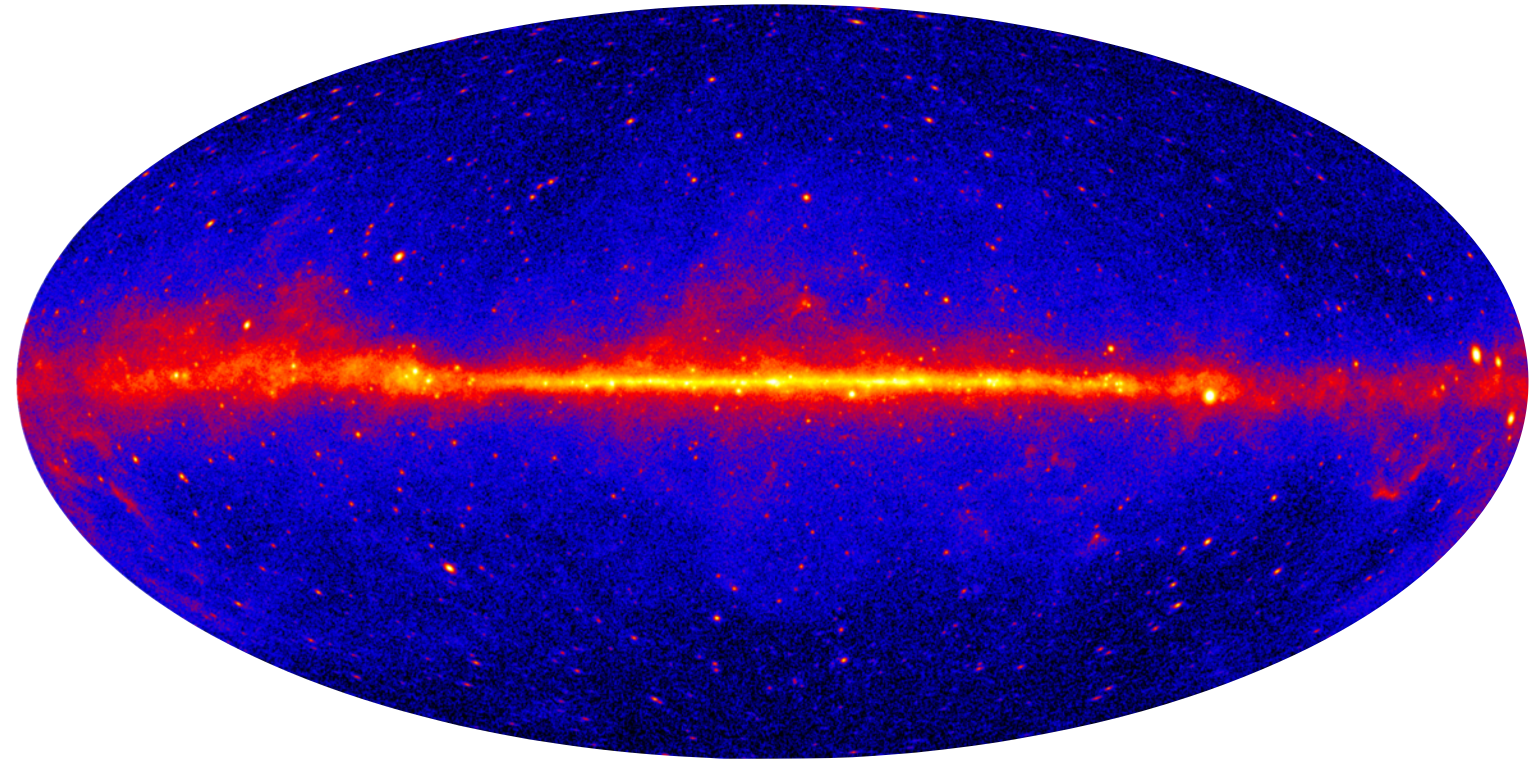
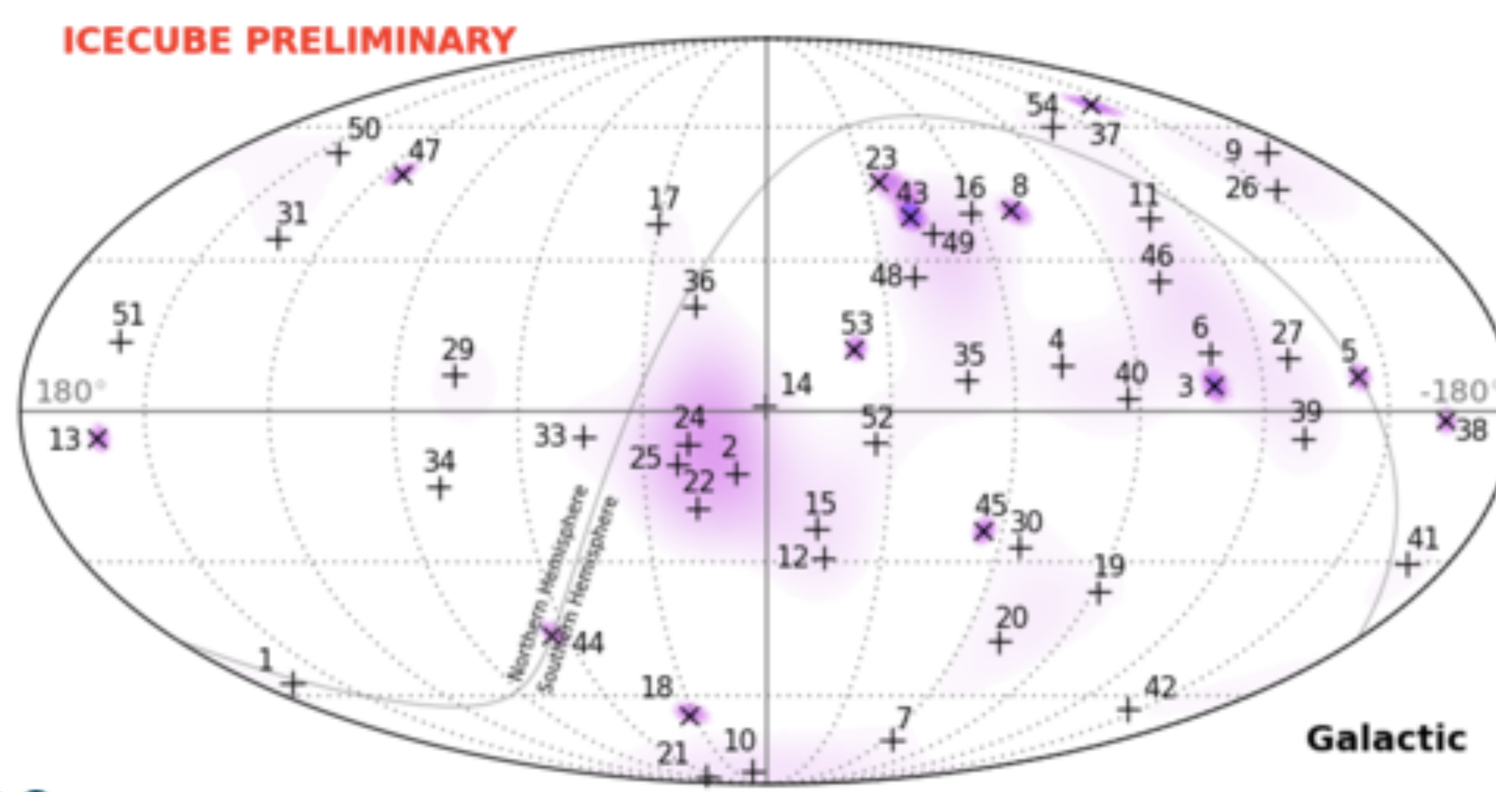


Neutrinos and gamma rays

Two complimentary messengers
of the non-thermal universe

Markus Ackermann
Humboldt Kolleg
Kitzbühel, 30.06.2016

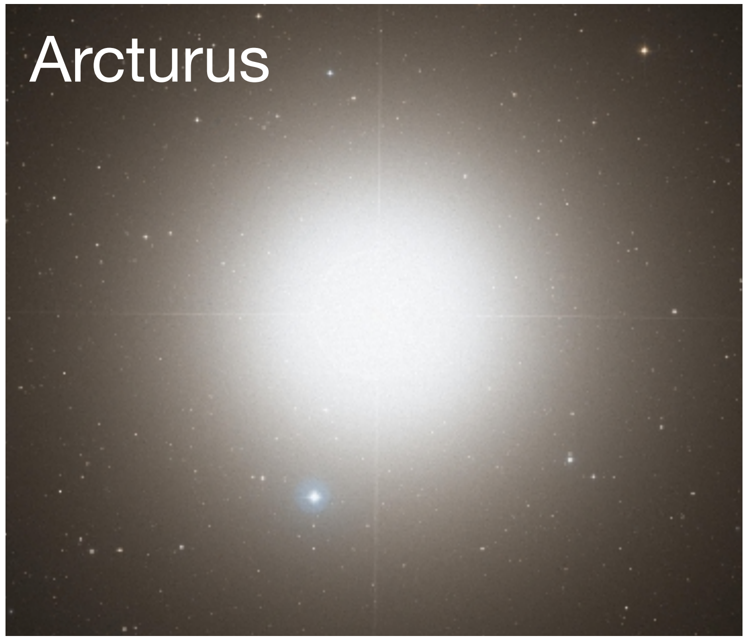


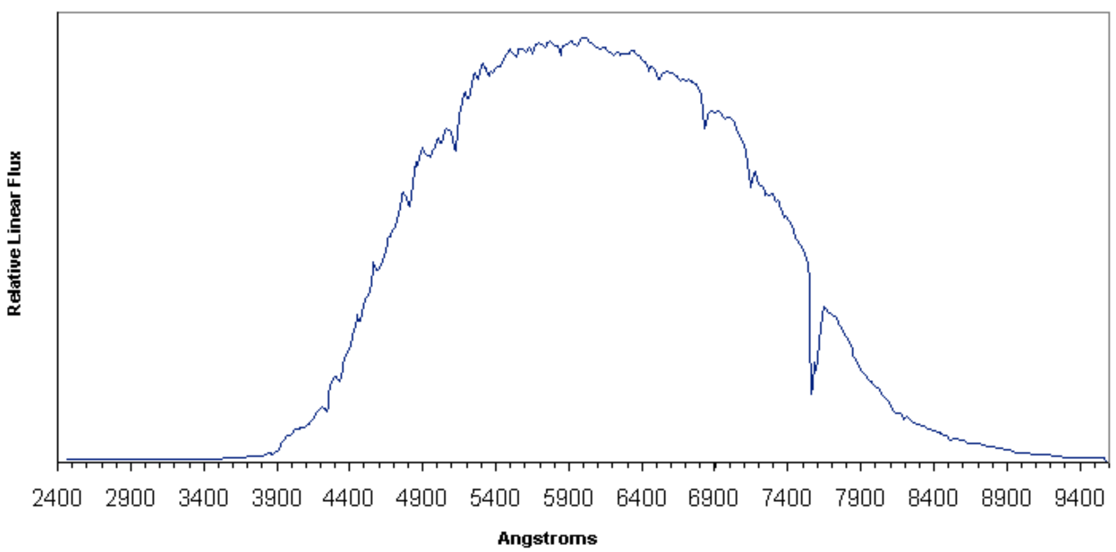
Alexander von Humboldt
Stiftung / Foundation

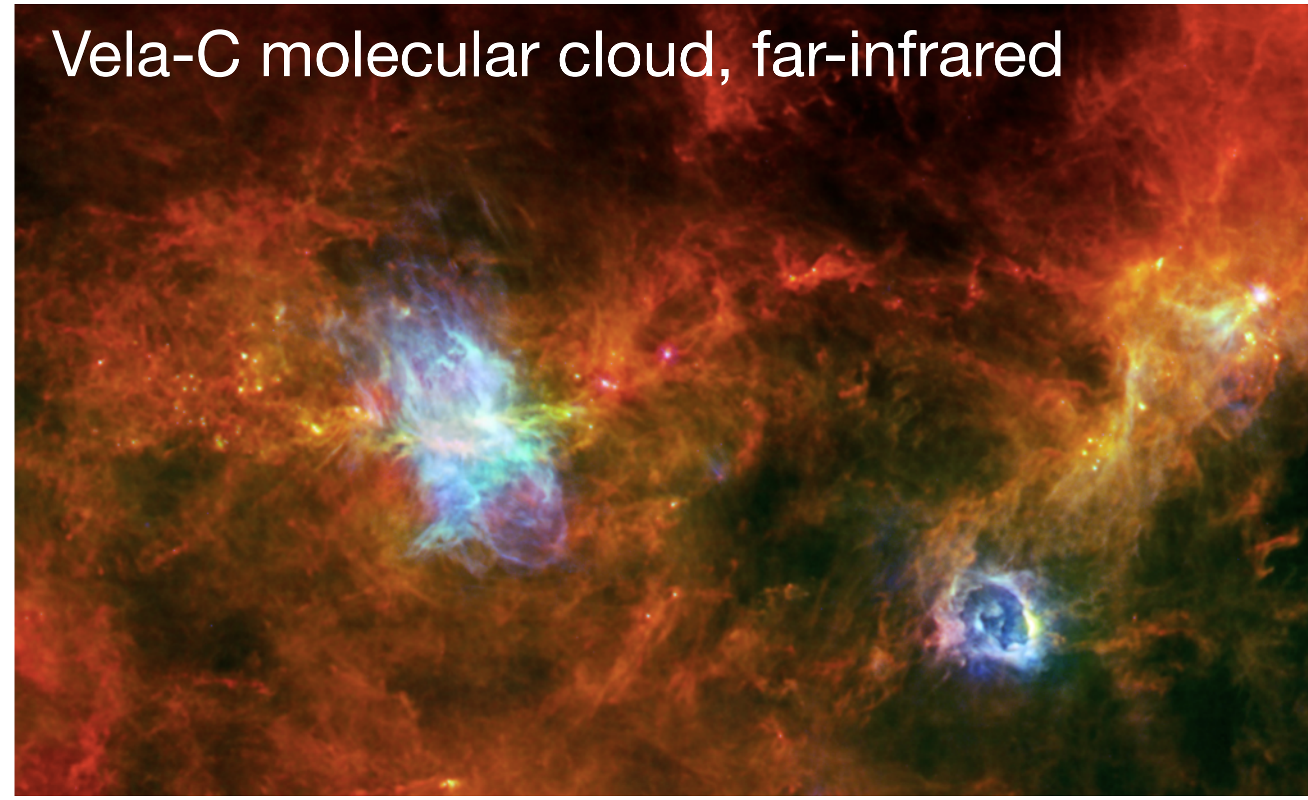
DESY

WIPAC
Wisconsin IceCube
Particle Astrophysics Center

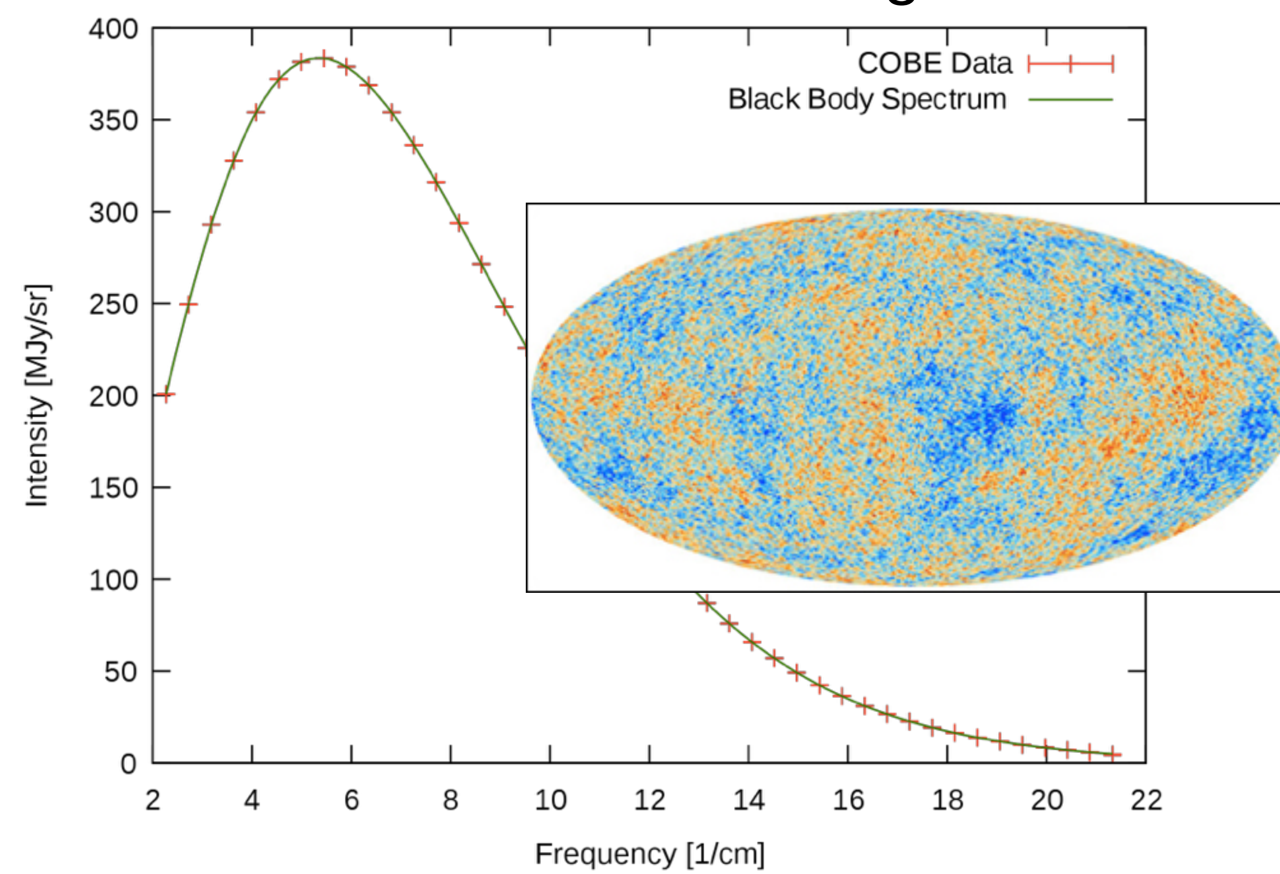
The thermal universe





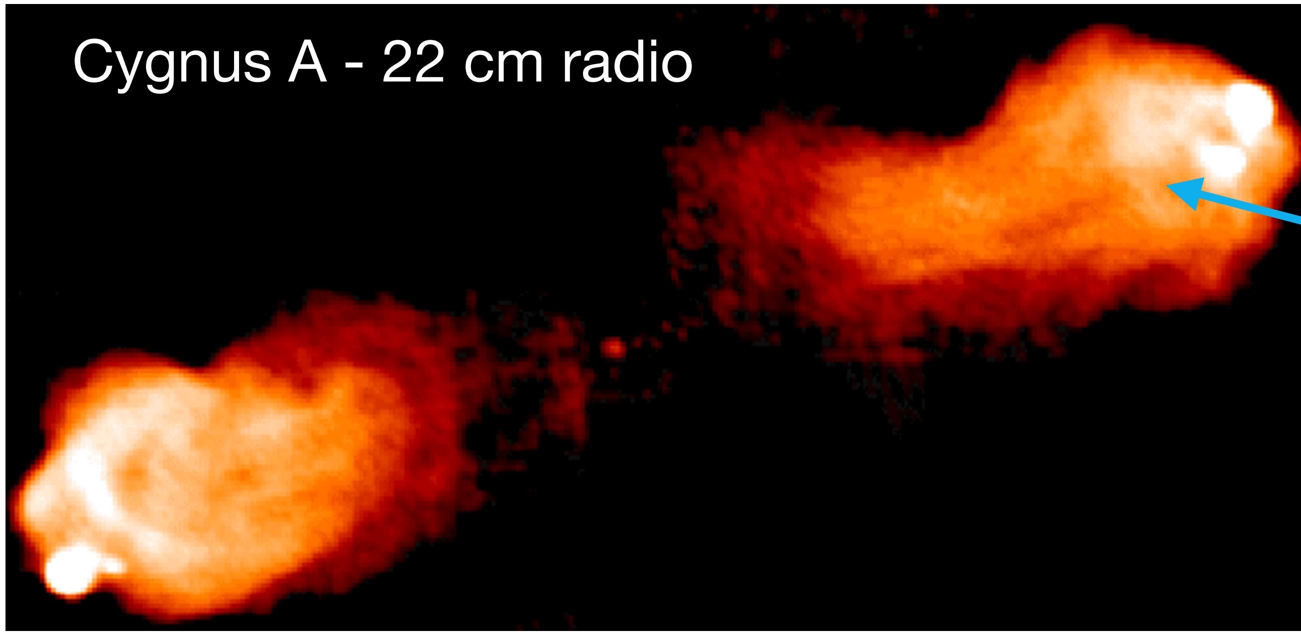


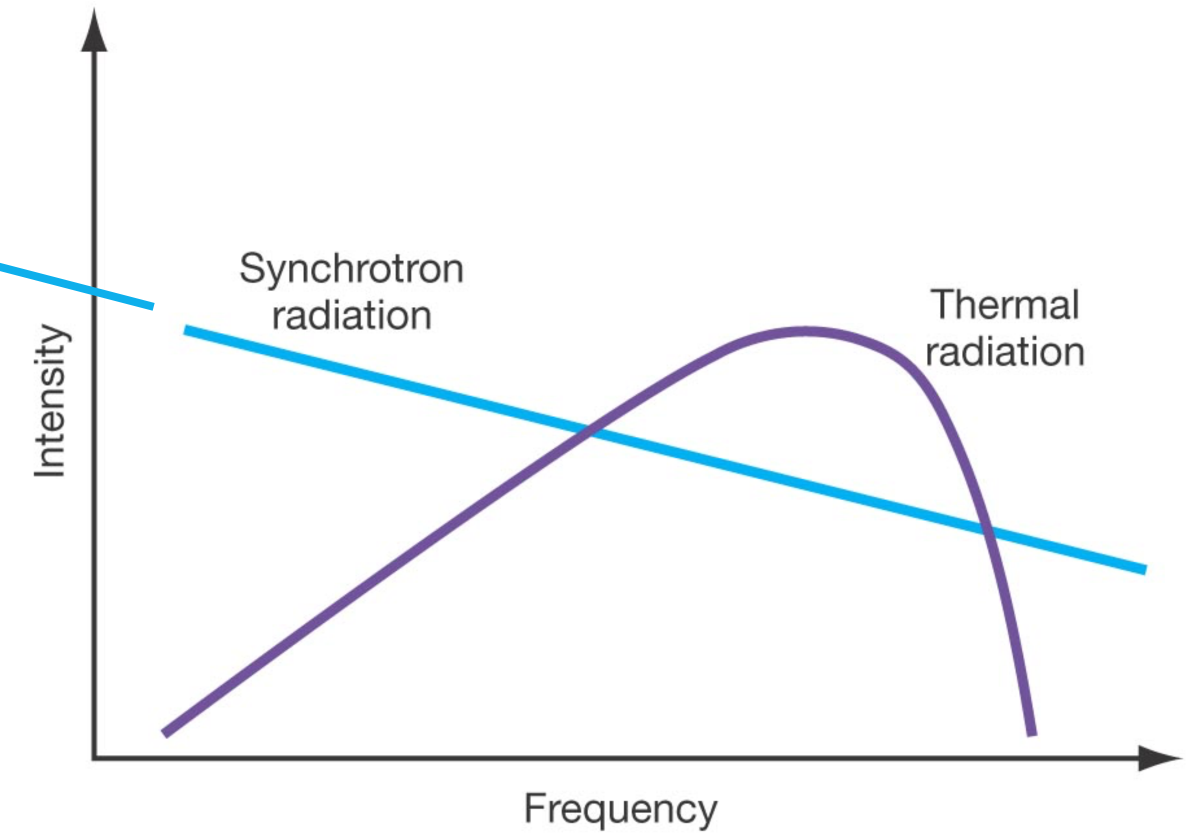
Cosmic Microwave Background



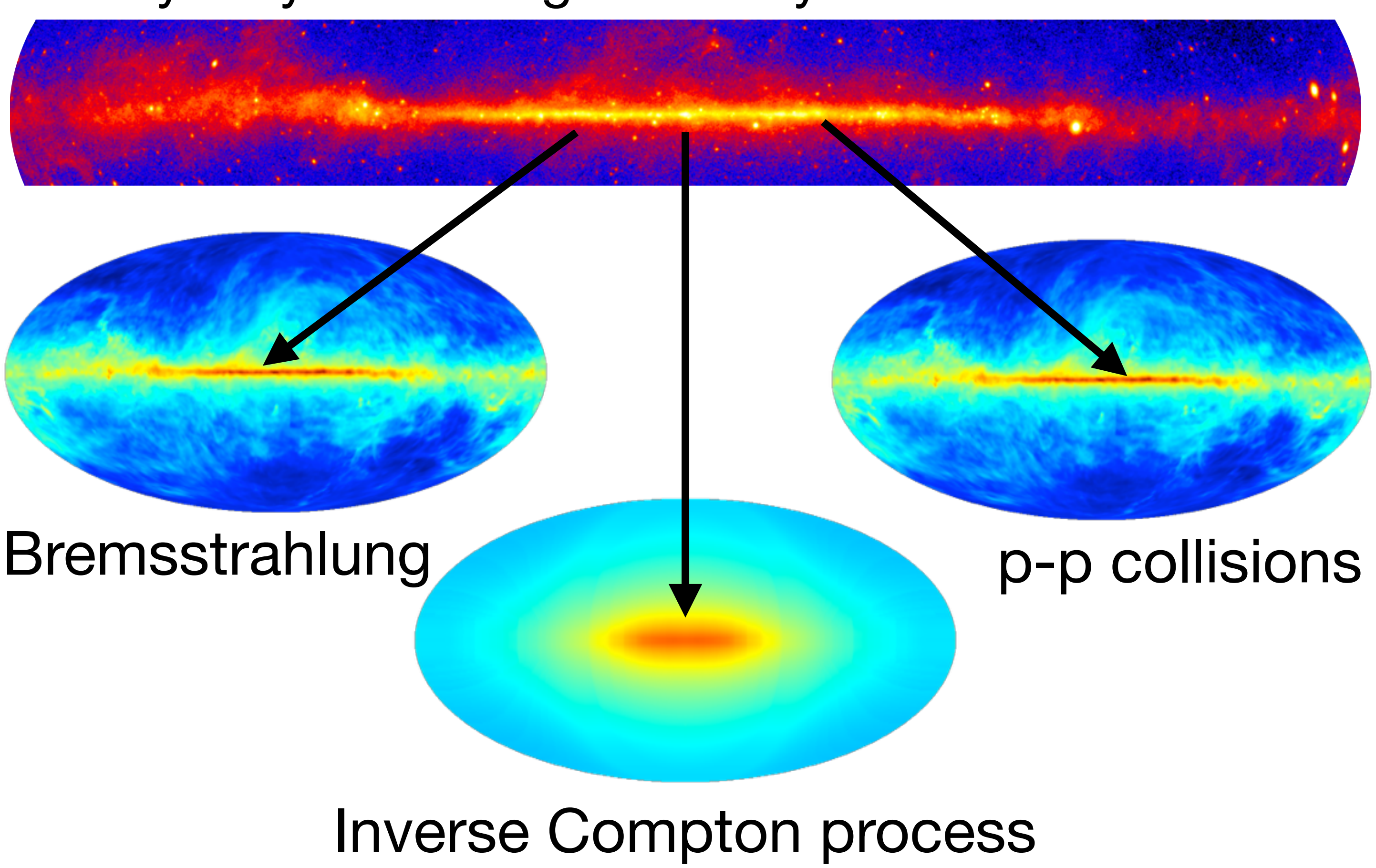
- The “classic” astrophysical messenger: Thermal emission and spectral lines.
- Thermal emission is seen throughout the spectrum from radio to x-ray wavelengths.

