Einstein's Vision and the Quantum Universe

Jim Hartle, UCSB, SFI

Fermilab, October21, 2015

100th Anniversary of Einstein's relativistic theory of gravity

General Relativity

Key Points about Gravity

- The weakest of the four basic forces:

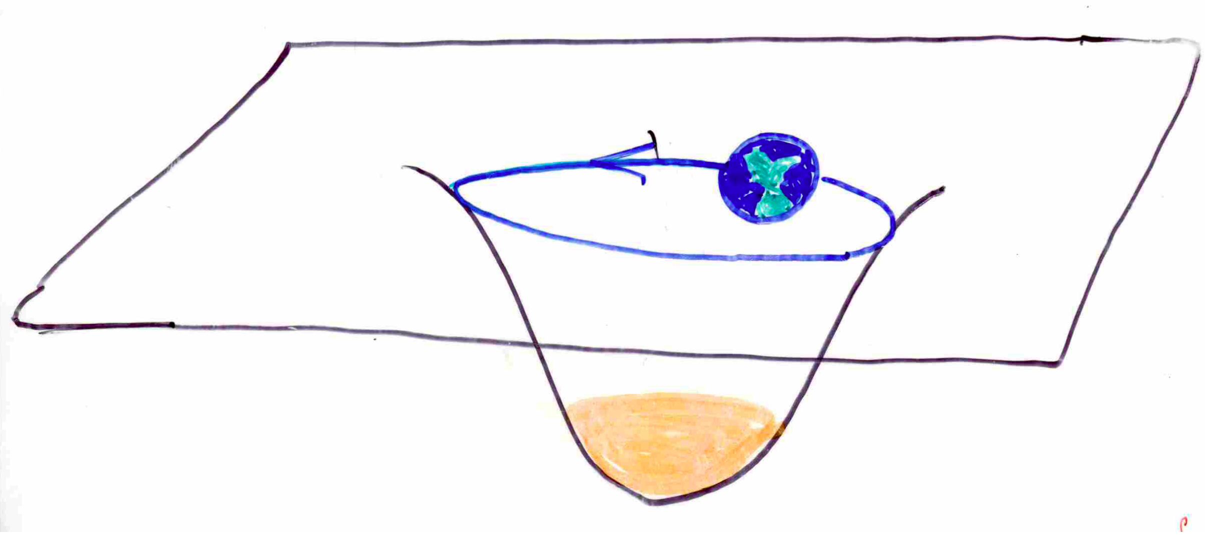
$$\frac{F_{grav}}{F_{em}} = \frac{Gm_p^2/r^2}{e^2/r^2} = \frac{Gm_p^2}{e^2} \sim 10^{-40}$$

- Universal - couples to all mass-energy.
- Long range $F = Gm_1 m_2/r^2$
- Unscreened - no negative gravitational "charge".

Gravity governs the structure of matter on the largest scales of the universe.

Key Facts about General Relativity

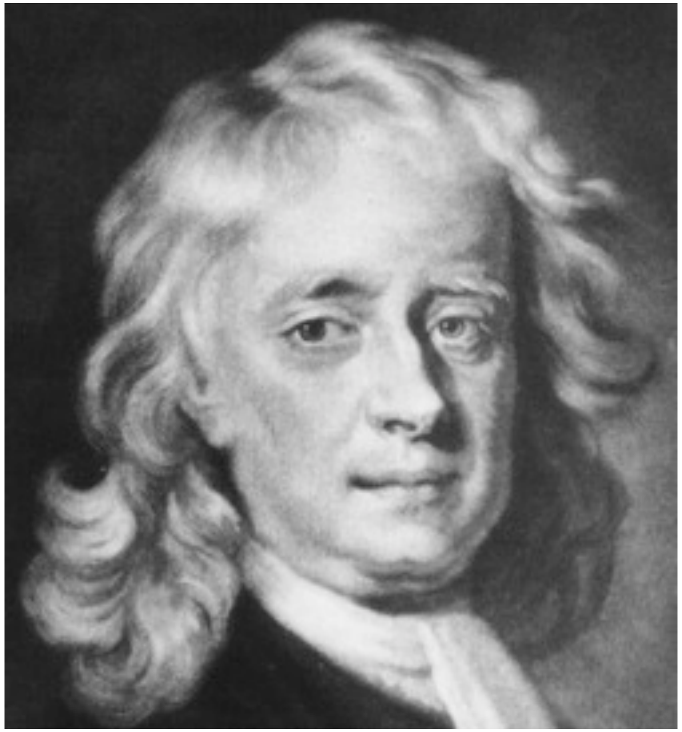
- Gravity is the geometry of curved spacetime.
- Mass-energy curves spacetime.
- Free mass moves on straight paths in curved spacetime.



Quantum theory of gravity means
a quantum theory of spacetime geometry

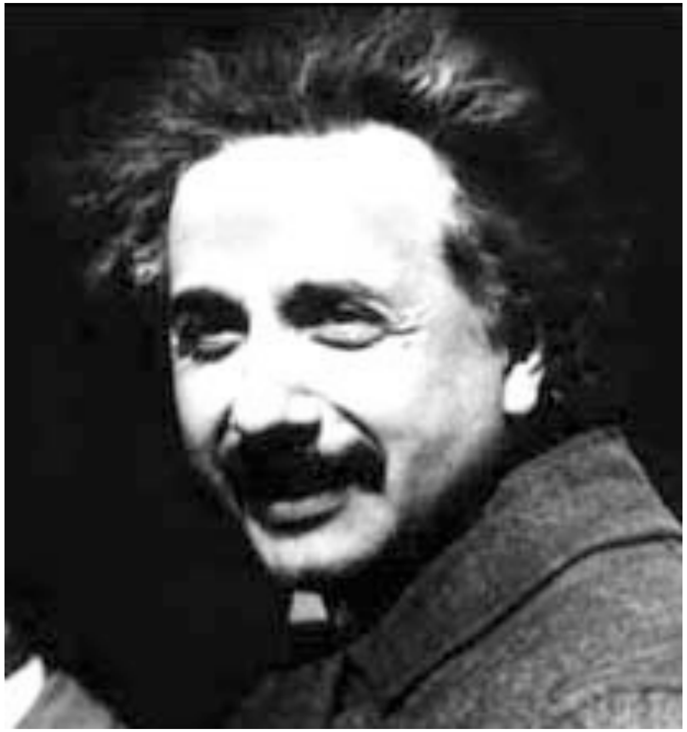
Newtonian Gravity (1687)

The Earth travels around the Sun because the Sun pulls on it with the force of gravity.



General Relativity (1915)

No force! The Earth travels around the Sun because it is following the straightest path in the curved spacetime produced by the Sun's mass.



EINSTEIN EQUATION

Uyuni, Bolivia

J. Broedel

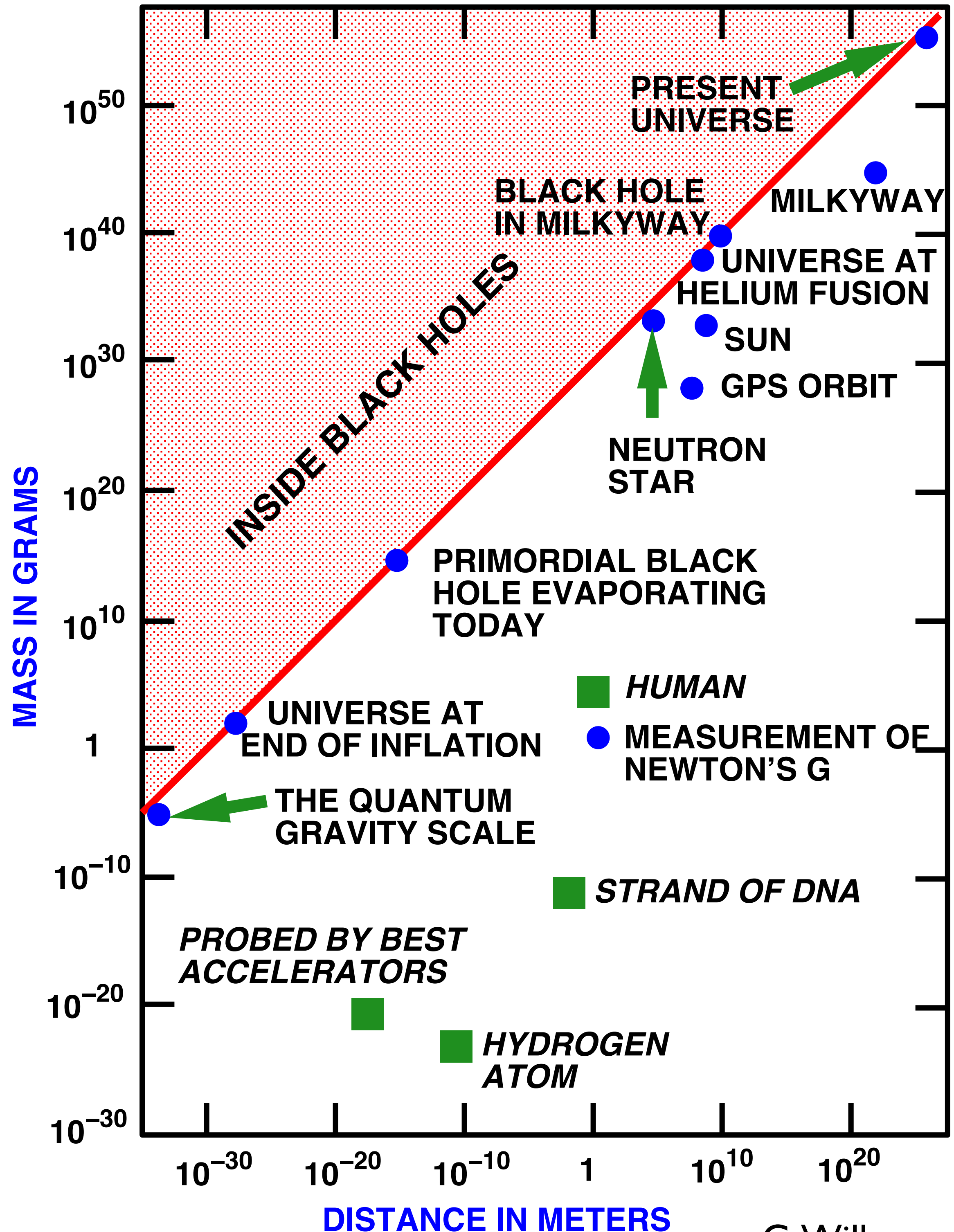
Where is General Relativity Important in Today's Physics?

FRONTIER OF LARGE SCALES

Relativistic Gravity is Important when:

$$\frac{GM}{Rc^2} \sim 1$$

- Sun: 10^{-6}
- Neutron Star: 10^{-1}
- Black Hole: 1/2
- Universe: 1



C.Will

FRONTIER OF SMALL SCALES

Planck Length and Energy:

$$\ell_{\rm Pl} = (G\hbar/c^3)^{1/2} \approx 10^{-33} cm$$

$$E_{\rm Pl} = (\hbar c^5/G)^{1/2} \approx 10^{19} Gev$$

These are the scales characterizing:

- Unified Theories of the Four Basic Forces
- The Union of Gravity and Quantum Mechanics

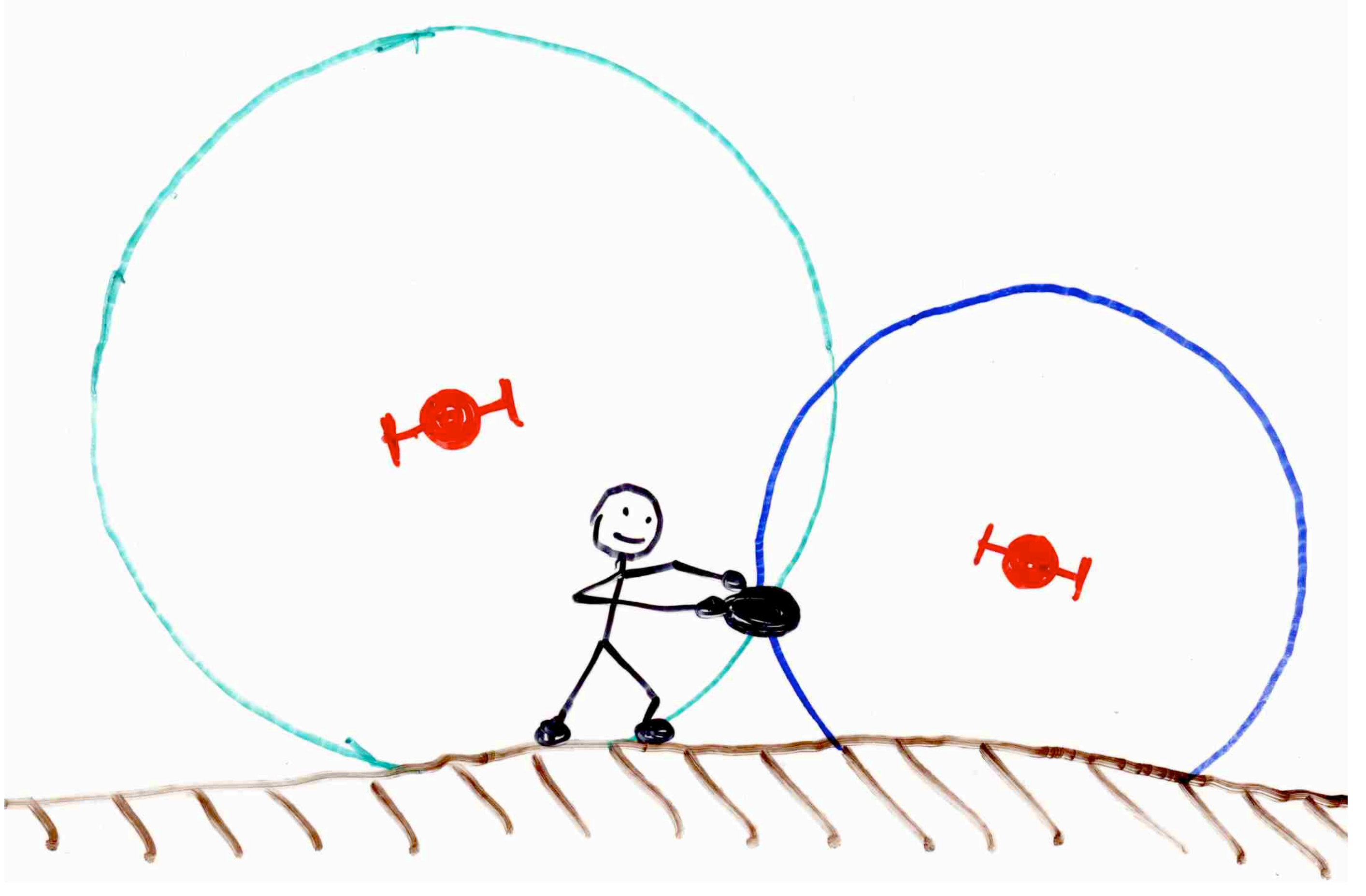
Impt. for Big Bang and the evaporation of black holes

