Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

DESY.

Astroparticle theory and phenomenology, group of professor G. Sigl

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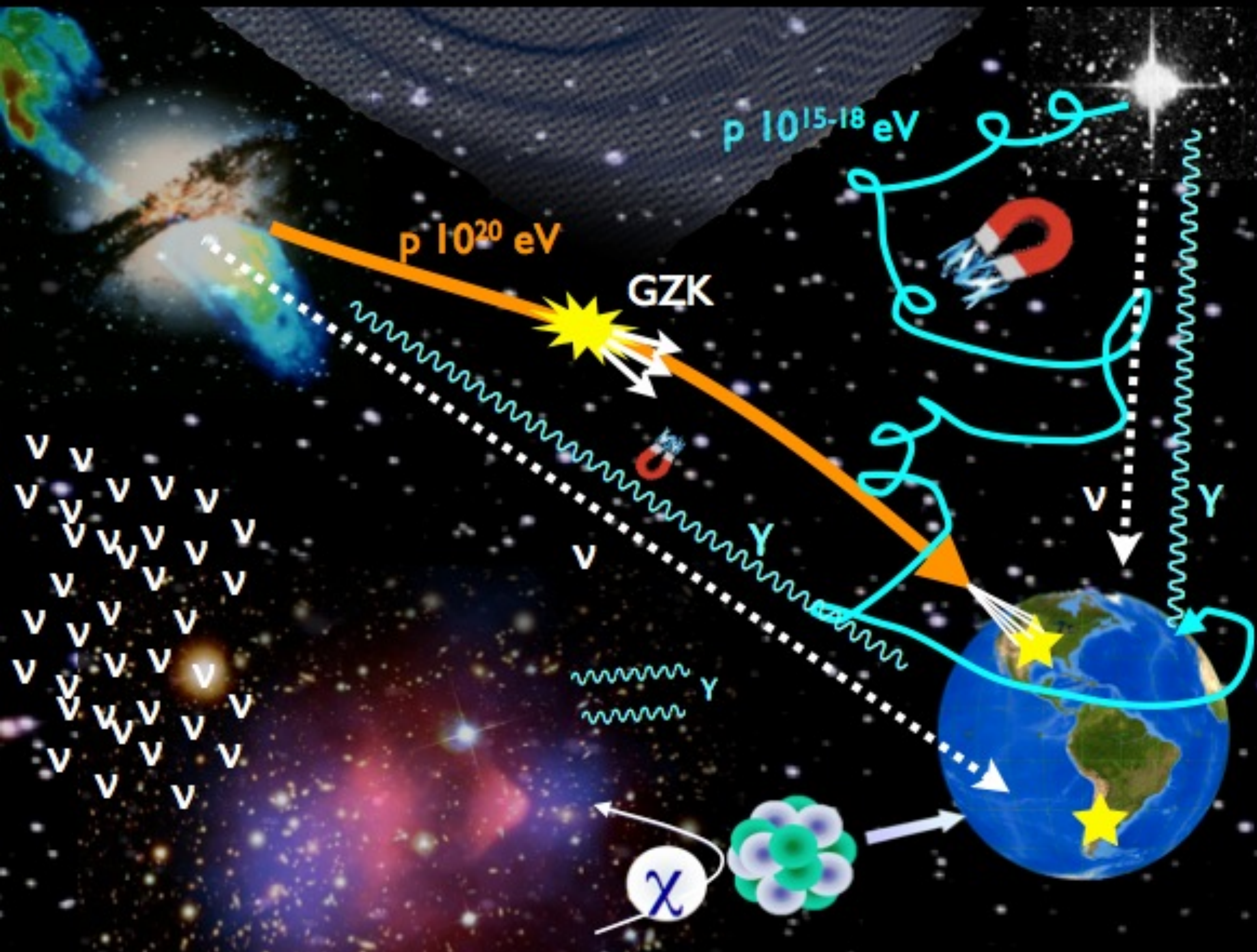
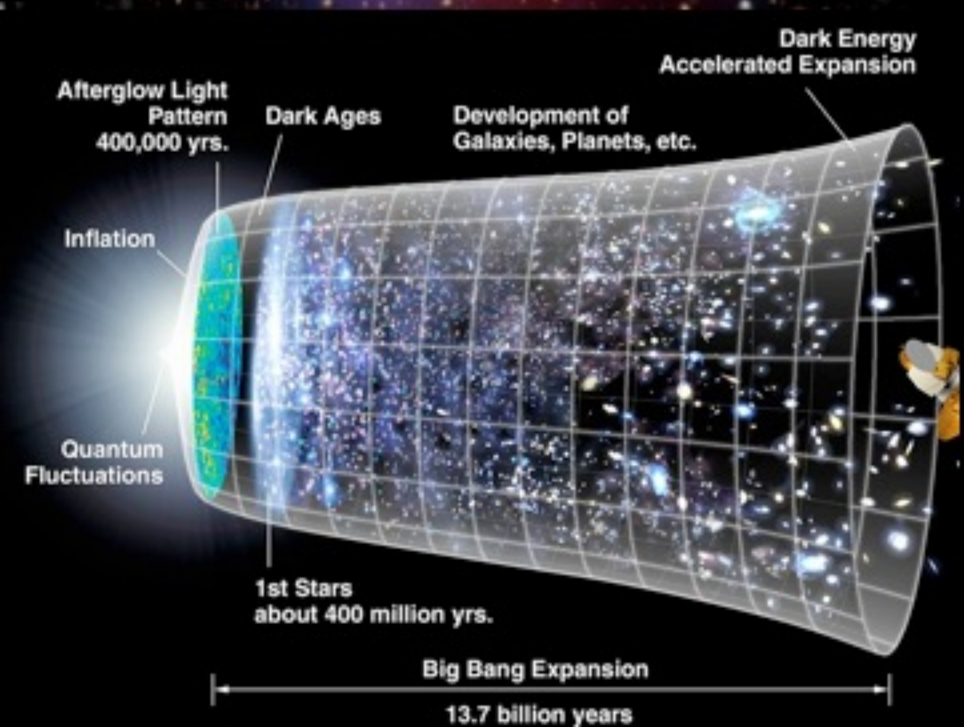
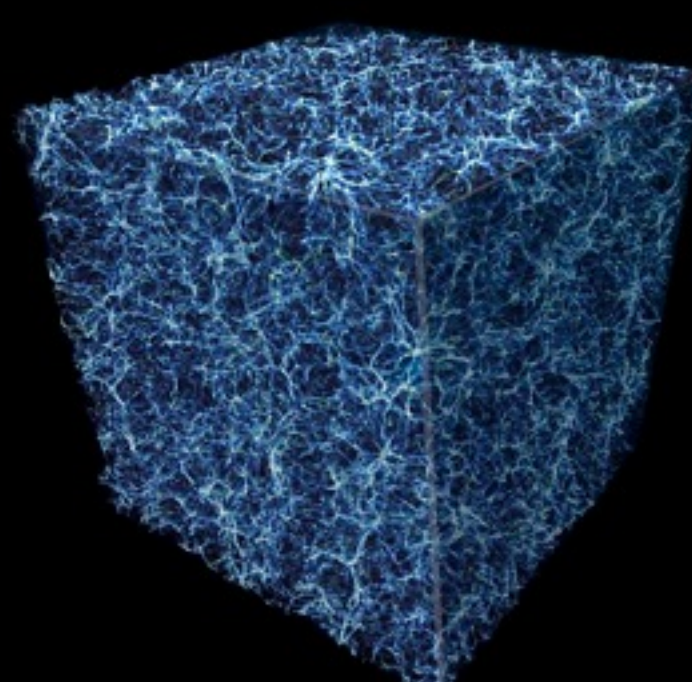
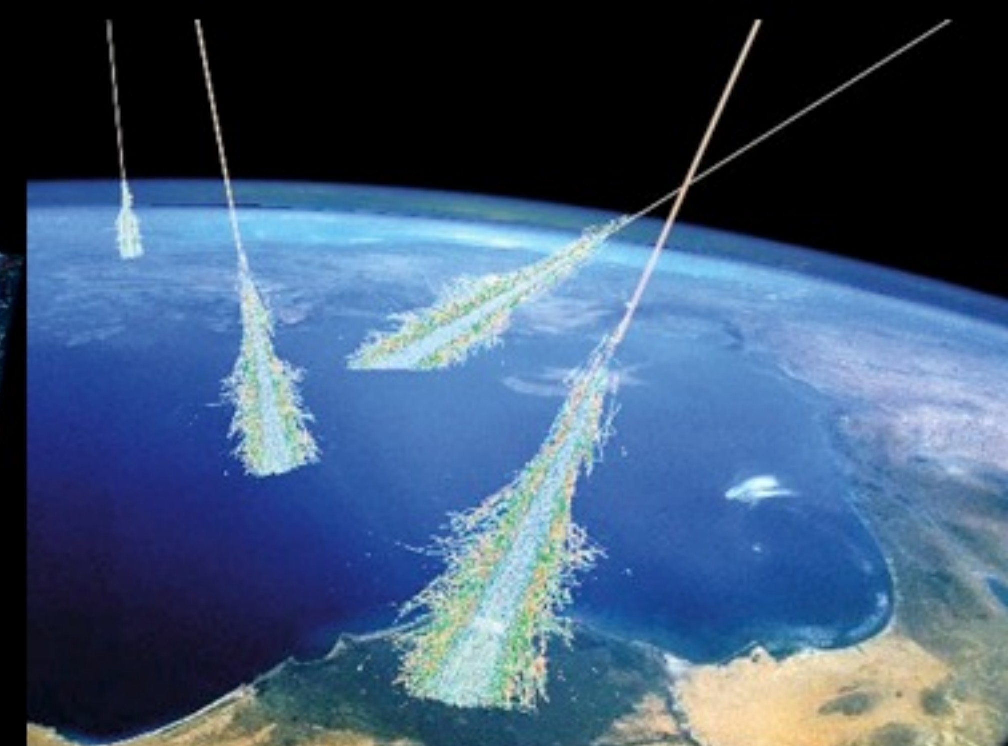
Bundesministerium
für Forschung, Technologie
und Raumfahrt