The non-thermal universe



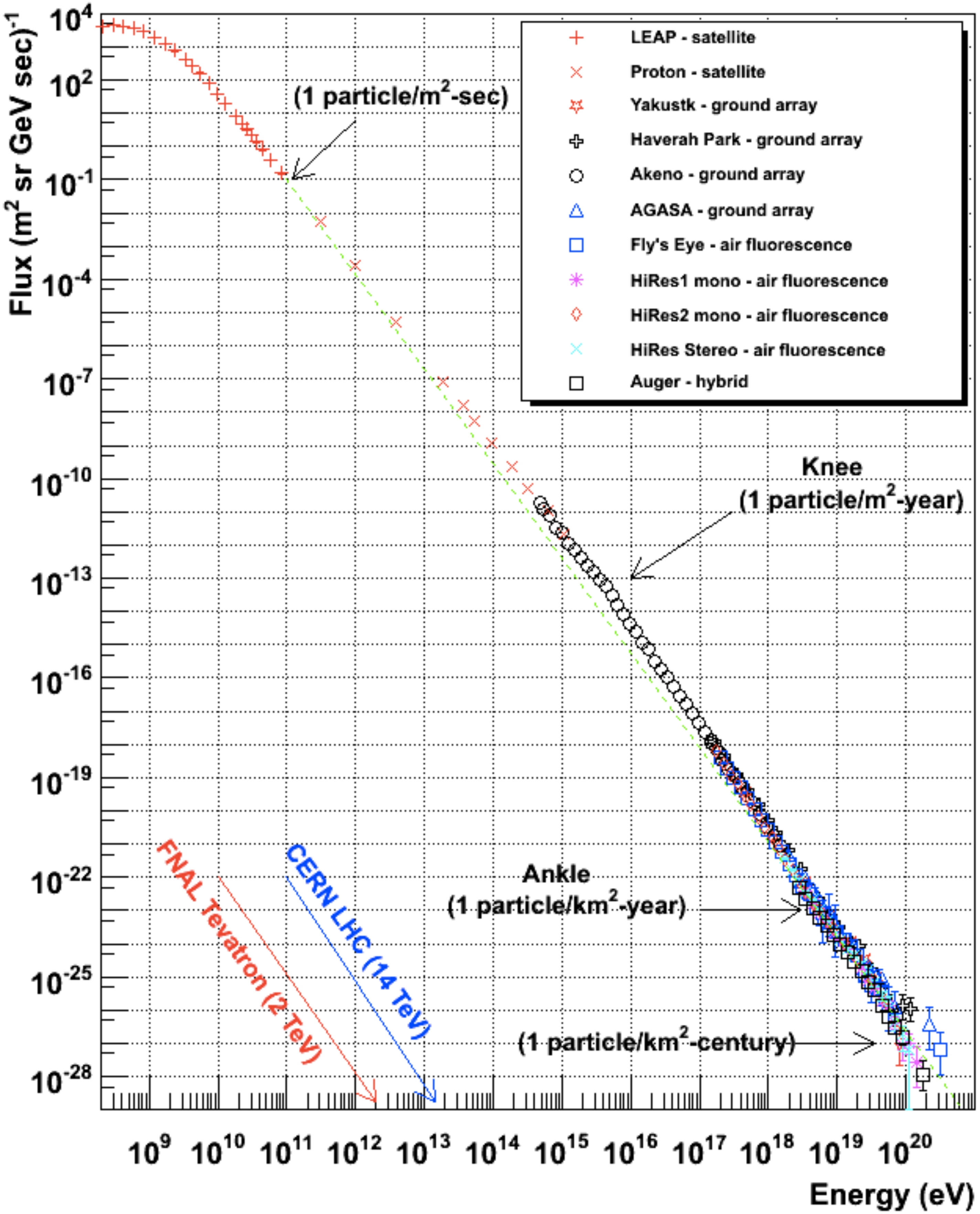


Milky Way > 1 GeV gamma rays



- Non-thermal emission is produced by radiative energy loss processes of high-energy particles
- Production of high-energy particles:
  - Acceleration in astrophysical environments !
  - Decay or annihilation of non-standard model particles ?

Particle acceleration in the universe



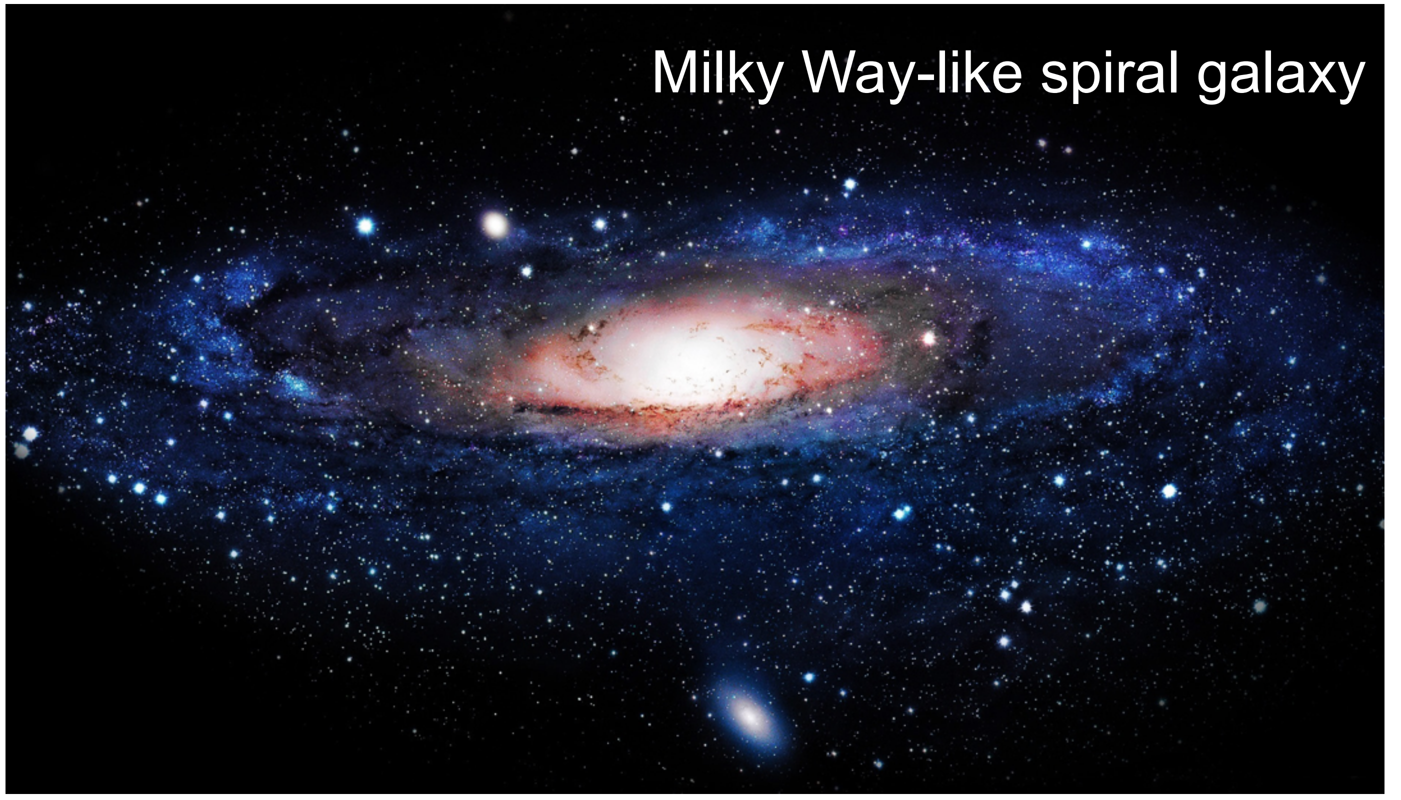
- We know that efficient particle accelerators must exist in the cosmos !
- Cosmic rays with energies > 10^{20} eV hit our atmosphere every day.

- What is the **connection** of the observed **non-thermal emission** to the **cosmic rays** at Earth ?
- What are **the sites** that can accelerate particles to > 10^{20} eV?
- Which **cosmic accelerators** dominate the CR flux in which energy range ?

Are cosmic rays important ?

Energy densities in the Milky Way

	Energy density
Cosmic rays	**0.8 eV / cm^3**
CMB	0.3 eV / cm^3
Starlight	0.5 eV / cm^3
Magnetic fields	~ 0.3 eV / cm^3
Gas pressure	~ 0.5 eV / cm^3

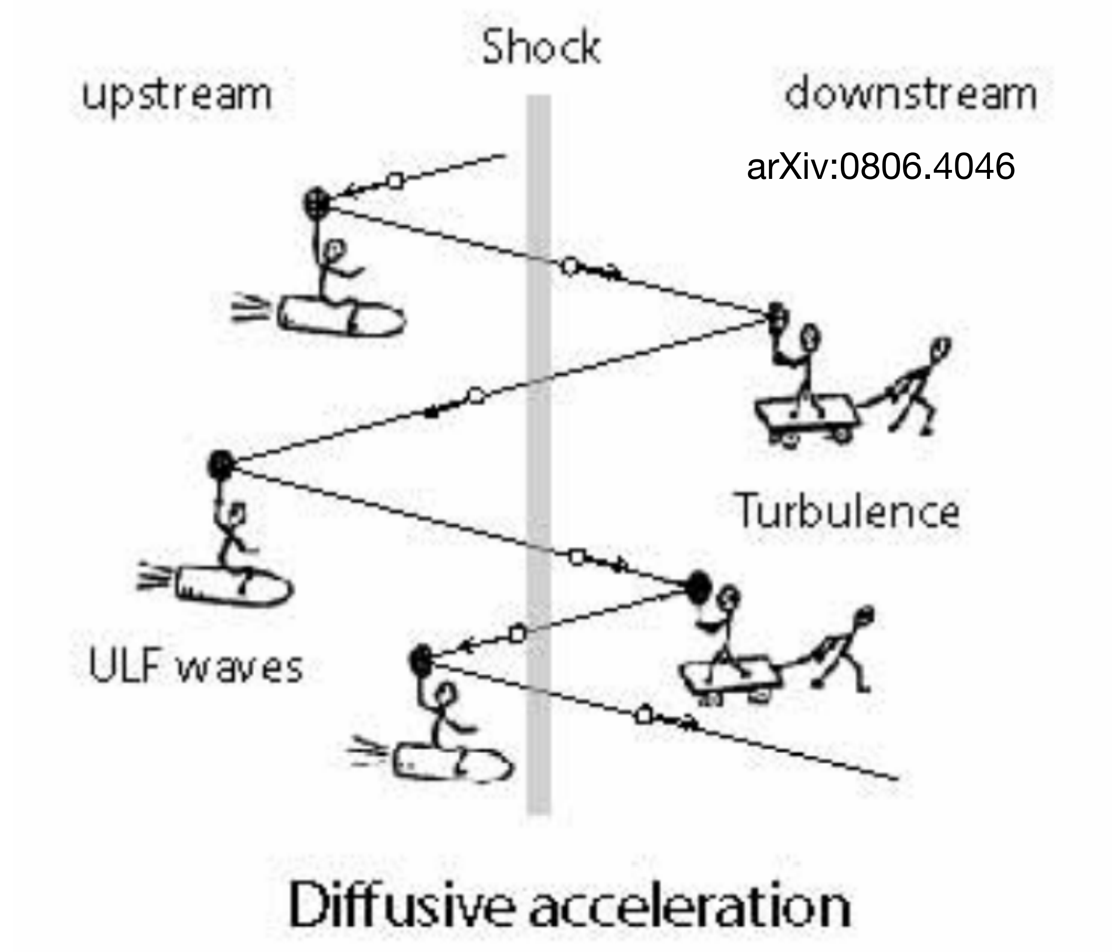


- Cosmic rays
  - **heat** the interstellar gas
  - **interact** with the magnetic fields
  - **influence** star formation

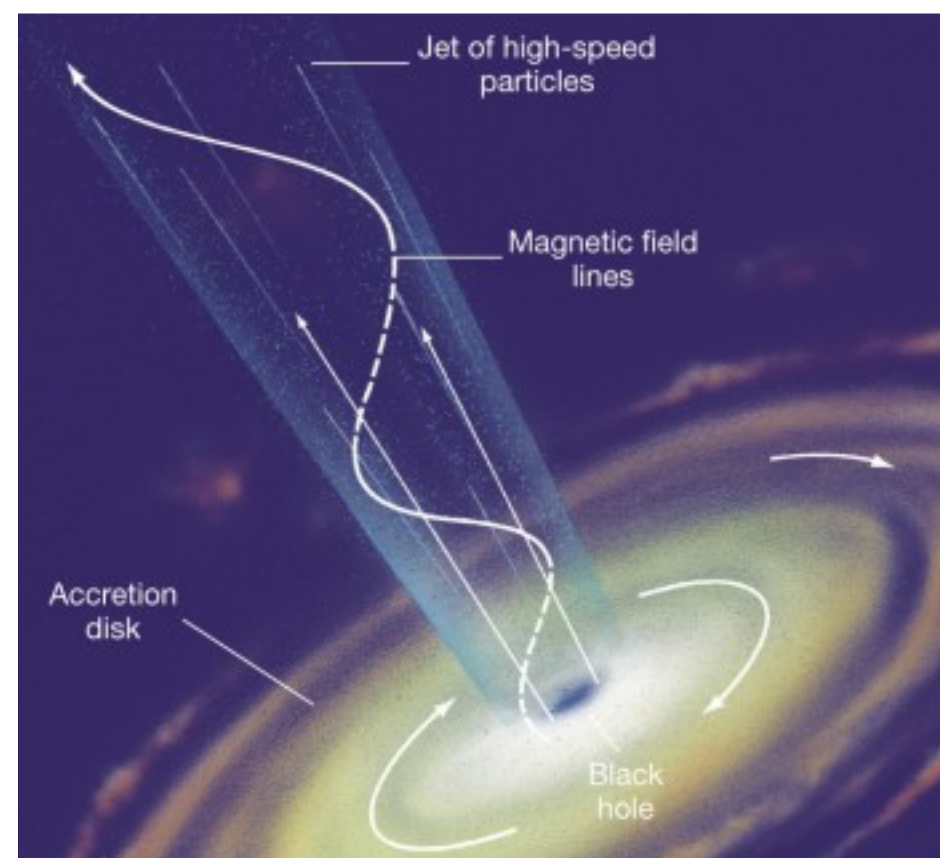
→ **They are important for Galaxy dynamics**

Acceleration mechanisms

- **What are the mechanisms driving such extreme particle acceleration ?**
  - Diffusive shock acceleration
  - Acceleration in plasma turbulence
  - Magnetic reconnection
  - Electrostatic gaps

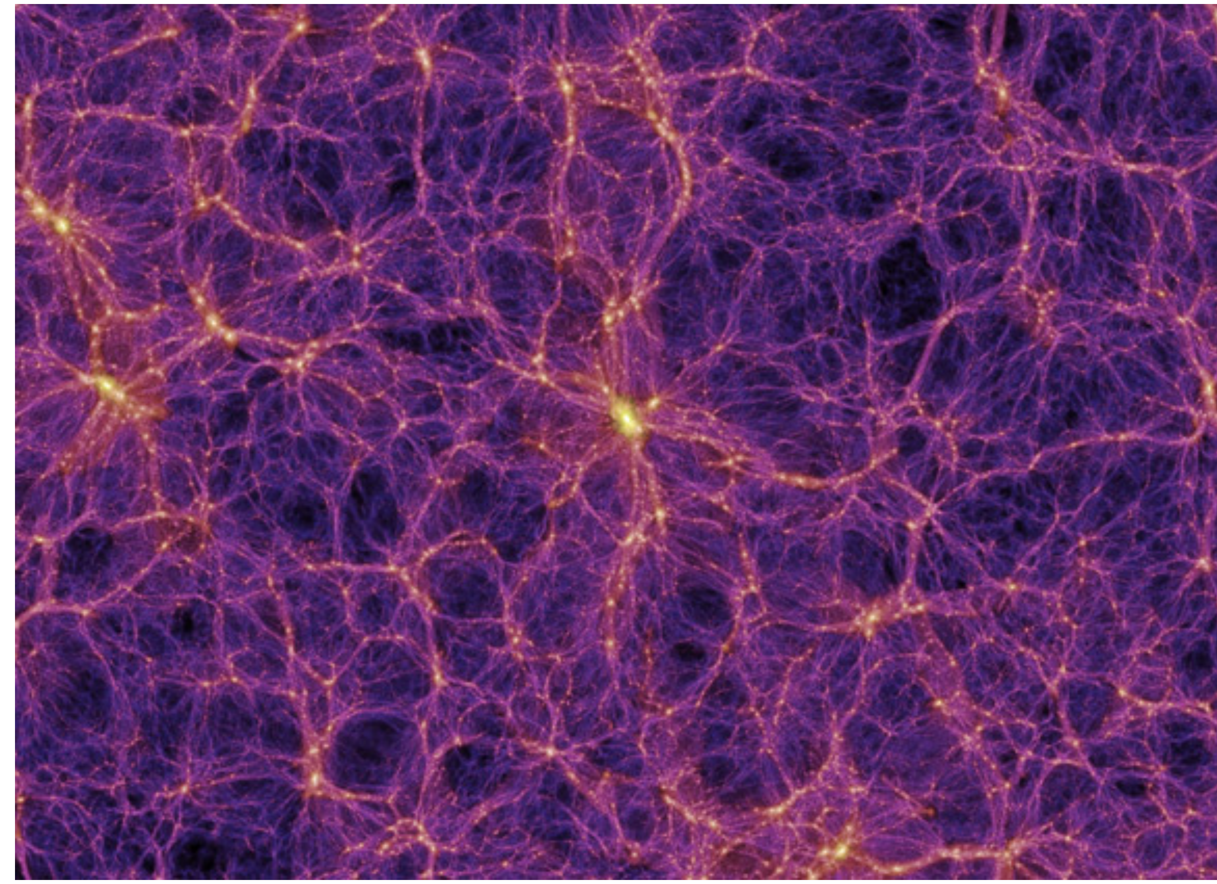


- **What can we learn about the astrophysical environments ?**
  - gas & photon densities
  - magnetic fields
  - bulk motion

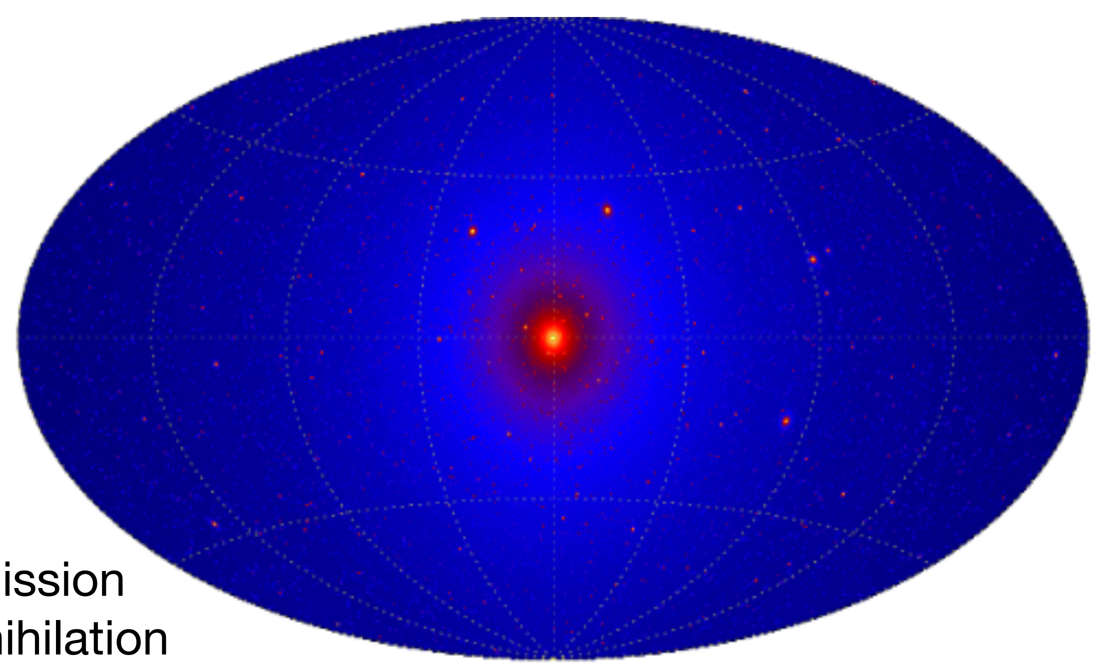


Signatures of new physics in the universe

- Some **high-energy particles** might have been produced in the **annihilation** or decay of non-standard model **particles**.
- Many particle physics motivated models for dark matter **predict observable signatures** in the **non-thermal sky**.



large scale dark matter distribution

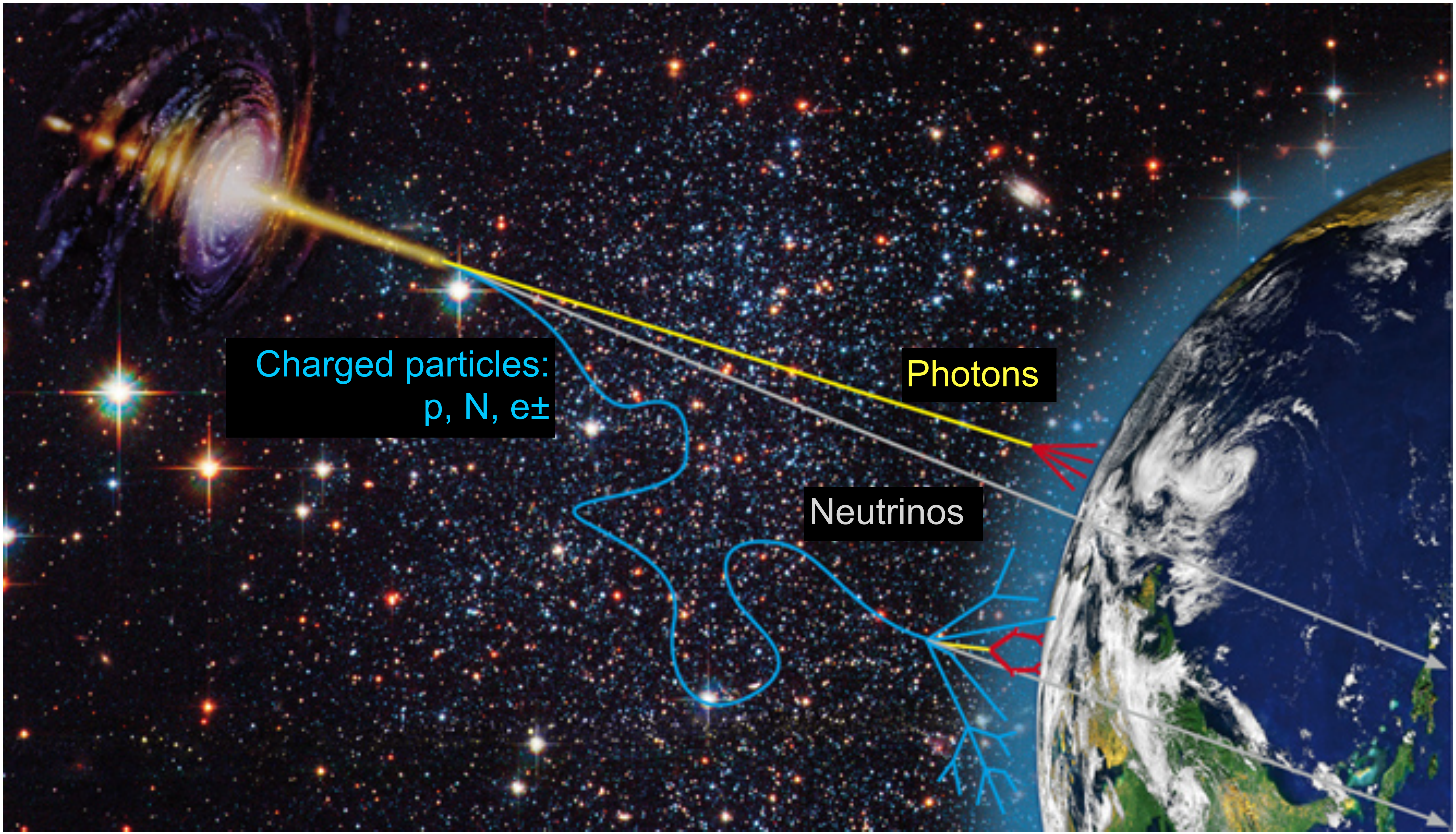


simulated γ-ray emission from dark matter annihilation

www.particlezoo.net

The multi-messenger paradigm

- Every messenger is unique.



