Physics beyond the Standard Model

Searches with IceCube

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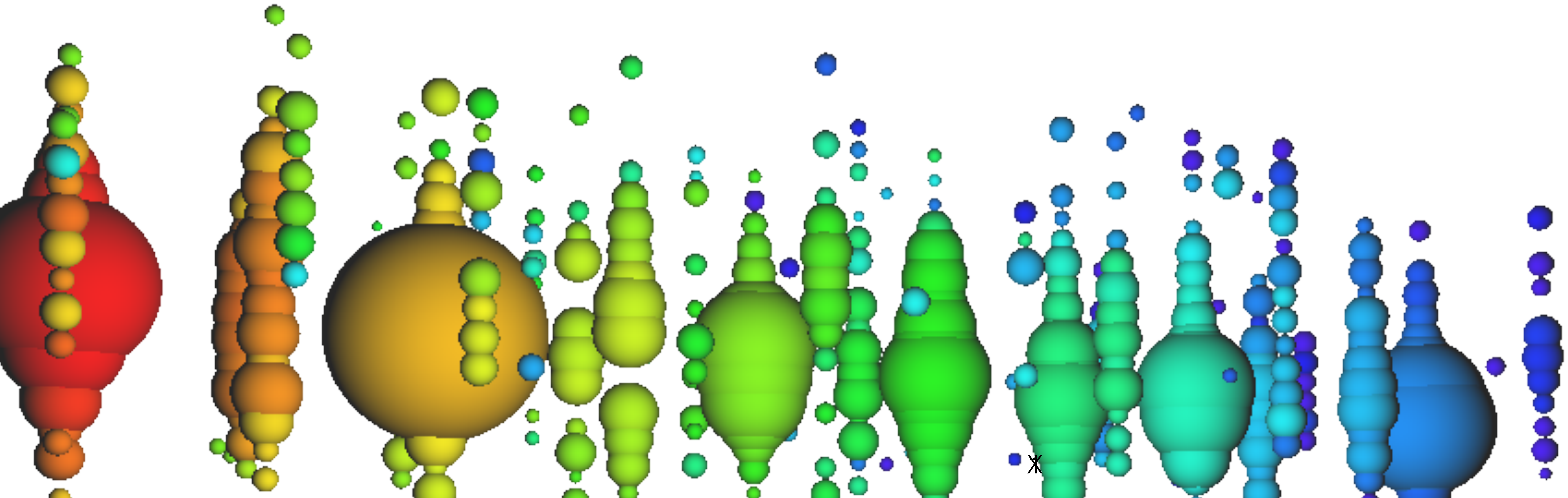

IceCube


South Pole
IceTop Array
81 stations
IceCube Laboratory
Cherenkov Light
InIce Array
125 m x
17 m
1450m –
charged particle
2450m –

IceCube


South Pole
IceTop Array
81 stations
IceCube Laboratory
InIce Array
125 m x
17 m
1450m –
DeepCore Array
40-70 m x
7 m
High Quantum Efficiency PMTs
in ~500 modules
2450m –
Cherenkov Light
charged particle

Research program @IceCube

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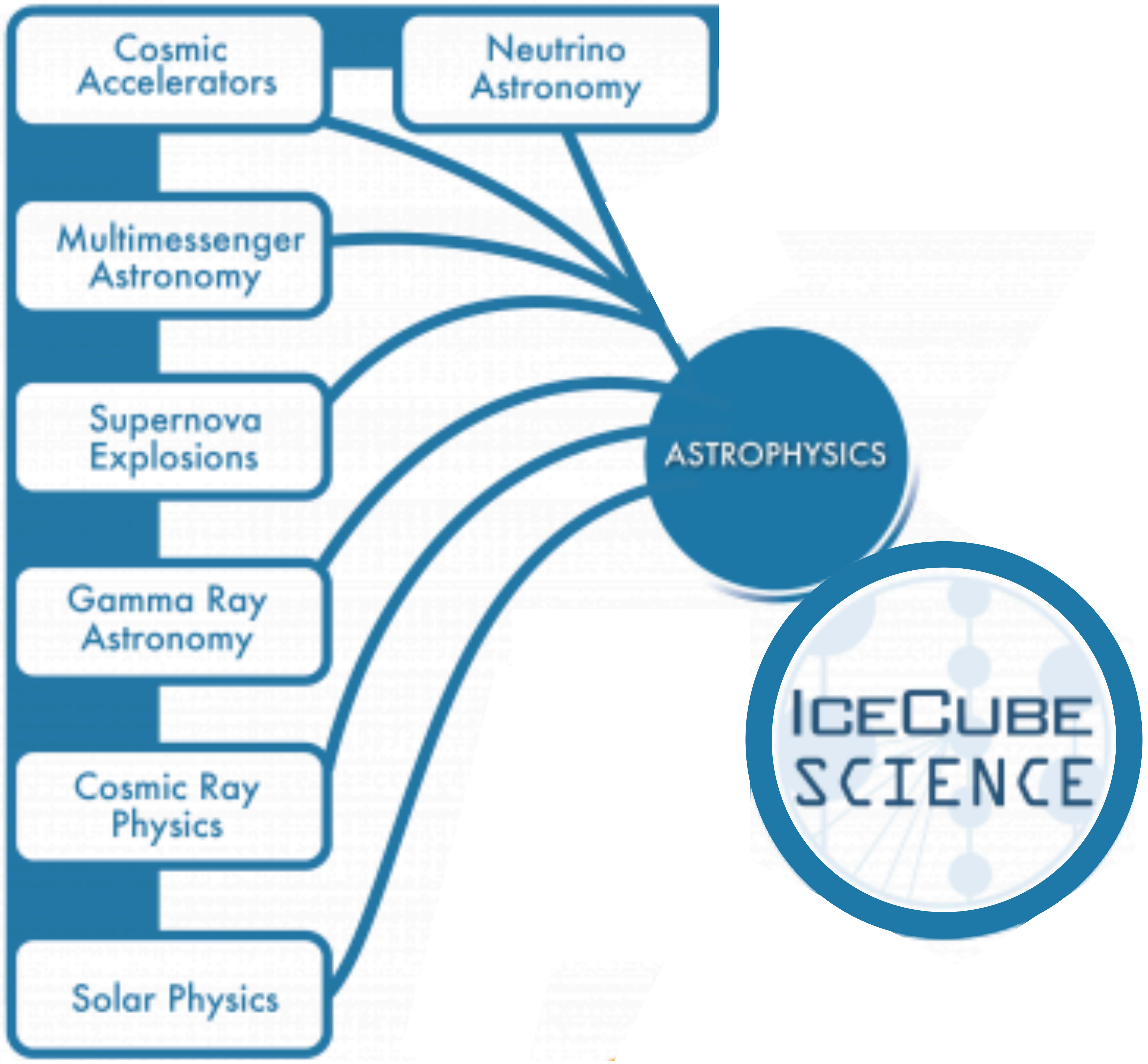
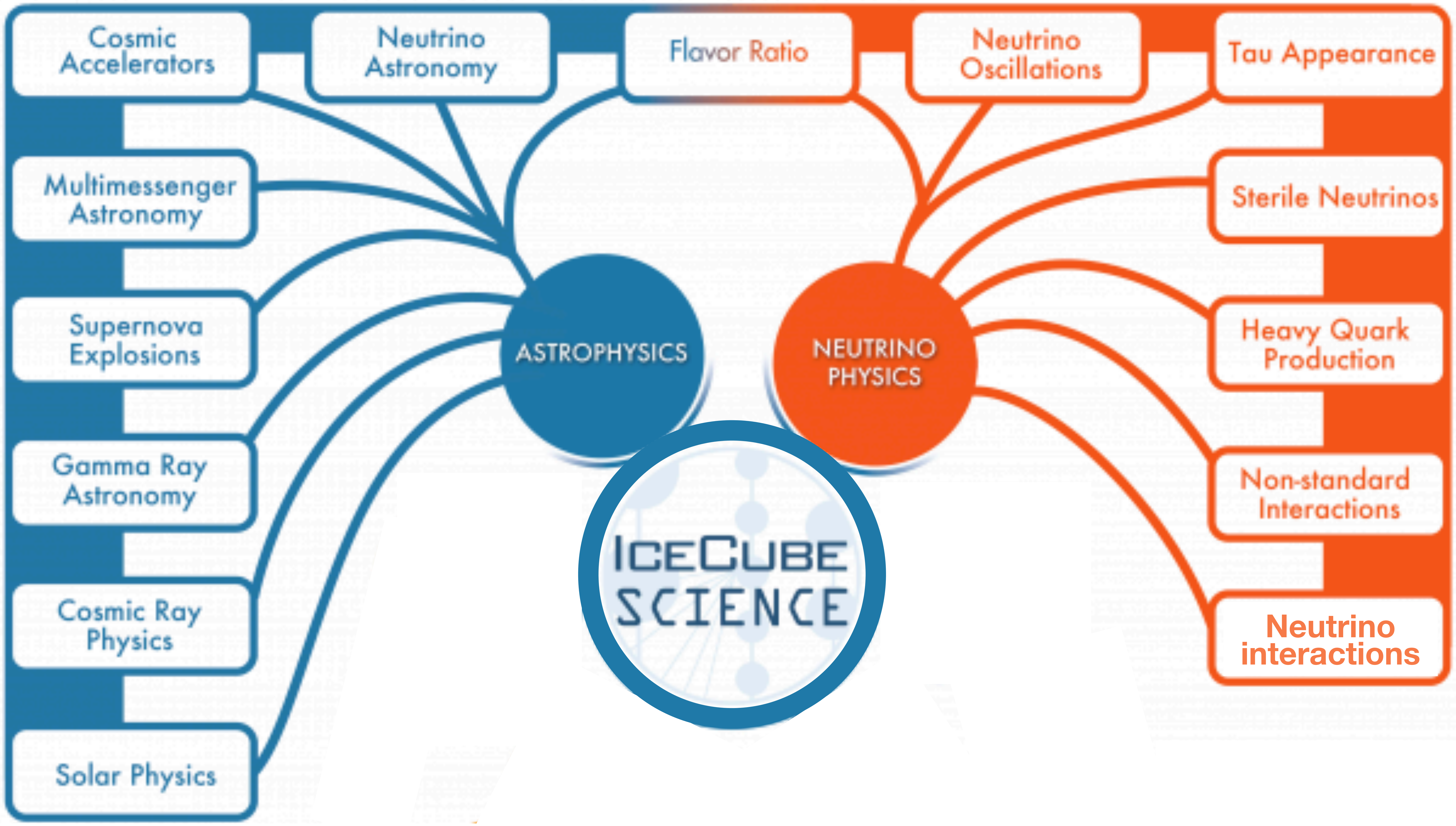
Research program @IceCube



