KEY FACTS ABOUT GRAVITY

- THE **WEAKEST** OF THE FOUR BASIC FORCES

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

- **UNIVERSAL** – COUPLES TO **ALL** MASS ENERGY.

- **LONG-RANGE** $F = \frac{Gm_1 m_2}{r^2}$

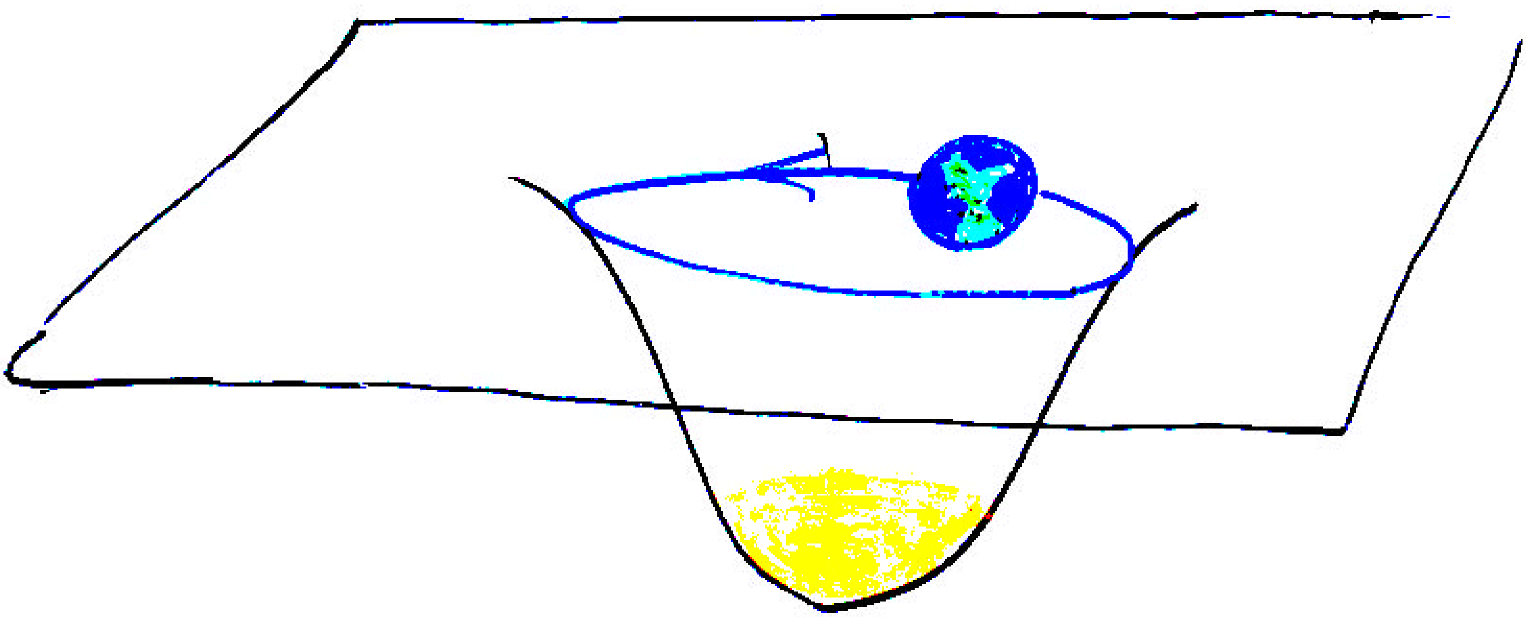
- **UNSCREENED** — NO NEGATIVE GRAVITATIONAL "CHARGE".

⇒ **GRAVITY GOVERNS THE STRUCTURE OF MATTER ON THE LARGEST SCALES.**

RELATIVISTIC GRAVITY

EINSTEIN'S GENERAL RELATIVITY

- GRAVITY IS GEOMETRY.
- MASS CURVES SPACETIME
- FREE MASS MOVES ON THE STRAIGHTEST PATHS IN CURVED SPACETIME.

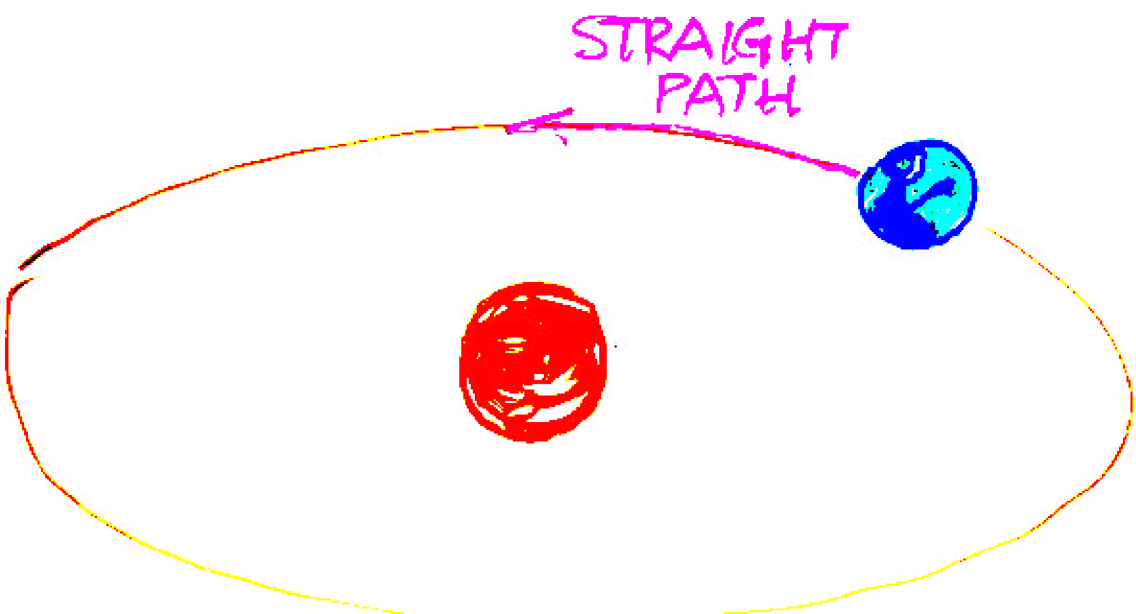


Newtonian Gravity (1687)

THE EARTH TRAVELS AROUND THE SUN BECAUSE IT IS PULLED BY THE GRAVITATIONAL FORCE EXERTED BY THE MASS OF THE SUN.

Einstein Gravity (General Relativity, 1915)

THE EARTH
TRAVELS
AROUND THE
SUN
BECAUSE
ITS FOLLOWING
THE STRAIGHTEST PATH
IN THE CURVED SPACETIME
PRODUCED BY THE SUN'S MASS



FRONTIER OF THE SMALLEST SCALES

PLANCK SCALE

$$\ell = \left(\frac{G\hbar}{c^3}\right)^{1/2} \sim 10^{-33}\, cm$$

PLANCK ENERGY

$$E_p = \frac{\hbar c}{\ell} = \left(\frac{\hbar c^5}{G}\right)^{1/2} \sim 10^{19}\, GeV$$

THIS IS THE SCALE CHARACTERIZING:

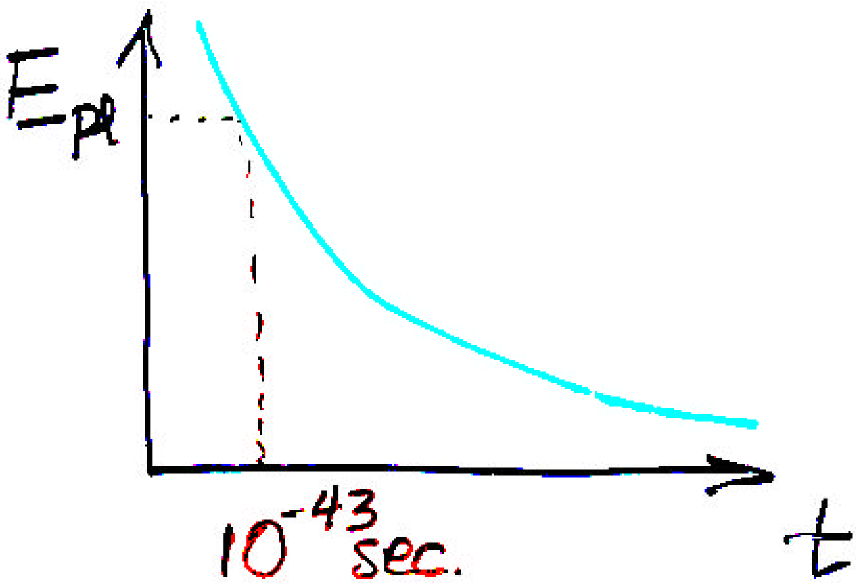
- UNIFIED THEORIES OF THE FOUR BASIC FORCES
  (e.g. STRING THEORY)

- THE UNION OF GRAVITY AND QUANTUM MECHANICS
  (e.g. QUATUM THEORY OF GEOMETRY)

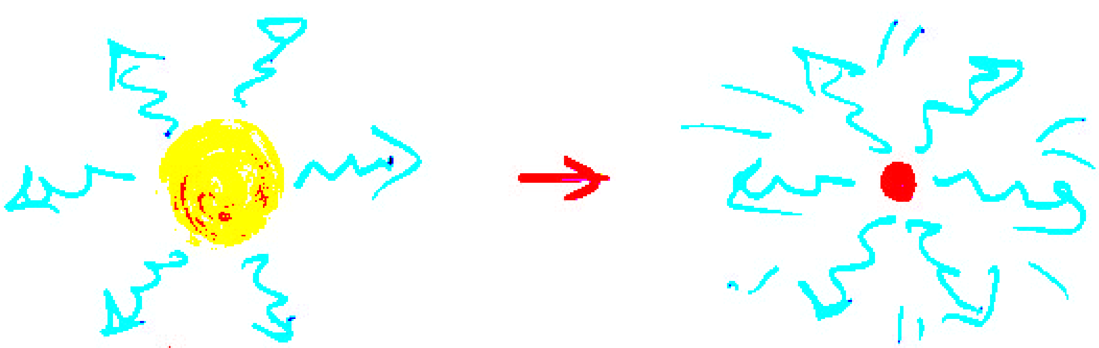
WHERE IN THE UNIVERSE ARE THE HIGHEST ENERGIES REALIZED?

$$E_{pl} = \left(\frac{\hbar c^5}{G}\right)^{1/2} \sim 10^{19}\,\mathrm{GEV}.$$

- THE BIG BANG:



- EXPLODING BLACK HOLES.



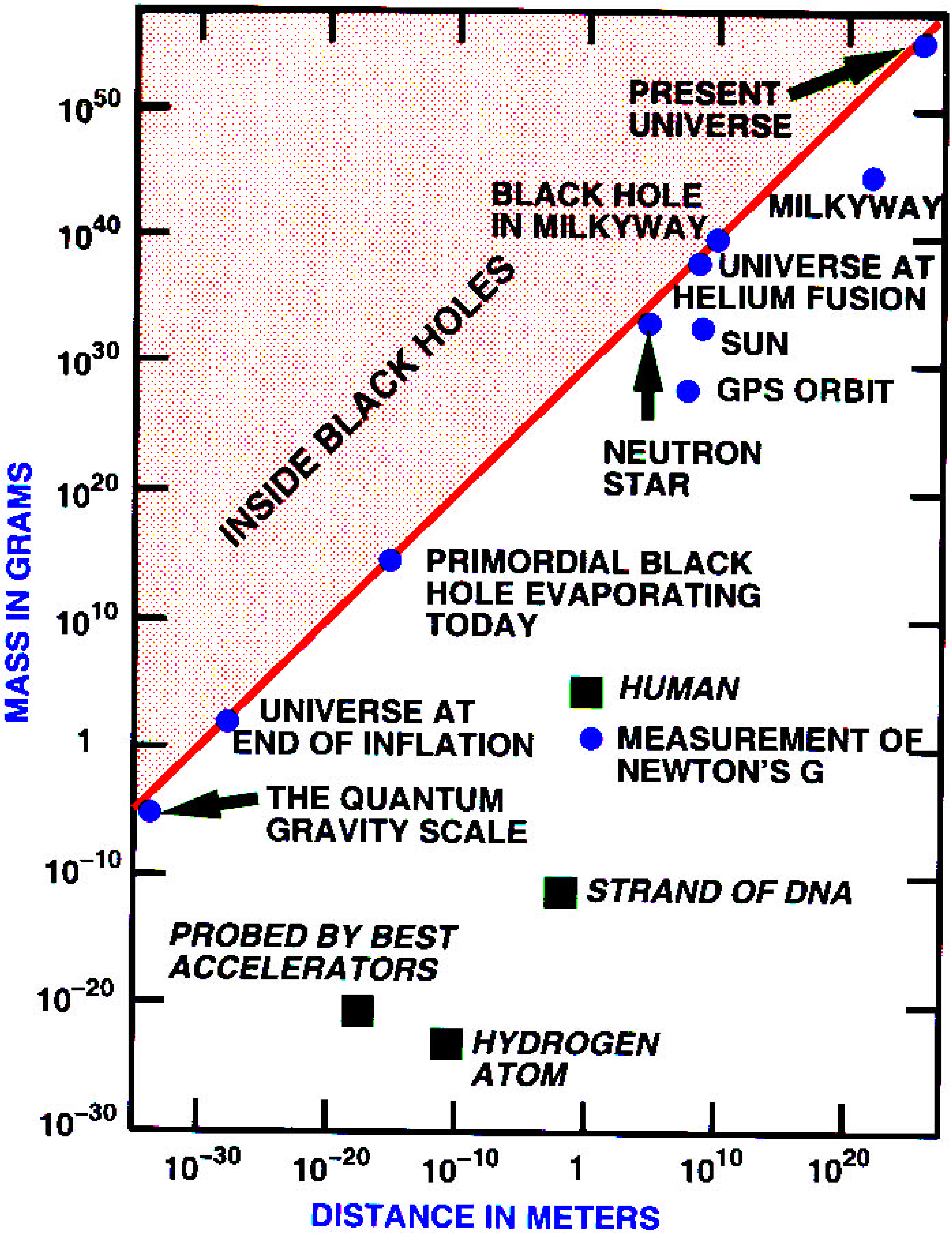
HAWKING EFFECT.

WHEN IS RELATIVISTIC GRAVITY IMPORTANT?

$$\frac{GM}{c^2R} \sim 1$$

- SUN $GM/Rc^2 \sim 10^{-6}$
- NEUTRON STAR $GM/Rc^2 \sim .1$
- BLACK HOLE $GM/Rc^2 = \frac{1}{2}$ (MAXIMUM VALUE)
- UNIVERSE $GM/Rc^2 \sim \frac{1}{2}$

Gravitational Physics: From Quantum to Cosmos

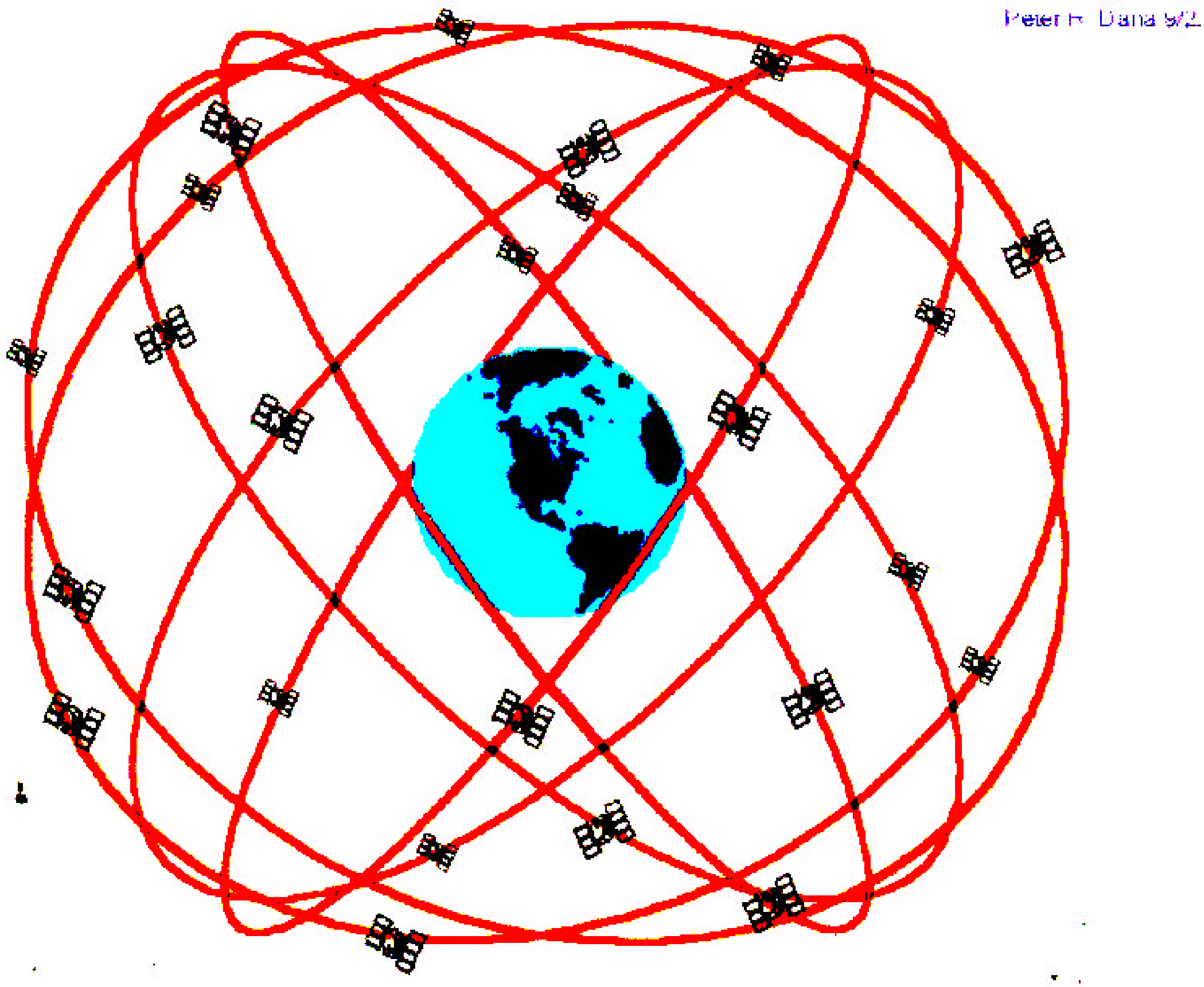


- THE LARGE SCALES OF ASTROPHYSICS AND COSMOLOGY ARE INCREASINGLY ACESSIBLE TO OBSERVATION.
- THE SMALLEST SCALES ARE INCREASINGLY ACESSIBLE TO THEORETICAL SPECULATION.

RESULT:

GENERAL RELATIVITY IS INCREASINGLY INTEGRATED WITH NEIGHBORING AREAS.

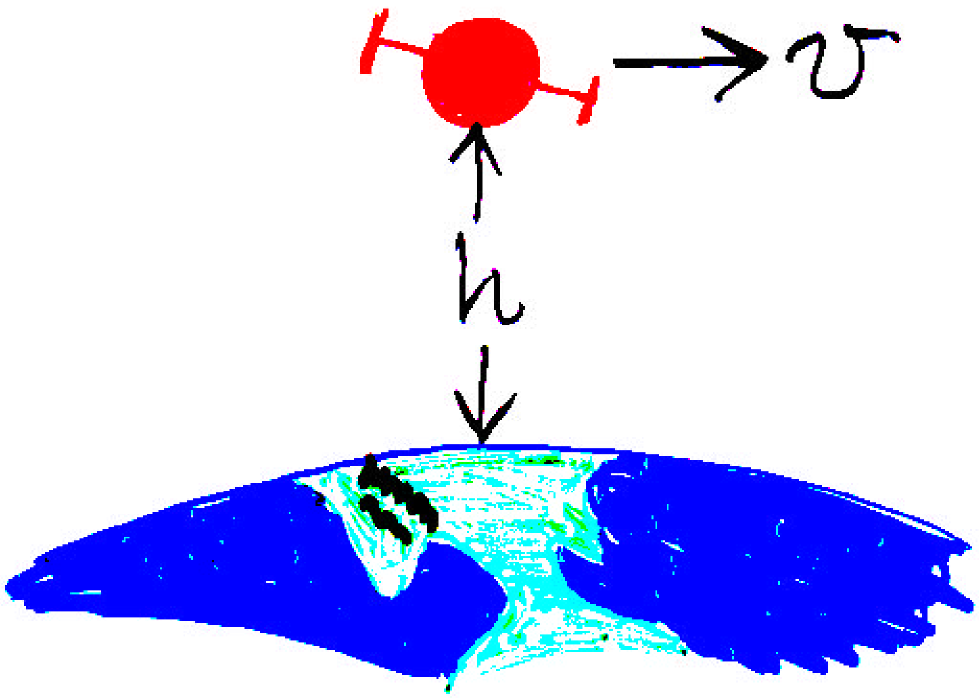
GENERAL RELATIVITY IS INCREASINGLY IN CONTACT WITH EXPERIMENT & OBSERVATION.



GPS Nominal Constellation
24 Satellites in 6 Orbital Planes
4 Satellites in each Plane
20,200 km Altitudes, 55 Degree Inclination


GPS

RELATIVISTIC EFFECTS IN GPS



- SPECIAL RELATIVITY

  MOVING CLOCKS RUN SLOW

  $$\sqrt{1-v^2/c^2} \rightarrow 1 - .8\times10^{-10}$$

- GENERAL RELATIVITY

  CLOCKS HIGHER IN A GRAVITATIONAL POTENTIAL RUN FAST.

  $$1+\frac{gh}{c^2} \rightarrow 1 + 5.2\times10^{-10}$$

CLASSICAL SOLAR SYSTEM TESTS

- GRAVITATIONAL REDSHIFT.
- BENDING AND TIME DELAY OF LIGHT.
- PRECESSION OF PERIHELION.