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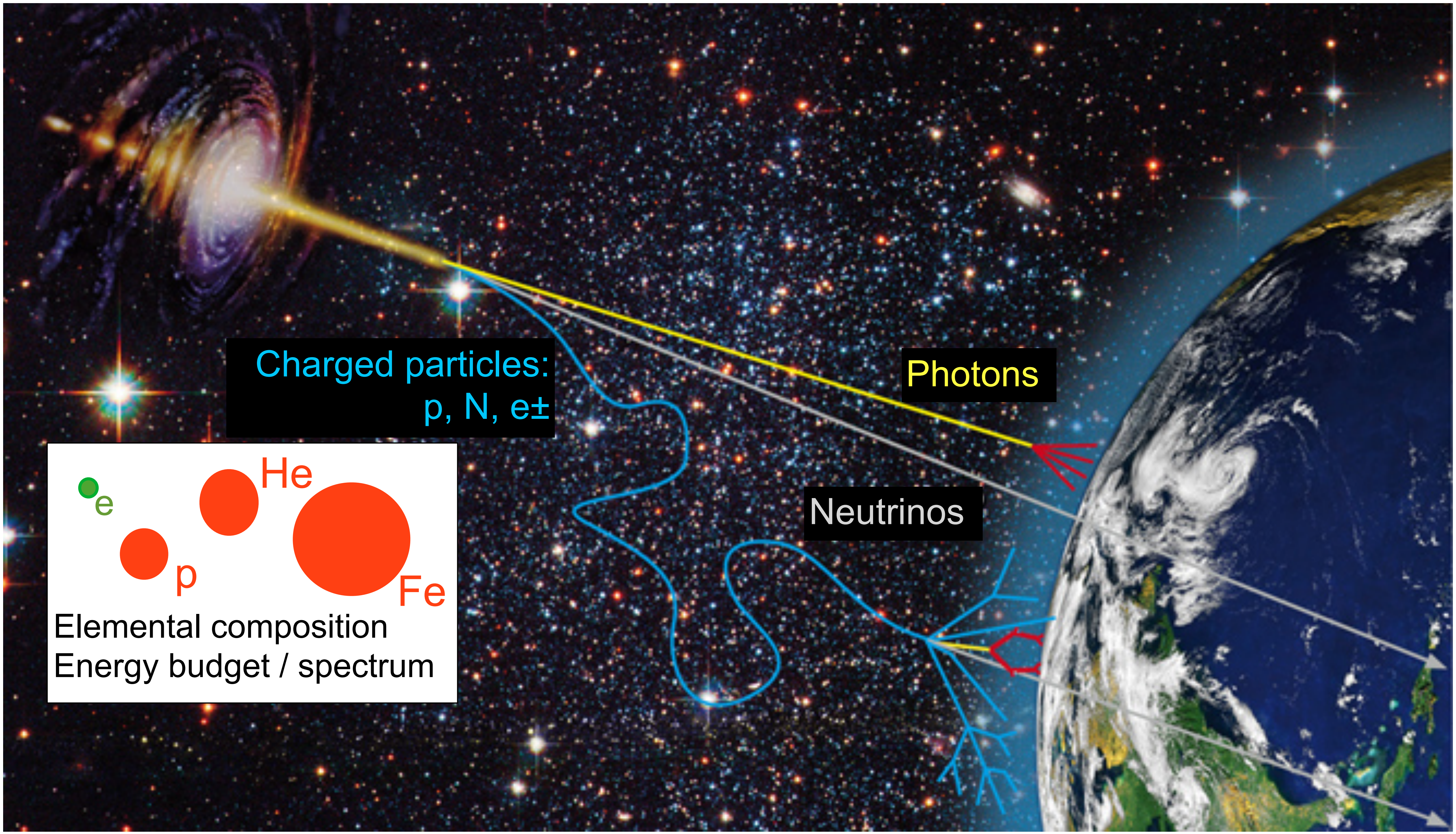

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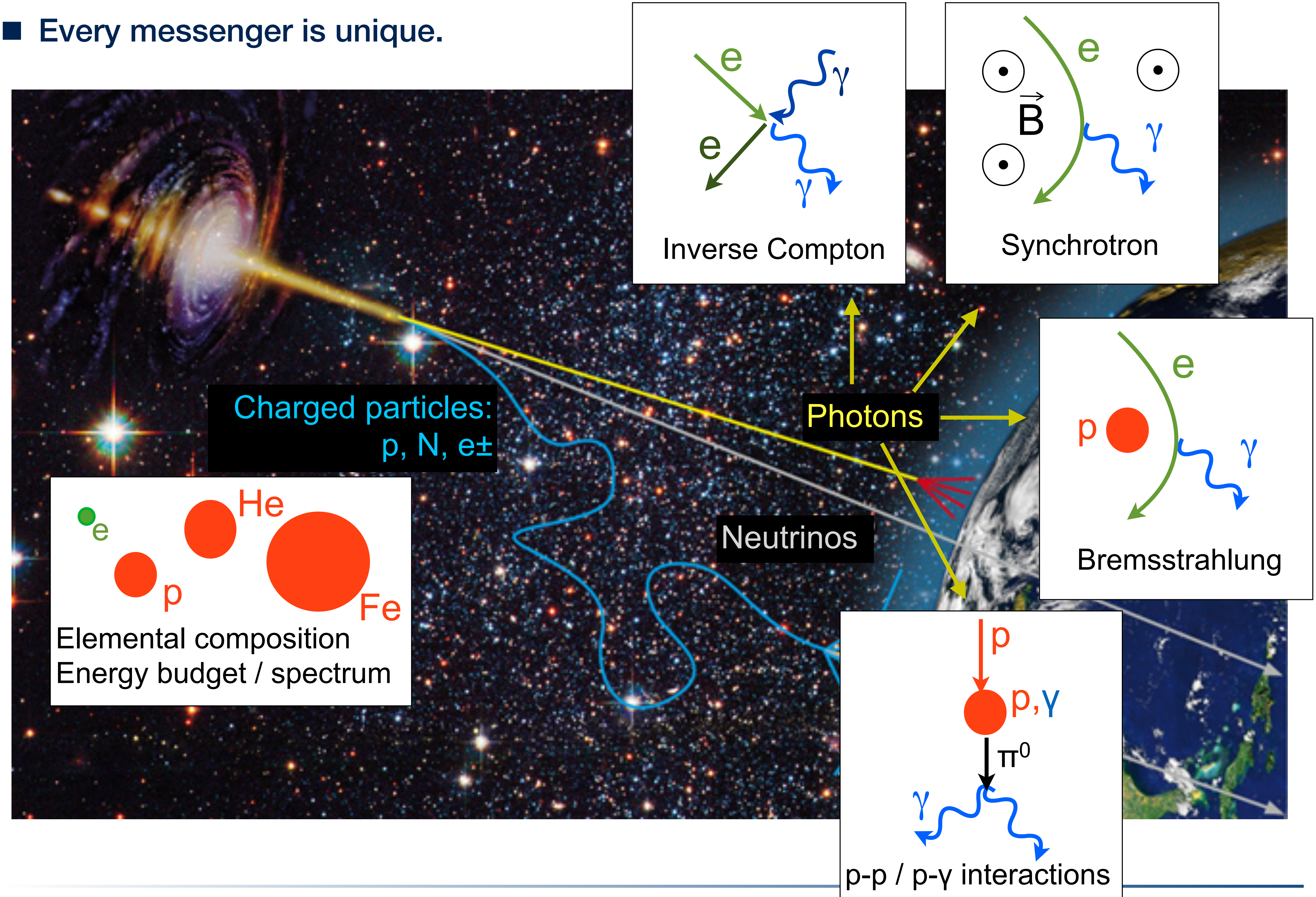

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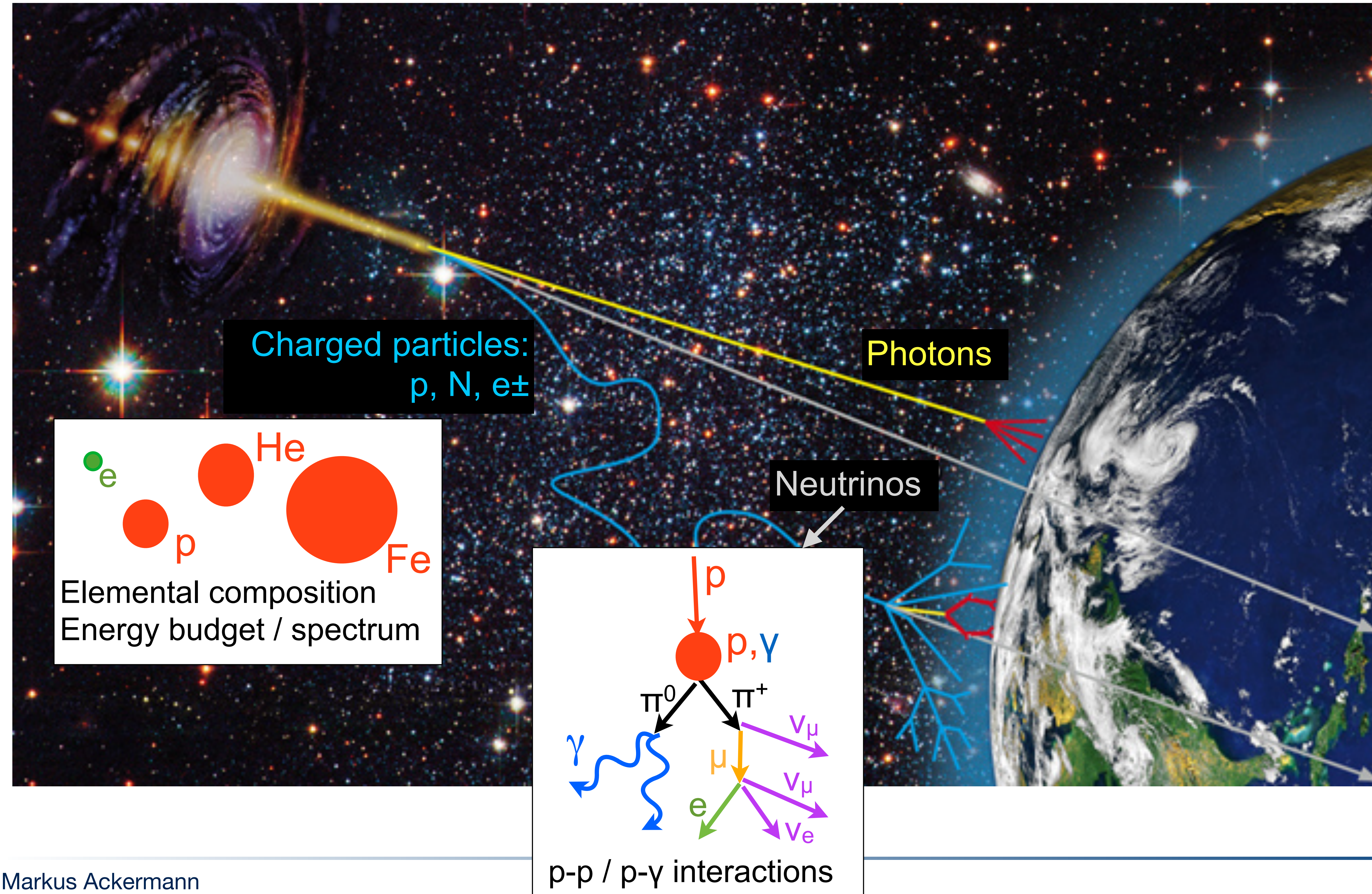
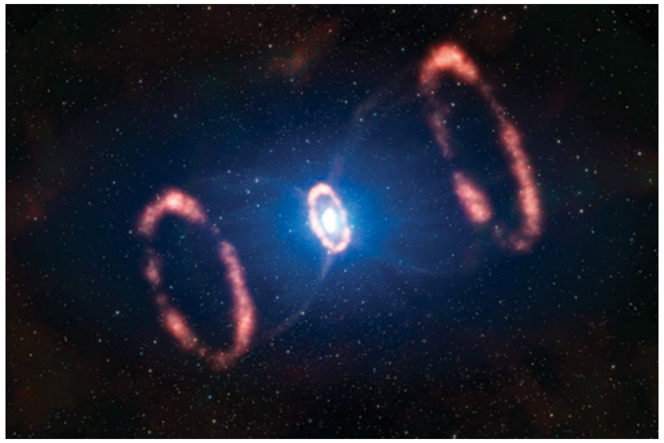
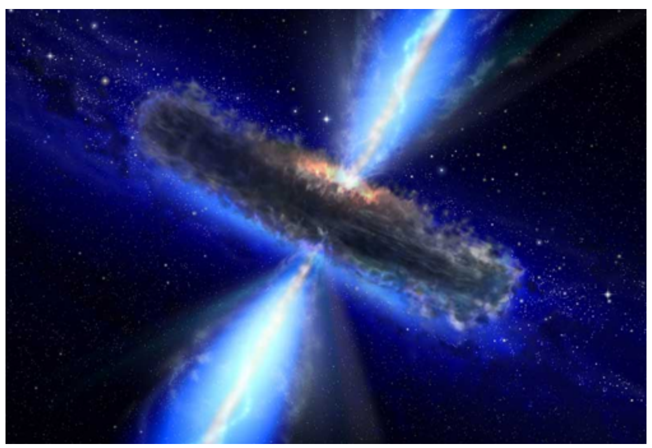


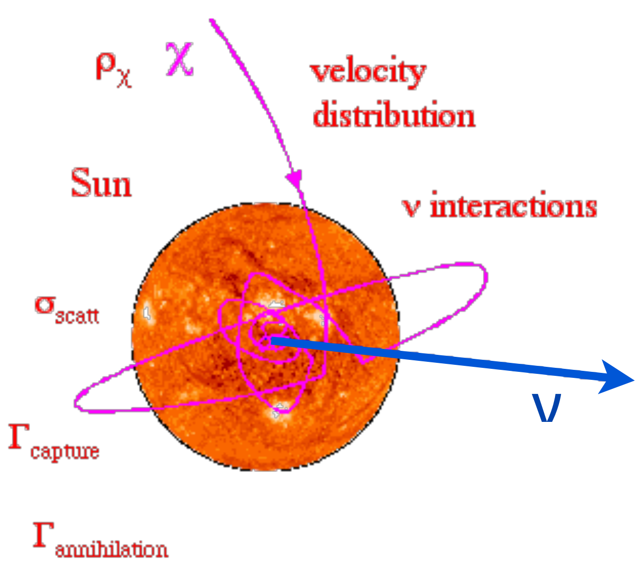
Neutrinos can escape dense environments



- High-energy neutrinos from core-collapse SNe. (e.g. Ando & Beacom, 2005)



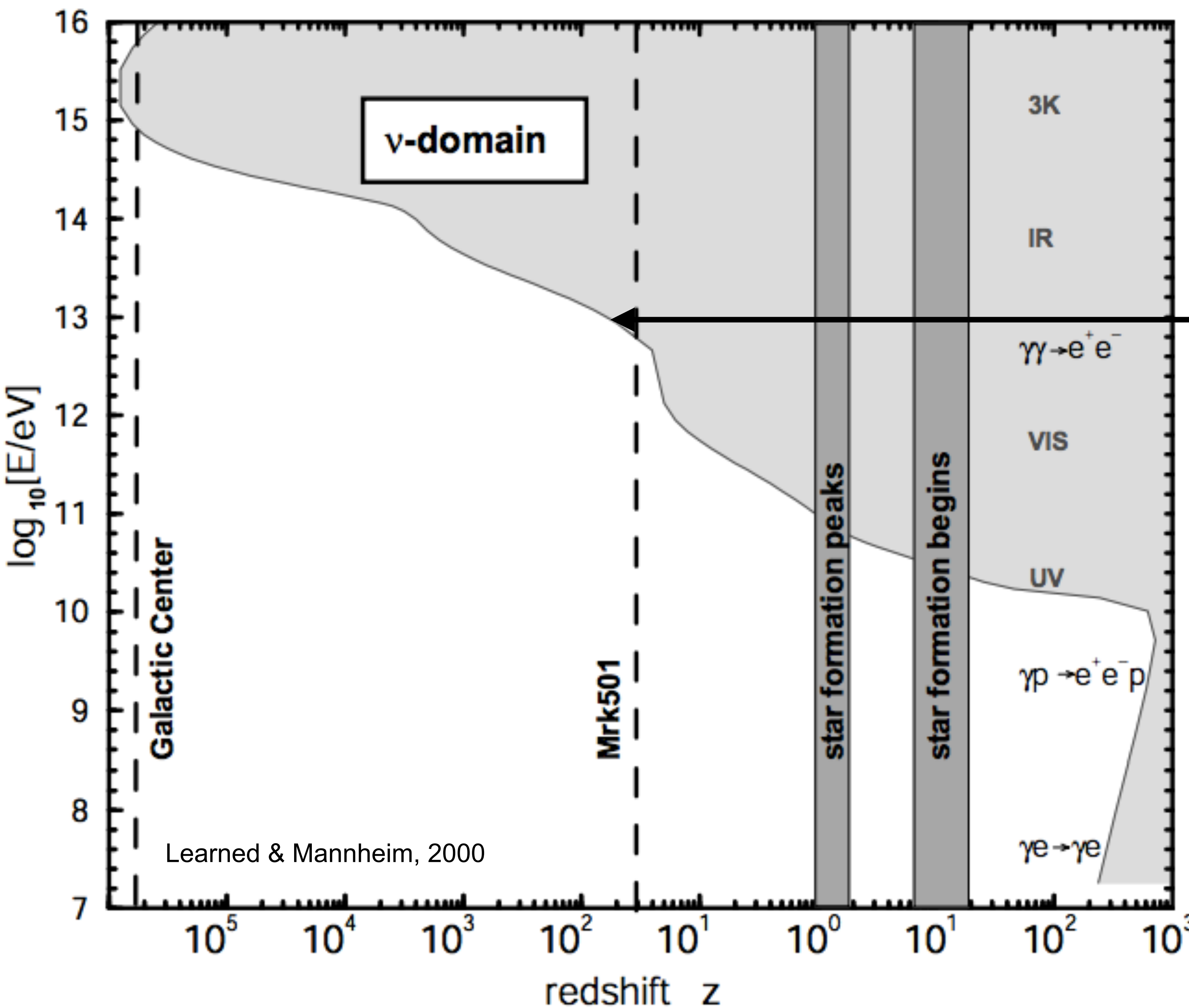
- Neutrinos from the cores of active galactic nuclei (e.g. Stecker et al., 1991)

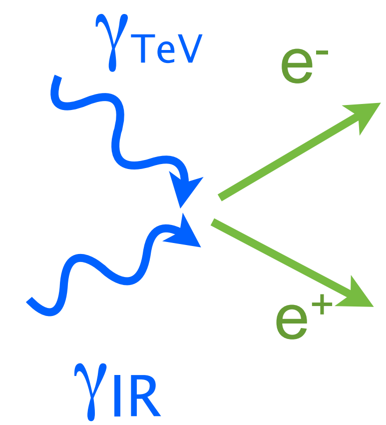


- High-energy neutrinos from dark matter annihilation in the sun.

The gamma-ray horizon

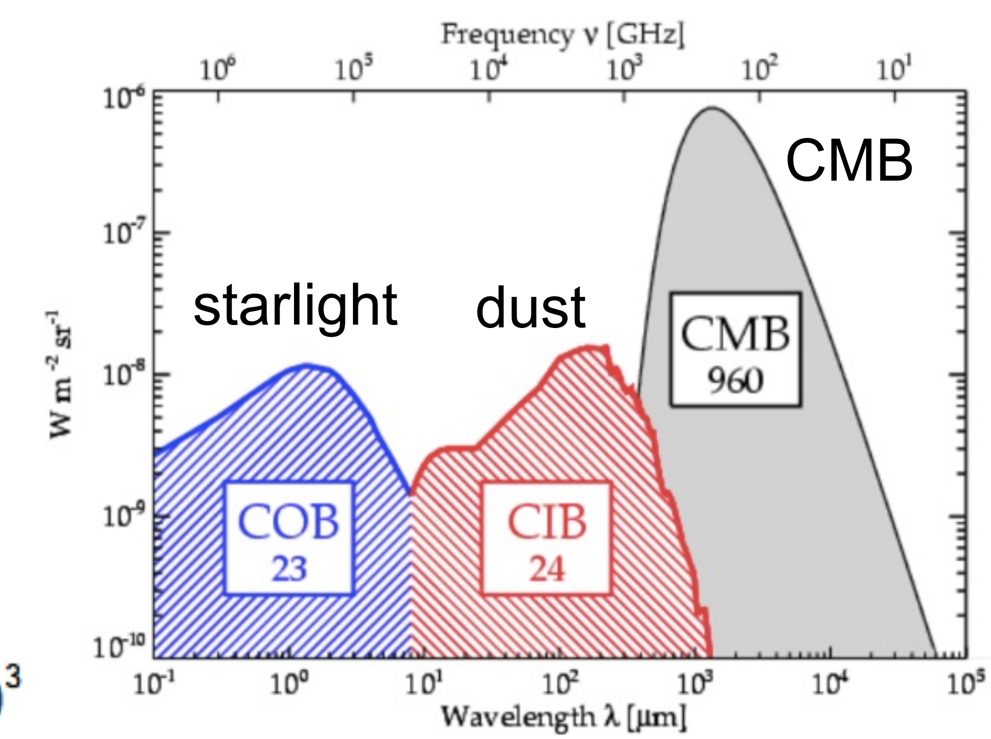
- Above 100 GeV the universe starts to turn opaque for γ-rays.
- Only neutrino telescopes can do astronomy at PeV/EeV energies.



