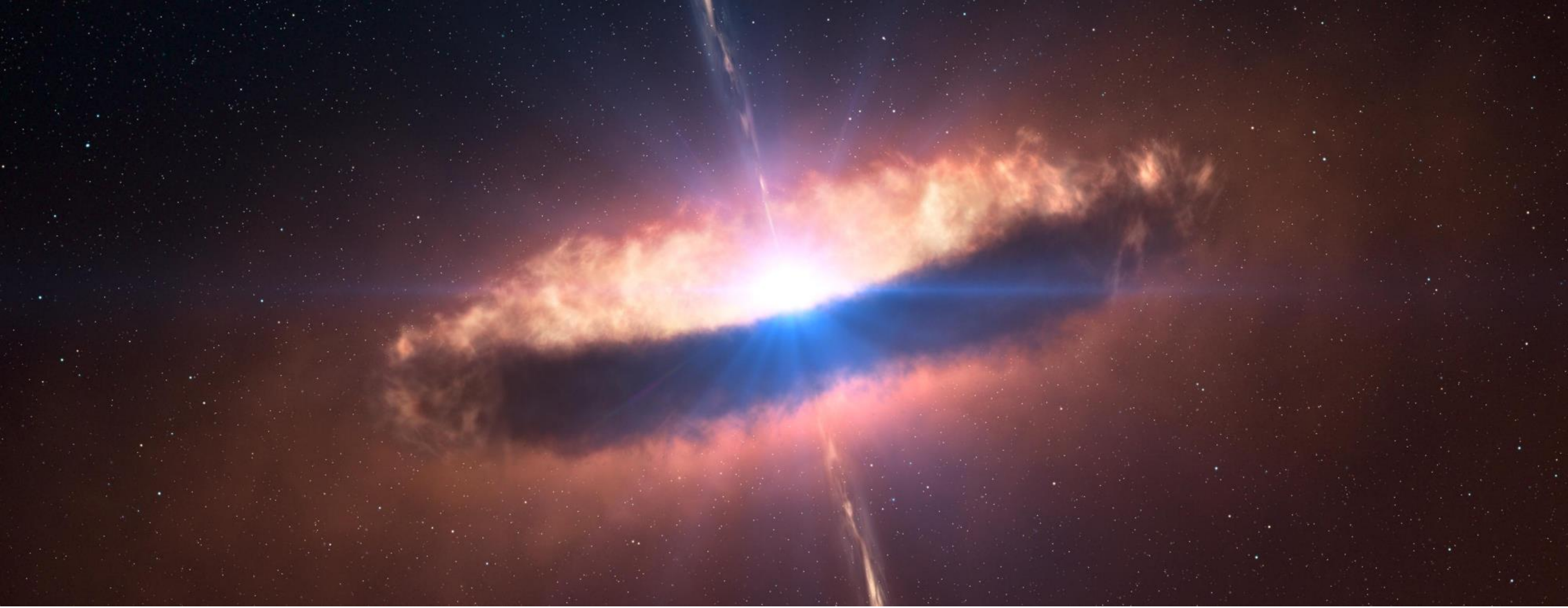

A Long Wavelength View of Cosmic Rays

Cosmic Rays in the Context of Multimessenger Astronomy

Joseph Lazio

Jet Propulsion Laboratory
California Institute of Technology

A Long Wavelength View of Cosmic Rays

- **What’s radio astronomy got to do with it?!?**
- **Neutrino-emitting blazars?**
- **Intergalactic magnetic field and the cosmic web**
- ***Cosmic structure formation and particle acceleration***

Radio Astronomy?

Frequency ν ~ 10 GHz

$E_\nu = h\nu \sim 40\ \mu\mathrm{eV}$

Radio Astronomy?

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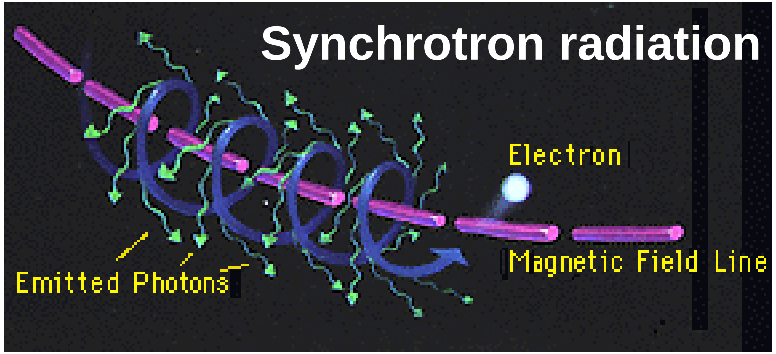


Synchrotron-emitting electron emits most radiation at

$$\nu_c \sim \gamma^2\,\nu_g = 2.8\ \text{MHz}\ \gamma^2\ (B/1\ \text{G})$$

Non-relativistic gyrofrequency

$$\nu_g = eB/(2\pi m_e)$$

Radio Astronomy?

