Exploring intergalactic magnetic fields as a window into new physics

Anastasia Sokolenko
The University of Chicago

Fermilab

KICP Kavli Institute for Cosmological Physics AT THE UNIVERSITY OF CHICAGO

THE UNIVERSITY OF CHICAGO 1890

cta cherenkov telescope array

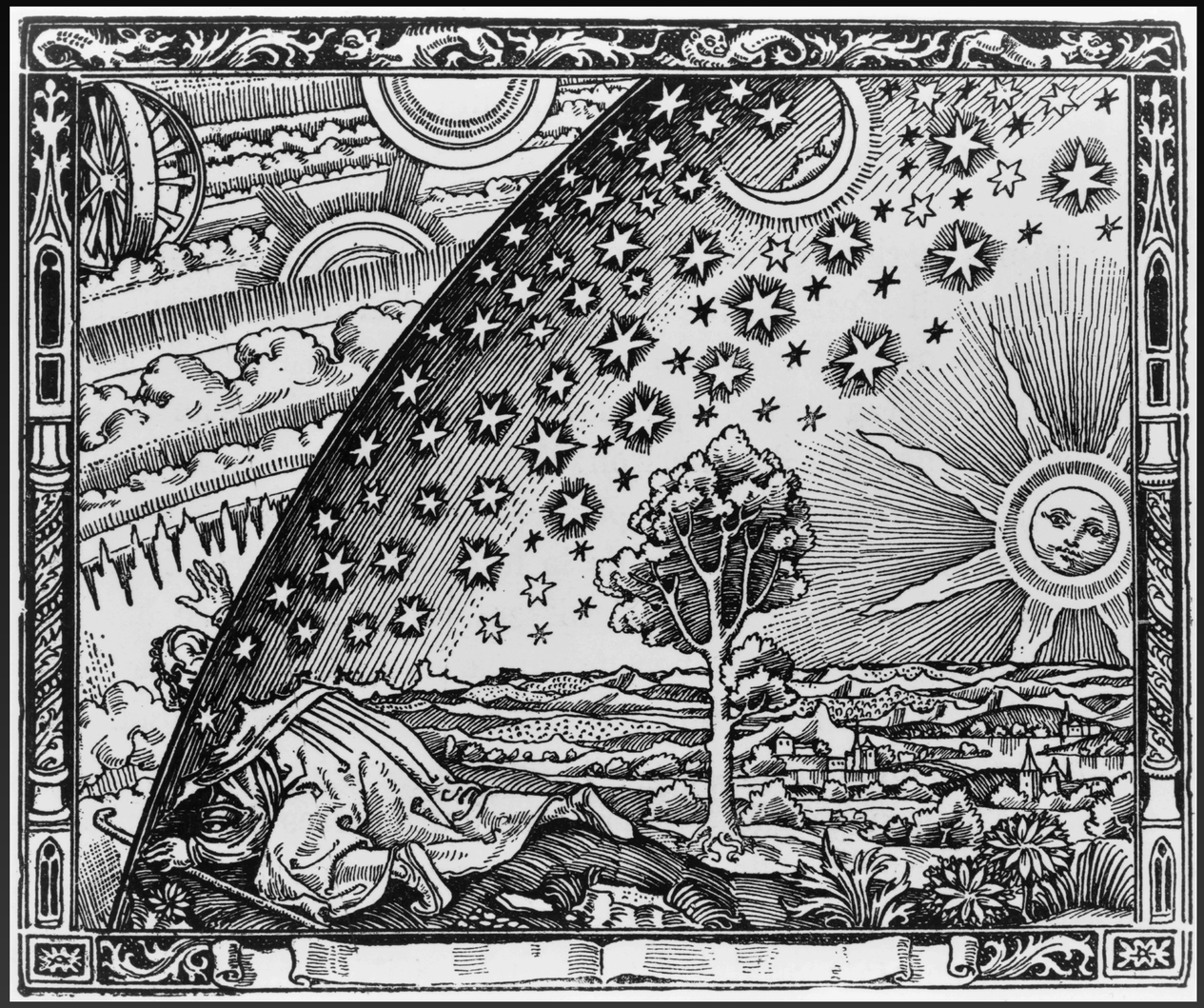
SHiP Search for Hidden Particles

Credit: IllustrisTNG

Scientific revolutions in XX century

The 20th century witnessed three major scientific revolutions

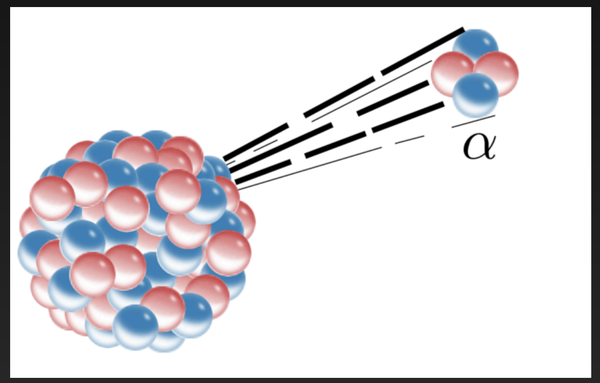
- **Quantum mechanics**
- **General relativity**
- **Discovery of the universe**



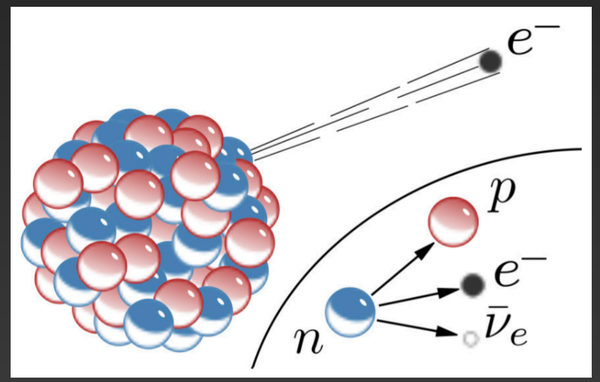
Credit: Flammarion

New fundamental forces!

Atomic and nuclear physics (radioactivity) demonstrated that there are **non-electromagnetic interactions**, with neutral particles involved



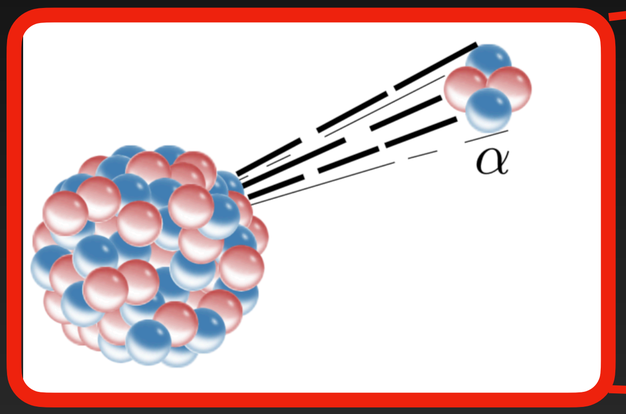
α-decay



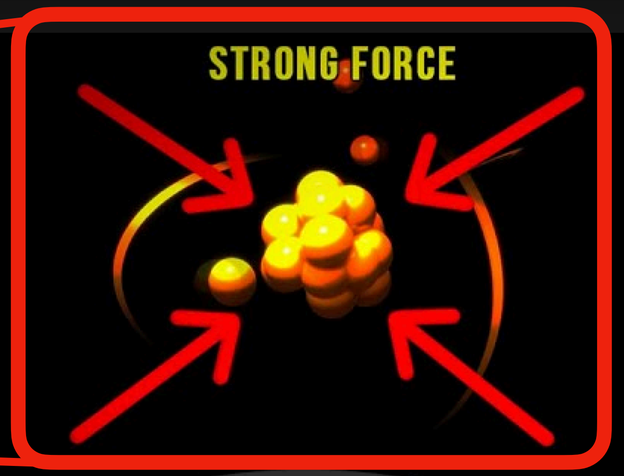
β-decay

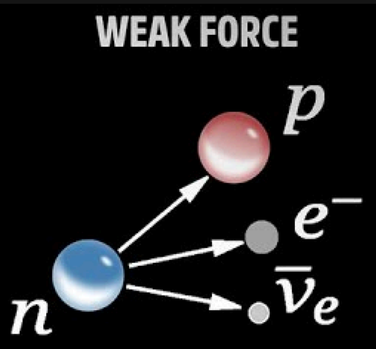
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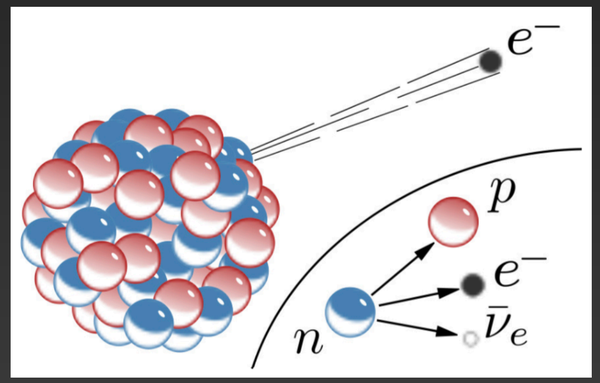
We have **four fundamental forces in nature**: gravitational, electromagnetic, strong, and weak



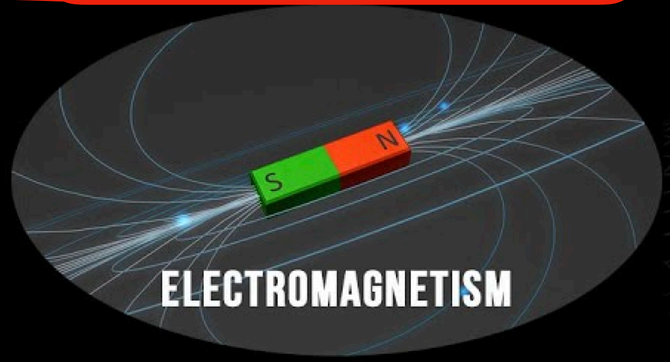
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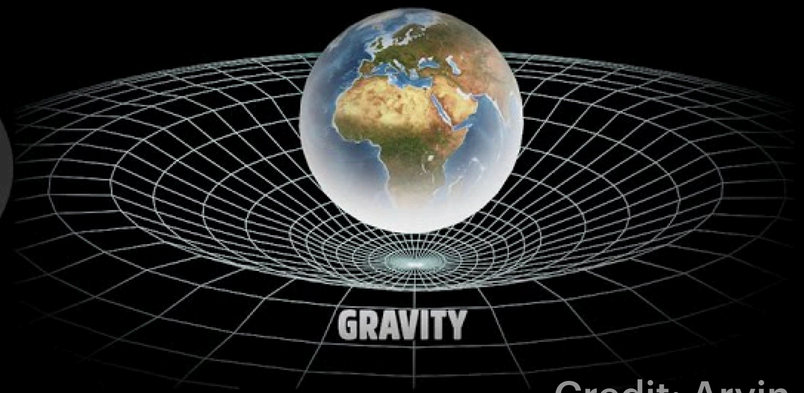






β-decay

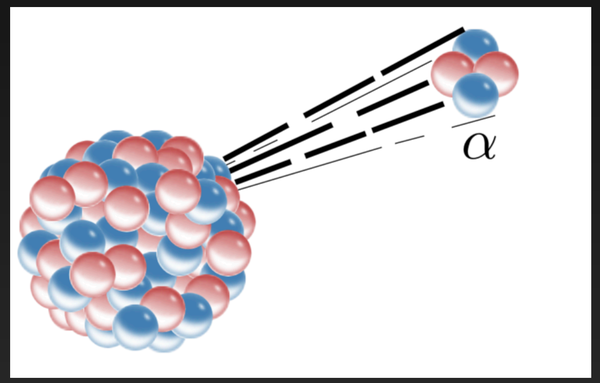




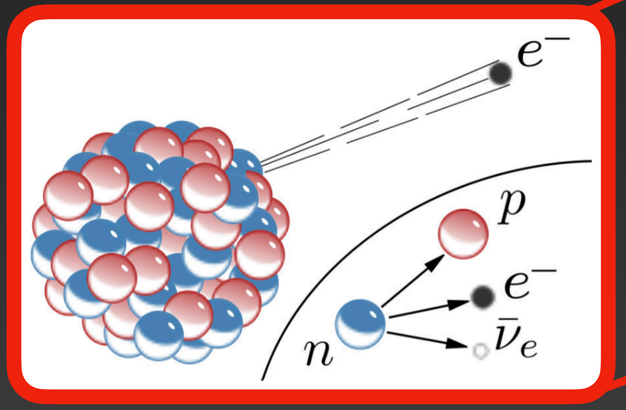
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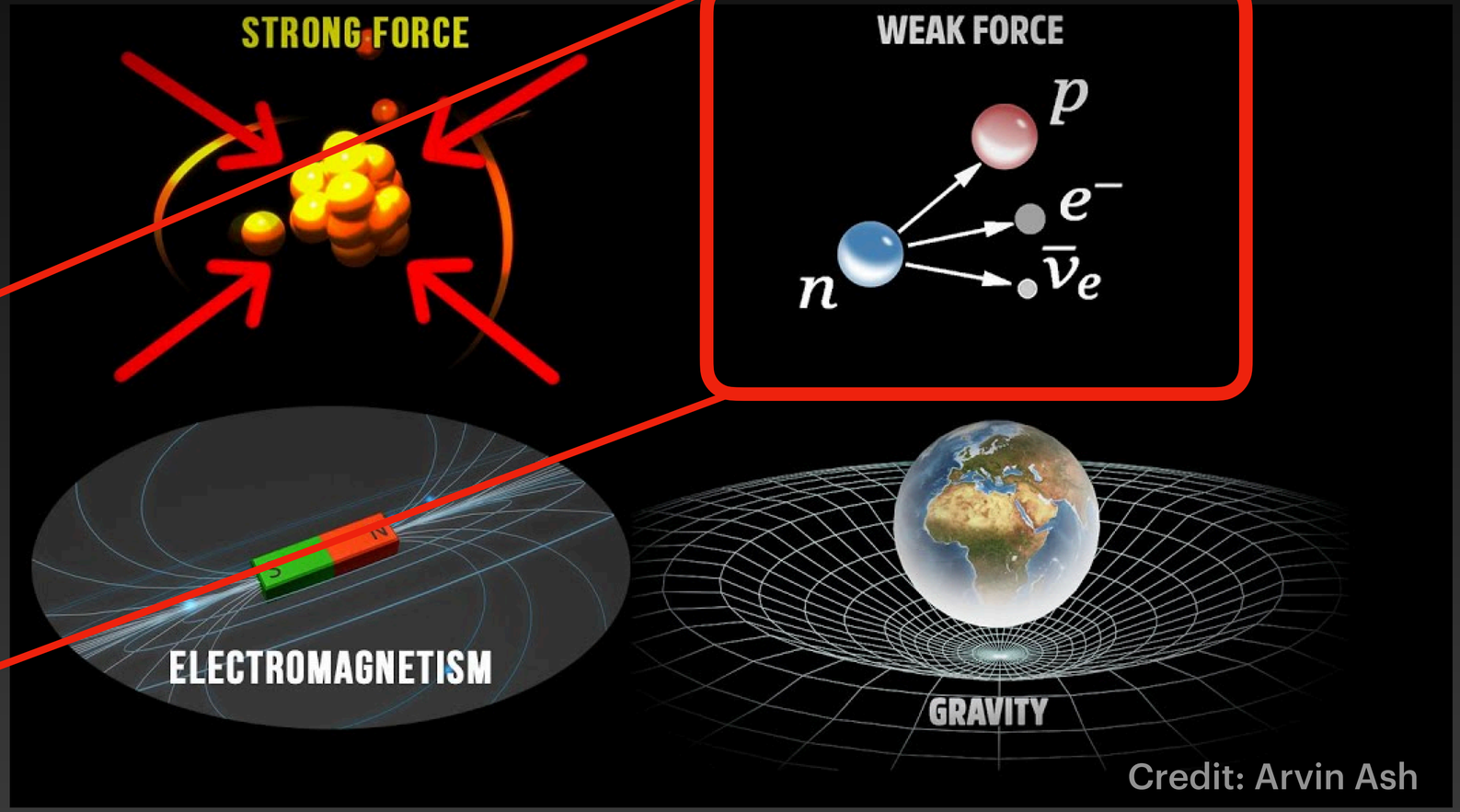
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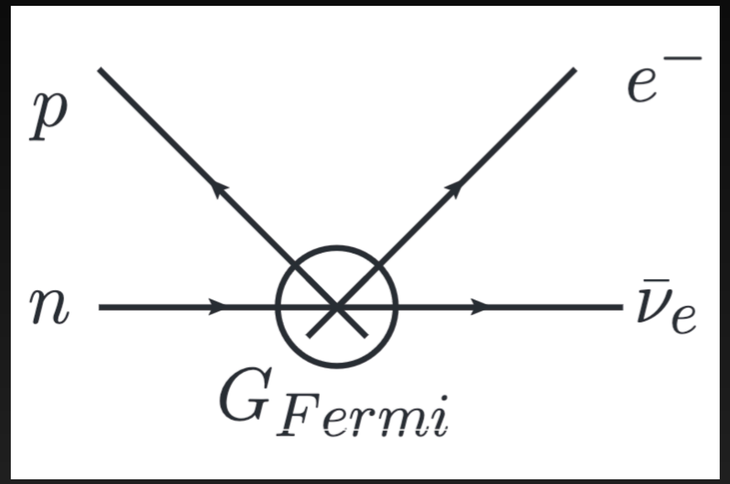


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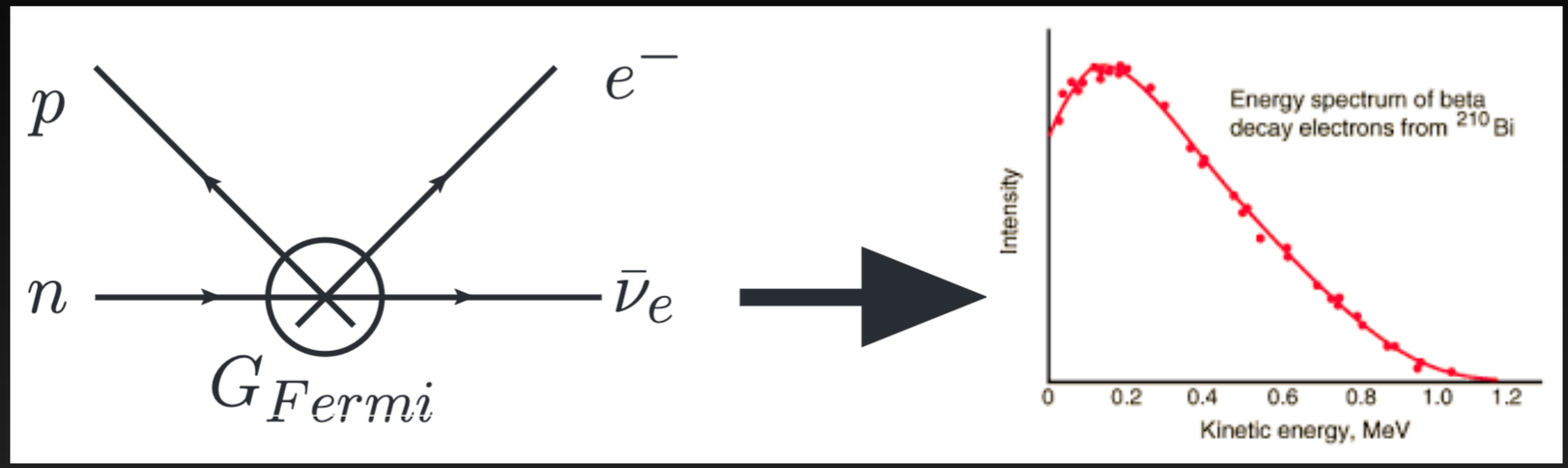
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From weak interactions to the SM



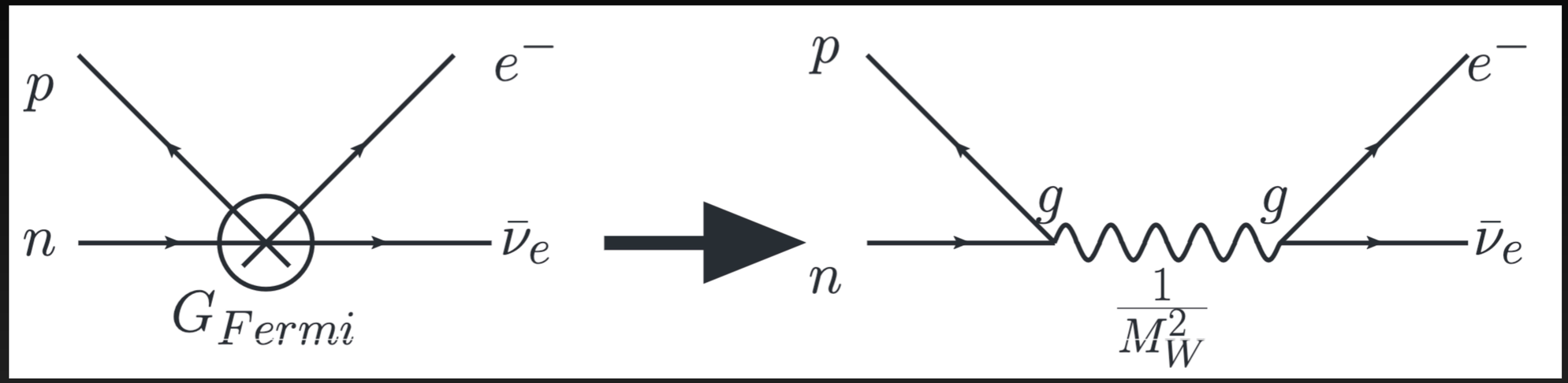
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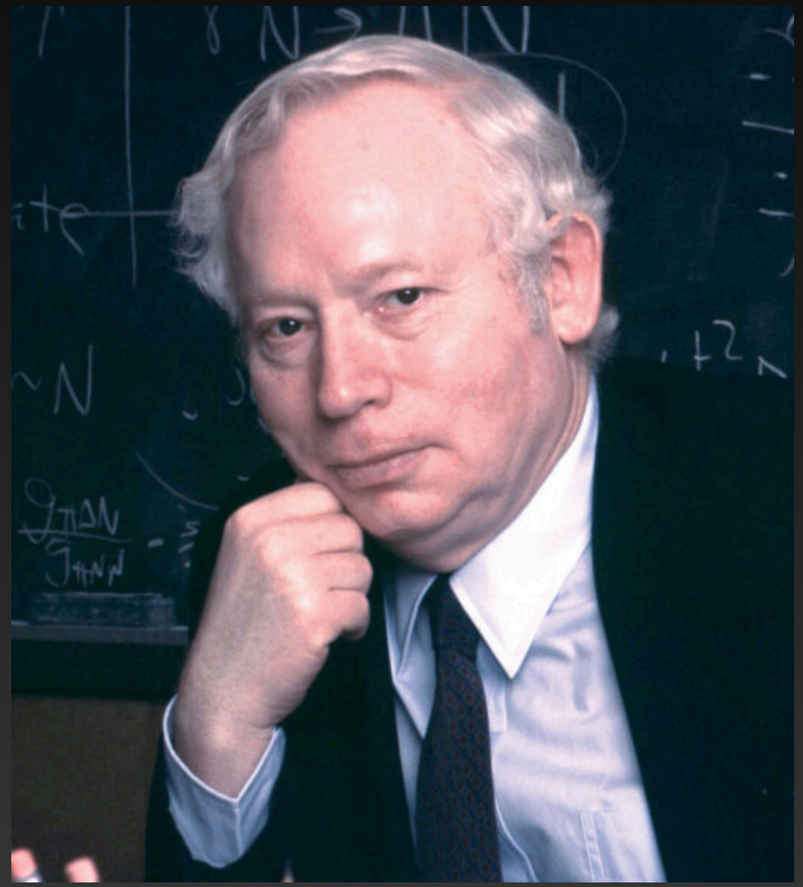
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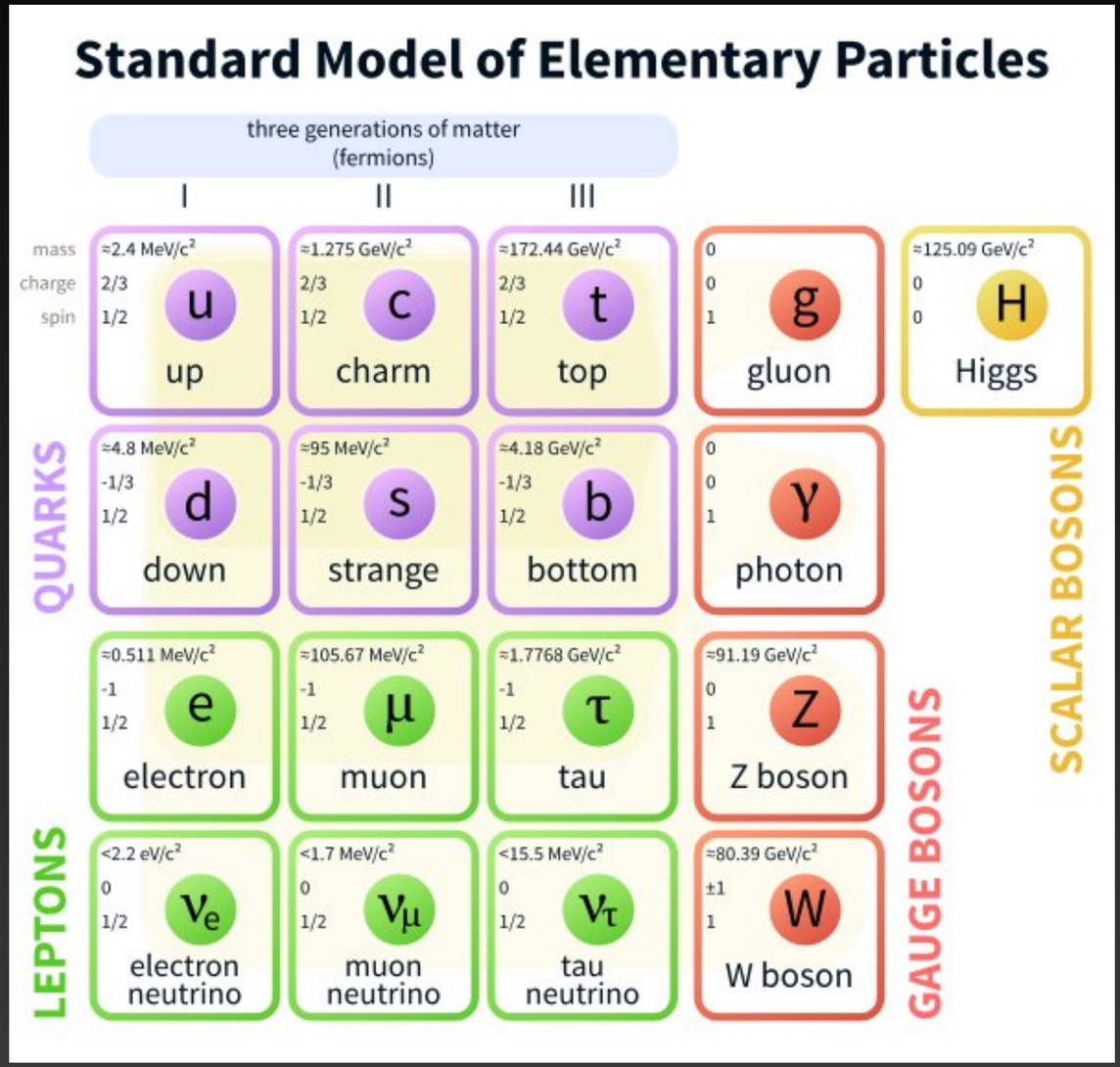


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- To "save" this theory, people were **FORCED** to assume the existence of a new heavy particle - W boson

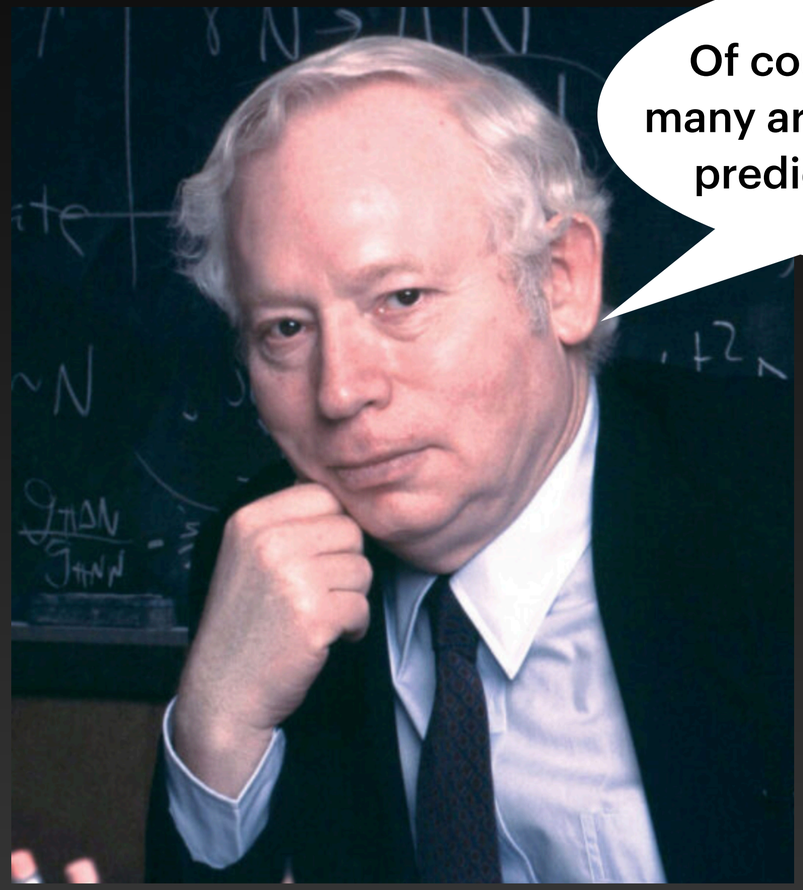
Puzzle completed: The Standard Model



Steven Weinberg, 1967

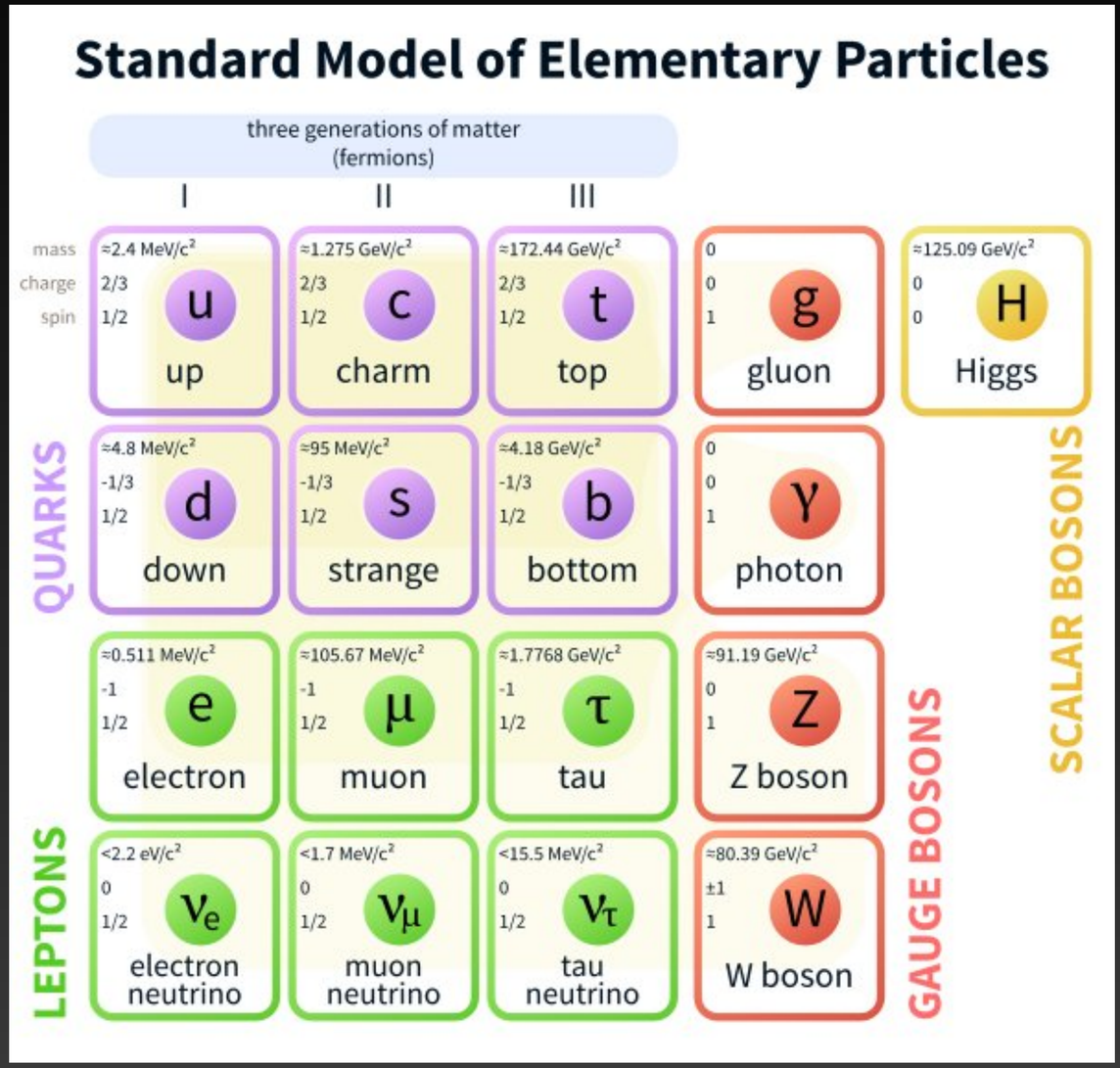


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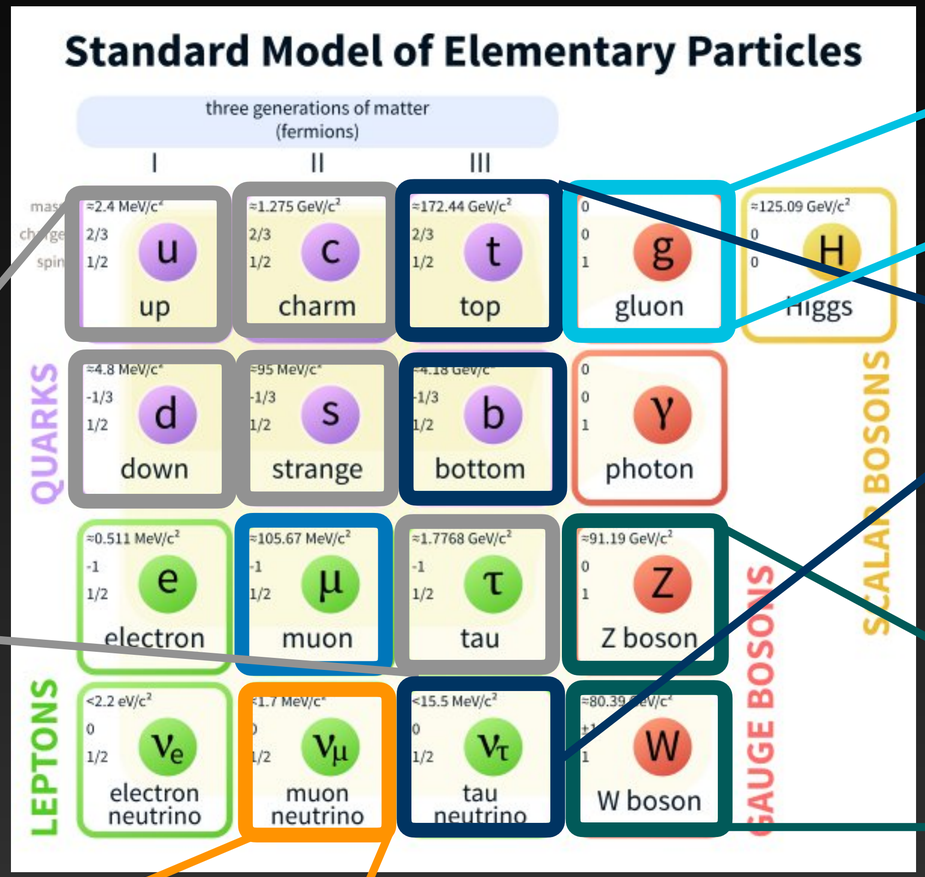


S.Weinberg:
Of course our model has too many arbitrary features for these predictions to be taken very seriously...

