



Blazar Jets

Connecting Gamma-Ray Polarization to Galactic Evolution

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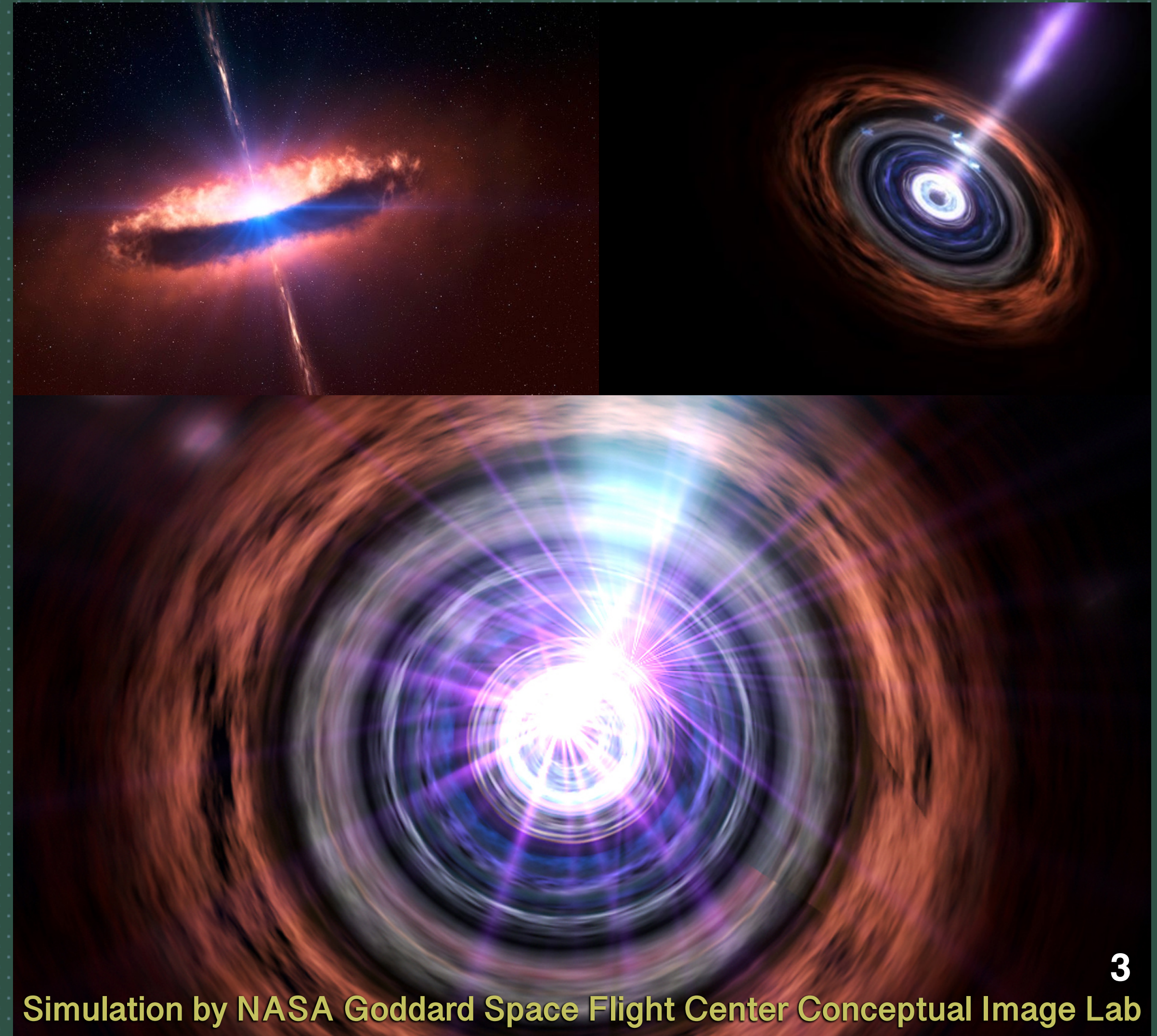


How Does the Universe Work?

- **Supermassive black hole formation and evolution**
 - SMBH - galaxy coevolution emphasizes high accretion in the active phase
 - Major mergers
 - Direct collapse & Dark Matter halos
- **Cosmic Evolution**
 - High-redshift blazars
 - Extragalactic background light
 - Star Formation History
- **How are particles accelerated to the highest energies?**
 - Cosmic Ray spectrum
 - Particle acceleration in astrophysical jets
- **How are astrophysical jets launched?**
 - Environment around compact objects
 - Accretion disks and magnetic field dragging