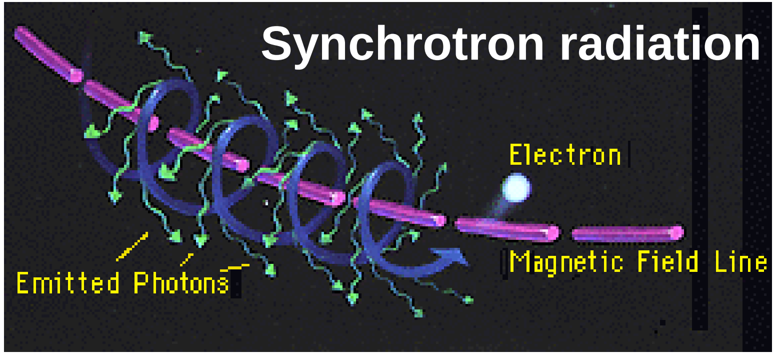
Frequency $\nu \sim 10$ GHz

$E_\nu = h\nu \sim 40\ \mu\text{eV}$

- $E_e \sim 30$ GeV or
- $\gamma \sim 60{,}000$

B ~ 1 μG

Radio-wavelength photons may be low energy, but the emitting electrons are high energy



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A Long Wavelength View of Cosmic Rays

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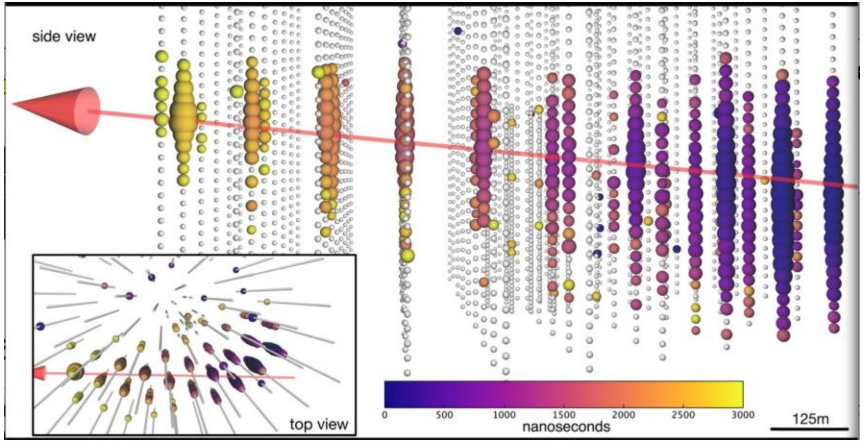
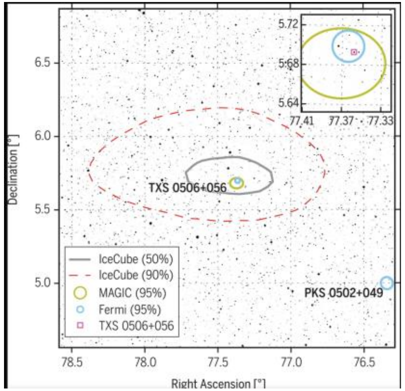
Neutrino-Emitting Blazars?



IceCube 170922A

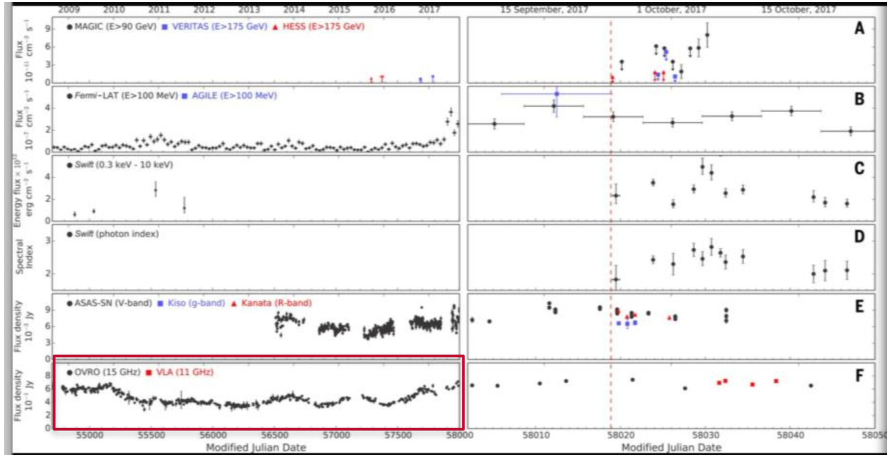


IceCube Collaboration et al.

2017 September 22, IceCube detects 24 TeV ν_μ

- **Track of ν_μ pointed to TXS 0506+056**
  - **TXS 0506+056 identified in Texas 365 MHz survey (Douglas et al. 1996)**
  - **What is a "blazar"? Radio source with jet pointed toward observer, significant variability**

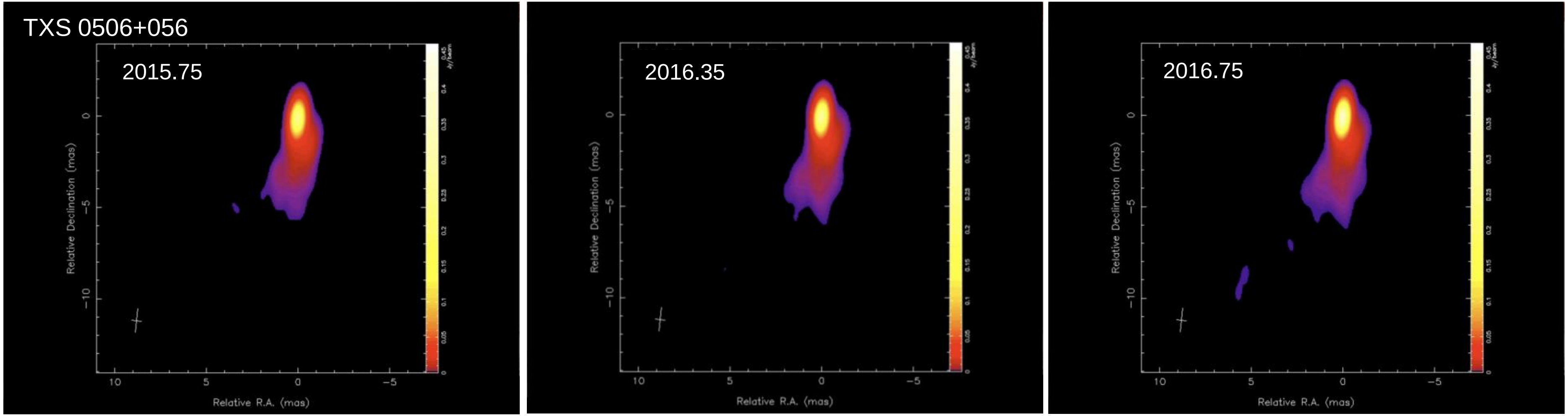
Neutrino-Emitting Blazars and Radio Astronomy