Steven Weinberg, 1967



Predictions taken seriously



DESY, 1978

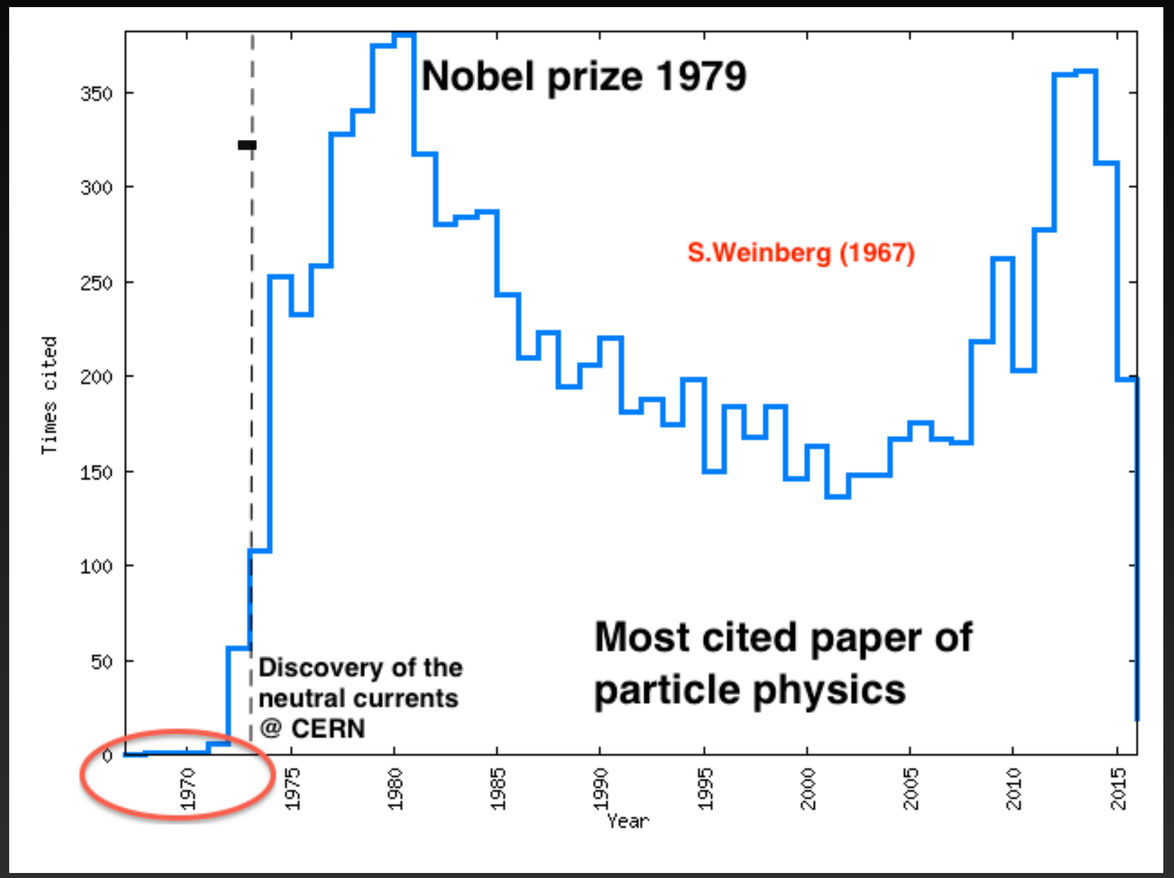
Fermilab, 1977 - 2000

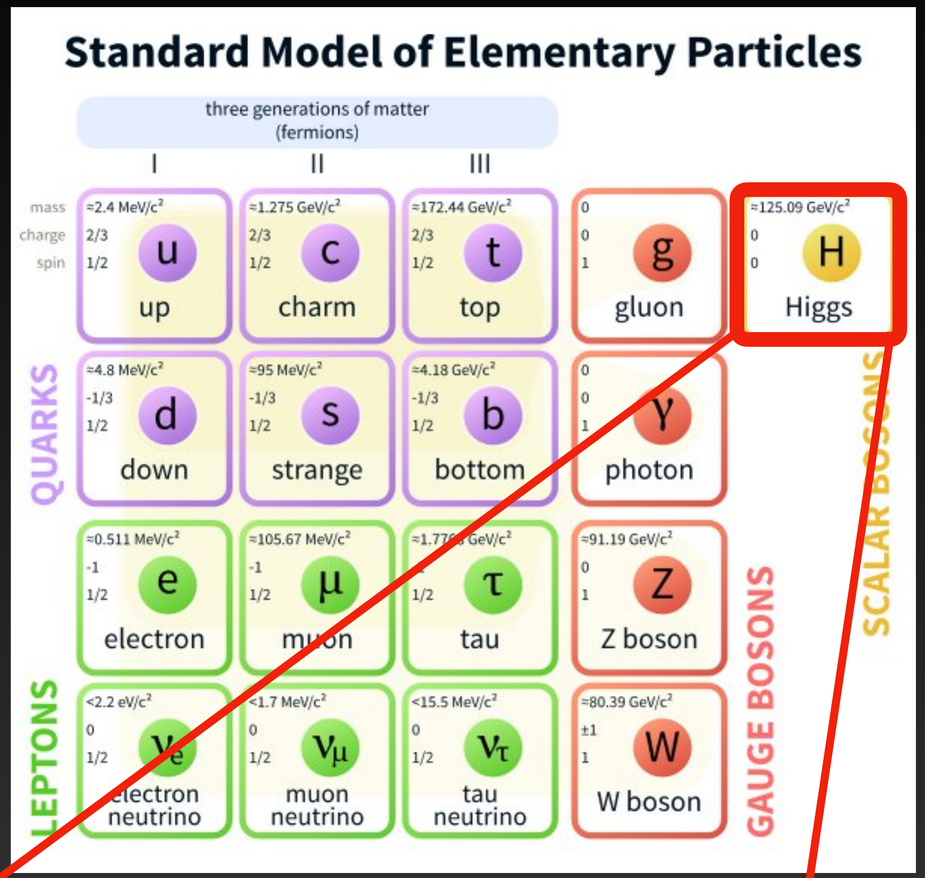
SLAC, 1968 - 1975

CERN, 1983

BNL, 1962

Standard Model of Particle Physics: 1967 - 2012





The Higgs boson was predicted in the late 1960s but was only discovered at the LHC in 2012

Beyond the SM problems

Particle physics is facing a great challenge:

We are certain that the SM does not explain all phenomena in Nature

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Indeed, a number of experimentally established evidence **cannot be explained by the Standard Model**, including:

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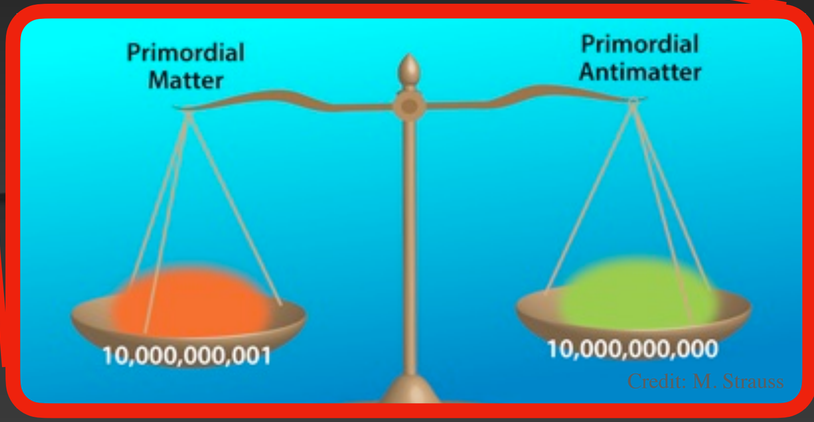
Credit: Ana Kova

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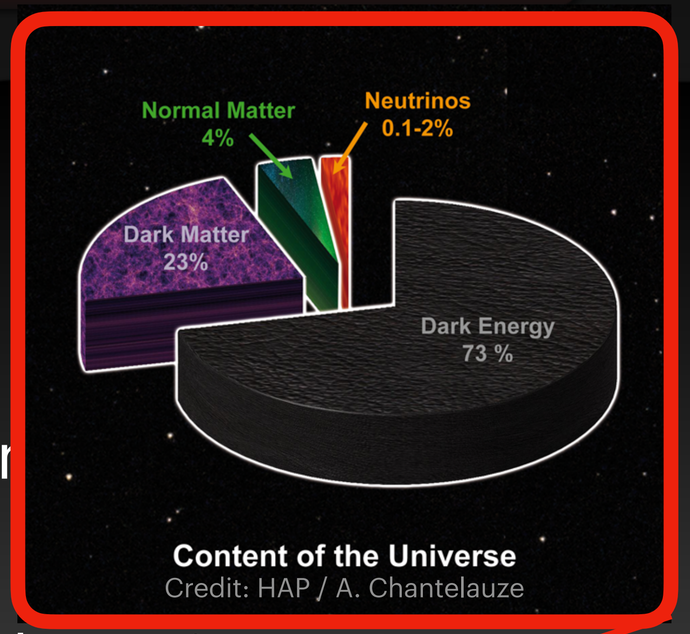


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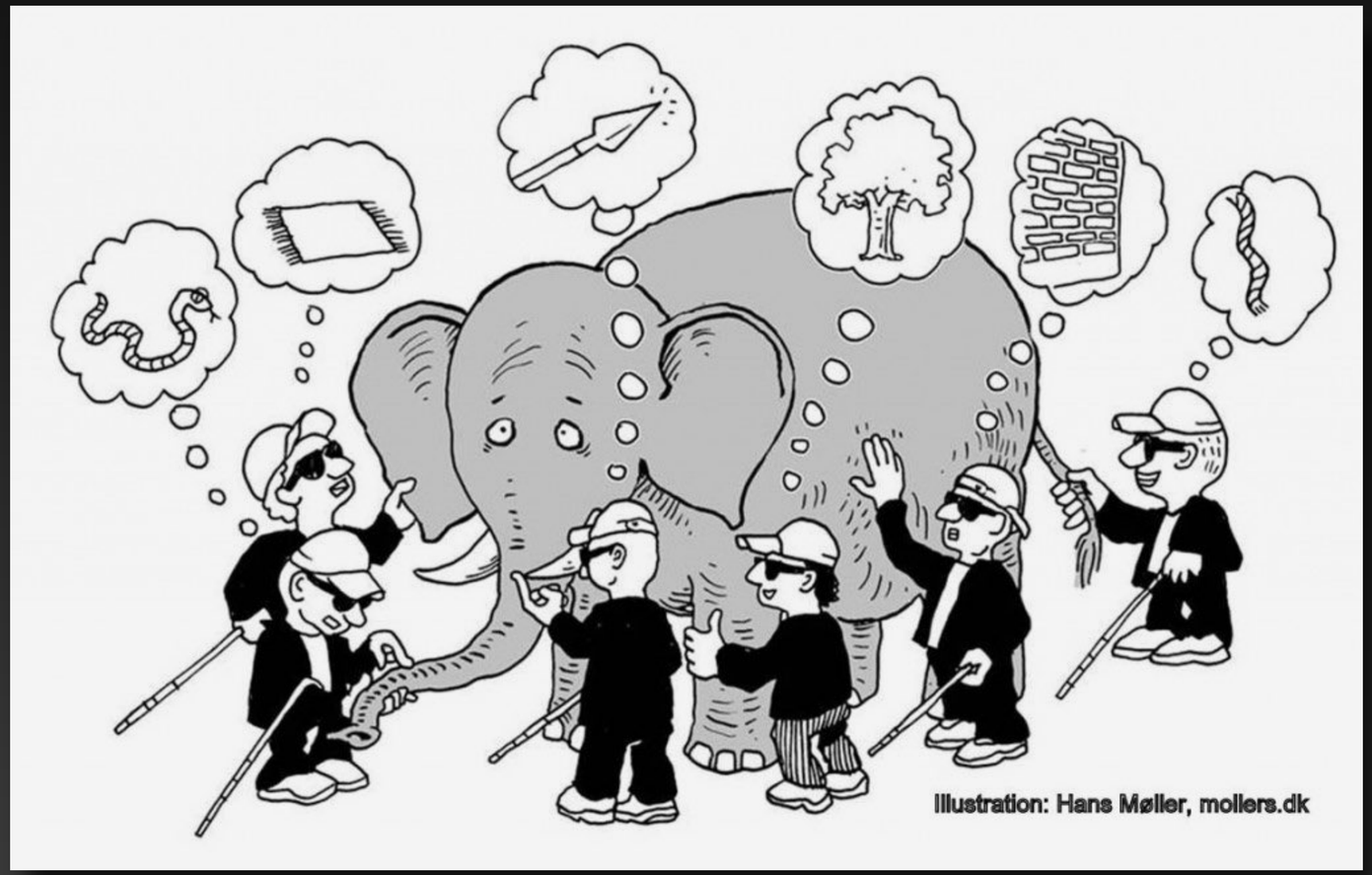
- **Neutrino masses**: Why do neutrinos have a mass?
- **Baryon asymmetry of the Universe**: What mechanism matter-antimatter imbalance in the early Universe?
- **Dark Matter**: What is the prevalent kind of matter in the Universe?



Content of the Universe
Credit: HAP / A. Chantelauze

New revolution?

No solid signature of new physics was found, nor was an explanation of the big puzzles provided

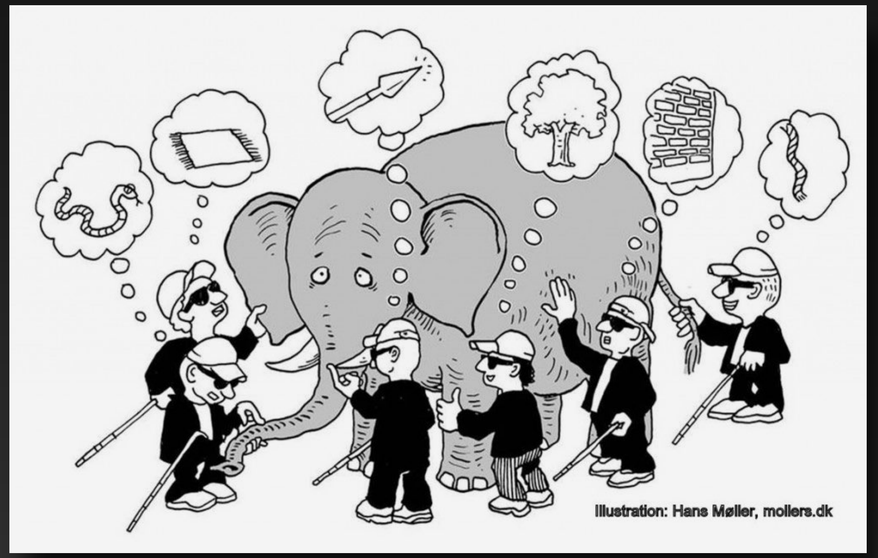


New revolution?

Physics beyond the Standard Model

Particle Physics

- New experiments



Astrophysics and Cosmology

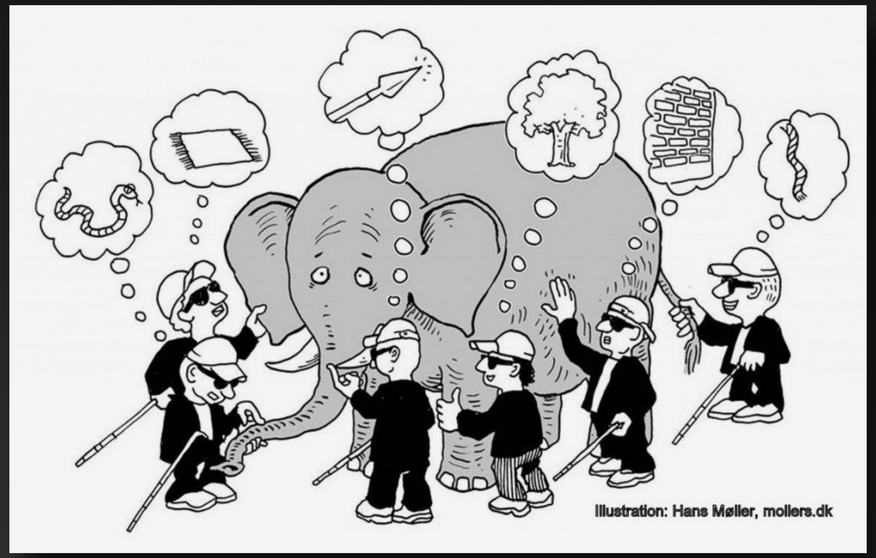
- Exploring extreme systems
- Studying dark matter
- Searching for relics from the early Universe
- ...

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Physics beyond the Standard Model

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Scientific revolution: Universe

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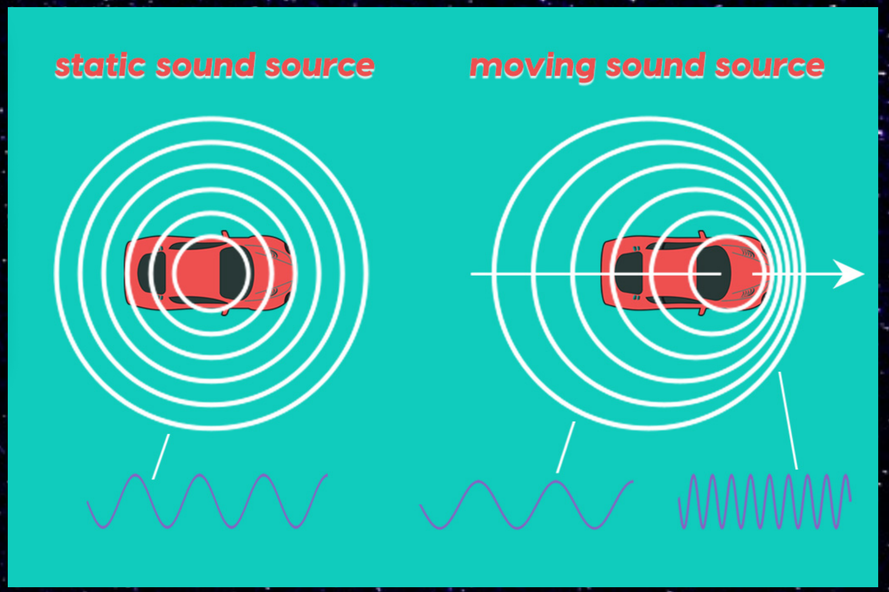
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In addition, the **velocities of galaxies** were measured using the Doppler effect

Velocity is proportional to the **distance** to the object

$$v = H_0 \times R$$

where $H_0 \simeq 70$ km/s/Mpc



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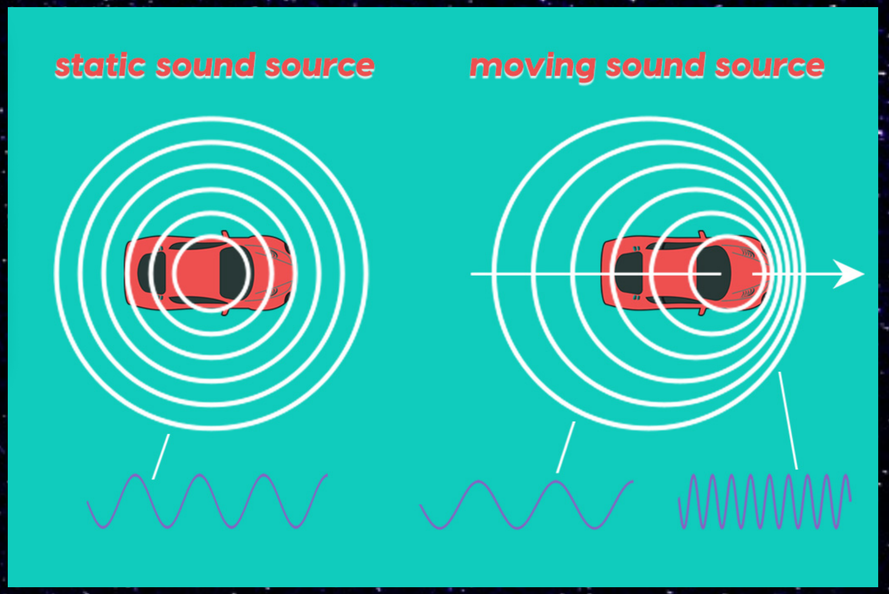
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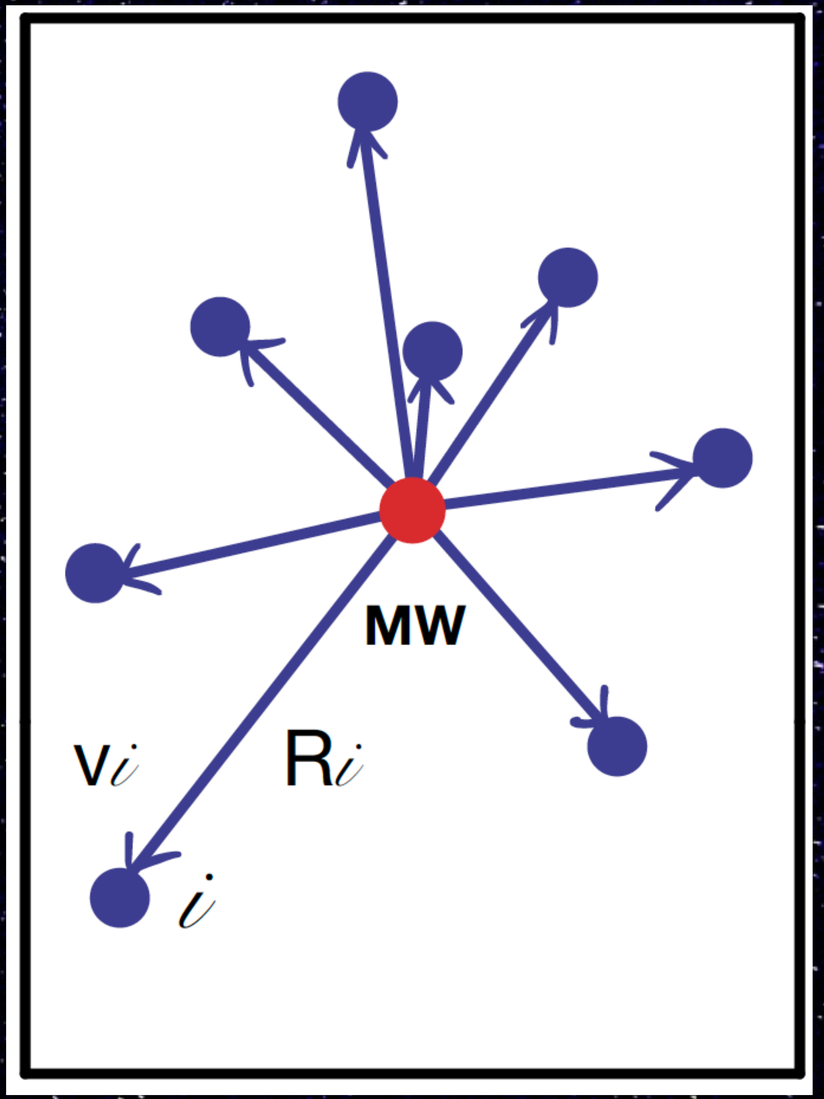
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Our Universe is expanding!



Are we at the center of the Universe?



Are we at the center of the Universe?

Some time ago, the galaxy "i" was near our galaxy:

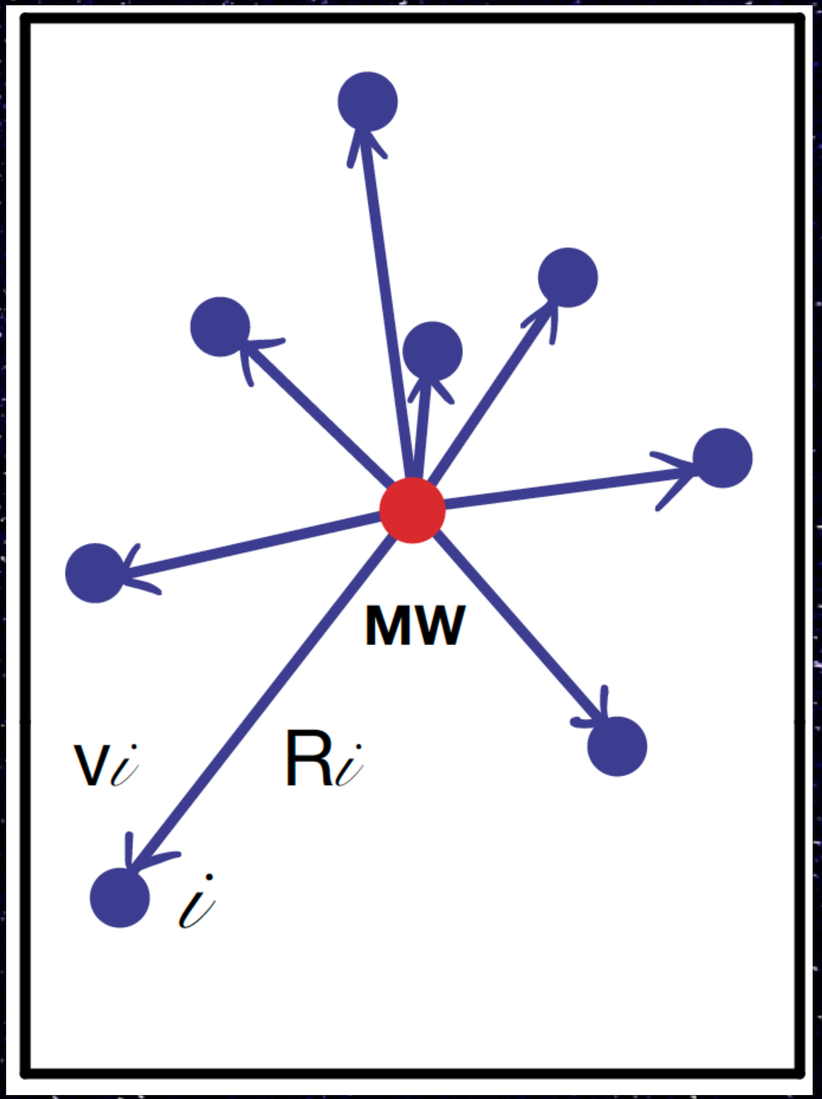
$$t_i = \frac{R_i}{v_i}$$

From Hubble's law we know that $v_i = H_0 \, R_i$, so

$$t_i \sim \frac{1}{H_0}$$

This time is the same for **every galaxy**

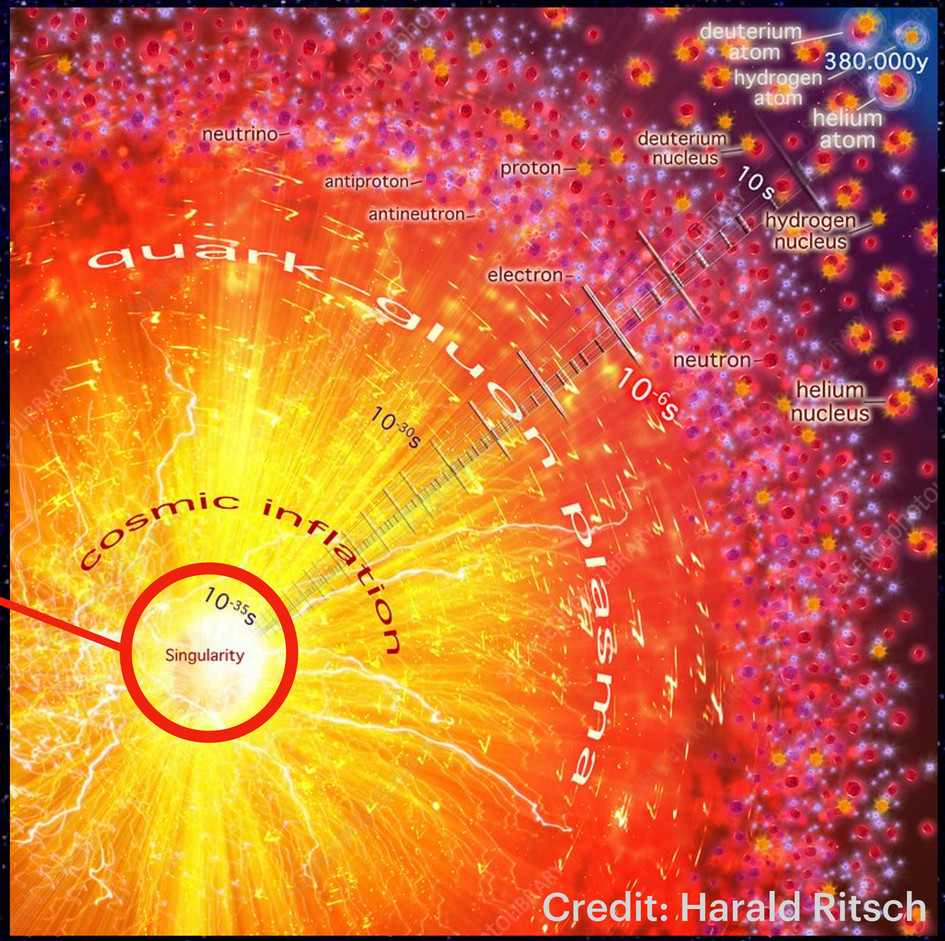
A very long time ago all the galaxies were together!



Big Bang

If we extrapolate the current state of the Universe back in time, we arrive at an **initial state** when **everything was compressed**

Big Bang

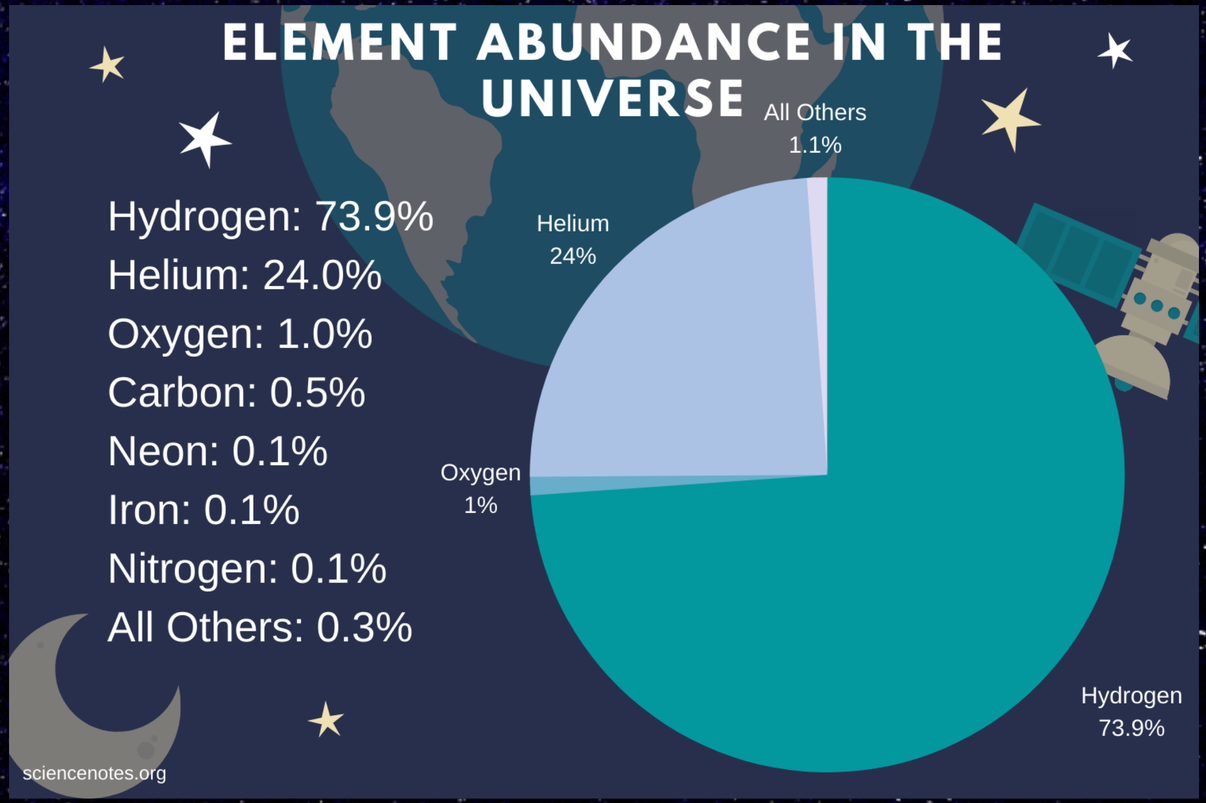


Hot early Universe

What was this initial state?

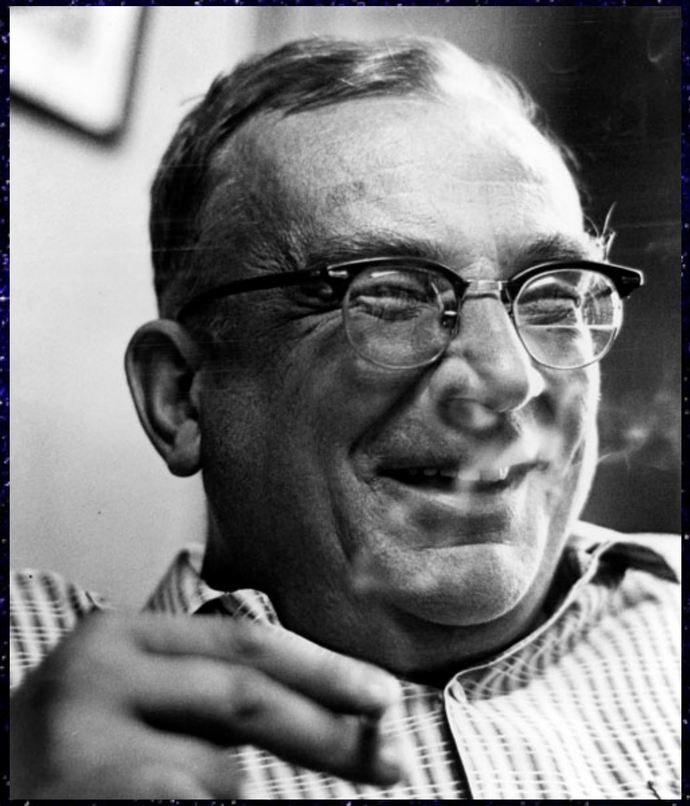
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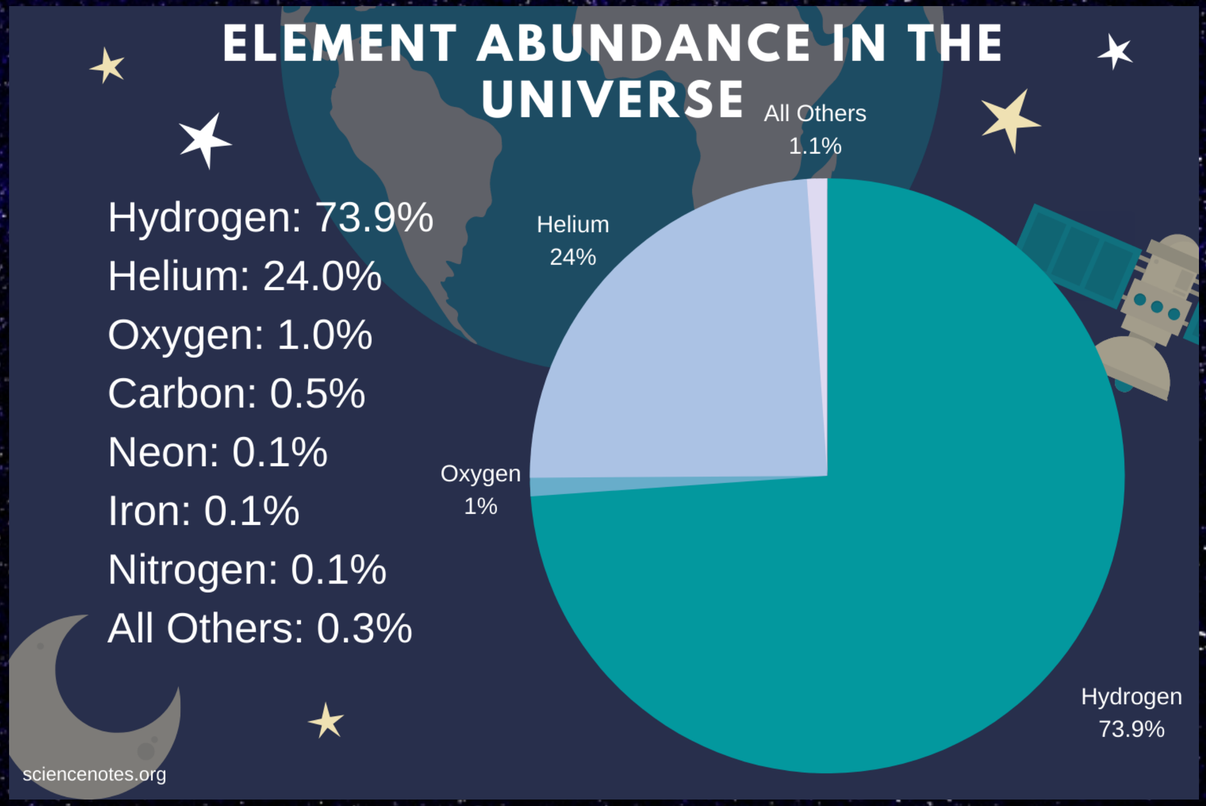


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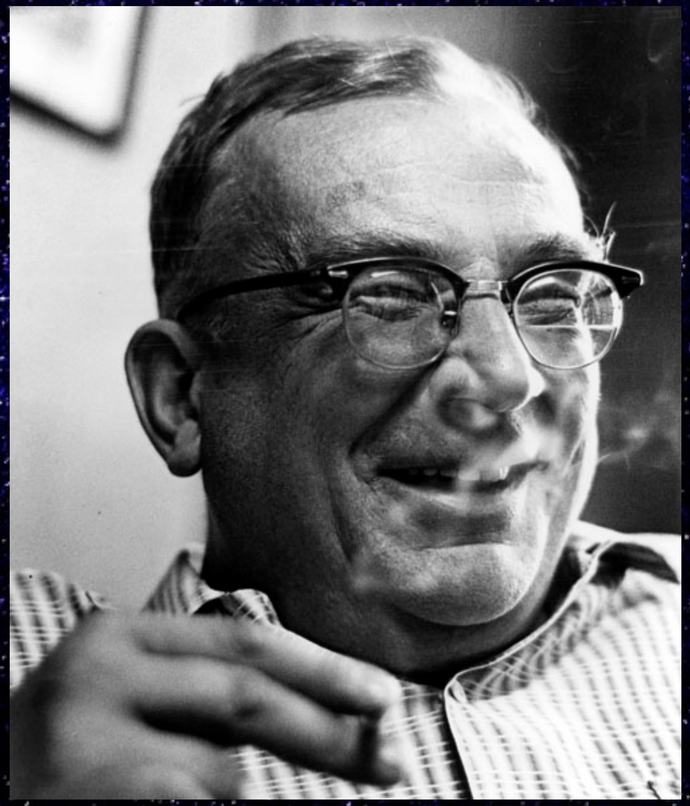


George Gamow

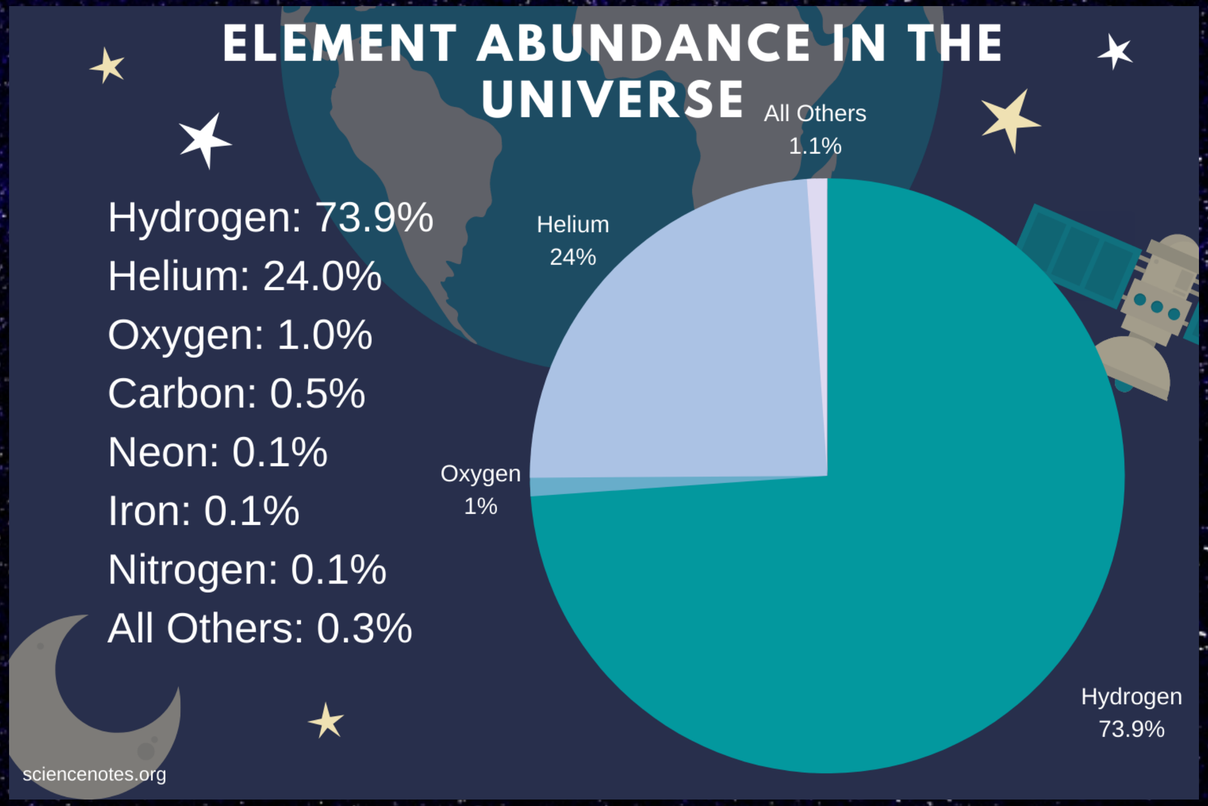


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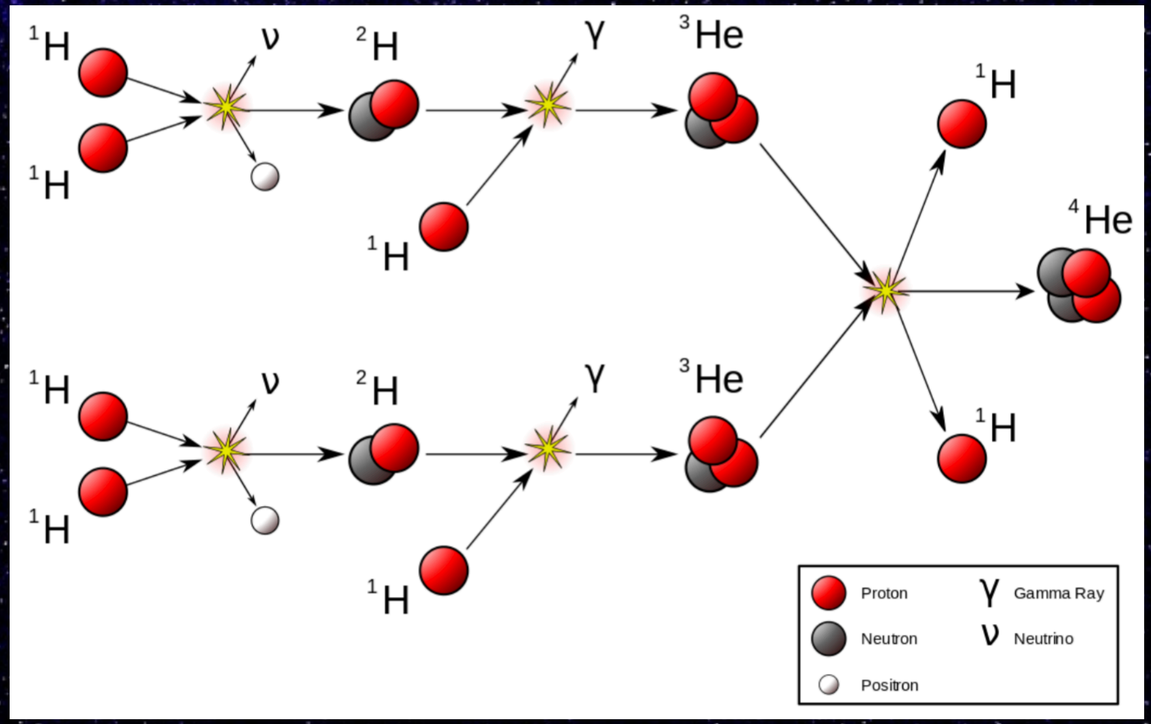
Gamow wanted to explain this **chemical** composition as a result of **processes in the early Universe**

Hot early Universe

- When gas is compressed, it becomes very hot!