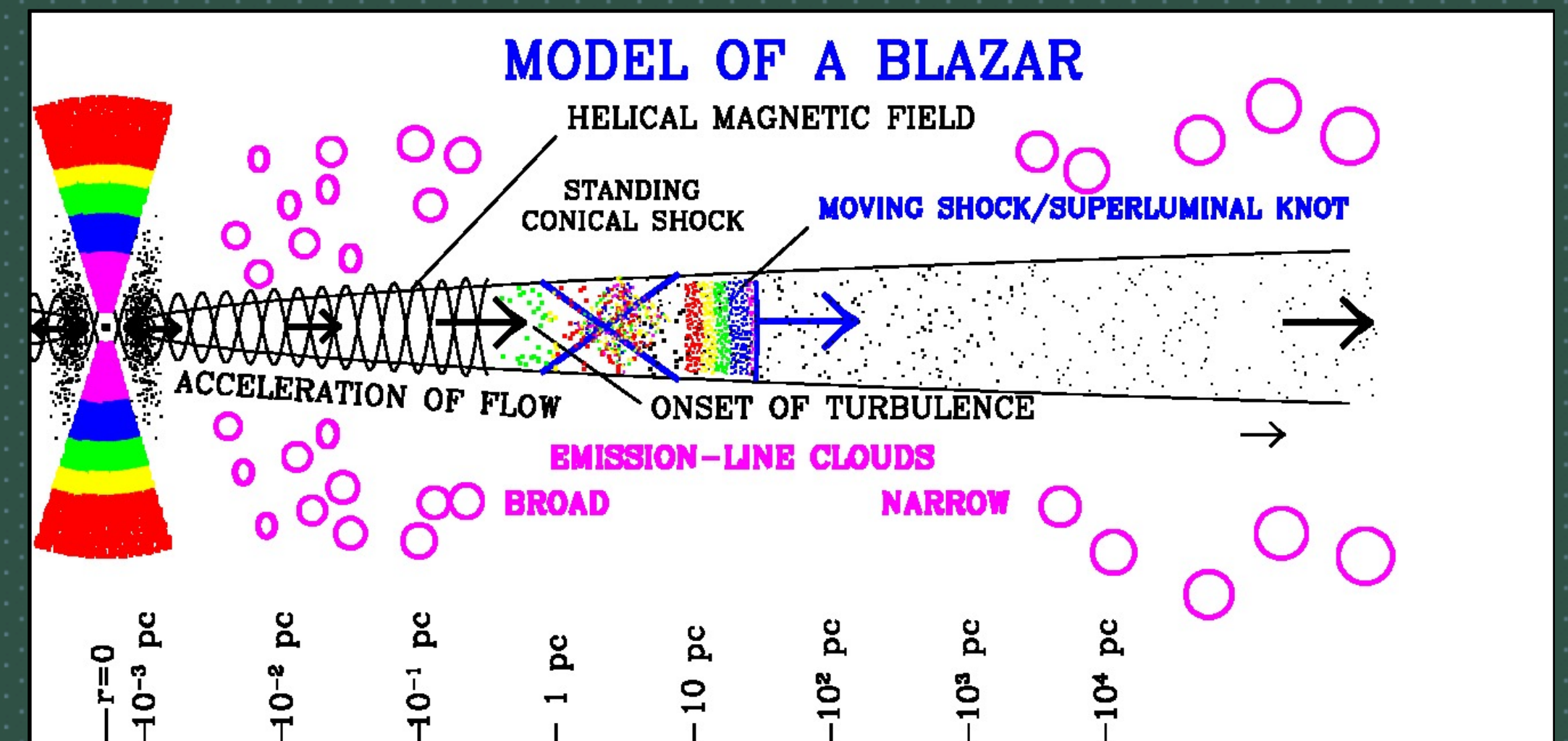
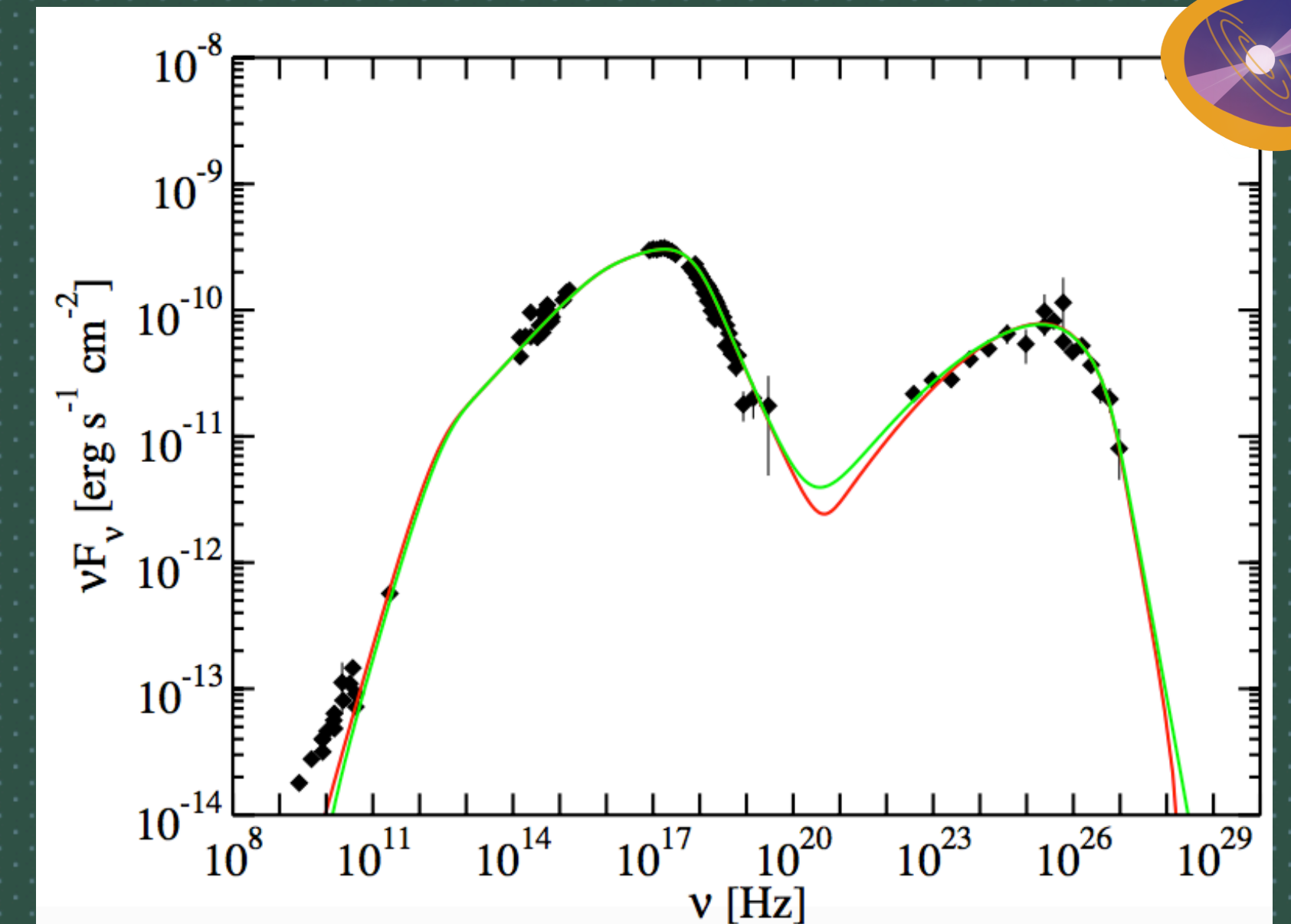
Blazars

- Blazars are the largest particle accelerators in the universe.
 - Blazars are the most energetic sustained source in the universe.
 - They are the most numerous extragalactic sources of X-rays and gamma rays
- Blazars are jetted active galaxies with one jet pointed toward Earth.
 - Relativistic beaming provides a unique view of the physics at the base of the jet.



