Quantum Gravity inside the Cosmic Horizon

Yasha Neiman

Student collaborators:

Lucas Hackl, Illan Halpern

1509.05890 (JHEP), 1502.06685 (JHEP), 1502.04106 (PLB),
1409.6753 (PRD), 1406.3291 (JHEP), 1312.7842 (PRD)

Okinawa Institute of Science and Technology

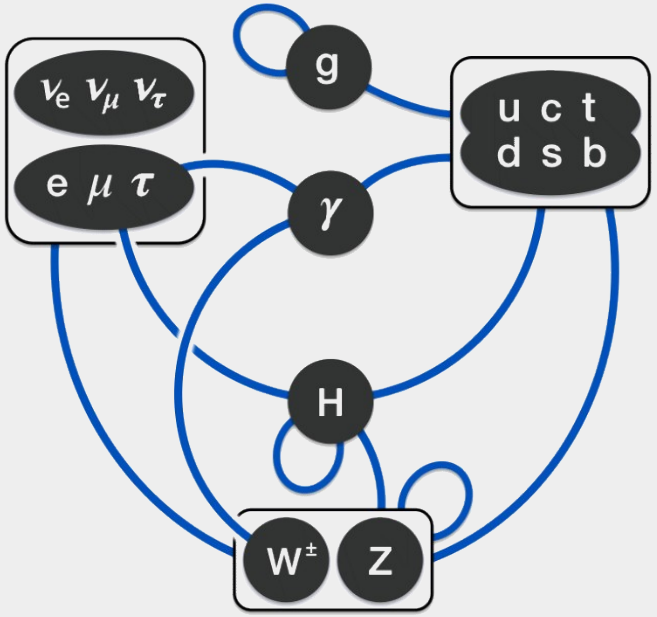
April 26, 2016

Everything is a field

Everything is a field

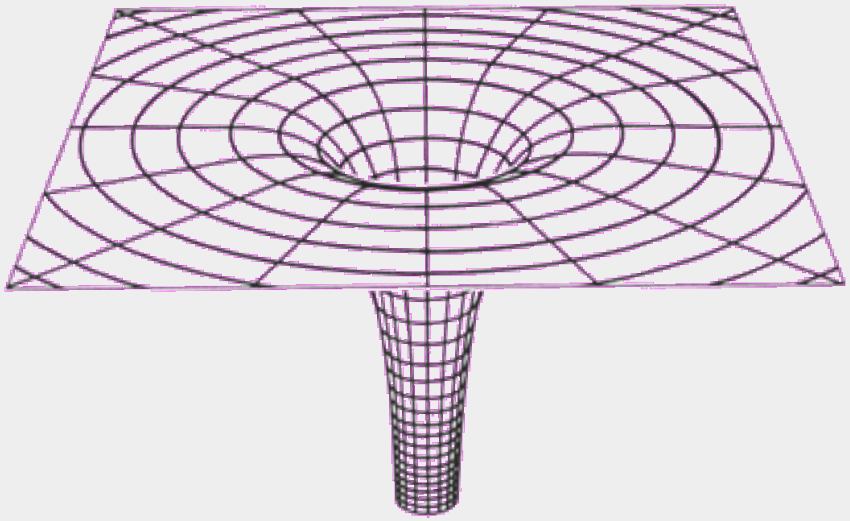
Two fragments of reality

Standard Model (almost everything)



19 fields (or types of particles)

General Relativity (gravitation)



1 field (or type of particle)

Two fragments of reality

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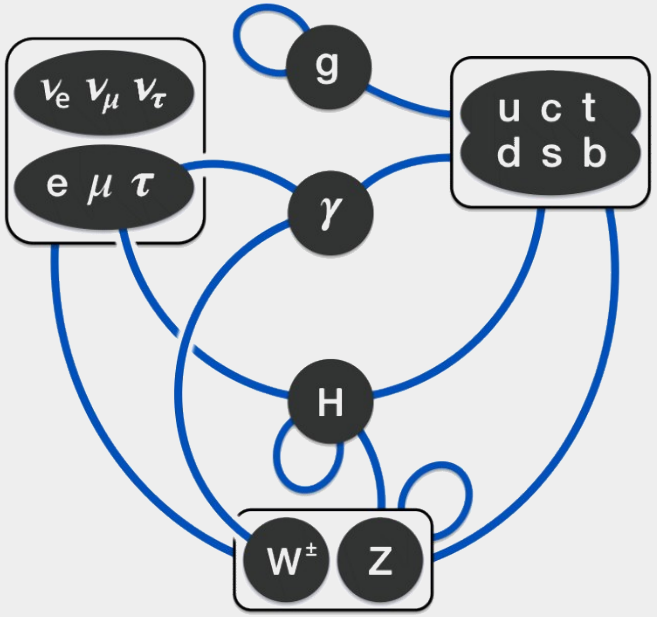

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Quantum

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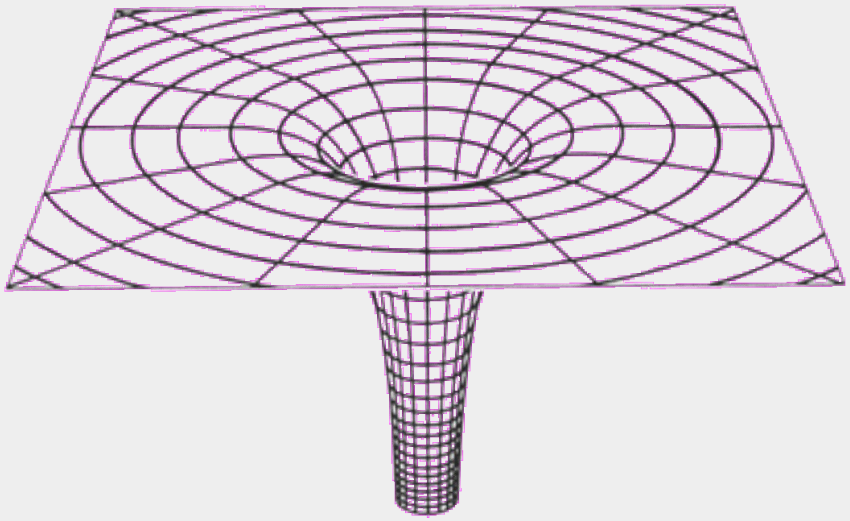

1 field (or type of particle)

Not yet

Plan of the talk

1) Gravity: the spin-2 field

2) Quantum gravity through holography

3) The challenge from the cosmic horizon

4) Constructing a model

5) Current work & Outlook

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It's all about spin

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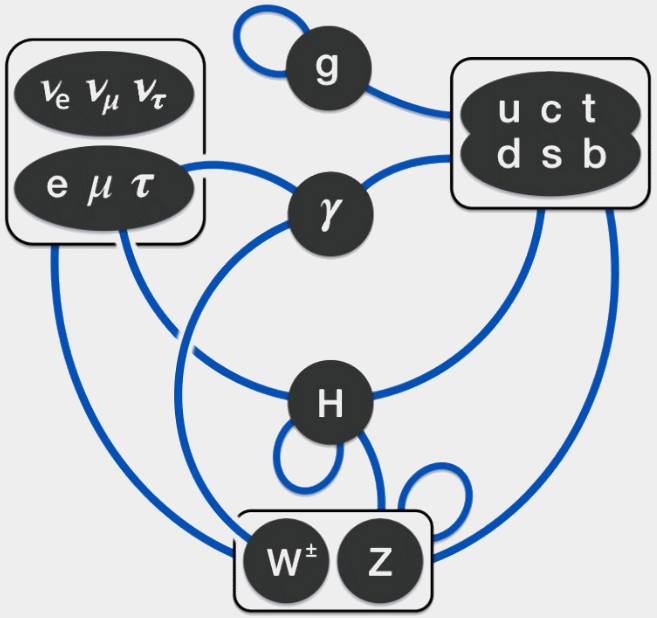

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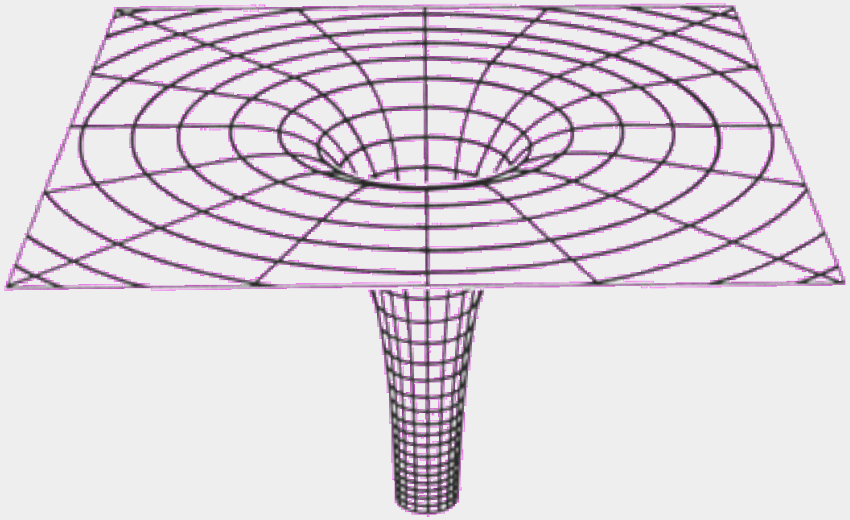

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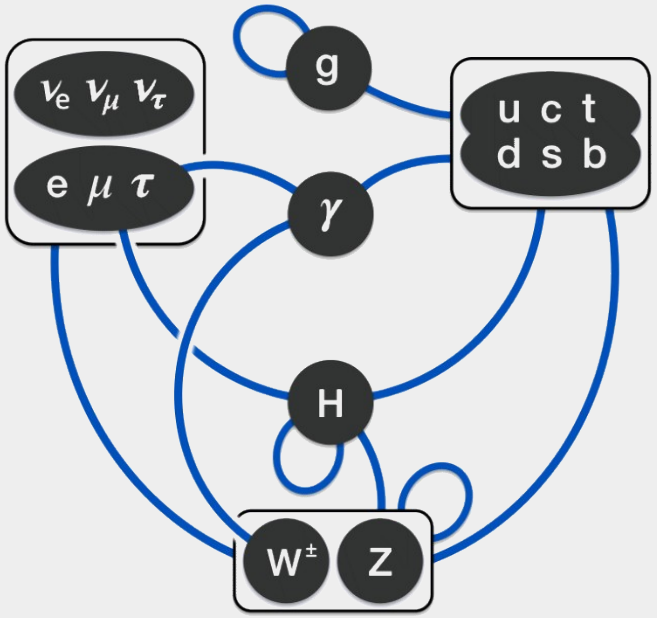

Spin = 0,1/2,1

General Relativity
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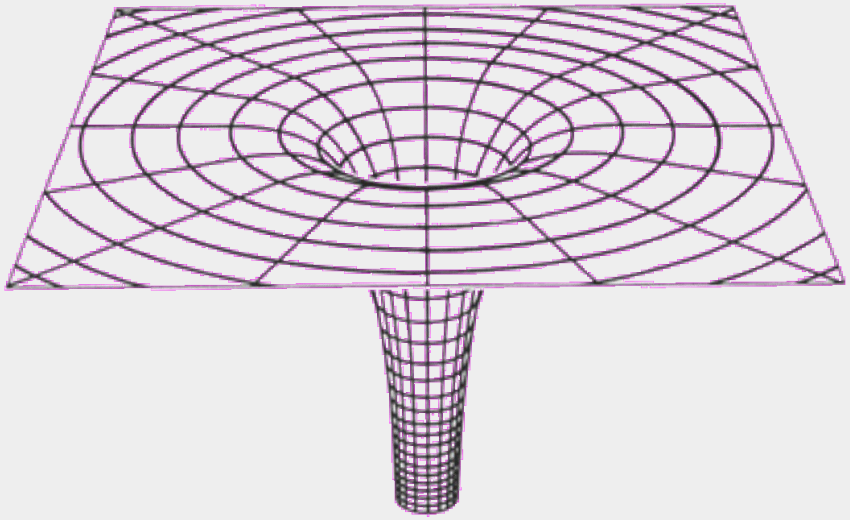
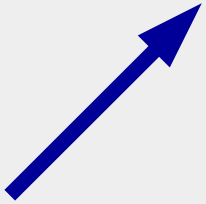


Spin = 2

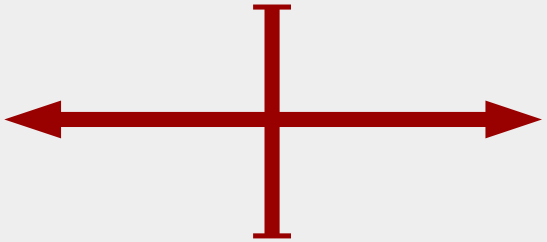
What is spin?

The shape of a field at each point in space.

Spin = 0
(Higgs)



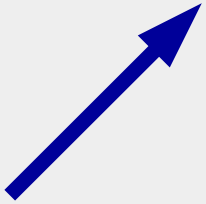
Spin = 1
(Electromagnetic)

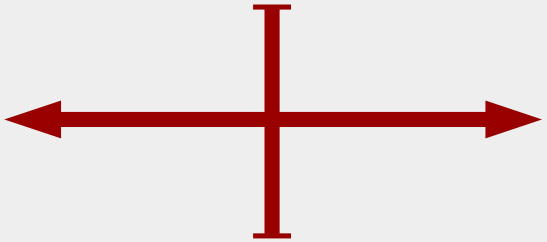


Spin = 2
(Gravity)

What is spin?

The shape of a field at each point in space.





Spin = 0
(Higgs)

Spin = 1
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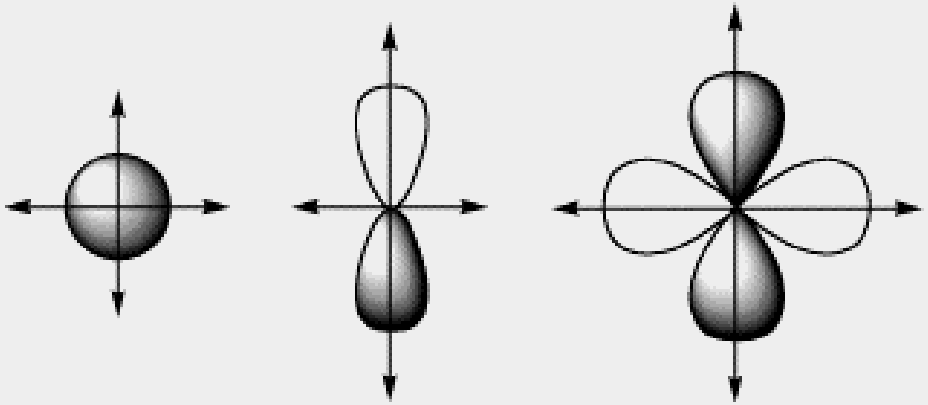
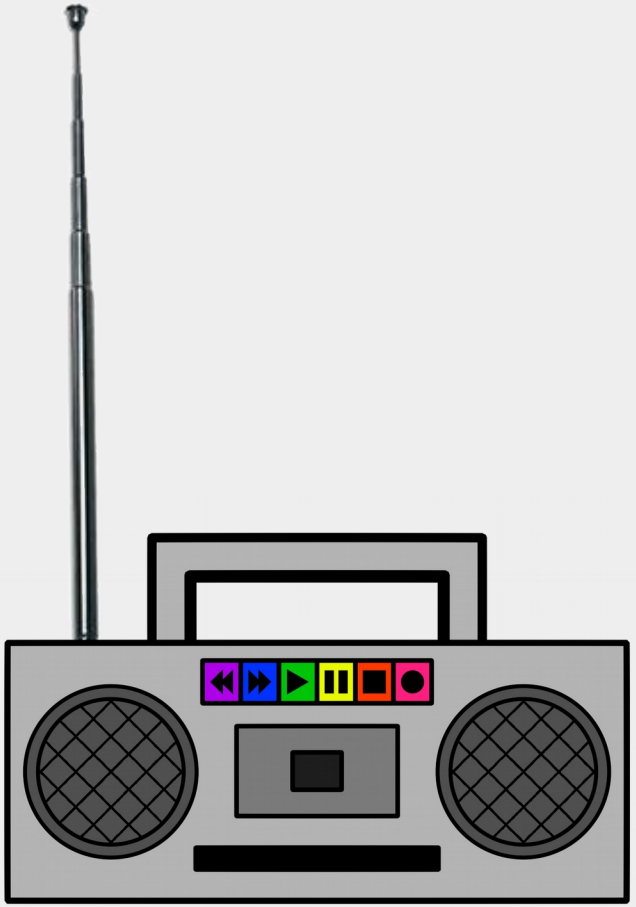
Spin = 2
(Gravity)

Analogy: Shapes of
atomic orbitals (s,p,d,...)