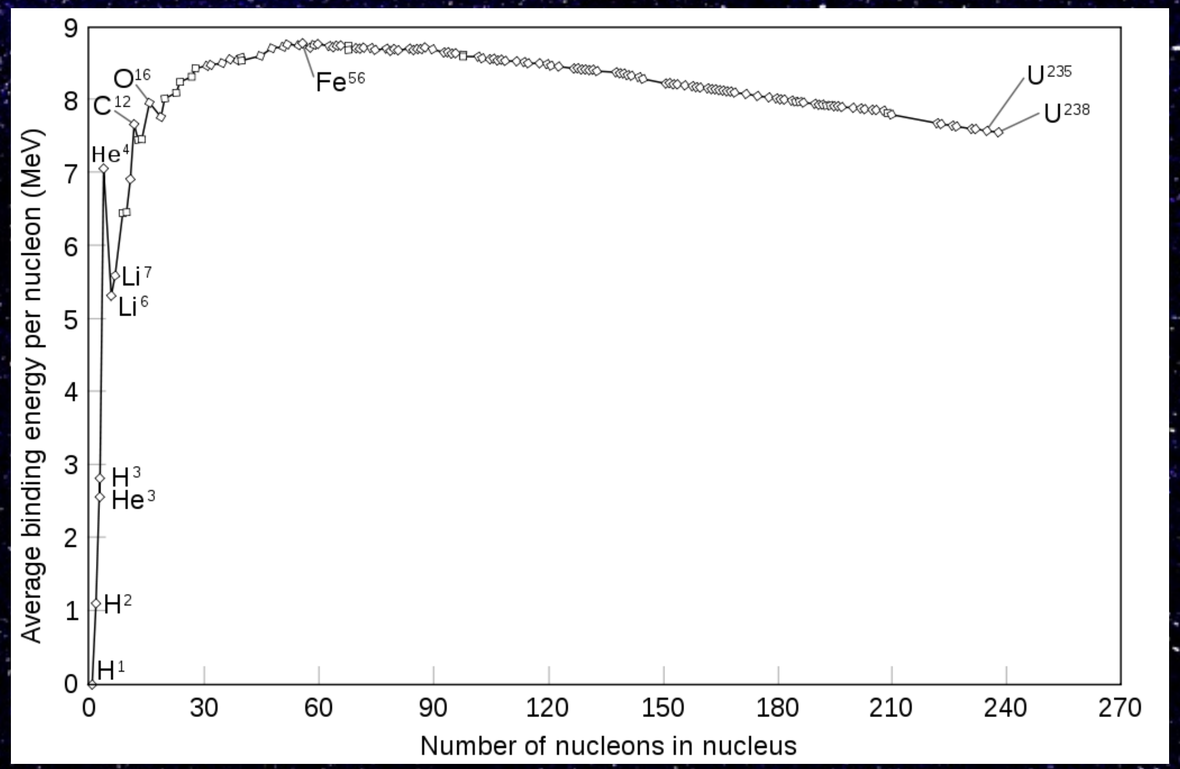
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- When gas is compressed, it becomes very hot!
- Later, gas cools down with the expansion of the Universe, **nuclear reactions start** creating bound systems, e.g Helium



Hot early Universe

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- Later, gas cools down with the expansion of the Universe, **nuclear reactions start** creating bound systems, e.g Helium
- If you let nuclear reactions **go on forever**, everything will turn into **Iron**



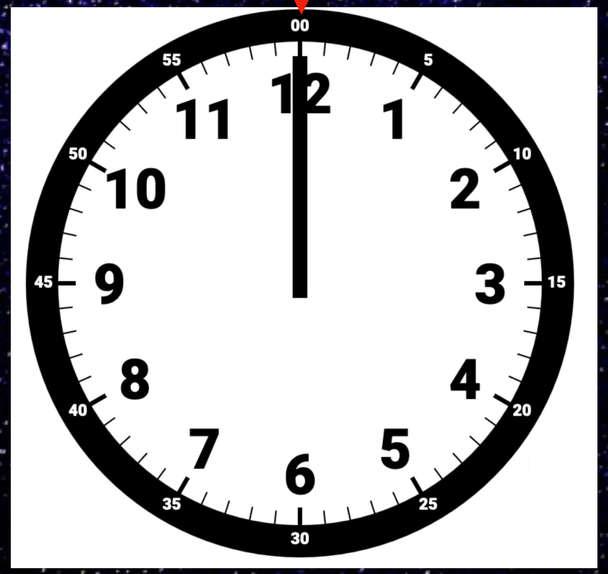
Hot early Universe

Why do **we see** primordial **Helium** and **Hydrogen** and **no traces** of primordial heavier elements, up to **Iron**?

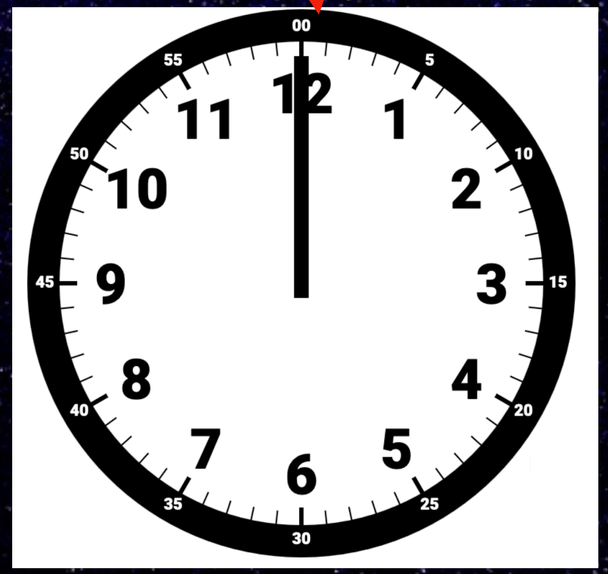
Hot early Universe

Gamow suggested that **primordial heavier elements were not created** because nuclear reactions only work for a **very limited time!**

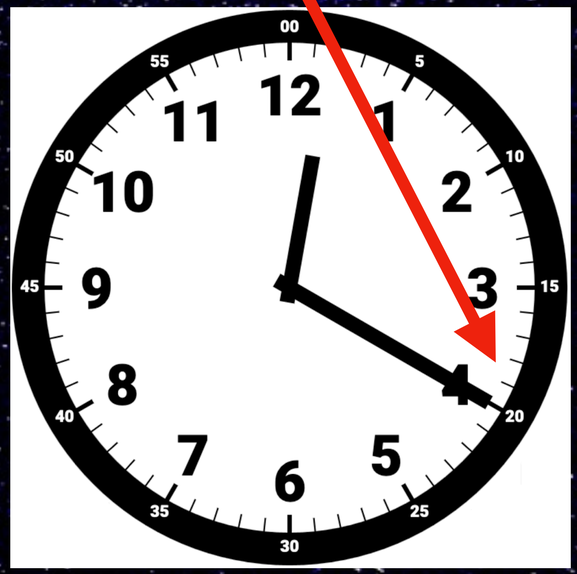
Big Bang



BBN starts

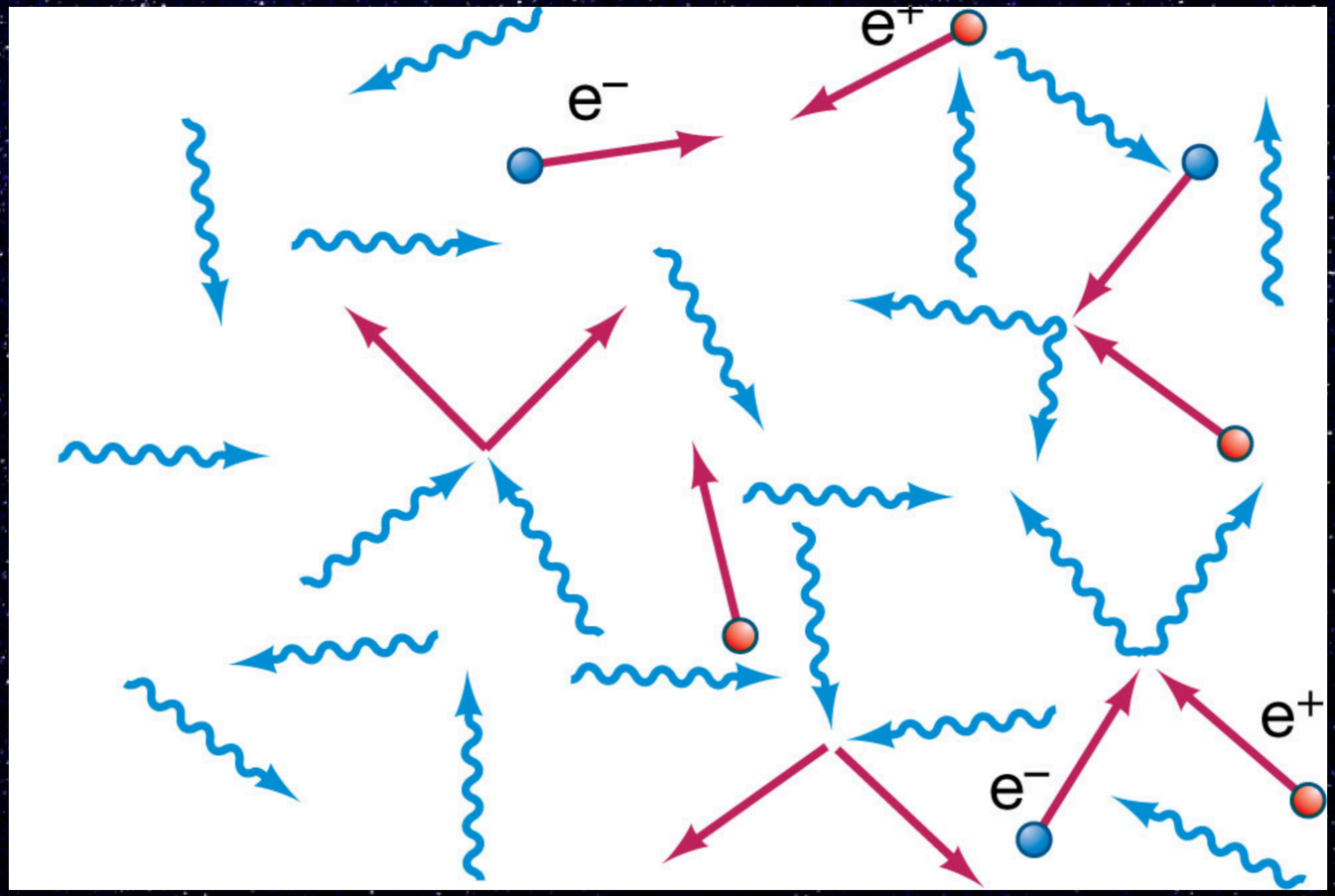


BBN ends



Hot early Universe

There are 10^{10} photons per each proton!



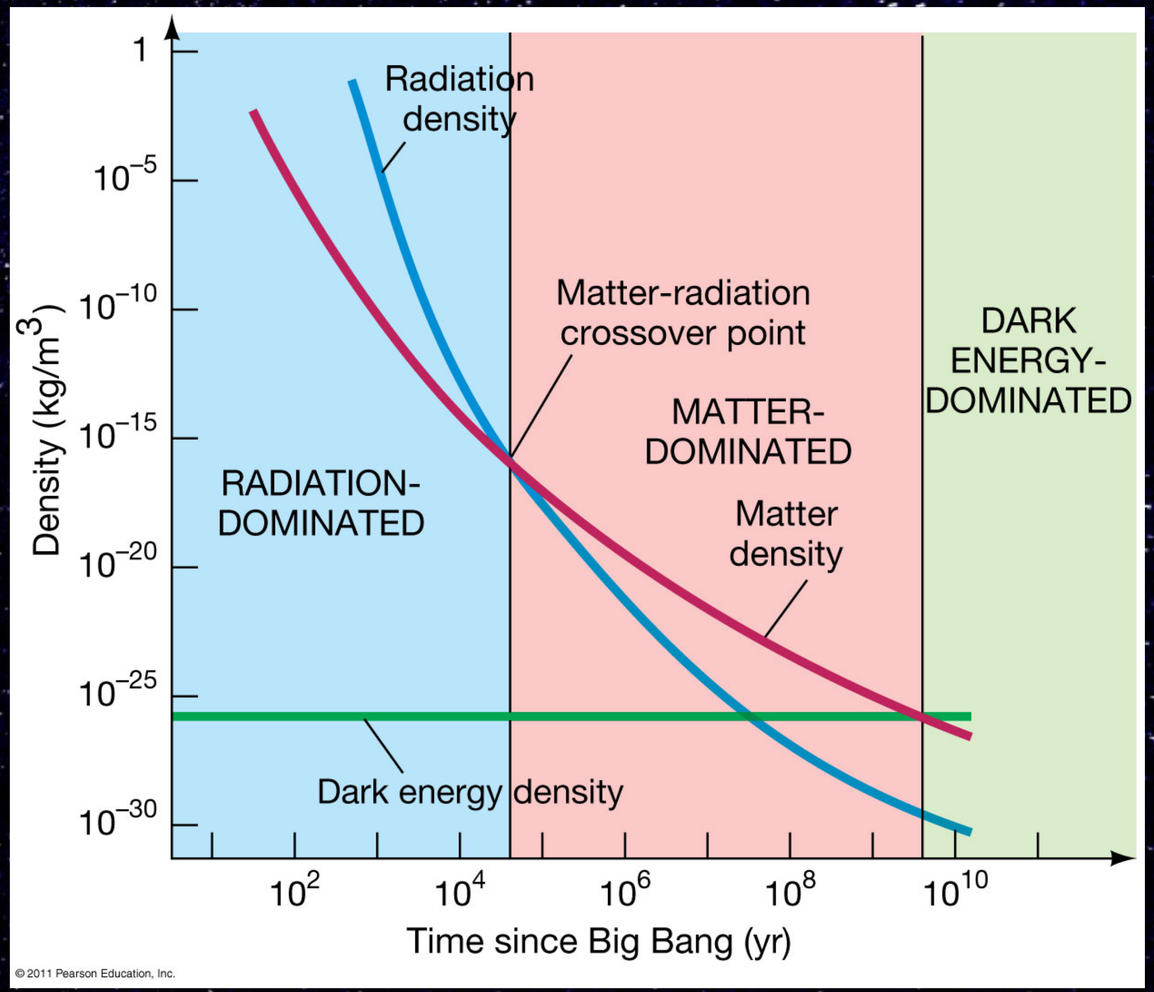
Hot early Universe

What happens to these photons during the expansion of the Universe?

Hot early Universe

What happens to these photons during the expansion of the Universe?

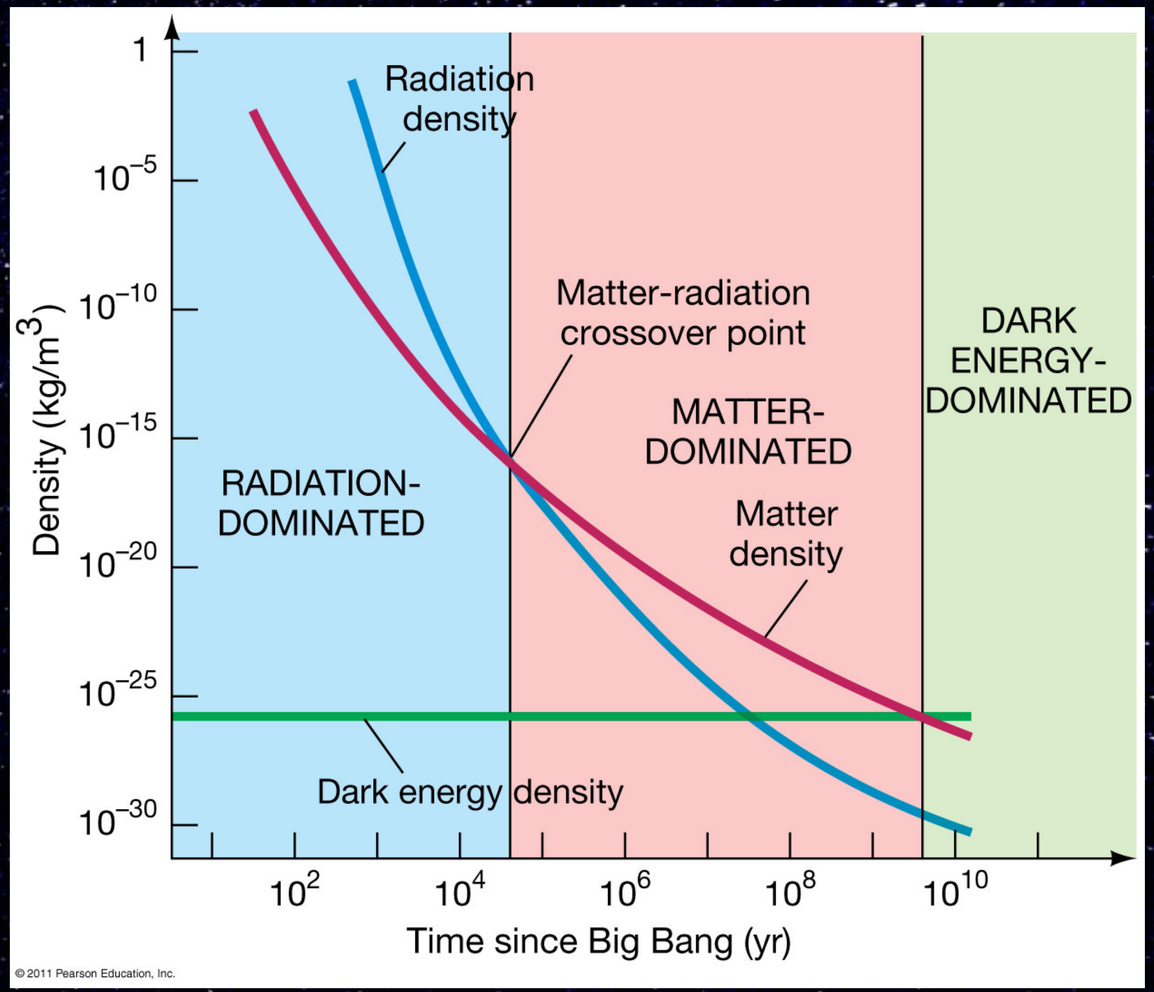
- They are still **around us**, 10^{10} relic photons per proton in the Universe
- Their energy density was **diluted** with the expansion of the Universe much faster than for matter



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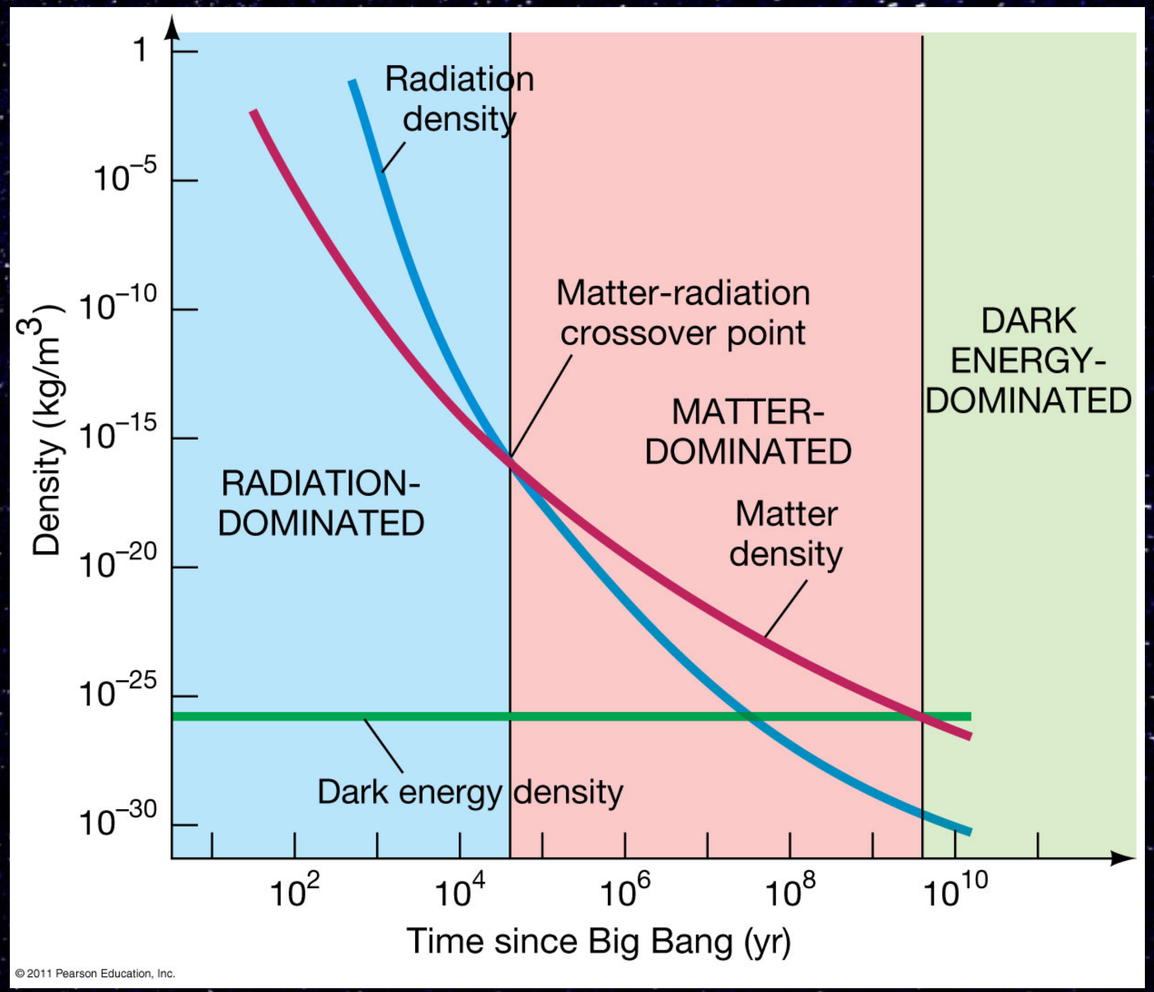
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Hot early Universe

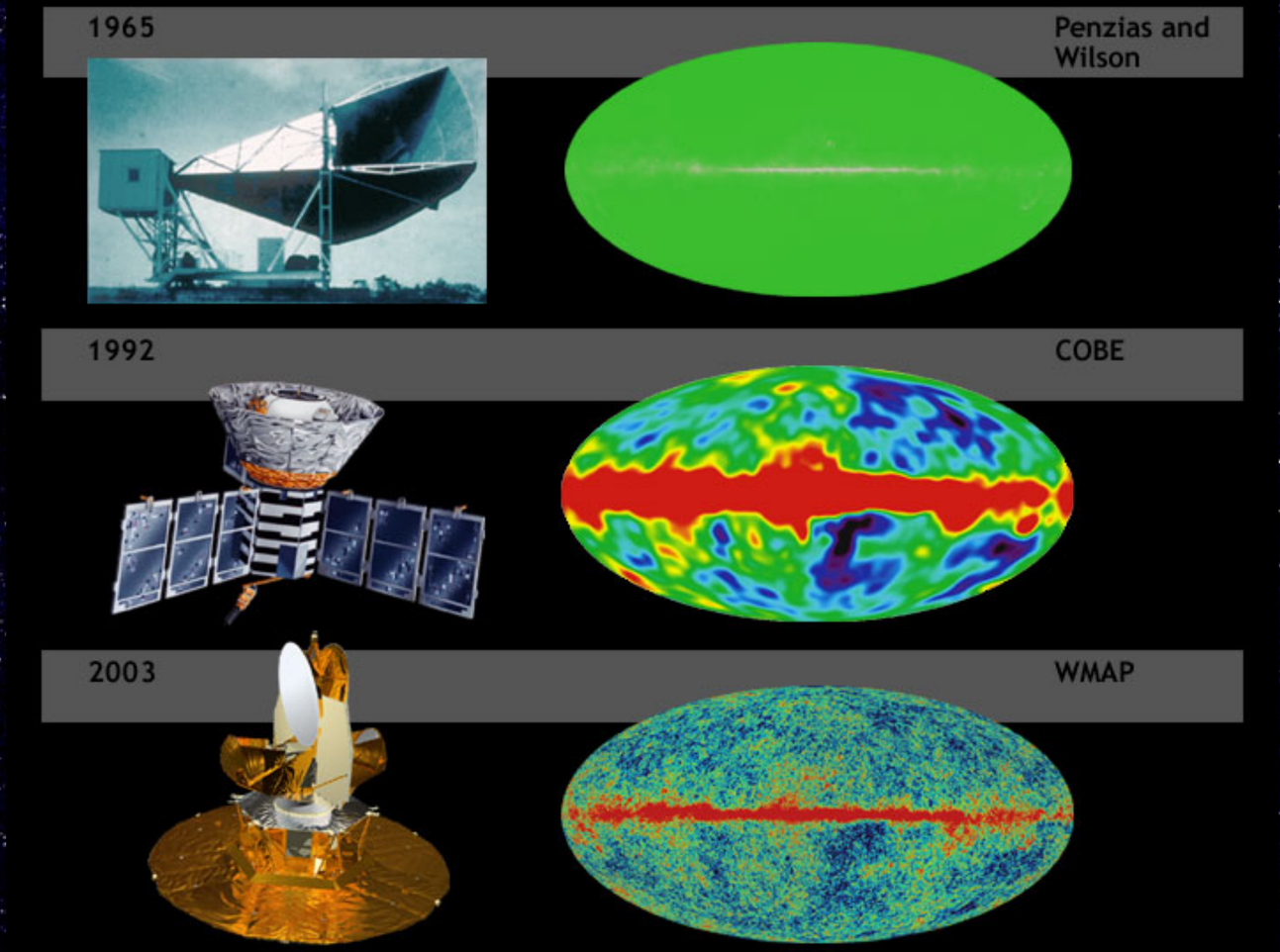
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- Nevertheless, we **managed to detect** and **study** them!



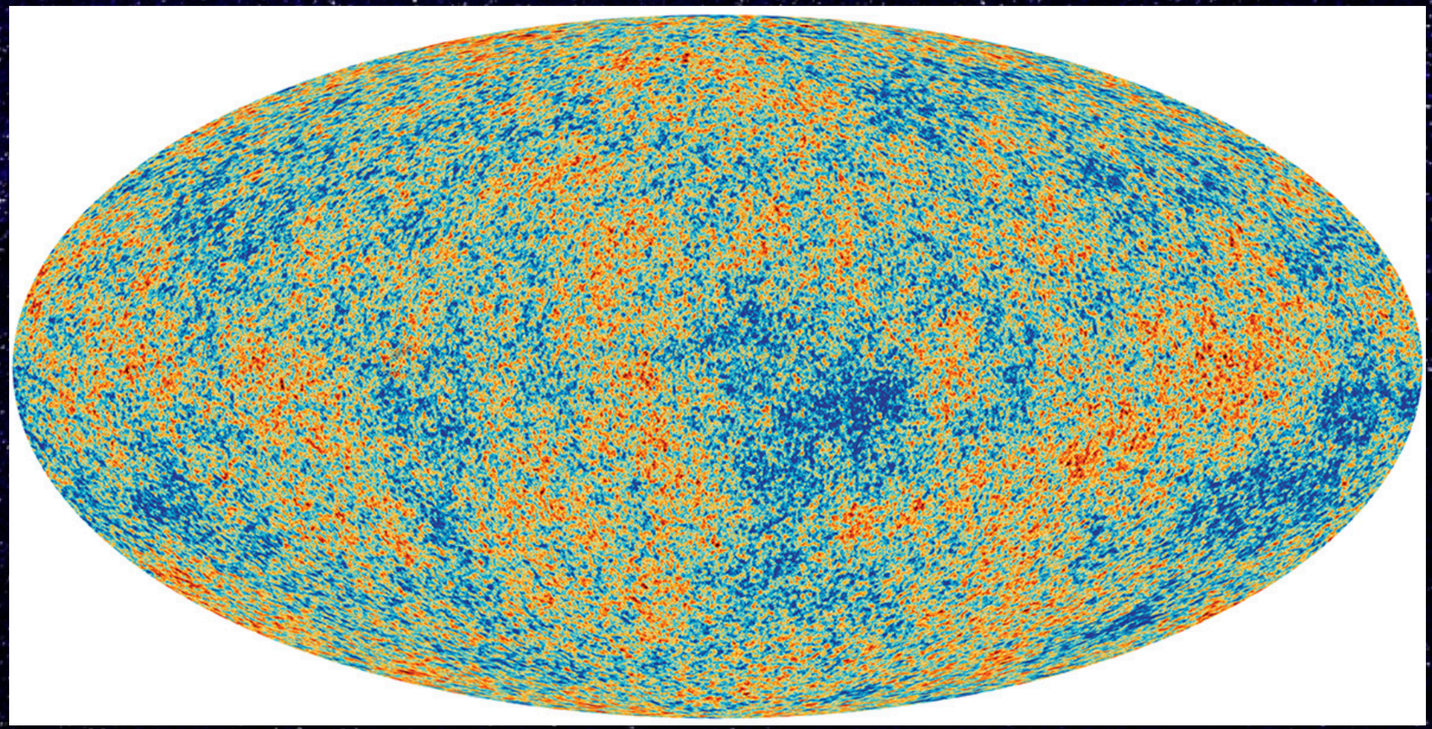
Big Bang predictions: CMB

We detected the **first relic** from the early Universe!