Blazar Jets

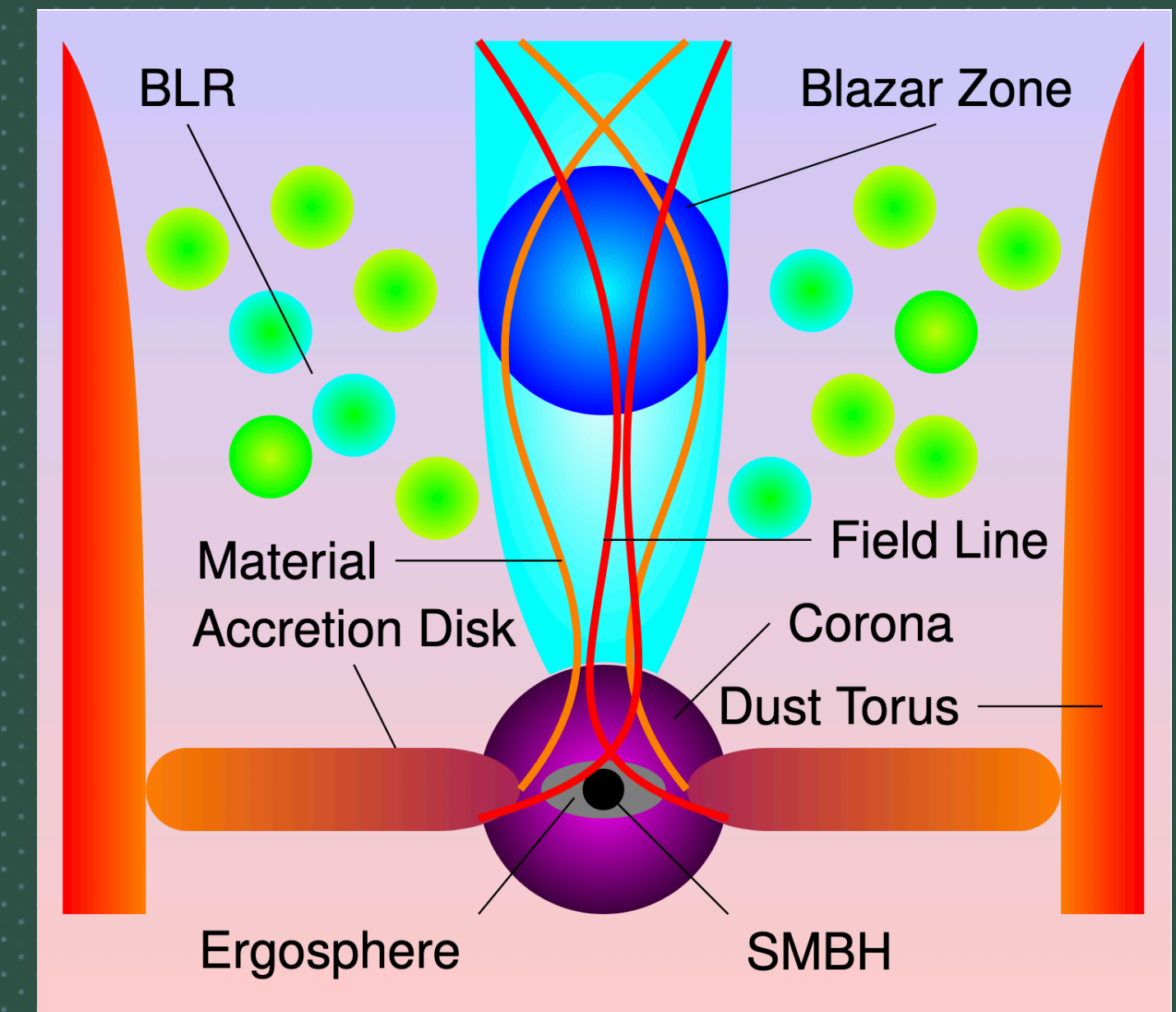
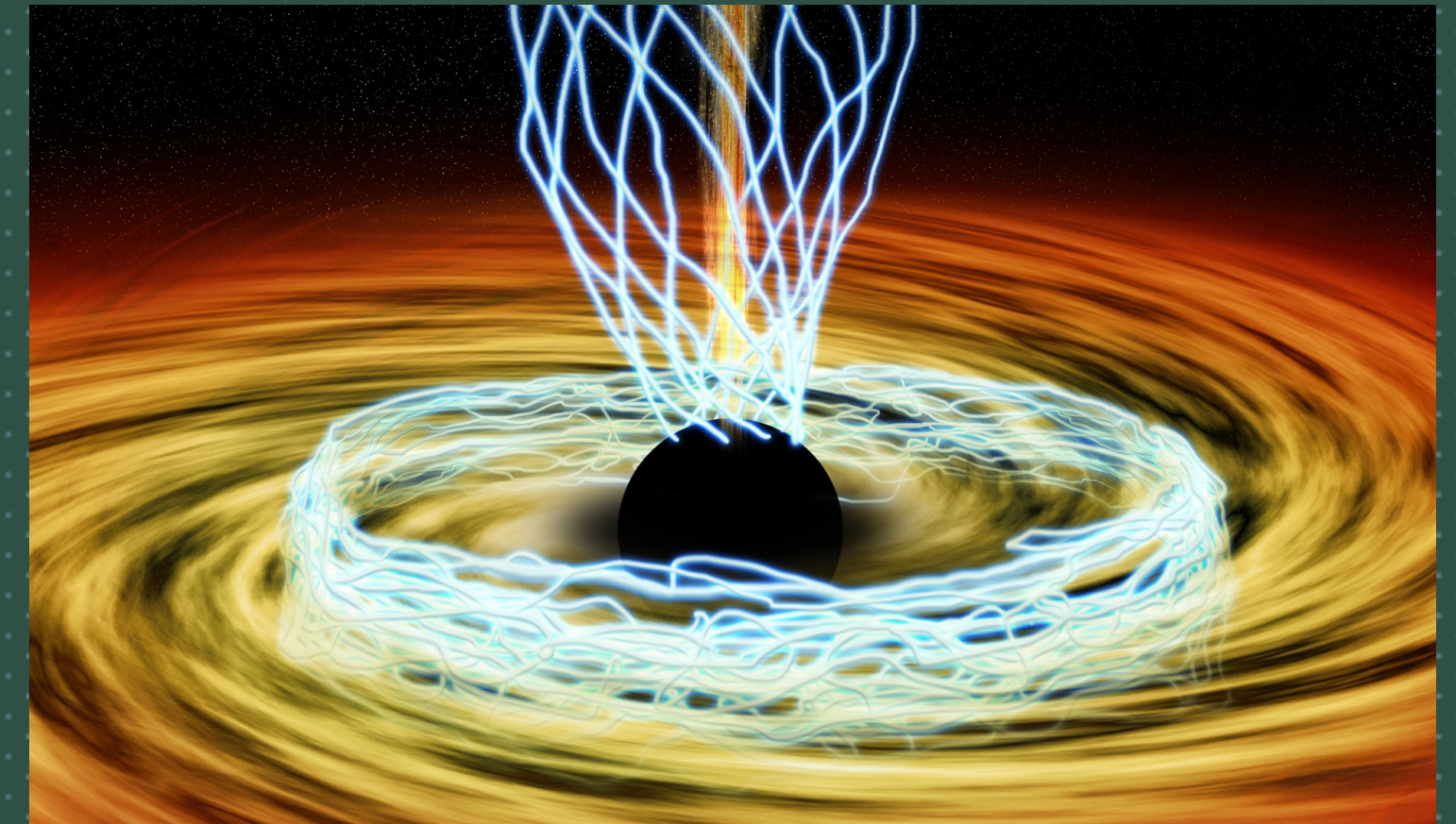
- **Jets form near the SMBH**
 - They are composed of subatomic particles
 - Those particles are accelerated to relativistic speeds
- **Emit across the electromagnetic spectrum**
 - Characterizing them requires relatively complete simultaneous observations.
 - Polarization can distinguish what spectra cannot
 - One blazar is associated with neutrinos



