引力波，引力波源、引力波探测

赵文
中国科学技术大学天文学系

内容提纲

- 广义相对论及其观测检验
- 引力波理论
- 引力波源
- 引力波探测

广义相对论及其观测检验

- 牛顿力学与伽利略变换

  牛顿三大运动定律+万有引力定律

  $x'=x-ut$, $y'=y$, $z'=z$, $t'=t$ (伽利略变换)

  $v'_x=v_x-u$, $v'_y=v_y$, $v'_z=v_z$ (速度是相对的)

  $a'_x=a_x$, $a'_y=a_y$, $a'_z=a_z$ (加速度是绝对的)

- 电动力学与光速不变

$\nabla\times H=J+\frac{\partial D}{\partial t}$	全电流定律
$\nabla\times E=-\frac{\partial B}{\partial t}$	法拉第电磁感应定律
$\nabla\cdot B=0$	磁通连续性原理
$\nabla\cdot D=\rho$	高斯定理

真空中的光速是个常数(绝对速度)

$$c=\frac{1}{\sqrt{\mu_0\varepsilon_0}}=2.99792458\times10^{8}\,\mathrm{m\,s^{-1}}$$

狭义相对论

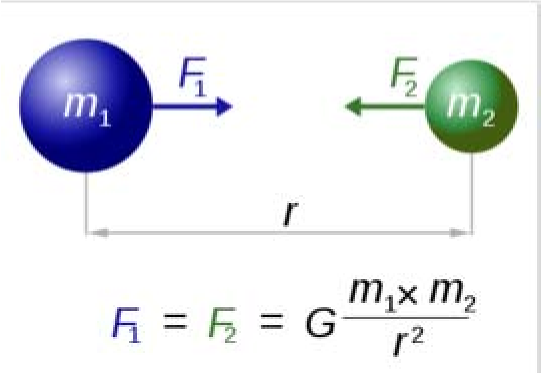
- 狭义相对论与洛仑兹变换

$$\begin{cases} x' = \dfrac{x - vt}{\sqrt{1-\frac{v^2}{c^2}}} \\ y' = y \\ z' = z \\ t' = \dfrac{t - \frac{v}{c^2}x}{\sqrt{1-\frac{v^2}{c^2}}} \end{cases}$$

任何物理规律都应该在"洛仑兹变换"下保持不变

任何物理方程中"时间"和"空间"处于对等的地位

- 万有引力定律与洛仑兹变换不相容



Warped Space and Time

Albert Einstein
1905 -- 1915

General Relativity:

- Space and time are warped by matter and energy
- That warping is responsible for gravity

Photo courtesy Albert Einstein Archives of the Hebrew University of Jerusalem

“度规”→ 描述时空的性质

- **3**维欧式空间

$$d\ell^2 = dx^2 + dy^2 + dz^2$$

- **3+1**维闵氏空间

$$ds^2 = -dt^2 + dx^2 + dy^2 + dz^2$$

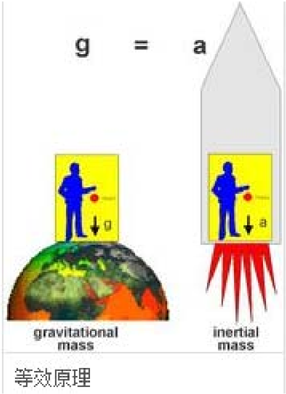
- **3+1**维弯曲时空

$$ds^2 = \sum_{i=0,3} \sum_{j=0,3} g_{ij} dx^i dx^j$$

广义相对论

- 等效原理

引力质量=惯性质量



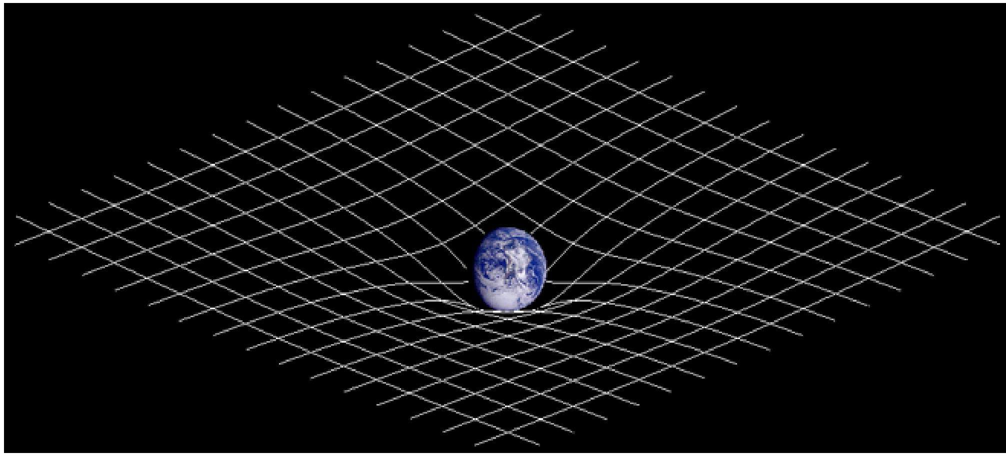
引力几何化

- 爱因斯坦场方程

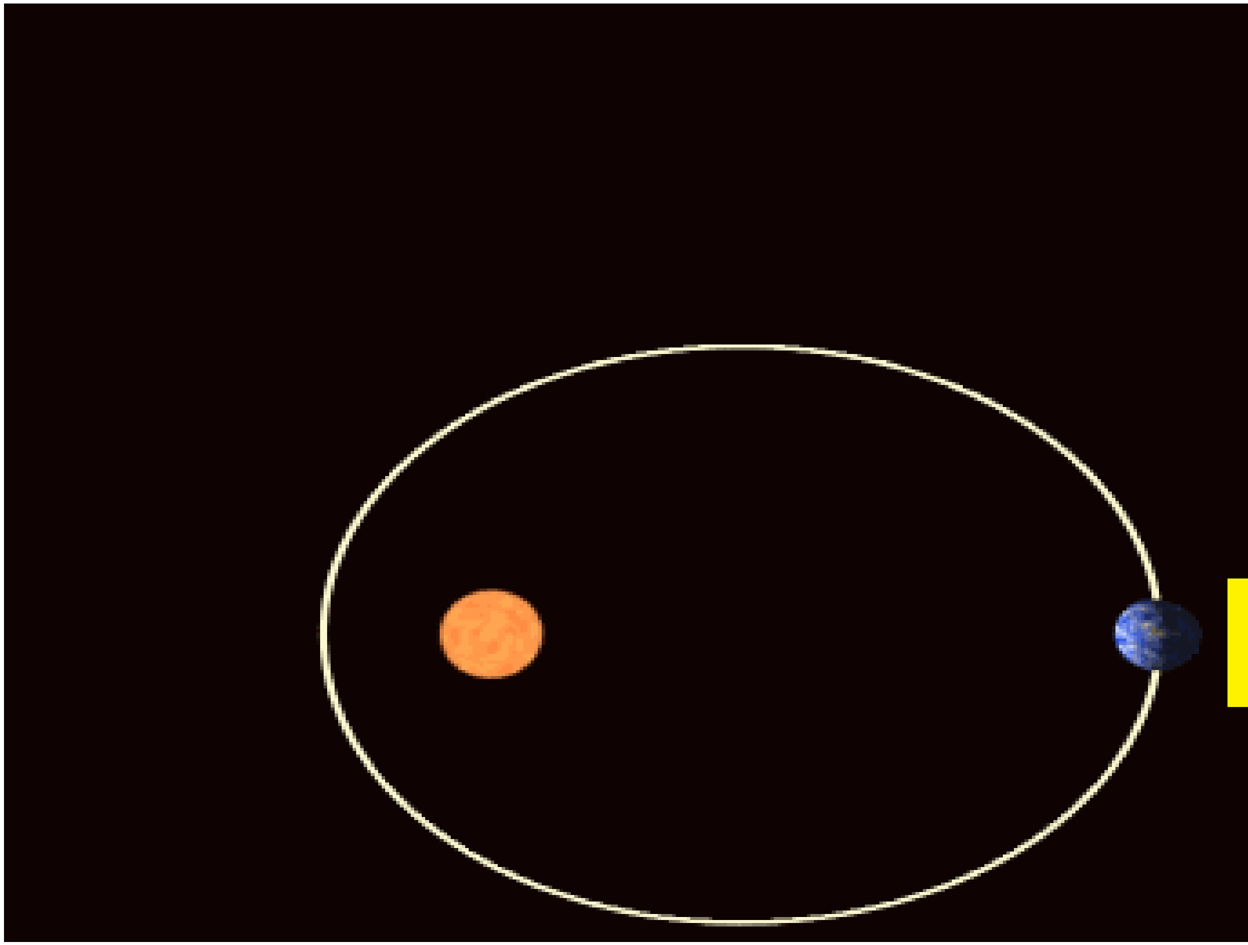
$$R_{\mu\nu} - \frac{1}{2}R\,g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

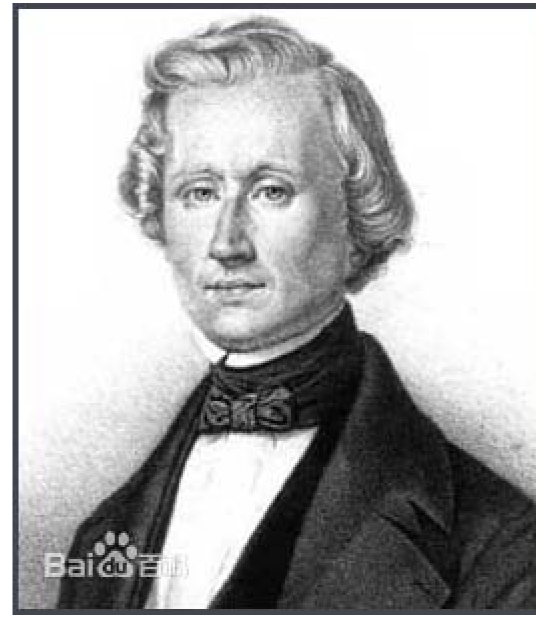
$$R_{\alpha\beta} = R^{\rho}{}_{\alpha\rho\beta} = \partial_\rho \Gamma^\rho_{\beta\alpha} - \partial_\beta \Gamma^\rho_{\rho\alpha} + \Gamma^\rho_{\rho\lambda}\Gamma^\lambda_{\beta\alpha} - \Gamma^\rho_{\beta\lambda}\Gamma^\lambda_{\rho\alpha}$$

$$\Gamma^{i}{}_{k\ell} = \frac{1}{2}g^{im}\left(\frac{\partial g_{mk}}{\partial x^\ell} + \frac{\partial g_{m\ell}}{\partial x^k} - \frac{\partial g_{k\ell}}{\partial x^m}\right)$$