Frontier of Large Scales: The Classical Universe

Weak Field Gravity

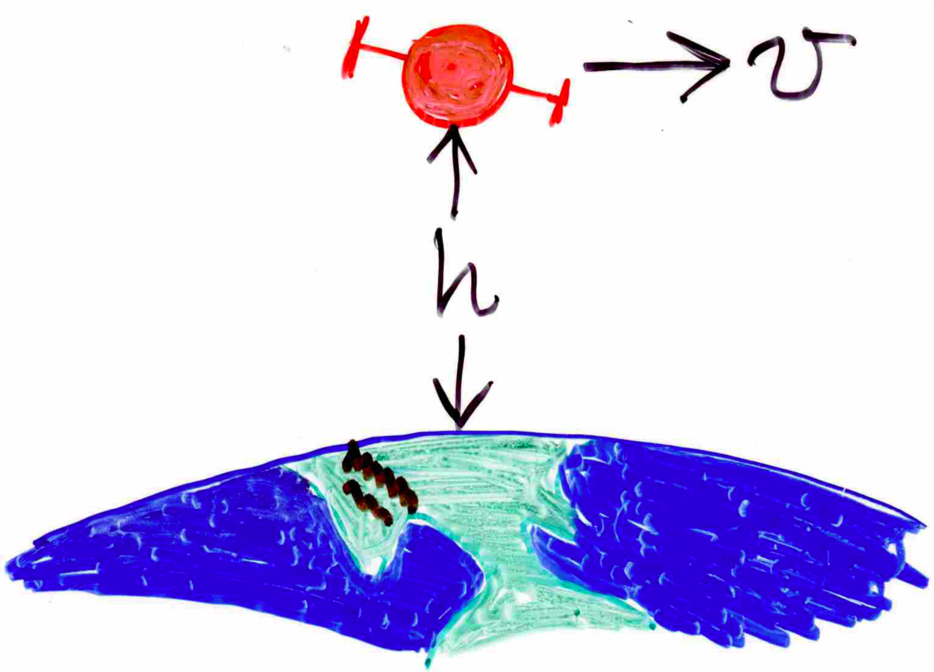
GPS OPERATION

(Cartoon Version)



Signals from four satellites determine a location in spacetime.

RELATIVISTIC EFFECTS IN GPS



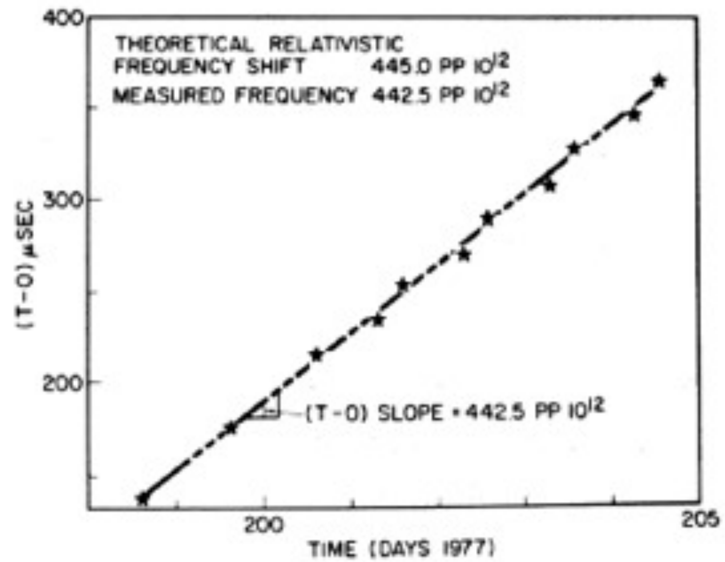


Fig. 20 - Cesium frequency via (T-O) slope

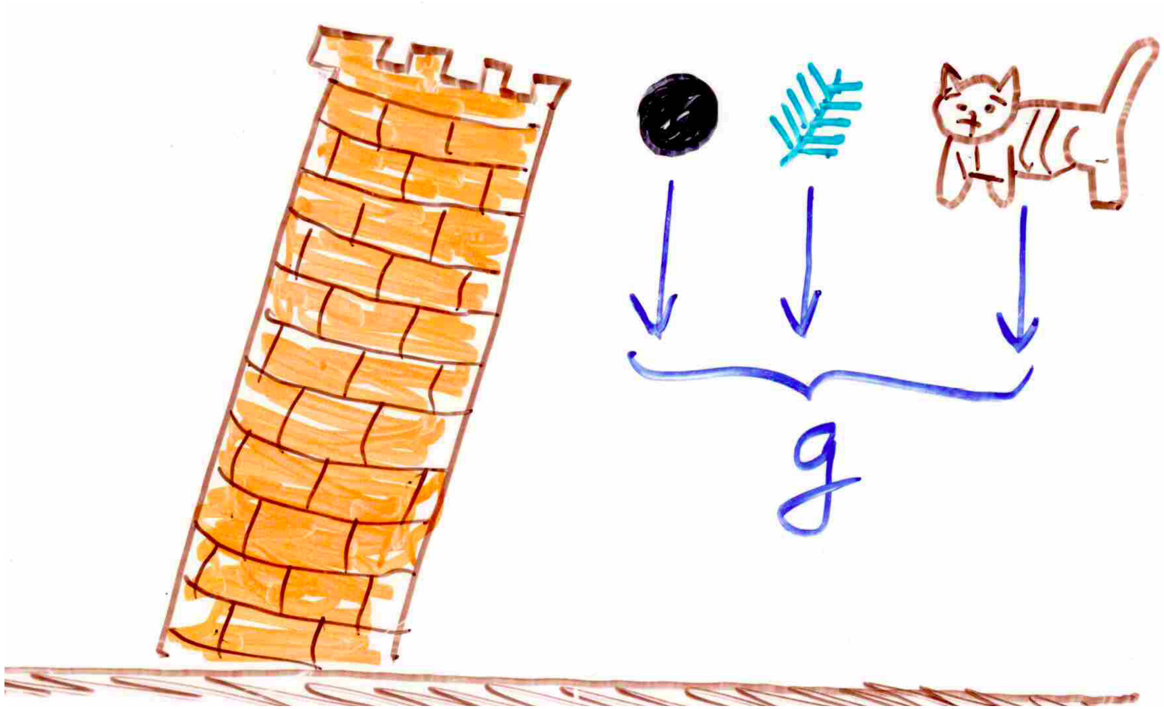
- Special Relativity - moving clocks run slow.

$$\sqrt{1 - v^2/c^2} \approx 1 - .8 \times 10^{-10}$$

- General Relativity - clocks higher in a gravitational potential run fast.

$$1 + gh/c^2 \approx 1 + 5.2 \times 10^{-10}$$

PRINCIPLE OF EQUIVALENCE

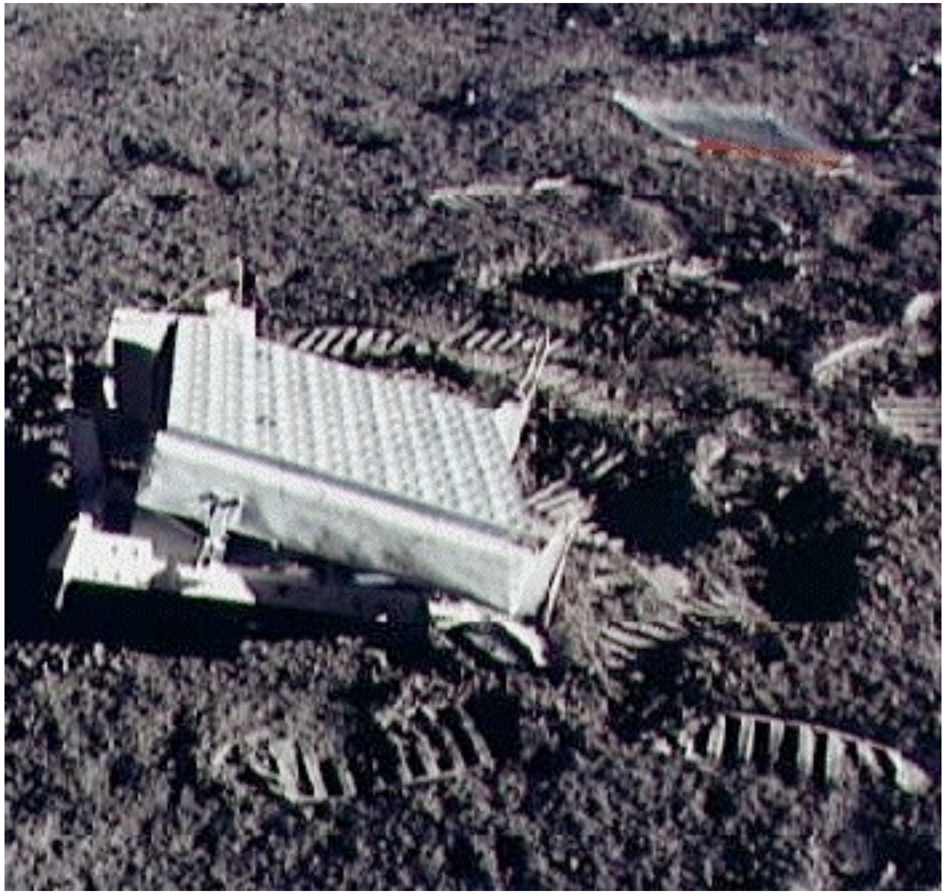


g's equal to 1.5×10^{-13}

(lunar laser ranging)

- Central to a geometric theory of gravity.
- Violations would signal either a breakdown of our notions of spacetime or new forces.

LUNAR LASER RANGING



Position of the Moon to a few cm. now and a few mm in the future (Apollo).

CASSINI γ

Measure differential time delay w. 2-way signal

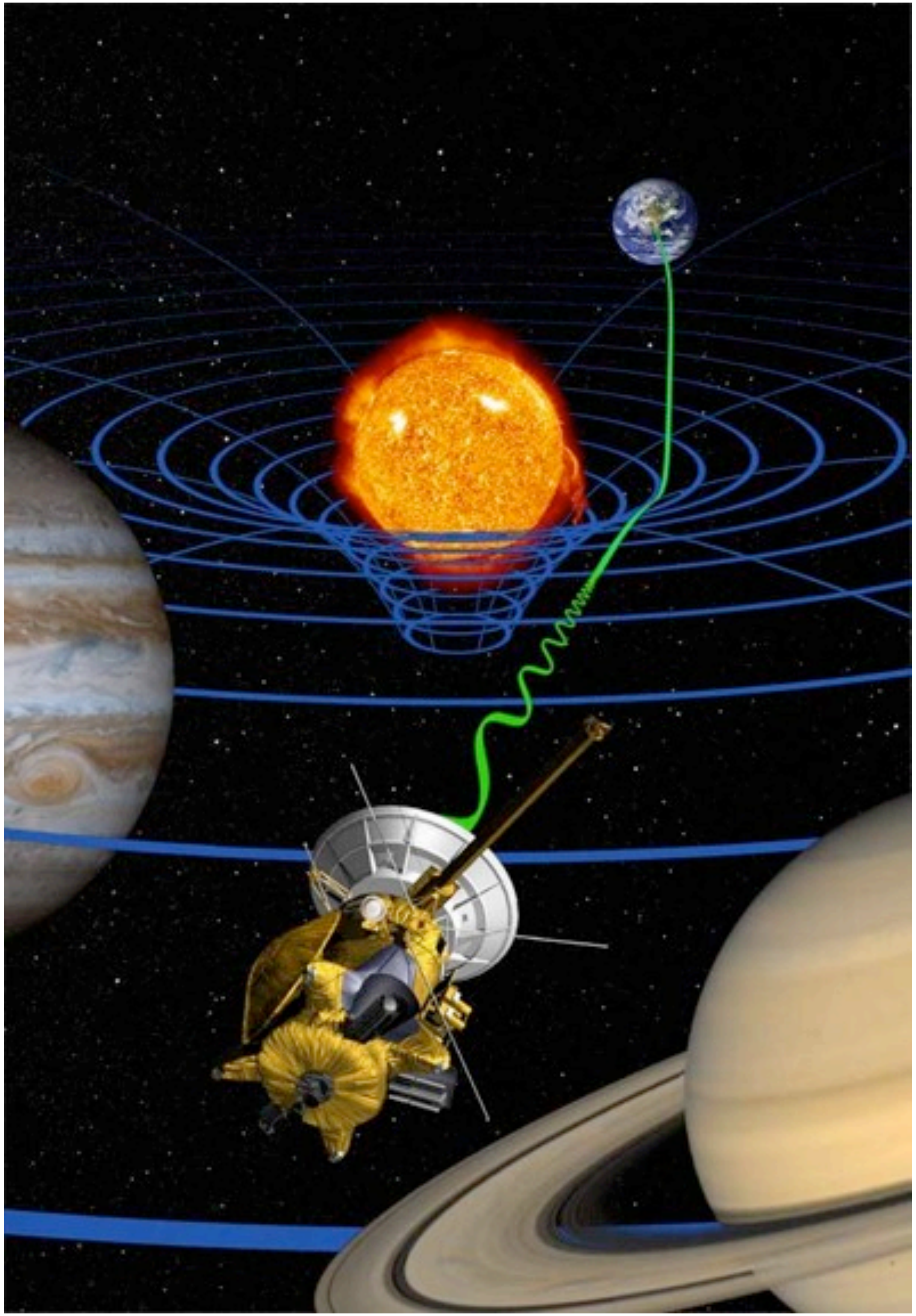
$$y \equiv \frac{\nu_{rec'd} - \nu_{trans}}{\nu_{trans}}$$

$$y_{gr} \approx 4(1+\gamma)\frac{GM_{\odot}}{bc^3}\frac{db}{dt}$$

b=closest approach to sun

Three up-downlink pairs allow for accurate correction for solar corona.