Credit: Alan Marscher, Svetlana Jorstad, et al. (bottom) Abdo et al. 2011 (top)

Jet Launching Mechanisms

- How does accretion interface with the black hole?
 - If disk material follows magnetic field lines that avoid the black hole, then we expect electrons and protons in the jet.
 - If disk material is all consumed by the black hole, then we expect primarily electrons and positrons in the jet from pair formation.
 - If clouds or stars fall into a leptonic jet, it may temporarily gain protons.
- It is possible that both pictures are true in different objects or in different phases.
 - This motivates population-level characterization with the potential to discover subclasses.



Leptonic vs Leptohadronic Blazars

- There are spectral signatures of leptonic vs leptohadronic jets, but they are also model-dependent.
- Spectropolarimetry provides additional constraints that should differentiate the physics across specific models.
- **Leptonic Jets**
 - External Compton from the electrons should have a very low polarization degree
- **Leptohadronic Jets**
 - High-energy hadronic emission is expected to be highly polarized, but may be attenuated by field turbulence.

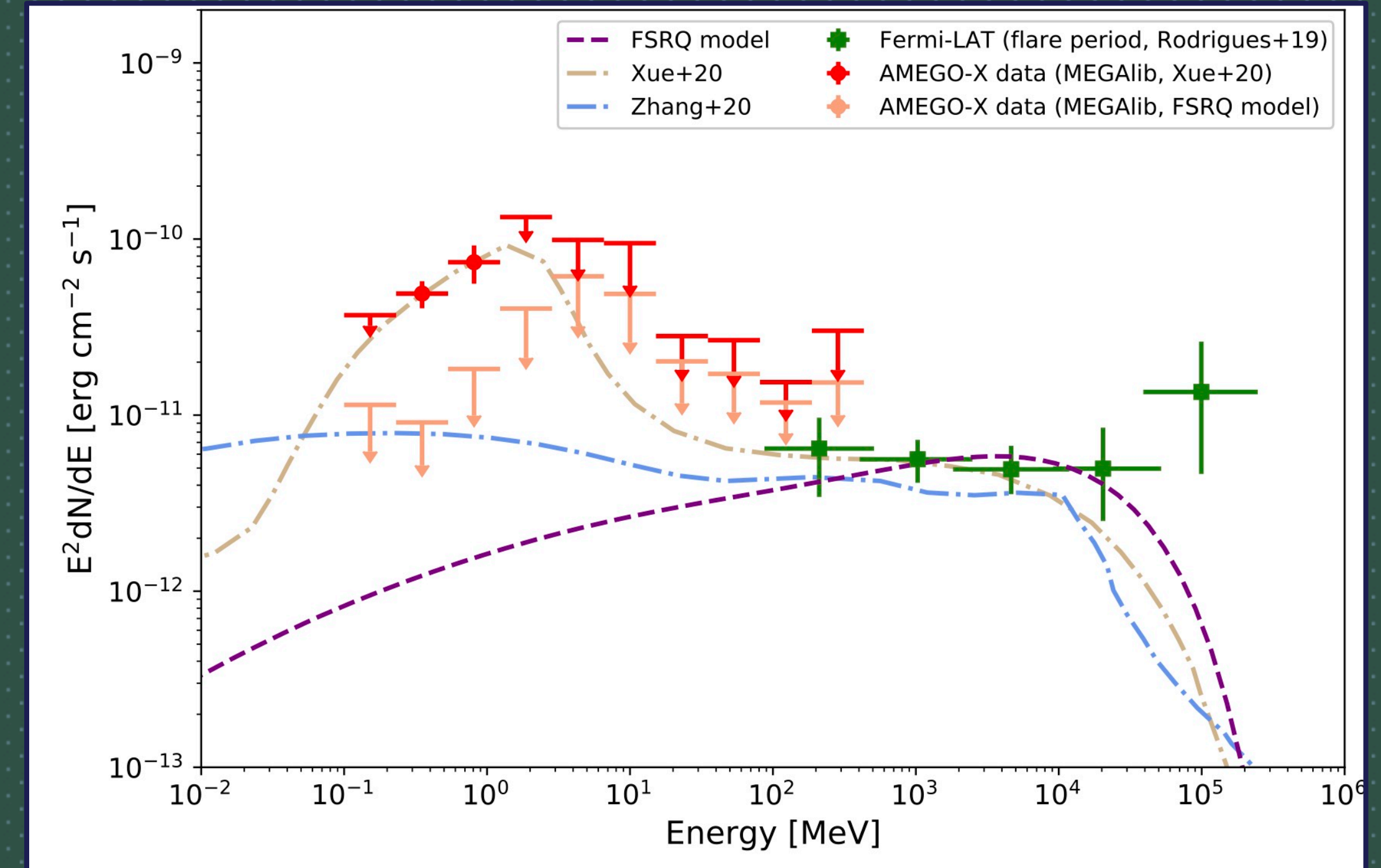


Figure: Fermi-LAT data is in green for TXS 0506+056 during the winter 2014/15 neutrino flare. Simulated AMEGO-X data in red (for tan model) & peach (for blue/purple models). The purple simulation is from an Inverse Compton model. The blue simulation includes hadronic cascades. The tan simulation required 2 zones with coronal gamma-gamma absorbed cascade emission in the MeV, but inverse Compton in the GeV. [Credit: Caputo et al. 2022 and arXiv:2111.10600]

Supermassive Black Holes



- **Galaxy Formation**

- Dark matter anisotropies pull hydrogen into a deep gravitational well
- SMBHs form via direct collapse

- **Active phase of galaxy evolution**

- A period of rapid accretion and associated SMBH growth
- Quench star formation
- Redistributes material from the nuclear region out into intergalactic space

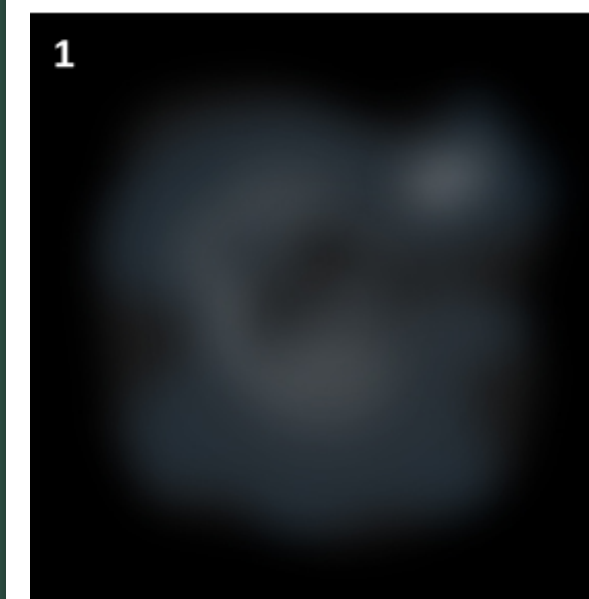
- **Major mergers can initiate an active phase**

- SMBHs may merge or be kicked out of the resulting galaxy

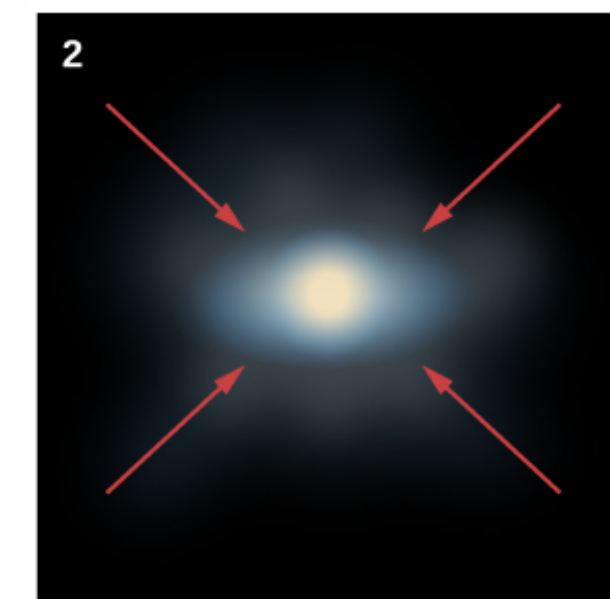
Development of Massive Elliptical Galaxies



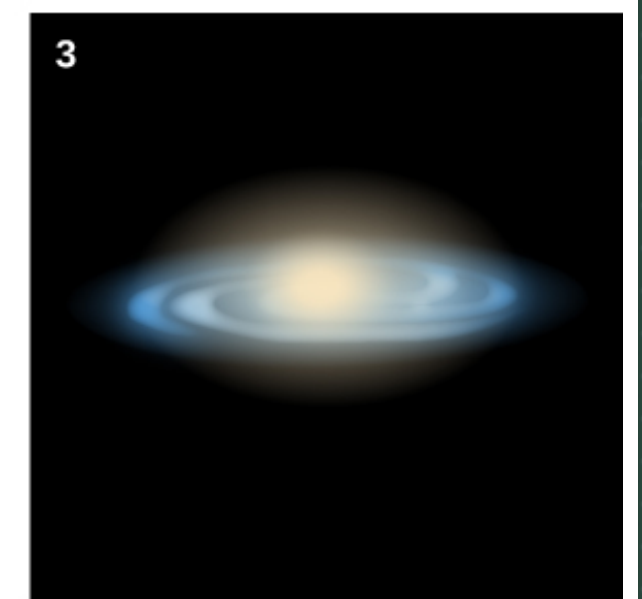
(Image Credit: NASA, ESA, Sune Toft, & Ann Feild)