I. **Modest-sized radio telescopes can provide long light curves for characterizing source behavior**
   - **Owens Valley Radio Observatory 40 m @ 15 GHz**
   - **Metsähovi Radio Observatory 14 m @ 22 GHz and 37 GHz**
   - ***Univ. Michigan Radio Astronomy Observatory 26 m @ 4.8 GHz, 8 GHz, 14.5 GHz***
   - **GAVRT 34 m @ 8 GHz?**

IceCube Collaboration et al.

Neutrino-Emitting Blazars and Radio Astronomy



I. Modest-sized radio telescopes can provide long light curves for characterizing source behavior

II. **Sub-parsec resolution obtained, enabling tests of models for neutrino (and cosmic ray) generation**
   - **Single vs. multiple zones?**
   - **Leptonic or hadronic?**

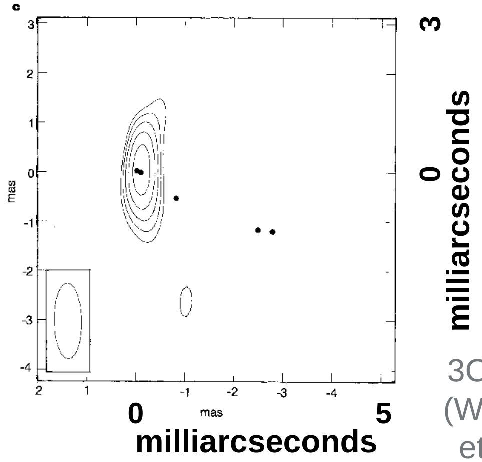
MOJAVE Collaboration: Lister et al.

Neutrino-Emitting Blazars and Radio Astronomy

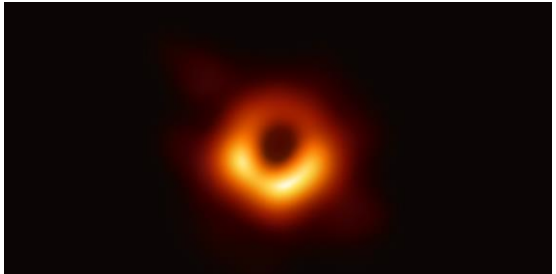
Coming Attraction?

I. Modest-sized radio telescopes can provide long light curves for characterizing source behavior

II. Sub-parsec resolution obtained, enabling tests of models for neutrino (and cosmic ray) generation
   - Single vs. multiple zones?
   - Leptonic or hadronic?
     - ➢ Circularly polarized jets could indicate leptonic jet (e^{-}-e^{+})



3C 279 (Wardle et al.)

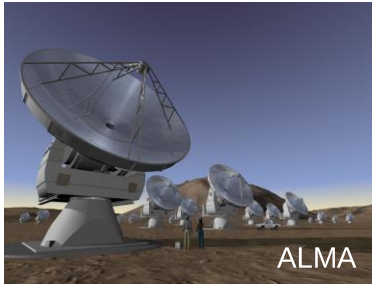


M87 (EHT Collaboration)

