Desperately Seeking Susy

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tl;dr

- Supersymmetry (Susy) is a symmetry that predicts a new partner particle for each species of elementary particles.
- Not a single one of them has ever been observed.
- WTF?!?

The Standard Model (of Particle Physics)

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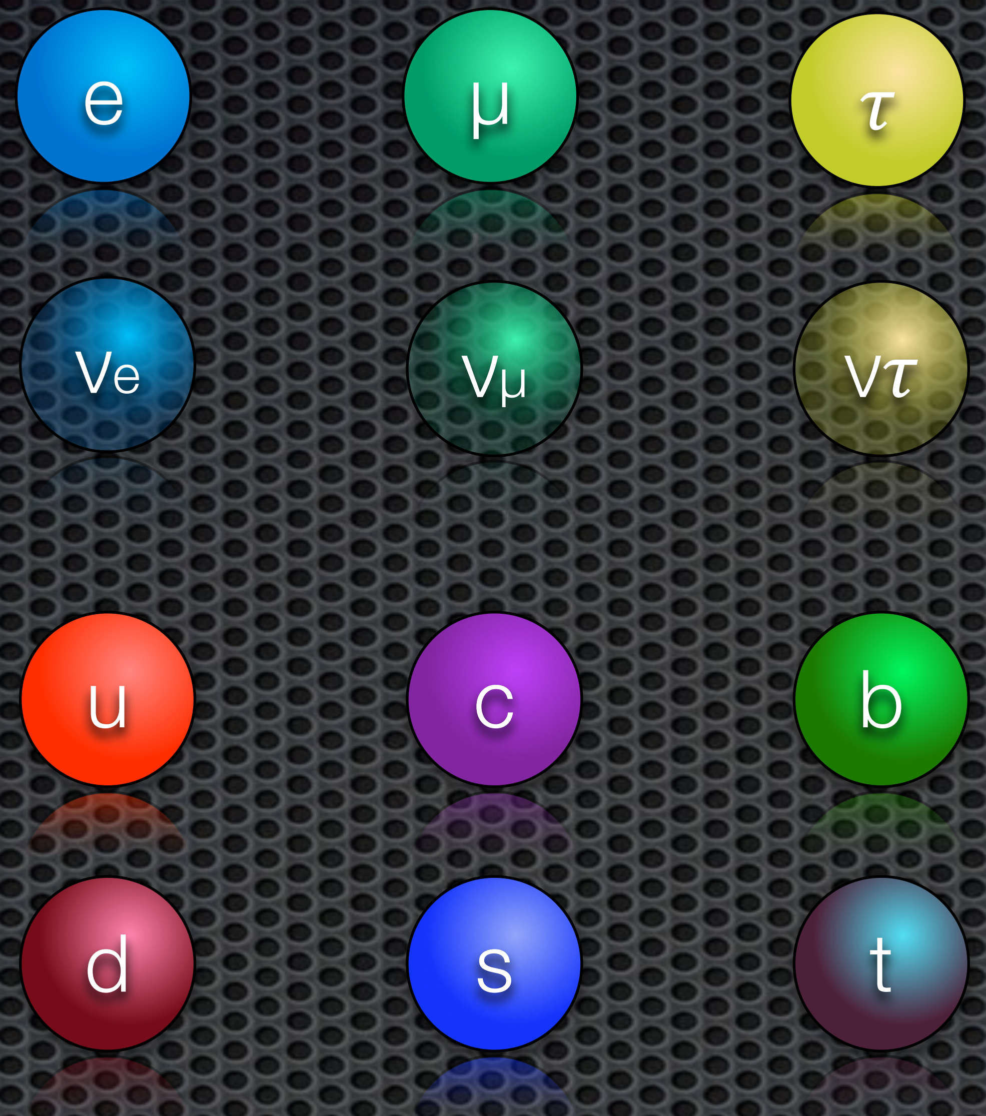

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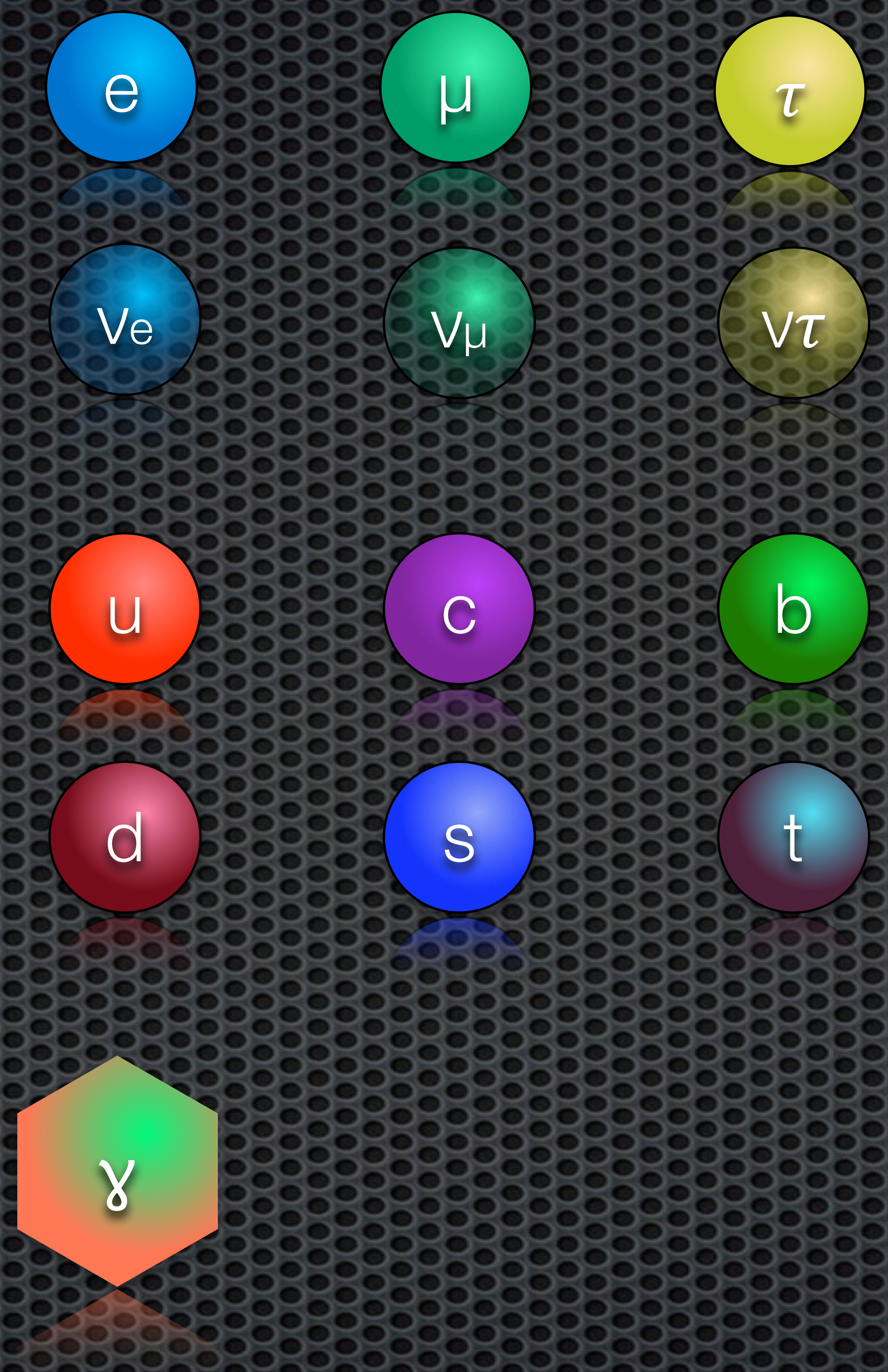

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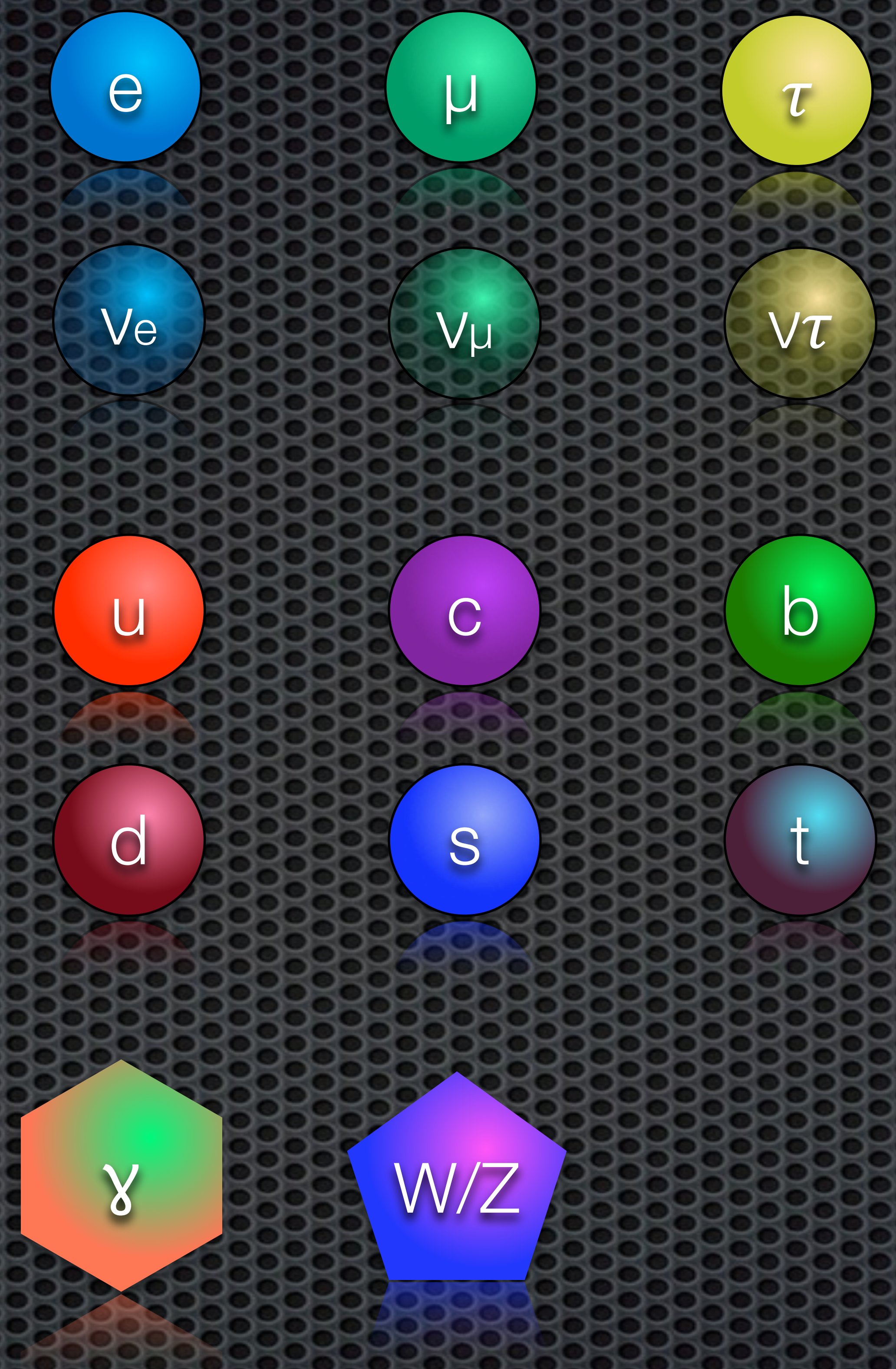

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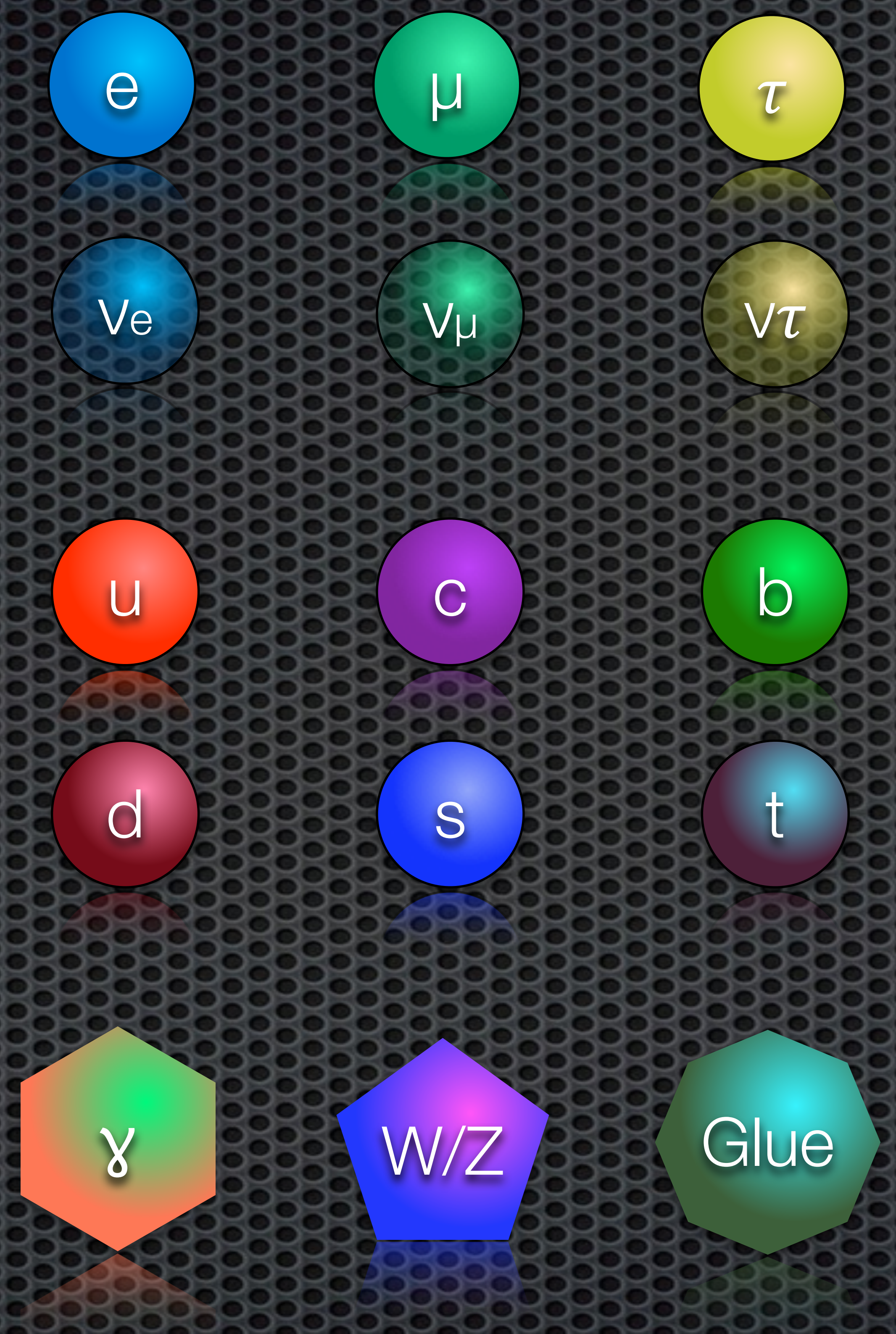

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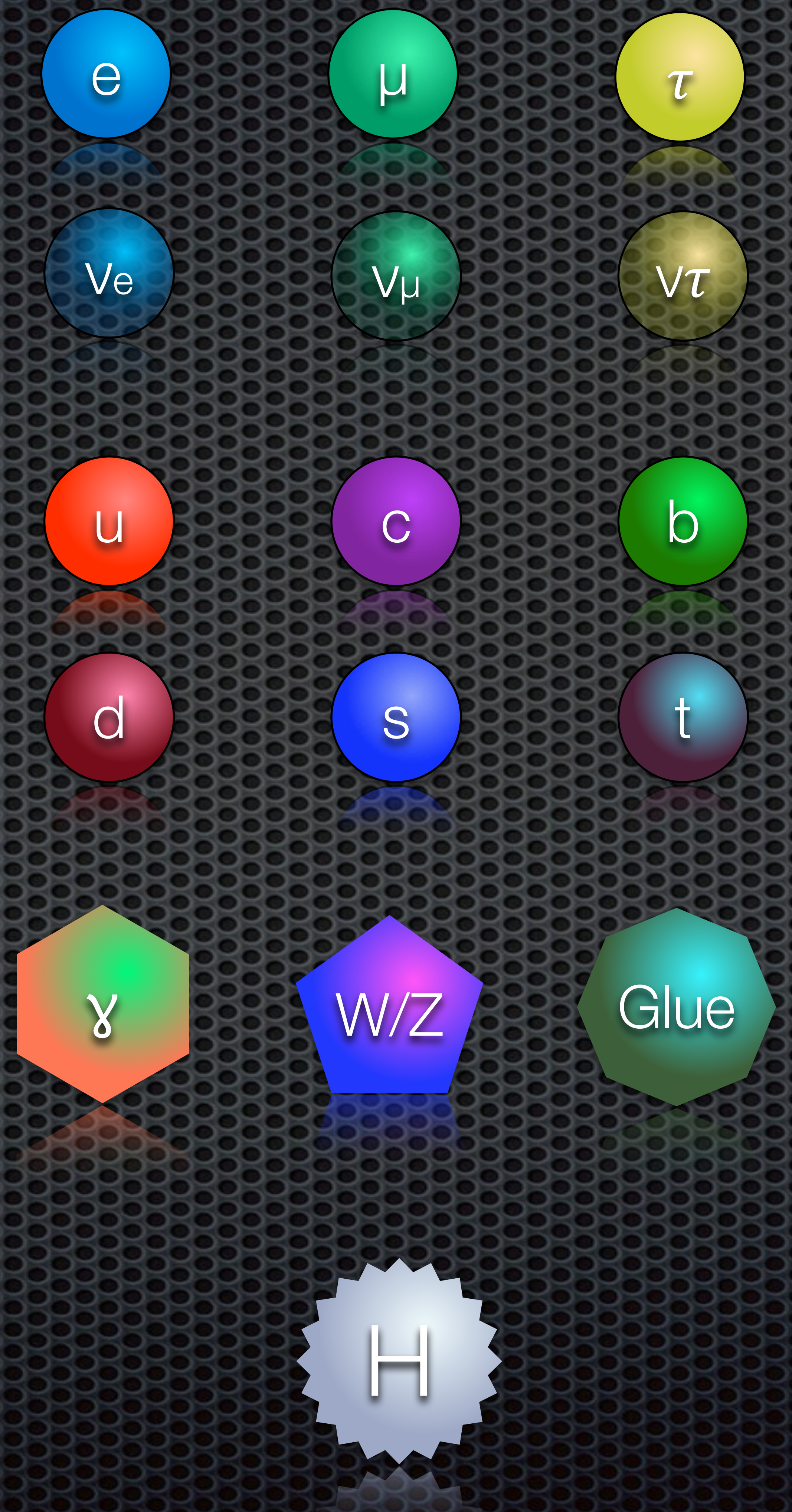

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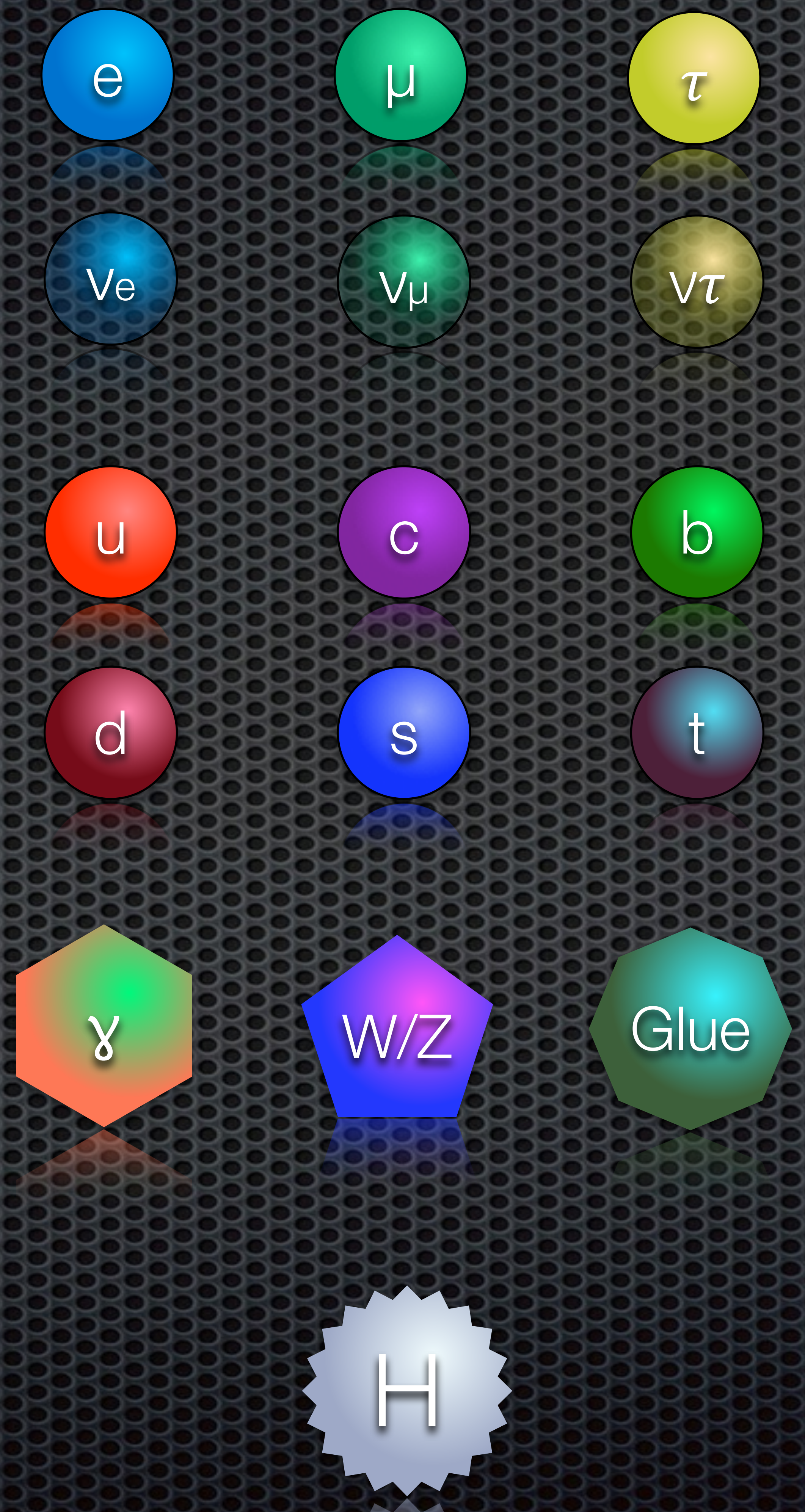

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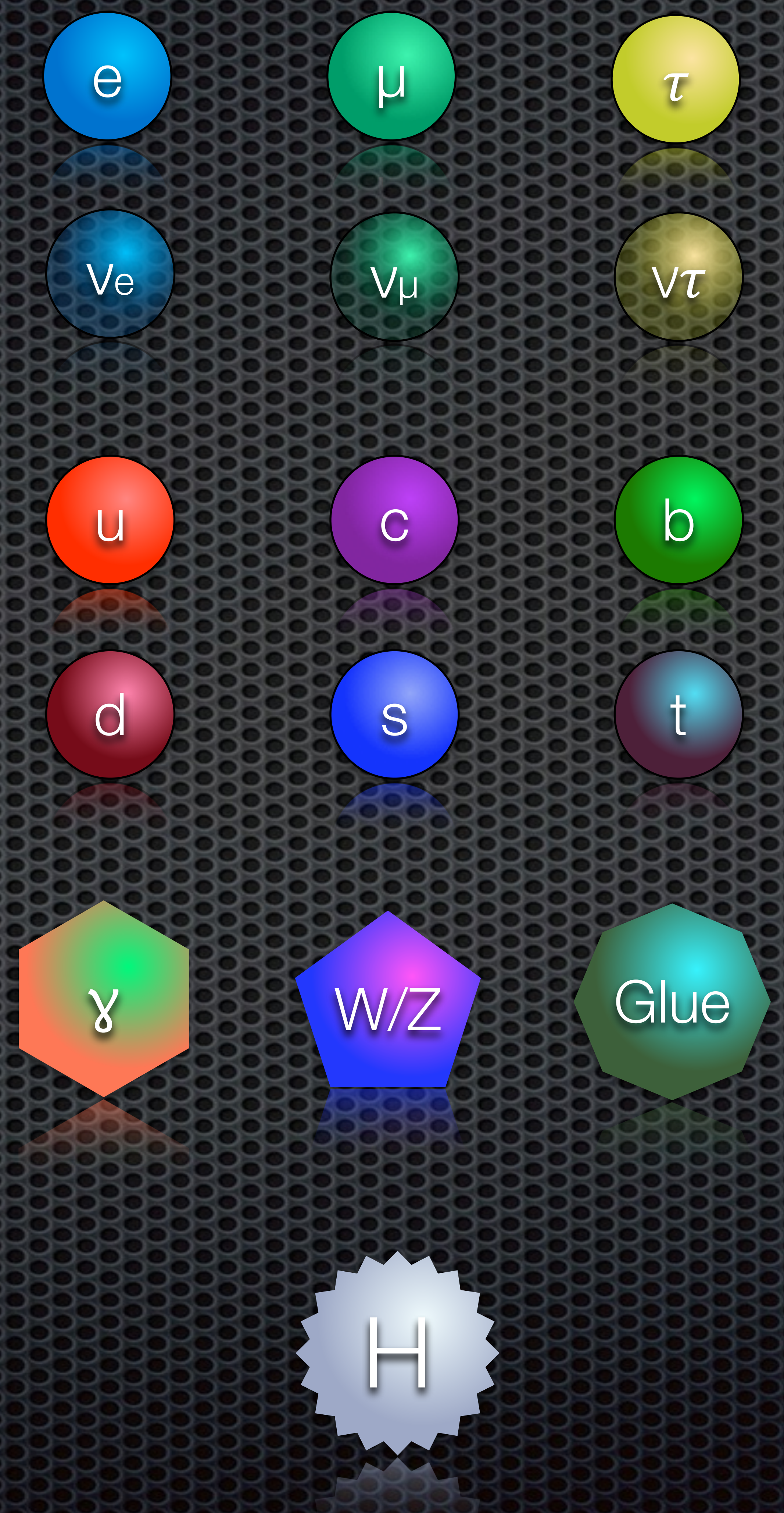

