BERGISCHE
UNIVERSITÄT
WUPPERTAL

IceCube

Beyond standard model physics

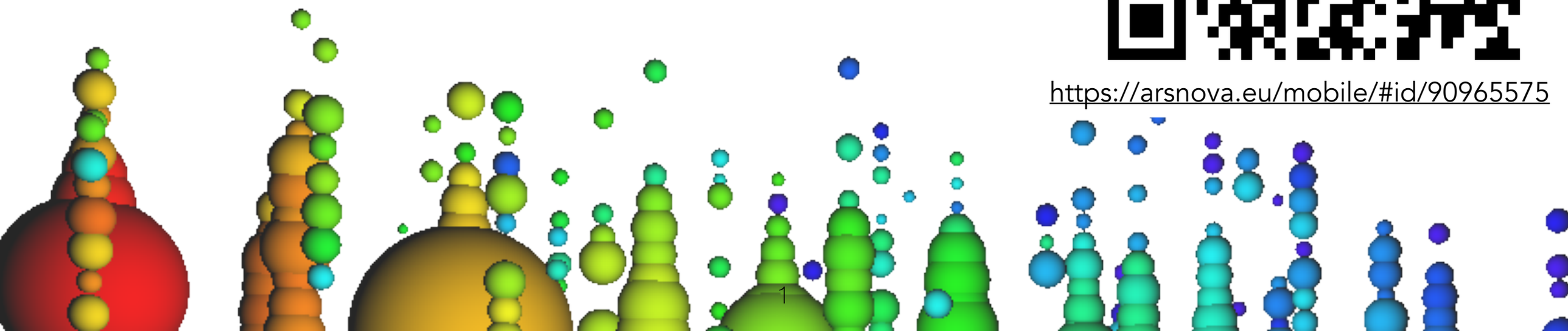
with IceCube

Please test that you can open

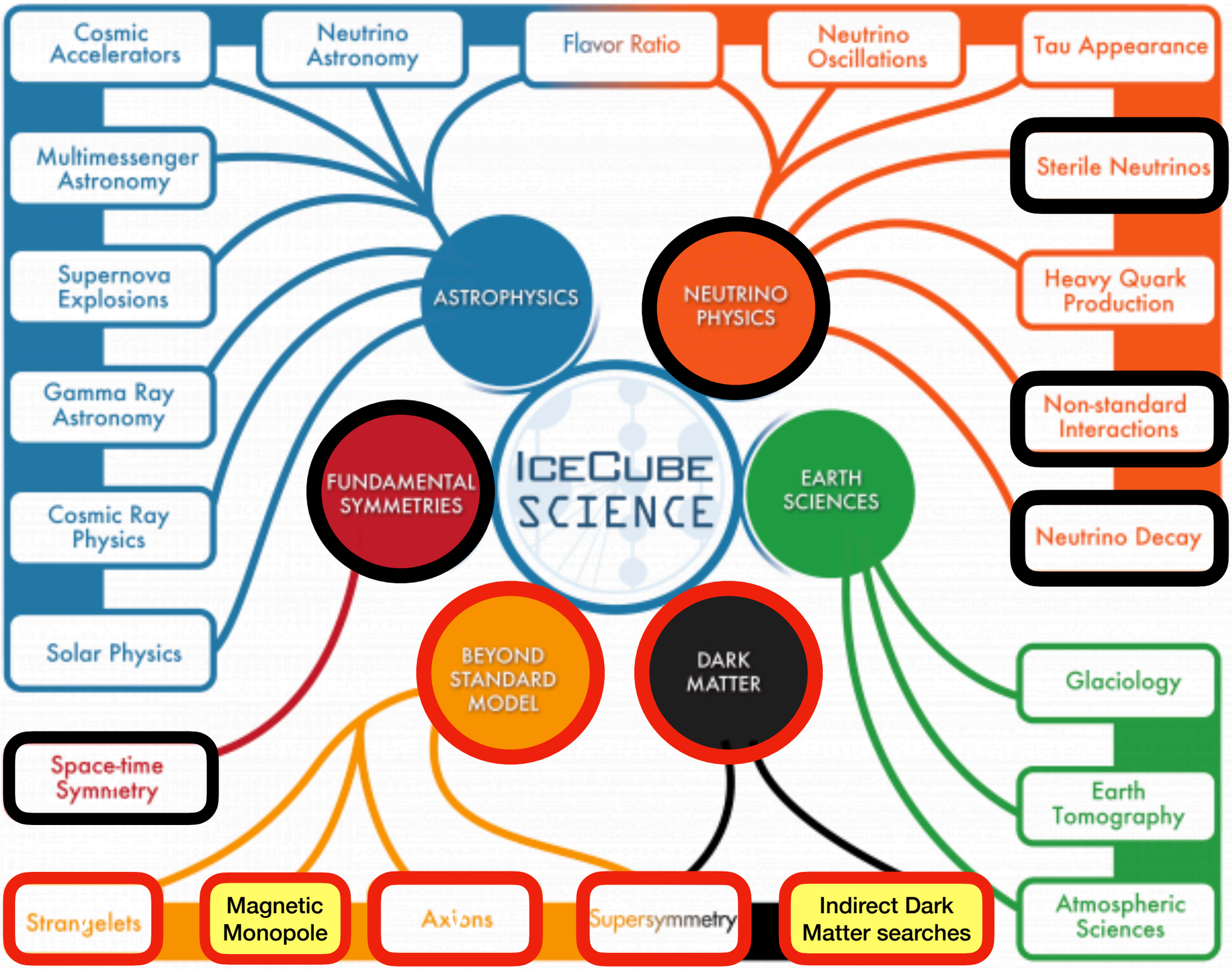
https://arsnova.eu/mobile/#id/90965575

Anna Pollmann

anna.pollmann@uni-wuppertal.de



Research program at large neutrino telescopes



Repetition

Which obstacle can hinder different messengers of the universe to reach Earth based detectors?

A. Neutrinos: the Earth at neutrino energies beyond 1 PeV (10^{15} eV)
B. Photons: interstellar matter and the Earth atmosphere
C. Protons: galactic magnetic fields and the Earth atmosphere

Which statements about neutrinos are correct?

A. There are 3 neutrino flavors, named after the 3 boson generations
B. Neutrinos interact via the weak force only (charged current and neutral current interaction)
C. The neutrino mass is constricted by experiments to > 1.2 eV/c^2

From which sources do we detect neutrinos at various energies on Earth?

A. Nuclear power plants at comparably high energies (up to TeV range)
B. Sun at comparably high energies (up to PeV range)
C. Earth atmosphere at comparably high energies (up to TeV range)
D. Far galaxies at comparably low energies (MeV range)

Which statements about IceCube are correct?

A. IceCube is the biggest detector on Earth judging by instrumented volume which is $(100m)^3$
B. the photomultipliers, used to record the light emitted by particles in IceCube, use the photo-electric effect to transform photons into electrons
C. neutrinos and muons cross IceCube with the speed of light in vacuum, thus they need about 60 ns to cross horizontally through the detector
D. most common signatures of particles in IceCube are tracks (long line of light emission) and cascades (~ spherical light explosion)

Which statements about Cherenkov light are correct?

A. It has a wavelength around 450nm (blue)
B. It is produced by a particle with a velocity of 90% speed of light in the medium
C. Constructive interference leads to the emission of this light from a cone around the particle
D. Particles crossing IceCube emit Cherenkov light only

Open with any device

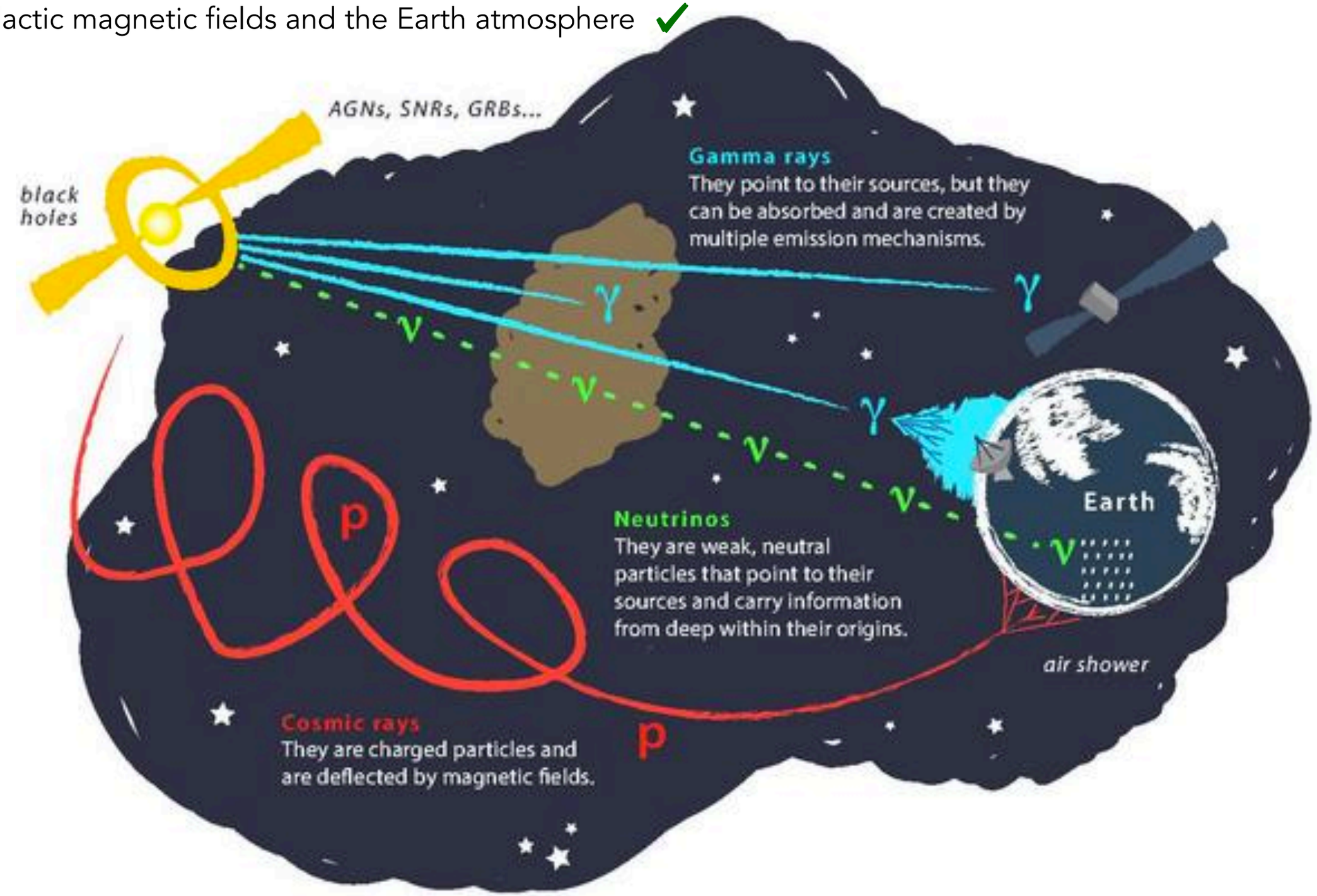
Answer questions 1-5

https://arsnova.eu/mobile/#id/90965575

Repetition

Which obstacle can hinder different messengers of the universe to reach Earth based detectors?

A. For neutrinos: the Earth at neutrino energies beyond 1 PeV (10^{15} eV) ✓
B. For photons: interstellar matter and the Earth atmosphere ✓
C. For protons: galactic magnetic fields and the Earth atmosphere ✓



Repetition

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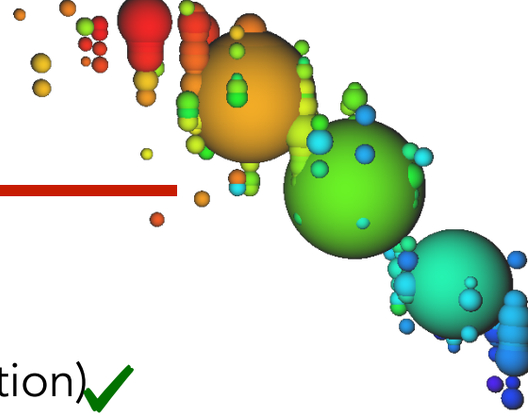
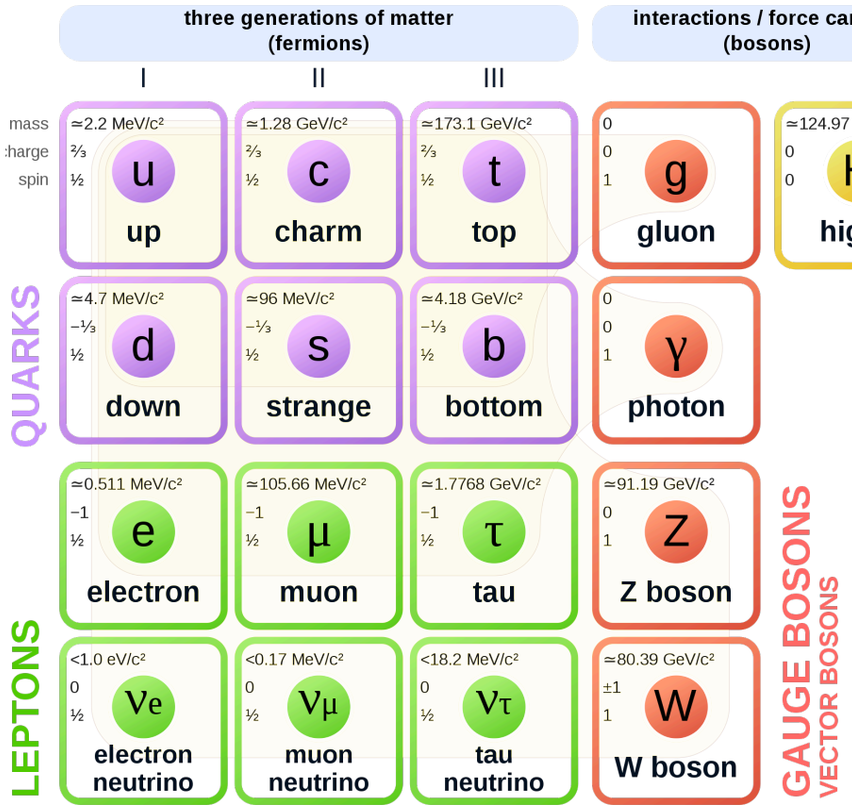
A. There are 3 neutrino flavors, ~~named after the 3 boson generations~~ ✗

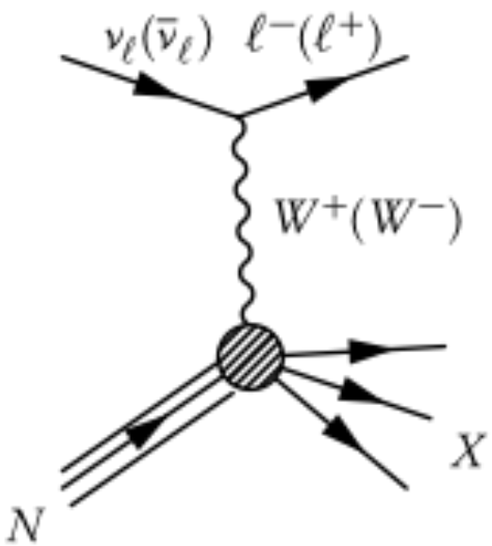
B. Neutrinos interact via the weak force only (charged current and neutral current interaction) ✓

C. The neutrino mass is constricted by the KATRIN experiments ~~to > 1.2 eV/c²~~ ✗ *< 1.1 eV / c²*





Charged current interaction (CC)



Neutal current interaction (NC)

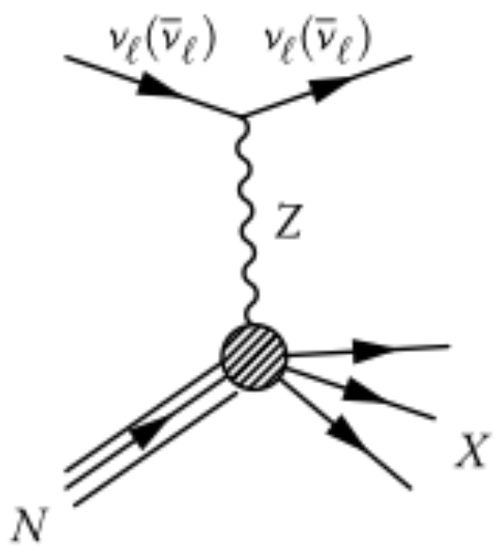


Image: A. Sandrock

anna.pollmann@uni-wuppertal.de

Repetition

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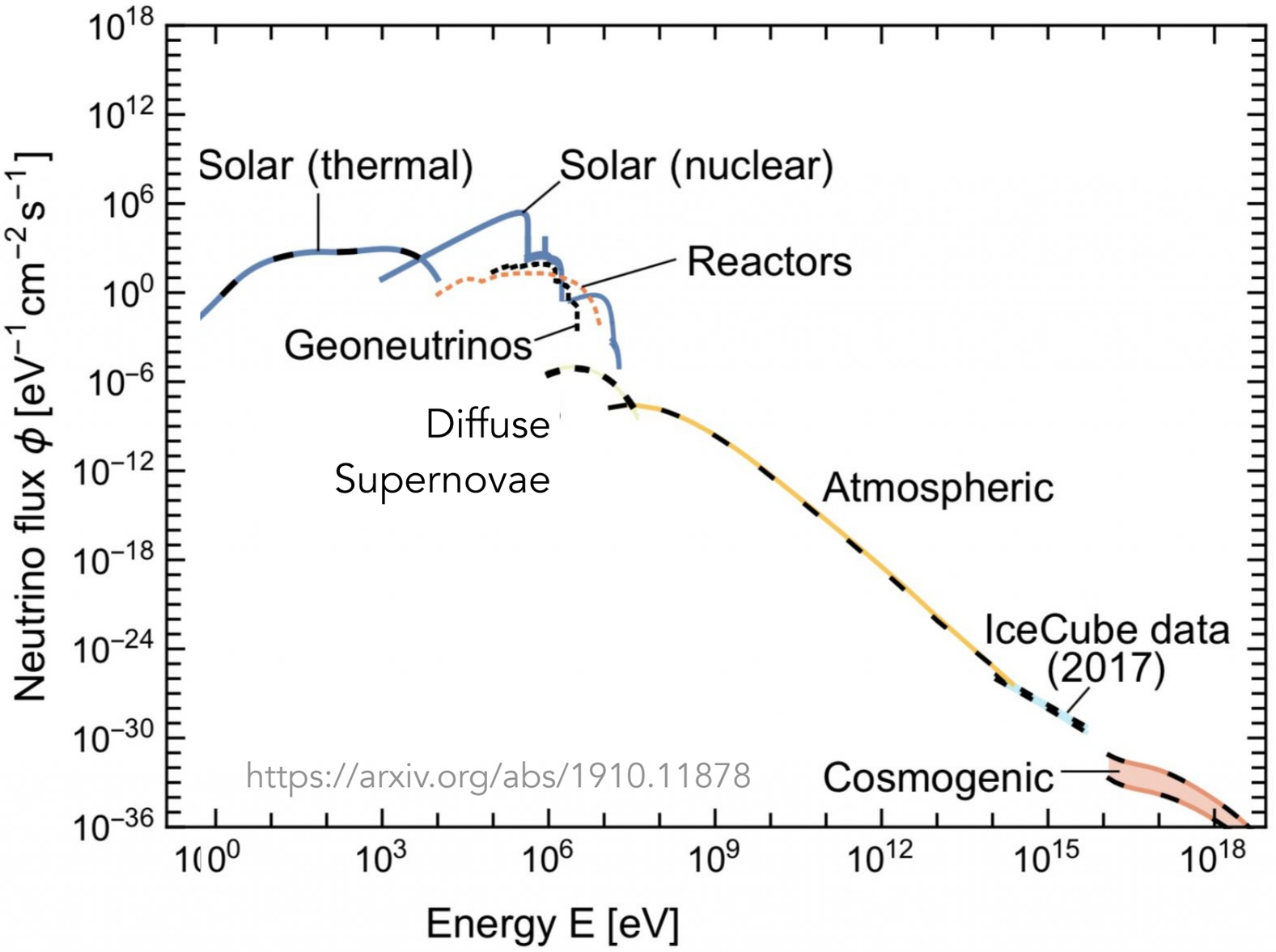
A. Nuclear power plants at comparably ~~high energies (up to TeV range)~~ ✗ *low energies ~MeV*

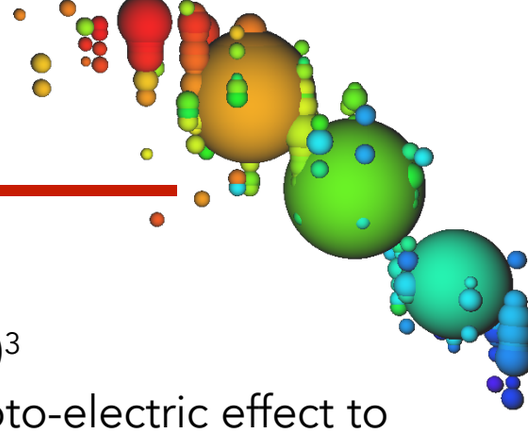
B. Sun at comparably ~~high energies (up to PeV range)~~ ✗ *low energies < MeV*

C. Earth atmosphere at comparably high energies (up to 100 TeV range) ✓

D. Far galaxies at comparably ~~low energies (MeV range)~~ ✗ *high energies ~ PeV*



Repetition



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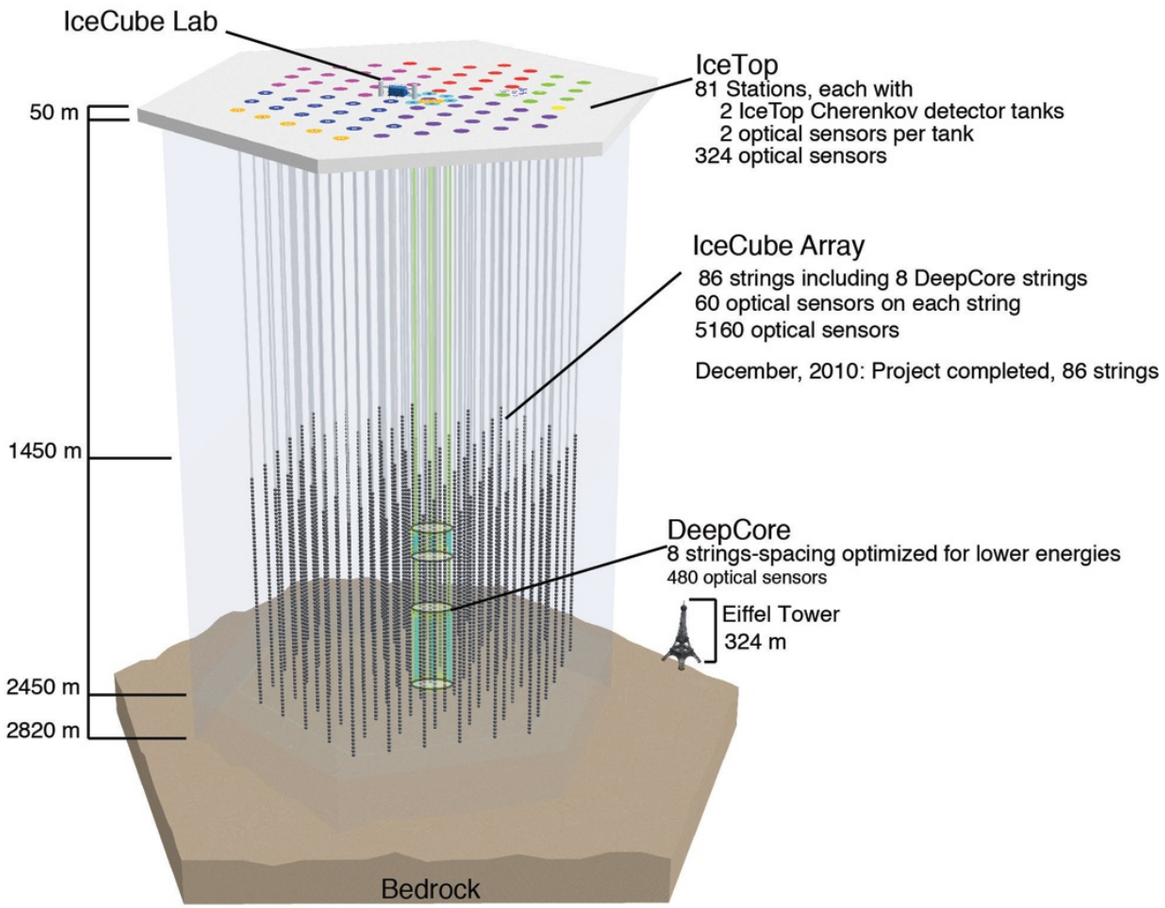