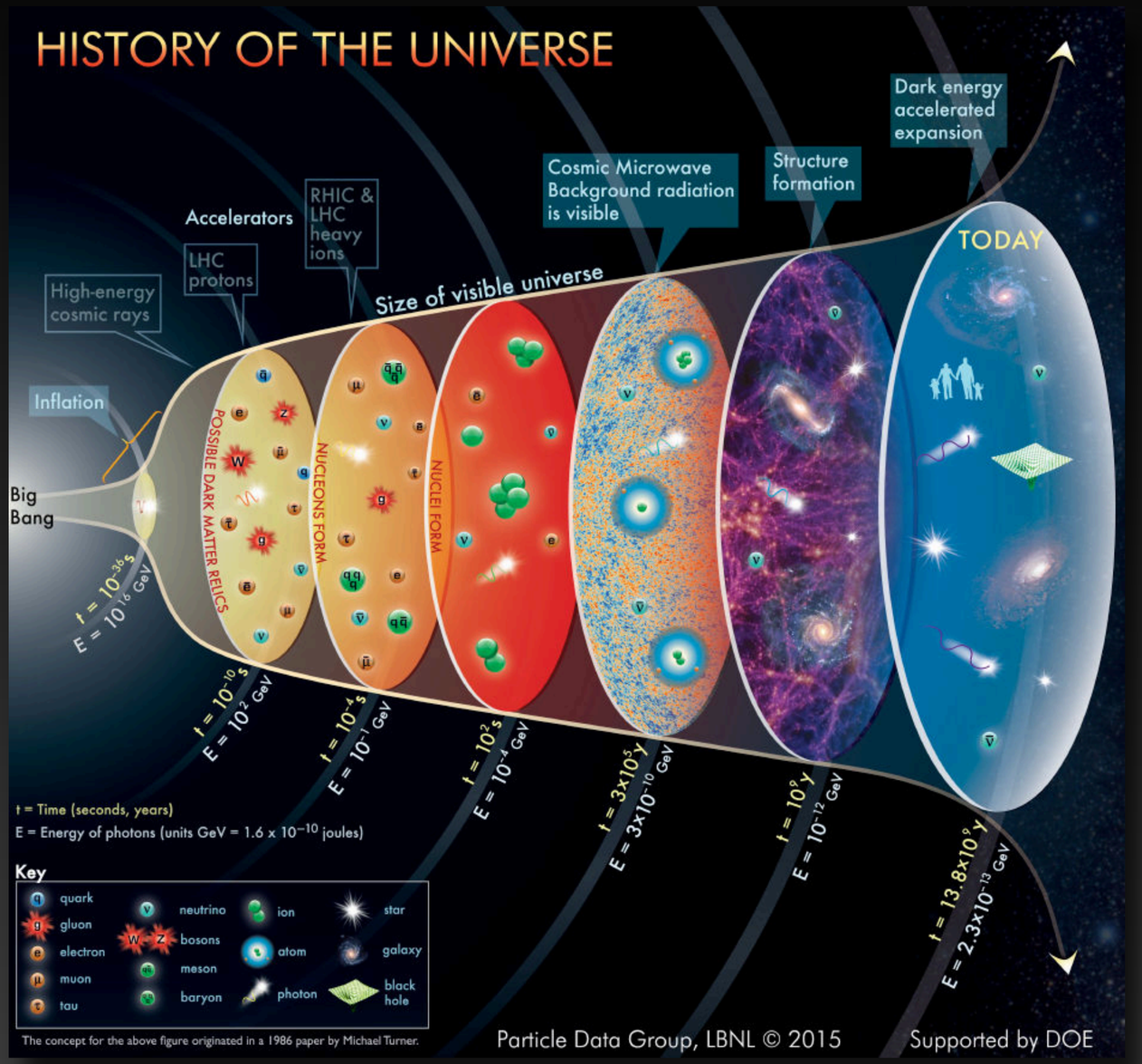
Big Bang predictions: CMB

The CMB tells us much about the early Universe



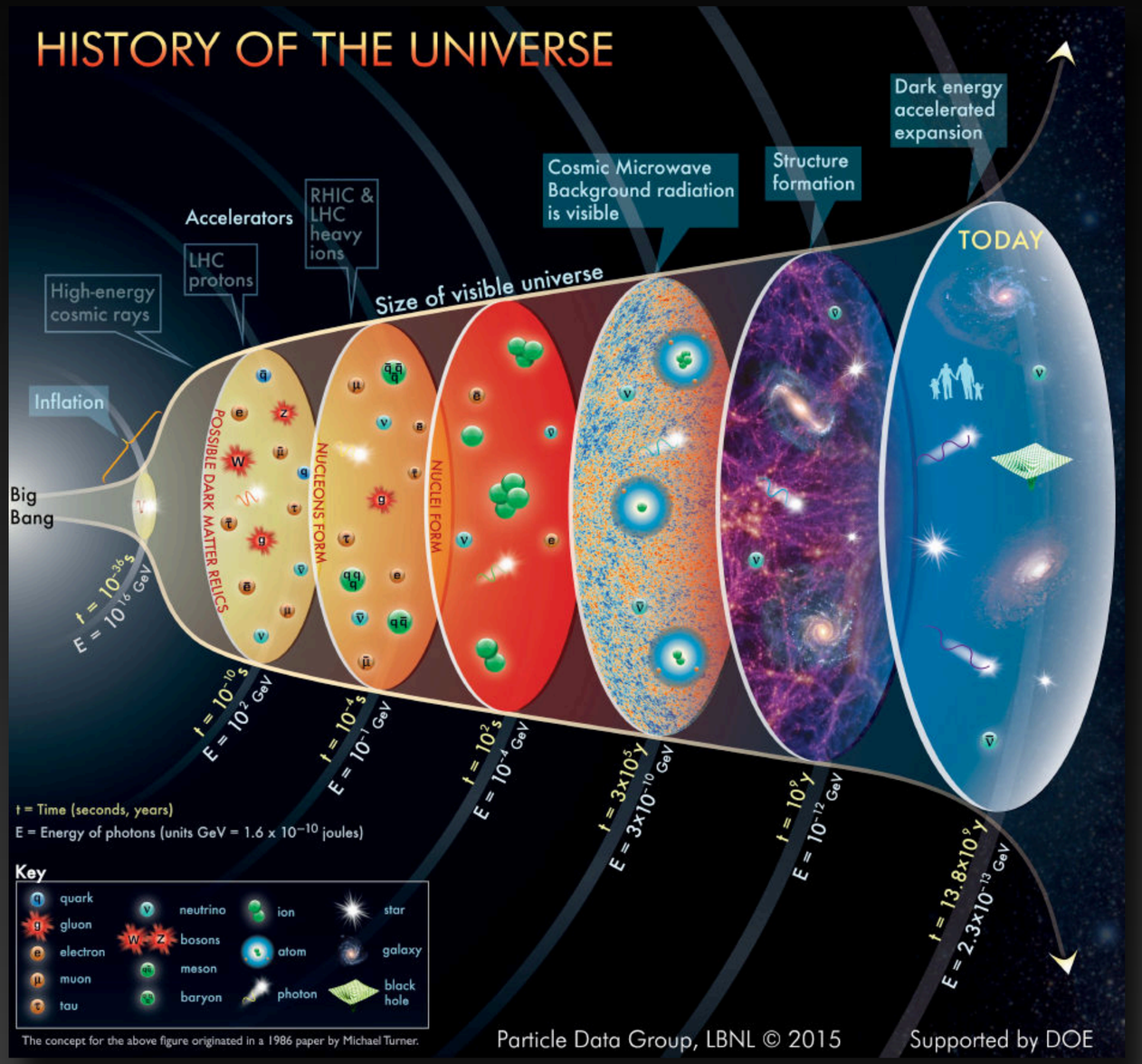
Credit: Planck Collaboration and ESA

New relics?


HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Cosmic Microwave Background radiation is visible
Structure formation
TODAY
Accelerators
RHIC & LHC heavy ions
LHC protons
High-energy cosmic rays
Size of visible universe
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^-36 s
E = 10^16 GeV
t = 10^-10 s
E = 10^2 GeV
t = 10^-4 s
E = 10^-1 GeV
t = 10^2 s
E = 10^-4 GeV
t = 3x10^5 y
E = 3x10^-10 GeV
t = 10^8 y
E = 10^-12 GeV
t = 13.8x10^9 y
E = 2.3x10^-13 GeV
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6 x 10^-10 joules)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
The concept for the above figure originated in a 1986 paper by Michael Turner.
Particle Data Group, LBNL © 2015
Supported by DOE

New relics?

We would like to probe the Universe from **much earlier epochs** (1<s)

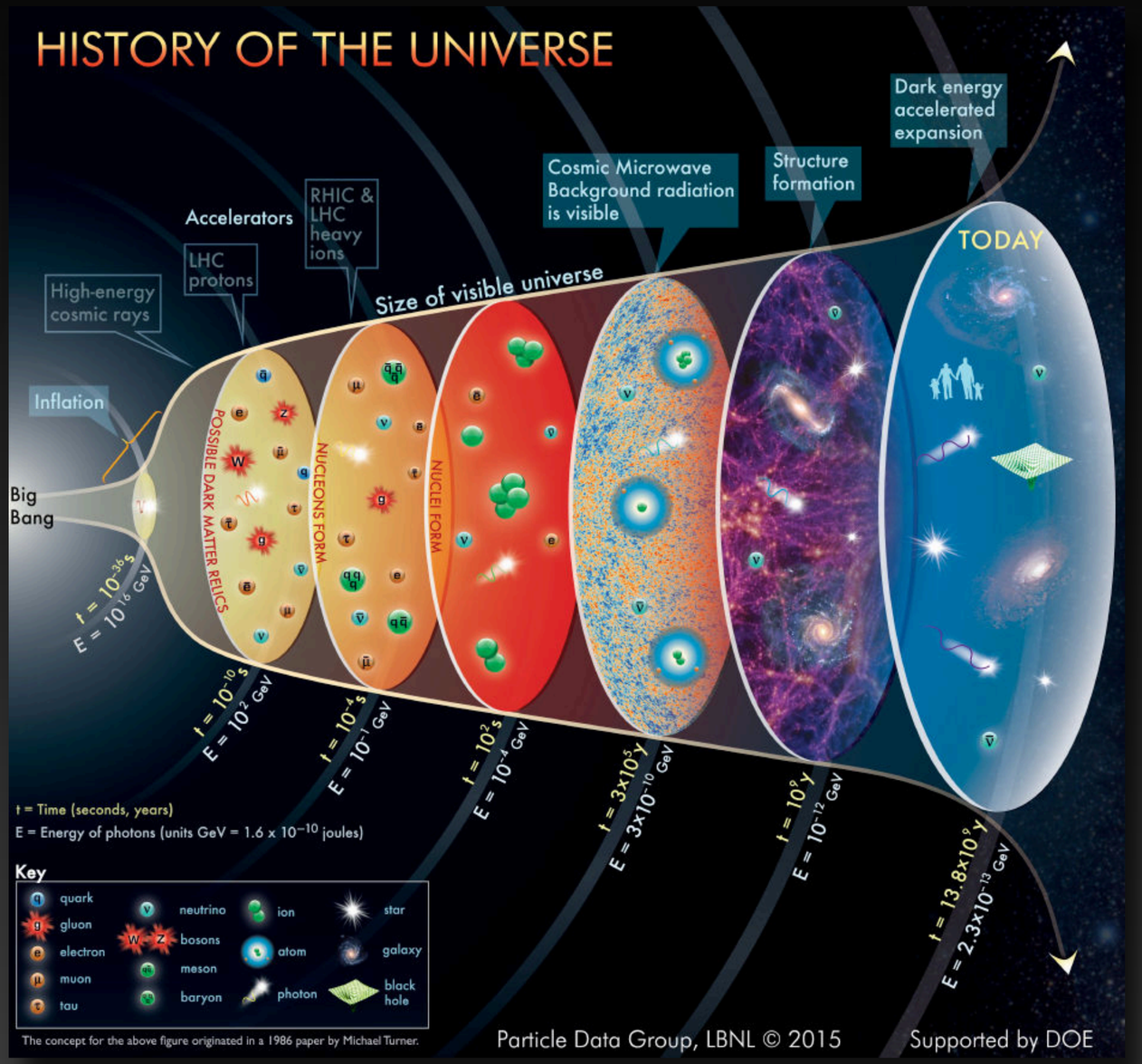


New relics?

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There are other potential messengers from the early Universe:

- Cosmic Neutrino Background

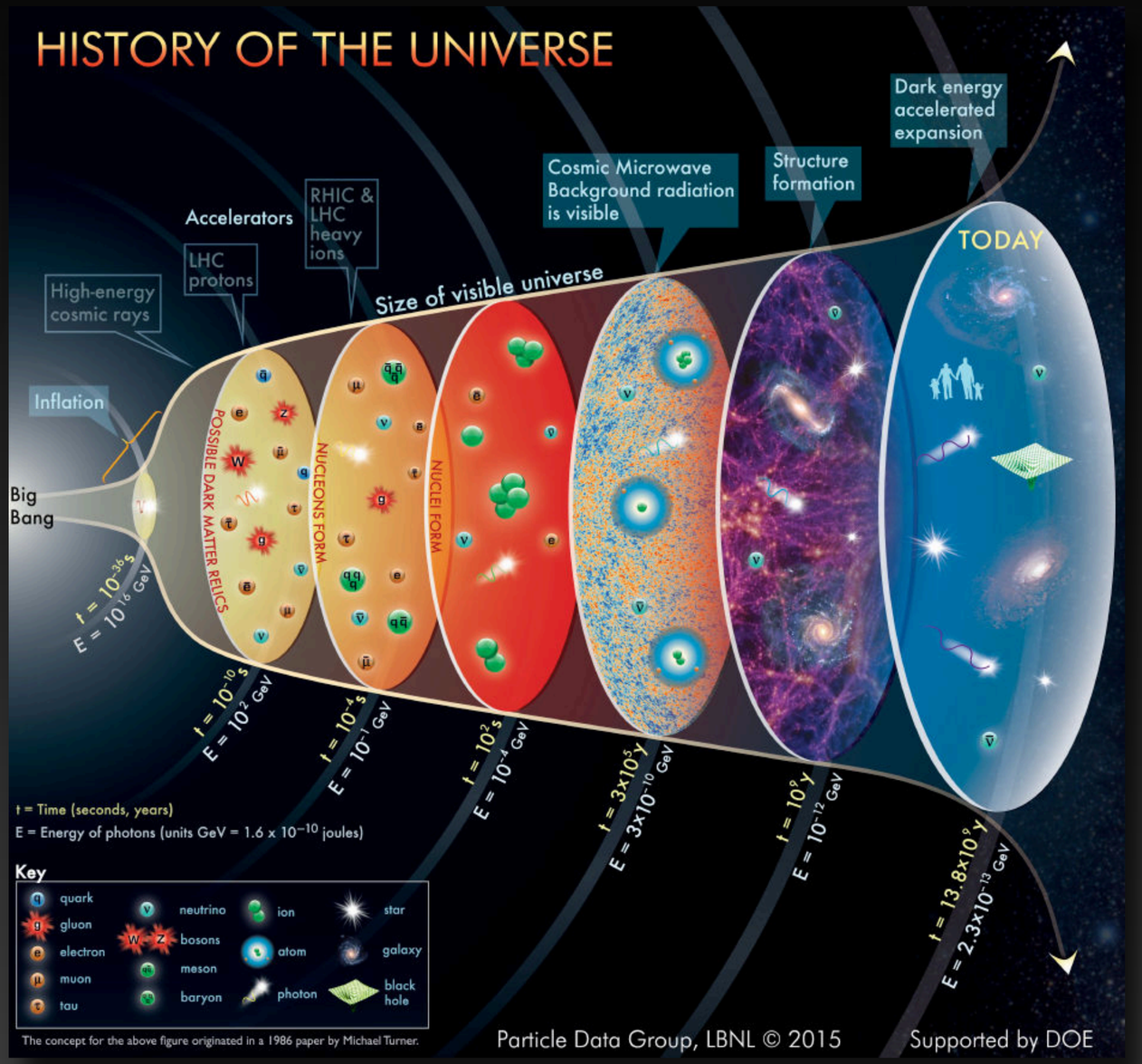


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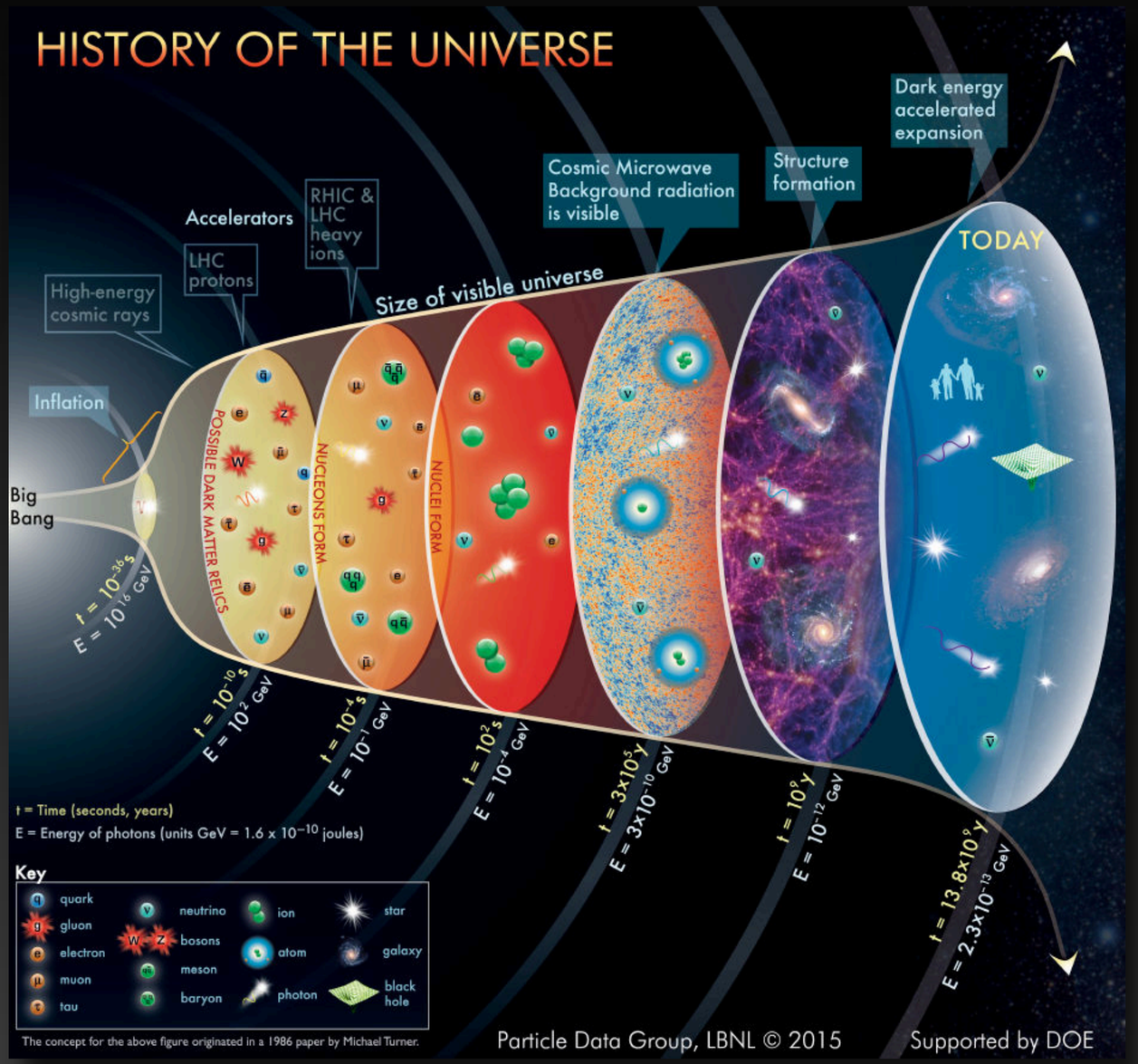


New relics?

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There are other potential messengers from the early Universe:

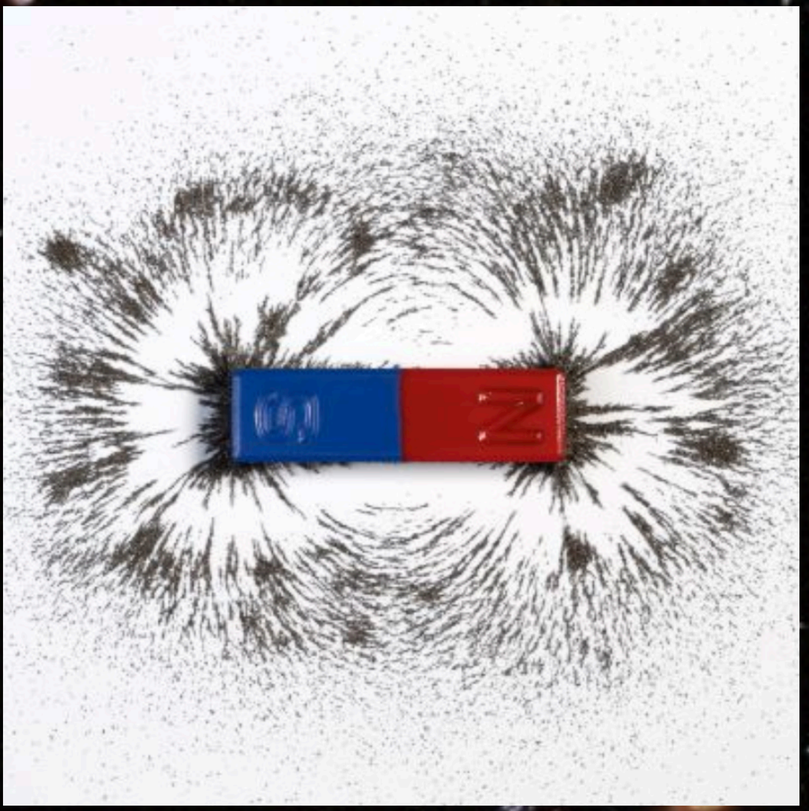
- Cosmic Neutrino Background
- Primordial gravitational waves?
- **Primordial magnetic fields?**



Man-made magnetic fields

Typical magnets

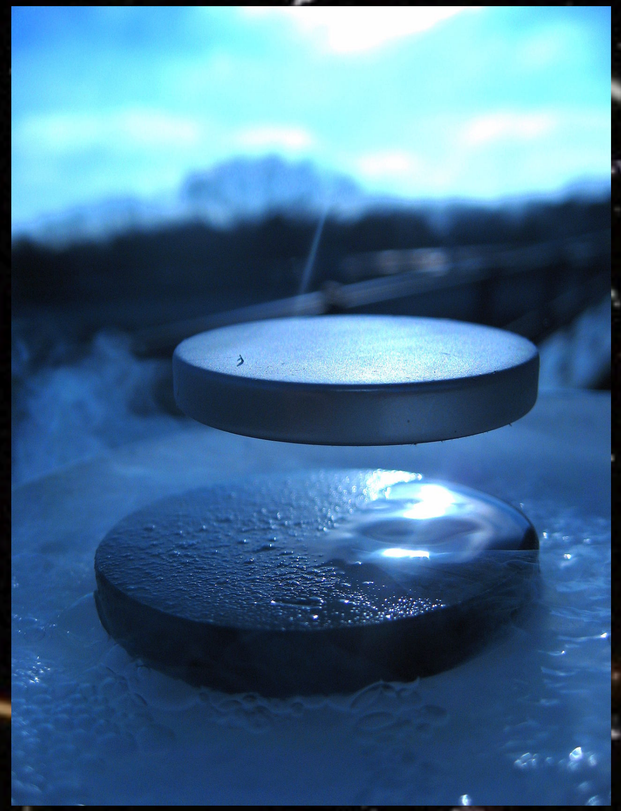
Credit: usmagnetix.com



~50 - 100 G

Industrial

Credit: Wikipedia



~ 10,000 - 50,000 G

LHC

Credit: CERN

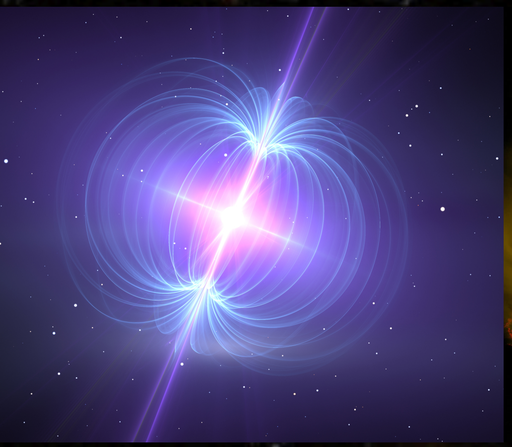


~ 100,000 G

Magnetic fields in the Universe

Pulsars

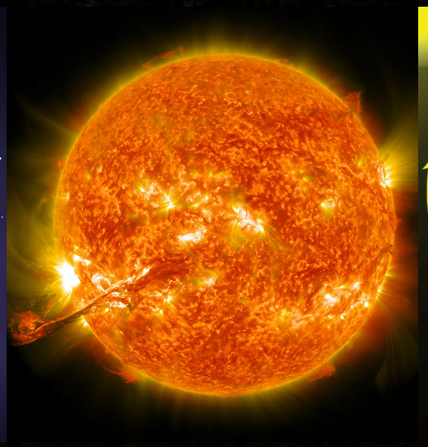
Credit: quantamagazine



$\sim 10^{12} - 10^{15}$ G

Stars

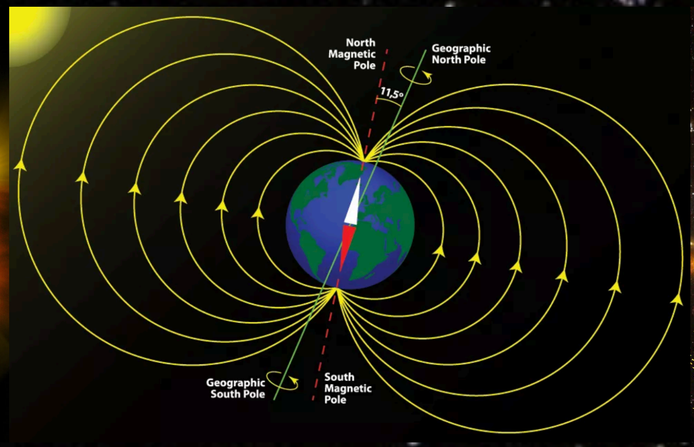
Credit: NASA



~1 - 100 G

Planets

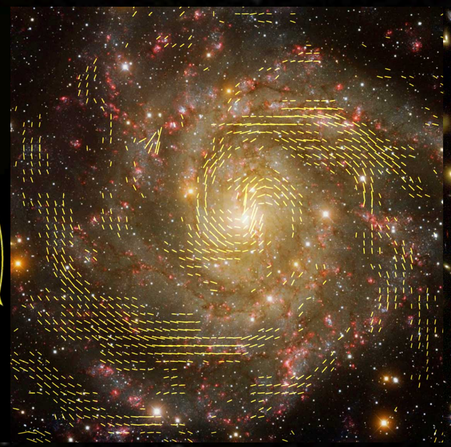
Credit: shutterstock.com



~0.1 - 10 G

Galaxies

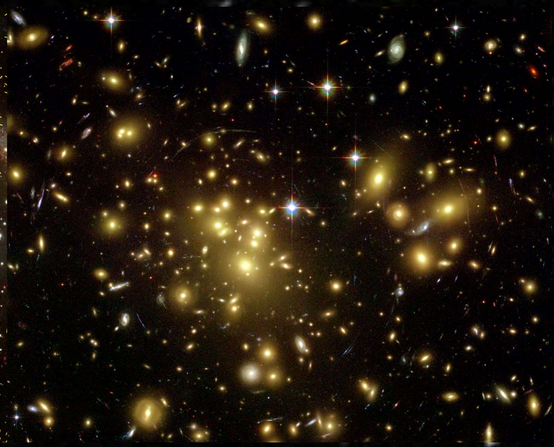
Credit: Beck, NSF



~1 μG - 0.1 mG

Galaxy clusters

Credit: NASA

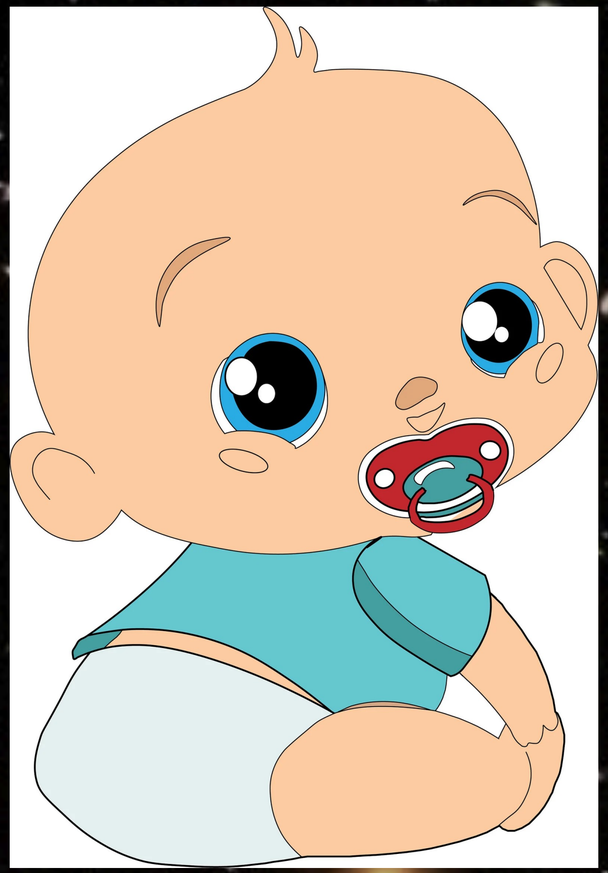


~0.1 - 10 μG

Magnetic fields in structures

In order to create e.g. galactic magnetic fields, we need some **seed magnetic field**

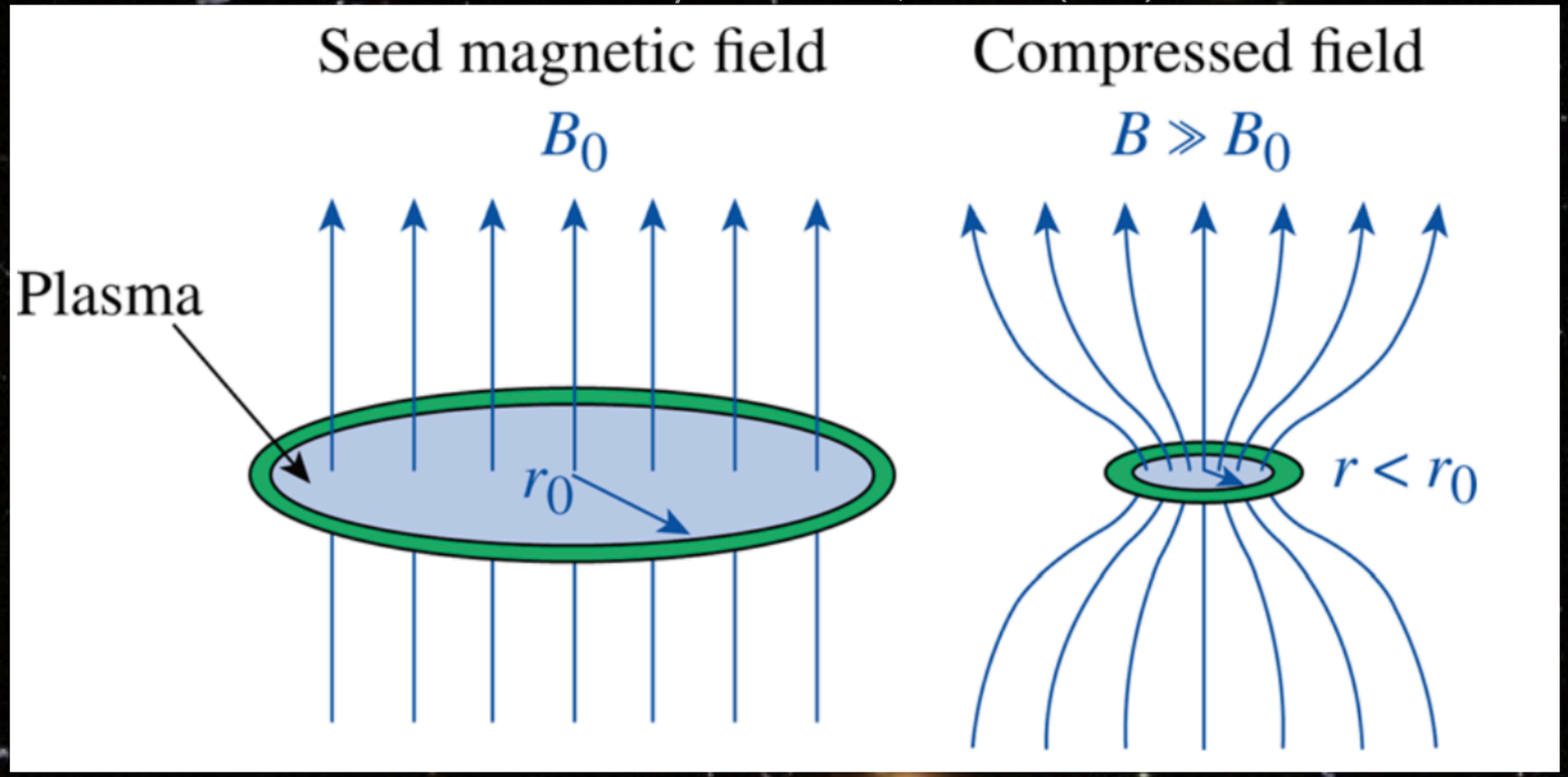
Credit: etsy.com



Magnetic fields in structures

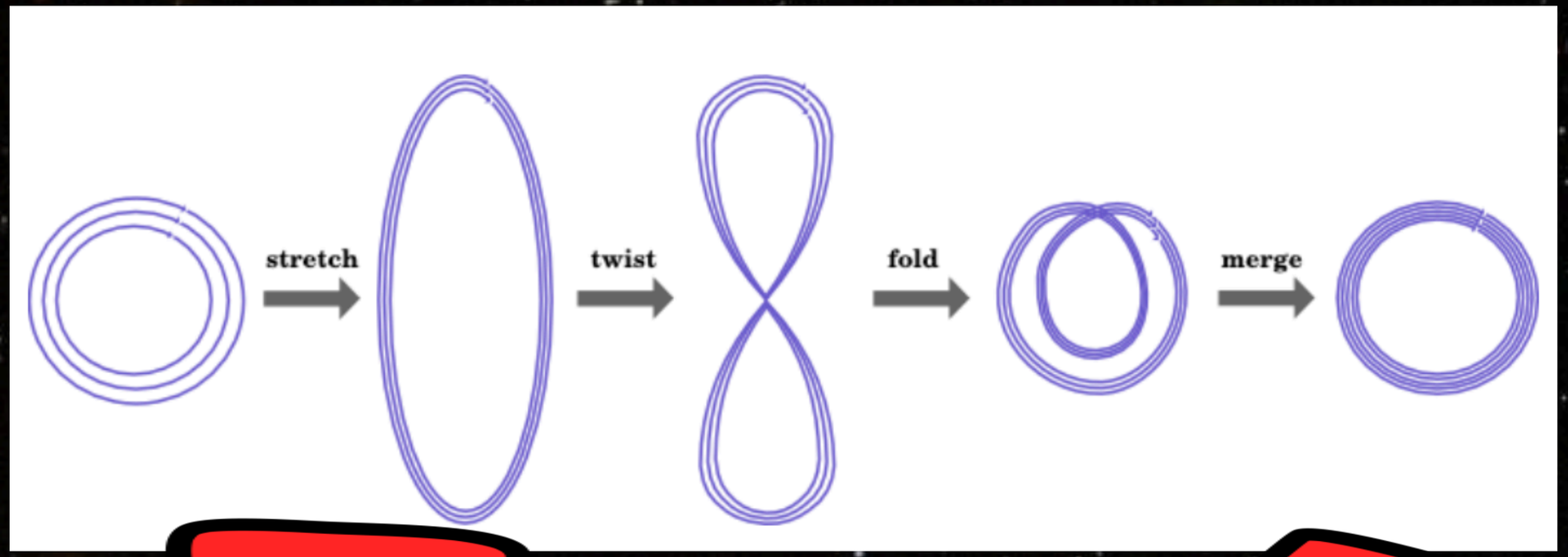
Magnetic fields in collapsed structures were <u>contracted</u> during structure formation

Credit: Phys. Plasmas 19, 056306 (2012)



Magnetic fields in structures

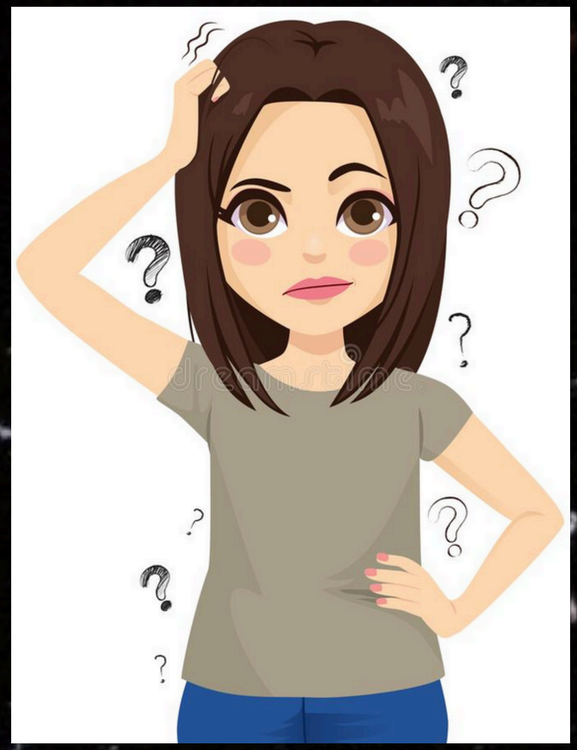
and exponentially **amplified** by turbulent dynamos



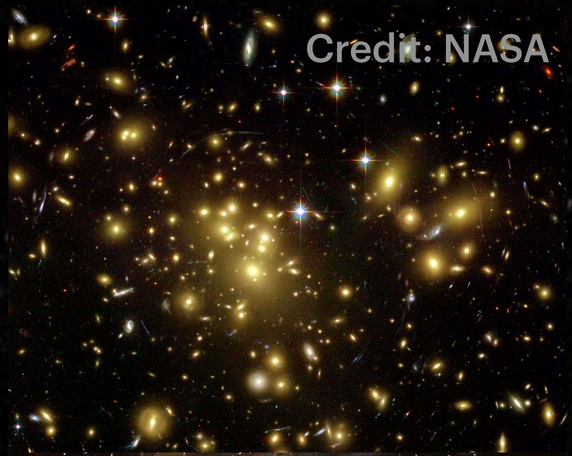
Credit: J. Schober

Magnetic fields in structures

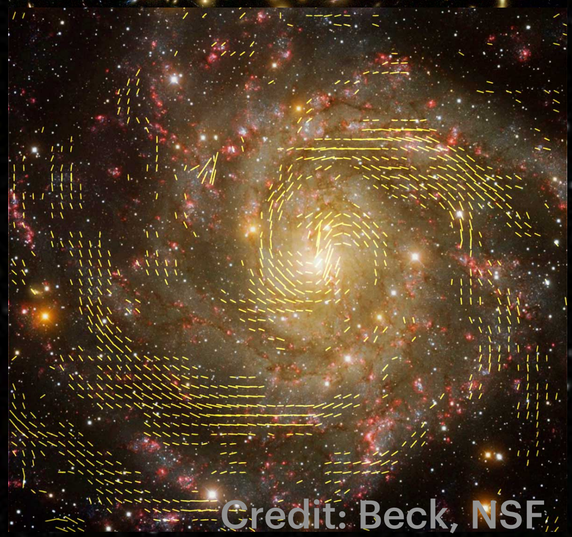
Magnetic fields in collapsed structures “**forget**” their initial conditions



Credit: dreamstime.com



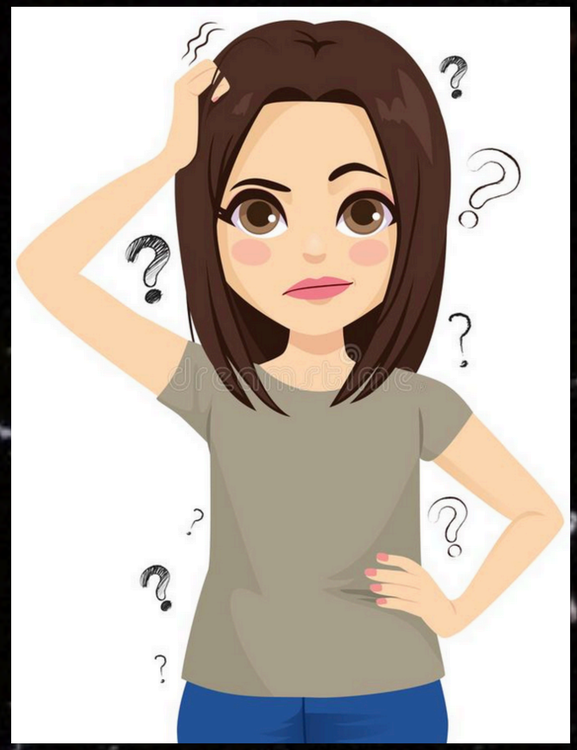
Credit: NASA



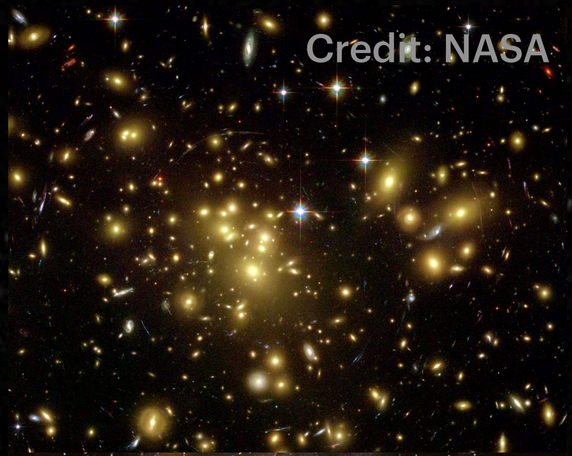
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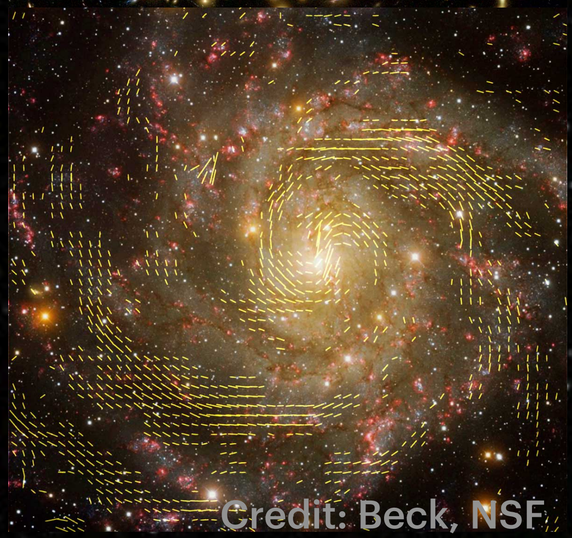
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Credit: NASA

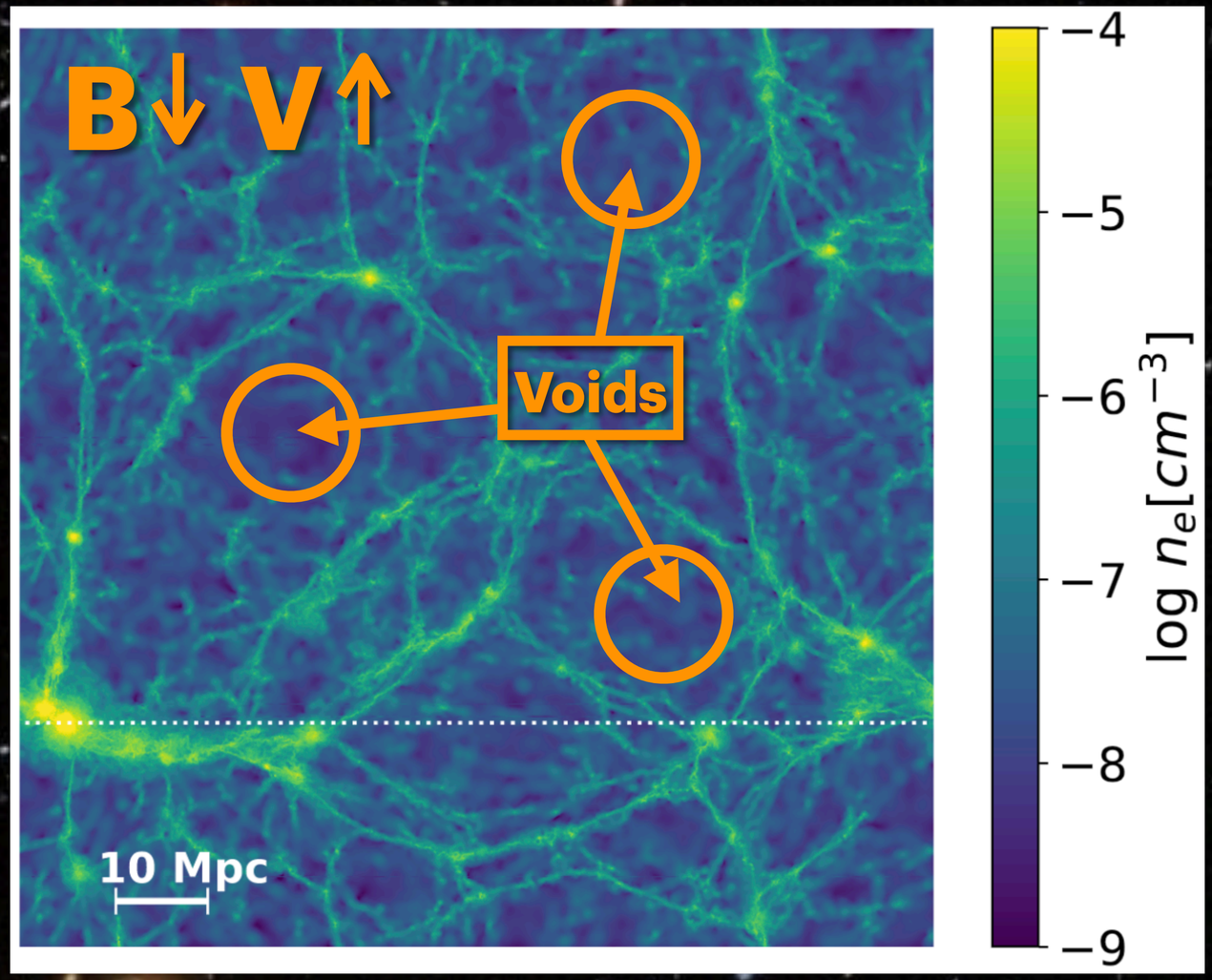


Credit: Beck, NSF

How can we study the primordial magnetic fields?