广义相对论的验证: 水星近日点进动





法国天文学家勒威耶（海王星的发现者之一）

1859年发现了水星近日点进动现象

”火神星”，

你在哪里？

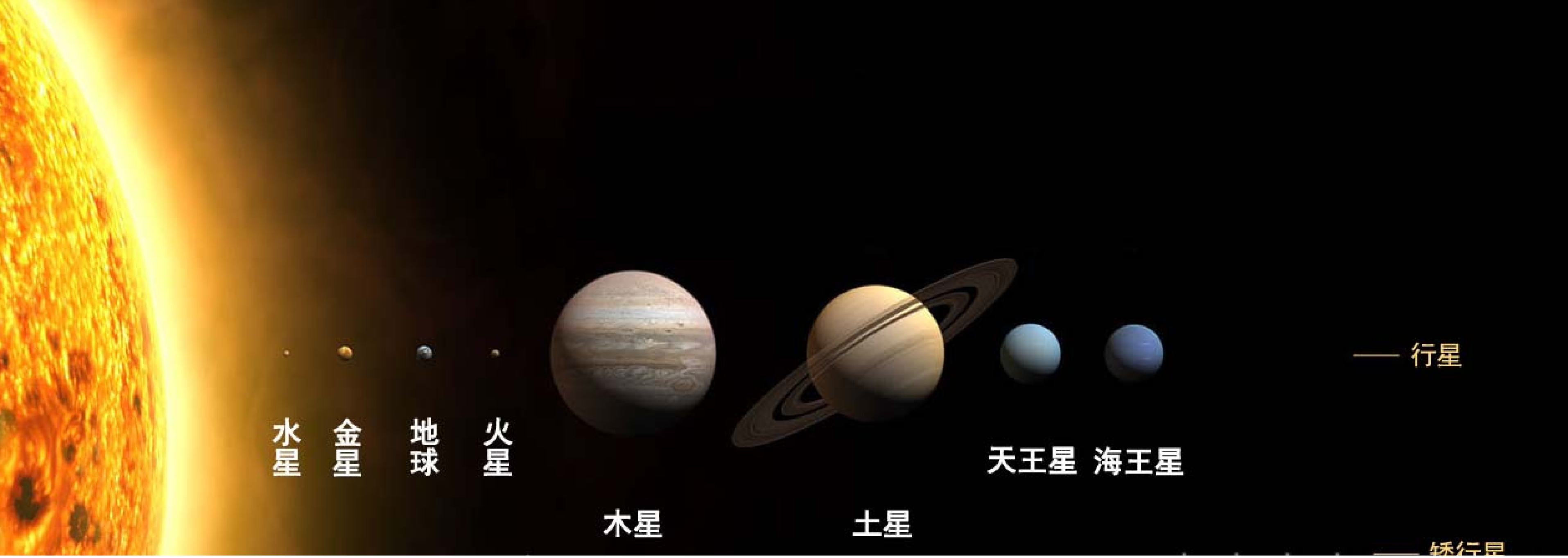
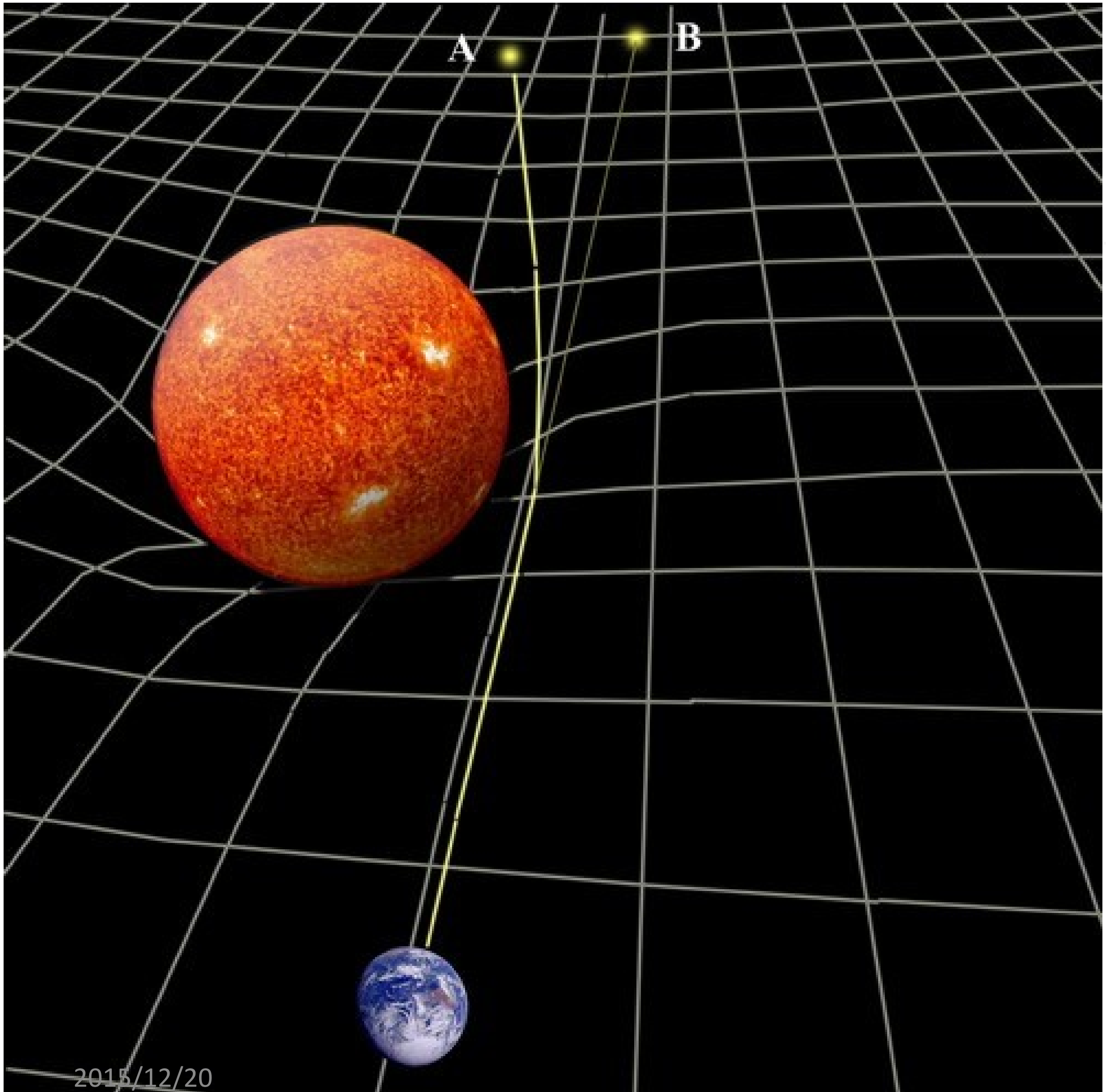
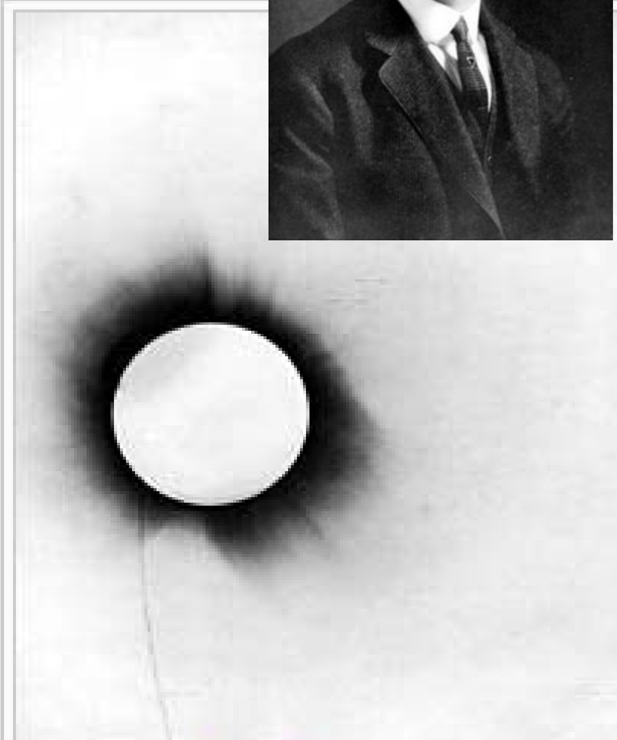


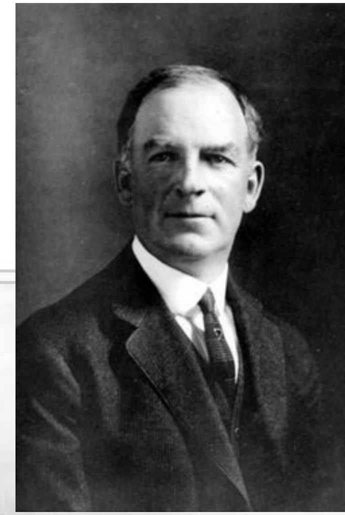
表 8.3　行星轨道每百年进动的理论值和观测值比较

行　星	a (10^6 km)	e	$\frac{6\pi MG}{L}$	圈/百年	$\Delta\varphi$（秒/百年）	
					广义相对论	观测值
水星(☿)	57.91	0.2056	0.1038″	415	43.03	43.11±0.45
金星(♀)	108.21	0.0068	0.058″	149	8.6	8.4±4.8
地球(⊕)	149.60	0.0167	0.038″	100	3.8	5.0±1.2
Icarus 星	161.0	0.827	0.115″	89	10.3	9.8±0.8