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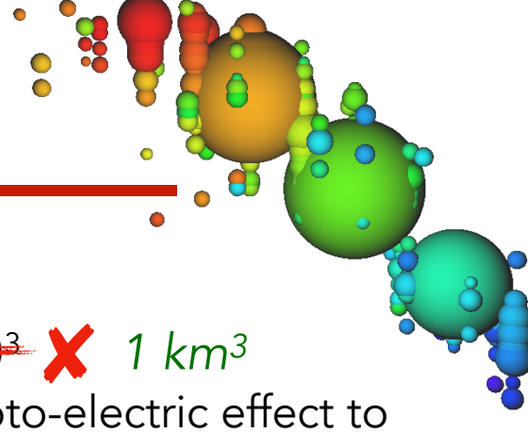

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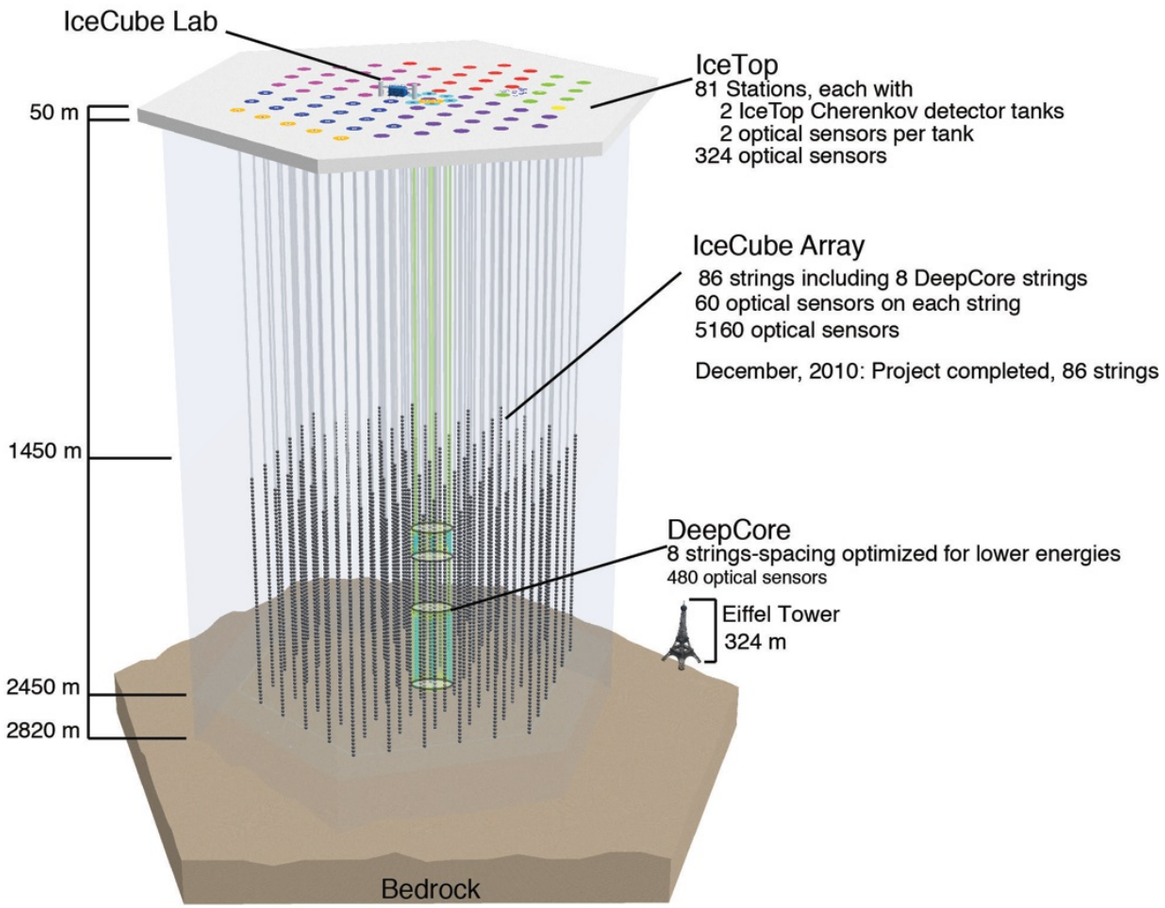

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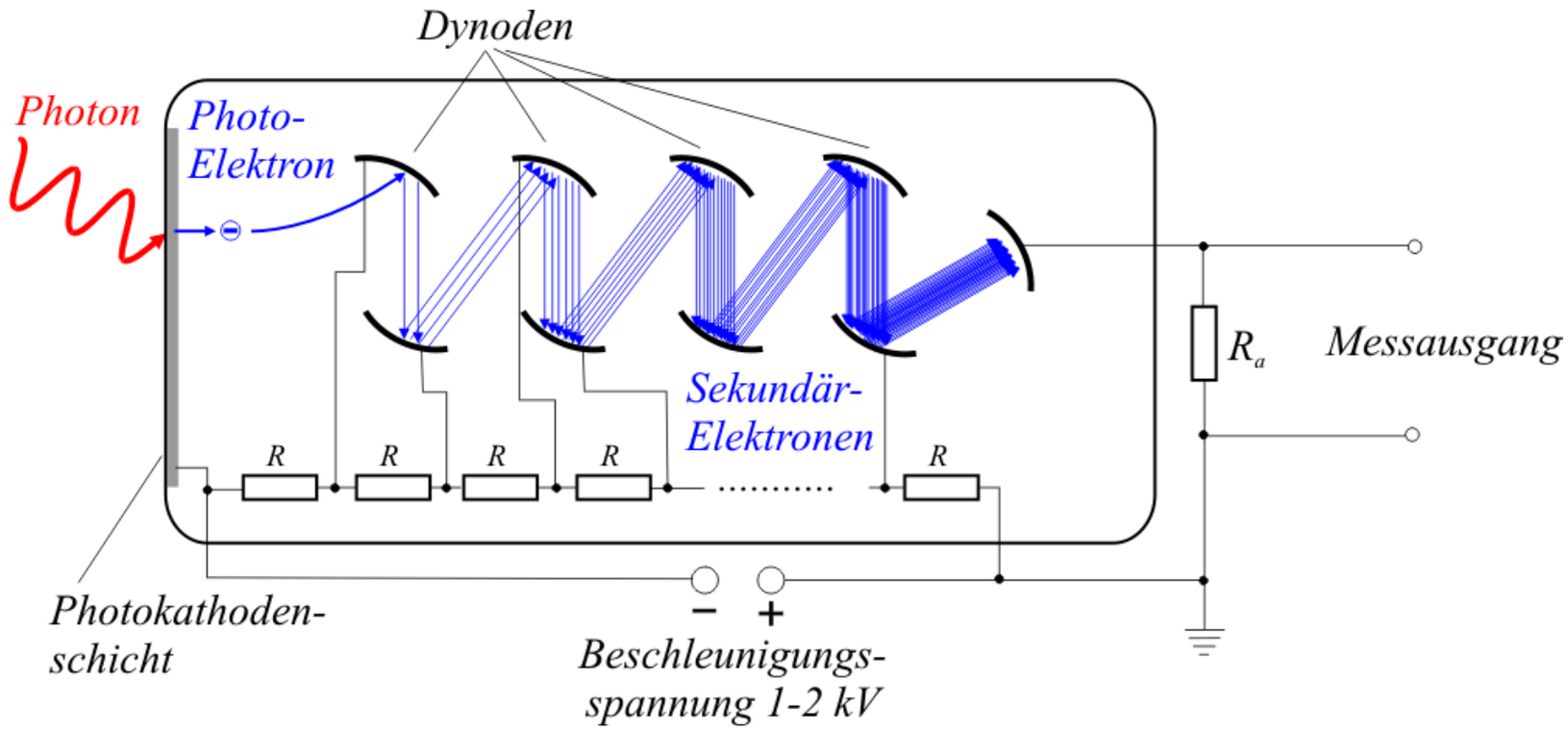

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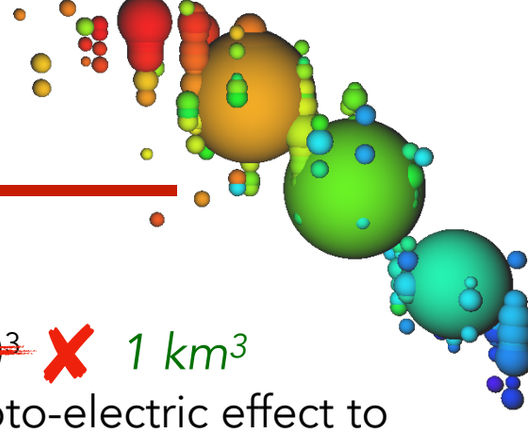

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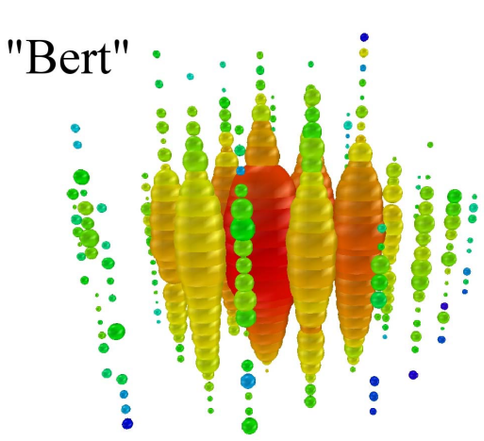
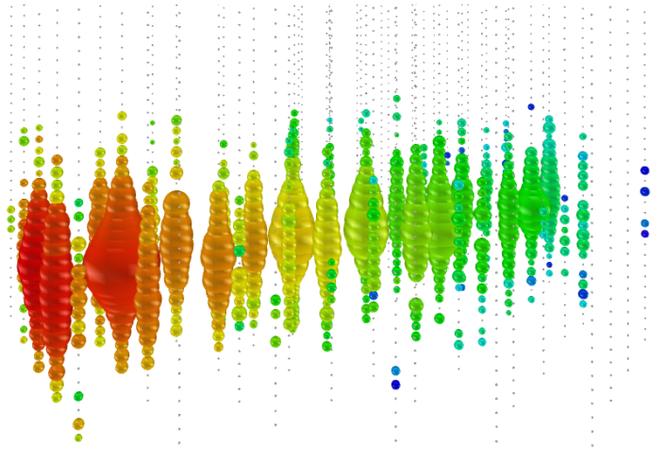
C. Neutrinos and muons cross IceCube with the speed of light in vacuum, thus they need about ~~60 ns~~ to cross horizontally through the detector ✗ *0.3 m/ns · 1000 m =300 ns*

D. Most common signatures of particles in IceCube are tracks (long line of light emission) and cascades (~ spherical light explosion) ✓



Cascade like events:

- ν_e - CC and all flavour NC interactions
- Interaction inside instrumented volume
- Poor angular resolution $\approx 15°$
- Good energy resolution



Track like events:

- ν_μ - CC interactions
- Interaction may happen outside instrumented volume
- Good angular resolution $\approx 1°$
- Poor energy resolution

Repetition

Which statements about Cherenkov light are correct?

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B. It is produced by a particle with a velocity of 90% speed of light in the medium
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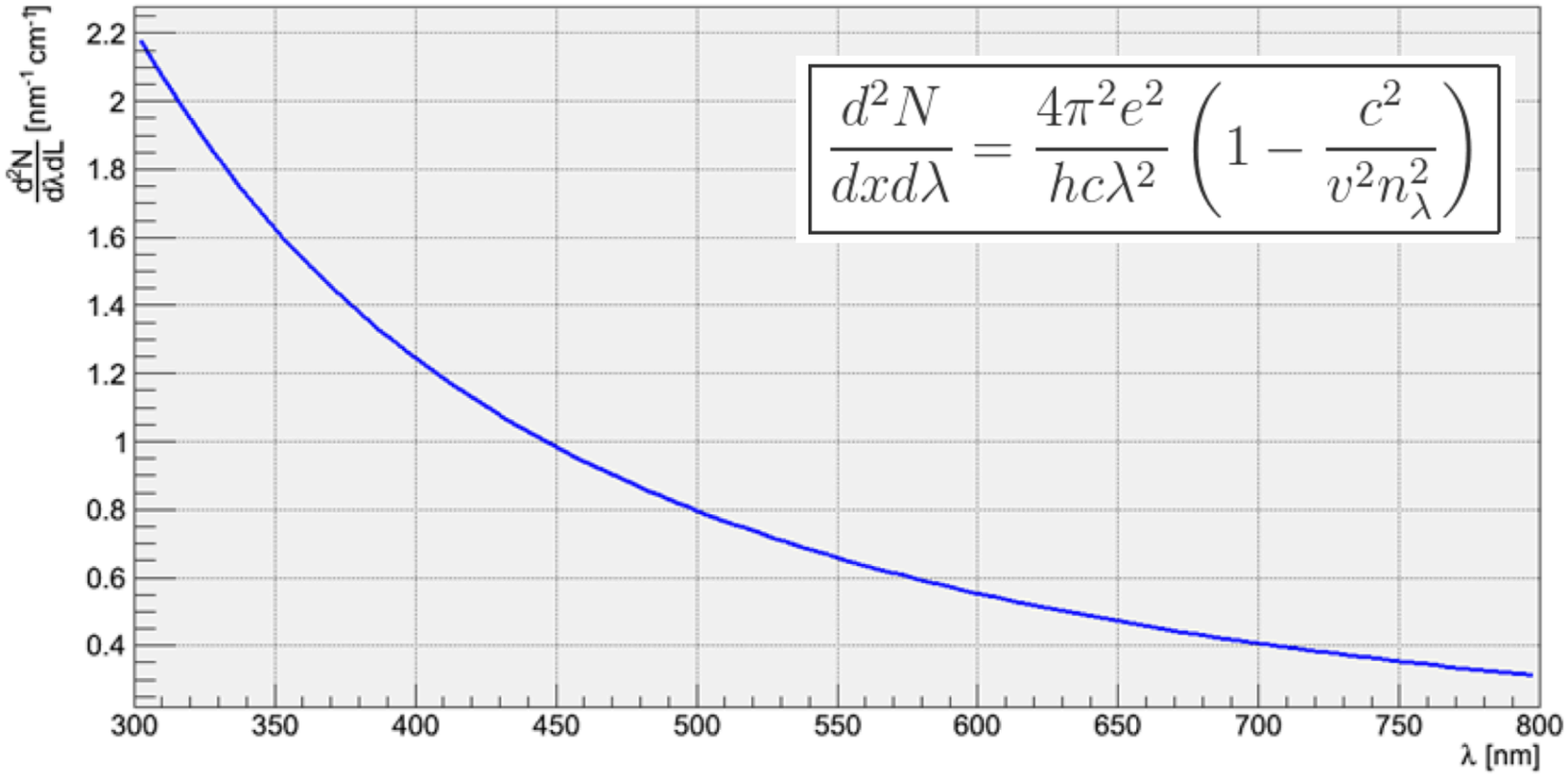


Repetition

Which statements about Cherenkov light are correct?

A. It has a wavelength around 450nm (blue) ✗ *The Cherenkov spectrum increases towards smaller wavelengths*

B. It is produced by a particle with a velocity of 90% speed of light in the medium ✗ *by charged particles exceeding the speed of light in the medium*

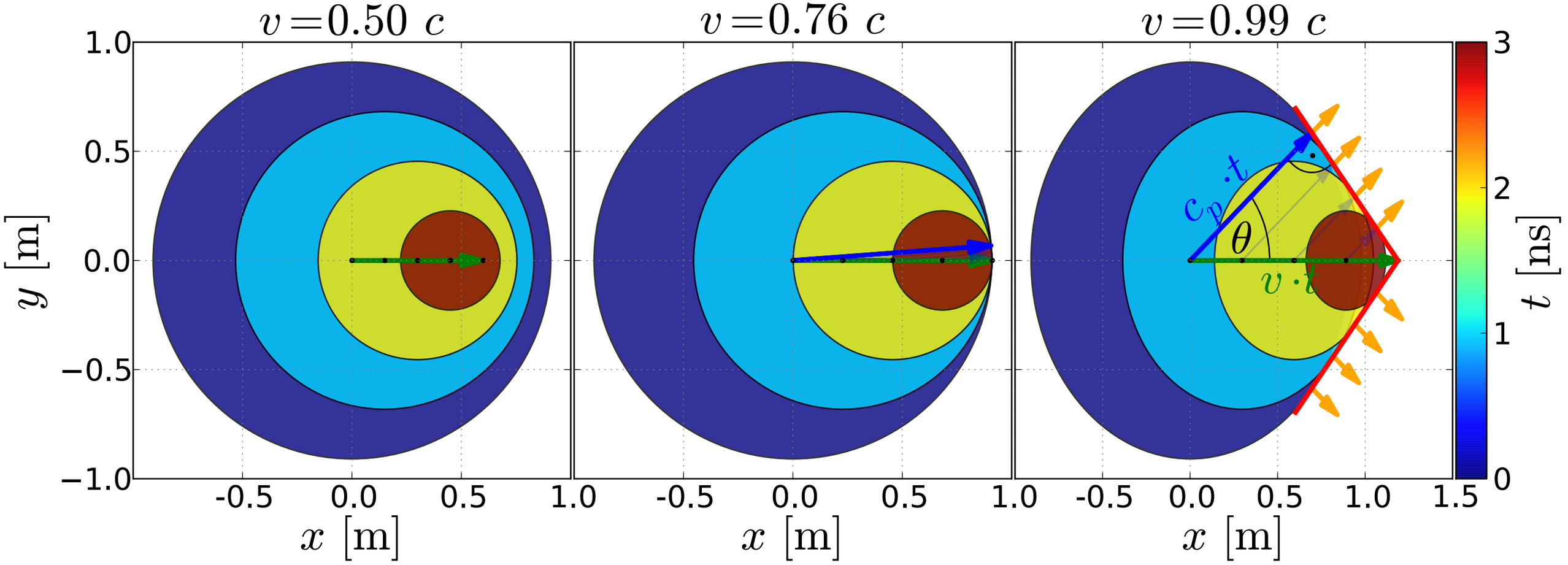
C. Constructive interference leads to the emission of this light from a cone around the particle ✓

D. Particles crossing IceCube emit Cherenkov light only and no other light ✗ *Other energy losses are photonuclear interactions, bremsstrahlung, pair production. These daughter particles produce not only Cherenkov light .*

Light waves through polarization

Cherenkov threshold

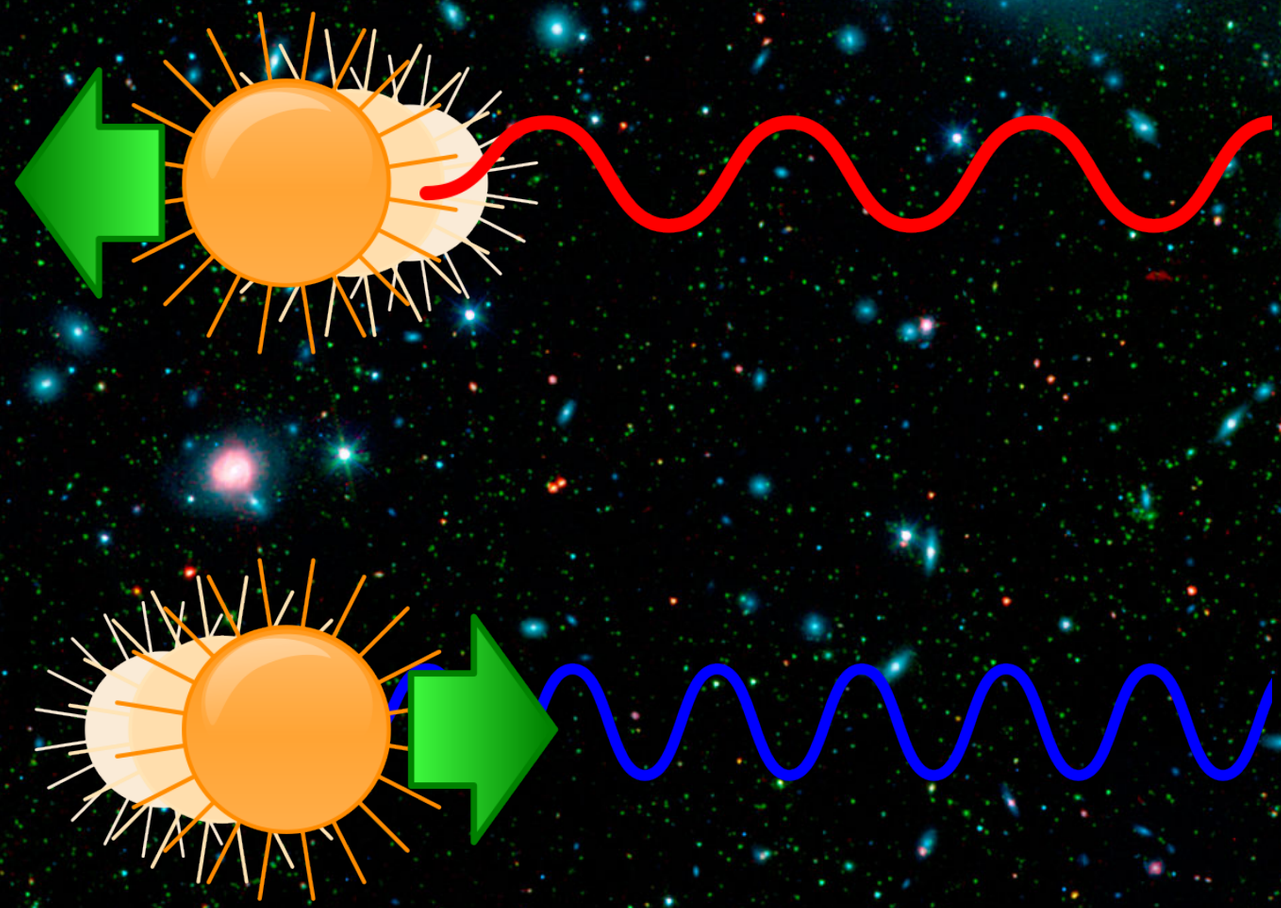
Cherenkov cone



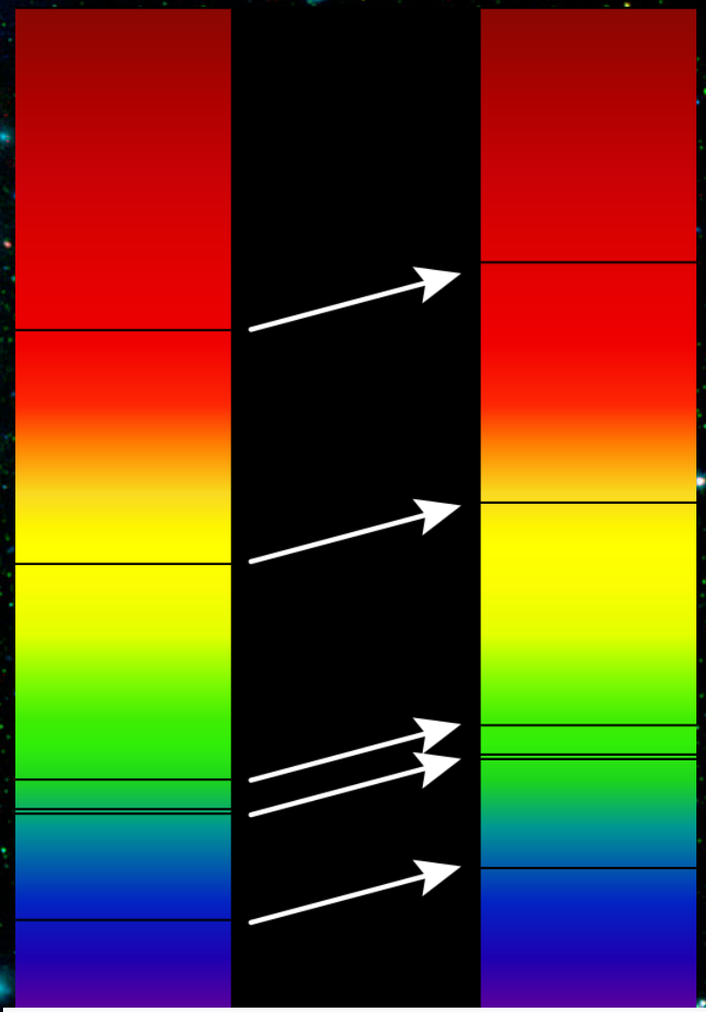
Hints for Dark Matter

Zwicky's observation of galaxies' movements in the Coma-Cluster (1933)