Searching for primordial MF

- **Intergalactic magnetic fields in voids** (IGMF) should be **very close** to the **initial conditions** (if they exist) and could come from the early Universe

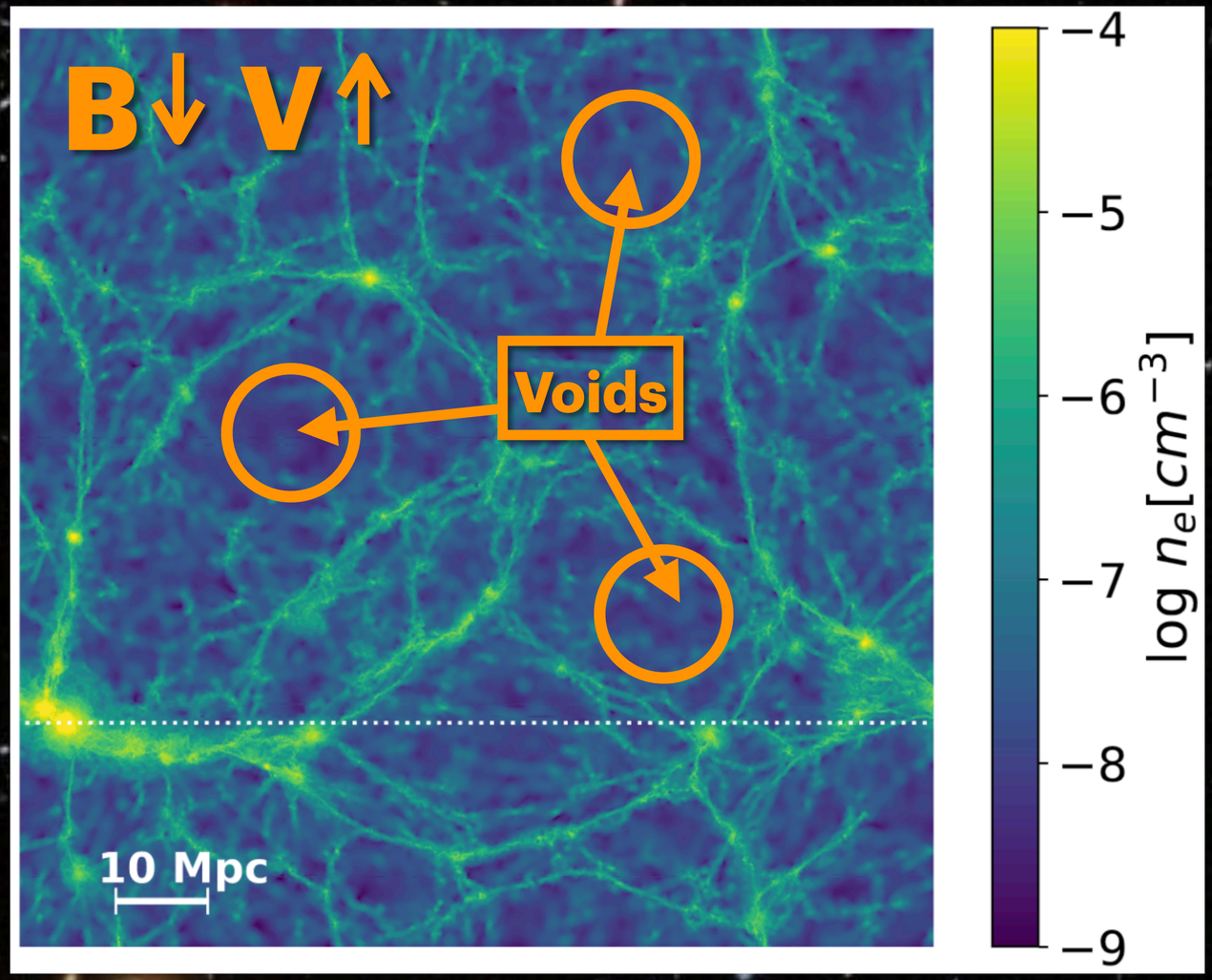


[A. Aramburo-Garcia, AS et al., JCAP, 2020]

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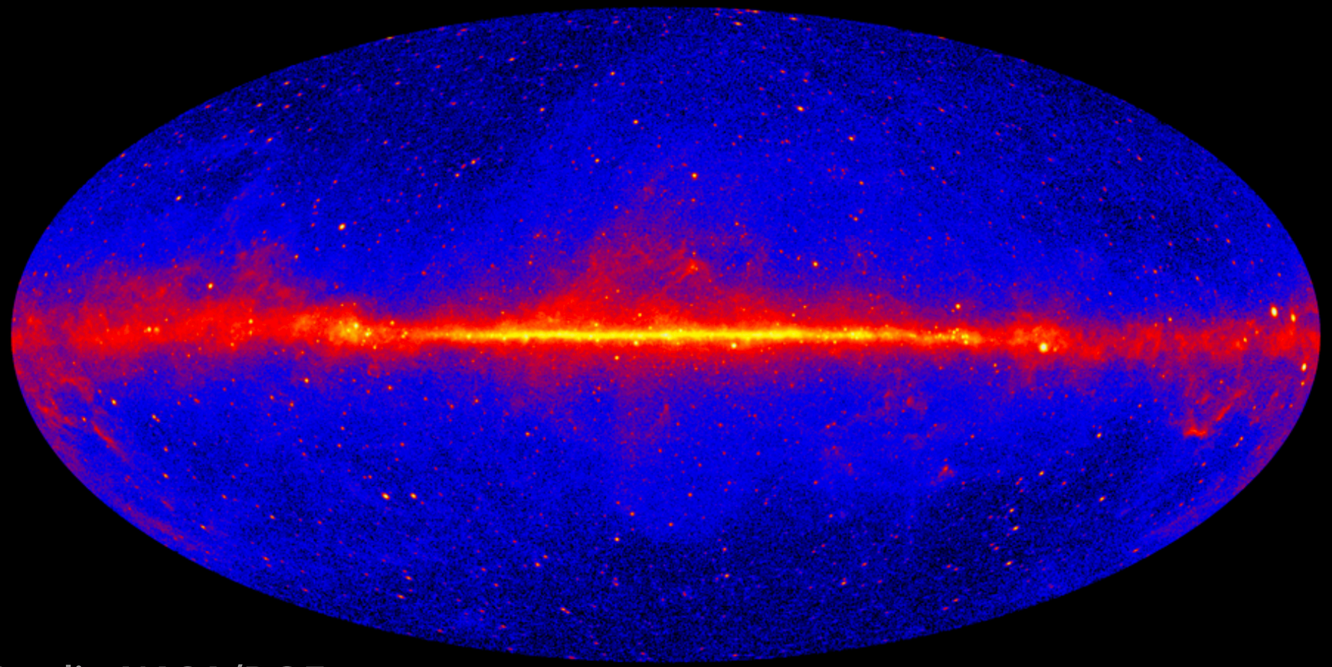
How to measure the IGMF?



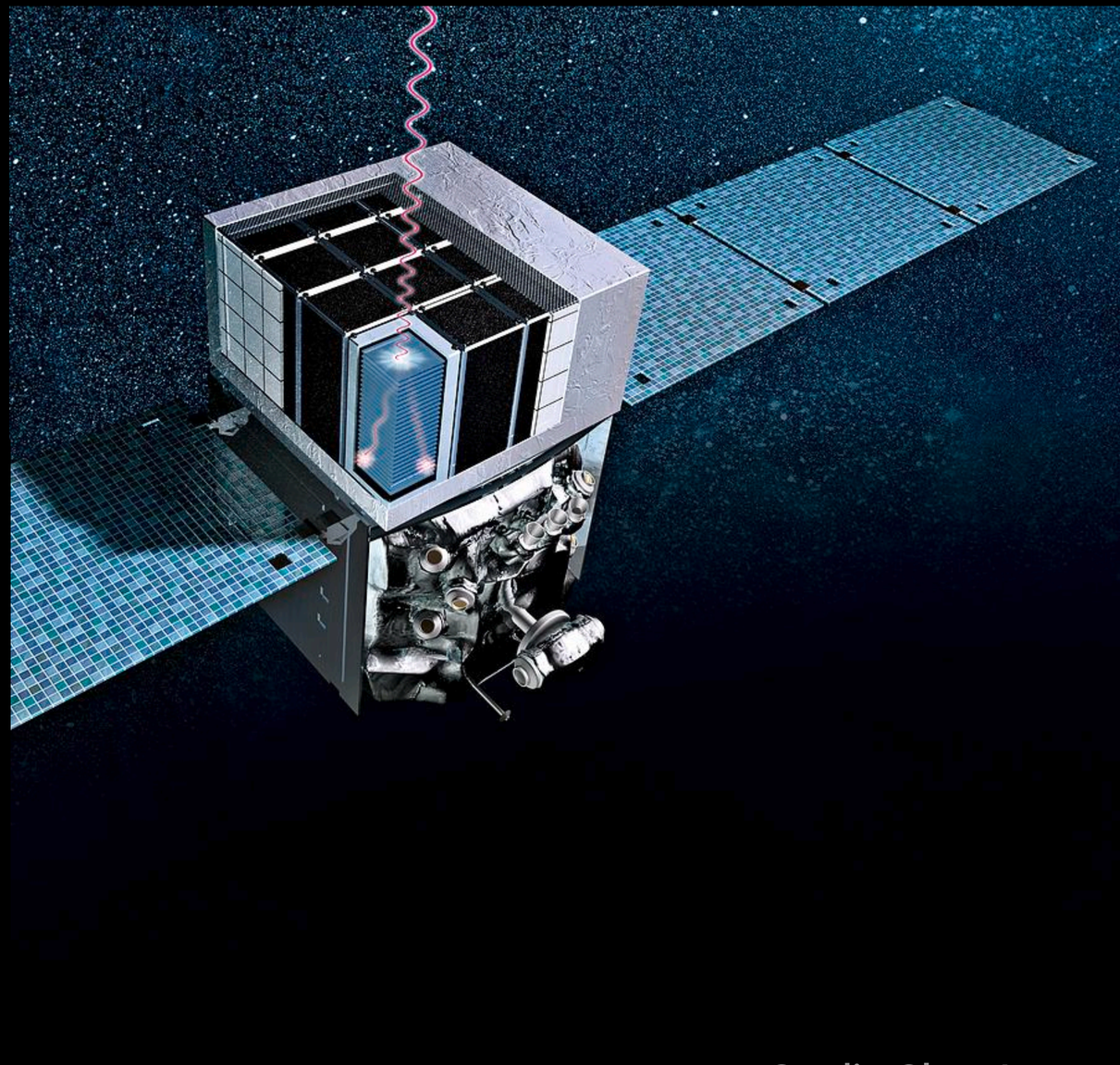
[A. Aramburo-Garcia, AS et al., JCAP, 2020]

Space-based telescopes

High-energy photons produce **showers** (cascades) of relativistic particles interacting with a medium



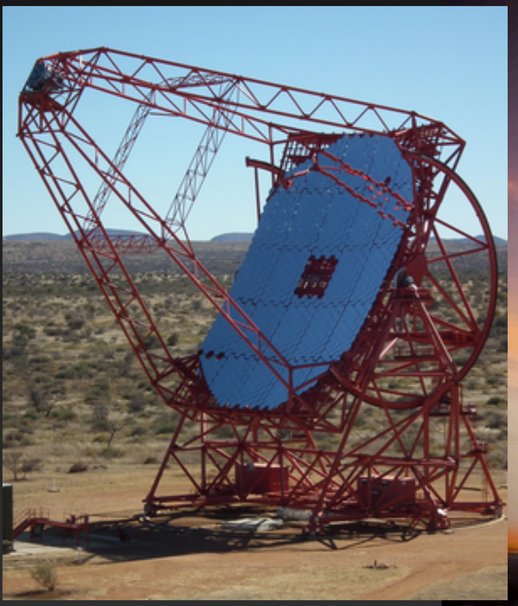
Credit: NASA/DOE



Credit: Claus Lunau

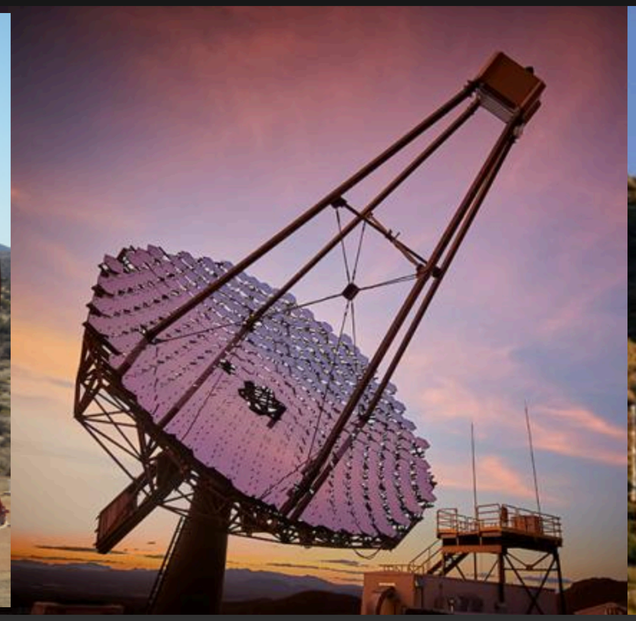
Main ground-based γ-ray telescopes

HESS



Credit: mpi-hd.mpg.de

VERITAS



Credit: CfA/Rick Peterson

MAGIC



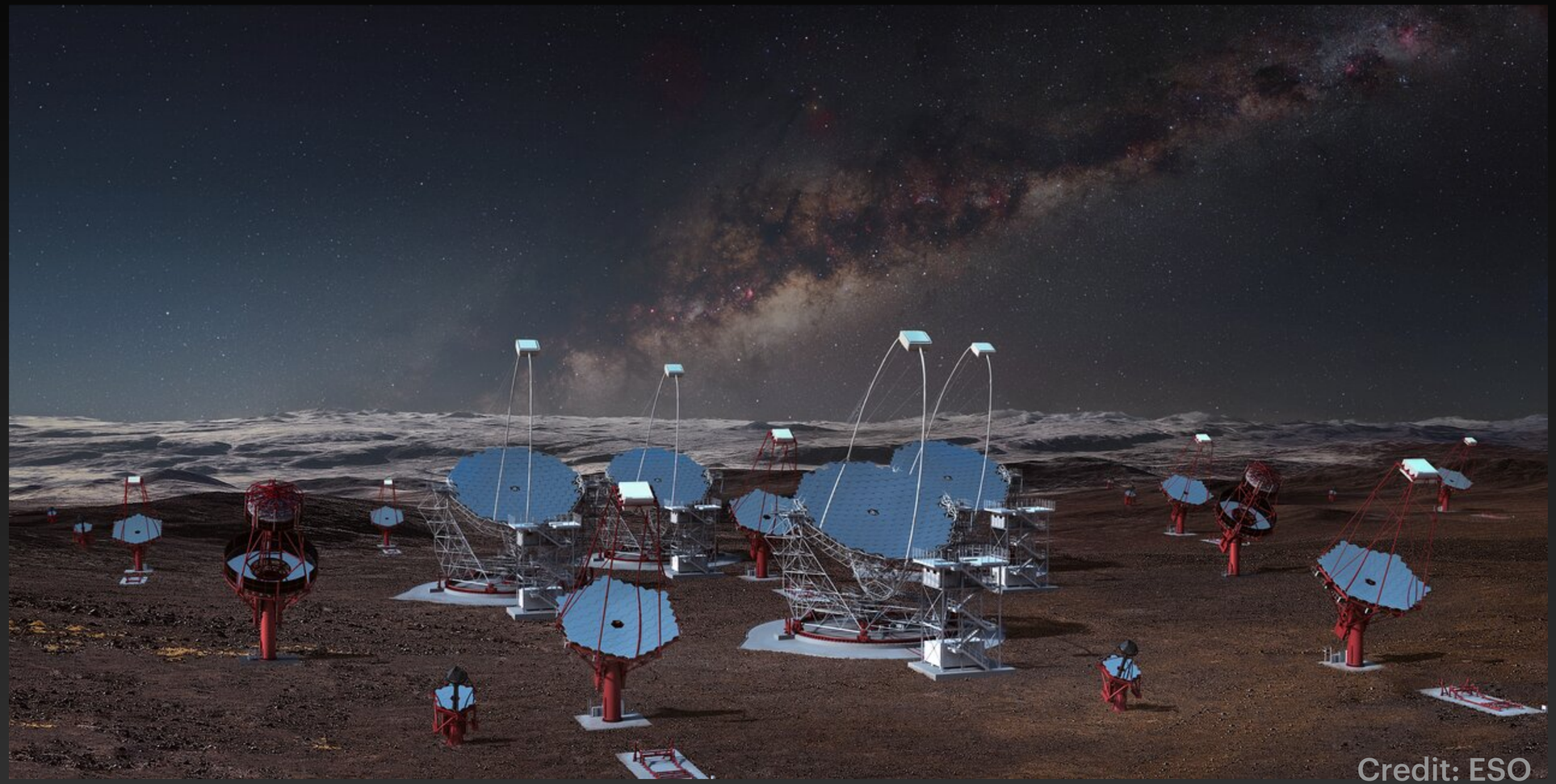
Credit: R. Wagner

HAWC



Credit: HAWC

Future ground-based γ-ray telescopes

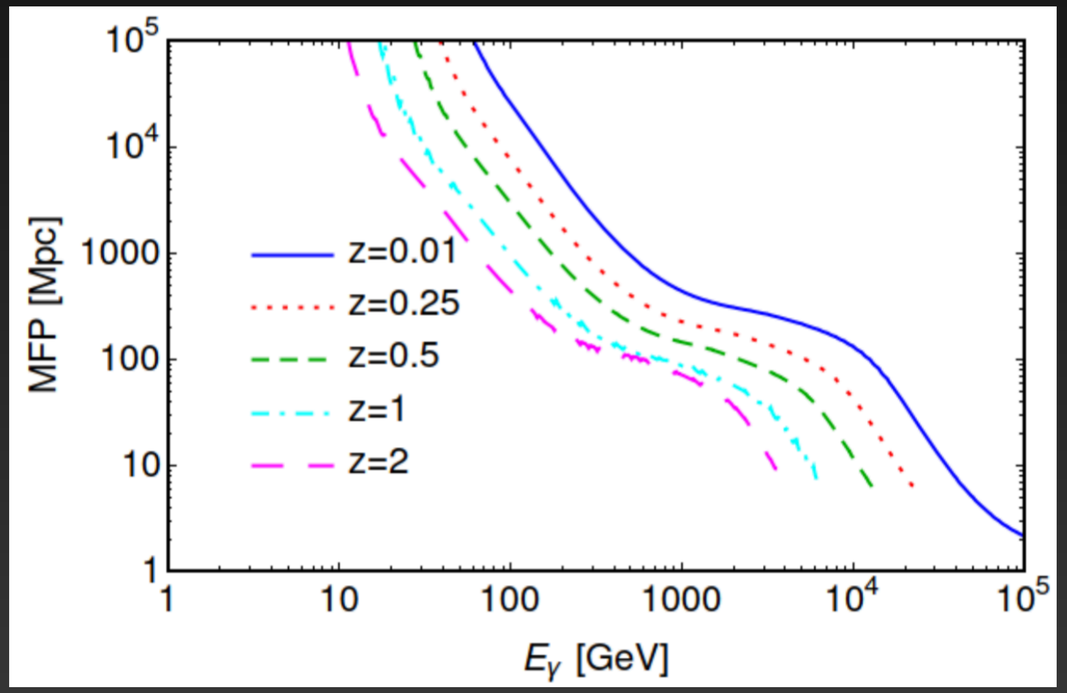


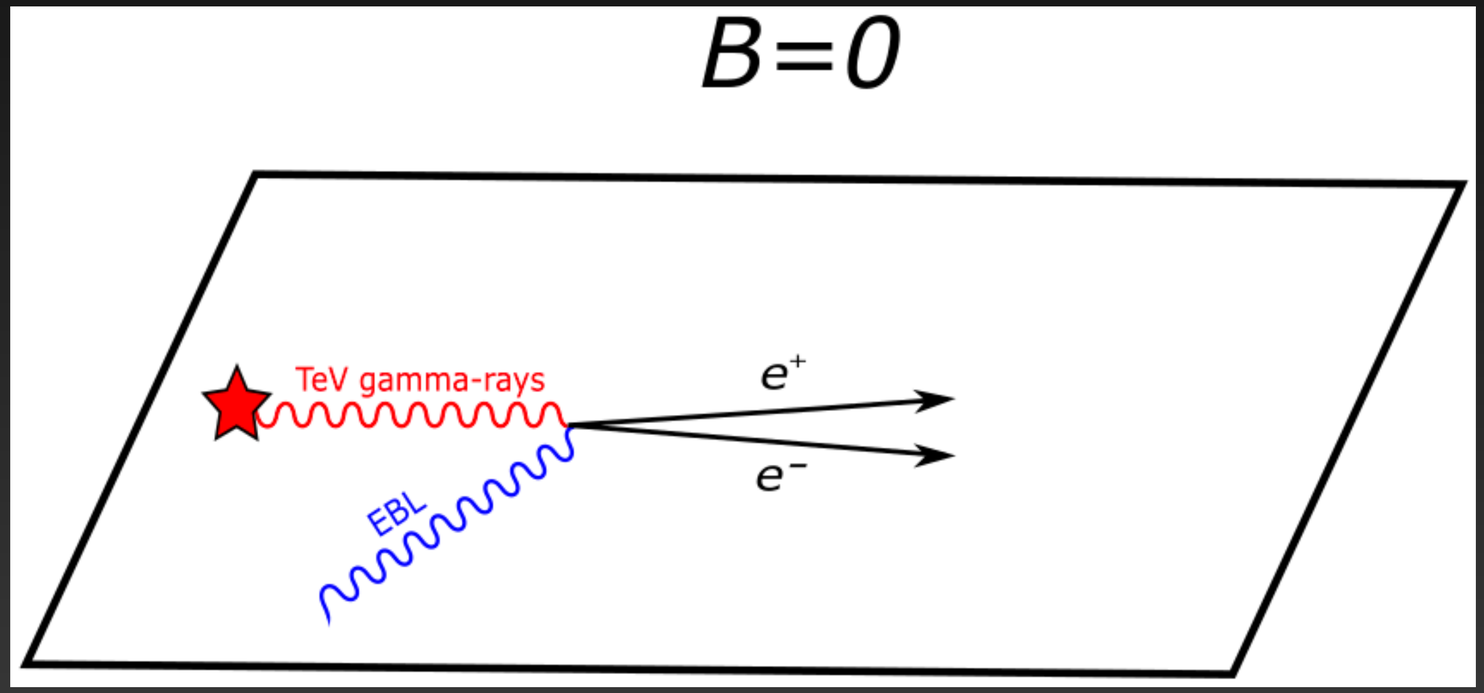
The Cherenkov Telescope Array (CTA) will soon become the **new flagship** of γ-ray astronomy

How to measure the IGMF?

Secondary emission: prediction

Our Universe is **not transparent** for TeV photons: they can interact with EBL photons and create an **electron-positron** pair





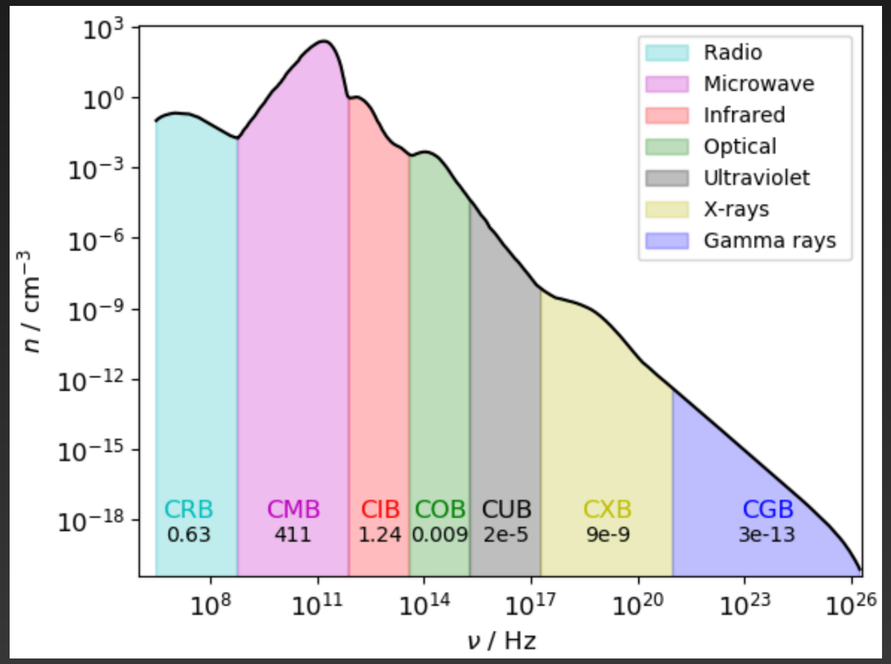
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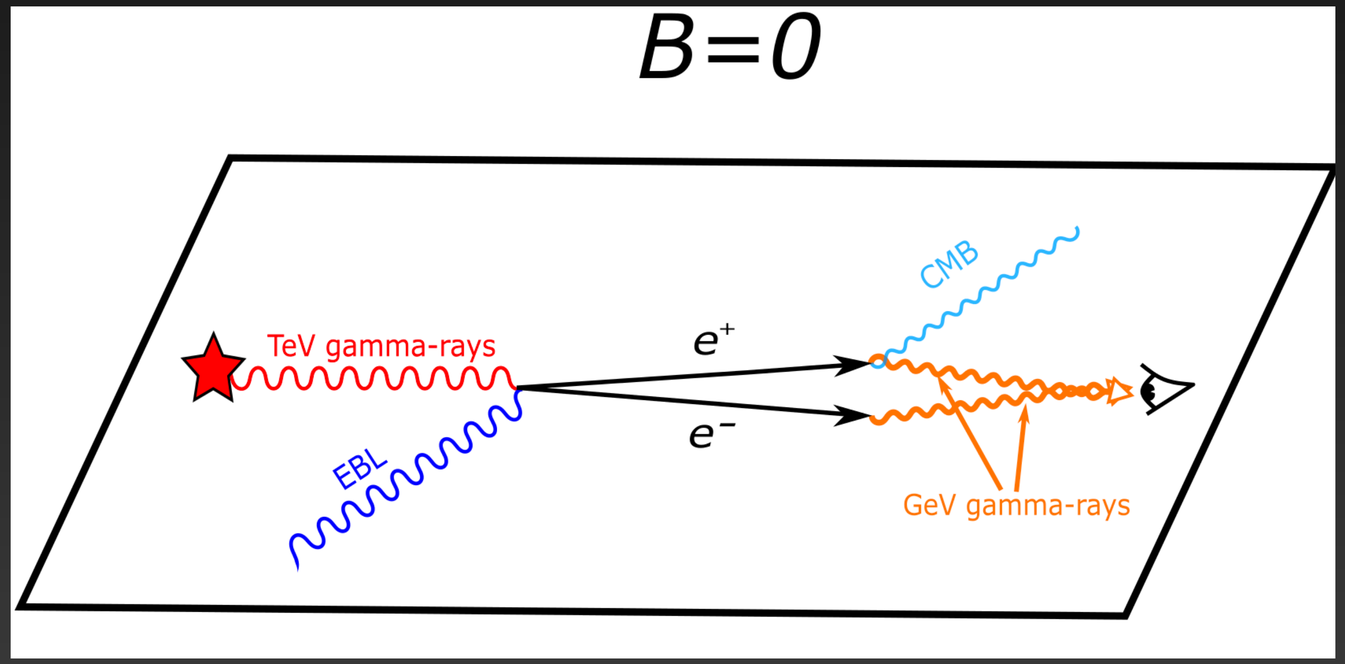
Secondary emission: prediction

Charged particles interact with CMB photons via the inverse Compton effect.

This results in the production of GeV photons propagating in the

same direction as the original TeV photons

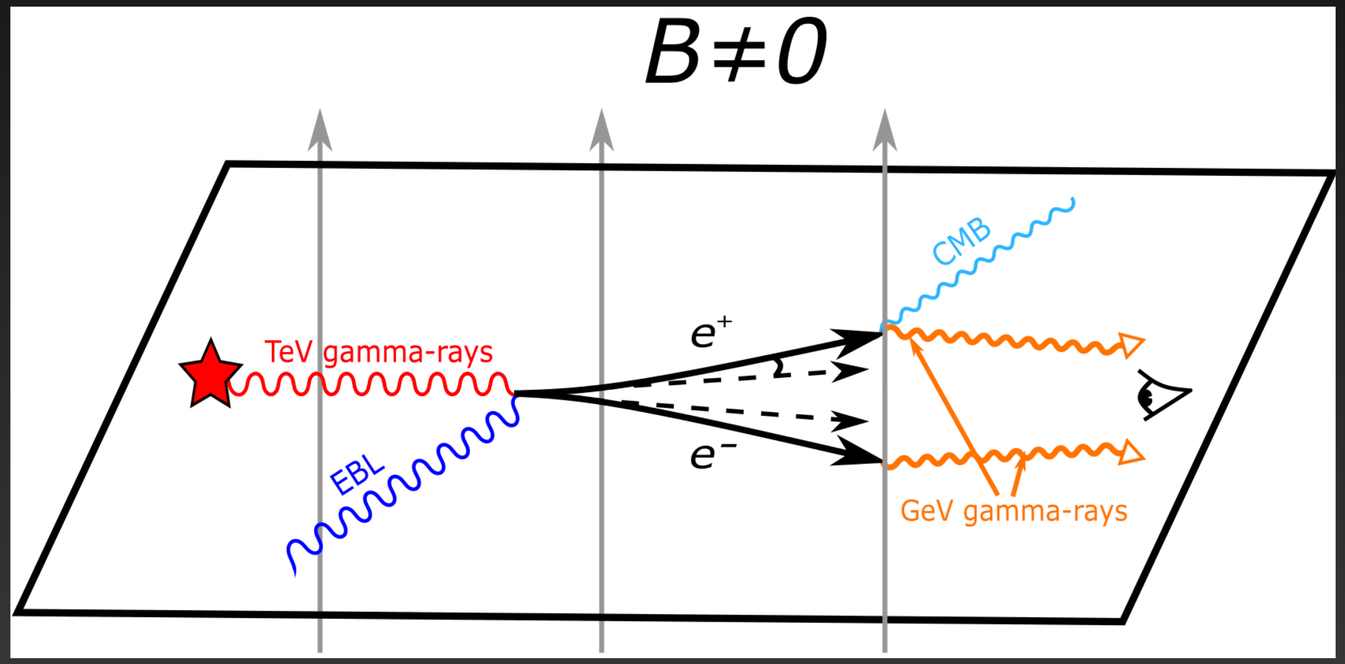




How to measure the IGMF?

Secondary emission: prediction

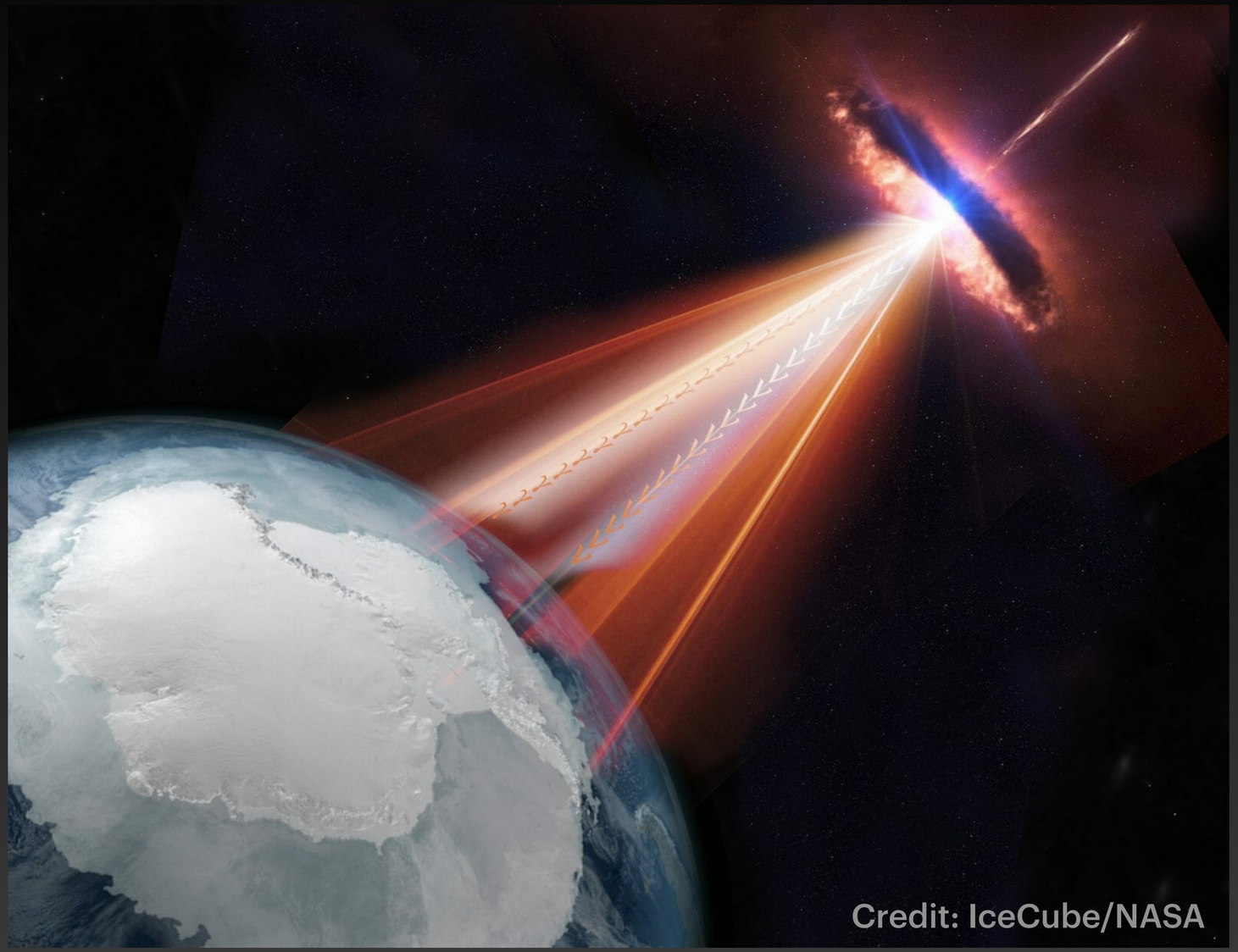
However, if there is a **magnetic field** in between, e^+/e^- will be deflected and **GeV photons** might create an extended emission around TeV point sources



How to measure the IGMF?