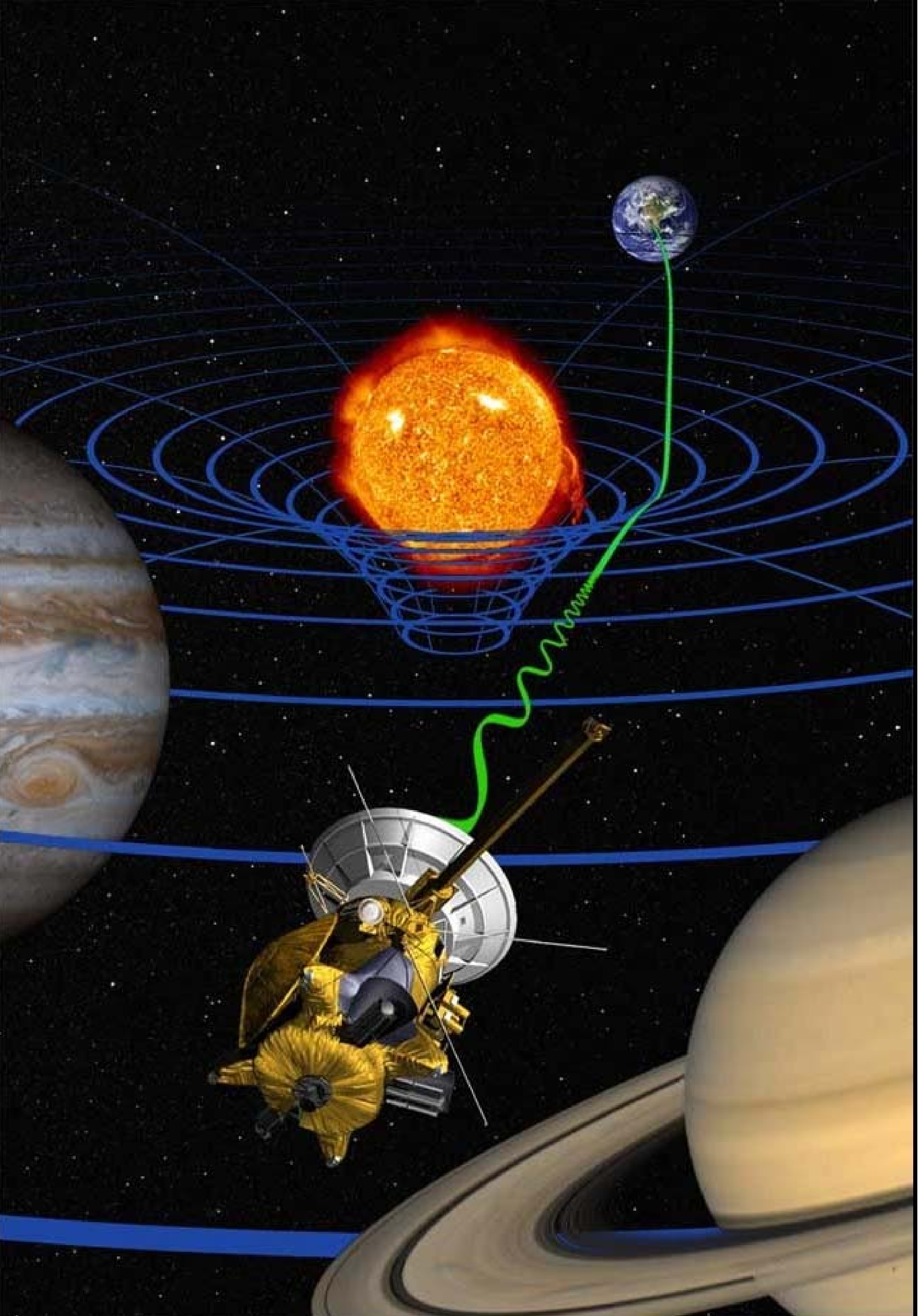
广义相对论的验证: 光线偏折







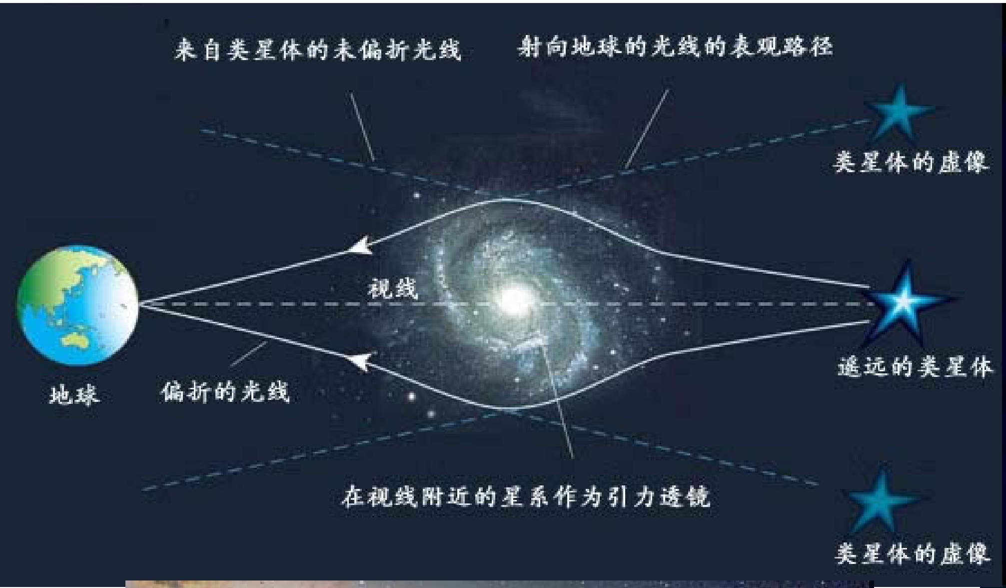
1919年亚瑟・爱丁顿爵士所测里的星光在太阳引力场中的偏折实验使得广义相对论在全世界范围内被广为接受

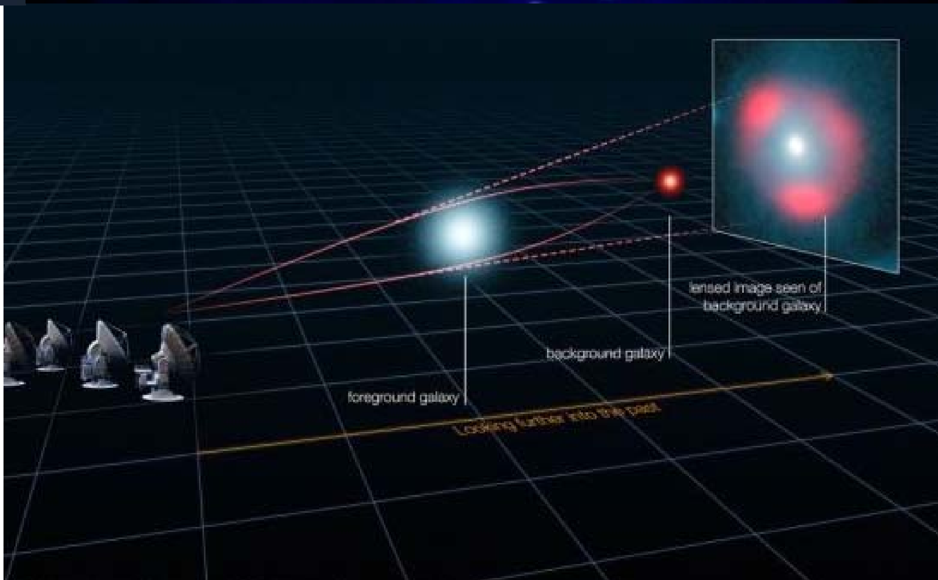


雷达回波延迟

High-precision test of general relativity by the Cassini space probe (artist's impression): radio signals sent between the Earth and the probe (green wave) are delayed by the warping of spacetime (blue lines) due to the Sun's mass.

光线偏折,引力透镜,爱因斯坦环





引力波理论

- **Maxwell**从理论上预言电磁波的存在(**1865**年)，**Hertz**发现电磁波(**1888—**利用振荡电偶极子发射**EMW**，利用共振电偶极子接收**EMW)**。

- **Einstein**（**1916**）从理论上预言引力波的存在，谁去发现引力波呢？**----**“理论家的天堂，实验家的地狱”？？！！

爱因斯坦广义相对论的引力场方程

$$R_{\mu\nu}-\frac{1}{2}g_{\mu\nu}R=\frac{8\pi G}{c^4}T_{\mu\nu}$$

广义相对论是一种把时空结构几何化的引力理论，它认为，物质分布将影响时空的几何结构，而时空结构又会反过来影响物质的分布。

$g_{\mu\nu}$ ——描述时空结构,平直时空为 $\eta_{\mu\nu}=\begin{pmatrix}1&0&0&0\\0&-1&0&0\\0&0&-1&0\\0&0&0&-1\end{pmatrix}$

$T_{\mu\nu}$ ——描述物质分布

弱场近似下，上述方程退化为：

$$\Box h_{\mu\nu} = \frac{16\pi G}{c^4}\left(T_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu}T\right)$$

此时的时空结构为平直时空度规再加上一个微扰 $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$
在无质量时空区域可简化为常见的波动方程：

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)h_{\mu\nu} = 0$$

与电磁场波动方程作一比较，作一由此及彼的推测，应该能够得到什么？

电磁波不存在单极辐射，至少是电偶极辐射；而引力波不存在单极和偶极辐射，至少是质量四极矩辐射。因此强度非常弱！

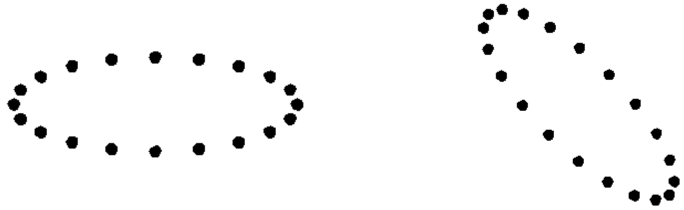
$$-\frac{dE}{dt}=\frac{K}{45c^5}\left(\frac{d^3D_{ik}}{dt^3}\right)\left(\frac{d^3D_{ik}}{dt^3}\right)$$

$$D_{ik}=\int\mu(3x_i x_k-\delta_{ik}x_j x_j)dV$$

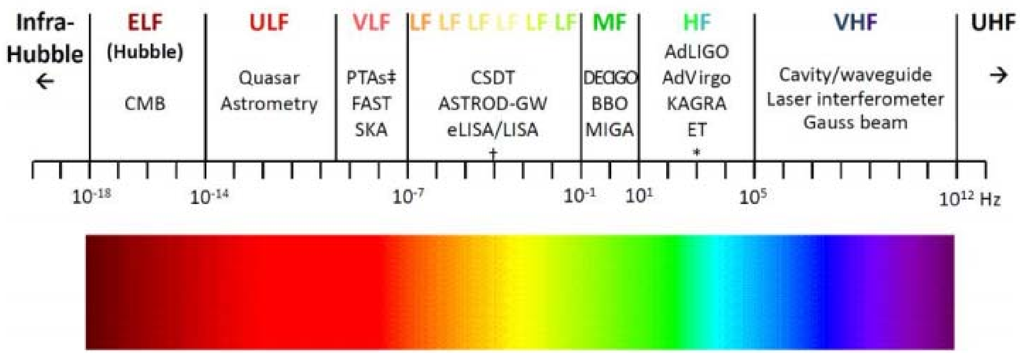
重复指标表示求和，每个指标由1到4(时间1维，空间3维)。

- 从理论上预言了引力波的存在，它以光速传播。
  由波动方程直接导出。
- 引力波是横波。
  原因是取谐和坐标，并假定引力波沿某一方向（比如X方向）传播，则它只对Y方向和Z方向的度规造成扰动。
- 不存在单极和偶极引力辐射。
  引力波带有能量，可以被探测，但引力辐射的最低极矩是四极矩，这就是为什么引力波非常弱而难以探测的原因。

- 在GR中，引力波有两种偏振模式，分别是“正极化”和“叉极化”

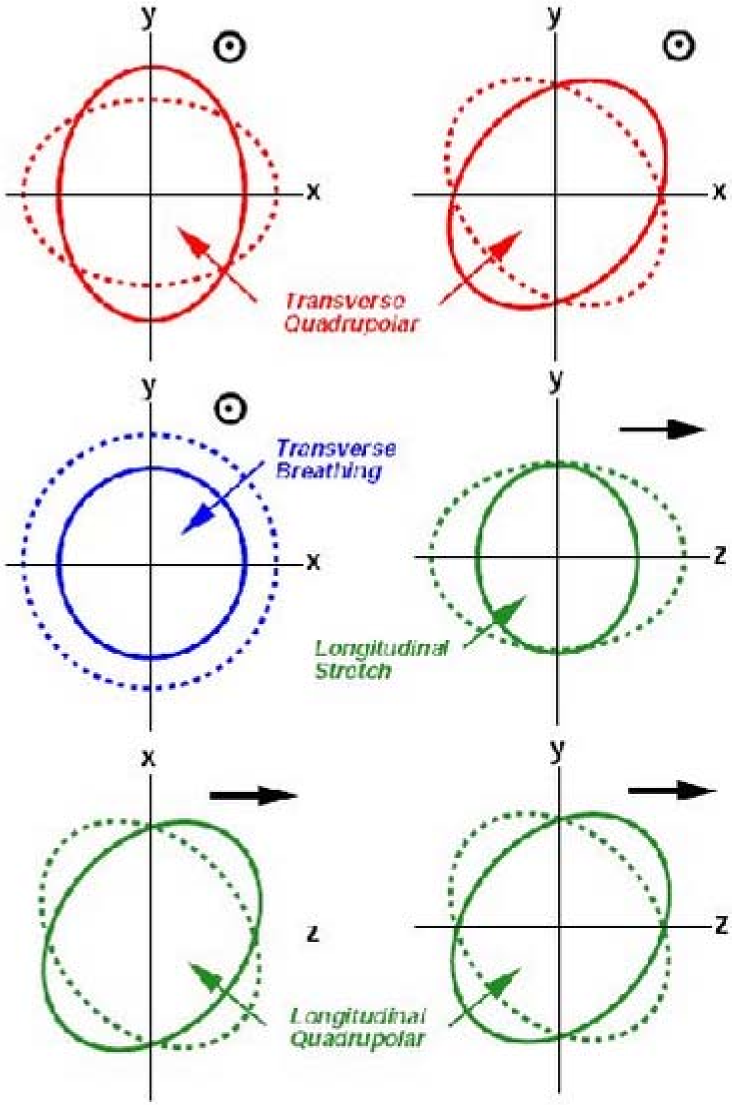


- 相对于电磁波来说，一般引力波都是“长波”，也就是说我们实际上是在“听”引力波，而不是“看”引力波。



- 探测器真正探测是的引力波的振幅|h|，而不是能流，这也是和电磁波探测不一样的地方。因此探测器的灵敏度提高一个量级，其探测的宇宙空间范围将增大“3个量级”！

Beyond Einstein



引力波探测与相对论检验

GR = Newton Theory + terms (v) + terms (v^2) + ……

- perihelion advance of mercury (1915, v≈ 1.0e-10)
- Light bending (1919, v≈1.0e-6)
- Gravitational redshift (1965, v≈1.0e-10)
- Gravitational time delay (1968, v≈1.0e-10)
- Indirect evidence of GW (1978, v≈1.0e-6)
- Gravitational draging (2010, v≈1.0e-10)
- GW detection (?, v≈1)

