Gravity, Astrophysics and Cosmology

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Vienna University of Technology

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*supported by START prize

Outline

Introduction
- Cosmology
- Astrophysics
- Gravity

Black holes
- How can we observe black holes?
- Why are black holes interesting for quantum gravity?
- Holography: An Introduction

3D gravity
- Motivation
- Topologically massive gravity
- Research directions

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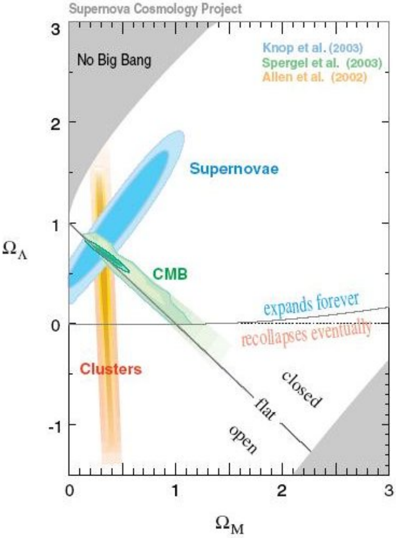
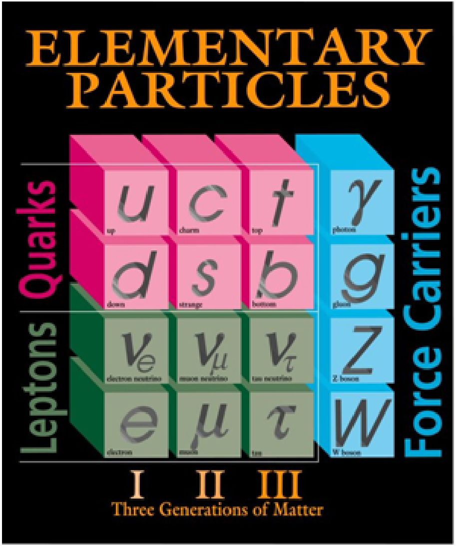
The Standard Models





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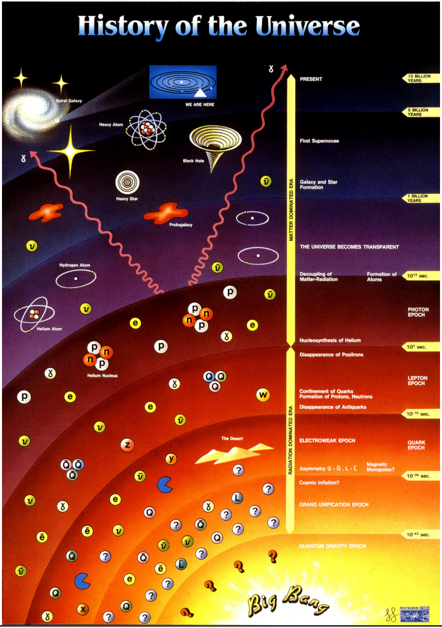
Brief history of the Universe



CMB:

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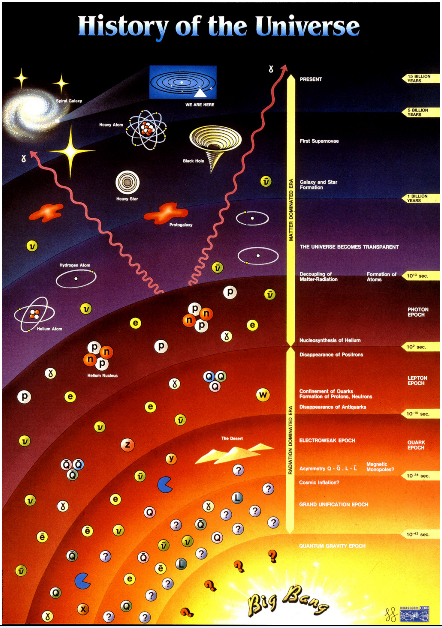

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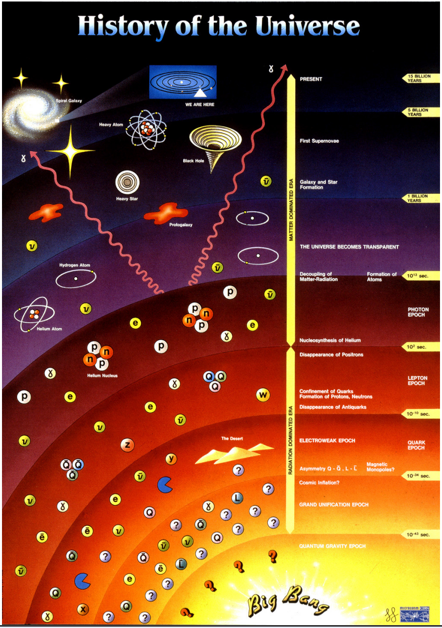

