

# CTA in the 2020s

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# Multi-Messenger Astronomy

Wavelength ← **Electromagnetic** → Frequency  
Radio IR UV X-ray Gamma ray

Waves



Particles  
Photons



Cosmic Rays



Neutrinos



Gravitational Radiation

1zeV

1ZeV

140 Octaves to Explore

# Some Recent Highlights

- Gravitational radiation - BH, NS
- PeV neutrinos - TXS 0506+056 290 TeV
- Neutron stars radiating  $> 300 \times F_{\text{Eddington}}$
- GeV-EeV cosmic rays
- SS433, M87, Sgr A\*, 3C279
- Millisecond pulsars

Enabled by new observatories:

LV, EHT, VLT/Gravity, FGST, ACT, WCT,  
NuSTAR, IceCube, CHIME, Auger, AMS...

Most of this involves TeV

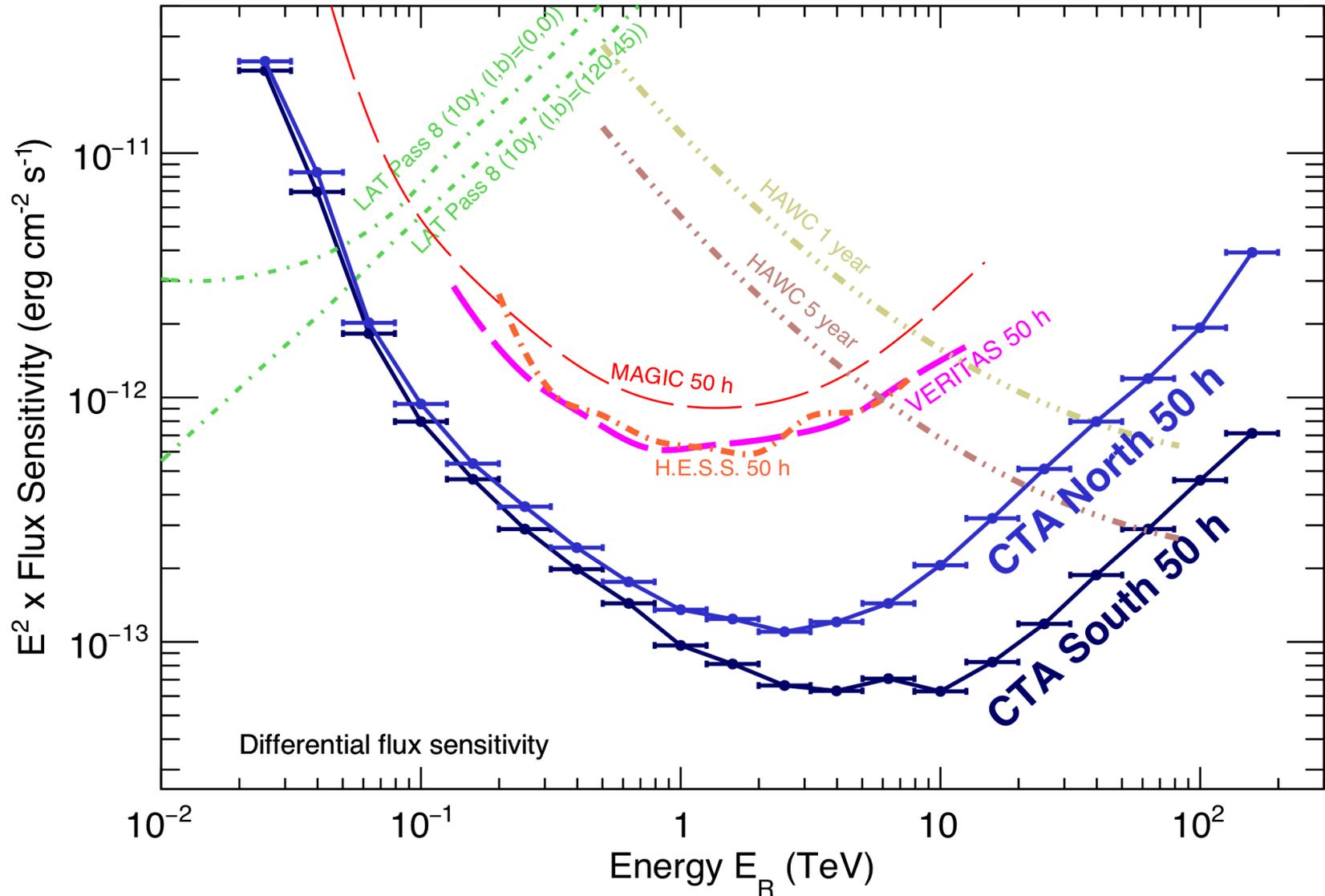
# Some Questions

- Does gamma-ray astronomy use the same “messenger” as radio astronomy?
- How can we improve triggers, notifications and telescope deployment in the LSST era?
- What is the plan for “all-sky” optical facilities like ATLAS?
- What are the prospects for real time neutrino alerts?
- How do we adapt and make new discoveries?