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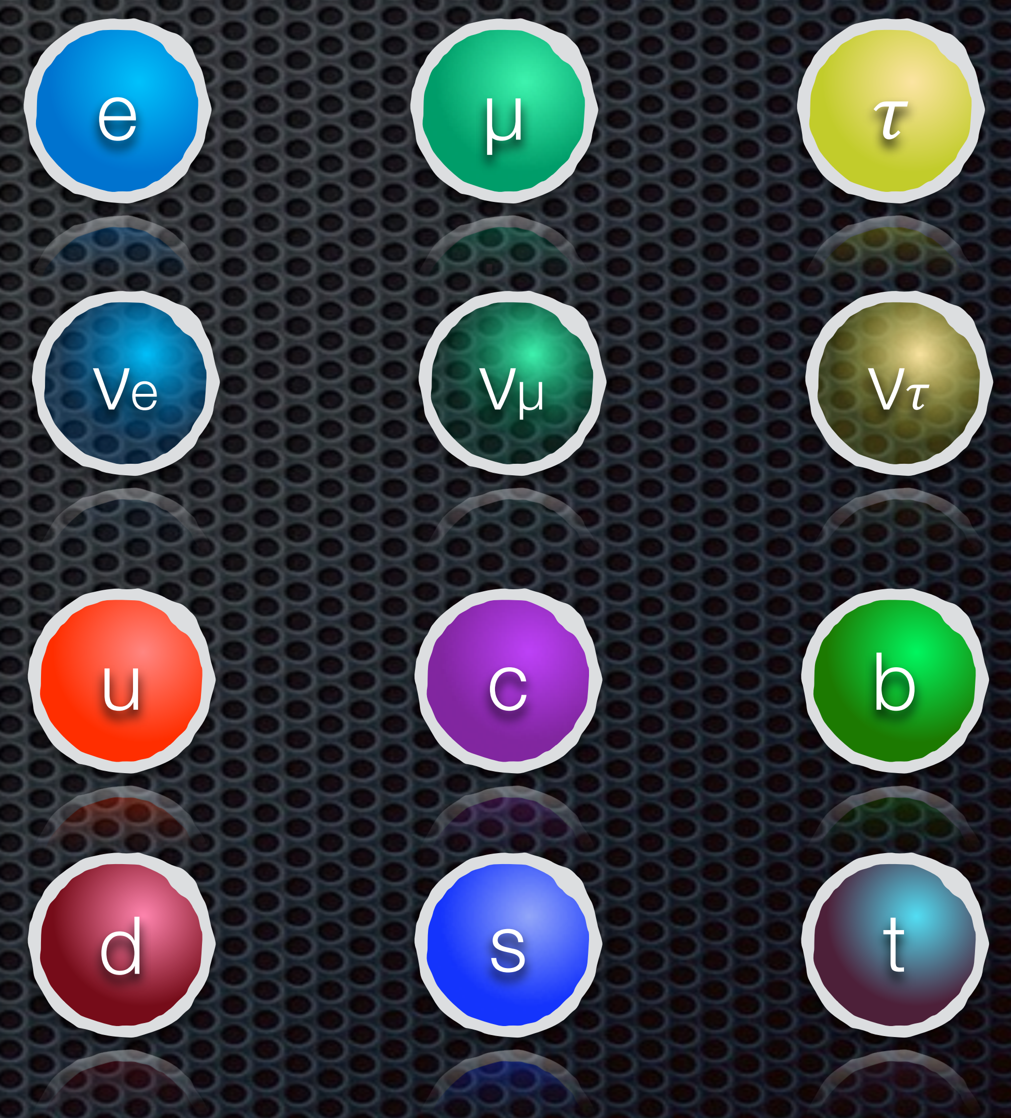

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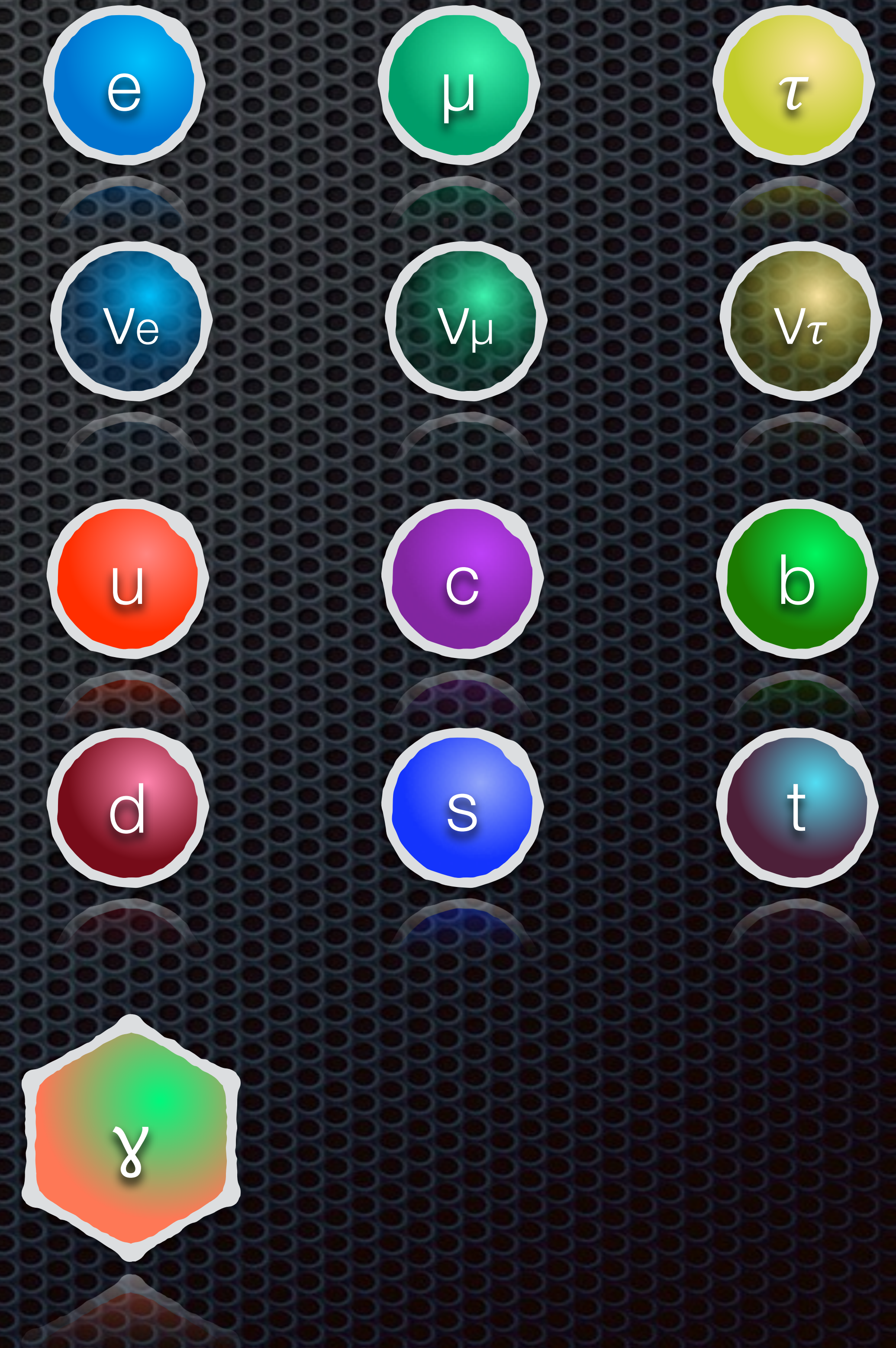

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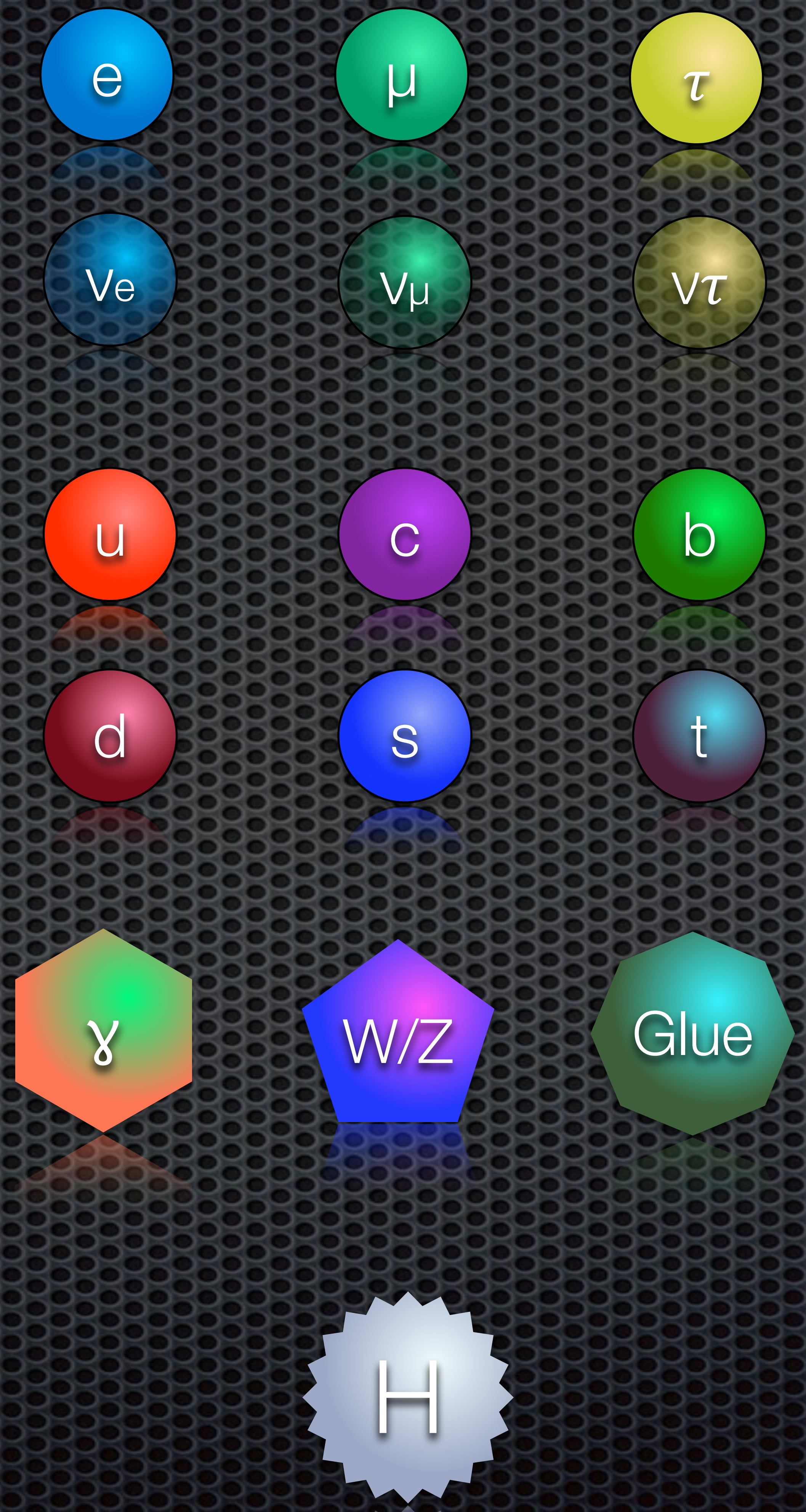

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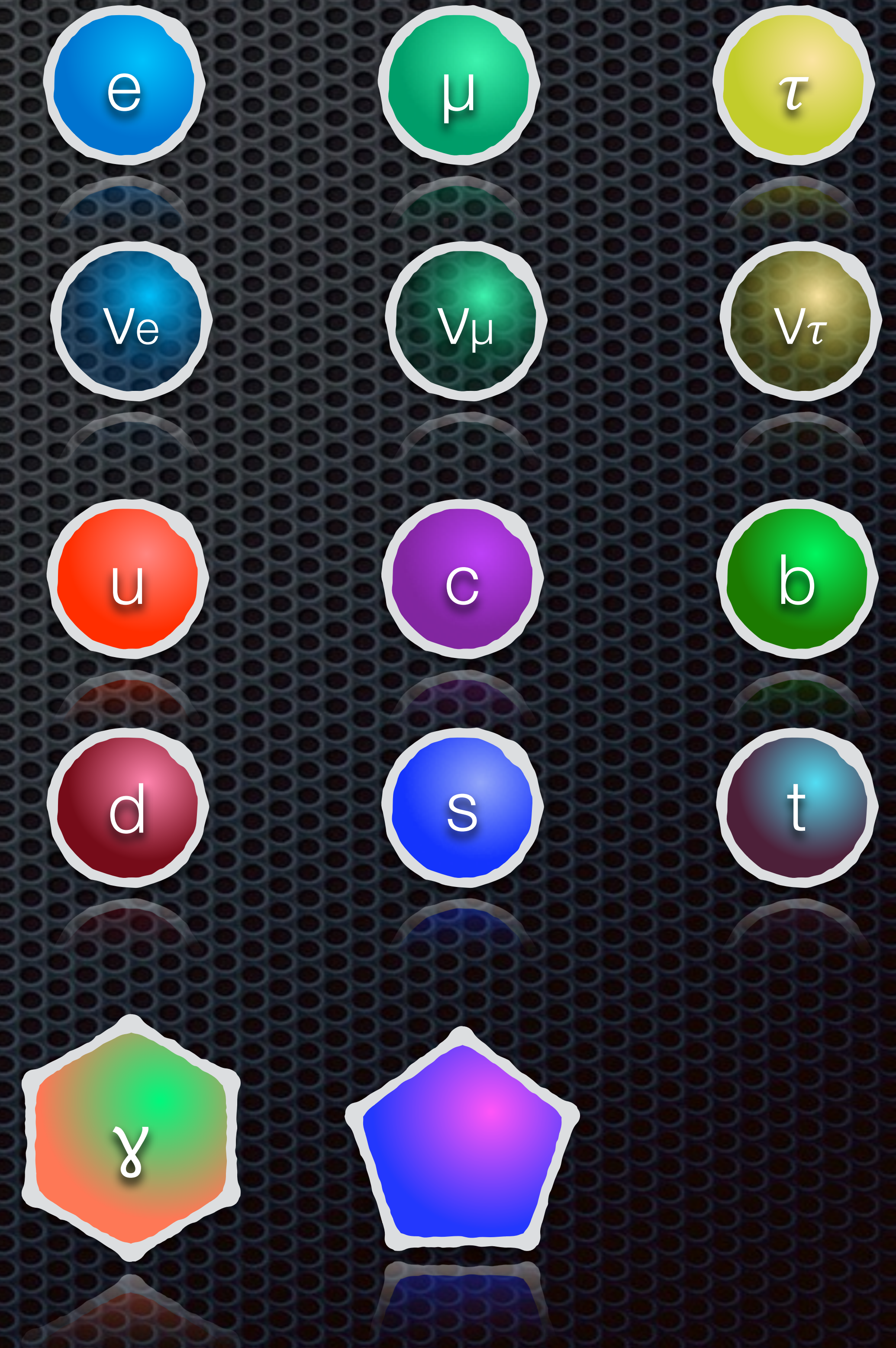

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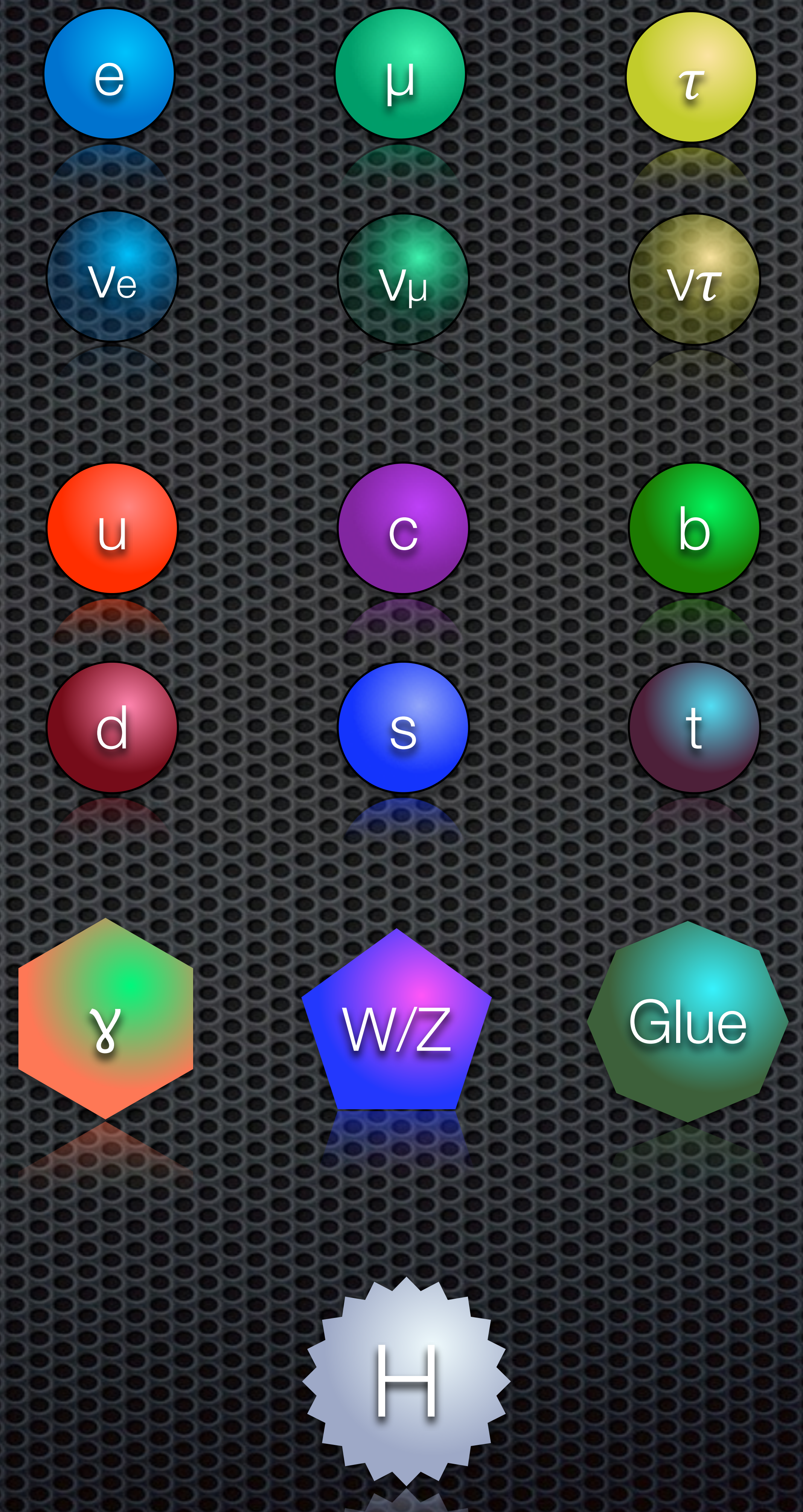

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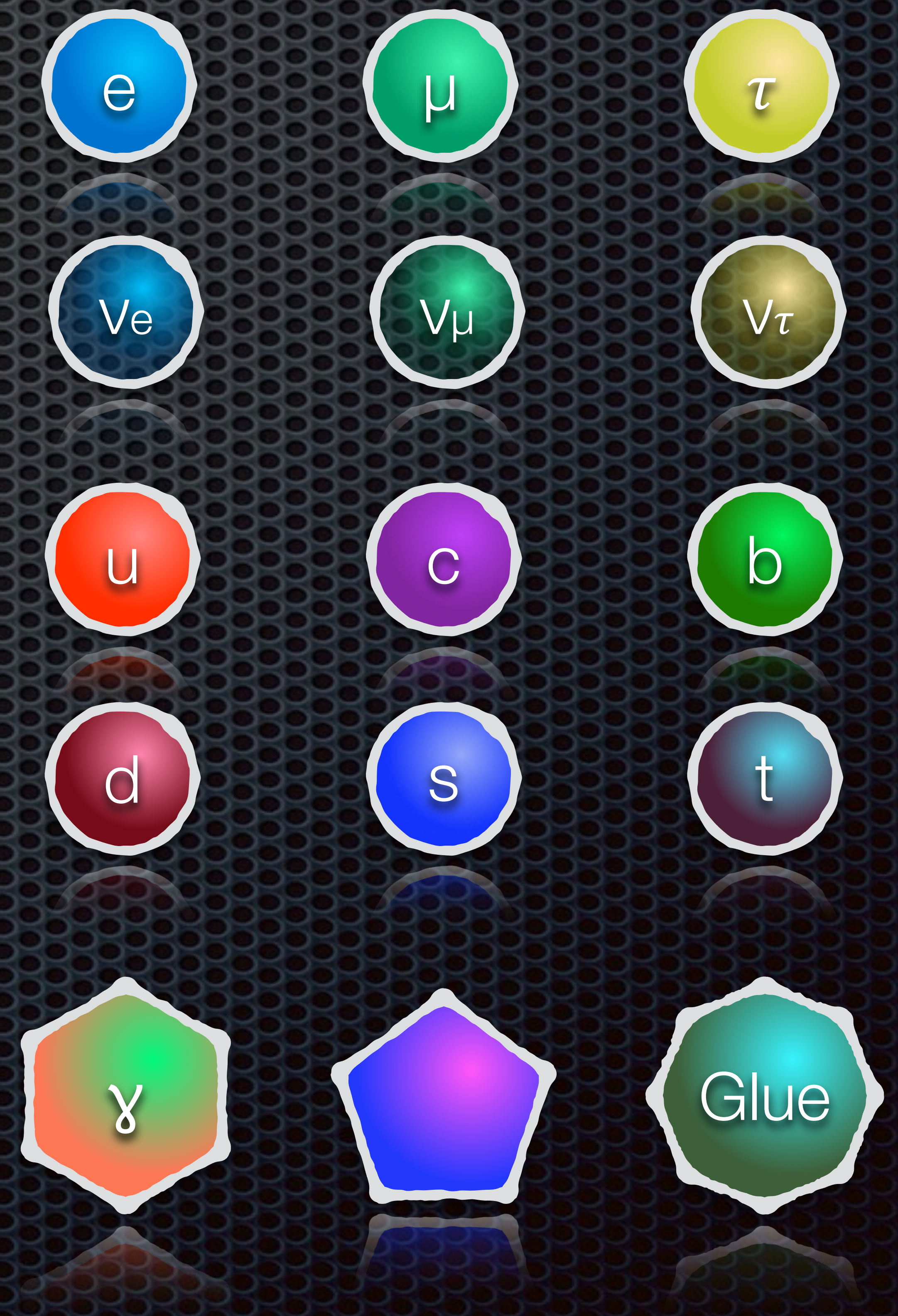

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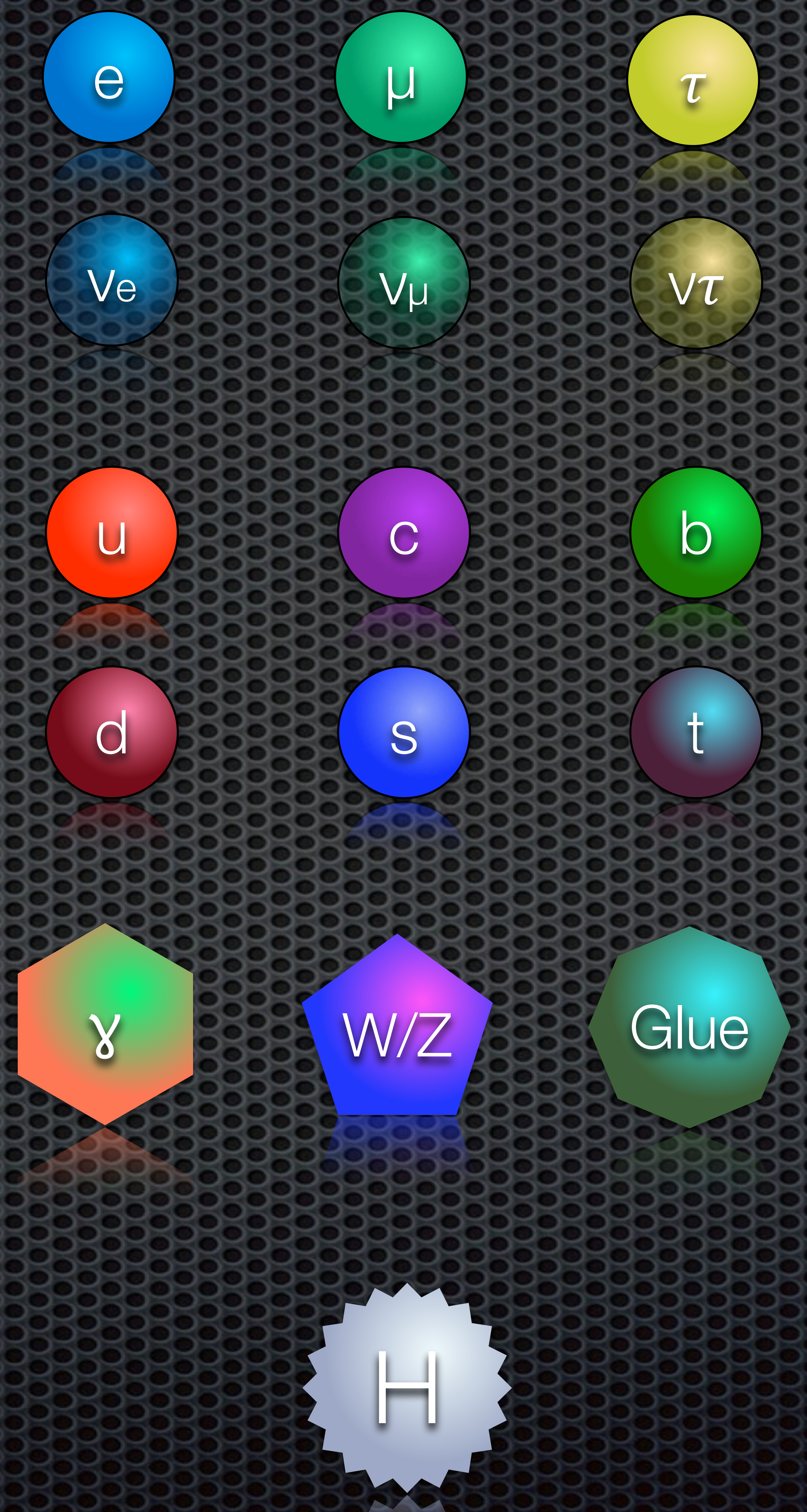

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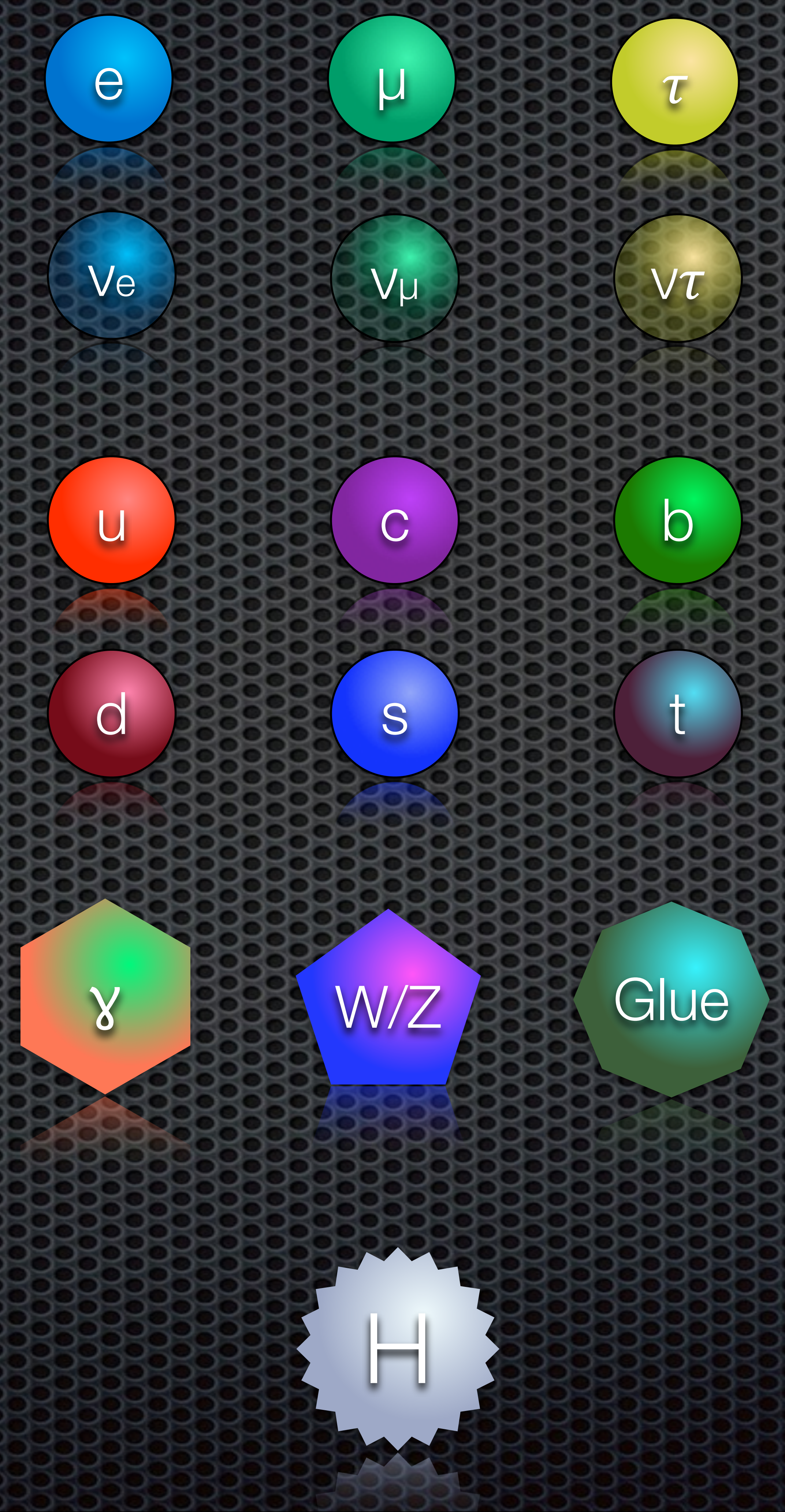