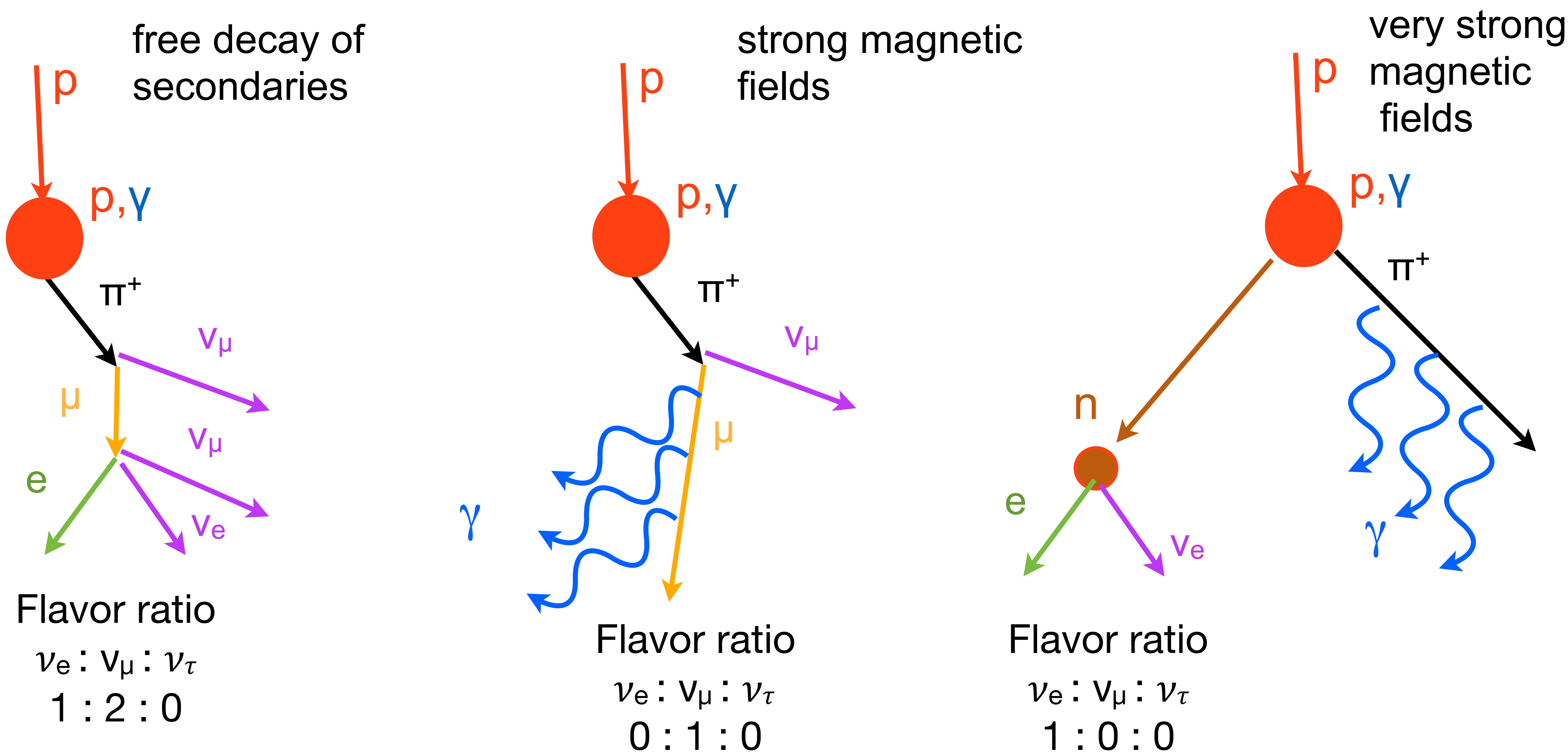


γ-ray horizon

Pair production in intergalactic photon fields



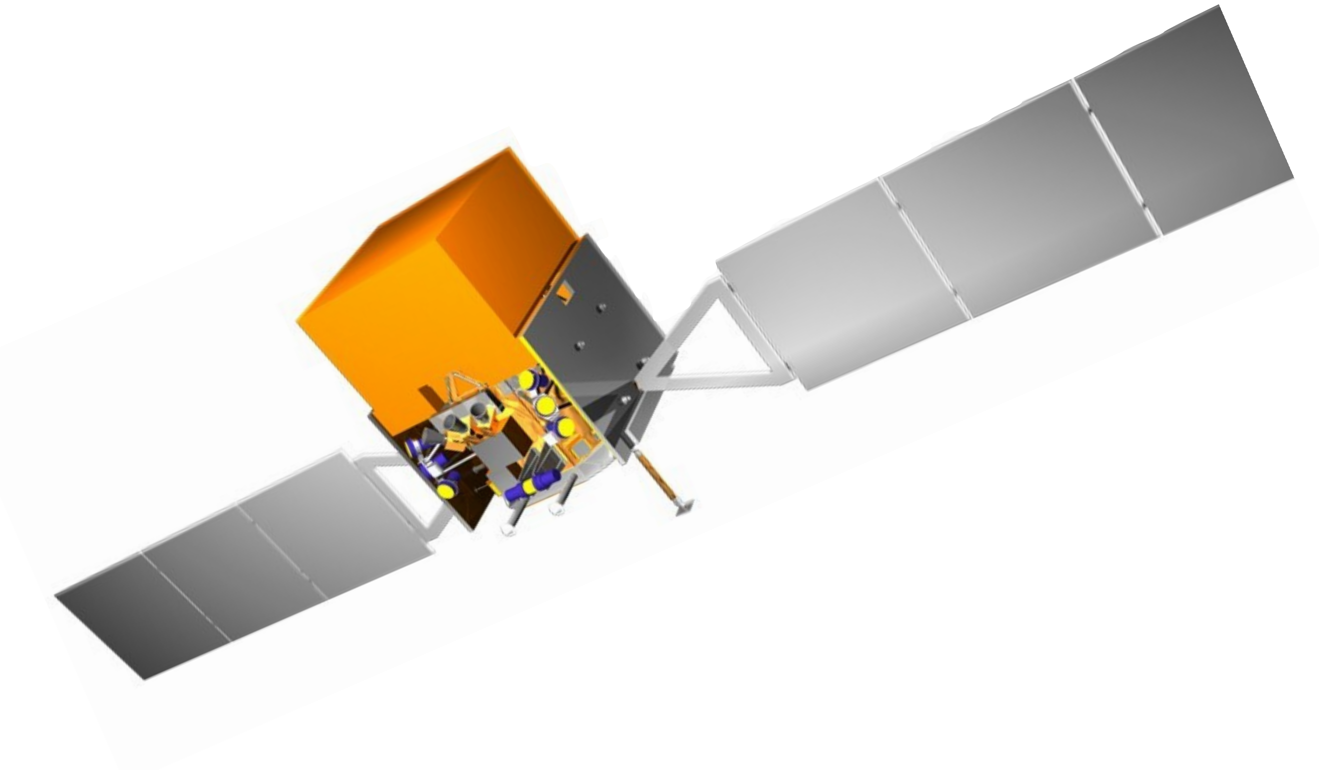
Neutrinos carry flavor



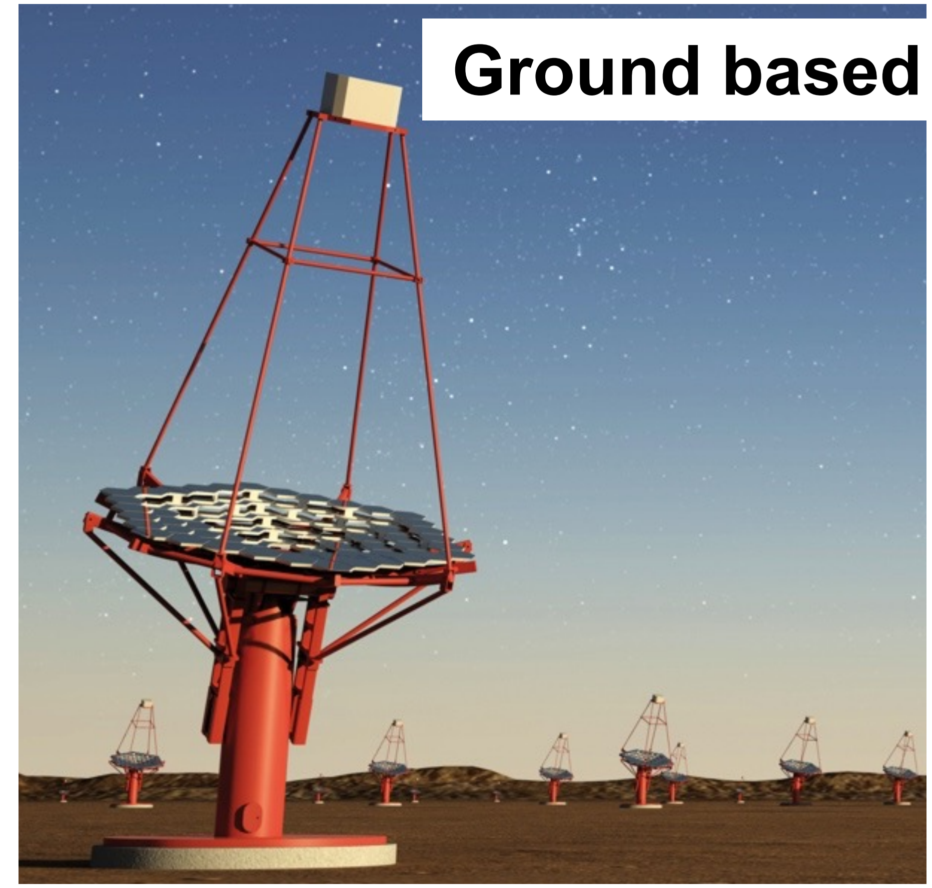
- Study of flavor ratios can help to distinguish production processes and environments
- Flavor ratios at Earth different to flavor ratios at source due to neutrino oscillations.

Detecting photons and neutrinos: Gamma-ray telescopes

Space based



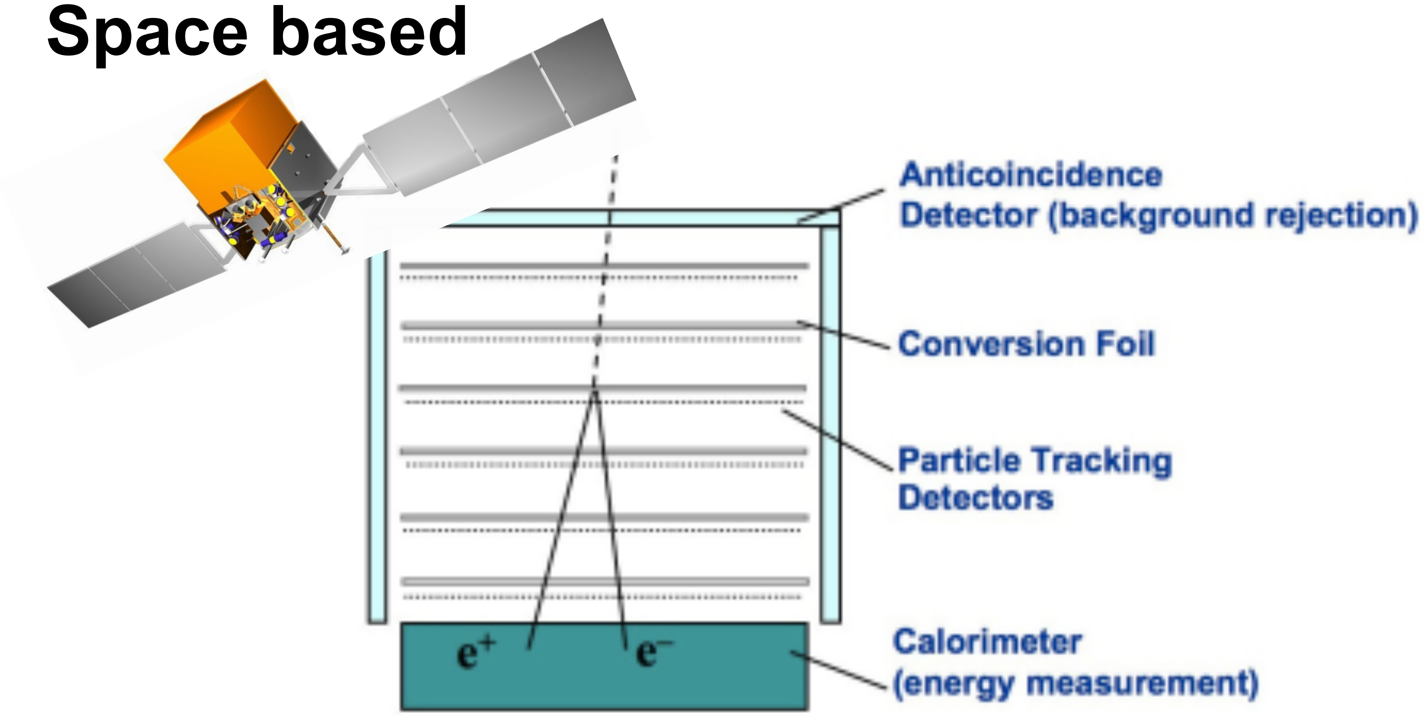
Ground based

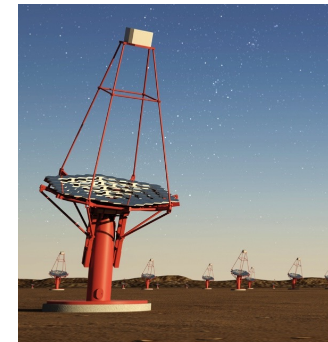


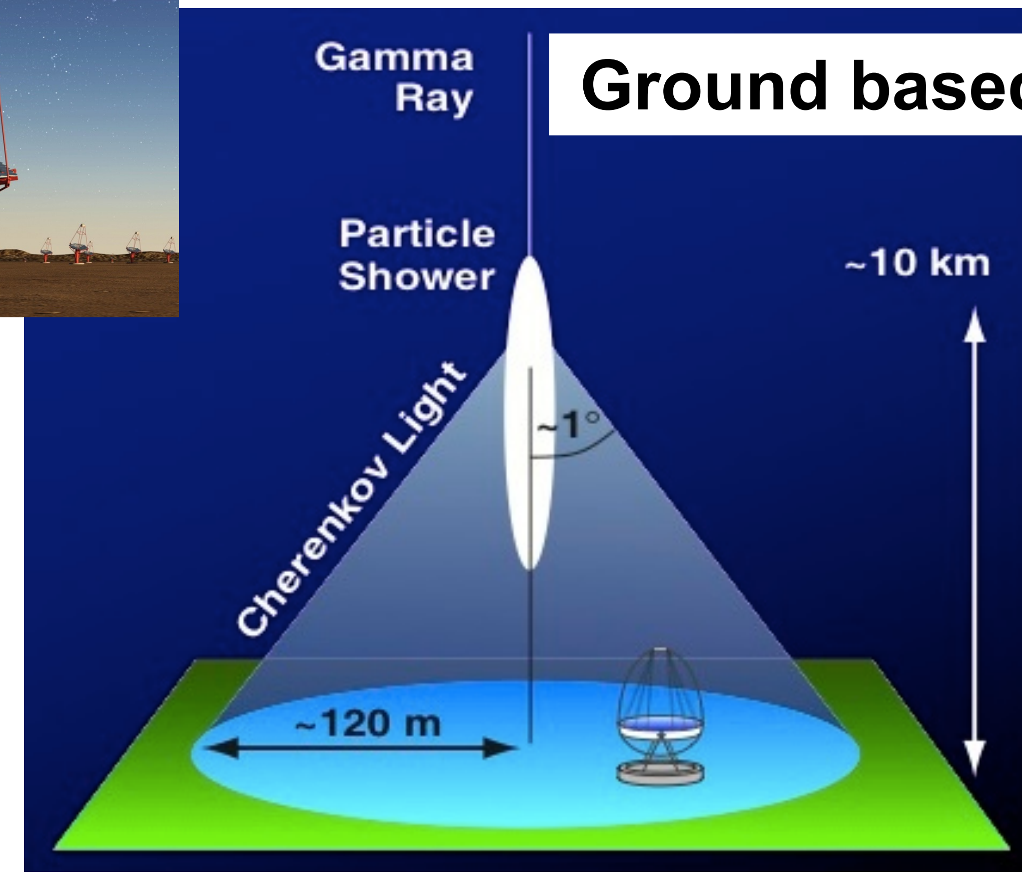
Fermi LAT	Instruments	HESS, MAGIC, Veritas
30 MeV - 1 TeV	**Energy range**	50 GeV - 100 TeV
20% of the sky	**Field-of-view**	~ 0.02% of the sky
~1 m^2	**Effective area**	~10000 m^2
85% of the year	**Duty cycle**	10% of the year

Gamma-ray telescopes

Space based







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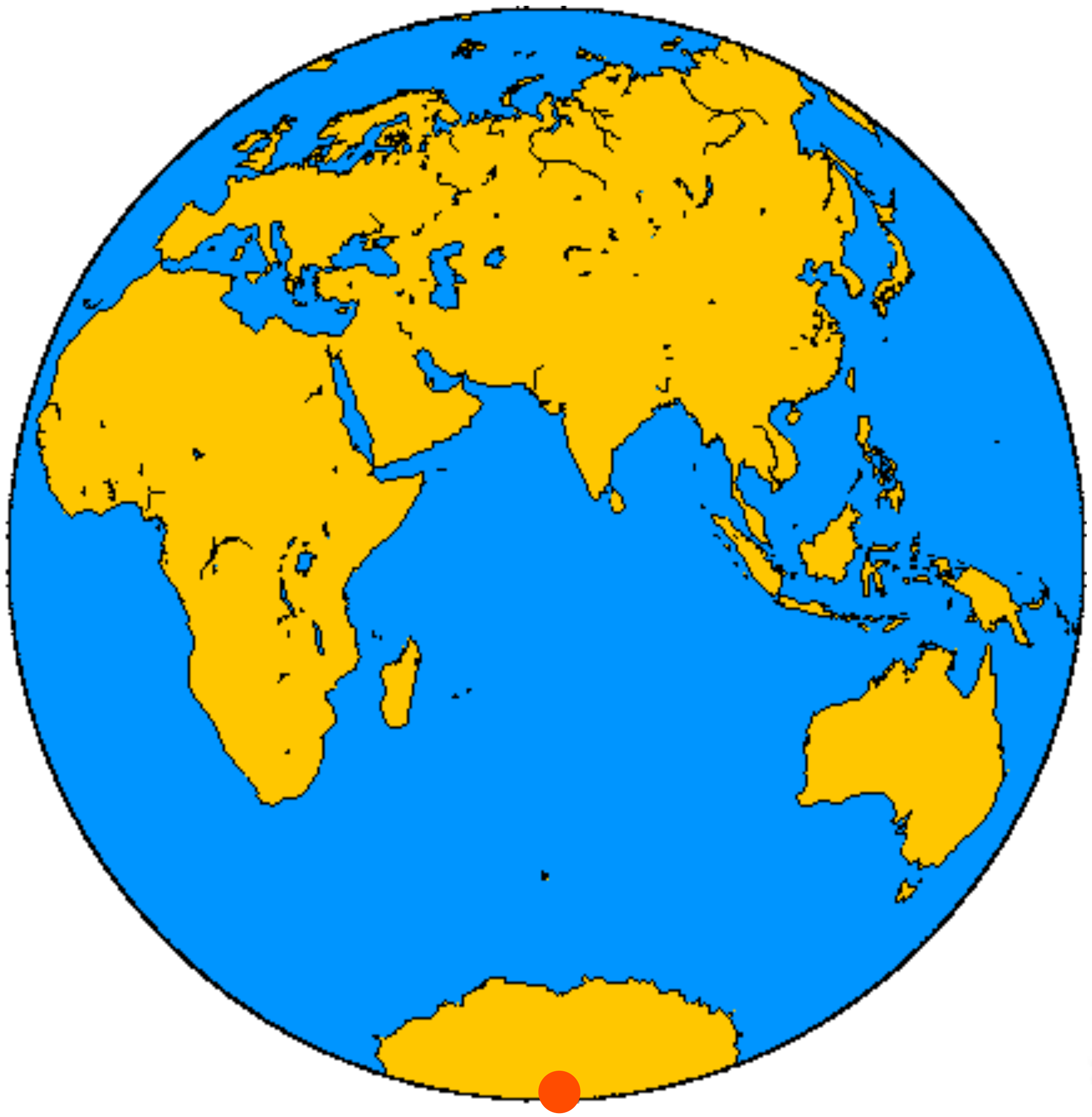
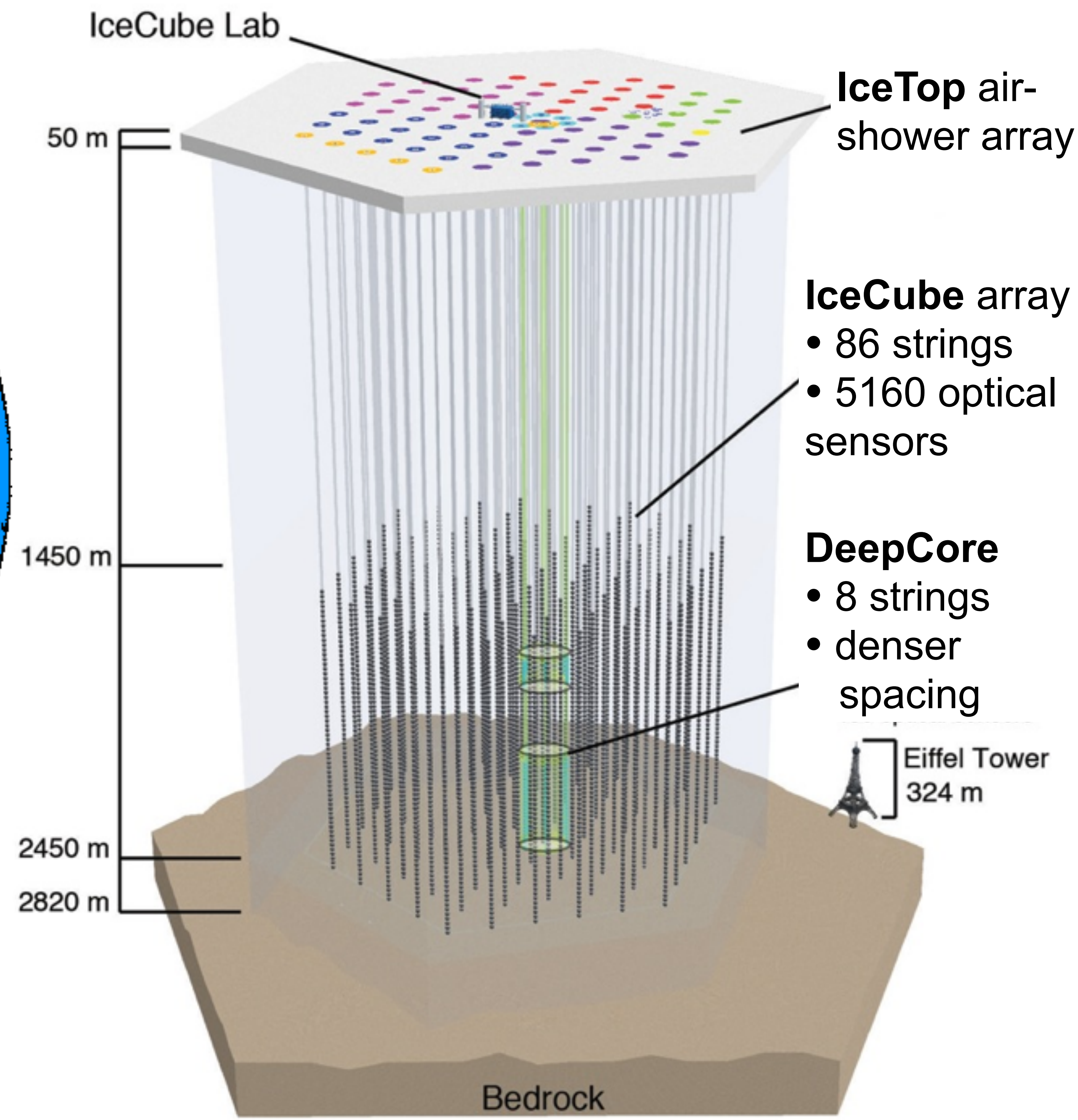
Neutrino Telescopes