Antenna shapes: Spin = 1

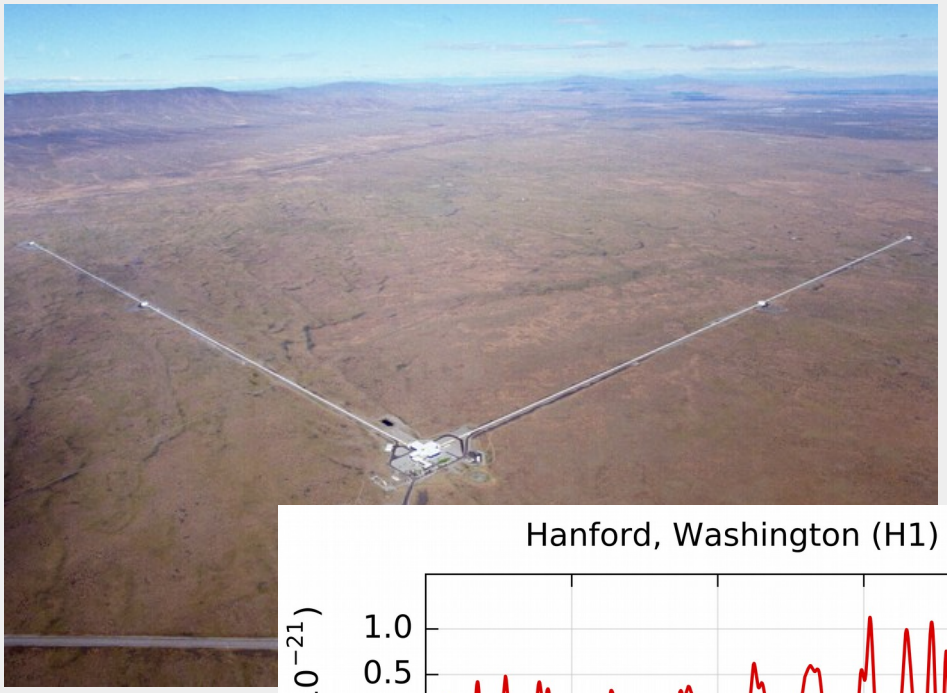


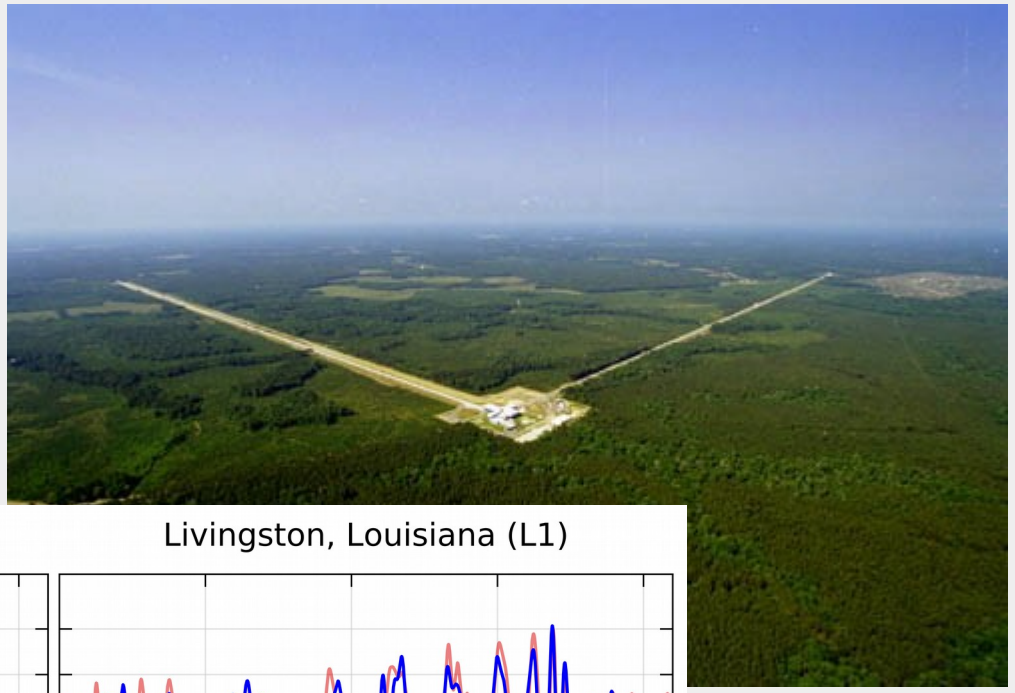
Antenna for spin-1 electromagnetic waves
($5 on eBay, in use since 1888)

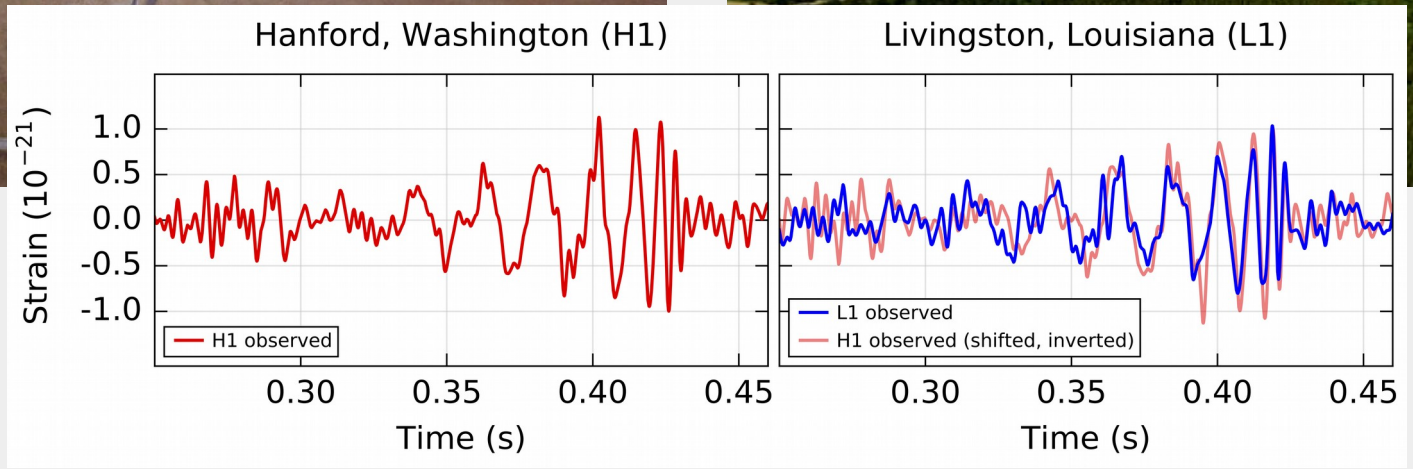
Antenna shapes: Spin = 2

Antenna for spin-2 gravitational waves
(LIGO, $500 million, first signal in 2015)

Antenna shapes: Spin = 2







Antenna for spin-2 gravitational waves
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Challenge and beauty with increasing spin

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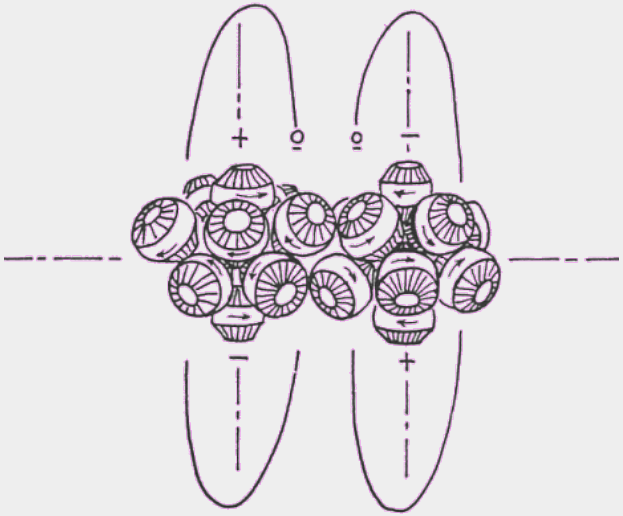
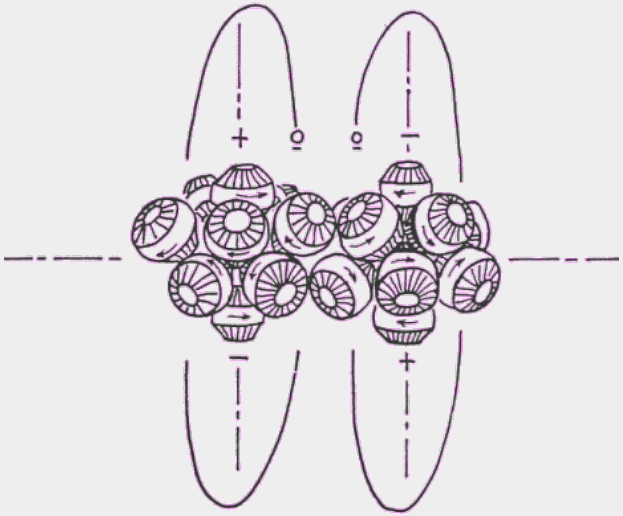


- More complicated shapes.
- Harder to invent consistent interactions.
- All the more so with quantum uncertainty.

Challenge and beauty with increasing spin

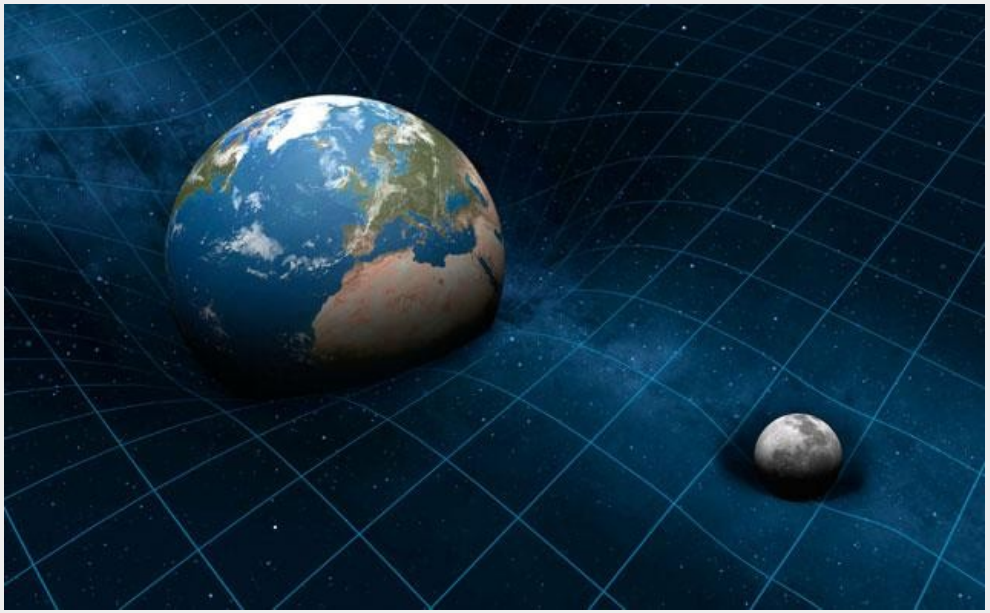


- More complicated shapes.
- Harder to invent consistent interactions.
- All the more so with quantum uncertainty.
- Consistent theories are more unique and mathematically special.

Gravity: the spin-2 theory

Uniqueness:
Can only have a single spin-2 field, describing fluctuations in the geometry of spacetime.

Difficulty:
At the quantum level, still work in progress.



$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = T_{\mu\nu}$$

Plan of the talk

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Why quantum gravity is hard

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Theoretically:

Quantum fluctuations make geometry ill-defined at

$$\ell_{\mathrm{Planck}} \sim \sqrt{\hbar G} \approx 10^{-35}\mathrm{m}$$

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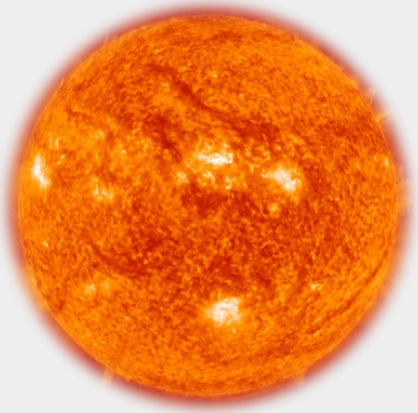
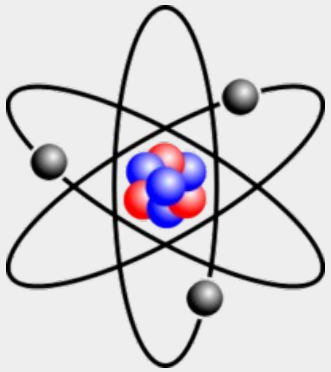
Experimentally:

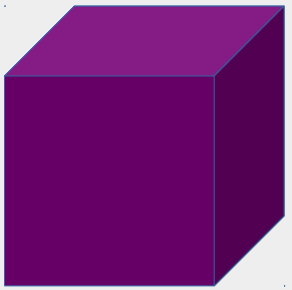
Gravity is weak $\iff$ Planck length is small



$10^{9}{\rm m}$

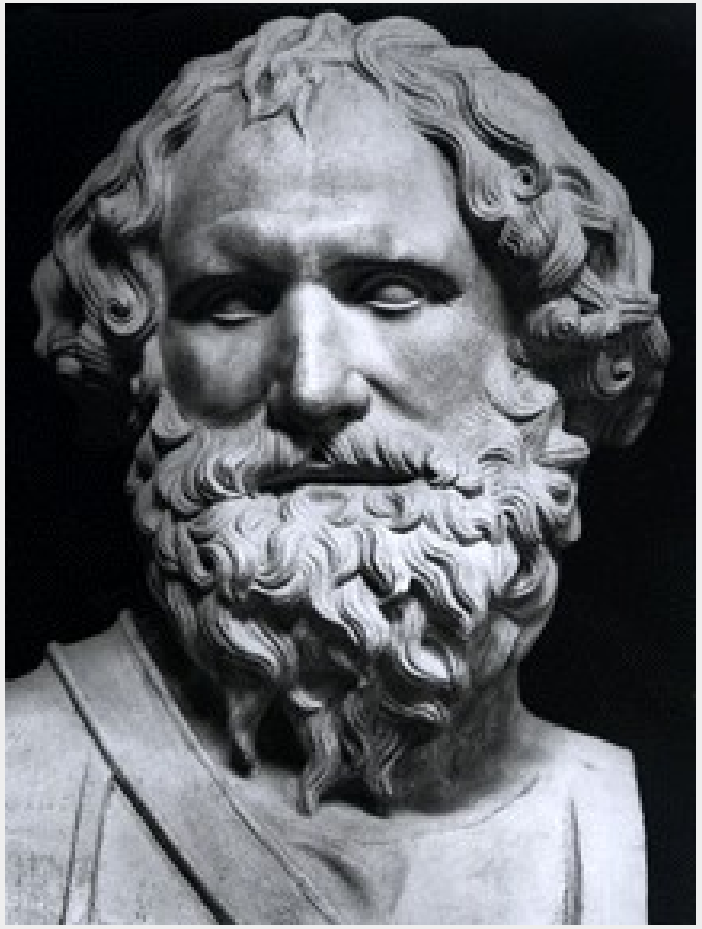


$10^{-10}{\rm m} \sim 10^{-15}{\rm m}$



$10^{-35}{\rm m}$

Archimedes' solution



“Give me a place to stand where the Planck length vanishes,

and I will write a theory of quantum gravity”