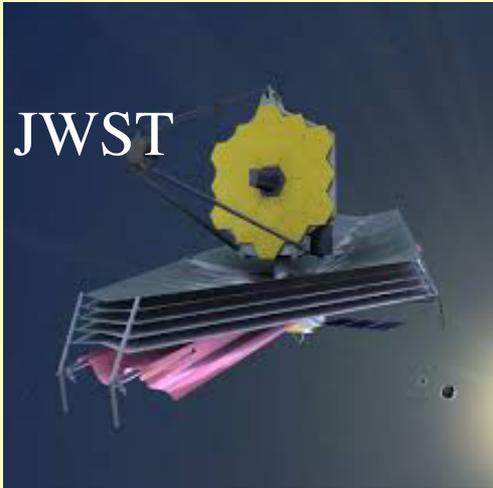
# Current $\gamma$ -ray Telescopes

- Fermi, AGILE
- HESS, MAGIC, VERITAS
- HAWC

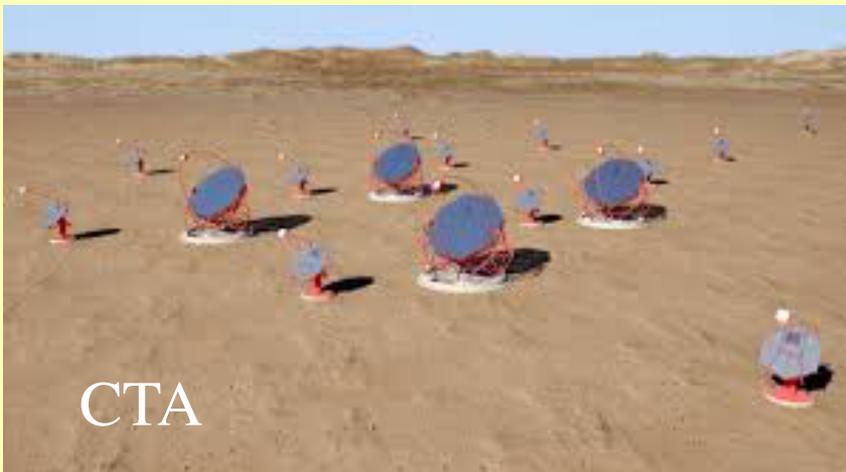
# CTA Performance



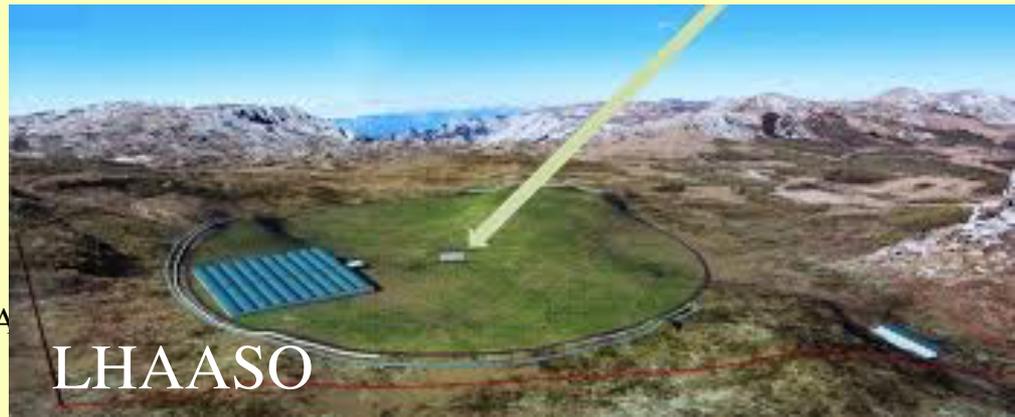
# Future Telescopes



EHT



CTA



# Some Questions

How long will Fermi operate?

- For LIGO-VIRGO?
- For CTA?

New space-based GeV satellite?

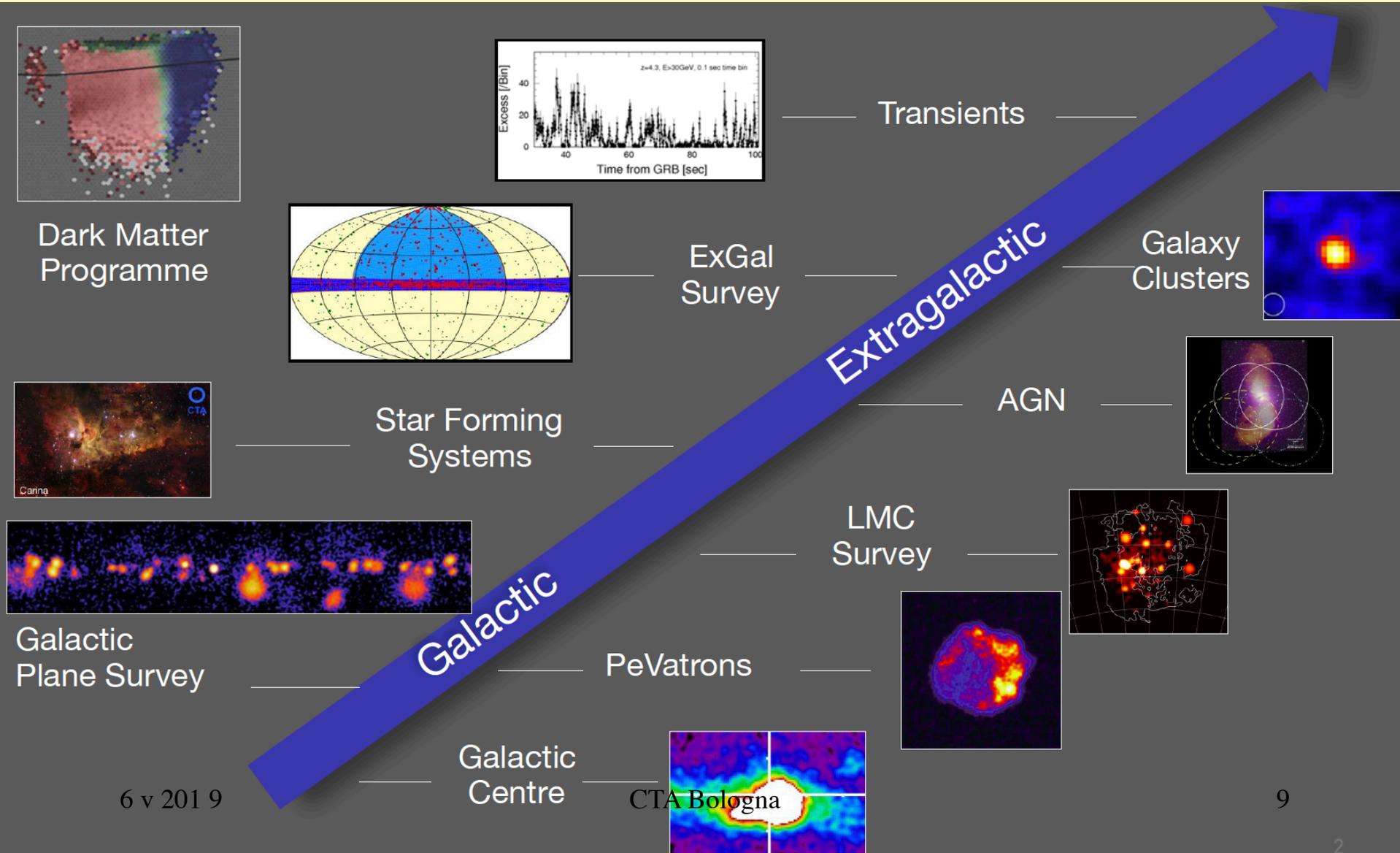
Will there be a new MeV telescope?

- e-ASTROGRAM

Southern HAWC?

Existing TeV facilities in CTA era?

# Key Science Program



# Gather information about MWL/MM needs



| KSP \ WG    | Galactic               | X-Gal                      | Cosmic-Rays      | Transients                  | DM+FPh |
|-------------|------------------------|----------------------------|------------------|-----------------------------|--------|
| GP Survey   | MWL Association        |                            | ISM emission     | Binaries; Pulsars; ...      |        |
| EGal Survey |                        | Redshift Det; Counterparts | Diffuse Emission |                             |        |
| Gal. Center |                        |                            |                  |                             |        |
| AGNs        |                        |                            |                  | Neutrinos                   |        |
| Dark Matter |                        |                            |                  |                             |        |
| LMC Survey  |                        |                            |                  |                             |        |
| Clusters    |                        |                            | X-rays           |                             |        |
| PeVatrons   |                        |                            |                  |                             |        |
| SFRs        |                        |                            | MWL surveys      |                             |        |
| Transients  | Binaries; Pulsars; ... | AGN variability; GRBs      |                  | GWs; Opt. Telescope; ToO... |        |