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Quantum mechanics:
These particles are fields
that are particles.
Fnord

Open Problems Solved by Susy

- Mathematics of Quantum Field Theory
- Naturalness
- Unification of Gauge Interactions
- Dark Matter
- Realistic String Models

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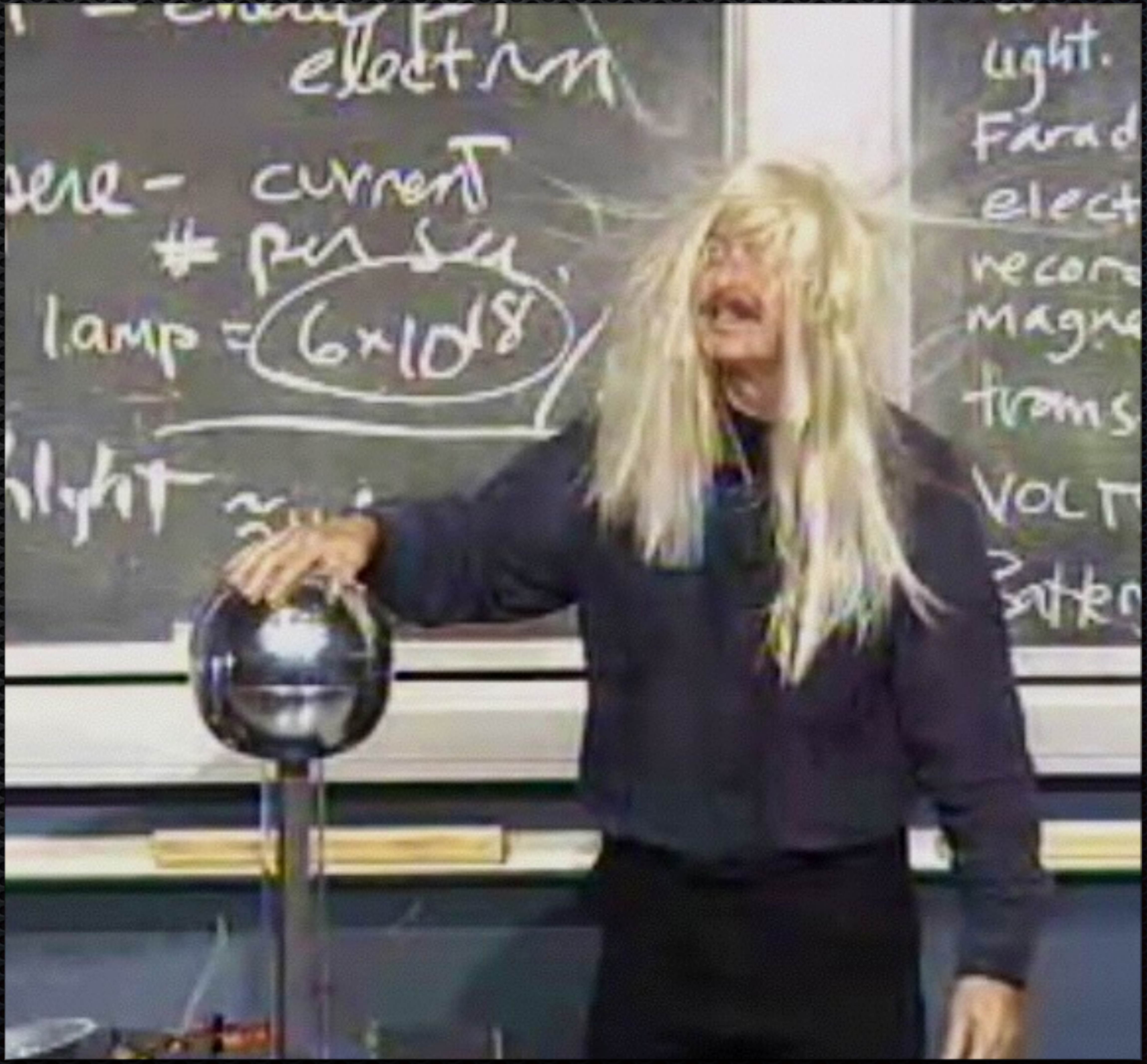
Electro-magnetism as a Gauge Theory

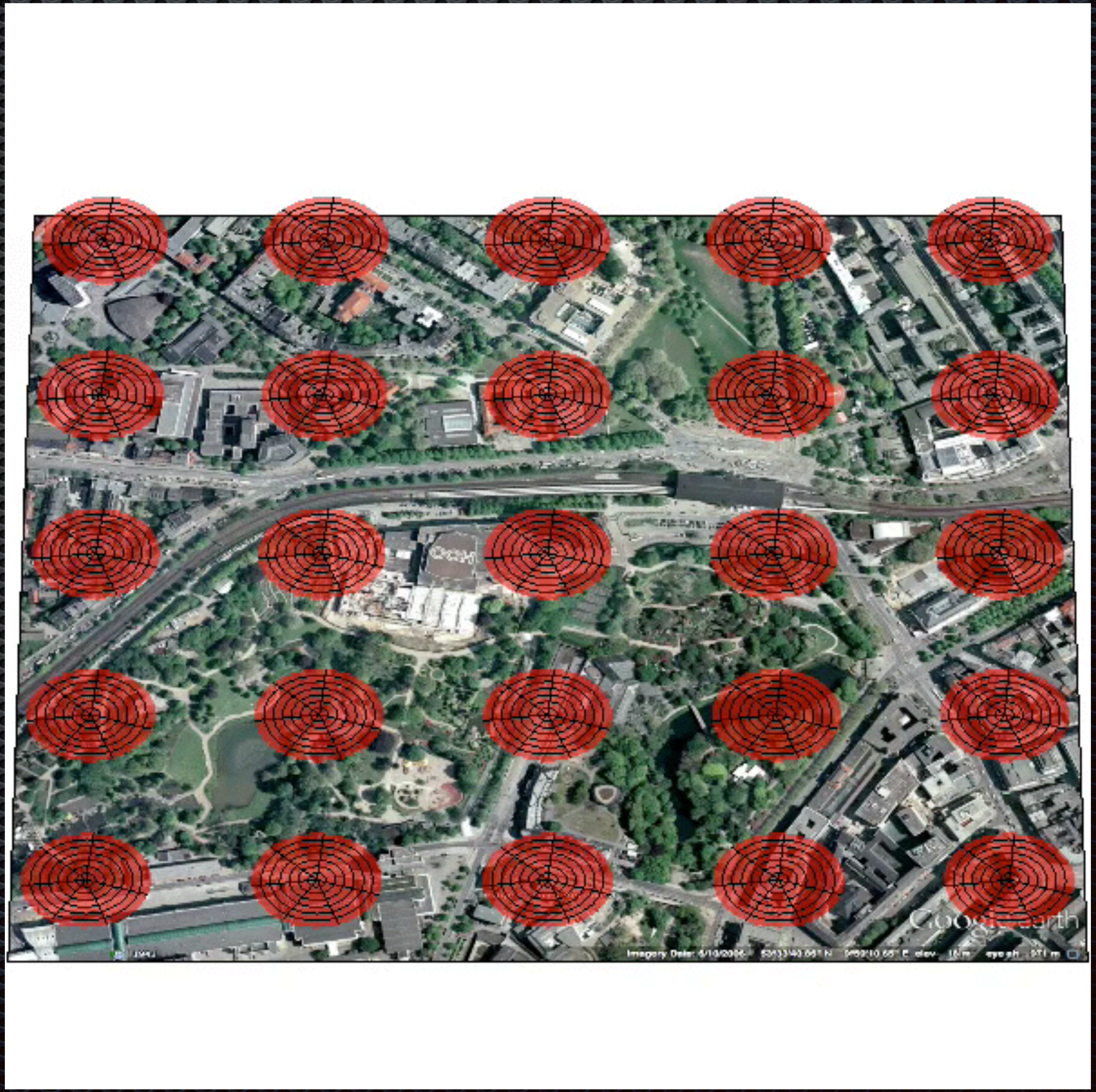
Let’s take a different angle on electro-magnetism!

Instead of charges and electric and magnetic fields…



Electro-magnetism as a Gauge Theory

… attach a virtual/abstract/"internal" plane to each point of space



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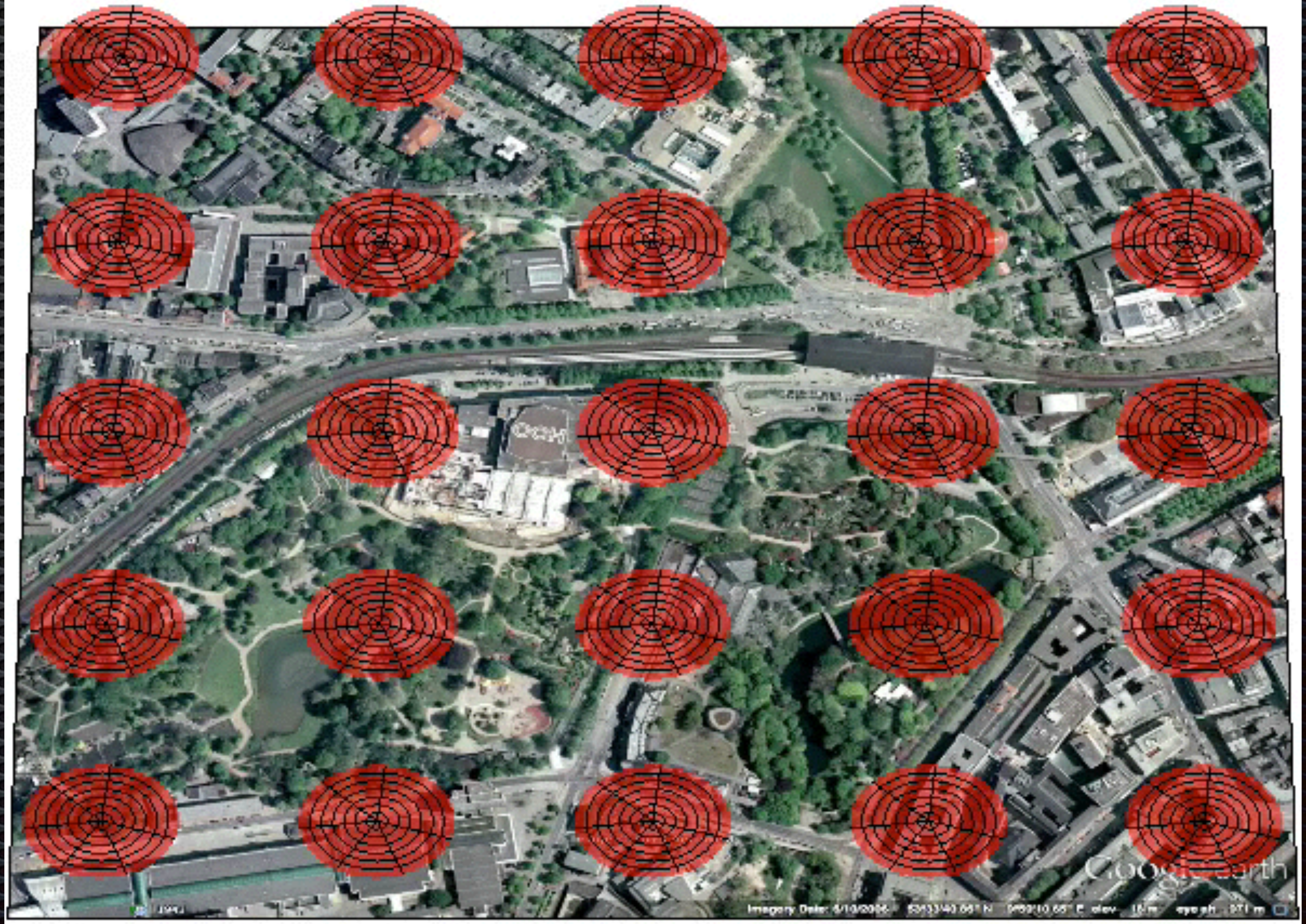

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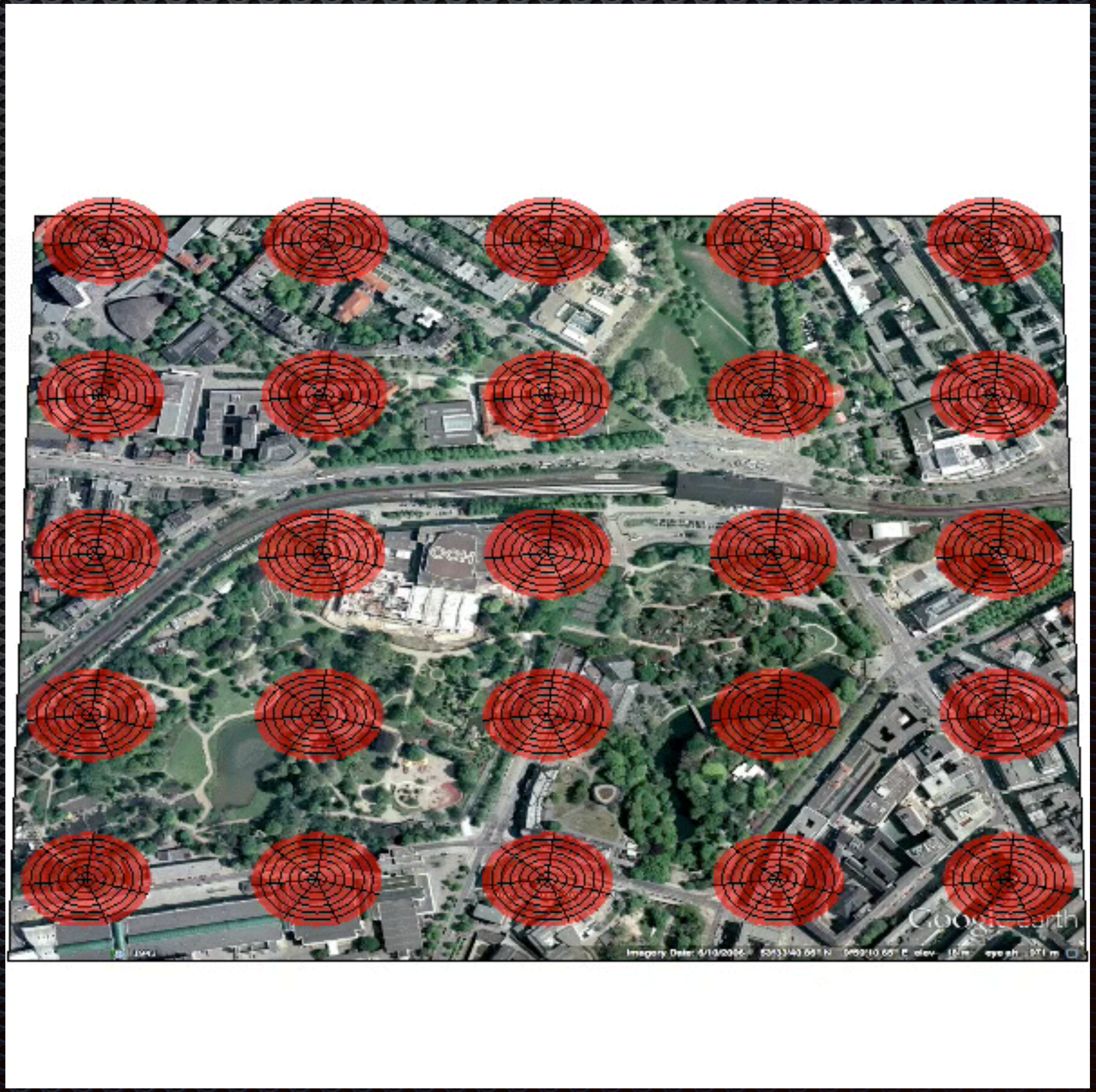

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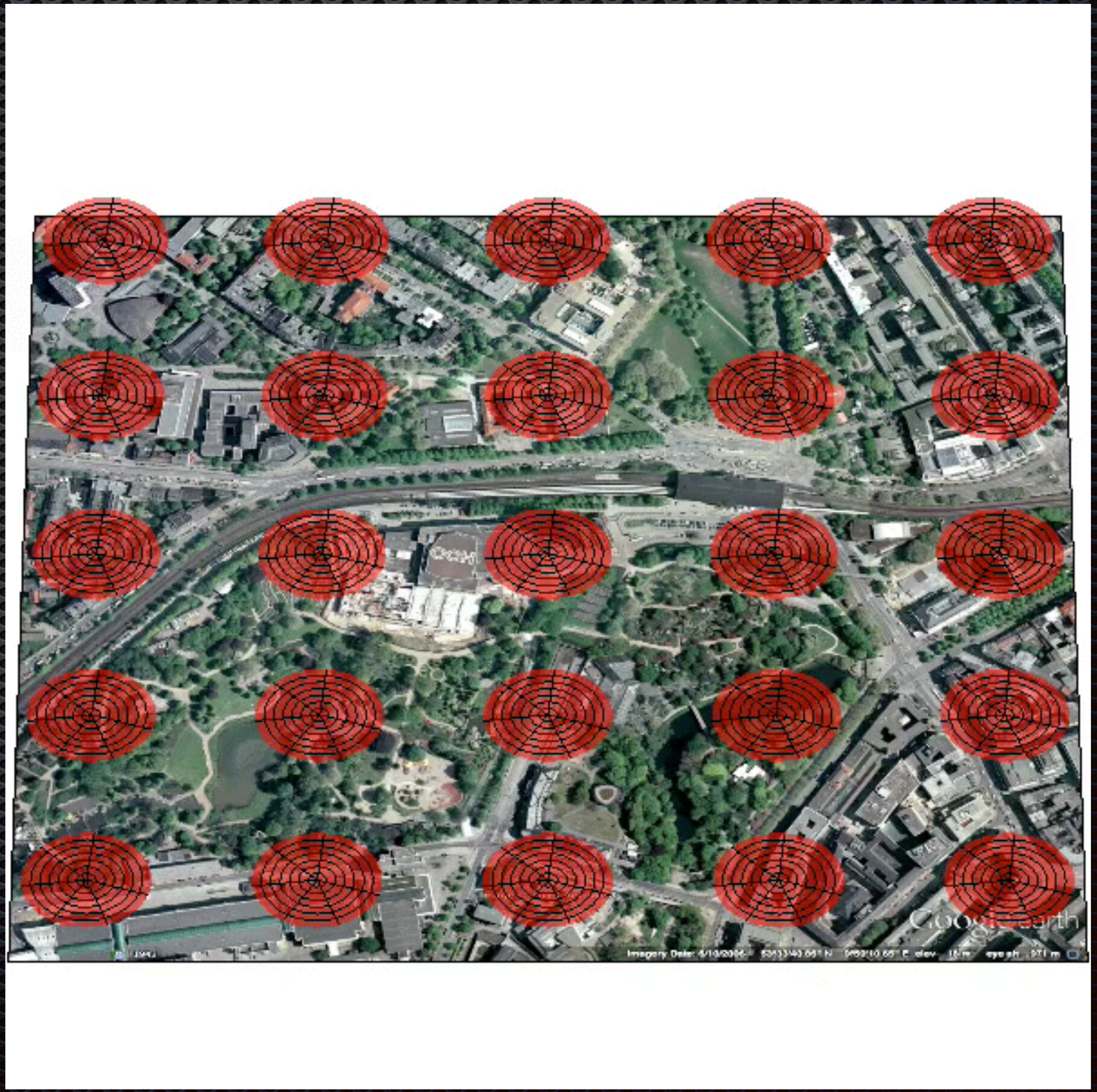

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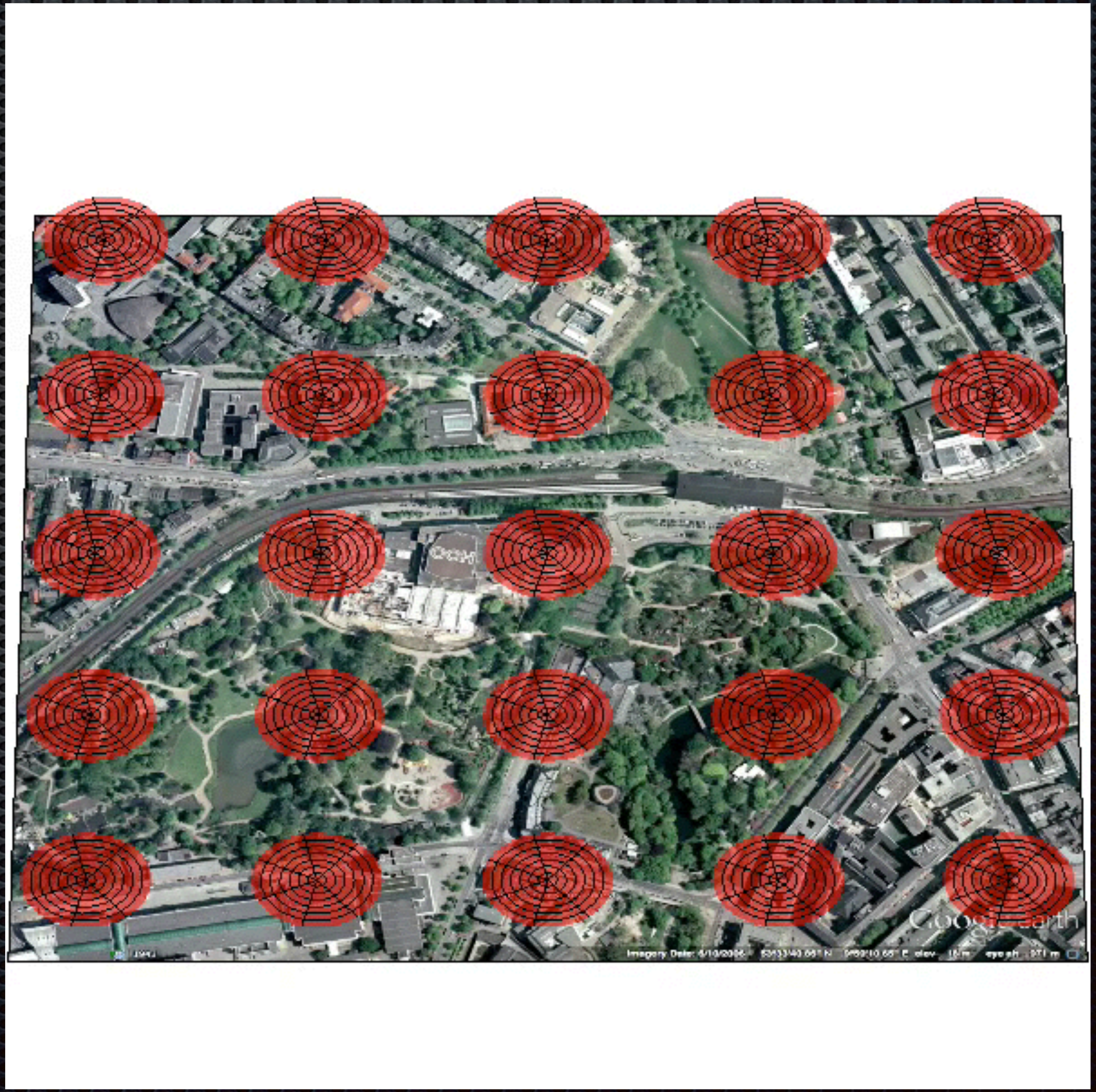
You can rotate each plane independently.