Holography: the foothold at infinity

At greater distances, the Planck length becomes more and more negligible

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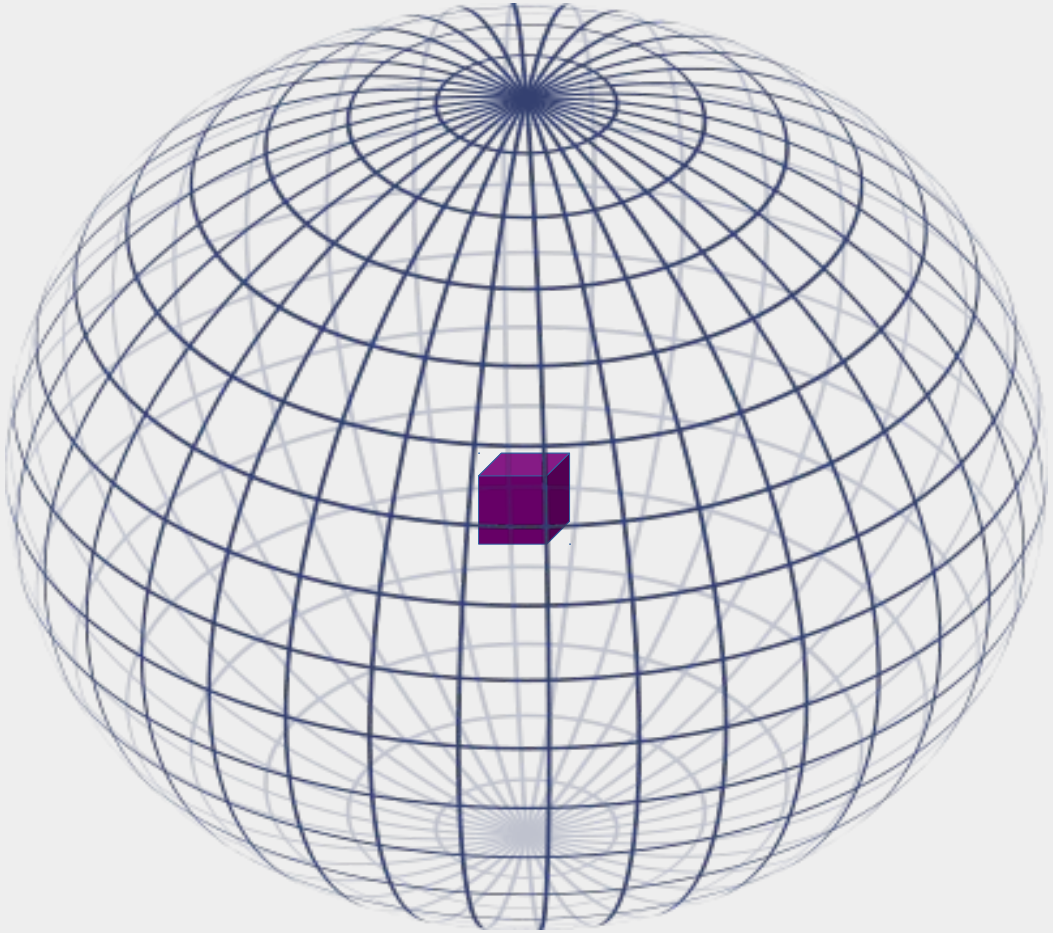
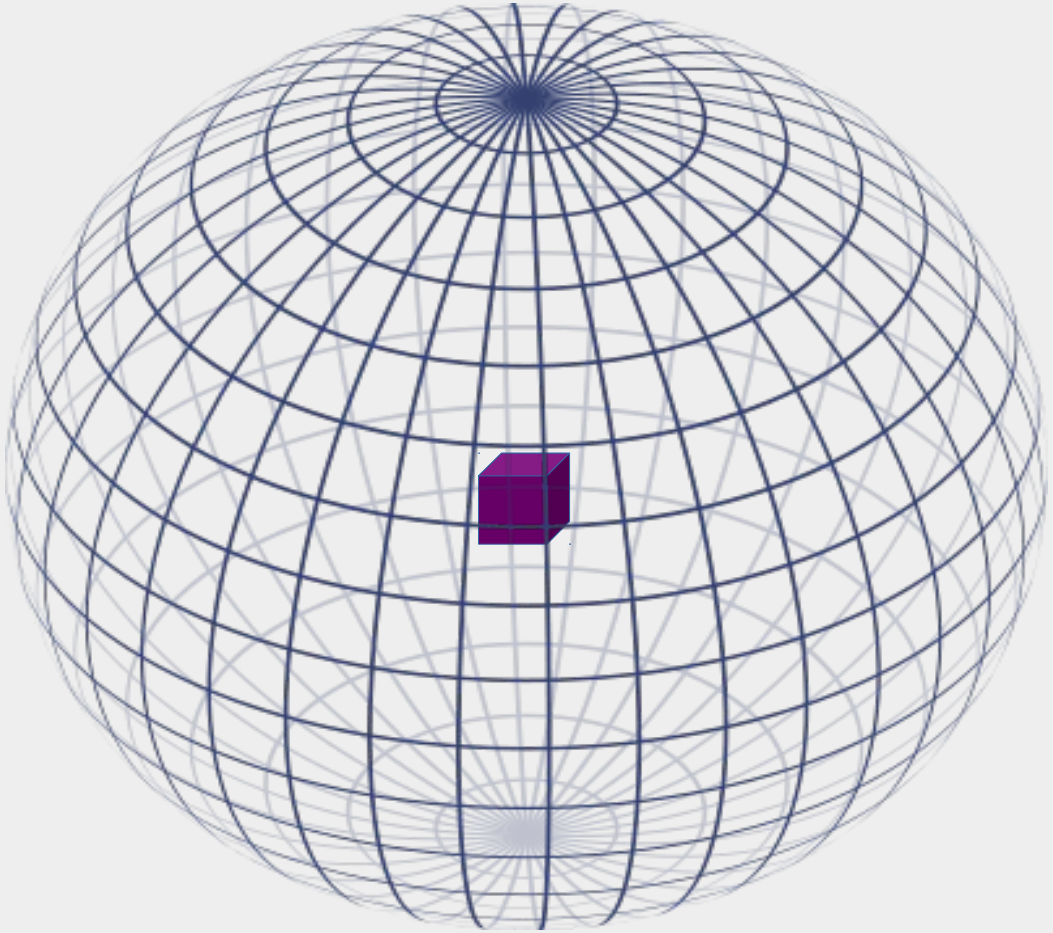


Do your physics from here

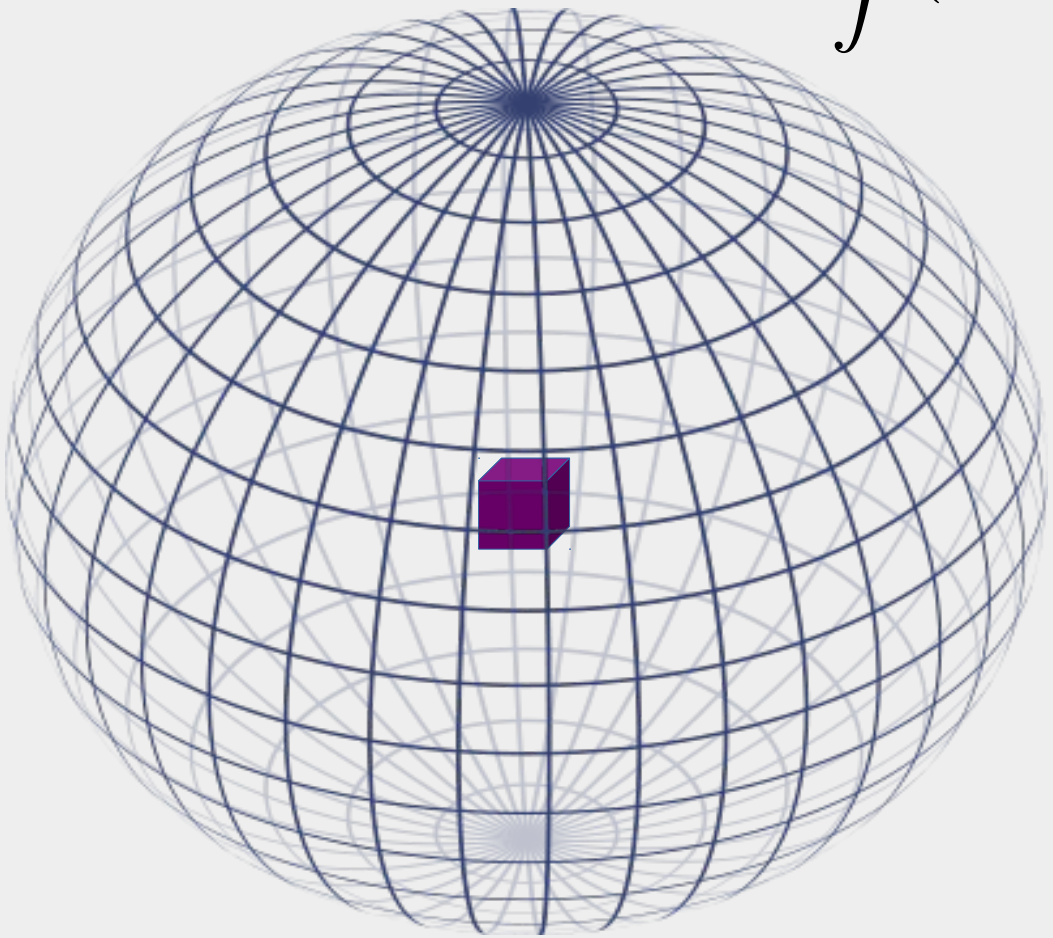
Holography in familiar physics



Holography in familiar physics

Gauss' law

$$Q = \int (\text{Electric field}) dS$$



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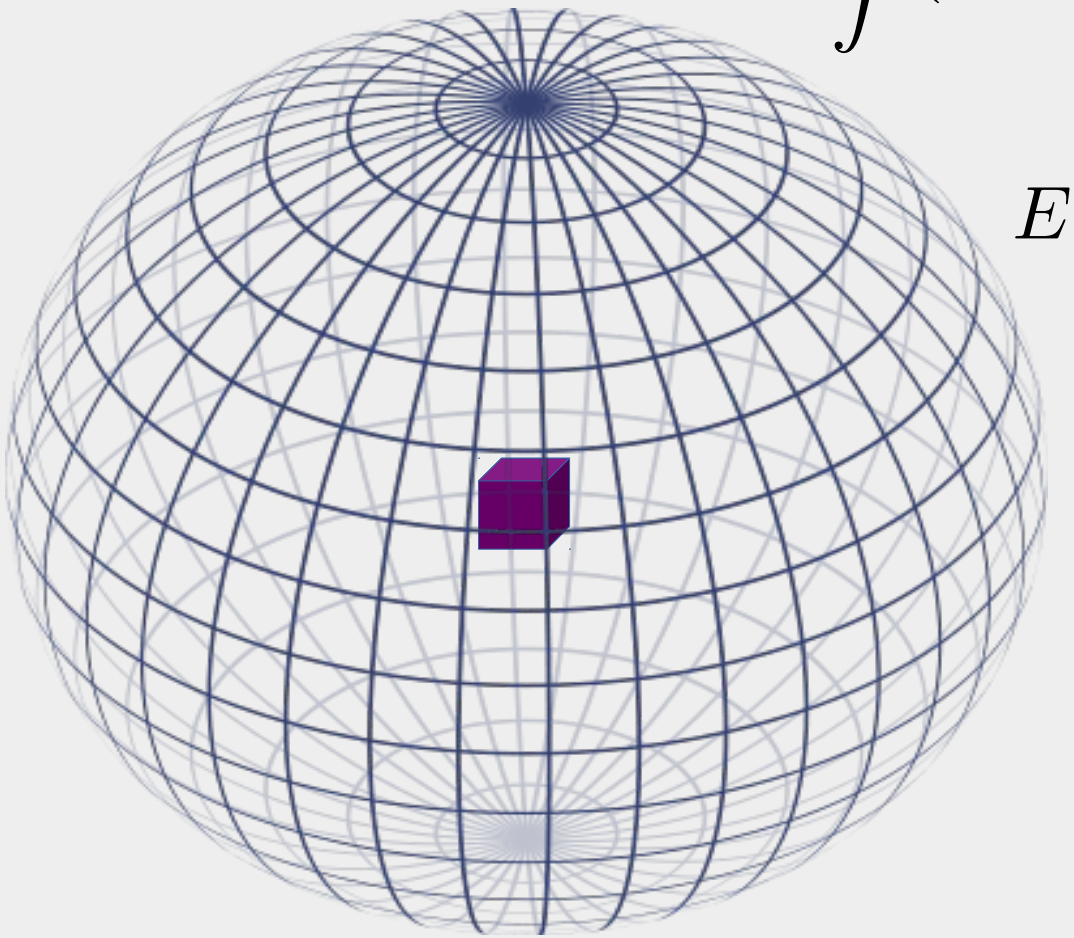

$$E = \int (\text{Gravitational field}) dS$$

Holography in familiar physics

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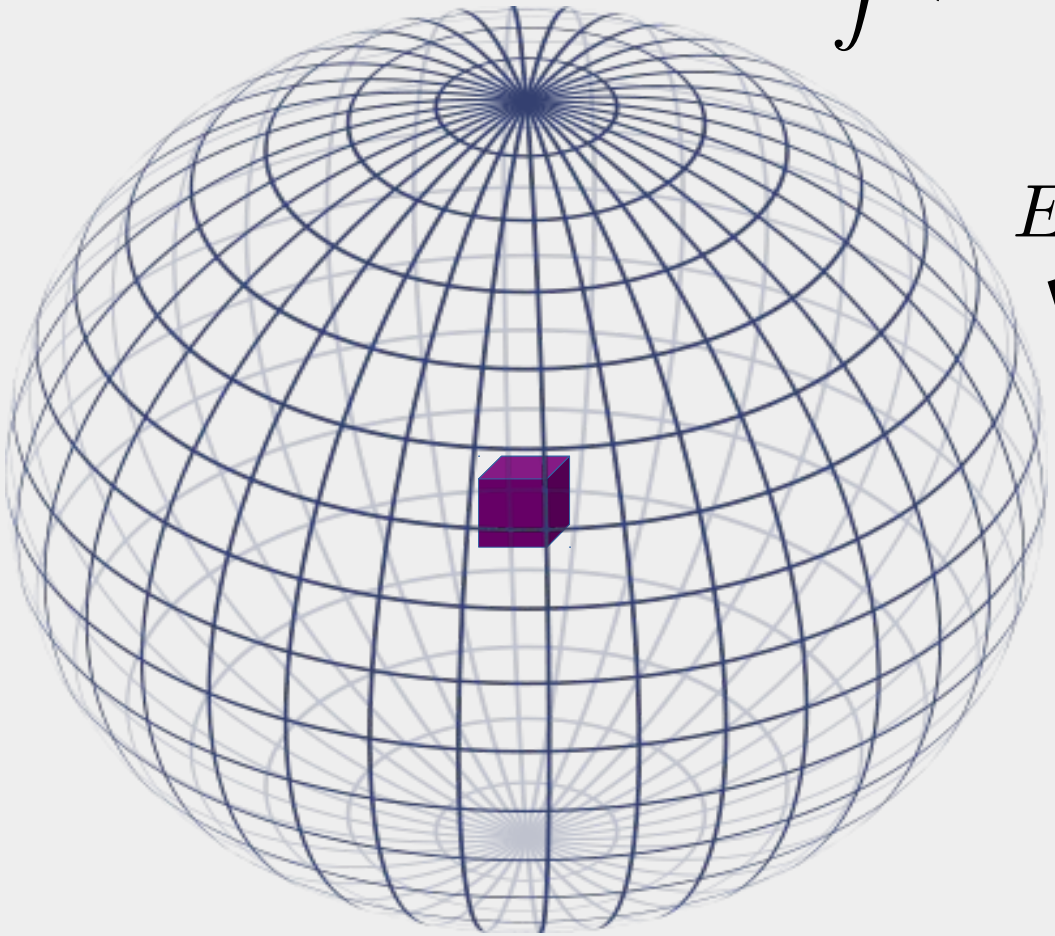
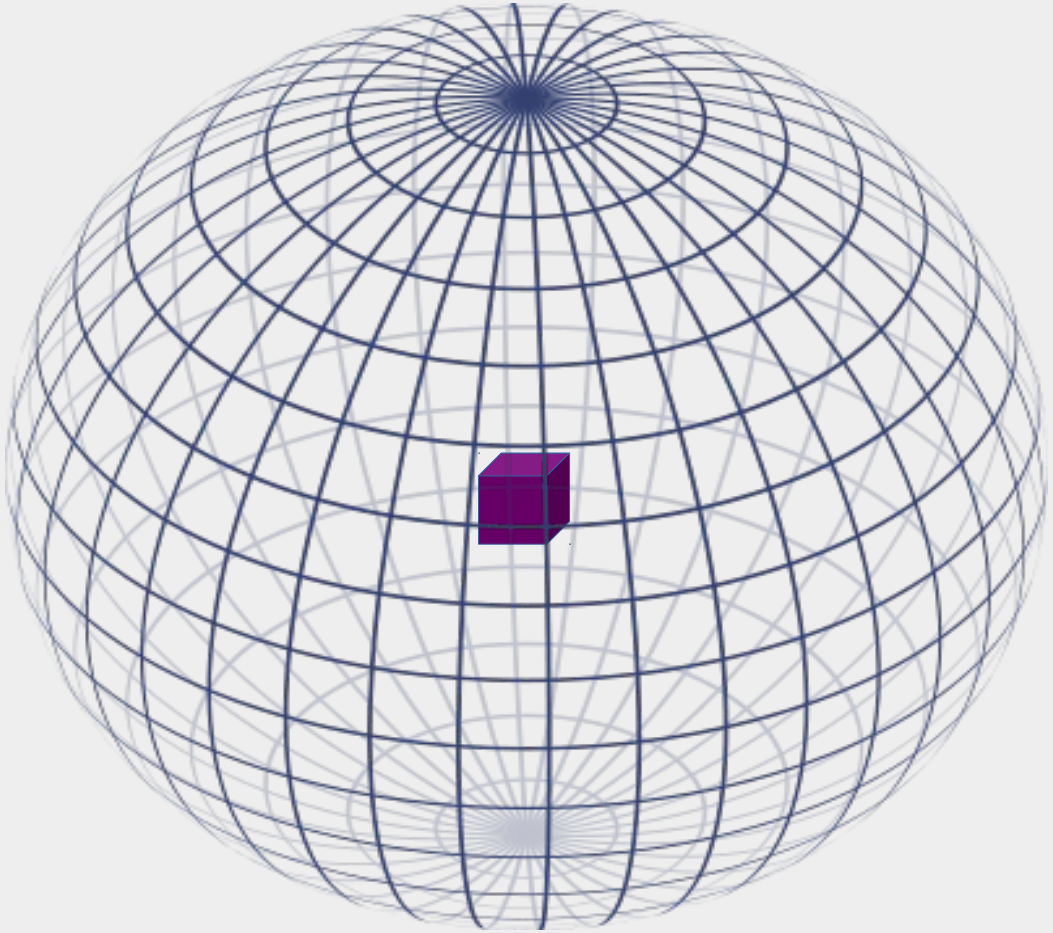


$$E = \int (\text{Gravitational field}) dS$$

$$\hat{H}\Psi = i\hbar \frac{d}{dt}\Psi$$

Full realization: AdS/CFT

Quantum gravity described by a non-gravitational field theory (CFT) at spatial infinity