1
Primordial hydrogen cloud.



2
Cloud collapses under gravity.



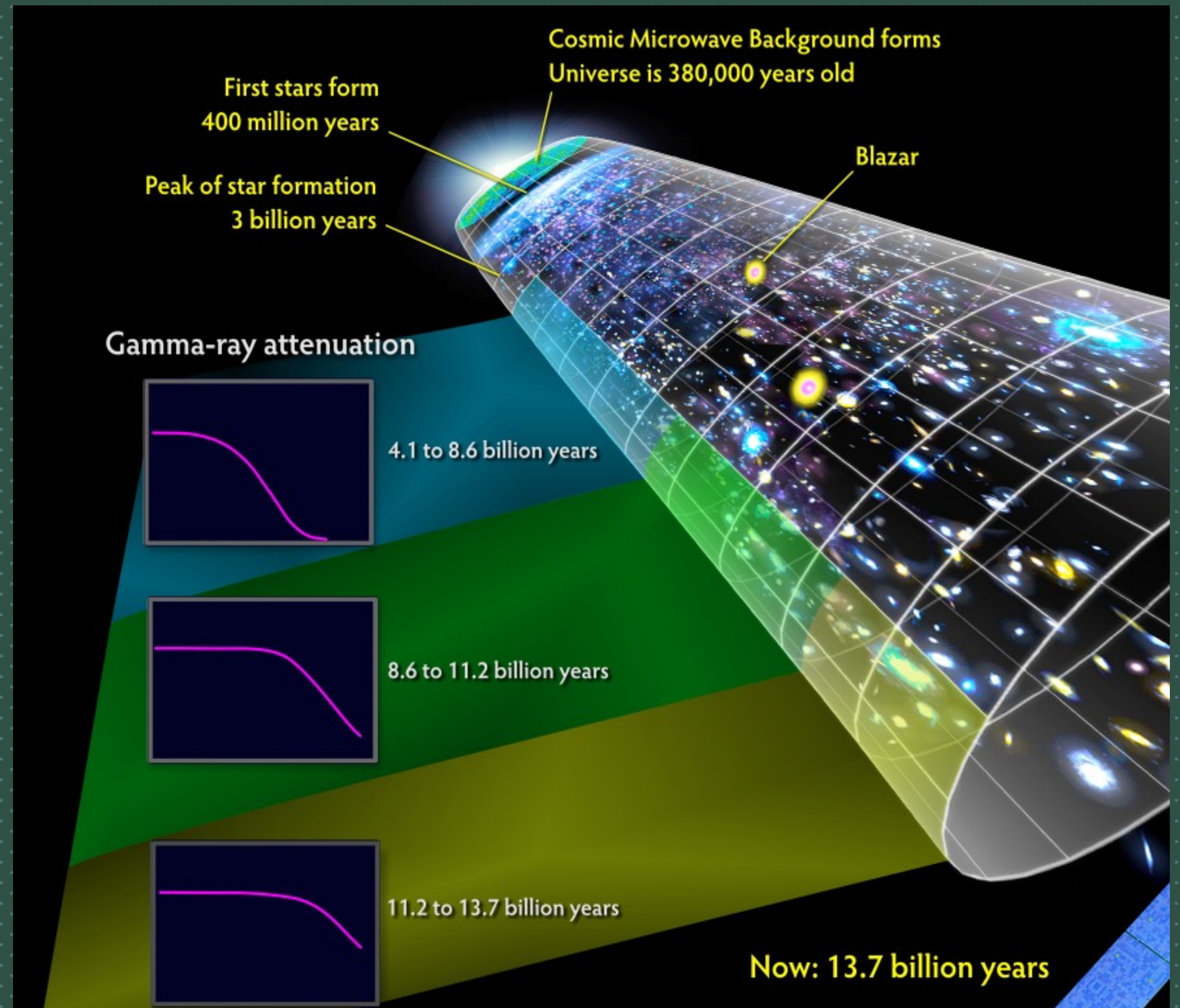
3
Large bulge of ancient stars dominates galaxy.

Image Credit: "The Formation and Evolution of Galaxies and Structure in the Universe" from *Astronomy* by Andrew Fraknoi, David Morrison, and Sidney Wolff



Extragalactic Background Light

- The EBL is composed of all of the starlight that ever existed in the universe
 - The EBL is primarily IR, optical and UV
- The EBL attenuates the gamma-ray spectrum via pair production
 - Measuring the EBL requires gamma-ray spectra from blazars
 - The shape of the attenuation indicates the star formation history and the cutoff moves to lower energies with distance





High-Redshift Blazars

- Billion solar mass black holes in this era require formation via direct collapse
 - Seed black holes from a redshift of 3 are observationally unconstrained
- The highest redshift blazars seen with Fermi are around $z \lesssim 4$
 - These sources are from the most luminous subclass
 - Their high-energy peak falls in the MeV
- Sensitive detectors are required because the flux is low and blazars vary on short timescales