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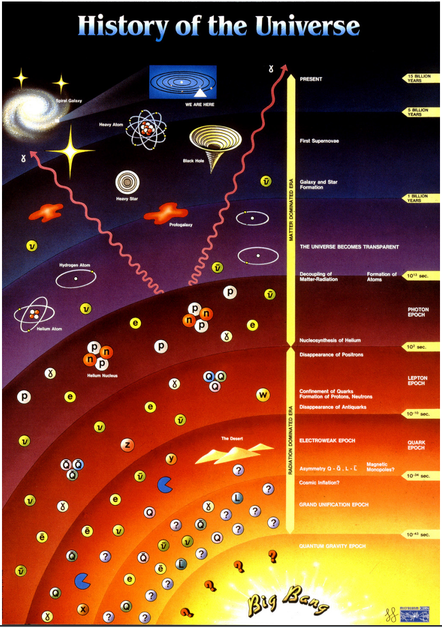

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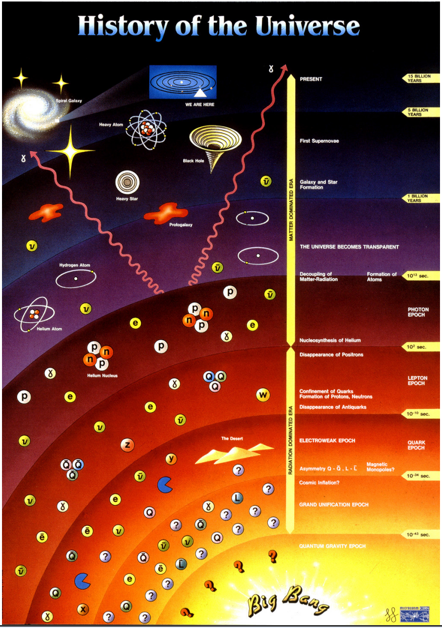

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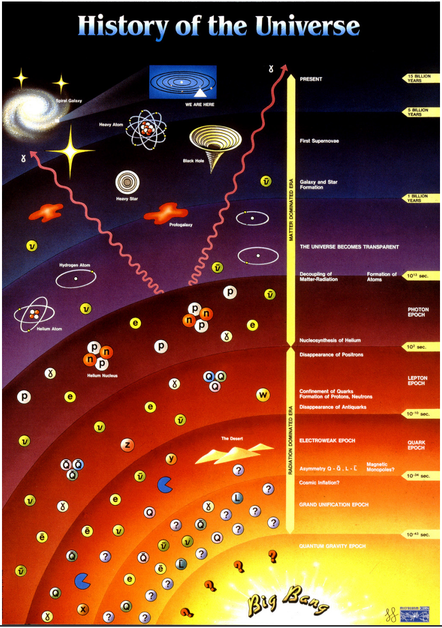

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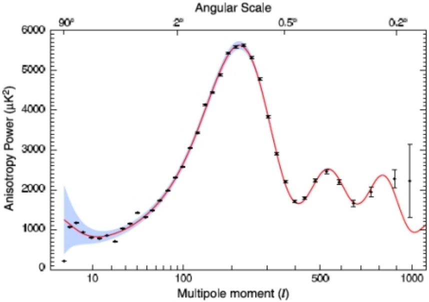
- COBE (1989-1993), WMAP (since 2001), Planck (since 2009)



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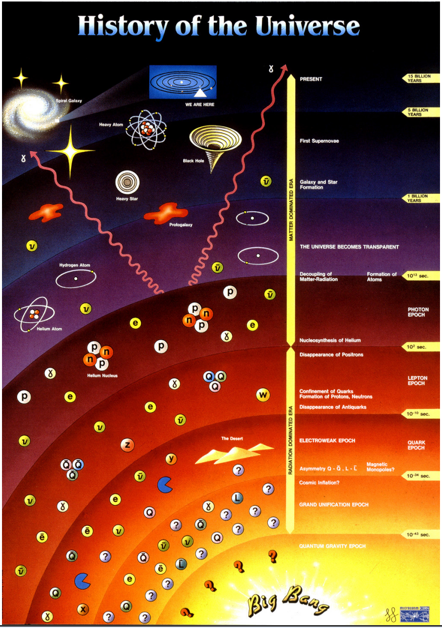

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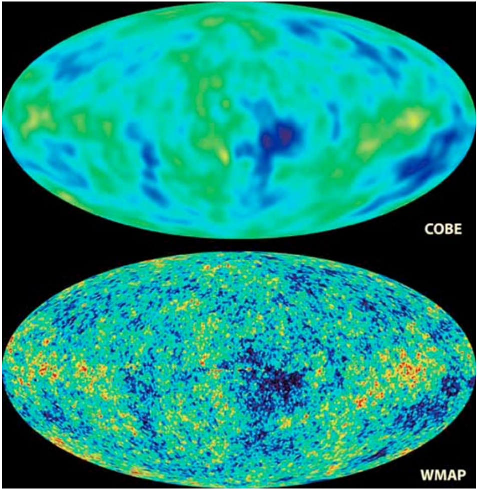
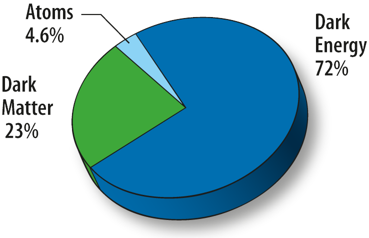


Above: COBE satellite (900km)
Below: WMAP satellite at Lagrange point L2 ($1.5 * 10^6$km)

What is the Universe made of?