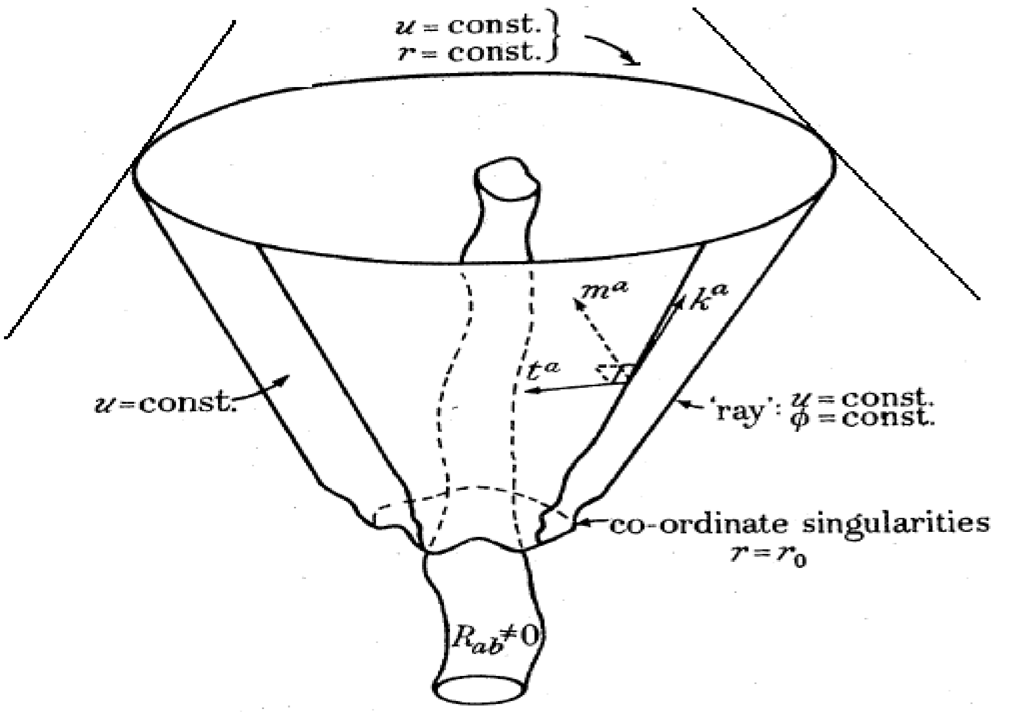
Einstein与引力波

- **1915,　general relativity**
- **1916-2, based on post-Newtonian approximation, claimed "there are no gravitational waves analogous to light waves"**
- **1916-10, based on linear approximation found monopole radiation. 1918, corrected it to quadruple radiation**
- **1936, showed that GW does not exist**

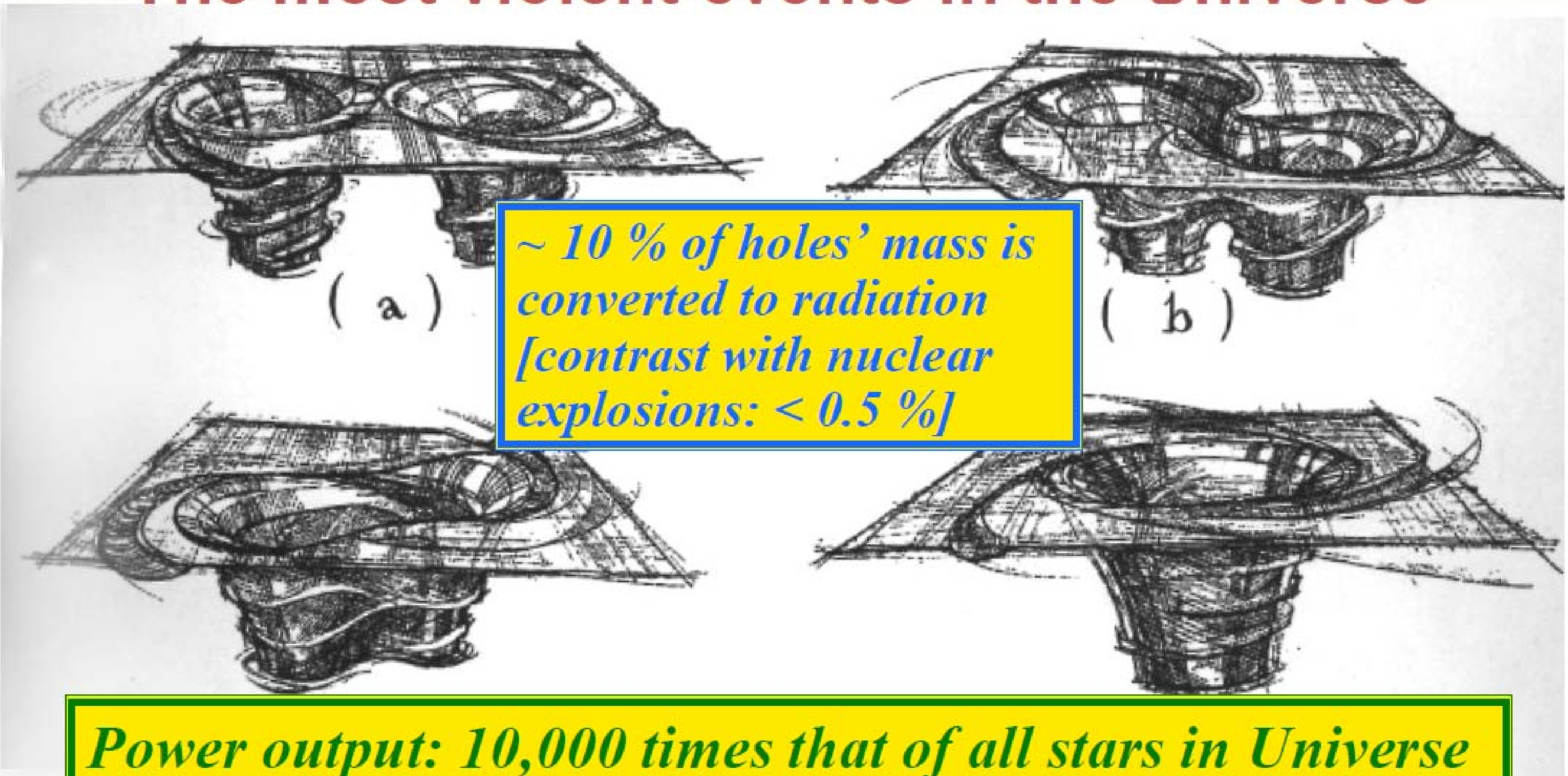
引力波存在吗（理论上）？

- **1936-1962, debate**

- **1962, Bondi convinced people the existence of GW**



Collisions of Black Holes: The most violent events in the Universe

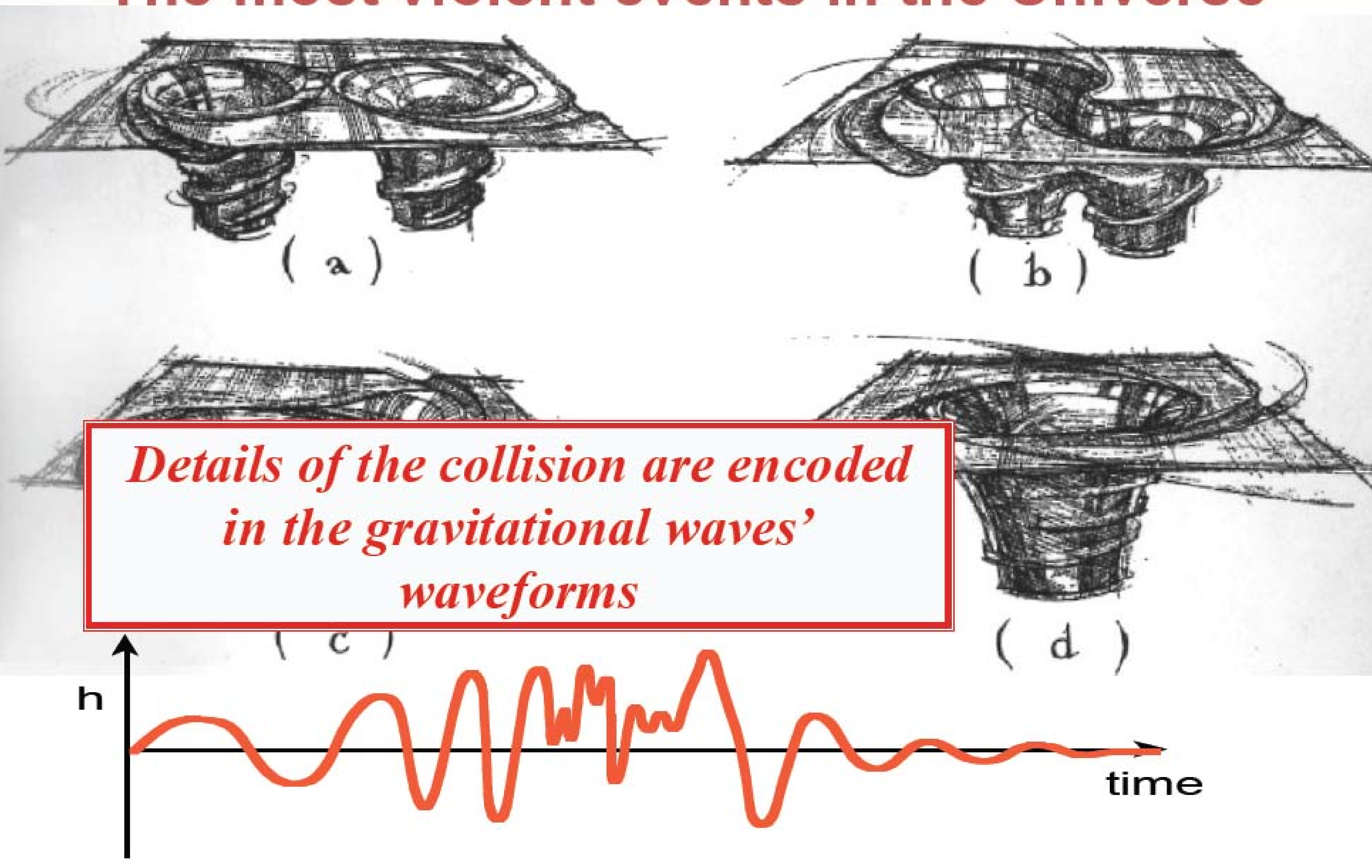


~ 10 % of holes' mass is converted to radiation [contrast with nuclear explosions: < 0.5 %]