IceCube

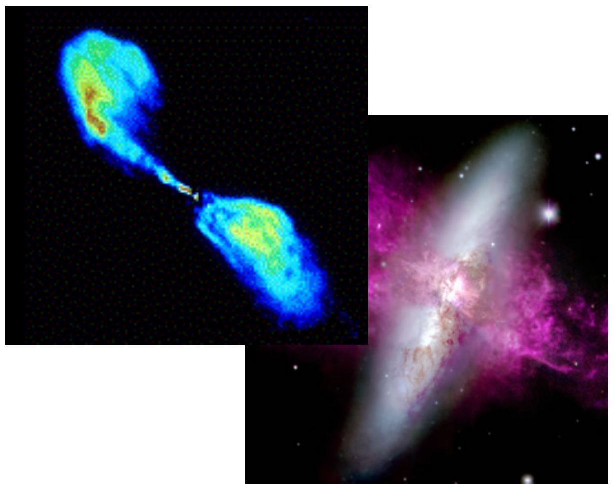


- Construction completed in 2010
- see talk by F. Halzen for details

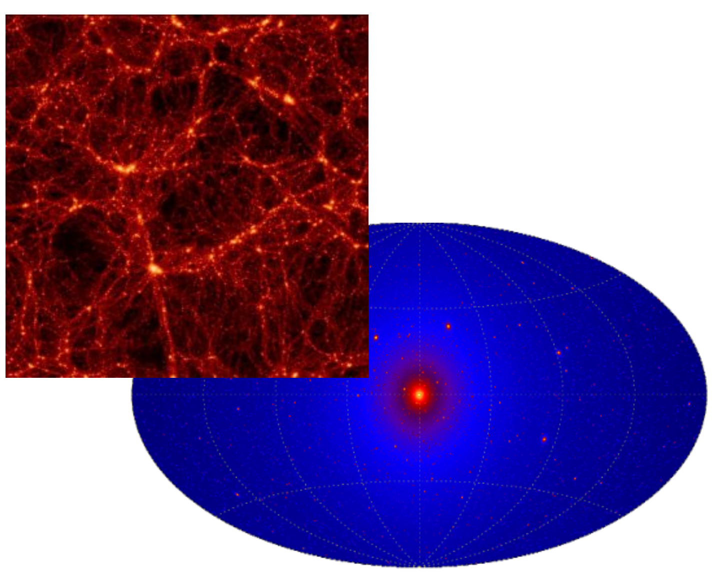
14

Science with gamma-ray and neutrino telescopes

.... two examples

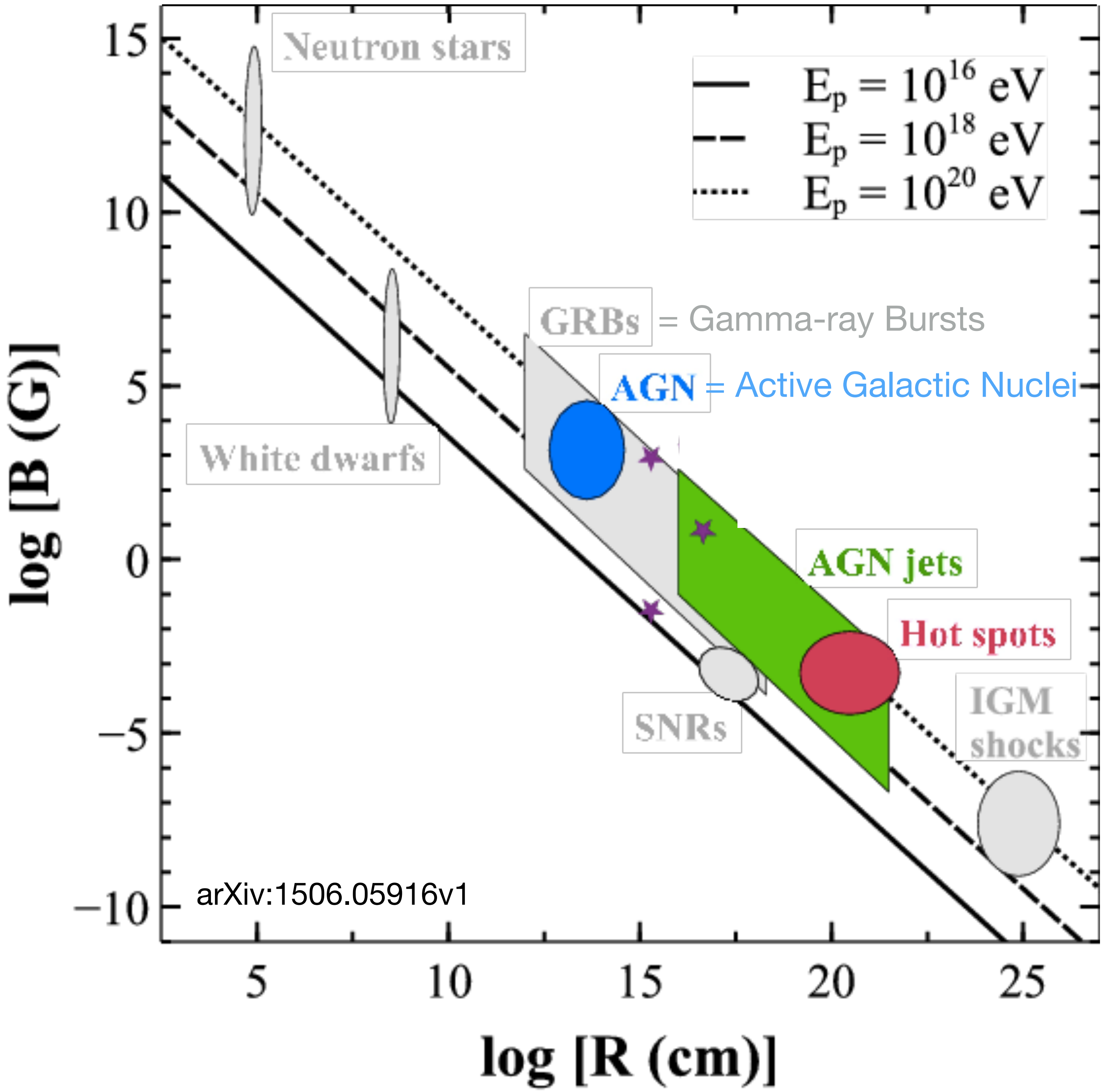


- What are the extragalactic sources that produce the highest energy cosmic rays?



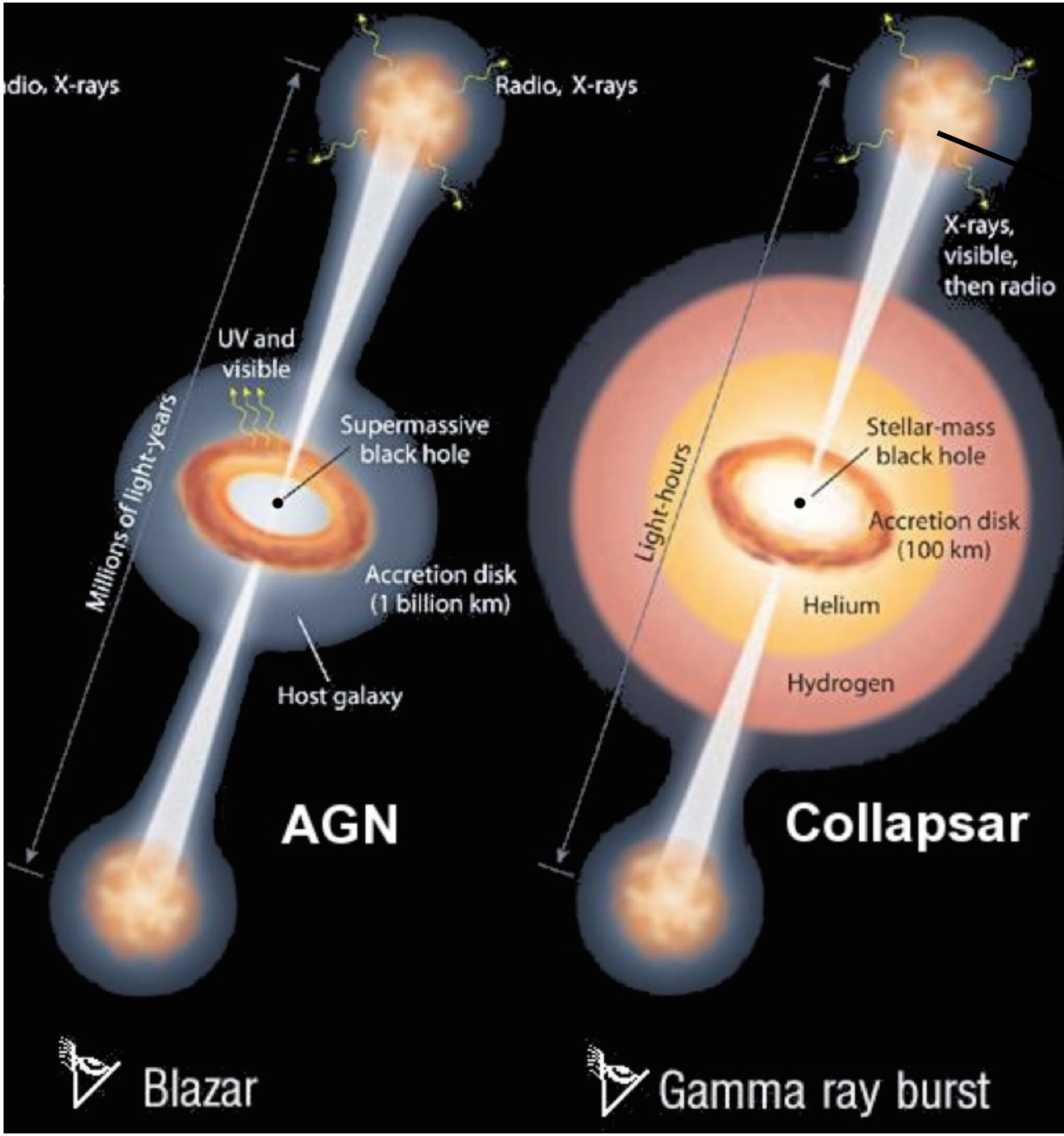
- What can we learn about WIMP dark matter ?

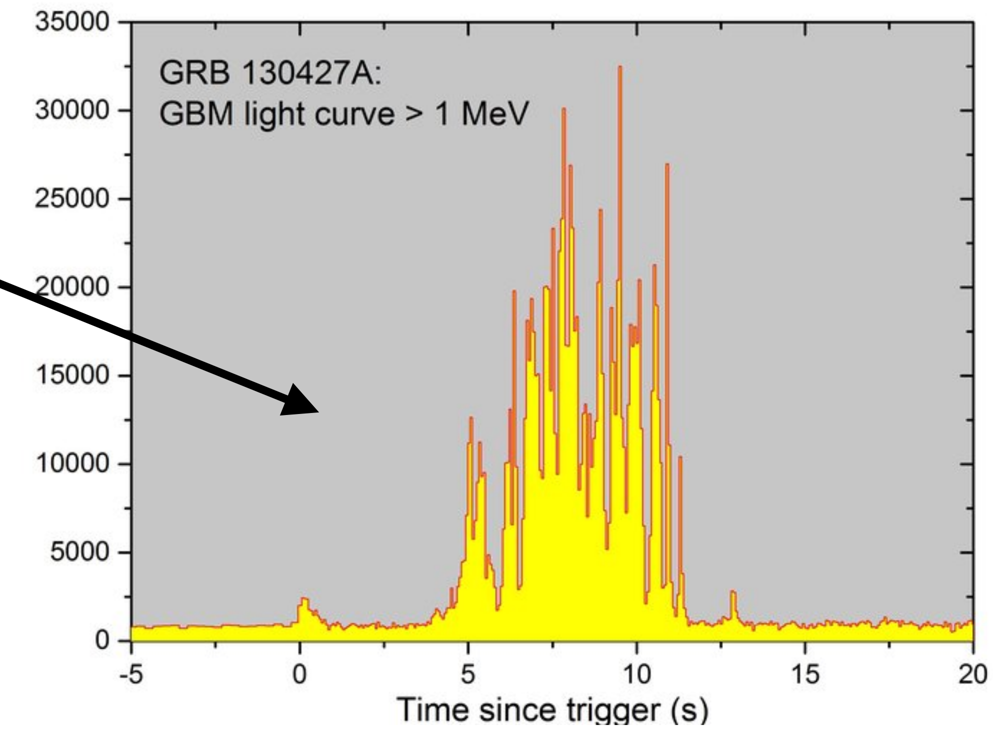
Why are the highest energy cosmic rays extragalactic ?



- **Hillas criterion:** Particle must be confined in acceleration region to be accelerated further
- Larmor radius <= size of acceleration region
- E_{max} <= q B r_{acc}
- Galactic accelerators do not have large enough B x r_{acc} to reach 10^{20} eV
- Caution: necessary but not sufficient criterion

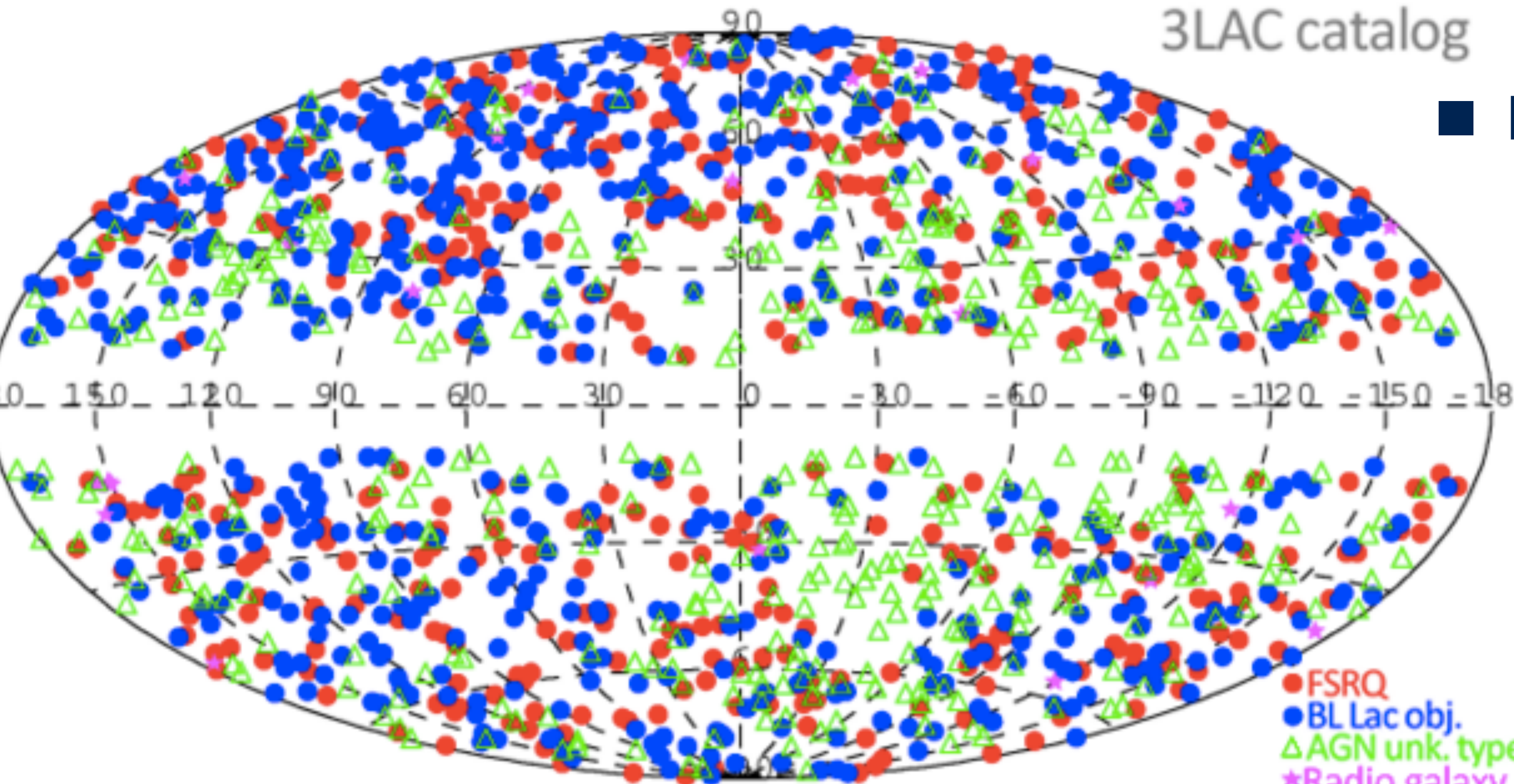
Active Galactic Nuclei and Gamma-ray bursts





- **Active Galactic Nucleus:** Accretion of matter around supermassive black hole produces relativistic jets
- **Gamma-ray Bursts:** Stellar core collapse produces short-lived highly relativistic jets

Active Galactic Nuclei and Gamma-ray bursts in gamma rays

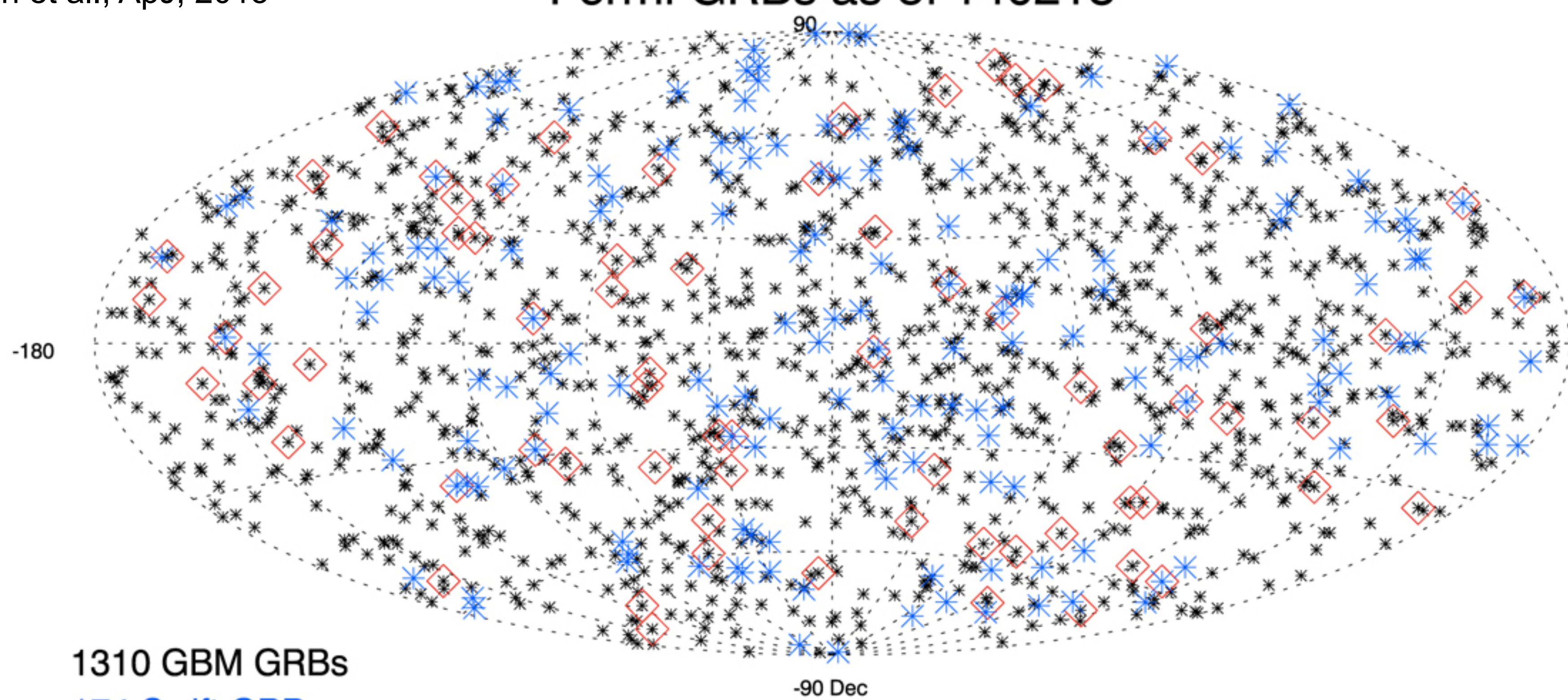


Ackermann et al., ApJ, 2015

- **Blazars:**
  - Most abundant extragalactic source of high-energy gamma rays
  - Responsible for >~ 90% of total extragalactic gamma-ray radiation

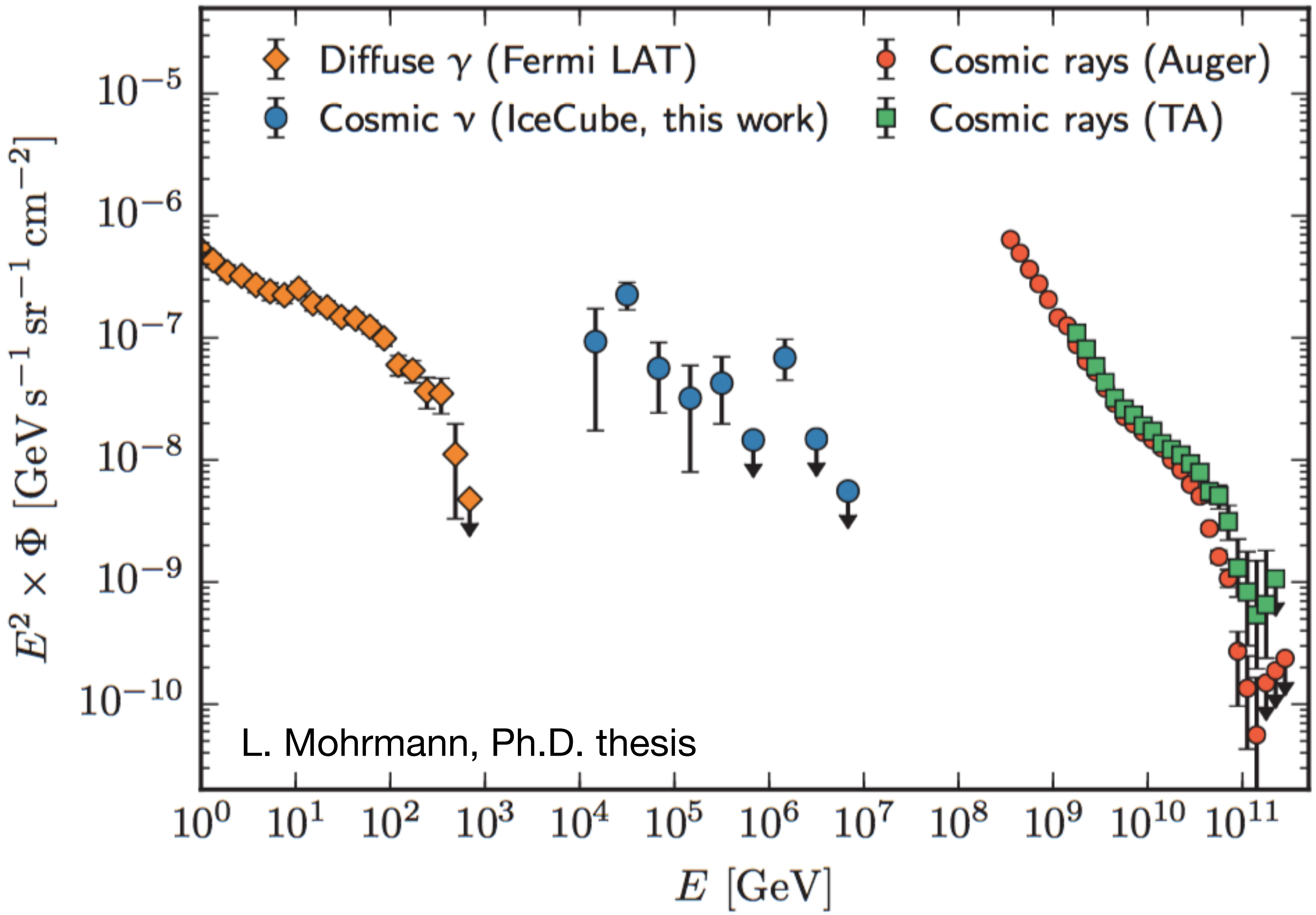
- **Gamma-ray Bursts:**
  - Dominant transient phenomenon on gamma-ray sky