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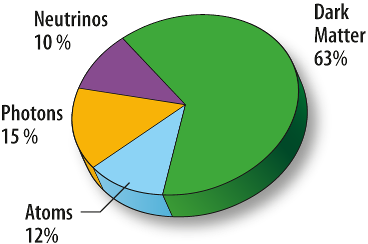

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Building blocks of our Universe:

- Progress: we understand less than 5% of the Universe!

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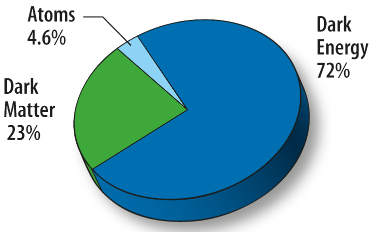

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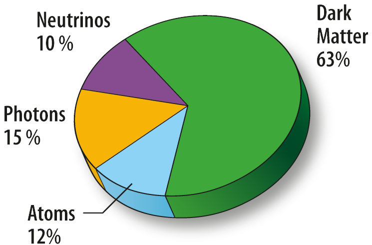

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- Dark Matter: many indications, many candidates

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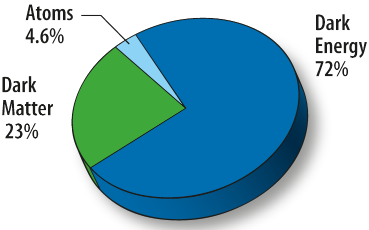

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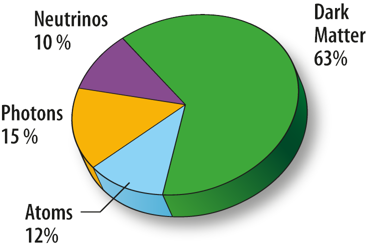

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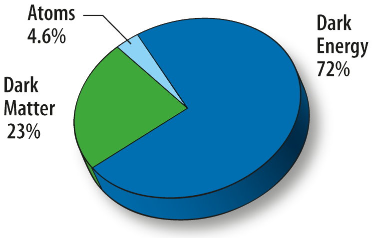

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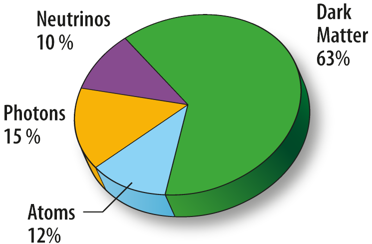

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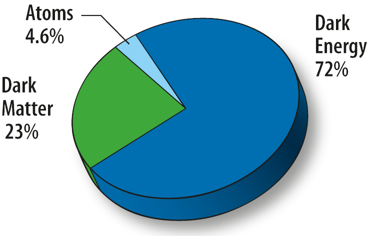

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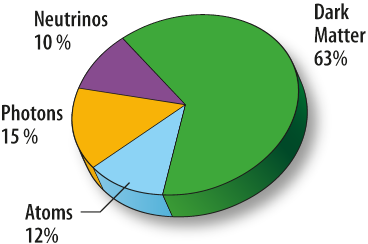

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- Less plausible, but logically possible: dark matter is gravitational effect

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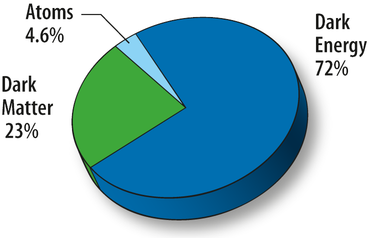

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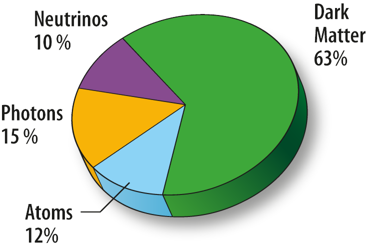

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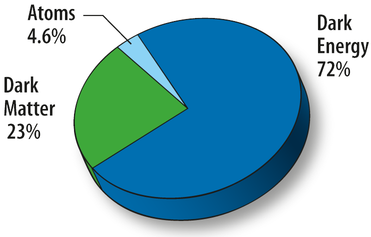

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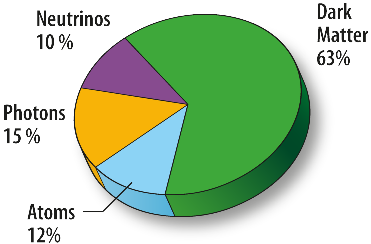

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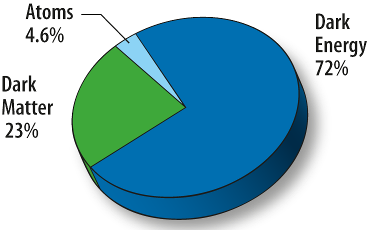

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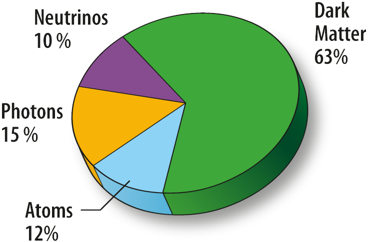

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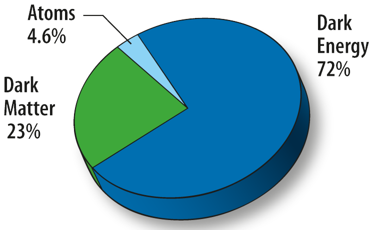