Measurement
- luminosity of galaxies → mass of galaxies
- red shift of galaxies → velocity of galaxies



Redshift of spectral lines
due to Doppler effect



kipedia.org/wiki/Datei:Redshift.svg

$$z = \frac{\lambda_{\text{obsv}} - \lambda_{\text{emit}}}{\lambda_{\text{emit}}}$$

https://de.wikipedia.org/wiki/Coma-Galaxienhaufen#/media/Datei:Ssc2007-10a1.jpg

Hints for Dark Matter

Zwicky's observation of galaxies' movements in the Coma-Cluster (1933)

Measurement
- luminosity of galaxies → mass of galaxies
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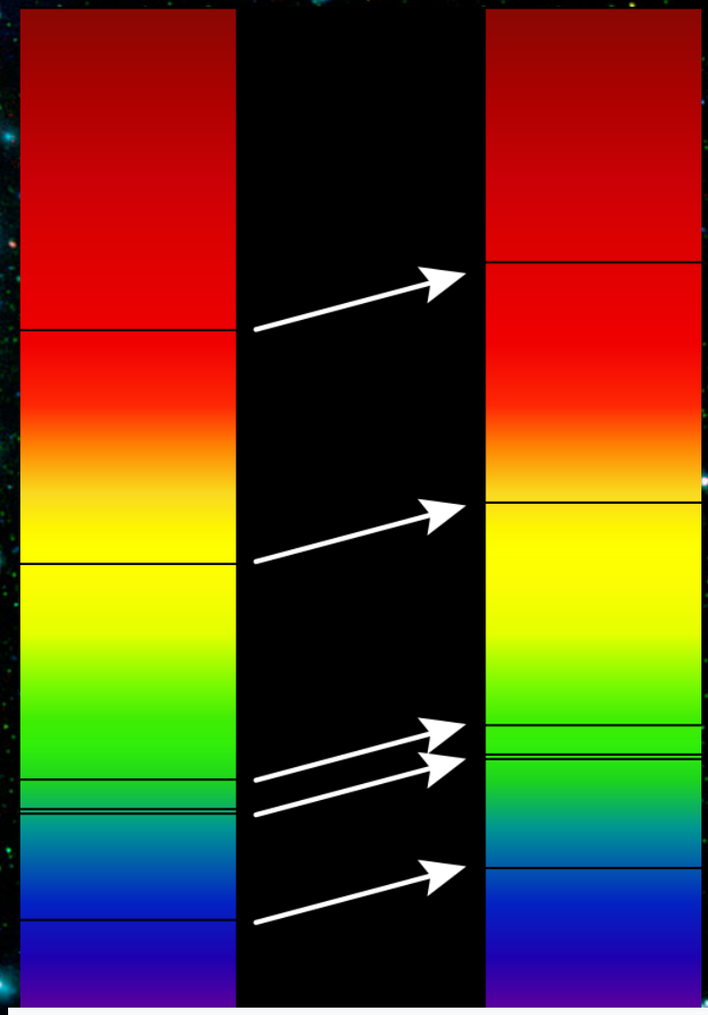
Virial theorem:

$$\langle T \rangle = -\frac{1}{2} \sum_{k=1}^{N} \langle \mathbf{F}_k \cdot \mathbf{r}_k \rangle$$

Result:
Galaxies are too fast to stay in the cluster.

Conclusion:
The cluster needs to be have more mass than estimated

Redshift of spectral lines
due to Doppler effect



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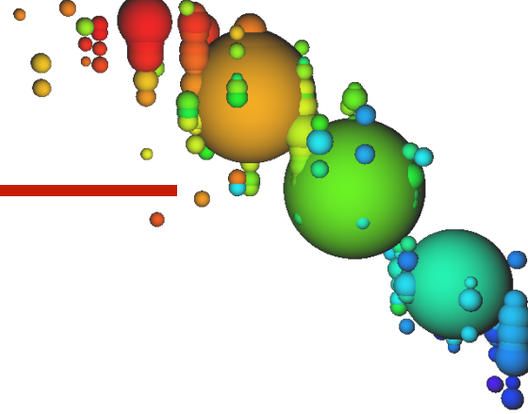
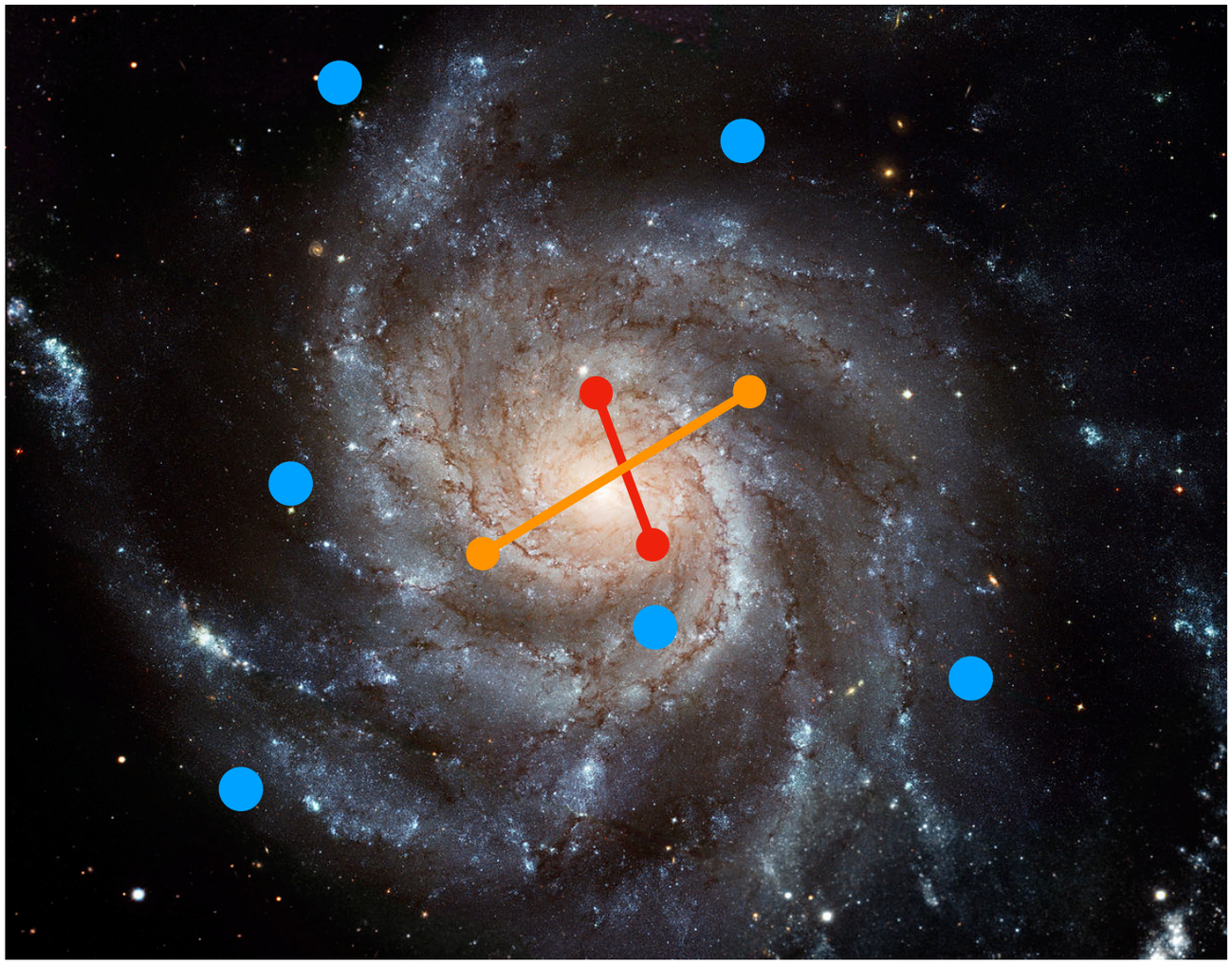
Hints for Dark Matter



Vera Rubin's measurements of the rotation curves

Measurement:

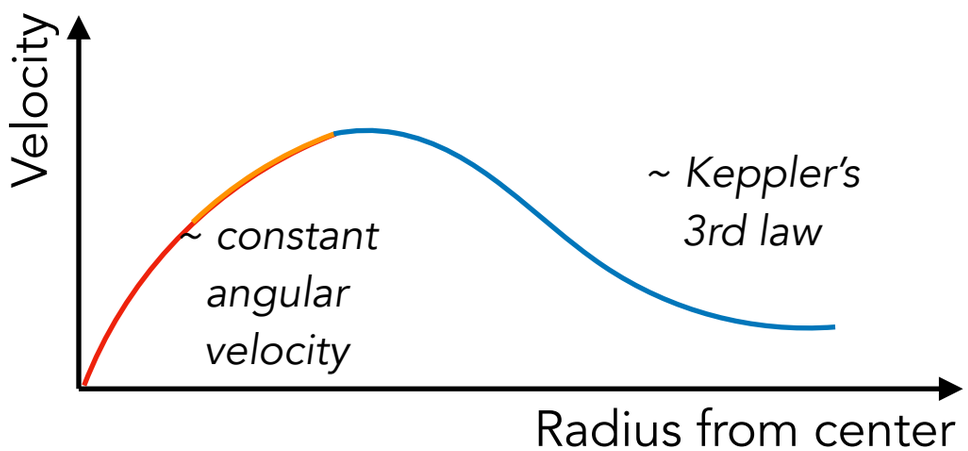
Position and velocity of stars in different galaxies



Expectation:

Fixed or strong connection between stars

Loosely bound stars



Hints for Dark Matter

Vera Rubin's measurements of the rotation curves (1970)

Measurement:
Position and velocity of stars in different galaxies

Observation:
Velocity does not decrease as expected

Interpretation:
Galaxies must have further *invisible* mass

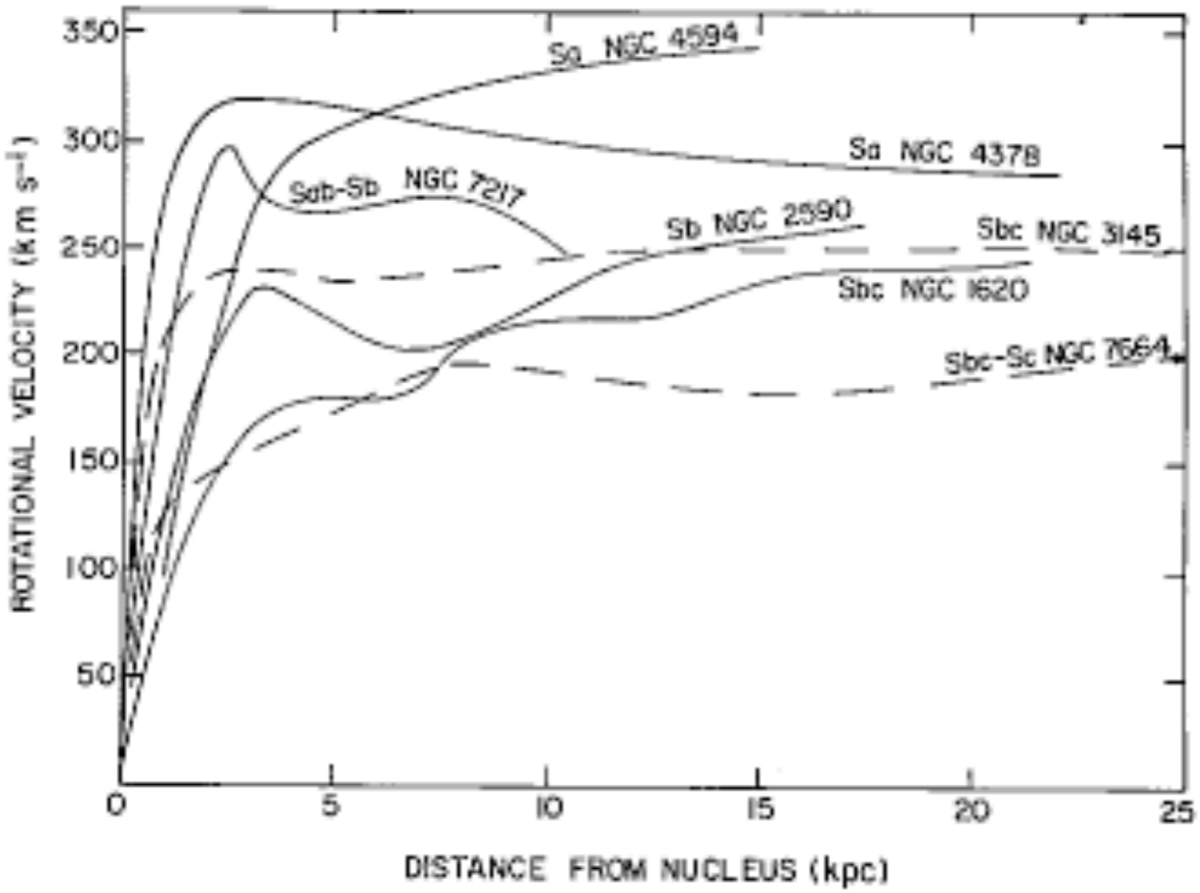


Figure from Rubin, Ford, and Thonnard (1978), Ap. J. Lett., 225, L107

Hints for Dark Matter

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Measurement:
Position and velocity of stars in different galaxies

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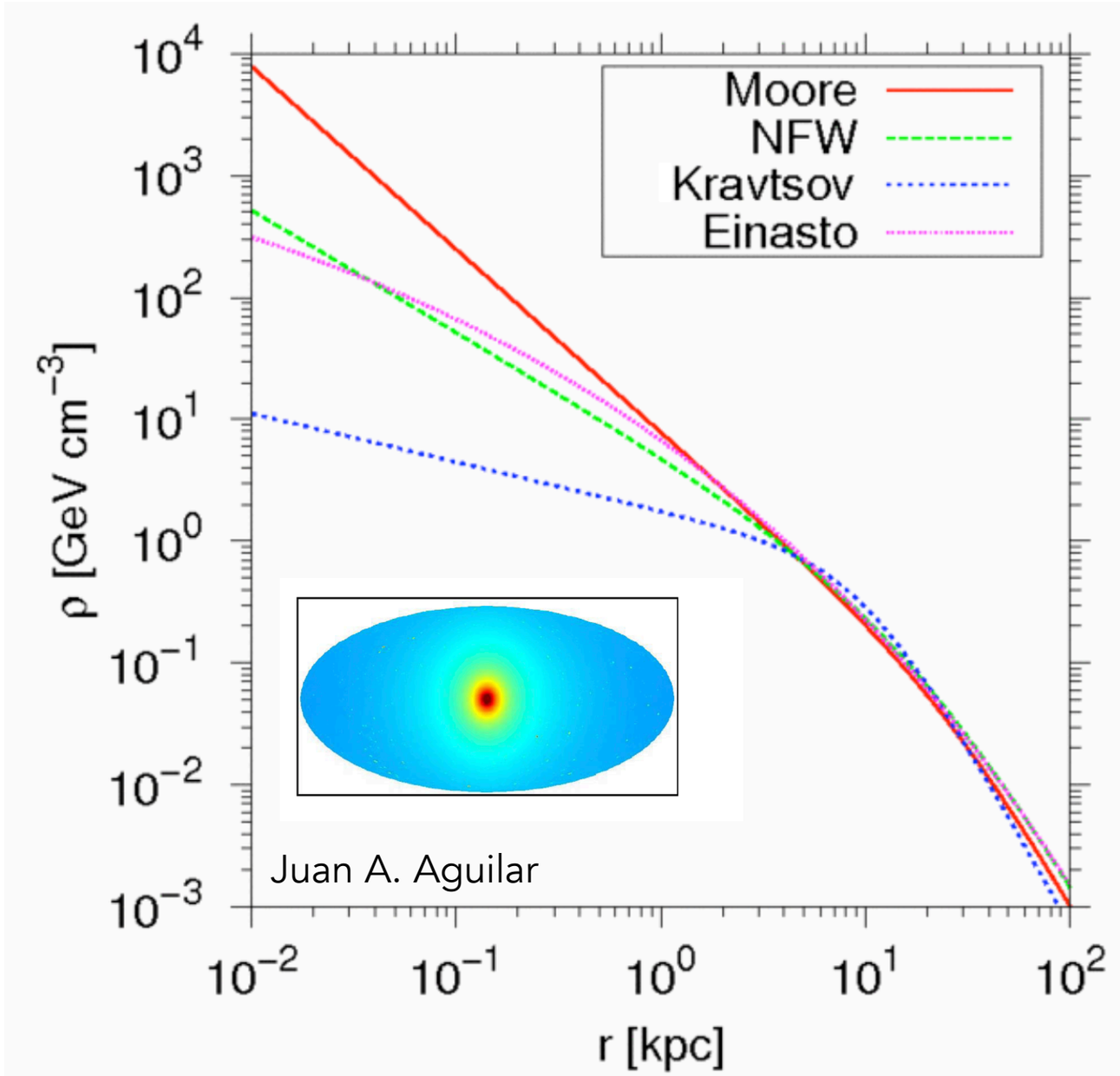
Velocity does not decrease as expected

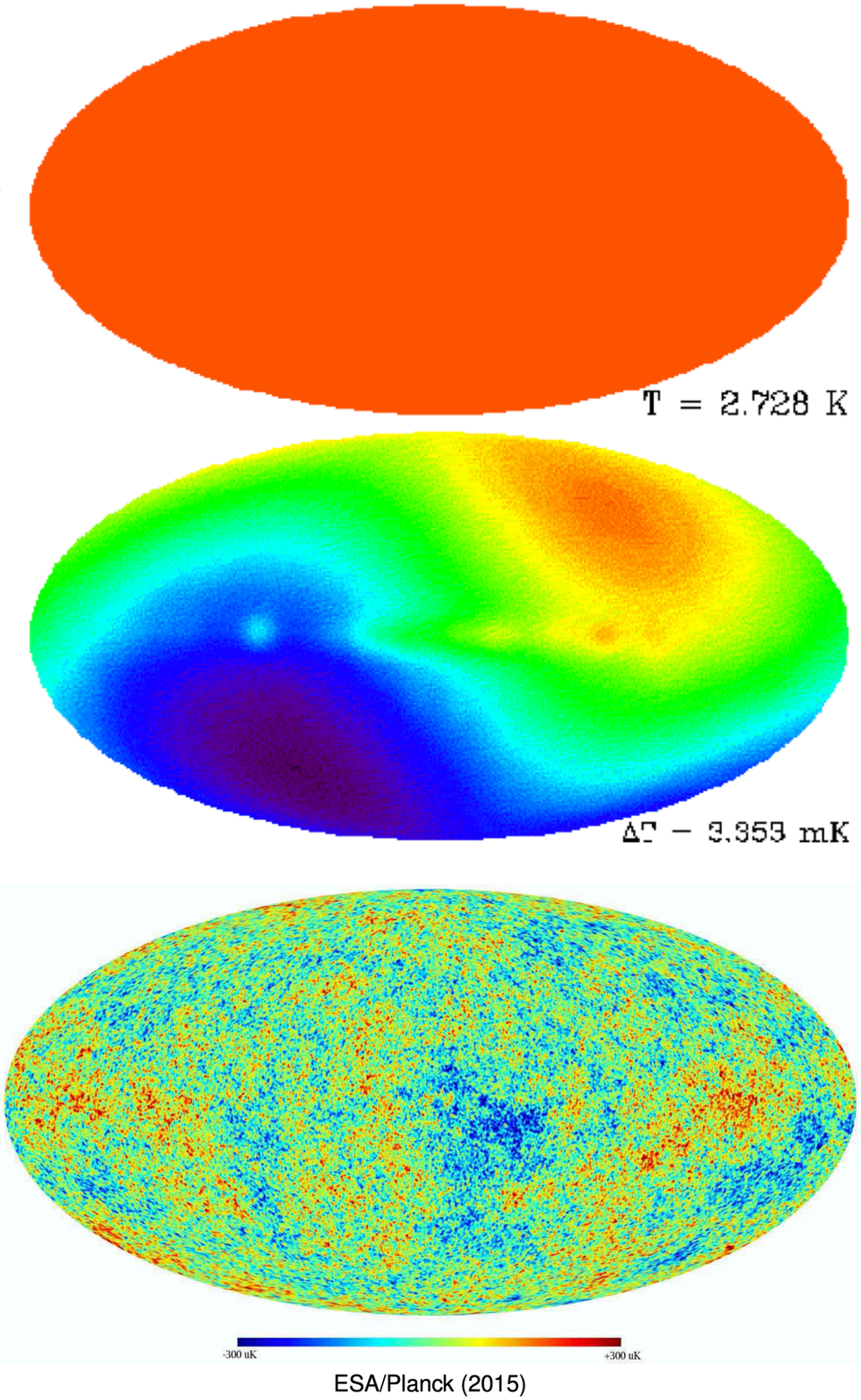
Interpretation:
Galaxies must have further *invisible* mass