Research program @IceCube



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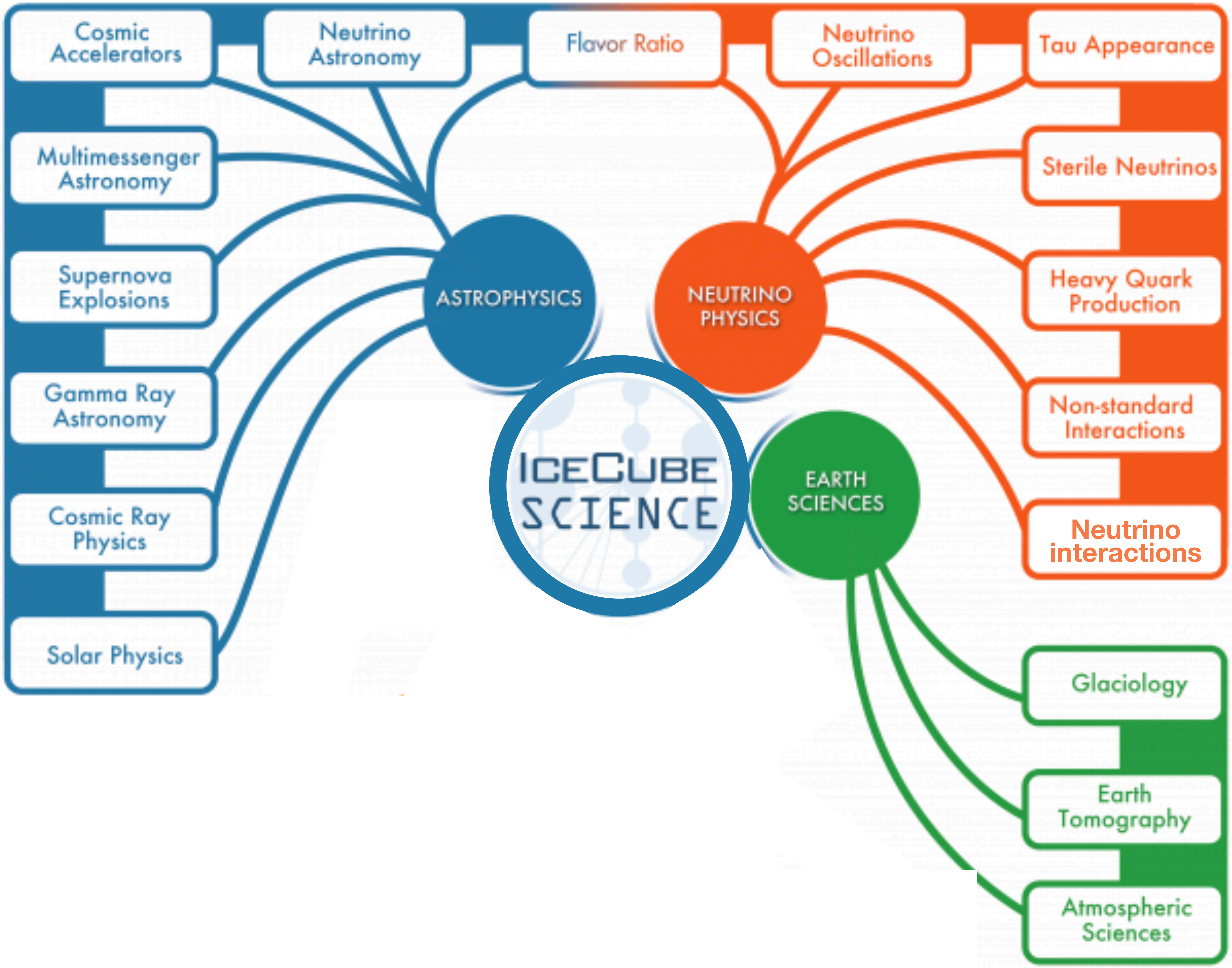
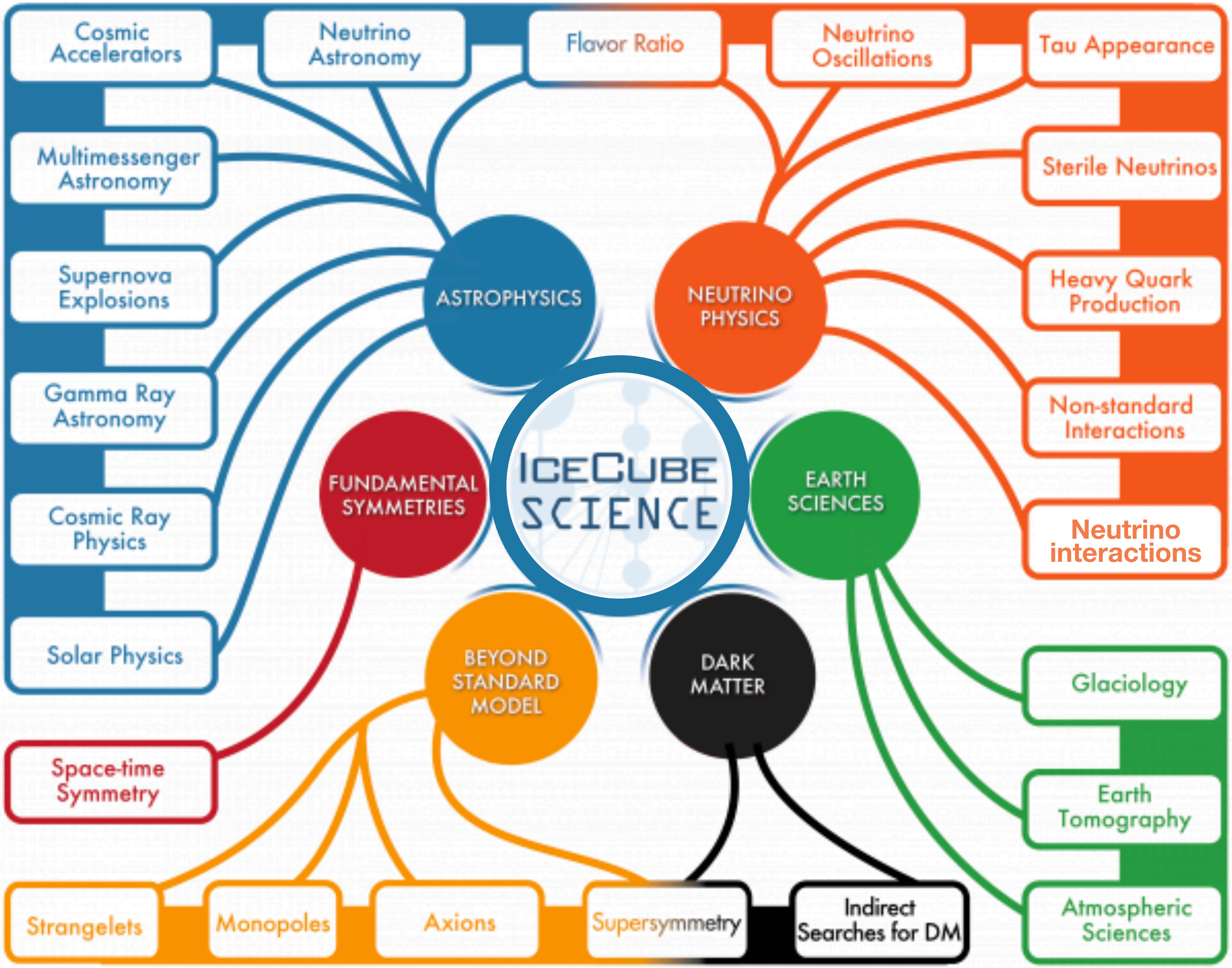
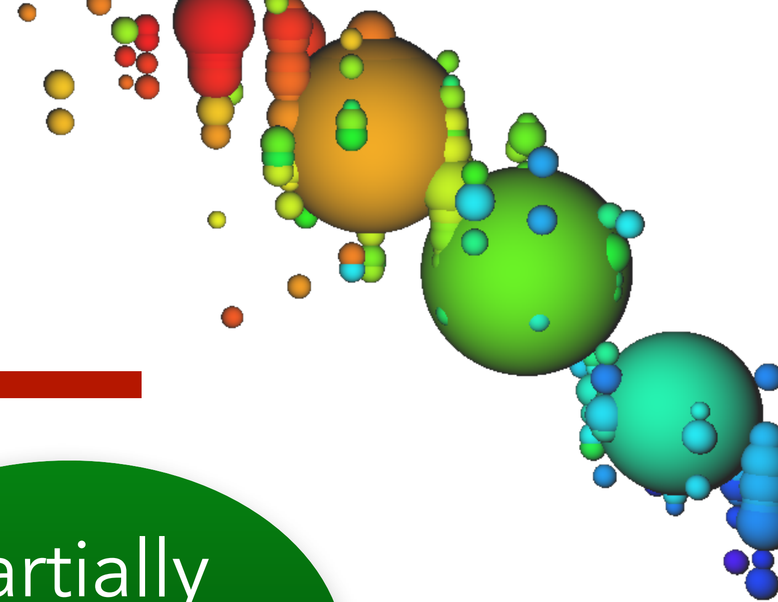


Research program @IceCube



Beyond standard model searches in IceCube



fundamental laws

partially charged particles

Indirect detection

- new physics influences propagation/development of particle fluxes
- exotic source of particles contributes to particle flux

dark matter

Direct detection

- IceCube detects what
  - reaches the detector
  - induces light production in ice

ν inter-actions

sterile ν

… and many more

Q-balls / nuclearites

… and many more (not even thought off)

magnetic monopoles

Advantages to use ν-detectors for exotic physics

- large detector volume
- **for indirect detection:** high statistics
- **for direct detection:** few conditions on particle properties

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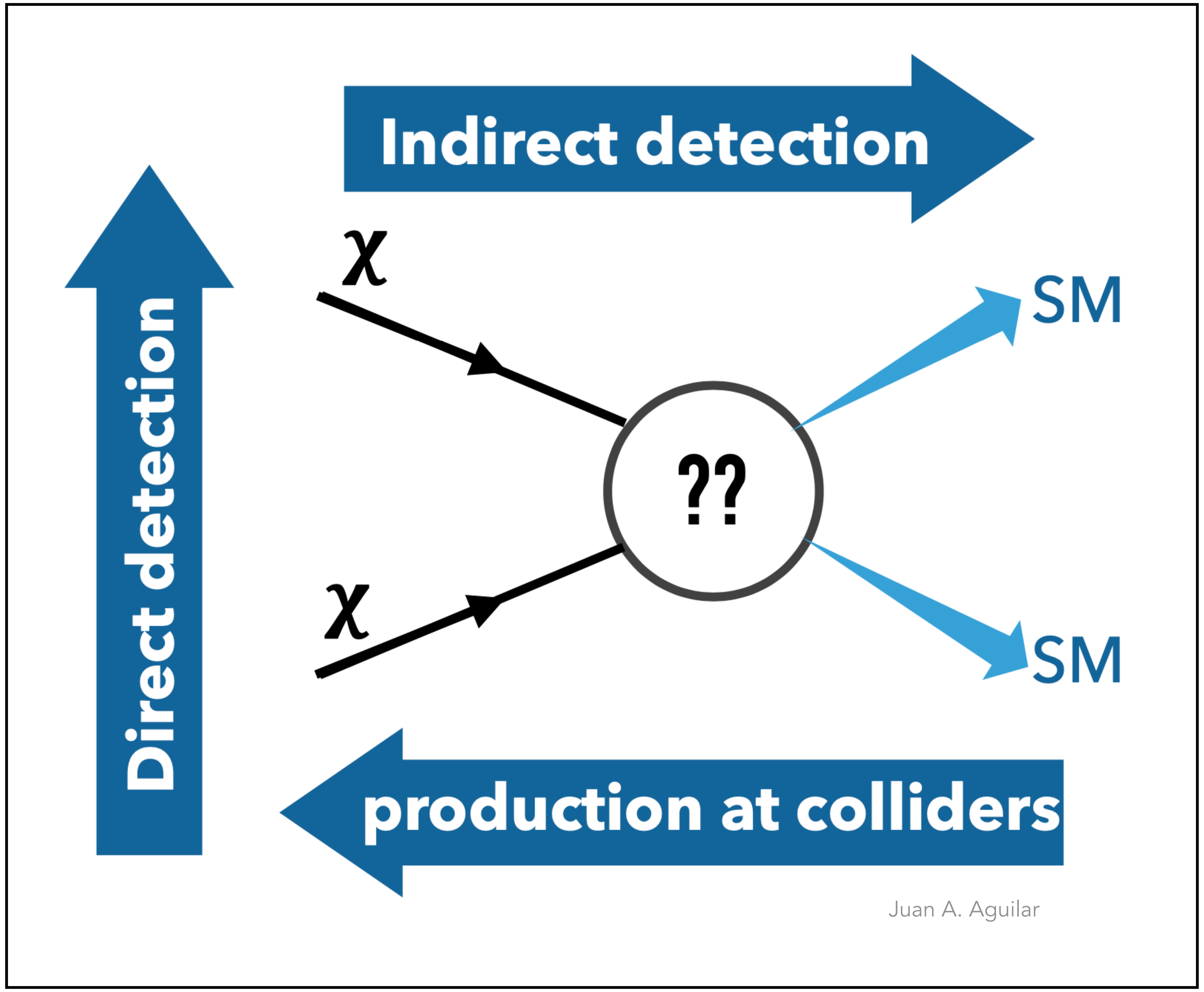
Dark Matter search strategies



Direct detection

- not "standard" WIMPs in IC but
- exotic extremely massive, highly ionizing particles
  → working on some interesting candidates like Q-balls, nuclearites, ..