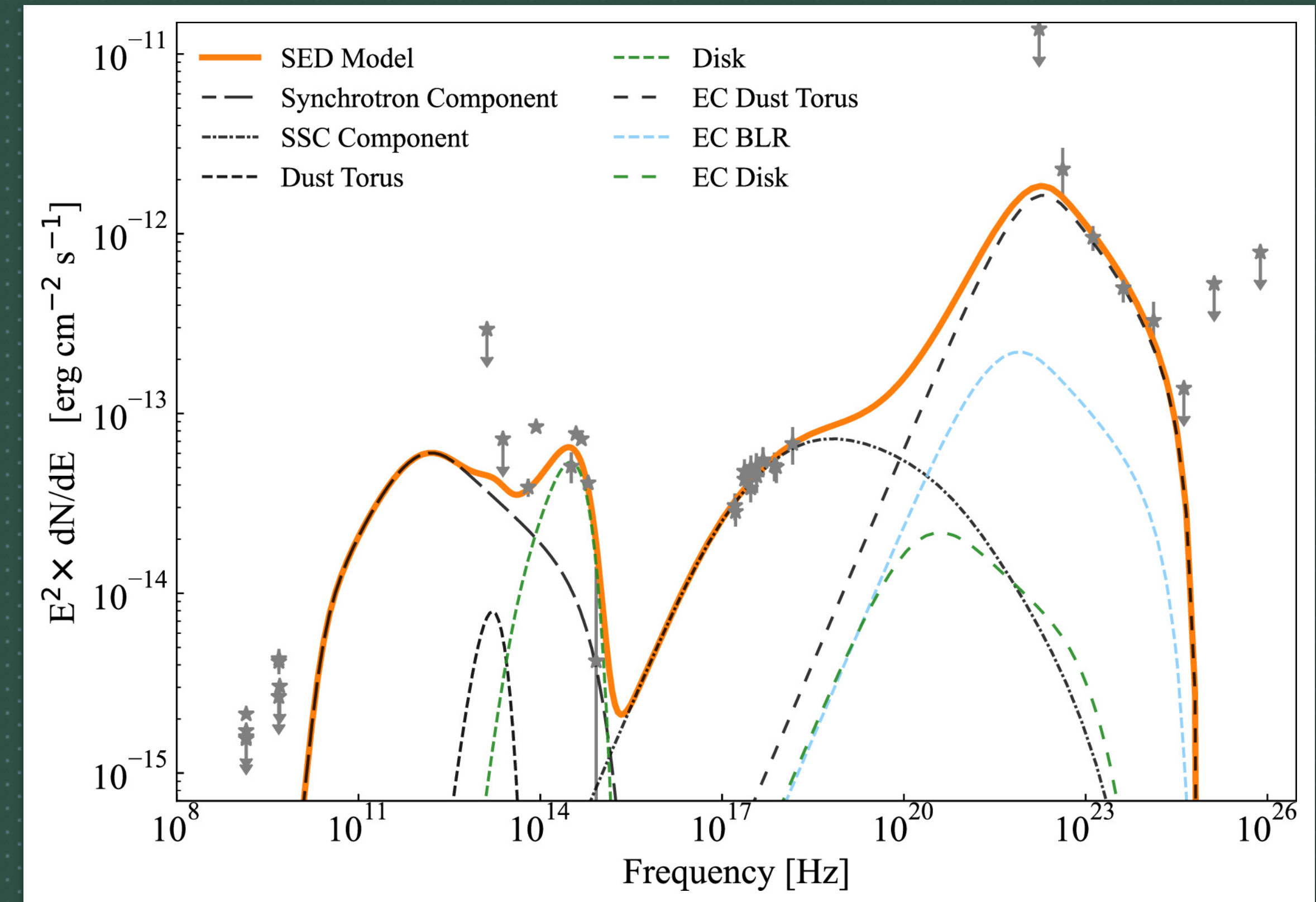


Image Credit: Sanchez Zaballa et al. (2025)

Highly Variable Steady Sources

- Blazars are intrinsically steady sources in that they do not turn off
- They are highly variable and their states are not predictable.
- Historically, there is a strong observational bias for bright or flaring sources
- Blazars can change states in days to weeks - detections must be in less time
- Polarization reconstruction requires dividing photons, so there need to be more of them
- Blazar variability could indicate acceleration physics and has been detected down to every timescale measured.