Fermi GRBs as of 140218



1310 GBM GRBs
174 Swift GRBs
73 LAT GRBs

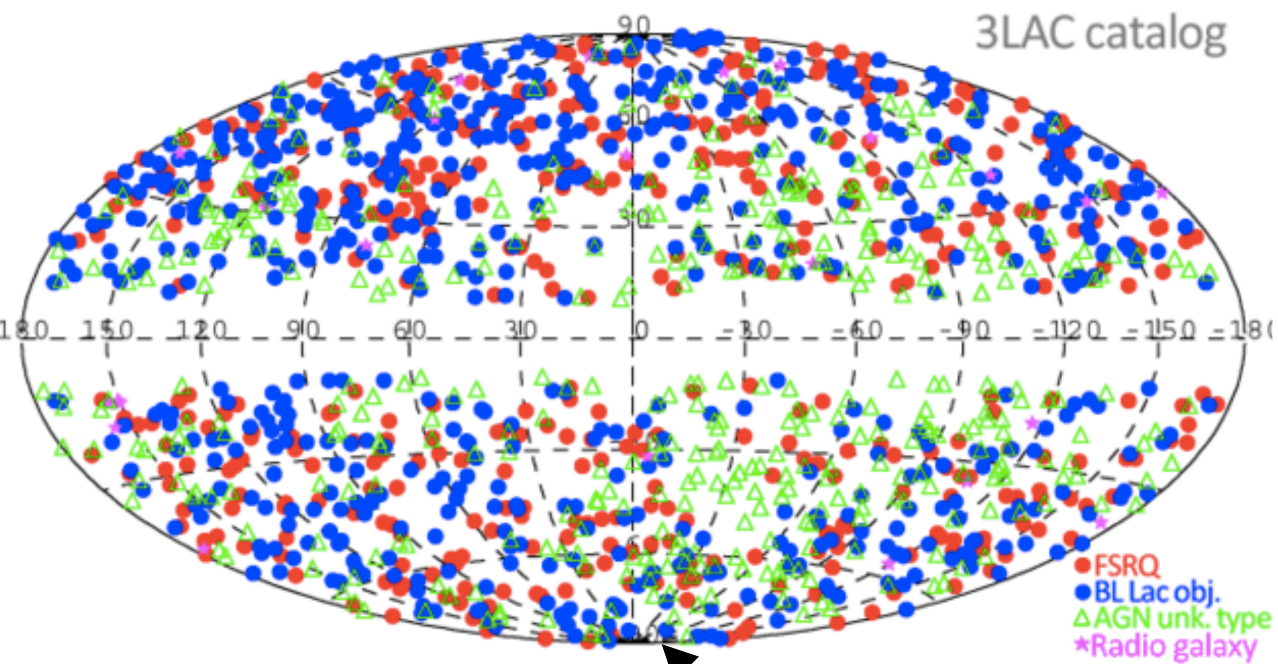
Connection to neutrinos and cosmic rays

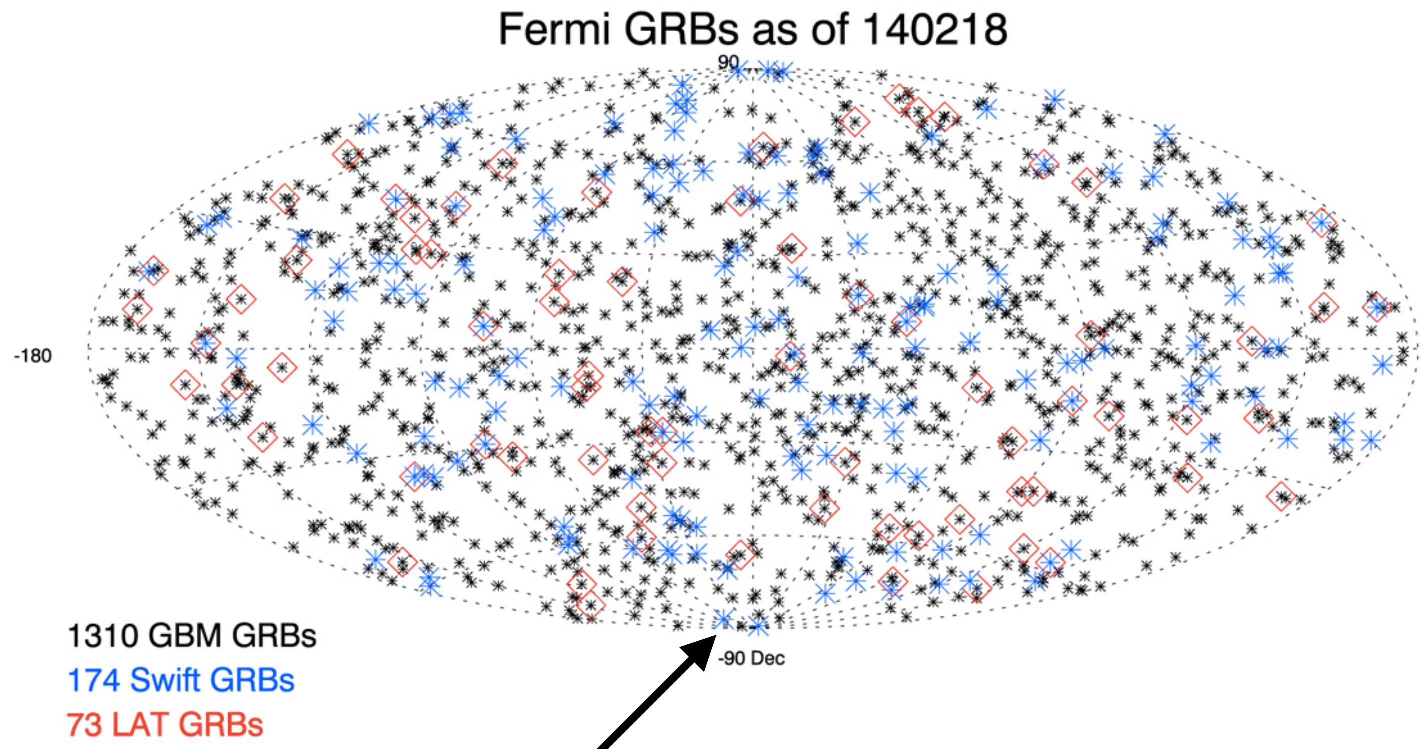


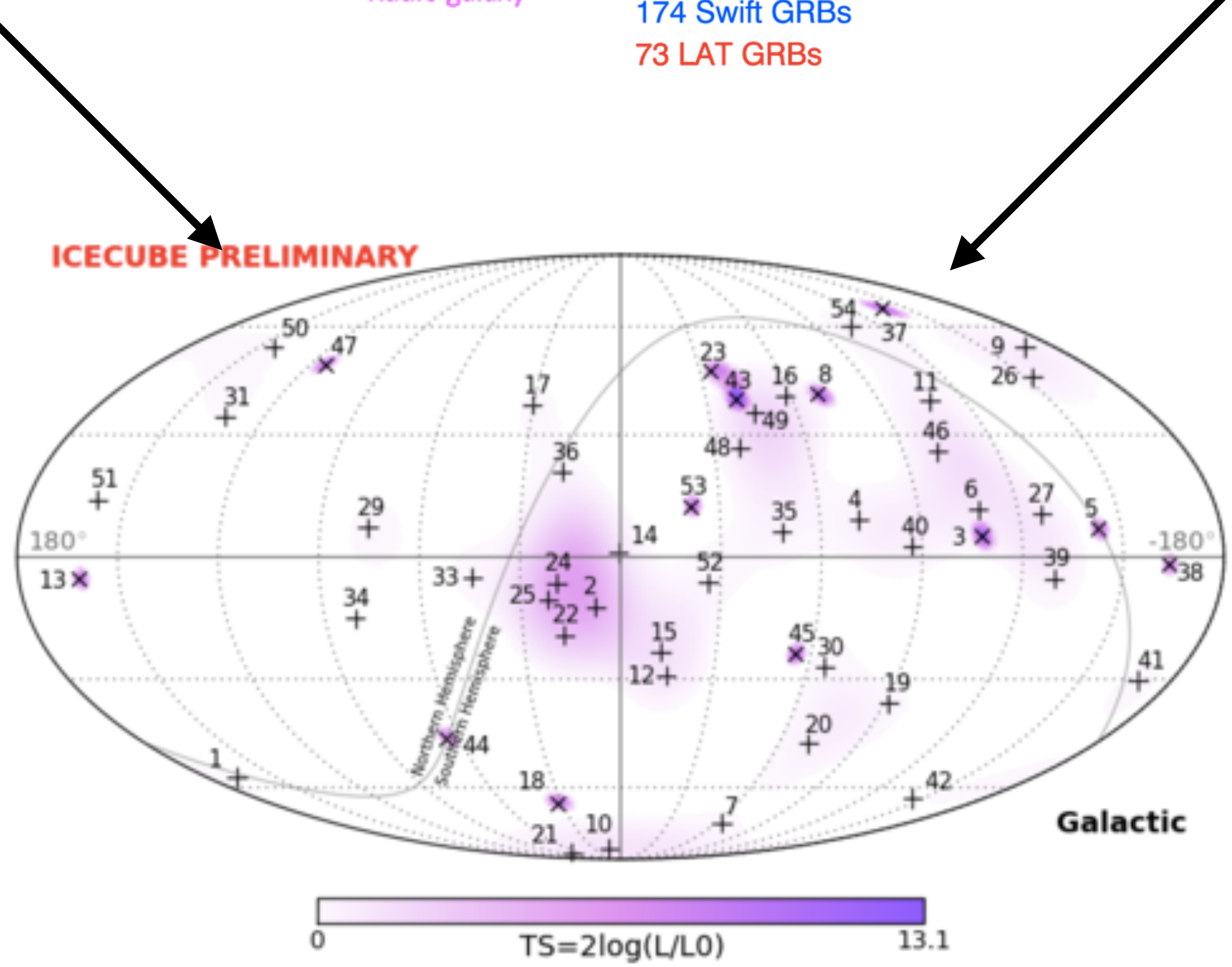
- **Gamma rays alone cannot probe the presence of ultra-high-energy cosmic rays.**
  - GeV gamma-rays could be produced by interactions of TeV electrons

- **A correlation to the observed cosmic neutrinos would be a strong indication that we indeed see the accelerators of UHECR.**

Correlation between AGN, GRB and cosmic neutrinos

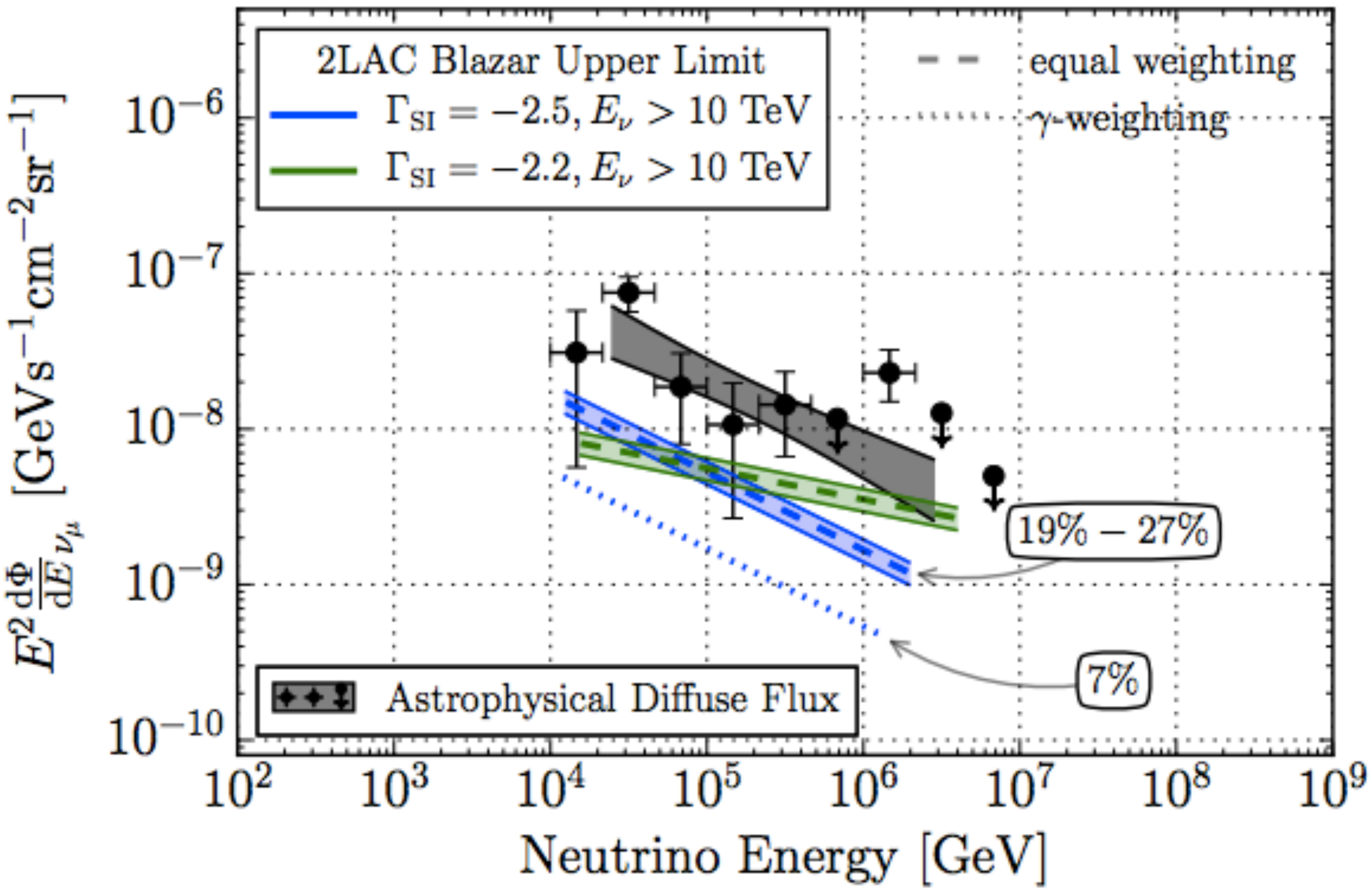






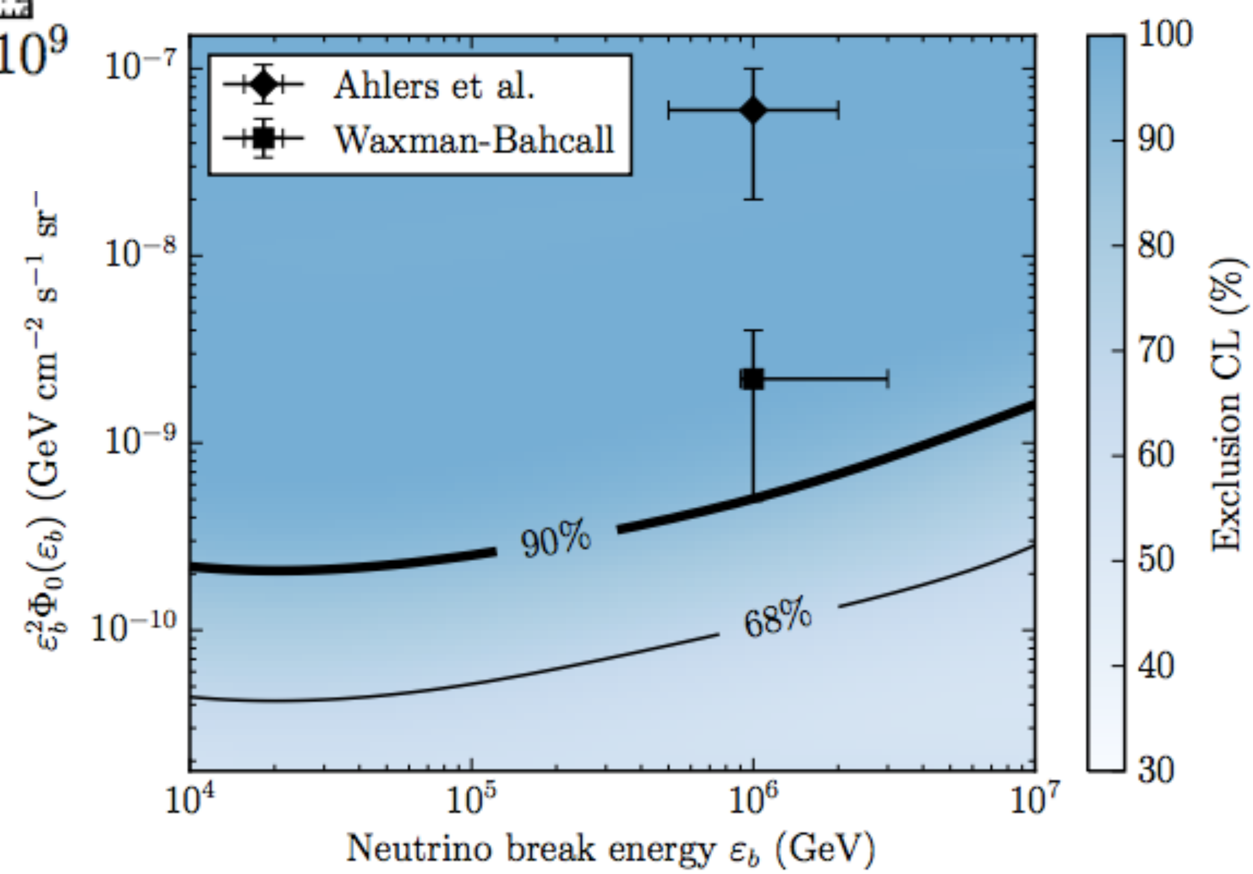
- No correlation found between neutrinos and Gamma-ray Blazars or GRBs

Implications

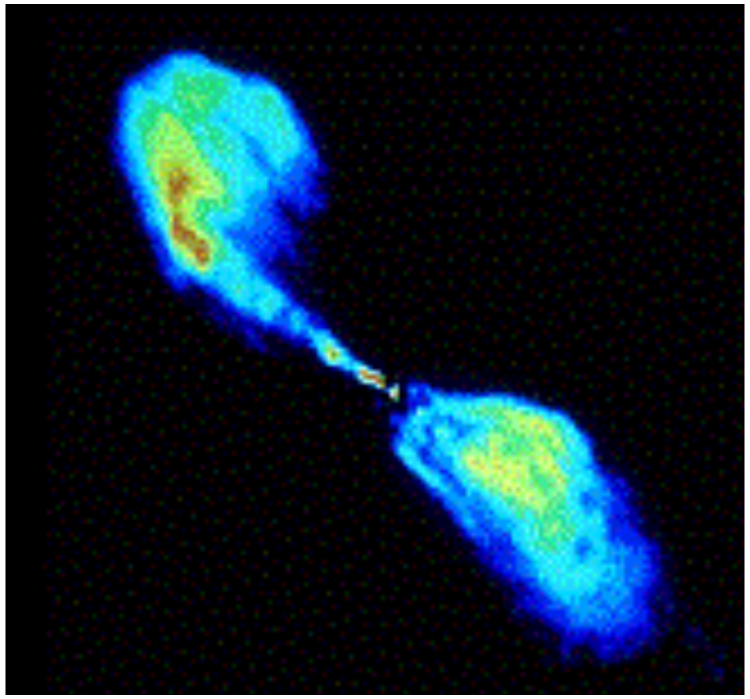


- Gamma-ray Blazars can contribute only a small fraction to the observed neutrino flux
- Non-observation of neutrinos in coincidence with GRBs excludes model predictions (which assume that they are the dominant CR production sources)

- **Implications:**
  - Source properties could suppress neutrino production
  - Observed neutrino signal is unrelated to sources producing UHECR
  - Other sources are responsible for UHECR (see next slide)
  - Gamma rays from these sources are suppressed through internal absorption



Other source candidates



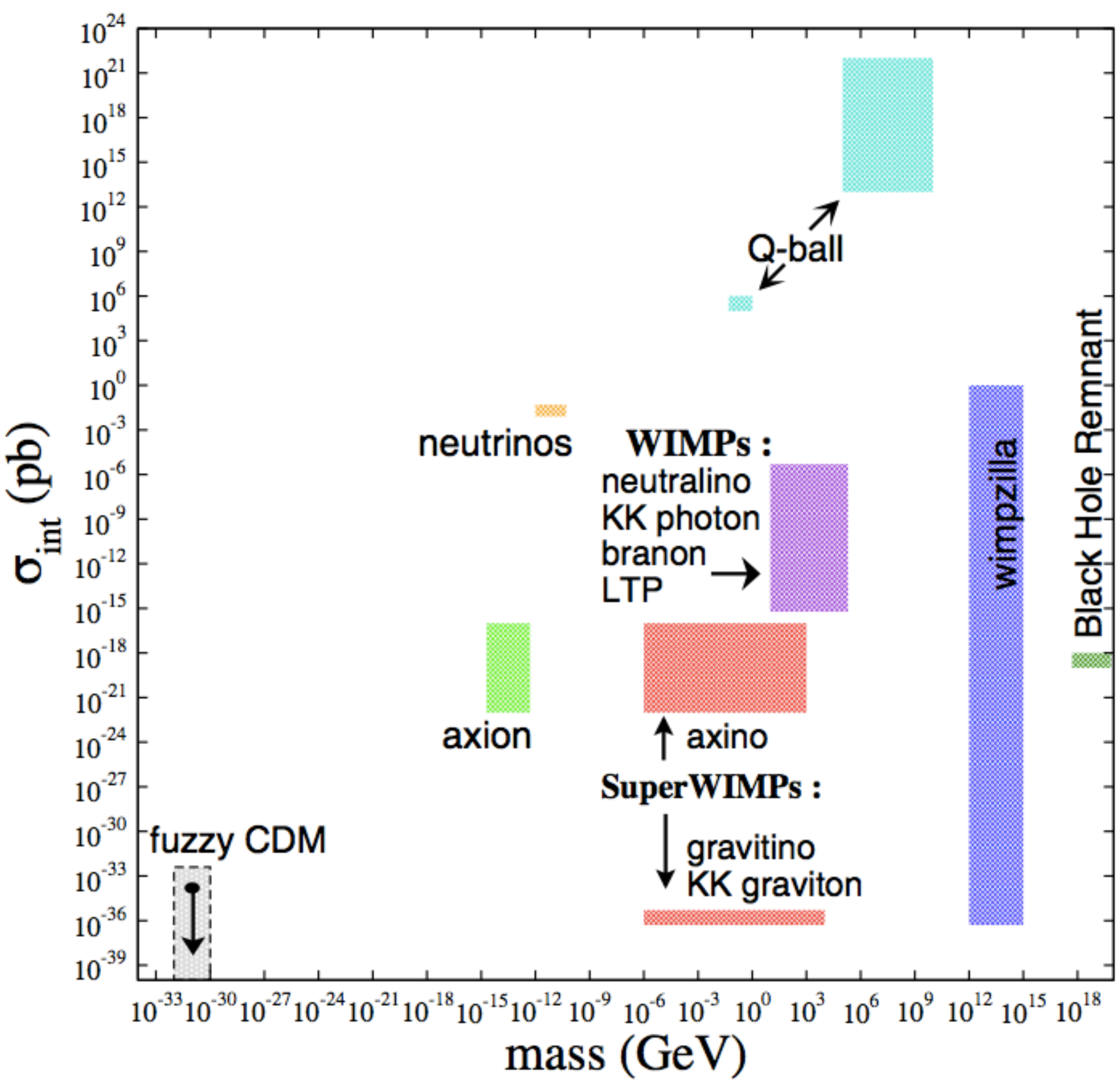
- **Cores / accretion disks of Active Galactic Nuclei**
  - Shocks in accretion disk or magnetic reconnection could accelerate particles.
  - Intense UV - X-ray photon fields might absorb gamma rays and present a good target for neutrino production.
  - 10^{20} eV seems difficult to reach with shock acceleration

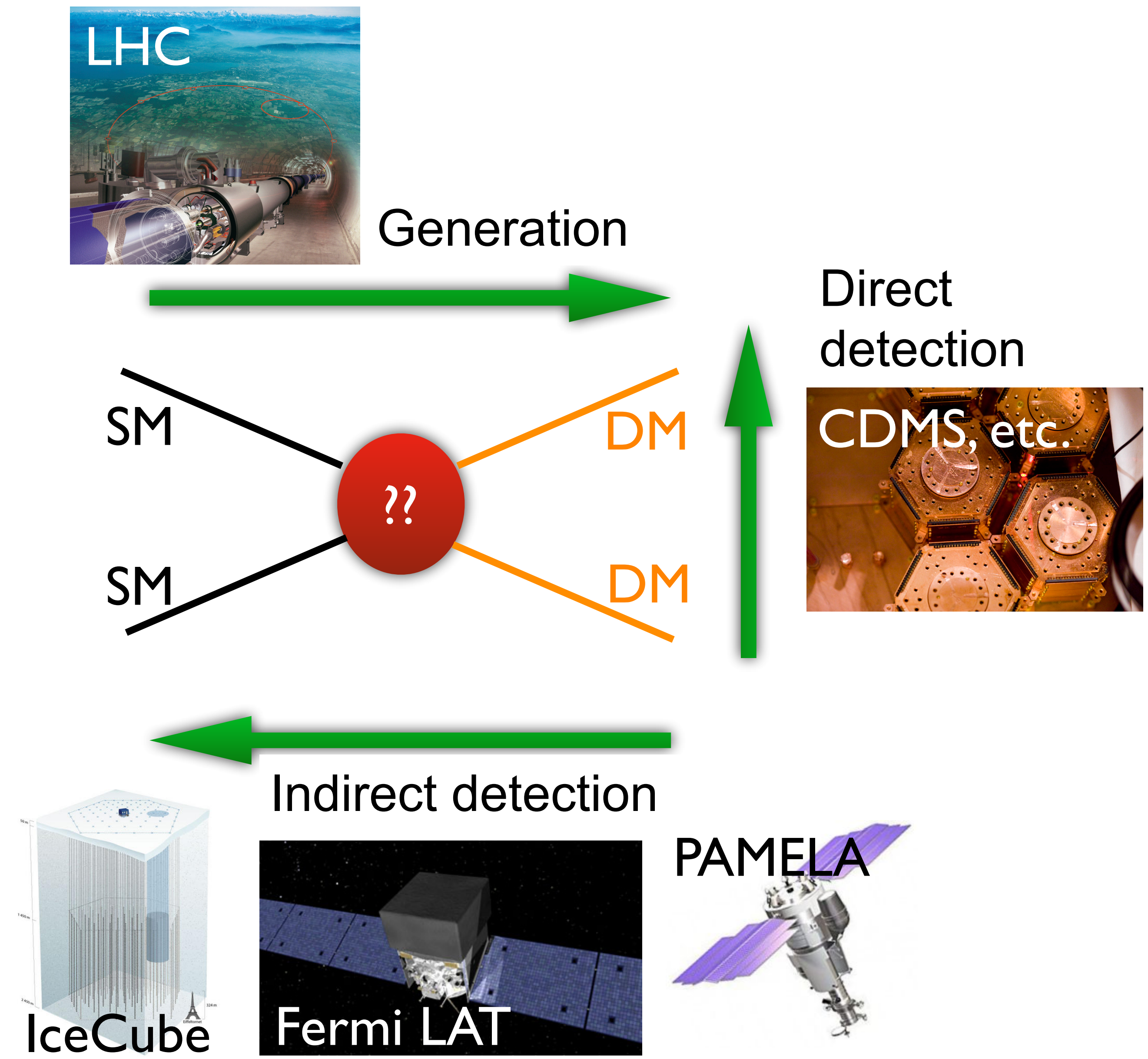
- **Starburst Galaxies**
  - Galaxies with extreme rates of star formation in specific regions (starburst region)
  - Not clear if shocks in starburst region are strong enough to accelerate particles to 10^{20} eV
  - Usually assumed transparent to gamma-rays —> difficult to reconcile with observed gamma-ray sky

… the puzzle just has gotten more interesting.