SMALL EFFECT
DIFFICULT TO DETECT

↓

PRECISION MEASUREMENT $\lesssim 1\%$

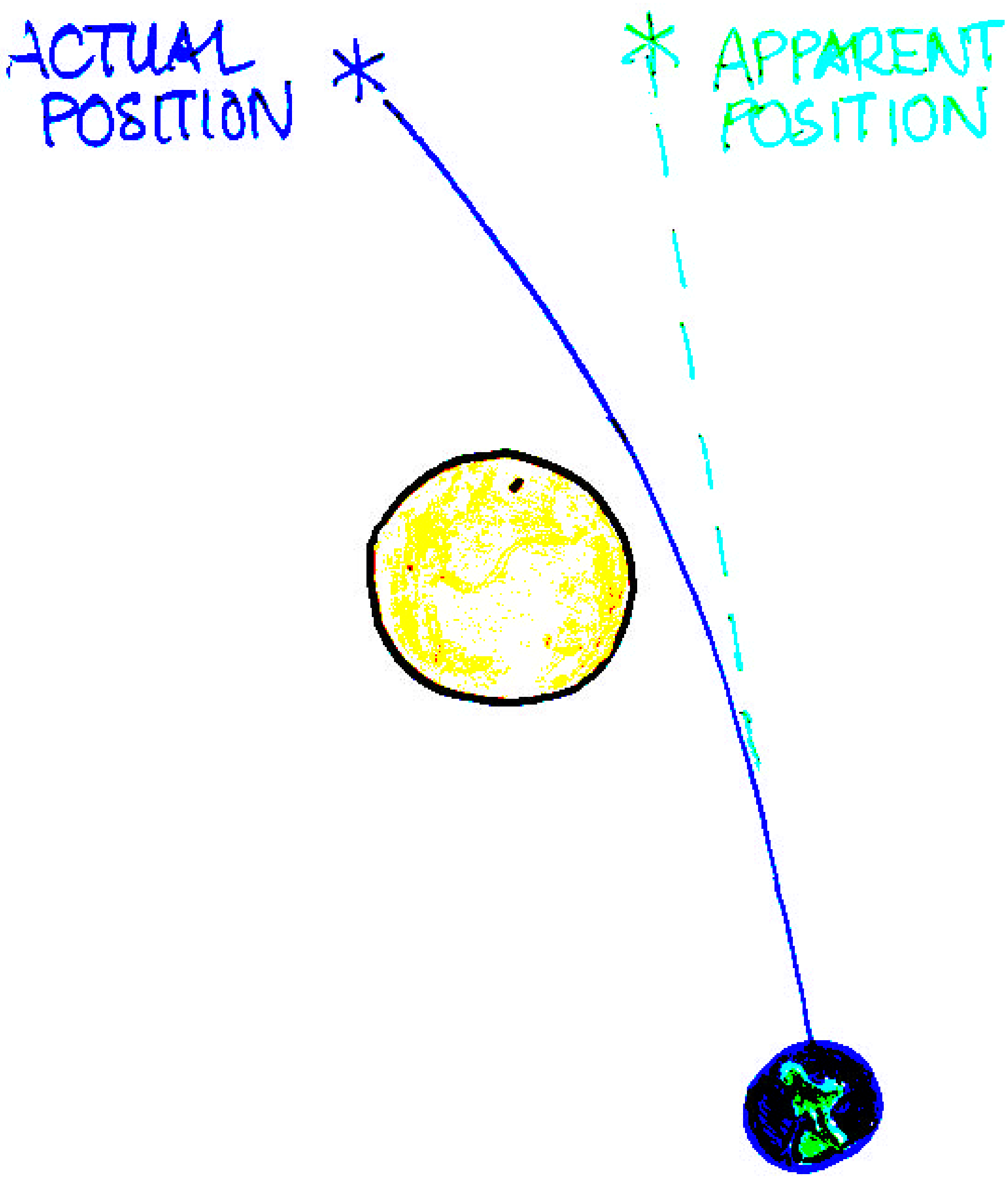
↓

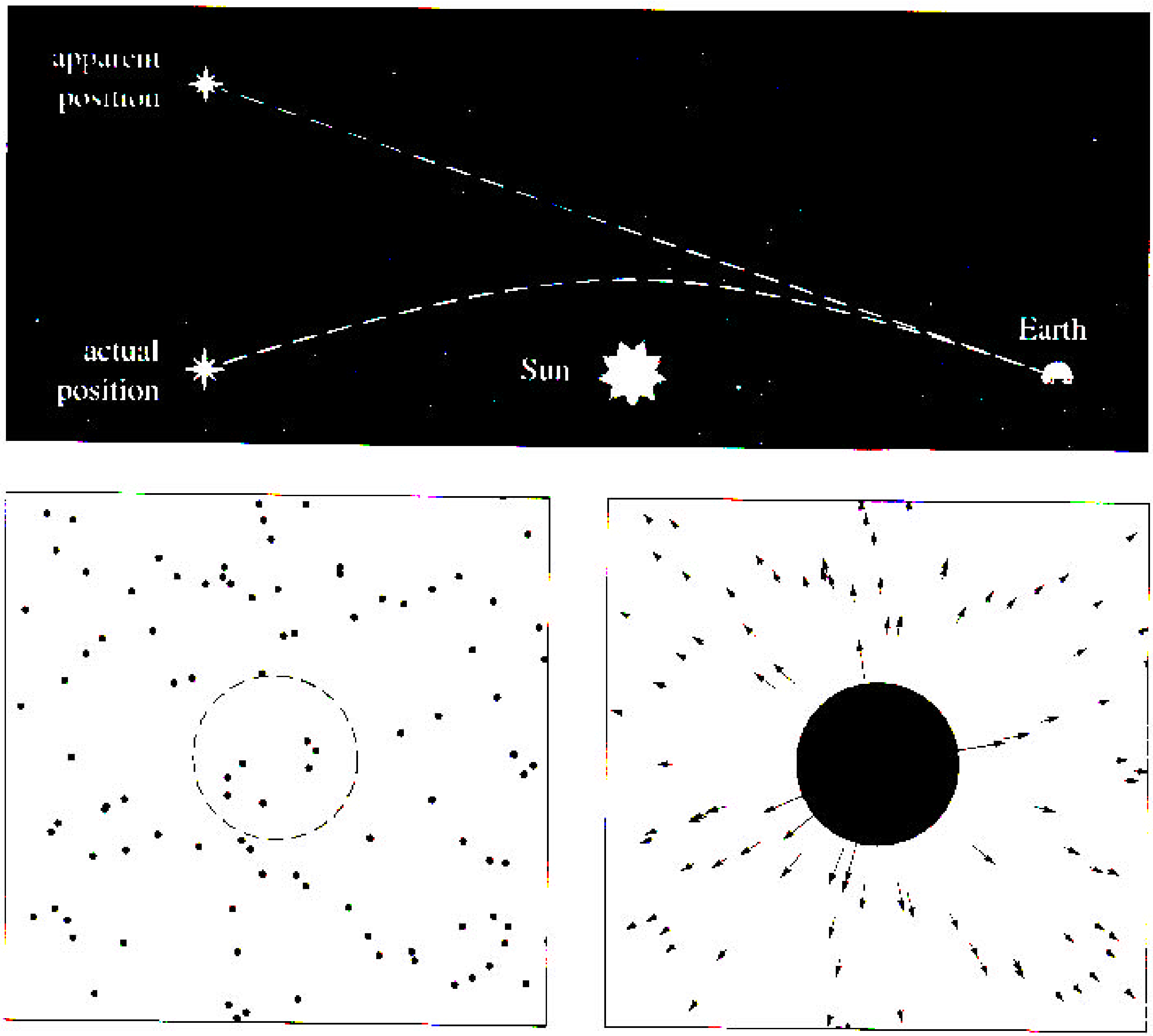
ANNOYING CORRECTION
IN OTHER PRECISION MEASUREMENTS

↓

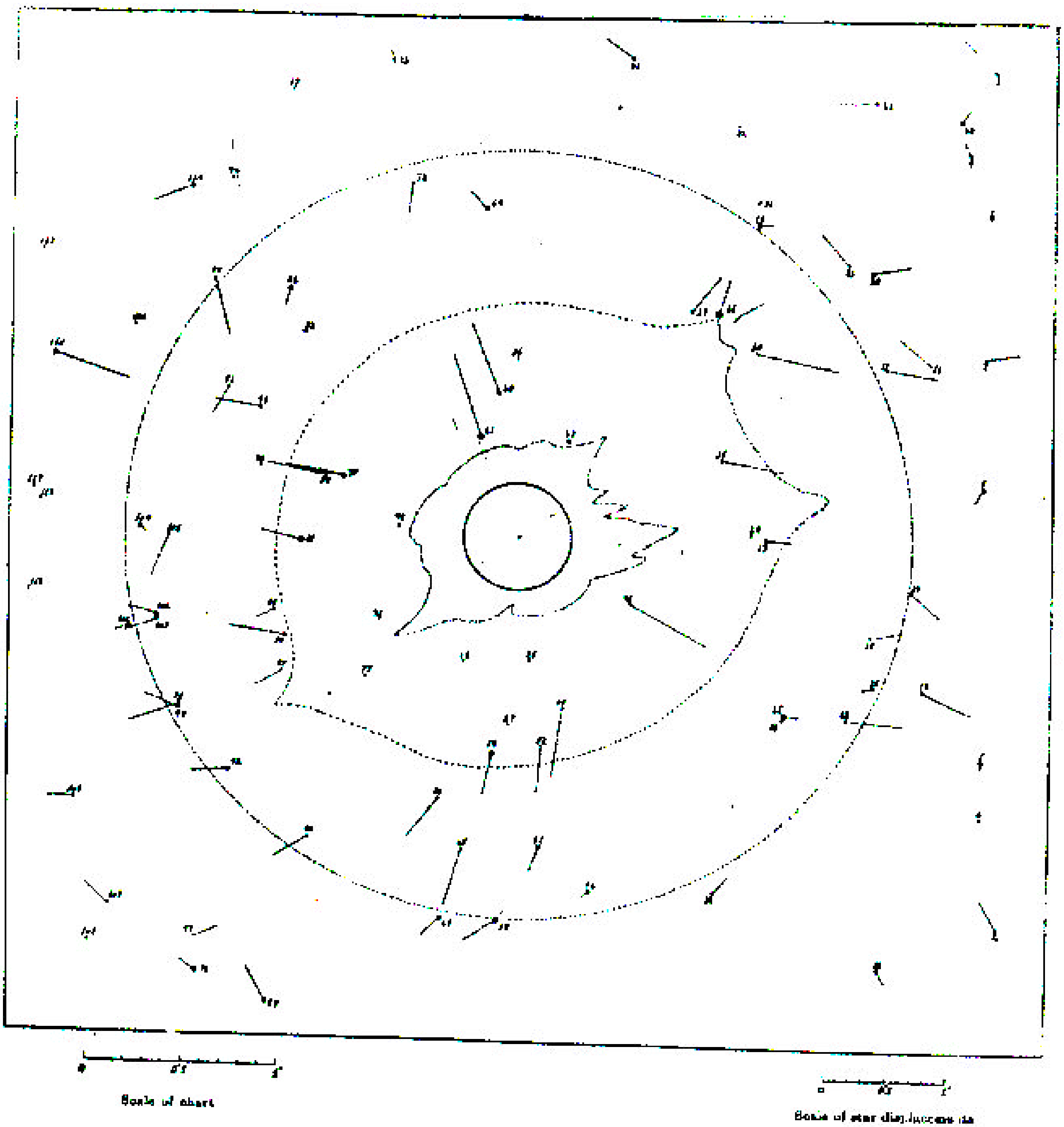
NEW TOOL

BENDING OF LIGHT BY THE SUN




apparent
position
actual
position
Sun
Earth

Solar Eclipse 1922

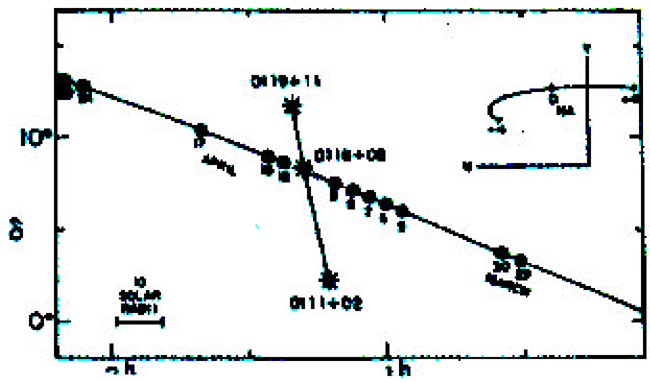


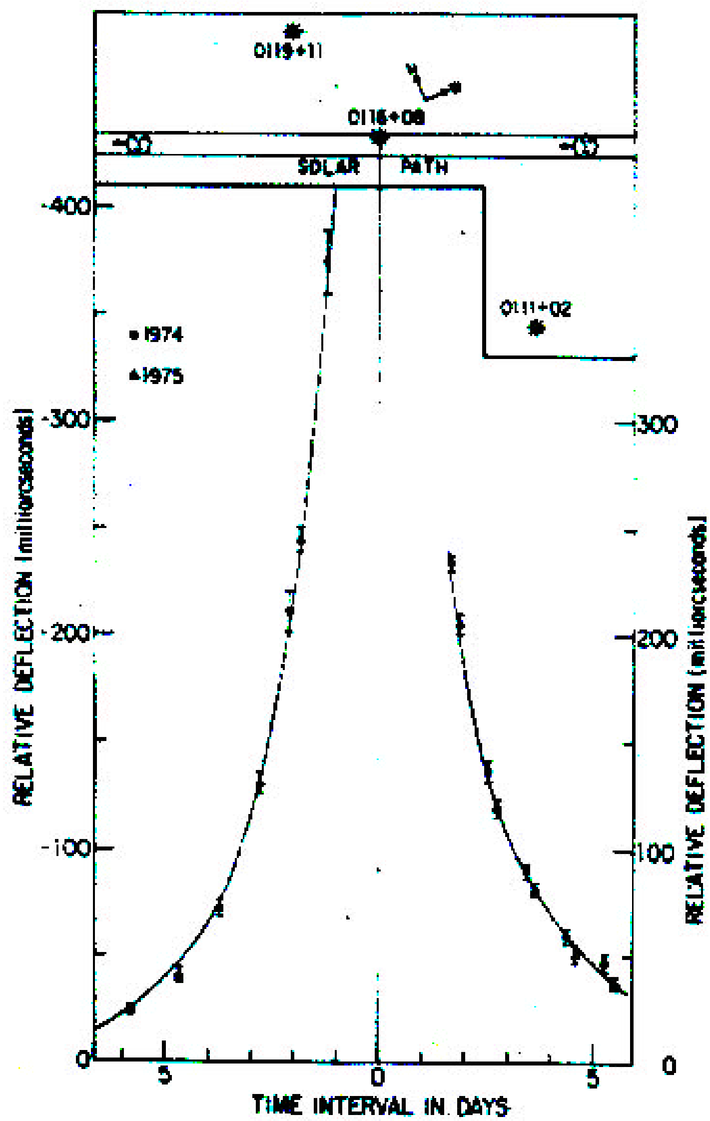
Campbell & Trumpler

$\gamma = 1.007 \pm .009$

1975

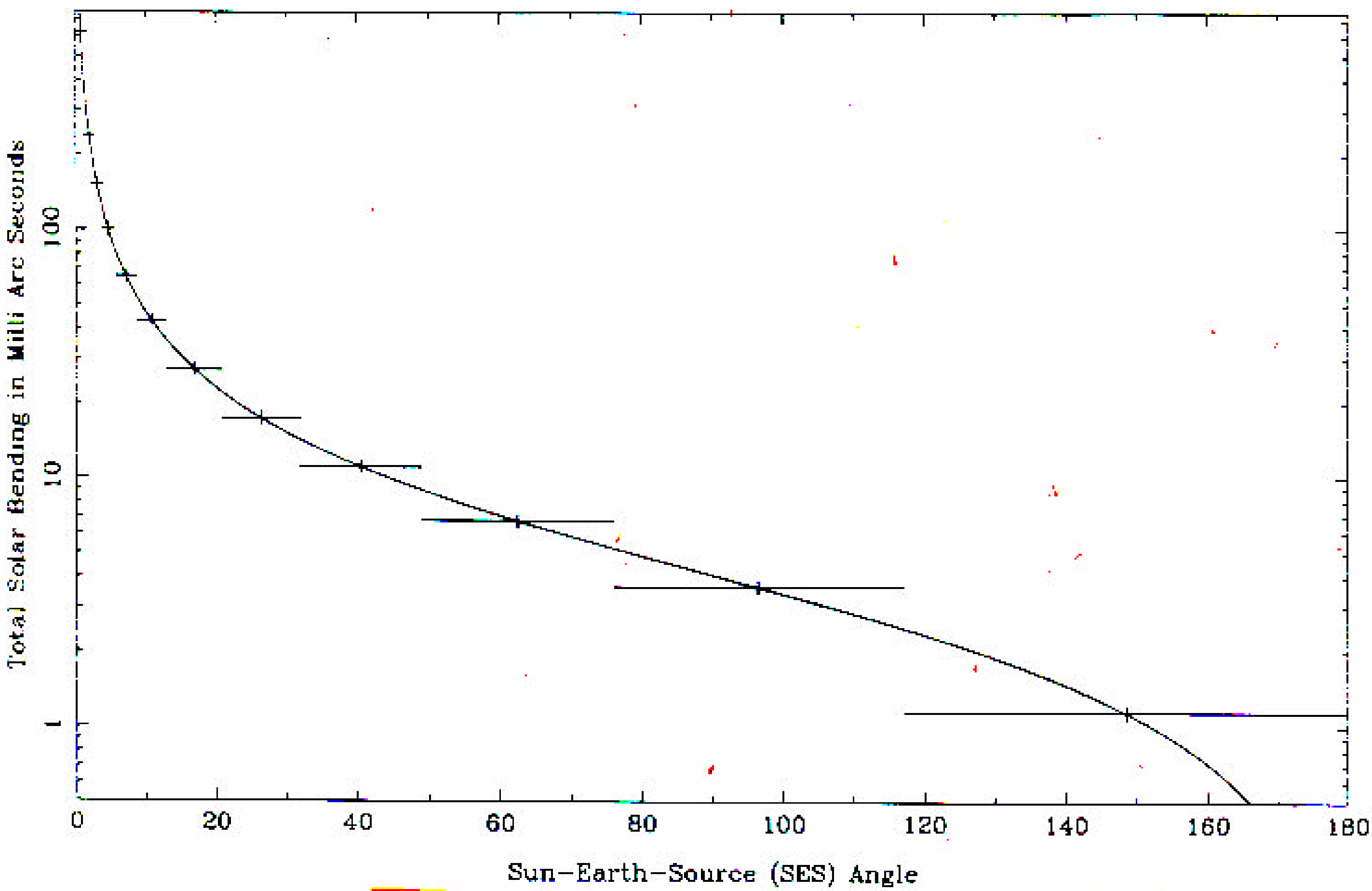
LBI Bending of Light by the Sun





Fomalont & Sramek

VLBI Measurements of Bending of Light

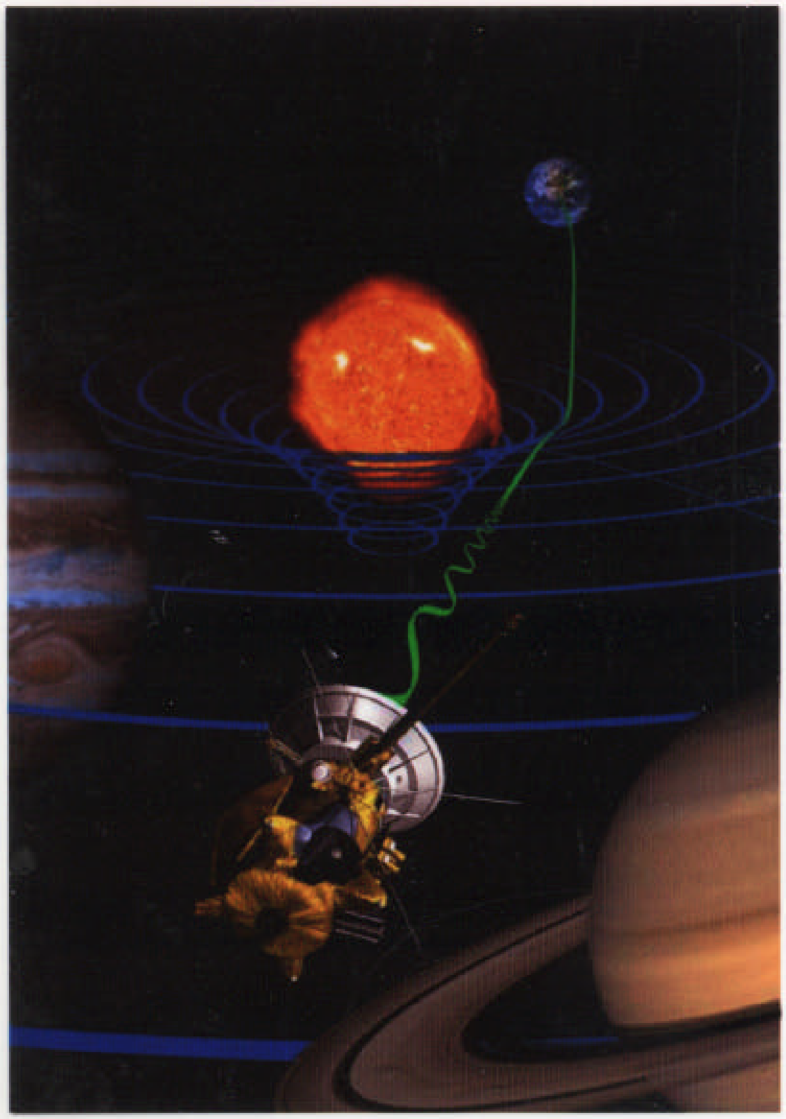


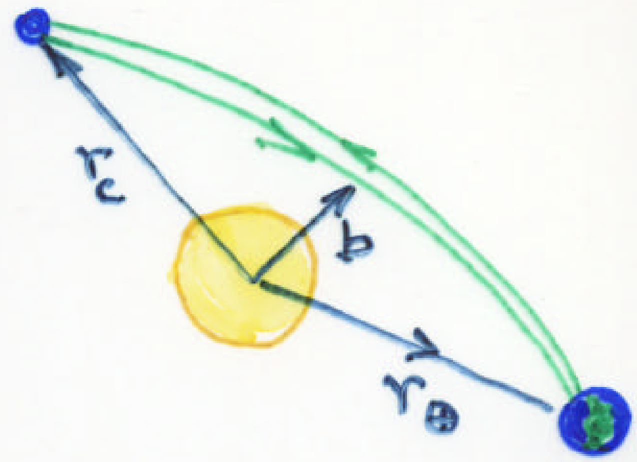
$\gamma = 0.99983 \pm .00045$

S. Shapiro, et. al (2004)

M. Eubanks, et. al. (unpub)

CASSINI DETERMINATION OF γ





MEASURE FREQUENCY SHIFT OF TWO-WAY RADIO SIGNAL

$$y \equiv \frac{\nu_{REC'D} - \nu_{TRANS}}{\nu_{TRANS}}$$

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

THREE DIFFERENT UP-DOWNLINK PAIRS (XX, KK, XK) ALLOW FOR CORRECTION BY SOLAR CORONA

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

HEWLETT PACKARD HEWLETT PACKARD HEWLETT PACKARD HEWLETT PACKARD

COLEY, TYSON, & TURNER (1996)

USING THE SUN AS A LENS

OBSERVATORY IN THE KUIPER BELT.