p 10^15-18 eV
p 10^20 eV
GZK
ν
γ
χ


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years





Theoretical and phenomenological questions at the interface of particle and astrophysics

-> origin and propagation of particles of the highest know energies in Nature ($\sim 10^{20}$ eV)

-> light axions as dark matter and their astrophysical signatures through mixing with photons, in particular radio lines

-> Phenomenology of the early Universe (for example primordial magnetic fields)

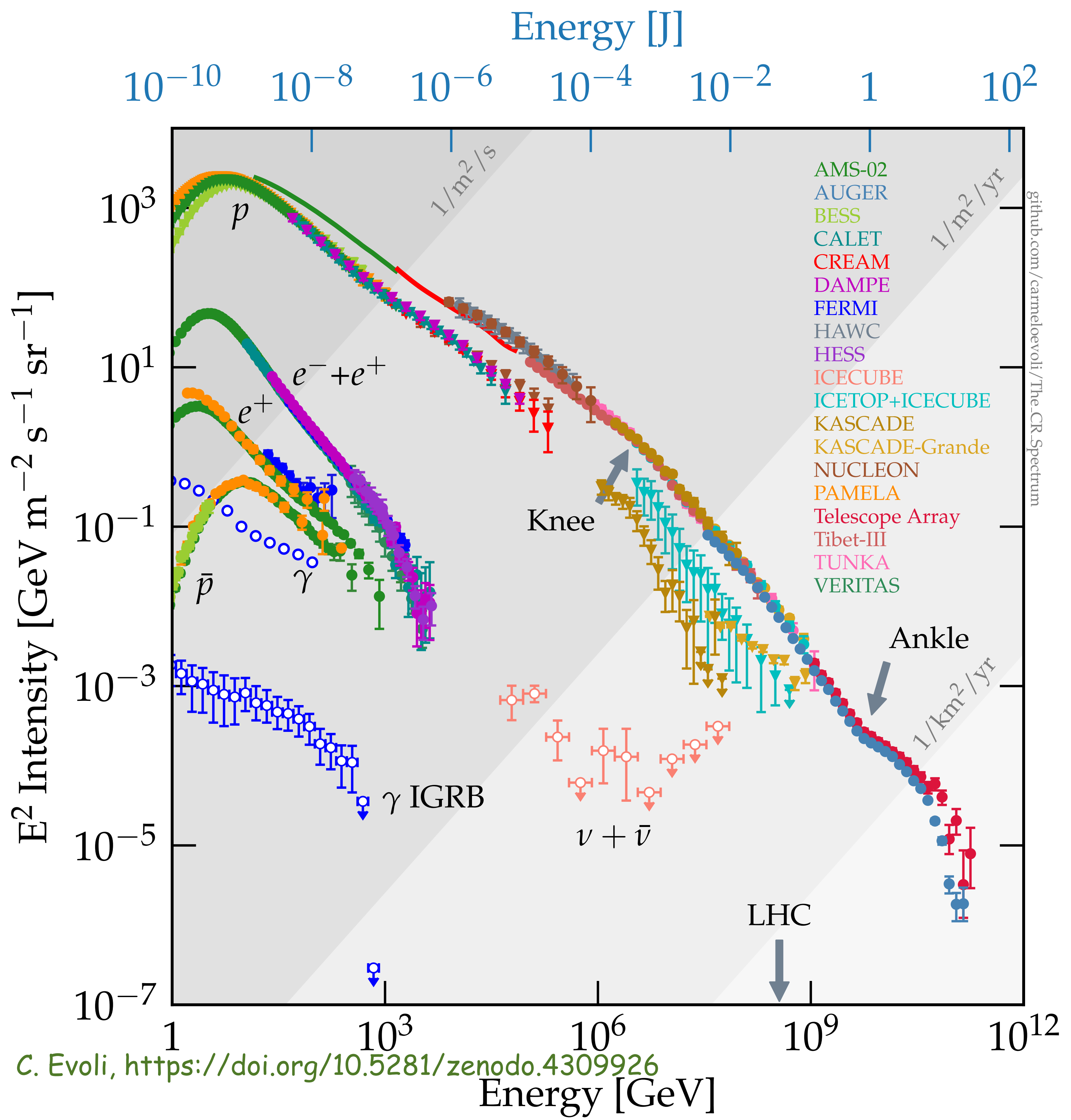
-> role of weakly interacting particles such as neutrinos in supernovae and in the early Universe, collective neutrino oscillations