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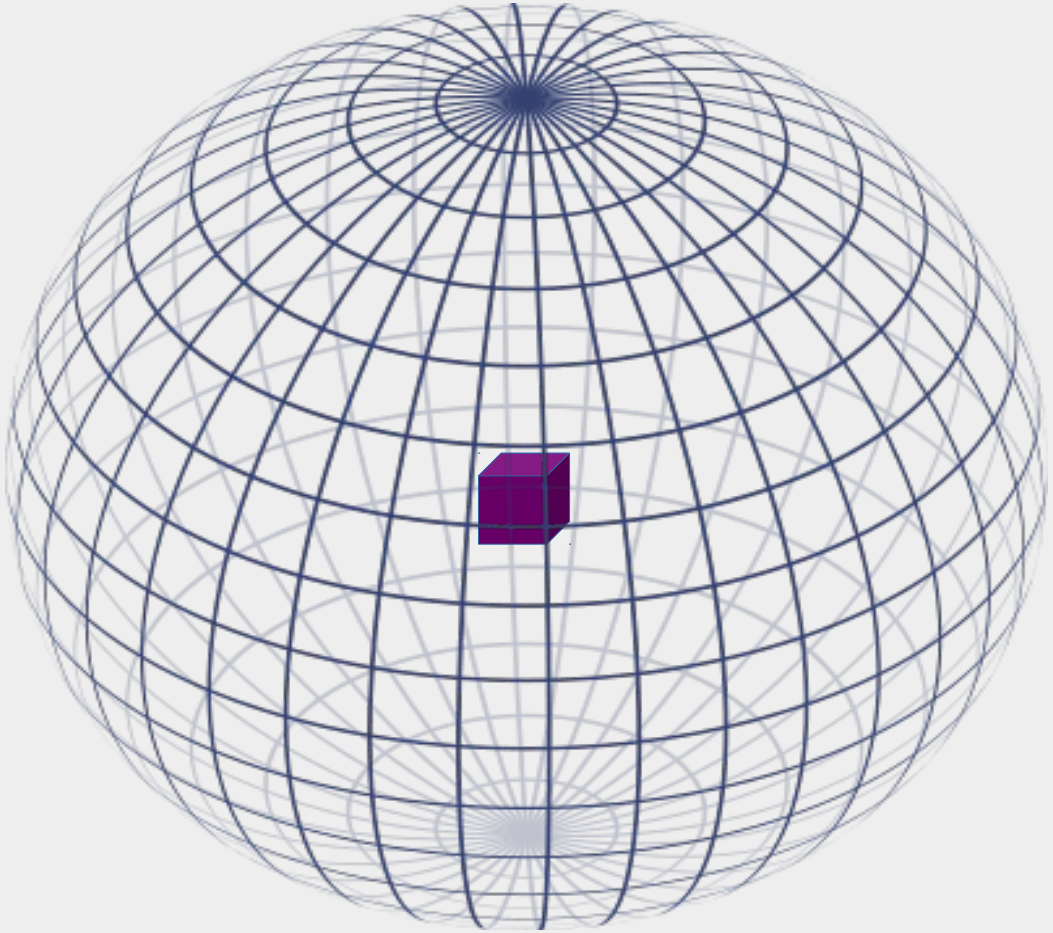
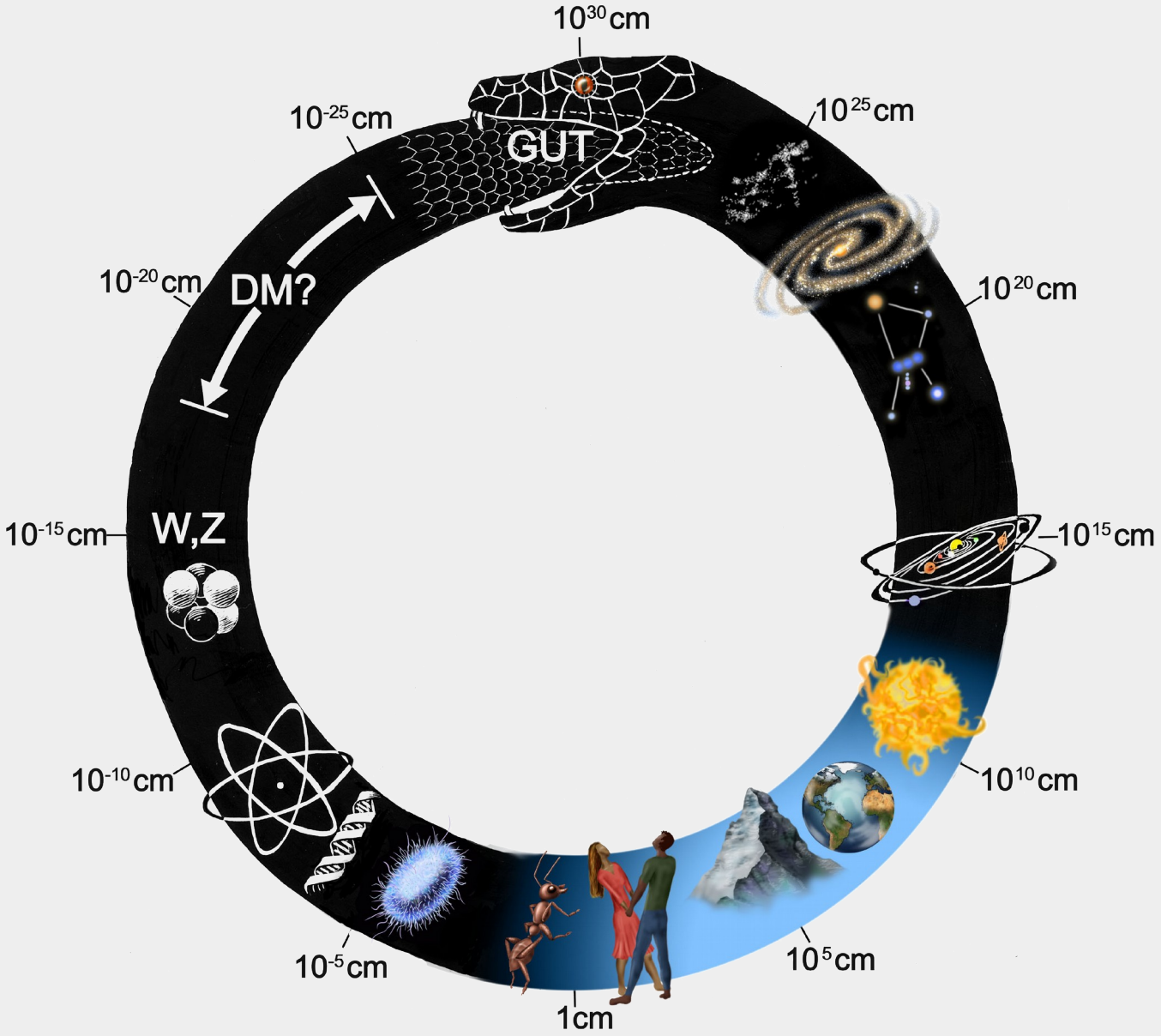


A reversal of roles between the large and the small!

Straddling the length scales



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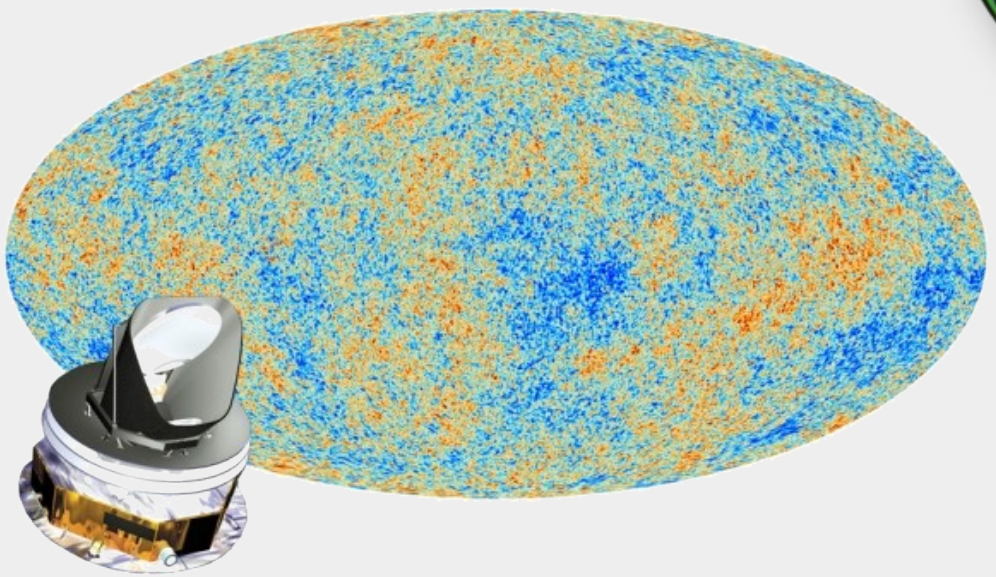
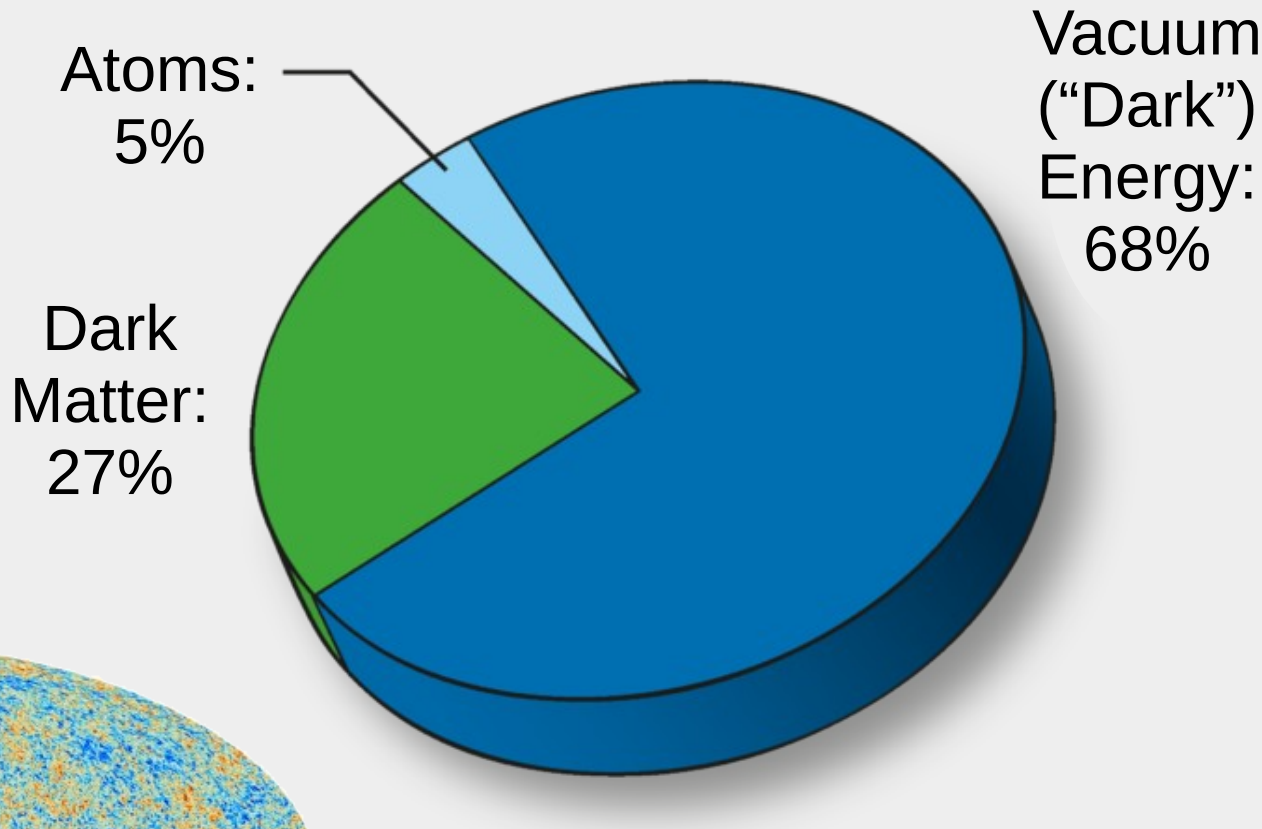
At the largest scales: Cosmology





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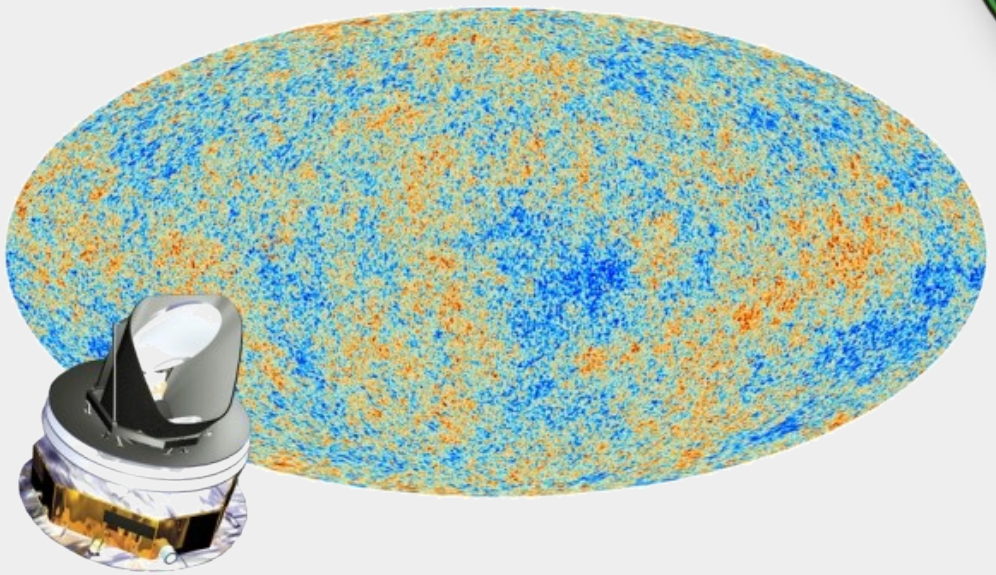