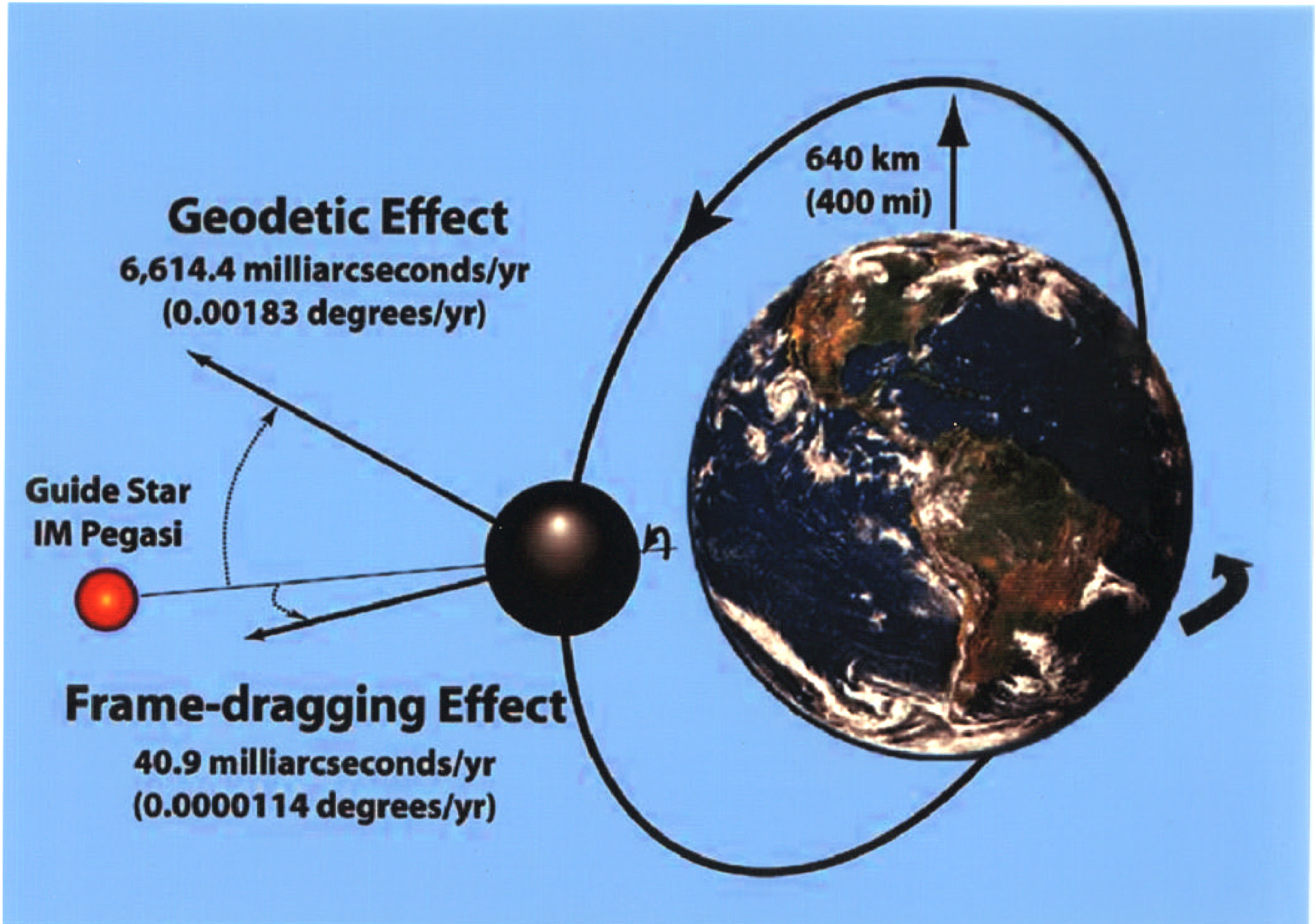
SOME NEXT STEPS IN PRECISION TESTS

- GRAVITOMAGNETIC EFFECTS ($\sim 1/c^3$)

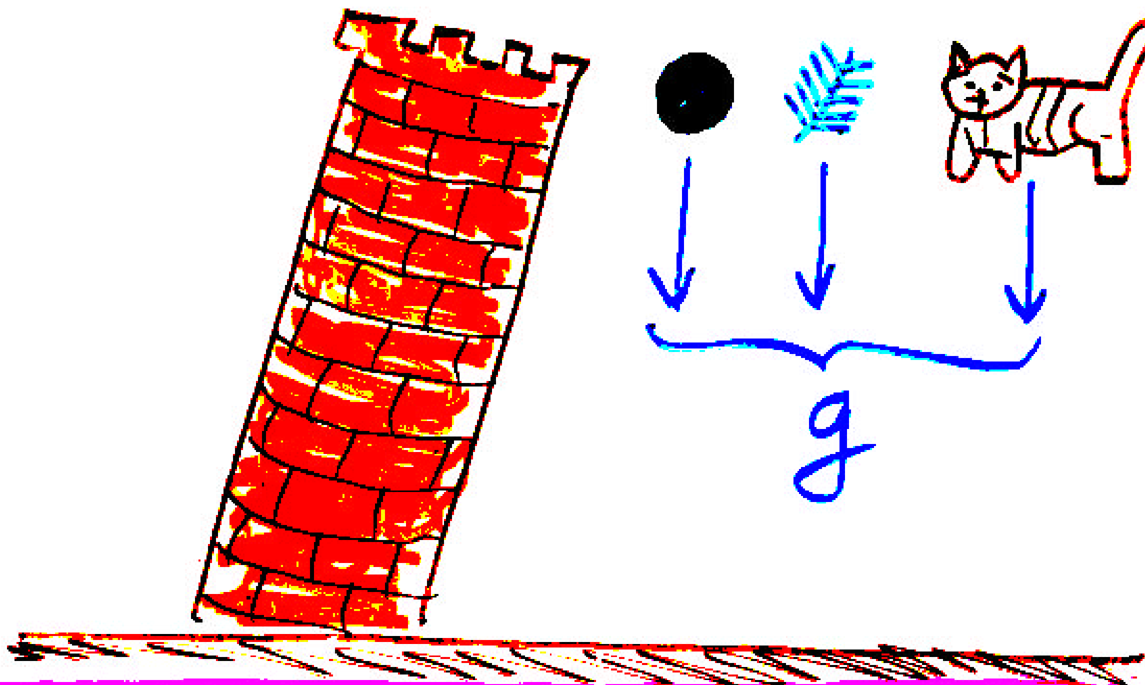
  GP-B (April **20**, 2004
  Sept 29, 2005)

- NEW TESTS OF THE PRINCIPLE OF EQUIVALENCE

  STEP (~?)


640 km
(400 mi)
Geodetic Effect
6,614.4 milliarcseconds/yr
(0.00183 degrees/yr)
Guide Star
IM Pegasi
Frame-dragging Effect
40.9 milliarcseconds/yr
(0.0000114 degrees/yr)

PRINCIPLE OF EQUIVALENCE



g's EQUAL TO 1.5×10^{-13}

- CENTRAL TO A GEOMETRIC THEORY OF GRAVITY.
- VIOLATIONS WOULD SIGNAL
  - BREAKDOWN OF OUR NOTIONS OF SPACETIME
  - NEW FORCES

Lunar Laser Ranging

POSITION OF THE MOON TO ~few cm.

Los Angeles Times

CO[redacted] PAGES

SPACE & TIME DOOMED?
WITTEN

COLUMN ONE

Time, Space Obsolete in New View of Universe

■ Many physicists are embracing a revolutionary, still mysterious idea called string theory. The concept rejects several familiar notions and includes the existence of 11 dimensions.

Now, some physicists are taking this revolutionary line of thinking one step further: If their theories are right, in the words of Edward Witten of the Institute for Ad-

OF SPACE, TIME AND STRINGS

Rocking the foundations of physics

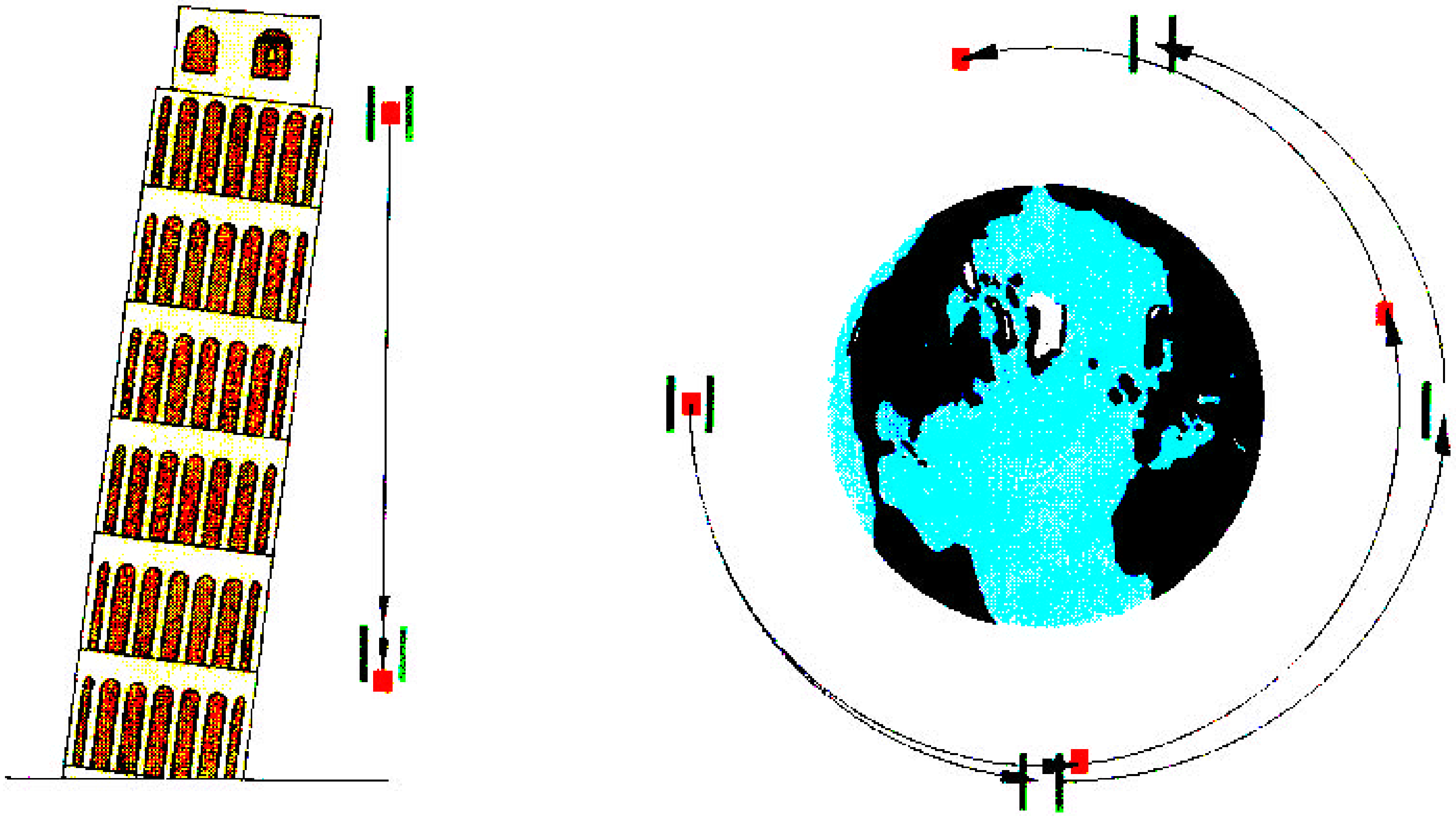
■ First in a series

vanced Study in Princeton, space and time may be "doomed."

Concurs physicist Nathan Seiberg, also of the institute: "I am almost certain that space and time are illusions. These are primitive notions that will be replaced by something more sophisticated."

SPACE & TIME ARE ILLUSIONS!
SEIBERG

THEORY: Bizarre Concept Could Explain Universe



$\Delta g/g \sim 10^{-18}$

MAJOR THEME

OF THE THIS DECADE:

THE EXPLORATION OF

STRONG

GRAVITATIONAL FIELDS

STRONG GRAVITY

- GRAVITATIONAL WAVES
- BLACK HOLES
- COSMOLOGY

GRAVITATIONAL WAVES

EINSTEIN'S THEORY PREDICTS

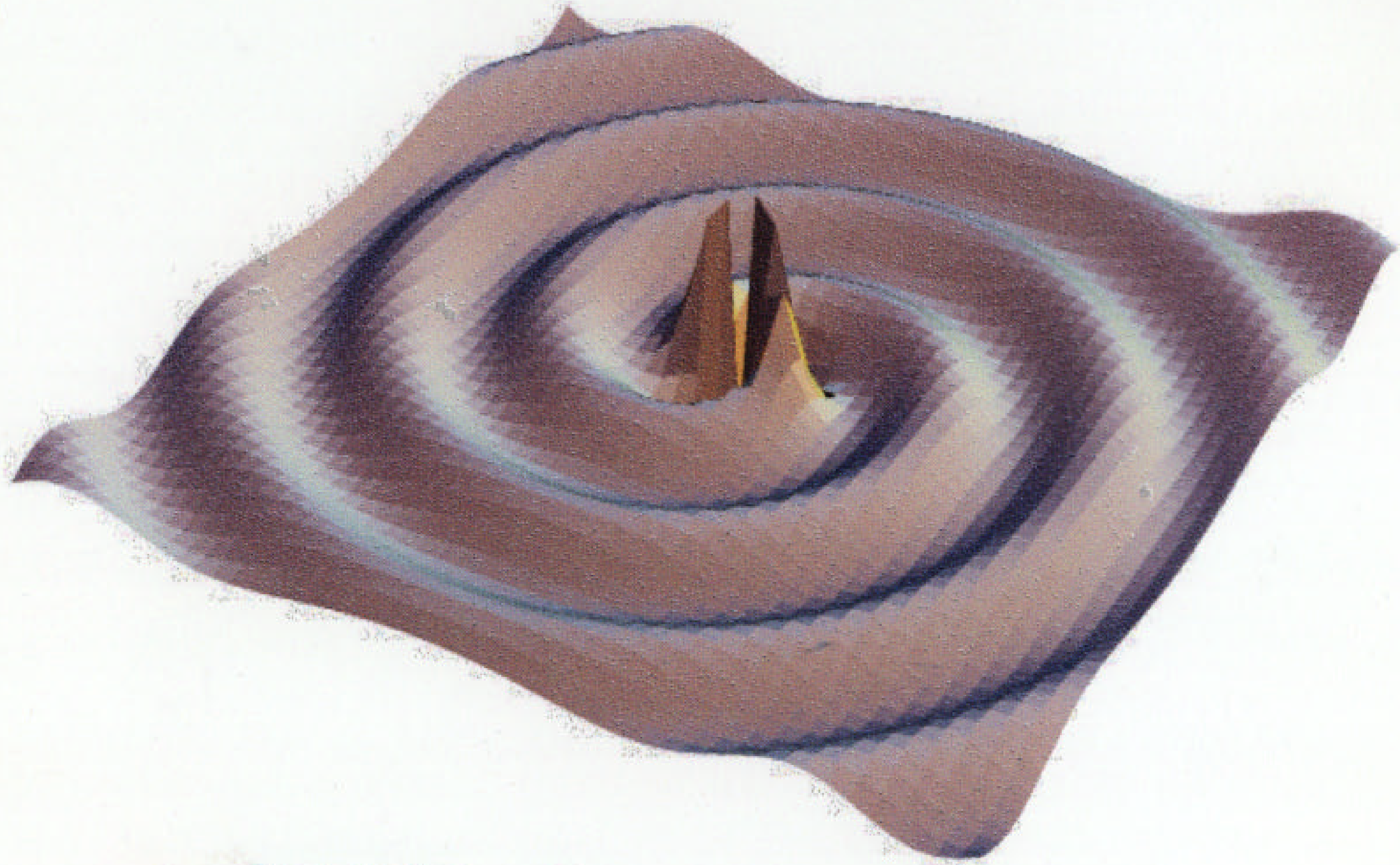
PROPAGATING RIPPLES

IN

SPACETIME CURVATURE.

GRAVITATIONAL WAVES

PROPAGATING RIPPLES IN CURVATURE



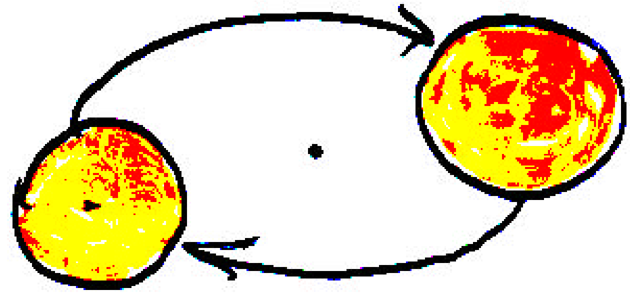
- SPEED C
- TWO POLARIZATIONS

MASS IN MOTION

THE SOURCE OF GRAVITATIONAL WAVES

- BINARY STARS

$$L^{GW} \sim L^{EM}_{\odot} \left(\frac{M}{M_{\odot}} \frac{1\,hr}{P} \right)^{10/3}$$



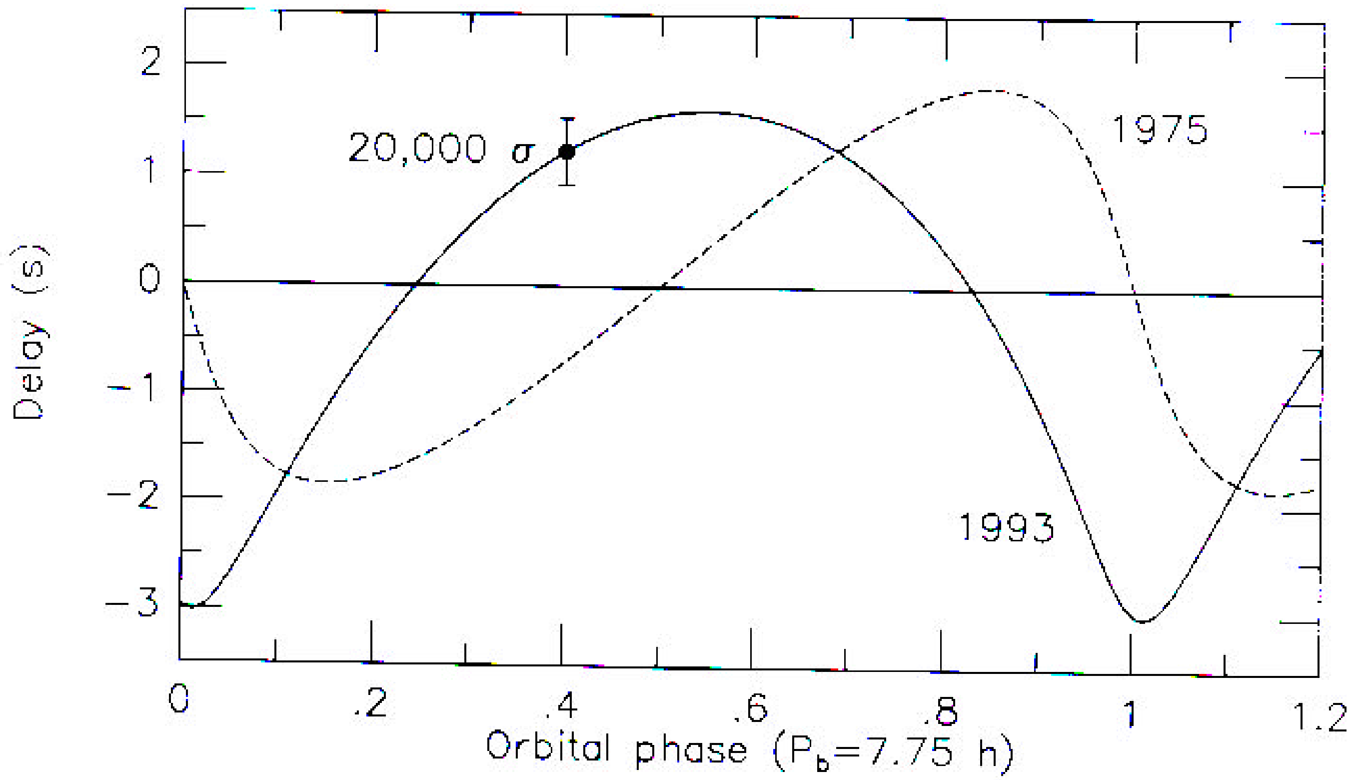
BINARY STARS
MASS M, PERIOD P.