**INVENTORY & COORD. OF MWL NEEDS FOR ALL SCIENCE CASES**

# Some Big Astrophysics Questions

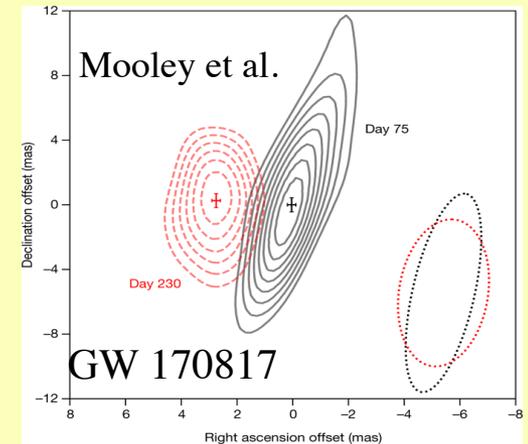
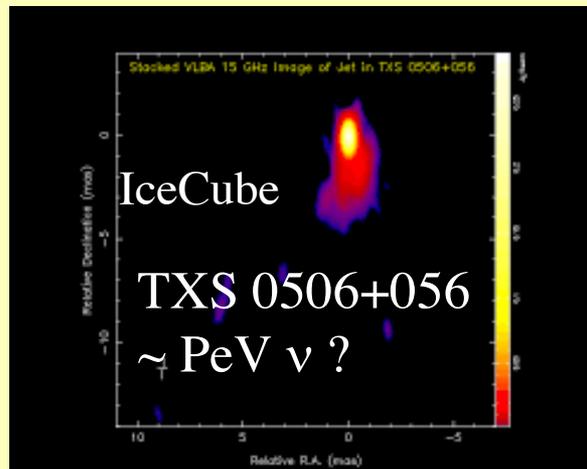
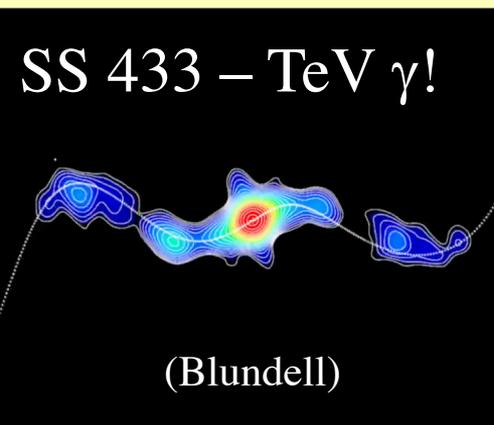
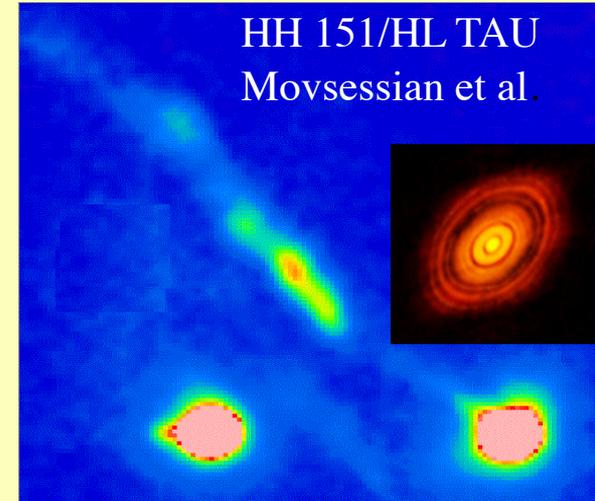
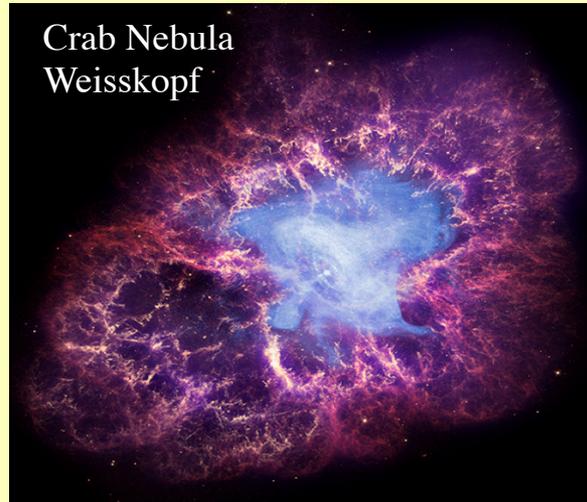
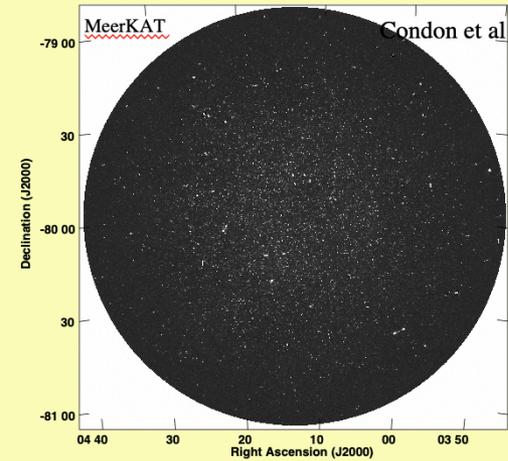
- Identification of dark matter
- Early galaxy formation and evolution
- Accretion, jets from protostars to quasars
- Neutron stars
- Intergalactic medium
- Transients
- Exoplanets

Also fundamental cosmology  
TeV observations involved in much

# Jets and TeV astronomy

- EHT, Gravity, VLBI,  $\gamma$ -ray variation
  - Probing BH scales
- SS433
  - c/4 jets make 30 TeV  $\gamma$ -rays
- GW 170817
  - Short GRB make jets
- GRB190114C
  - $>300$  GeV emission
- TXS 0506+056
  - Hadronic acceleration?