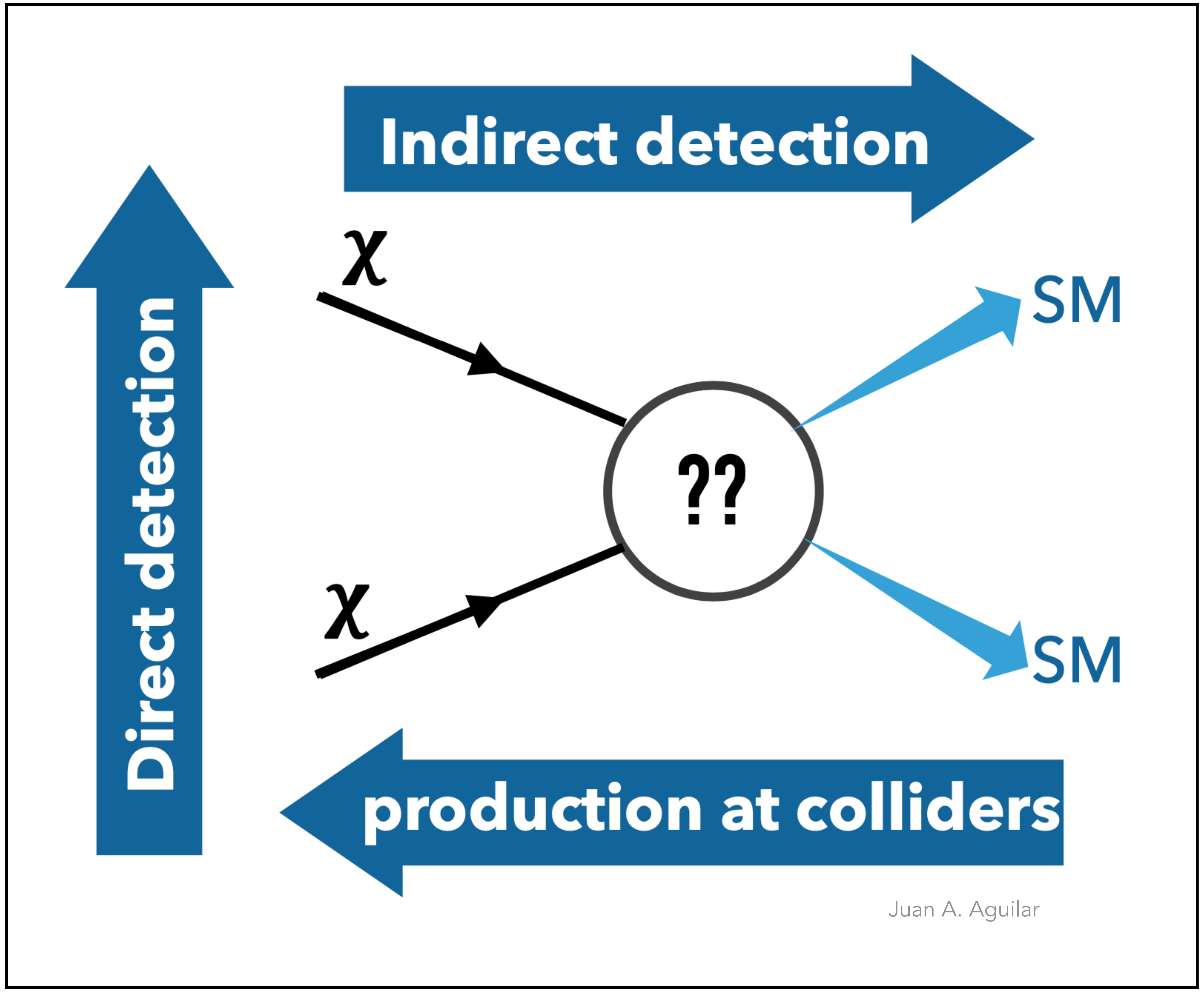
Indirect detection

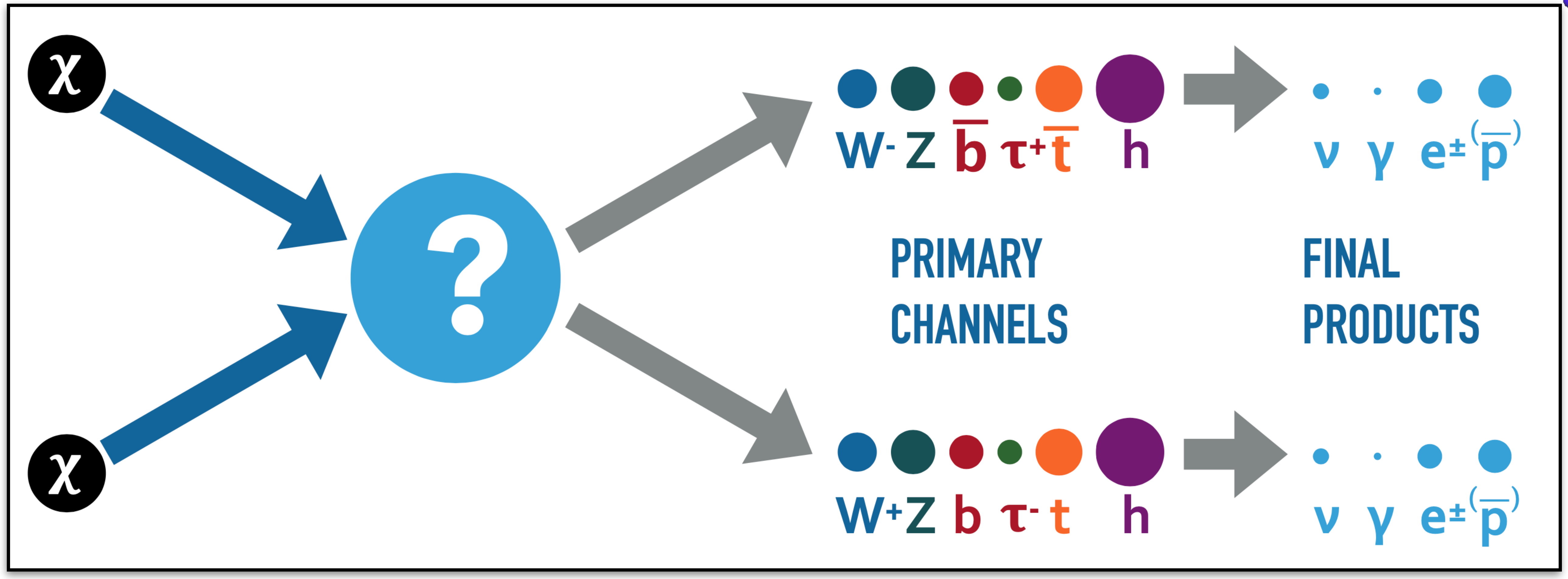
No need of specialized detectors, instead use: neutrino/ gamma ray/cosmic ray telescopes

Focus on large reservoirs of dark matter

- celestial bodies: Earth, Sun (only with neutrinos)
- galactic sources: halo, center
- intergalactic sources: dwarf spheroidal galaxies, galaxy clusters

Dark Matter search strategies





Indirect detection

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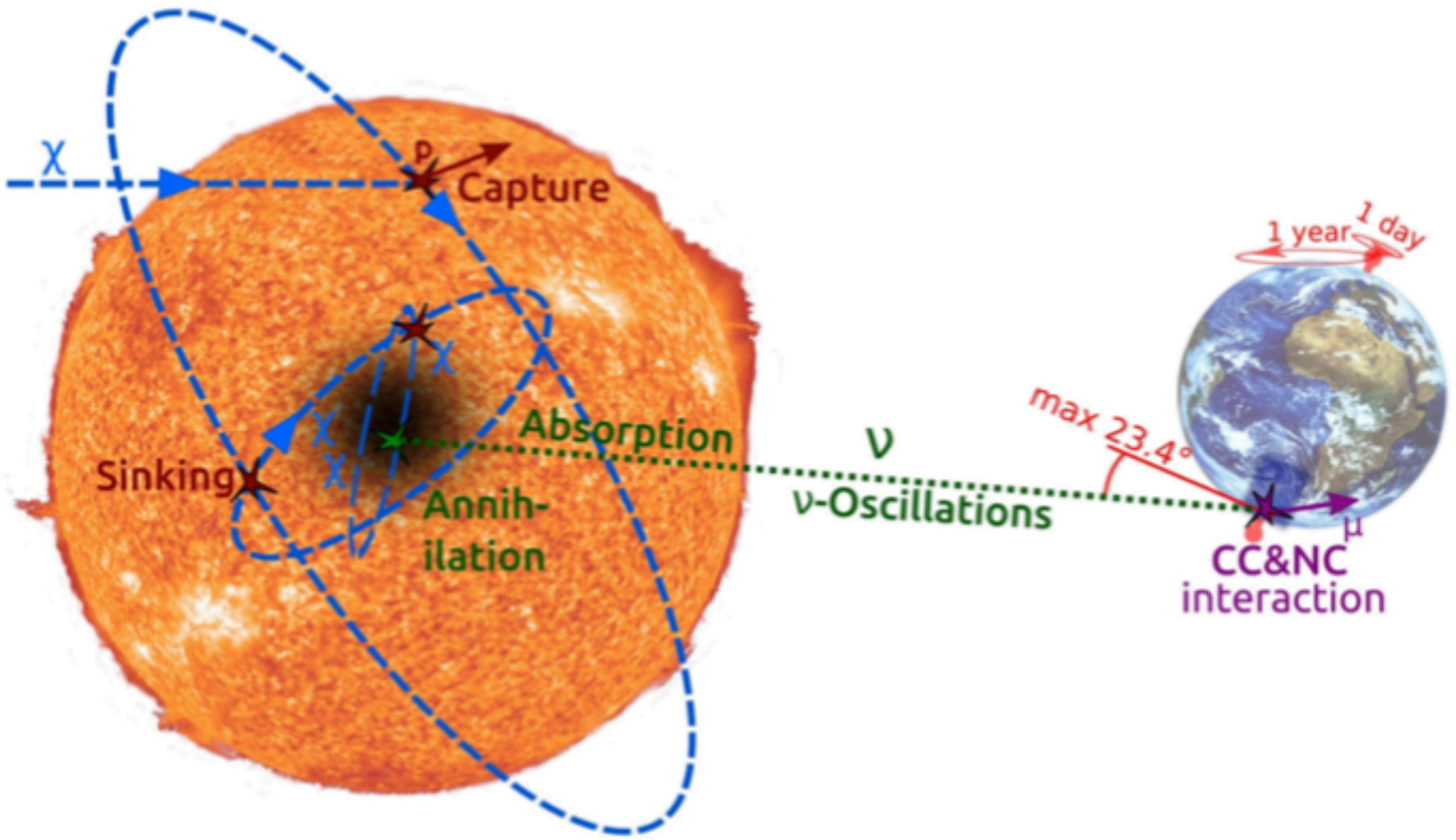
Dark Matter from the Sun

- DM from galactic halo gravitationally bound in potential of body
- weak scattering off nuclei in Sun decelerates DM towards center → $\sigma_{\chi\text{-}p}$
- DM self-annihilates at center with SM particle emission → different spectra *(only of neutrinos)*
- neutrino rate & energy at detector depends on
    - DM mass & annihilation cross section
    - DM halo density spectrum

equilibrium!

$$\Phi_\nu^{limit} \rightarrow \Gamma_A \rightarrow C_c \rightarrow \sigma_{\chi-N}$$



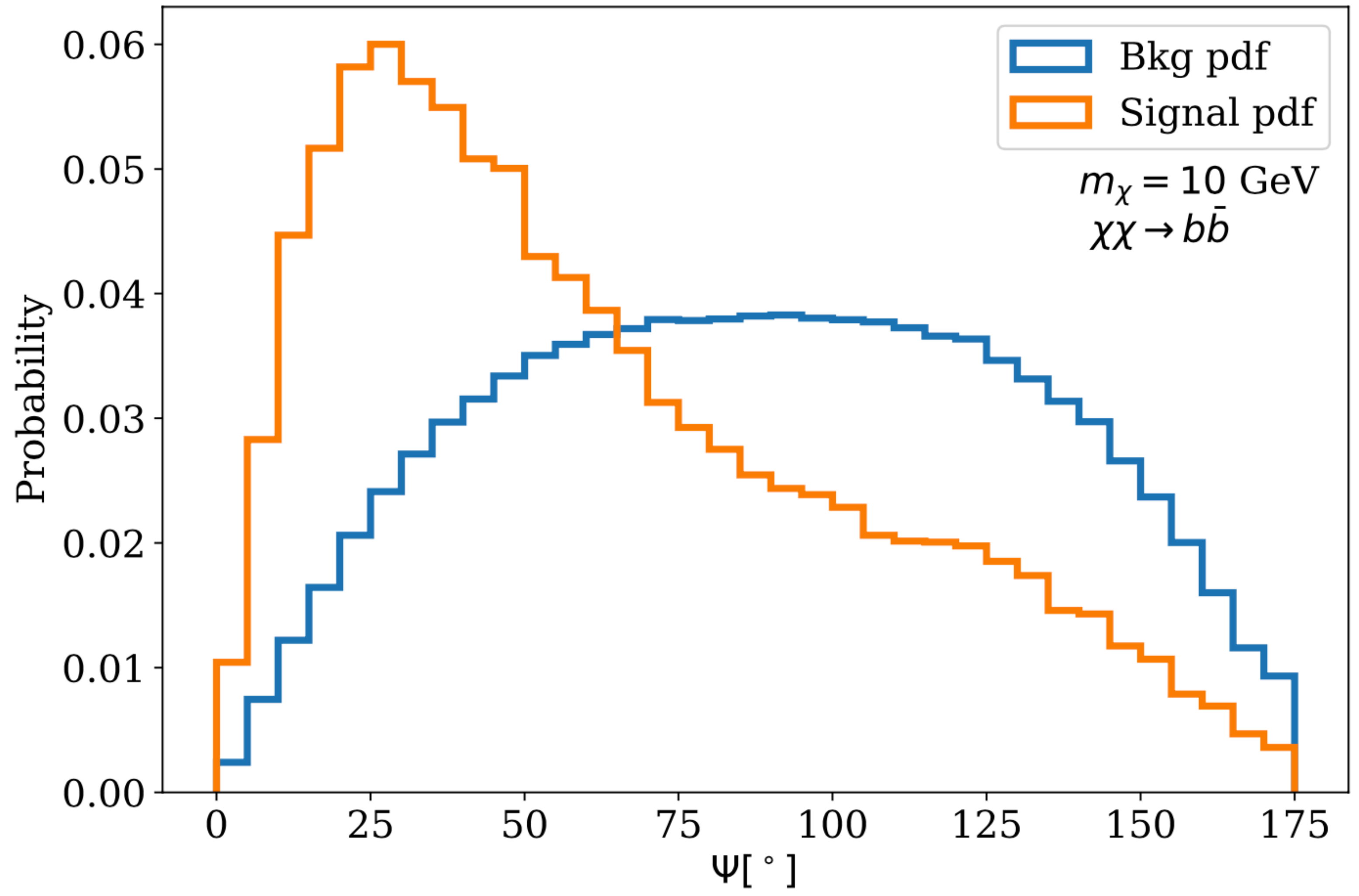
Dark Matter from the Sun

arXiv:2111.09970
Accepted by Phys. Rev. D

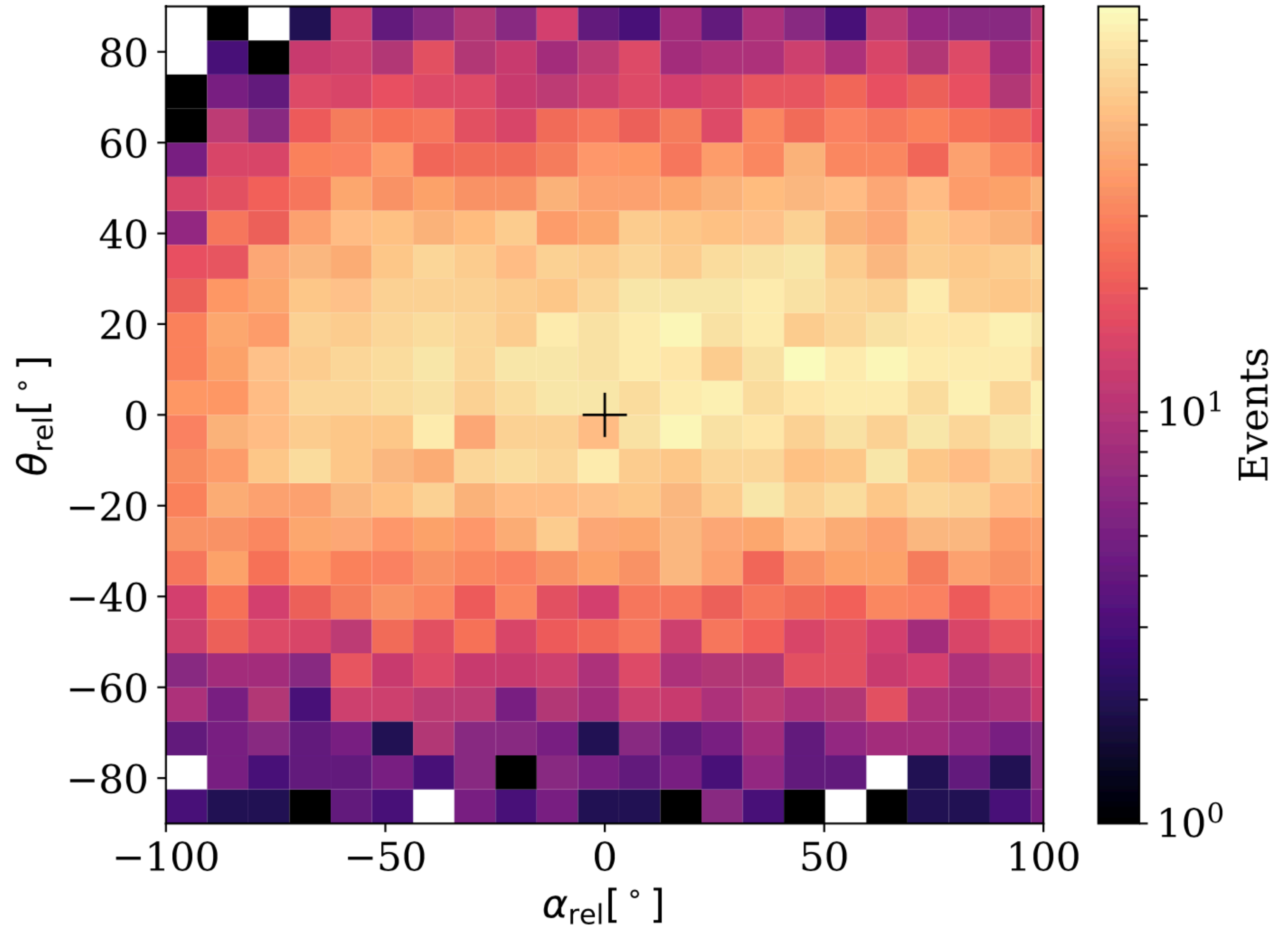
Analysis strategy:

- use low energy sub-detector *DeepCore*
- use standard IceCube as veto
- distinguish muon tracks and cascade-like signatures
- reconstruct direction (angular resolution 5-35°)
- unbinned LLH

Expectation / Model:



Observation



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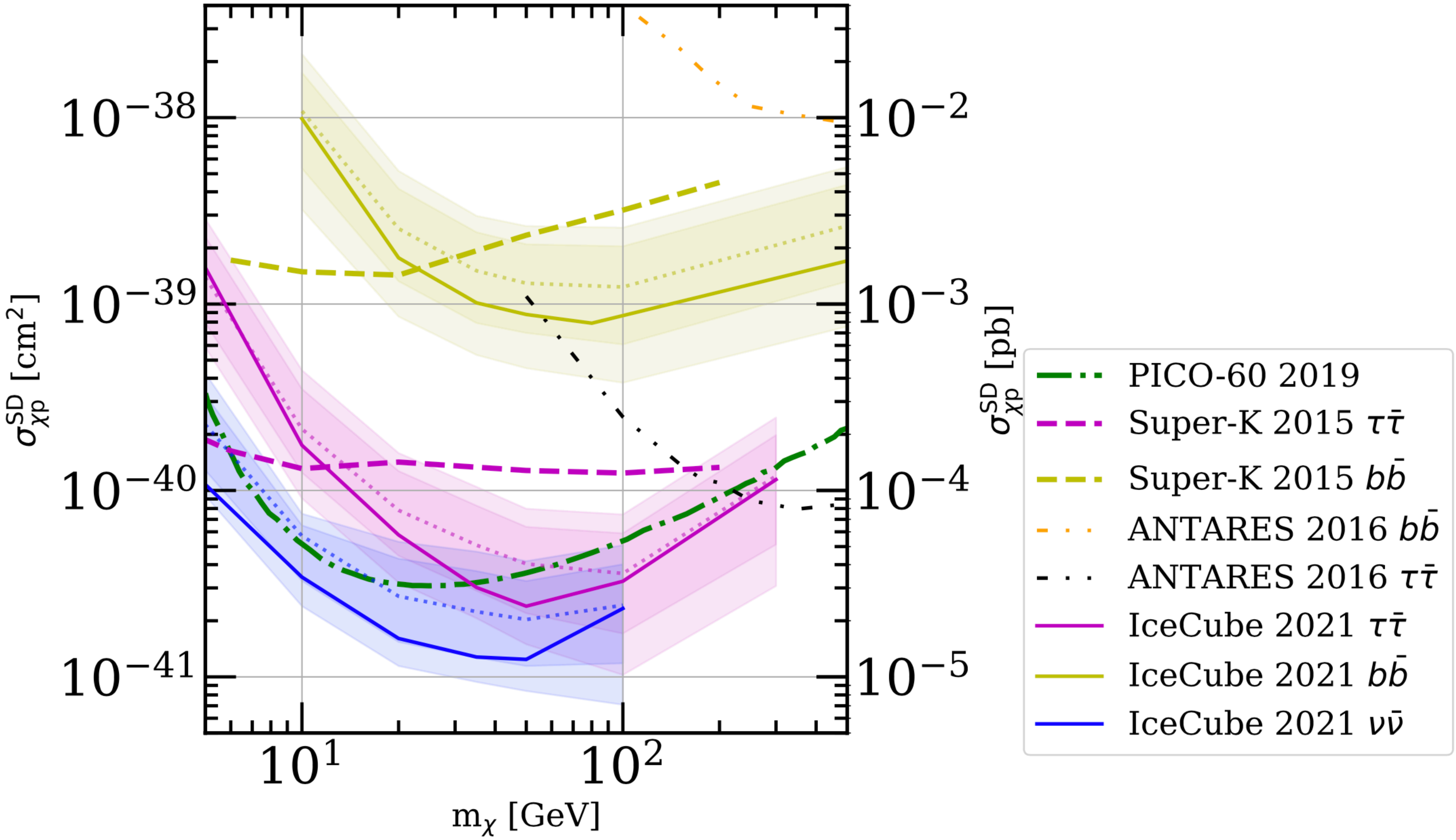
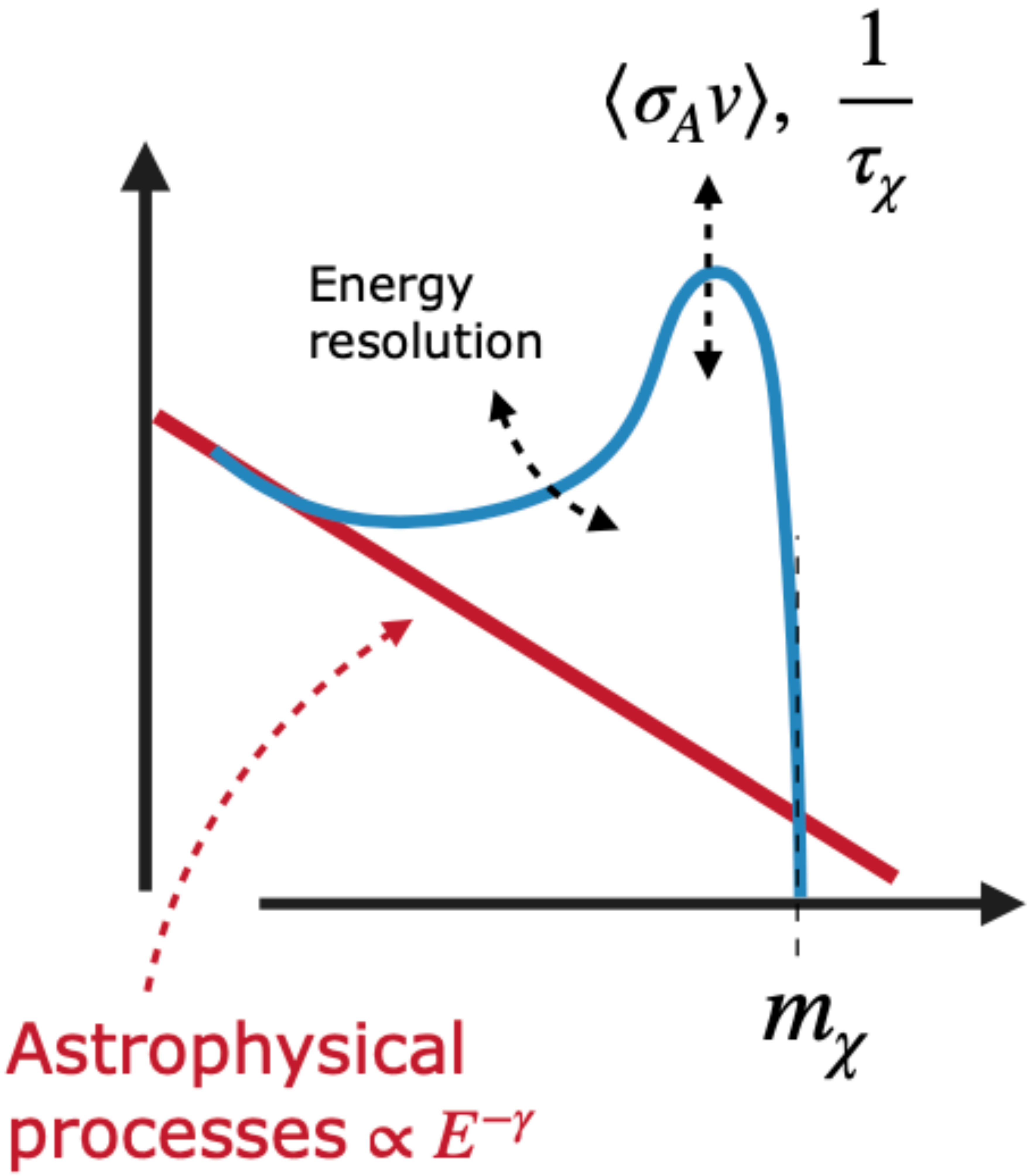


Neutrino lines from DM

Publication in Preparation

Analysis strategy:

- focus on annihilation / decay into neutrinos
- no background **!**
- 5 years of data up to 40 TeV
- cascade events with energy resolution of approximately 30%