EXPLOSIVE COLLAPSE
IS MUCH BRIGHTER

- ONCE PRODUCED, LITTLE IS ABSORBED

WE COULD POTENTIALLY SEE
TO THE SURFACE OF BLACK HOLES,
AND TO THE EARLIEST TIMES
OF THE BIG BANG WITH
GRAVITATIONAL WAVES

PSR B1913+16



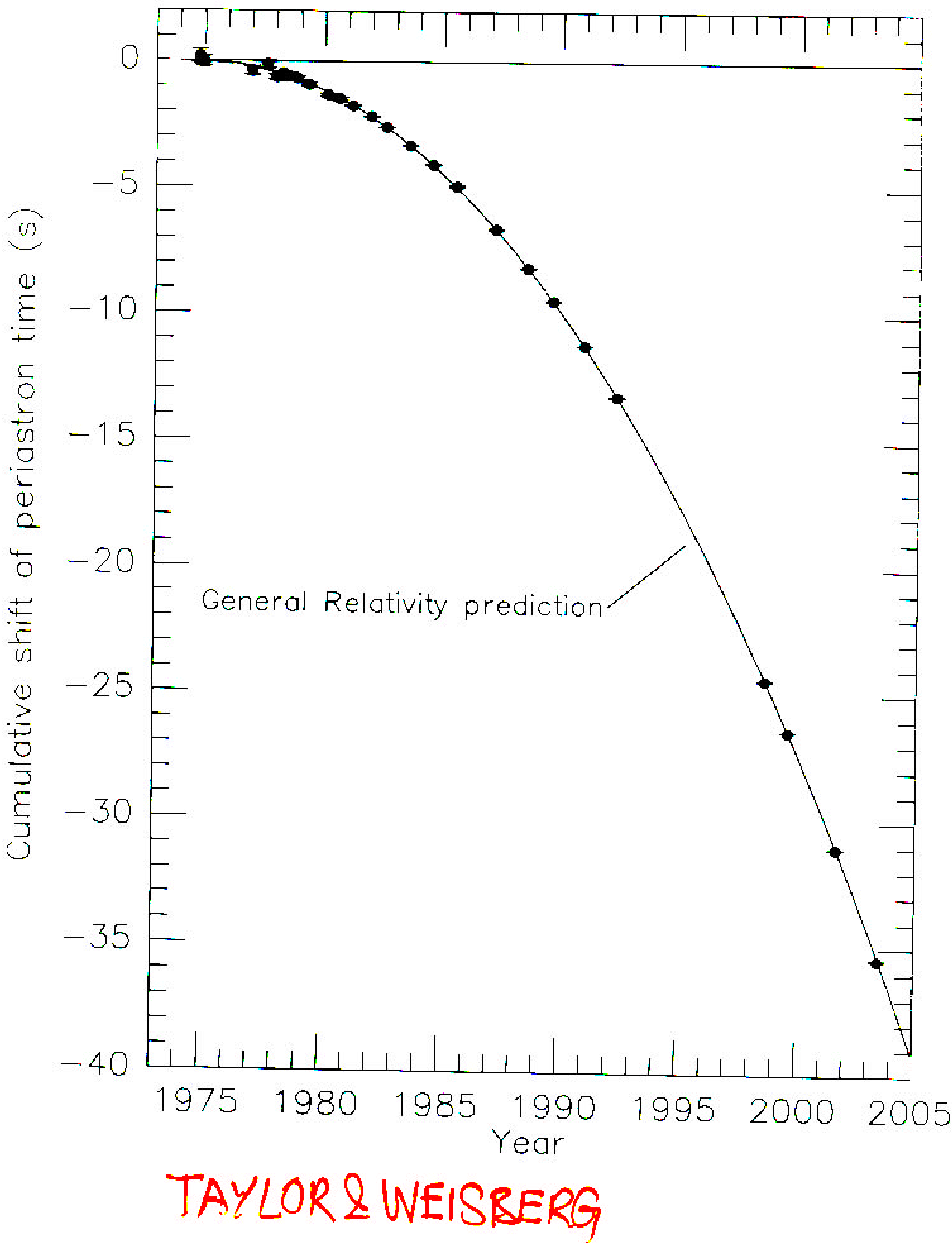
$P_{rot} = 0.059029997929613 \pm .000000000000007\,s$

(July 7, 1984 ~ 6h GMT)

PLAN AHEAD

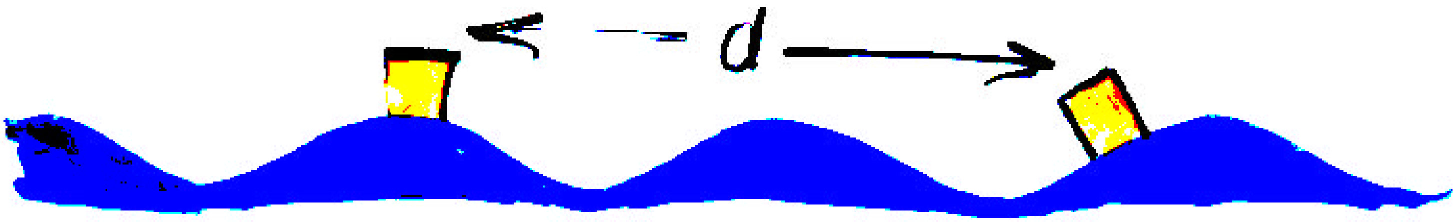
$P_{orbit} = 7.75$ hr.

(DECREASE DUE TO GRAV. RAD) ≙ 10 μs / yr.

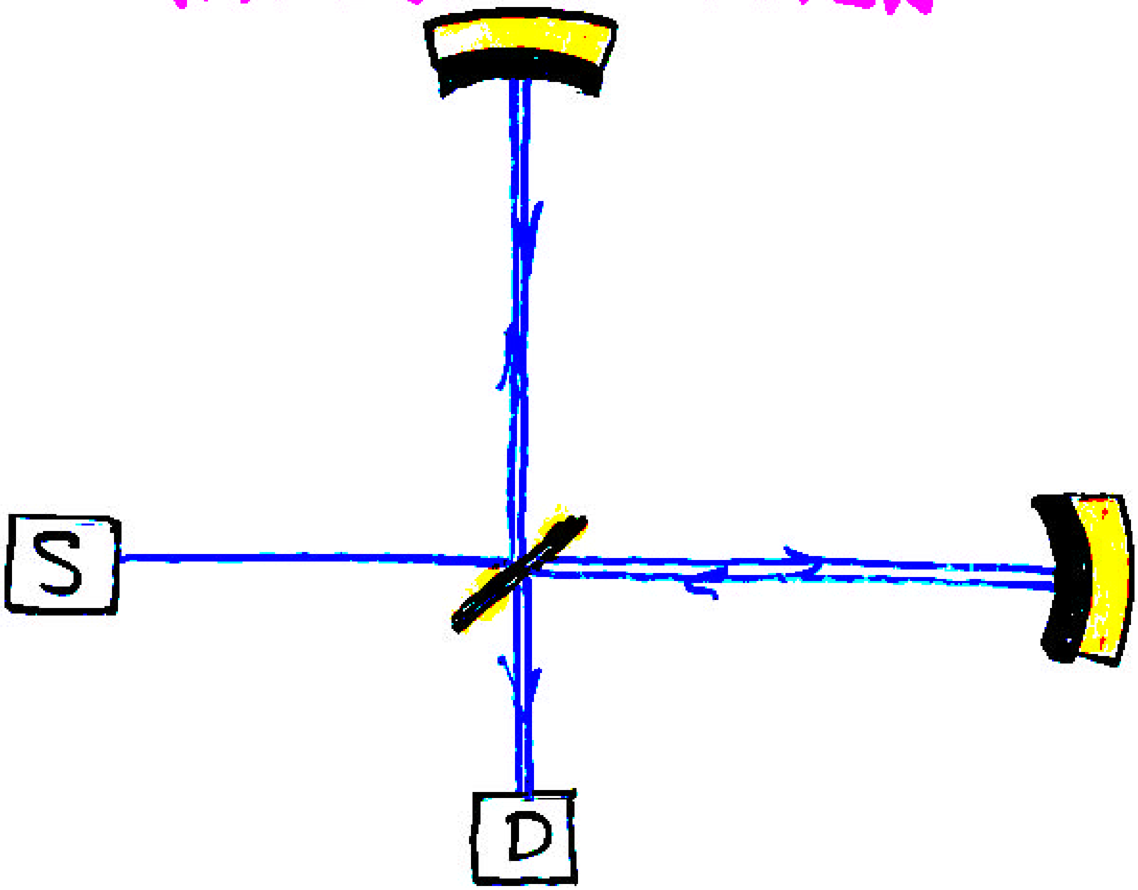


0
−5
−10
−15
−20
−25
−30
−35
−40
Cumulative shift of periastron time (s)
General Relativity prediction
1975
1980
1985
1990
1995
2000
2005
Year
TAYLOR & WEISBERG

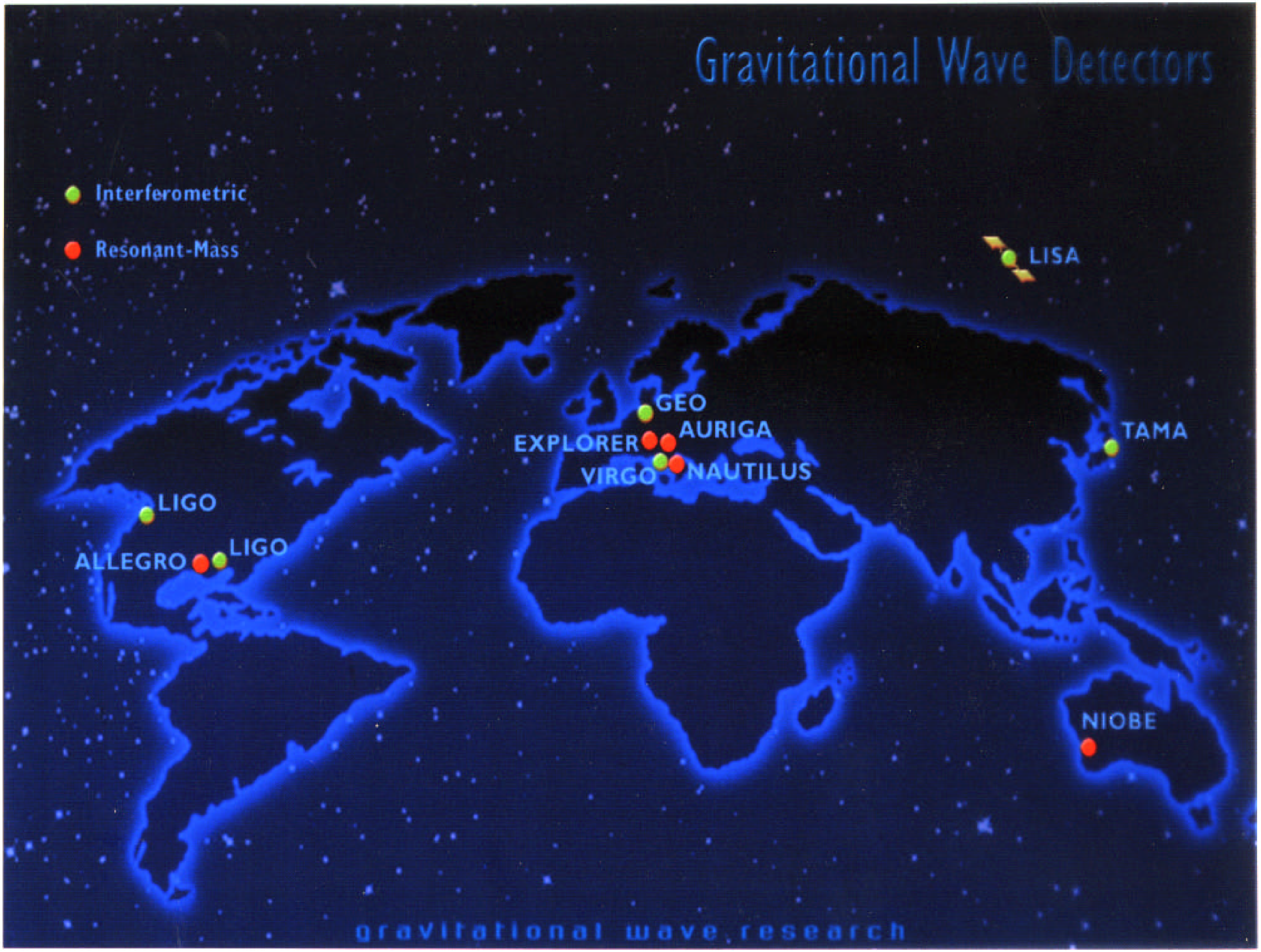
DETECTION OF GRAVITATIONAL WAVES



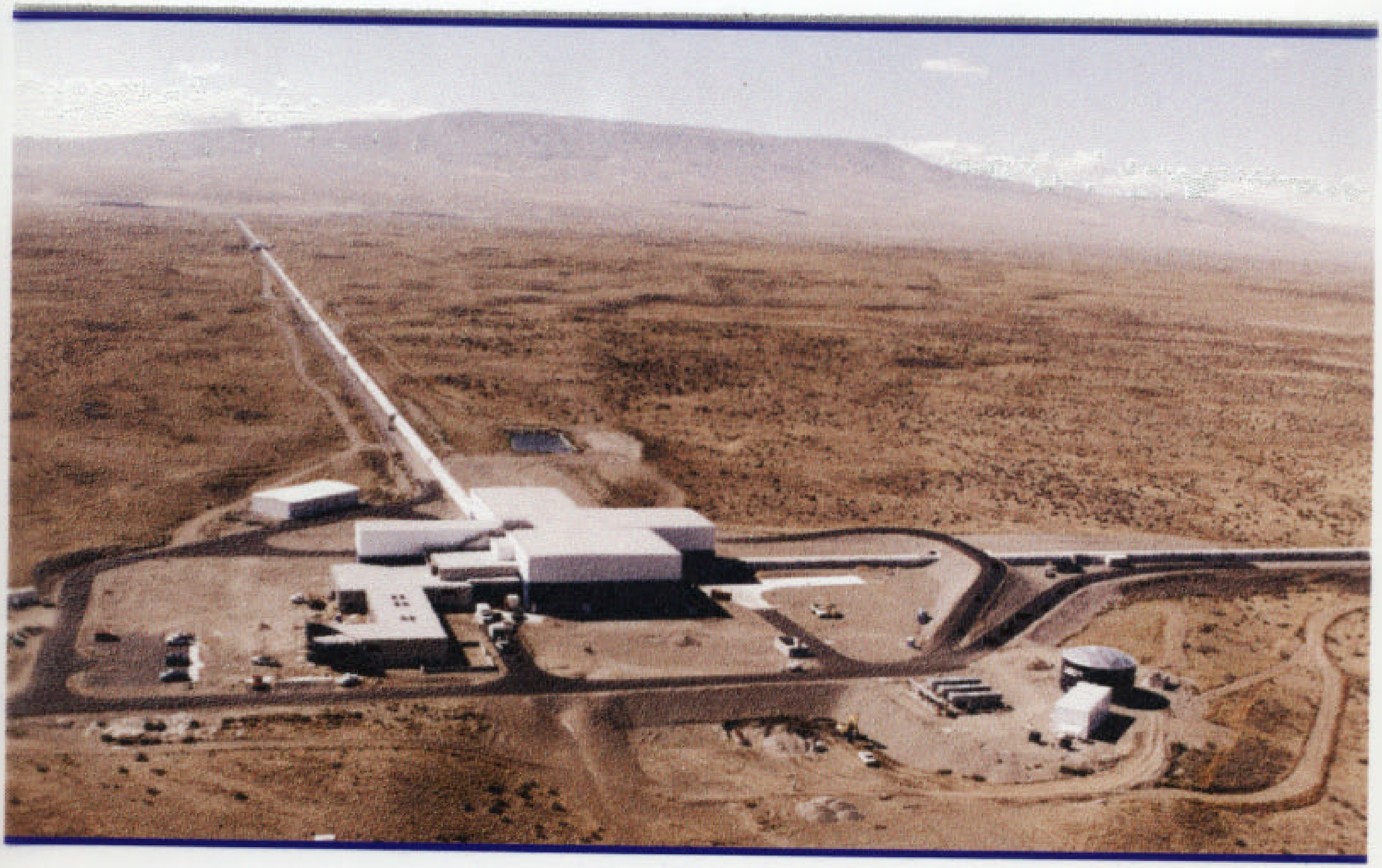
LASER INTERFEROMETER



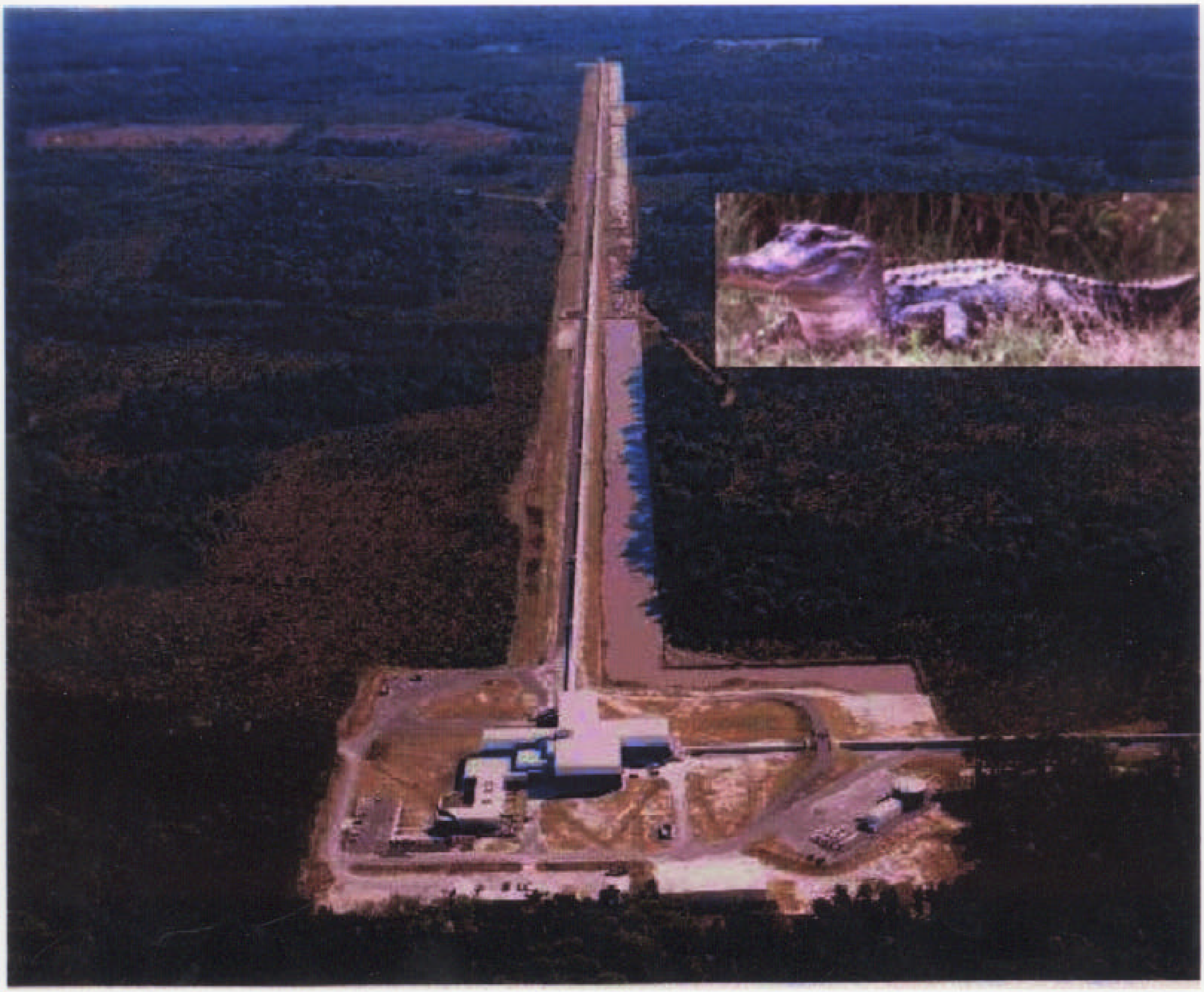
BIG INTERFEROMETERS CAN DETECT DIFFERENCES IN LENGTH OF A FRACTION OF THE SIZE OF THE NUCLEUS OF AN ATOM!