Dark Matter density is maximal near center, but extends far outside visible region → *dark matter halo*

Dark matter halo density profiles
modeled from N-body simulations

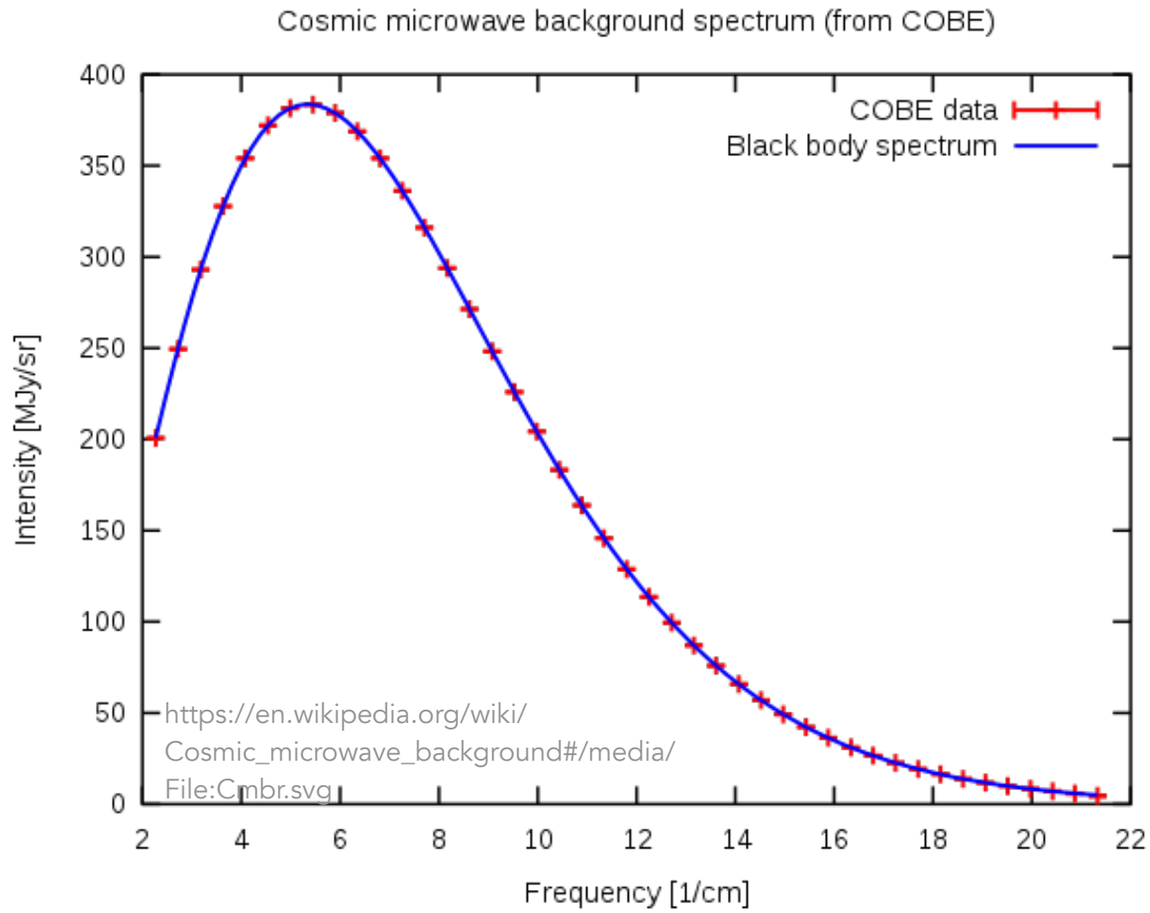


Cosmic Microwave Background



https://indico.cern.ch/event/634061/attachments/1476161/2333296/lesson2.pdf

Photon radiation from all directions (1965) at ~3 K with perfect black body spectrum

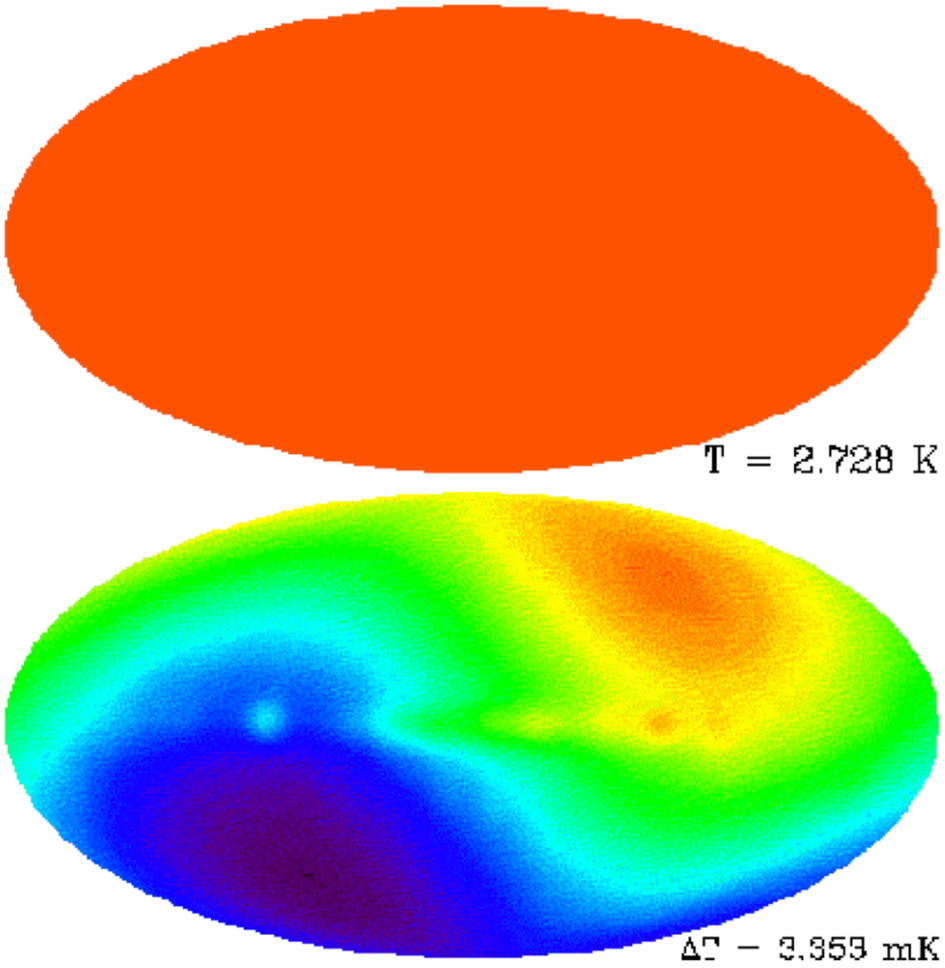


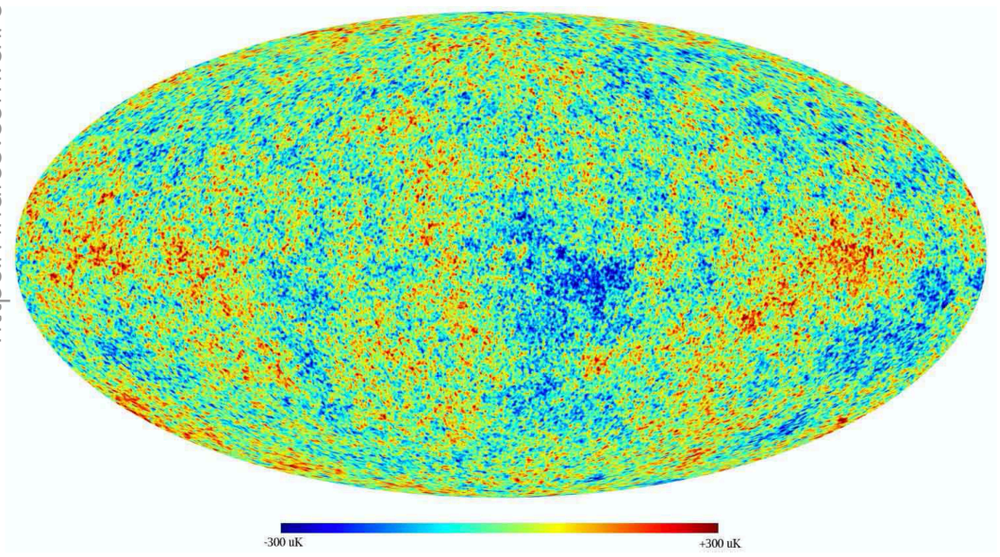
After Big Bang: matter and radiation are coupled

380,000y: universe cooled down -> radiation decouples / escapes at 3000 K

expansion: radiation cooled down to 3 K

Cosmic Microwave Background





ESA/Planck (2015)

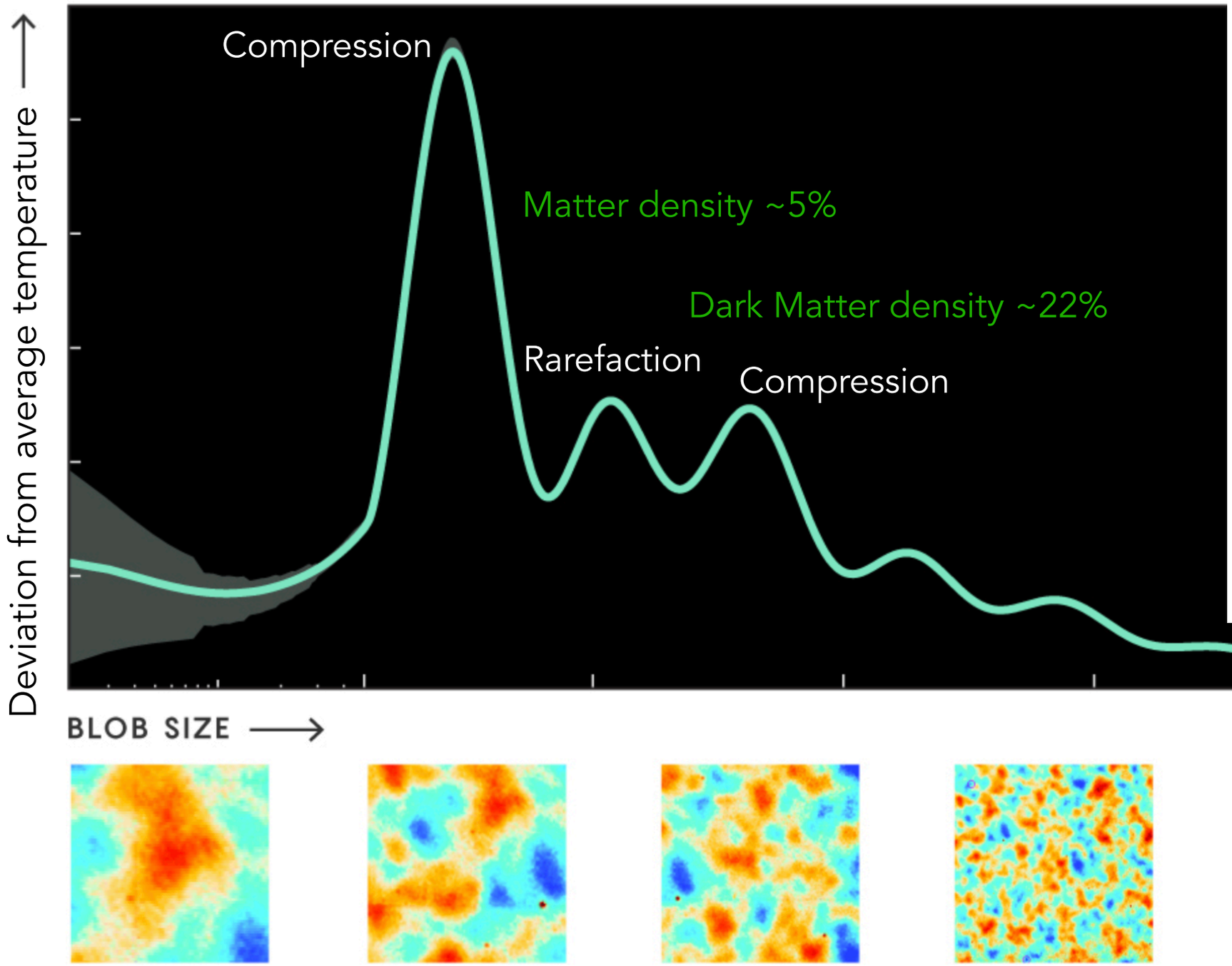
https://indico.cern.ch/event/634061/attachments/1476161/2333296/lesson2.pdf

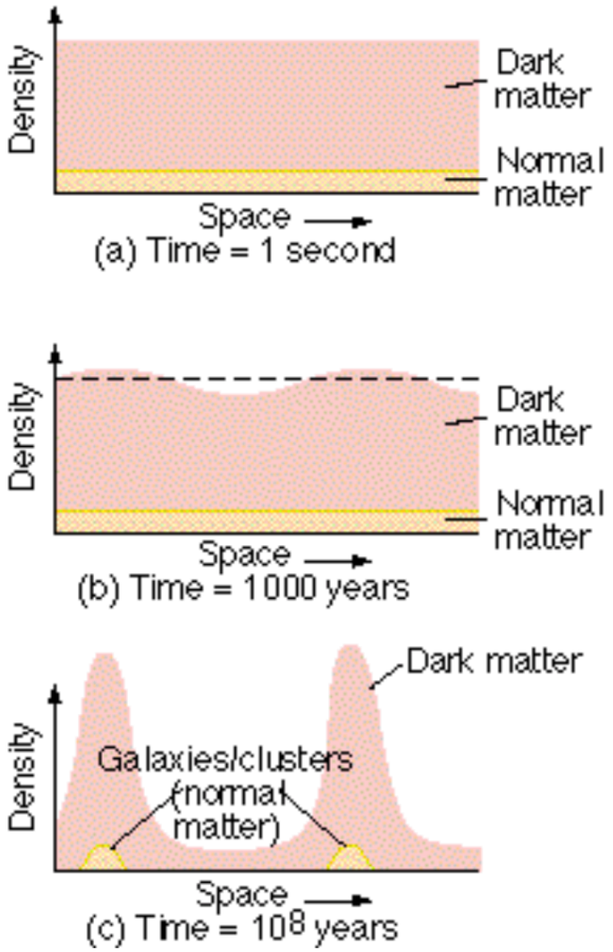
Dipole feature in CMB:
Movement of solar system with respect to the emission / last scattering surface

Subtracting monopole and dipole
-> small scale fluctuations

Cosmic Microwave Background

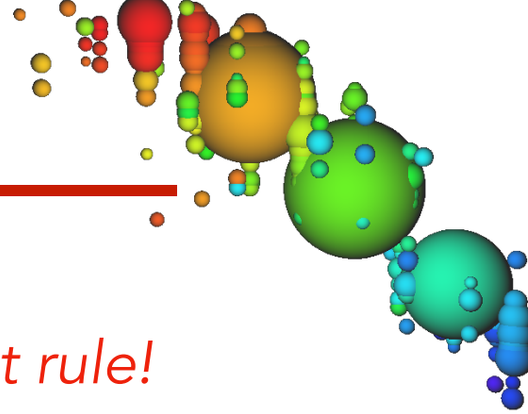
https://www.quantamagazine.org/how-the-cosmic-microwave-background-reveals-the-universes-contents-20200128/





Chaisson, Eric and McMillan, Steve: *Astronomy Today*, Prentice Hall (1998), p. 640

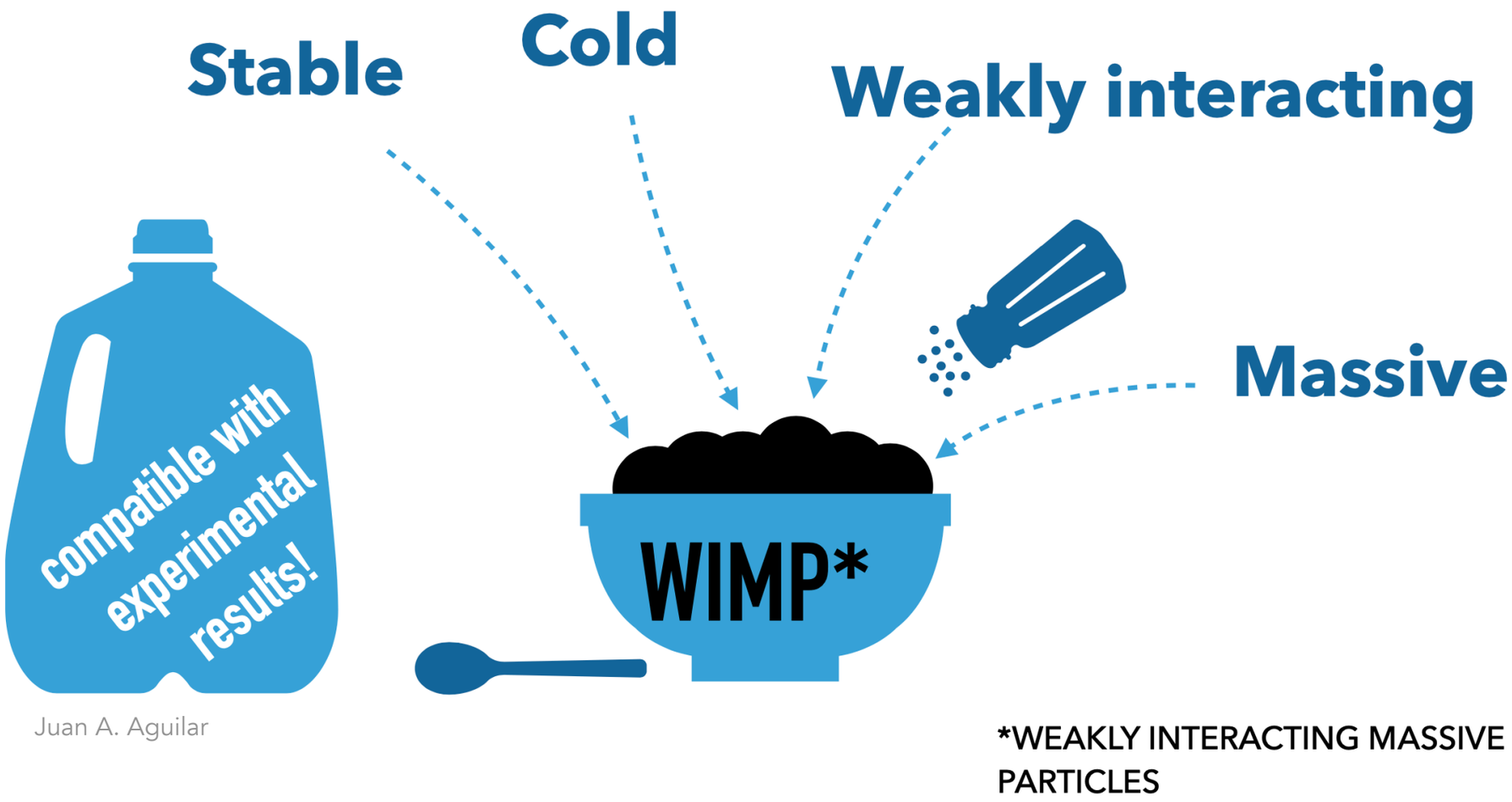
Candidates for Dark Matter



Requirements for particle dark matter:

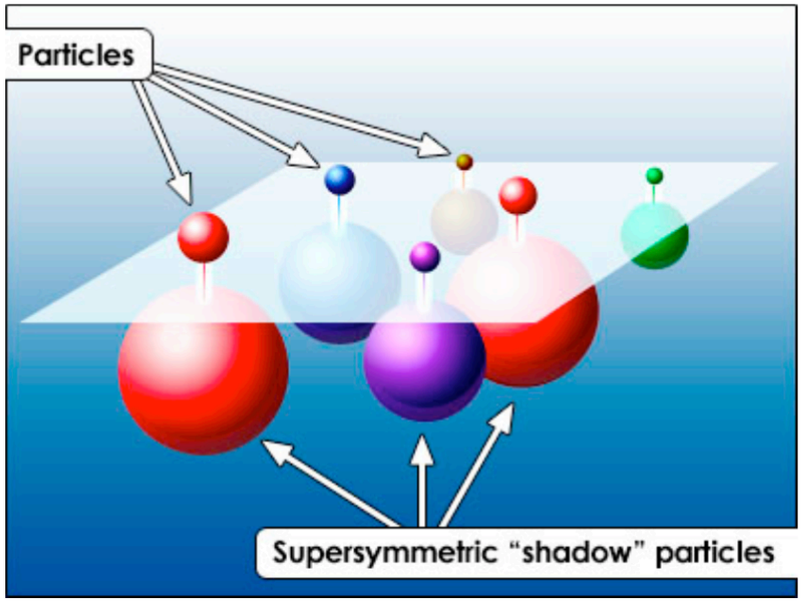
- stable (on the scale of the lifetime of the universe)
- no/low interaction with ordinary matter (effectively)
- mass density ~23%
- allow structure formation (mostly "cold")

No single strict rule!
Interplay of these properties is important



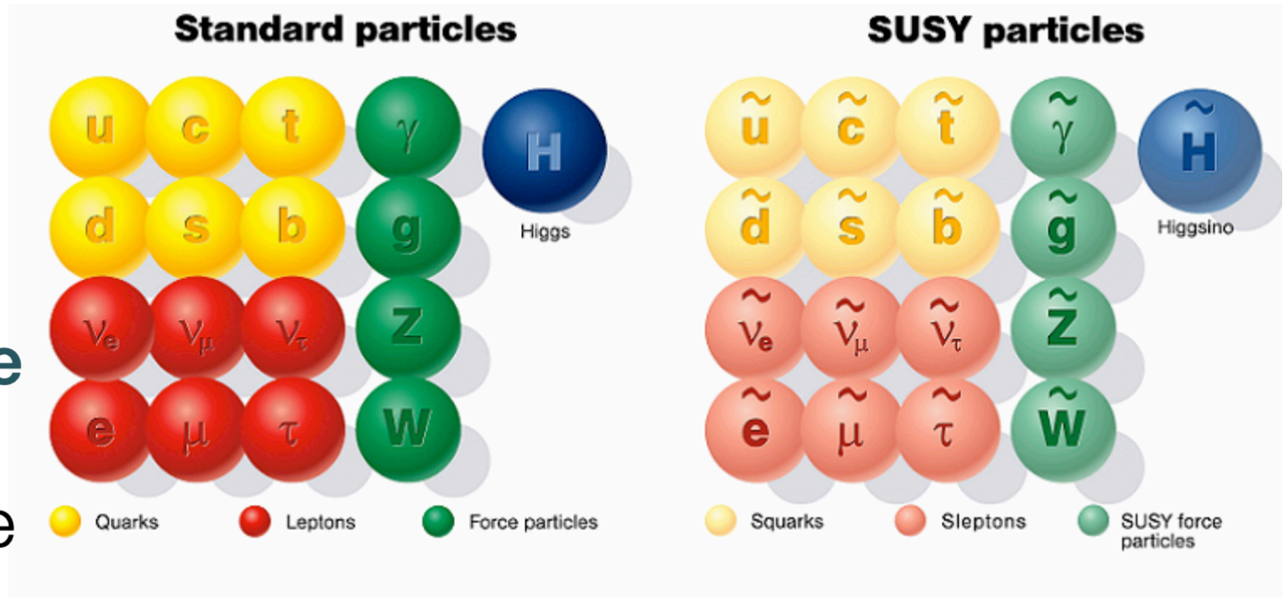
Candidates described by various theories, e.g. Supersymmetry