Neutrino-Emitting Blazars and Radio Astronomy

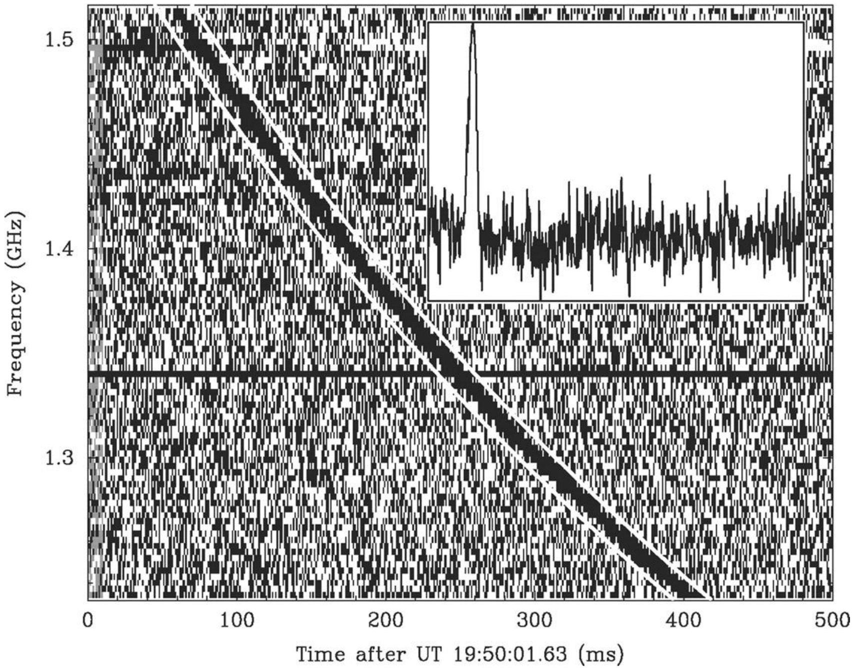
The Future

- **Powerful complement of (VLBI-relevant) facilities available or in development**
  - **Very Long Baseline Array (VLBA)**
  - **European Very Long Baseline Interferometry Network (EVN)**
  - **Australian Long Baseline Array (LBA)**
  - **Atacama Large Millimeter/submillimeter Array (ALMA)**
  - **Event Horizon Telescope (EHT)**
  - **East Asian Very Long Baseline Interferometry Network (EAVN)**
  - **Next-generation Very Large Array (ngVLA) – design & development**
  - **Square Kilometre Array Phase 1 (SKA1-Mid) – construction initiated**
- **Monitoring programs quite feasible**
  - ➢ **Too often perceived as “not novel”☹**



Credit: JAO; NRAO/AUI; SKAO

Fast Radio Bursts (FRBs) and Neutrinos?



- **Fast radio bursts (FRBs) = intense millisecond duration decimeter-wavelength bursts (~ 1 Jy ms @ 1 GHz) of extraterrestrial orgin**

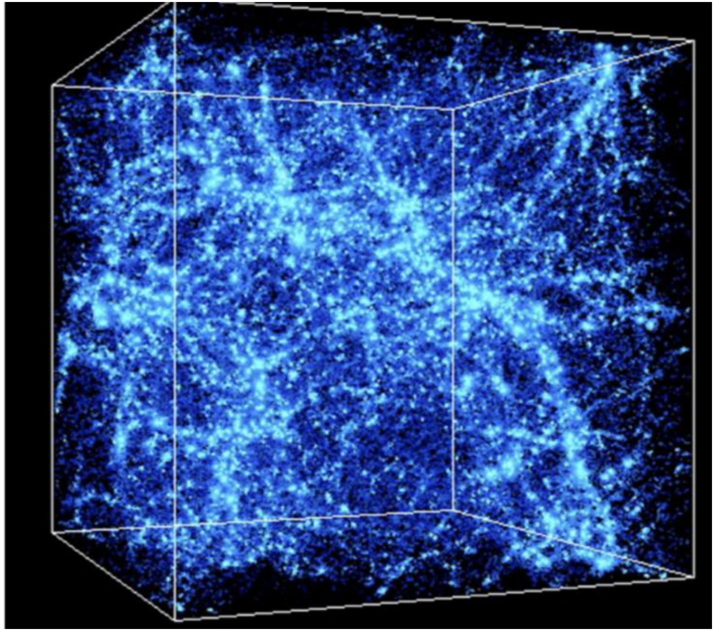
  … and FRB 200428/SGR 1935+2154

- **High brightness temperature (> 10^{32} K) → extreme conditions of emitter**
  - **Strong magnetic fields, ultra-relativistic shocks, …**
  - **No definitive counterparts … yet?**

A Long Wavelength View of Cosmic Rays

- **What's radio astronomy got to do with it?!?**
  - **Radio photons typically produced by cosmic ray electrons**
- **Neutrino-emitting blazars? (and FRBs?)**
- **Intergalactic magnetic field and the cosmic web**
- ***Cosmic structure formation and particle acceleration***

Intergalactic Magnetic Field and the Cosmic Web

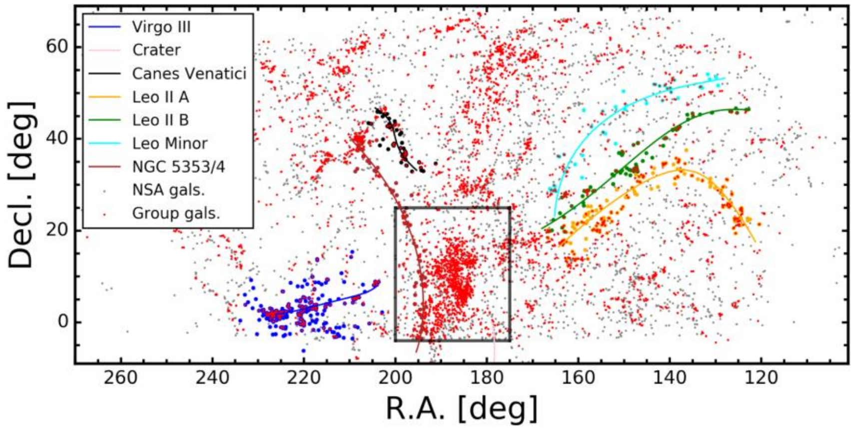


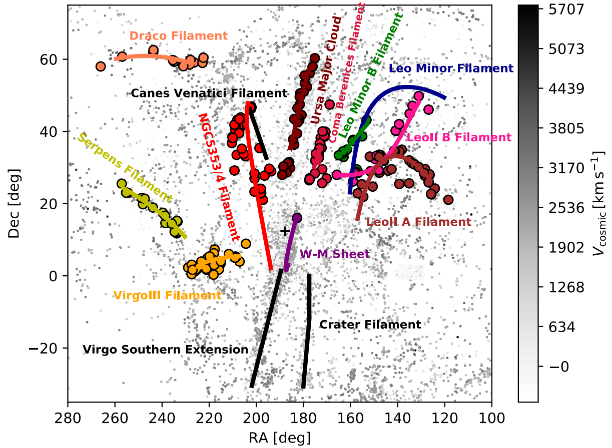
Credit: A. Kravtsov (Univ. Chicago), A. Klypin (NMSU)