“multi-messenger” signatures of dark matter in the electromagnetic spektrum from radio to gamma radiation, in neutrinos and in charged cosmic rays

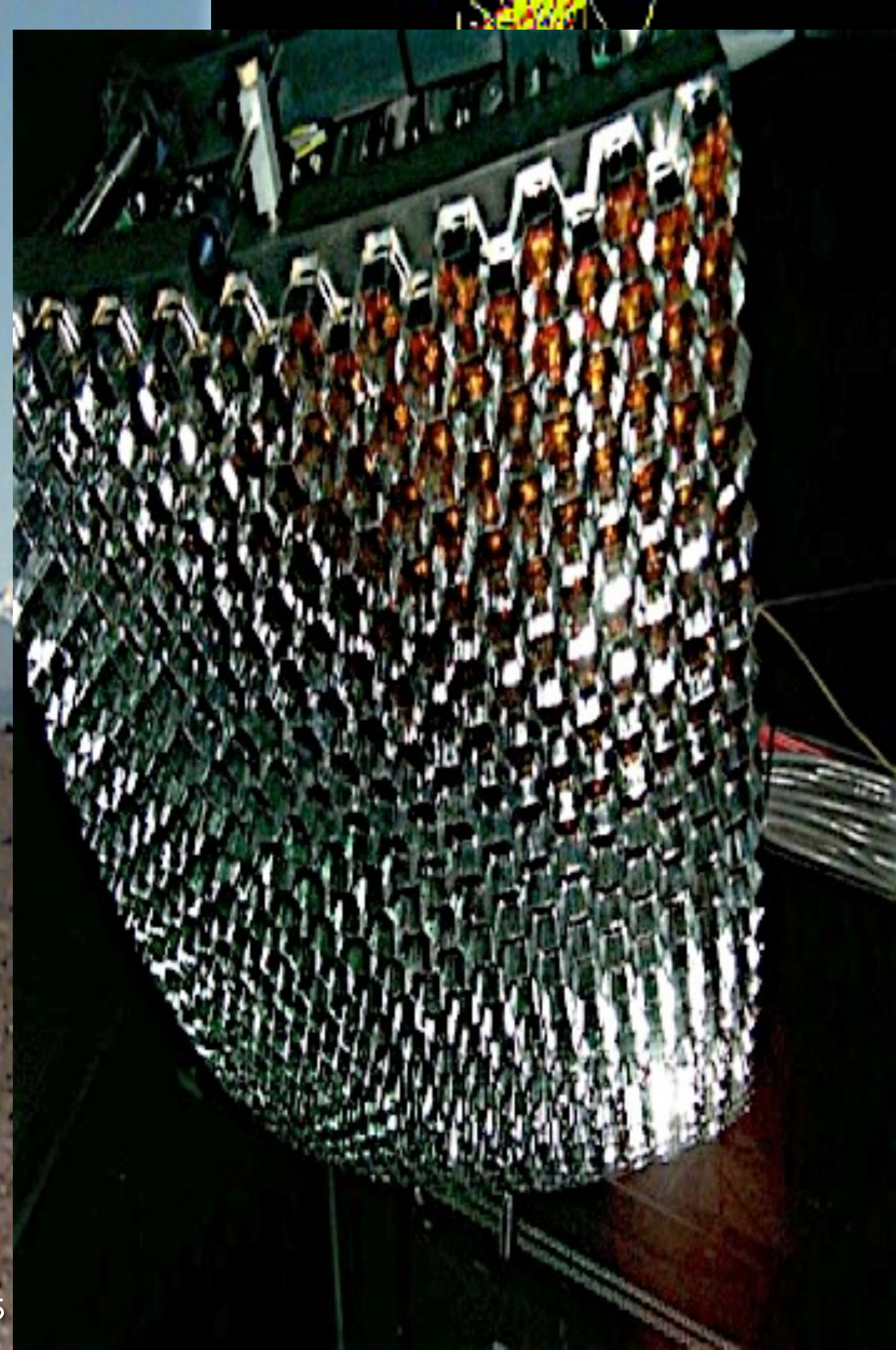
connections to gravitational wave astronomy und to particle physics at accelerators such as the LHC.

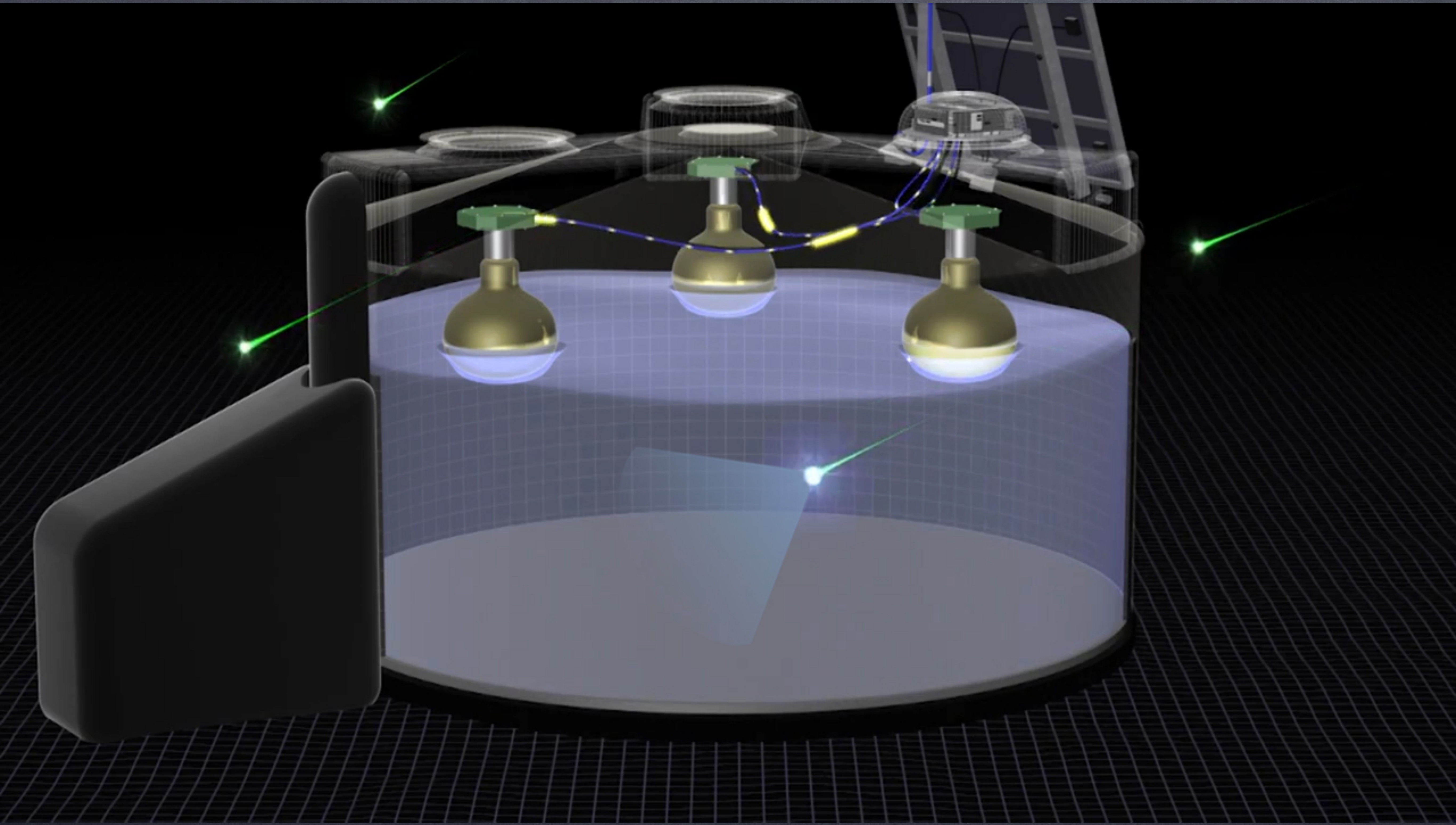
collaboration with experimental astroparticle physics and the Sternwarte