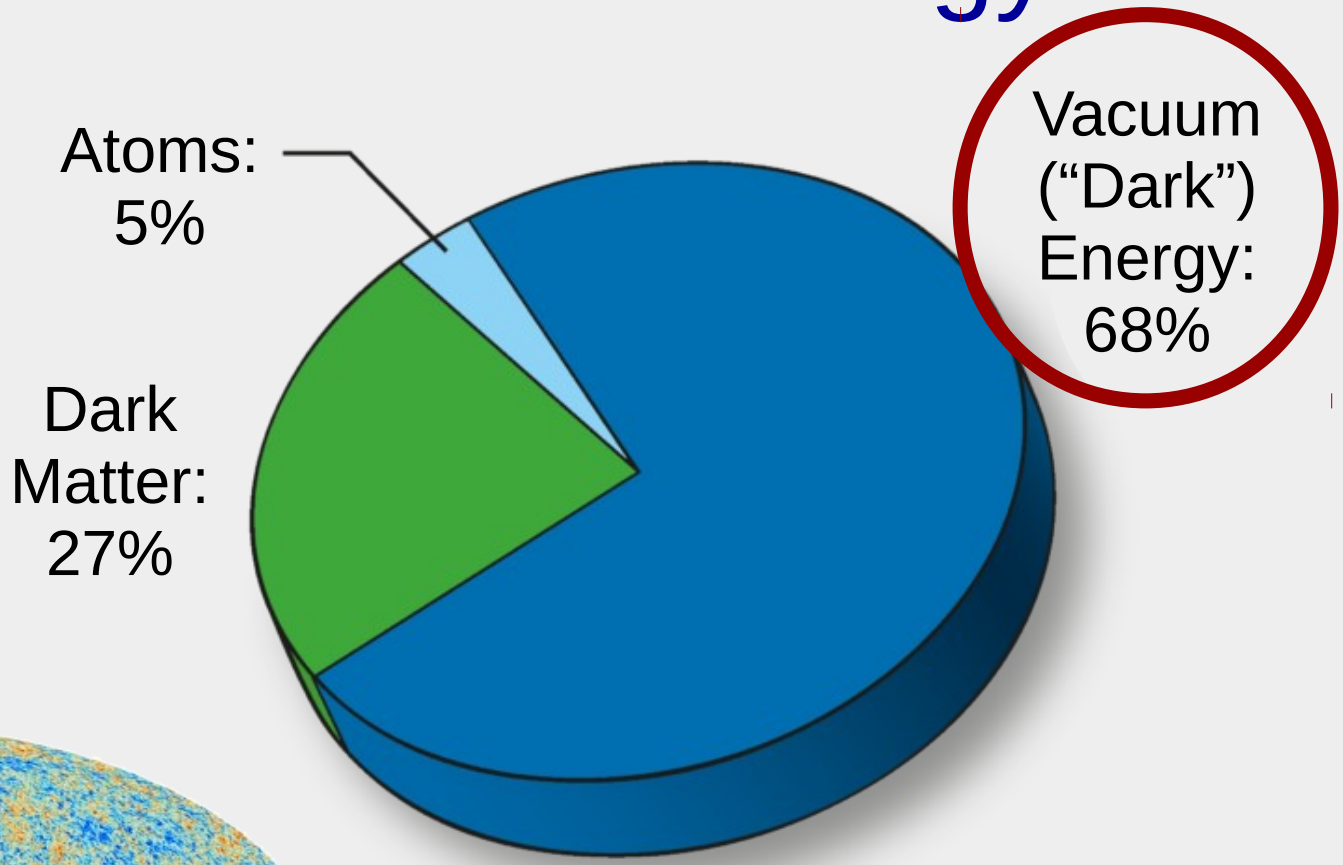

Vacuum energy density

- Share of total: 68% and rising
- Value: $\Lambda \approx 10^{-9}\mathrm{J/m}^3$

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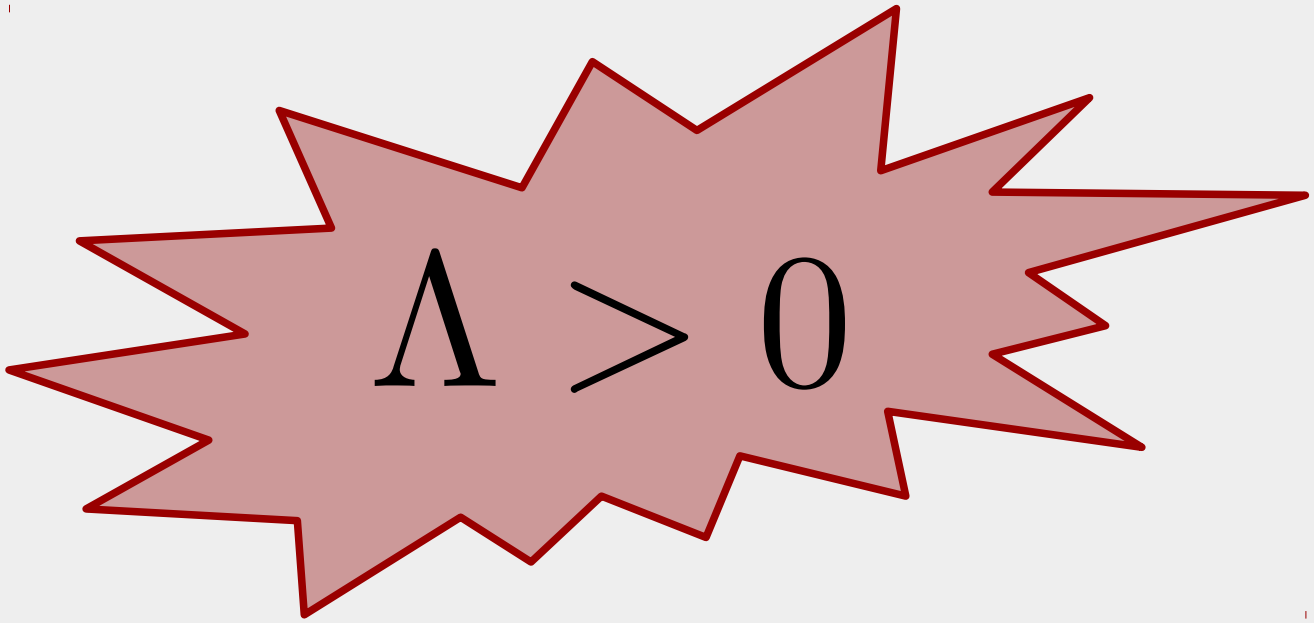
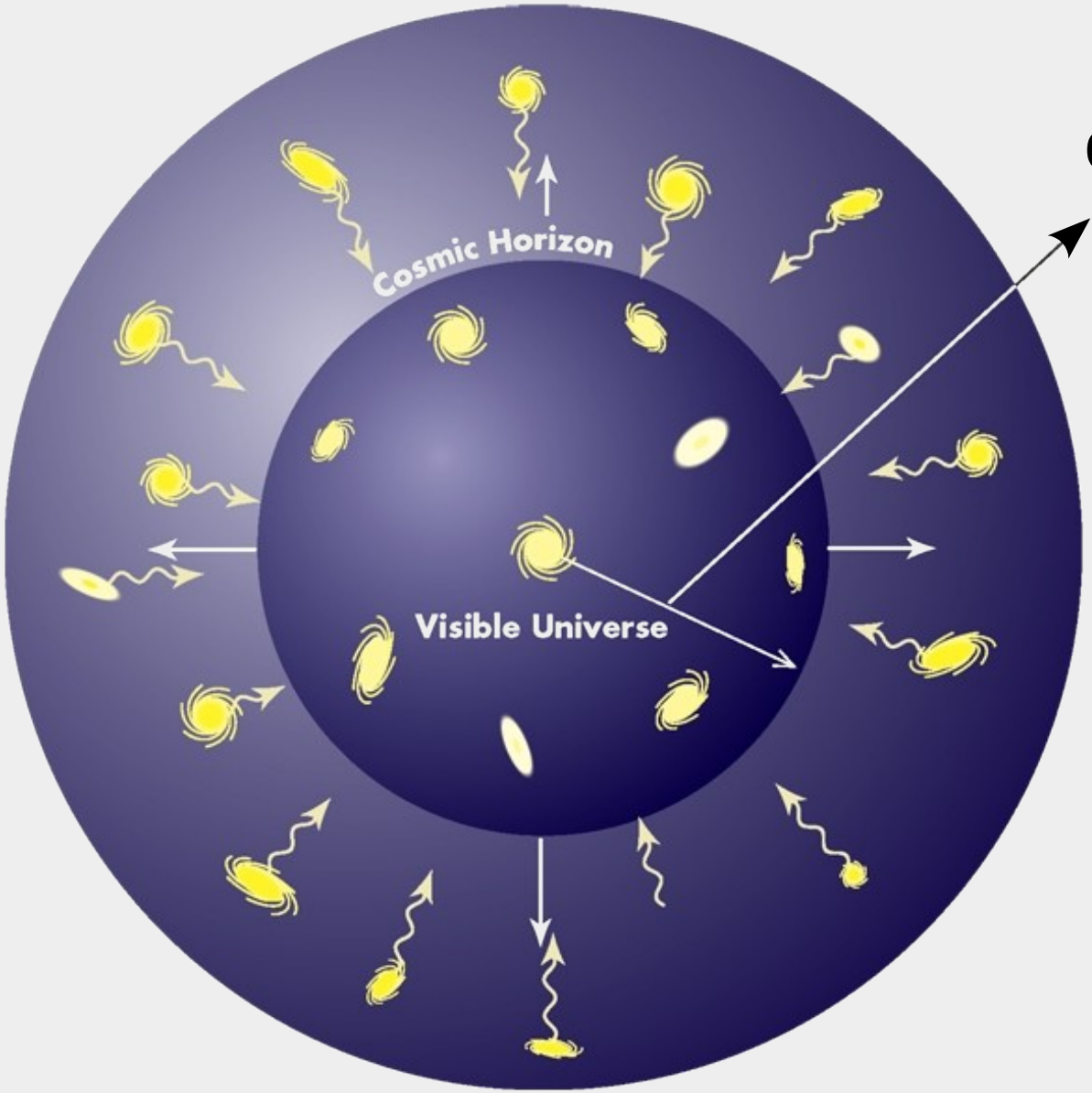


$\Lambda > 0$ driving accelerated expansion



Largest observable distance

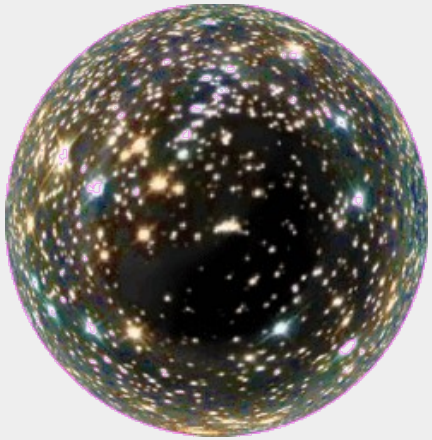
Life between the Planck length and the cosmological horizon

Smallest meaningful distance:

$$\ell_{\rm Planck} \sim \sqrt{\hbar G} \approx 10^{-35}{\rm m}$$

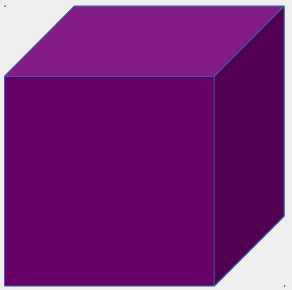
Largest meaningful distance:

$$\ell_{\rm Horizon} \sim 1/\sqrt{\Lambda} \approx 10^{26}{\rm m}$$



$10^{26}{\rm m}$

$1{\rm m}$



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Losing the foothold at infinity

Can no longer zoom away from the breakdown of geometry at ℓ_{Planck}

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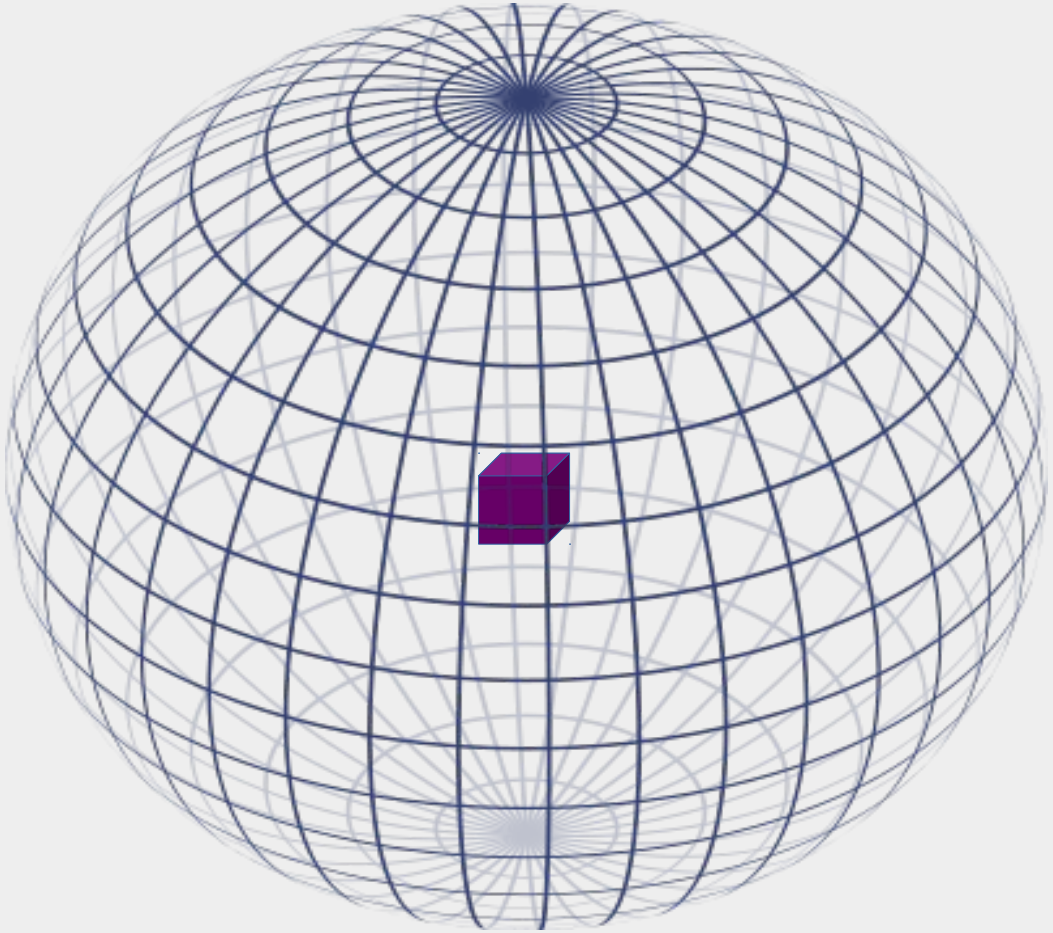