Most baryons likely in "cosmic web" --- Mpc-scale filaments connecting clusters of galaxies

- **If magnetized, scatter or "steer" ultra-high energy CRs (UHECRs)?**

Intergalactic Magnetic Field and Local Cosmic Web





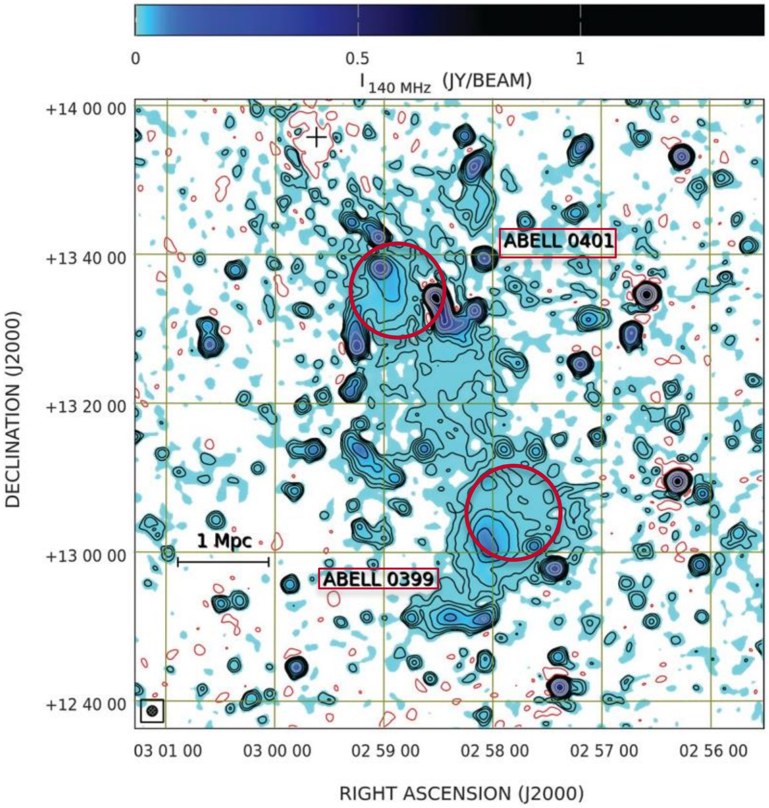
Two views of local cosmic web --- toward Virgo Cluster

- **If magnetized, scatter or "steer" ultra-high energy CRs (UHECRs)?**
- **M87 often considered local accelerator**

P.S. Right Ascension is supposed to be in sexagesimal notation (HH:MM)

Lee et al.; Castignani et al.

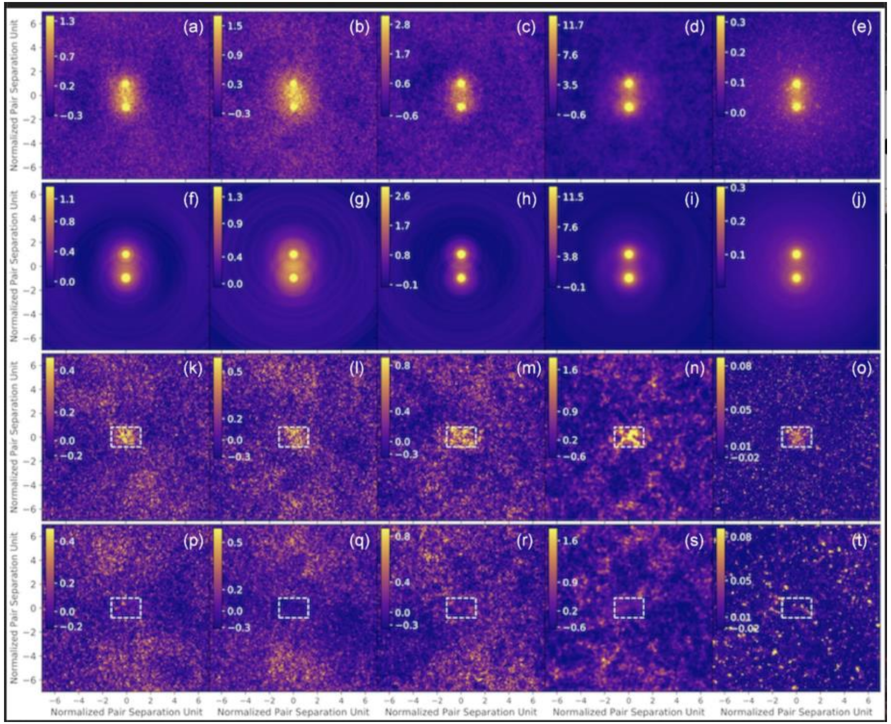
Radio Bridges and the Cosmic Web



A399-A401 (Govoni et al.)