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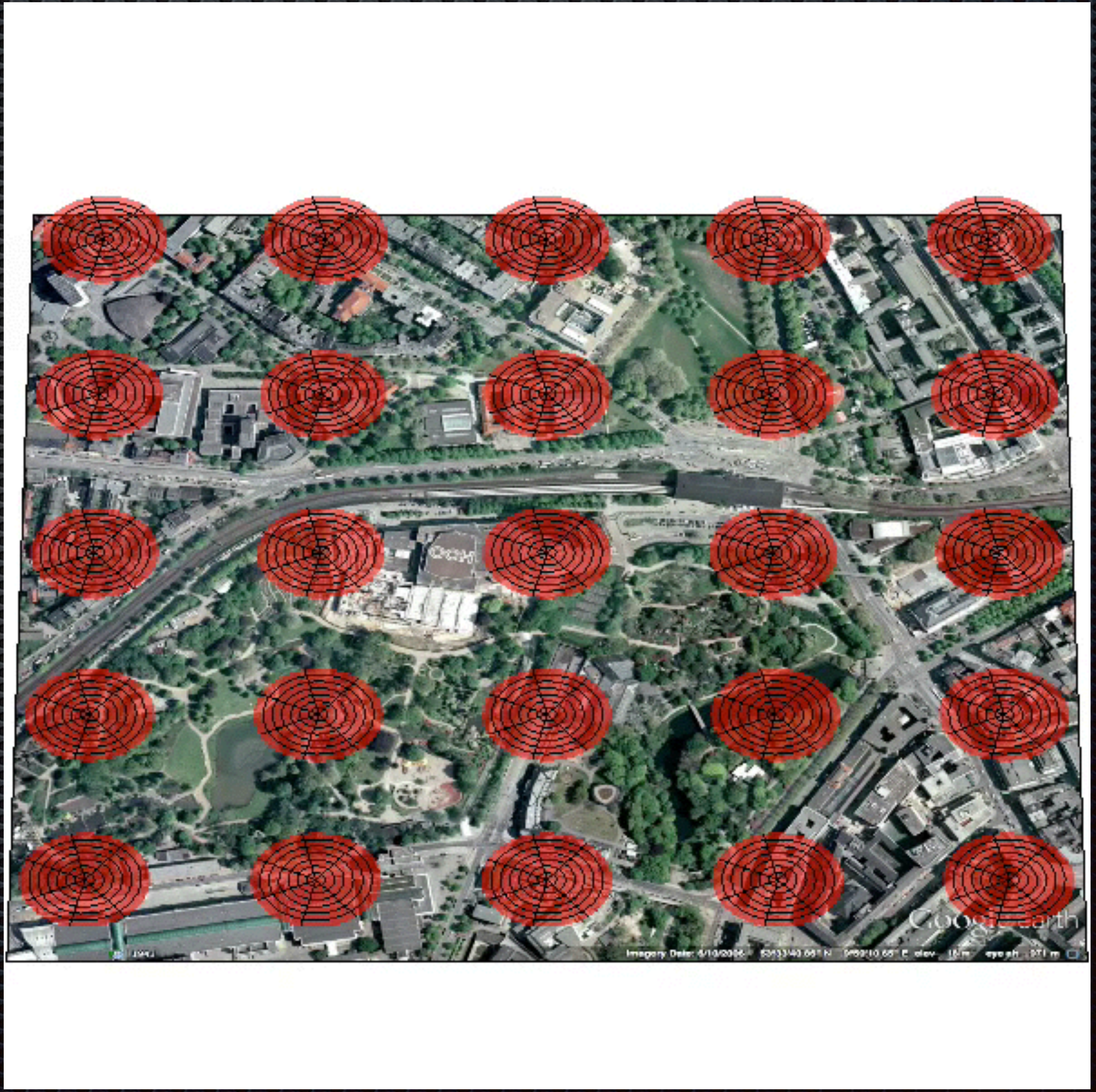
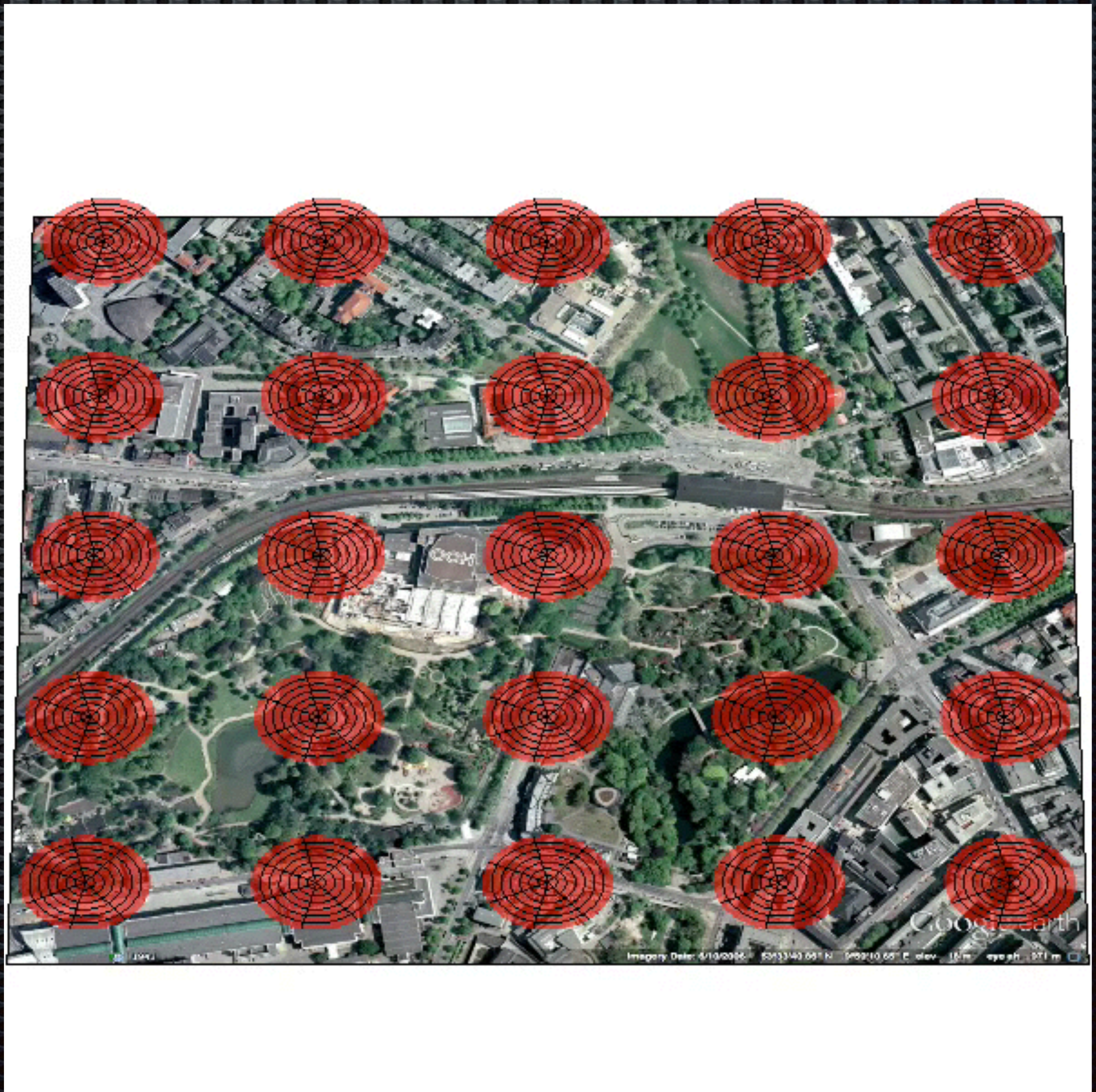


Electro-magnetism as a Gauge Theory

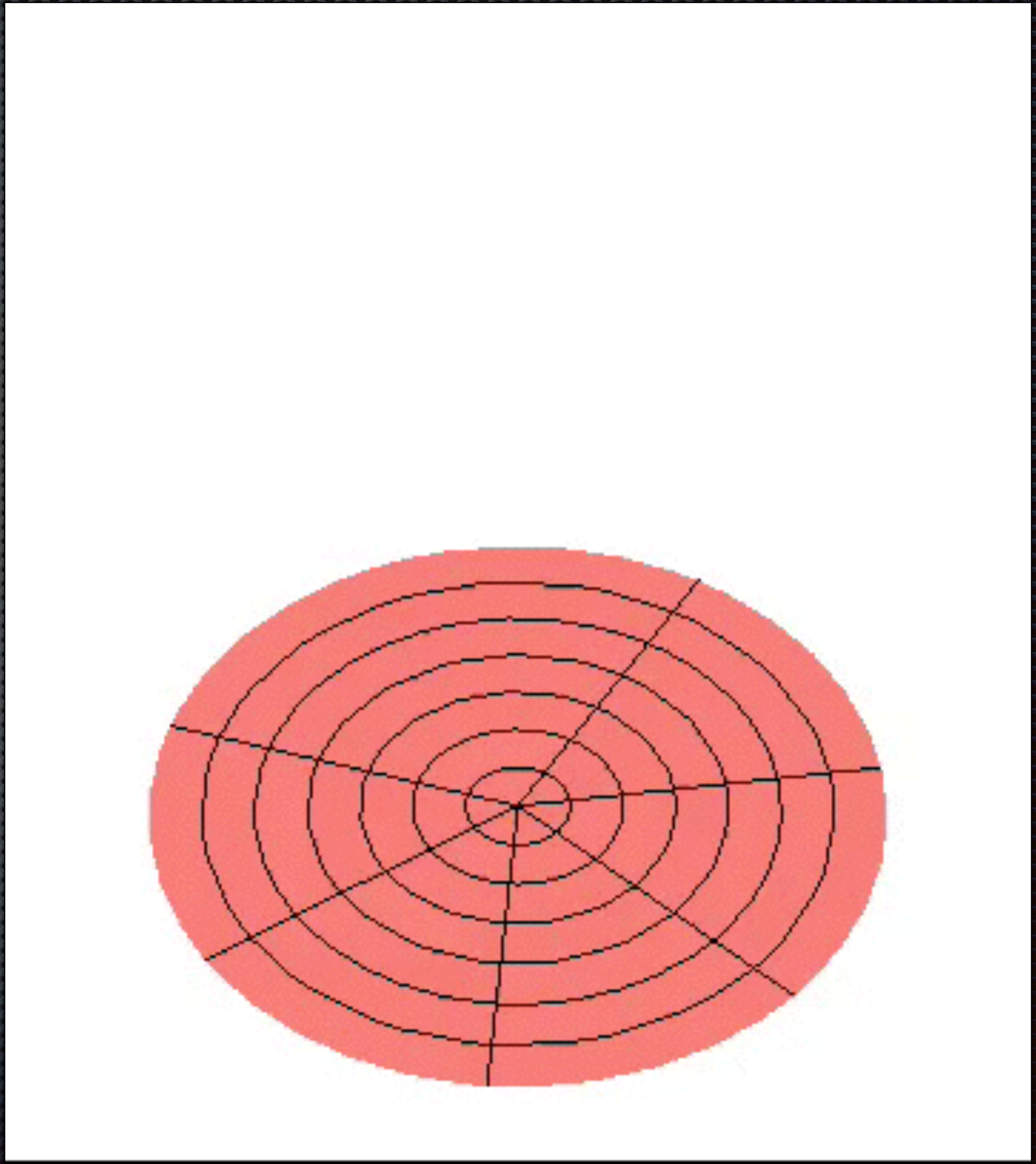
You can rotate each plane independently.

The electromagnetic field is the description of this rotation.



Gauge Theories

- In fact, all elementary forces are of this type



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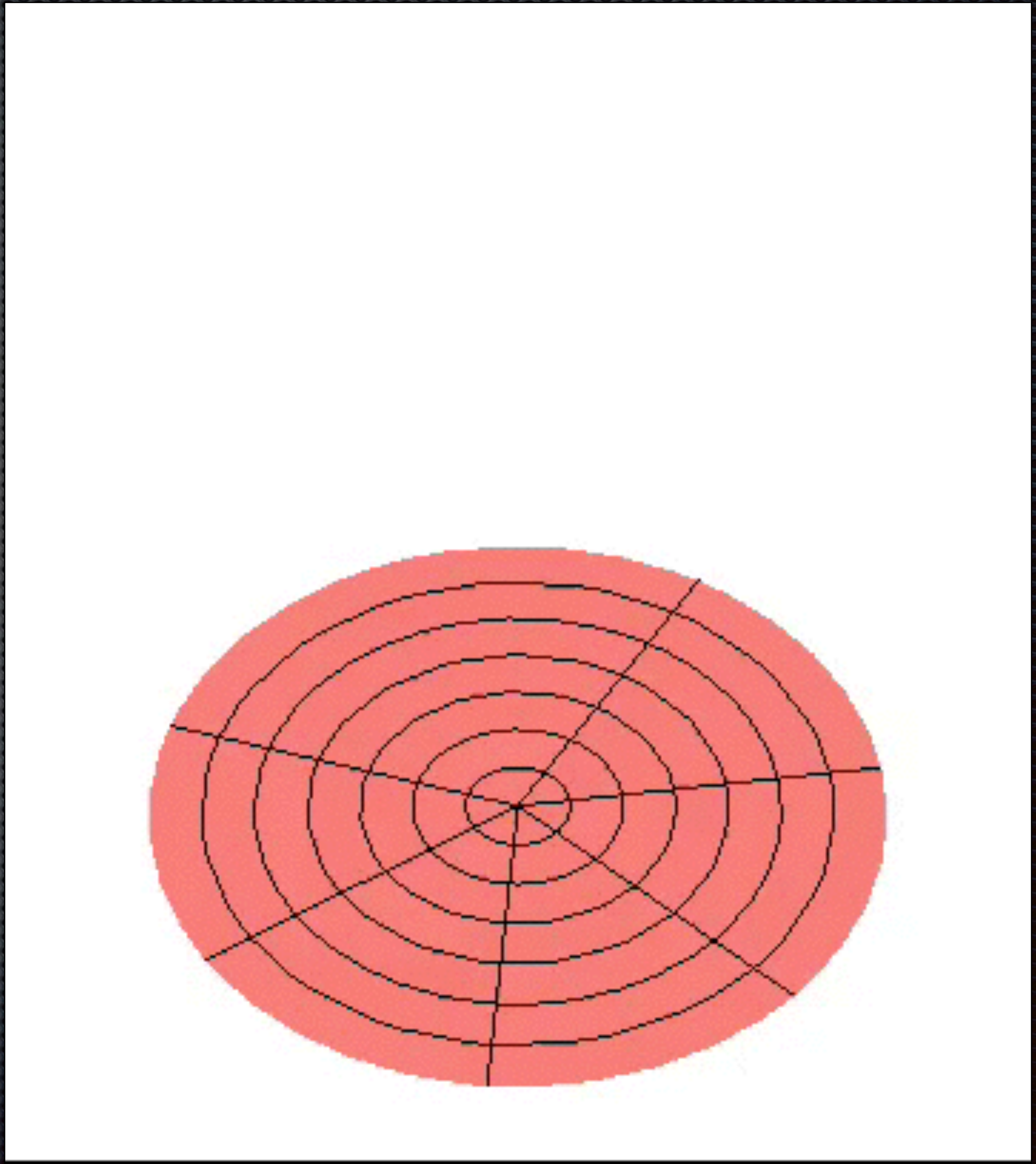

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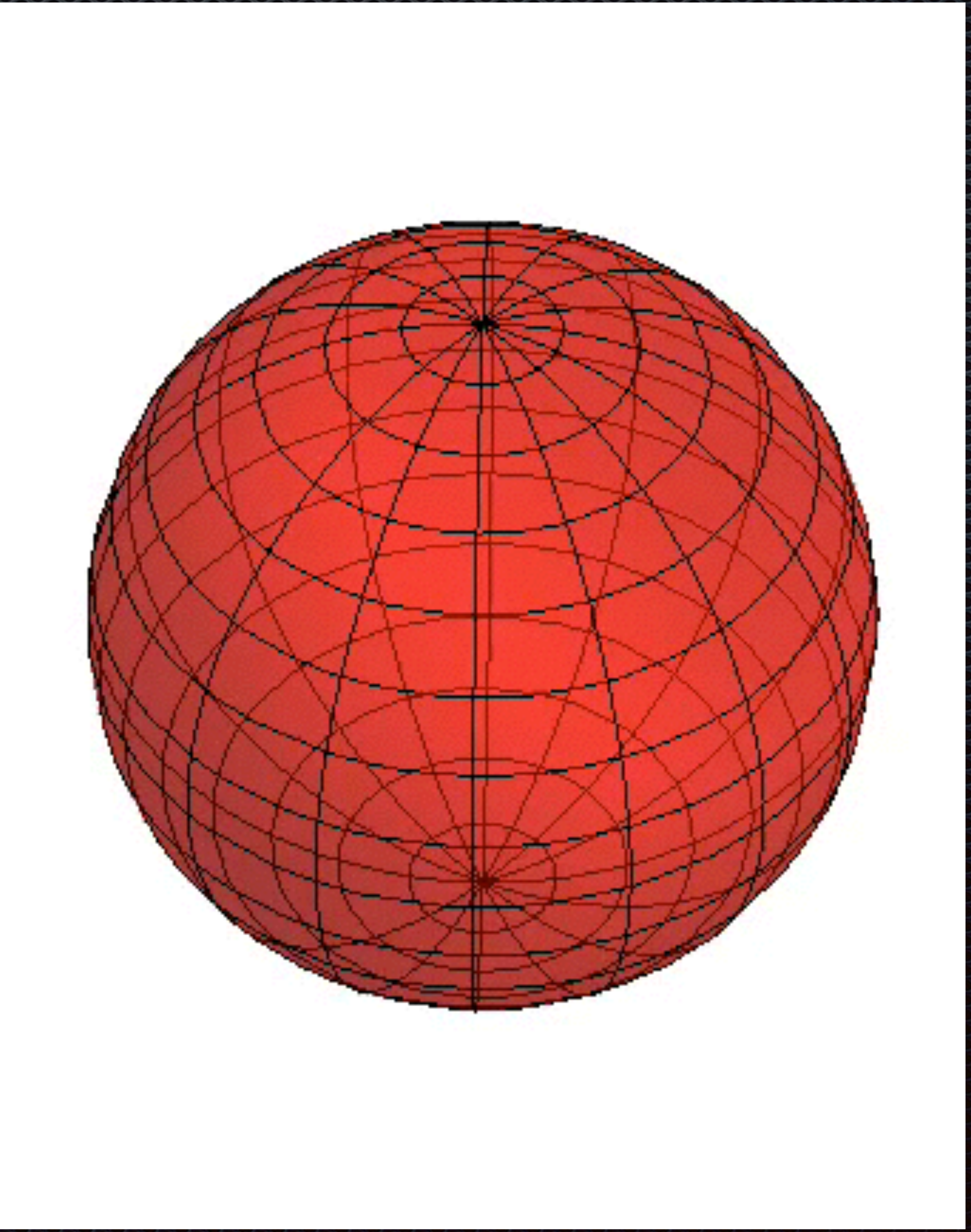

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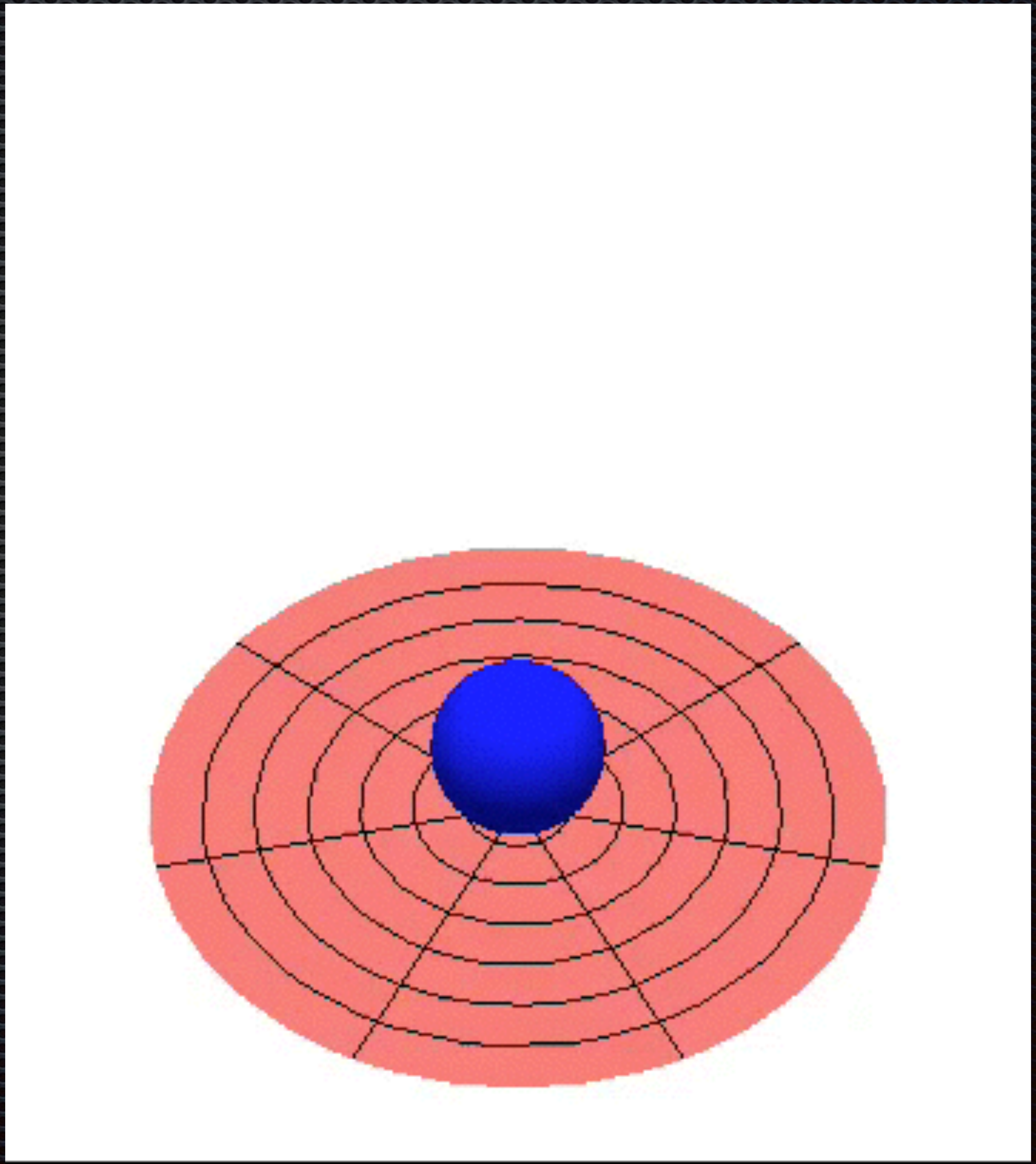
Higgs effect

- Add a “Higgs field” that takes a position in the plane.



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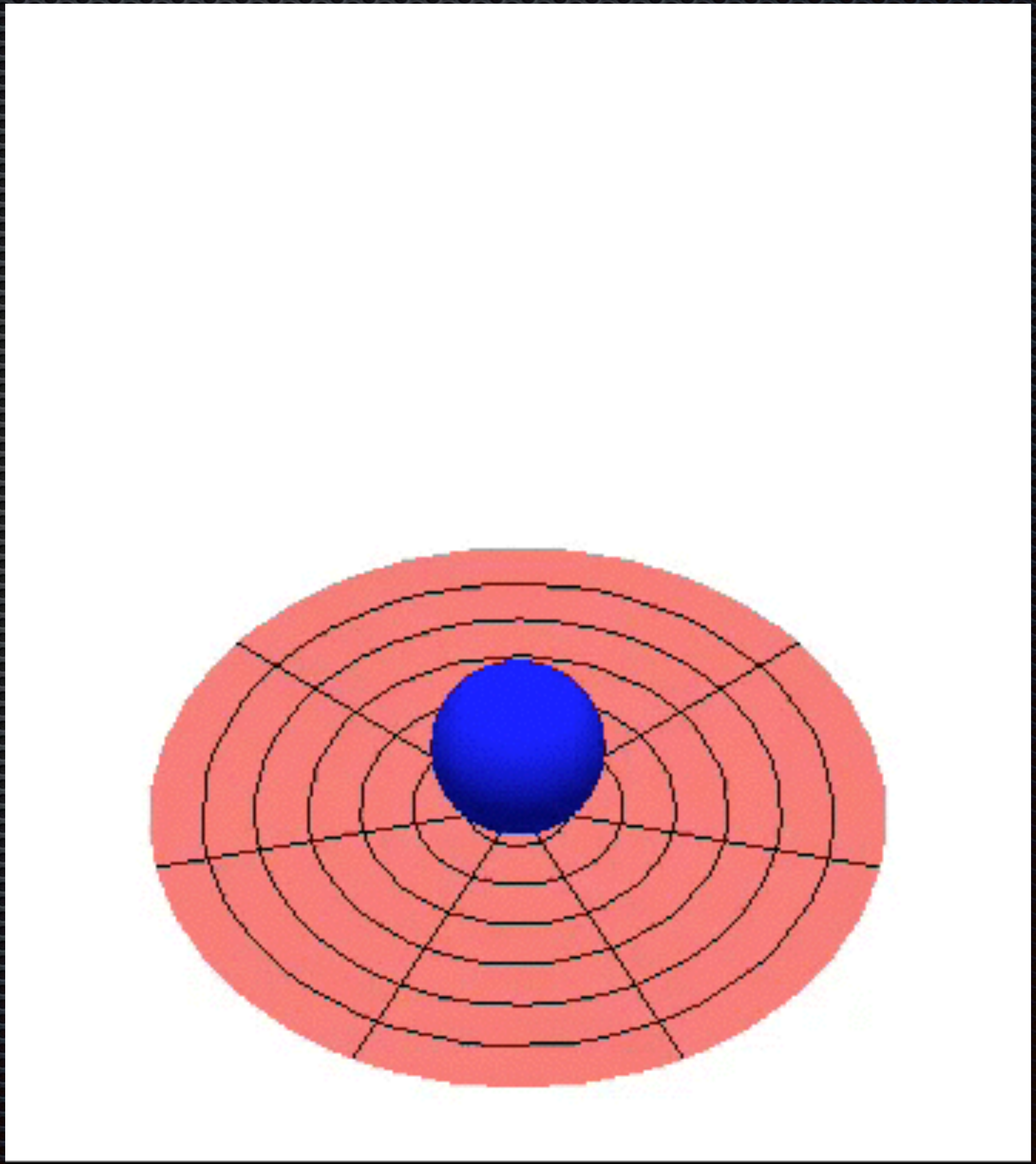

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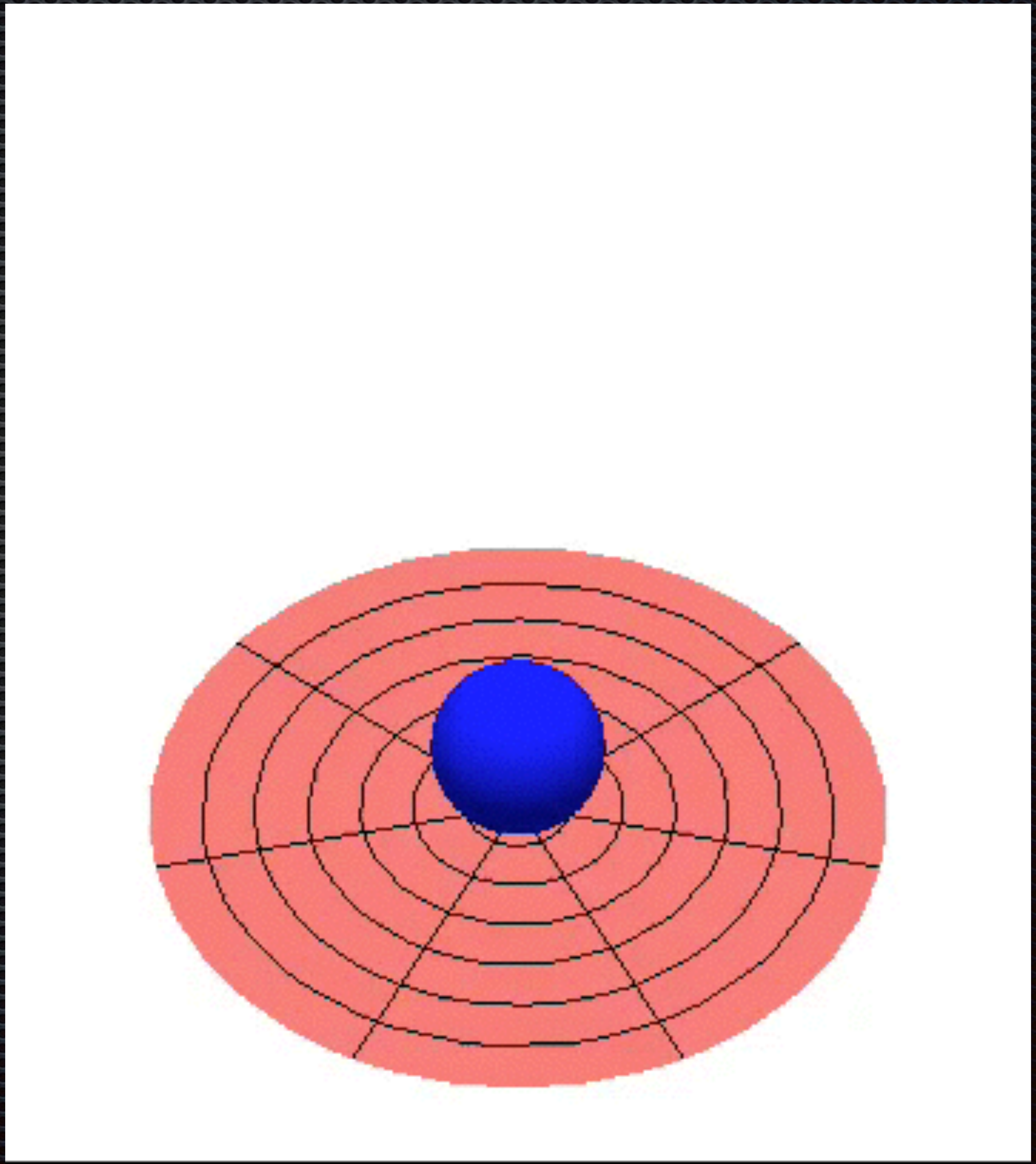