Supersymmetry



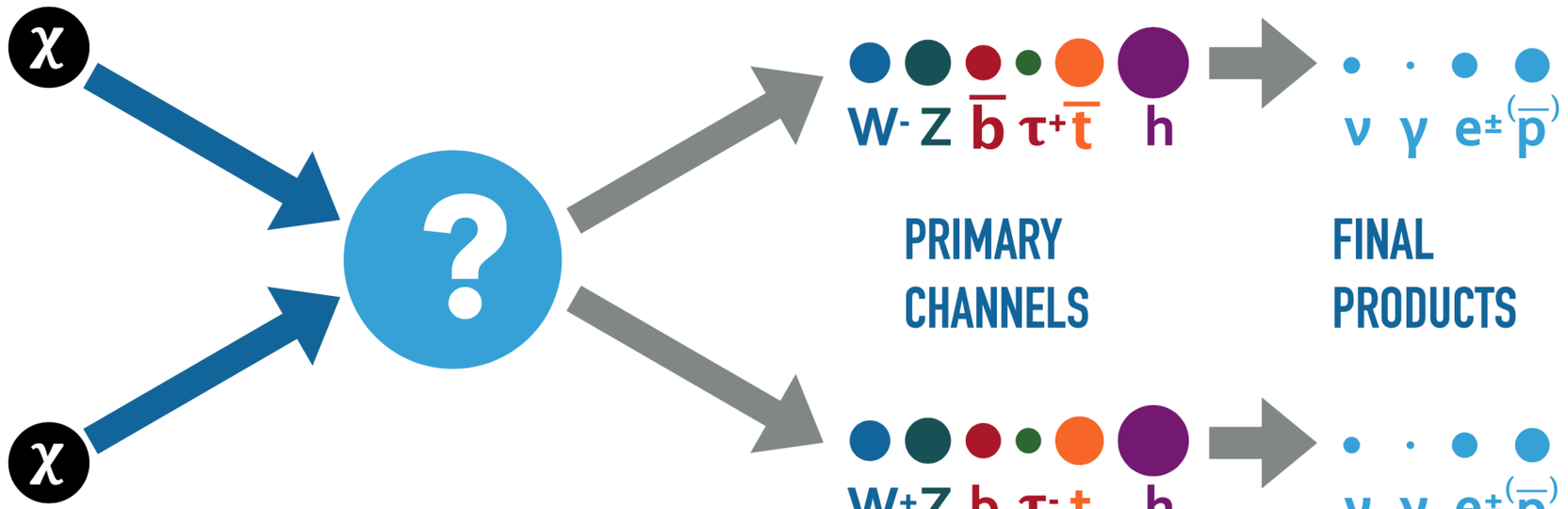
- **Supersymmetry** is a property of a model that treats mass and forces equally. A **supersymmetric model** is such that includes supersymmetry.
- SUSY introduces a symmetry between fermions and bosons

- Since these supersymmetric particles have never been observed it is theoried that they have large masses.
- The lighest of these particles, **the neutralino**, will be stable (under R parity conservation) and will be a candidate for Dark Matter.

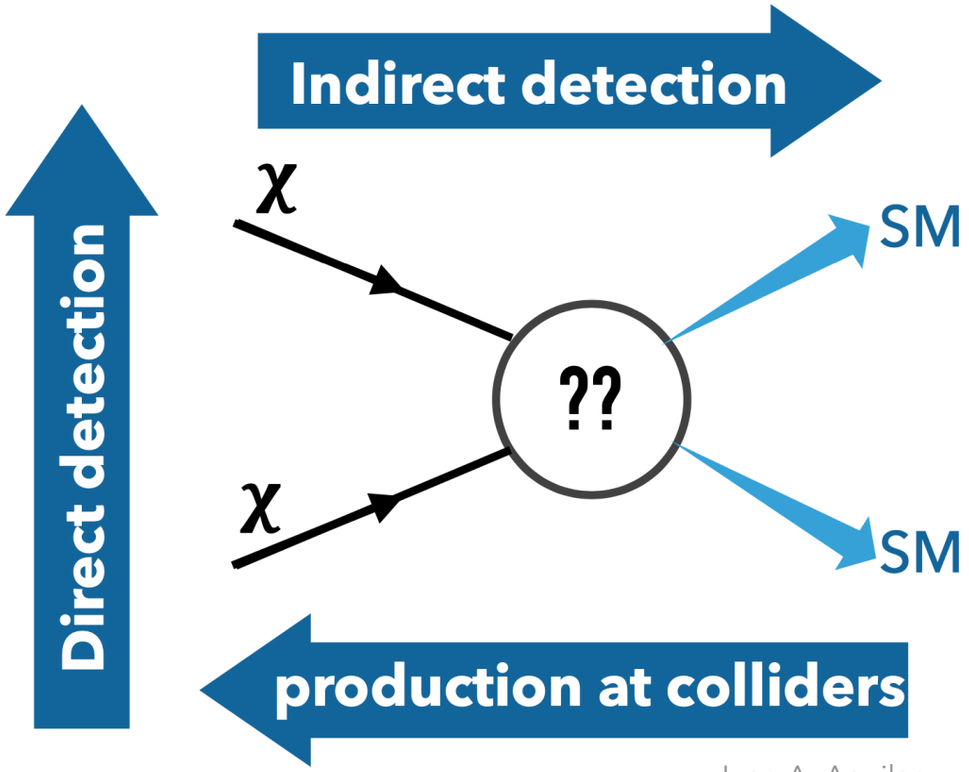


Dark Matter searches

Indirect detection: dark matter annihilation products



Strategies



Juan A. Aguilar

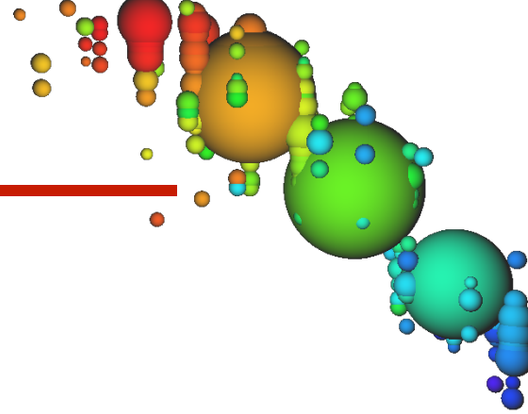
No need of specialized detectors, instead use:

- neutrino telescopes
- gamma ray telescopes

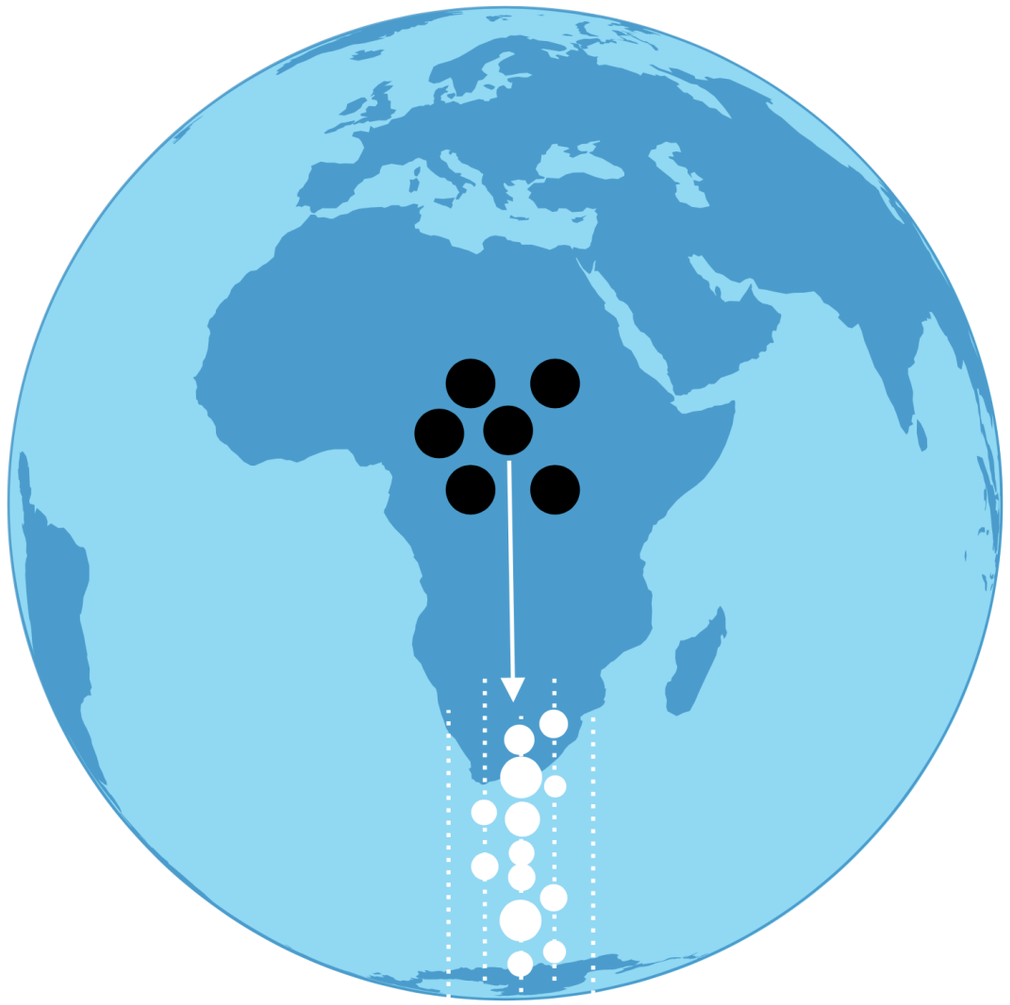
Focus on large reservoirs of dark matter

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

Dark Matter annihilation in Earth



- DM from galactic halo gravitationally bound in potential of body
- weak scattering off nuclei in Earth decelerates DM via center → $\sigma_{\chi\text{-}N}$
- 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 *(from observations ~0.3 GeV/cm^3)*
  - DM velocity spectrum *(from simulations)*
  - chemical composition of Earth *(capture rate increases at nuclei of similar mass)*
- search strategy with IceCube
  - use low energy sub-detector *DeepCore*
  - use standard IceCube as veto
  - search "upgoing" muons (muons leave *tracks*)



Dark Matter annihilation in Earth

- DM from galactic halo gravitationally bound in potential of body
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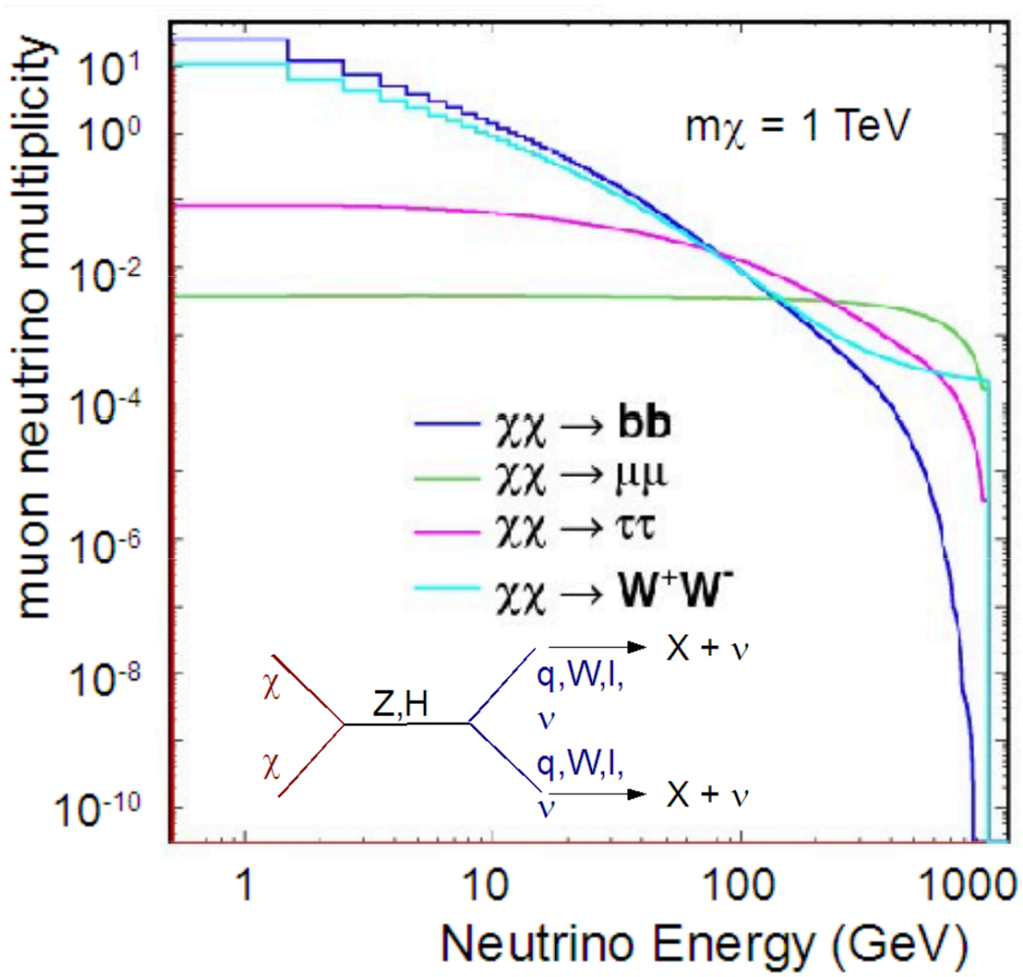
WIMP annihilation into neutrinos



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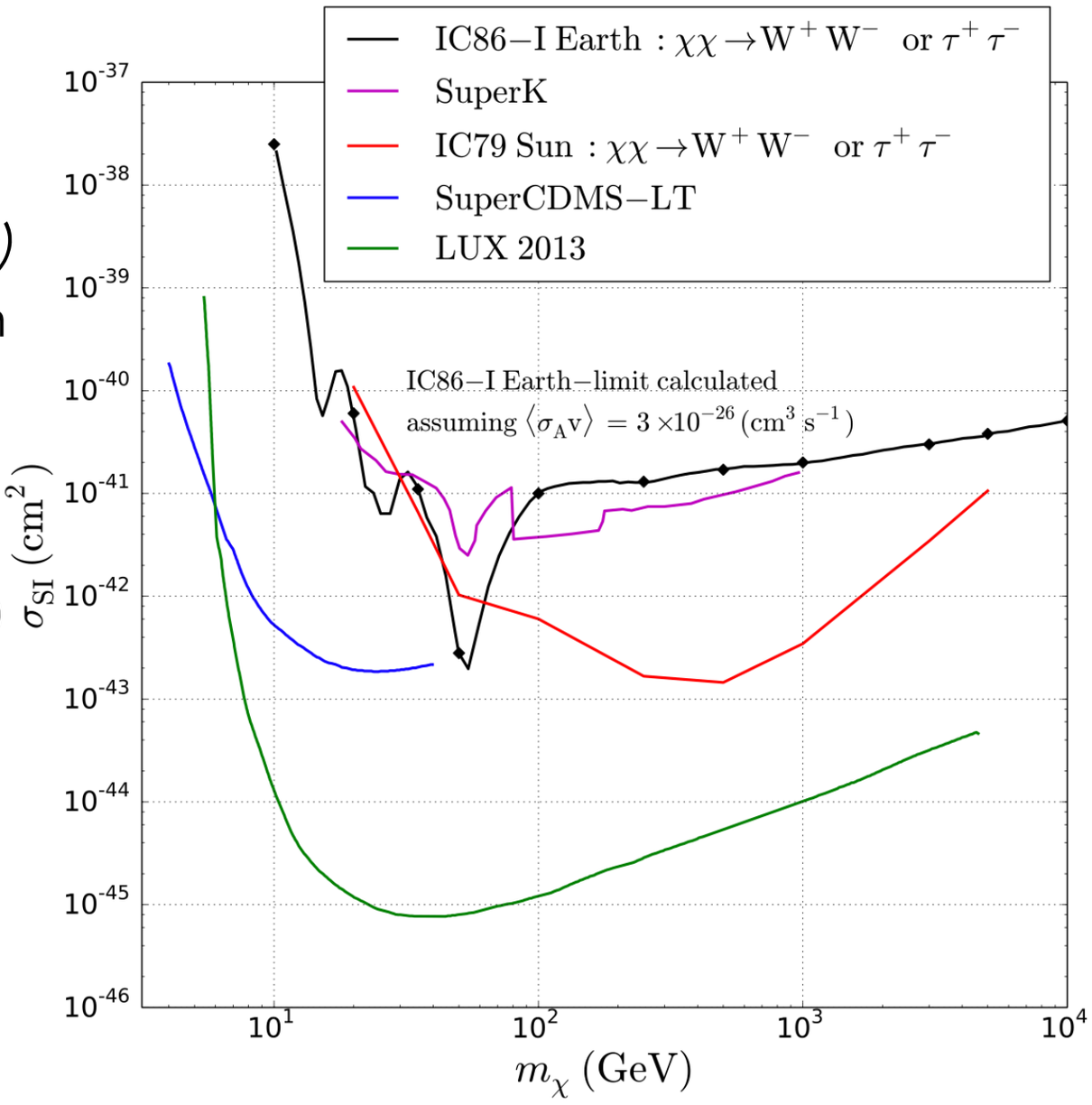
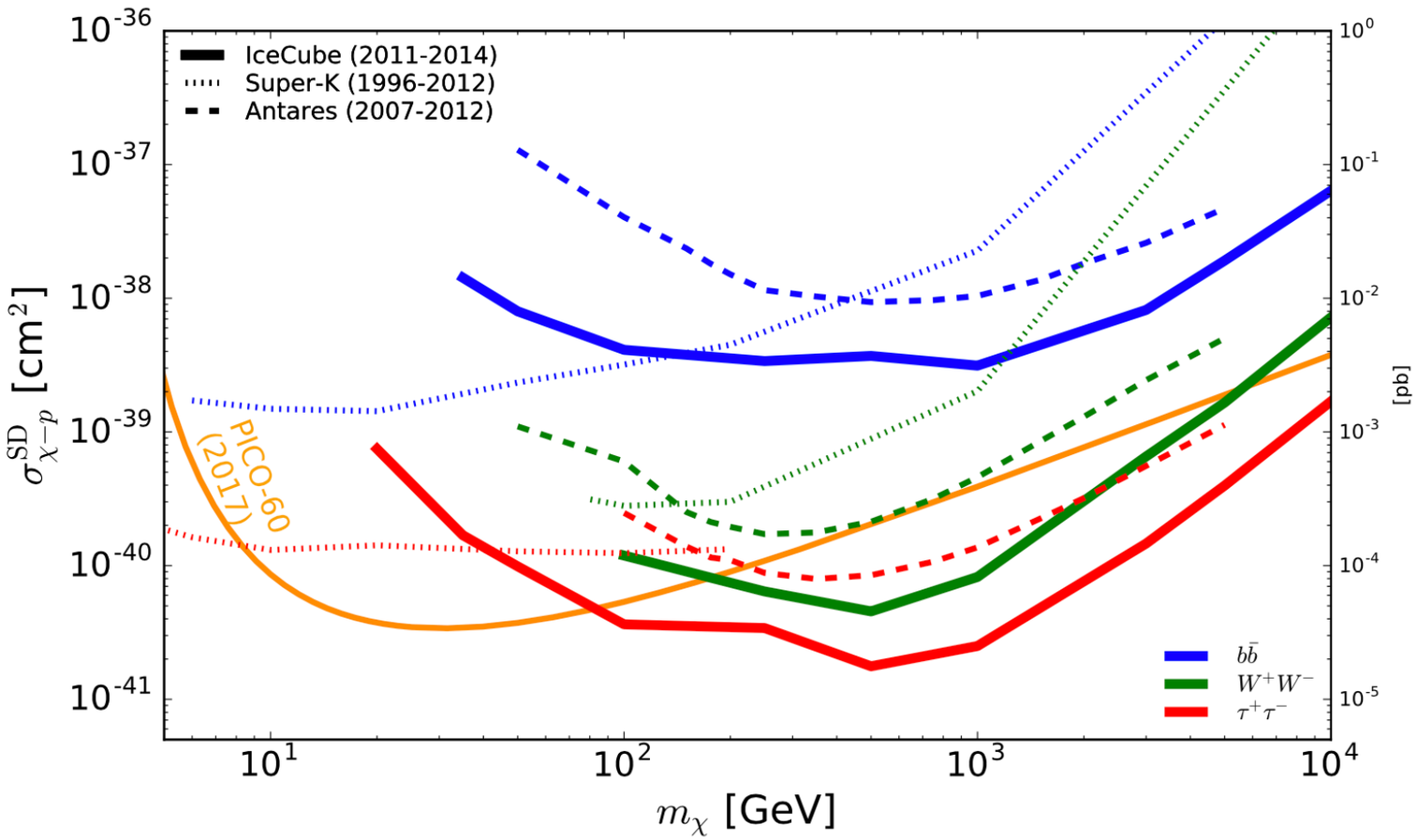


Dark Matter annihilation in Sun

equilibrium!