- **Multi--Mpc-scale “radio bridges” being found between merging clusters of galaxies**
- **Synchrotron emission**
  - **What’s the acceleration mechanism?!?**
  - **Magnetic fields clearly present**

Radio Emission from the Cosmic Web



GLEAM 154 MHz	GLEAM 118 MHz	GLEAM 88 MHz	OVRO-LWA 73 MHz	*ROSAT* (0.1 keV–2.4 keV)

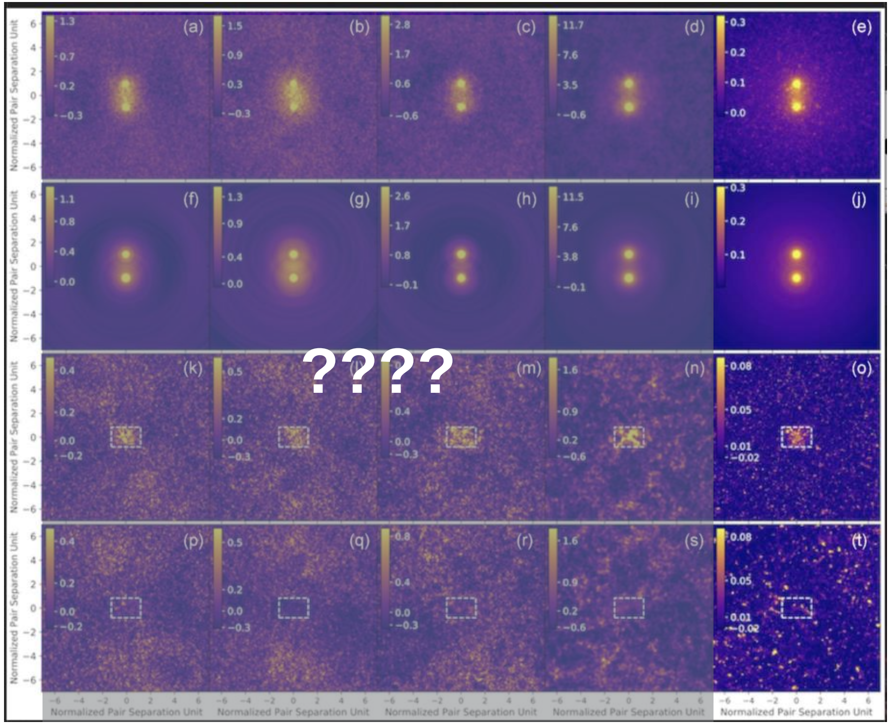
Consider pairs of luminous red galaxies (LRG)---trace cosmic overdensities

1. **Stack them;**
2. **Subtract point source model; …**

- ➢ **Find excess synchrotron radio emission**
- ➢ **Find excess hot gas**

(Vernstrom et al.)

Radio Emission from the Cosmic Web



ROSAT
(0.1 keV–2.4 keV)

Consider pairs of luminous red galaxies (LRG)---trace cosmic overdensities

1. Stack them;
2. Subtract point source model; …

- Find excess synchrotron radio emission
- Find excess hot gas
- **Or not? Viz. Hodgson et al. vs. Vernstrom et al.**

(Vernstrom et al.)

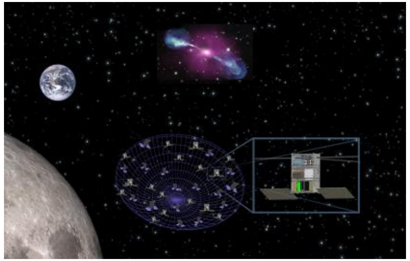
Intergalactic Magnetic Field and the Cosmic Web

Future

Some current and emerging facilities

- ➢ Need high surface brightness to detect diffuse cosmic web
- ➢ Need (very) long wavelengths to detect low-energy CR electrons (because acceleration is not efficient within cosmic web? or CR electrons have diffused significantly from site of acceleration?)

- Australian SKA Pathfinder
- SKA1-Mid(?)
- LOFAR
- Future space-based telescope?



Credit: ATNF; SKAO; ASTRON

A Long Wavelength View of Cosmic Rays

Summary

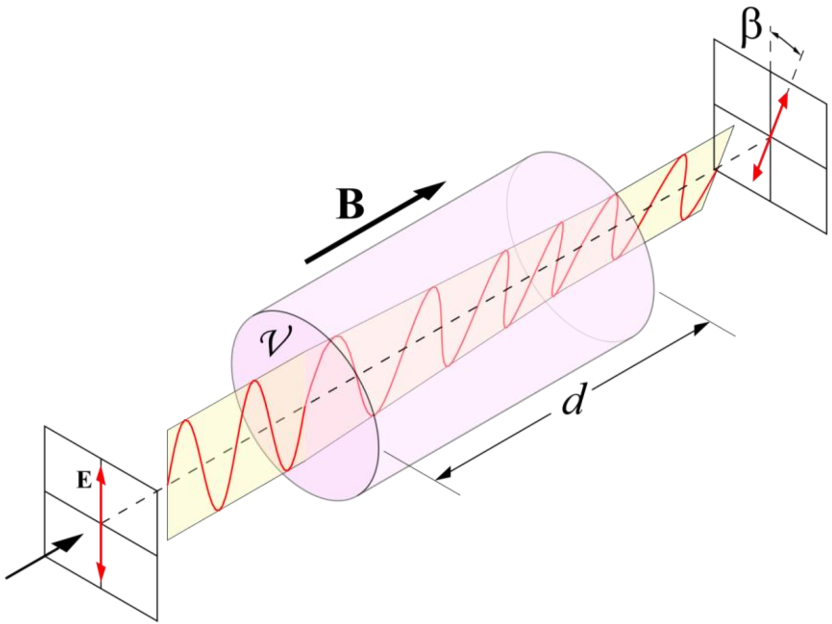
- **What's radio astronomy got to do with it?!?**
    - ➢ **Radio photons typically produced by cosmic ray electrons**
- **Neutrino-emitting blazars? (and FRBs?)**
    - – **Radio-wavelength observations have been key to identifying potential neutrino-emitting sources**
    - – **Powerful probe of where jet is being launched, potentially neutrinos being produced**
- **Intergalactic magnetic field (IGMF) and the cosmic web**
    - – **Structure of IGMF will affect (UHR)CR propagation**
    - – **Radio-wavelength observations revealing aspects of IGMF, both locally and cosmologically**
- ***Cosmic structure formation and particle acceleration***