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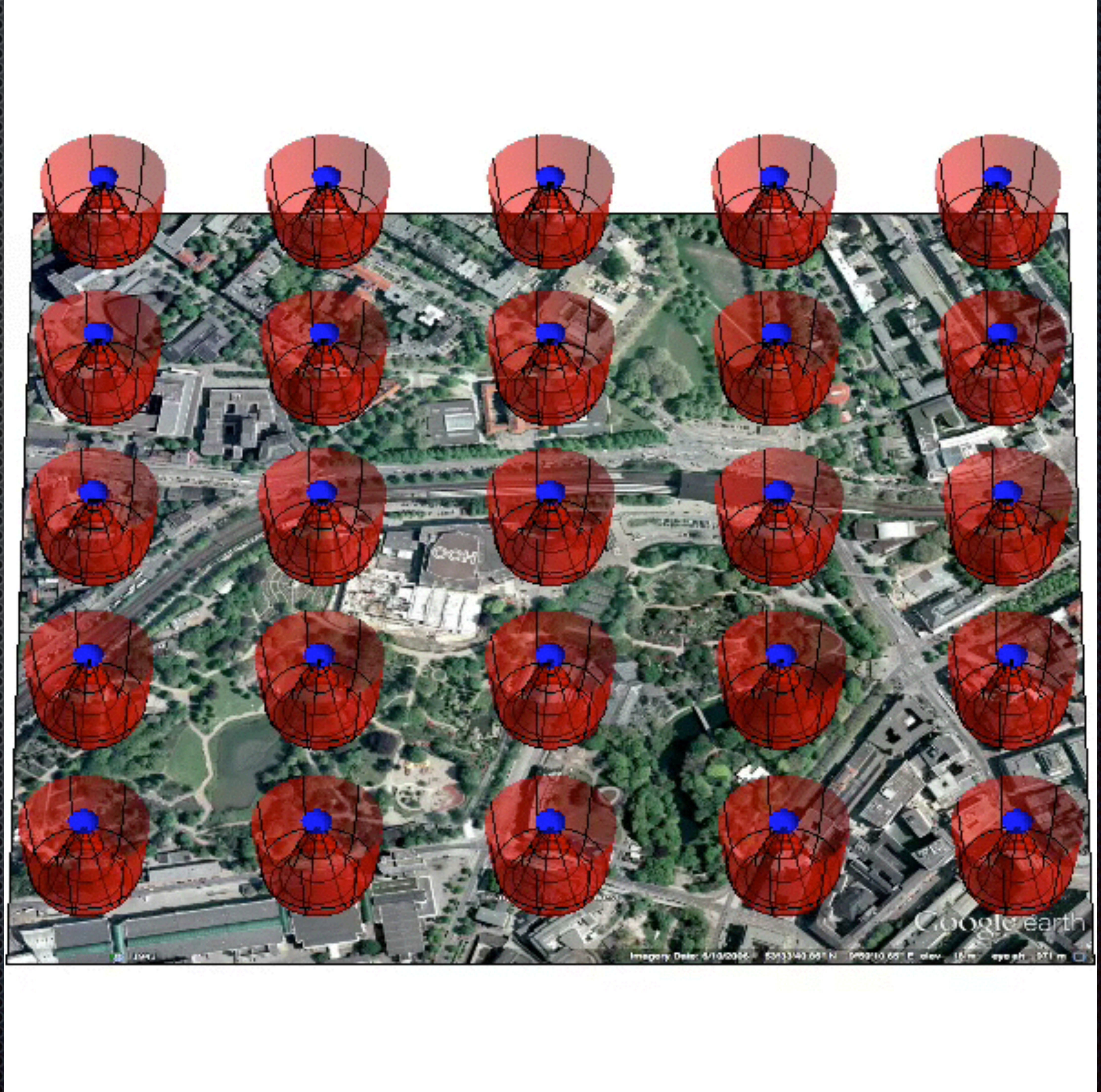

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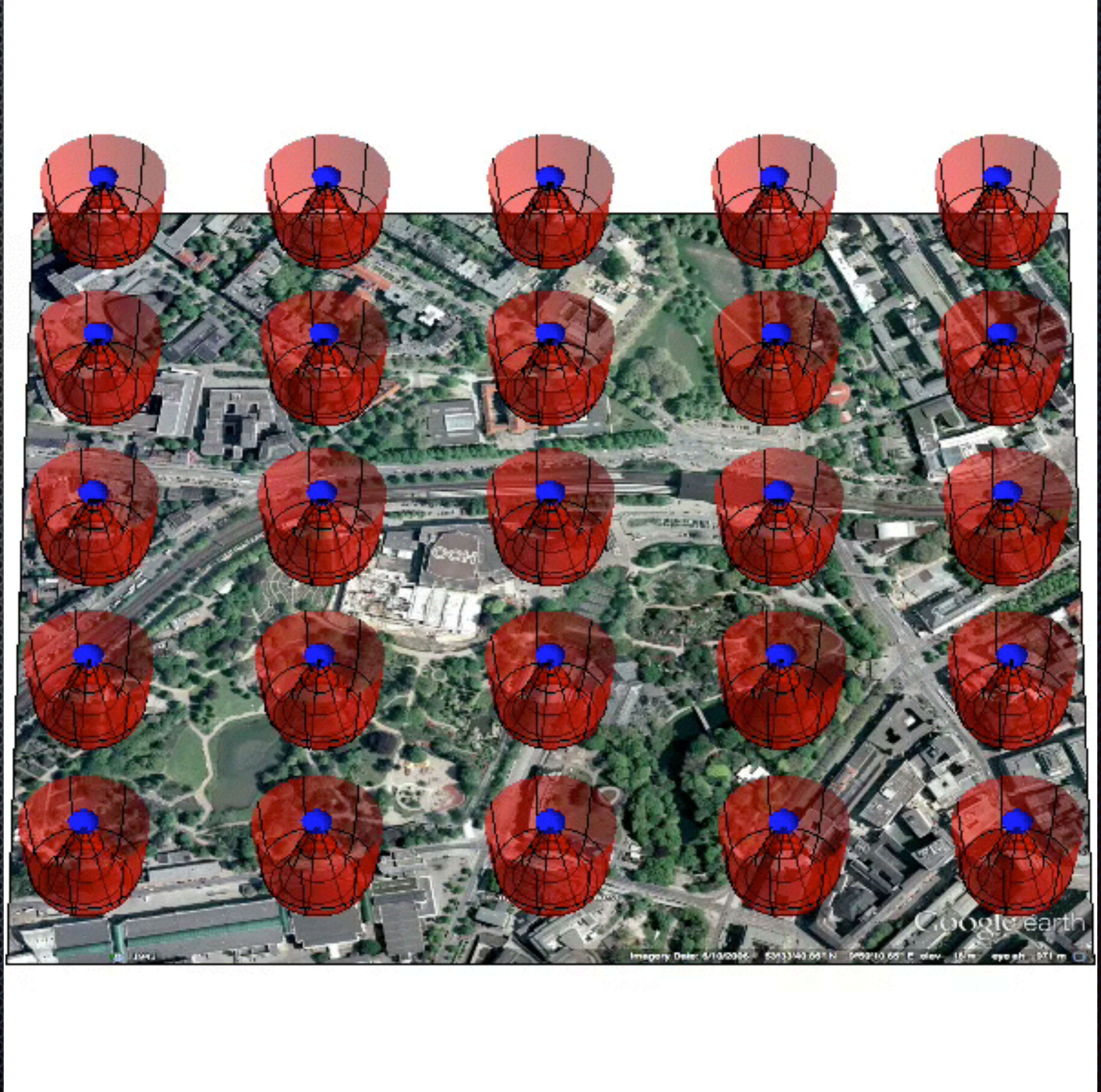

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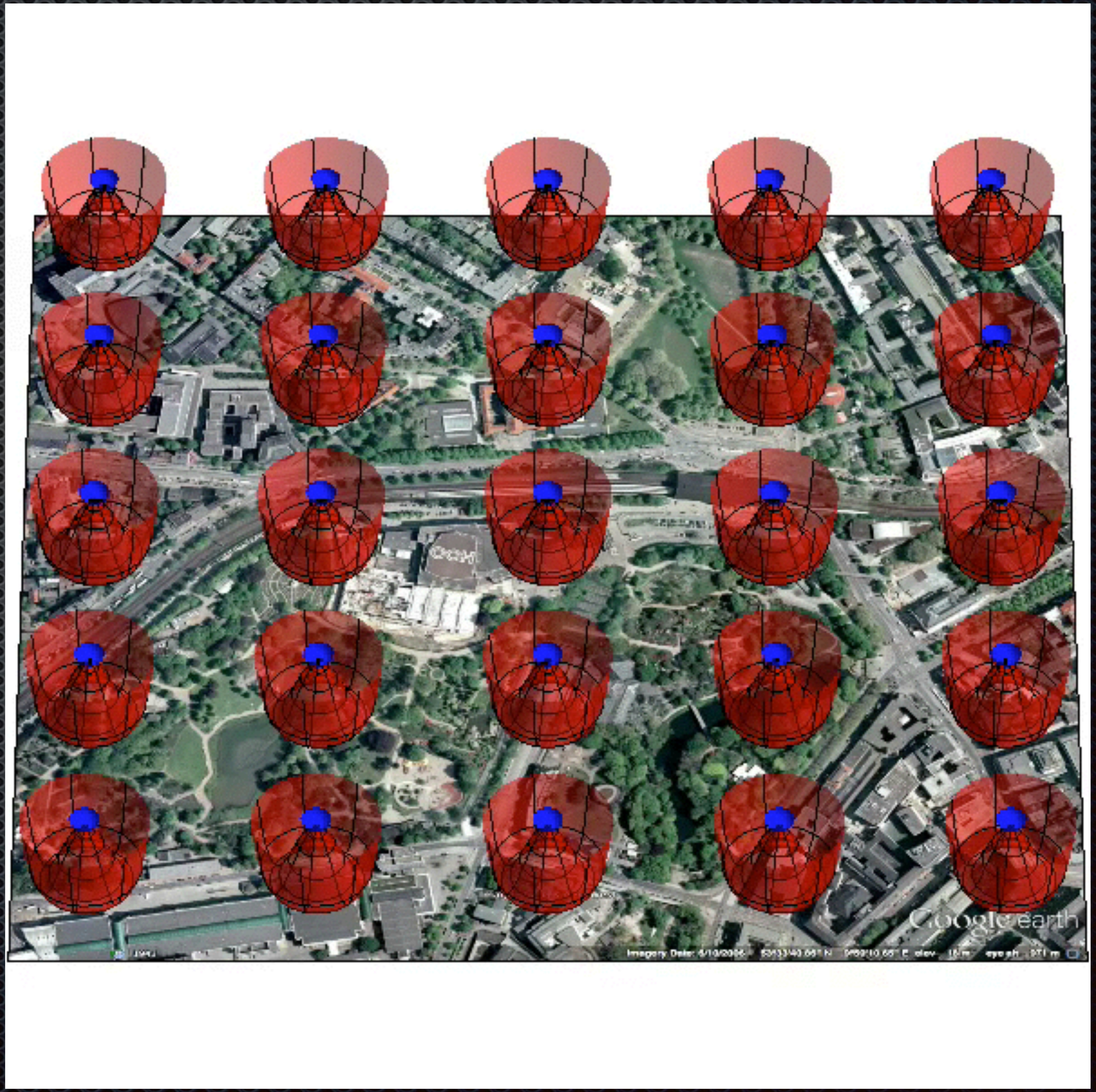

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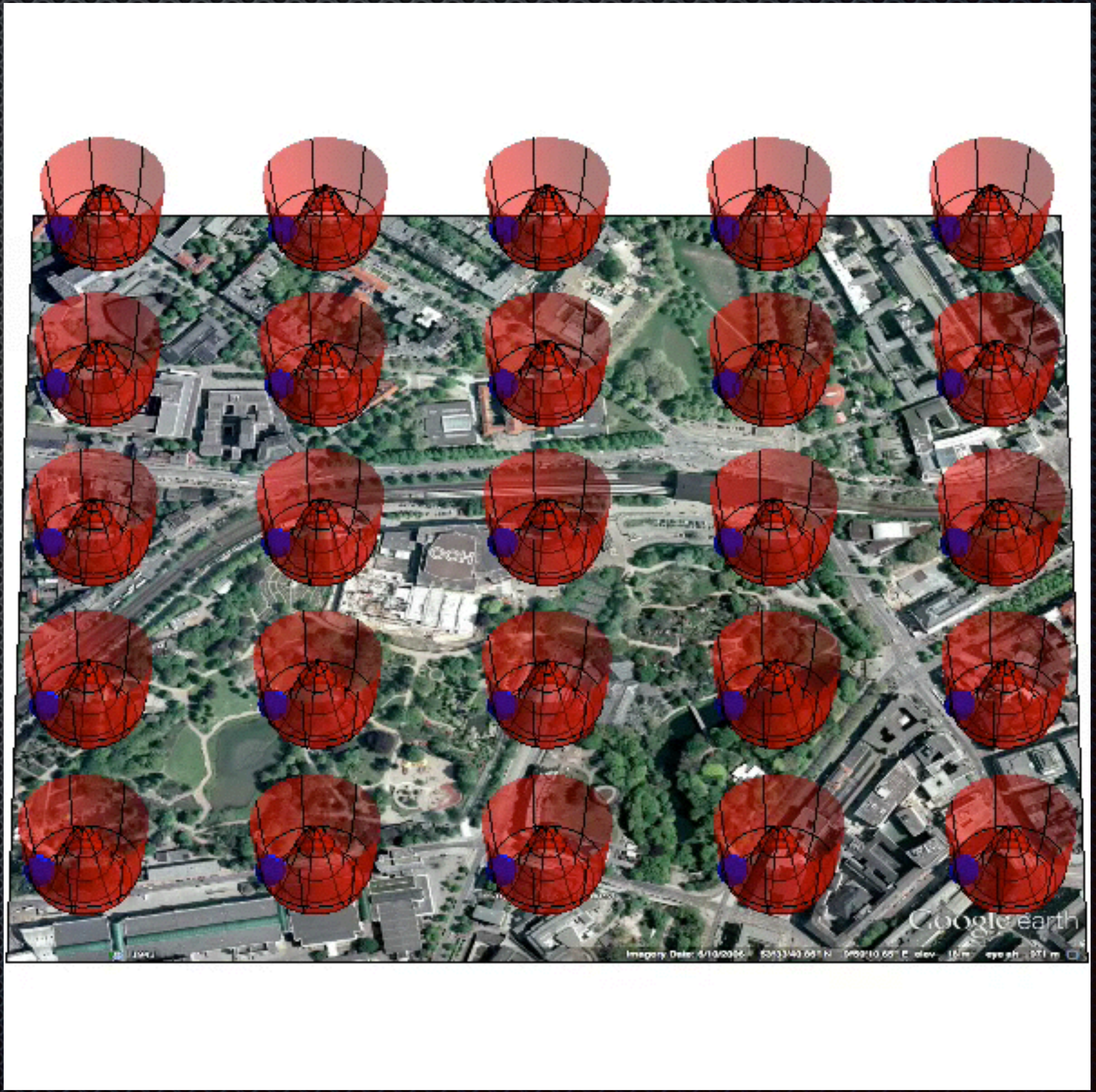

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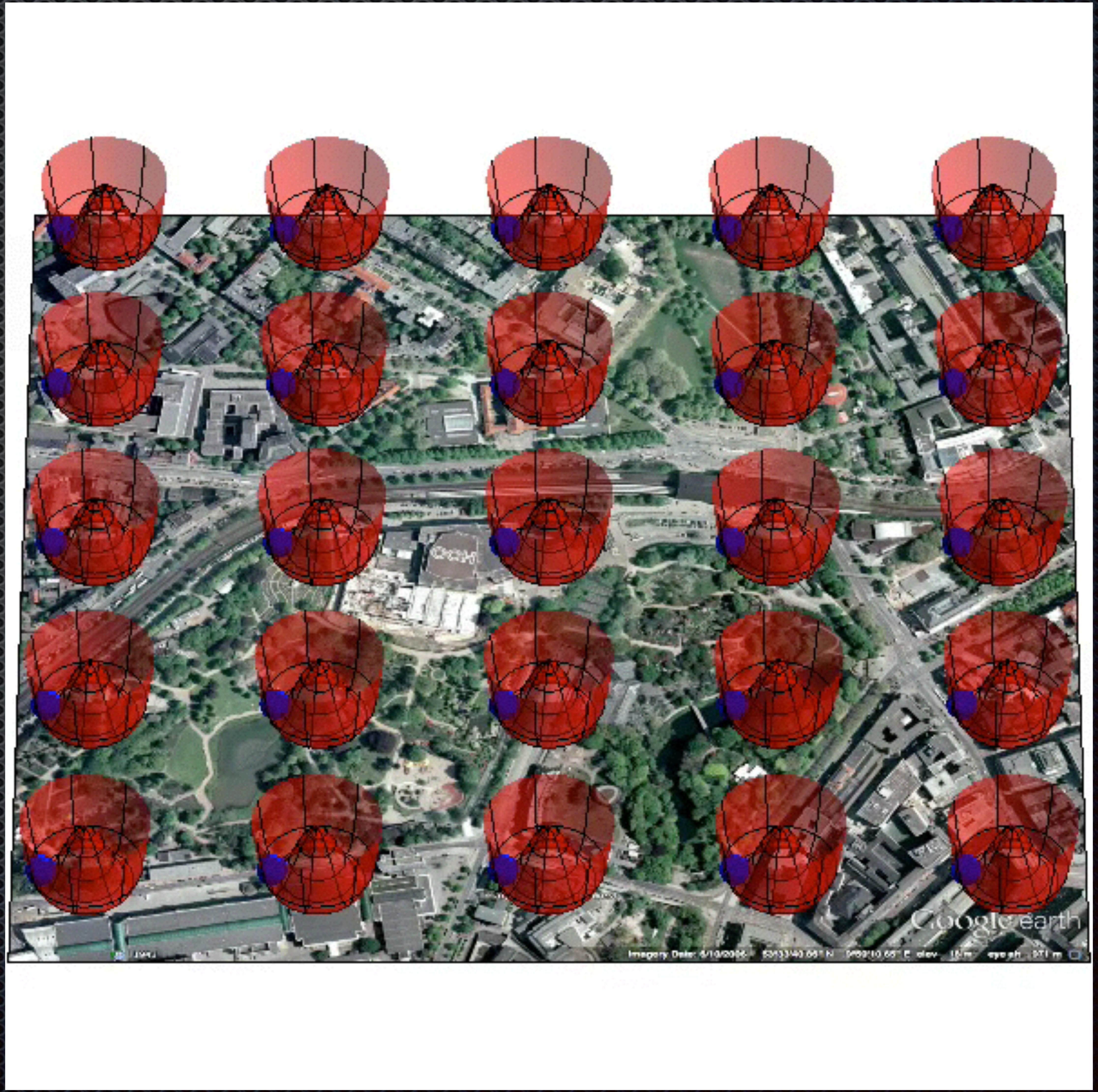

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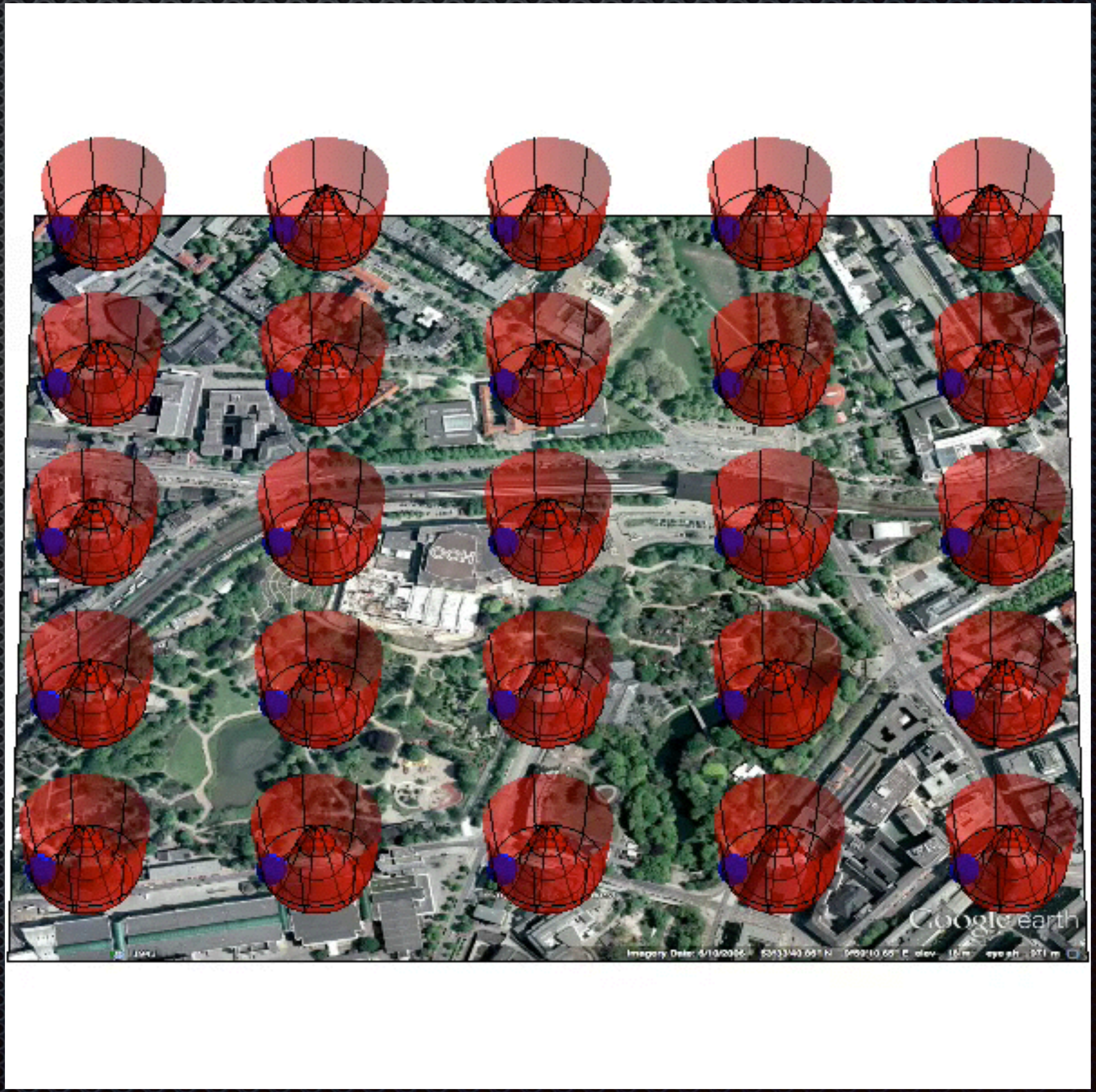

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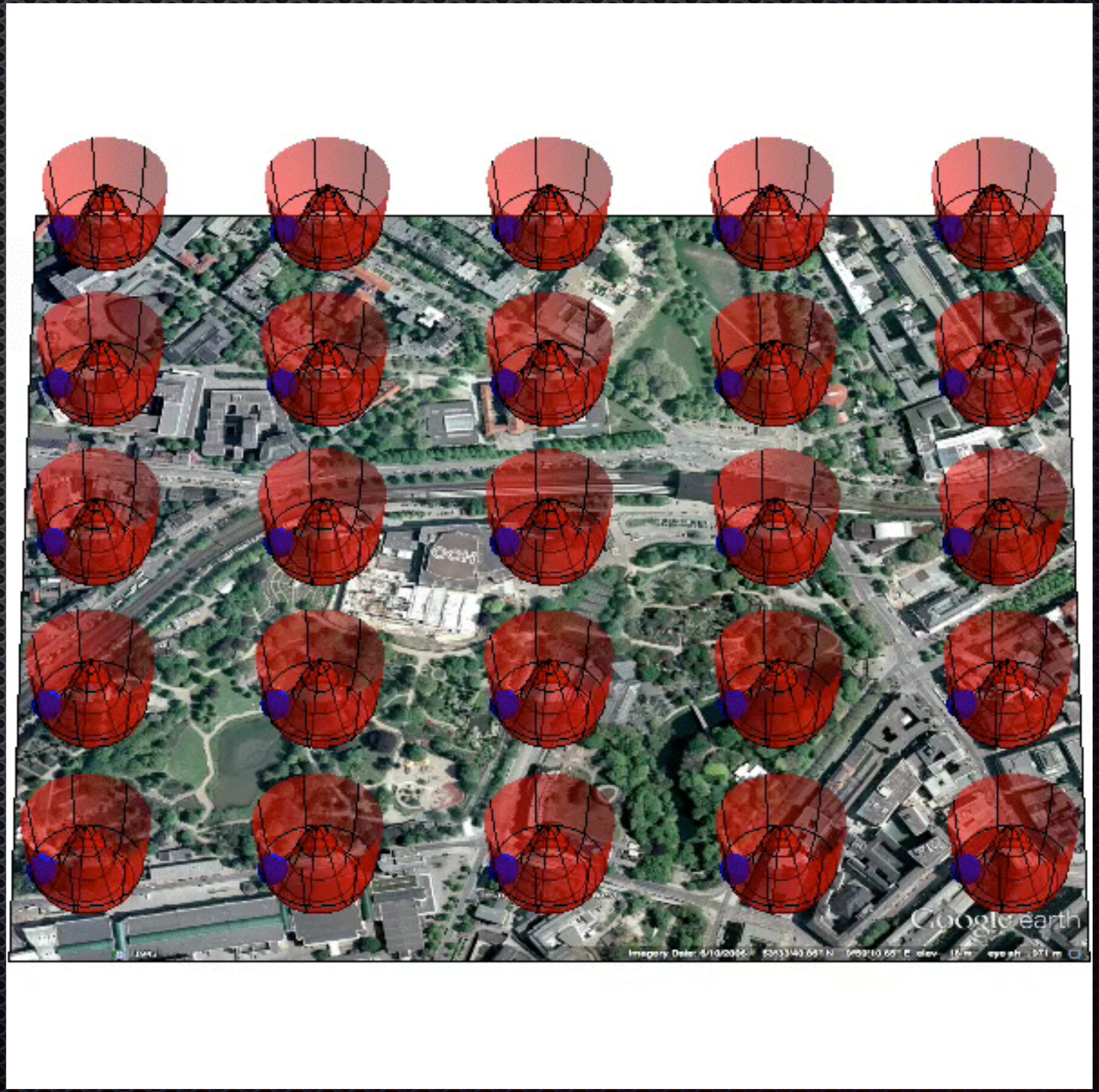
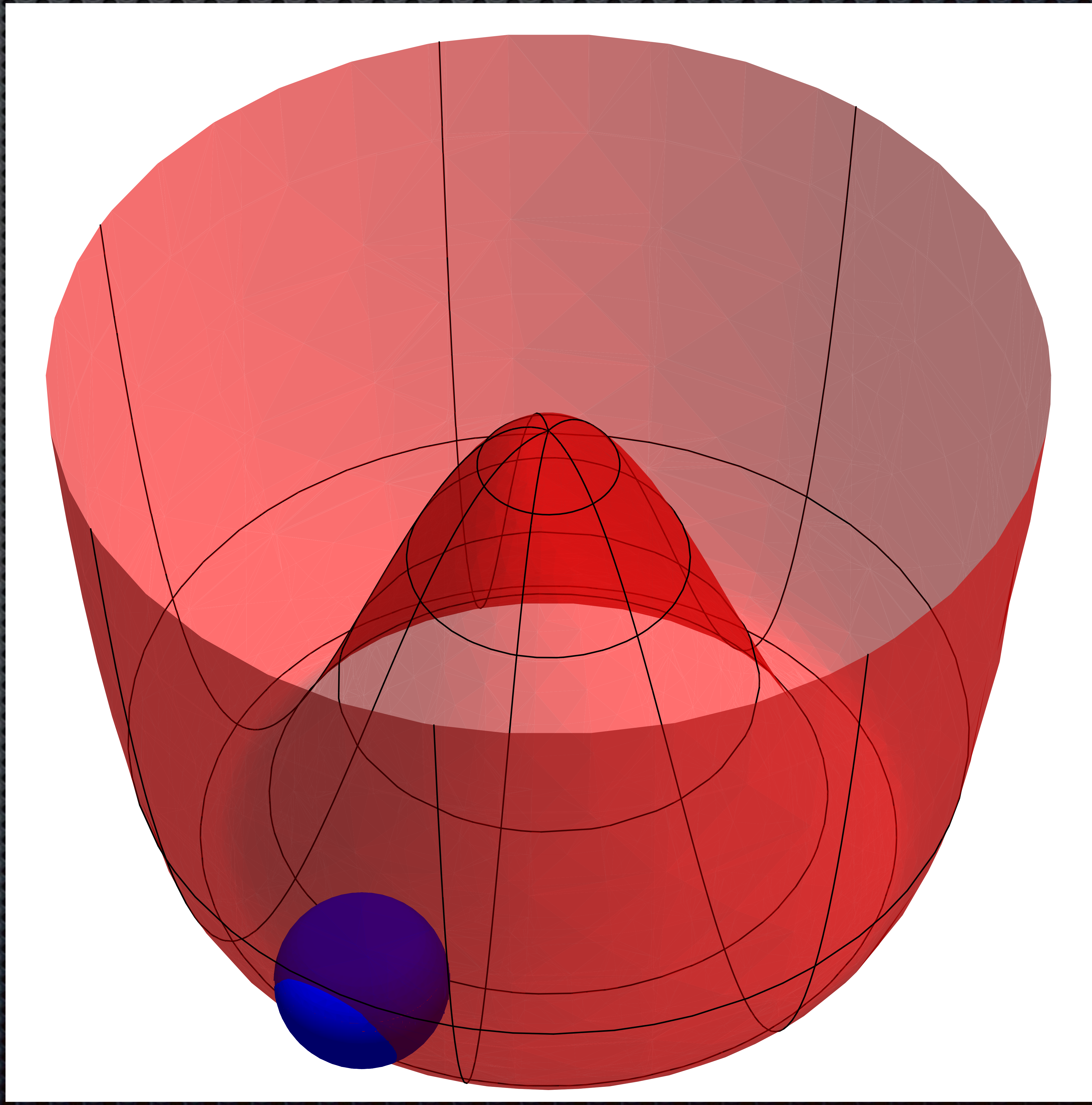