# Jets Everywhere

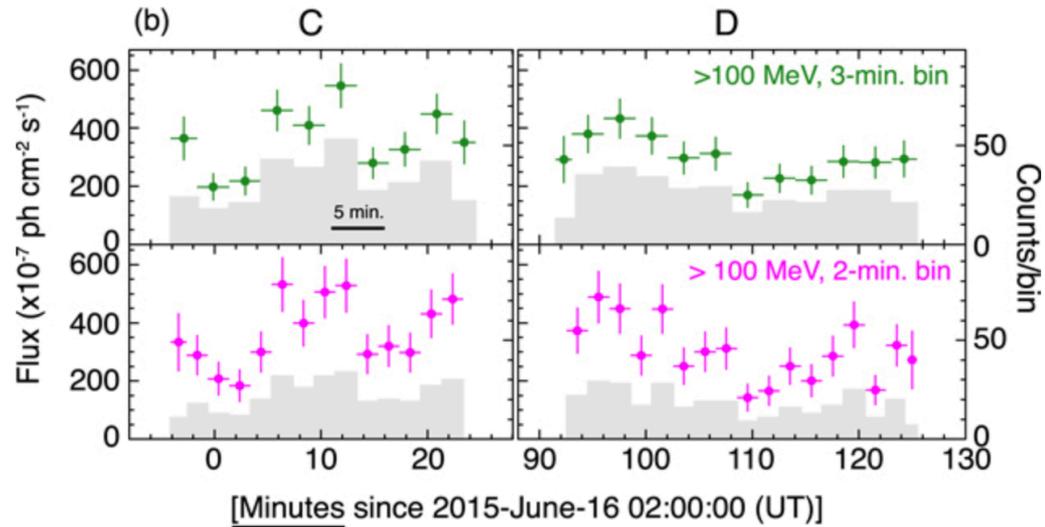
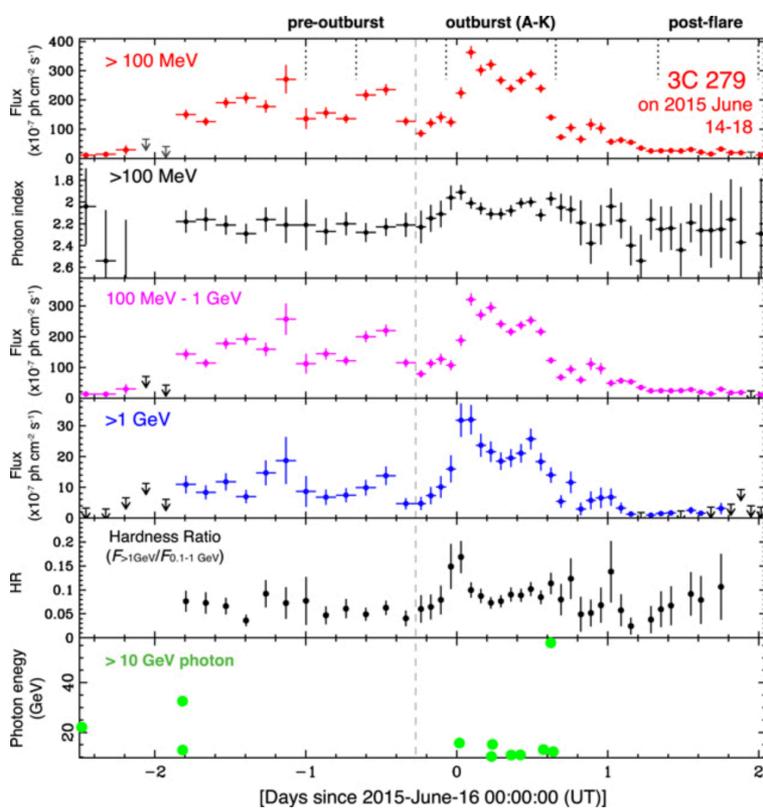


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CTA Bologna

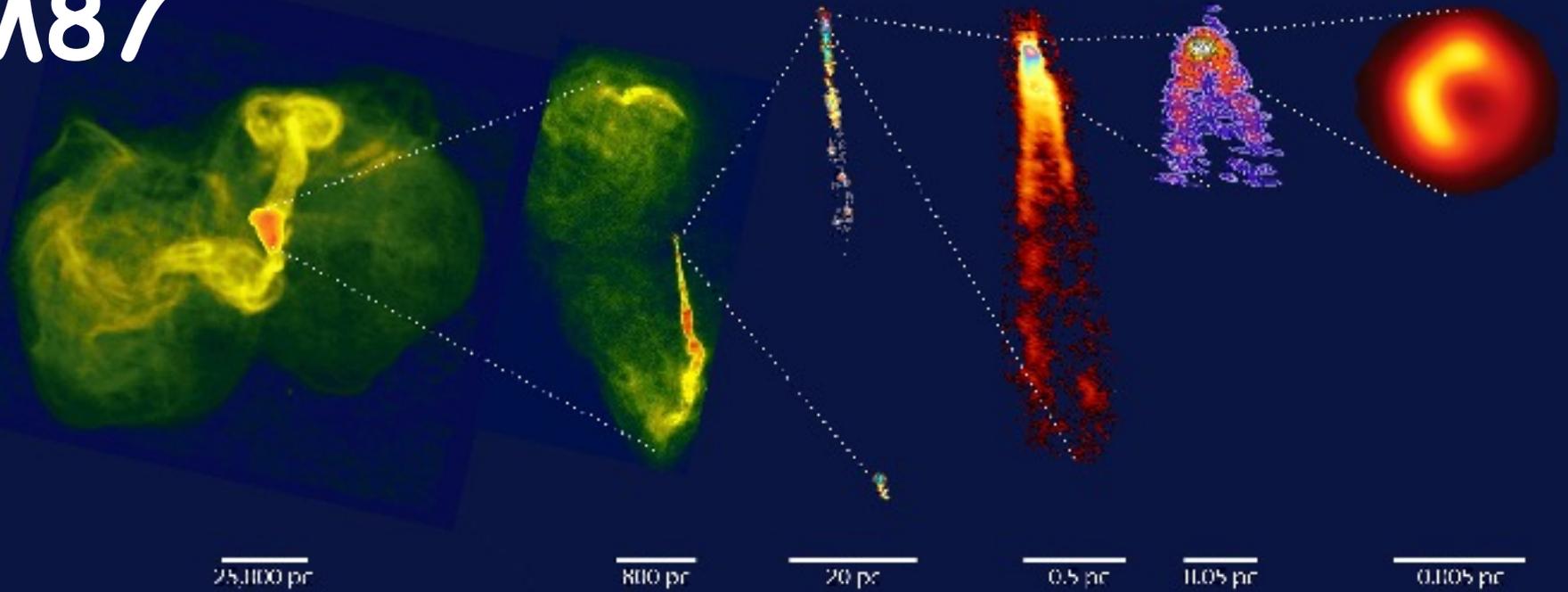
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# 3C 279



- Minute  $\gamma$ -ray variation in quasars  $\Rightarrow$  compact source
- But,  $\gamma$ -rays from inner jet absorbed by UV;  $\sigma_{\gamma\gamma} \sim 0.2\sigma_T$

# M87



- $M_{\text{hole}} = 6.5 \times 10^9 M_{\text{sun}}$
- $L_{\text{jet}} > 10^{43} \text{ erg s}^{-1} = 300 L_{\text{disk}} \sim 10^{-5} L_{\text{Edd}}$
- EM jet from spinning hole  $\Rightarrow B > 1 \text{ kG}, t_{\text{rad}} < 30 \text{ s}$
- $\Rightarrow U_{\text{em}} < 10^{42} \text{ erg} \sim 10^{-10} U_{\text{mag}}$  within ring!!