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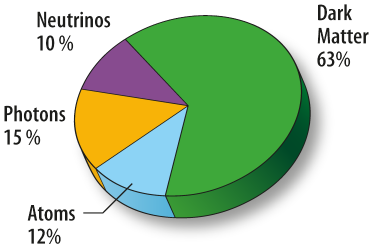

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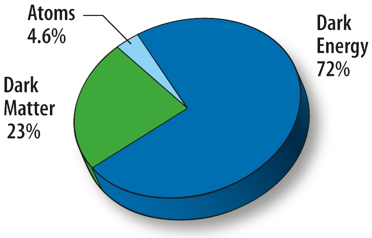

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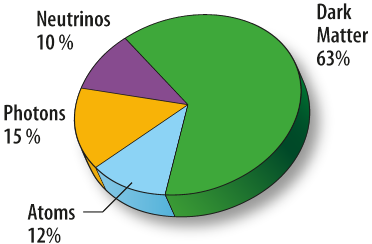

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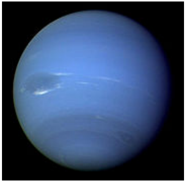
To address these issues we need to understand GRAVITY!

Astrophysics

Dark Matter hypothesis: Early success...

Neptune:



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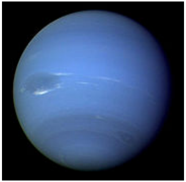

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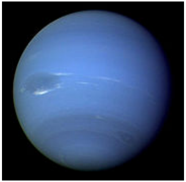

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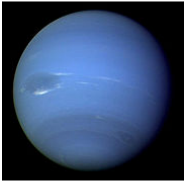

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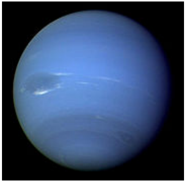

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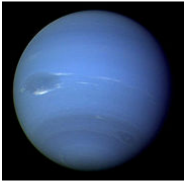

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Discovery of Neptune was first success of the Dark Matter concept!

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Dark Matter hypothesis: ...and early failure

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Non-discovery of Vulcan was first failure of the Dark Matter concept!

What is Dark Matter?

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Some crucial facts about the Dark Side of life:

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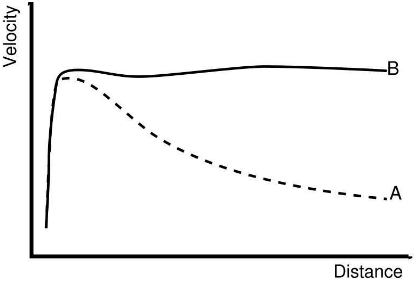

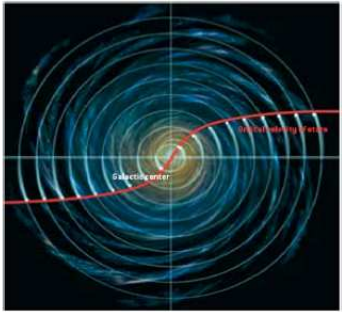

Not only galactic rotations curves (see pictures), but also: galaxy clusters, gravitational lensing, velocity dispersion of galaxies, CMB data, structure formation, bullet cluster, sky surveys, Lyman α forest,

indirect confirmations like type Ia supernovae and theoretical motivations like inflationary models, string theory, etc.

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- Fact 1: Vulcan scenario is unlikely for Dark Matter
- Reason 1: experimental data!
- Reason 2: modified gravity usually does not work
  Constraints from solar system tests, astrophysical observations, Cosmology, Earth based precision experiments (see talk by Hartmut Abele)

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- Reason 1: important for precision experiments
  Note: there are couple of tentative experimental anomalies in the deep IR besides Dark Matter and Dark Energy: Pioneer anomaly, fly-by anomaly, increase of astronomical units, ...

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  Some quantum theories of gravity predict modifications of GR in the deep IR, others do not — deep IR physics might be a useful (and unexpected) experimental window for quantum gravity

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- Fact 3: Even more challenging is to understand gravity in the deep UV
- Reason 1: experimentally difficult to access

$$E_{\text{Planck}} \sim 10^{19}\text{GeV} \gg 10\text{TeV}$$

See Manfred Krammers talk for state of the art of particle detectors in high energy physics

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- Reason 2: relevant to test theories
- Fact 3: Even more challenging is to understand gravity in the deep UV
- Reason 1: experimentally difficult to access
- Reason 2: need quantum gravity theory
  See also talk by Harald Skarke on string theory (currently the only quantum theory of gravity consistent with all experiments)

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- Reason 1: experimentally difficult to access
- Reason 2: need quantum gravity theory
- Summary: we understand gravity above micro-meter scale and up to solar system scale. GR migth be correct at arbitrarily big length scales, but it is a logical possibility that there are IR modifications of GR.