Blazars

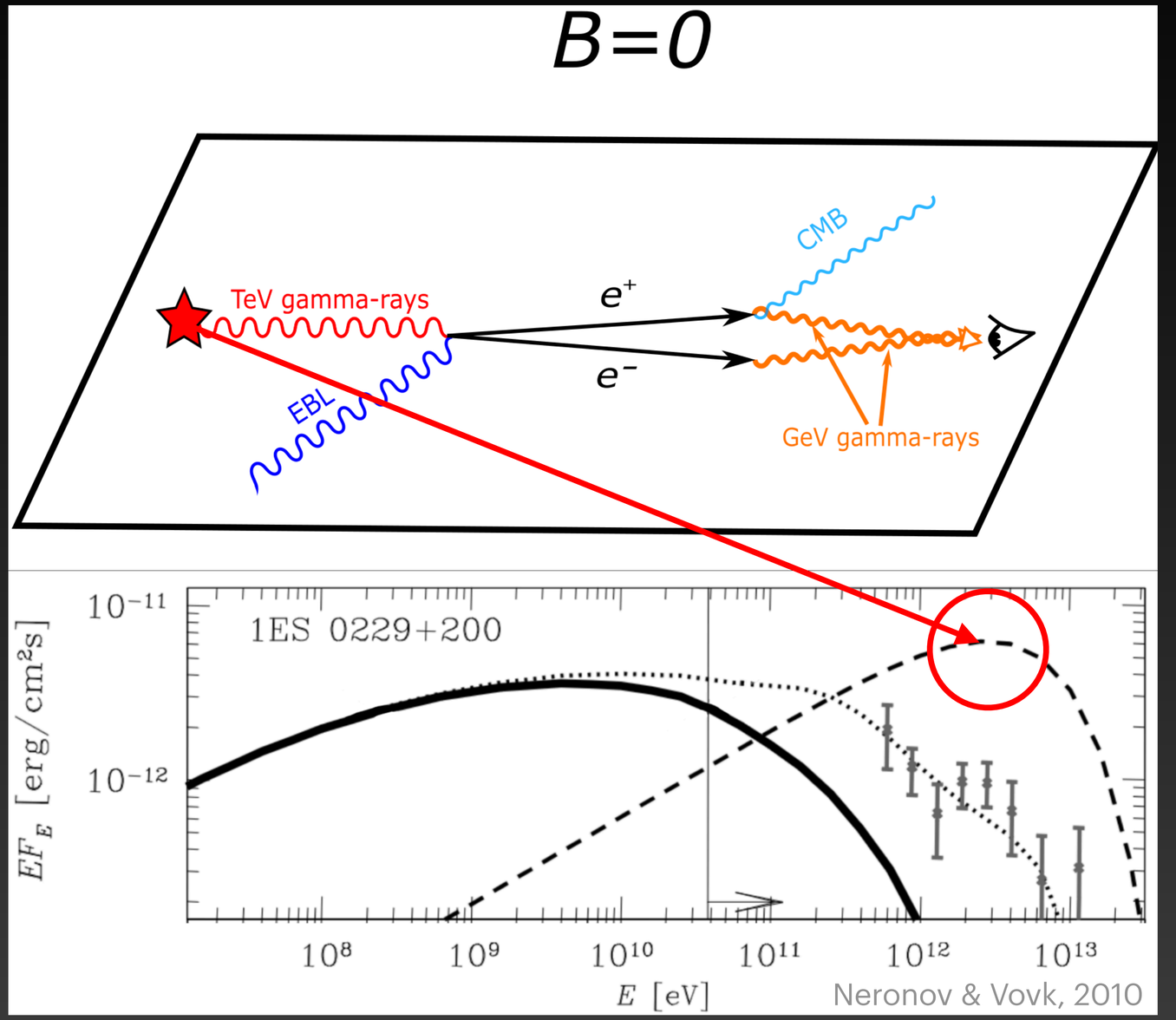
Blazars are active galactic nuclei with a **jet** of high energy particles directed **towards Earth**



How to measure the IGMF?

Secondary emission: prediction

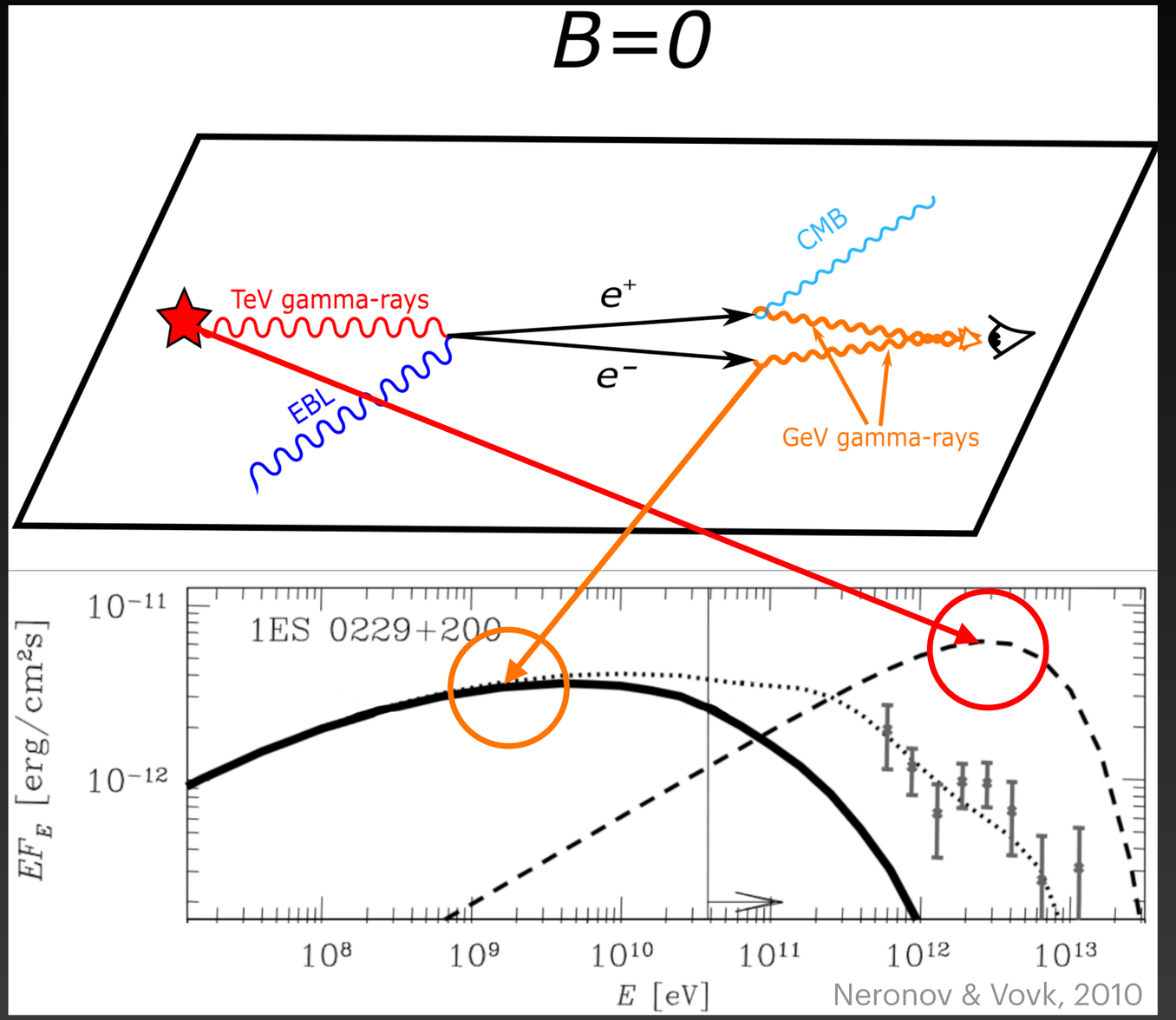
- **Blazars** have an intrinsic spectrum that grows with energy and emit TeV photons



How to measure the IGMF?

Secondary emission: prediction

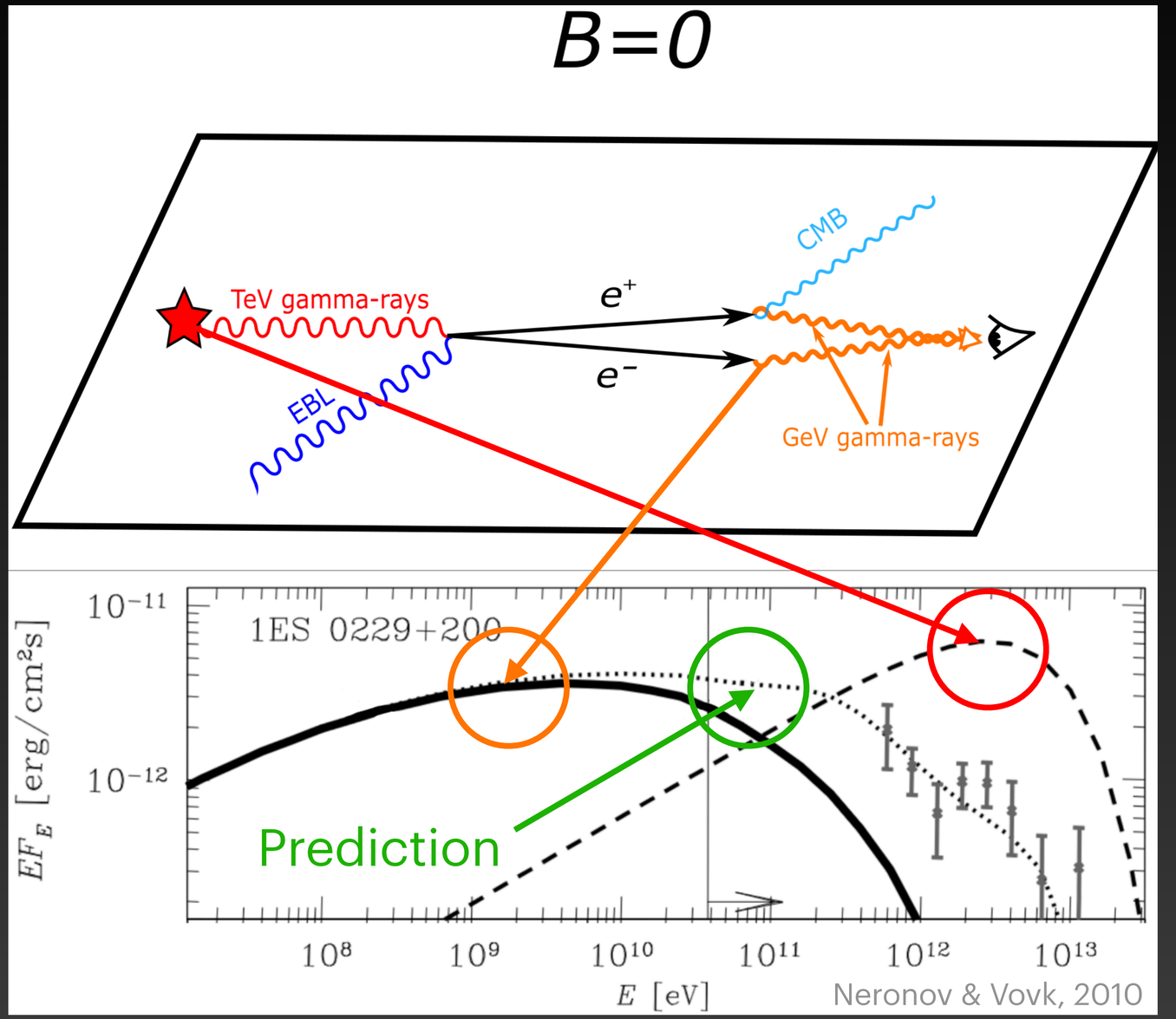
- **Blazars** have an intrinsic spectrum that grows with energy and emit TeV photons
- If there is **no IGMF**, we expect to detect secondary GeV photons



How to measure the IGMF?

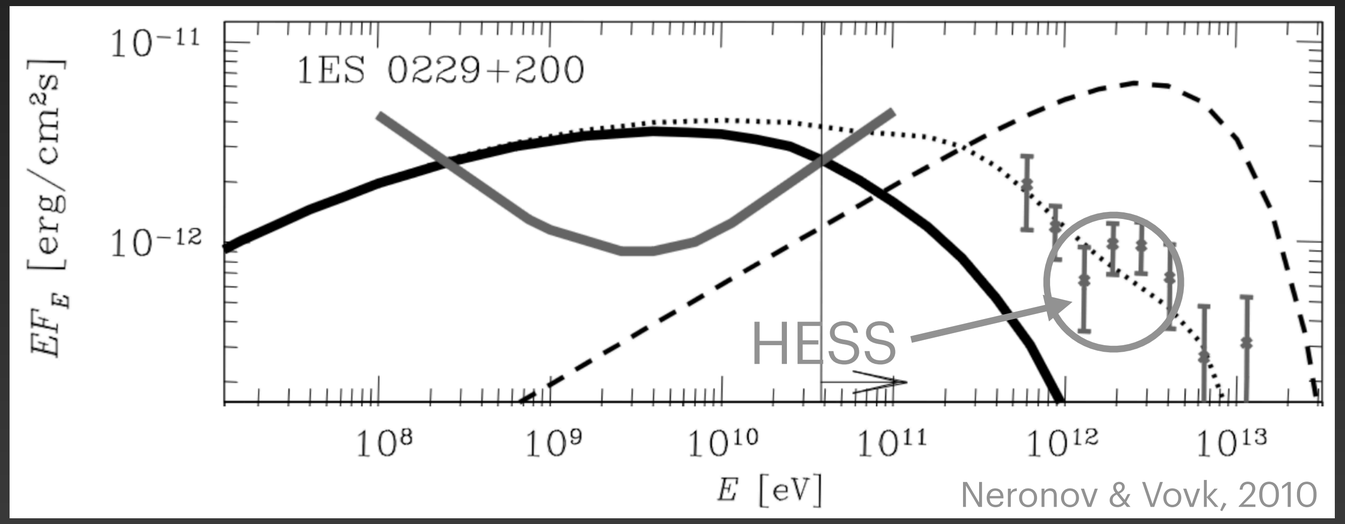
Secondary emission: prediction

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How to measure the IGMF?
Secondary emission: observation

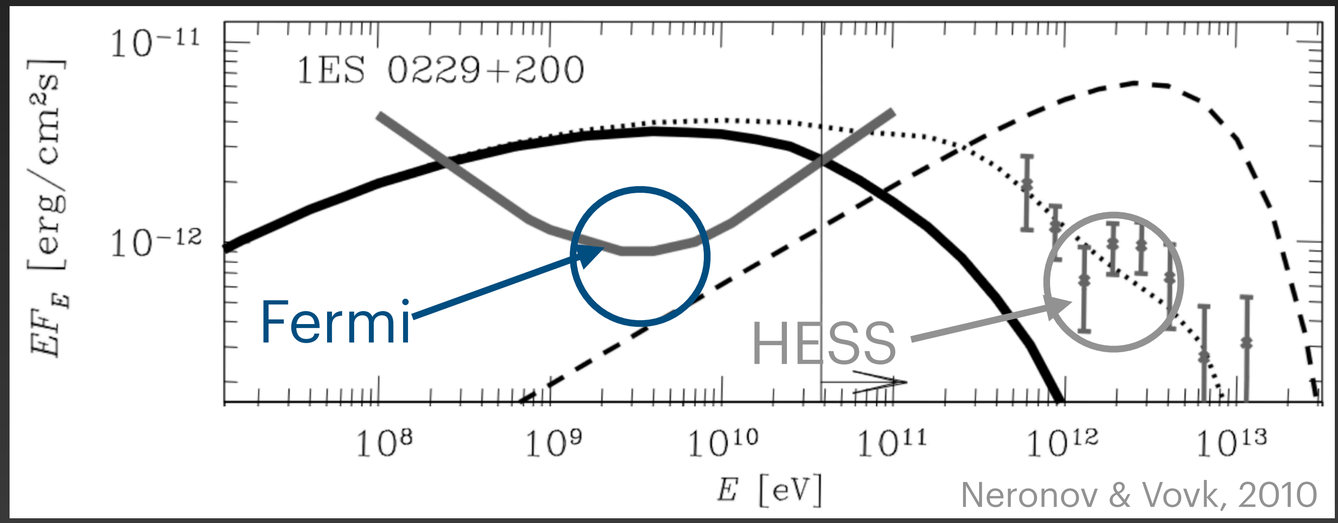
- **HESS** observed the source in the TeV range



Neronov & Vovk, 2010

How to measure the IGMF?
Secondary emission: observation

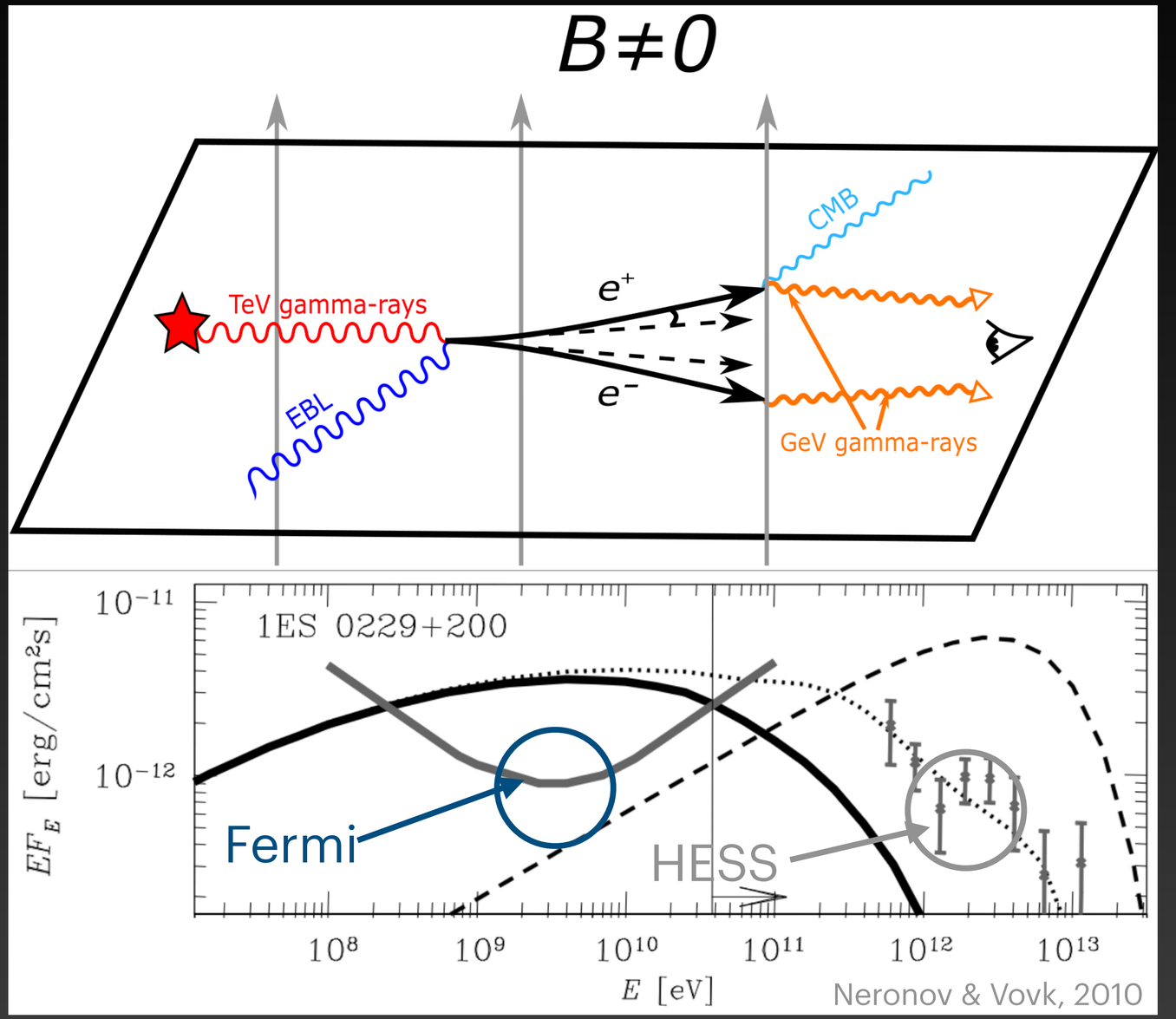
- **HESS** observed the source in the TeV range
- However, **Fermi** did not observed the predicted GeV emission



How to measure the IGMF?

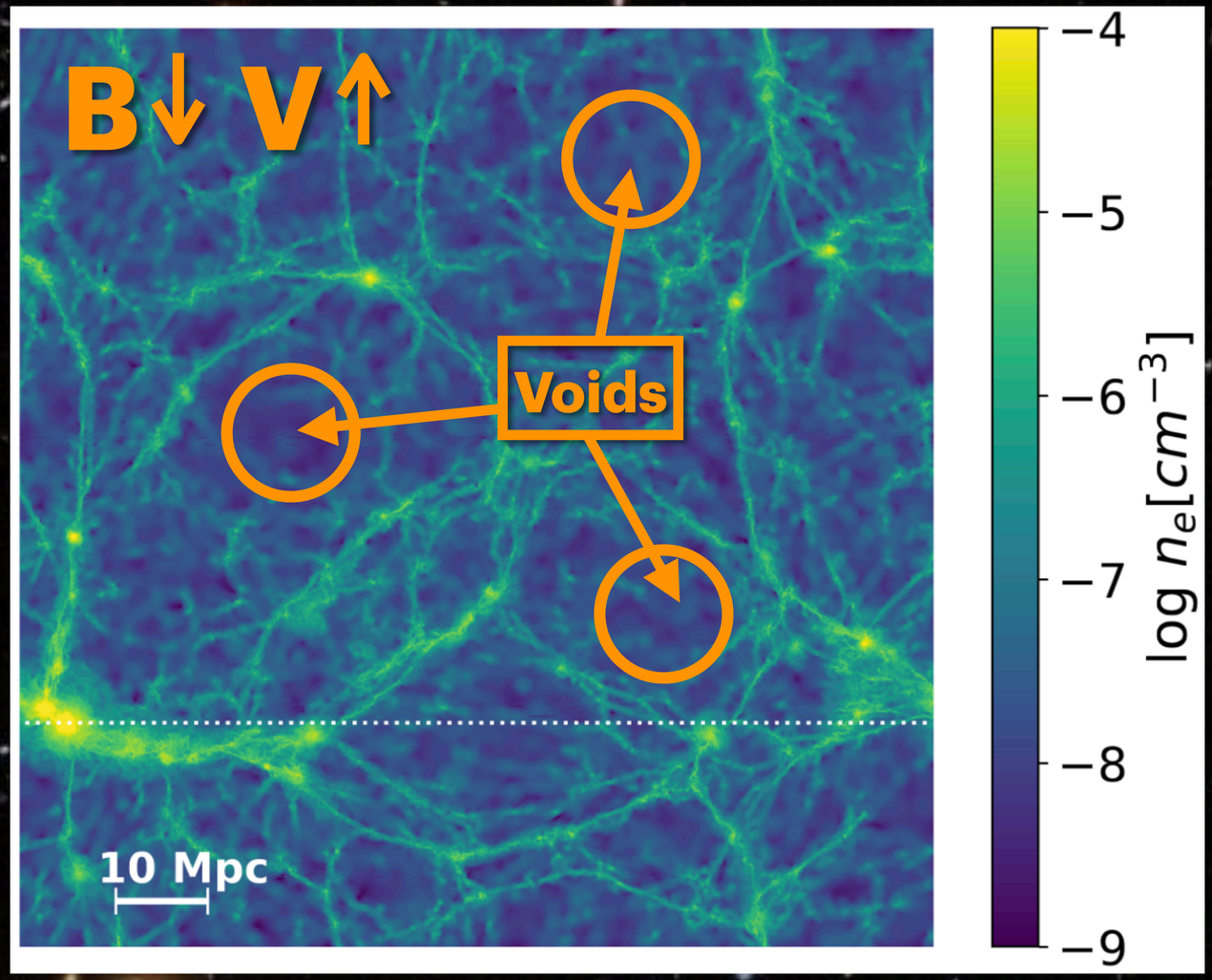
Secondary emission: explanation

- **HESS** observed the source in the TeV range
- However, **Fermi** did not observed the predicted GeV emission
- This might indicate that we have the **IGMF** where charged particles deflect from their initial trajectories



Is the IGMF primordial?

- We discussed IGMF measurement
- **IGMF** should be close to the **seed field** as little amplifications occur in voids
- Nevertheless, we should be careful as **galactic outflows** could spoil the game!



[A. Aramburo-Garcia, AS et al., JCAP, 2020]

Galactic feedback

The “genuine’’ properties of the IGMF can be affected by processes within galaxies

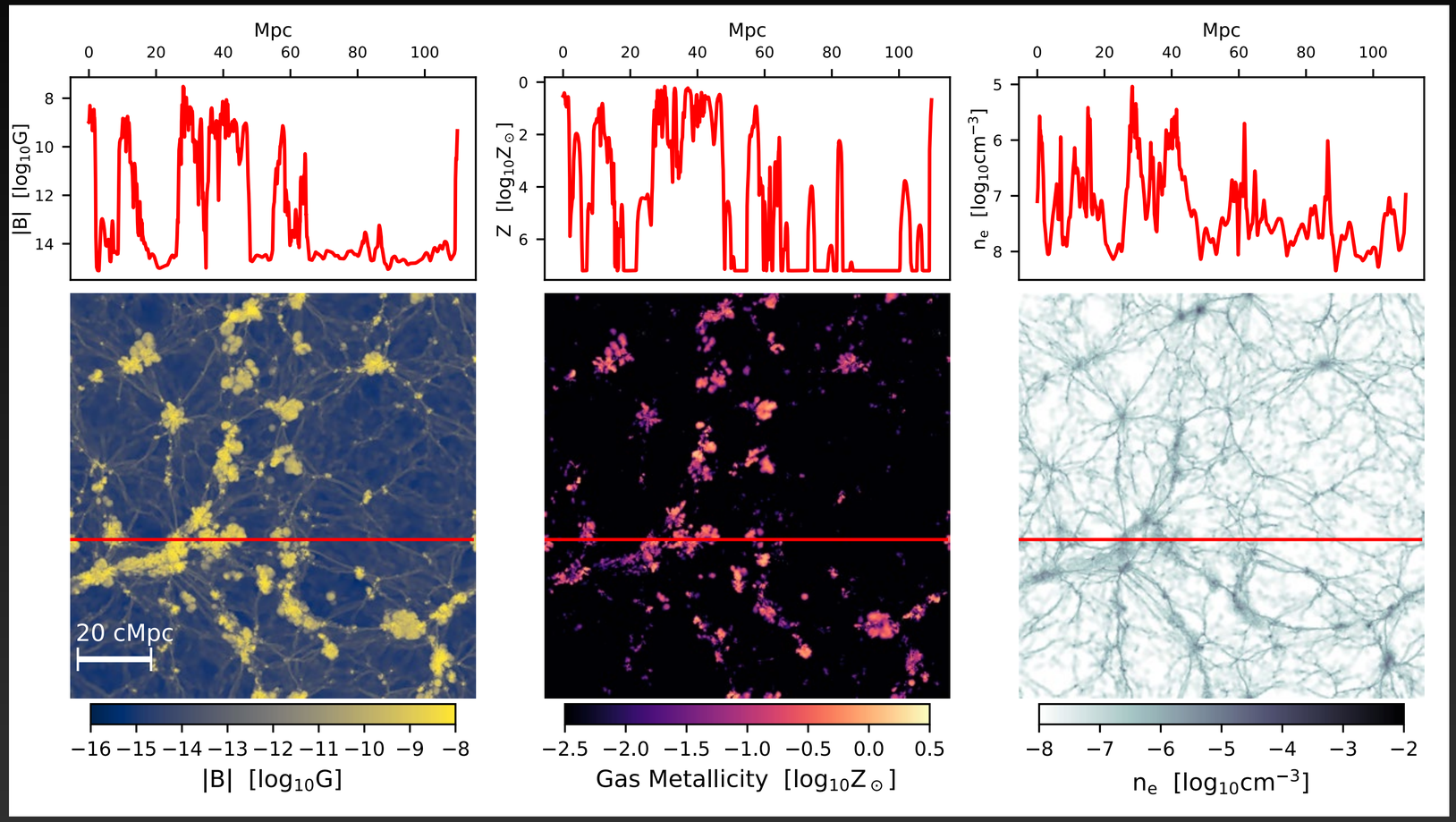
Indeed, **feedback** from **supernovae and active galactic nuclei** (AGNs) could spread out galactic matter and magnetic field at some distance around galaxies



To what extend are the IGMF affected by galactic feedback?
We use cosmological numerical simulations to analyze this question

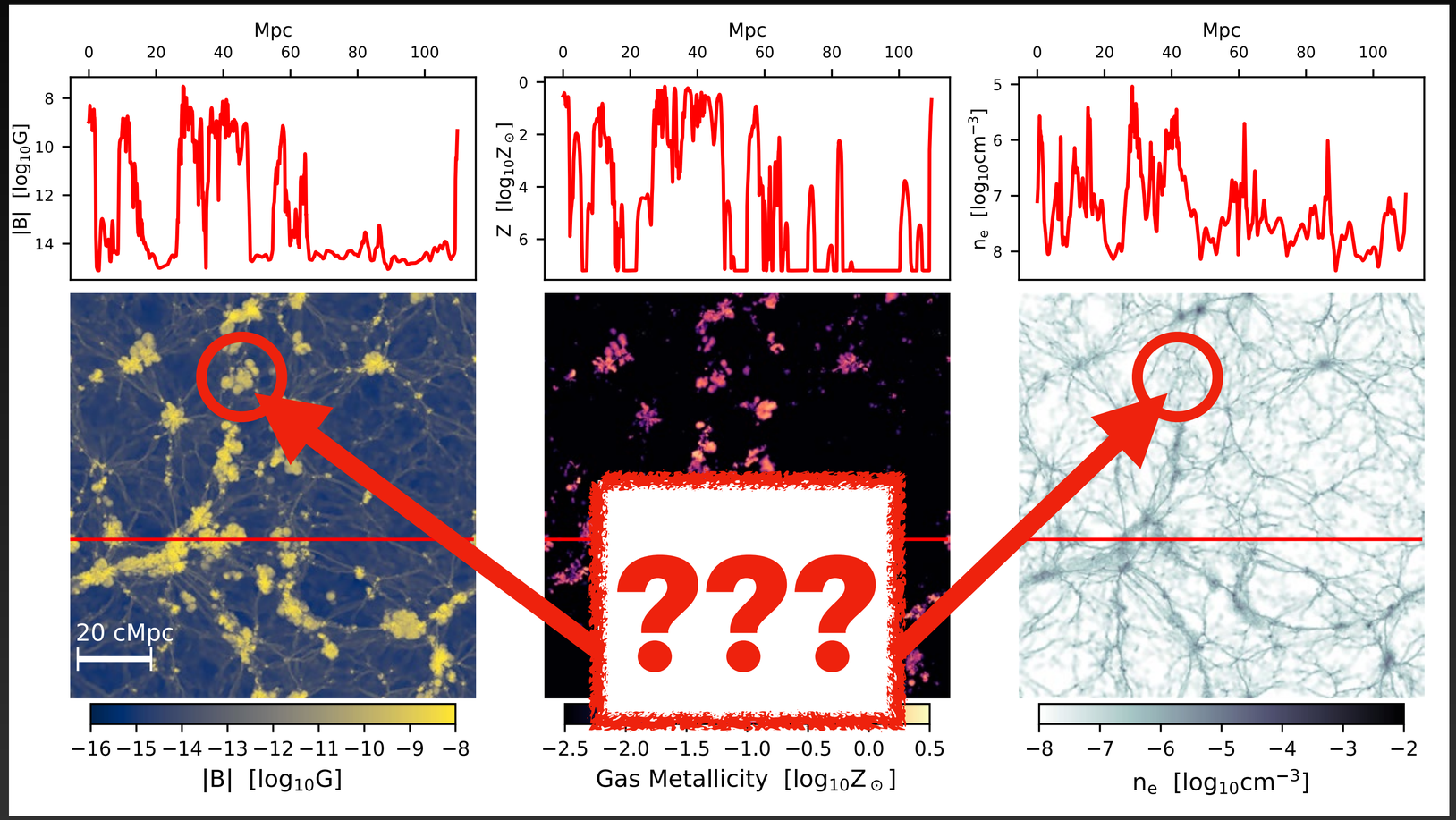
Credit: IllustrisTNG

Over-magnetized bubbles in IllustrisTNG simulations



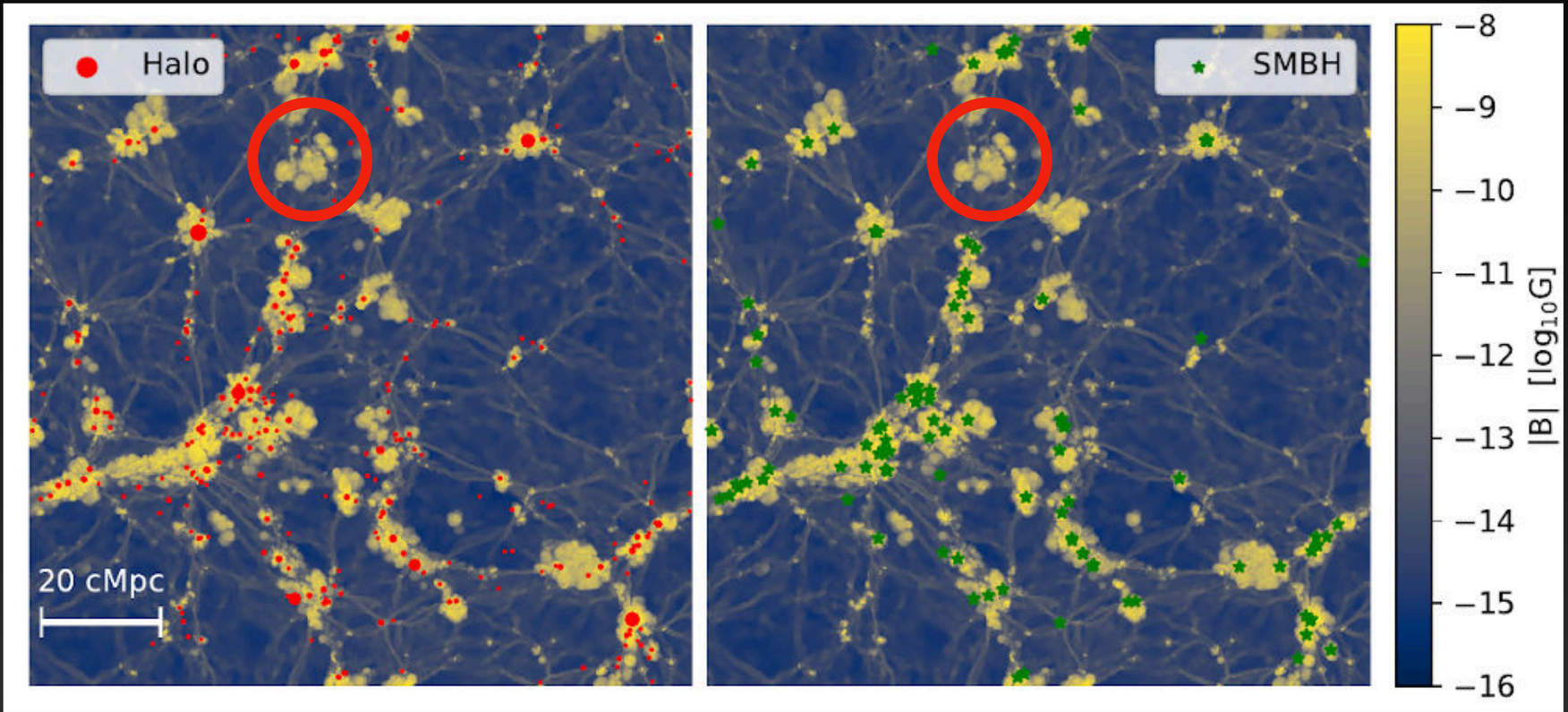
[A. Aramburo-Garcia, AS et al., MNRAS, 2021]

Over-magnetized bubbles in IllustrisTNG simulations



[A. Aramburo-Garcia, AS et al., MNRAS, 2021]