# Astrophysical Black Holes

- Kerr Metric
  - $a < m$ ;  $Q, \dots = 0$ , classical event horizons

- Observed Black Holes

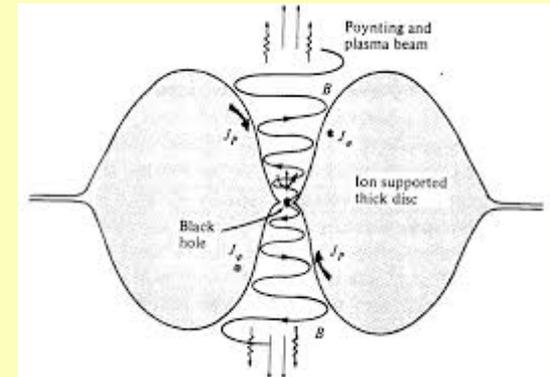
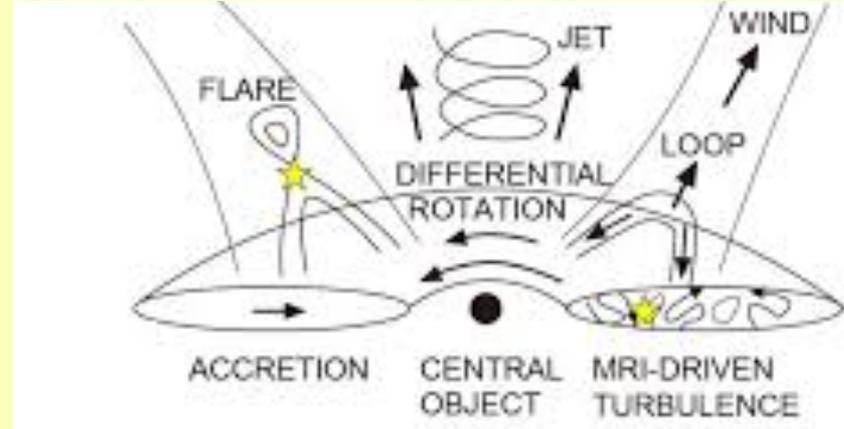
- BH binaries  $\sim 3 - \sim 80 M_{\text{sun}}$
- AGN  $\sim 10^5 - \sim 10^{10} M_{\text{sun}}$
- $a \sim m$  often

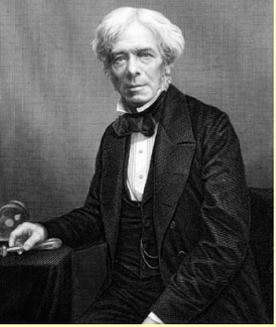
- Accretion Disks

- Rotating gas forms disk
- Accreting gas radiates binding energy
- Low  $\rightarrow$  thick ion disk (Fender, Cotter)
- Intermediate  $\rightarrow$  thin, radiative disk
- High  $\rightarrow$  thick radiation disk

- Magnetic Field

- Strong field **IN** disk (MRI)
- Strong field **THROUGH** disk and hole





# In E&M We Trust



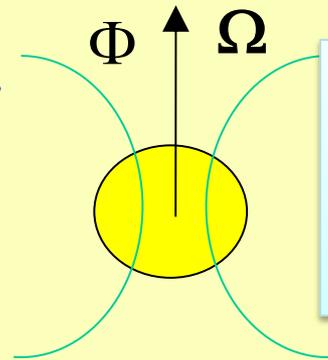
Unipolar induction  
by spinning, magnetized body

$$V \sim \Omega \Phi / 2\pi \sim E_{\max} / Ze$$

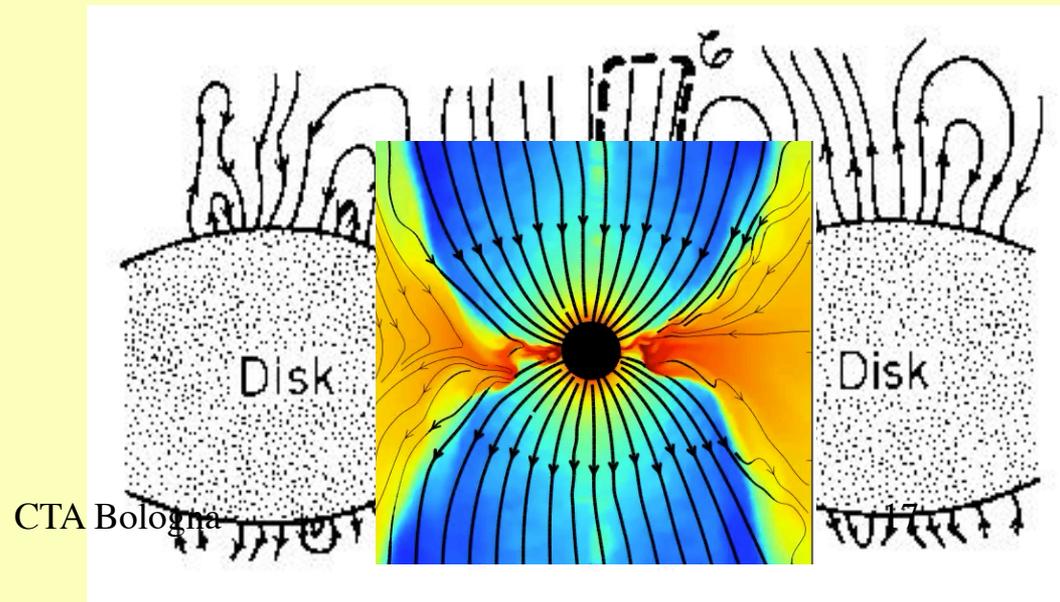
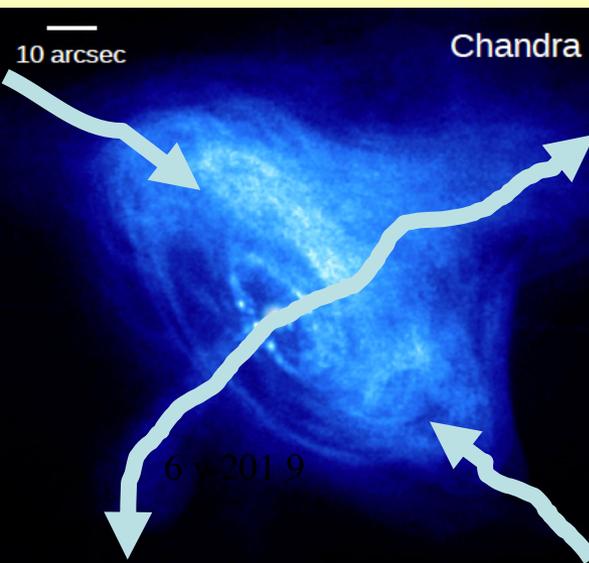
$$I \sim (V / Z_0)(c/v)$$