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



Repetition

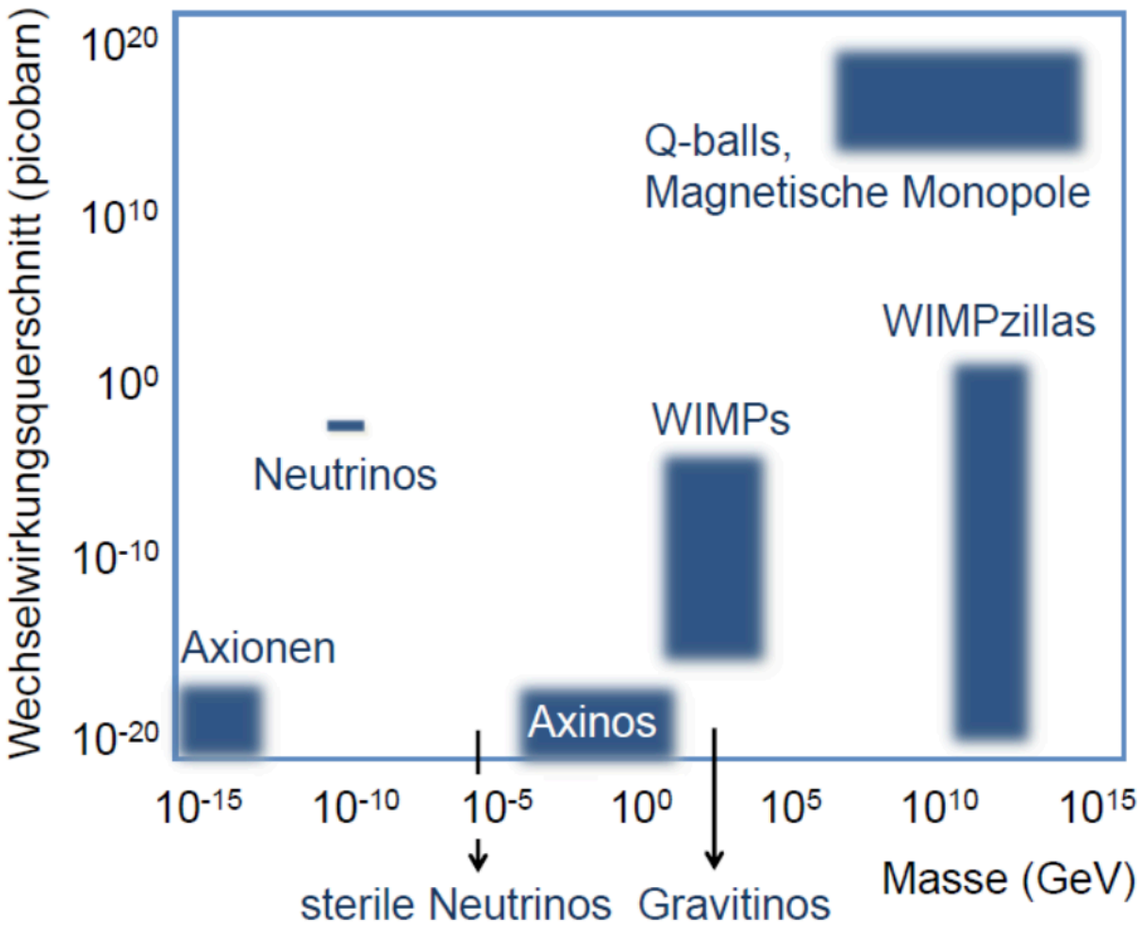
Which statements about Dark Matter are correct?

A. A particle, which interacts electromagnetically, could be a DM candidate if it is extremely massive and very rare. ✓

B. Neutrinos could be cold, i.e. slow, Dark Matter since they only interact weakly. ✗ *due to their small mass, they were too fast for structure formation*

C. Because Dark Matter halo density peaks far from galaxy centers, the speeds of stars is not decreasing with distance from the center as expected. ✗

D. Dark Matter interaction products, muon neutrinos, leave detectable light tracks in IceCube ✗



Open with any device

Answer question 6

https://arsnova.eu/mobile/#id/90965575

https://www-zeuthen.desy.de/~csspier/www/buecher/Dunkle_Materie_fa.pdf

Magnetic monopoles

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

1864

$\nabla \cdot D = 4\pi\rho_e$

$\nabla \cdot B = 4\pi\rho_m$

$\nabla \times E - c^{-1}\dot{B} = 4\pi c^{-1} j_m$

$\nabla \times H - c^{-1}\dot{D} = 4\pi c^{-1} j_e$

James C… Maxwell

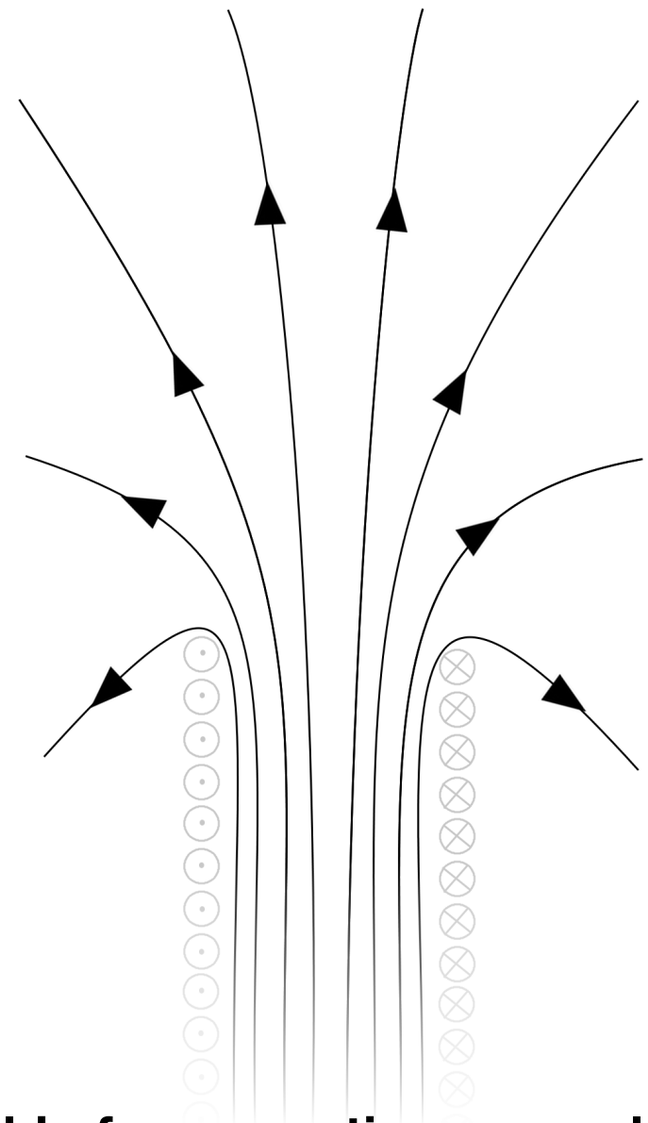
1931

Search: Quantization of electric charge e

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

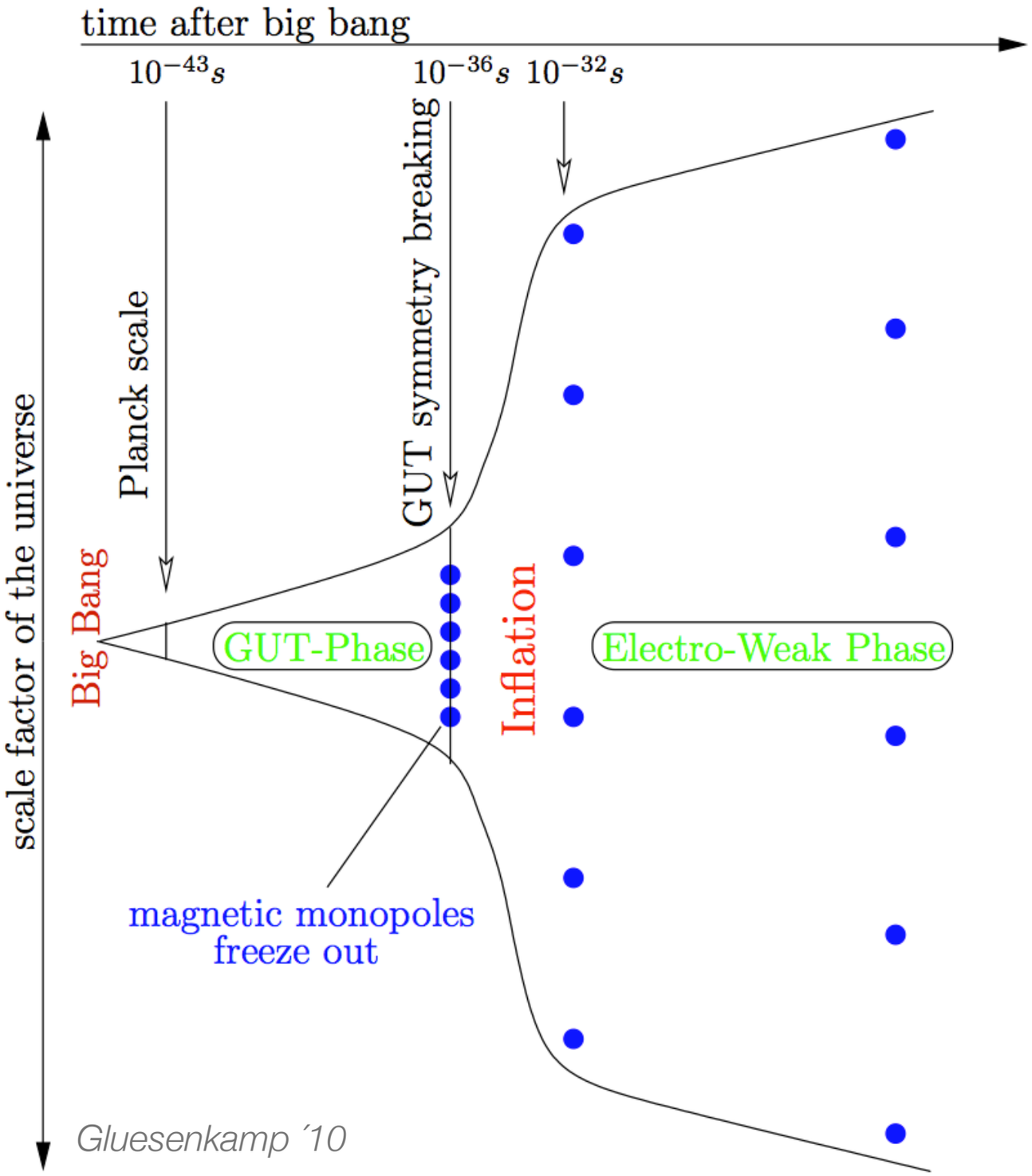
Result: Dependence on a magnetic charge g

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



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

Grand Unified Theories (and similar)



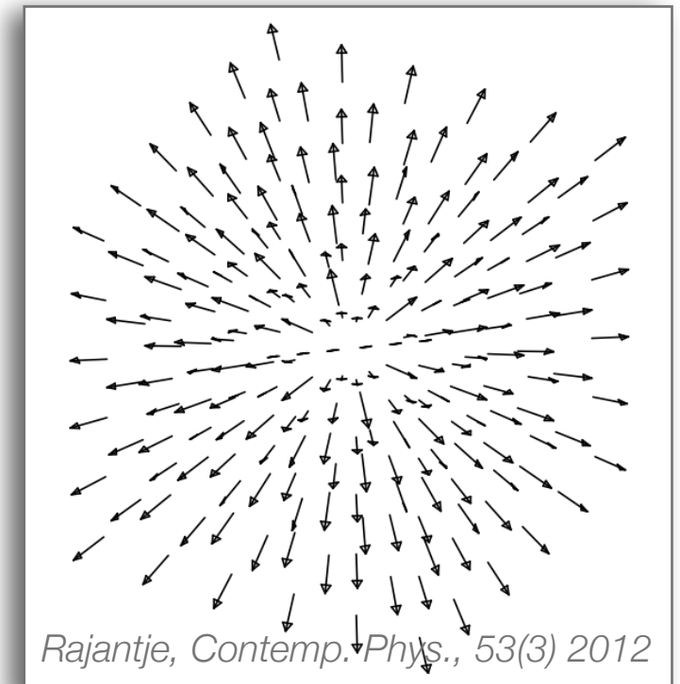
Gluesenkamp ´10

Grand Unification:

- unification of electro-magnetic, weak and strong force at high energies
- breaks at lower temperatures, locally

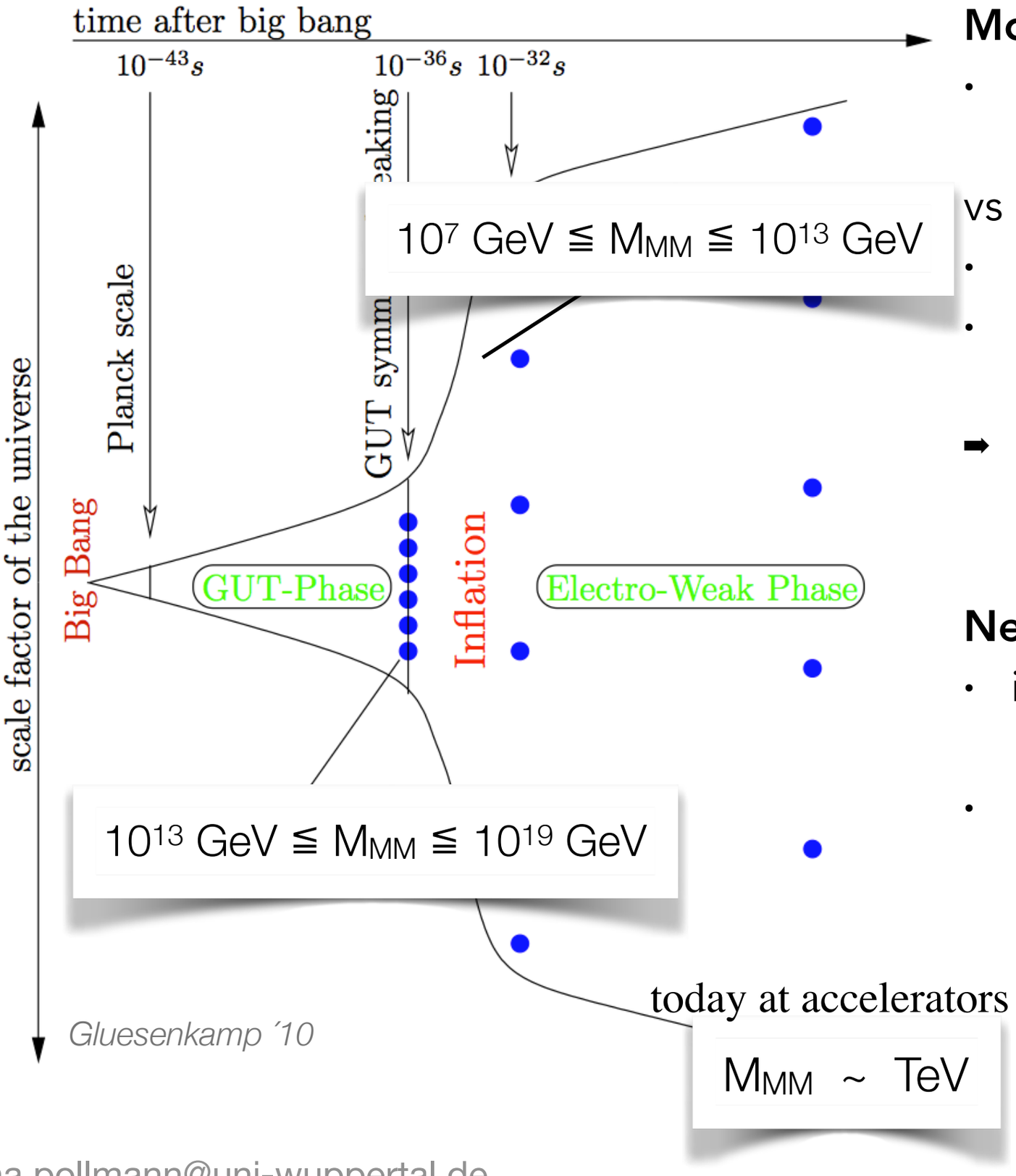
Magnetic Monopoles

- no smooth transition at domain borders → GU preserved as topological defect
- leap of energy behaves as particle with magnetic charge



Rajantje, Contemp. Phys., 53(3) 2012

Monopole mass & density



Gluesenkamp ´10

Monopole Problem

- Kibble mechanism (one monopole per domain)

vs

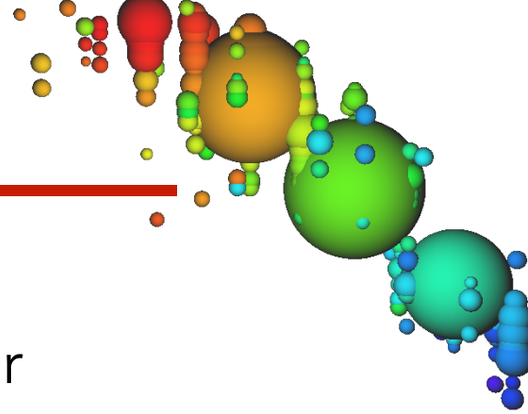
- mass density of the universe
- Parker bound:
  - dissipation of magnetic fields

➡ monopole flux lower than 10^{-15} cm^{-2} sr^{-1} s^{-1}

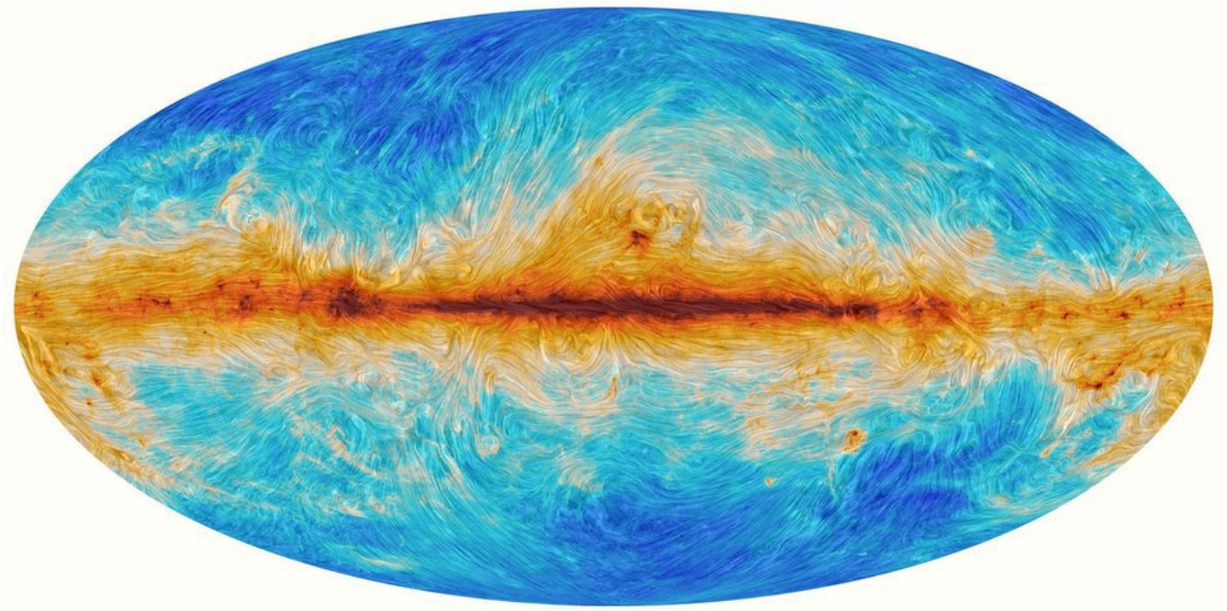
New Models

- inflationary phase of the universe
  ➡ dilution of monopoles
- (later) symmetry breaking through intermediate steps
  ➡ smaller monopole masses

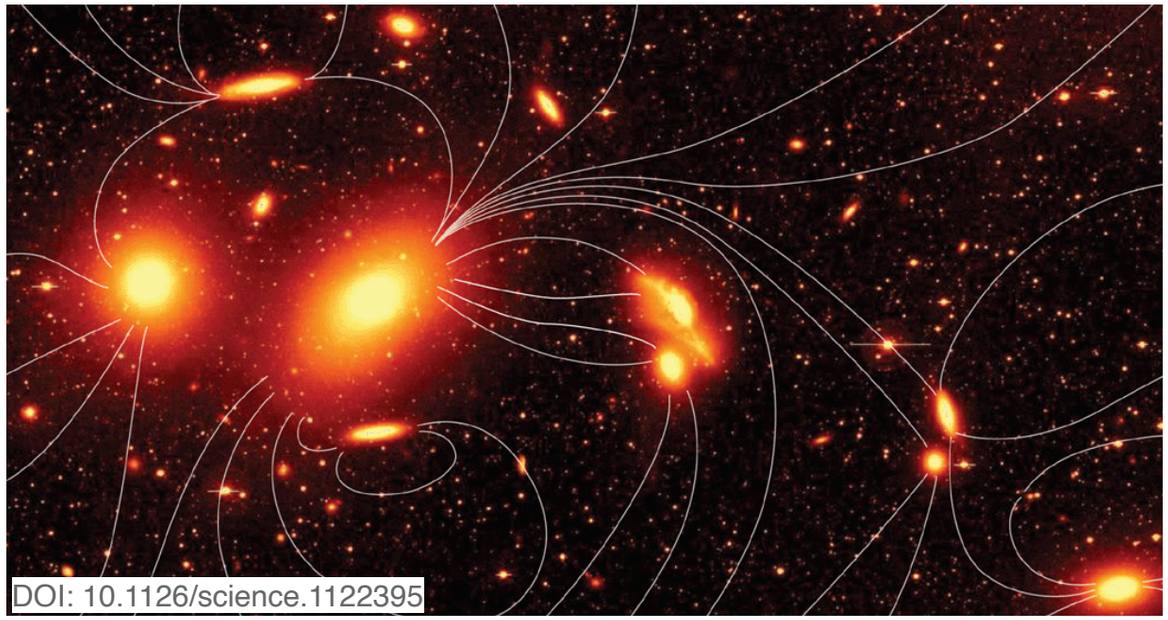
Monopole properties



Magnetic field of the Milky way [Planck]



Virgo Cluster



Acceleration in magnetic fields

$E_{kin} \leqq 10^{13}$ GeV

Gravitational trap around galaxy, sun, Earth

$v \sim 10^{-3}$ / 10^{-4} / 10^{-5} c

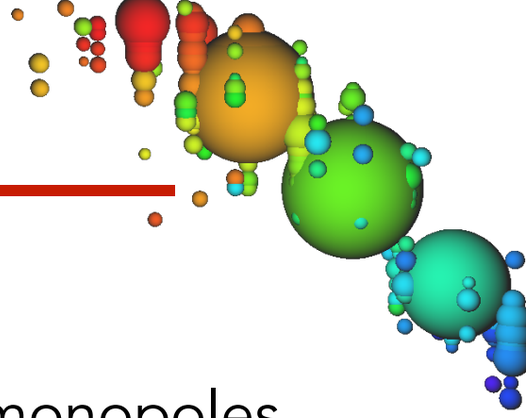
Ionization power

$E_{dep} \sim g^2$ (Muons: $\sim Z^2 / \beta^2$)

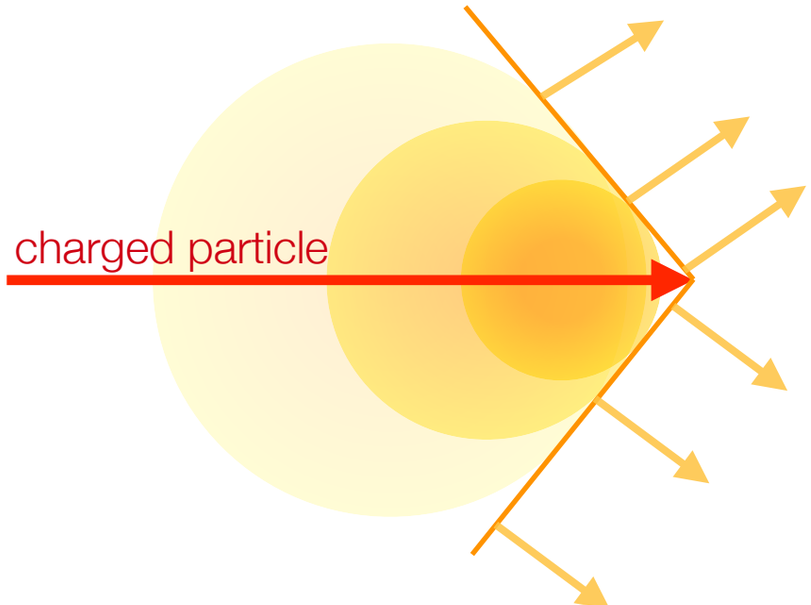
Heavy monopoles are slow,
Light monopoles can be relativistic