Power output: 10,000 times that of all stars in Universe

No Electromagnetic Waves emitted whatsoever

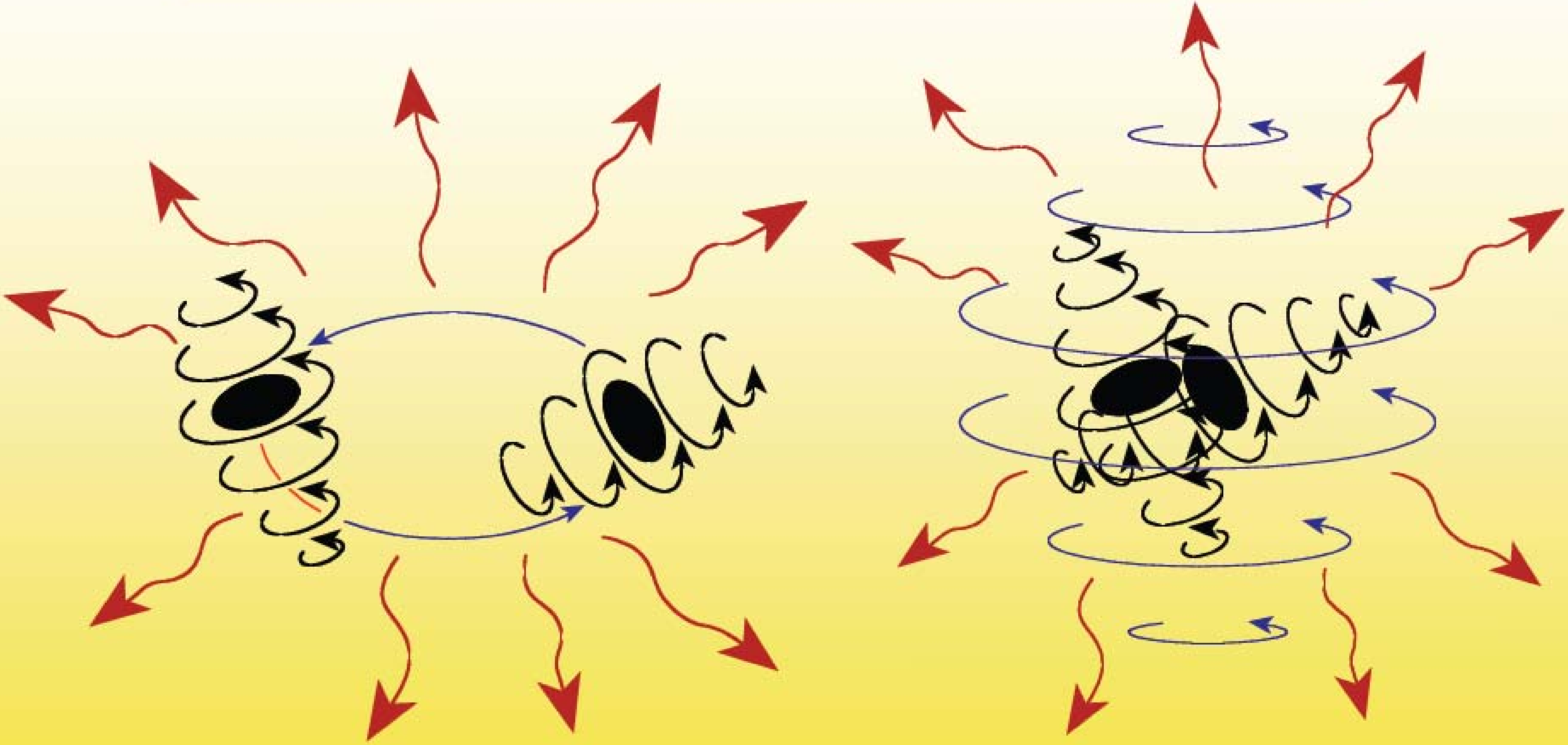
Collisions of Black Holes: The most violent events in the Universe

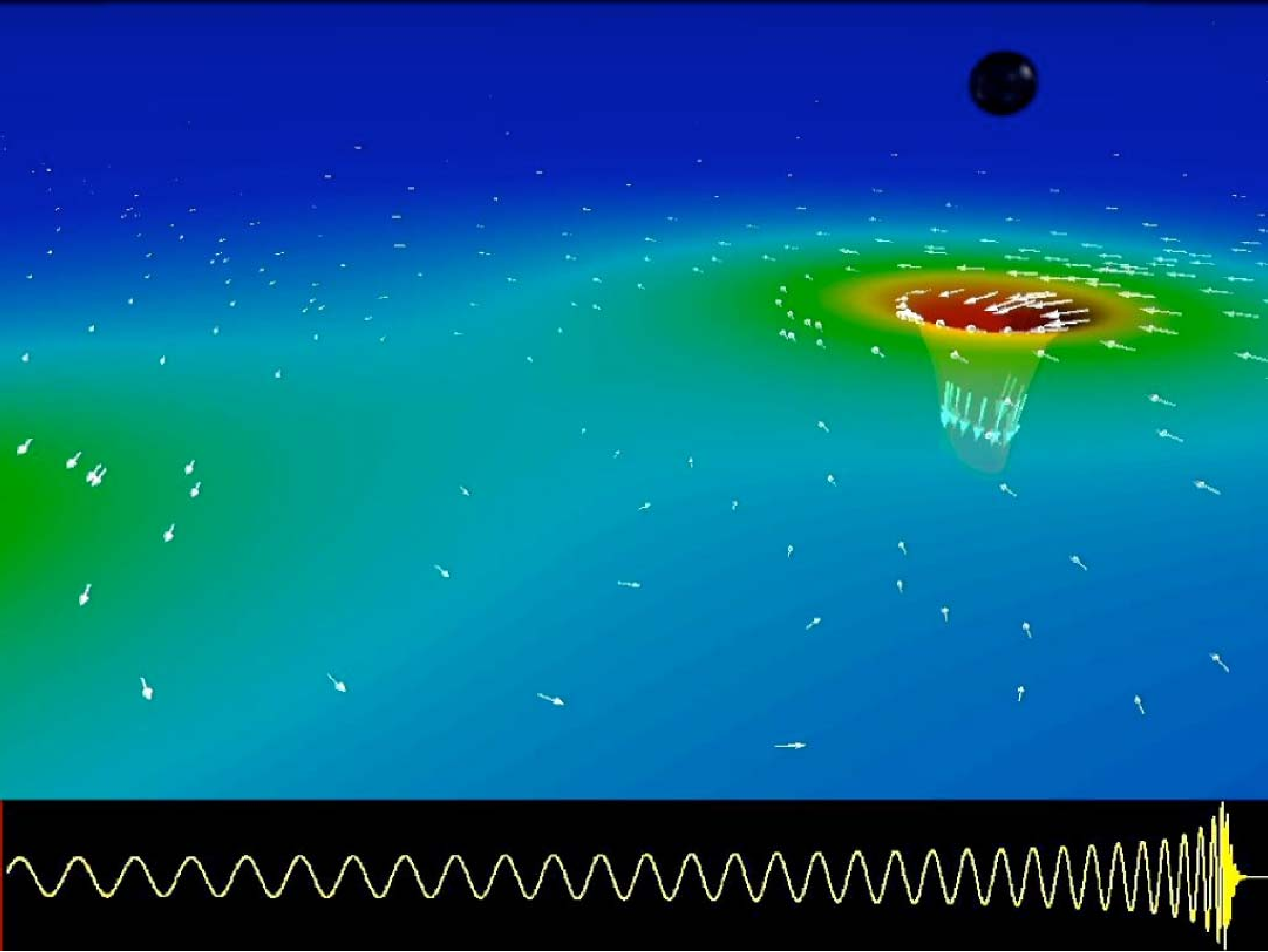


Details of the collision are encoded in the gravitational waves' waveforms

Why are Black-Hole Collisions Interesting?

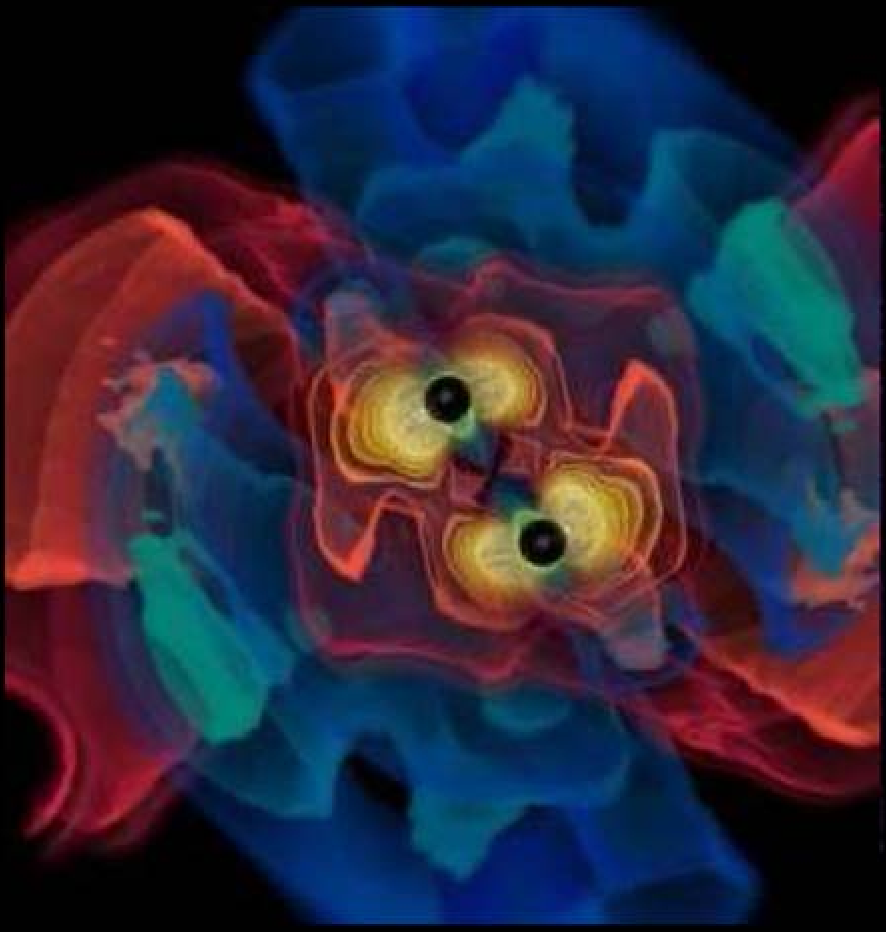
Wild vibrations of warped spacetime





Astronomical Sources

- Compact binary mergers
  - Binary neutron stars
  - Binary black holes
  - Black hole-neutron star binaries
- Gravitational wave bursts
  - Black hole collisions
  - Supernovae
  - gamma-ray bursts
- Continuous waves
  - Rapidly spinning neutron stars or other objects
- Stochastic background
  - Primordial background
  - Astrophysical background