Gravitational Wave Detectors
Interferometric
Resonant-Mass
LISA
GEO
AURIGA
EXPLORER
TAMA
VIRGO
NAUTILUS
LIGO
ALLEGRO
LIGO
NIOBE
gravitational wave research

LIGO

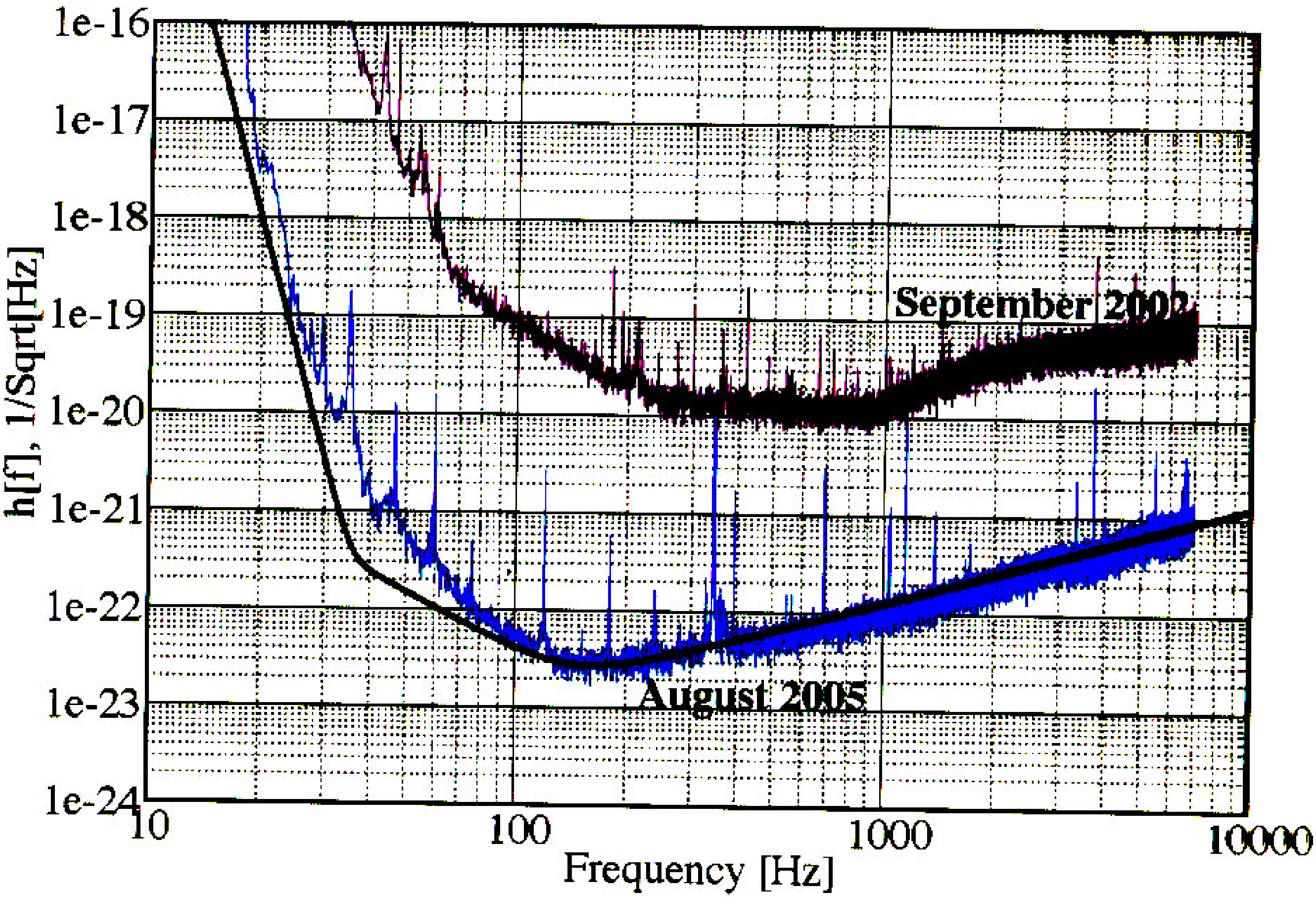


HANFORD, WA.

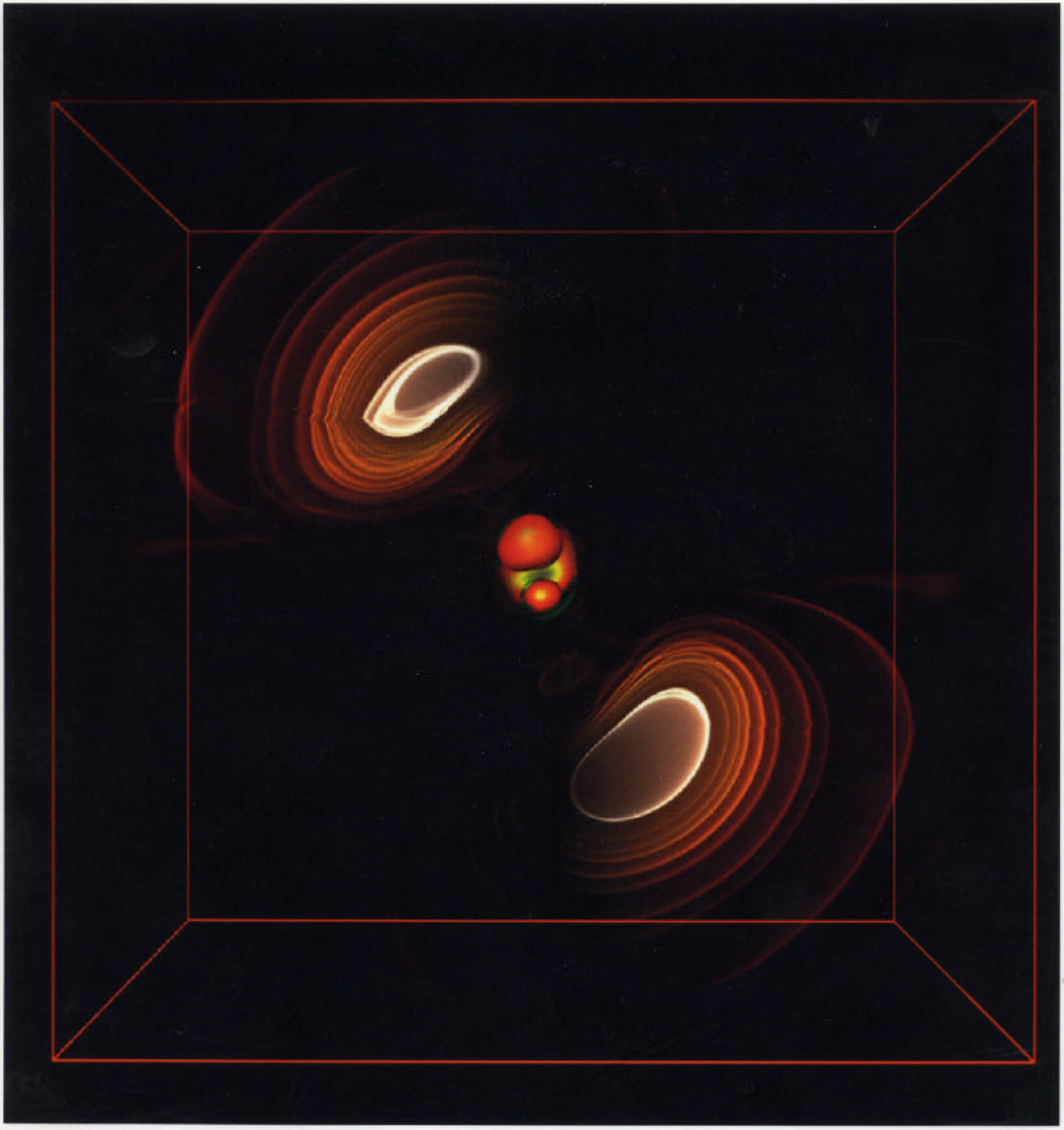


HANFORD 4km

Strain Sensitivities for the LIGO Interferometers

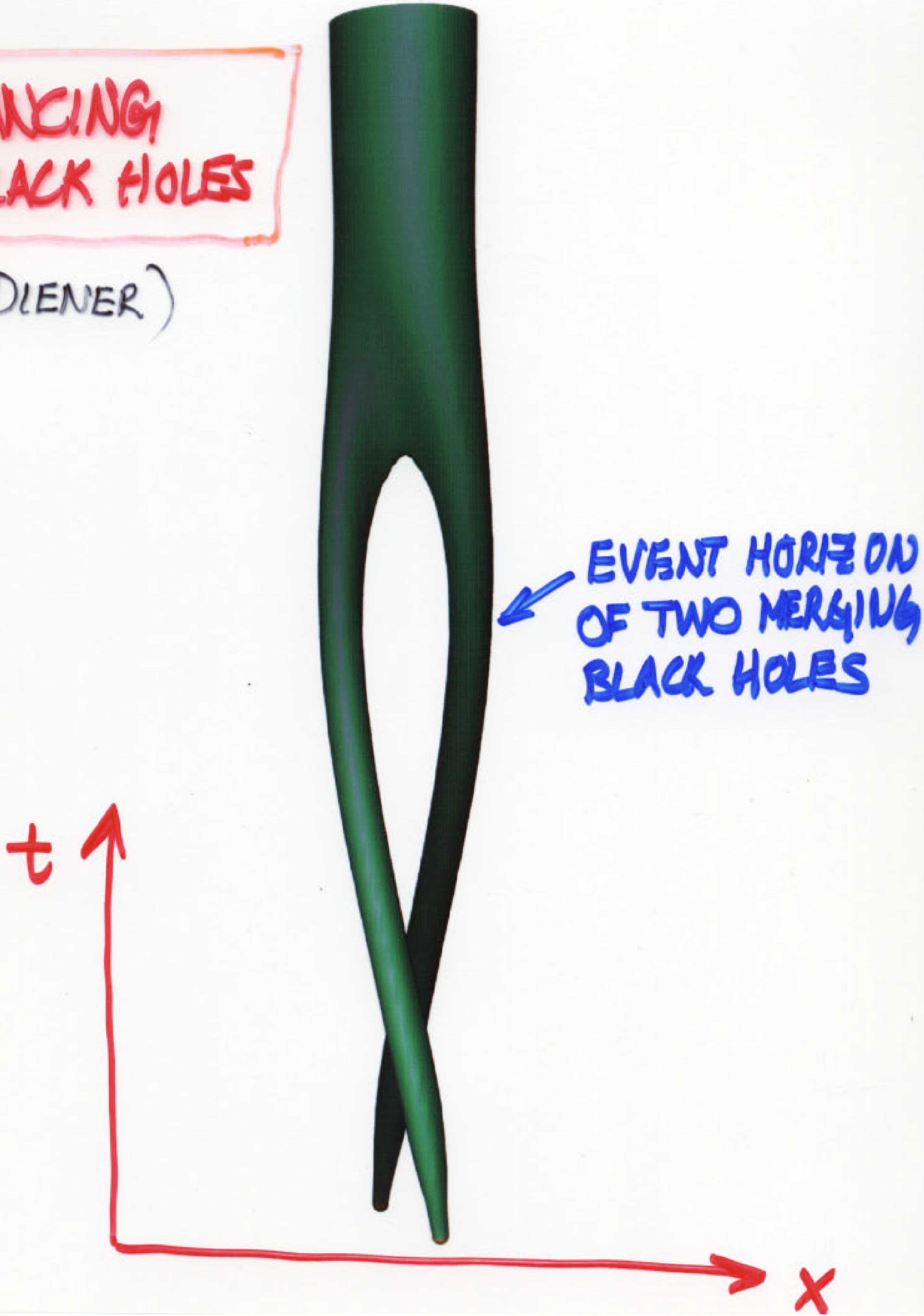


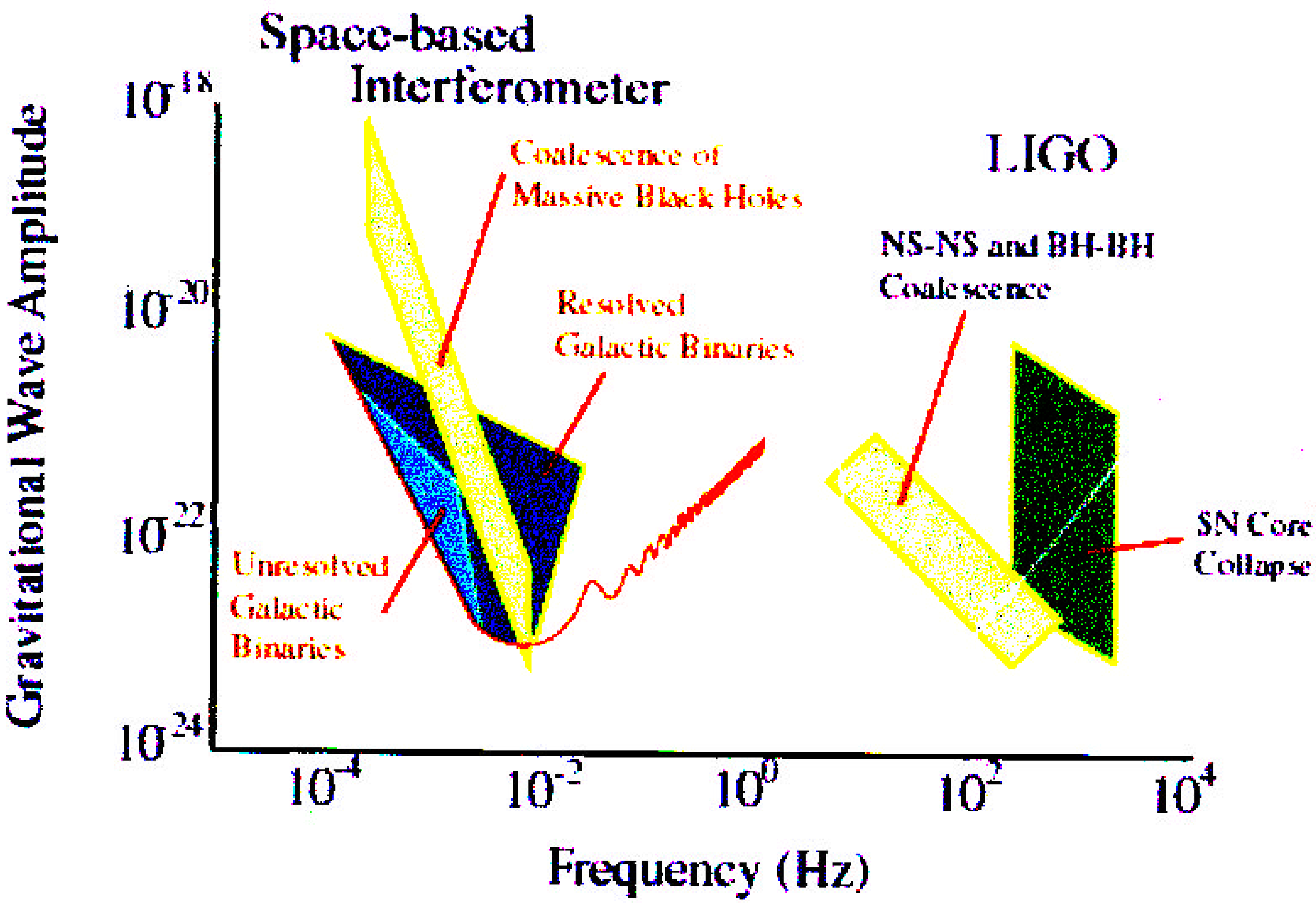
H1 Performance adapted from LIGO-G050483-01-Z



DANCING BLACK HOLES

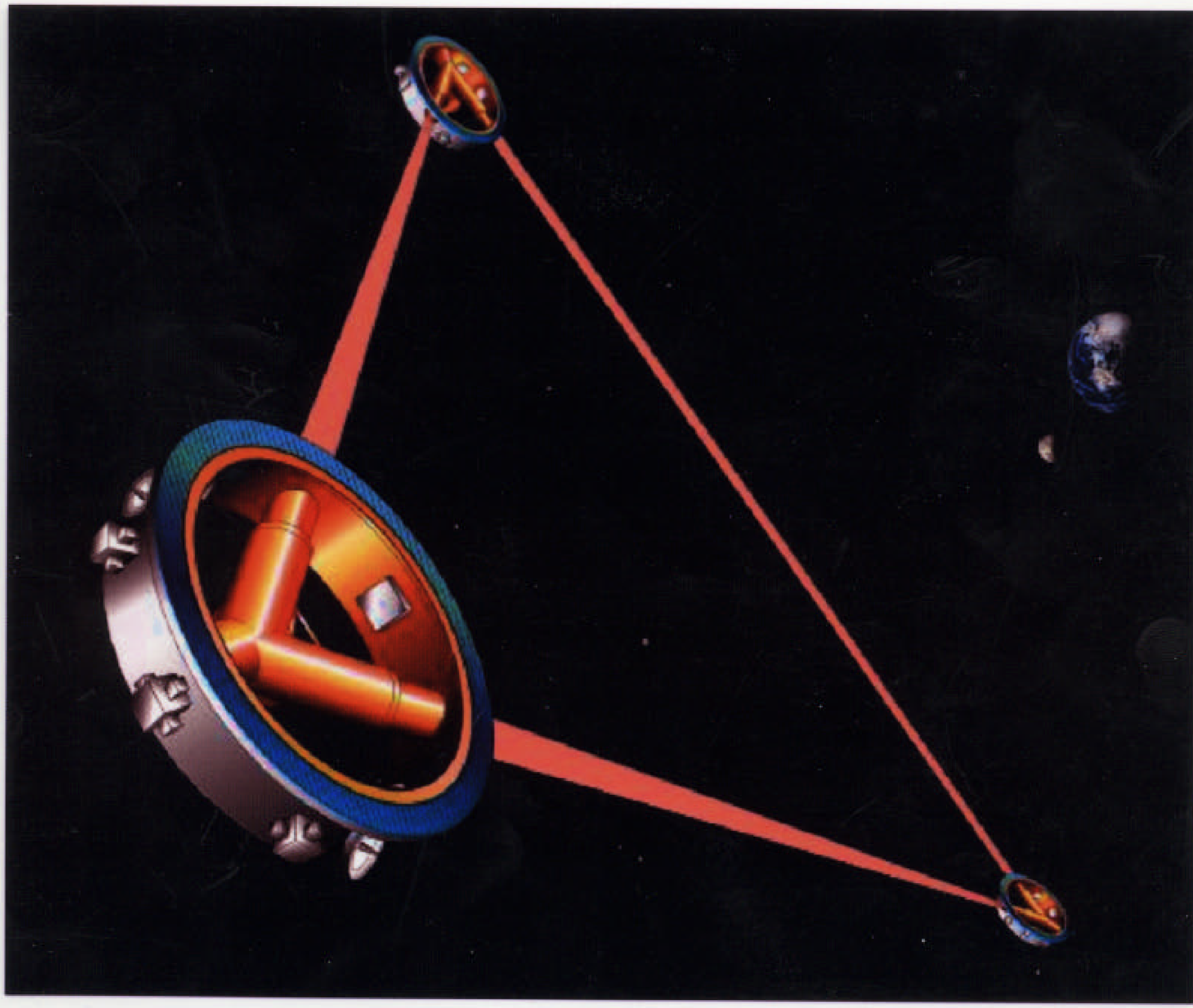
(P. DIENER)



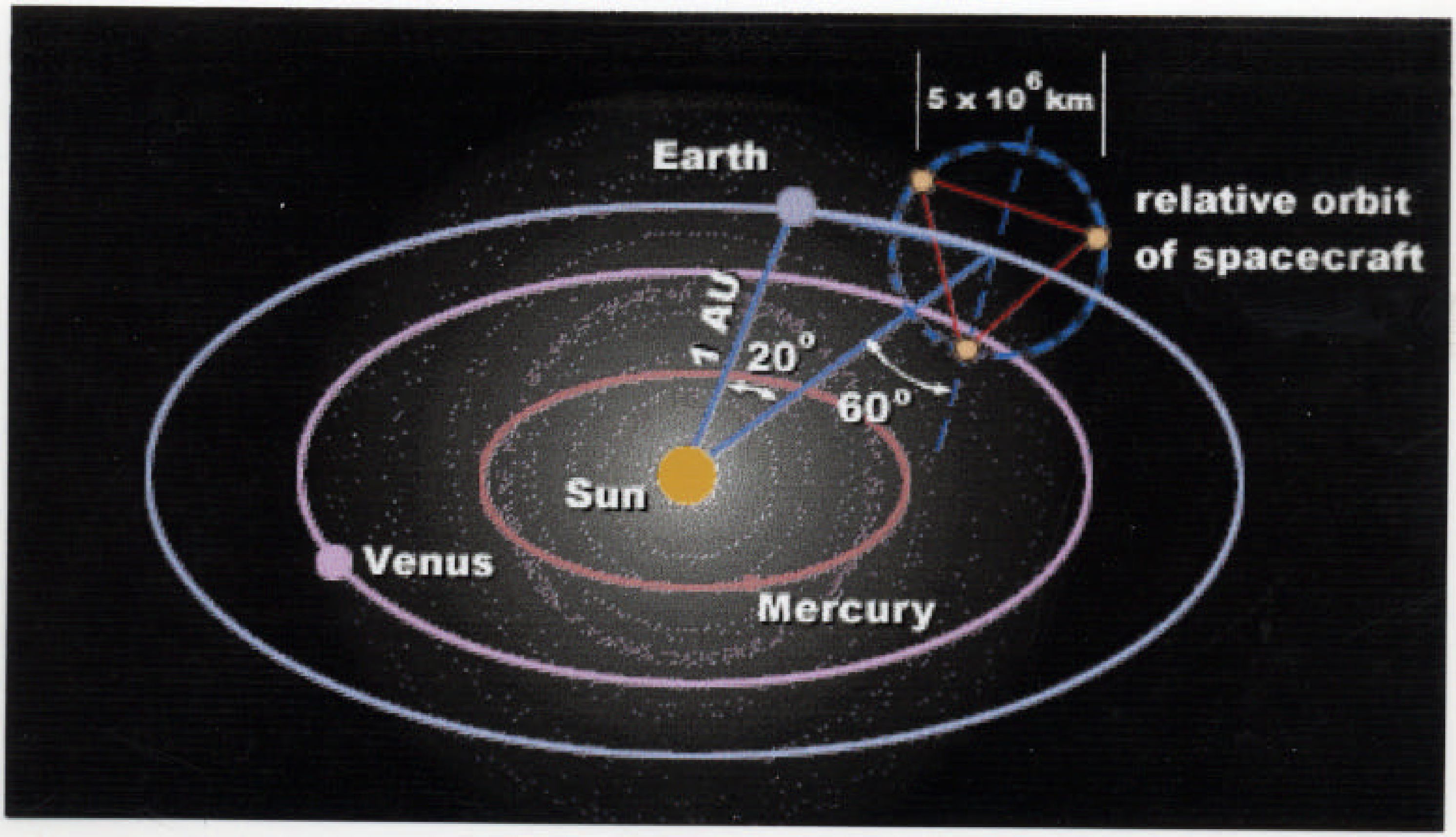


MASS IN MOTION PRODUCES GRAVITATIONAL WAVES.