$$Z_0 \sim 100\Omega$$

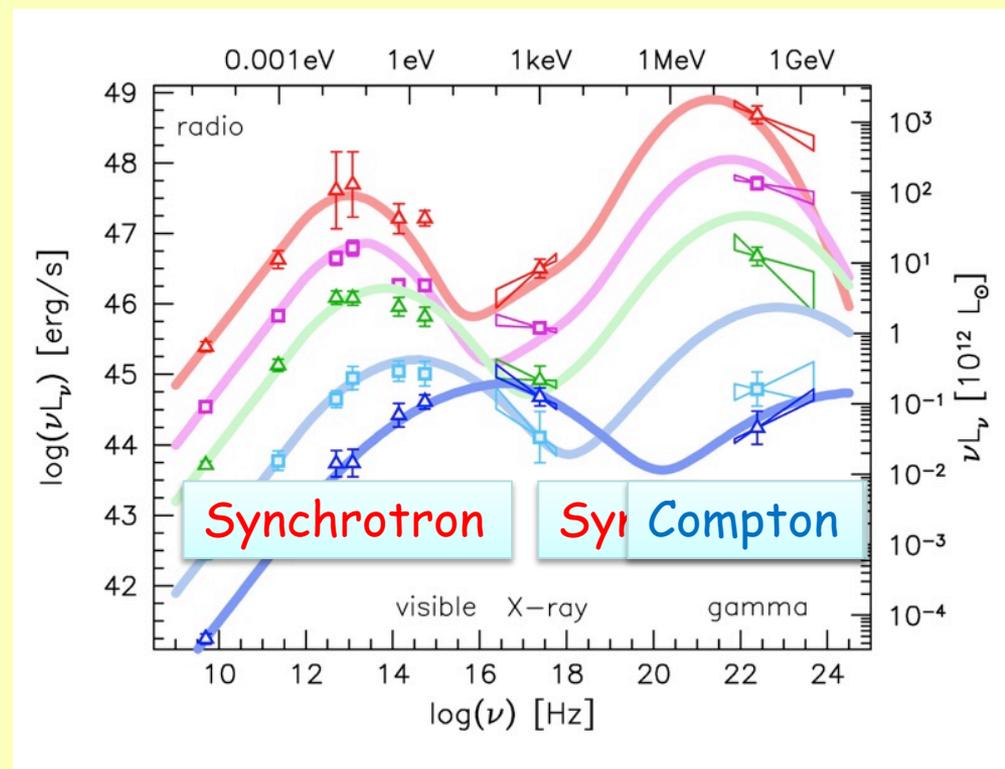
$$P \sim VI \sim (V^2 / Z_0)(c/v)$$



Sun -  $V \sim 100 \text{ MV}$ ,  $I \sim 1 \text{ GA}$ ,  $P \sim 100 \text{ PW}$   
 Crab -  $V \sim 30 \text{ PV}$ ,  $I \sim 300 \text{ TA}$ ,  $P \sim 10^{31} \text{ W}$   
 AGN -  $V \sim 1 \text{ ZV}$ ,  $I \sim 10 \text{ EA}$ ,  $P \sim 10^{40} \text{ W}$   
 GRB -  $V \sim 0.1 \text{ YV}$ ,  $I \sim 1 \text{ ZA}$ ,  $P \sim 10^{44} \text{ W}$

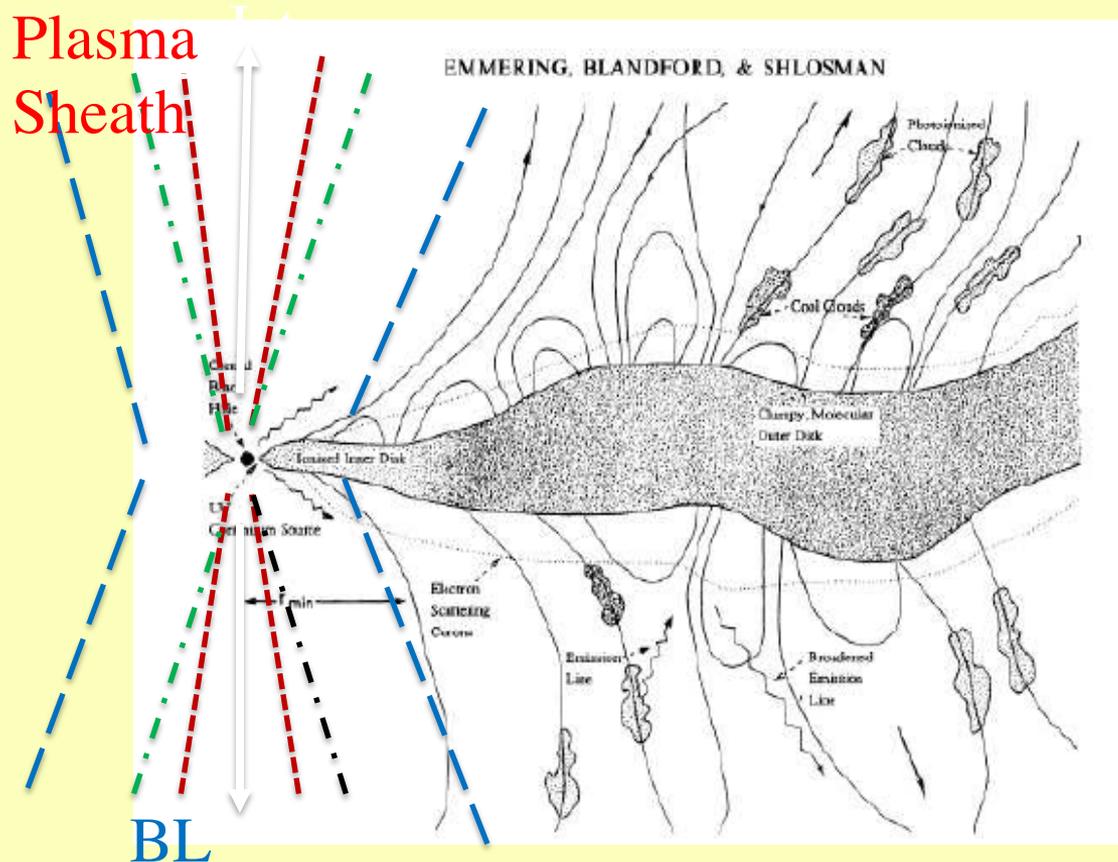


CTA Bologna



- Compton model incompatible with strongly magnetized jets
- Quasar jet  $\gamma$ -rays vary in minutes
- Near jets opaque to  $\gamma$ -rays,  $\sigma_{\gamma\gamma} \sim 0.2\sigma_T$
- Direct electron acceleration limits photons to  $\sim 100\text{MeV}$
- Protons can be accelerated efficiently to PeV-EeV energy
- 100 MeV/PeV pairs,  $\sigma_{BH} \sim \alpha \sigma_T$ , efficient; cf  $\sigma_\pi$