超新星爆发

时间/年	方位	视星等	距离/光年
185	半人马座	-8.0	9800
369	仙后座	-3.0	暂无数据
386	人马座	1.5	16000
393	天蝎座	0.0	34000
1006	豺狼座	-9.5	3500
1054	金牛座	-5.0	6500
1181	仙后座	0.0	8800
1572	仙后座	-4.0	7500
1604	蛇夫座	-3.0	12500
1987	箭鱼座（大麦哲伦星系）	2.8	160000
2014	大熊座（M82）	8	12000000

蟹状星云与SN 1054

凡十一日沒三年三月乙巳出東南方大中祥符四
年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅
前星西北大如桃速行經軒轅大星入太微垣掩右執
法犯次將歷屏星西北凡七十五日入濁沒明道元
年六月乙巳出東北方近濁有芒彗至丁巳凡十三
日沒至和元年五月己丑出天關東南可數寸歲餘
稍沒熙寧二年六月丙辰出箕度中至七月丁卯犯
箕乃散三年十一月丁未出天囷元祐六年十一月
辛亥出參度中犯掩側星壬子犯九游星十二月癸
酉入奎至七年三月辛亥乃散紹興八年五月守婁

宋史志卷九

SN1987A

1987年2月

Figure 7.10 Supernova 1987A in the Large Magellanic Cloud. Image: European Southern Observatory.

超新星 SN 1987A 的中微子记录

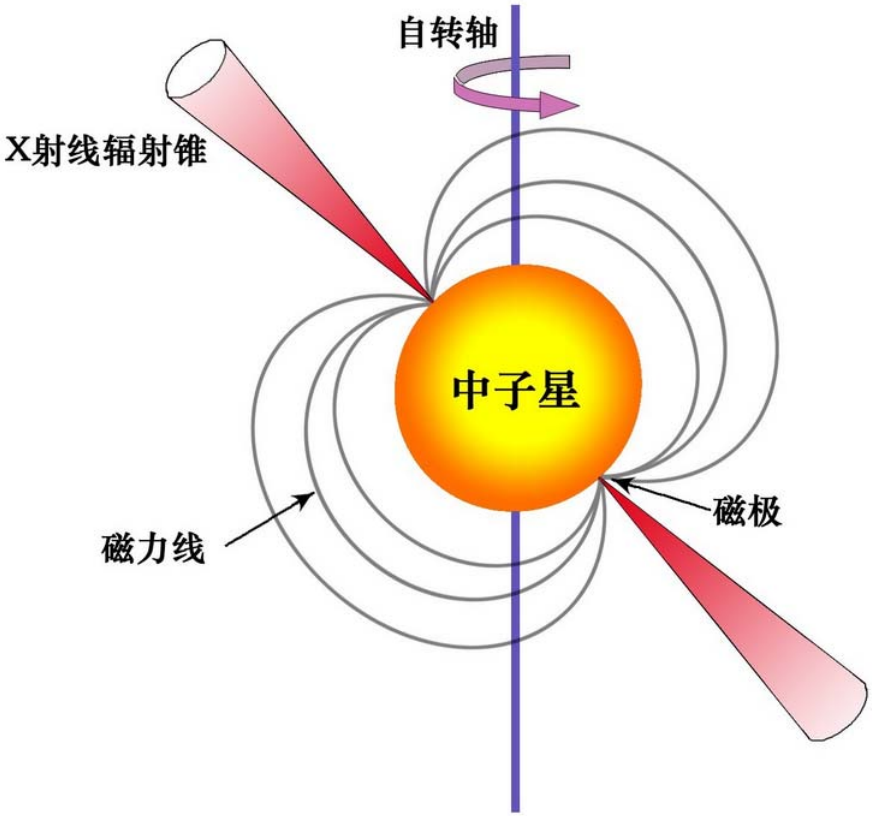
探测器地点	中微子数目	持续时间
日本神冈，铅矿	11	12.439s
美国俄亥俄，莫顿盐矿	8	5.58s
USSR, 巴克衫	5	不确定性～1min
意大利，Gran Sasso	5?	(中微子比光学爆发提前4.6h，但其他组为3h）

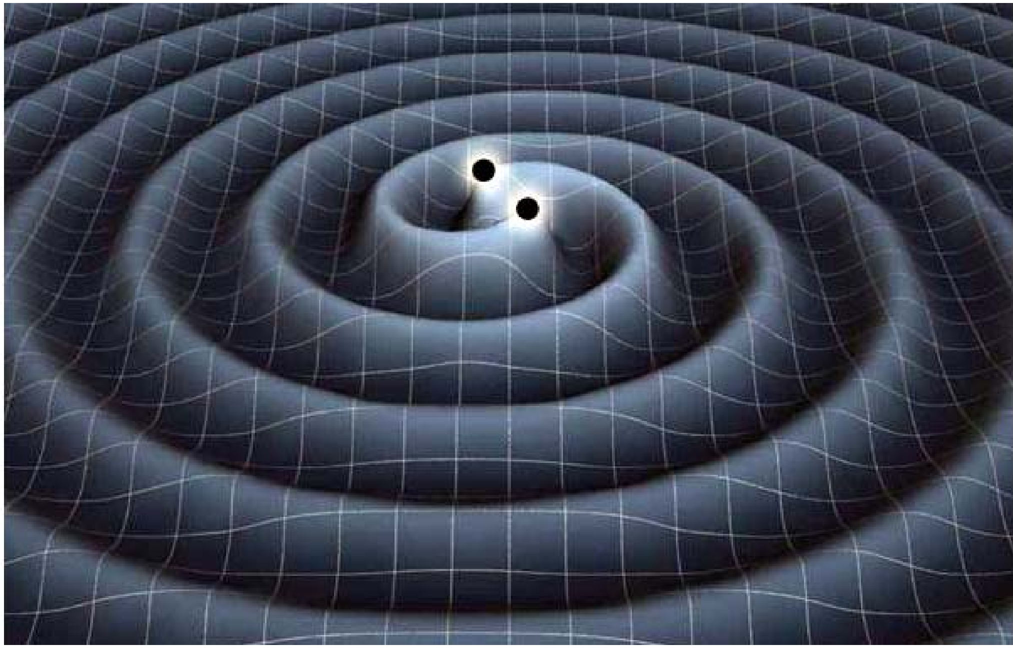
观测到来自SN1987A中微子的意义：

1）验证了核塌缩超新星爆发的图像：~10^{58}个中微子

2）得到了中微子质量的上限：~7-16eV

致密星体





- Luminosity:

$$P = \frac{G}{5c^5} < \dddot{Q}^{ij}\dddot{Q}_{ij} > \approx \varepsilon \cdot \frac{c^5}{G}\left(\frac{R_S}{R}\right)^2\left(\frac{v}{c}\right)^6$$

- Amplitude:

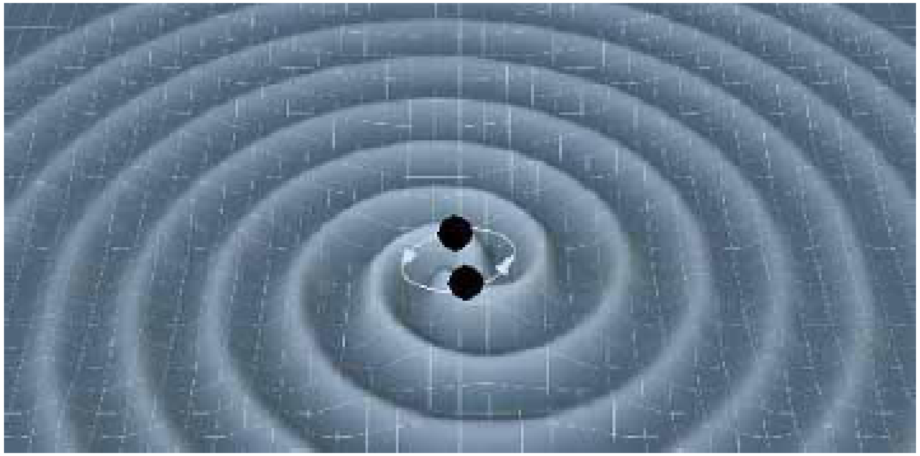
$$h_{\mu\nu} = \frac{2G}{c^4} \cdot \frac{1}{r}\ddot{Q}_{\mu\nu}$$