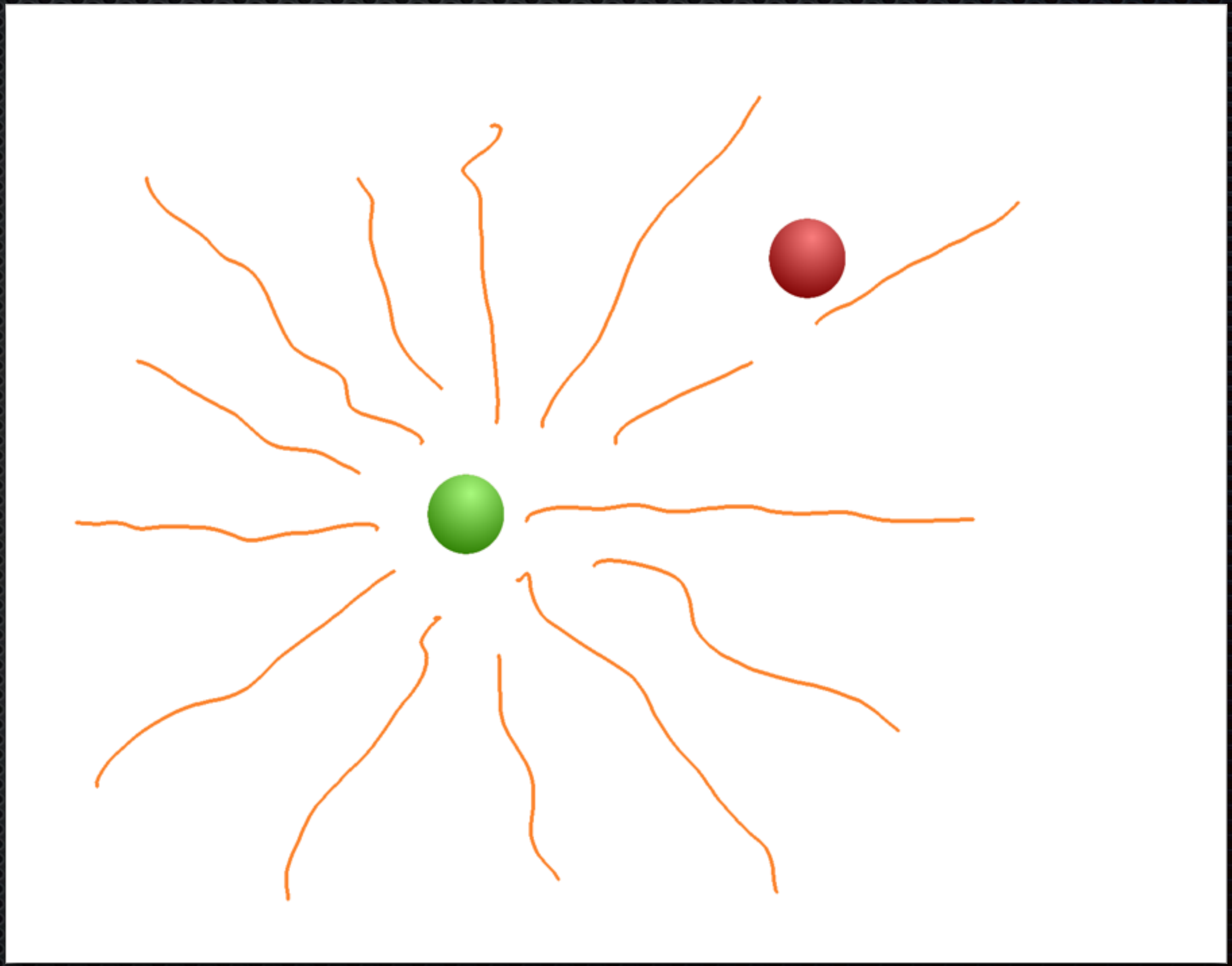
Electroweak symmetry breaking

- In nature, the rotational symmetry of electro-magnetism is not broken. The photon remains massless.
- The Higgs effect takes place for the weak interaction. The W- and Z-particles, obtain their masses of about 100GeV this way.
- This corresponds to the distance of the blue ball from the center



Renormalization

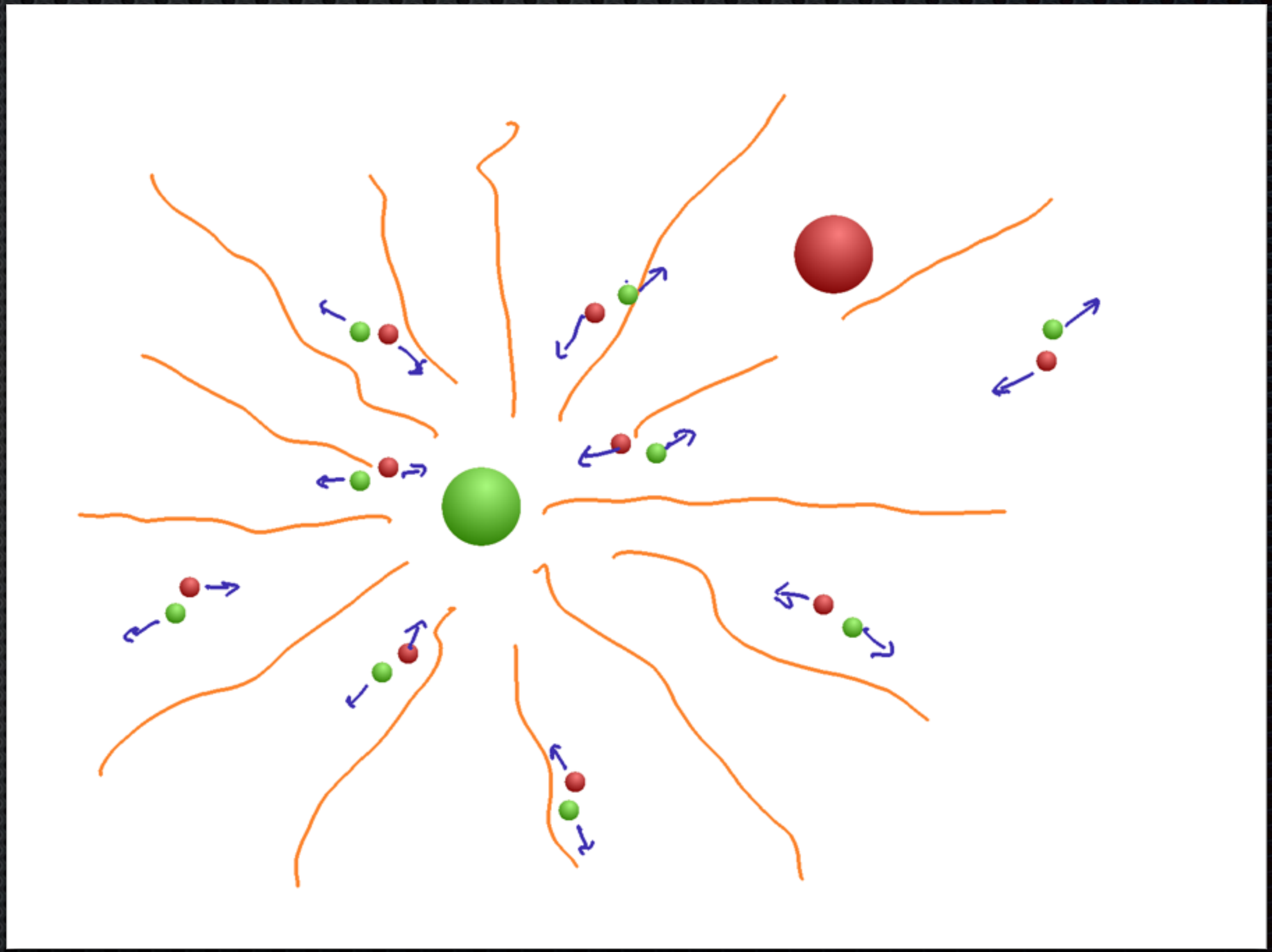
- A positron sees the electric field of an electron
- Coulomb: $E \sim \frac{Q}{r^2}$



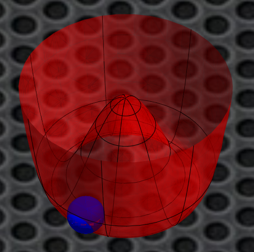
Renormalization

- Quantum mechanics: The charge depends on the distance
- The vacuum is full of virtual electron-positron pairs.
- These align in the electric field.
- Shielding effect
- Effect stronger with stronger field = shorter distance
- Observed charge is depends on distance scale

$$E \sim \frac{Q(r)}{r^2}$$



Running couplings

- A similar effect applies to other particle properties like for example the mass.
- For almost all these properties, the dependence is weak (logarithmic) as
$$Q(r) = \beta_Q \log(R)$$
- β_Q depends on the particle types participating in the shielding.
- Only the shape of the potential  depends strongly (quadratically) on the distance:
$$m(r) = \alpha_m R^2$$
- Thus it (and also the W- and Z-masses) are very sensitive to R. Their small mass of 100GeV would not be stable but driven to the much higher Planck scale.
- "100GeV is not natural!"

Susy saves naturalness

- In super-symmetric theories the partner-particles contribute with opposite signs to the quadratic shielding.
- In total $m(r) = 0 \cdot R^2$
- Naturalness is saved.

Susy has to be broken

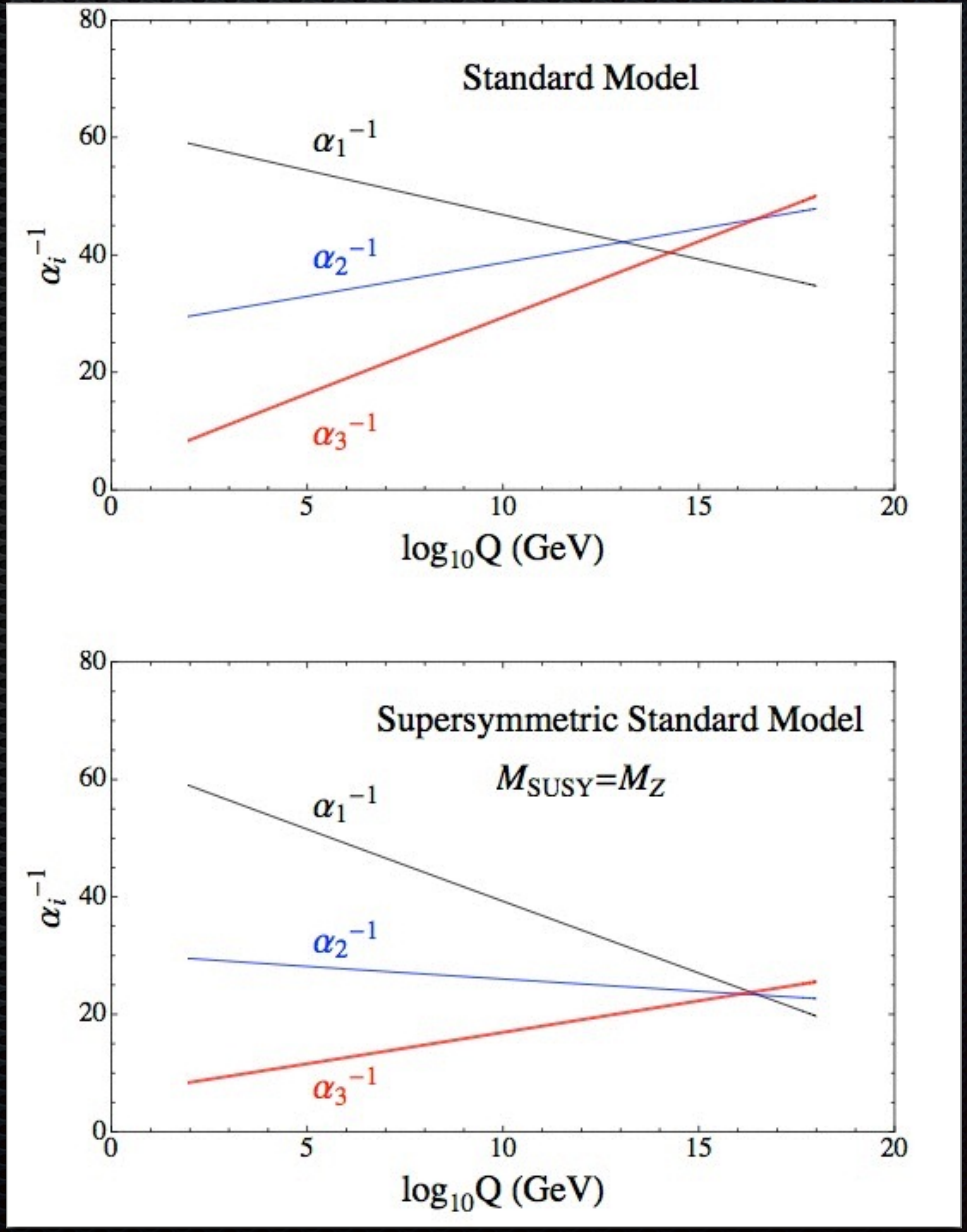
- Supersymmetry predicts the mass of a particle and its partner to be the same.
- This is not observed in nature (no boson with 512keV).
- Thus supersymmetry has to be broken itself (like in the Higgs effect) preserving naturalness.
- Then the super-partners can have larger mass.
- Naturalness kicks in at about the mass of the super-partners.
- Thus naturalness suggests super-partner masses of about 100GeV

Open Problems Solved by Susy

- Mathematics of Quantum Field Theory
- Naturalness
- **Unification of Gauge Interactions**
- Dark Matter
- Realistic String Models

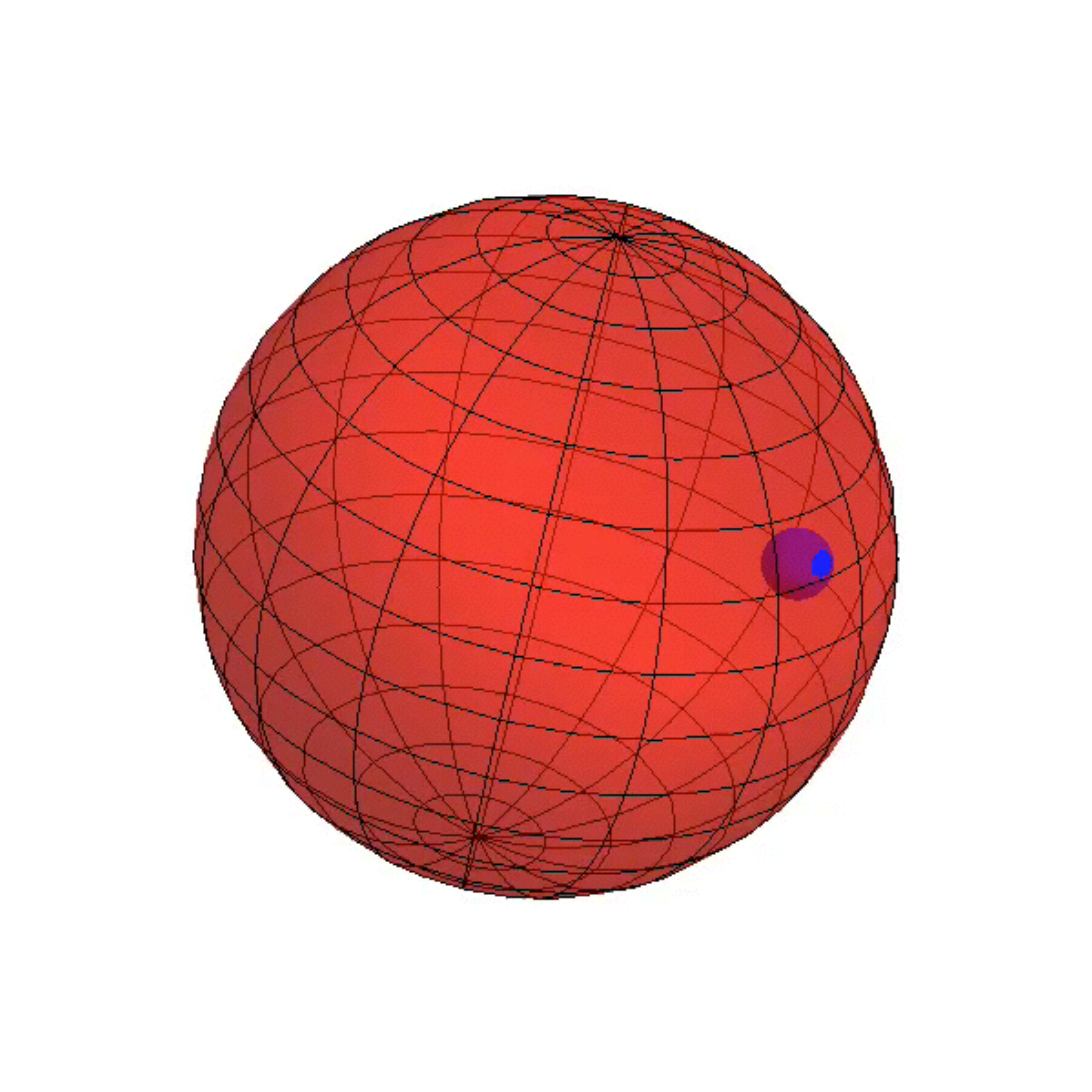
Gauge unification

- As the logarithmic running can be computed, the charges $Q(R)$ can be extrapolated for all gauge interactions.
- Only with Susy they meet in a single point.



Gauge unification

- This points to the possibility that they come from a unified (rotation) symmetry that is broken by a Higgs mechanism.



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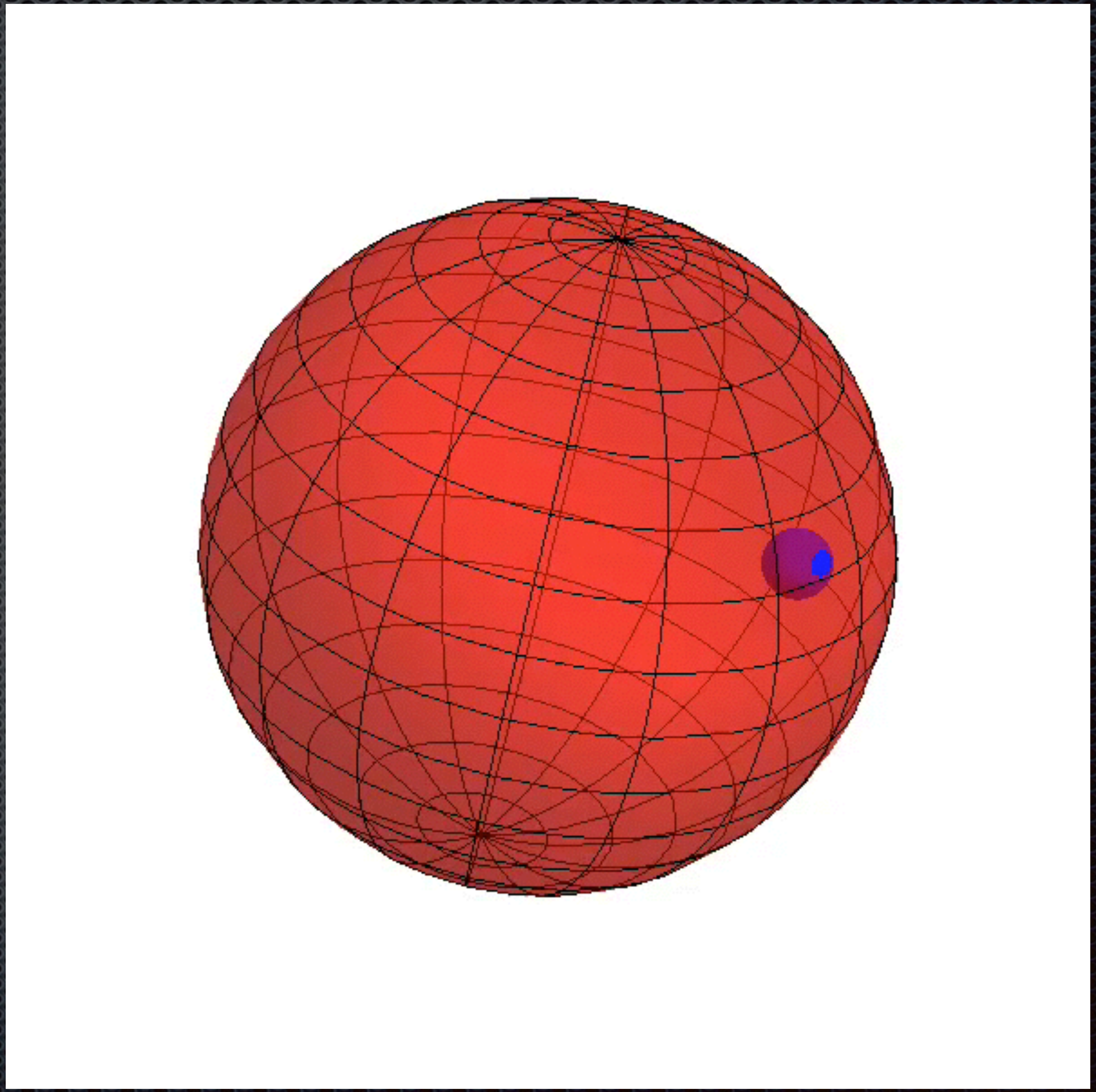
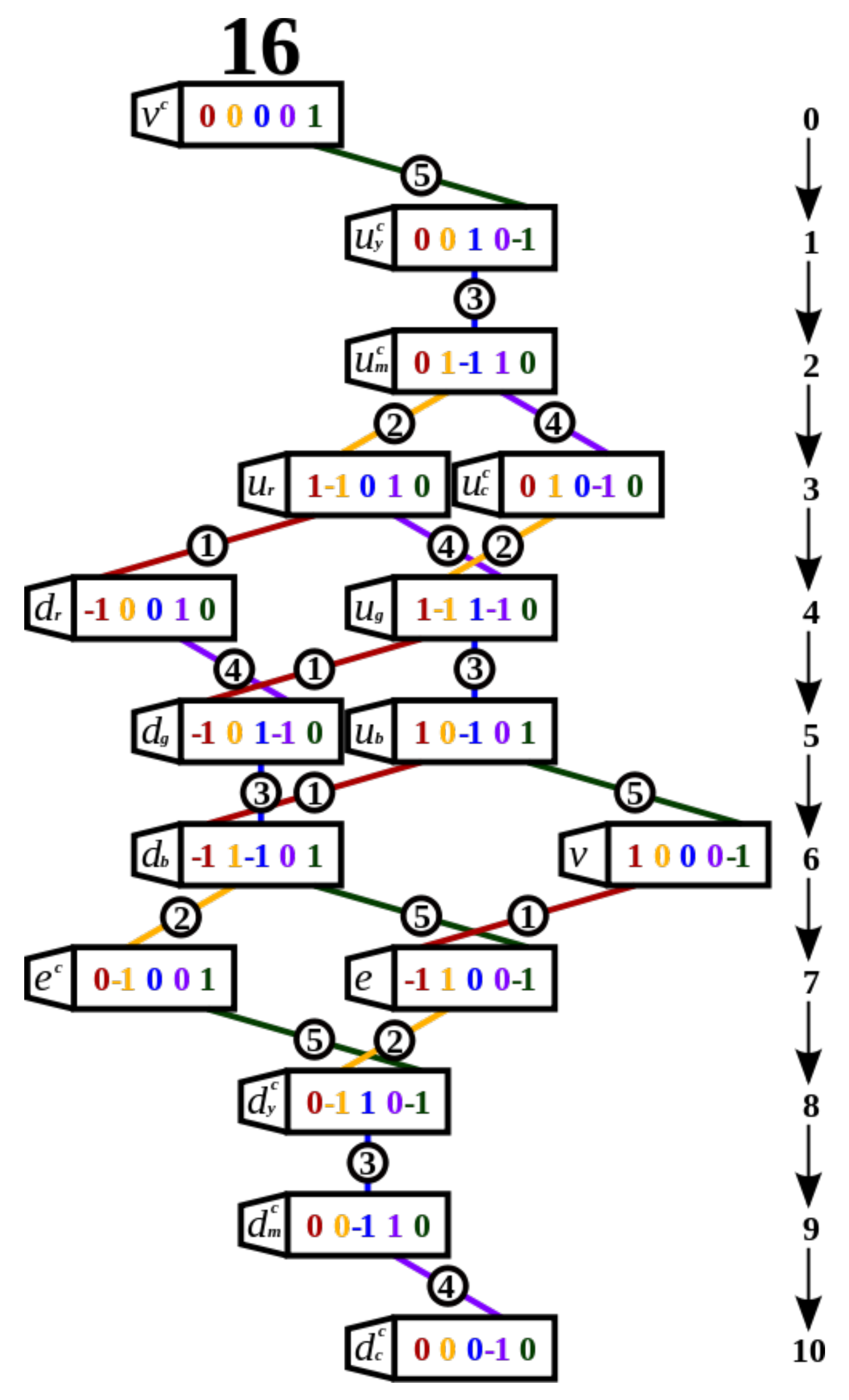


Gauge unification

- This points to the possibility that they come from a unified (rotation) symmetry that is broken by a Higgs mechanism.
- There are further hints towards such a symmetry (multiplets, neutrino masses)