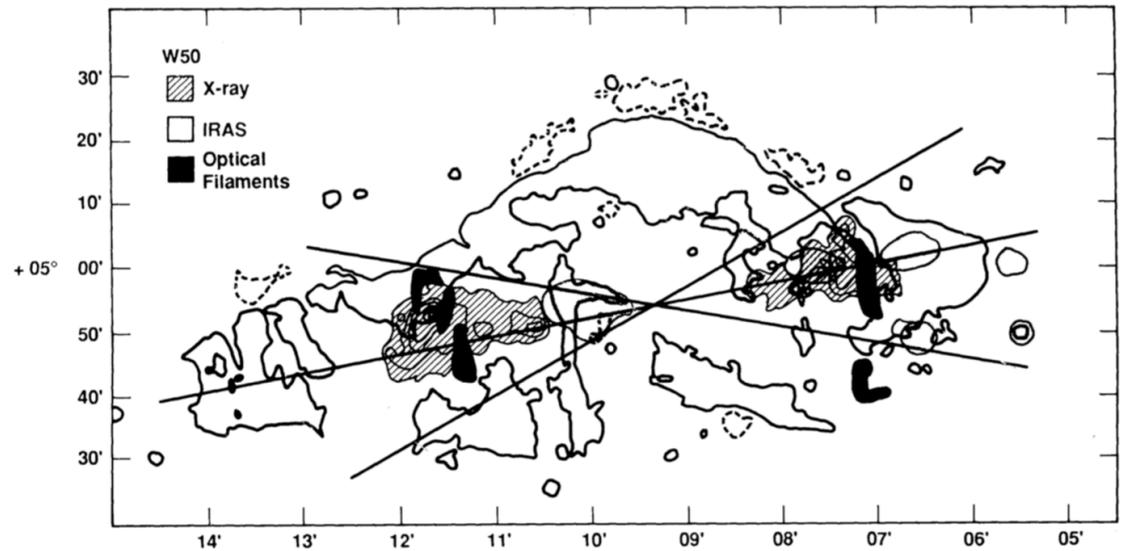
# Emission Lines Formed by Magnetic Wind



- Gamma rays can vary in minutes, even in quasars
- Shielding  $>13.6\text{eV}$  with plasma sheath avoids pair production
- Emission line clouds are magnetically-confined disk outflow

# SS433

- HAWC source
- Up to 25 TeV
- From jets !
- $V_{\text{jet}} \sim 0.26c$ , precess, gas clouds,
- From disk
  - Invisible BH jet??
- Shock acceleration of PeV protons
- Bethe-Heitler pair secondaries?



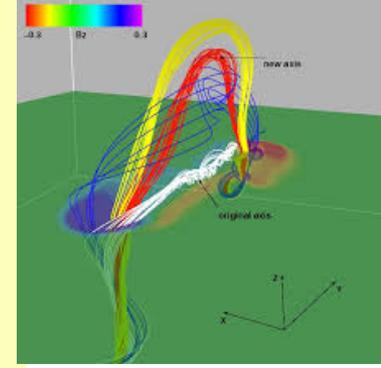
# Some Questions

- How are BL Lac jets powered and collimated,
- Where and how do they radiate?
- What is going on in Sgr A\*
  - Pevatron?
- What does imply for quasar, microquasar neutron star, protostellar... jets?

# Particle Acceleration

- **Observation challenges theory**
  - Rapid variation, energy density in blazars, Crab...
- **Simulation**
  - PIC codes
- **Experiments**
  - HED/laser experiments
- **Mechanisms**
  - Non-relativistic shocks, relativistic reconnection, unipolar induction, magnetoluminescence...

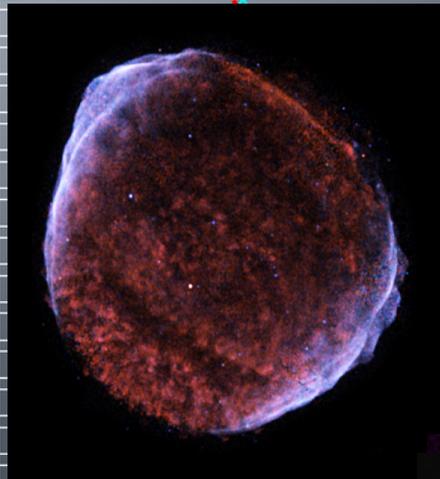
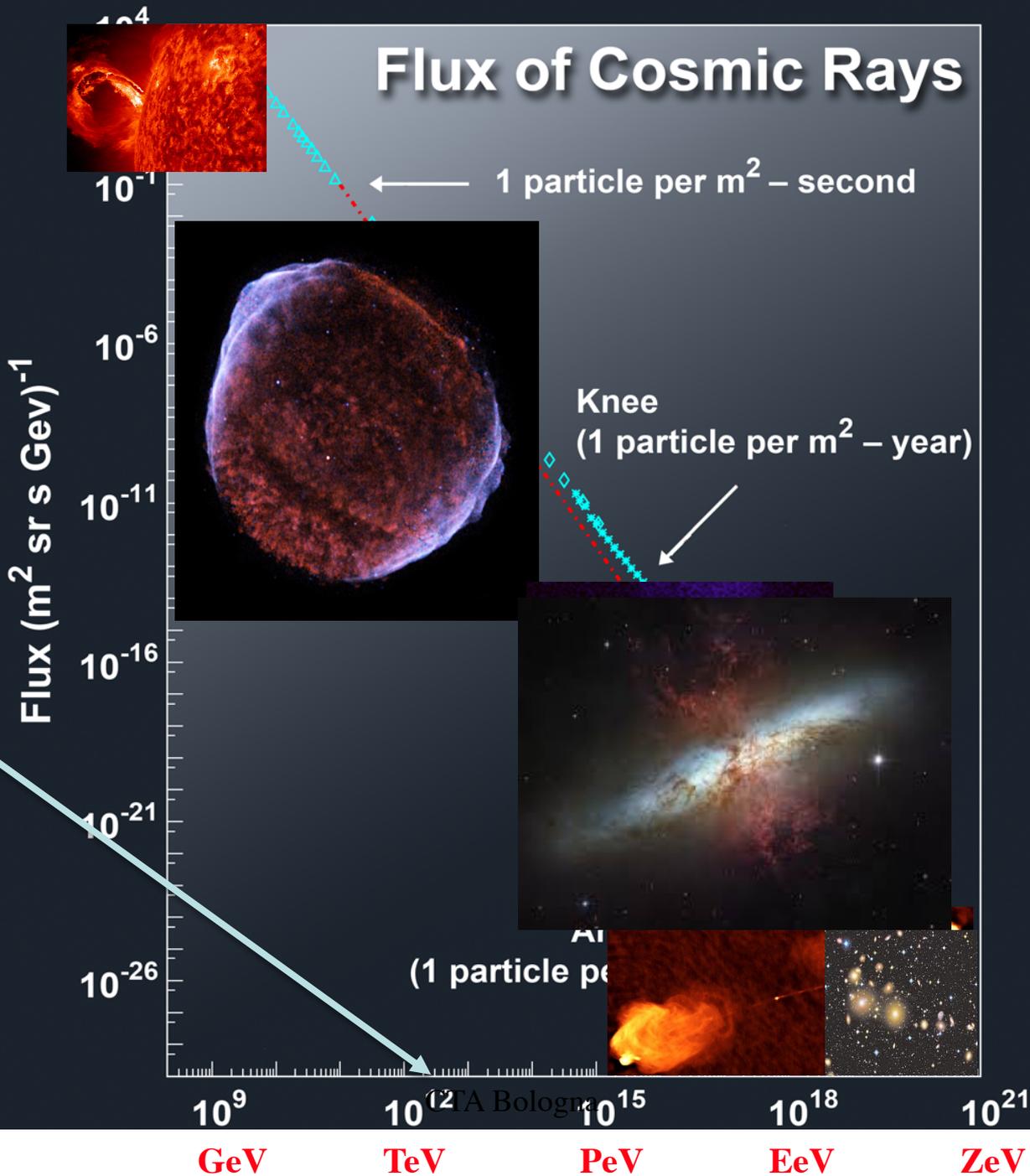
# Magnetoluminescence