Compactness C

1	for BH
0.3	for NS
10^{-4}	for WD

Efficient sources of GW must be asymmetric, compact and fast

GW detectors sensitivity expressed in amplitude h : $1/r$ attenuation

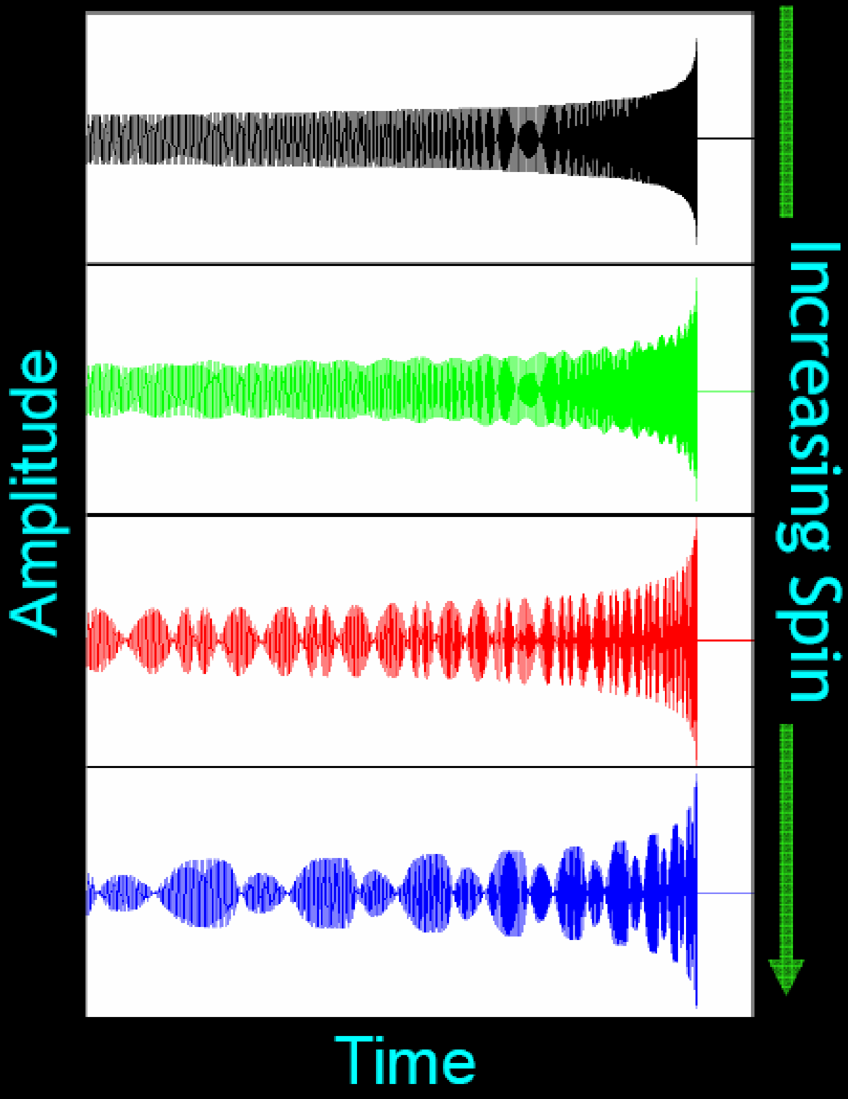


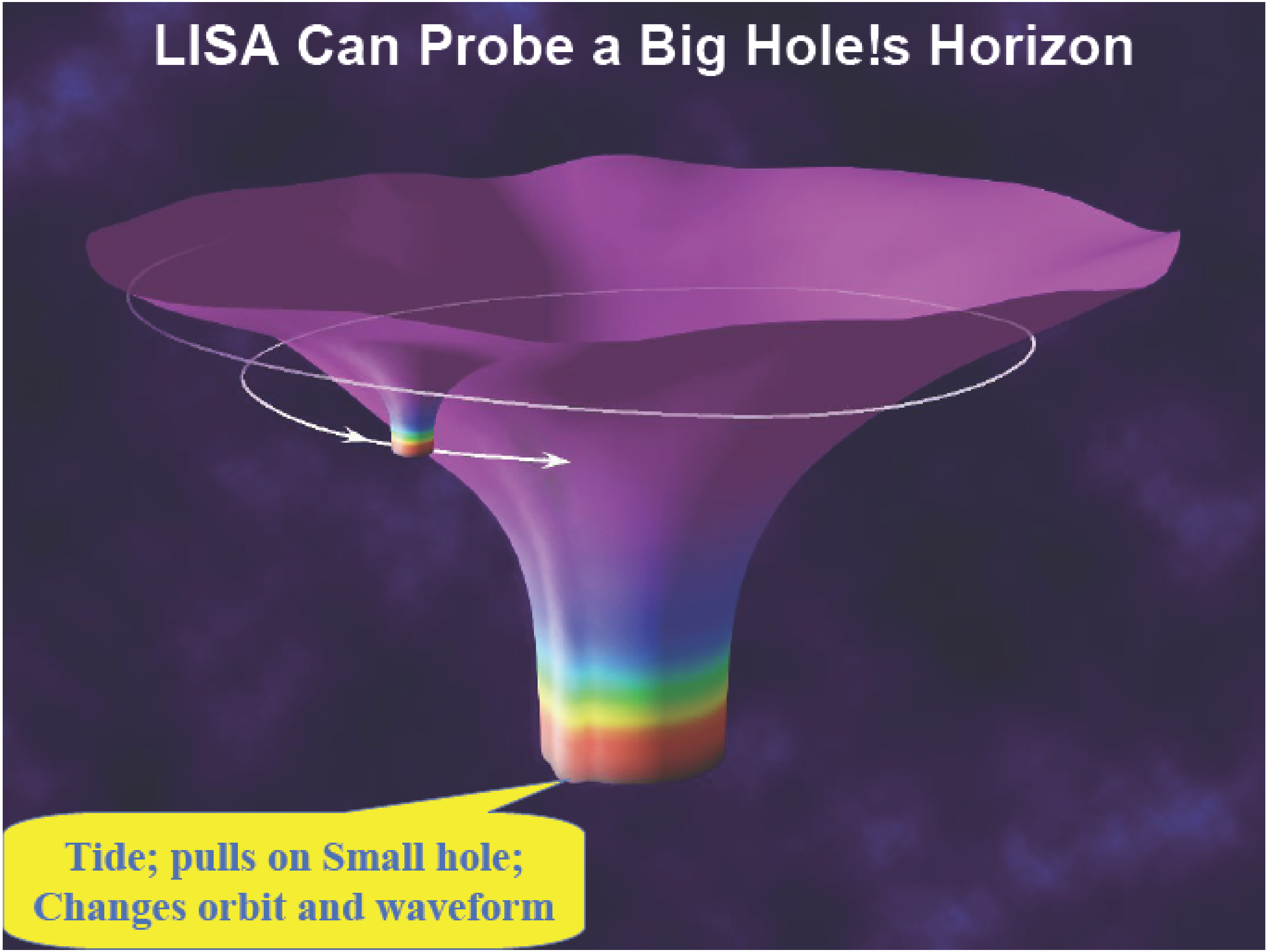
Example target amplitude:
coalescing NS/NS in the Virgo cluster
(r ~10 Mpc)

➡ $h \sim 10^{-21}$

Targeting the biggest discovery of our times through ARCCA

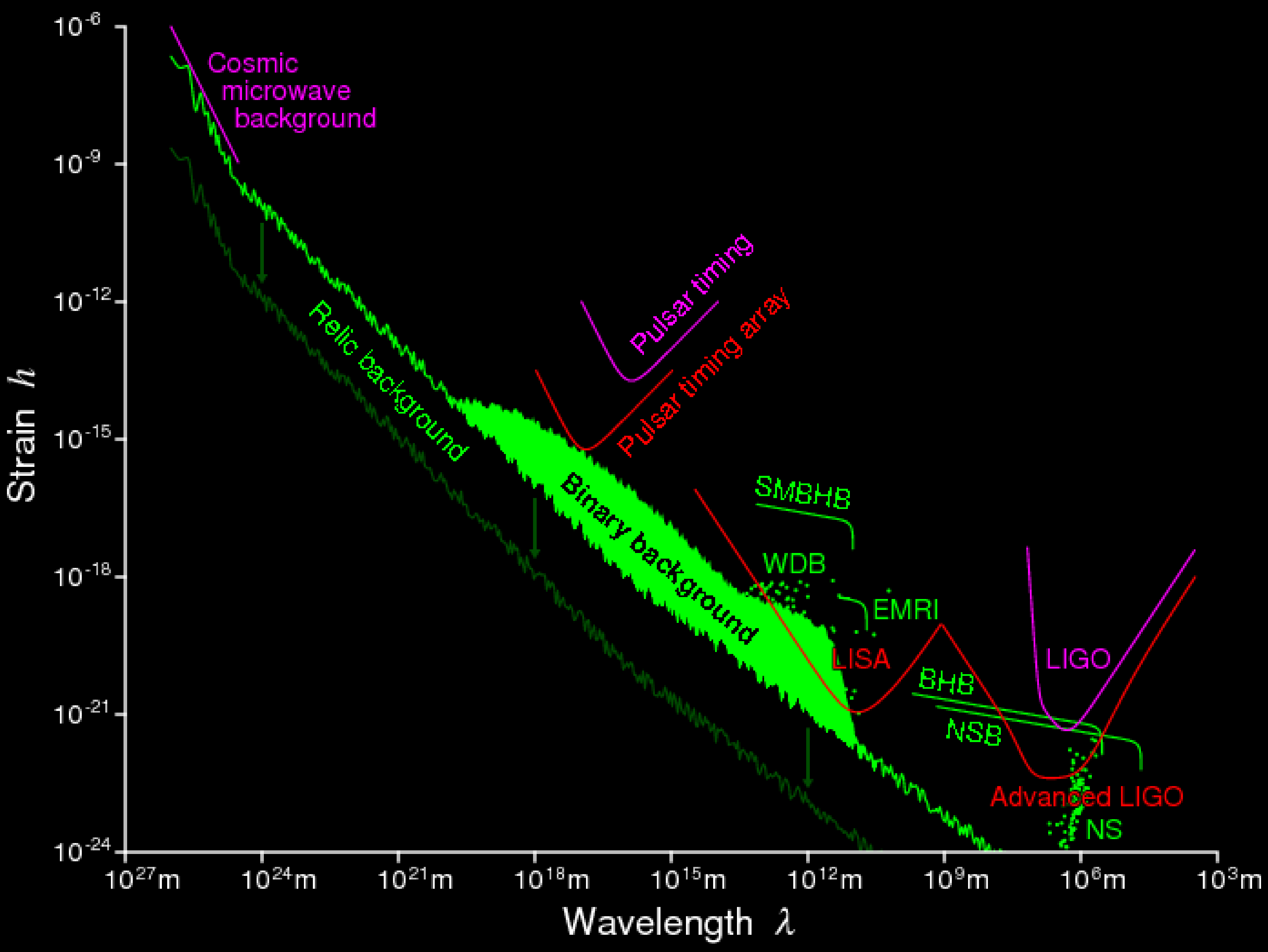
- Here are some signals from colliding black holes as predicted by Einstein's theory
  - Black hole spins modulate the waveform
- We use matched filtering to search for signals buried in noise
  - Pattern matching algorithm
- But matched filters, i.e. templates used in the search, depend on many parameters
  - A search in 17-dimensional space involving the masses, spins of the stars, position on the sky, etc.
- About 100 million shapes must be searched for in each piece of data




LISA Can Probe a Big Hole!s Horizon
Tide; pulls on Small hole;
Changes orbit and waveform

引力波“背景”

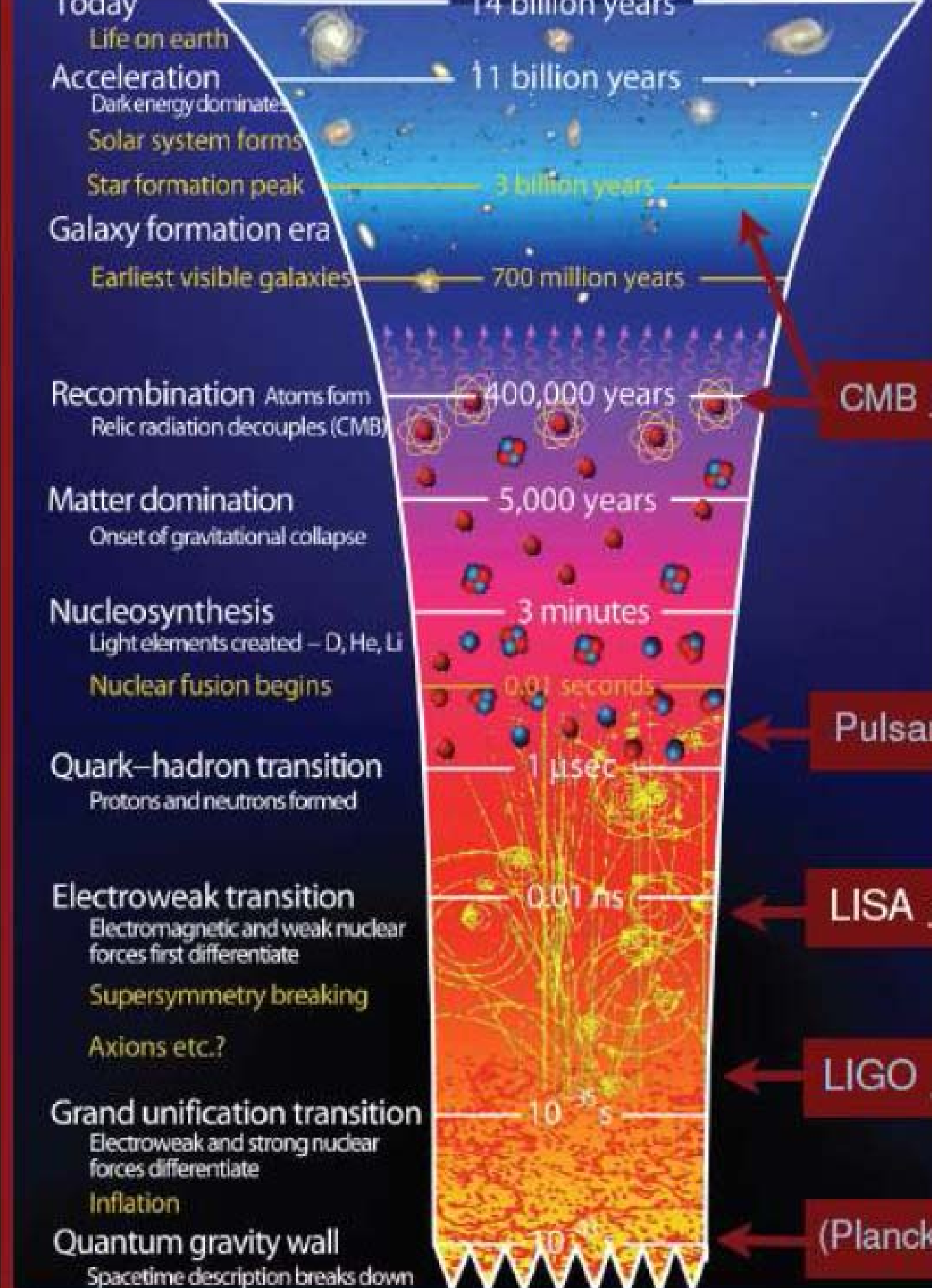
- 天体物理起源的“背景”
- 宇宙学起源的“背景”