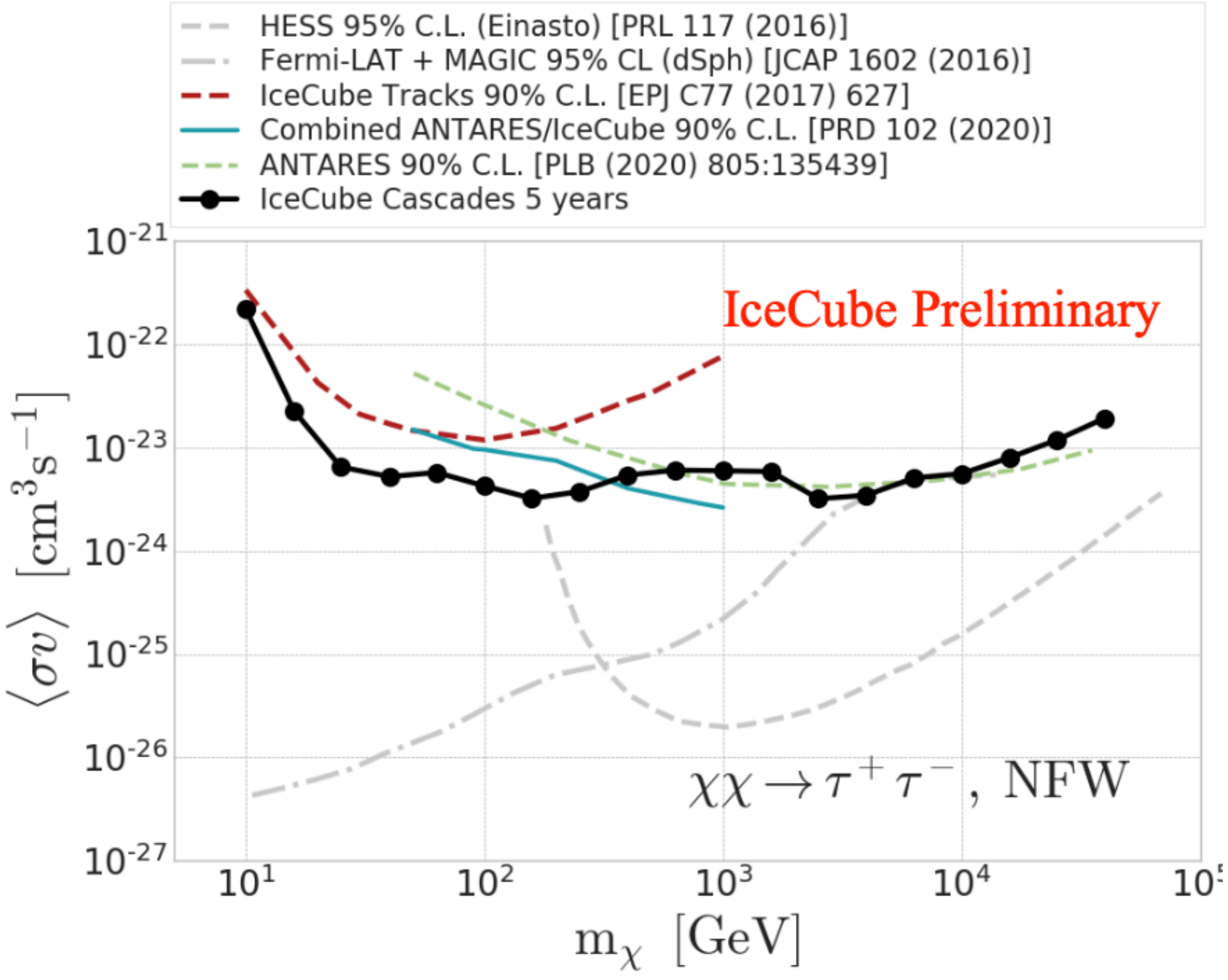


Juan A. Aguilar

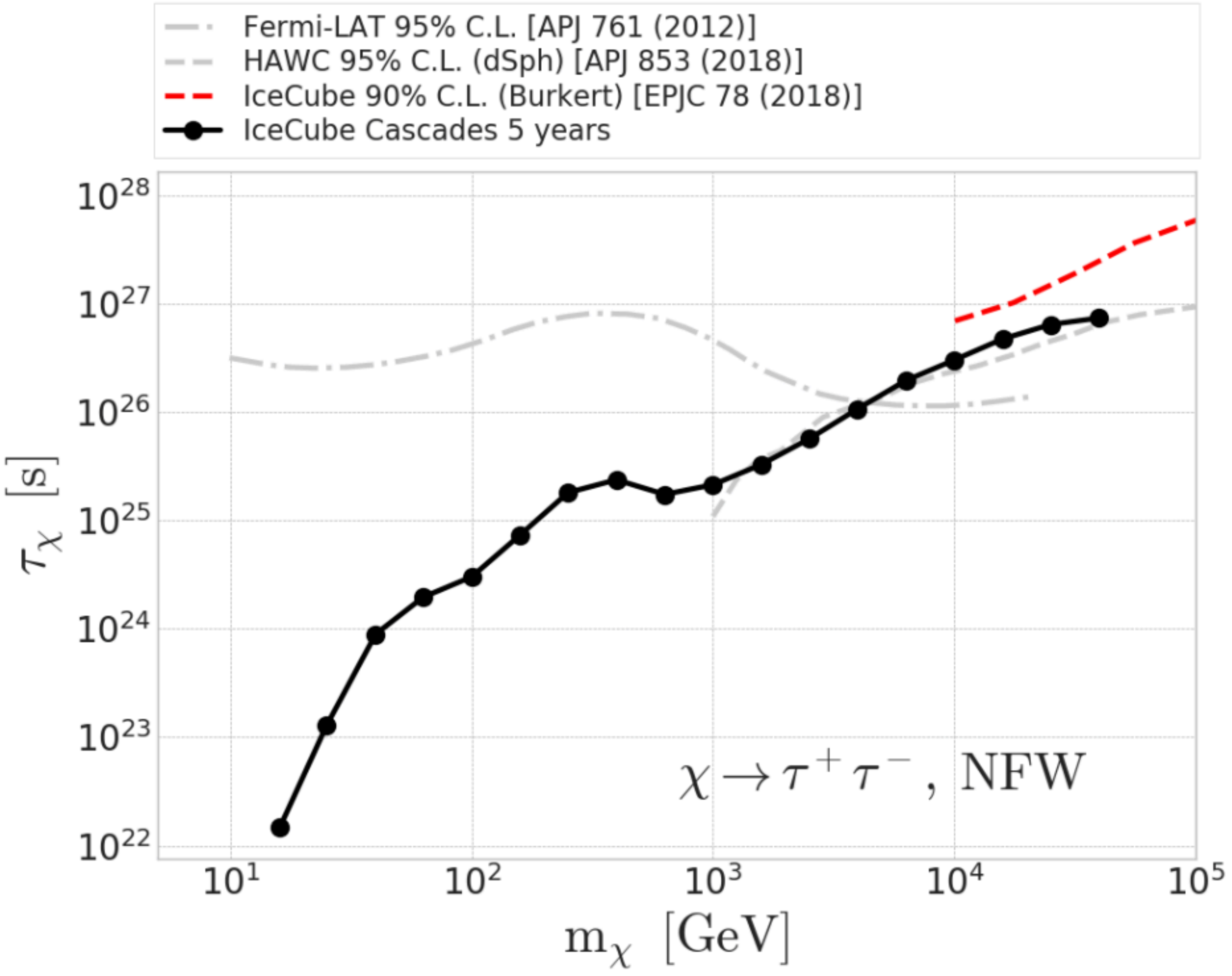
Neutrino lines from DM

Publication in Preparation

Annihilation

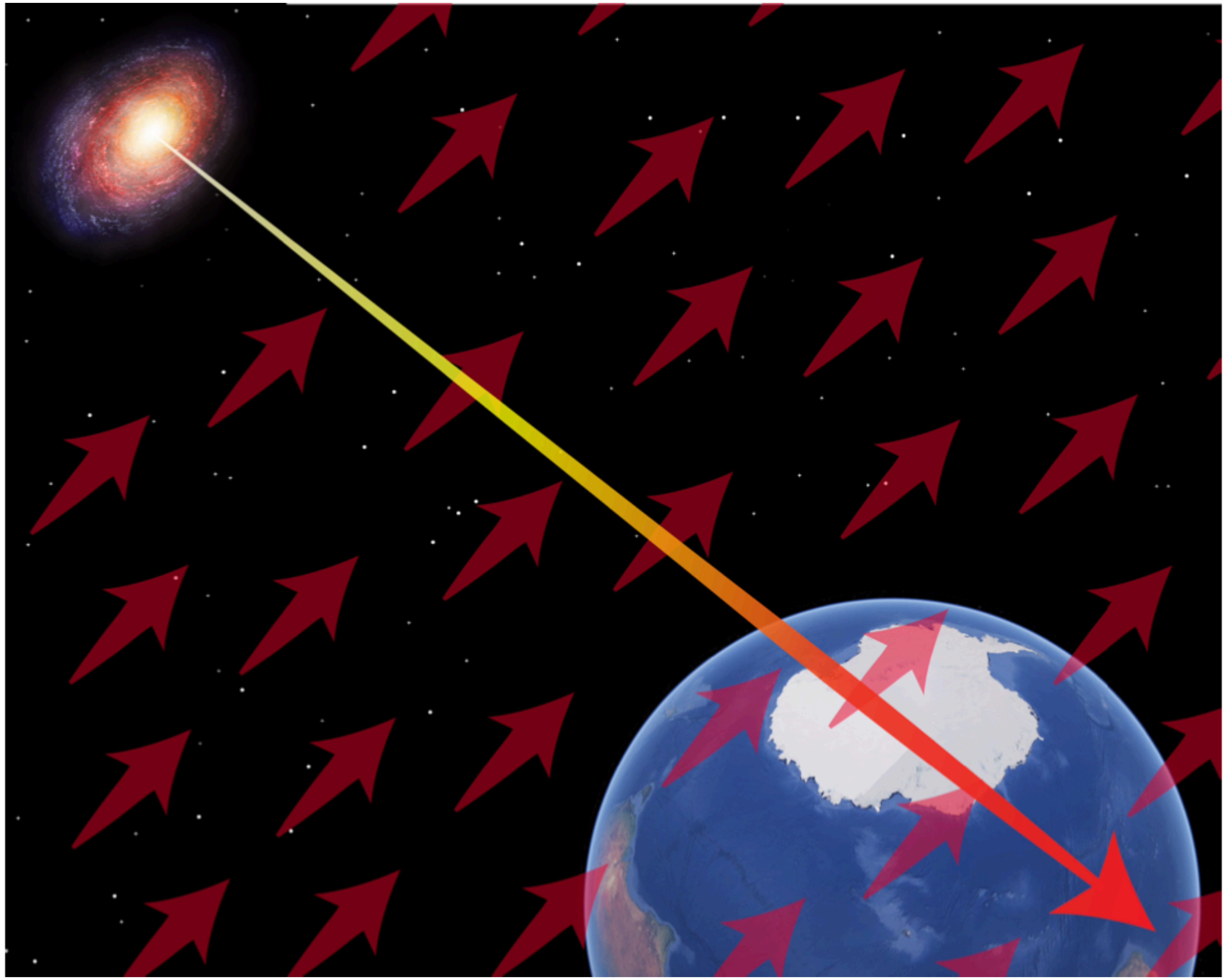


Decay



Quantum Gravity

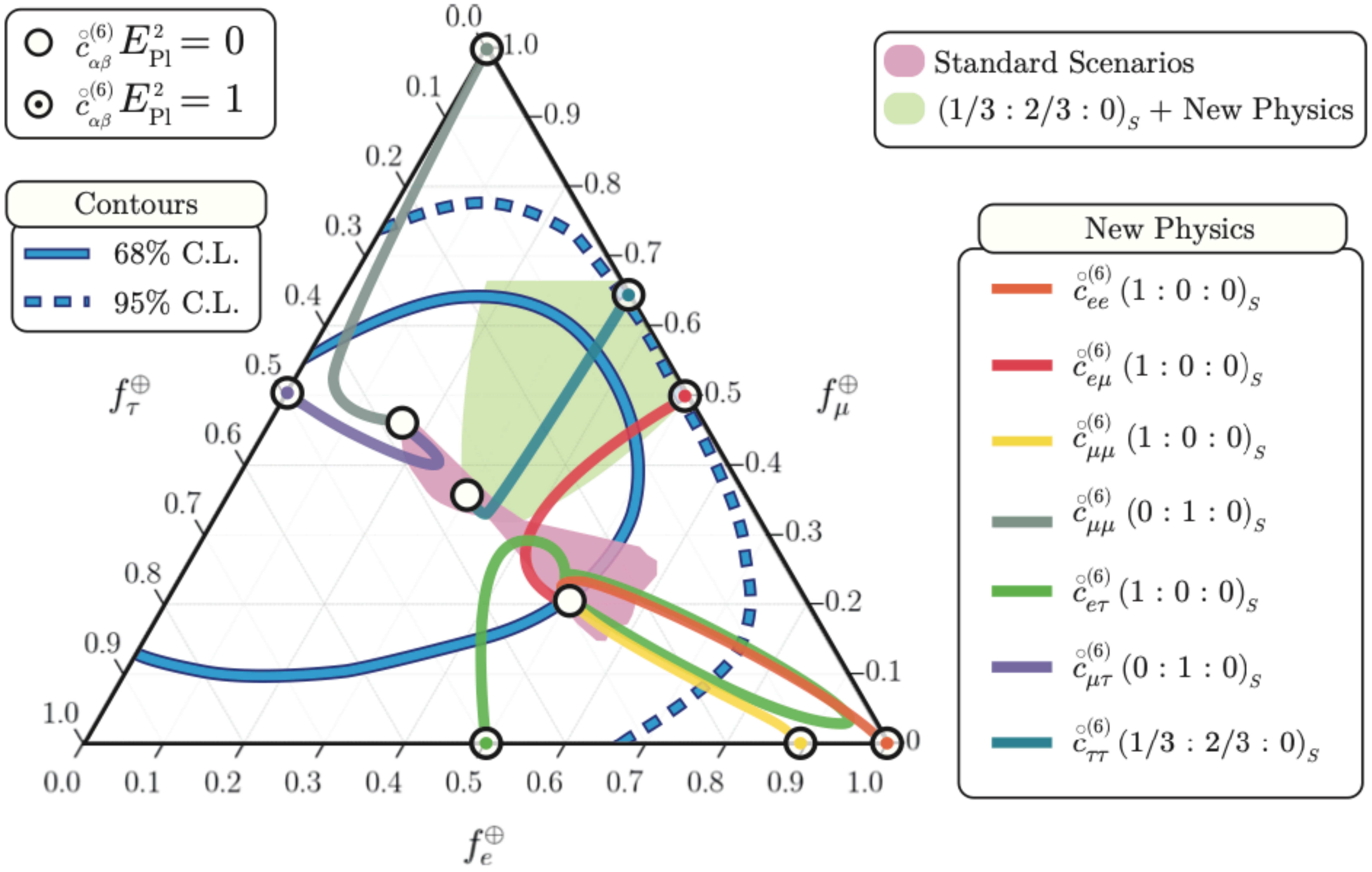
- neutrinos from distant sources oscillate into other flavours
- space-time defects might have directional dependence
- flavour ratio at Earth might deviate from expectation



Quantum Gravity

Analysis strategy:

- neutrino energies up to 2 PeV
- trace oscillation from source to Earth
- no new physics → expect approx 1:1:1 at Earth
- increasing the strength of new physics leads to extreme ratios at Earth



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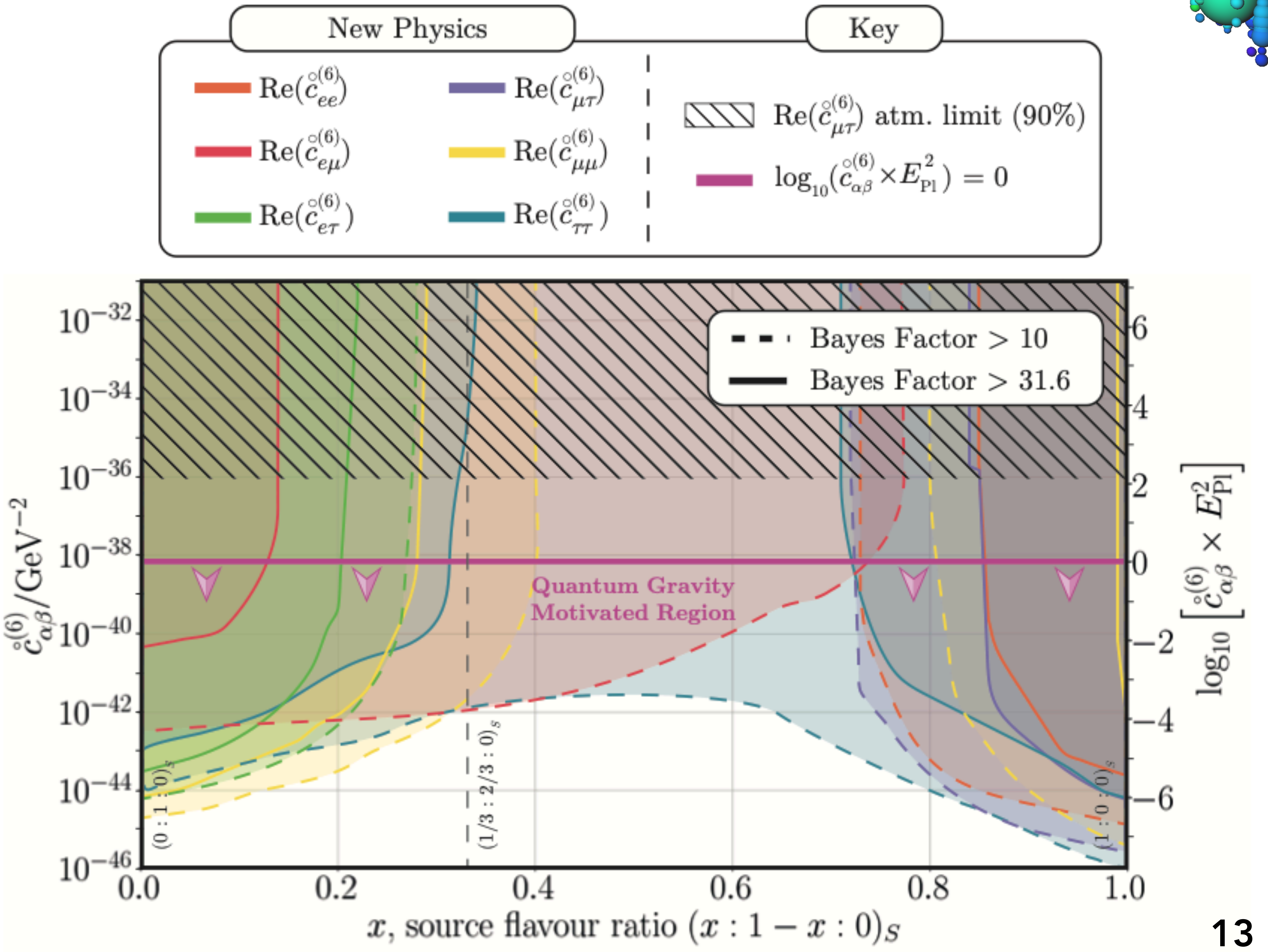
Quantum Gravity



Analysis strategy:

- describe new physics as higher dimensional additions to Hamiltonian
- dimension 6 has strongest exclusion limits