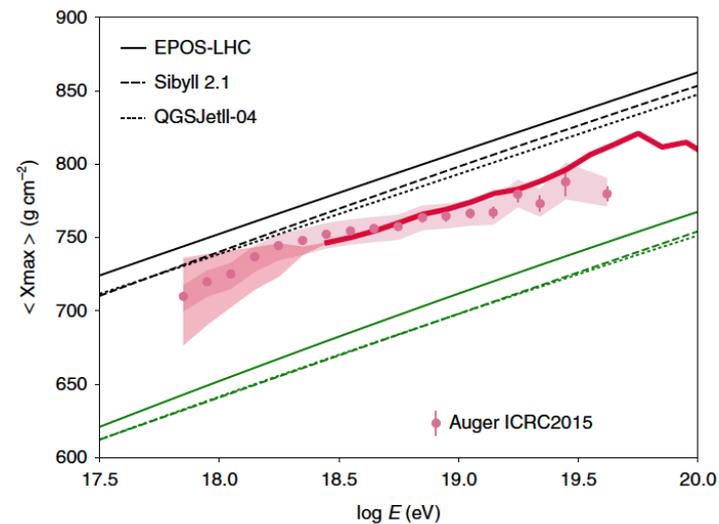
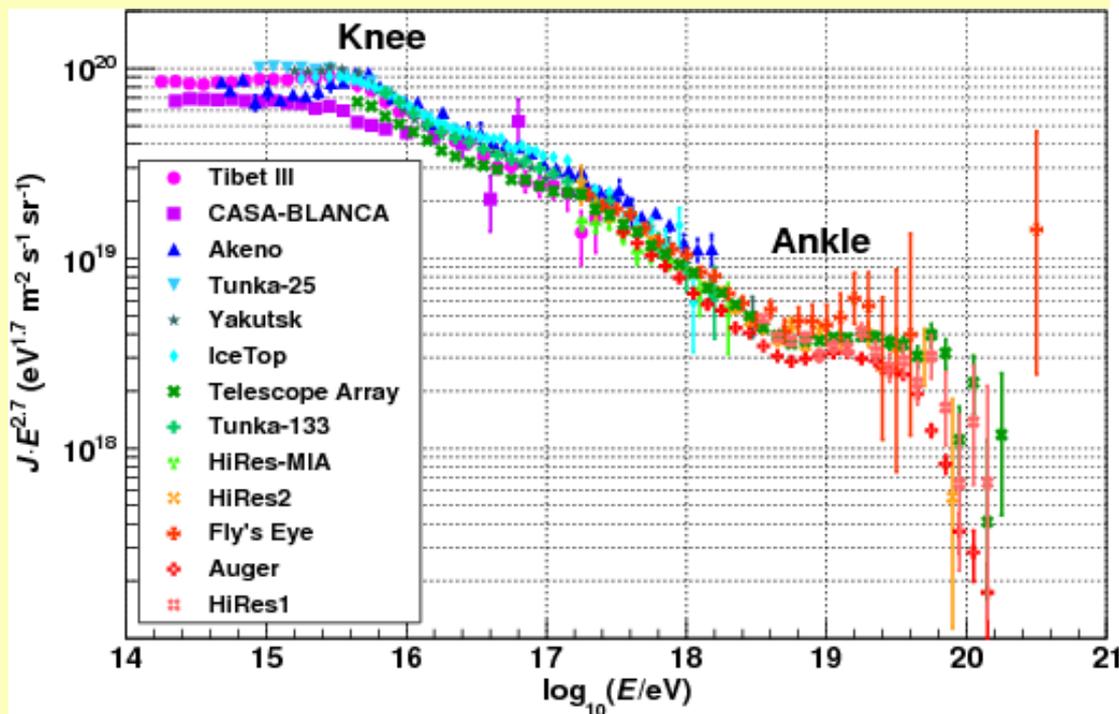
- Magnetic jets unstable
  - Tangled magnetic “ropes”?
- Magnetically reconnect knot
  - Change topology
    - Tait, Alexander, Jones...:  $t+t^3-t^4$
  - Slow  $< c/\log$
- Untangle magnetic rope
  - Same topology
  - Fast  $\sim c$
  - Charge starvation  $\rightarrow$  Electric friction E.B
  - Proton acceleration,  $\gamma$ -ray emission



# Flux of Cosmic Rays

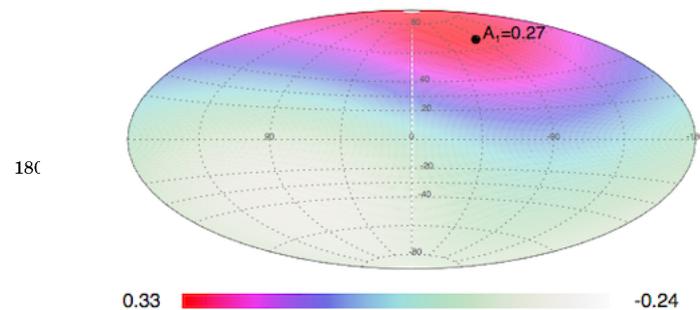


# UHECR: Spectrum, Composition, Sources



*Globus*

- Higher  $Z$  at higher  $E$
- Rigidity ( $\mathcal{R} \sim E/Ze$ ) cutoff
- Dipole anisotropy
- Hierarchical Shock Acceleration



# Some Questions

- Are some TeV gamma rays synchrotron?
- Where are UHECR accelerated?
- Can we reconcile limited dynamical range of experiments, simulations with those of astrophysical sources?

# $\gamma$ -ray pulsars

- More frequent than anticipated
- $\gamma$ -rays account for large fraction of energy lost
- Crab pulsar observed to  $\sim 300$  GeV

# Some Questions

- How do pulsars shine?

# Star-forming Galaxies

- Prominent  $\gamma$ -ray sources
- Particle acceleration in SNR plus high radiation and gas density  $\rightarrow$  high emissivity
- Extragalactic Background Light

# Some Questions

- Are TeV  $\gamma$ -rays a useful measure of star formation
- What are the effective mechanisms for stimulating star formation?
- How do cosmic rays mediate the evolution of molecular clouds?

# Cosmic Probes and Fundamental Physics

- No evidence yet for new fundamental physics from  $\gamma$ -ray astronomy
  - cf neutrinos, dark matter
- Searches for LIV, ALP, DM signals
  - Impressive upper limits

# Some Questions

- What constitutes acceptable evidence for new physics?
  - DM identification, QG manifestation...
- What physics do we NOT question?
  - Classical EM, GR, QED?
- Primordial magnetic field?
  - Portal to earlier universe?
  - UHECR propagation

# CTA “Unscripted” Discoveries??

- Double degenerate Type Ia
- New TeV transients (cf FRBs)
- GRBs
- BH Binaries
- Flares from PWN like Crab
- Sun, nearby stars

Multi-wavelength/messenger astronomy is essential