance violation



# first clear detection of a GRB in VHE gamma rays: GRB 190114C by MAGIC

>20σ above 300 GeV

## First time detection of a GRB at sub-TeV energies; MAGIC detects the GRB 190114C

ATel #12390; ***Razmik Mirzoyan on behalf of the MAGIC Collaboration***
*on **15 Jan 2019; 01:03 UT***
*Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)*

Subjects: Gamma Ray, >GeV, TeV, VHE, Request for Observations, Gamma-Ray Burst

Referred to by ATel #: 12395

Tweet

The MAGIC telescopes performed a rapid follow-up observation of GRB 190114C (Gropp et al., GCN 23688; Tyurina et al., GCN 23690, de Ugarte Postigo et al., GCN 23692, Lipunov et al. GCN 23693, Selsing et al. GCN 23695). This observation was triggered by the Swift-BAT alert; we started observing at about 50s after Swift T0: 20:57:03.19. The MAGIC real-time analysis shows a significance >20 sigma in the first 20 min of observations (starting at T0+50s) for energies >300GeV. The relatively high detection threshold is due to the large zenith angle of observations (>60 degrees) and the presence of partial Moon. Given the brightness of the event, MAGIC will continue the observation of GRB 190114C until it is observable tonight and also in the next days. We strongly encourage follow-up observations by other instruments. The MAGIC contact persons for these observations are R. Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de) and K. Noda (nodak@icrr.u-tokyo.ac.jp). MAGIC is a system of two 17m-diameter Imaging Atmospheric Cherenkov Telescopes located at the Observatory Roque de los Muchachos on the Canary island La Palma, Spain, and designed to perform gamma-ray astronomy in the energy range from 50 GeV to greater than 50 TeV.

Papers in preparation, please stay tuned!

# high-energy neutrinos

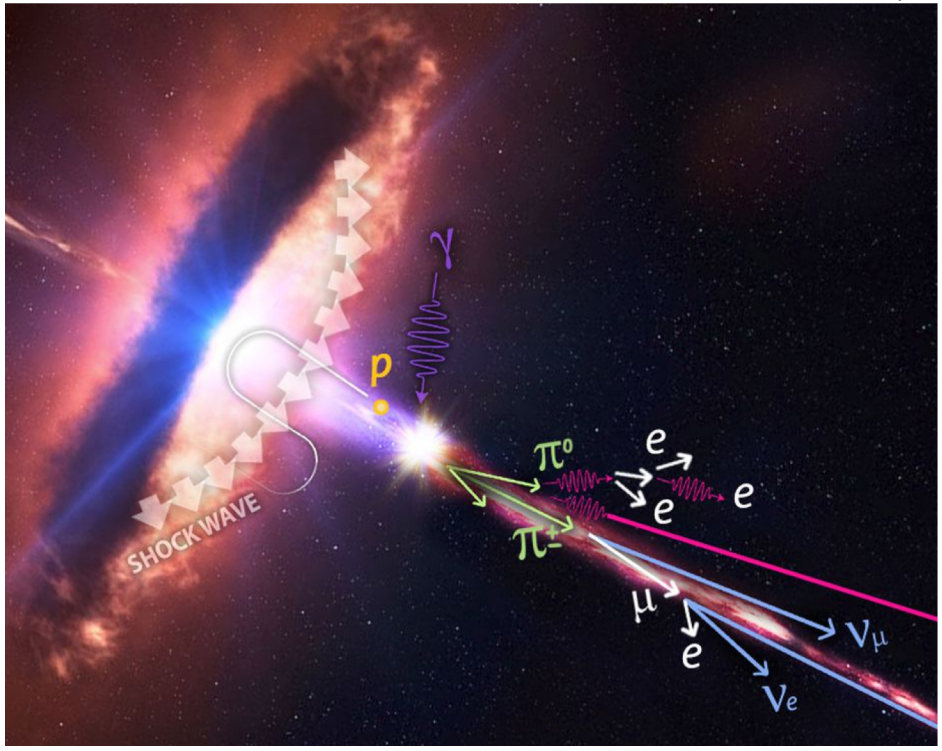
New window onto the Universe, turned new mystery