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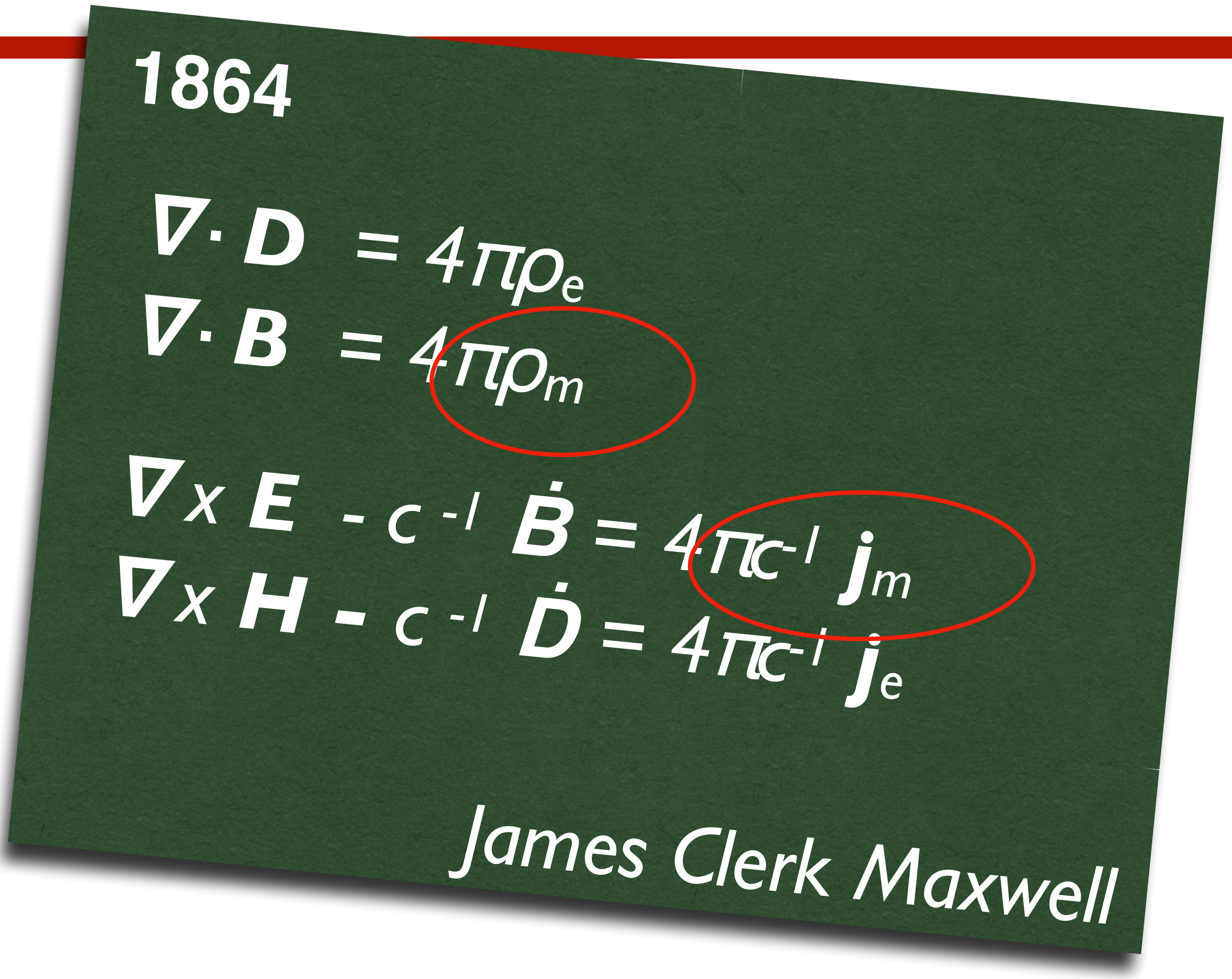
Magnetic monopoles

http://sse.royalsociety.org/2015/media/8749/mq_iron_filings-full-size.png



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Magnetic monopoles

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1864

$$\nabla \cdot \mathbf{D} = 4\pi\rho_e$$
$$\nabla \cdot \mathbf{B} = 4\pi\rho_m$$
$$\nabla \times \mathbf{E} - c^{-1}\dot{\mathbf{B}} = 4\pi c^{-1}\mathbf{j}_m$$
$$\nabla \times \mathbf{H} - c^{-1}\dot{\mathbf{D}} = 4\pi c^{-1}\mathbf{j}_e$$

James Clerk Maxwell

1931

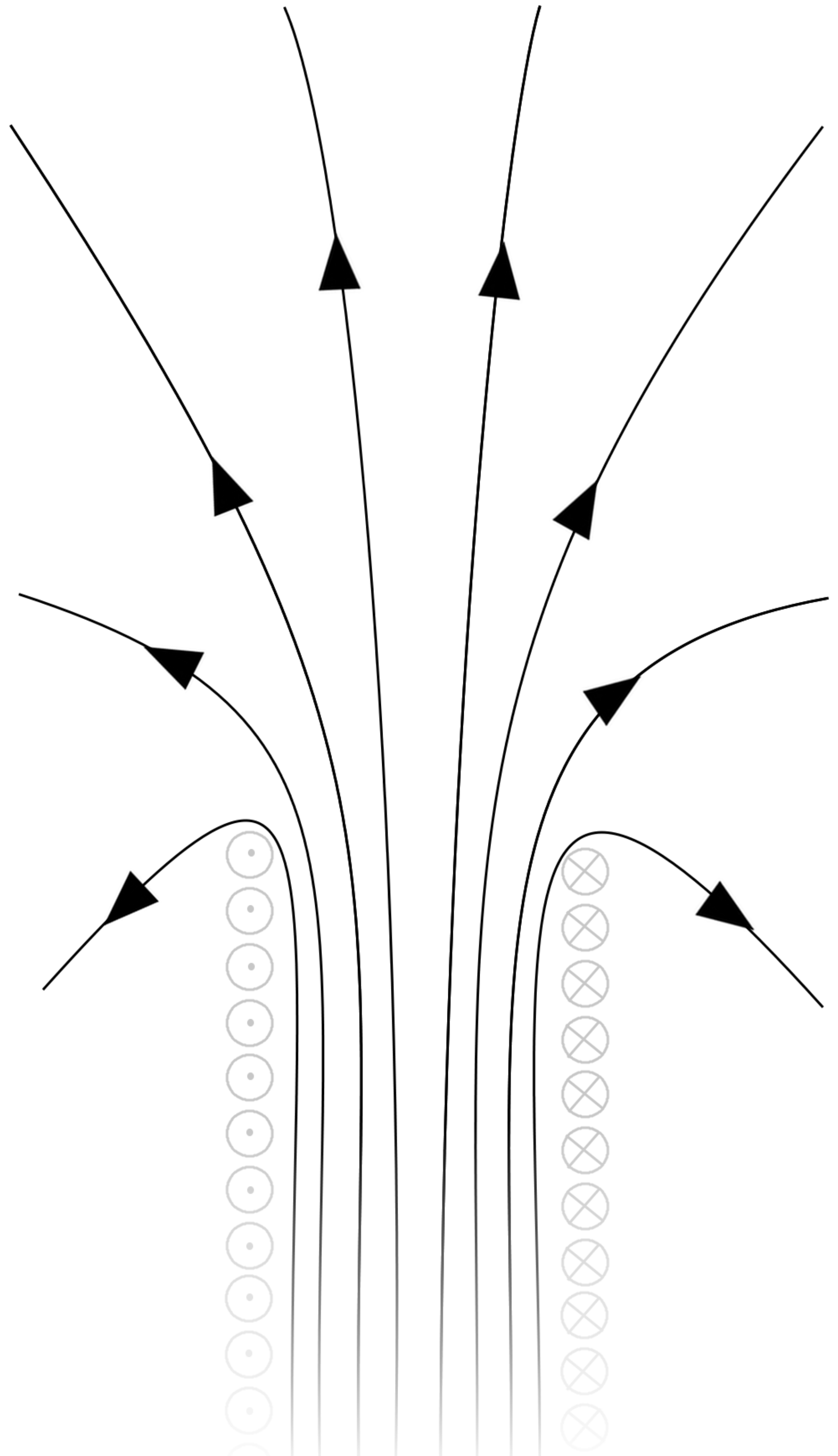
Search: Quantization of electric charge e

$$e = \sqrt{\hbar c \alpha}$$

Result: Dependence on a magnetic charge g

$$g = k\frac{e}{2\alpha} \approx 68.5\ e$$

Paul Dirac



Field of a magnetic monopole (analogous to the end of a solenoid)

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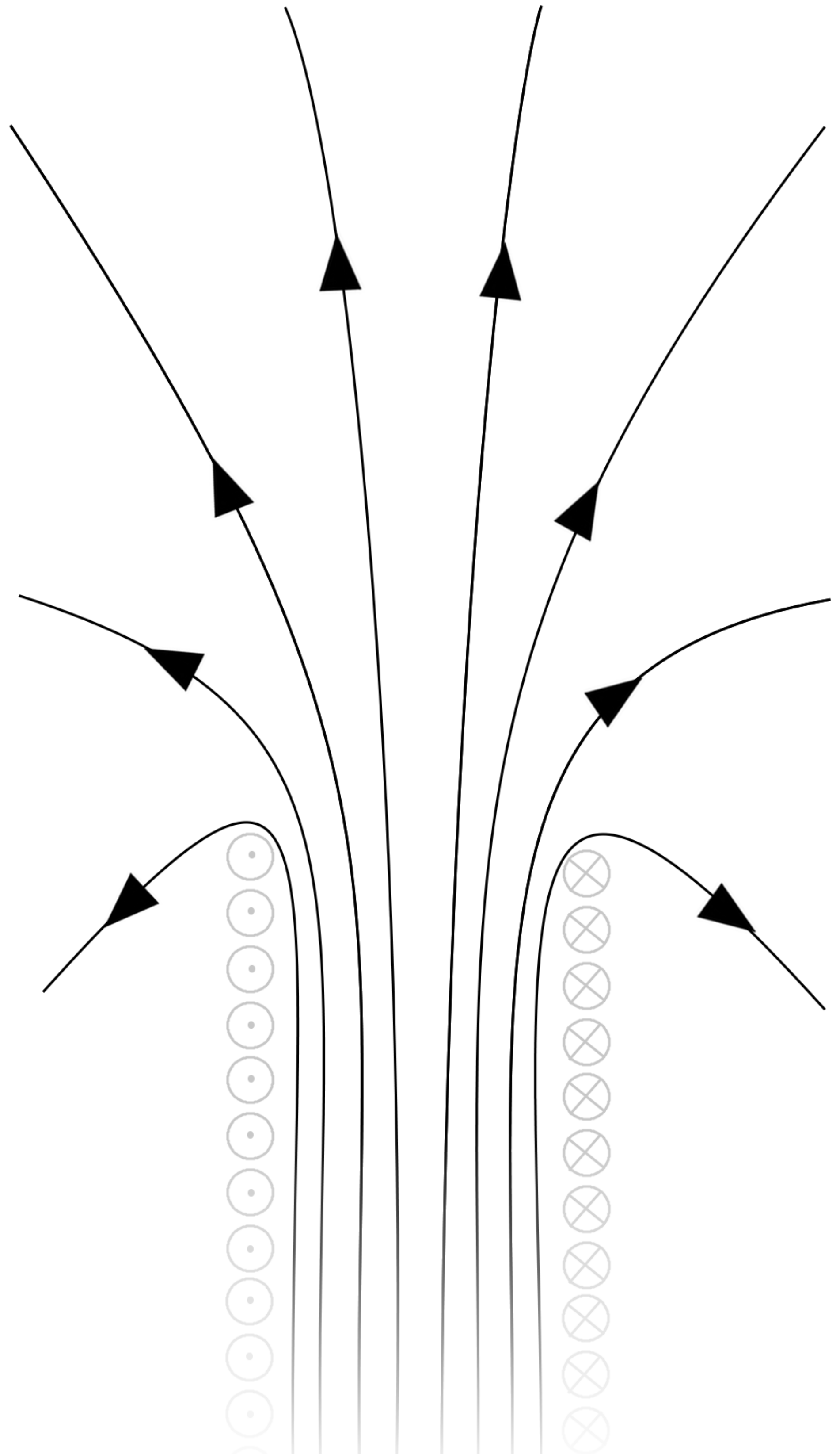
Paul Dirac

predicted by many BSM theories

- isolated magnetic charge (~n x 68·e)
- massive (up to 10^{19} GeV)
- slow or relativistic
- low flux possible
- highly ionising



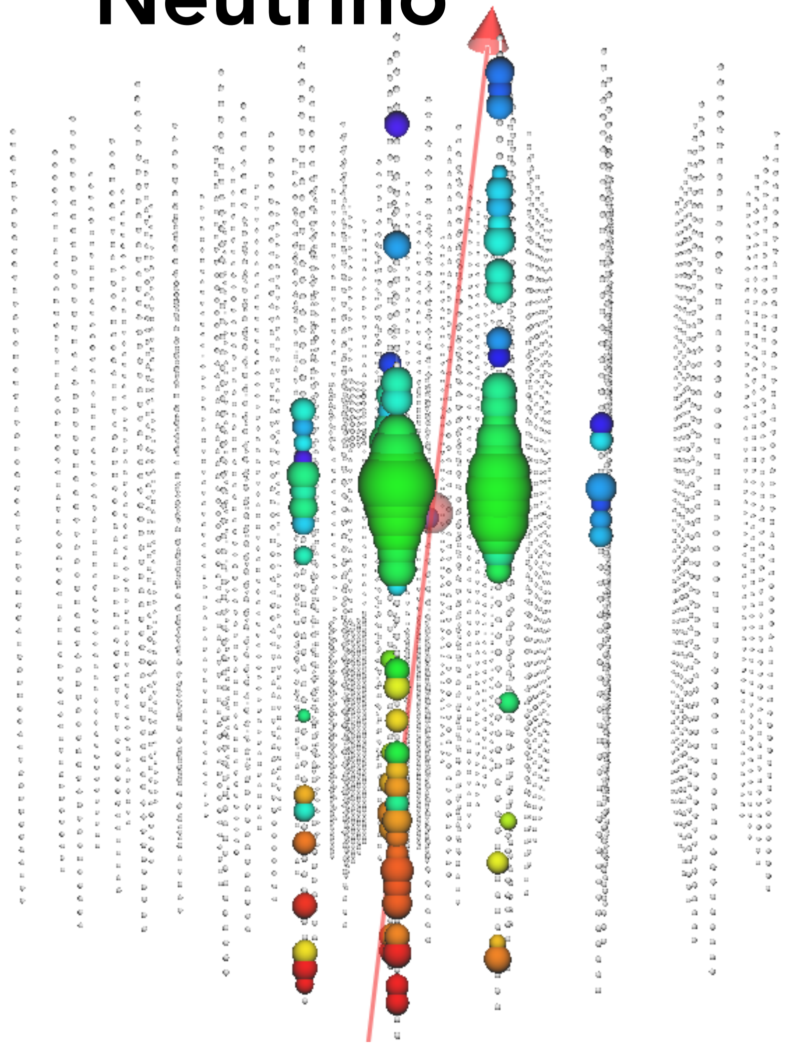
Field of a magnetic monopole (analogous to the end of a solenoid)