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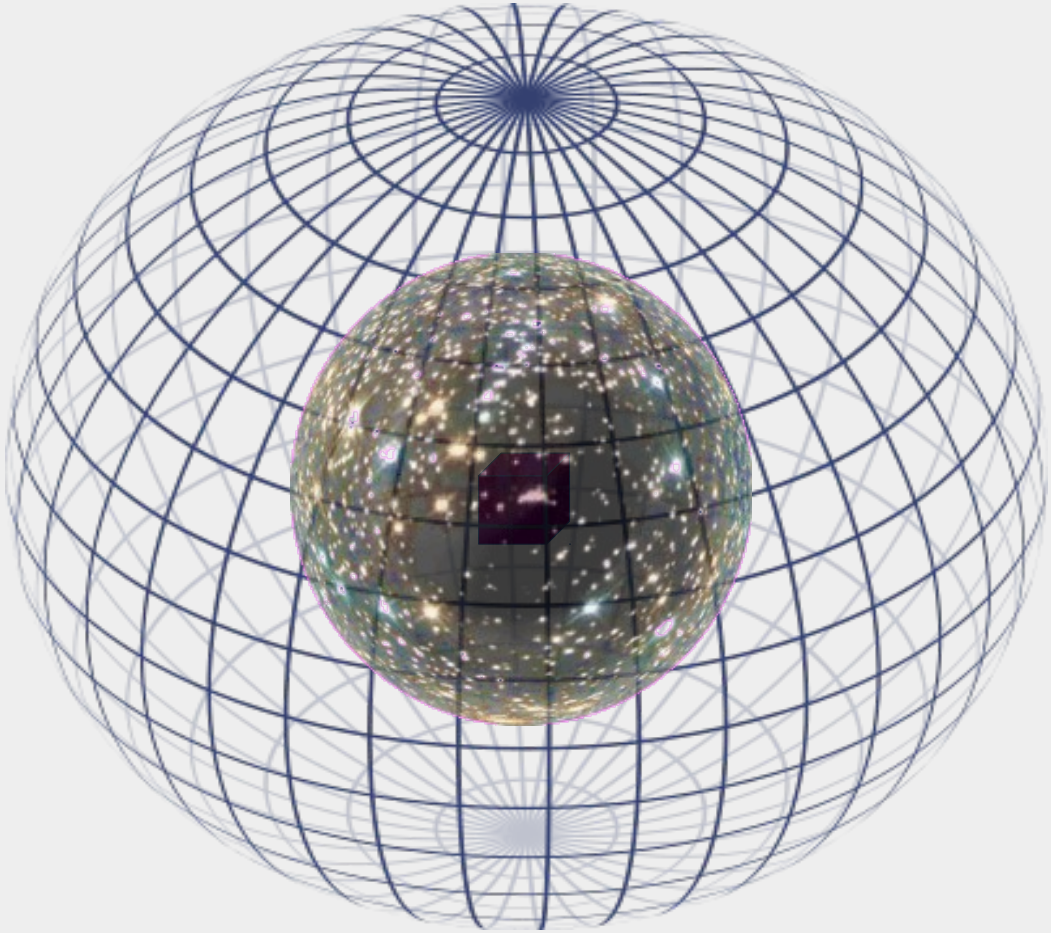
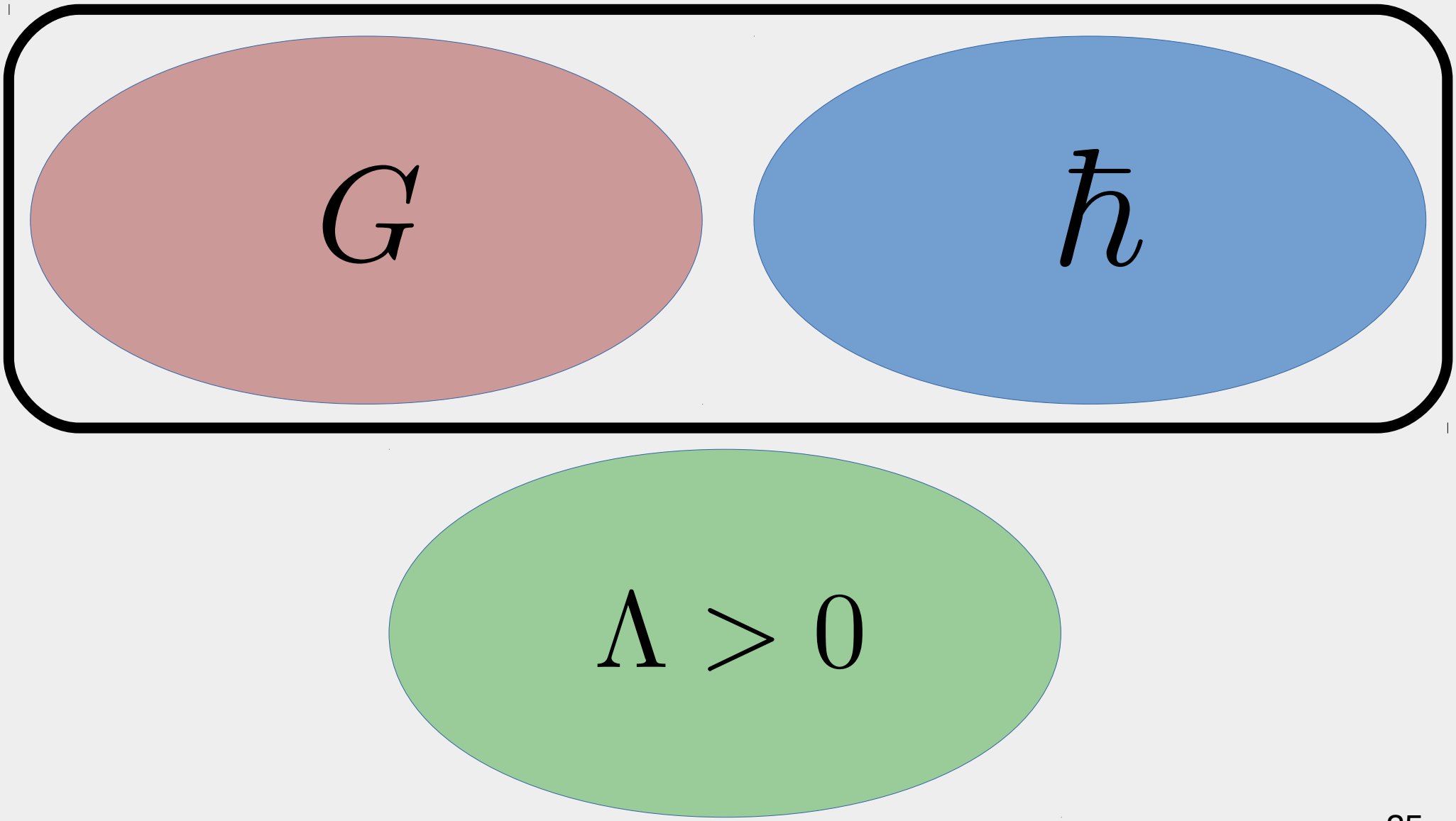


Spatial infinity is physically accessible and has the required mathematical properties only for $\Lambda < 0$

Holography's performance sheet

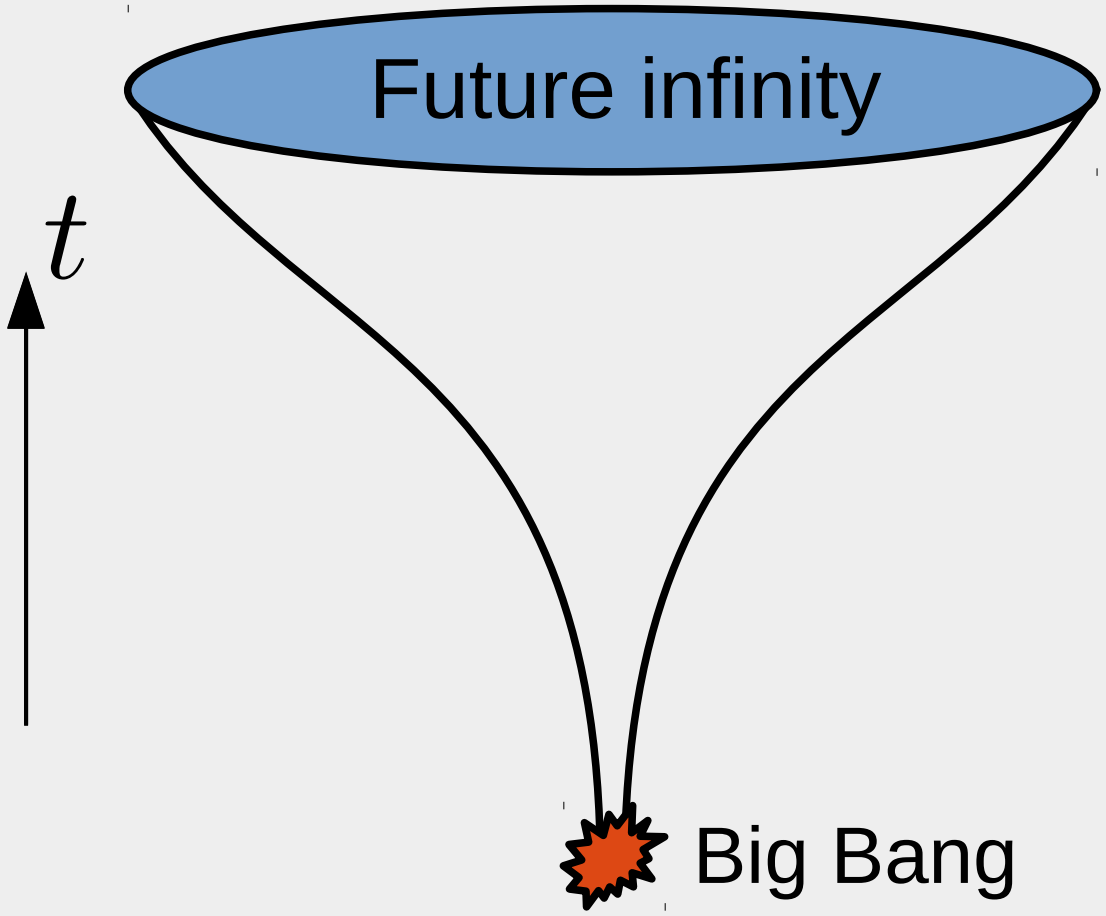


Quantum gravity, guided by observation!

instead of

Trying to adapt what works: Holography with $\Lambda > 0$

Describe quantum gravity by a non-gravitational field theory (CFT) at future infinity



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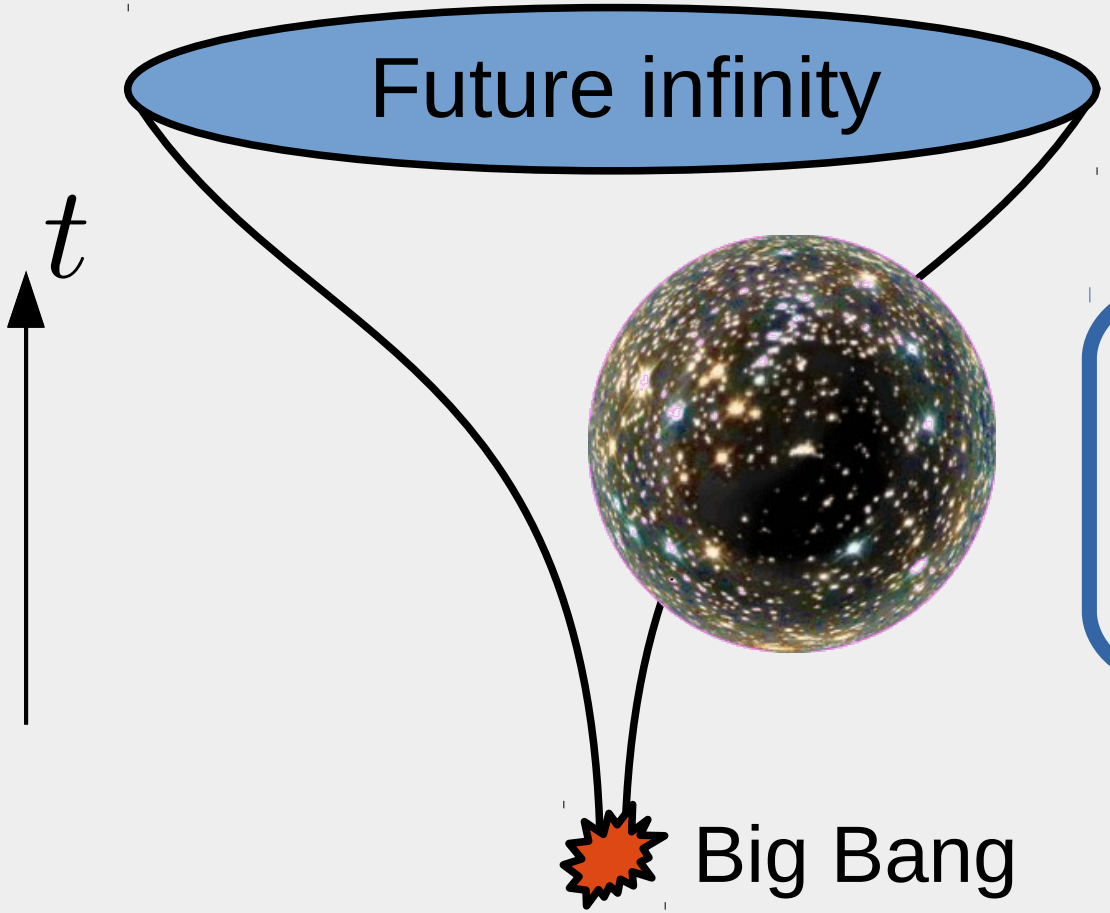

Must be translated into physics inside observable regions!

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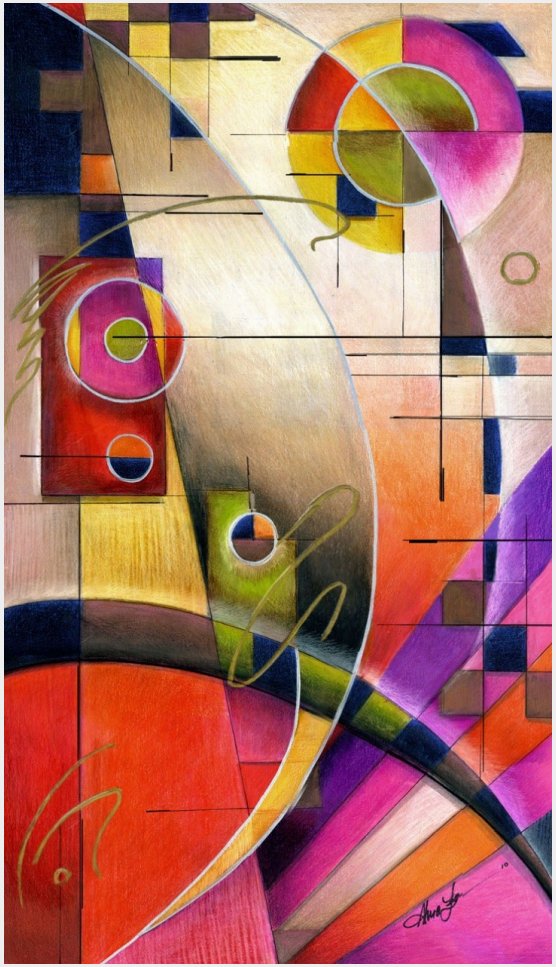
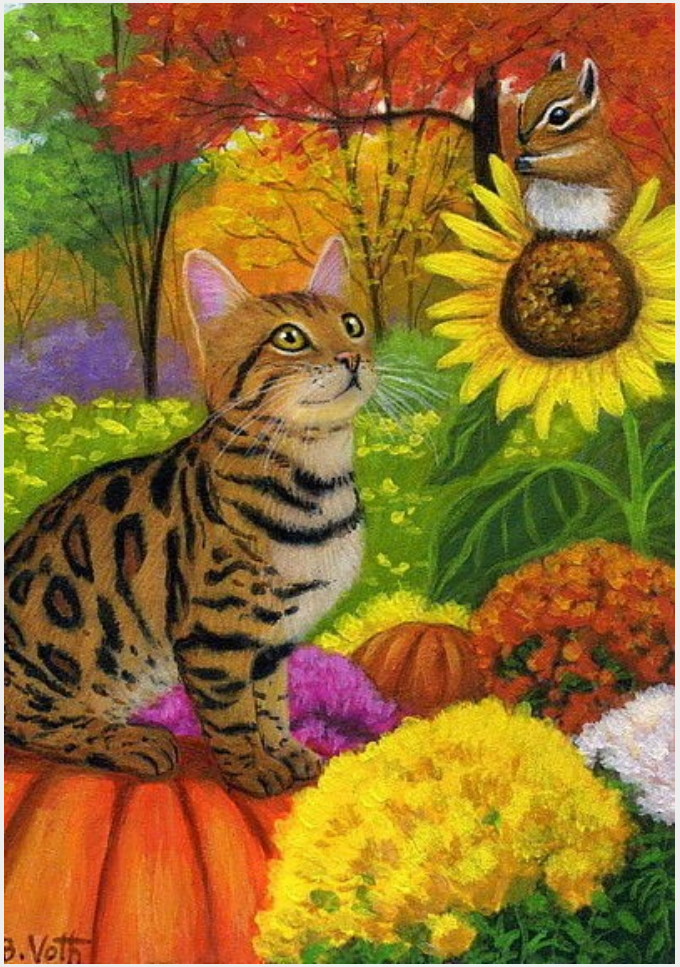
A small confession



Math

Mathematical physics



Physics

$\Lambda > 0$ quantum gravity as a project

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Existing model:
Holography for higher-spin gravity.
Calculates global state at $t = \infty$

[Anninos, Hartman, Strominger '11]

$\Lambda > 0$ quantum gravity as a project

Existing model:
Holography for higher-spin gravity.
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Idea for relating $t = \infty$ to observable regions:
Work in the elliptic de Sitter universe

[Parikh, Savonije, Verlinde '02]

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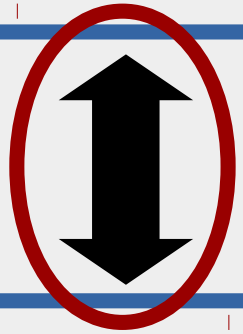
What I do



Idea for relating $t = \infty$ to observable regions:
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[Parikh, Savonije, Verlinde '02]

1. Vasiliev's higher-spin gravity

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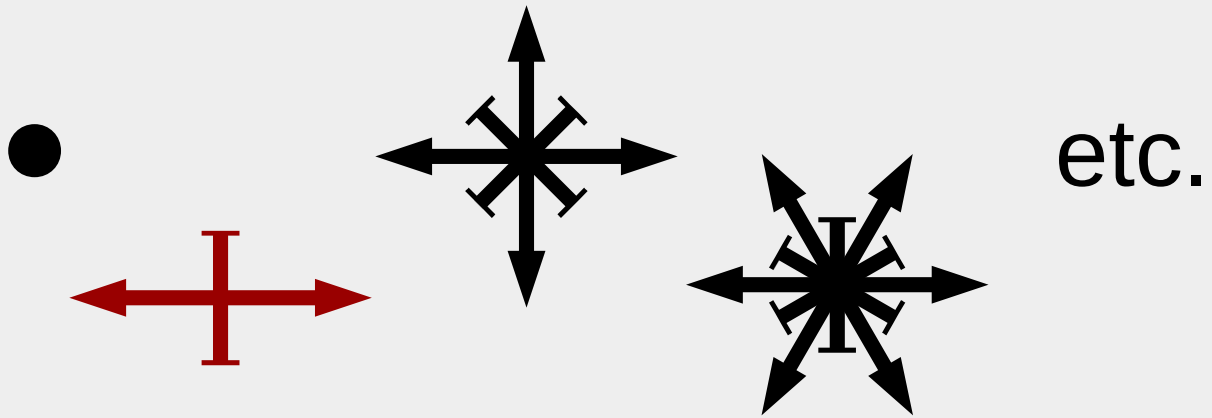
- Theory of interacting fields of all spins 0,2,4,6,...