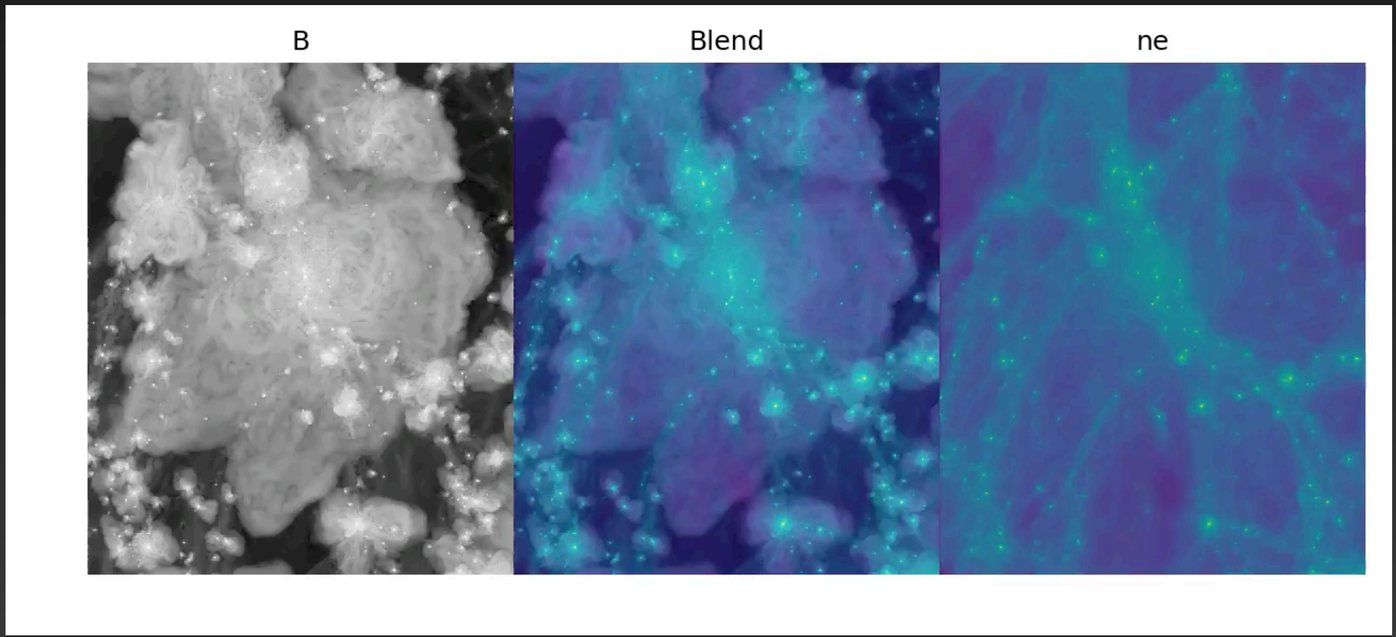
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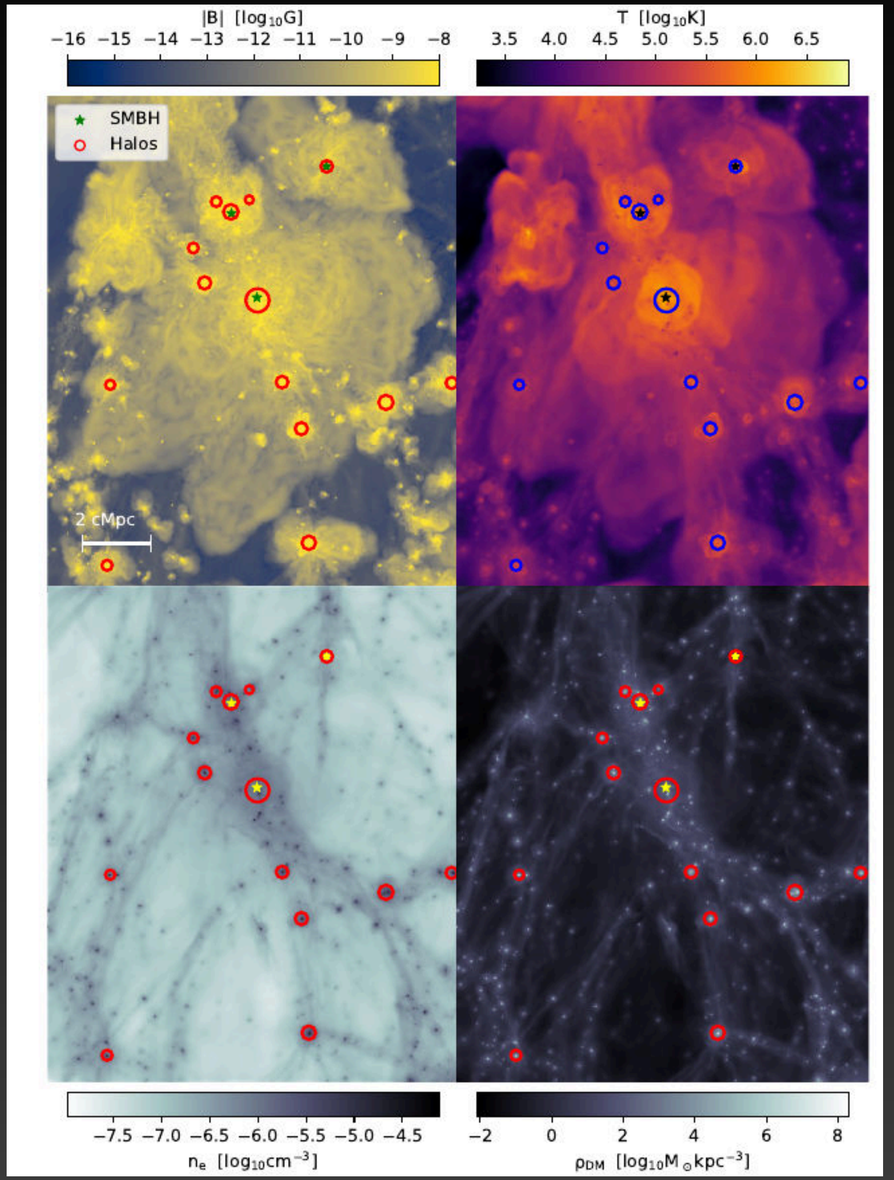


Hypothesis: magnetic bubbles are **caused by the outflows** caused by AGNs and supernovae. We see that **some bubble does not correspond to any halo or AGN**. How could this be?

Over-magnetized bubbles in IllustrisTNG simulations

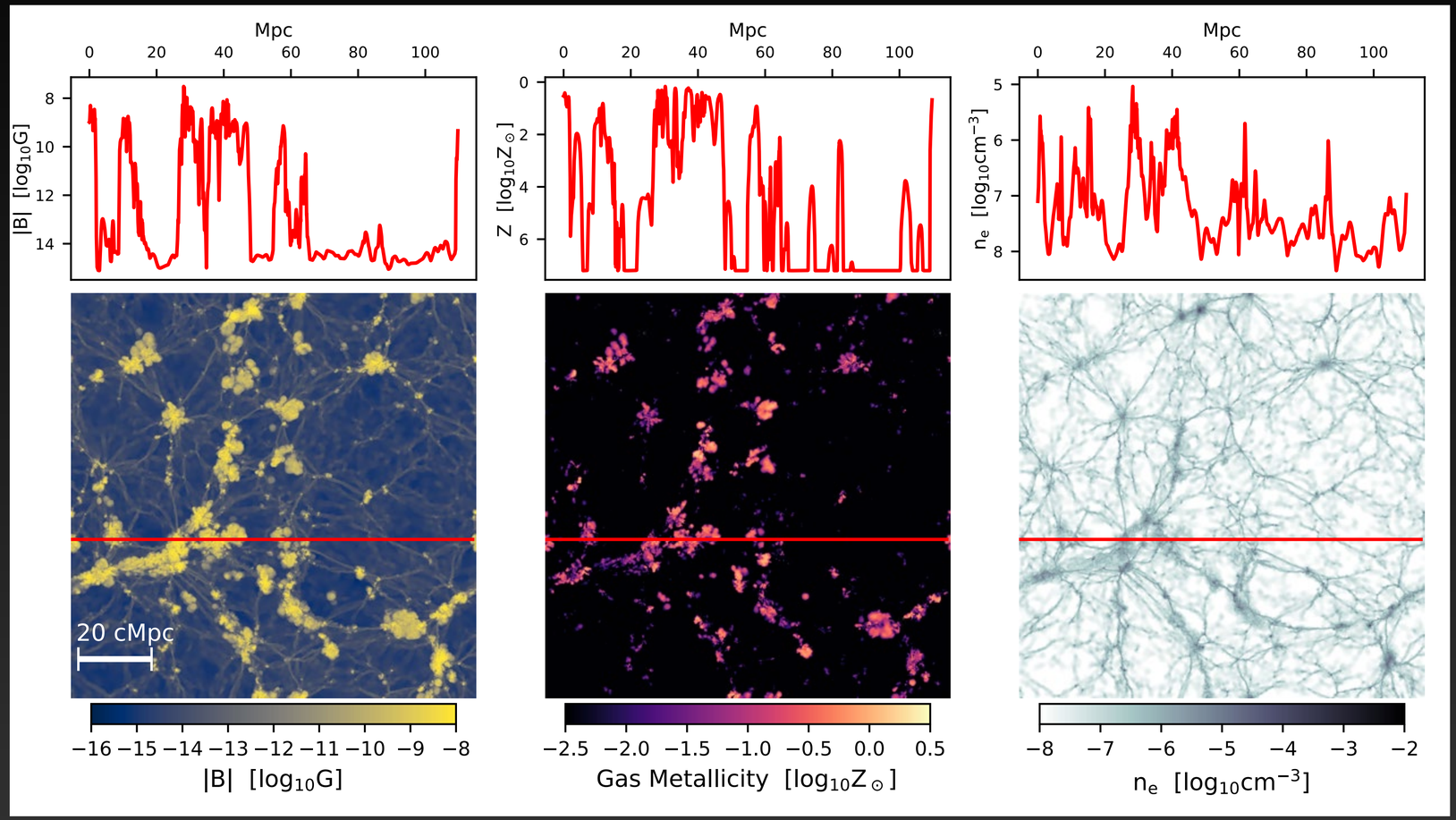
Zooming in to the volume occupied by this magnetic bubble we found the the source!





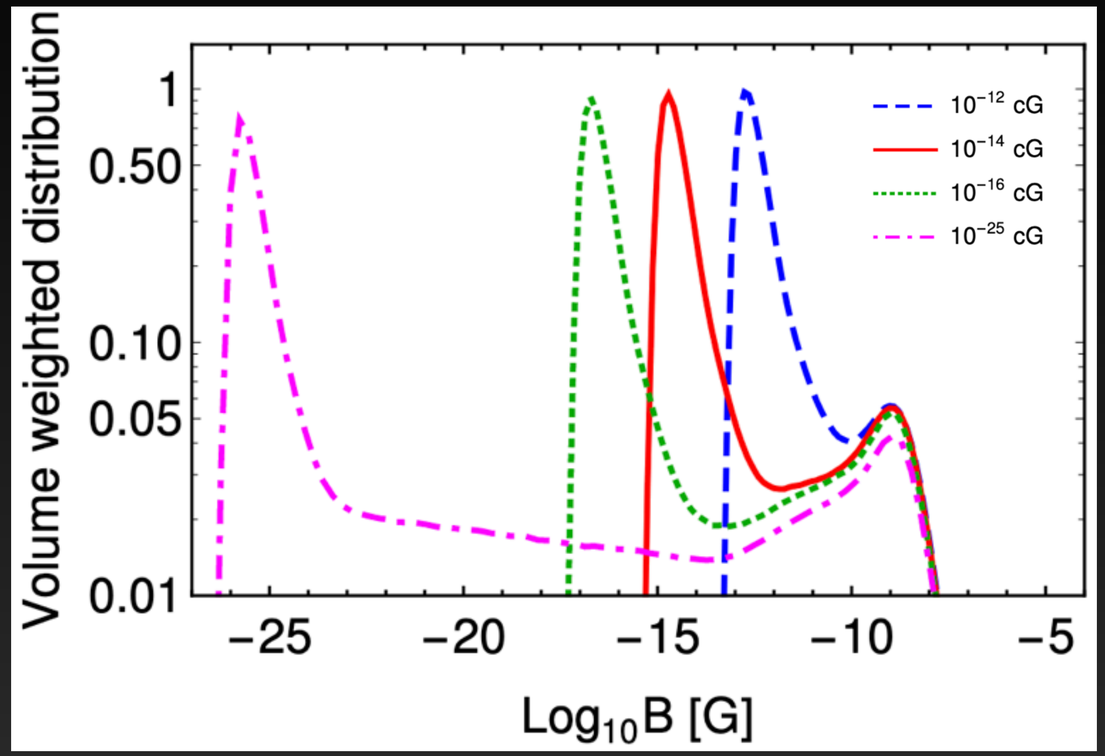
Over-magnetized bubbles in IllustrisTNG simulations

In IllustrisTNG we have observed **macroscopic (tens Mpc) regions** around clusters of galaxies with **electron densities** as **low** as in the intergalactic medium (IGM) and **magnetic fields** as **strong** as in clusters - over-magnetized bubbles



Typical sizes of the bubbles are of an **order of magnitude** larger than the virial radii of their parent clusters.

Magnetic fields in bubbles forget initial conditions!



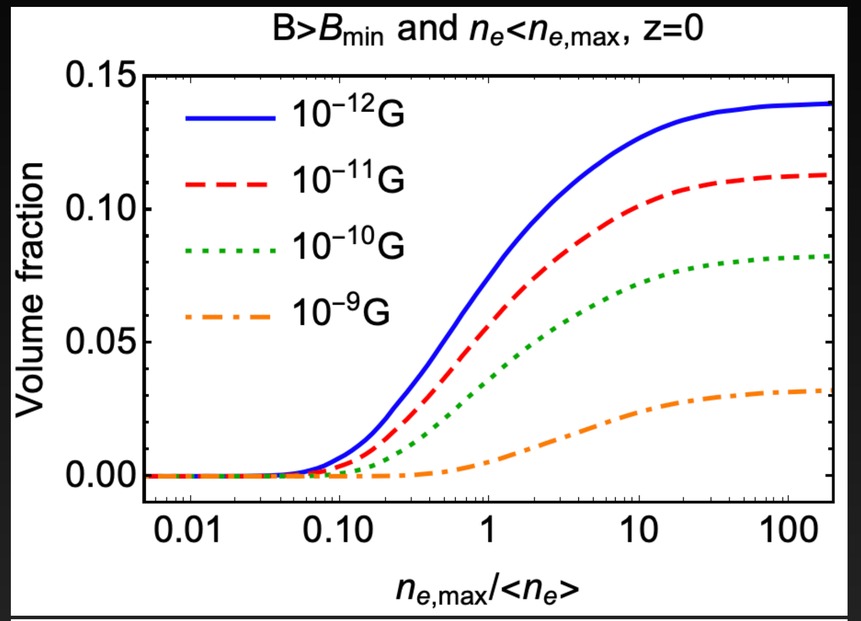
- Distributions of magnetic fields are calculated for TNG25 simulations with **different initial conditions** for the initial fields
- The distribution of **large magnetic fields is the same** regardless of the initial value of the magnetic field

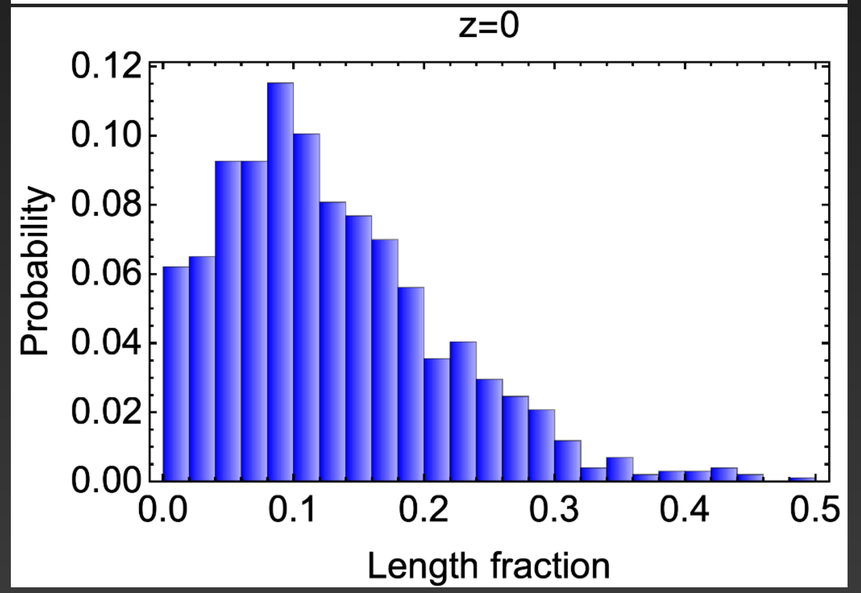
Over-magnetized bubbles in IllustrisTNG simulations

At z = 0, the magnetic field is **stronger** than 10^{-12} G in **15% of the volume**, while it is stronger than 10^{-9} G in 3% of the volume

More than **50% of random lines of sight** pass through magnetic bubbles and spend **more that 10%** of their length there

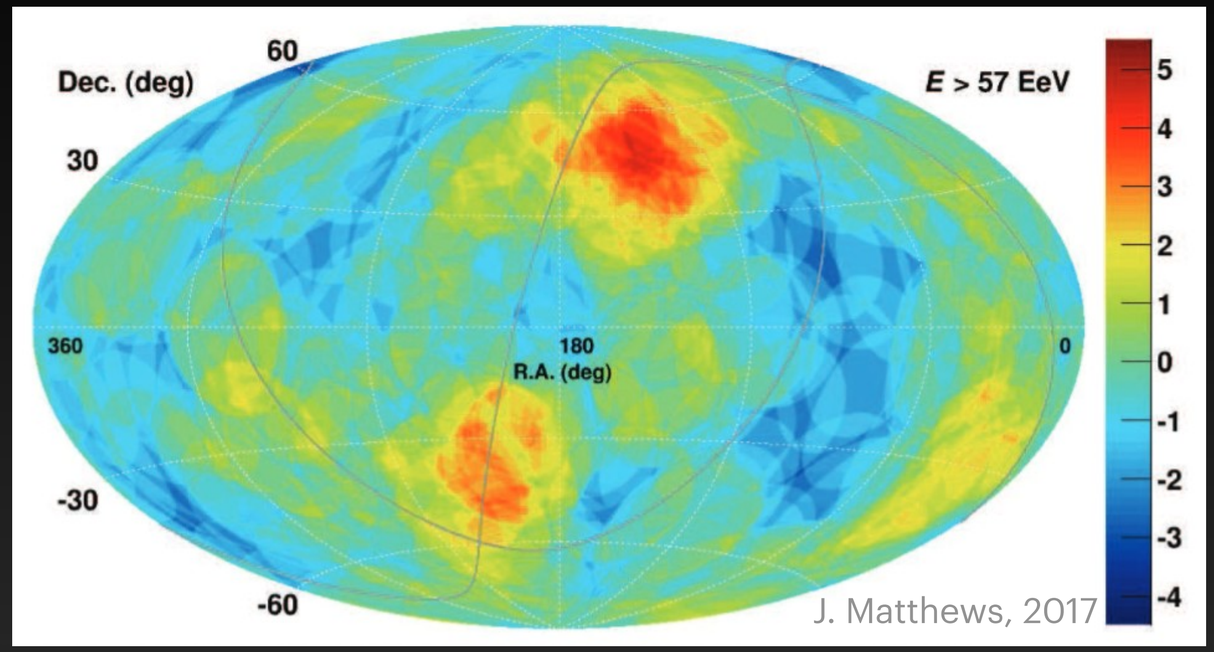
This makes these bubbles **important** for e.g. radio and **γ-ray astronomy**





Impact of magnetic bubbles
Ultra-High Energy Cosmic Rays (UHECRs)

- **Finding UHECRs sources**: a central problem of astroparticle physics
- **No signatures of sources**: UHECRs show a surprisingly high level of isotropy

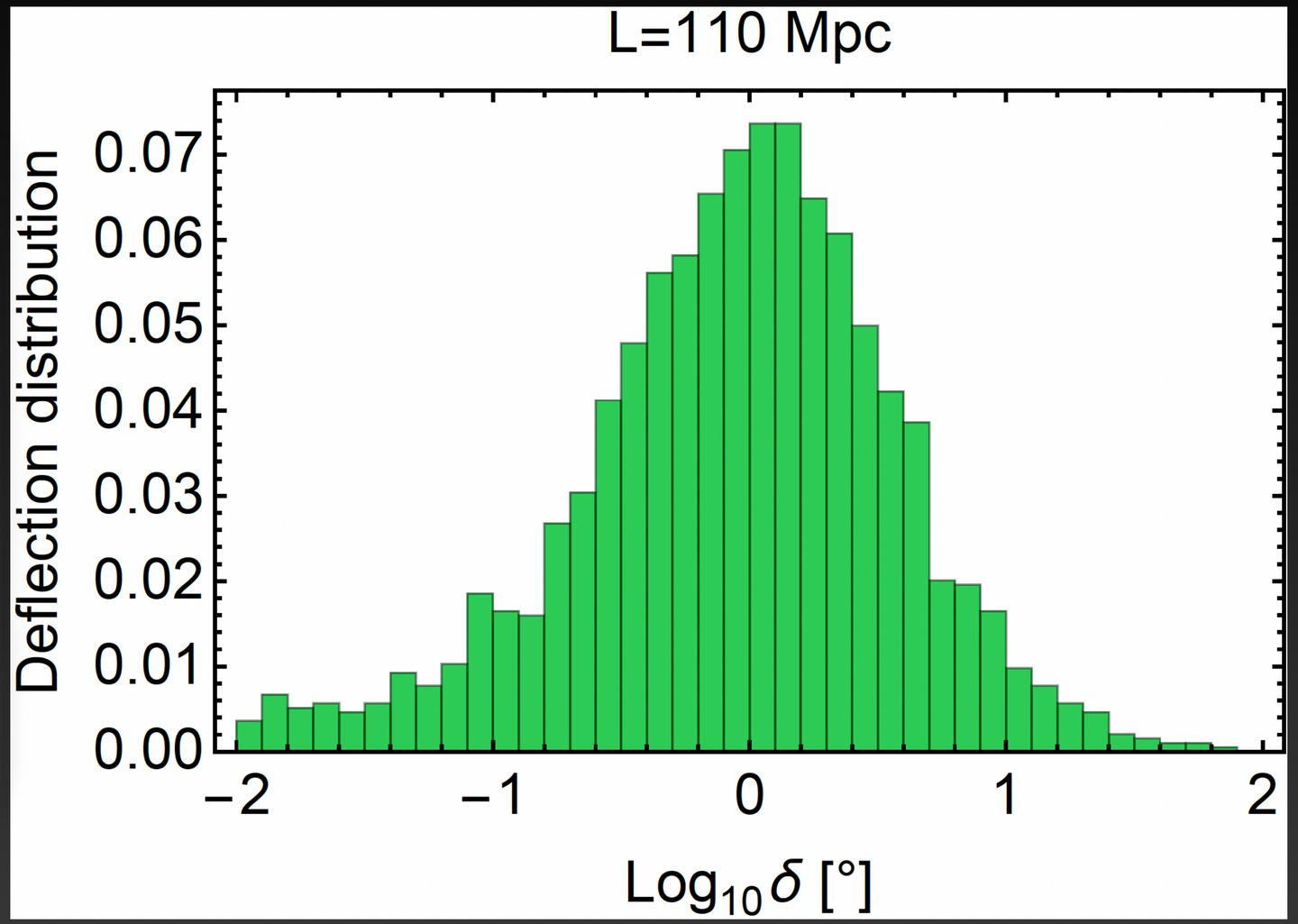


- This absence of small-scale clustering is believed to arise from the **deflection of UHECRs in magnetic fields**
- *Common picture:* CRs in the disk diffuse to high angles. CRs transverse to the disk are deflected only while crossing the plane, for $E \sim 5 \times 10^{19}$ eV the angle is $\sim 1^{\circ}$

Kachelriess, Semikoz, 2019

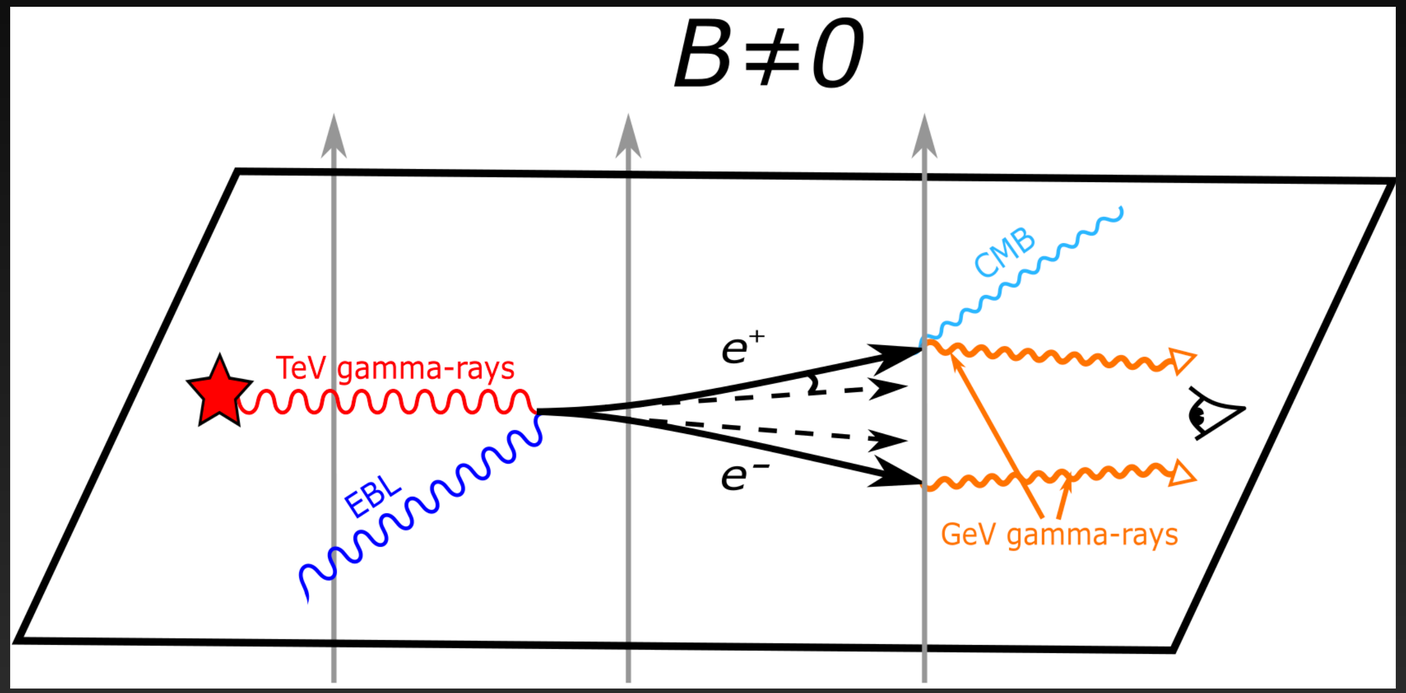
Impact of magnetic bubbles
Ultra-High Energy Cosmic Rays (UHECRs)

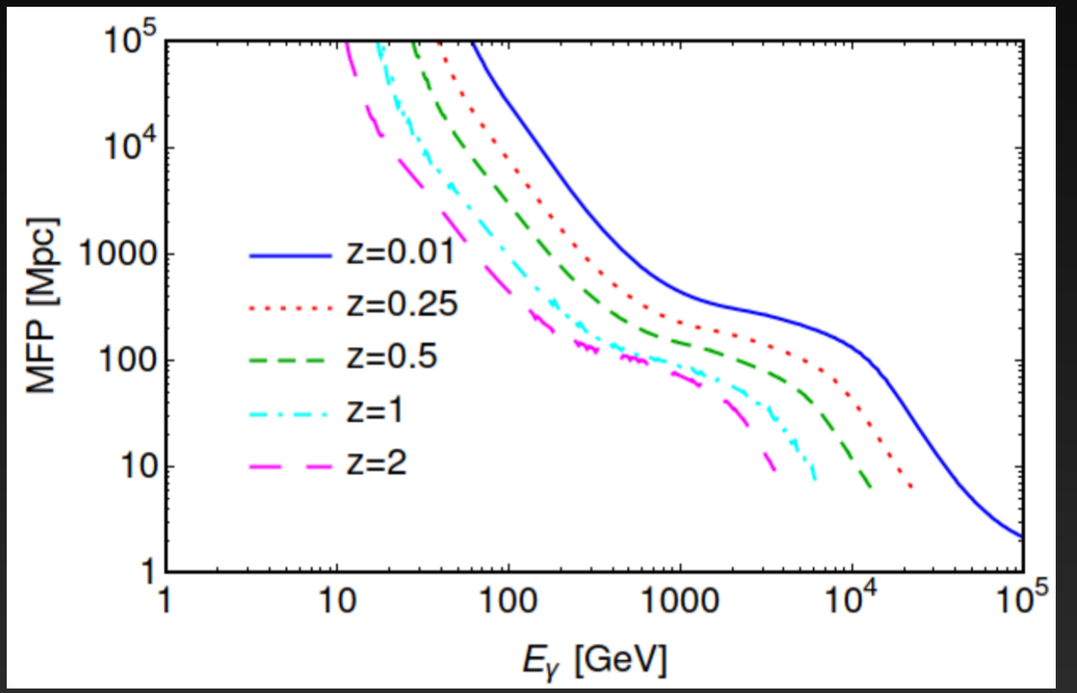
- The **distribution of deflection angles is quite wide** with an average value around 1°
- The influence of **intergalactic magnetic fields** on the **propagation of the UHECRs** could be **important**



[A. Aramburo-Garcia, AS et al., PRD, 2021]

Can the lower bound on the IGMF be affected by bubbles?

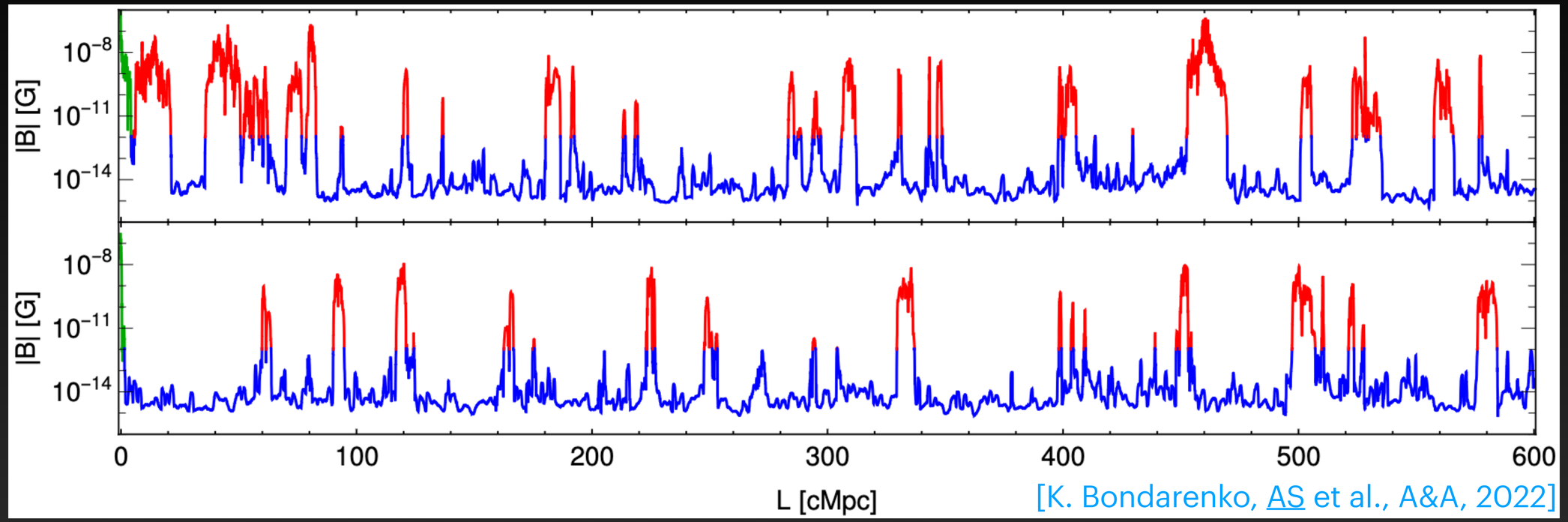




[K. Bondarenko, AS et al., A&A, 2022]

Blazars are very likely **surrounded** by magnetic bubbles. Very **high-energy photons** might convert into an electron-positron pair **inside a magnetic bubble**

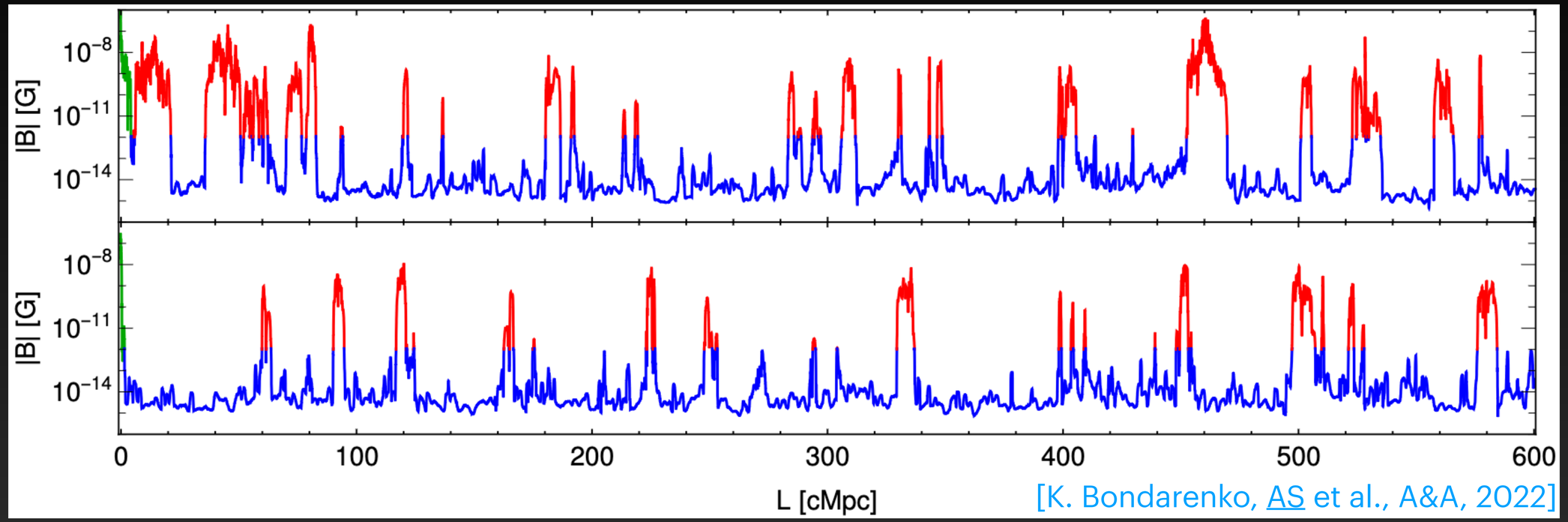
Can the lower bound on the IGMF be affected by bubbles?



[K. Bondarenko, AS et al., A&A, 2022]

- **Individual sources** can be “unlucky” and have an **extended over-magnetized bubble** along the line of sight to the Earth
- For individual objects, **up to 70% of the energy of secondary emission was lost**, but for most of the systems, the missing energy fraction is below 50%

Can the lower bound on the IGMF be affected by bubbles?



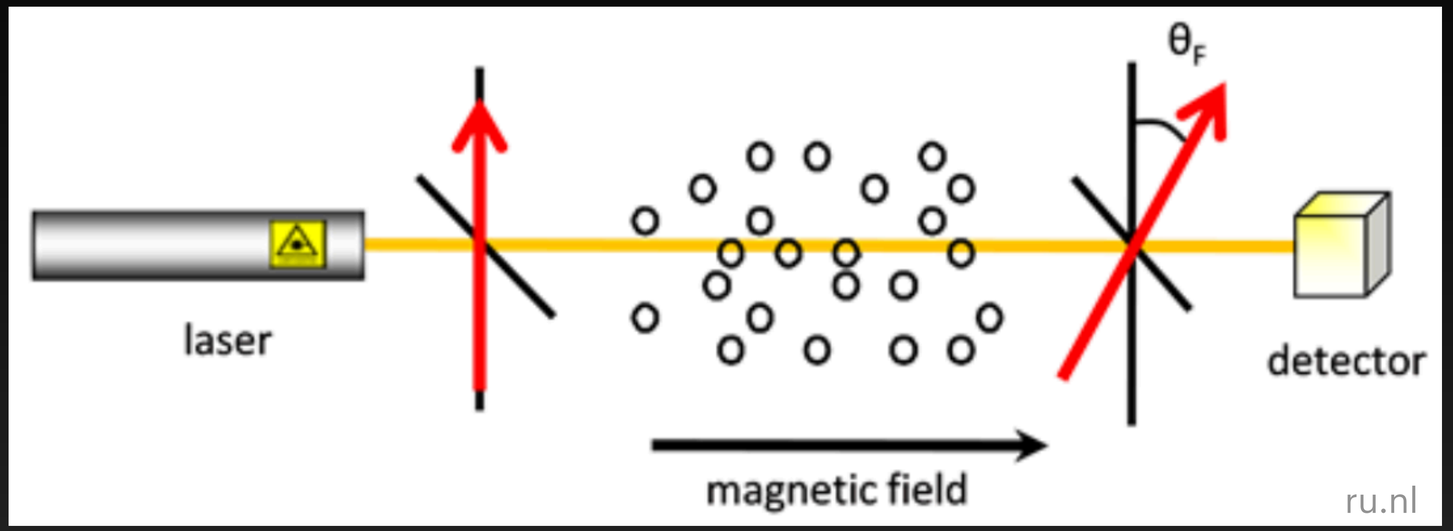
[K. Bondarenko, AS et al., A&A, 2022]

- One way to deal with this problem is to **increase statistics**
- With the **CTA**, we will **significantly increase** both the quantity and quality of observed sources

How to detect these bubbles?