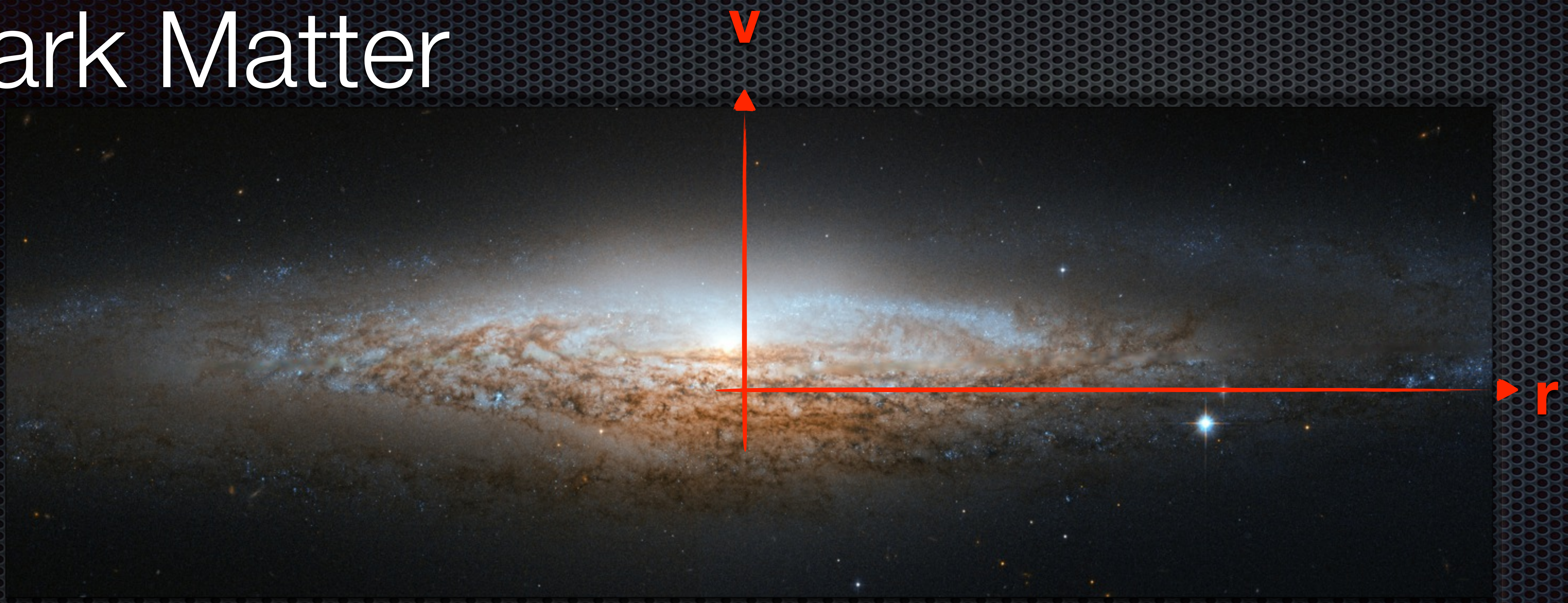


Open Problems Solved by Susy

- Mathematics of Quantum Field Theory
- Naturalness
- Unification of Gauge Interactions
- **Dark Matter**
- Realistic String Models

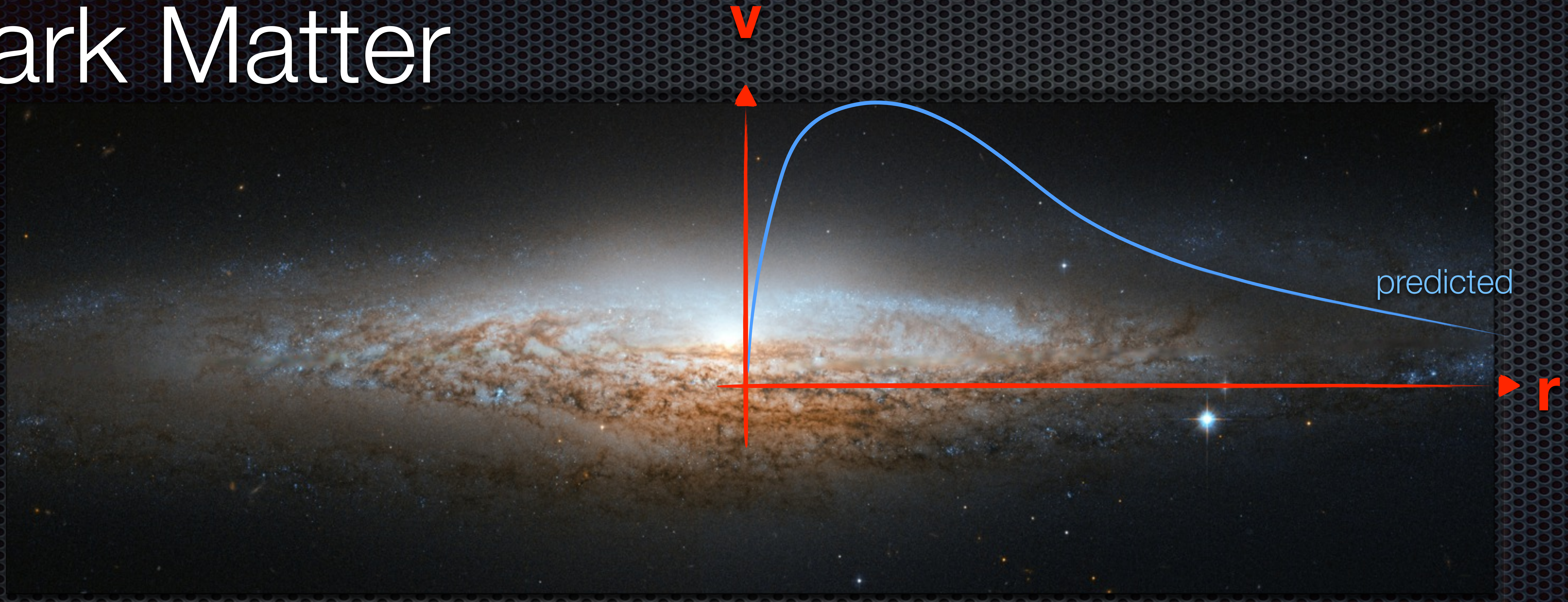
Dark Matter

Dark Matter



- Rotational velocity of stars can be measured.

Dark Matter



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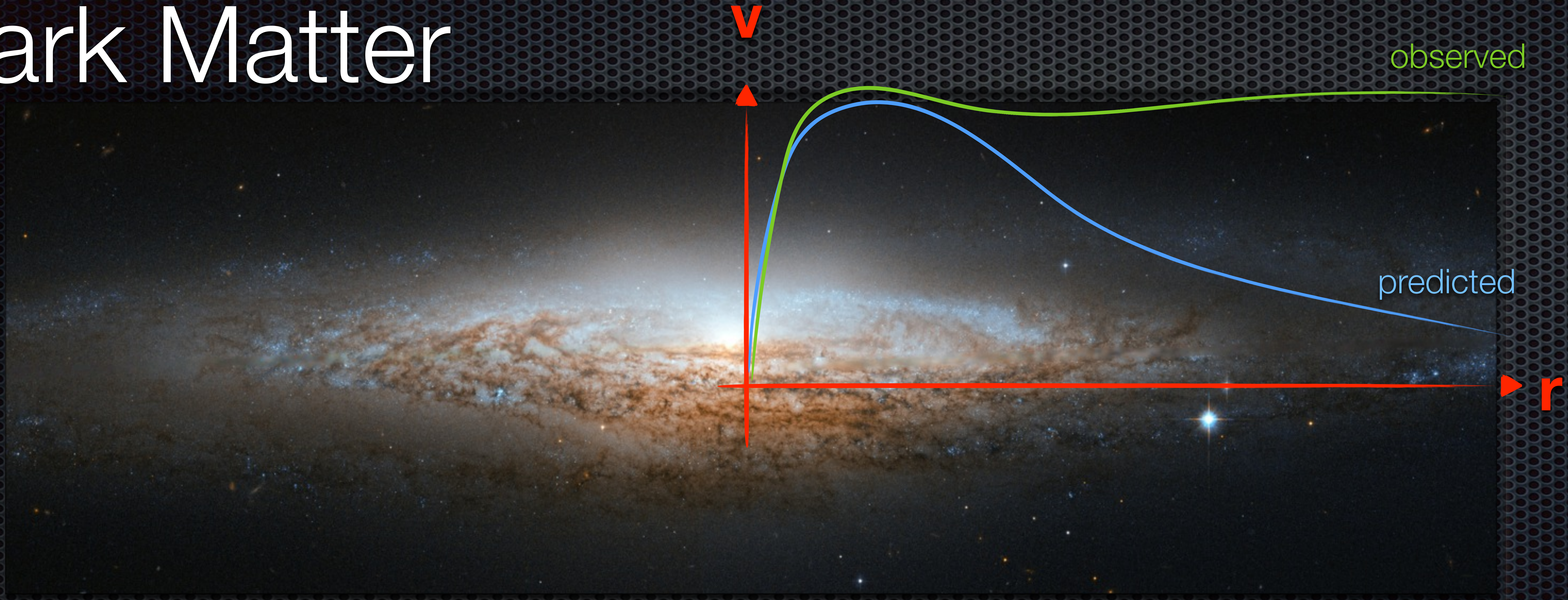
Dark Matter



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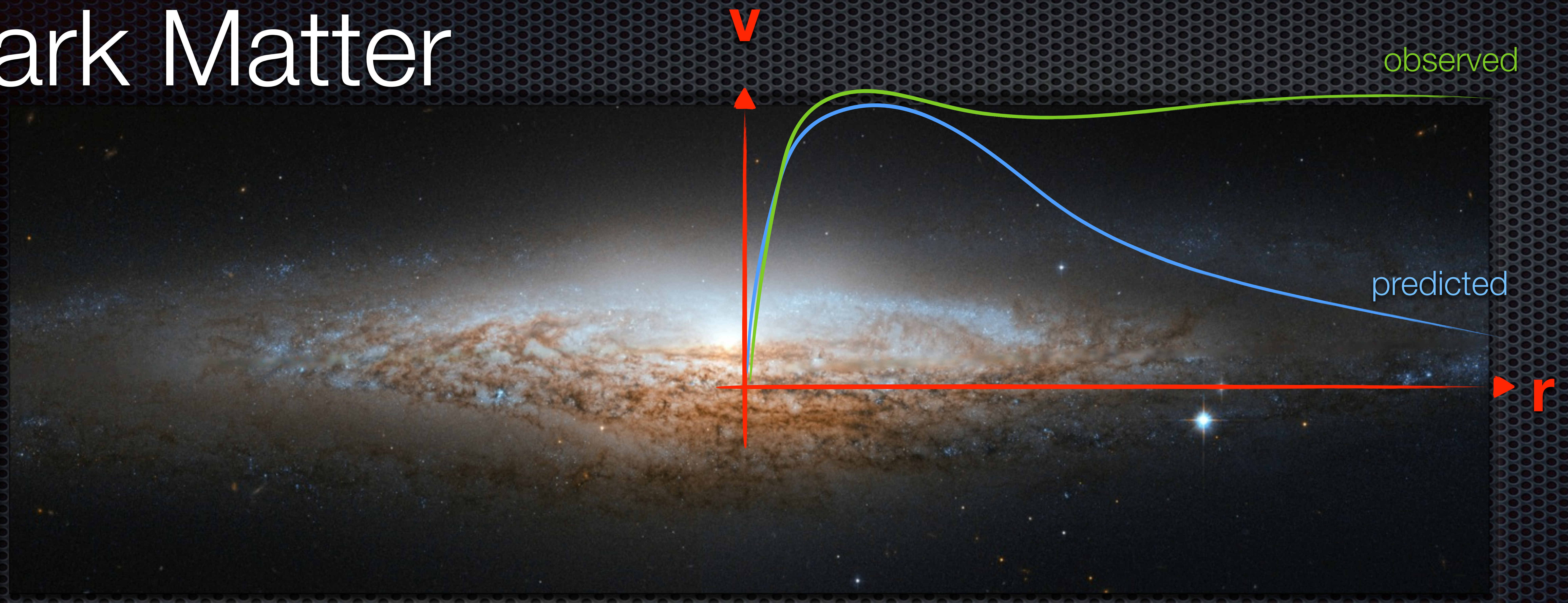

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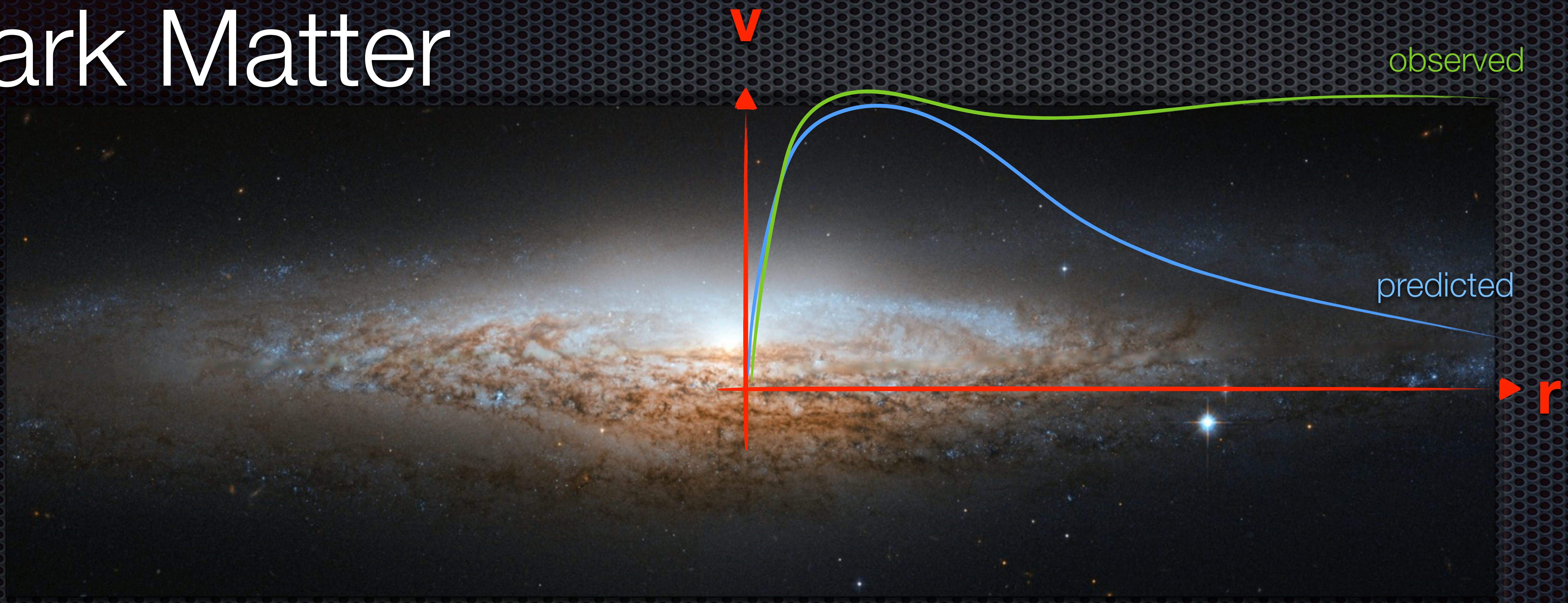

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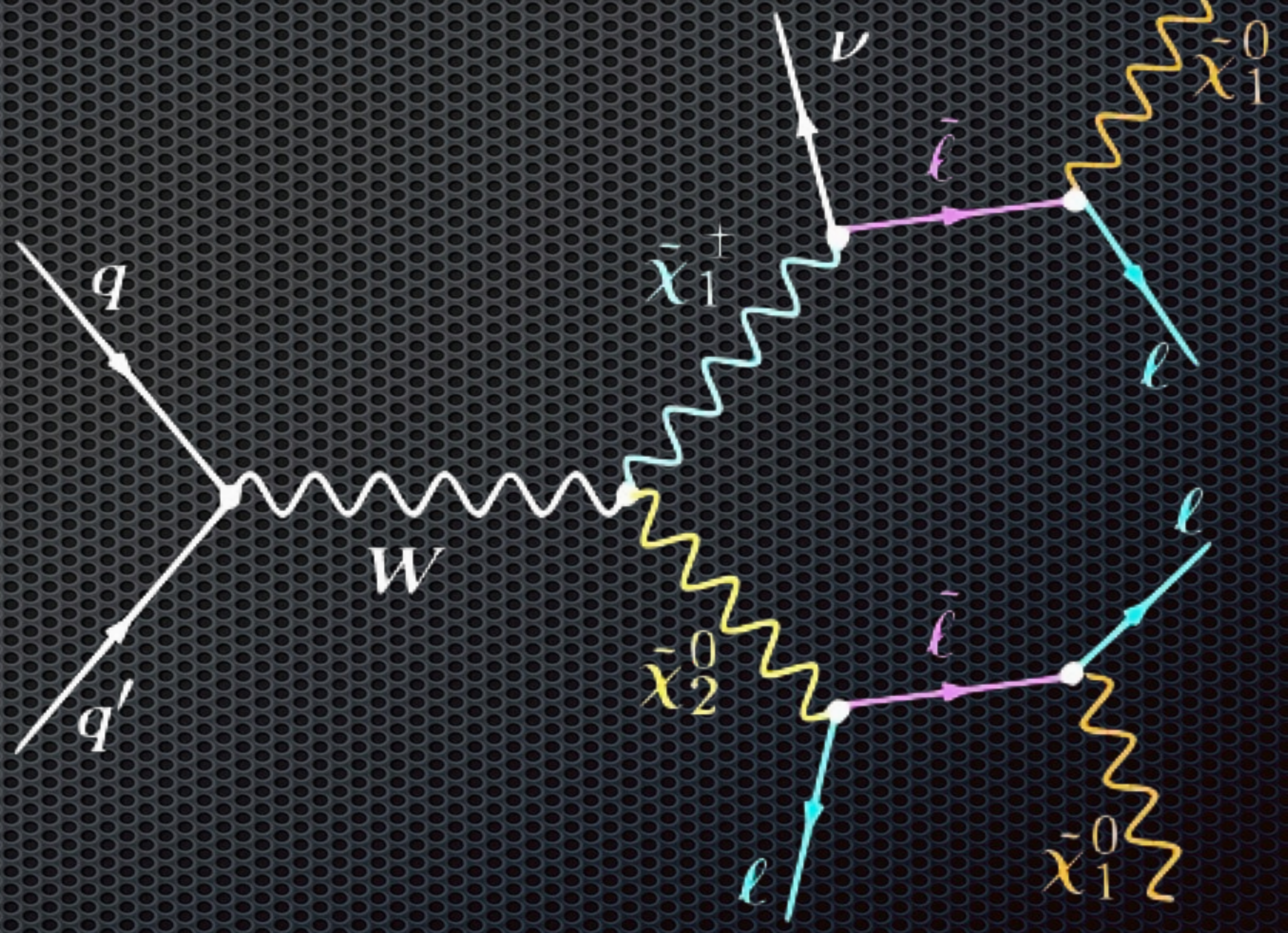
- Observation attributed to invisible mass exceeding visible mass of stars 5 times
- This mass has to be in the form of heavy stable particles only subject to gravity and the weak force (no electric or strong charge): “WIMP”
- No WIMPS amongst known particles.

Susy provides Dark Matter

- Susy particles have a property "R-parity".
- They can only be created in pairs.
- In the decay products of a super-partner there has to be an odd numbers of super-partners.
- This makes the lightest super-partner stable.
- This LSP is a WIMP candidate.



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Superstrings

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char s[MAXBUF];
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- If you are more ambitious and want to bring in quantum gravity as well, string theory is the way to go.
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Superstrings

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Let's look for it

What to look for?

- Susy breaking is not unique. It comes with 120 new parameters.
- Compare to 19 of standard model
- Some ruled out by absence proton decay, dipole moments of electrons an neutrons an FCNCs…
- Plenty of room to avoid detection
- Every measurement relative to some choices for parameters.

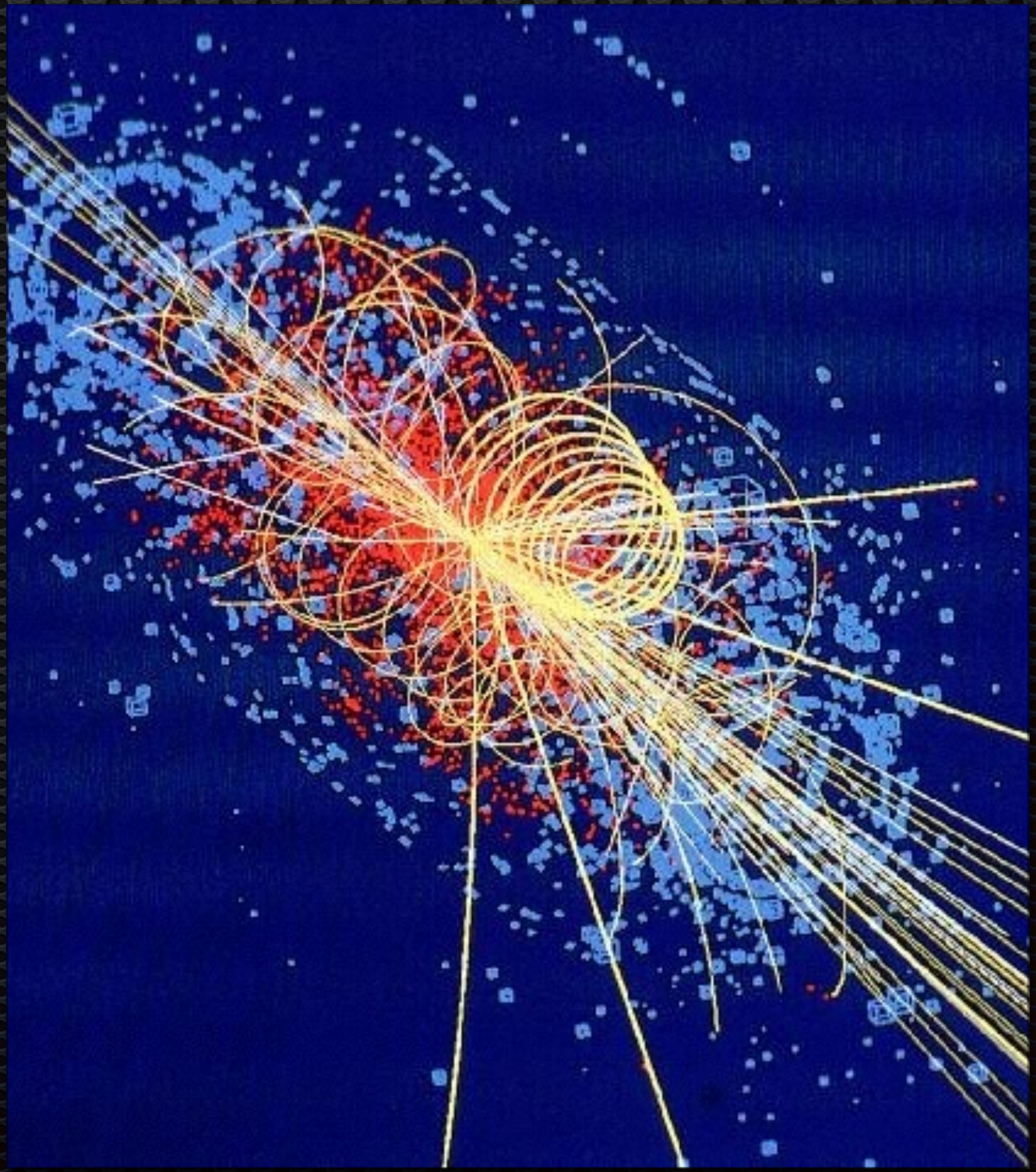
Symbol	Description	Renormalization scheme (point)	Value
m_e	Electron mass		511 keV
m_μ	Muon mass		105.7 MeV
m_τ	Tau mass		1.78 GeV
m_u	Up quark mass	μMS = 2 GeV	1.9 MeV
m_d	Down quark mass	μMS = 2 GeV	4.4 MeV
m_s	Strange quark mass	μMS = 2 GeV	87 MeV
m_c	Charm quark mass	μMS = m_c	1.32 GeV
m_b	Bottom quark mass	μMS = m_b	4.24 GeV
m_t	Top quark mass	On-shell scheme	172.7 GeV
θ_{12}	CKM 12-mixing angle		13.1°
θ_{23}	CKM 23-mixing angle		2.4°
θ_{13}	CKM 13-mixing angle		0.2°
δ	CKM CP-violating Phase		995
g_1 or g'	U(1) gauge coupling	μMS = m_Z	357
g_2 or g	SU(2) gauge coupling	μMS = m_Z	652
g_3 or g_s	SU(3) gauge coupling	μMS = m_Z	1.221
θ_{QCD}	QCD vacuum angle		~0
v	Higgs vacuum expectation value		246 GeV
m_H	Higgs mass		~ 125 GeV (tentative)

Large Hadron Collider

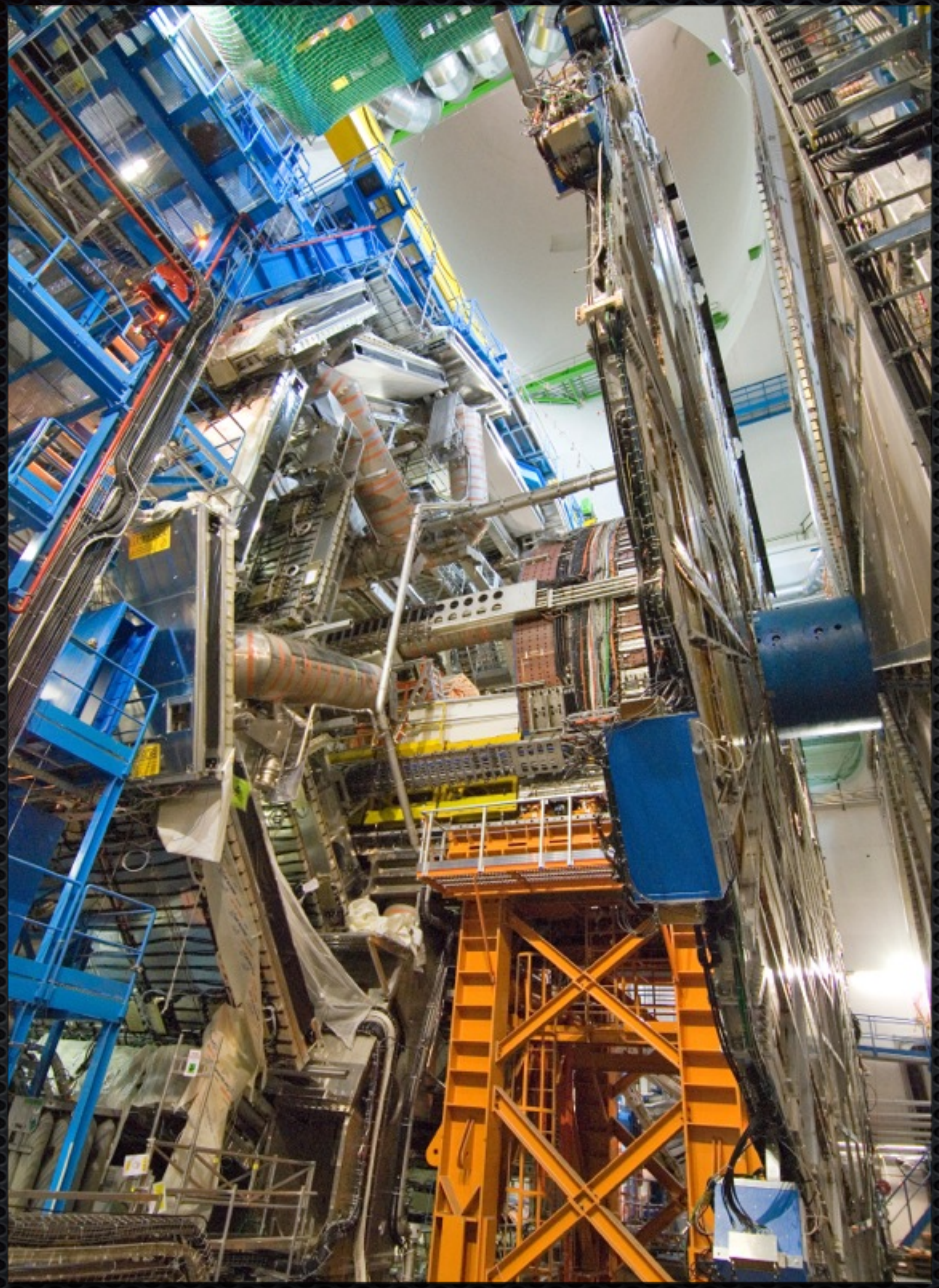
- Two beams of protons collide with an energy of 8TeV
- Two general-purpose experiments: ATLAS and CMS