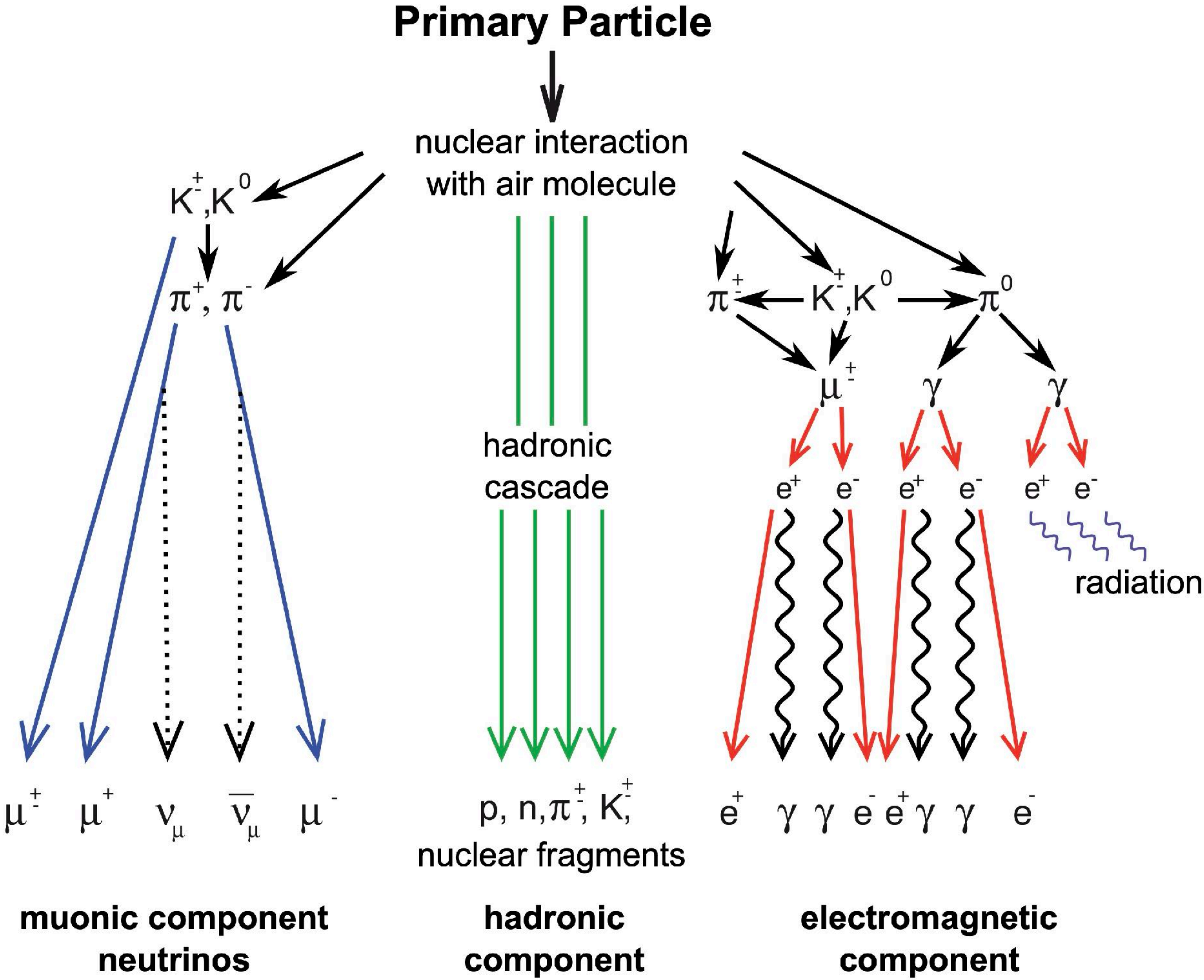
High Energy Cosmic Rays



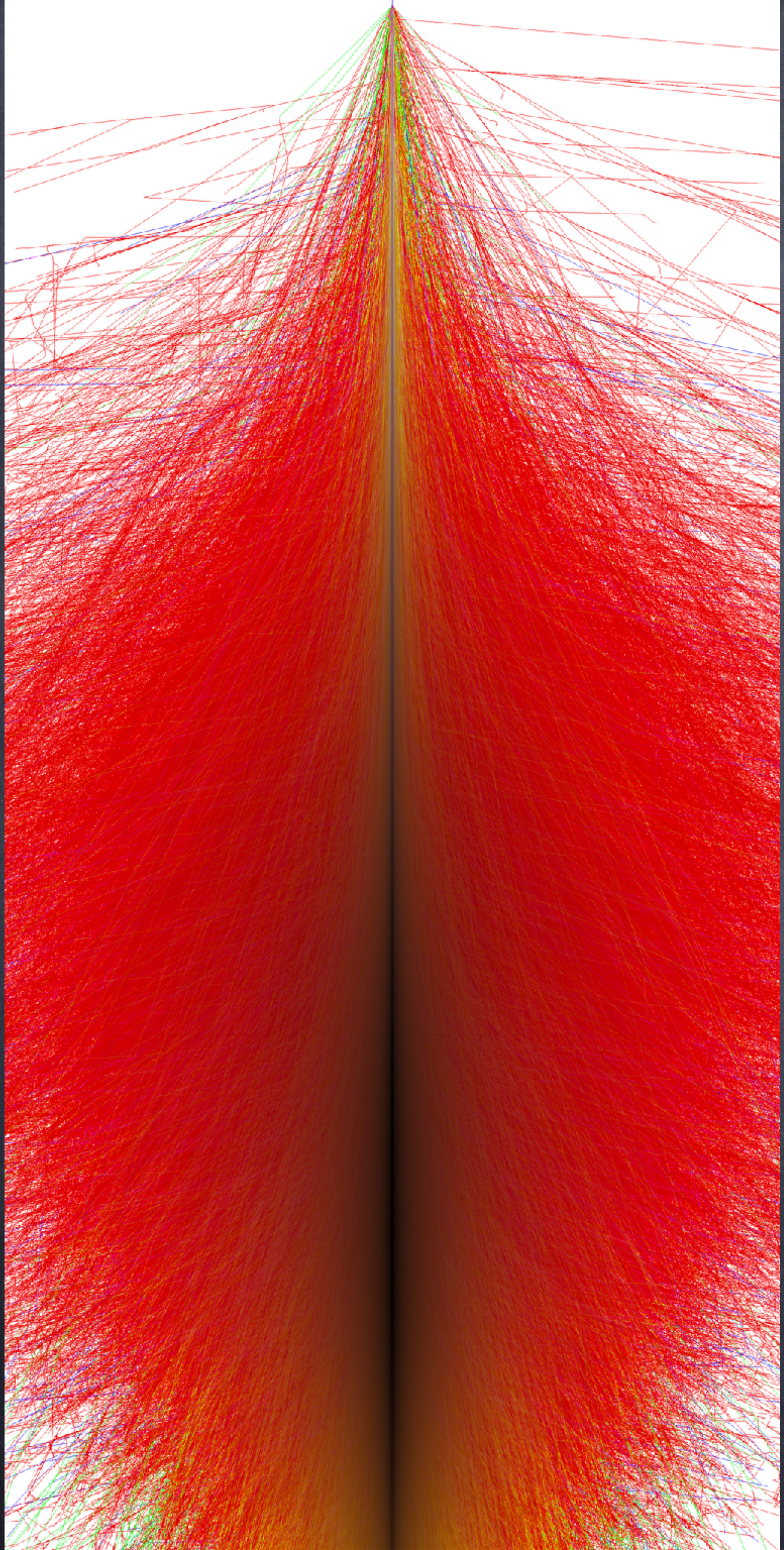
C. Evoli, https://doi.org/10.5281/zenodo.4309926