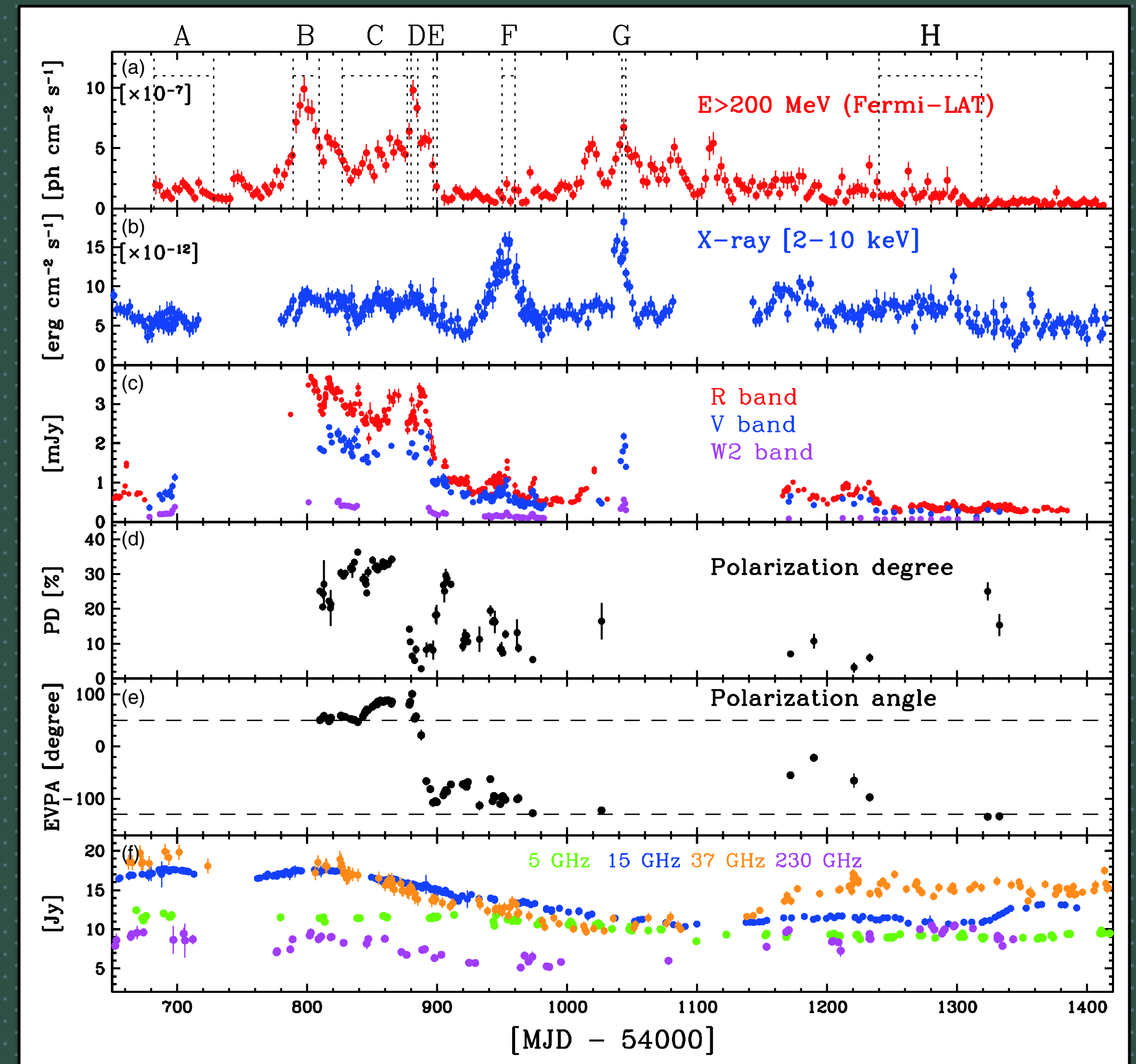


Image Credit: Hayashida et al. (2012)

MeV Missing Data

- The high-energy peak in blazars is in the MeV-GeV range
 - The contested emission process
- Spectropolarimetry is needed to constrain physics of jet launching and composition across models
 - Leptonic vs Leptohadronic
 - Magnetic field structure
- The FIGSAG Report found that a continuum sensitivity of 10^{-13} erg cm^{-2} s^{-1} is needed in 1 week

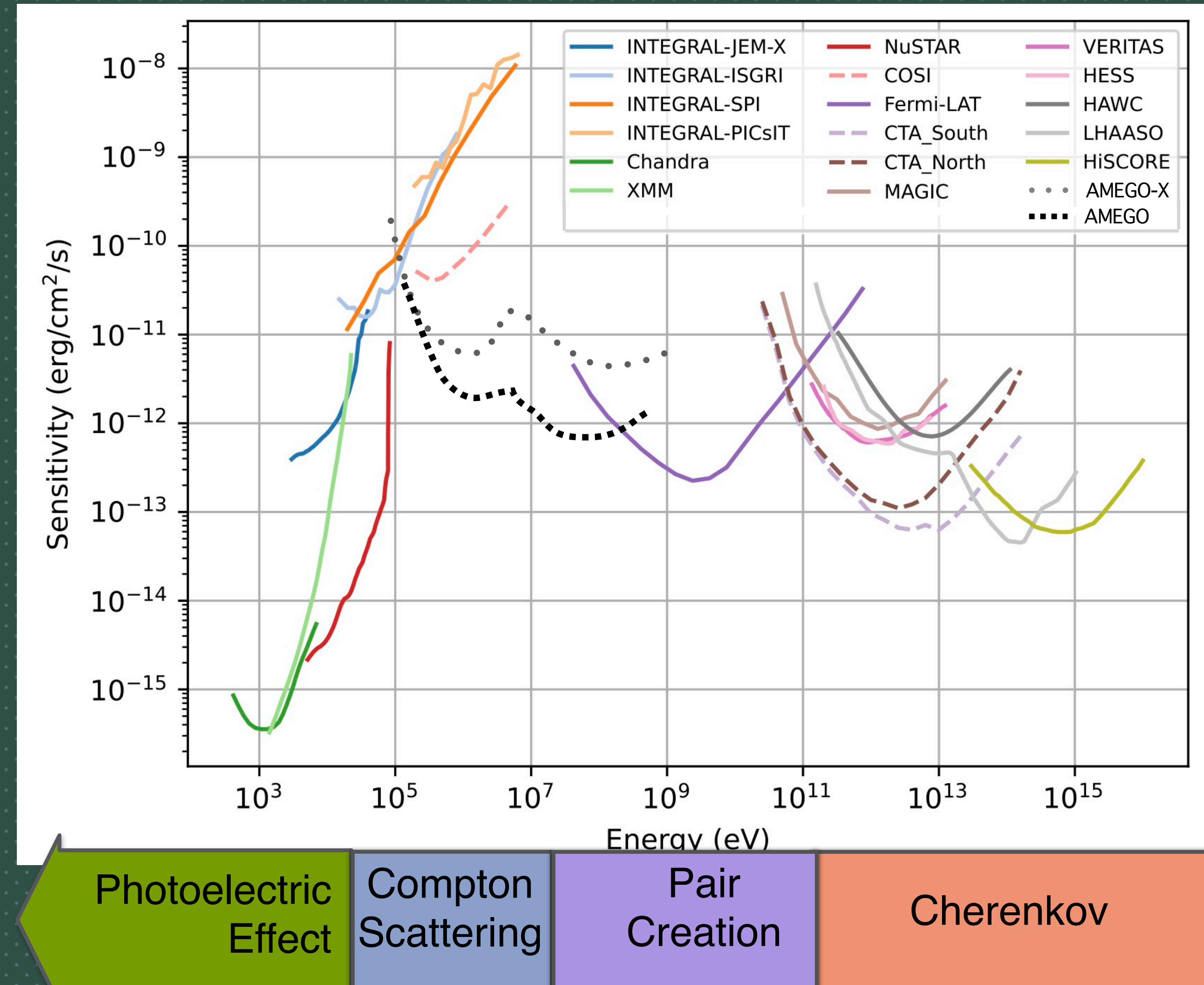


Image Credit: Henrike Fleischhack for "The Future of Gamma-Ray Experiments in the MeV-EeV Range" arXiv:2203.07360



Questions?



Abstract

Galaxies and supermassive black holes co-evolve through cosmic time, but the precise mechanisms are not well understood. We know that the active phase is significant to both elements, as well as the distribution of energy in the universe when these systems produce jets. The jet launching mechanism for active galaxies is not directly observed, but it is possible to constrain through the composition of the jet itself. Blazars emit at all wavelengths, but their high-energy emission process is uncertain and points to their composition. While spectra alone are insufficient to differentiate between models, polarization measurements from 100 keV to 100 MeV would be instrumental. This discovery space contributes important insights for the broader galaxy and cosmic evolution communities because it reveals a key phase of SMBH co-evolution. As some of the most sustained astrophysical jets, blazars are also a touchstone source class for observationally elucidating astrophysical jet physics.