$\gamma - 1 = (2.1 \pm 2.3) \times 10^{-5}$



Double Pulsar

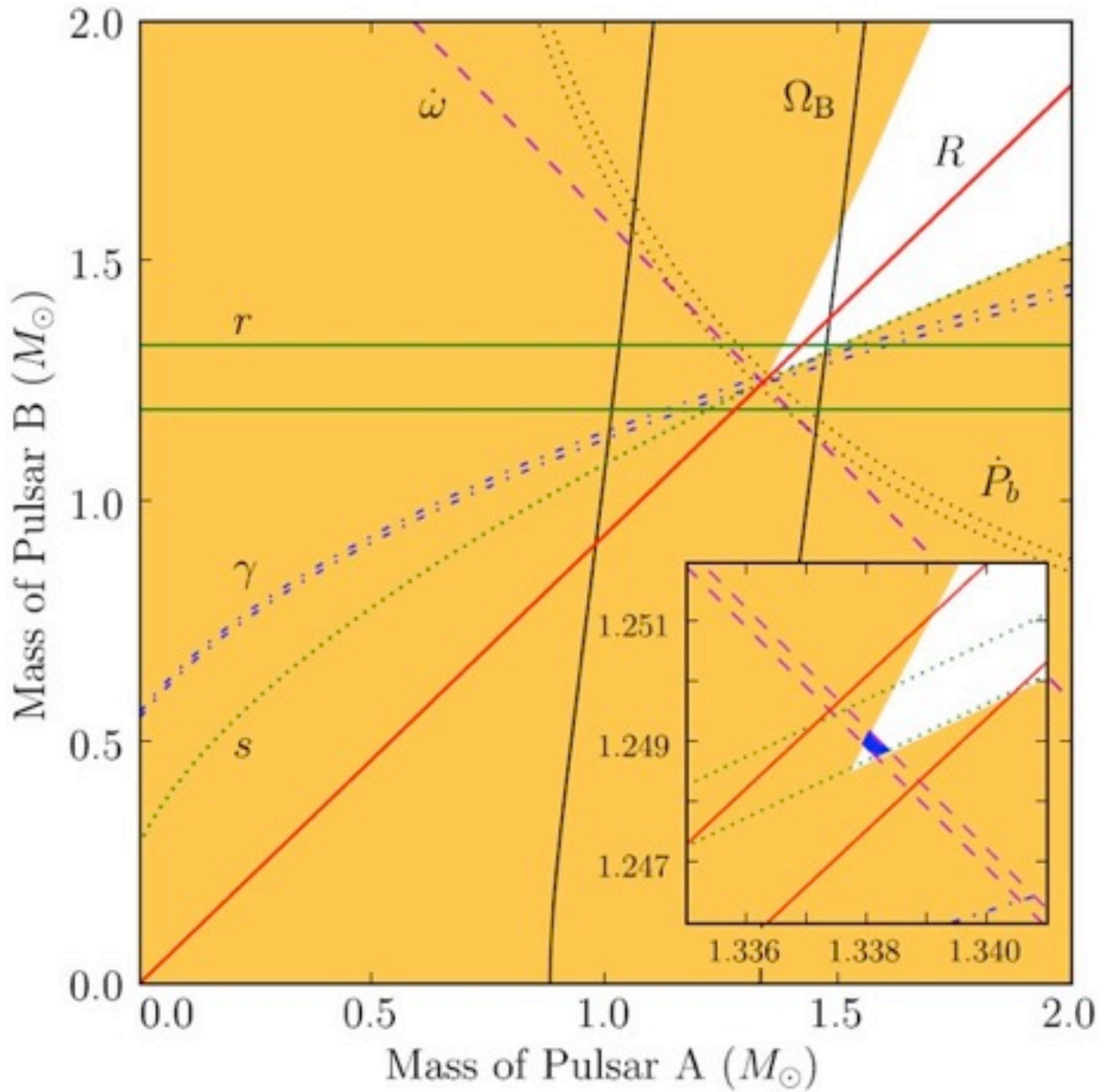
PSR J0737-3037
a double pulsar

Prec. of Periastron = 16.89947(68) deg/yr

Post-Keplerian parameters
$\dot{\omega}, \dot{P}_b, \gamma, s, r, \Omega_B$

Intersection at one point provides 5 tests of GR at the $10^{-(4-5)}$ level.

M. Kramer, et al 2006, 2008



THE PROGRESS OF THE CLASSICAL TESTS

Redshift, Deflection and delay of light, Prec. of perihelion.

- Small effects difficult to detect.
- Precision tests to fractions of a percent.
- Annoying corrections in other experiment (earth orientation measurements).
- New tools for exploring the universe (lensing, planets)

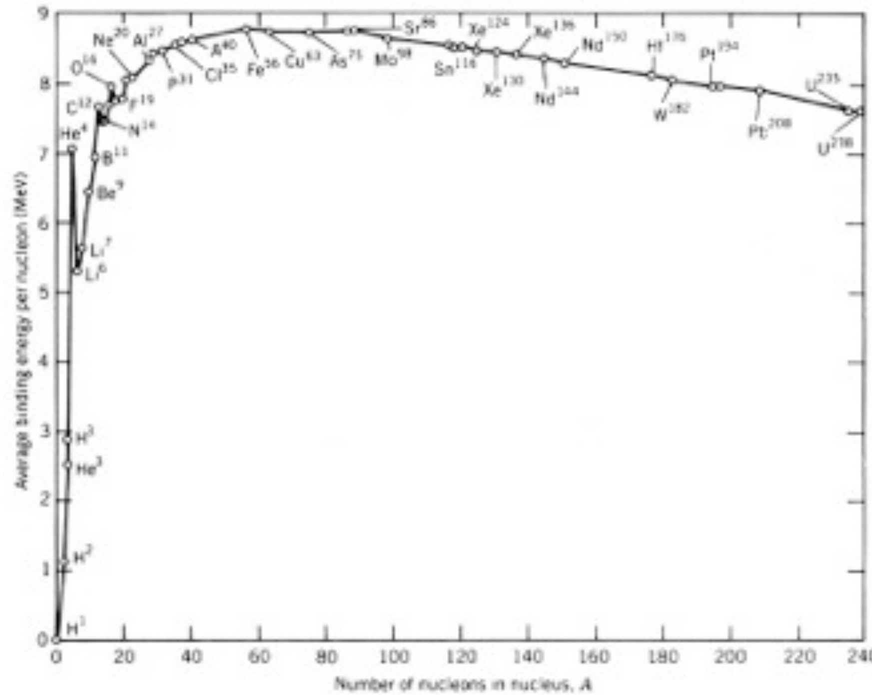
Strong Field Gravity

Grav. Binding vs Thermonuclear Fusion

Fusion Binding:

$$4H^1 \rightarrow He^4 + energy$$

$$\frac{energy\,out}{rest\,energy\,in} \leq 1\%$$

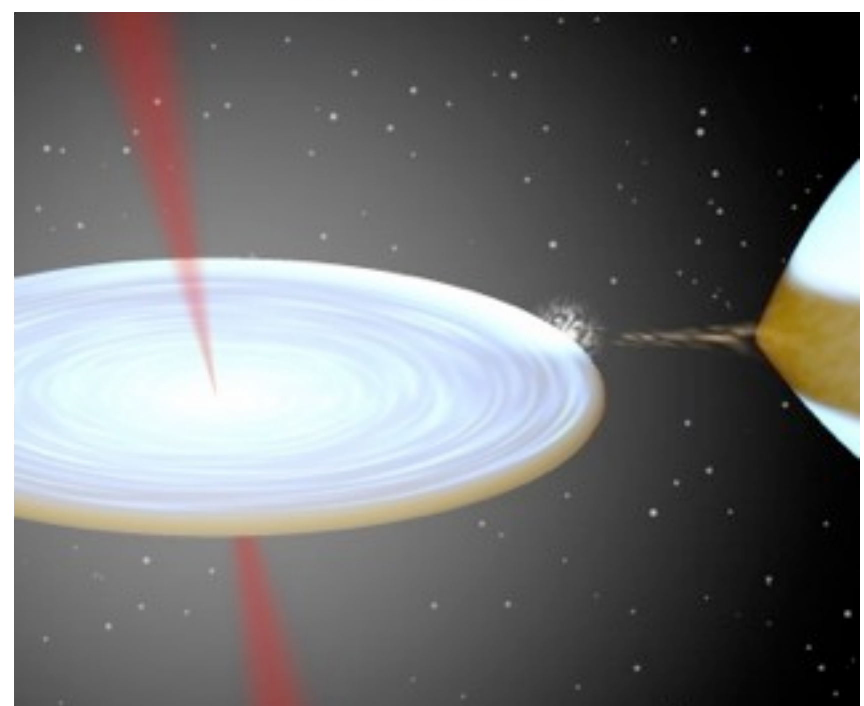


Grav. Binding:

$$\text{Unbound} \rightarrow \text{Bound ISCO} + energy$$

$$\frac{energy\,out}{rest\,energy\,in} \sim 6\%$$ neutron star

$$\frac{energy\,out}{rest\,energy\,in} \sim 30\%$$ extreme rot. black hole



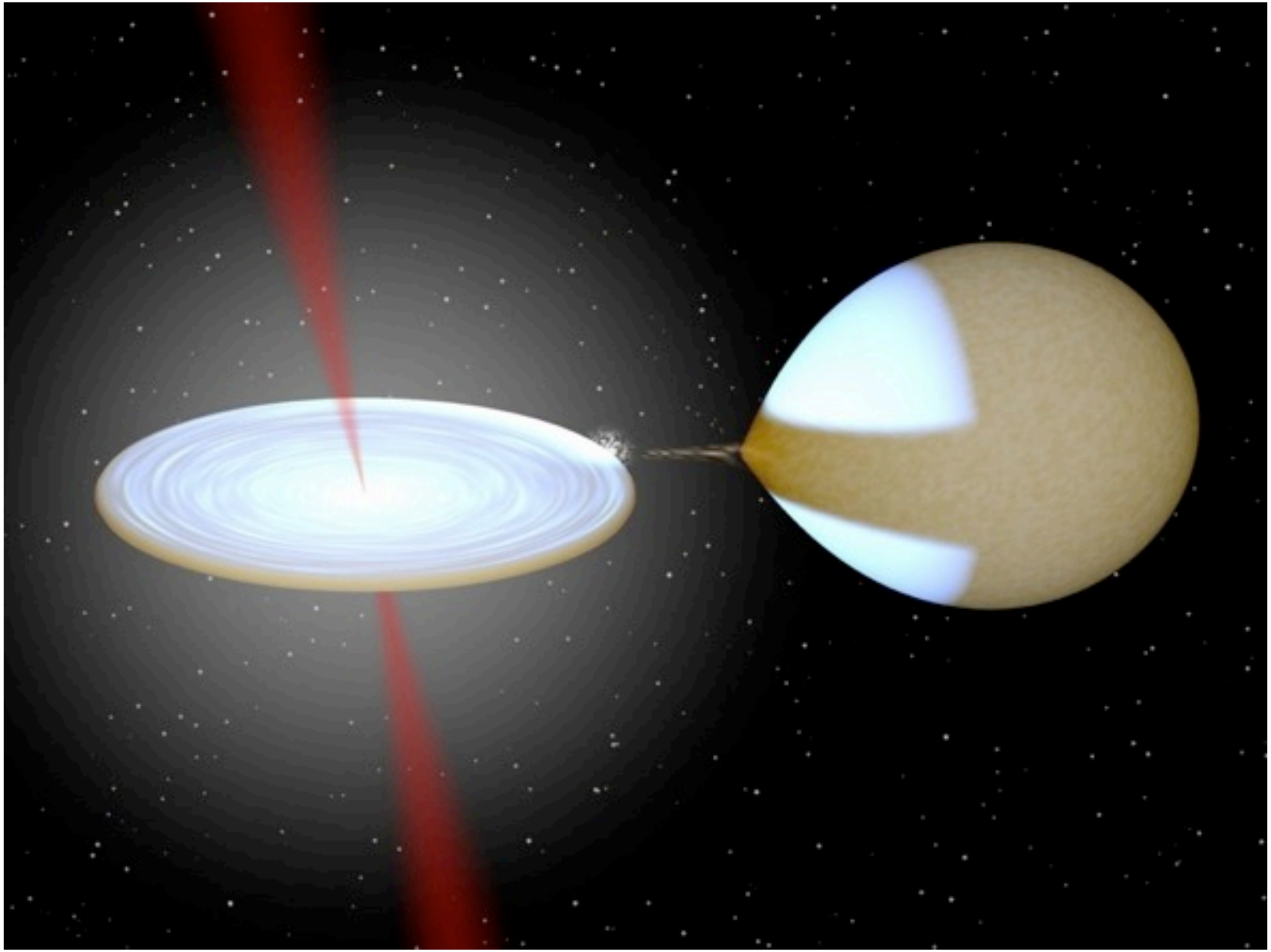
POWER FROM BLACK HOLES

X-RAY SOURCES

$$L_X \sim 10^{38}$$

$$L_\odot \sim 10^{33}$$

$$(erg/s)$$



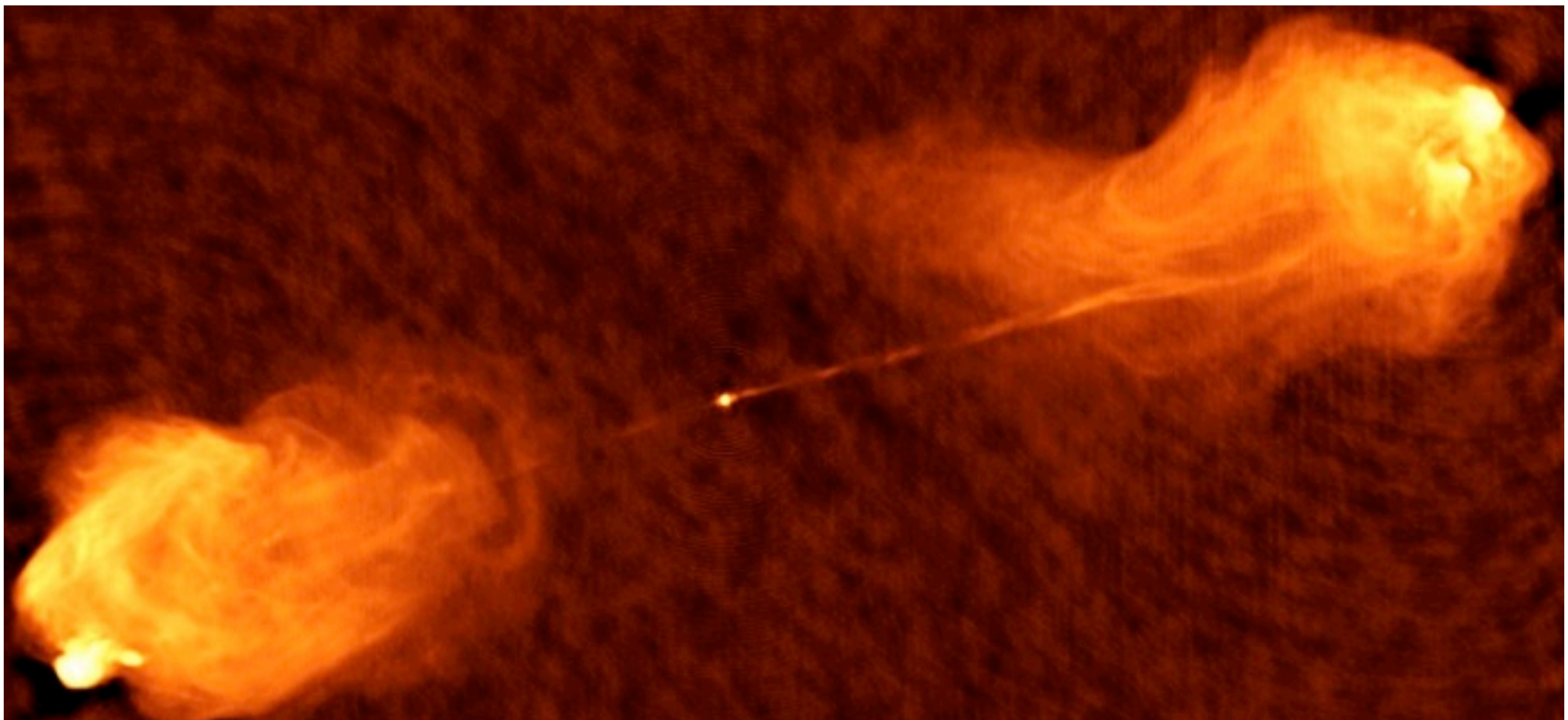
R. Hynes

POWER FROM BLACK HOLES

Active Galactic Nuclei

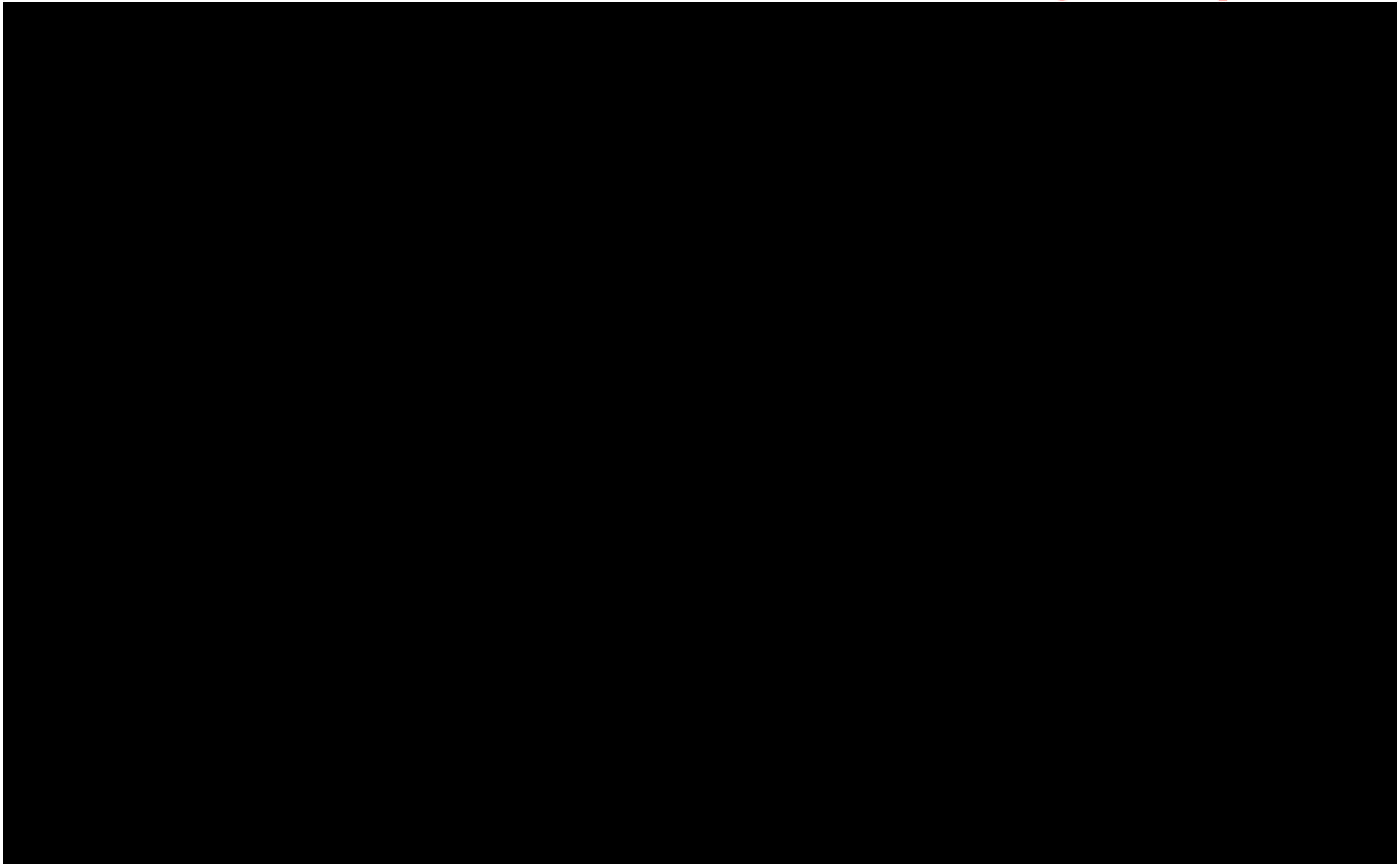
$$L_{AGN} \sim 10^{42} - 10^{48} erg/sec$$

$$L_{gal} \sim 10^{44} erg/sec$$



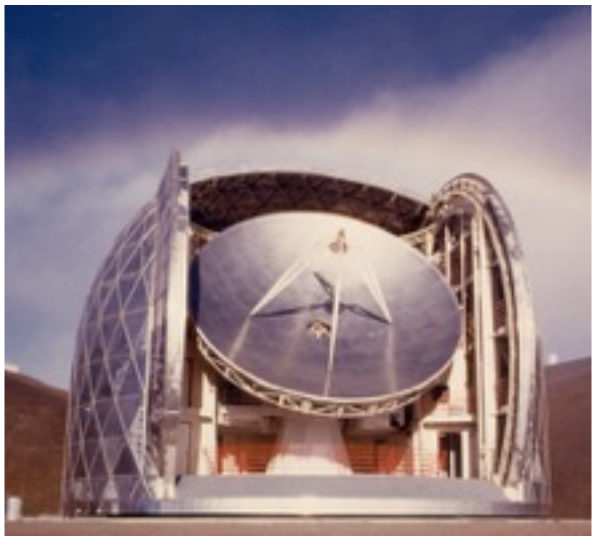
Cygnus X-1 C. Carilli

The 4 Million solar mass black hole at the center of our galaxy

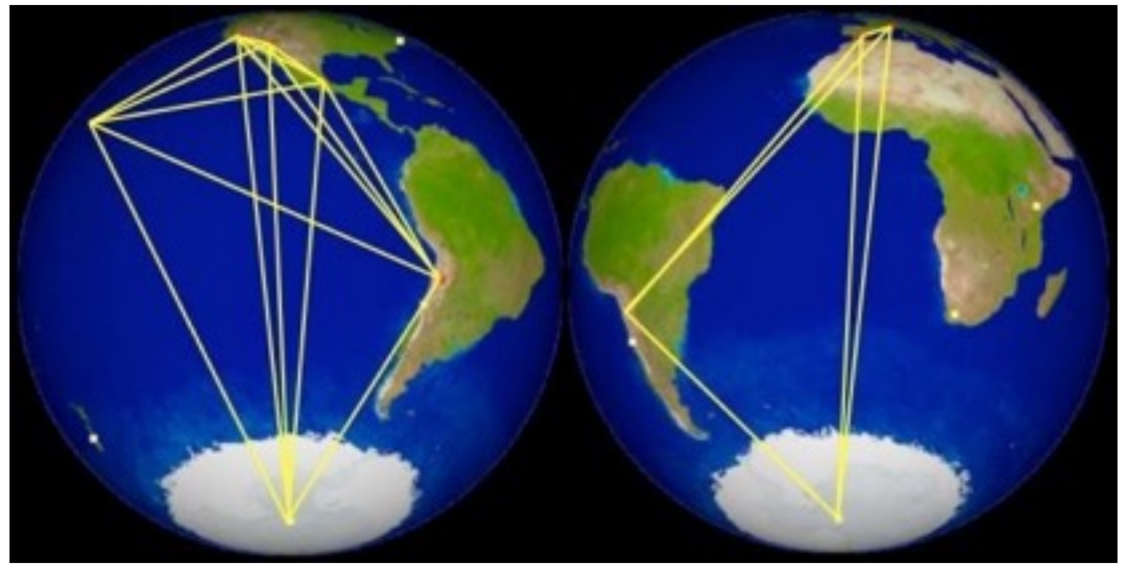


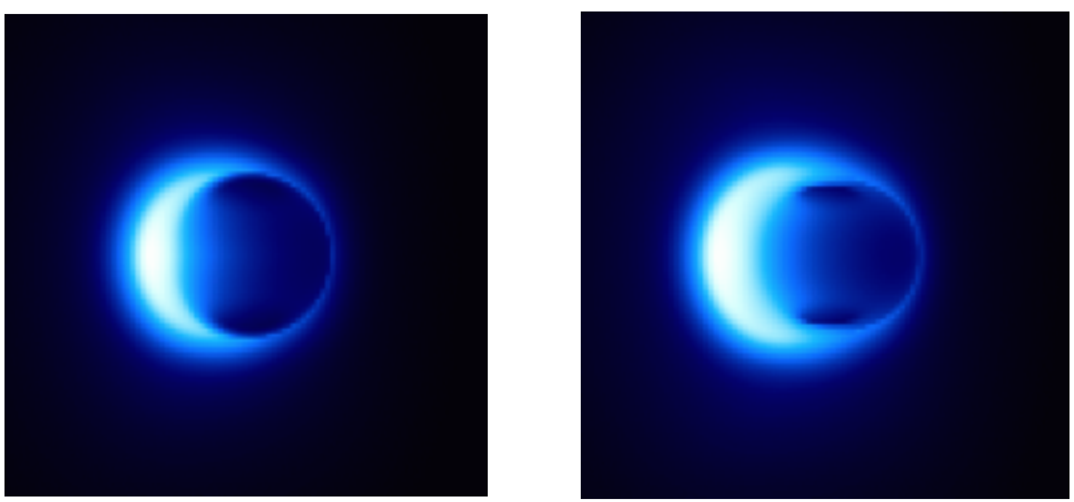
Event Horizon Telescope

VLBI with mm radio to image our galaxy's black hole



Caltech, Mona Kea





Shape of black hole shadow tests strong field predictions of GR for the uniqueness of black holes.


Interstellar

LIGO

Hanford, WA

PHYSICAL REVIEW D **69**, 122001 (2004)