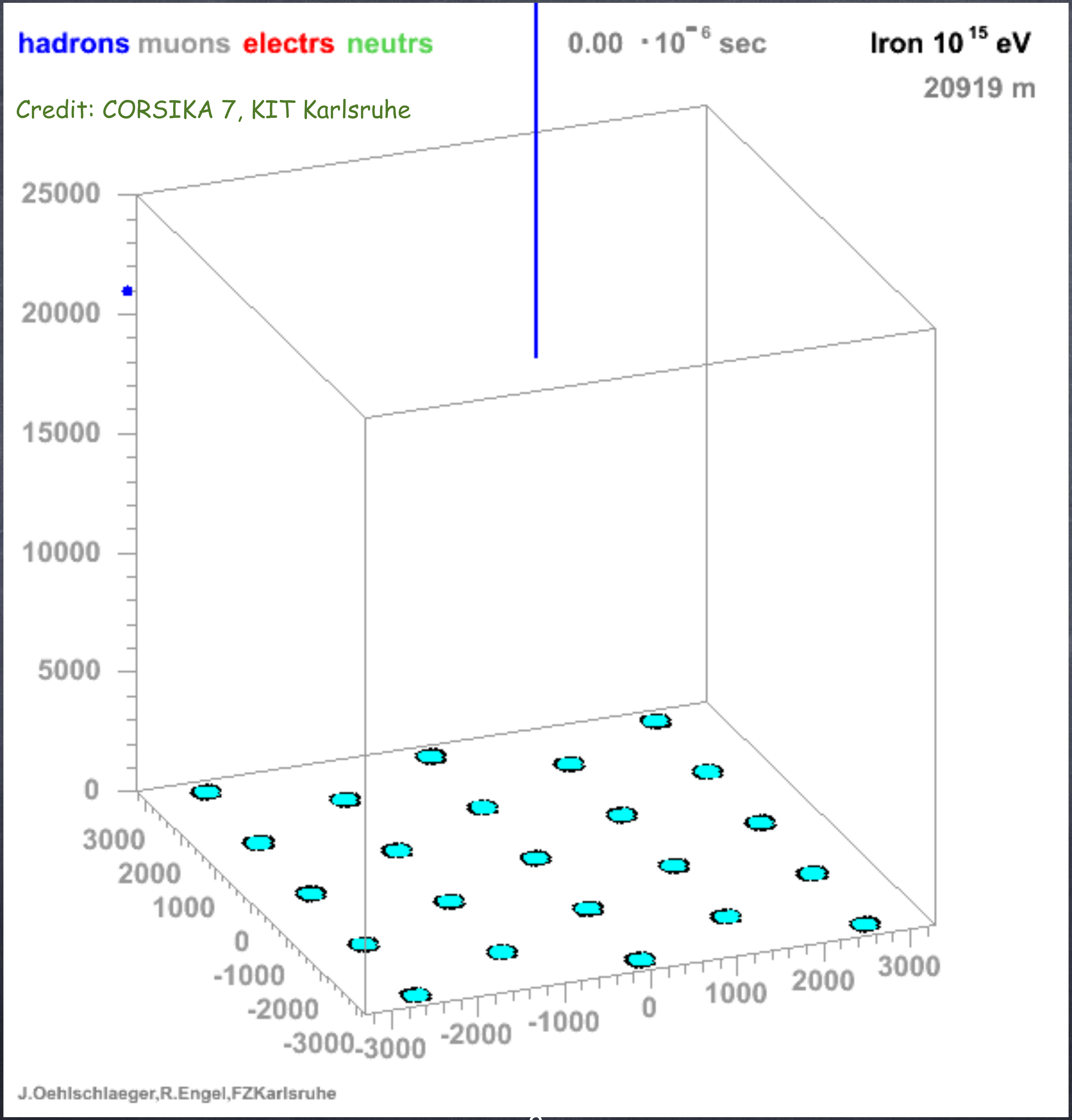


Primary Particle
nuclear interaction
with air molecule
$K^{\pm}, K^0$
π^+, π^-
$\pi^{\pm}$
$K^{\pm}, K^0$
π^0
$\mu^{\pm}$
γ
γ
hadronic
cascade
e^+ e^- e^+ e^- e^+ e^-
radiation
$\mu^{\pm}$ μ^+ ν_μ $\bar{\nu}_\mu$ μ^-
p, n, $\pi^{\pm}$, $K^{\pm}$,
nuclear fragments
e^+ γ γ e^- e^+ γ γ e^-
muonic component
neutrinos
hadronic
component
electromagnetic
component