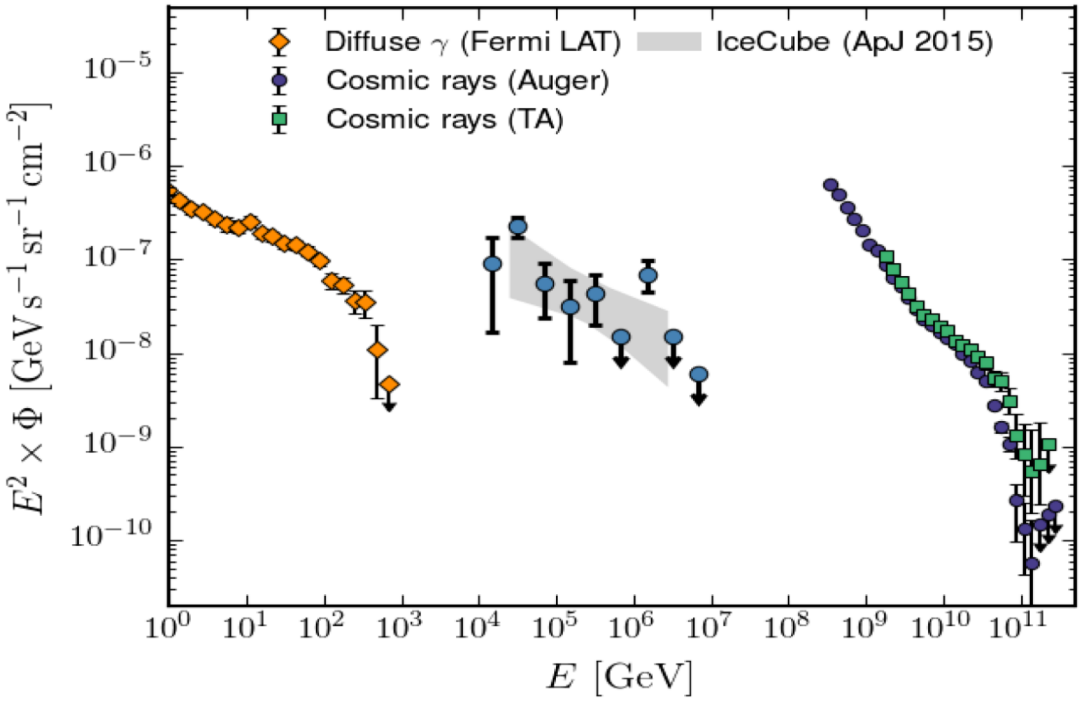
- clear indicators of VHE/UHE cosmic ray production
- being detected by IceCube, but no correlation with promising sources (bright GRBs, bright blazars) until recently