Neutrinos, gamma rays & new physics

- We know that cold dark matter dominates the matter in the universe
- Many candidate dark matter particles from particle physics (theory).
- Identification of DM particles by observation of
  - creation in accelerators,
  - scattering in direct detection experiments
  - annihilation/decay





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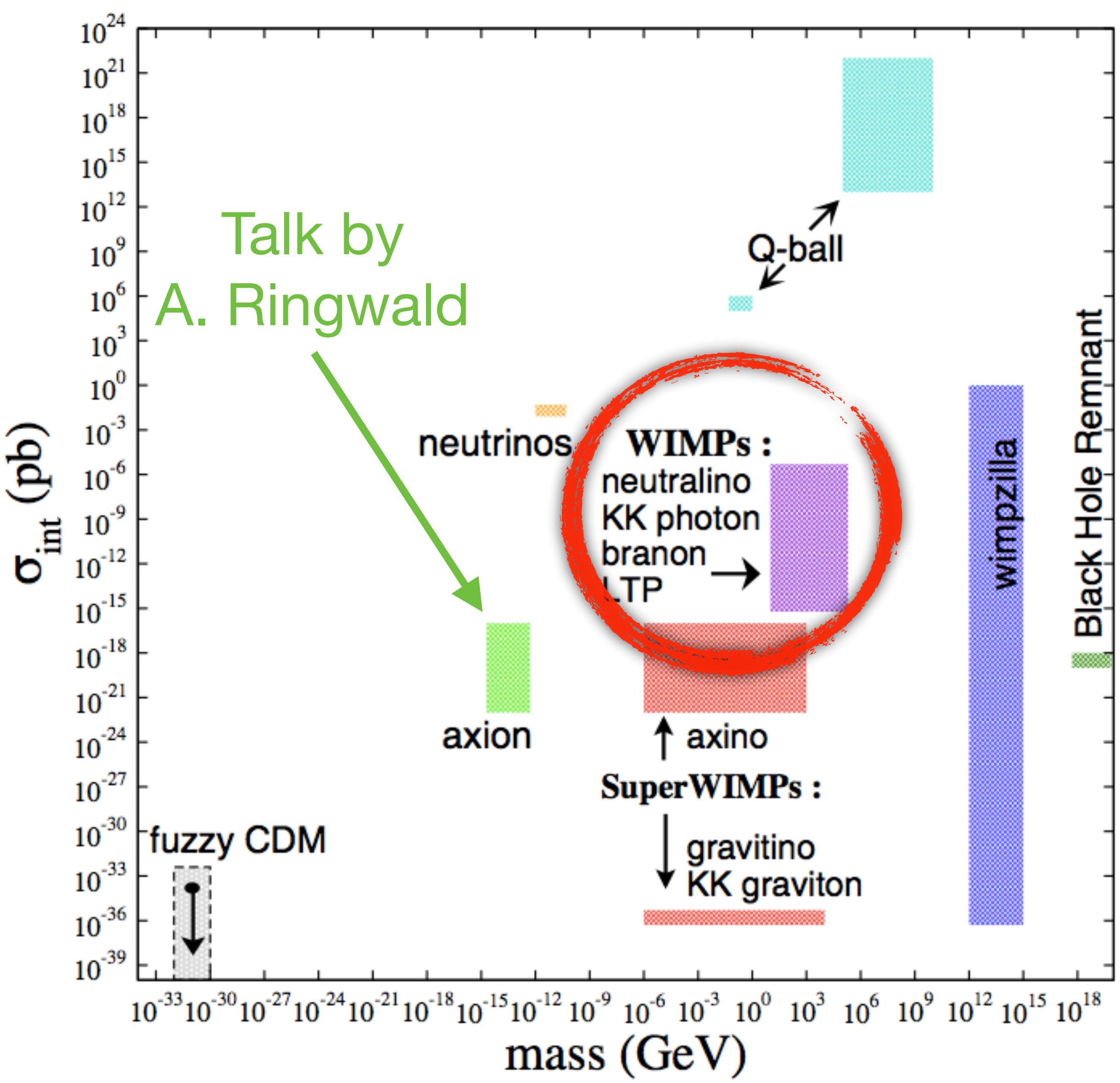
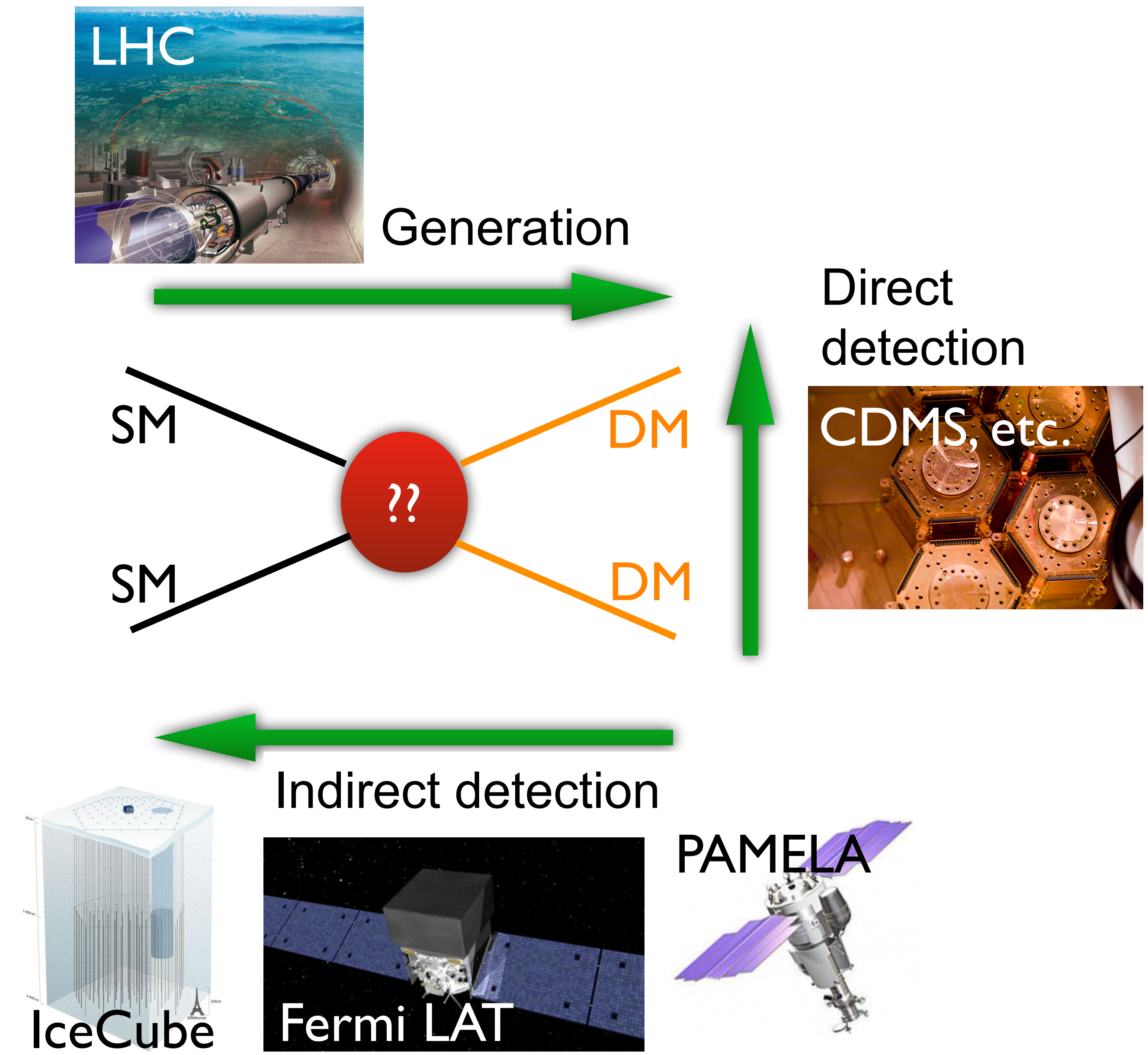
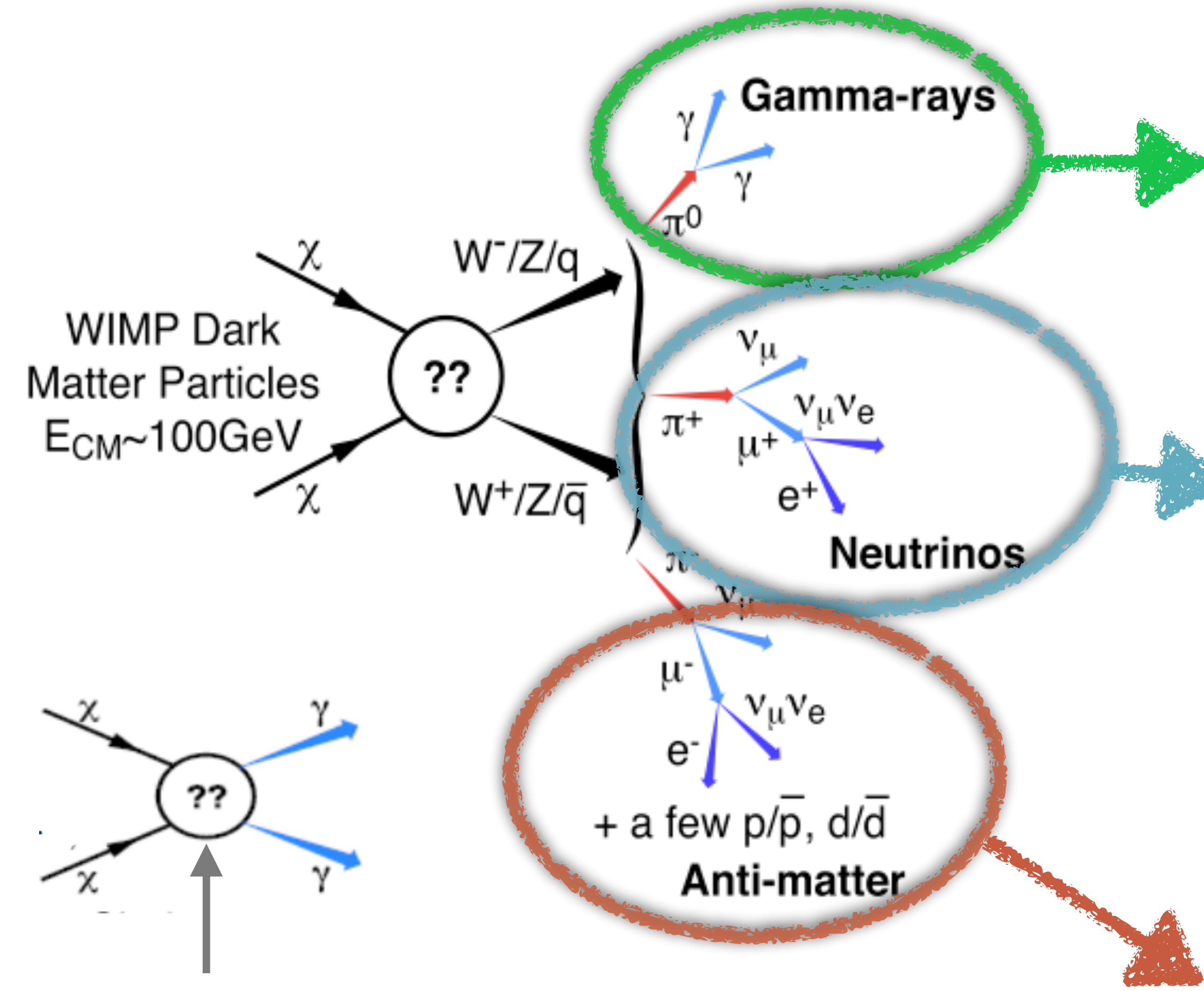
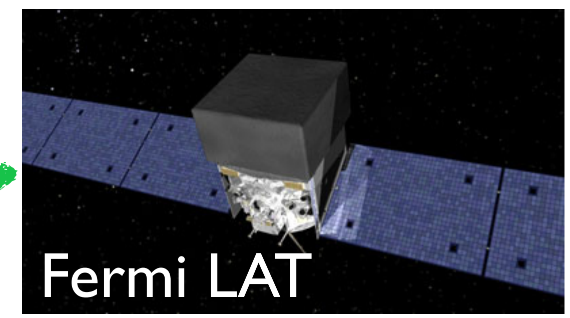


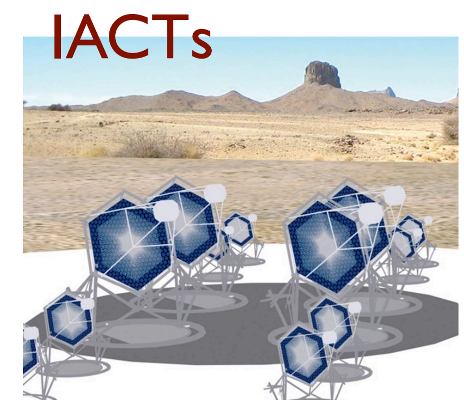


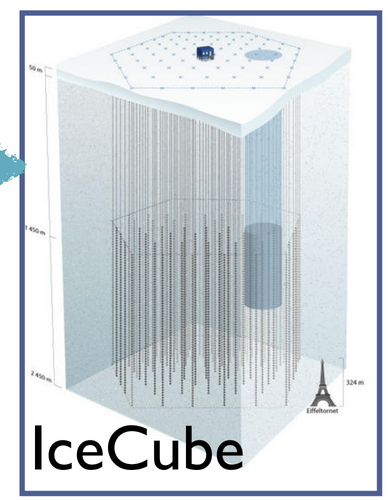
Indirect searches for WIMP dark matter

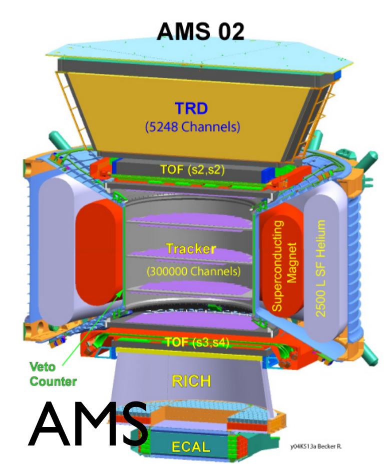
- Search for secondaries from the DM annihilation/decay process.
- Gamma-rays or neutrinos from regions with high DM densities.
- Fraction and spectrum of antiparticles in the cosmic rays.





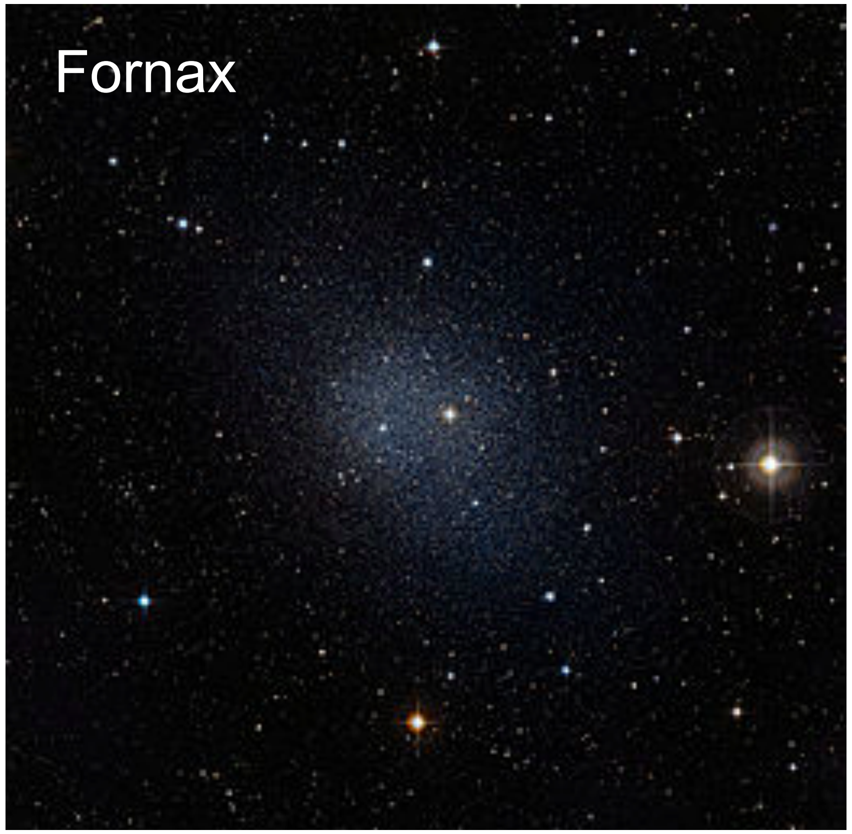


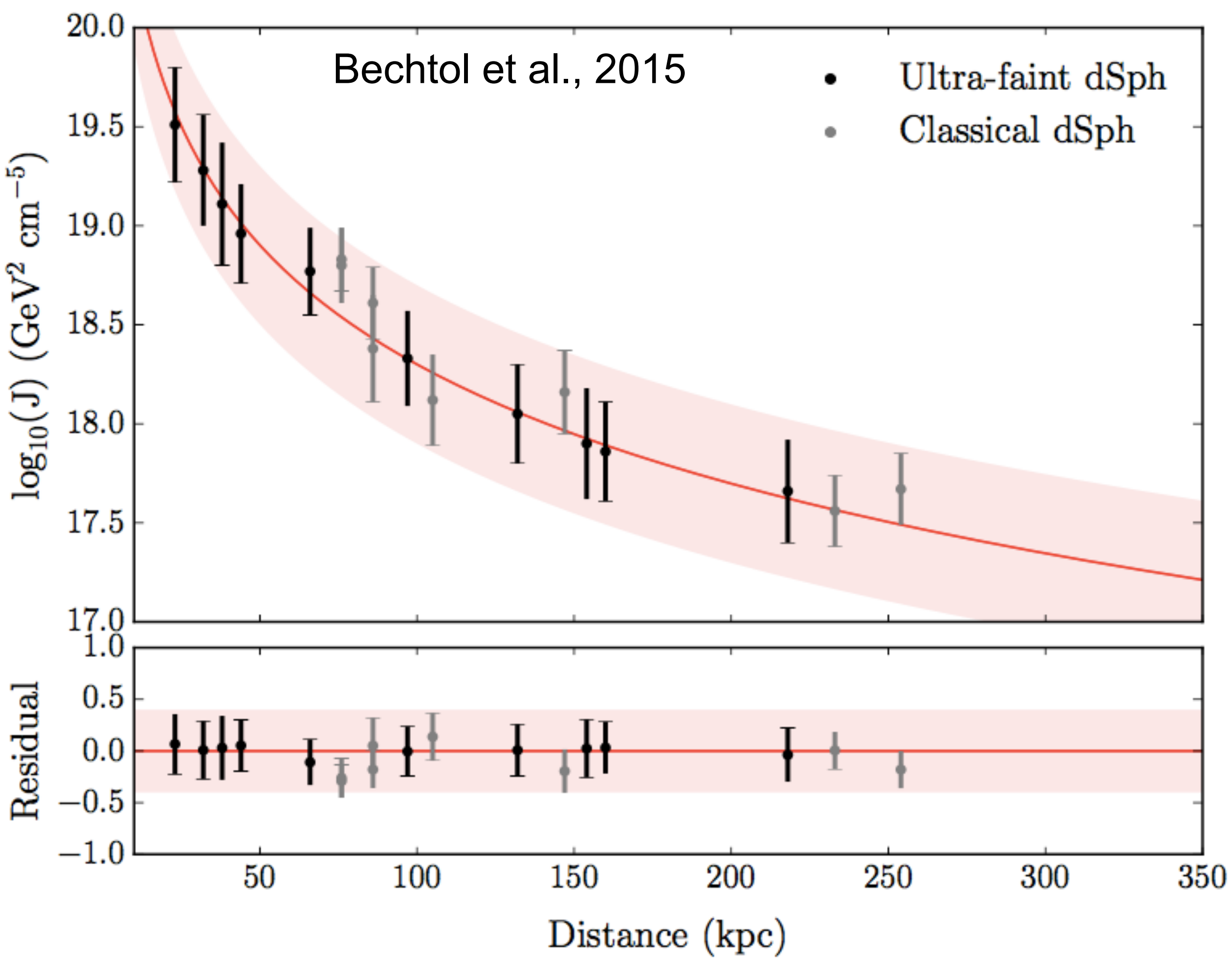




direct annihilation into gamma rays suppressed in most models by factor 10^{-3} - 10^{-4}.

The clearest signal: Gamma rays from dSph galaxies





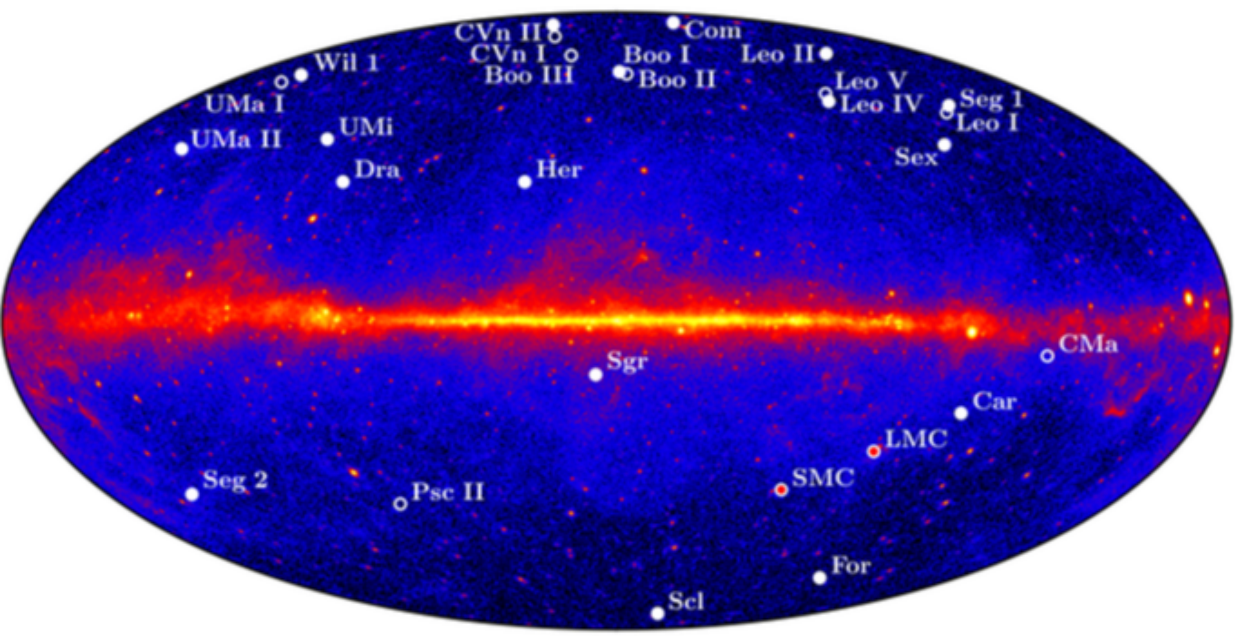
- **Small spheroidal galaxies in the vicinity of the Milky way.**
  - Almost no star formation
  - Almost no gas
  - Very high mass-to-light ratio (>>100)
- **Little astrophysical background for DM searches in dSph galaxies.**
- **Estimate of dwarf mass from stellar velocity dispersion and half-light radius.**
- **20 dSph galaxies in 2014 (continuously increasing)**