Faraday rotation

- In dense structures we can **measure magnetic fields** using the **Faraday effect**
- Polarized **light rotates** by θ_F in the **magnetic field**

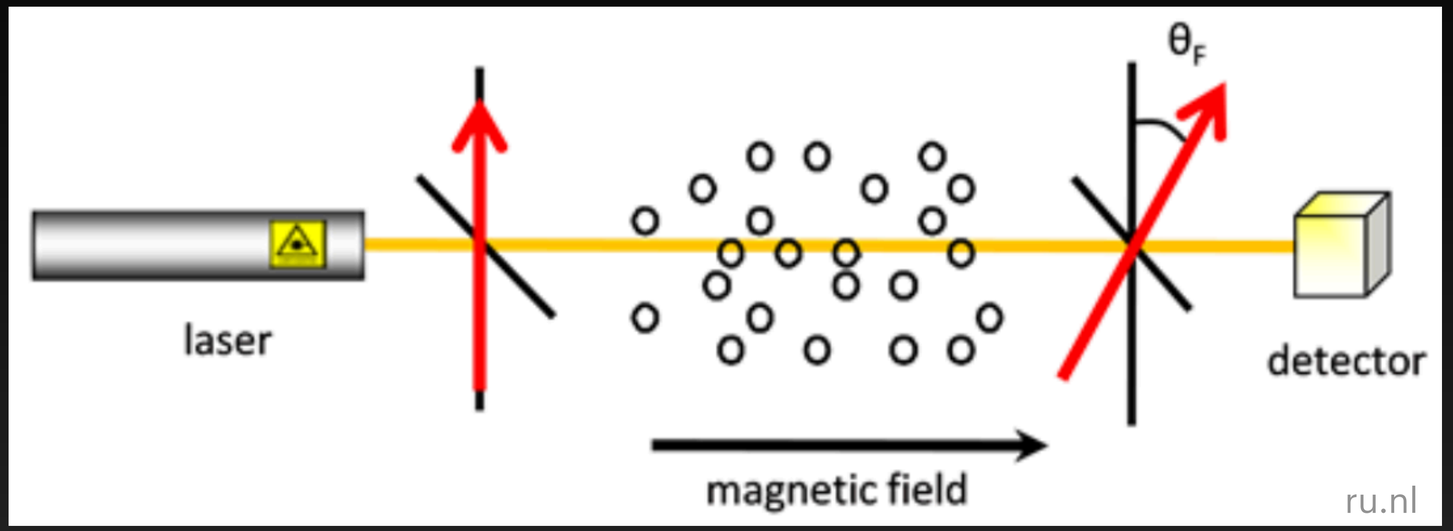


$$\Delta\theta_F = \mathrm{RM} \cdot \lambda^2, \qquad \mathrm{RM} = \frac{e^3}{2\pi m_e^2} \int \frac{n_e \cdot B_{||}}{(1+z)^2} \frac{dl}{dz} dz$$

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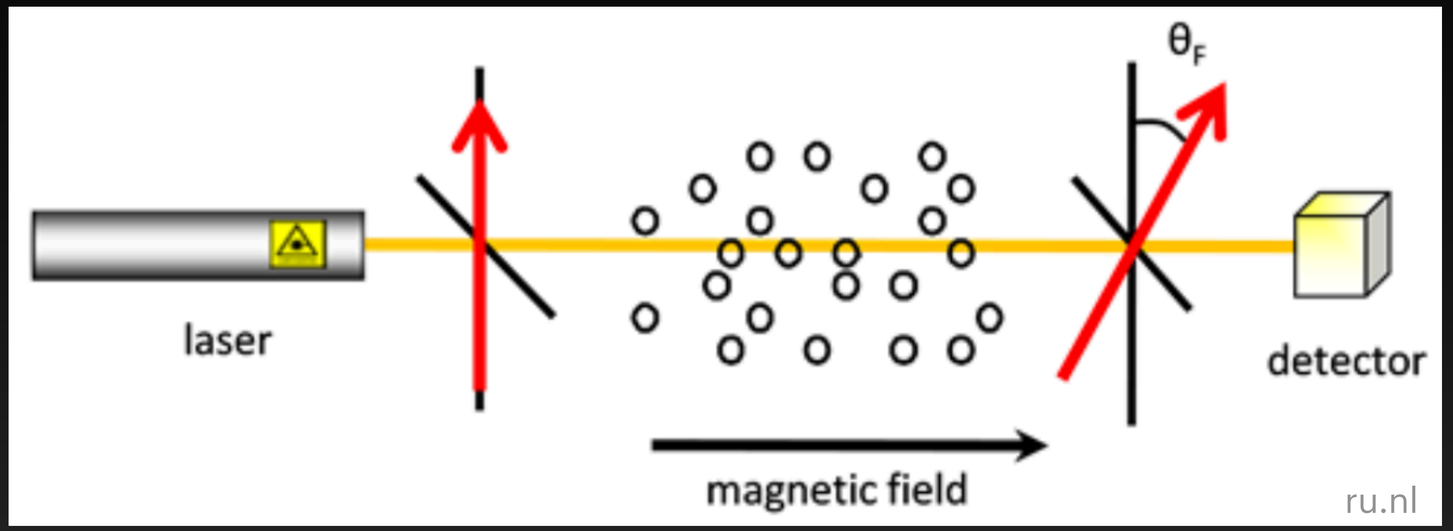
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light wavelength

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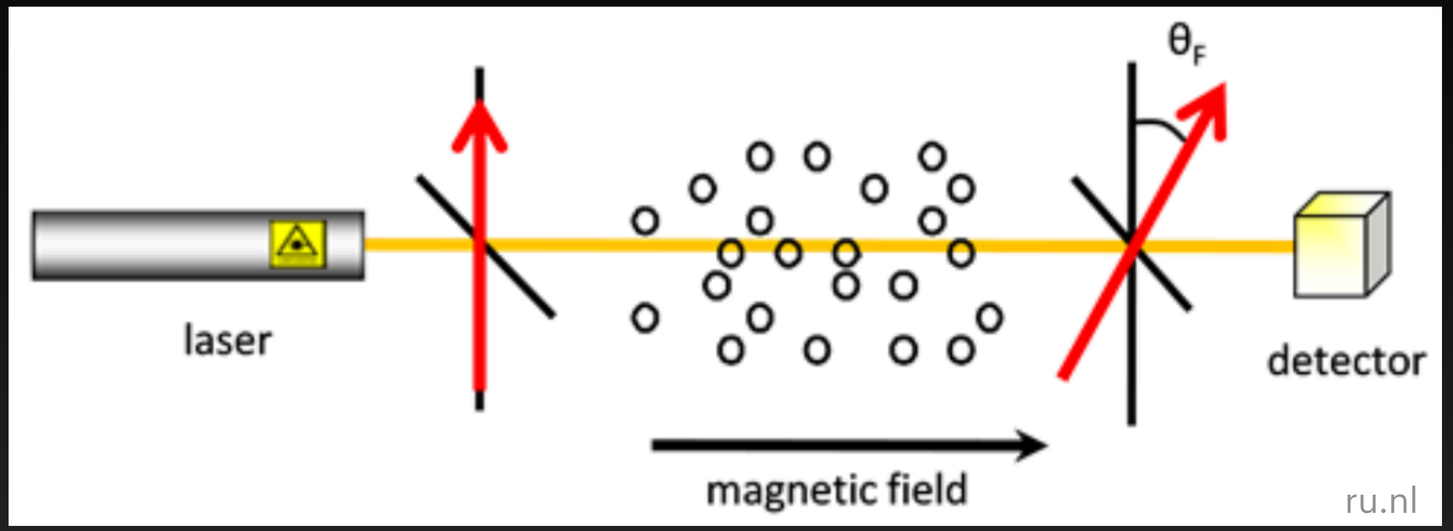


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Faraday Rotation Measure

How to detect these bubbles?
Faraday rotation

- In dense structures we can **measure magnetic fields** using the **Faraday effect**
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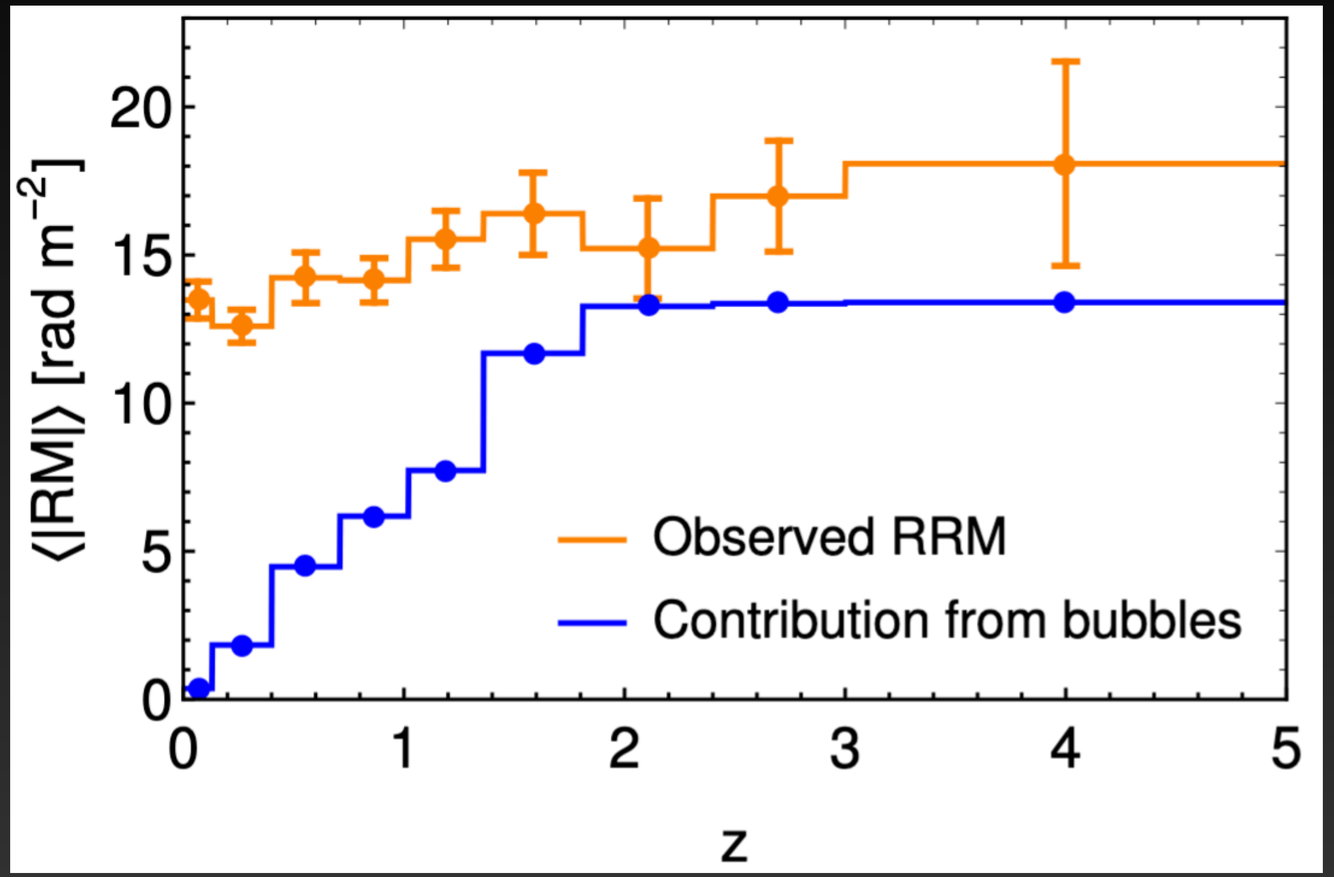


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number density of charged particles × magnetic field

Constraints from Faraday rotation

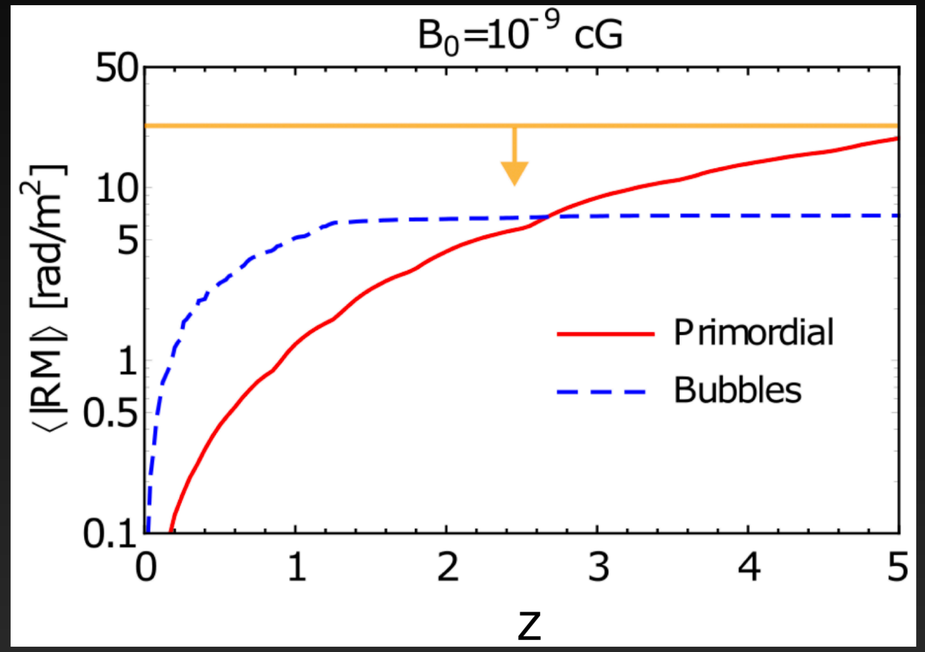
- The **Faraday rotation** technique provides a powerful probe of astrophysical magnetic fields
- We used the catalog of radio sources NRAO VLA Sky Survey (NVSS) Hammond et al., 2012 and **predicted** mean and median values of **RM** from TNG as a function of redshift



[A. Aramburo-Garcia, AS et al., MNRAS, 2022]

Future: exploring magnetic bubbles

- **If** IllustrisTNG is **correct**, tens Mpc regions with **large magnetic field surround galaxy clusters**
- Eagle is implementing MHD, will provide an alternative picture of the MF dynamics during galaxy formation. Compare predictions of different simulation suits
- Observationally, it is challenging to detect a bubble, stacking might work

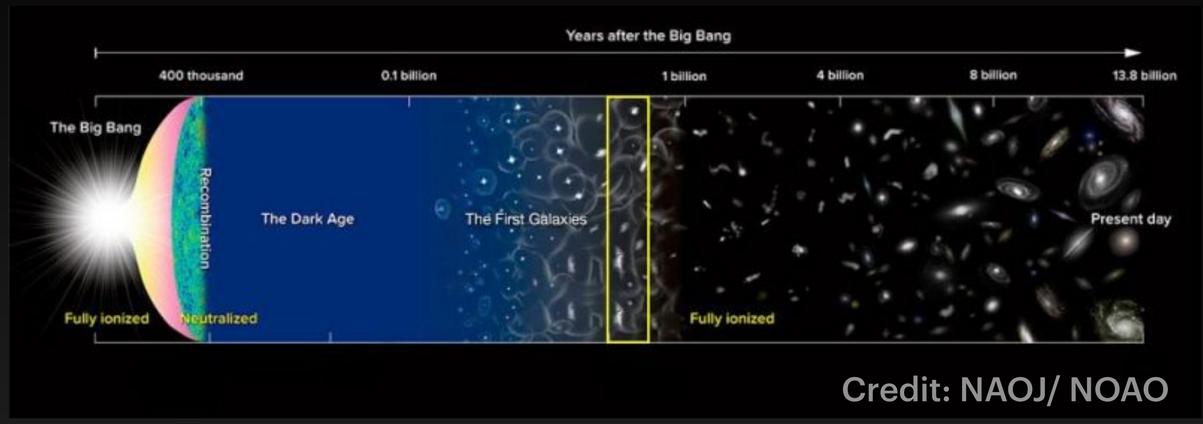


New LOFAR data and SKA will improve the results

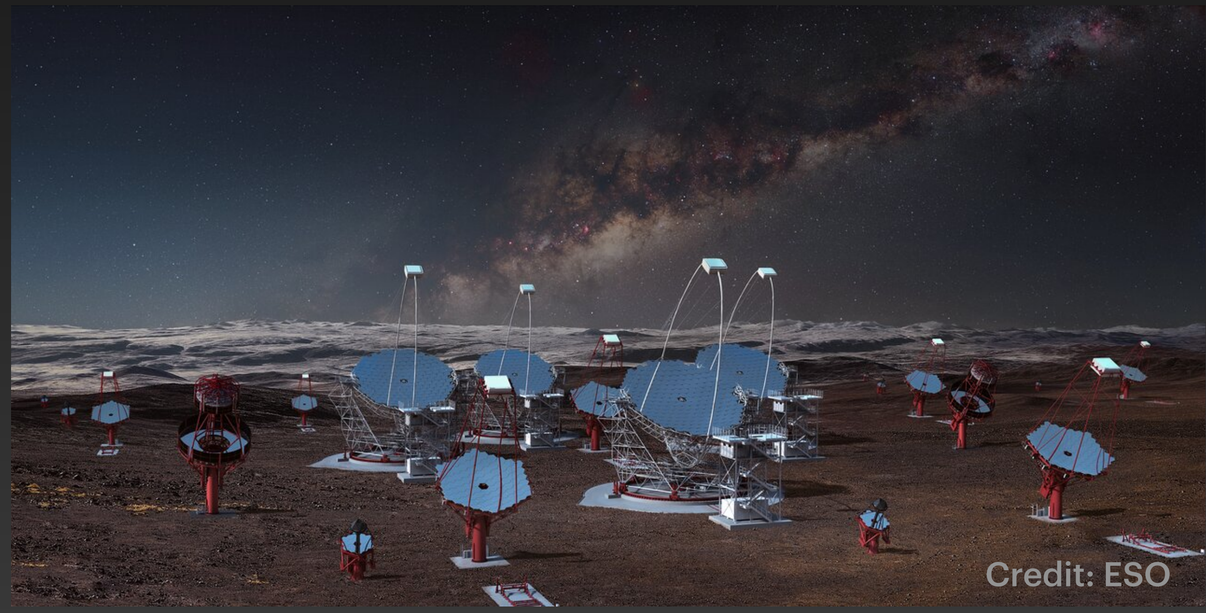
Future: searching for the IGMF

Switching from non-observation of GeV emission to **observation** of GeV emission from a deflected electron-positron pair would be much more convincing - an **extended GeV halo** around a TeV source

Is it possible to reconstruct the value of the seed fields from the cumulative effects along the entire line of sight?



Credit: NAOJ/ NOAO

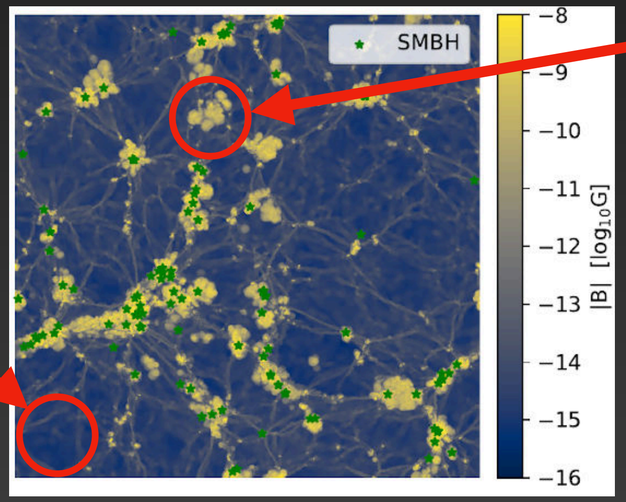

Credit: ESO

Future: searching for the IGMF

Intergalactic magnetic field

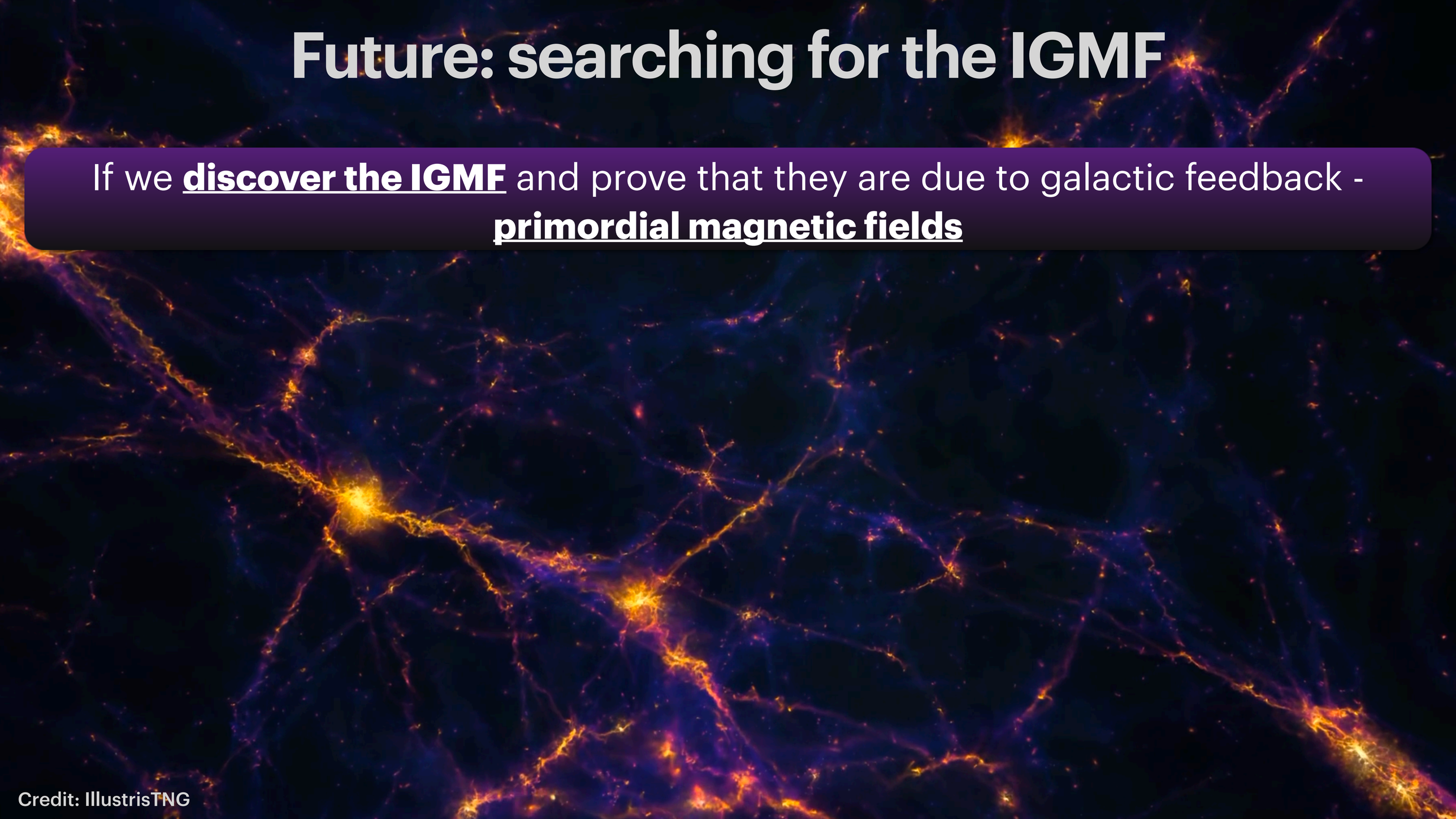
Voids: primordial?

Magnetic bubbles: galactic?



Future: searching for the IGMF

If we **discover the IGMF** and prove that they are due to galactic feedback - **primordial magnetic fields**

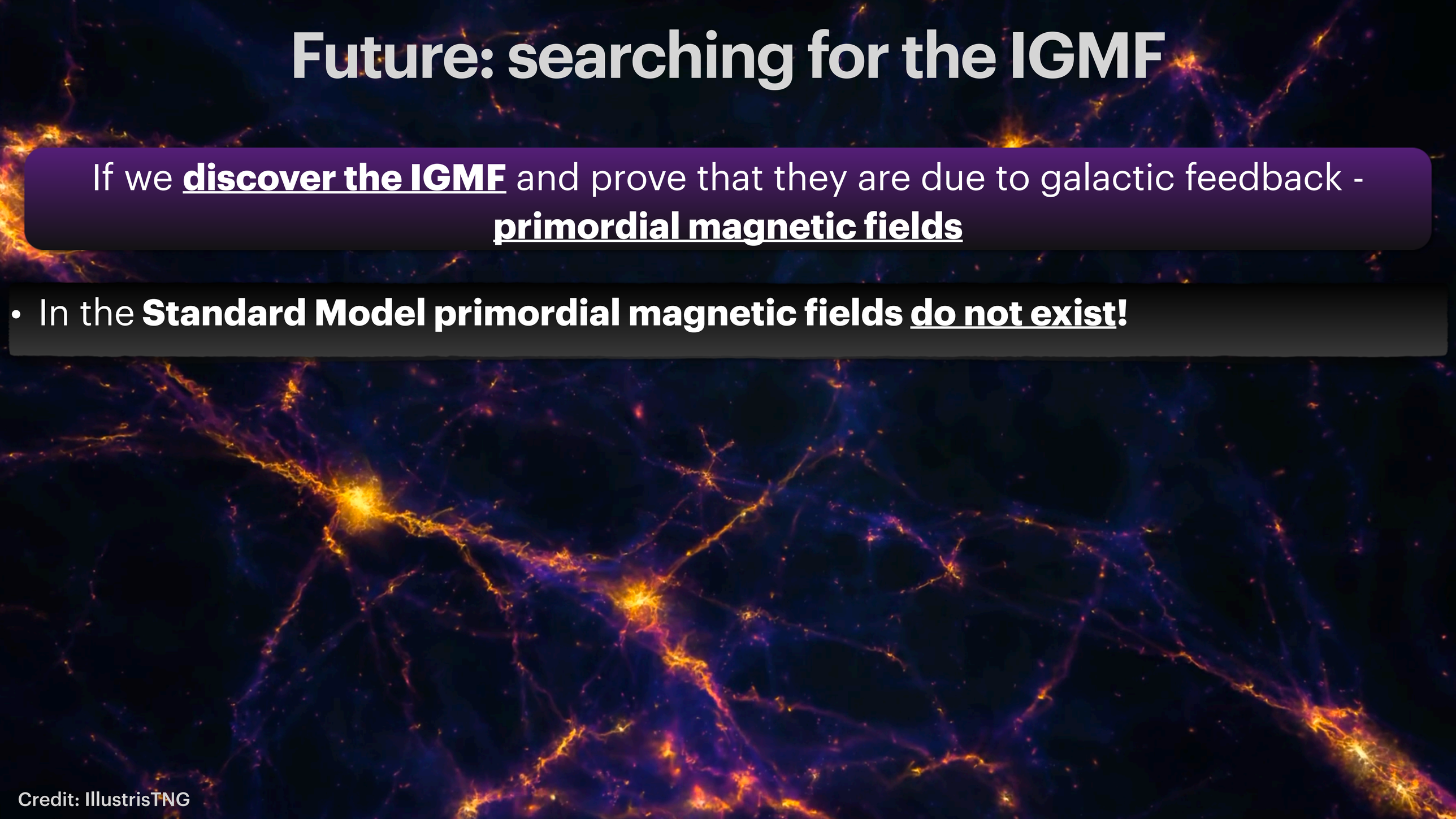


Credit: IllustrisTNG

Future: searching for the IGMF

If we **discover the IGMF** and prove that they are due to galactic feedback - **primordial magnetic fields**

- In the **Standard Model primordial magnetic fields do not exist!**

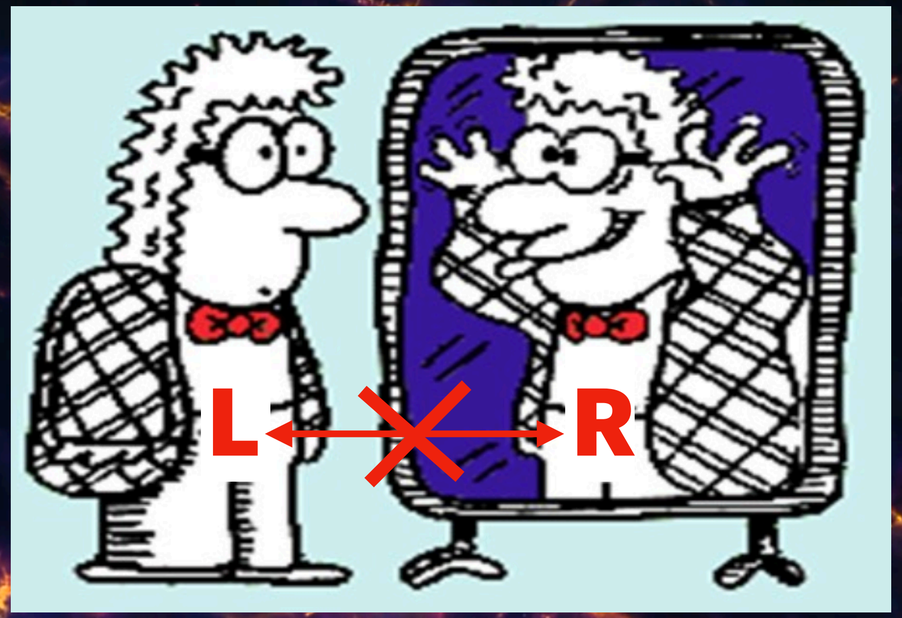


Credit: IllustrisTNG

Future: searching for the IGMF

If we **discover the IGMF** and prove that they are due to galactic feedback - **primordial magnetic fields**

- In the **Standard Model primordial magnetic fields do not exist!**
- **Parity must be violated** in the electromagnetic sector to create primordial magnetic fields



Credit: IllustrisTNG

Future: searching for the IGMF

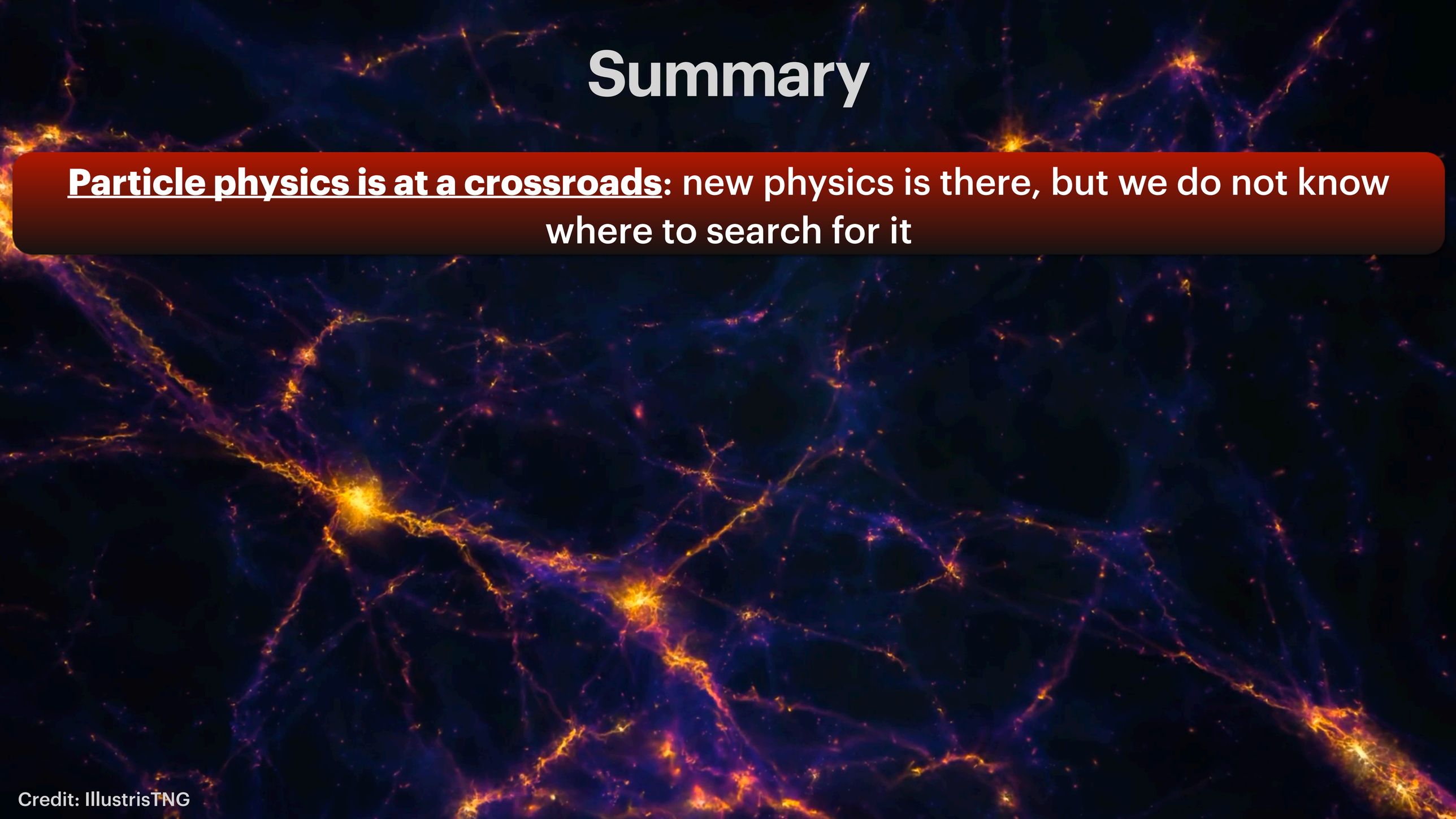
If we **discover the IGMF** and prove that they are not due to galactic feedback - **primordial magnetic fields**

- In the **Standard Model primordial magnetic fields do not exist!**
- **Parity must be violated** in the electromagnetic sector to create primordial magnetic fields
- There are several **classes of extensions of the SM** which violate parity:
  1. **Fermions**: sterile neutrinos, ...
  2. **Bosons**: axions, ...
  3. **Phase transitions**: topological defects, ...

Credit: IllustrisTNG

Summary

Particle physics is at a crossroads: new physics is there, but we do not know where to search for it

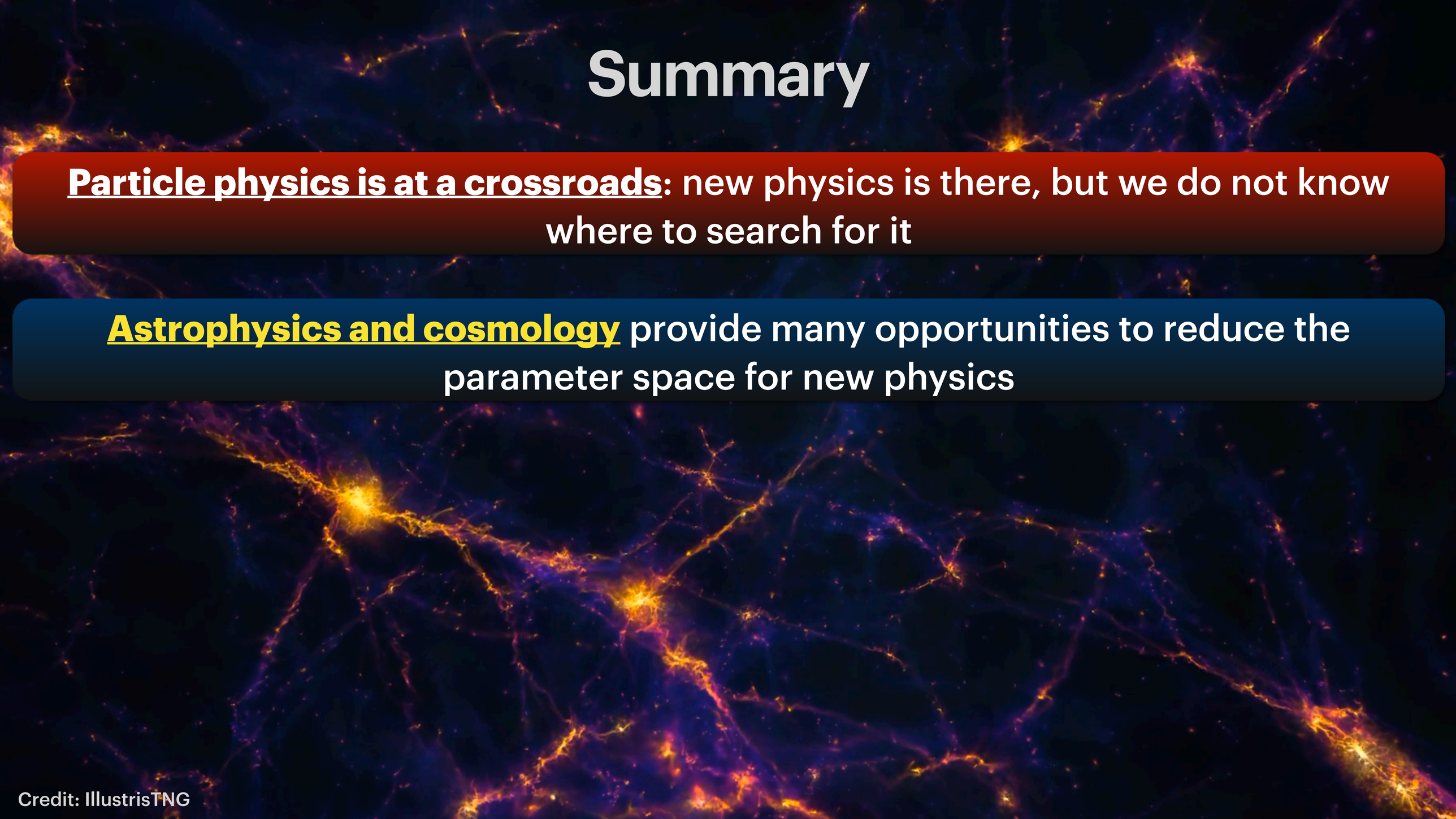


Credit: IllustrisTNG

Summary

Particle physics is at a crossroads: new physics is there, but we do not know where to search for it

Astrophysics and cosmology provide many opportunities to reduce the parameter space for new physics



Credit: IllustrisTNG

Summary

Particle physics is at a crossroads: new physics is there, but we do not know where to search for it

Astrophysics and cosmology provide many opportunities to reduce the parameter space for new physics

- **Intergalactic magnetic fields** likely have a **primordial origin** and can become a **new pillar of cosmology**
- To achieve this ***ambitious goal***, dedicated efforts in γ-ray and radio astronomy, combined with progress in the understanding of galaxy formation, are required

Credit: IllustrisTNG