Monopoles have a very high cross section! → Simple direct detection

Monopole interactions giving light for detection in IceCube



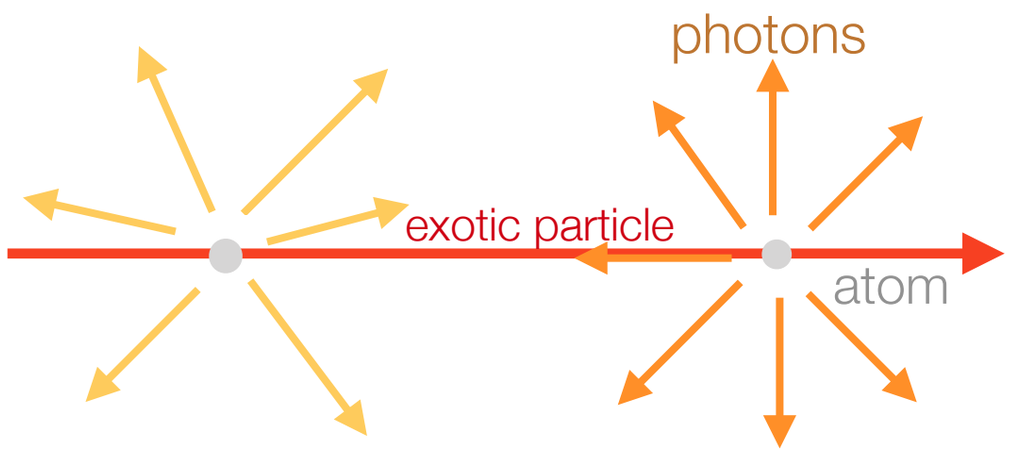
High speed: Cherenkov light

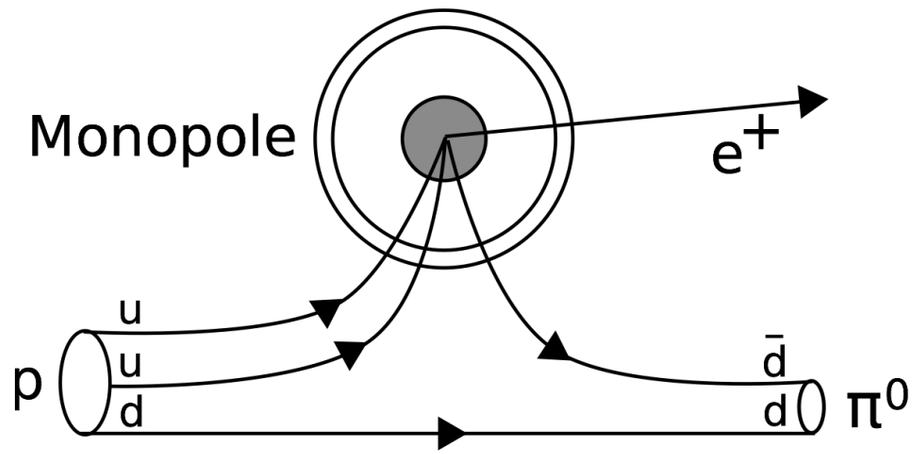


Cherenkov light by magnetic monopoles
or by electrons (from ionized atoms)

also: Luminescence light for all speeds
(still under investigation)

Low speed: Proton decay





Monopole interactions giving light for detection in IceCube

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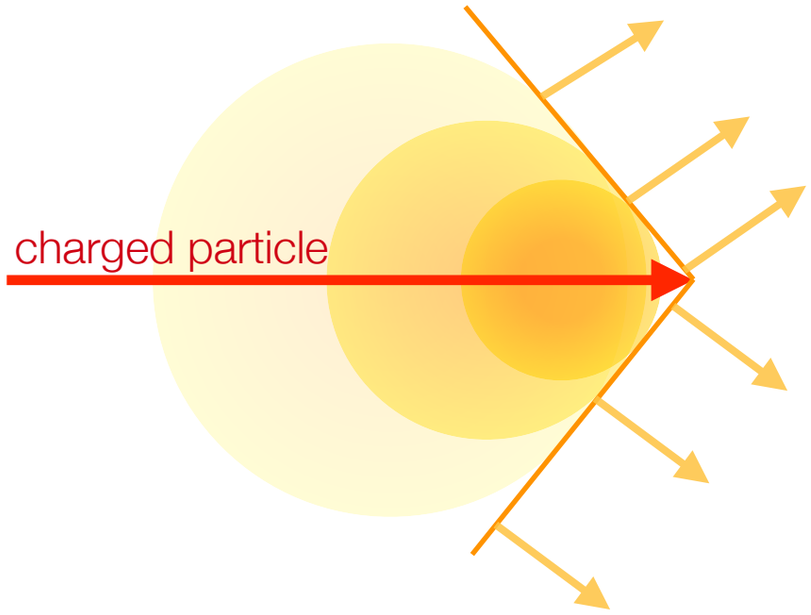

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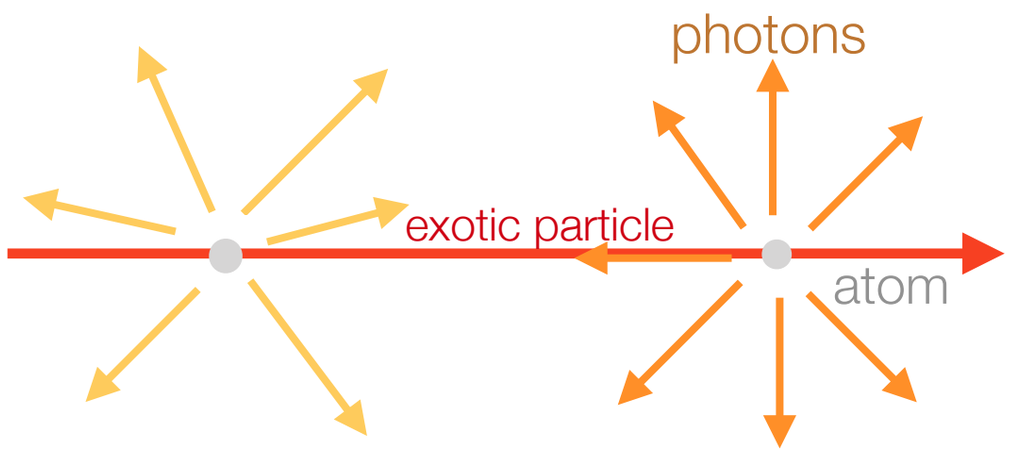
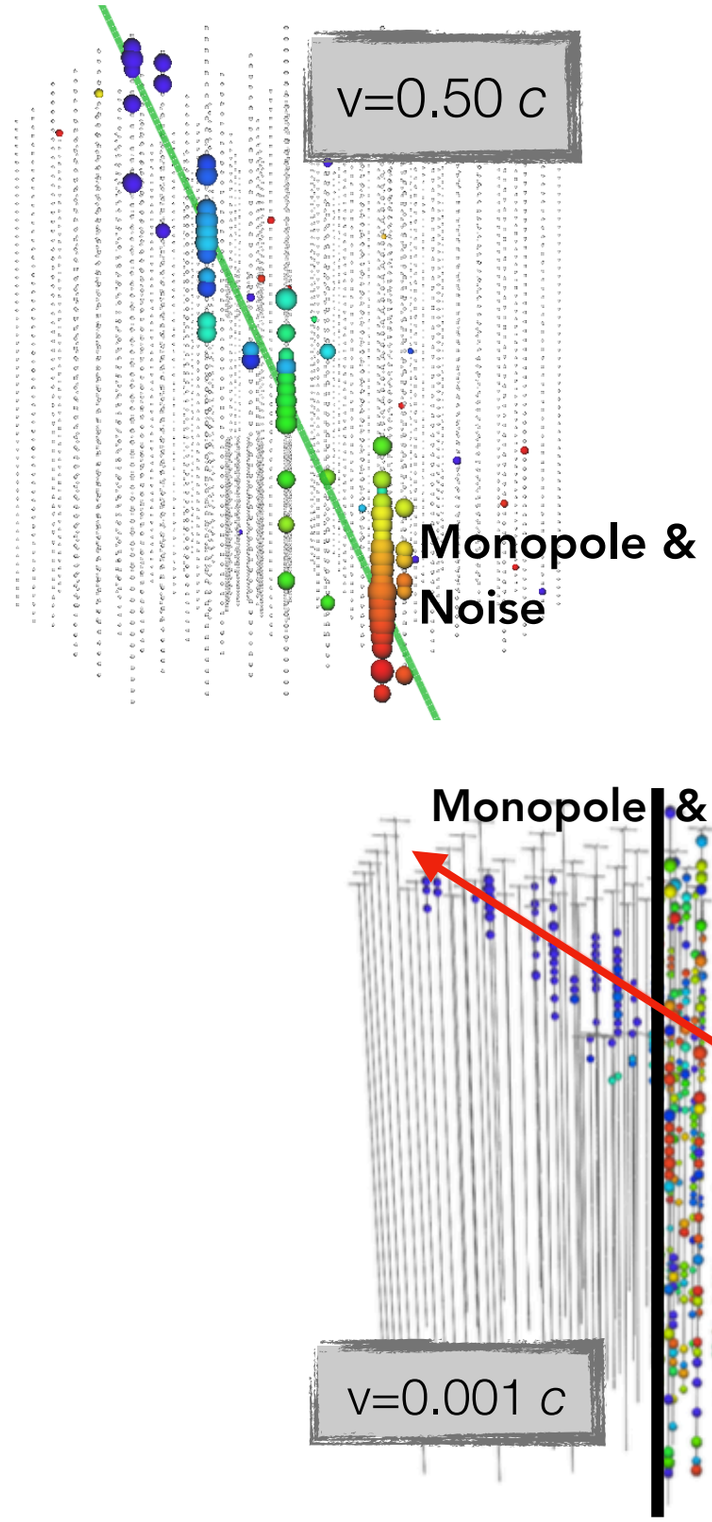
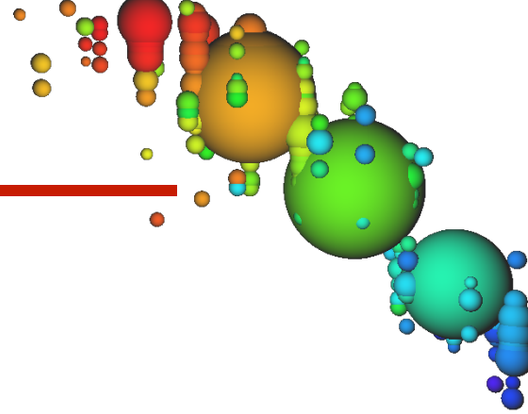


Signatures in IceCube



optical sensors Late hits Early hits Track

Distinguishing signal and background for fast particles



Magnetic Monopole

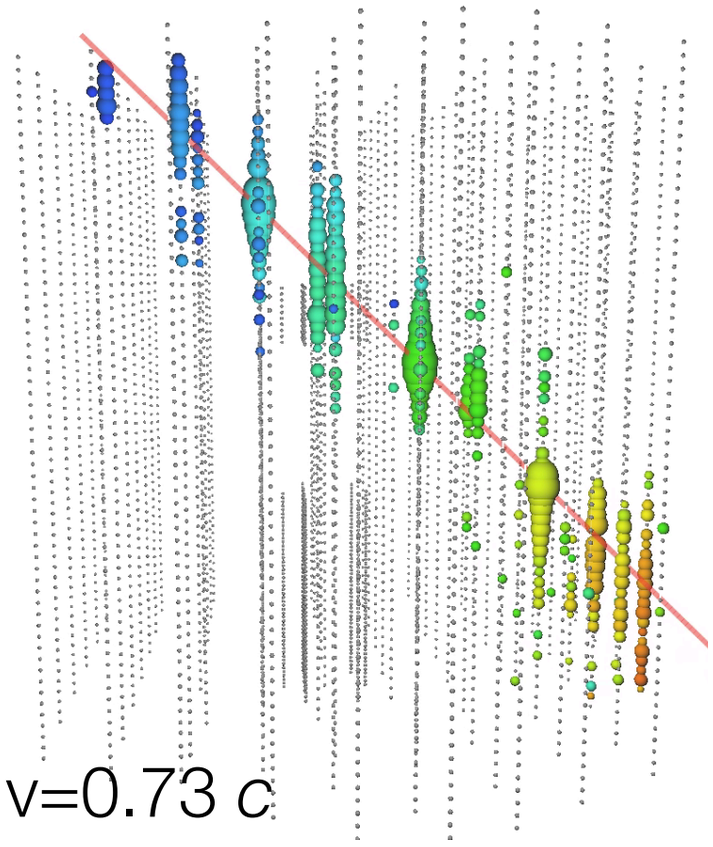
- through-going
- homogenous brightness
- homogenous velocity

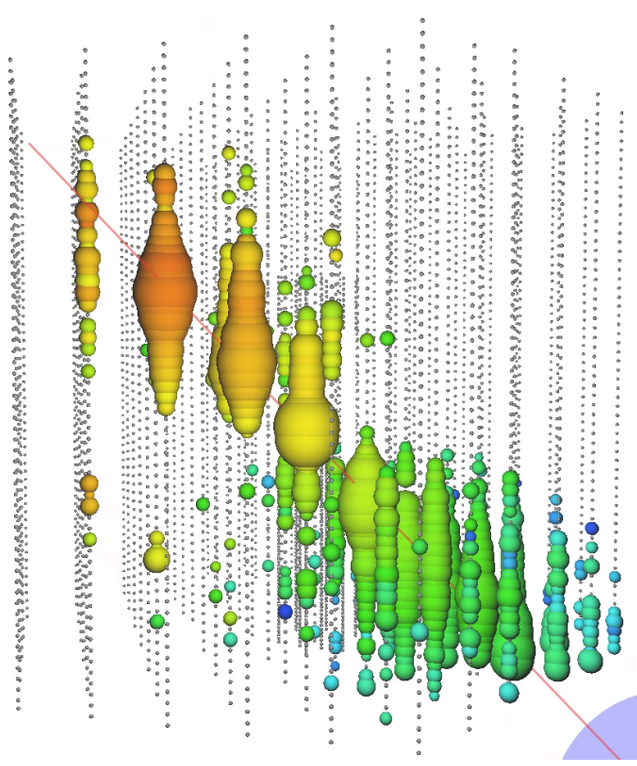
Cosmic ray shower (muons)

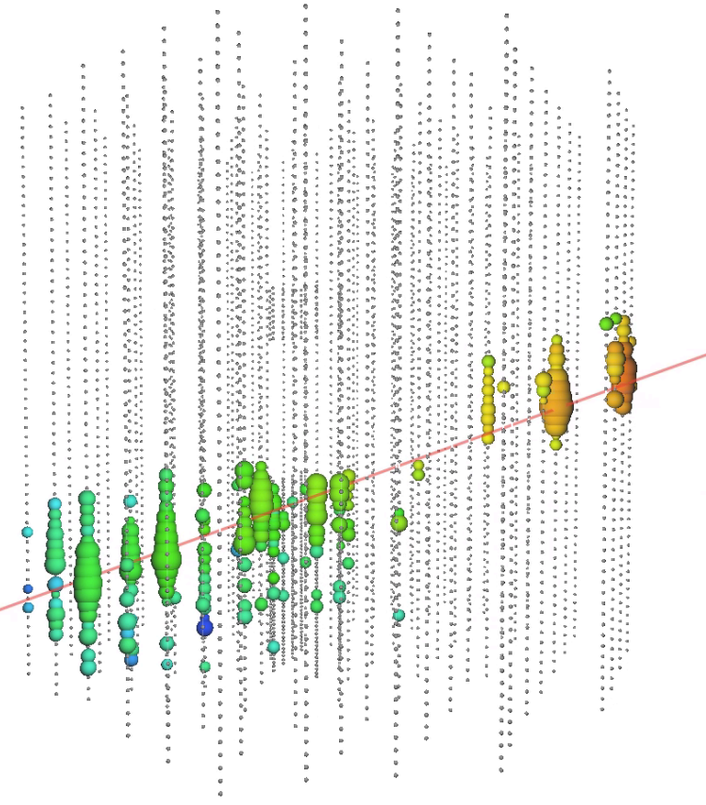
- muon produced in an air shower
- non-homogenous brightness
- speed of light
- coming from the top
- often: several showers at once

Neutrino secondary (single muon)

- neutrino produced in an air shower
- non-homogenous brightness
- speed = c
- isotropic direction of origin







optical sensors Late hits Early hits Track

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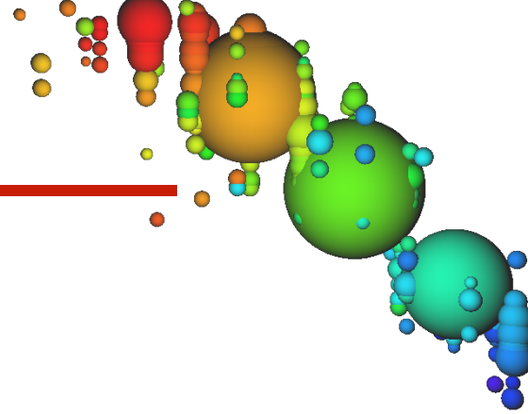

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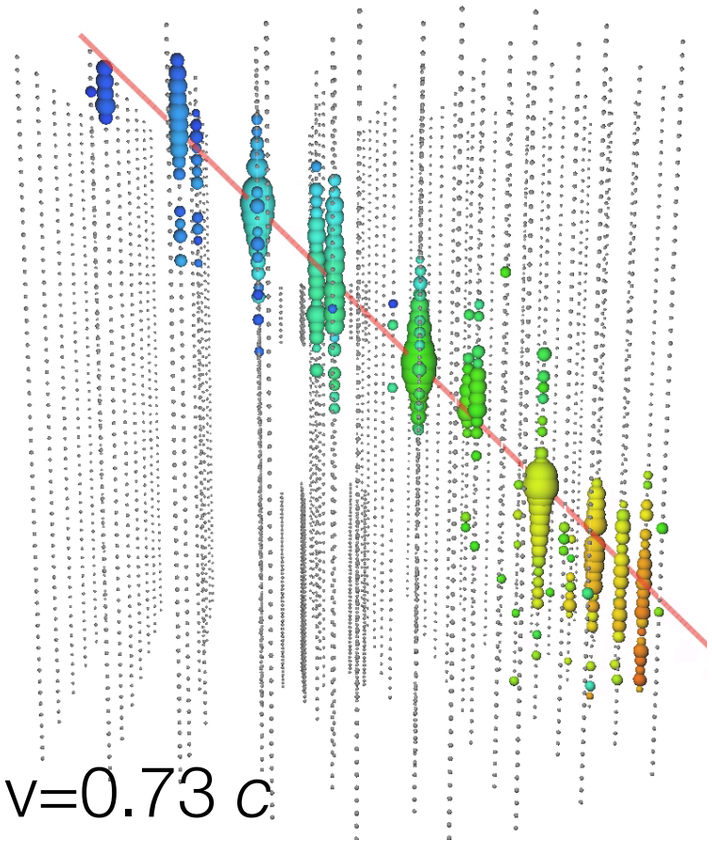


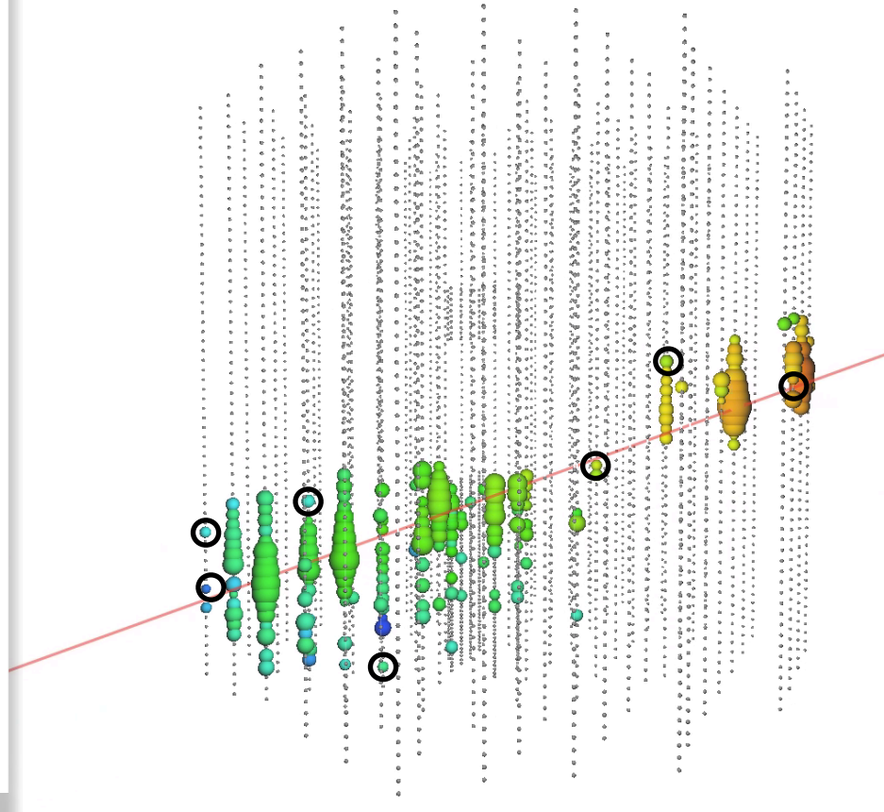
Selection variables

- number of sensors recording a hit
- speed
- direction
- gap within the hits
- …..