**VHE γ follow-up**

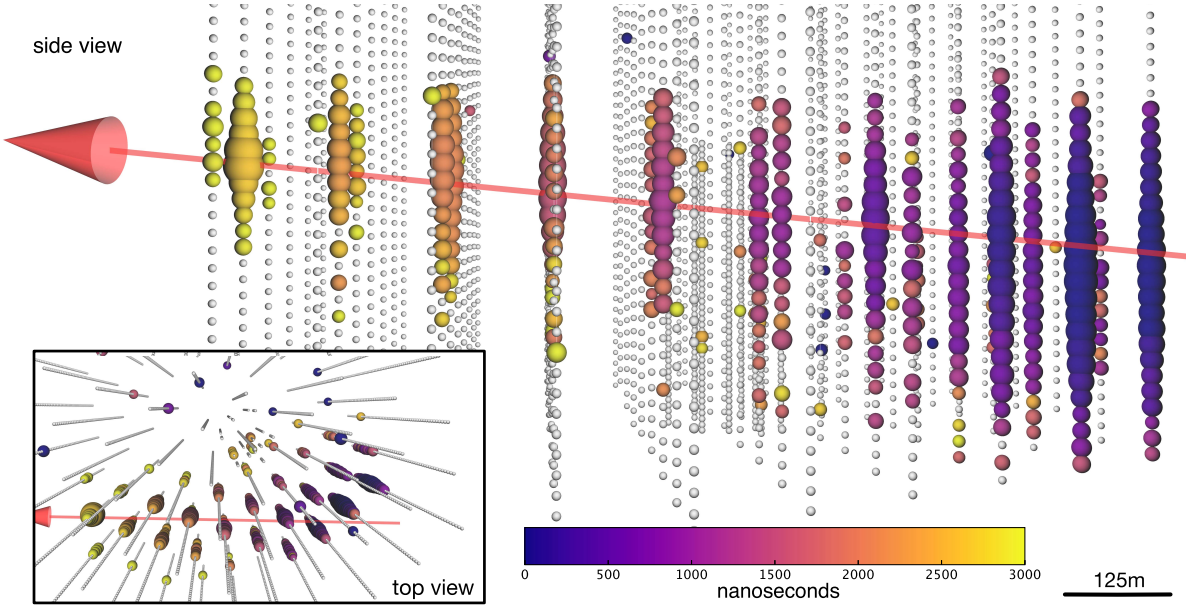
identify via co-produced γ rays (either leptonic or hadronic):

- neutrino sources (if γ-rays escape + propagate)
- VHE/UHECR sources (if γ-rays + CRs escape+propagate)



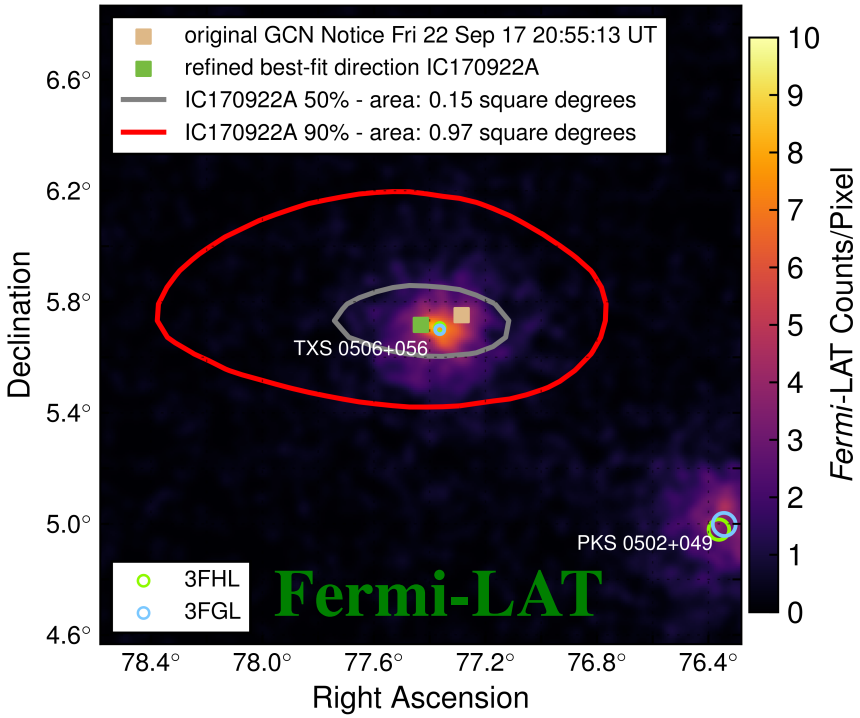



# ν / EM observations of IC-170922A / TXS 0506+056




**IceCube**

- 56.5% probability of being astrophysical ν
- alert after 43s
- well localized, <<1 deg
- $E_\nu$~290 TeV (183 TeV - 4.3 PeV 90% C.L. assuming -2.13 spectrum)




**Fermi-LAT**

- coincident with blazar TXS 0506+056 in bright state (0.5 yr-long)
- significance of association ~3σ
  -> possible source of possible astrophysical high-energy neutrino