Jet Propulsion Laboratory
California Institute of Technology

jpl.nasa.gov

Intergalactic Magnetic Field and the Cosmic Web

Faraday Rotation

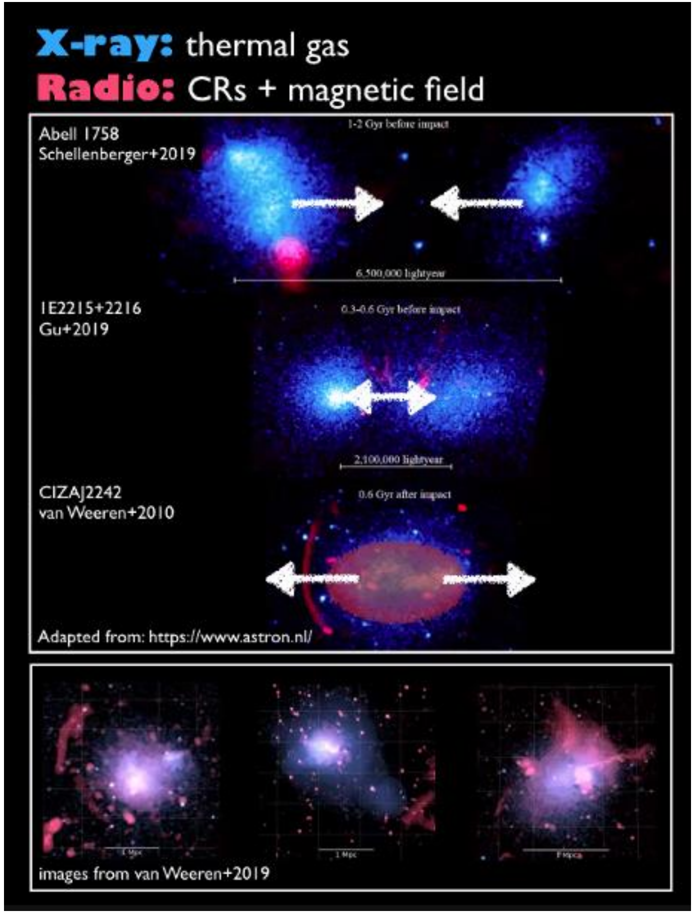


Position angle of linearly-polarized radiation rotates as it traverses magnetized region

- **Rotation angle $\chi = \int n_e \vec{B} \cdot \vec{dl}$**
- **Formally: different propagation speeds for Ordinary and eXtraordinary modes**

Wikipedia

Cosmic Structure Formation and Particle Acceleration



- **Two clusters (M ~ 10^{14} $M_\odot$) fall towards each other …**
  - **Collide with speeds > 1000 km/s**
  - **Merge on time scale ~ 1 Gyr**

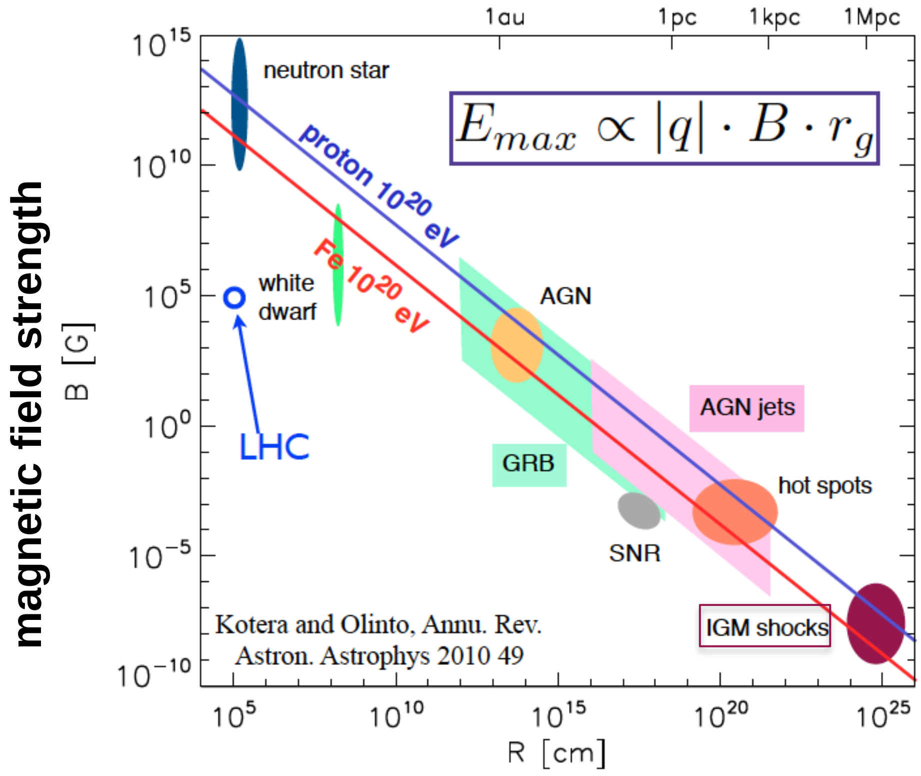
Ricker & Sarazin 2001

- **As two clusters pass through each other, significant energy (~ 10^{63} ergs) injected into intracluster medium (ICM)**
  - **large-scale bulk disturbances,**
  - **fast-travelling shocks, and**
  - **cluster-wide turbulence**