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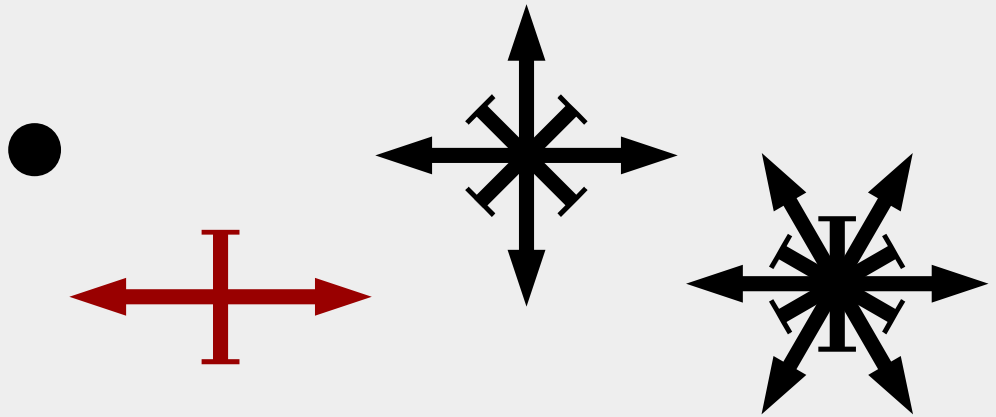

etc.

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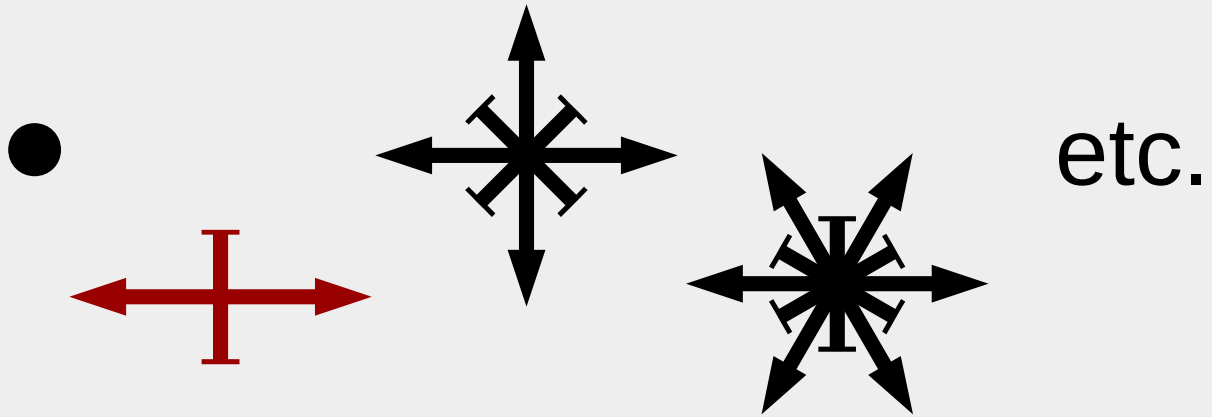

- Described holographically by the simplest CFT (non-interacting spin-0 fields)
- Formulation: 1990's. Holography: 2000's. Holography with $\Lambda > 0$: 2010's.

2. Elliptic de Sitter space

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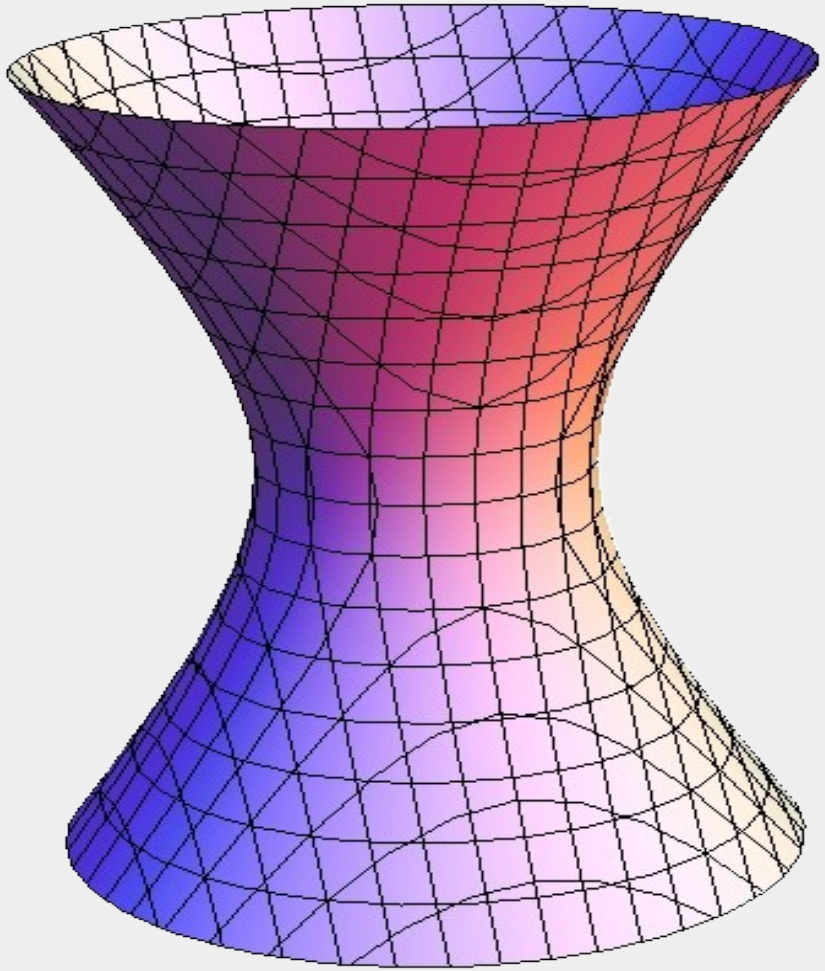

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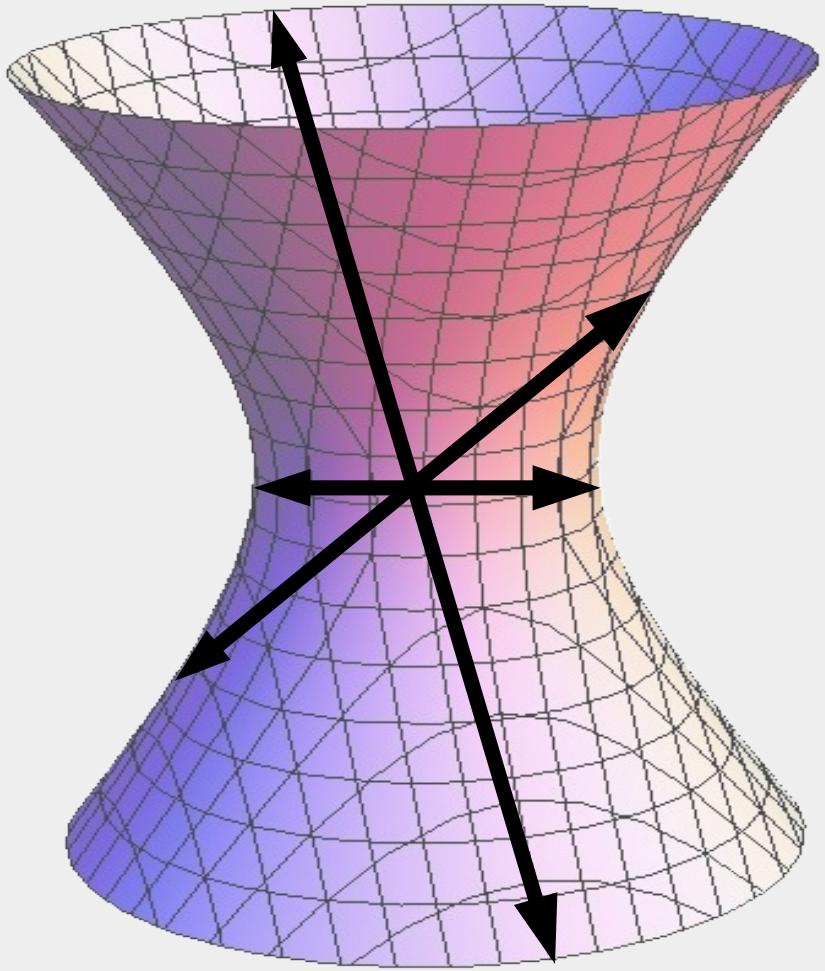

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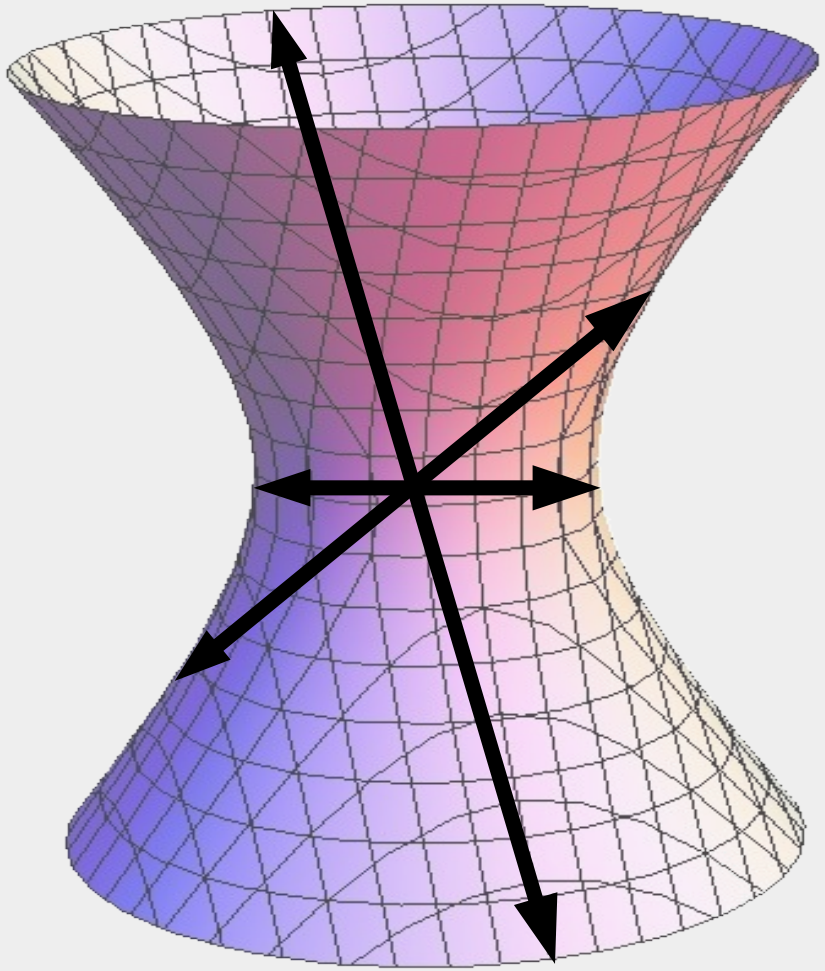

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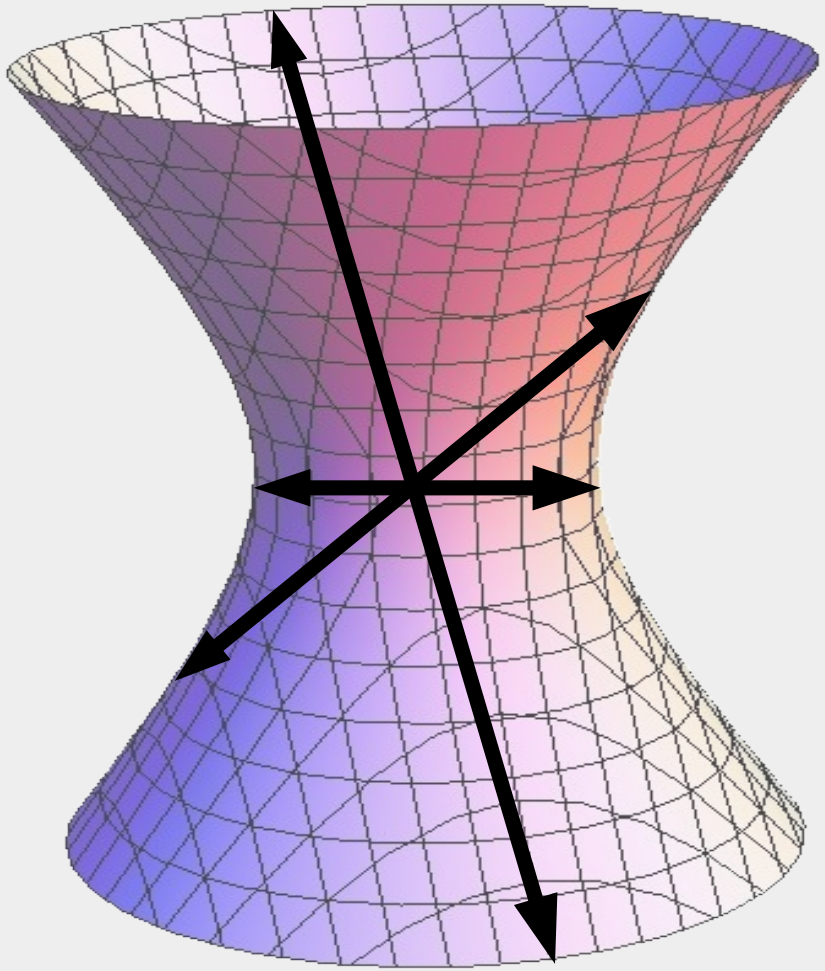
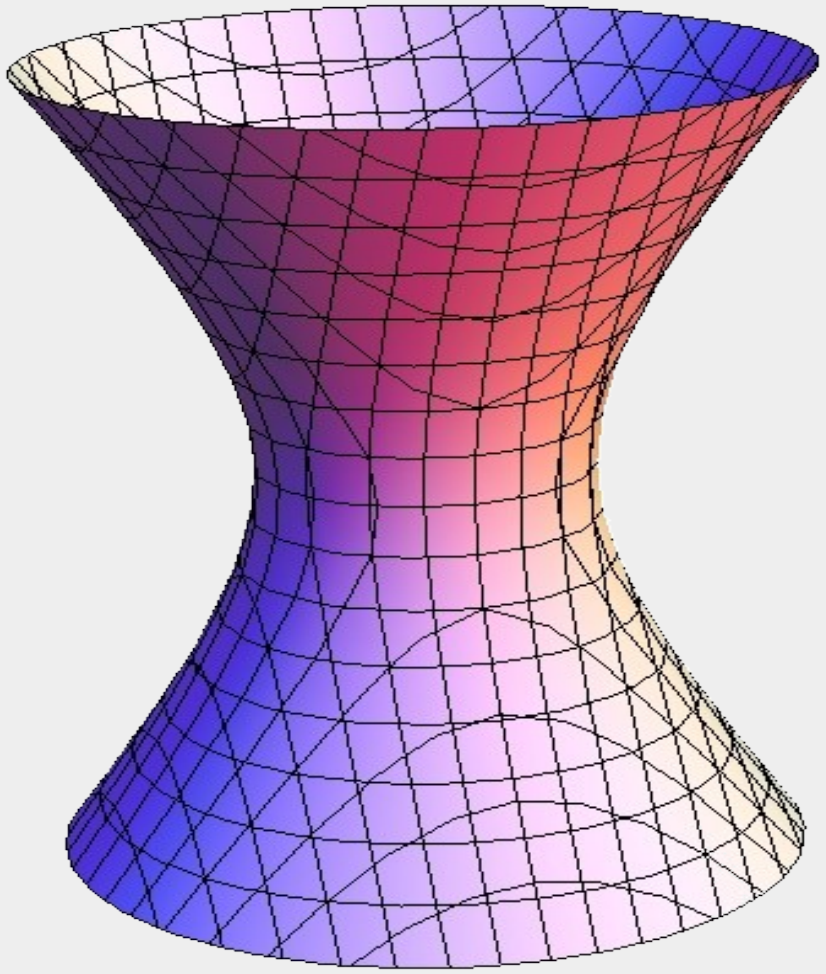