Analysis of LIGO data for gravitational waves from binary neutron stars

B. Abbott,[13] R. Abbott,[16] R. Adhikari,[14] A. Ageev,[21,28] B. Allen,[40] R. Amin,[35] S. B. Anderson,[13] W. G. Anderson,[30] M. Araya,[13] H. Armandula,[13] F. Asiri,[13,a] P. Aufmuth,[32] C. Aulbert,[1] S. Babak,[7] R. Balasubramanian,[7] S. Ballmer,[14] B. C. Barish,[13] D. Barker,[15] C. Barker-Patton,[15] M. Barnes,[13] B. Barr,[36] M. A. Barton,[13] K. Bayer,[14] R. Beausoleil,[27,b] K. Belczynski,[24] R. Bennett,[36,c] S. J. Berukoff,[1,d] J. Betzwieser,[14] B. Bhawal,[13] I. A. Bilenko,[21] G. Billingsley,[13] E. Black,[13] K. Blackburn,[13] B. Bland-Weaver,[15] B. Bochner,[14,e] L. Bogue,[13] R. Bork,[13] S. Bose,[41] P. R. Brady,[40] V. B. Braginsky,[21] J. E. Brau,[38] D. A. Brown,[40] S. Brozek,[32,f] A. Bullington,[27] A. Buonanno,[6,g] R. Burgess,[14] D. Busby,[13] W. E. Butler,[39] R. L. Byer,[27] L. Cadonati,[14] G. Cagnoli,[36] J. B. Camp,[22] C. A. Cantley,[36] L. Cardenas,[13] K. Carter,[16] M. M. Casey,[36] J. Castiglione,[35] A. Chandler,[13] J. 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Libbrecht,[13] P. Lindquist,[13] S. Liu,[13] J. Logan,[13,r] M. Lormand,[16] M. Lubinski,[15] H. Lück,[32,2] T. T. Lyons,[13,r] B. Machenschalk,[1] M. MacInnis,[14] M. Mageswaran,[13] K. Mailand,[13] W. Majid,[13,h] M. Malec,[32] F. Mann,[13] A. Marin,[14,s] S. Márka,[13] E. Maros,[13] J. Mason,[13,t] K. Mason,[14] O. Matherny,[15] L. Matone,[15] N. Mavalvala,[14] R. McCarthy,[15] D. E. McClelland,[3] M. McHugh,[19] P. McNamara,[36,u] G. Mendell,[15] S. Meshkov,[13] C. Messenger,[34] V. P. Mitrofanov,[21] G. Mitselmakher,[35] R. Mittleman,[14] O. Miyakawa,[13] S. Miyoki,[13,v] S. Mohanty,[1,w] G. Moreno,[15] K. Mossavi,[2] B. Mours,[13,x] G. Mueller,[35] S. Mukherjee,[1,w] J. Myers,[15] S. Nagano,[2] T. Nash,[10,y] H. Naundorf,[1] R. Nayak,[12] G. Newton,[36] F. Nocera,[13] P. Nutzman,[24] T. Olson,[25] B. O'Reilly,[16] D. J. Ottaway,[14] A. Ottewill,[40,z] D. Ouimette,[13,q] H. Overmier,[16] B. J. Owen,[29] M. A. Papa,[1] C. Parameswariah,[16] V. Parameswariah,[15] M. Pedraza,[13] S. Penn,[11] M. Pitkin,[36] M. Plissi,[36] M. Pratt,[14] V. Quetschke,[32] F. Raab,[15] H. Radkins,[15] R. Rahkola,[38] M. Rakhmanov,[35] S. R. Rao,[13] D. Redding,[13,h] M. W. Regehr,[13,h] T. Regimbau,[14] K. T. Reilly,[13] K. Reithmaier,[13] D. H. Reitze,[35] S. Richman,[14,27] R. Riesen,[16] K. Riles,[37] A. Rizzi,[16,28] D. I. Robertson,[36] N. A. Robertson,[36,27] L. Robison,[13] S. Roddy,[16] J. Rollins,[14] J. D. Romano,[30,29] J. Romie,[13] H. Rong,[35,m] D. Rose,[13] E. Rotthoff,[29] S. Rowan,[36] A. Rüdiger,[20,2] P. Russell,[13] K. Ryan,[15] I. Salzman,[13] G. H. Sanders,[13] V. Sannibale,[13] B. Sathyaprakash,[7] P. R. Saulson,[28] R. Savage,[15] A. Sazonov,[35] R. Schilling,[20,2] K. Schlaufman,[29] V. Schmidt,[13,30] R. Schofield,[38] M. Schrempel,[32,ee] B. F. Schutz,[1,7] P. Schwinberg,[15] S. M. Scott,[3] A. C. Searle,[3] B. Sears,[13] S. Seel,[13] A. S. Sengupta,[12] C. A. Shapiro,[29,ff] P. Shawhan,[13] D. H. Shoemaker,[14] Q. Z. Shu,[35,gg] A. Sibley,[16] X. Siemens,[40] L. Sievers,[13,h] D. Sigg,[15] A. M. Sintes,[13,h] K. Skeldon,[36] J. R. Smith,[2] M. Smith,[14] M. R. Smith,[13] P. Sneddon,[36] R. Spero,[13,h] G. Stapfer,[16] K. A. Strain,[36] D. Strom,[38] A. Stuver,[29] T. Summerscales,[29] M. C. Sumner,[13] P. J. Sutton,[29,y] J. Sylvestre,[13] A. Takamori,[13] D. B. Tanner,[35] H. Tariq,[13] I. Taylor,[7] R. Taylor,[13] K. S. Thorne,[6] M. Tibbits,[29] S. Tilav,[13,hh] M. Tinto,[4,h] K. V. Tokmakov,[21] C. Torres,[30] C. Torrie,[13,36] S. Traeger,[32,ii] G. Traylor,[16] W. Tyler,[13] D. Ugolini,[31] M. Vallisneri,[6,jj] M. van Putten,[14] S. Vass,[13] A. Vecchio,[34] C. Vorvick,[15] S. P. Vyachanin,[21] L. Wallace,[13] H. Walther,[20] H. Ward,[36] B. Ware,[13,h] K. Watts,[16] D. Webber,[13] A. Weidner,[20,2] U. Weiland,[32] A. Weinstein,[13] R. Weiss,[14] H. Welling,[32] L. Wen,[13] S. Wen,[17] J. T. Whelan,[19] S. E. Whitcomb,[13] B. F. Whiting,[35] P. A. Willems,[13] P. R. Williams,[1,kk] R. Williams,[4] B. Willke,[32,2] A. Wilson,[13] B. J. Winjum,[29,d] W. Winkler,[20,2] S. Wise,[35] A. G. Wiseman,[40] G. Woan,[36] R. Wooley,[16] J. Worden,[15] I. Yakushin,[16] H. Yamamoto,[13] S. Yoshida,[26] I. Zawischa,[32,ll] L. Zhang,[13] N. Zotov,[18] M. Zucker,[16] and J. Zweizig[13]

(LIGO Scientific Collaboration)[mm]

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Merging Supermassive Black Holes

- All large galaxies have black holes.
- Galaxies merge at least once in their lifetimes.
- Merging black holes emit copious gravitational radiation.

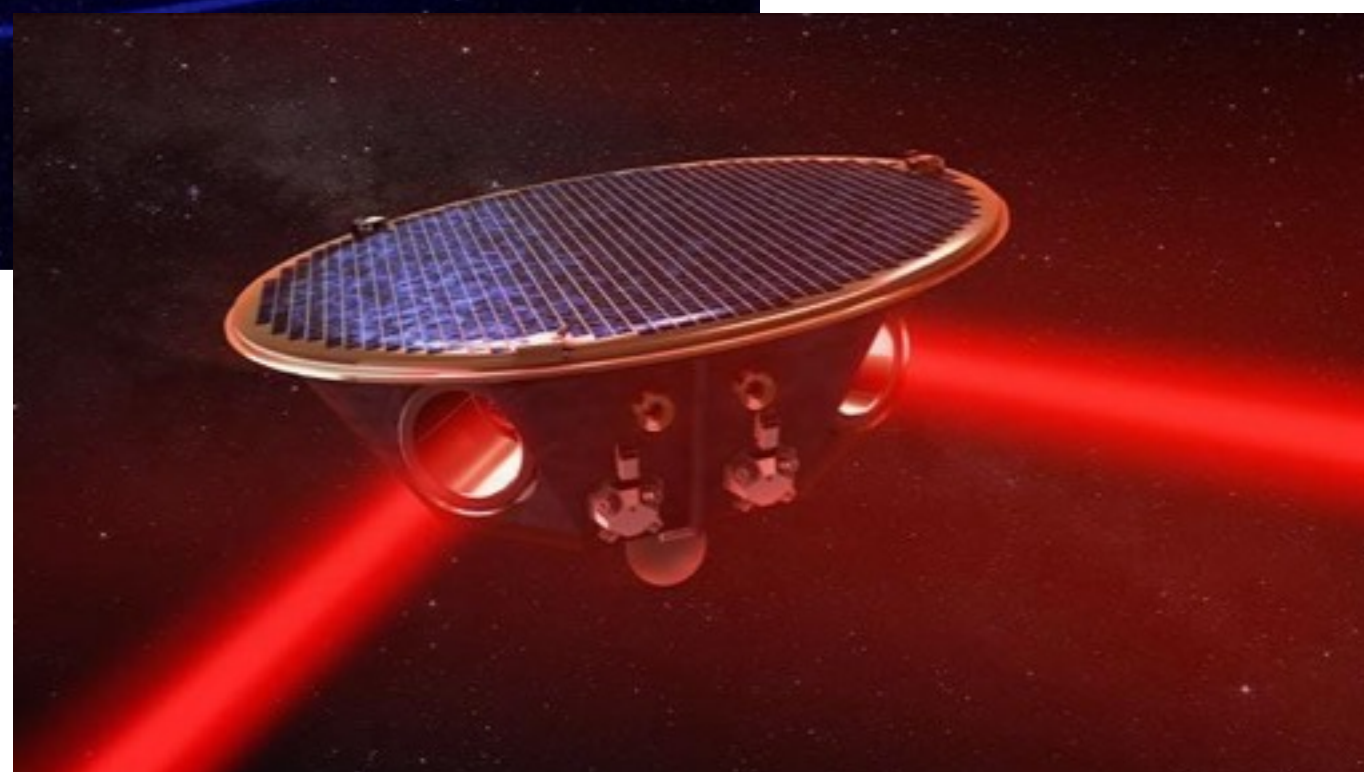
$$E \sim Mc^2, \quad t \sim GM/c^3$$

$$L_{GW} \sim c^5/G \sim 10^{59} erg/s$$

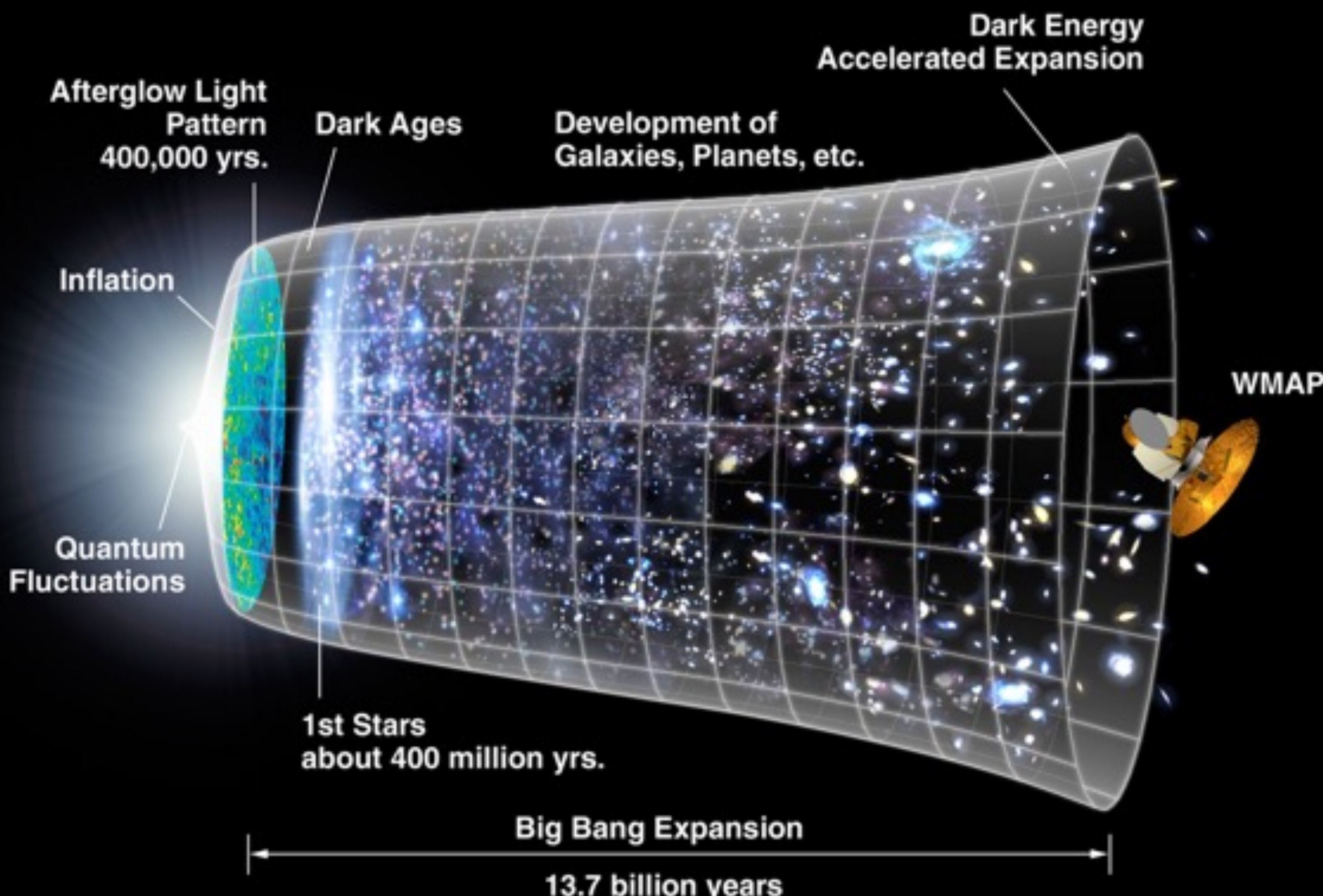
Mostly in GW.
Visible to the horizon with LISA at a rate of a few per month.

ELisa

Laser interferometric gravitational wave detector.



The Universe



SCORECARD

	Weak Gravity	Strong Gravity
Lab. (attopc)	Equivalence Princ., 10^{-12} Fifth Force, 60μ	
Solar System (millipc)	Equivalence Princ 10^{-13} Grav. Redshift, 10^{-4} Bending of Light 10^{-4} Shapiro Time Delay 10^{-5} Prec. of Perihelion 10^{-4} Lense-Thirring Prec. (5-15%)	Grav. Rad. Bin. Pulsar 10^{-3} X-ray sources (black holes) Max. mass neutron stars.
Galactic (kilopc)	Lensing bending of light 10%	Models for pulsars, quasars, AGN, gamma ray bursts, etc.
Cosmological (Gigapc)	Gravitational waves from the early universe. Growth of structure.	Success of FRLW models.

Frontier of Small Scales: The Quantum Universe

Two Quantum Theories of Gravity

- Loop Quantum Gravity --- Classical general relativity quantized non-perturbatively using connections as variables and a mathematically precise construction of Hilbert space.
- String Theories --- Gravity unified with all other forces in both a many dimensional framework and its dual formulations.

Quantum Gravity: Experiment and Tests?

It seems unlikely that we will have laboratory experiments that test quantum gravity in the immediate future.

$$E_{\rm pl} \equiv \sqrt{\hbar c^5/G} \sim 10^{19} {\rm Gev}$$

But in the beginning and expansion of the universe we have and experiment already done where Planck energies are reached, and there is 14 Gyr of data scattered over 42 lyr of space.