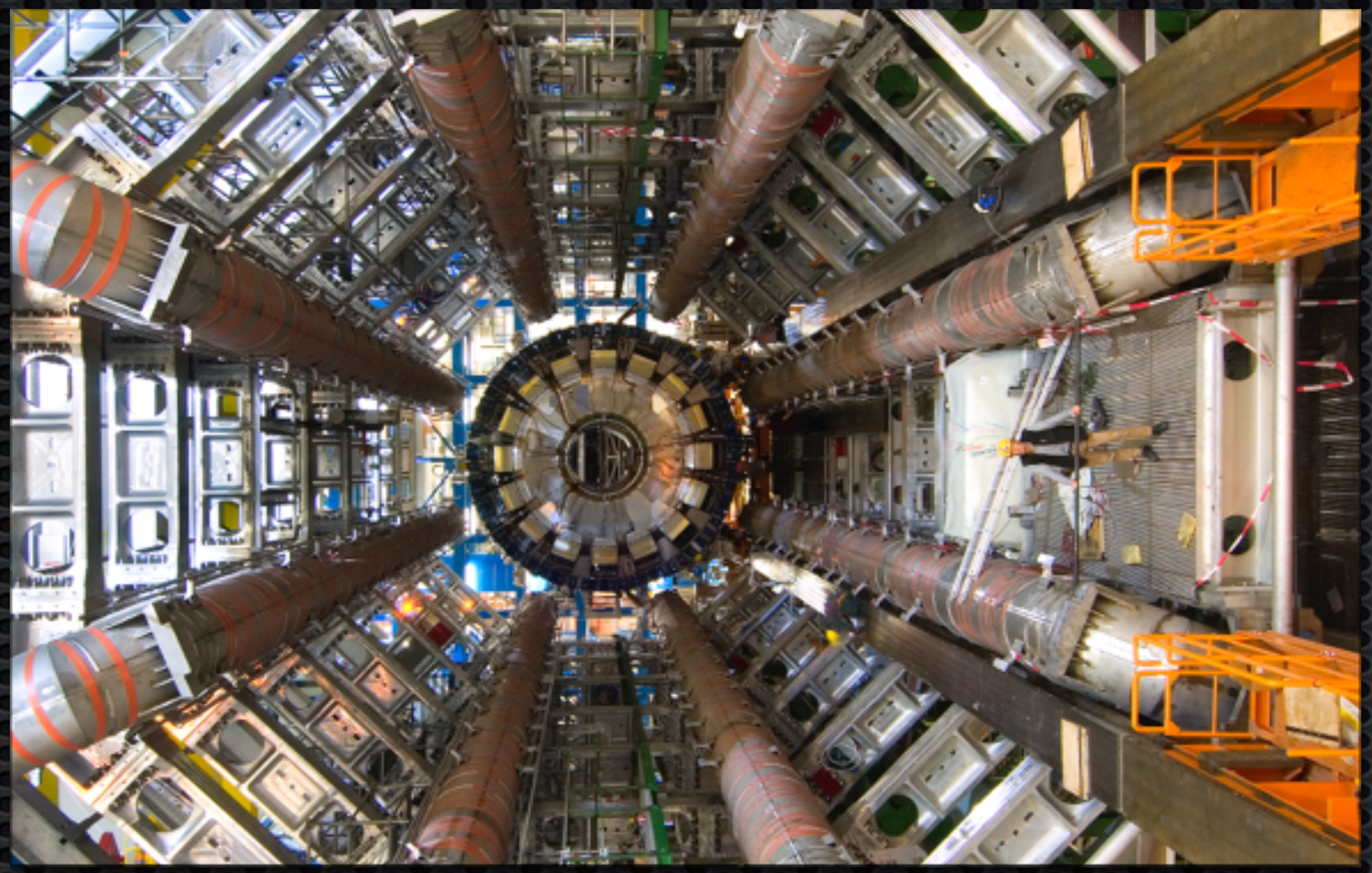
Large Hadron Collider

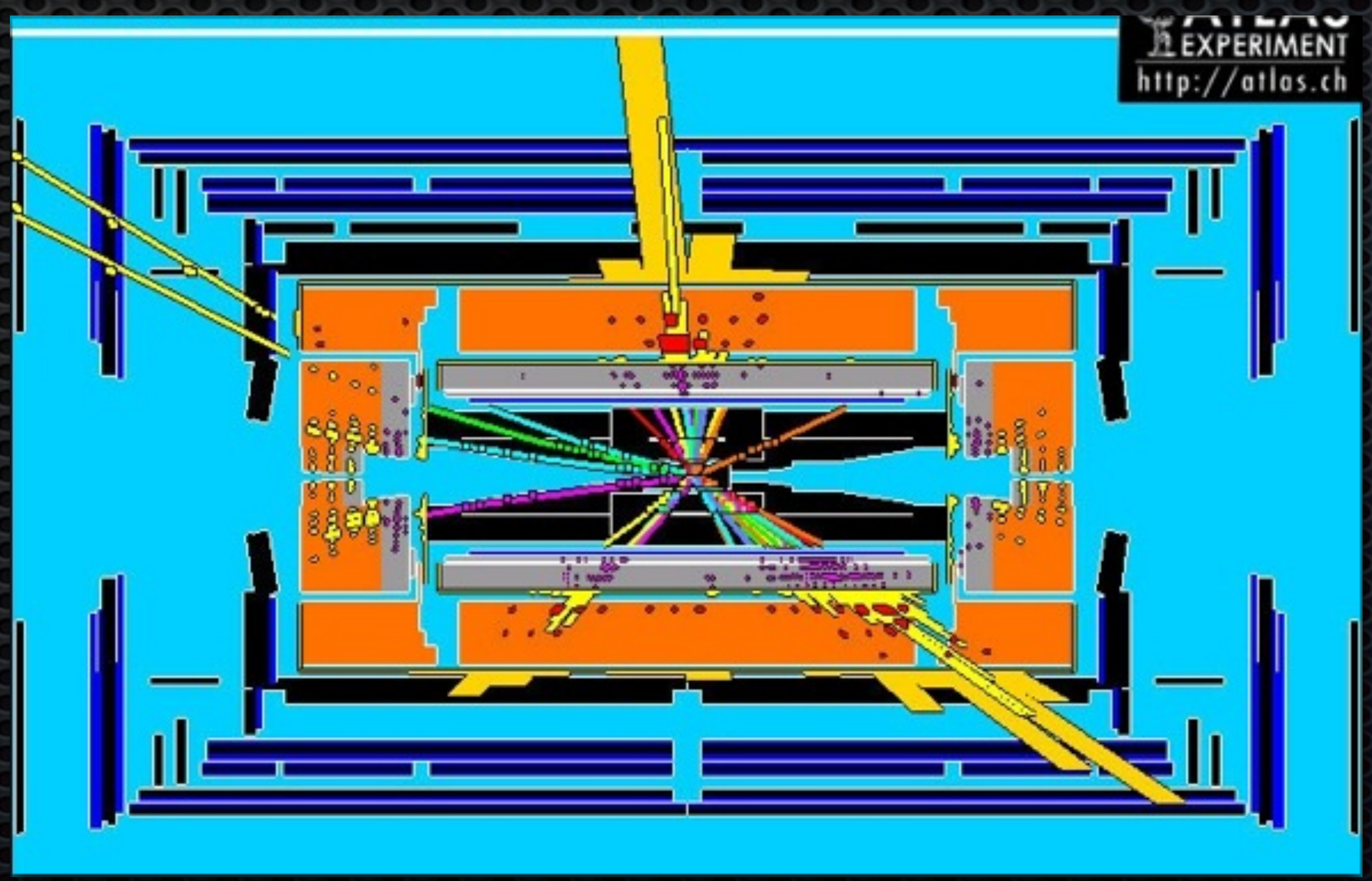
- Protons are easy to accelerate
- They are not elementary: 3 Quarks plus 2000 particles (quarks and gluons) from the vacuum sea
- The collision is between two such “partons”, the rest are by-standers.
- Collision happens with a small fraction of 7TeV
- Lots of debris, complicated signal



ATLAS

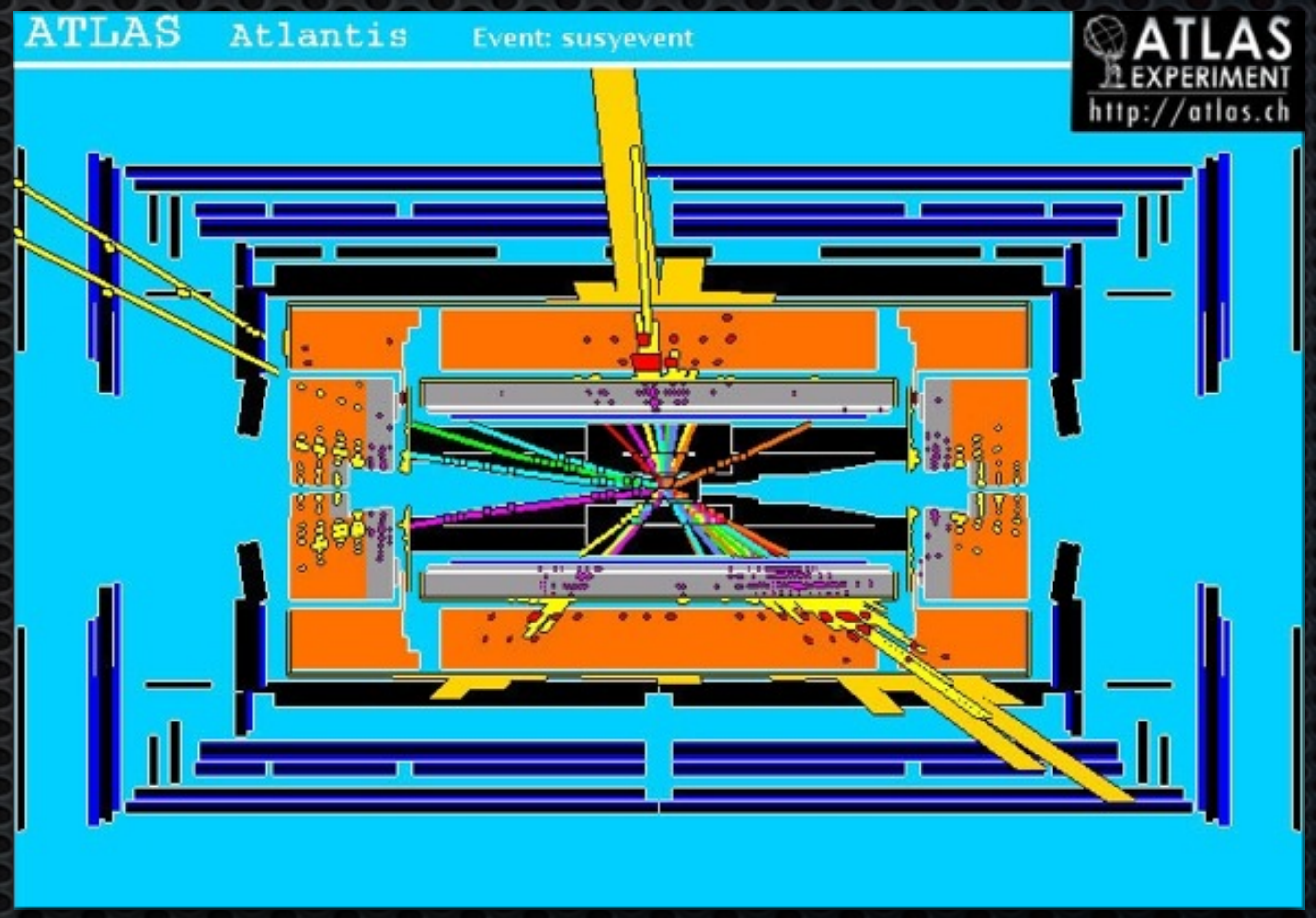


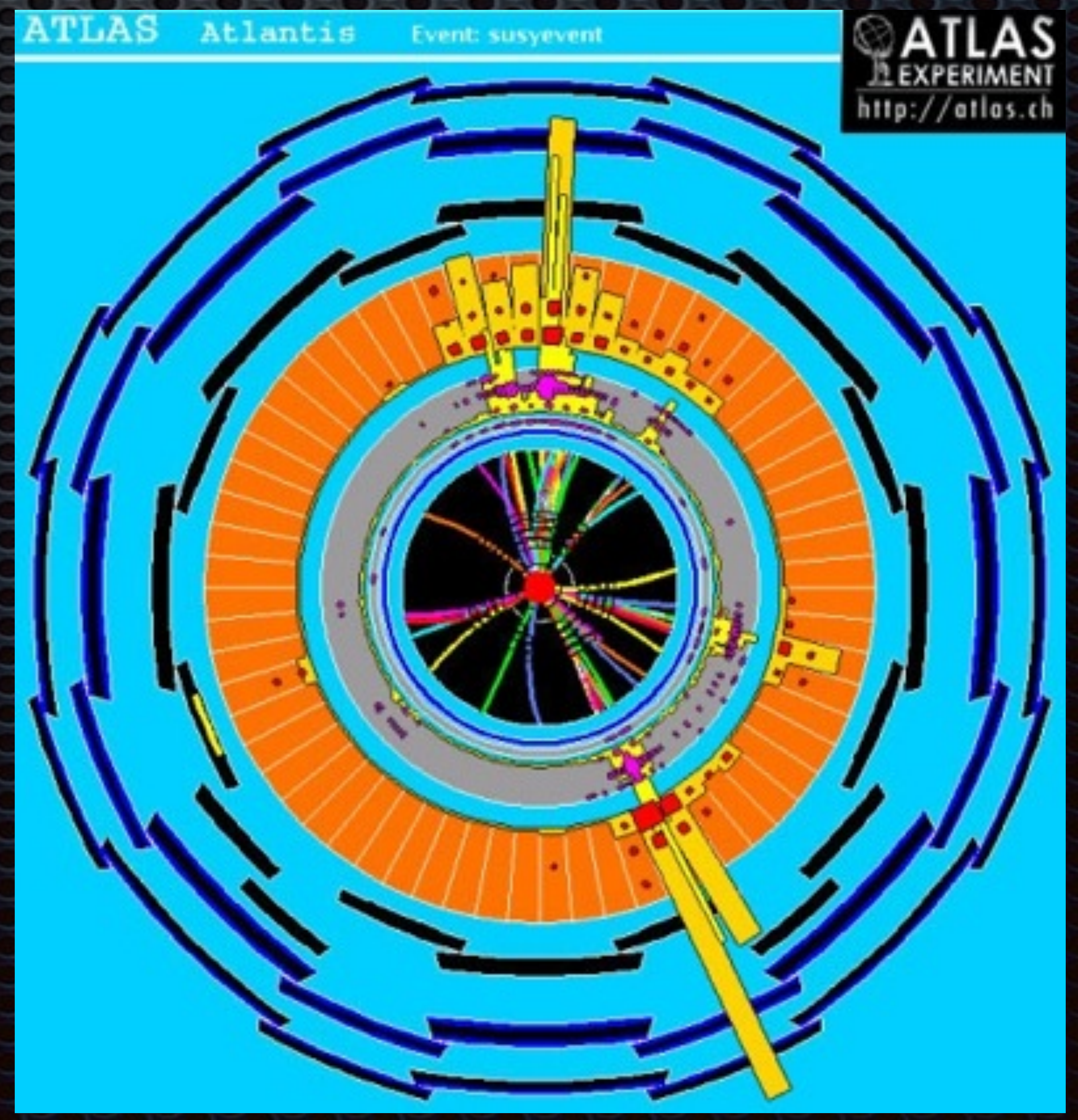


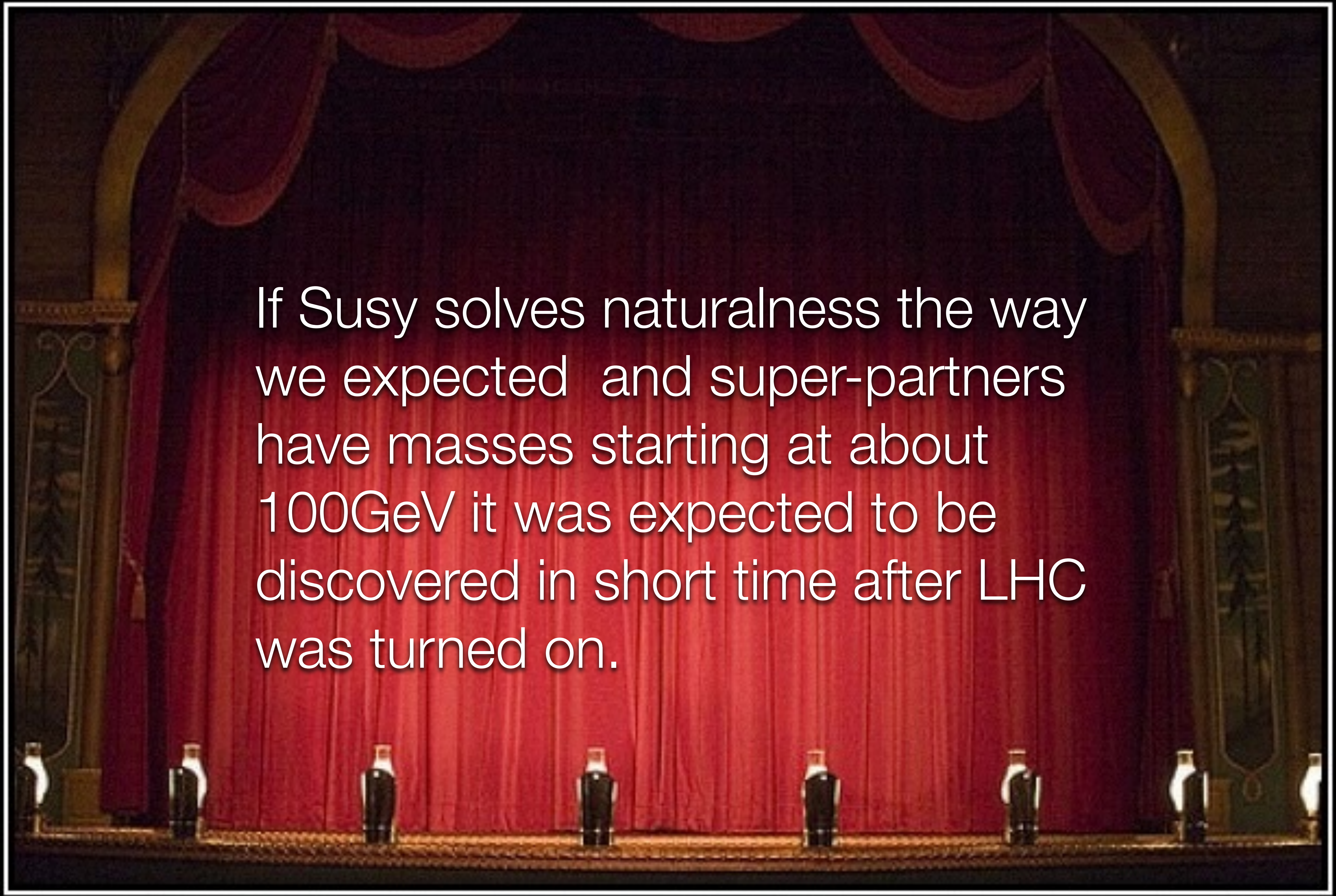


What would Susy look like?

- Smoking gun is that you don’t see it!
- LSP is invisible to detector
- Visible particles seem to violate momentum conservation…
- in transverse direction
- There are other, more subtle effects in branchings and cross sections





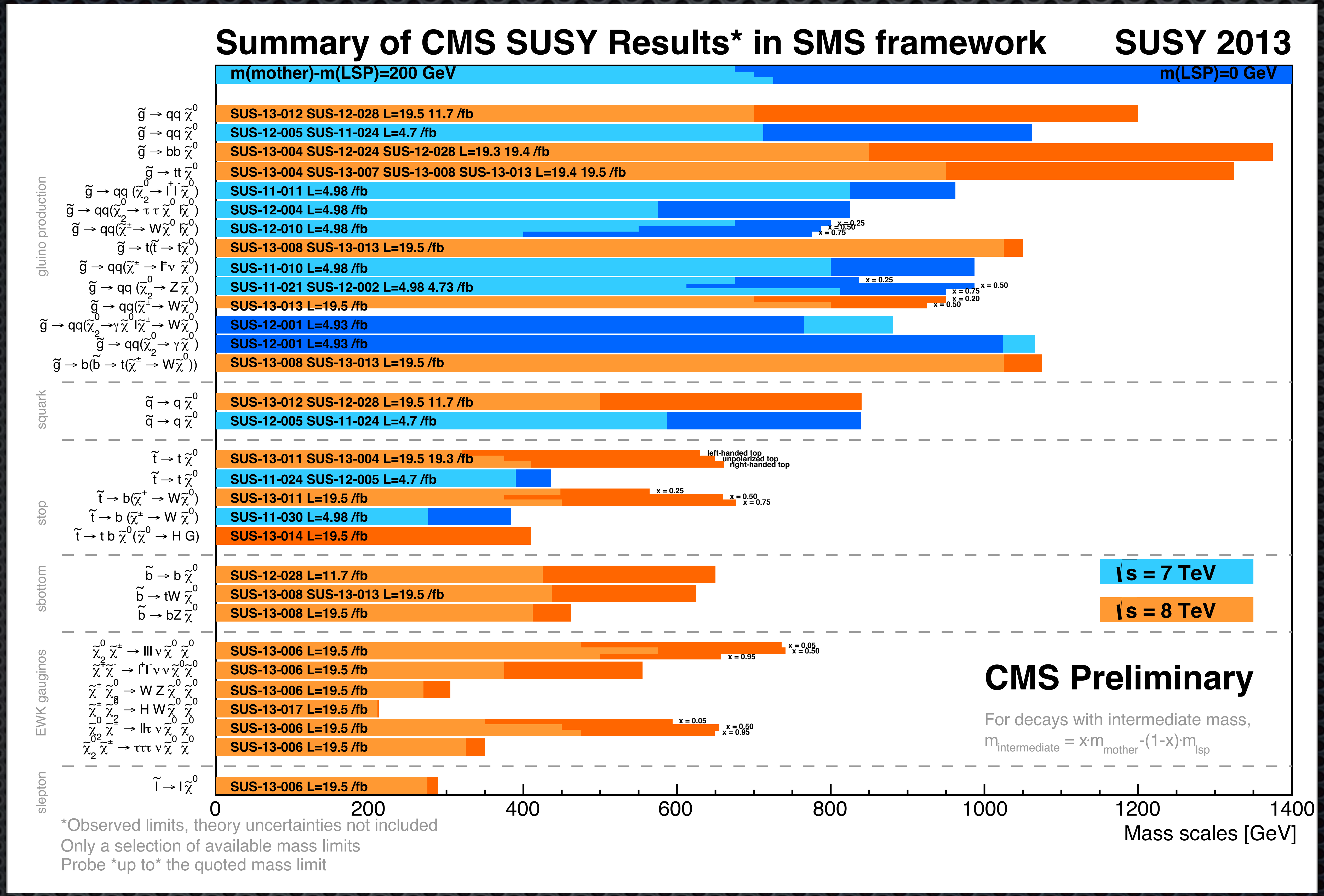


EXPECTATIONS

Please don't disappoint

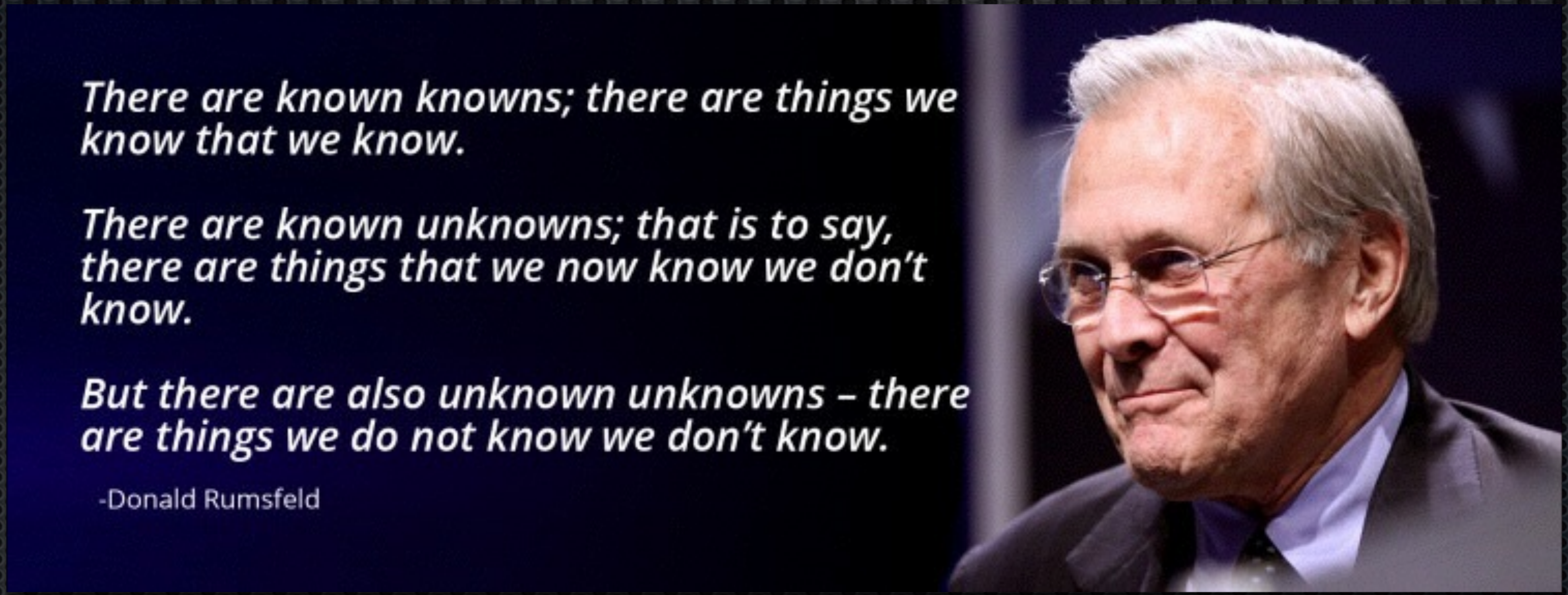
But…

Lower bounds on mass



If super-partners exist they have to be heavier than…

Now, what?



- There is still some room in parameter space
- This was only the simplest Susy extension. More contrived ones are still possible to hide.
- Or, 100GeV (electro-weak) scale Susy is not Nature's solution to Naturalness

Forget Susy?

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Then come up with fresh ideas for…

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Take home message

- Susy offers solutions to some of the most pressing open questions in physics.
- Despite expectations it remains to be found at LHC.

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