Same amount of information at infinity as in the observable region

Still need to find the dictionary between the two

The dictionary for non-interacting higher-spin fields



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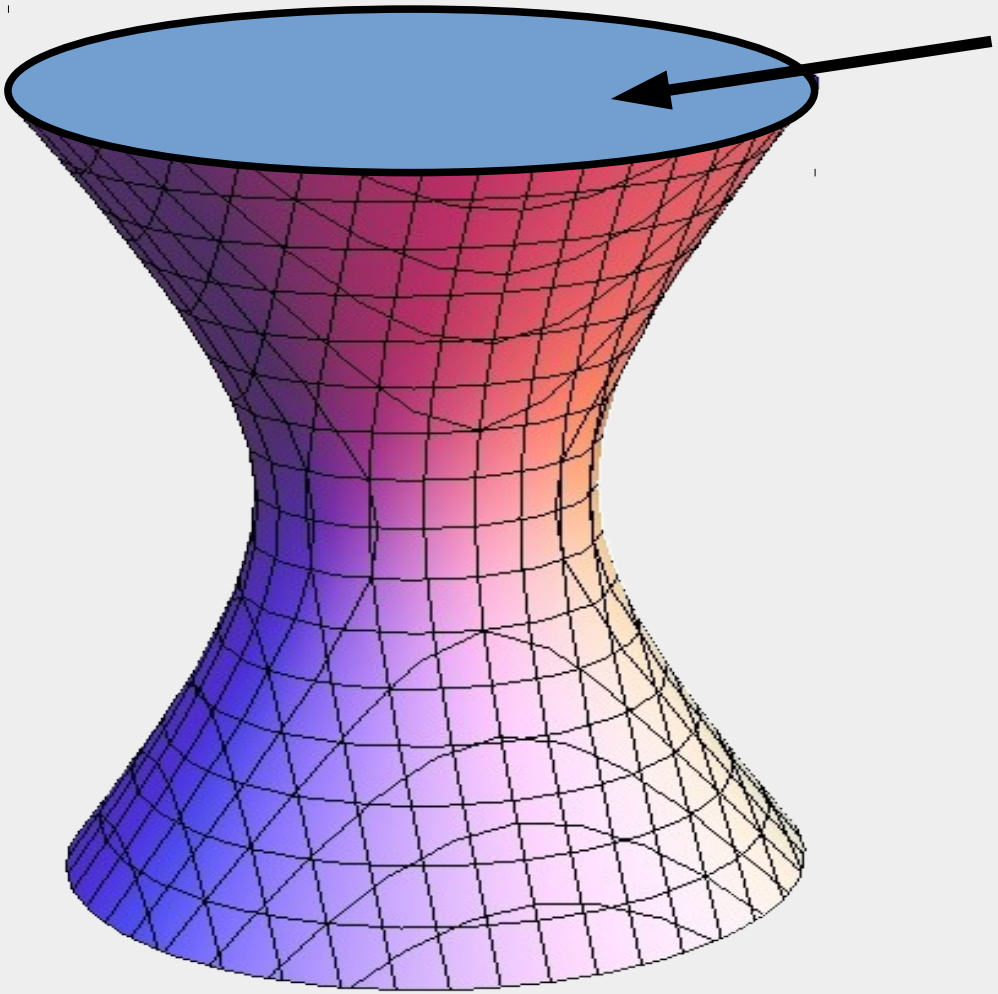

$$Z_{\mathrm{CFT}} = \exp\left(-\int_0^\infty \frac{d\omega}{2\pi} \sum_{lm} S_l(\omega)\, |c_{lm}(\omega)|^2\right)$$

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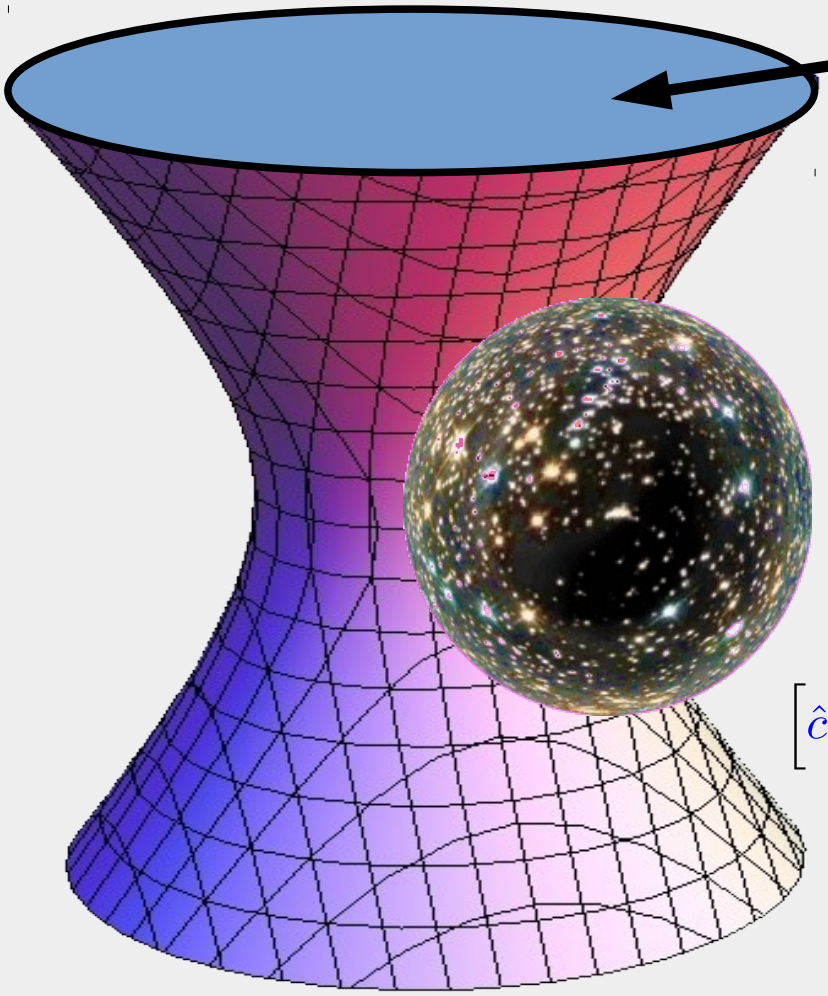

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$$\left[\hat{c}_{lm}(\omega), \hat{c}^\dagger_{l'm'}(\omega')\right] = \frac{4\pi}{S_l(\omega)}\left(\tanh\frac{\pi\omega}{2}\right)^{(-1)^l}\delta_{ll'}\delta_{mm'}\delta(\omega-\omega')$$

$$\hat{H} = \int_0^\infty \frac{d\omega}{2\pi}\sum_{lm}\frac{\omega}{2}\left(\coth\frac{\pi\omega}{2}\right)^{(-1)^l} S_l(\omega)\,\hat{c}^\dagger_{lm}(\omega)\,\hat{c}_{lm}(\omega)$$

[Halpern & YN '15]

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- Can keep using the tailored geometry of elliptic de Sitter space.
- Same encoding of the geometry in terms of fields at infinity.

Plan of the talk

1) Gravity: the spin-2 field

2) Quantum gravity through holography

3) The challenge from the cosmic horizon

4) Constructing a model

5) Current work & Outlook

What now?

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- Finish constructing this first model of quantum gravity inside horizons.

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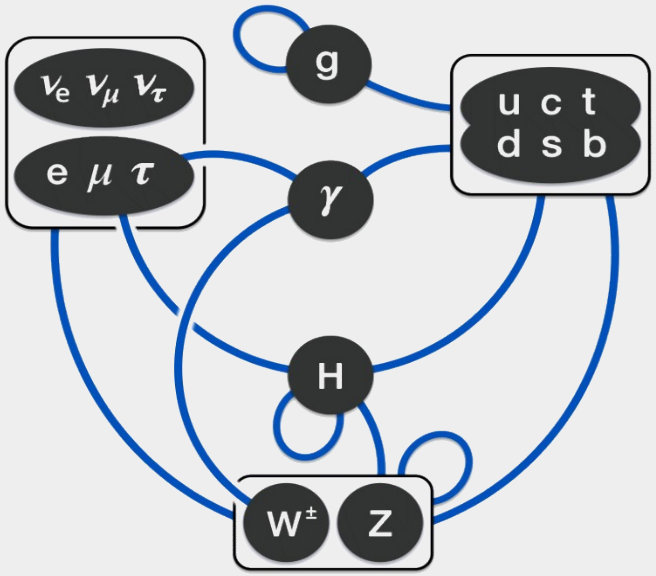
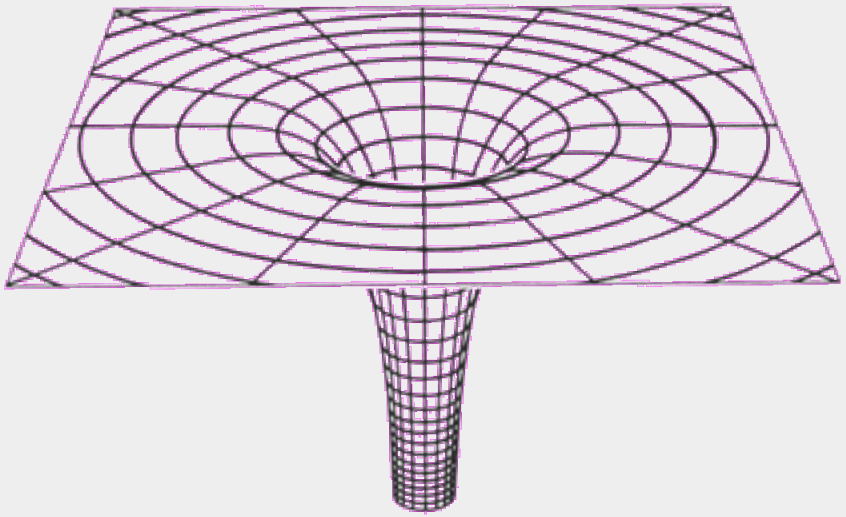
Higher-spin gravity as a bridge

Fixed geometry



Dynamical geometry



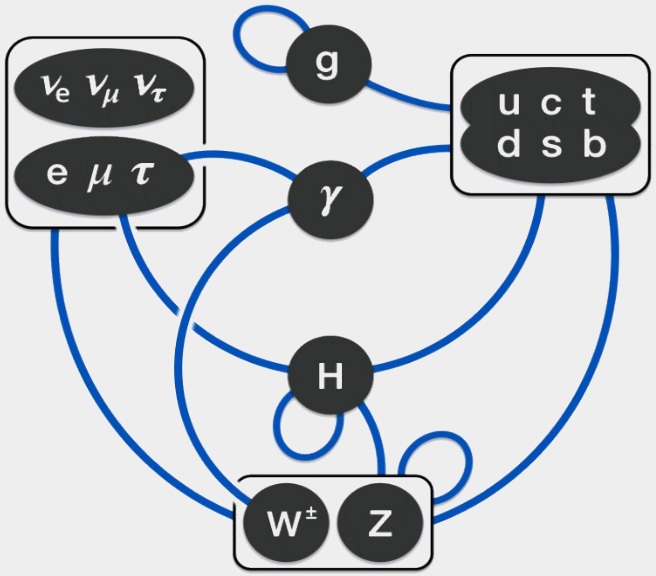
Higher-spin gravity as a bridge

$$\bar{s}_{\dot\alpha} \star \bar{s}^{\dot\alpha} - 2i = (s_\alpha \star s^\alpha - 2i) \star \kappa\bar\kappa \; ; \quad [s_\alpha, \bar{s}_{\dot\alpha}]_\star = 0$$

$$ds_\alpha + [W, s_\alpha]_\star = 0 \; ; \quad d\bar{s}_{\dot\alpha} + [W, \bar{s}_{\dot\alpha}]_\star = 0$$

$$dW + W \star W = 0$$

Fixed geometry



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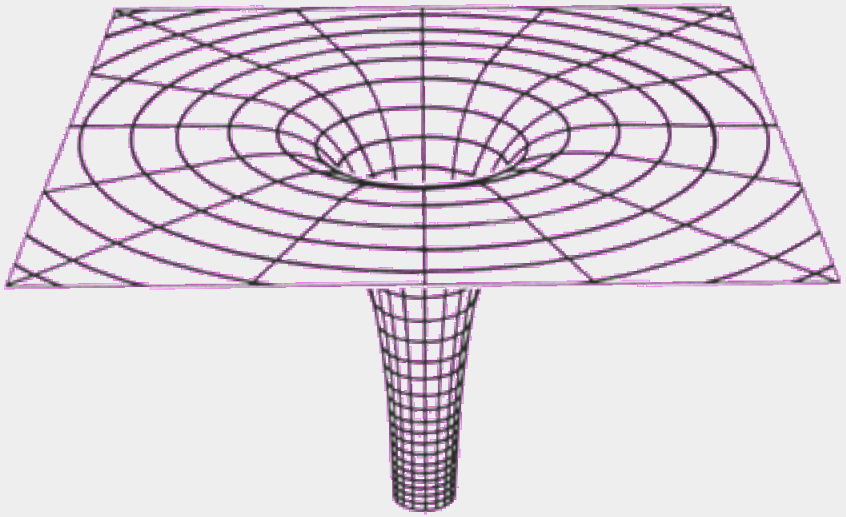

Higher-spin gravity as a bridge [YN, '15]

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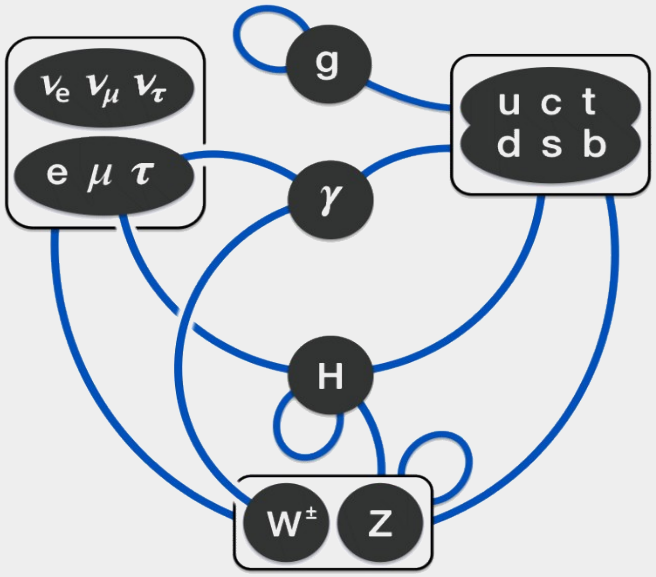
$$\nabla s_\alpha + [W, s_\alpha]_\star = 0 \; ; \quad \nabla \bar{s}_{\dot\alpha} + [W, \bar{s}_{\dot\alpha}]_\star = 0$$

$$dW + W \star W = \frac{i}{8}\left(dv^\alpha{}_{\dot\gamma}\, dv^{\beta\dot\gamma} s_\alpha \star s_\beta + dv_\gamma{}^{\dot\alpha}\, dv^{\gamma\dot\beta}\, \bar{s}_{\dot\alpha} \star \bar{s}_{\dot\beta} \right)$$

Fixed geometry



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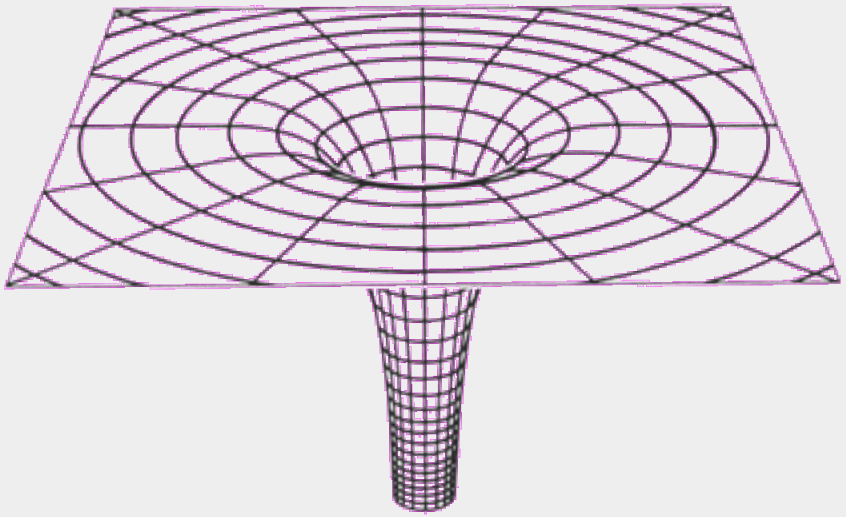

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- Make the model more realistic:
  General Relativity, Big Bang...