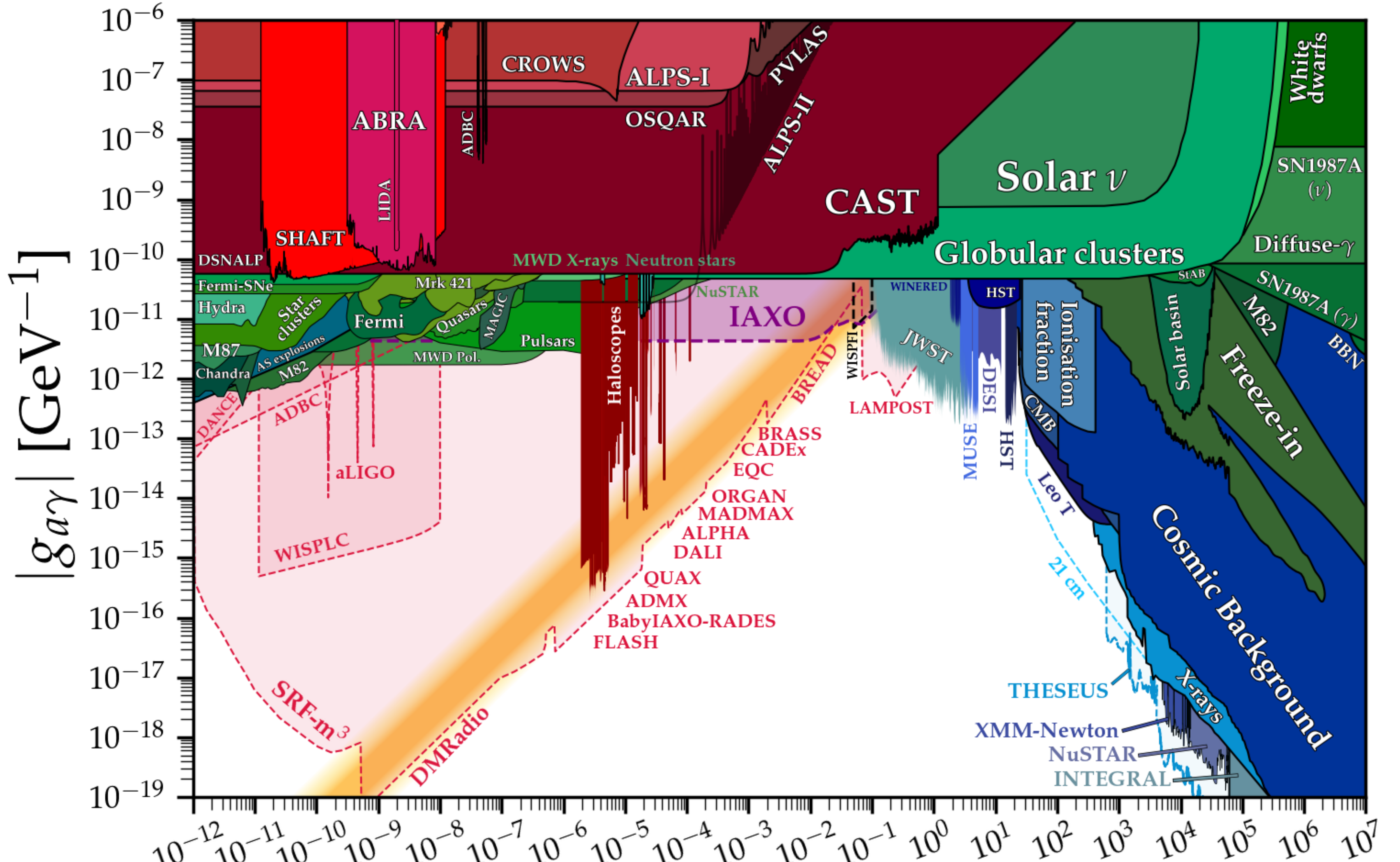
iron, 10^{15} eV

Credit: CORSIKA 7, KIT Karlsruhe

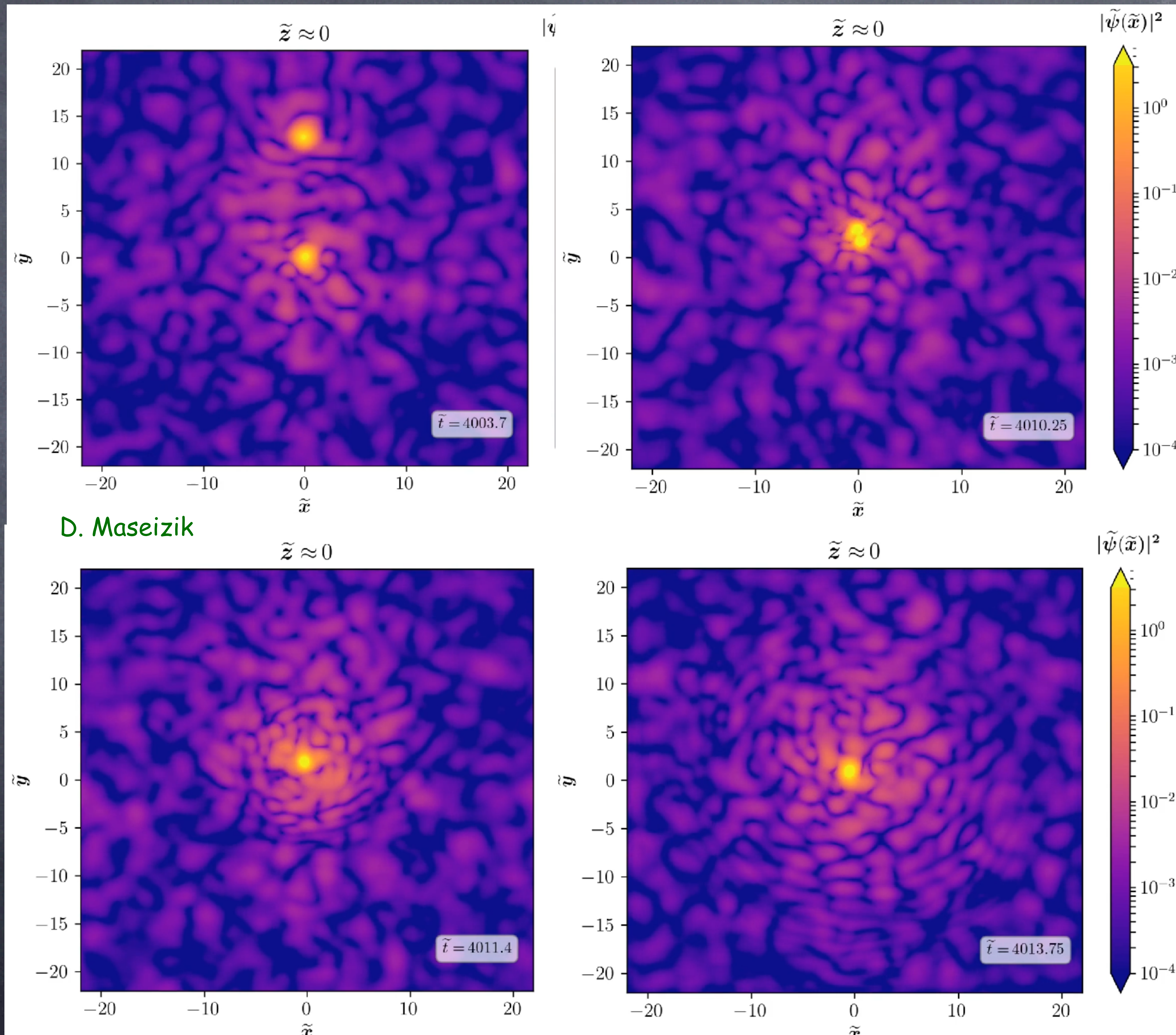


hadrons muons electrs neutrs
0.00 ·10^-6 sec
Iron 10^15 eV
20919 m
Credit: CORSIKA 7, KIT Karlsruhe
25000
20000
15000
10000
5000
0
3000
2000
1000
0
-1000
-2000
-3000
-3000
-2000
-1000
0
1000
2000
3000
J.Oehlschlaeger,R.Engel,FZKarlsruhe