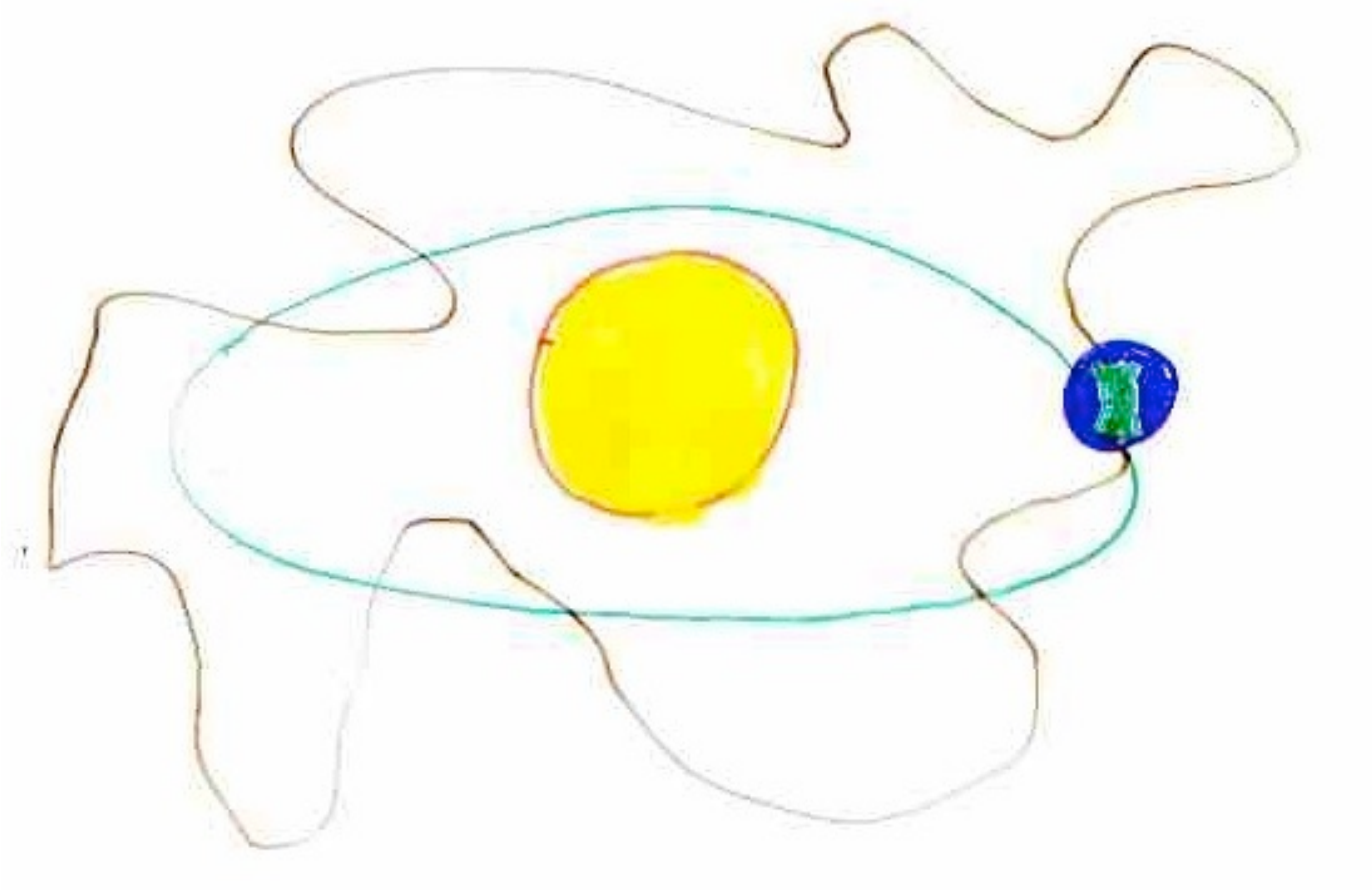
Quantum Cosmology

Cosmological Observations of the Universe's Classical History

Most of our observations of the universe on cosmological scales are of properties of its classical history:

- The homogeneity and isotropy on scales above 100Mpc. The vast age.
- The rate of expansion, the amounts of dark matter, dark energy, baryons, radiation.
- The evolution of fluctuations to make the CMB, galaxies, stars, planets, biota, us, etc.

Classical behavior is a matter of quantum probabilities for histories.



A Quantum Universe

If the universe is a quantum mechanical system it has a quantum state.
What is it?

Ψ

A theory of the quantum state is the objective of Quantum Cosmology.

Contemporary Final Theories Have Two Parts

$$H \qquad \Psi$$

Which regularities of the universe come mostly from H and which from ψ ?

An unfinished task of unification?

H	Ψ
• classical dynamics	• classical spacetime
• neutrino oscillation expts	• early homo/iso +inflation
• muon g-2 expts	• fluctuations in ground state
• all other lab expts	• arrows of time
	• CMB, large scale structure
	• isolated systems
	• topology of spacetime
	• num. of large and small dims.
	• num. of time dimensions
	• coupling consts. eff. theories

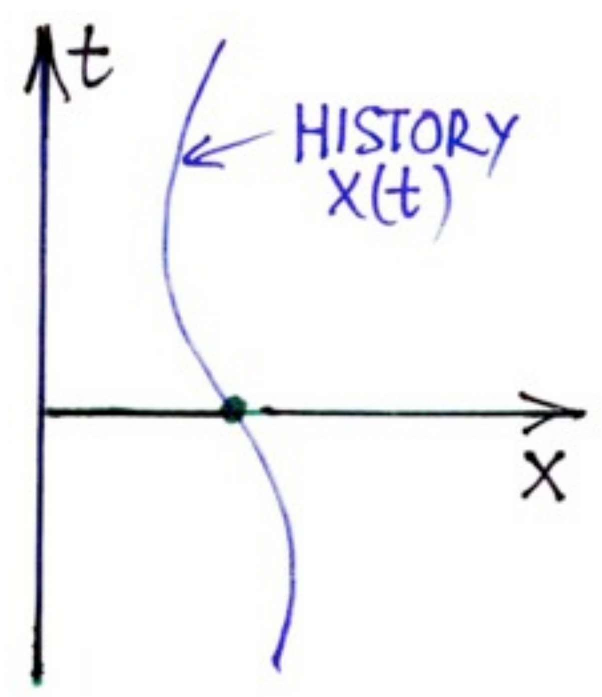
Wave Functions for the Universe

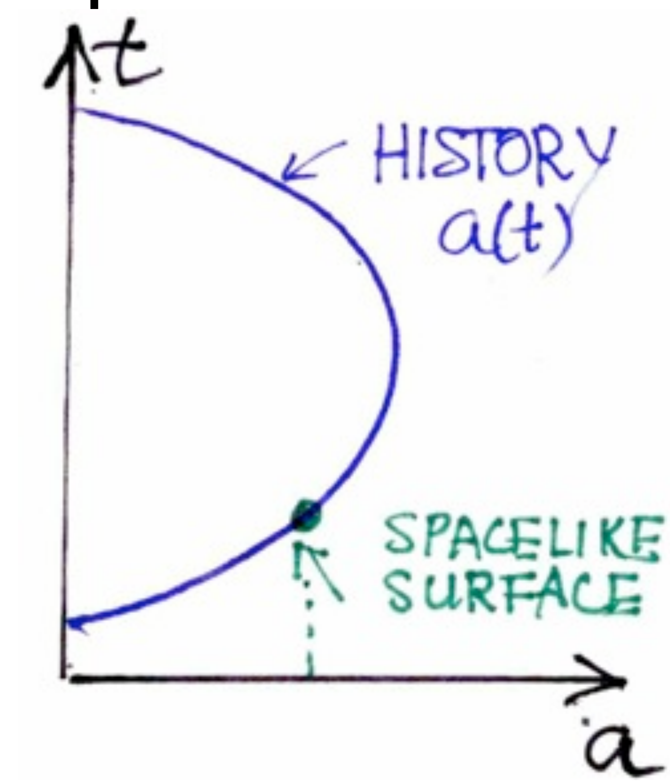
(minisuperspace models)

Geometry: Homogeneous, isotropic, closed.

$$ds^2 = -dt^2 + a^2(t)d\Omega_3^2$$

Matter: cosmological constant plus scalar field





$$\psi = \psi(x,t)$$

$$\Psi = \Psi(a,\phi)$$

Wave Functions of the Universe

The state is not an initial condition

It predicts probabilities for all possible alternative 4-d histories of the universe ---
what went on then
what goes on now
what will go on in the future.

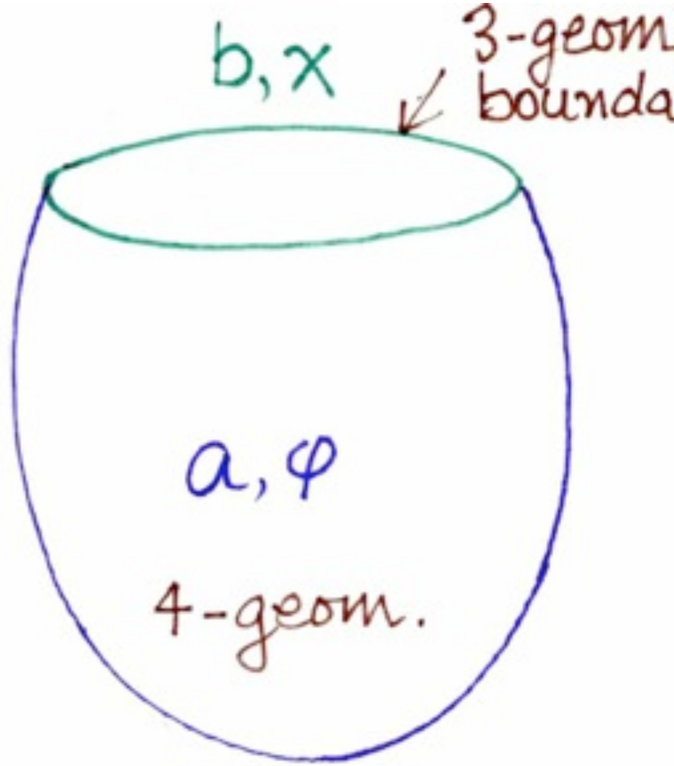
Ψ

Hawking's No-Boundary Wave Function

Cosmological analog of ground state

~~No H to be a lowest eigenvalue of,~~
~~for a closed universe $H = 0$~~

Euclidean sum over all four geometries with one boundary for the arguments of the wave function and no other.

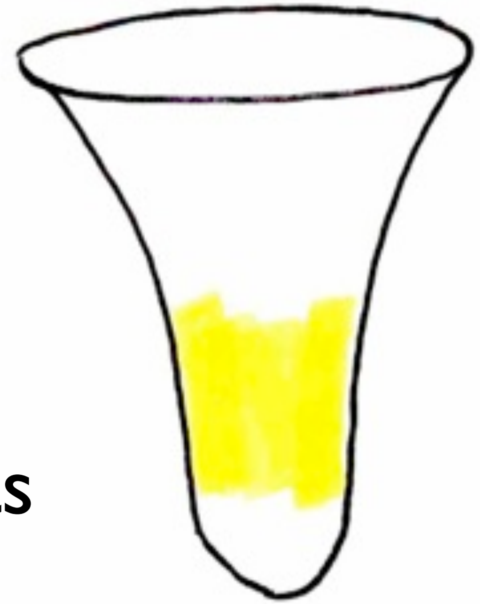


$$\Psi(b,\chi) \equiv \int \delta a \delta\phi \exp(-I[a,\phi]/\hbar)$$

.

The integral is over regular (a, ϕ) which match the (b, χ) on the boundary.

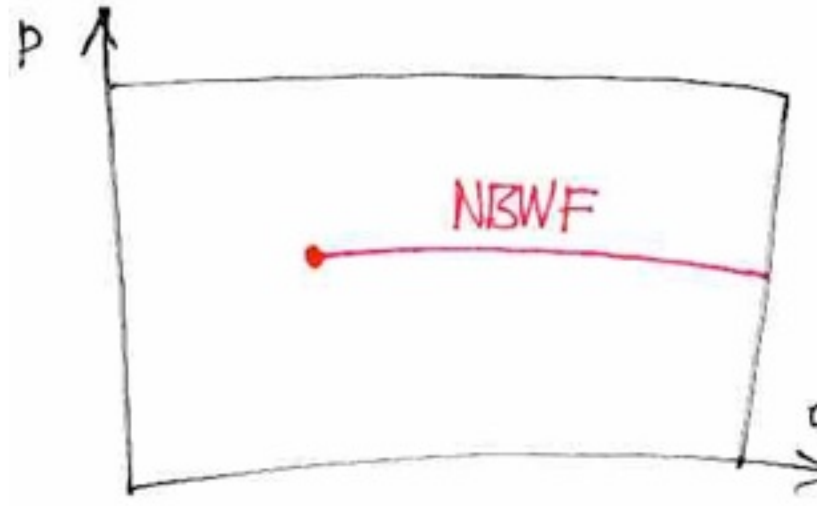
Classical Spacetime



The NBWF in the semiclassical approximation

$$\Psi(b,\chi) \approx \exp\{[-I_R(b,\chi) + iS(b,\chi)]/\hbar\}$$

where I_R and S are the real and imaginary parts of the action at a saddle point of the NBWF defining integral.



Predicted ensemble of classical histories (WKB):

$p_A = \nabla_A S$ (integral curves of S)

$\mathrm{prob(class\ hist)} \propto \exp(-2I_R/\hbar)$

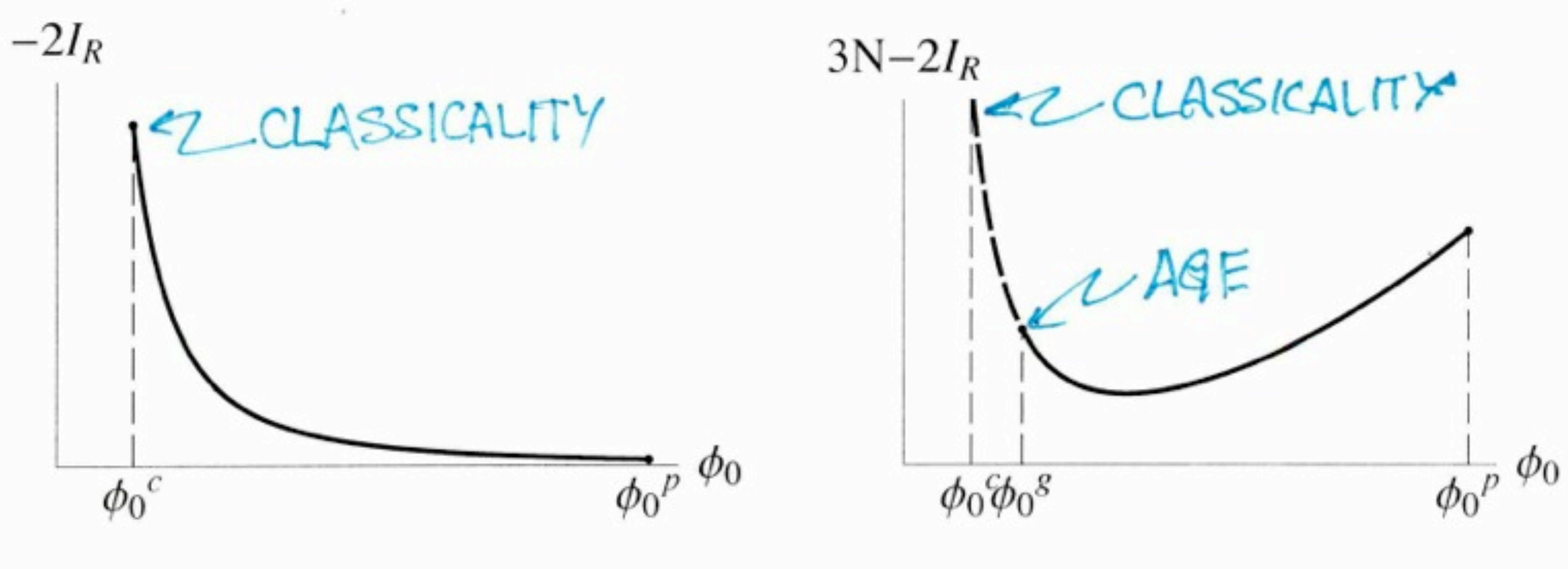
Provided! $|\nabla_A I_R| \ll |\nabla_A S|$ (classicality consdition)