Blackboard I

Model for gravity at large distances

Gravity in the deep UV

aka quantum gravity

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- We saw that the deep IR might contain new physics
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  - Fact 1: QED has Landau pole
  - Fact 2: Standard Model cannot be valid at arbitrary high energies
  - Indication 1: Singularities in GR are signal of new physics
  - Indication 2: Dimensional analysis: expect new physics at Planck energy 10^{19} GeV (or below)
  - Indication 3: General Relativity unlikely correct at Planck scale — non-renormalizable = typical sign of low-energy effective theories
  - Indication 4: Unification of forces below Planck scale (around 10^{16} GeV) likely from experimental data

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The Holy Grail of Theoretical Physics

Construct UV completion of gravity
aka Quantum Gravity

Gravity

Within the landscape of Physics:

Theoretical Physics

- Condensed matter physics
- Fundamental interactions

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- Cosmology
- Astrophysics
- Gauge/gravity correspondence
- Quantum gravity
- Model building

Gravity

Within the landscape of Physics:

Theoretical Physics

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BLACK HOLES

- Primordial BHs
- Stellar&supermassive BHs
- Dual BHs
- BHs as “hydrogen atom”
- BHs as litmus test

- Condensed matter physics
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Outline

Introduction

- Cosmology
- Astrophysics
- Gravity

Black holes

- How can we observe black holes?
- Why are black holes interesting for quantum gravity?
- Holography: An Introduction

3D gravity

- Motivation
- Topologically massive gravity
- Research directions

What is a black hole?

Fishy analogy (Bill Unruh '81):

The real stuff:

Above: black hole
(NASA picture)
Left: Waterfall

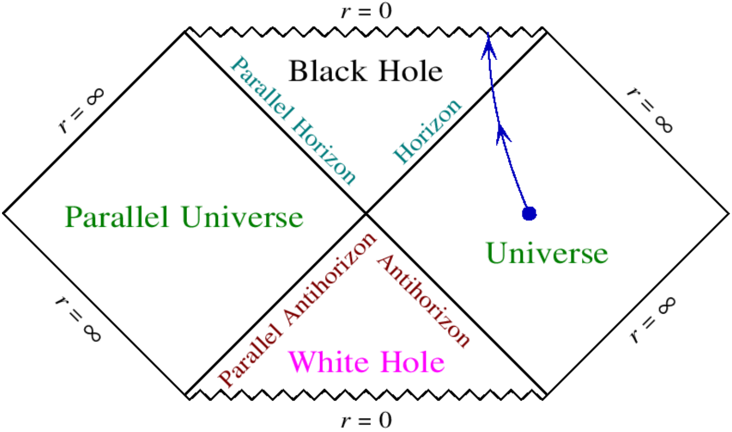
Analogy:
Infinity ↔ Lake

Horizon ↔ Point of no return

Singularity ↔ Waterfall

What is a black hole?

Example: causal structure of Schwarzschild black hole



Schwarzschild line-element:

$$\mathrm{d}s^2 = -\left(1 - \frac{2M}{r}\right)\,\mathrm{d}t^2 + \frac{\mathrm{d}r^2}{1 - \frac{2M}{r}} + r^2\,\mathrm{d}\theta^2 + r^2\sin^2\theta\,\mathrm{d}\phi^2$$

Why Study Black Holes?

Depending whom you ask you'll hear:

- General Relativist: because they are unavoidable
- Mathematician: because they are interesting
- Science Fiction Writer: because they are cool
- Astrophysicist: because they explain the data
- String Theoretician: because they hold the key to quantum gravity
- Particle Physicist: because they might be produced at LHC
- Cosmologist: because they exist
- Numerical Relativist: because they present challenge for coding skills
- Nuclear Physicist: because they are dual to a strongly coupled plasma
- Condensed Matter Physicist: because we can produce them in the lab
- Gravitational Wave Experimentalist: because we need to understand black holes to provide templates for gravitational wave detection

Many reasons to study black holes in physics!

Have to understand the physics of this...

Black hole observations

Confirmed stellar black holes in X-ray binaries

Objects whose mass is clearly beyond TOV limit $M > 3M_\odot$:

System	P_{orb} [days]	$f(M)$ [$M_\odot$]	Donor Spect. Type	Classification	M_{x} † [$M_\odot$]
GRS 1915+105[a]	33.5	9.5 ± 3.0	K/M III	LMXB/Transient	14 ± 4
V404 Cyg	6.471	6.09 ± 0.04	K0 IV	,,	12 ± 2
Cyg X-1	5.600	0.244 ± 0.005	09.7 Iab	HMXB/Persistent	10 ± 3
LMC X-1	4.229	0.14 ± 0.05	07 III	,,	> 4
XTE J1819-254	2.816	3.13 ± 0.13	B9 III	IMXB/Transient	7.1 ± 0.3
GRO J1655-40	2.620	2.73 ± 0.09	F3/5 IV	,,	6.3 ± 0.3
BW Cir[b]	2.545	5.74 ± 0.29	G5 IV	LMXB/Transient	> 7.8
GX 339-4	1.754	5.8 ± 0.5	–	,,	
LMC X-3	1.704	2.3 ± 0.3	B3 V	HMXB/Persistent	7.6 ± 1.3
XTE J1550-564	1.542	6.86 ± 0.71	G8/K8 IV	LMXB/Transient	9.6 ± 1.2
4U 1543-475	1.125	0.25 ± 0.01	A2 V	IMXB/Transient	9.4 ± 1.0
H1705-250	0.520	4.86 ± 0.13	K3/7 V	LMXB/Transient	6 ± 2
GS 1124-684	0.433	3.01 ± 0.15	K3/5 V	,,	7.0 ± 0.6
XTE J1859+226[c]	0.382	7.4 ± 1.1	–	,,	
GS2000+250	0.345	5.01 ± 0.12	K3/7 V	,,	7.5 ± 0.3
A0620-003	0.325	2.72 ± 0.06	K4 V	,,	11 ± 2
XTE J1650-500	0.321	2.73 ± 0.56	K4 V	,,	
GRS 1009-45	0.283	3.17 ± 0.12	K7/M0 V	,,	5.2 ± 0.6
GRO J0422+32	0.212	1.19 ± 0.02	M2 V	,,	4 ± 1
XTE J1118+480	0.171	6.3 ± 0.2	K5/M0 V	,,	6.8 ± 0.4