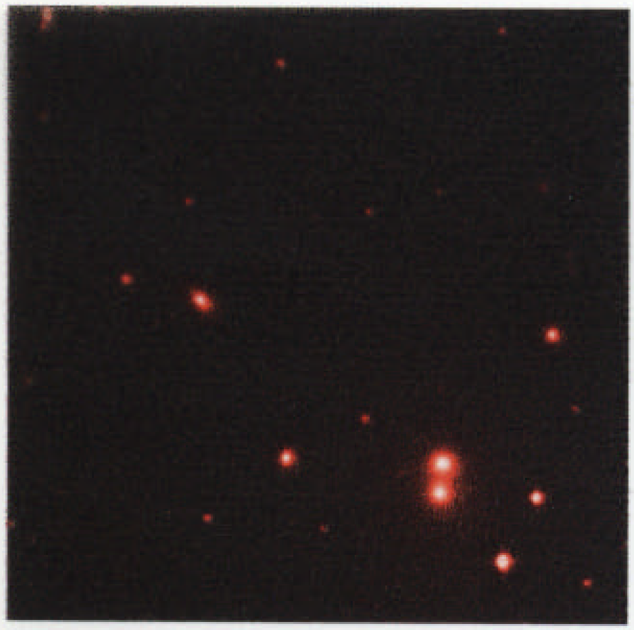
Walker



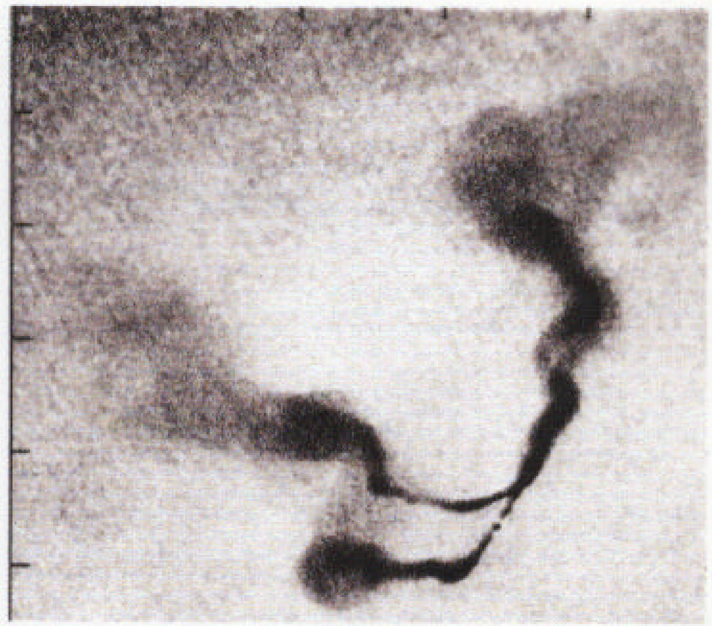
LISA


5 x 10^6 km
Earth
relative orbit
of spacecraft
1 AU
20°
60°
Sun
Venus
Mercury

Abell 400/ 3C75



Optical



Radio, Owen et al.

MERGING BLACK HOLES EMIT

$$E \sim (\text{fraction})\, Mc^2$$

IN A TIME

$$t \sim (\text{few}) \times \frac{GM}{c^3}$$

$$L_{GW} \sim \frac{Mc^2}{GM/c^3} \sim \frac{c^5}{G} \sim 10^{59}\ \text{ergs/sec}$$

MAXIMUM PHYSICAL LUMINOSITY.

$$L_{\text{GAMMA RAY BURST}} \sim 10^{52}\ \text{ergs/sec.}$$

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. Chapsky,[13,h] P. Charlton,[13] S. Chatterji,[14] Y. Chen,[6] V. Chickarmane,[17] D. Chin,[37] N. Christensen,[8] D. Churches,[7] C. Colacino,[42,2] R. Coldwell,[35] M. Coles,[16,i] D. Cook,[15] T. Corbitt,[14] D. Coyne,[13] J. D. E. Creighton,[40] T. D. Creighton,[13] D. R. M. Crooks,[36] P. Csatorday,[14] B. J. Cusack,[3] C. Cutler,[1] E. D'Ambrosio,[13] K. Danzmann,[32,2,20] R. Davies,[7] E. Daw,[17,j] D. DeBra,[27] T. Delker,[35,k] R. DeSalvo,[13] S. Dhurandhar,[12] M. Díaz,[30] H. Ding,[13] R. W. P. Drever,[4] R. J. Dupuis,[36] C. Ebeling,[8] J. Edlund,[13] P. Ehrens,[13] E. J. Elliffe,[36] T. Etzel,[13] M. Evans,[13] T. Evans,[16] C. Fallnich,[32] D. Farnham,[13] M. M. Fejer,[27] M. Fine,[13] L. S. Finn,[29] É. Flanagan,[9] A. Freise,[2,l] R. Frey,[38] P. Fritschel,[14] V. Frolov,[16] M. Fyffe,[16] K. S. Ganezer,[5] J. A. Giaime,[17] A. Gillespie,[13,m] K. Goda,[14] G. González,[17] S. Goßler,[32] P. Grandclément,[24] A. Grant,[36] C. Gray,[15] A. M. Gretarsson,[16] D. Grimmett,[13] H. Grote,[2] S. Grunewald,[1] M. Guenther,[15] E. Gustafson,[27,n] R. Gustafson,[37] W. O. Hamilton,[17] M. Hammond,[16] J. Hanson,[16] C. Hardham,[27] G. Harry,[14] A. Hartunian,[13] J. Heefner,[13] Y. Hefetz,[14] G. Heinzel,[2] I. S. Heng,[32] M. Hennessy,[27] N. Hepler,[29] A. Heptonstall,[36] M. Heurs,[32] M. Hewitson,[36] N. Hindman,[15] P. Hoang,[13] J. Hough,[36] M. Hrynevych,[13,o] W. Hua,[27] R. Ingley,[34] M. Ito,[38] Y. Itoh,[1] A. Ivanov,[13] O. Jennrich,[36,p] W. W. Johnson,[17] W. Johnston,[30] L. Jones,[13] D. Jungwirth,[13,q] V. Kalogera,[24] E. Katsavounidis,[14] K. Kawabe,[20,2] S. Kawamura,[23] W. Kells,[13] J. Kern,[16] A. Khan,[16] S. Killbourn,[36] C. J. Killow,[36] C. Kim,[24] C. King,[13] P. King,[13] S. Klimenko,[35] P. Kloevekorn,[2] S. Koranda,[40] K. Kötter,[32] J. Kovalik,[16] D. Kozak,[13] B. Krishnan,[1] M. Landry,[15] J. Langdale,[16] B. Lantz,[27] R. Lawrence,[14] A. Lazzarini,[13] M. Lei,[13] V. Leonhardt,[32] I. Leonor,[38] K. 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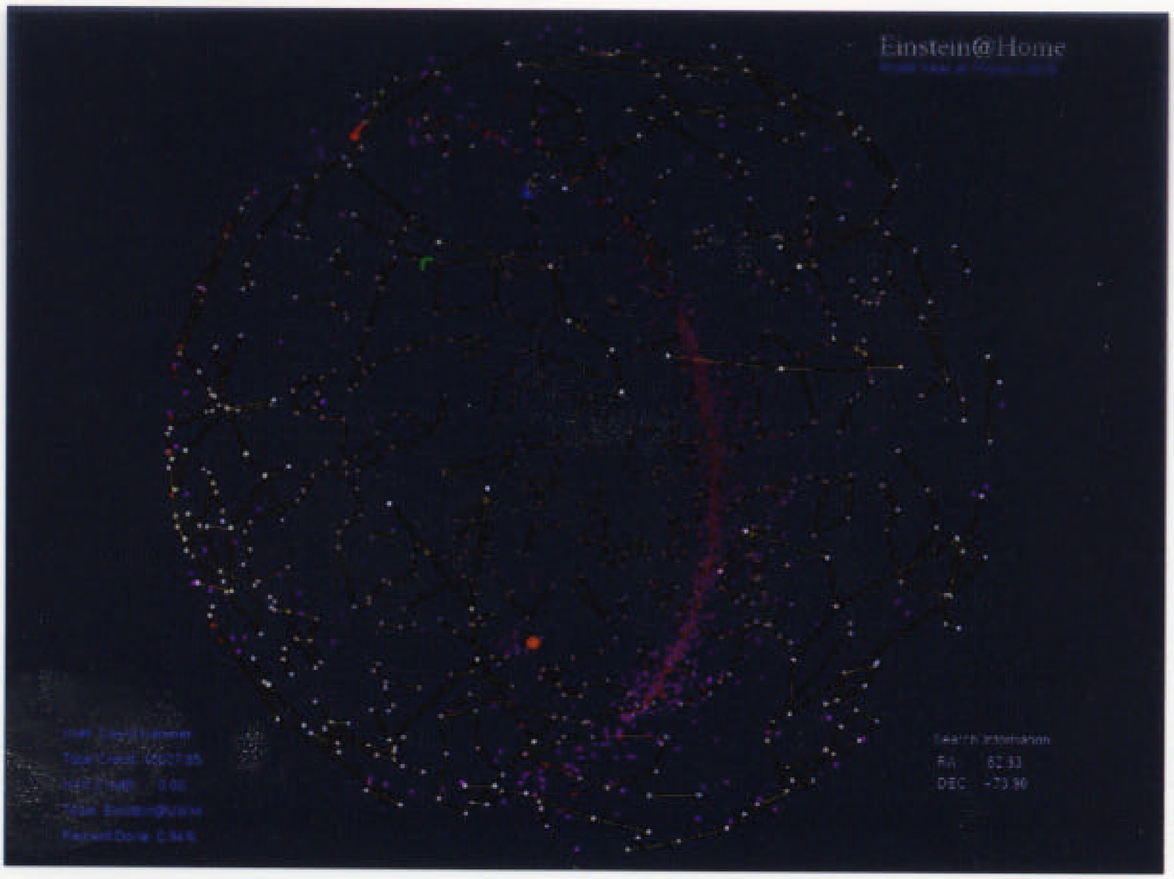


- CONTINUOUS WAVE (PULSAR) SEARCHES.
- 60,000 USERS (w. CREDIT)
- 25 Tflops CONTINOUSLY ($7k/DAY ELECTRIC BILL)
- NUMBER 3 IN BOINC BEHIND
  SETI @HOME
  CLIMATEPREDICTION.NET

http://einstein.phys.uwm.edu

BLACK HOLES

EINSTEIN'S THEORY PREDICTS
THAT WHEN
MASS IS COMPRESSED
TO A SMALL ENOUGH VOLUME
THE GRAVITATIONAL FORCE
IS SO STRONG
NOTHING CAN ESCAPE.

BLACK HOLES

- GENERAL RELATIVITY PREDICTS THAT THE GEOMETRY OF ASTROPHYSICAL BLACK HOLES IS CHARACTERIZED BY JUST TWO PARAMETERS:

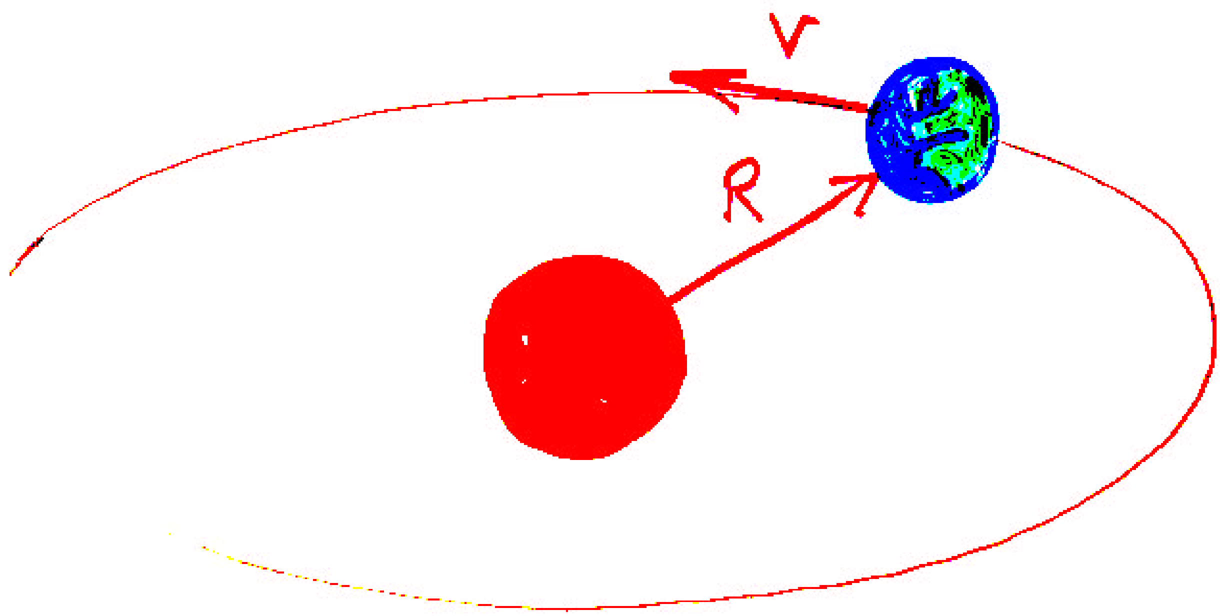
  M – MASS

  J – ANGULAR MOMENTUM

- BLACK HOLES PROVIDE THE CLEANEST CONNECTION BETWEEN ASTROPHYSICS AND FUNDAMENTAL PHYSICS

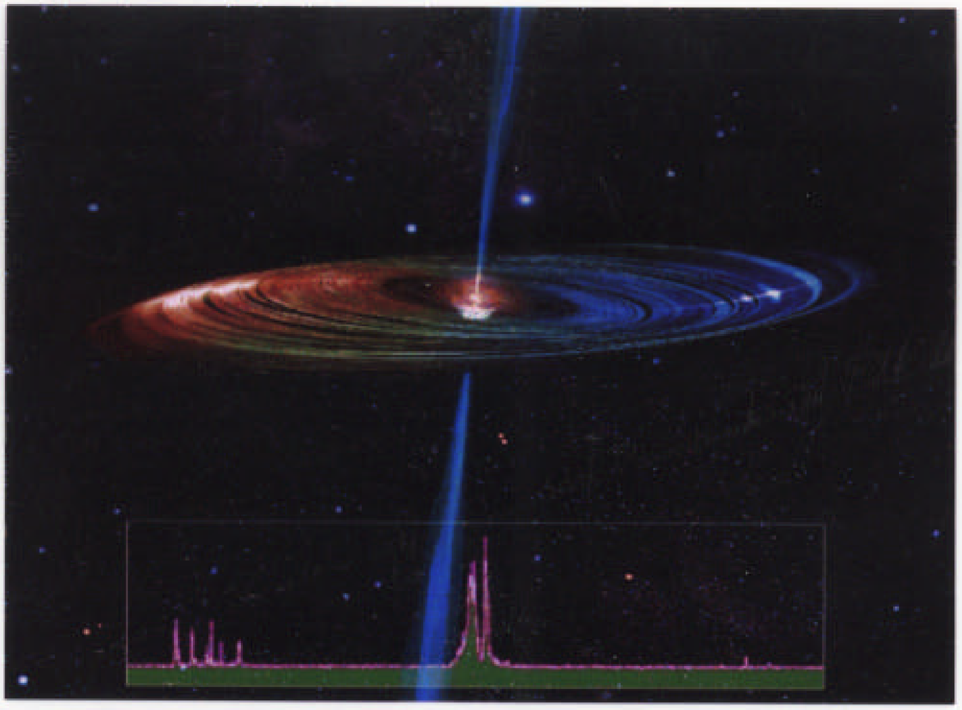
WEIGHING THE SUN

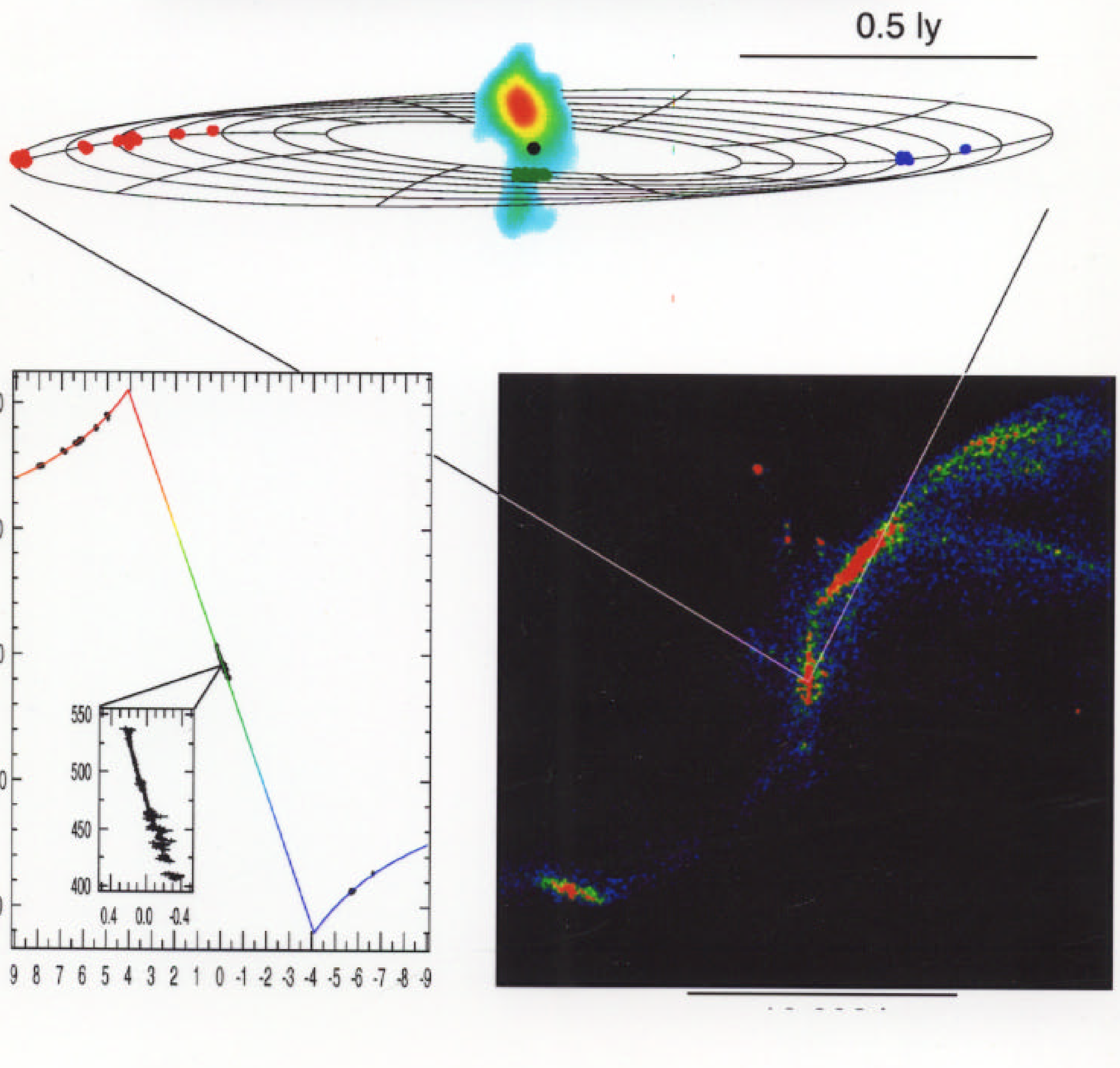
THE MASS OF THE SUN CAN BE DETERMINED FROM THE SPEED OF THE EARTH AND THE SIZE OF ITS ORBIT.