**MAGIC**

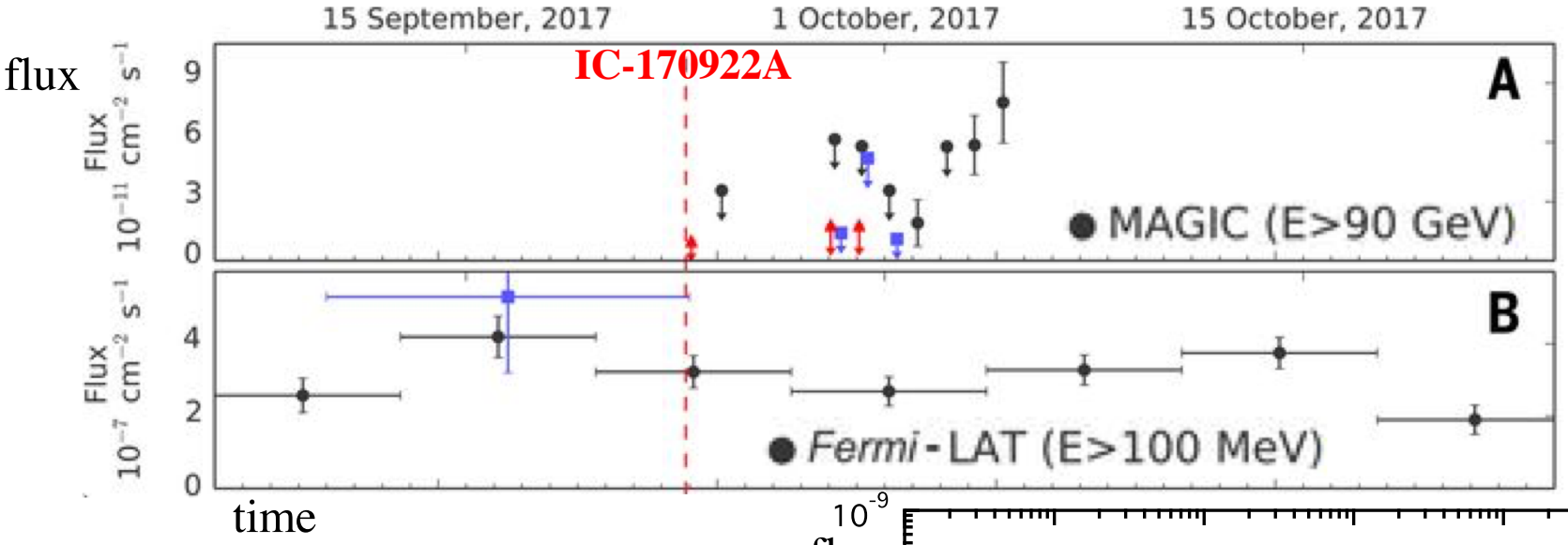
~6σ detection >~100 GeV

IceCube, Fermi, MAGIC+, 2018, Science 361, eaat1378

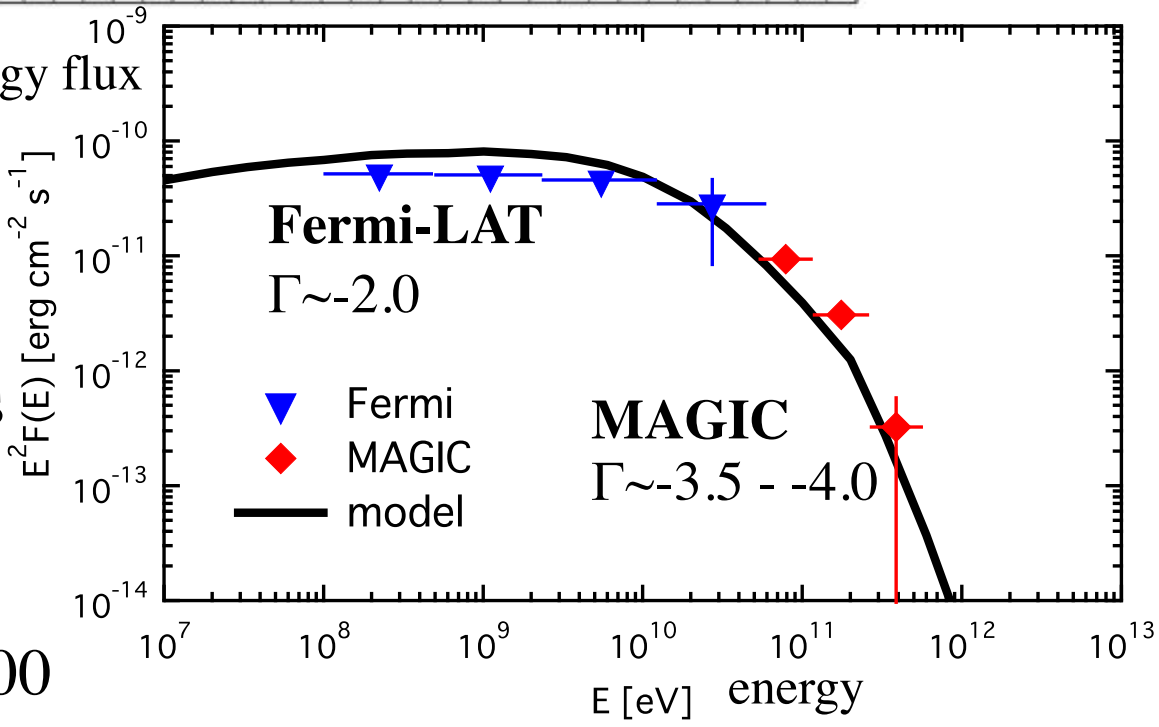
# VHE observations of TXS 0506+056

crucial contraints on physical conditions of source

- <day timescale flaring -> constraints on size of emission region




- prominent steepening of γ-ray spectrum at ~100 GeV -> consistent with internal γγ absorption with UV-X-rays = main targets for pγ neutrino production




MAGIC Col. arXiv:1807.04300

# issues for high-energy neutrino origin

questions

- plausibility of 1-zone interpretation of EM data + IC-170922A
- origin of 2014-2015 neutrino flare during low gamma-ray state (if real)
- relation to other blazars: why TXS 0506+056 and not others?
  high-frequency BL Lac objects, e.g. Mrk 421
  flat spectrum radio quasars, e.g. 3C279
- contribution to diffuse IceCube flux -> likely minor
- origin of dominant source(s) of diffuse IceCube flux