Source: J. Casares, `astro-ph/0612312`

Black holes in X-ray binaries particularly “simple” to detect

Recent milestones

- S. Dimopoulos and G.L. Landsberg; S.B. Giddings and S. Thomas (2001): Black holes at the LHC?
- Saggitarius A* (2002): Supermassive black hole in center of Milky Way
- R. Emparan and H. Reall (2002): Black rings in five dimensions
- S. Hawking (2004): concedes bet on information paradox — end of "black hole wars"
- P. Kovtun, D. Son and A. Starinets (2004): Viscosity in strongly interacting Quantum Field Theories from black hole physics
- F. Pretorius (2005): Breakthrough in numerical treatment of binary problem
- C. Barcelo, S. Liberati, and M. Visser (2005): "Analogue gravity"
- J.E. McClintock et al. (2006): Measuring of spin of GRS1915+105 — nearly extremal Kerr black hole!
- E. Witten (2007), W. Li, W. Song and A. Strominger (2008) and D. Grumiller, N. Johansson (2008): Quantum gravity in three dimensions?
- S. Gubser; S. Hartnoll, C. Herzog and G. Horowitz (2008): "Holographic superconductors"
- D. Son; K. Balasubramanian and J. McGreevy (2008): Black hole duals for cold atoms proposed
- O. Lahav, A. Itah, A. Blumkin, C. Gordon, and J. Steinhauer (2009): Sonic black hole in Bose-Einstein condensate

Why are black holes interesting for quantum gravity?

Black holes as the hydrogen atom of quantum gravity

Some properties of black holes (BHs):

- BHs are simple, much like elementary particles
- BHs are characterized by mass, spin and charges

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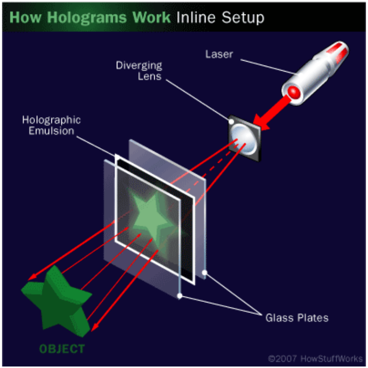
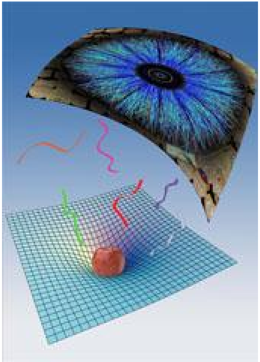
- Quantum-mechanically BH evaporation entails "information paradox"
- BHs are the simplest systems that allow to address conceptual problems of quantum gravity, for instance:
  unitarity of quantum gravity, microscopic understanding of BH entropy, holographic principle, modelling of BH evaporation, ...

Understanding quantum black holes and holography is milestone on road to quantum gravity!

Holography — Main idea

aka gauge/gravity duality, aka AdS/CFT correspondence





One of the most fruitful ideas in contemporary theoretical physics:

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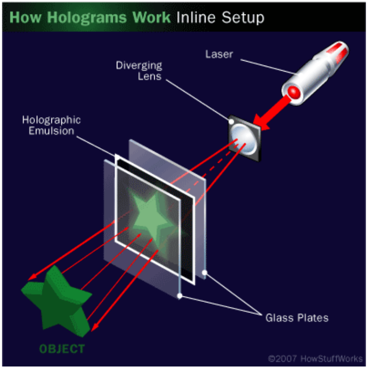

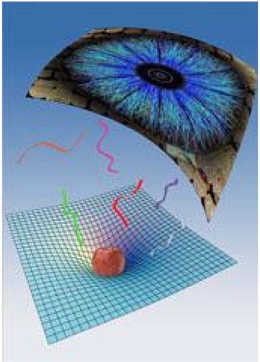

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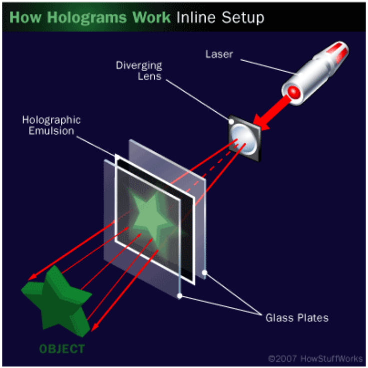

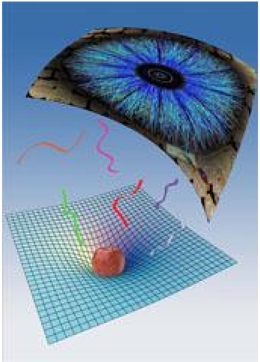

One of the most fruitful ideas in contemporary theoretical physics:

- The number of dimensions is a matter of perspective
- We can choose to describe the same physical situation using two different formulations in two different dimensions
- The formulation in higher dimensions is a theory with gravity
- The formulation in lower dimensions is a theory without gravity

Why gravity?