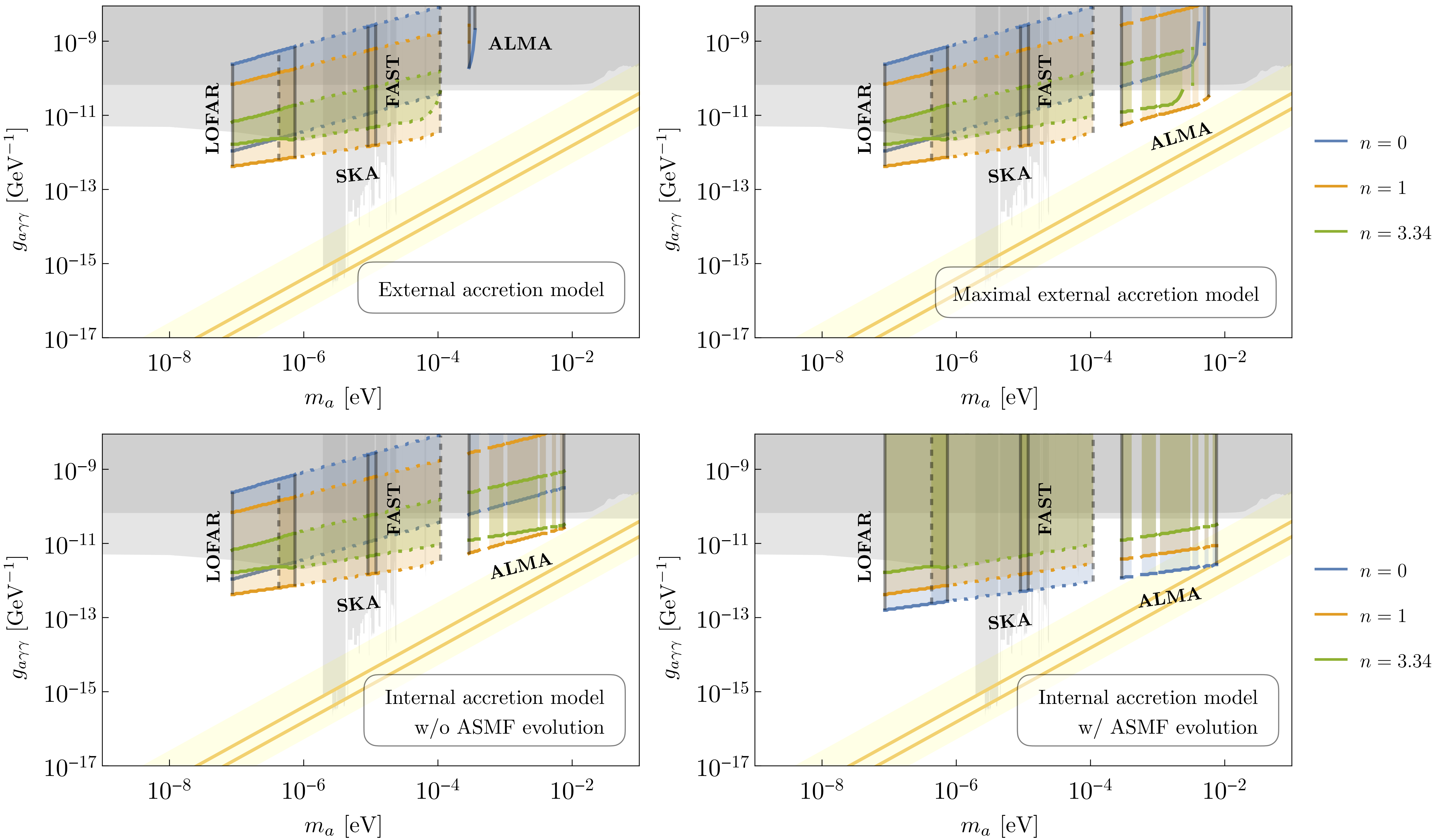
Axion-like Particles (ALPs)



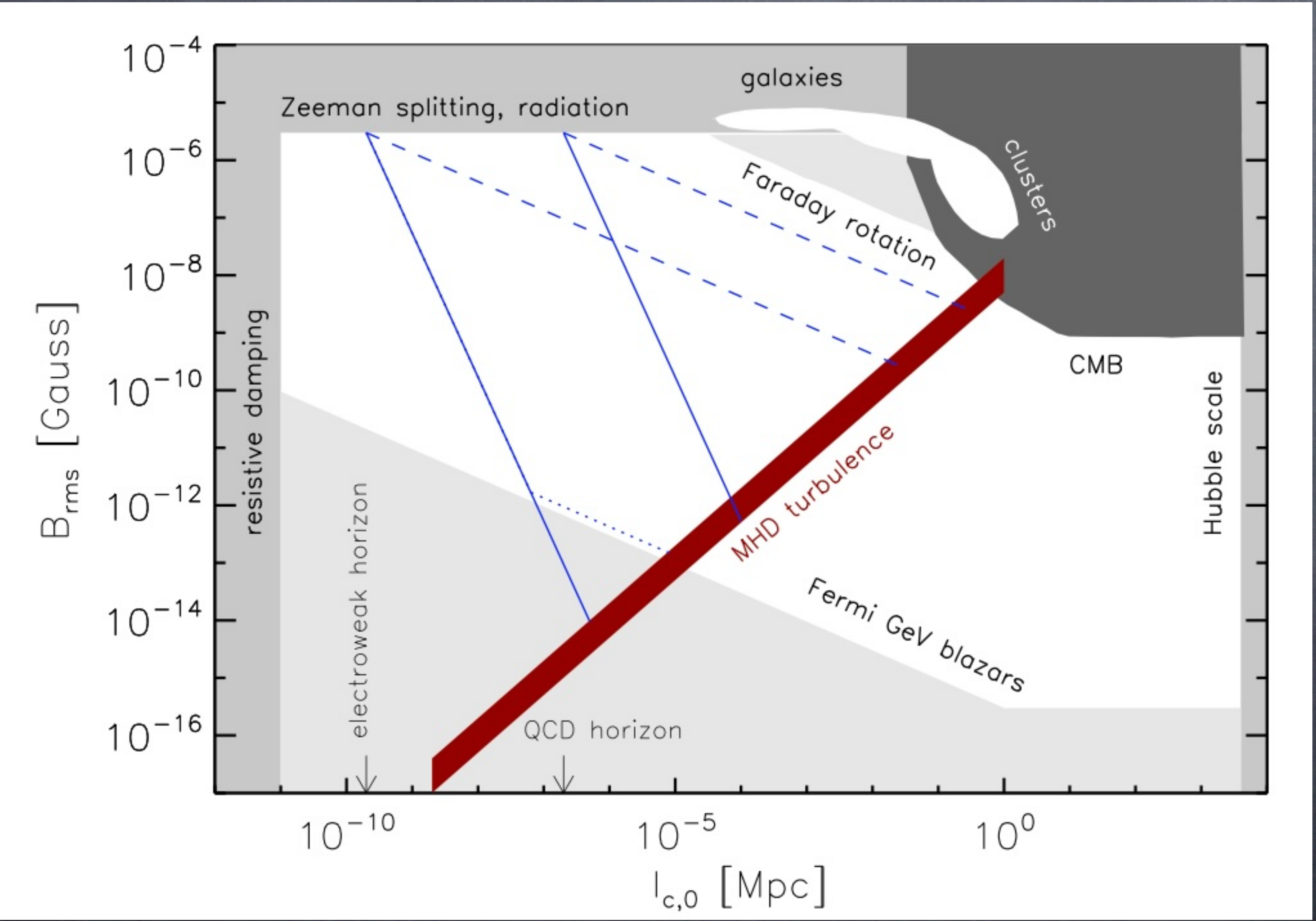
from git-hub repository https://cajohare.github.io/AxionLimits/ accessed on 24.11.2025 solving for the evolution of axion stars with Schrödinger-Poisson equations: accretion and mergers



constraints from radio telescopes:



Cosmic Magnetic Fields



integro-differential equations to solve for the evolution of primordial magnetic fields:

$$\partial_t M_q = q^2 \int_{-\infty}^{\infty} \frac{d\ln k}{\rho V} \tau_c \Bigg[-\frac{2}{3}\left(U_k + 2M_k\right) M_q + \frac{1}{3}\frac{k^2}{(4\pi)^2} H_q H_k \tag{3.288}$$

$$+ \int_0^{\pi} d\theta \, \frac{(q\sin\theta)^3}{2k_1^5}\left(q^2 + k^2 - qk\cos\theta\right) M_k U_{k_1} \Bigg] - 2\eta q^2 M_q$$

and

$$\partial_t U_q = q^2 \int_{-\infty}^{\infty} \frac{d\ln k}{\rho V} \tau_c \Bigg\{ -\frac{2}{3}\left(M_k + U_k\right) U_q \tag{3.289}$$

$$+ \int_0^{\pi} d\theta \Bigg[\frac{q^2 k \sin\theta}{4k_1^5}\left(qk\sin^2\theta + 2k_1^2\cos\theta\right) M_k M_{k_1} +$$

$$+ \frac{(q\sin\theta)^3 k}{4k_1^5}\left(3k - q\cos\theta\right) U_k U_{k_1} +$$

$$+ \frac{q^2 k^2 \sin\theta}{(16\pi)^2 k_1^3}\left(-2q - q\sin^2\theta + 2k\cos\theta\right) H_k H_{k_1} \Bigg]\Bigg\} - 2\nu q^2 U_q \,,$$

and for the helicity power spectrum H_q,

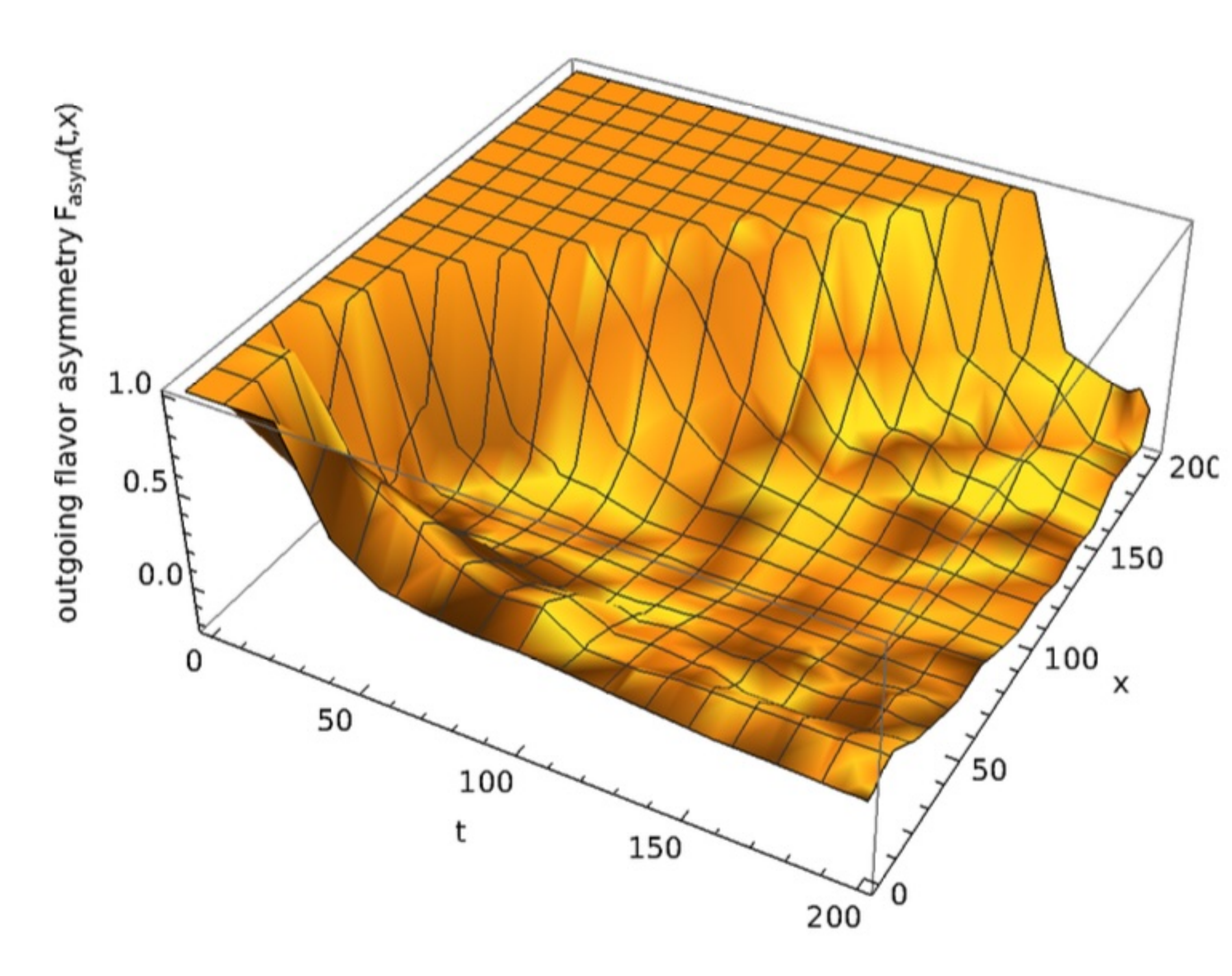
$$\partial_t H_q = \int_{-\infty}^{\infty} \frac{d\ln k}{\rho V} \tau_c \Bigg[\frac{4k^2}{3} M_q H_k - 4q^2 M_k H_q - \frac{2q^2}{3} U_k H_q +$$

$$+ \int_0^{\pi} \mathrm{d}\theta \, \frac{q^5 k^2}{2k_1^5} \sin^3\theta \, U_{k_1} H_k \Bigg] - 2\eta q^2 H_q \,, \tag{3.290}$$

Collective neutrino oscillations in compact objects

$$\partial_t \rho(\mathbf{r},\mathbf{p}) + \mathbf{v}(\mathbf{r},\mathbf{p}) \cdot \nabla_{\mathbf{r}} \rho(\mathbf{r},\mathbf{p}) = -i \left[\Omega^0_{\mathbf{p}} + \Omega_m(\mathbf{r}) + \Omega^{\mathrm{S}}(\mathbf{r},\mathbf{p}), \rho_{\mathbf{p}}\right] + \partial_t \rho(\mathbf{r},\mathbf{p})_{\mathrm{coll}} \,,$$

$$\Omega^{\mathrm{S}}(\mathbf{r},\mathbf{p}) = \sqrt{2} G_{\mathrm{F}} \int \frac{d^3\mathbf{q}}{(2\pi)^3} g_{\mathbf{p},\mathbf{q}} \left\{ G_{\mathrm{S}} [\rho(\mathbf{r},\mathbf{q}) - \bar{\rho}(\mathbf{r},\mathbf{q})] G_{\mathrm{S}} + G_{\mathrm{S}} \mathrm{Tr}\left[(\rho(\mathbf{r},\mathbf{q}) - \bar{\rho}(\mathbf{r},\mathbf{q})) G_{\mathrm{S}} \right] \right\} \,,$$



Planned openings within the cluster Quantum Universe

- spring 2026: PhD position on particle acceleration in neutron star mergers
- spring 2027: PhD position on multi-messenger signals of super-massive black holes