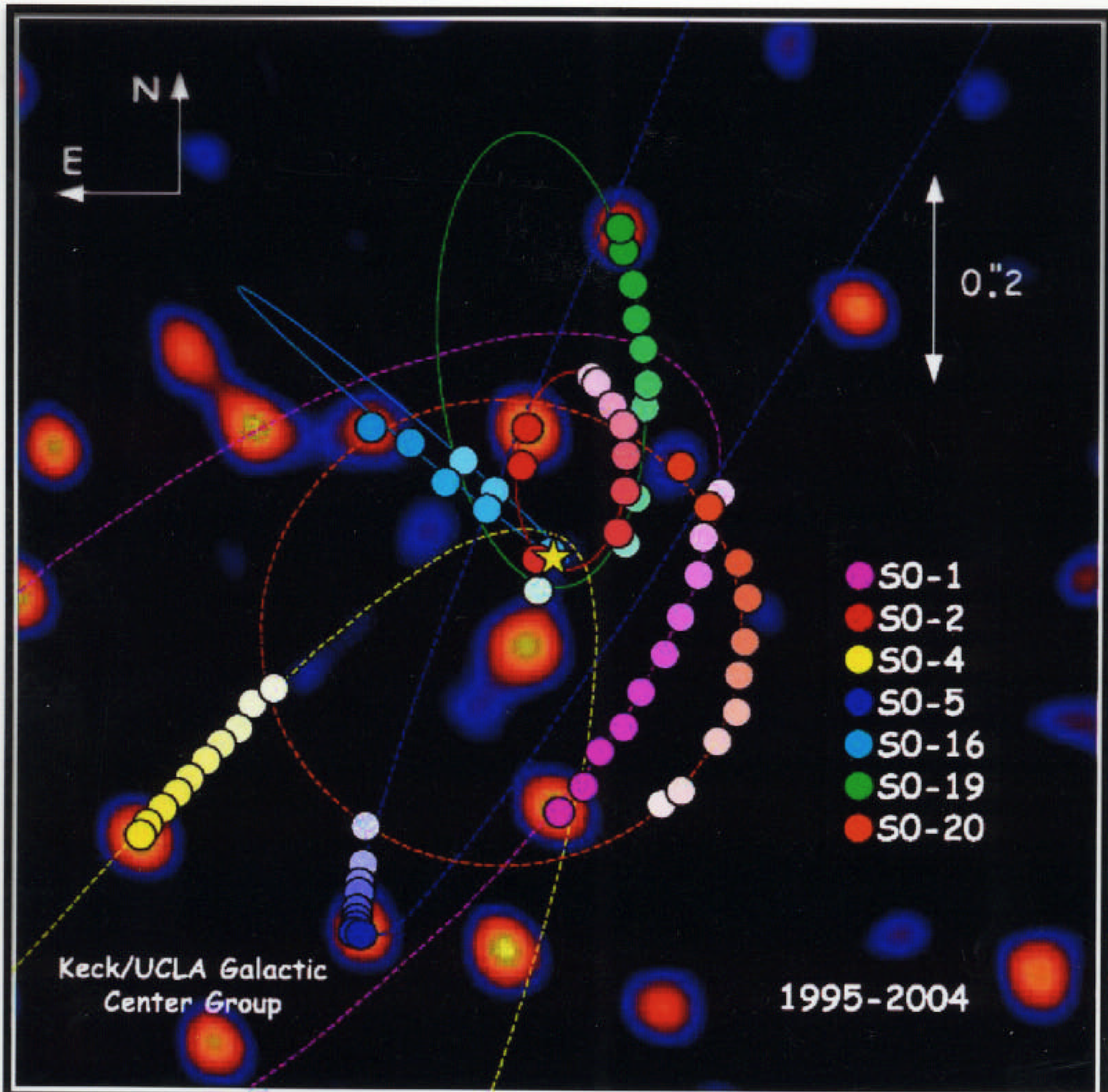
THE EARTH WOULD GO AROUND TWICE AS FAST IF THE SUN WERE FOUR TIMES MORE MASSIVE.

NGC 4258




0.5 ly
LSR Velocity (km s-1)
1500
1000
500
0
-500
550
500
450
400
0.4
0.0
-0.4
9 8 7 6 5 4 3 2 1 0 -1 -2 -3 -4 -5 -6 -7 -8 -9

THE BLACK HOLE IN OUR GALAXY



(A. Ghez, et. al. 2004)

BLACK HOLES POWER SOME OF THE MOST ENERGETIC PHENOMENA IN THE UNIVERSE.

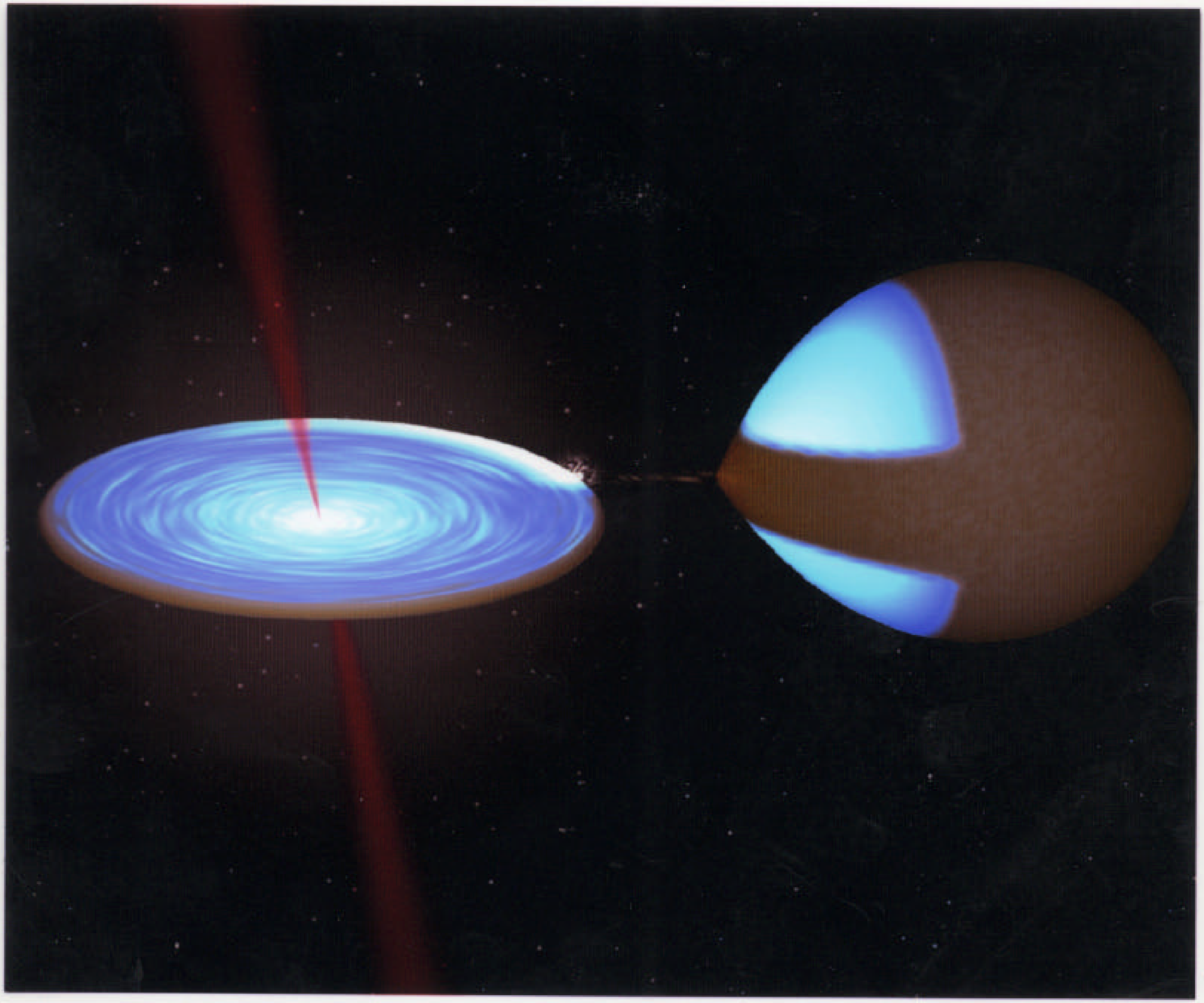
- X-RAY SOURCES

  $L_X \sim 10^{38}$ ergs/sec $\quad L_{\odot} \sim 10^{33}$ ergs/sec

- ACTIVE GALACTIC NUCLEI

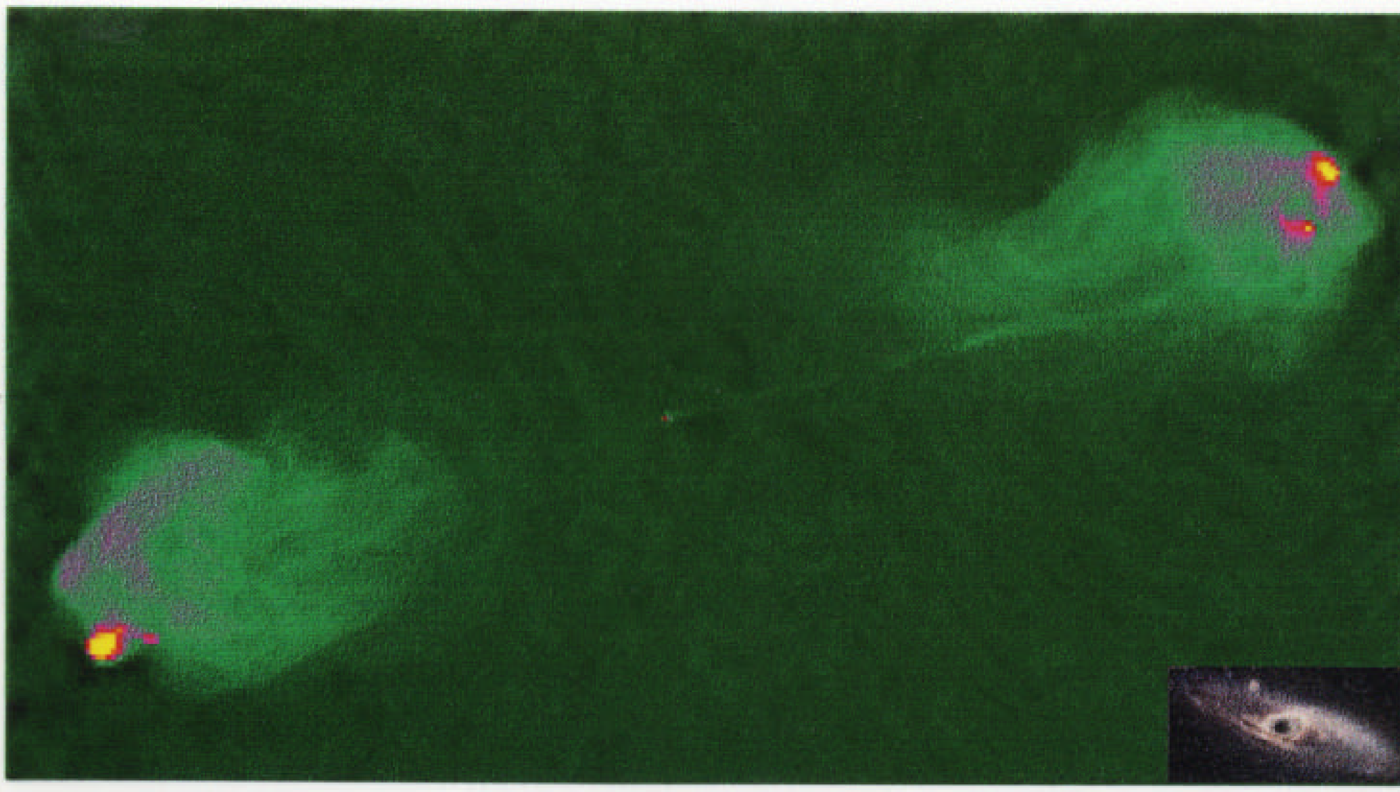
  $L \sim 10^{42} - 10^{48}$ ergs/sec

  $L_{galaxy} \sim 10^{44}$ ergs/sec.

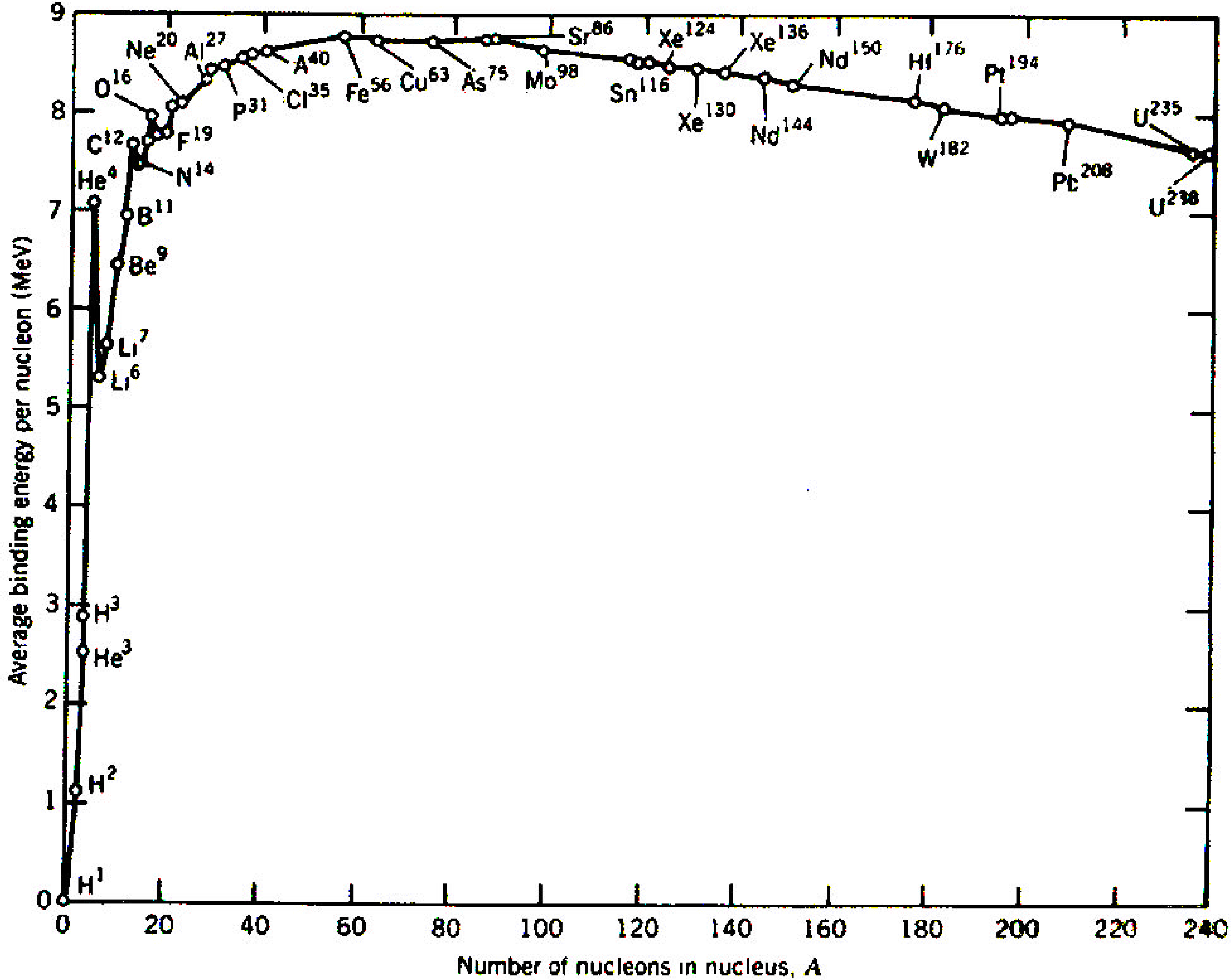


ACTIVE GALACTIC NUCLEI

$\frac{1}{100}$ - 10,000 TIMES BRIGHTER THAN ALL THE STARS IN THE GALAXY.



Cygnus A



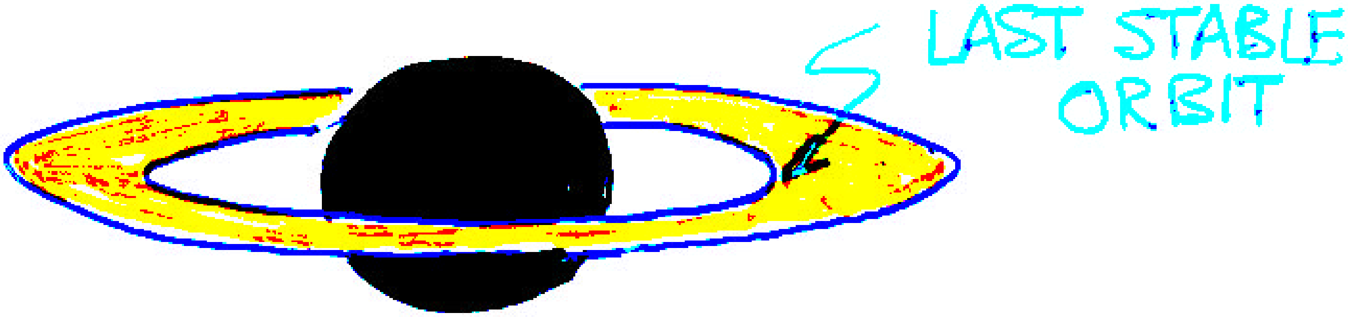
Average binding energy per nucleon (MeV)
Number of nucleons in nucleus, A
0
1
2
3
4
5
6
7
8
9
0
20
40
60
80
100
120
140
160
180
200
220
240
H1
H2
H3
He3
He4
Li6
Li7
Be9
B11
C12
N14
O16
F19
Ne20
Al27
P31
Cl35
A40
Fe56
Cu63
As75
Sr86
Mo98
Sn116
Xe124
Xe130
Xe136
Nd144
Nd150
Hf176
W182
Pt194
Pt208
U235
U238

GRAVITATIONAL BINDING VS THERMONUCLEAR FUSION

- **FUSION** $4H^1 \rightarrow He^4 + (\text{ENERGY OUT})$

$$\frac{(\text{ENERGY OUT})}{(\text{REST ENERGY IN})} \lesssim 1\%$$

- **GRAVITATIONAL BINDING**



NEUTRON STAR:

$$\frac{(\text{ENERGY OUT})}{(\text{REST ENERGY IN})} \sim 6\%$$

EXTREME ROTATING BLACK HOLE:

$$\frac{(\text{ENERGY OUT})}{(\text{REST ENERGY IN})} \sim 30\%$$

THE BLACK HOLES OF
GENERAL RELATIVITY (1915)
ARE THE MOST EFFICIENT
WAY OF REALIZING

$$E = mc^2$$

OF SPECIAL RELATIVITY (1905)

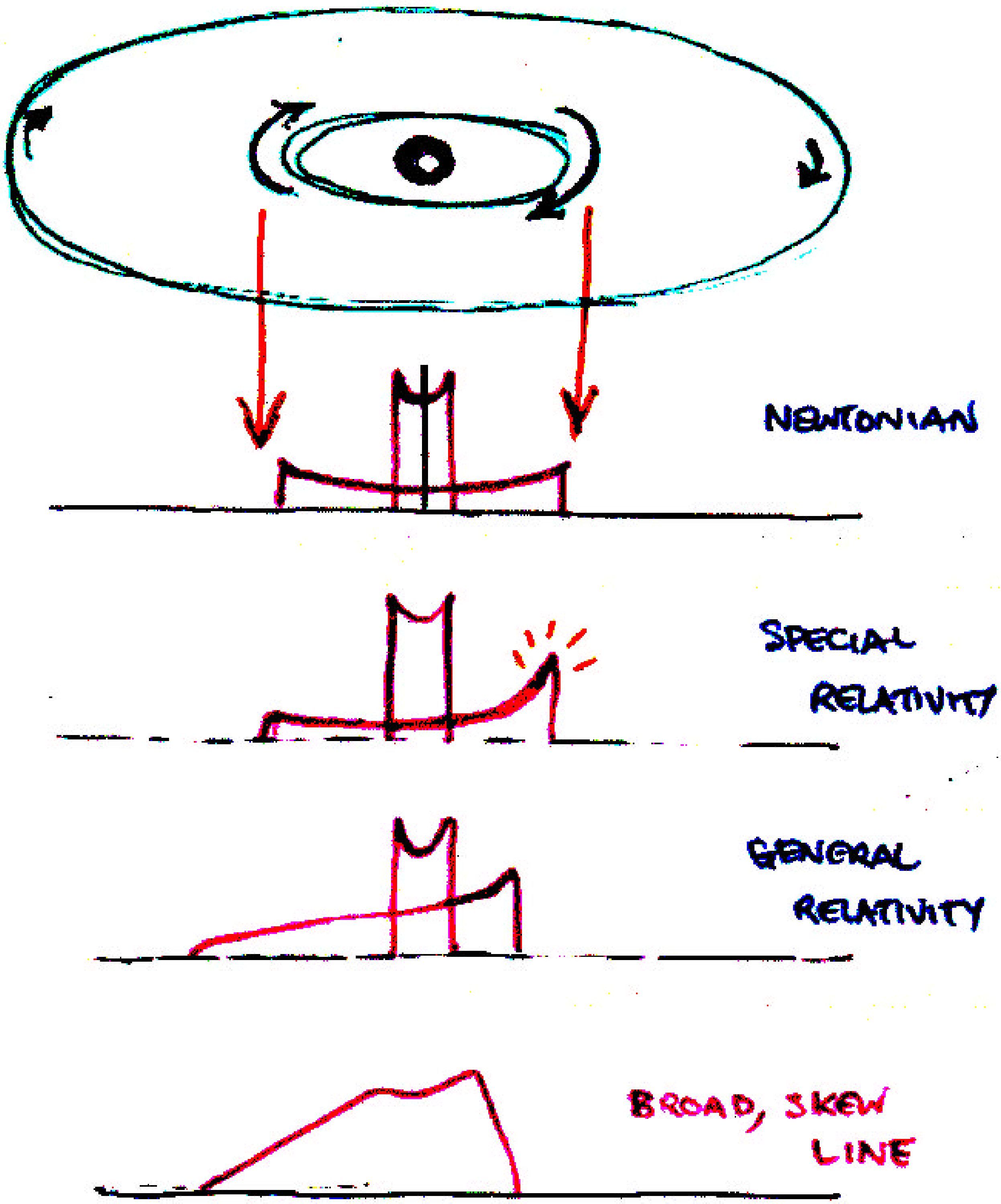
FUTURE OF BLACK HOLE PHYSICS

- **TODAY:** IDENTIFIED PLACES WHERE THERE IS MUCH MASS IN A SMALL VOLUME.
- **FUTURE:** CHECK THE DETAILED PREDICTION OF EINSTEIN'S THEORY FOR THE GEOMETRY AROUND BLACK HOLES.