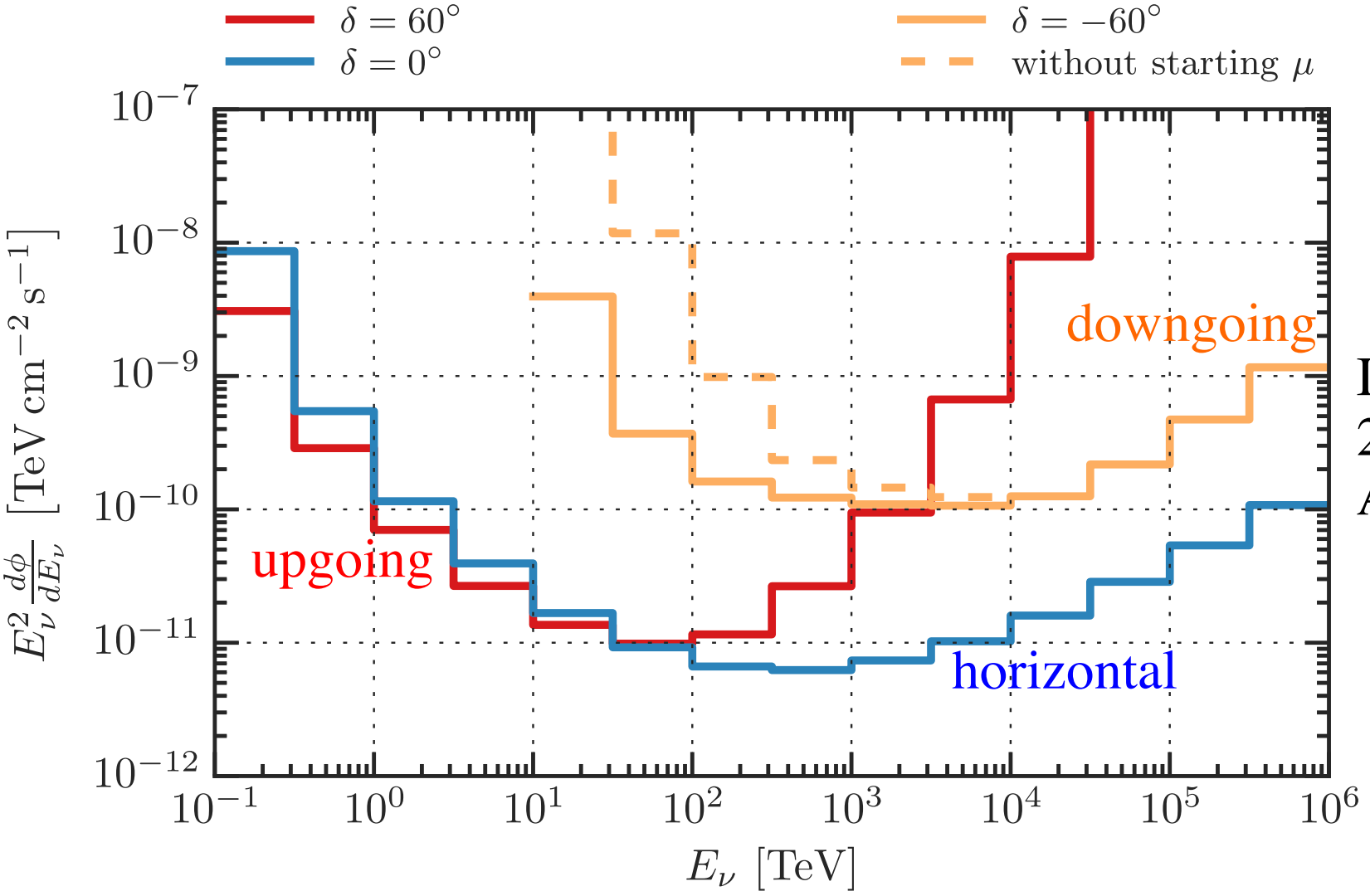
…

outlook

more neutrino+EM observations necessary

- X-rays for constraining cascade emission
- VHE for constraining $p\gamma$ target density via $\gamma\gamma$ absorption -> CTA
- extremely high-energy neutrinos for clarifying UHECR origin