The holographic principle in black hole physics

`Boltzmann/Planck`: entropy of photon gas in d spatial dimensions

$$S_{\text{gauge}} \propto \text{volume} \propto L^d$$

`Bekenstein/Hawking`: entropy of black hole in d spatial dimensions

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$$\text{e.g.} \quad \langle T_{\mu\nu}\rangle_{\text{gauge}} = T^{BY}_{\mu\nu} \qquad \delta(\text{gravity action}) = \int \mathrm{d}^d x \sqrt{|h|}\, T^{BY}_{\mu\nu}\, \delta h^{\mu\nu}$$

Blackboard II

Brown–York stress energy tensor and intro to holographic renormalization

Why should I care?

...and why were there > 7000 papers on holography in the past 13 years?

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We can expect many new applications in the next decade!

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Introduction

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- Astrophysics
- Gravity

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3D gravity

- Motivation
- Topologically massive gravity
- Research directions

Why gravity in three dimensions?

"As simple as possible, but not simpler"

Gravity simpler in lower dimensions

$11D$: 1144 Weyl, 66 Ricci, $5D$: 35 Weyl, 15 Ricci, $4D$: 10 Weyl, 10 Ricci
$3D$: no Weyl, 6 Ricci, $2D$: no Weyl, 1 Ricci

2D gravity: black holes!

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Applications:

- Solve conceptual problems of (quantum) gravity
  Black hole evaporation, information loss problem, gravity as emergent phenomenon, ...

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pioneering work by Deser, Jackiw and Templeton in 1980ies
2007 Witten rekindled interest in 3D gravity

Cosmological topologically massive gravity (CTMG)

Action!

$$I_{\text{CTMG}} = \frac{1}{16\pi\, G}\,\int \mathrm{d}^3x\sqrt{-g}\,\Big[R + \frac{2}{\ell^2} + \frac{1}{2\mu}\,\varepsilon^{\lambda\mu\nu}\,\Gamma^\rho{}_{\lambda\sigma}\big(\partial_\mu\Gamma^\sigma{}_{\nu\rho} + \frac{2}{3}\,\Gamma^\sigma{}_{\mu\tau}\Gamma^\tau{}_{\nu\rho}\big)\Big]$$

Equations of motion:

$$G_{\mu\nu} + \frac{1}{\mu}\,C_{\mu\nu} = 0$$

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Properties of CTMG

- Gravitons (topologically massive spin 2 excitations)
- Black holes (BTZ)
- Asymptotically anti-deSitter solutions (AdS/CFT!?)
- Higher derivative terms (third derivatives in EOM)
- Parity violating Chern–Simons term
- Related: new massive gravity (Bergshoeff, Hohm, Townsend 2009)

Linearized equations of motion

Linearization around AdS background

$$g_{\mu\nu} = \bar{g}_{\mu\nu} + h_{\mu\nu}$$

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leads to linearized EOM that are third order PDE

$$G^{(1)}_{\mu\nu} + \frac{1}{\mu}\, C^{(1)}_{\mu\nu} = (\mathcal{D}^R \mathcal{D}^L \mathcal{D}^M h)_{\mu\nu} = 0 \tag{1}$$

with three mutually commuting first order operators

$$(\mathcal{D}^{L/R})_\mu{}^\nu = \delta_\mu^\nu \pm \ell\, \varepsilon_\mu{}^{\alpha\nu} \bar{\nabla}_\alpha\,, \qquad (\mathcal{D}^M)_\mu{}^\nu = \delta_\mu^\nu + \frac{1}{\mu} \varepsilon_\mu{}^{\alpha\nu} \bar{\nabla}_\alpha$$

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Three linearly independent solutions to (1):

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Li, Song and Strominger (2008):

At chiral point left (L) and massive (M) branches coincide!

With Sachs: recently found and classified all soutions to linearized EOM

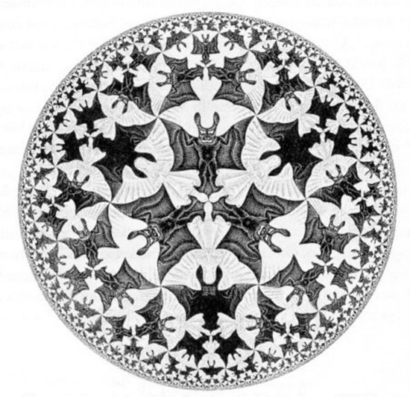
AdS/CFT – but which CFT?