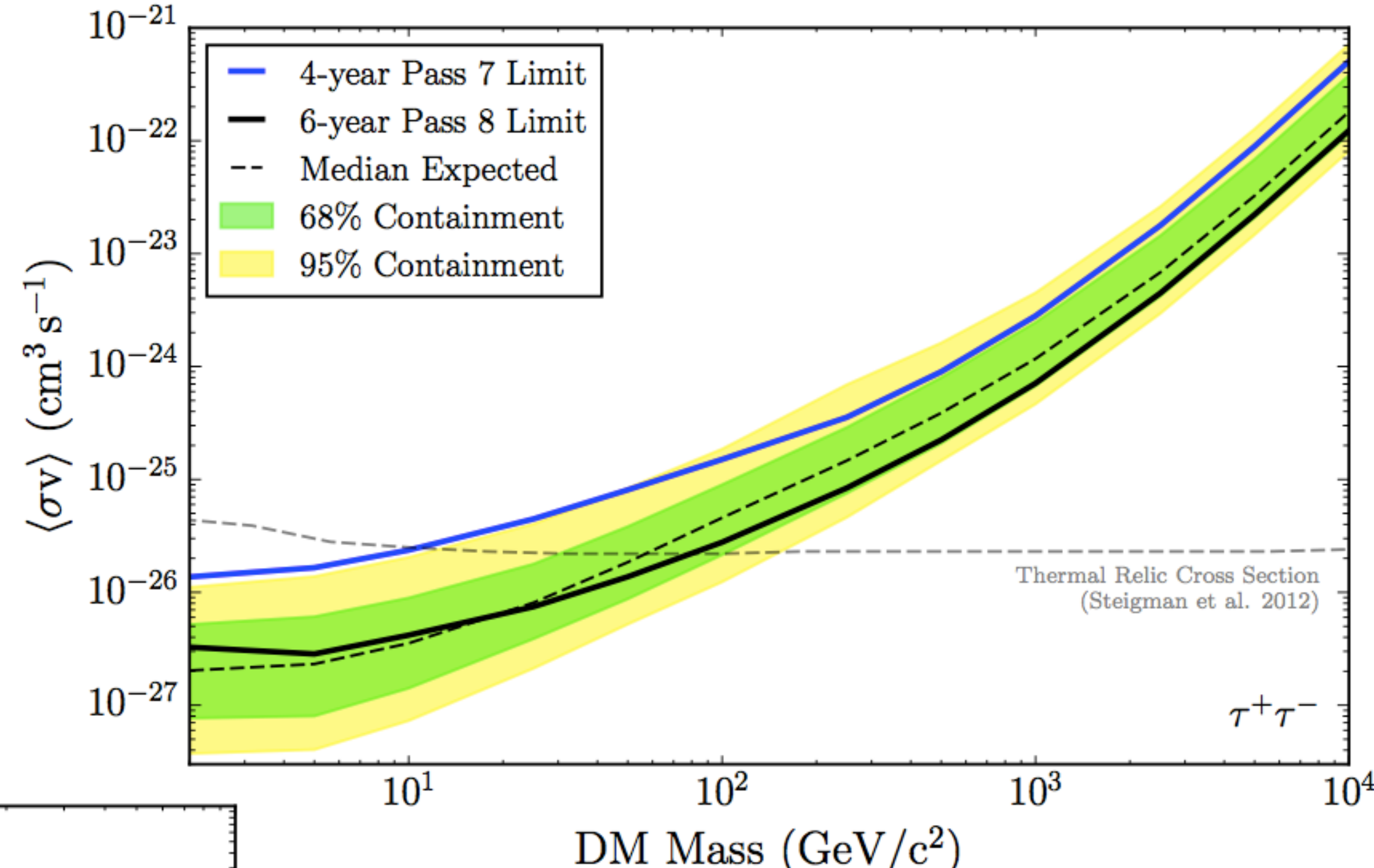
The J-factor

$$\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$

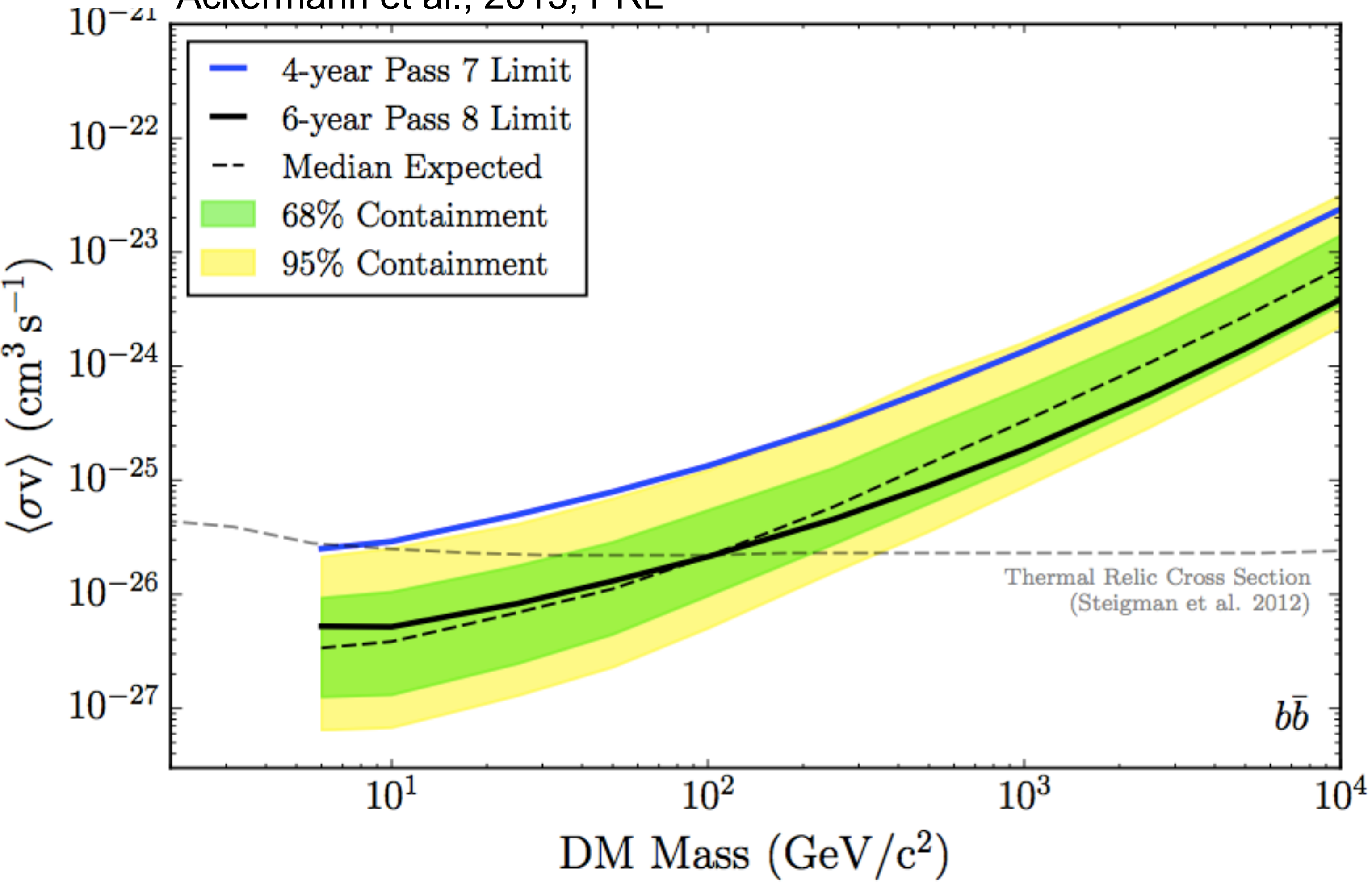
DM distribution

Limits on WIMP dark matter from Dwarf Sph Galaxies





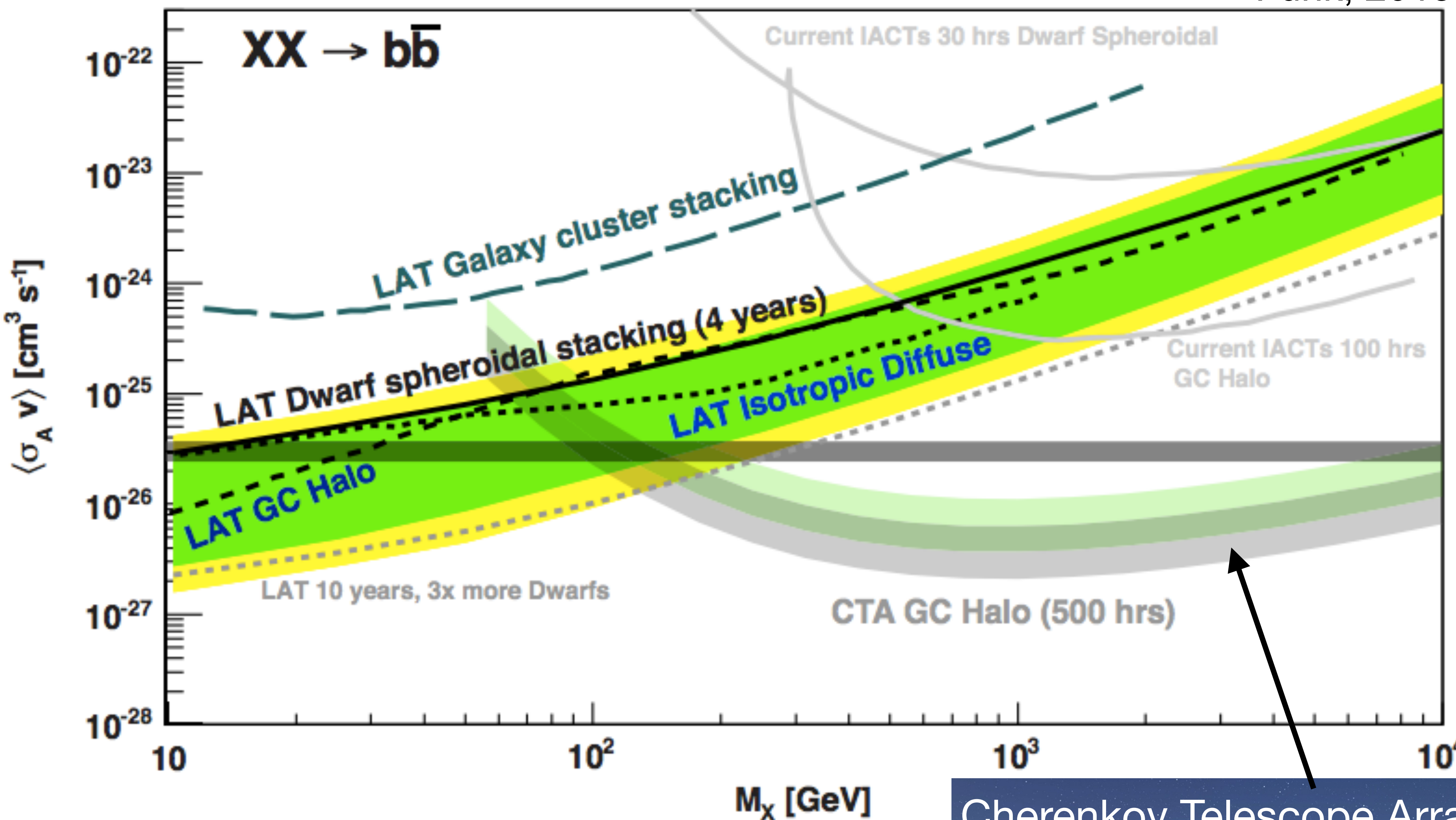
Ackermann et al., 2015, PRL



- **15 dwarf galaxies observed over 6 years with Fermi LAT.**
  - No signal observed.
  - The best limits on the DM annihilation cross section so far.
- **Exclusion limits below the thermal relic cross section for WIMP masses below 100 GeV**

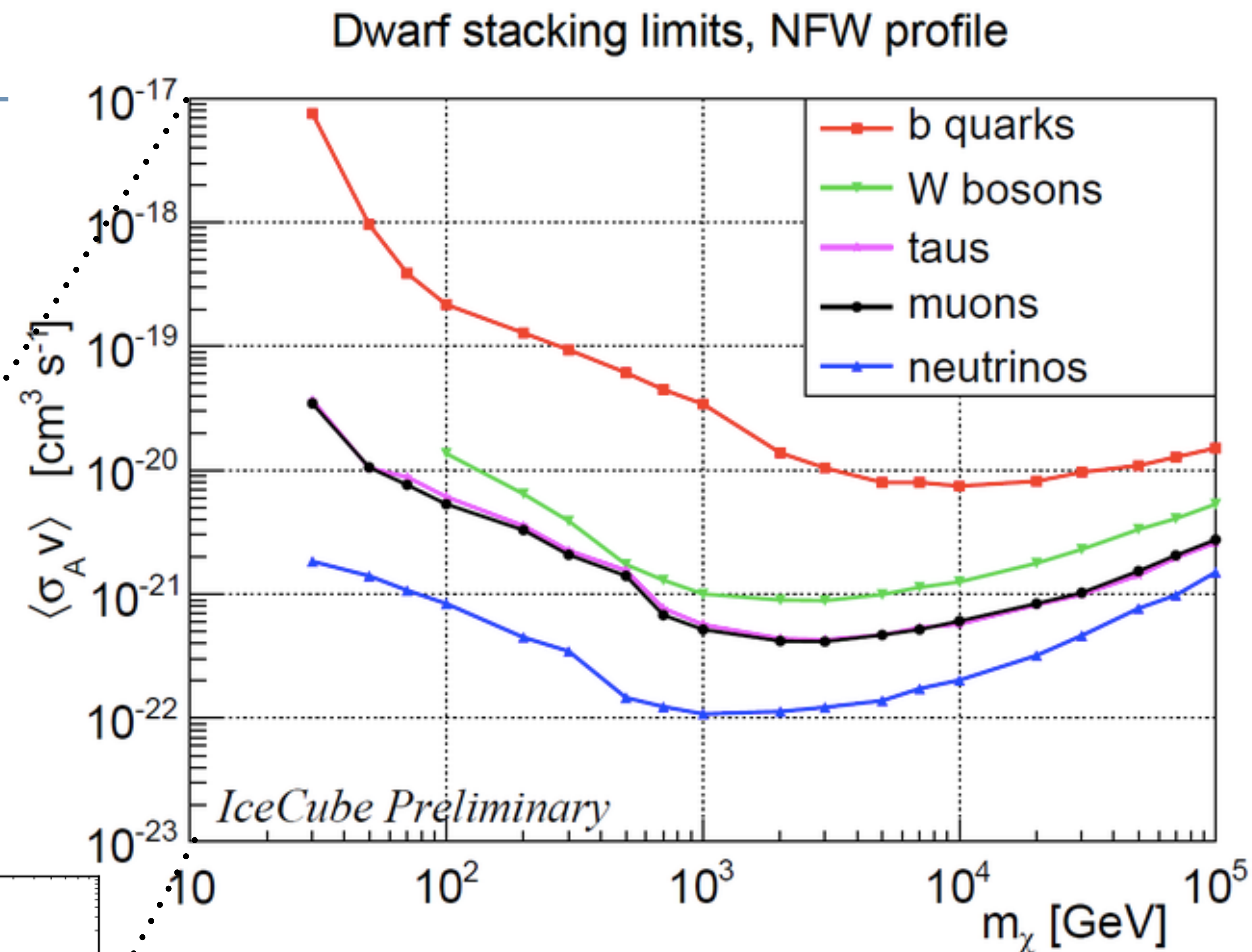
Future prospects

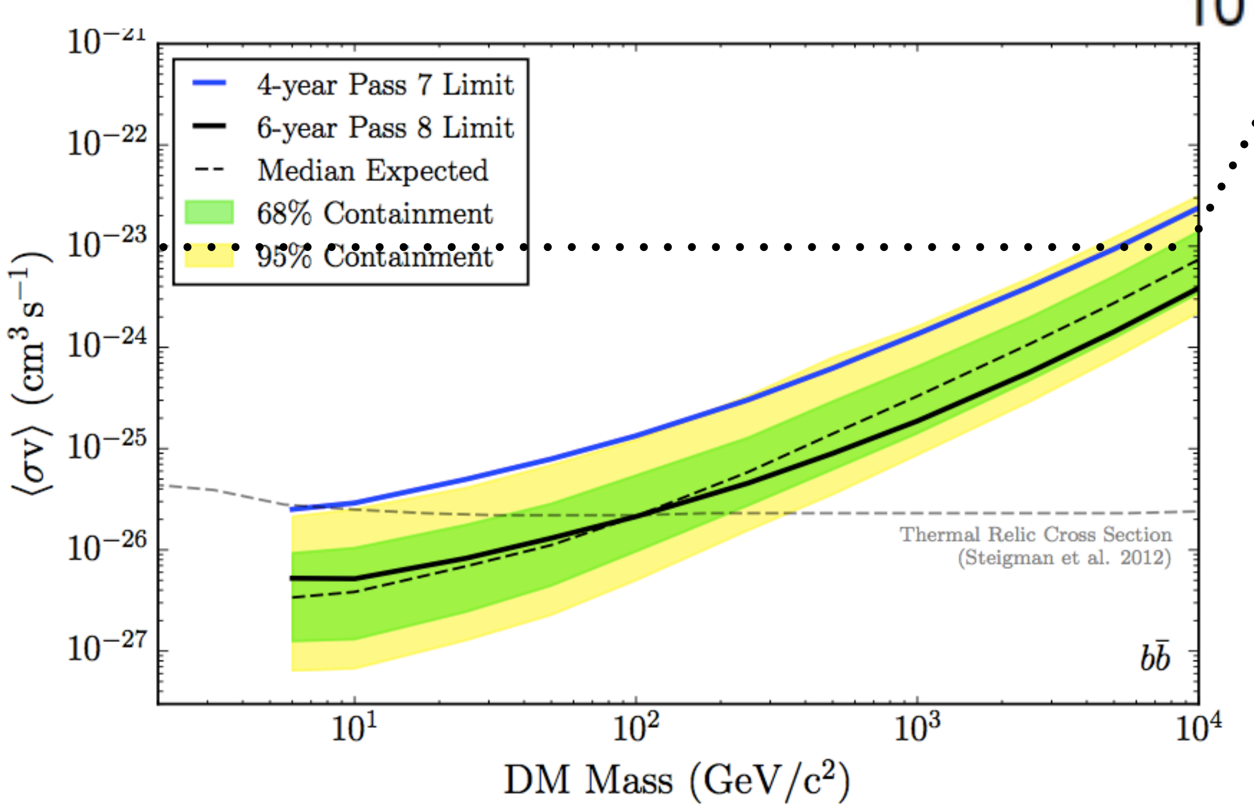
Funk, 2013



- Many candidate dSph galaxies recently discovered by optical surveys
- Future observations of the ground based CTA will cover the high-mass range

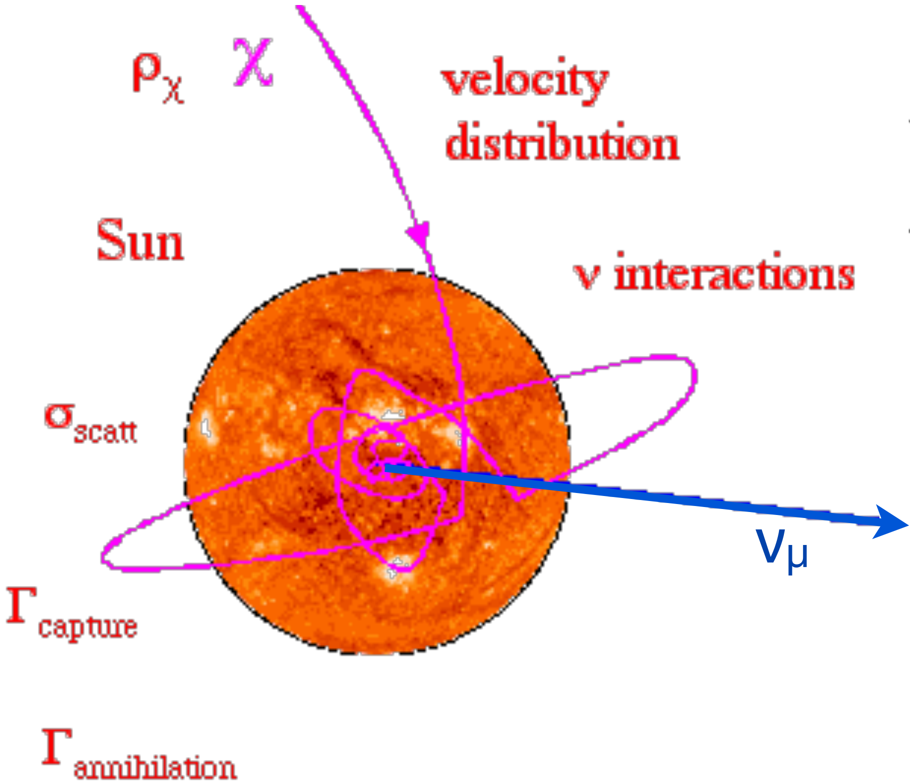
What about neutrinos ?

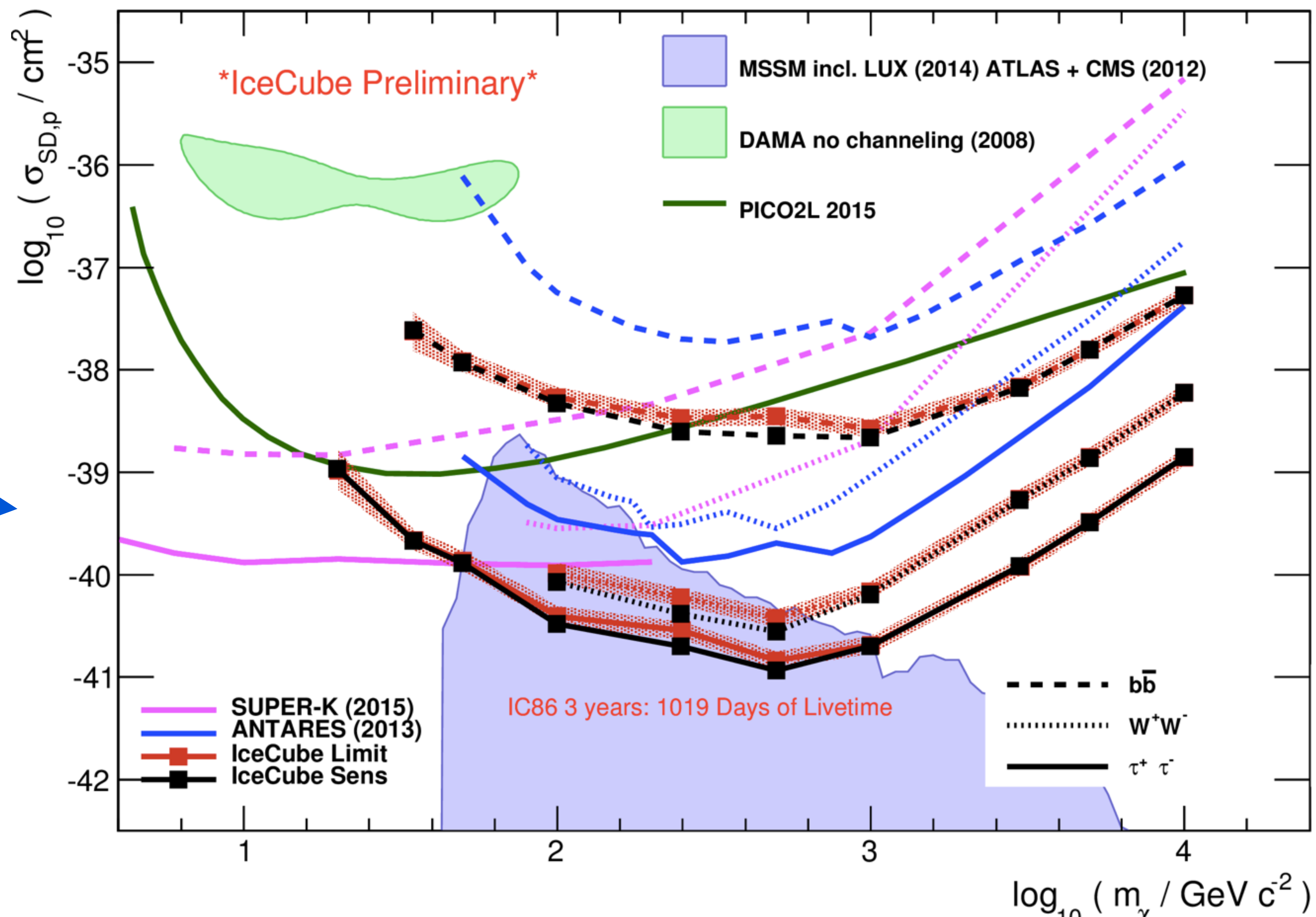




- Like gamma rays, neutrinos are produced in WIMP annihilation
- But limits on astrophysical sources are not competitive for most annihilation channels

The unique channel reserved for neutrinos





- Sun captures WIMPs that annihilate then in the core
- In equilibrium:
  - Capture rate = Annihilation rate
- Measuring WIMP annihilation in the sun is a measurement of the scattering cross section
- Sun is a hydrogen target → very good sensitivity on spin-dependent cross section.

Summary

- **Neutrinos and gamma-rays are two complementary channels to study the non-thermal universe**
- **They allow us new insights about cosmic particle acceleration as well as beyond-the standard model physics**
- **The most prominent extragalactic gamma-ray source populations do not produce the dominant fraction of the observed cosmic neutrinos.**
  - Interesting implications for the search for the sources of ultra-high-energy cosmic rays
- **Indirect searches for WIMP dark matter do not see a signal.**
  - Limits are below the thermal relic cross sections up to a WIMP mass of about 100 GeV
  - Future gamma-ray telescopes will be able to probe mass ranges up to tens of TeV
- **Non-observation of neutrinos from the sun provides the best limits on the spin-dependent scattering cross section so far.**