Not all classical spacetimes predicted

Inflation

By itself, the NBWF + classicality favor low inflation, but we are are more likely to live in a universe that has undergone more inflation, because there are more places for us to be.

$$p(\phi_0|H_0,\rho) \propto \exp(3N)p(\phi_0) \propto \exp(3N - 2I_R)$$



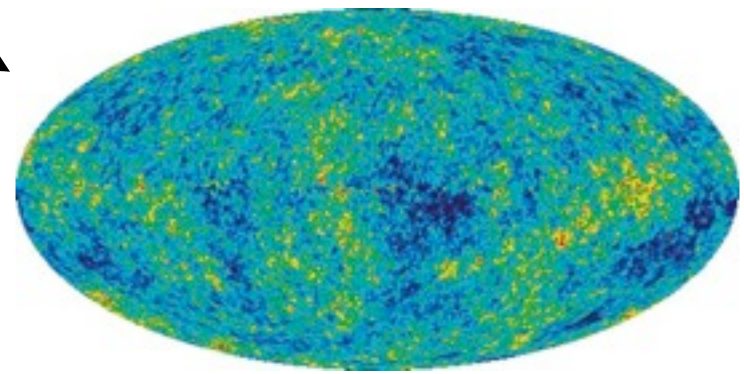
Fluctuation Probabilities

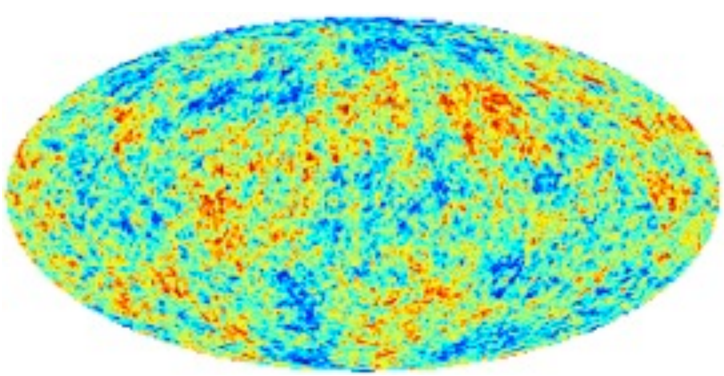
NBWF fluctuations start in their ground state. Essentially the Bunch-Davies vacuum.

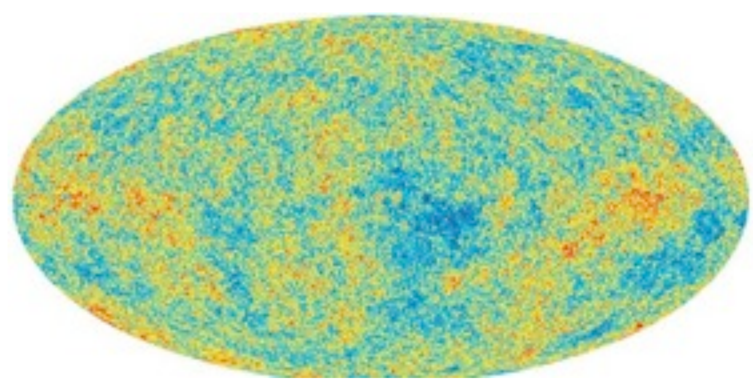
$$p(z_{(n)}|\phi_0) \approx \sqrt{\frac{\epsilon_* n^3}{2\pi H_*^2}} \exp\left[-\frac{\epsilon_*}{2H_*^2} n^3 z_{(n)}^2\right]$$

where ϵ_* and H_* are the slow roll and expansion parameters when the mode leaves the horizon.

The NBWF predicts probabilities for different CMB maps.







Arrows of Time

Our universe exhibits a number of arrows of time:

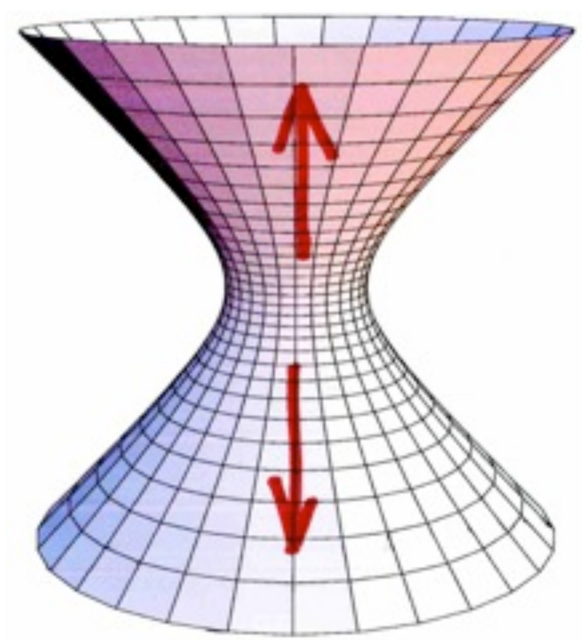
- Fluctuation Arrow ---- growth of fluctuations
- Thermodynamic arrow --- growth of entropy
- Radiation arrow --- retardation of E&M radiation
- Psychological arrow --- past, present, and future

These arrows can be explained by a special quantum state like the no-boundary wave function even when the dynamical laws (like GR+QM) are time reversal invariant.

NBWF Arrows of Time

Hawking, Page, Laflamme, Lyons, Hertog, a.o.

- NBWF fluctuations vanish at only one place on the fuzzy instanton --- the South Pole.
- This means that fluctuations are small at only one of the places where the universe is small.
- For example, for bouncing universe fluctuations increase away from the bounce on both sides.
- Time's arrow points in opposite directions on the opposite sides of the bounce.



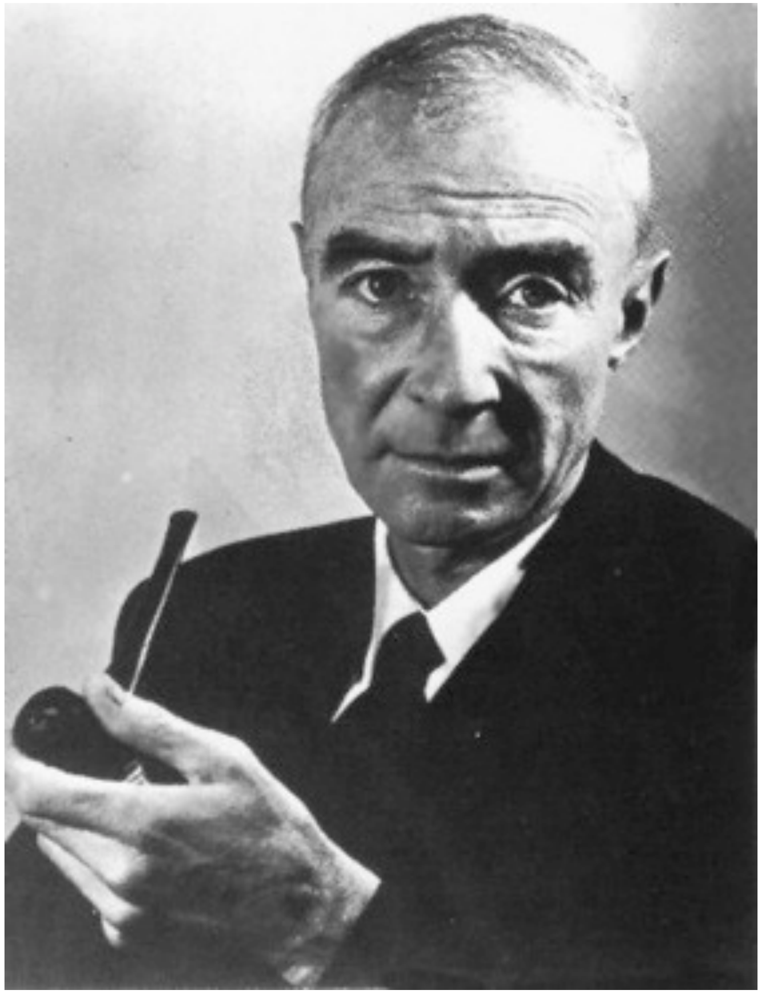
Ψ

- classical spacetime -- Yes
- early homo/iso w. inflation -- Yes
- fluctuations start in ground state -- Yes
- arrows of time --Yes
- CMB, large scale structure -- Yes
- isolated systems, separation of Planck scale -- Yes
- topology of spacetime
- num. of large and small dimensions
- number of time dimensions
- coupling consts. of effective theories

The Universe of GR in 1956

Einstein's obituary

``In the forty years that have elapsed [since the classic initial tests] these have remained the principal, and, with one exception the only connection between the general theory and experience."