Feed into machine learning algorithms…

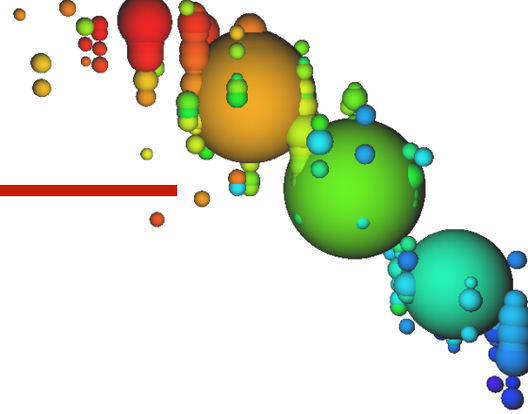
Neutrino secondary (single muon)

- neutrino produced in an air shower
- non-homogenous brightness
- speed = c
- isotropic direction of origin



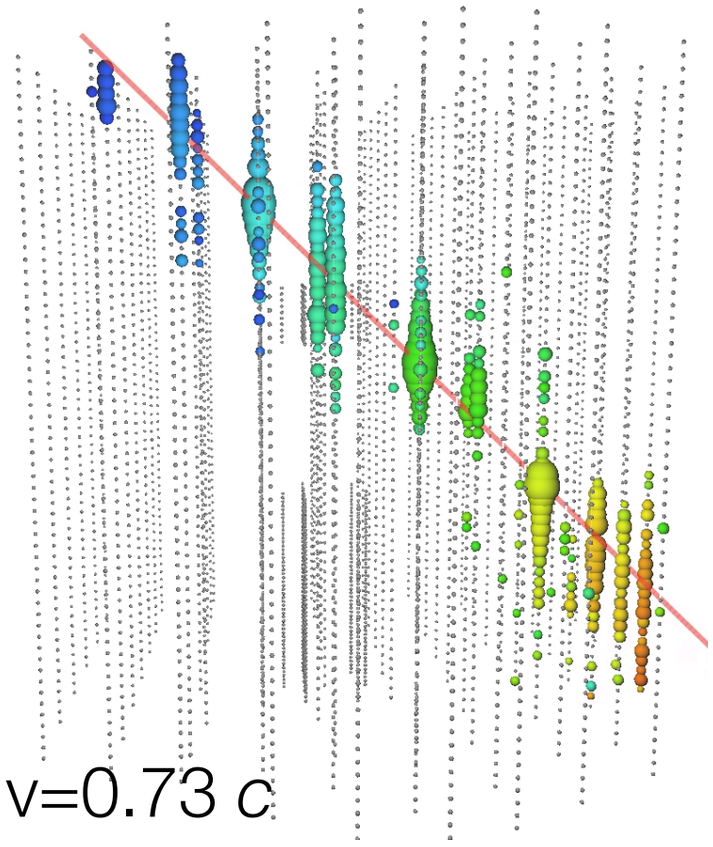
optical sensors Late hits Early hits Track

Distinguishing signal and background for fast particles



Magnetic Monopole

- through-going
- homogenous brightness
- homogenous velocity



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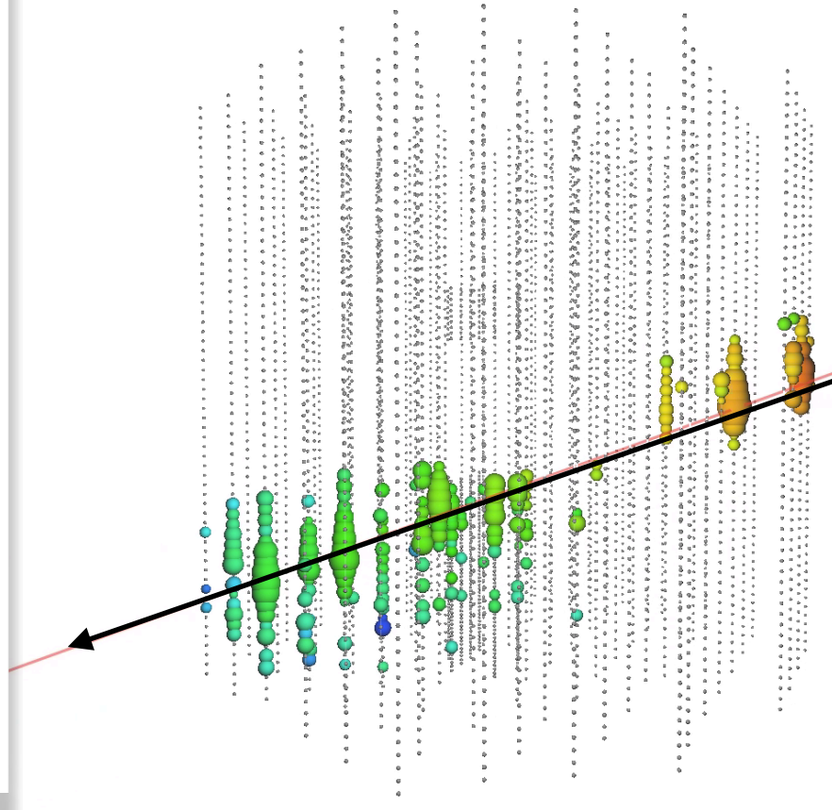
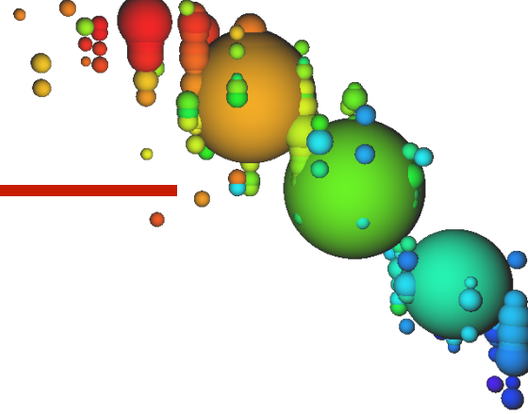


optical sensors Late hits Early hits Track

Distinguishing signal and background for fast particles



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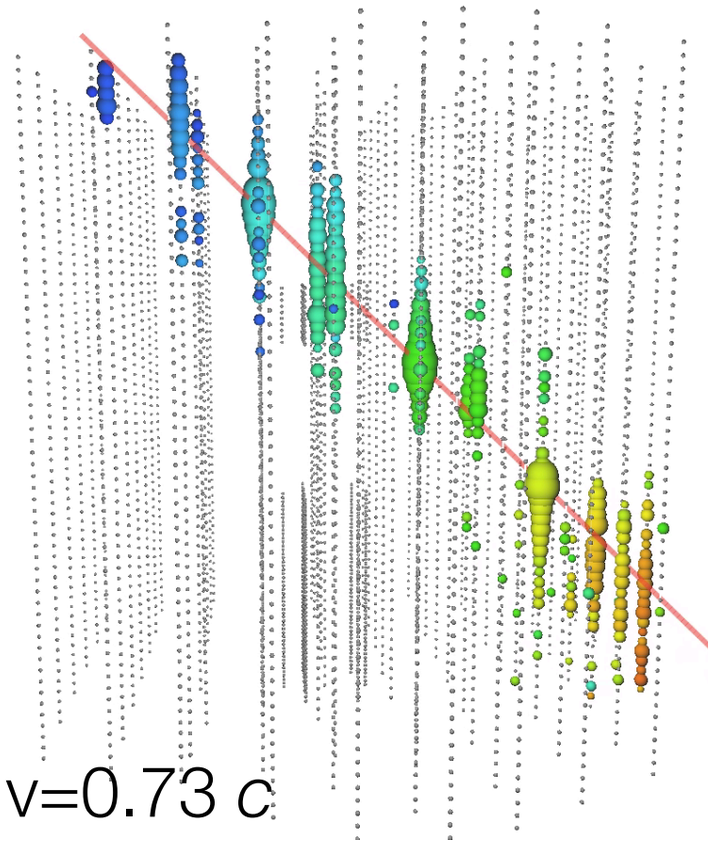

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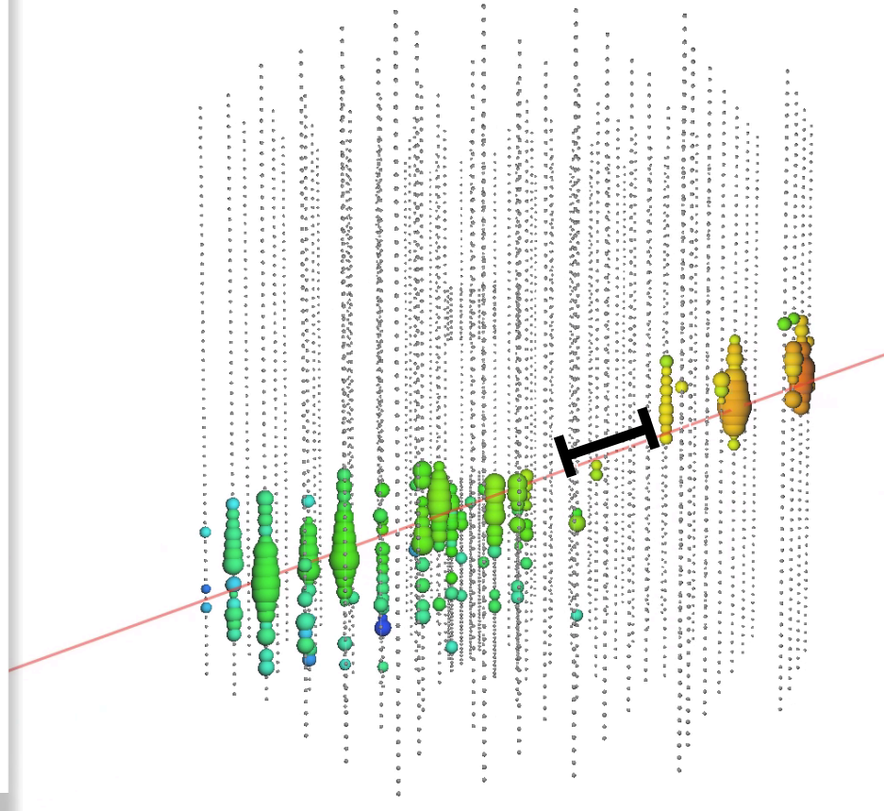
- neutrino produced in an air shower
- non-homogenous brightness
- speed = c
- isotropic direction of origin



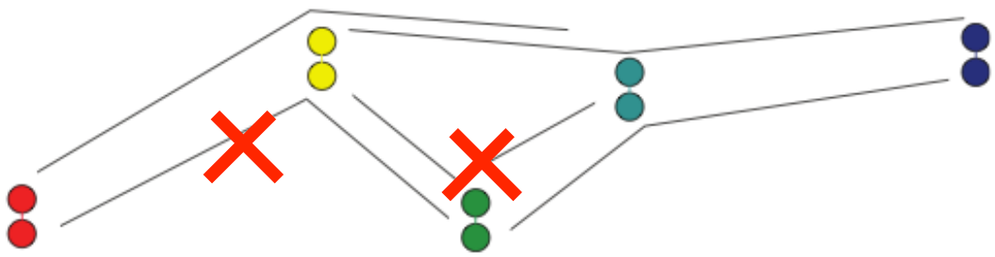
Selection variables

- number of sensors recording a hit
- speed
- direction
- gap within the hits
- …..

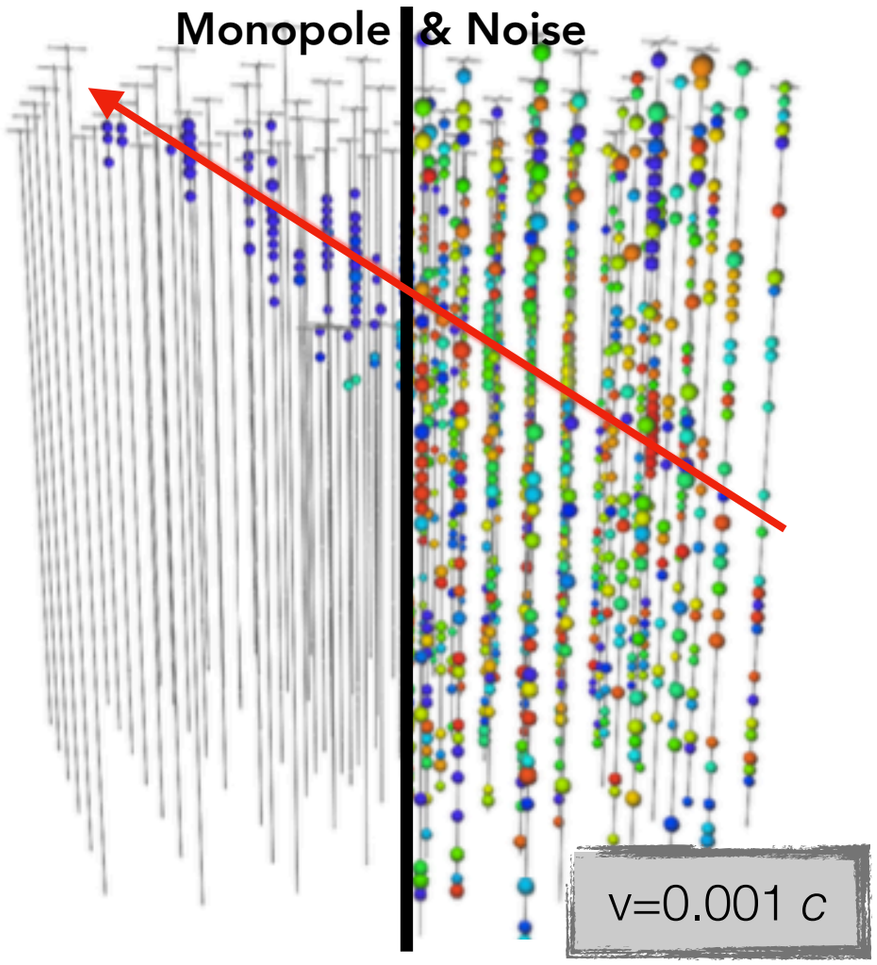
Feed into machine learning algorithms…

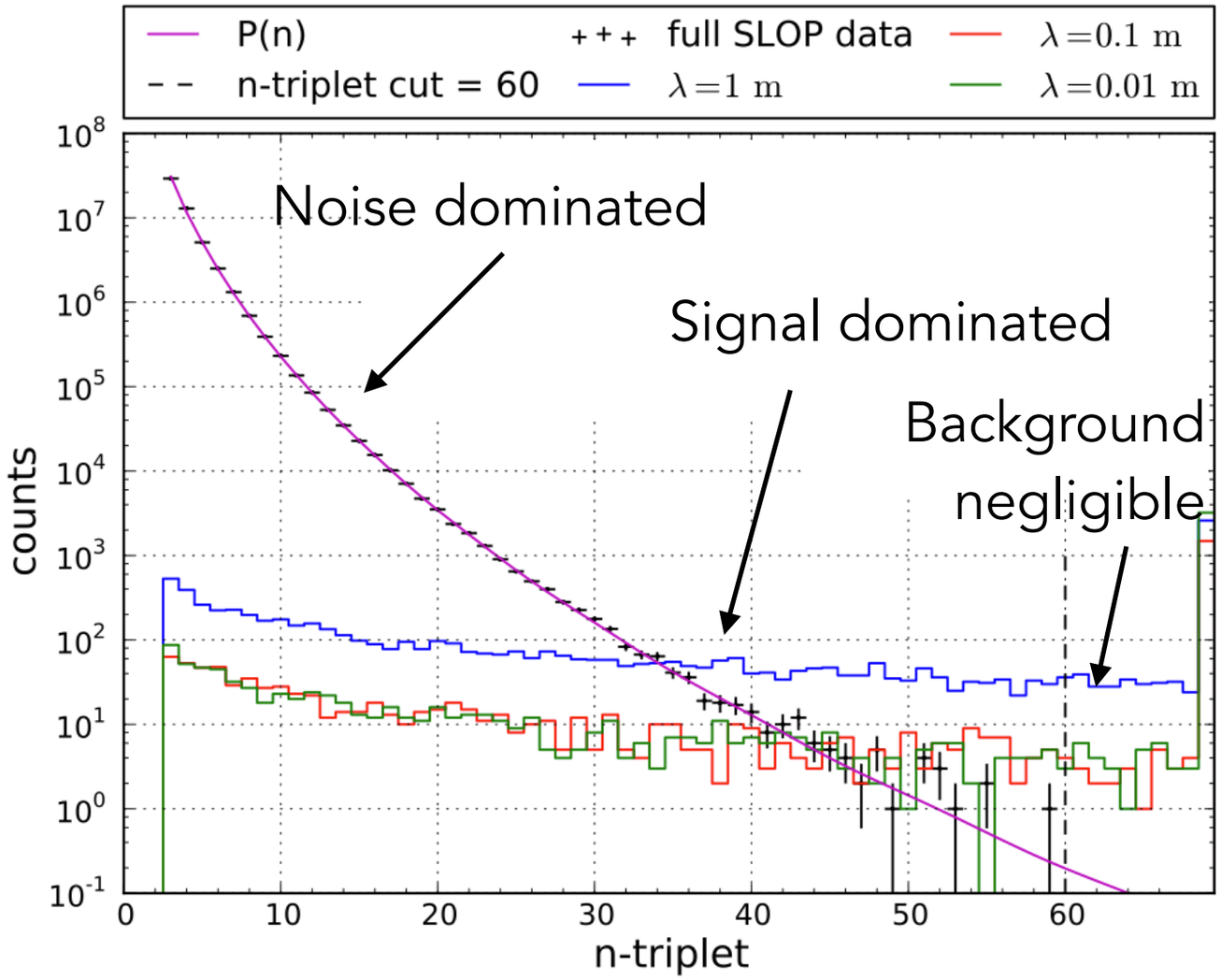
optical sensors Late hits Early hits Track

Distinguishing signal and background for slow particles



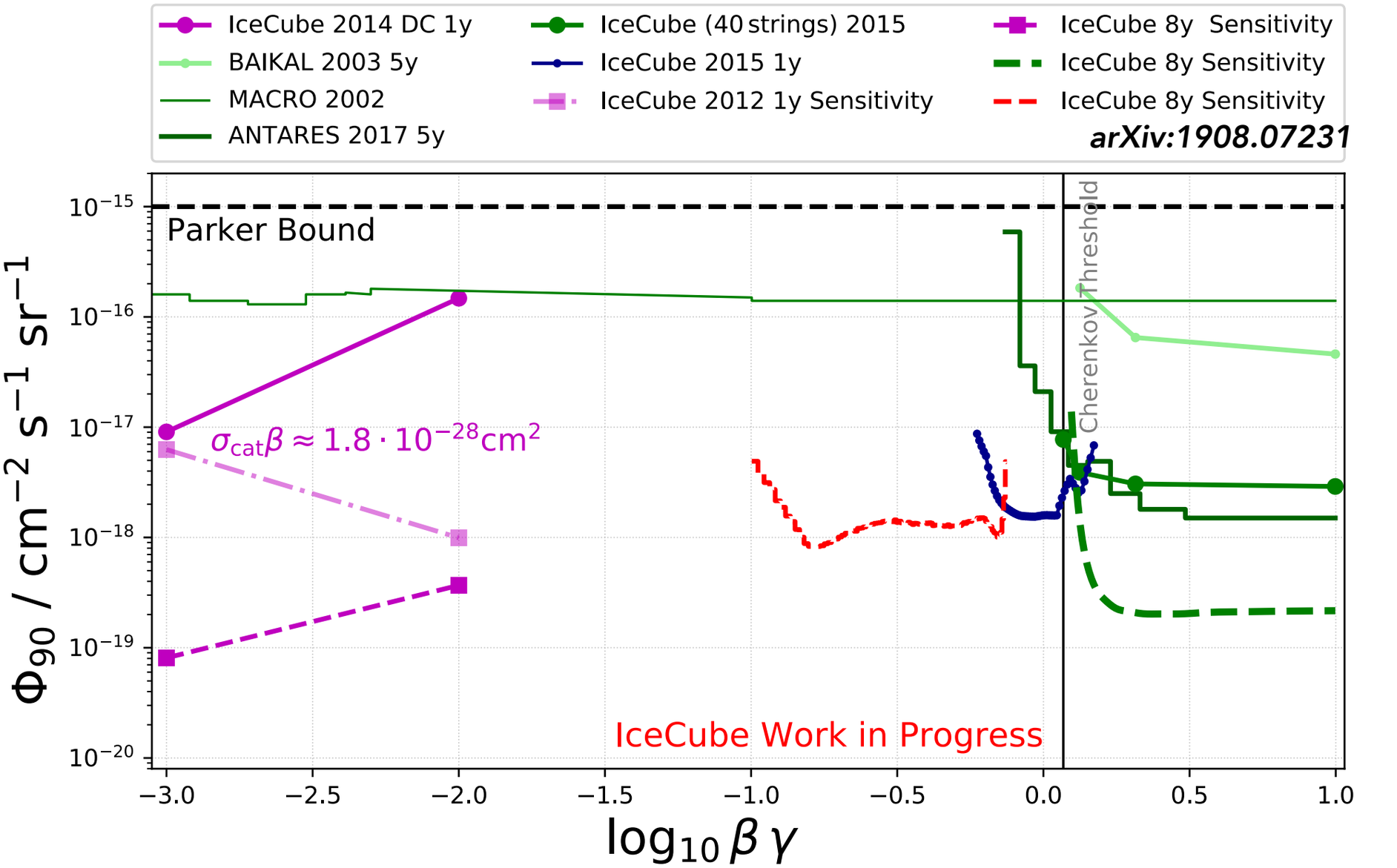
- Search for 3 pairs of hits
- Restrict allowed inner angle, speed, etc.
- Compare number of "triplets" in signal and background





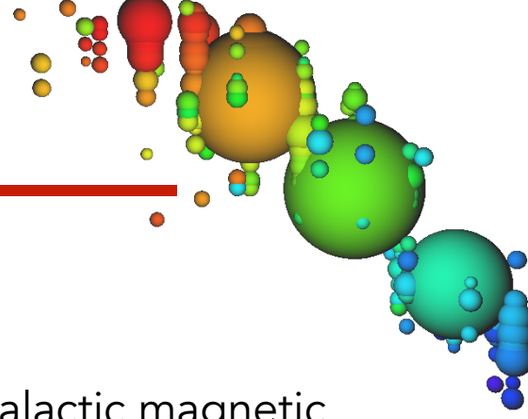
optical sensors Late hits Early hits Track

Exclusion of magnetic monopole fluxes



optical sensors Late hits Early hits Track

Repetition



Which statements about Magnetic Monopoles are correct?

A. The ~~heaviest possible~~ magnetic monopoles can be accelerated to relativistic speeds by intergalactic magnetic fields, not by galactic magnetic fields. ✗ *only intermediate mass / light monopoles*

B. *Inside* heavy magnetic monopoles a quark can be transformed into a lepton. ✓

C. Magnetic monopoles can be detected by searching for holes / traces in moon rocks. ✓ *they can be trapped in the stone or leave holes*

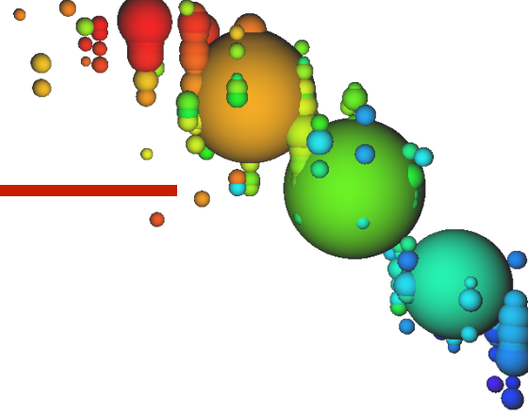
D. The strongest excluded density of magnetic monopoles is in the order of 1 particle / km^3 / year ✓

Open with any device

Answer question 7

https://arsnova.eu/mobile/#id/90965575

Summary



Dark Matter

- Dark Matter is one of the major questions in physics nowadays
- To find unambiguous evidence of its detection multiple search methods are required
- Indirect detection provides complementarity to other direct techniques as some astrophysical parameters are different
- Neutrino Astronomy has specific advantages for the indirect detection of Dark Matter

Magnetic Monopoles

- Predicted by most theories beyond the standard model
- Finding them could give much information about the development of the early universe

IceCube and beyond standard model physics

- Huge size of IceCube designed for high energy neutrinos, but also ideal for direct and indirect searches for new physics