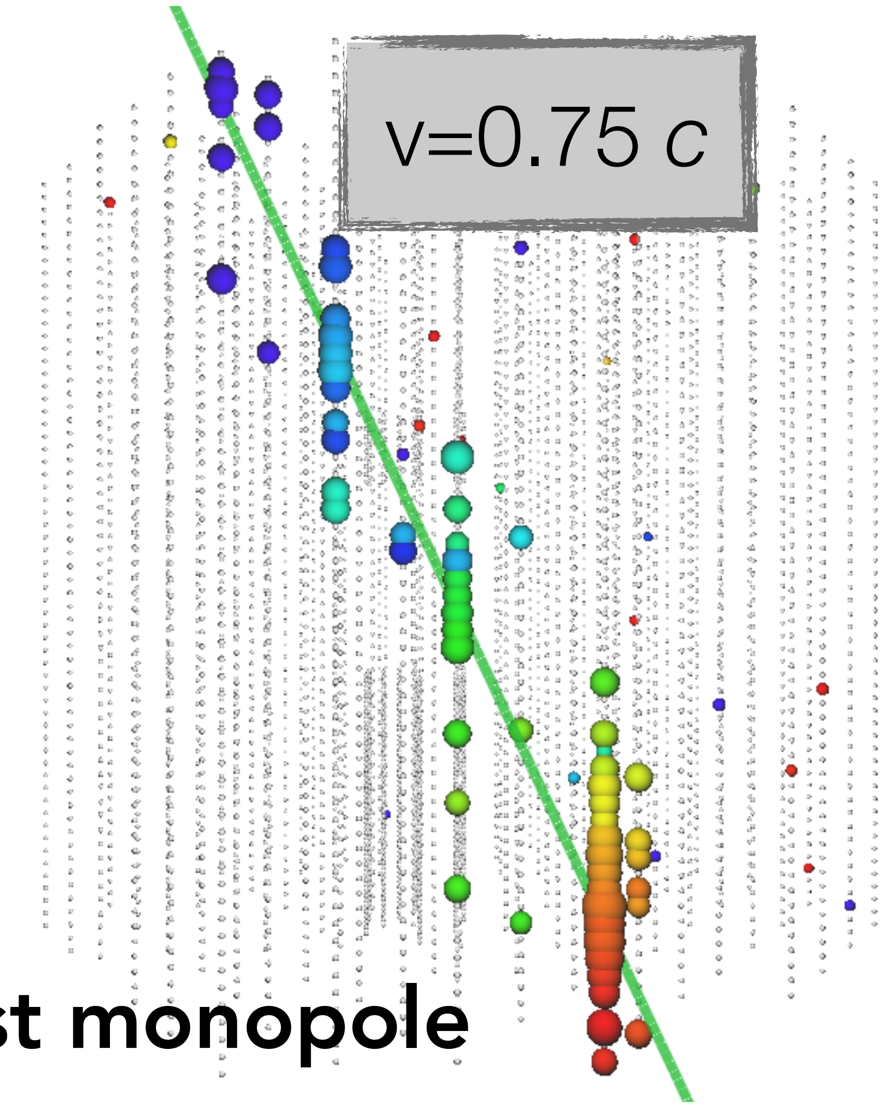
Signature of Magnetic Monopoles

searches for distinct signatures

- homogenously bright
- through-going
- slower than speed of light

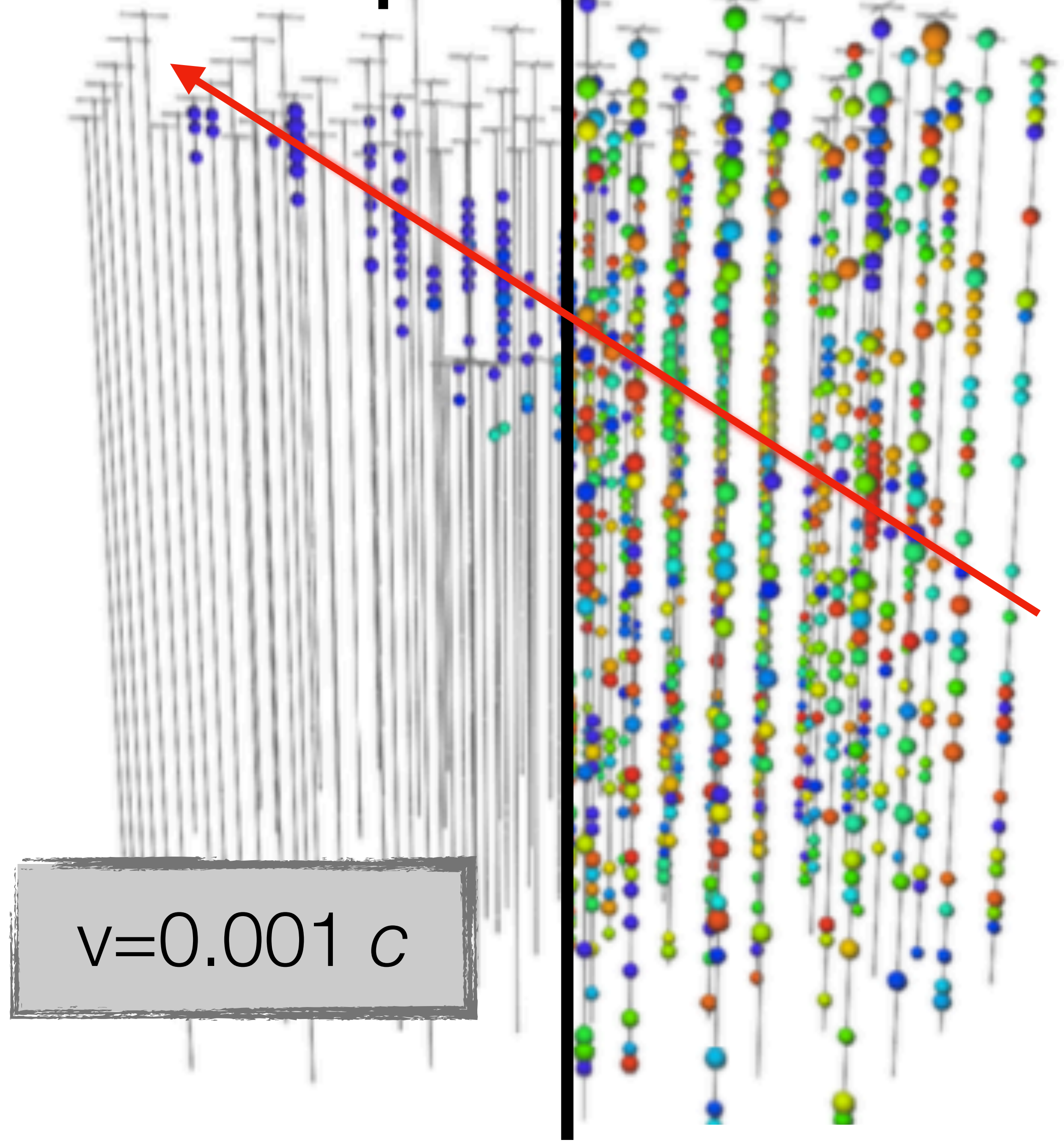
Neutrino



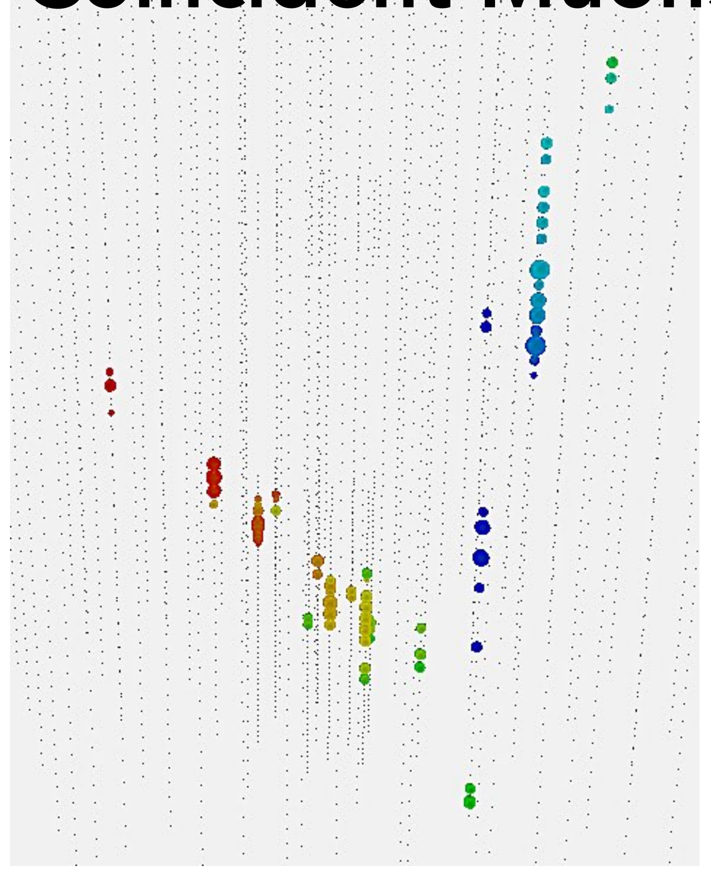


Fast monopole

Slow monopole & Noise

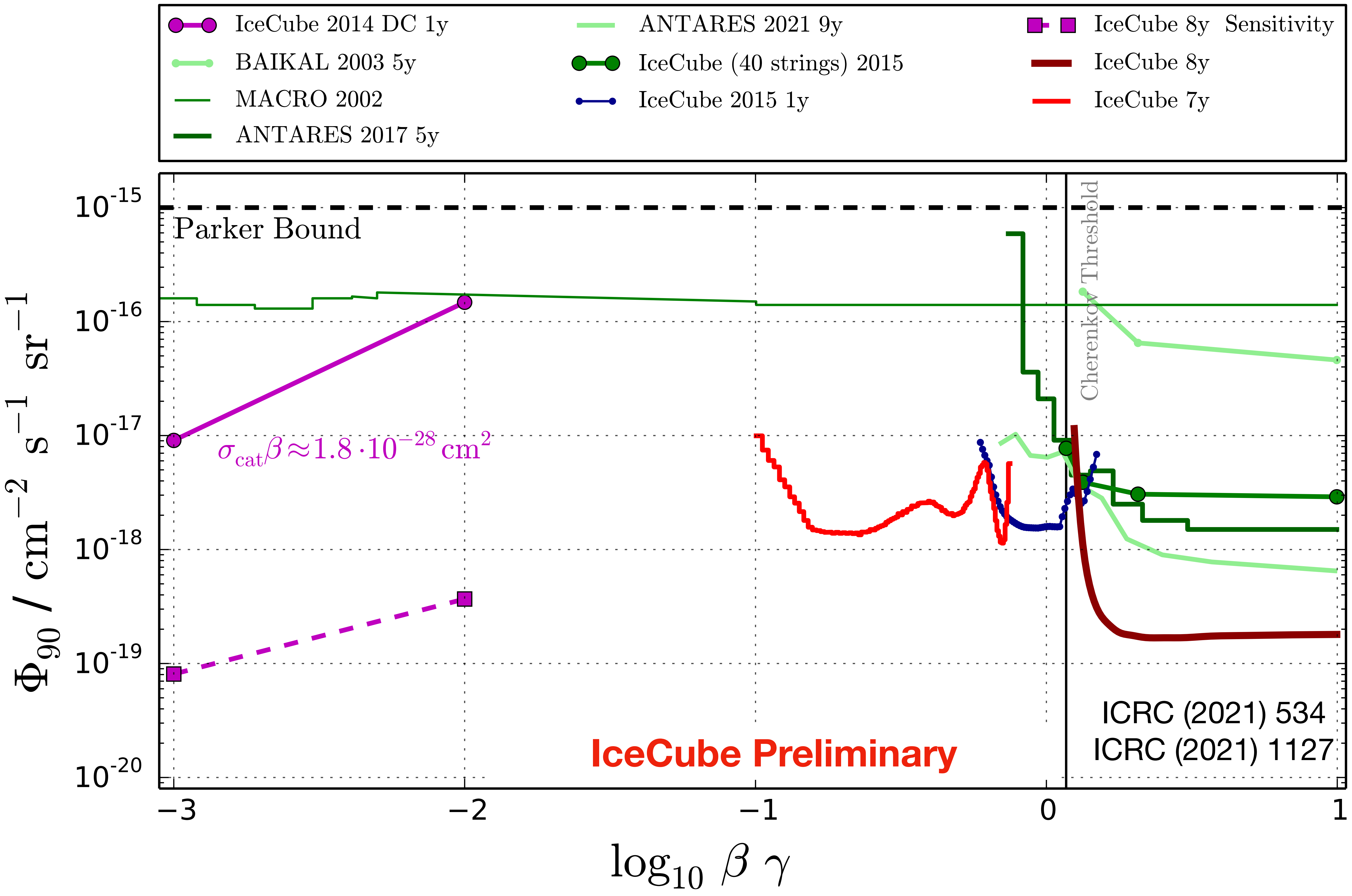


Coincident Muons



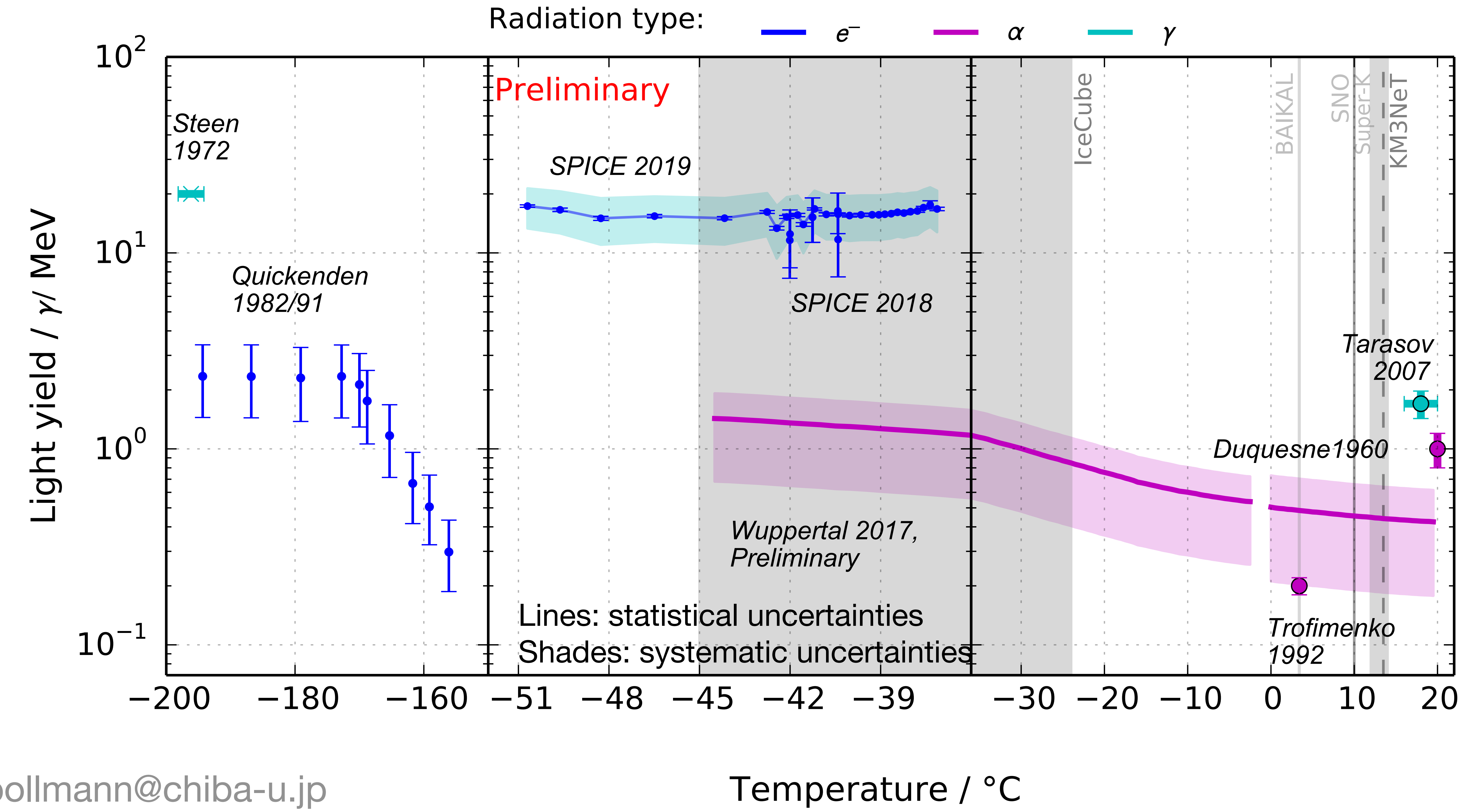
Fast magnetic monopoles

- astrophysical neutrinos as background
- searching for homogeneously bright tracks
- use variables which describe the topology of the signature in a BDT
- no events found

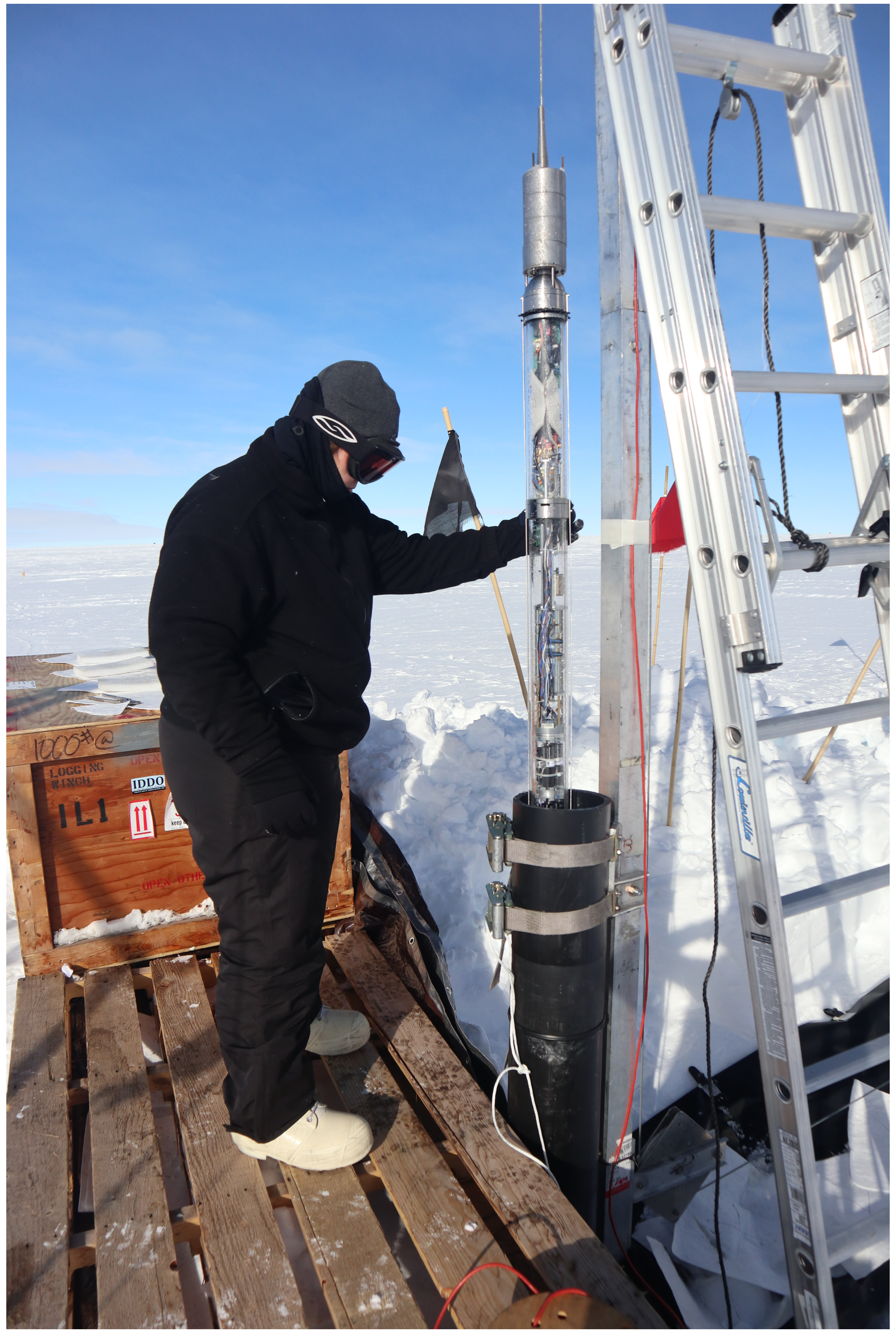


Luminescence of water and ice

- few previous measurements
- conducted laboratory and in-situ measurements
- measured properties are sufficient for use at neutrino telescopes



In Situ measurement @ South Pole 2019



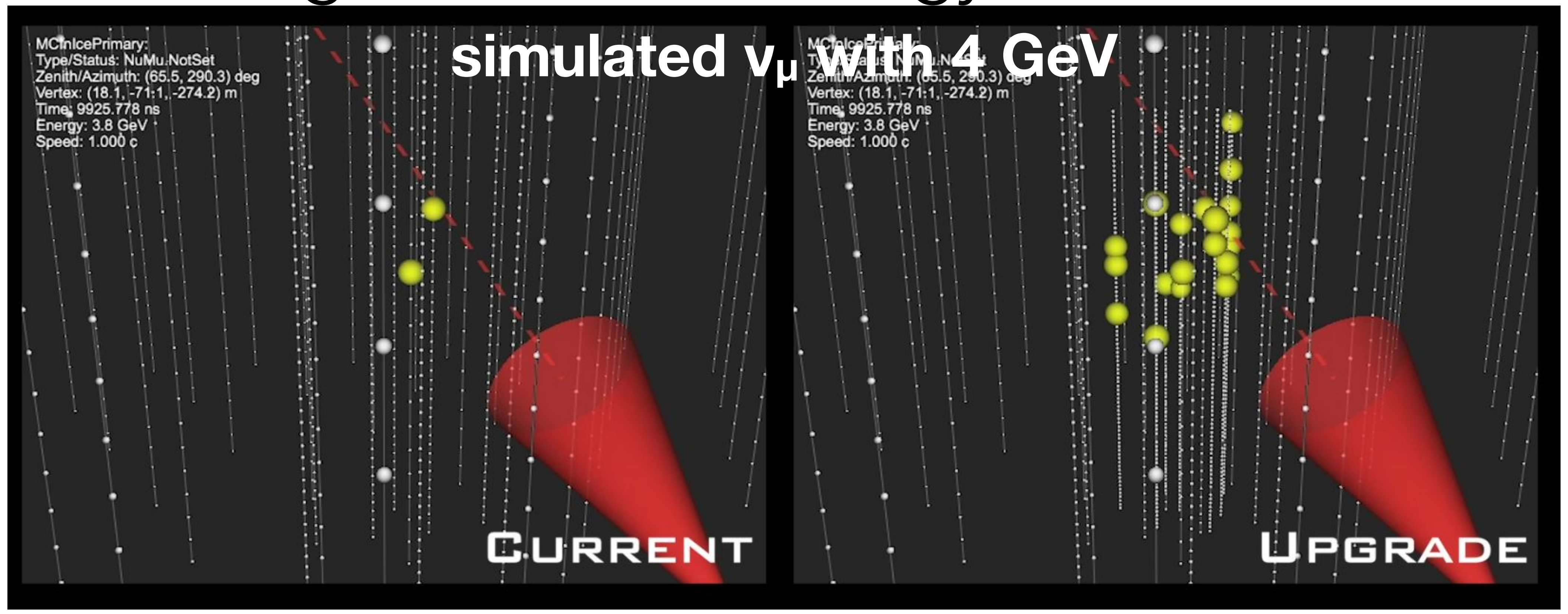