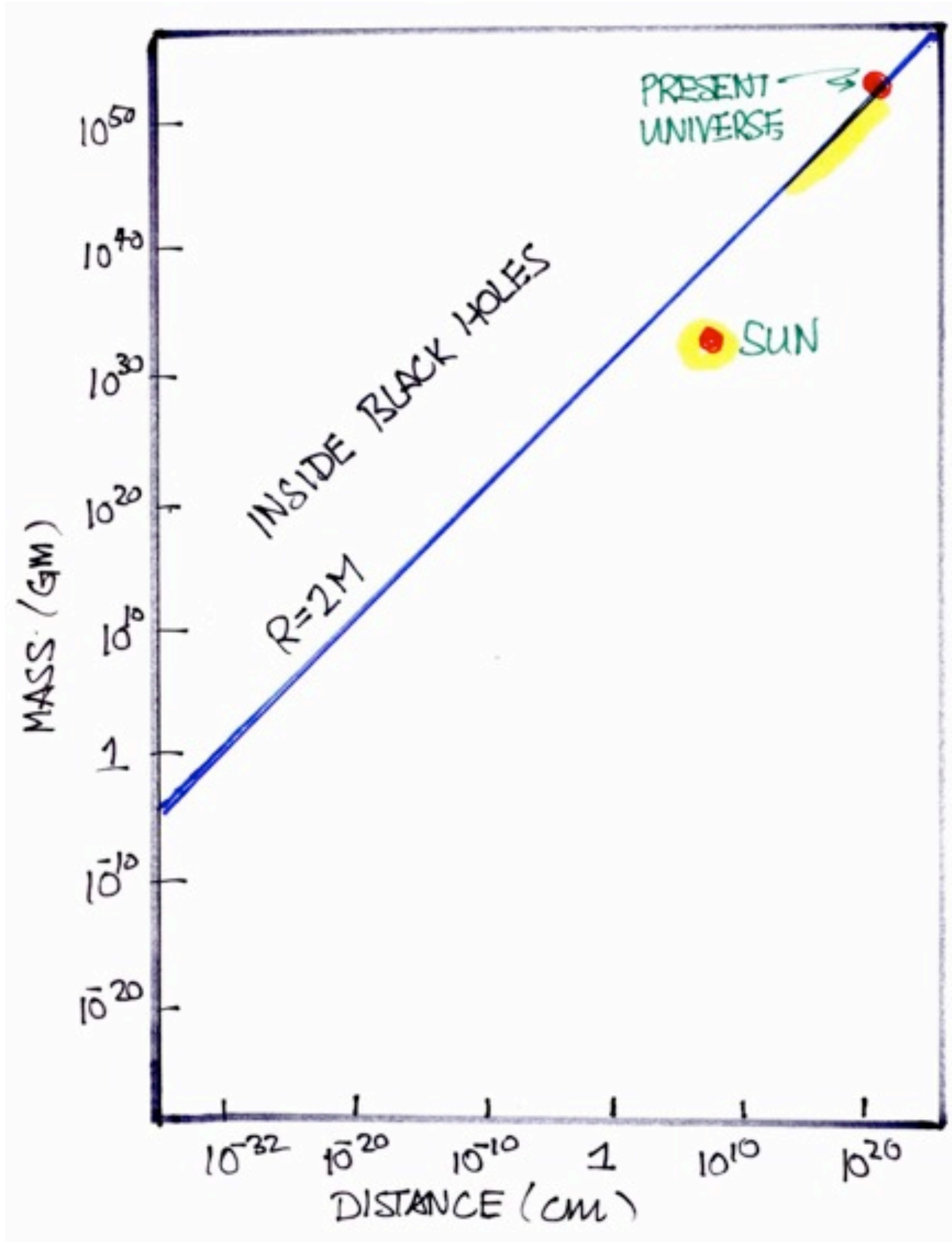


Robert Oppenheimer

The Universe of GR in 1956

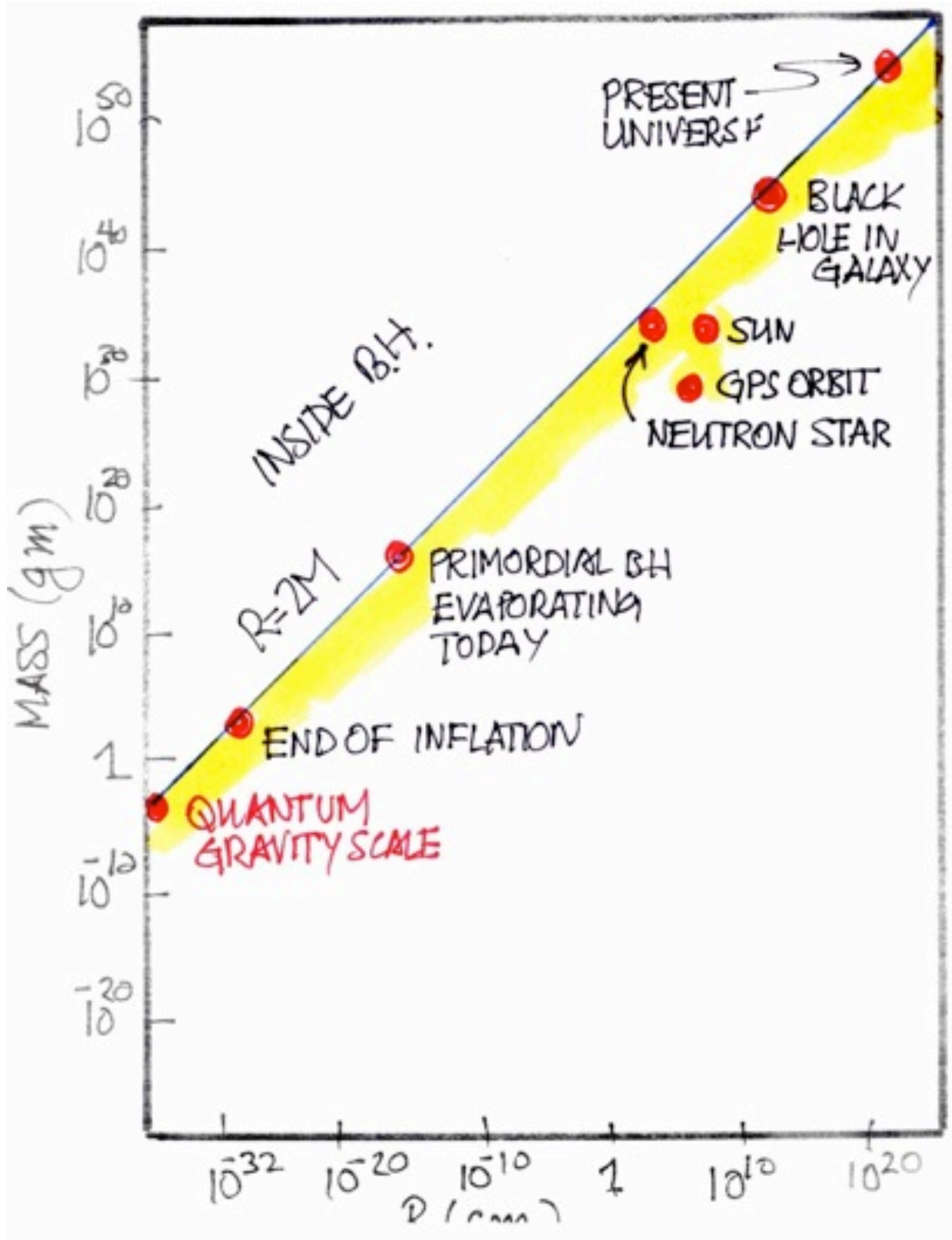
GR is important when:

$$\frac{GM}{Rc^2} \sim 1$$

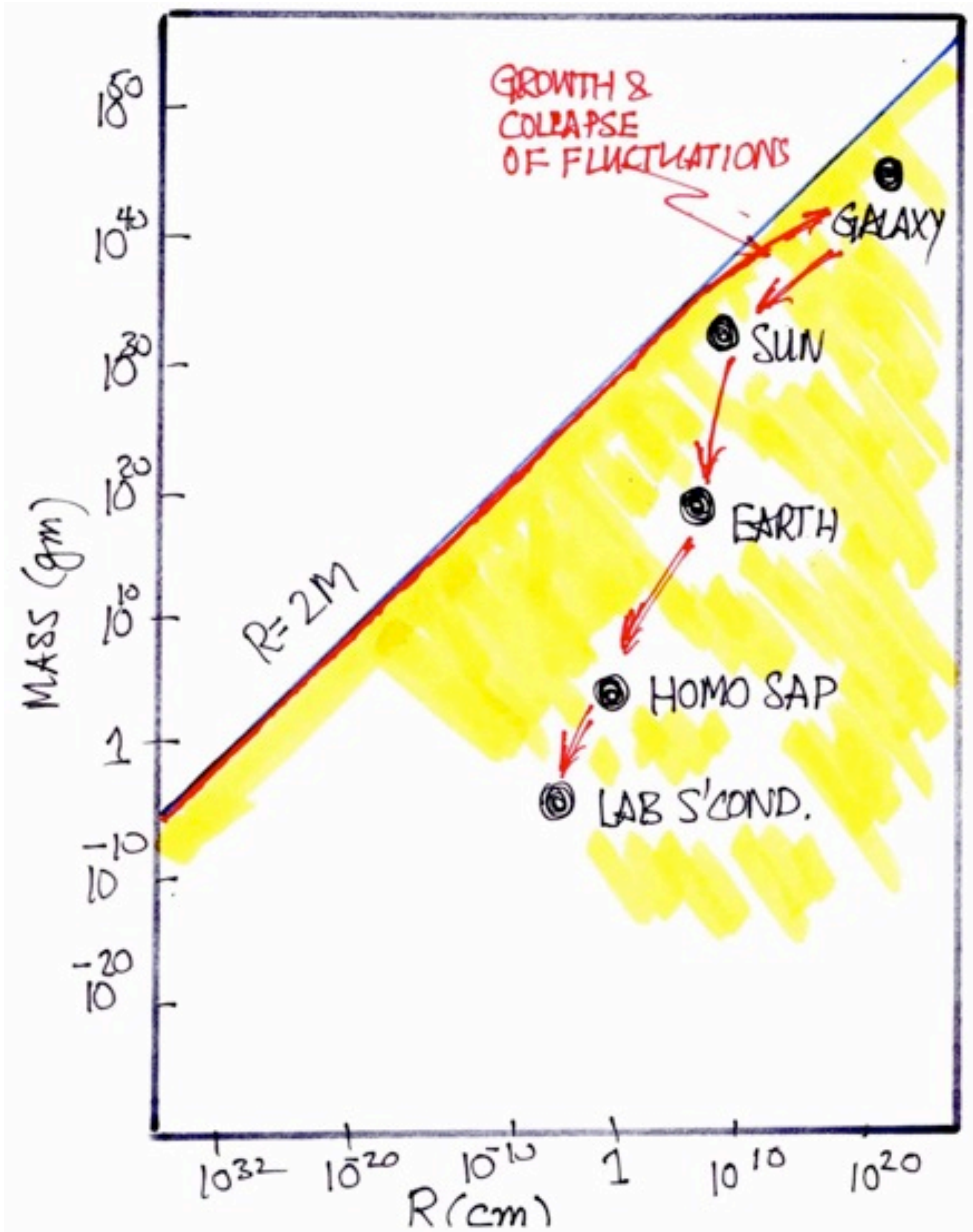


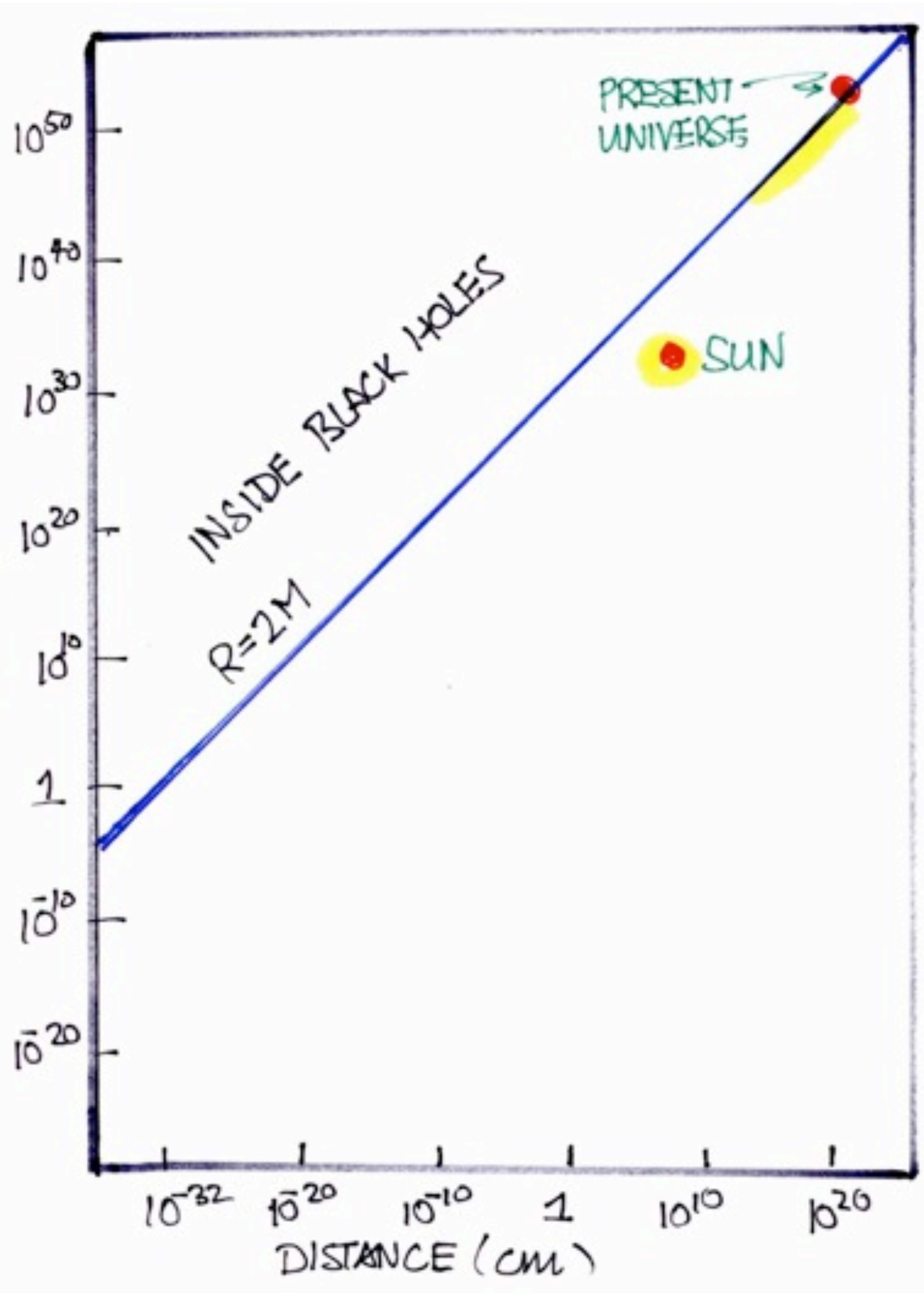
The Universe of GR Today

$$\frac{GM}{Rc^2} \sim 1$$

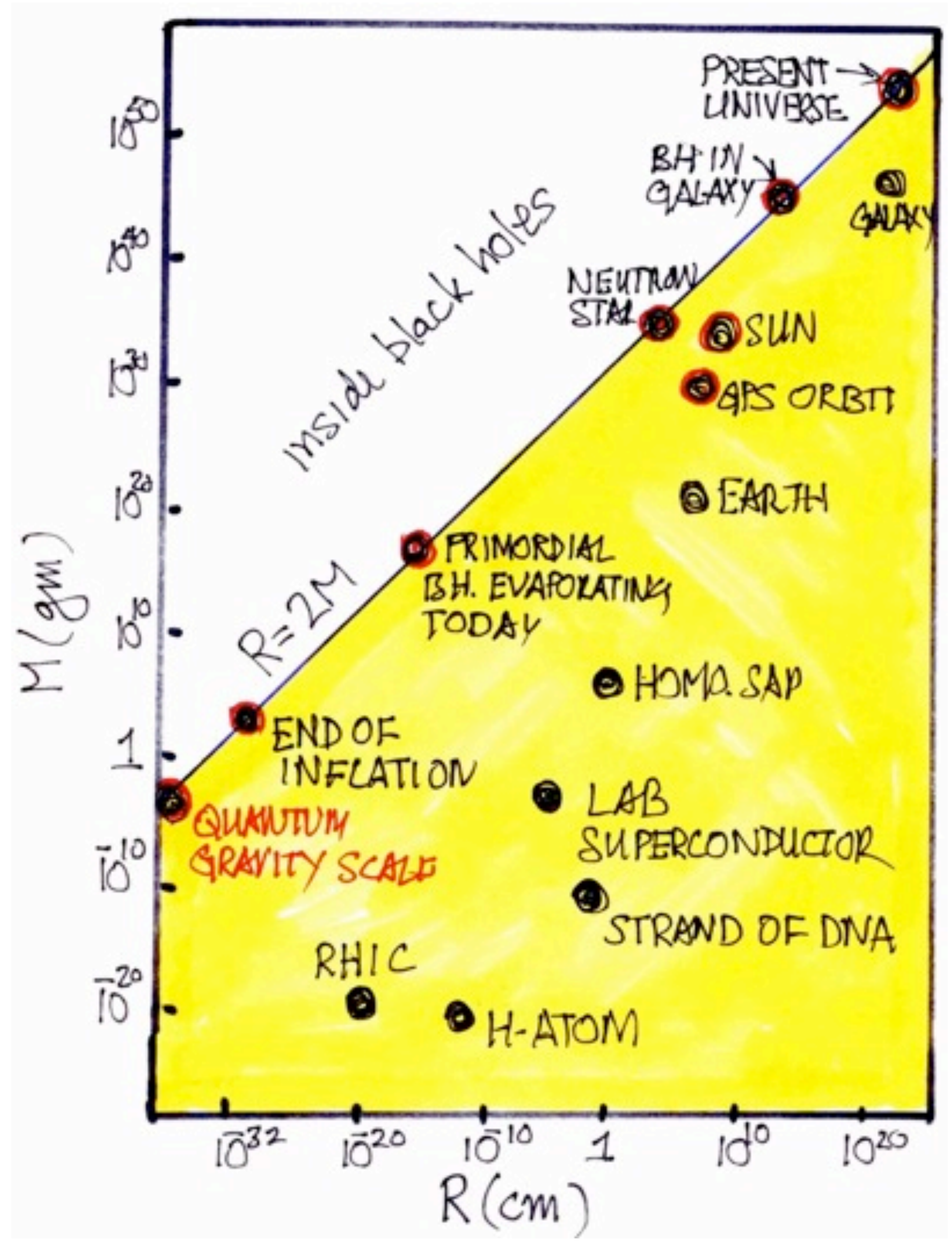


GR is the key to the quasiclassical realm and central to the origins and properties of today's isolated subsystems.





1956



The Future?

A century after is inception
Einstein’s general relativity
is central to physics
at the frontier of the largest scales
and also at the frontier of the
smallest.

A. Einstein, 1915

A theory is more impressive the greater the simplicity of its premises, the wider the diversity of things it predicts, and the more extended the area of its applicability.