Chiral versus logarithmic

Pre-cursor of AdS/CFT: Brown–Henneaux 1986

3D quantum gravity on AdS dual to 2D CFT with $c_L = c_R = 3\ell/2G_N$

Constant time slice of EAdS$_3$



Open Universe Looking from inside, boundary at infinity

- Boundary of AdS$_3$: cylinder

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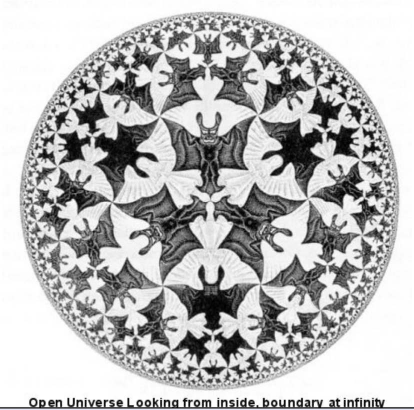

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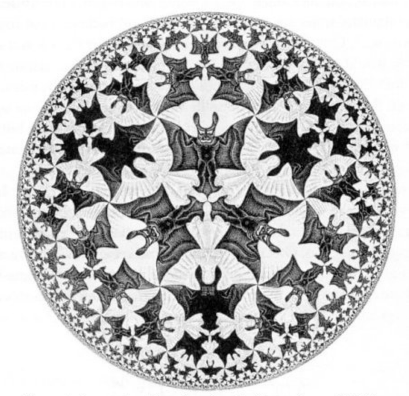


Open Universe Looking from inside, boundary at infinity

- Boundary of AdS$_3$: cylinder
- Dual CFT on cylinder
- Characterized by central charges
- $c_L = c_R$ in Einstein gravity

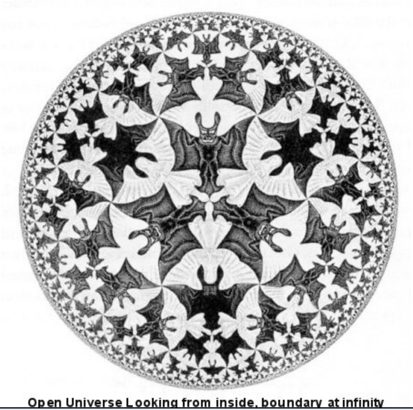
AdS/CFT – but which CFT?

Chiral versus logarithmic

Pre-cursor of AdS/CFT: Brown–Henneaux 1986

3D quantum gravity on AdS dual to 2D CFT with $c_L = c_R = 3\ell/2G_N$

Constant time slice of EAdS$_3$



Open Universe Looking from inside, boundary at infinity

- Boundary of AdS$_3$: cylinder
- Dual CFT on cylinder
- Characterized by central charges
- $c_L = c_R$ in Einstein gravity
- $c_L \neq c_R$ in CTMG
- $c_L = (1 - 1/\mu\ell)\, 3\ell/2G_N$
- Chiral point: $\mu\ell = 1$
- At chiral point $c_L = 0$

A tempting conjecture

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Observation (E: energy, J: angular momentum):

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- Until recently unknown which of these alternatives is realized!

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Results:

$$\langle \mathrm{right}(z,\bar{z})\,\mathrm{right}(0)\rangle = \frac{c_R}{2\bar{z}^4} \tag{2}$$

$$\langle \mathrm{left}(z,\bar{z})\,\mathrm{log}(0)\rangle = -\frac{b}{2z^4} \tag{3}$$

$$\langle \mathrm{log}(z,\bar{z})\,\mathrm{log}(0)\rangle = \frac{2b\,\ln\left(m^2|z|^2\right)}{z^4} \tag{4}$$

These are precisely the 2-point correlators of a logarithmic CFT!

3-point correlators also consistent with logarithmic CFT conjecture

3D gravity summary

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- Its dual CFT was conjectured to be logarithmic in work with Niklas Johansson 2008
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  Exciting possibility: gravity duals to strongly coupled logarithmic CFTs in condensed matter physics
  Examples: turbulence, critical polymers, percolation, disordered systems, sandpile model, quantum Hall effect, ...

It seems we have uncovered yet-another interesting chapter in the epic AdS/CFT saga...

Current projects

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Supplemented by collaborations with
MIT (Olaf Hohm, Roman Jackiw),
LMU Munich/AEI (Ivo Sachs),
Chicago U. (Robert McNees),
Perimeter Institute (Robert Mann),
McGill U. (Alejandra Castro),
Princeton U. (Nicolas Yunes),
Michigan U. (Finn Larsen),
YITP Stony Brook (Peter van Nieuwenhuizen),
etc.

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Directions implied by topics addressed in this talk:

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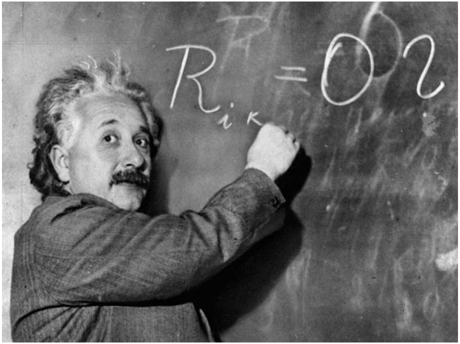
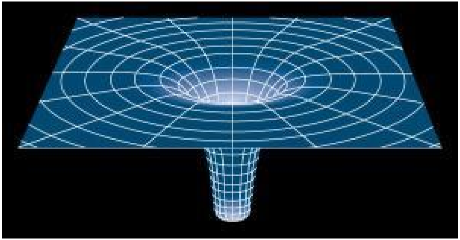
Many interesting topics for PhDs!

Thank you for your attention!

Black hole curves spacetime





Simple black hole analog