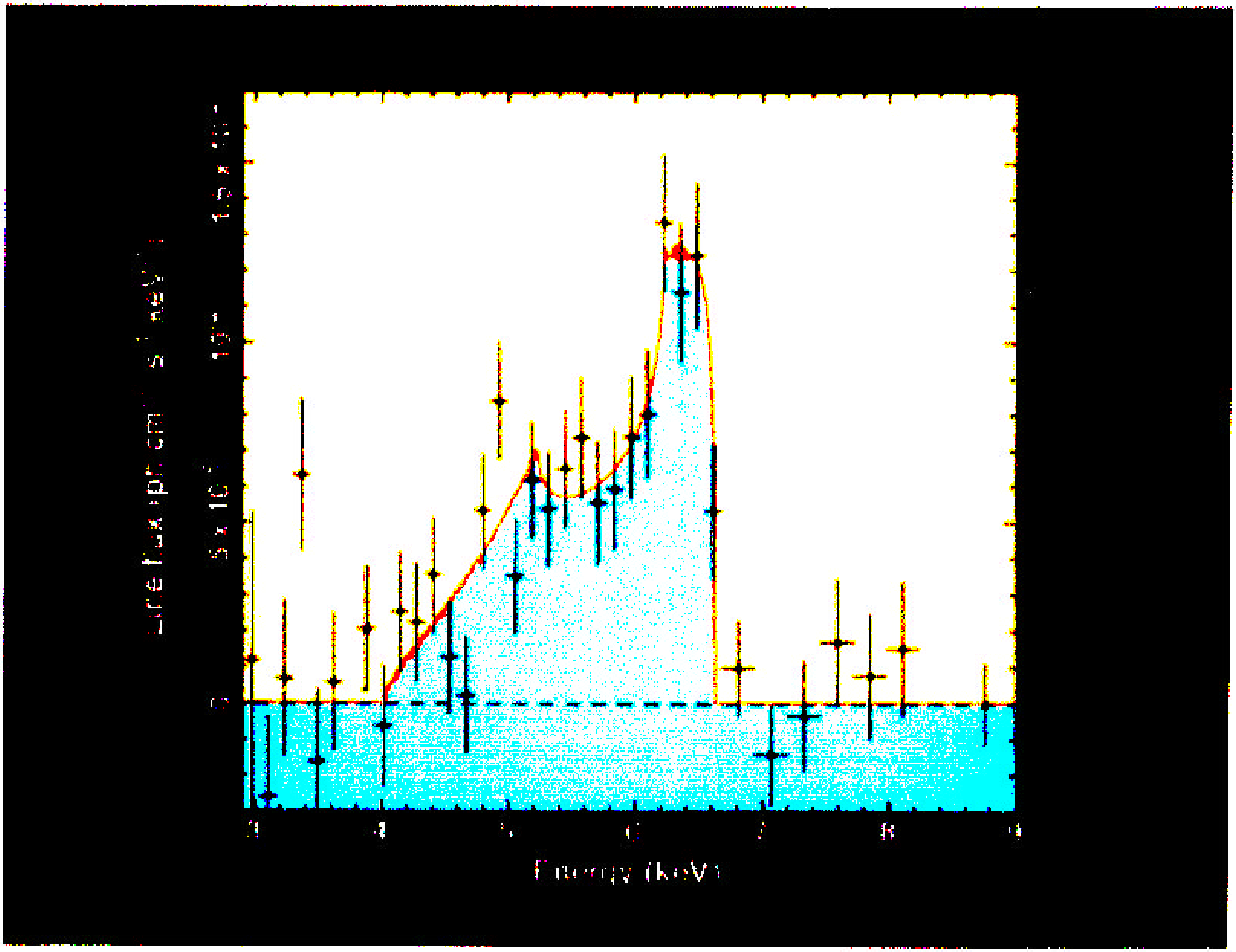
  X-Ray

  GRAVITATIONAL WAVES

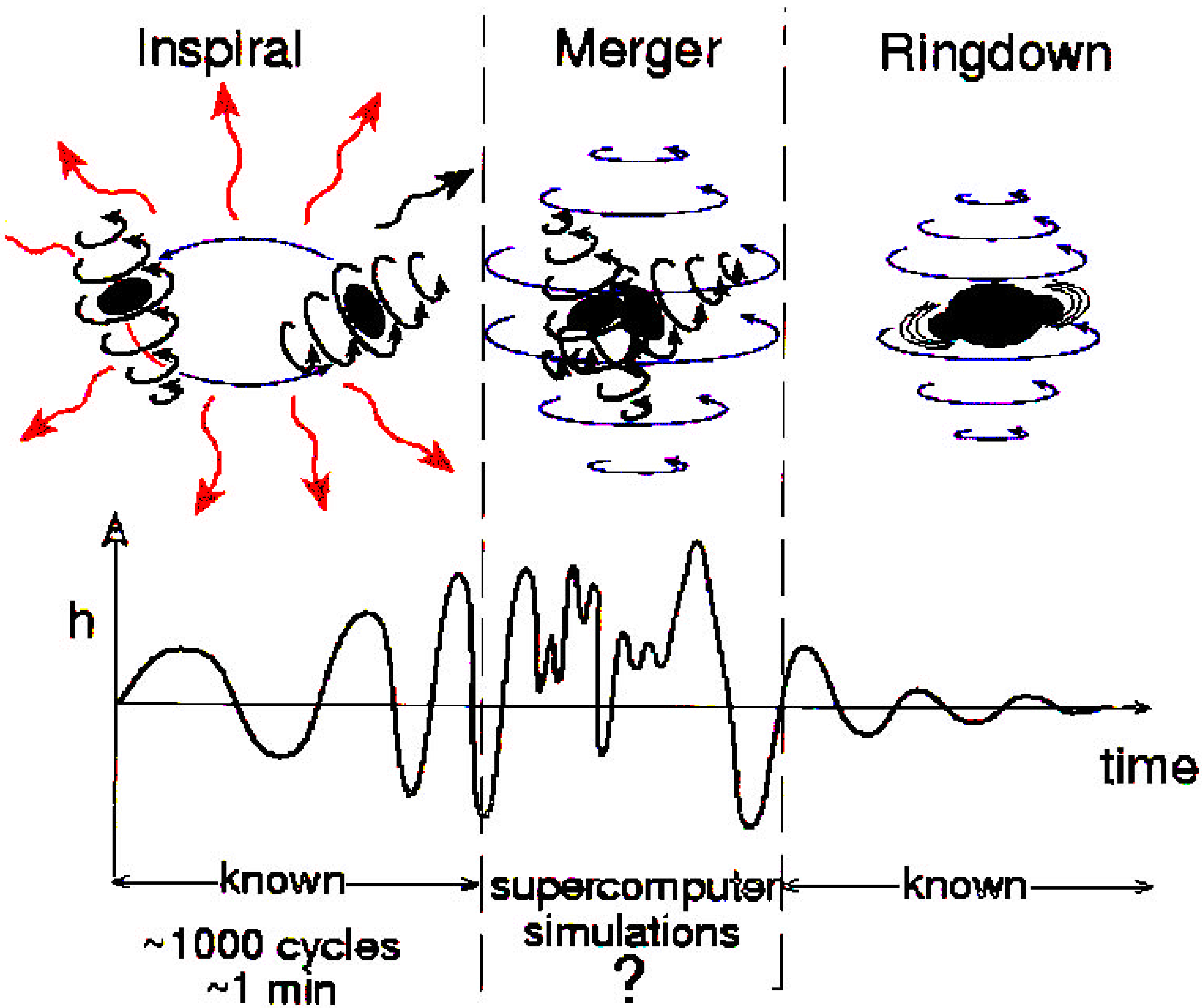
XMM


NEWTONIAN
SPECIAL RELATIVITY
GENERAL RELATIVITY
BROAD, SKEW LINE

Fe Line in MCG-6-30-15



Tanaka, et. al. (1995)


Inspiral
Merger
Ringdown
h
time
known
supercomputer
simulations
?
known
~1000 cycles
~1 min

COSMOLOGY

EINSTEIN'S THEORY PREDICTS

THE EXPANSION OF

THE UNIVERSE

FROM A BIG BANG.

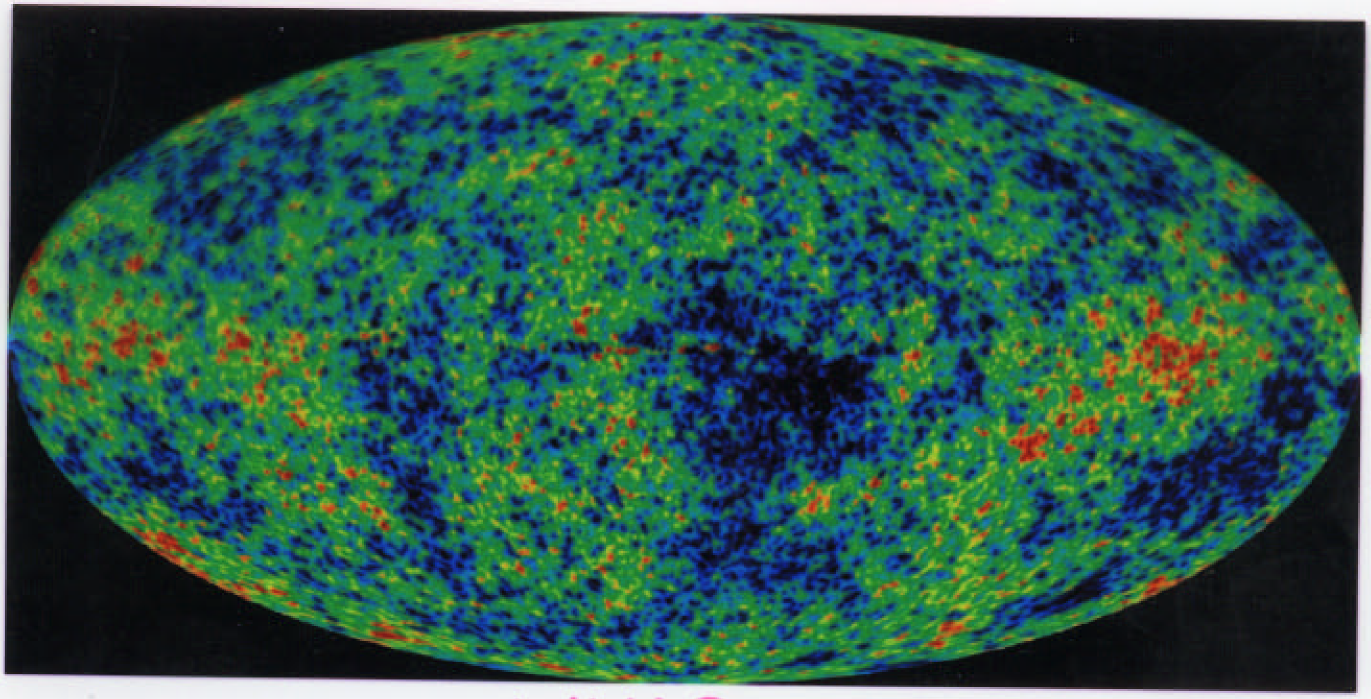
GRAVITATIONAL ISSUES IN COSMOLOGY

- WHAT IS THE GEOMETRY OF THE UNIVERSE?

- WHAT IS THE SOURCE OF CURVATURE?
  - DARK MATTER
  - VACUUM ENERGY (COSMOLOGICAL CONSTANT)

- DOES THE UNIVERSE OBEY THE EINSTEIN EQUATION?

COSMOLOGY TODAY



WMAP

- HOMOGENEOUS, ISOTROPIC ($d \gtrsim 100$ Mpc)
- INITIAL MATTER THERMAL EQUILIBRIUM

FRW MODELS

$H_0 = 71$ (km/s)/Mpc

$\Omega_{VACUUM} = .73$

$\Omega_{RADIATION} = 8\times10^{-5}$

$\Omega_{BARYON} = .04$

$\Omega_{DARK\cdot MATTER} = .23$

COSMOLOGICAL PARAMETERS.

COSMOLOGY TOMORROW

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G\, T_{\mu\nu}$$

IS EINSTEIN'S GRAVITATIONAL THEORY CORRECT ON THE SCALES OF COSMOLOGY?

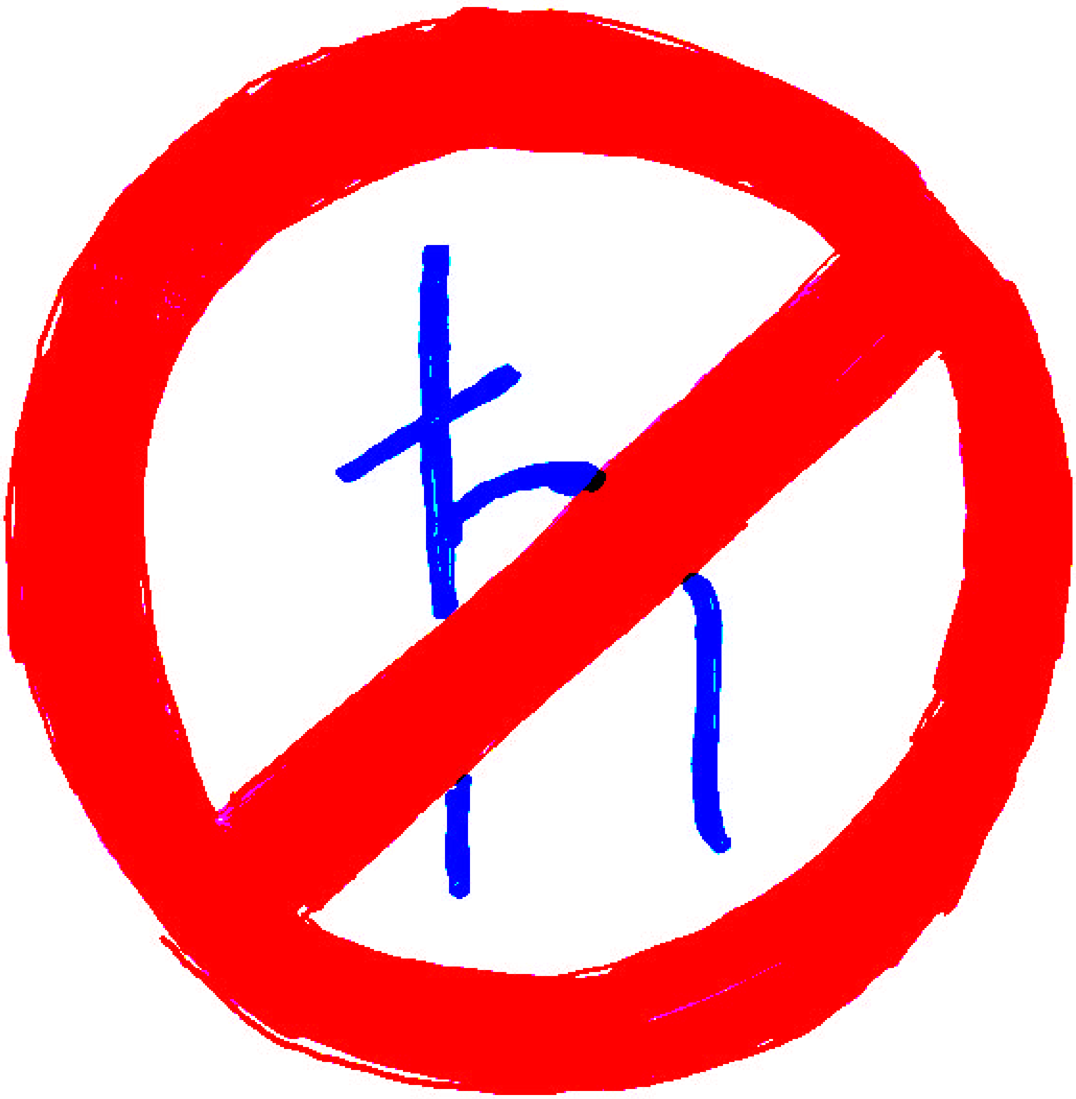
$\Omega_V = .73$

$\Omega_r = 8 \times 10^{-5}$

$\Omega_b = .04$

$\Omega_{DM} = .23$

96% OF UNCERTAIN CHARACTER



COSMOLOGY AND QUANTUM GRAVITY

- AT THE BIG BANG PLANCK ENERGIES ARE REACHED $E_p = \left(\frac{c^5}{\hbar G} \right)^{1/2}$ CHARACTERISTIC OF QUANTUM FLUCTUATIONS IN GEOMETRY AND THE CONJECTURED SCALE OF THE UNIFICATION OF ALL FORCES.

- AT THE BIG BANG WE ARE CLOSEST TO THE QUANTUM INITIAL CONDITION OF THE UNIVERSE. Ψ

- AT THE BIG BANG, LARGE AND SMALL ARE ONE.

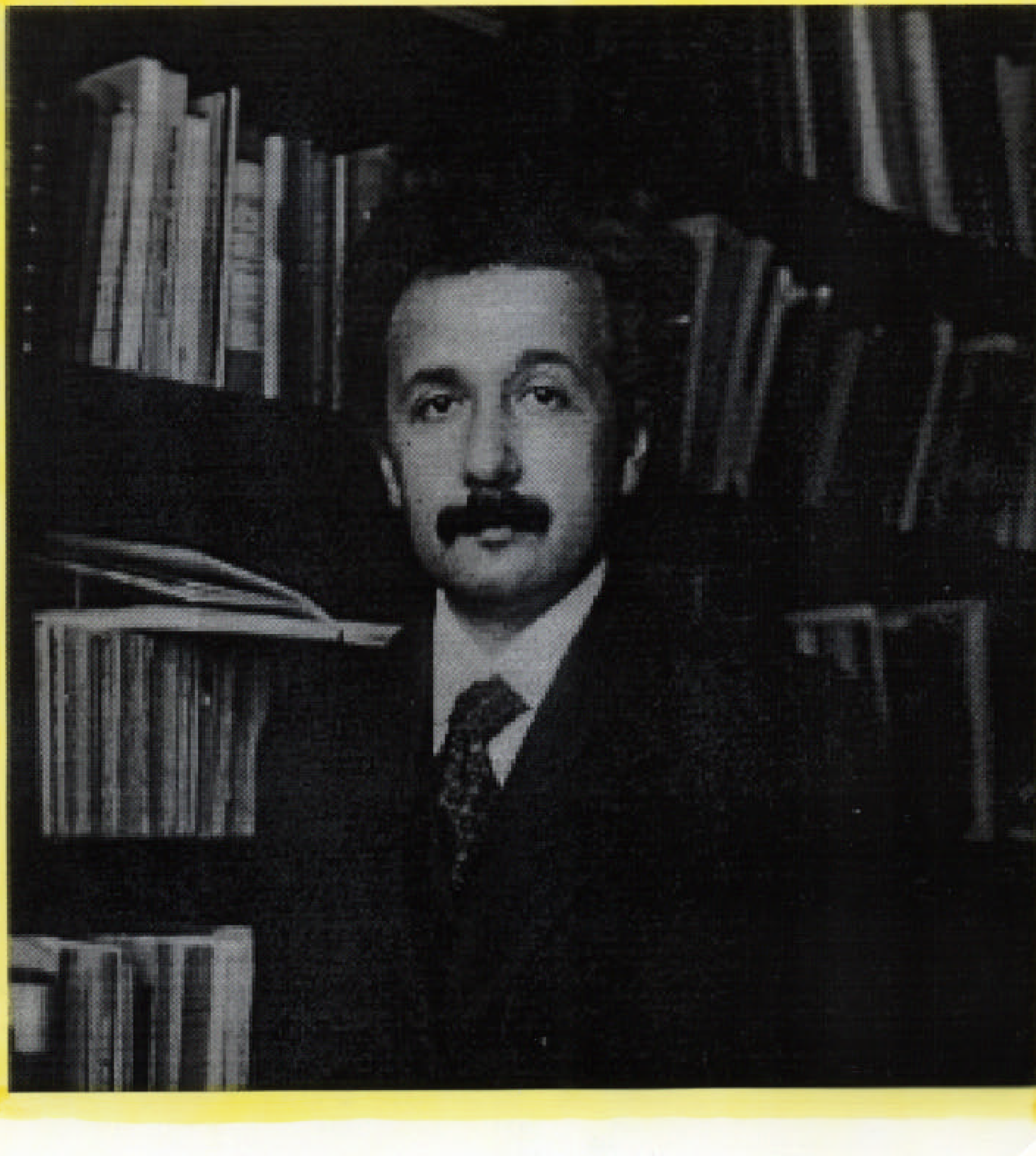
THIS DECADE AND THE NEXT

- THE DIRECT DETECTION OF GRAVITATIONAL WAVES AND THEIR APPLICATION TO PROBE REGIONS OF STRONG GRAVITY
- VERIFICATION OF THE DETAILED PREDICTIONS OF GR FOR THE GEOMETRY OUTSIDE BLACK HOLES.
- TESTS OF GENERAL RELATIVITY ON COSMOLOGICAL SCALES
- EXPLORATION OF THE LIMITS OF GENERAL RELATIVITY AND NEW PRECISSION TESTS.
- OBSERVATIONAL SIGNATURES OF QUANTUM GRAVITY.

A THEORY IS MORE IMPRESSIVE
THE GREATER THE SIMPLICITY
OF ITS PREMISES,
THE MORE DIFFERENT
KINDS OF THINGS IT RELATES,
AND THE MORE EXTENDED
ITS AREA OF APPLICABILITY.

A. EINSTEIN

ALBERT EINSTEIN



1916