# IceCube sensitivity: North vs South

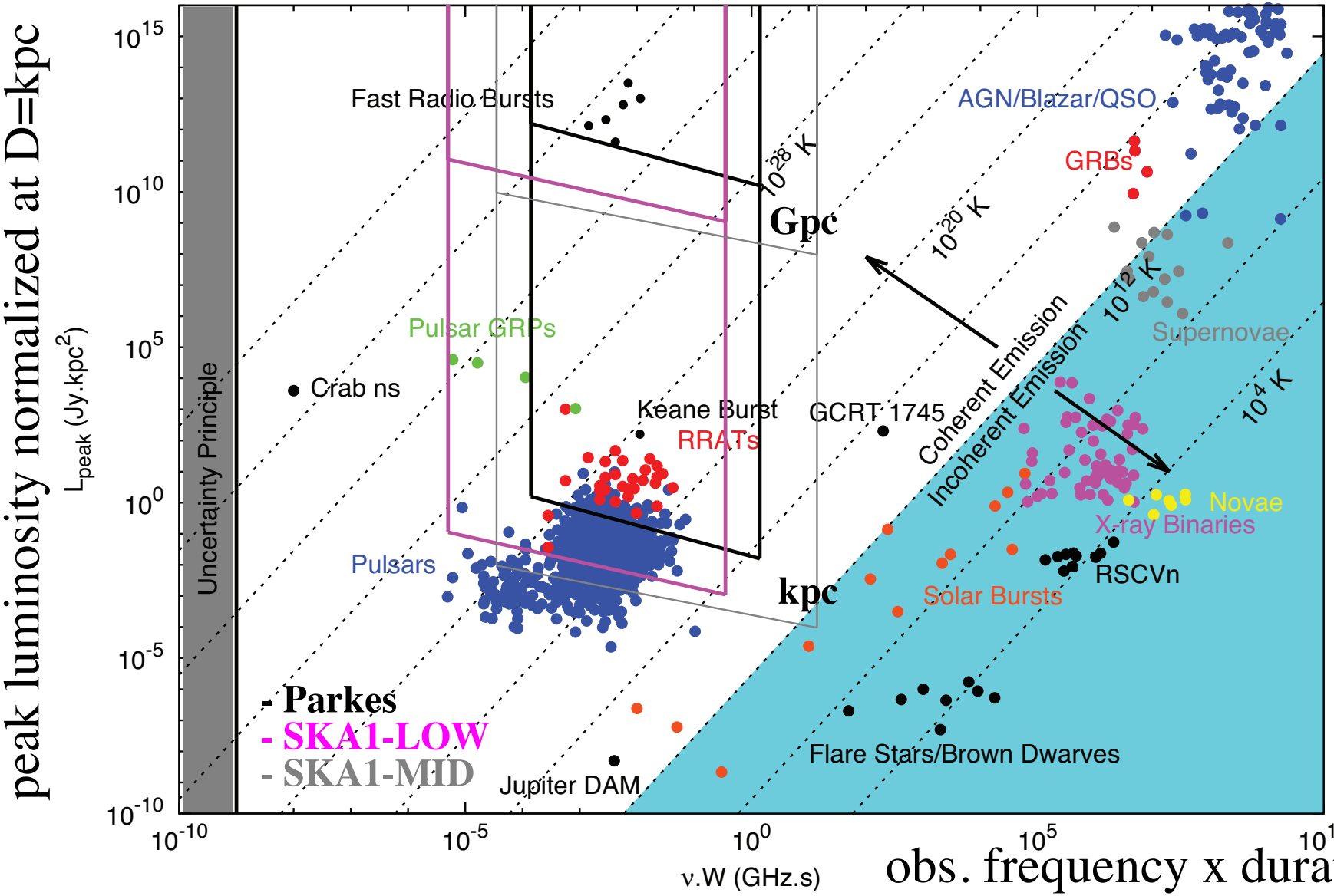



IceCube Col. 2017 ApJ 835, 151

- sub-PeV sensitivity: North > South
- PeV-EeV sensitivity: North < South, horizontal
  -> South LSTs for follow-up of EHE neutrinos