IceCube Upgrade

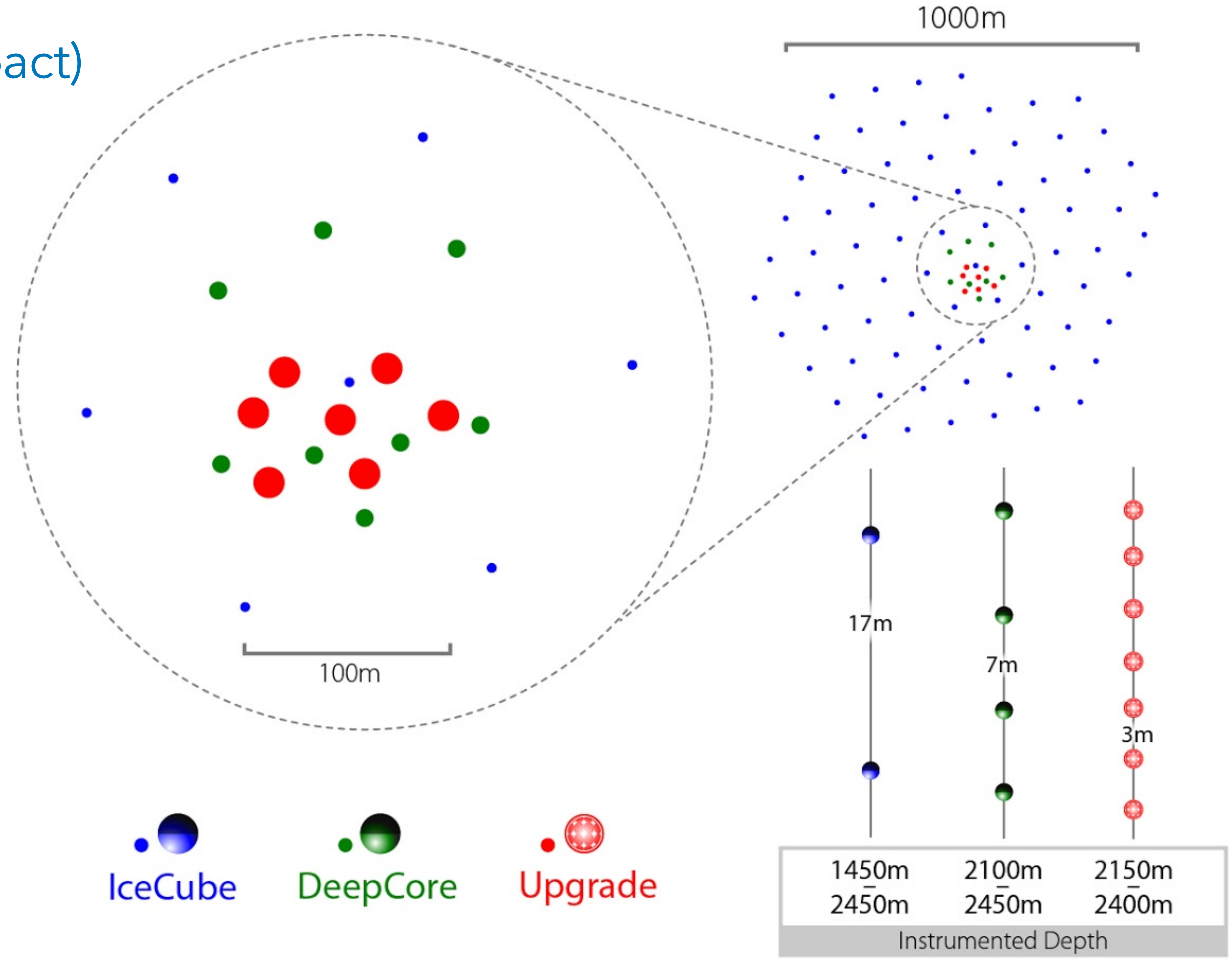
Construction

- 7 new strings á > 100 sensors
- construction austral summer ~~2021~~ → 2025 ? (Covid Impact)

Objectives:

- Unprecedented sensitivity to atmospheric neutrino mixing parameters and neutrino mass ordering extend to lower energies
- Detailed calibration of ice properties
- R&D for IceCube-Gen2
- Advantageous for low energy BSM searches





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Summary

- IceCube is
  - the largest instrumented detector on Earth
  - a multi-purpose detector (covering neutrino physics, Cosmic rays, astronomy, particle physics, beyond standard model physics, glaciology)
- Main results
  - first detections of astrophysical neutrinos
  - first evidence for an astrophysical source of neutrinos
  - leading sensitivity for many models predicted beyond the standard model