Stroe et al. 2020

- **Fantastic site for particle acceleration!**

Cosmic Structure Formation and Particle Acceleration

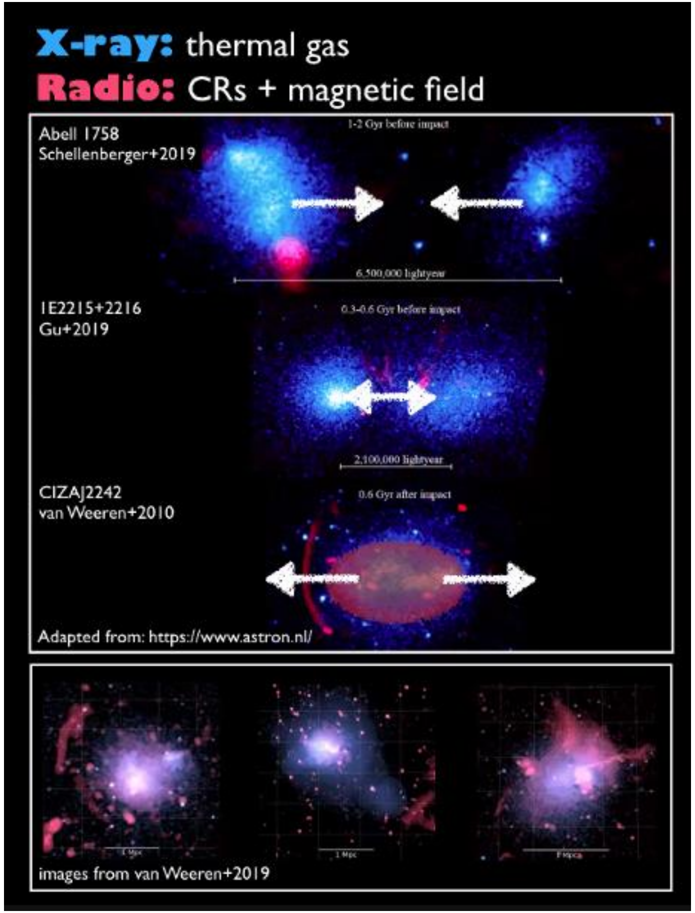


size of accelerating region

- **Maximum energy of accelerated particle depends on**
  - **charge (q);**
  - **magnetic field strength (B); and**
  - **size of accelerating region**
- **Intercluster or intergalactic medium is fantastic site for (ultra-)high energy CR acceleration!**

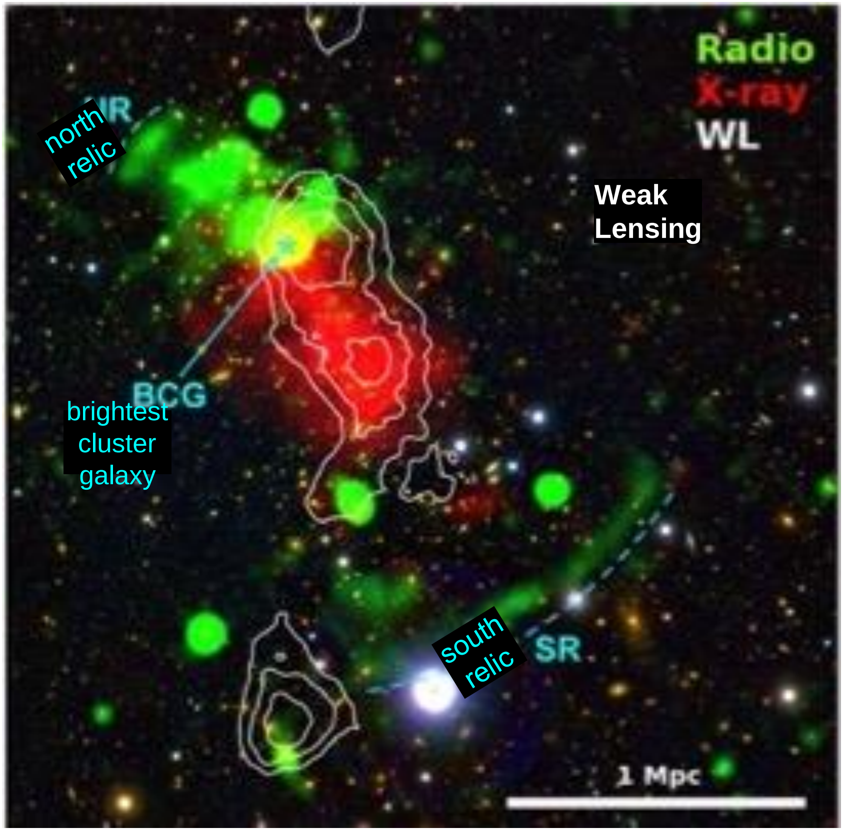
Correct? Maybe?

Cosmic Structure Formation and Particle Acceleration



- **Ample indications of CR electrons, as traced by (long-wavelength) radio emission in (energetic) merging clusters**
  - **Also injection from active galactic nuclei jets**
- **"The first clear detection of high-energy γ-ray emission from a galaxy cluster will undoubtedly constrain the baryonic particle content as well as the uncertainly in the estimates of the magnetic field, and consequently enable vastly improved modeling of galaxy clusters over the entire electromagnetic spectrum." (Atwood et al., "The Large Area Telescope on the Fermi Gamma-Ray Space Telescope Mission")**

Cosmic Structure Formation and Particle Acceleration



ZWCL 1447.2+2619

- **Merging clusters**
- **Northeast-southwest orientation**
- **Simulations guided by weak-lensing mass constraints**

  Potentially have made first pass, and are just starting to fall together again

Lee et al.