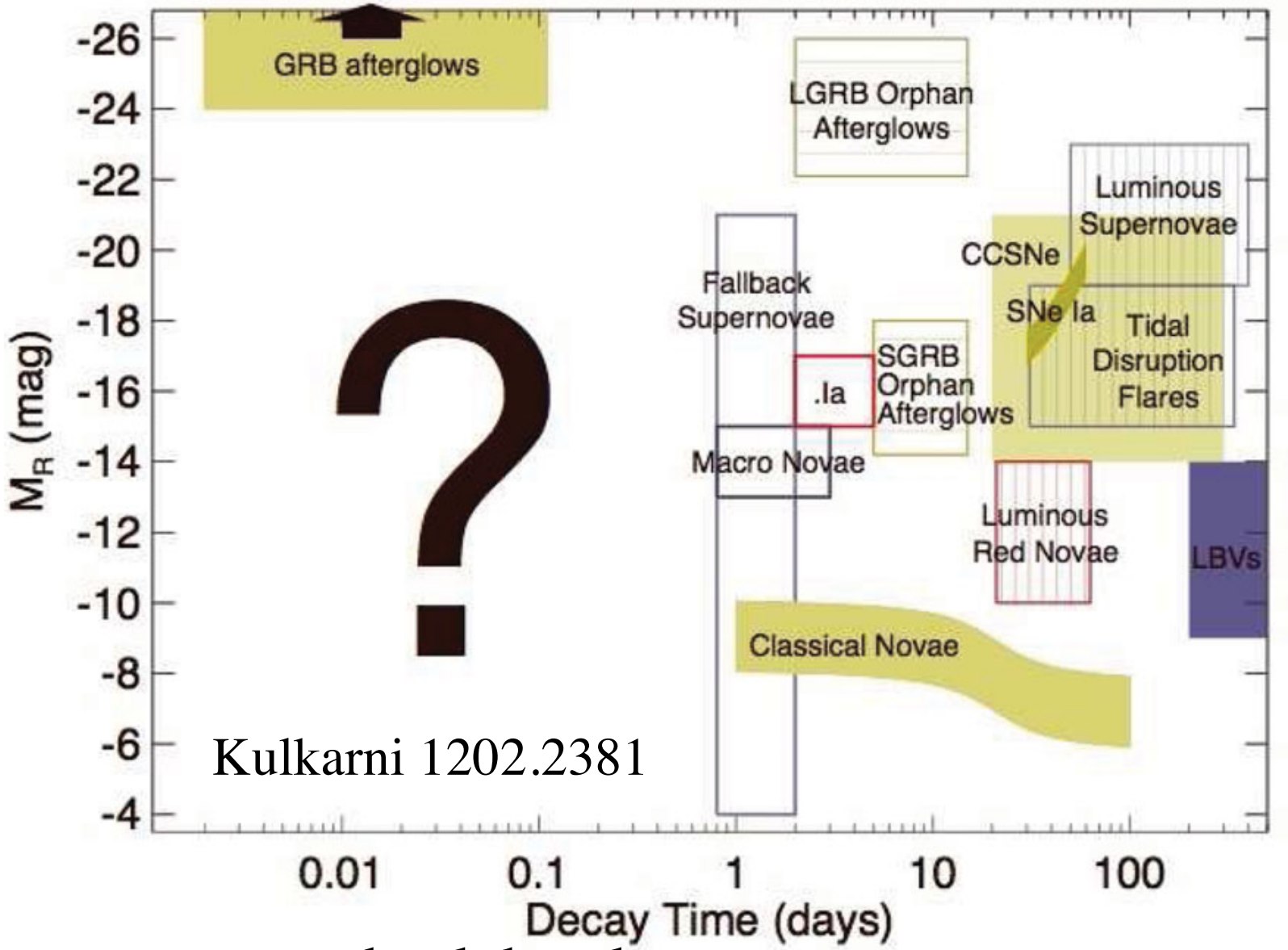
# radio transients

Pietka+ 15, Macquart+ 15




- e.g. fast radio bursts: extragal. (z~0.2-3), otherwise mysterious
  some predictions for GeV-TeV emission  e.g. Murase+ 16
- South LSTs for synergy with SKA and its pathfinders

# optical transients




- e.g. supernova shock breakout events
  some predictions for GeV-TeV, ν emission e.g. Kashiyama+ 13
- South LSTs for synergy with LSST

## summary

- LSTs crucial for studying:
  - extragalactic transients
  - GeV-TeV crossover regime of space and ground instruments
- necessary in South for studying:
  - Galactic CR sources, promising UHECR source
  - all-sky coverage of transients
- Galactic CR origin: SNR paradigm working
  except for Pevatrons, CR escape process -> S-LSTs
- UHECR origin: mysterious
  Cen A: unique γ-ray source, promising UHECR source
  -> study including S-LSTs
- transients
  - GRBs: great prospects
  - neutrinos: search initiated but still mysterious
    -> S-LSTs to follow-up EHE neutrinos (~UHECR accel.)
  - radio, optical -> S-LSTs for synergy with premier facilities