Cosmic microwave background
Pulsar timing
Pulsar timing array
Relic background
Binary background
SMBHB
WDB
EMRI
LISA
BHB
NSB
LIGO
Advanced LIGO
NS
Strain h
Wavelength λ
10^-6
10^-9
10^-12
10^-15
10^-18
10^-21
10^-24
10^27m
10^24m
10^21m
10^18m
10^15m
10^12m
10^9m
10^6m
10^3m

Slide by: P Shellard

A brief history of the Universe



CMB $f < 3 \times 10^{-17} h$ Hz probes 300,000yrs $< t_e <$ 14 Gyrs

Pulsars $f \sim 10^{-8}$Hz probe $t_e \sim 10^{-4}$s ($T \sim 50$MeV)

LISA $f \sim 10^{-3}$Hz probes $t_e \sim 10^{-14}$s ($T \sim 10$TeV)

LIGO $f \sim 100$ Hz probes $t_e \sim 10^{-24}$s ($T \sim 10^{8}$GeV)

(Planck scale $f \sim 10^{11}$Hz has $t_e \sim 10^{-43}$s ($T \sim 10^{19}$GeV)

宇 宙 暴 涨

- 标准大爆炸宇宙学模型遇到的困难

均匀性疑难？平坦性疑难？视界疑难？磁单极子疑难？

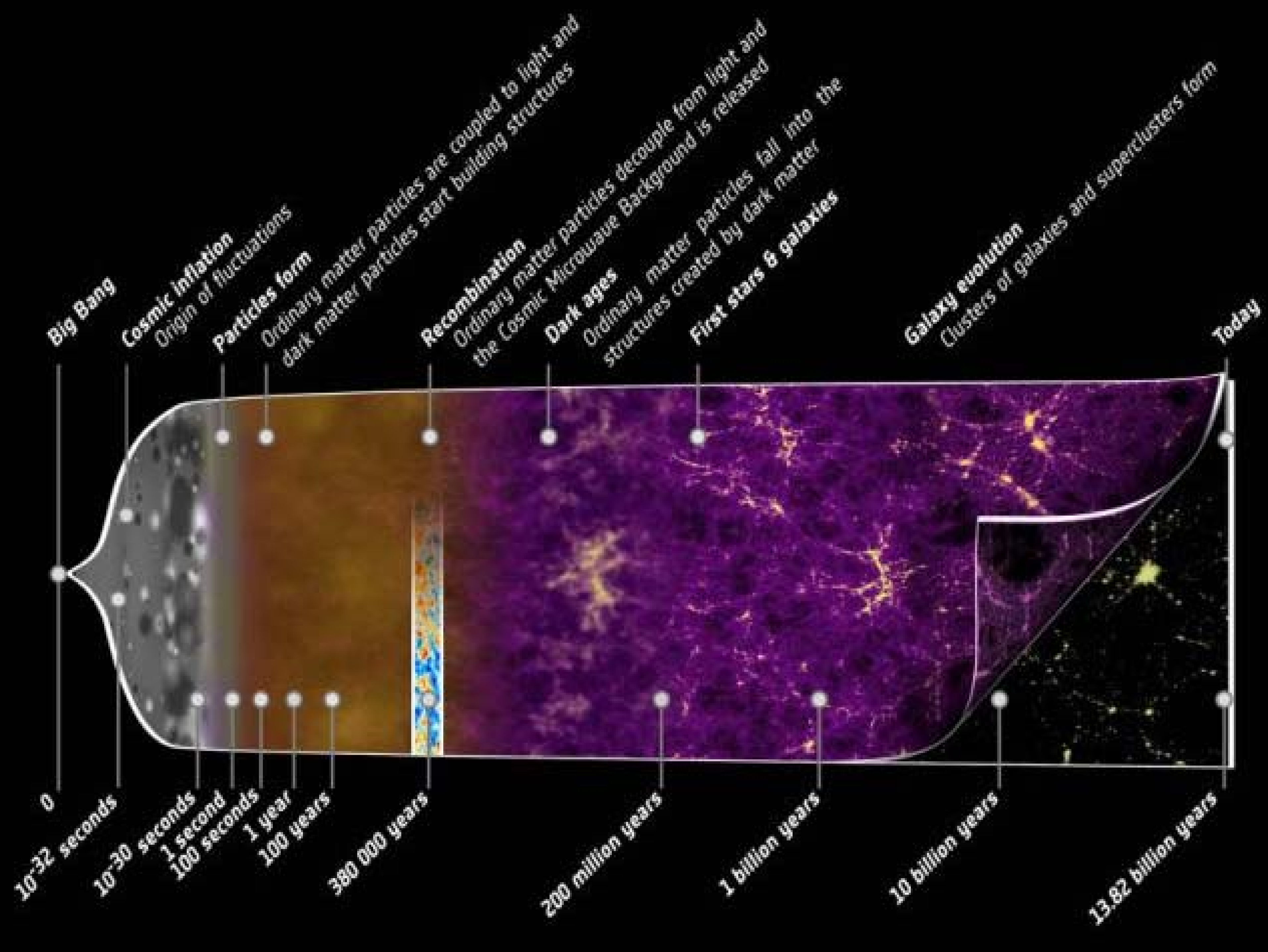
- 1980年，A. Guth提出第一个暴涨模型

  解决了上述所以疑难

  提供了宇宙结构形成的种子

  预言了原初扰动谱的存在（已经证实）

温度（K）	时间（秒）	时代(物理过程)	
10^{32}	10^{-44}	普朗克时代	“受精”
	$10^{-35,-33}$	暴胀阶段	“分娩”
??????	??????	物质生成	“诞生”
10^{13}	10^{-6}	强子时代	少年时代
10^{11}	10^{-2}	轻子时代	
10^{10}	1	中微子脱耦	
10^{9}	5	电子对湮灭	
10^{9}	3分钟	核合成时代	
10^{3}	38万年	宇宙背景辐射	青年时代
	4亿年	第一代恒星生成	
		星系形成	中青年? 中年? 老年?
2.7	138亿年	现代	



Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and
dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and
the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the
structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
0
10-32 seconds
10-30 seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years

普朗克卫星

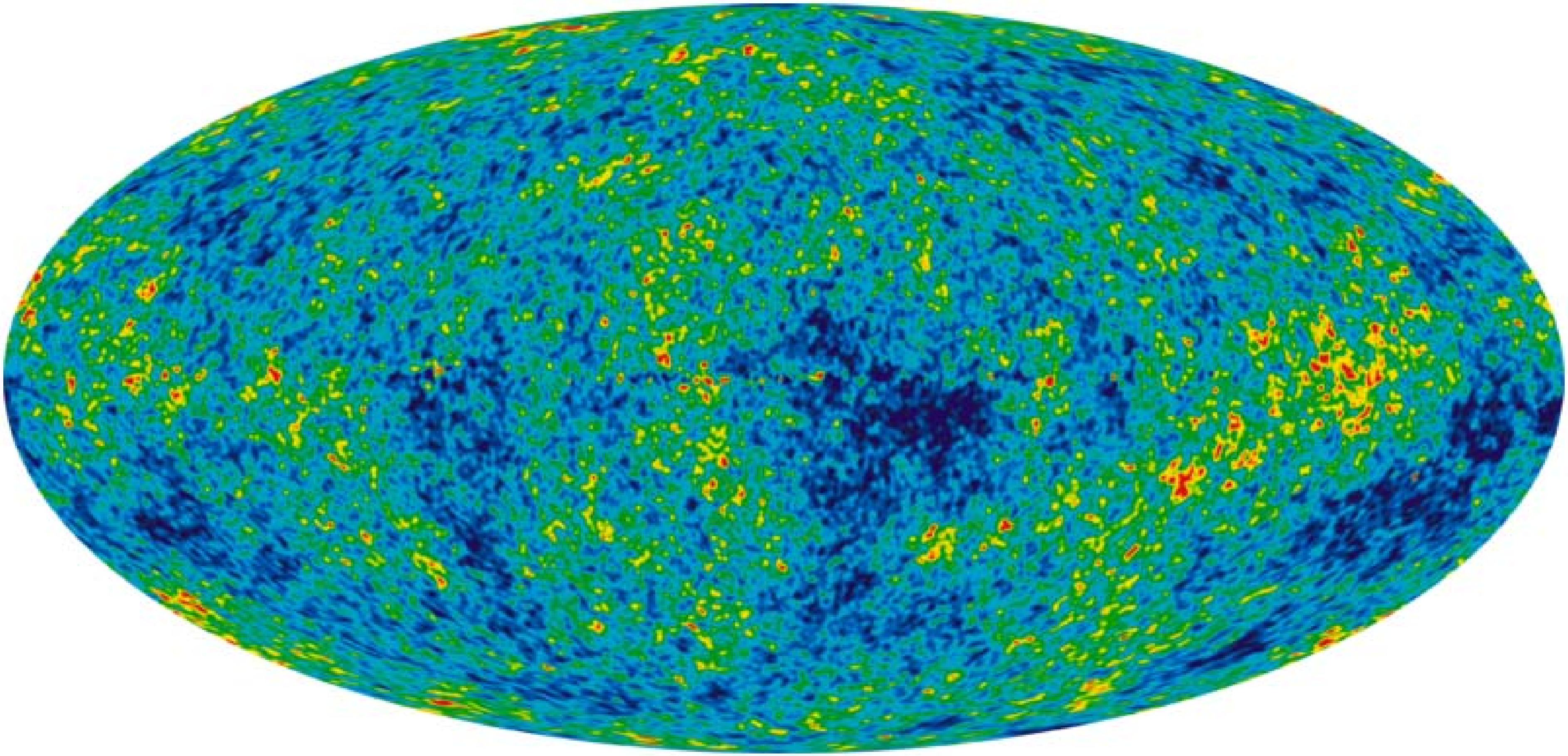
The Ariane 5 rocket launched from Europe's spaceport in South America

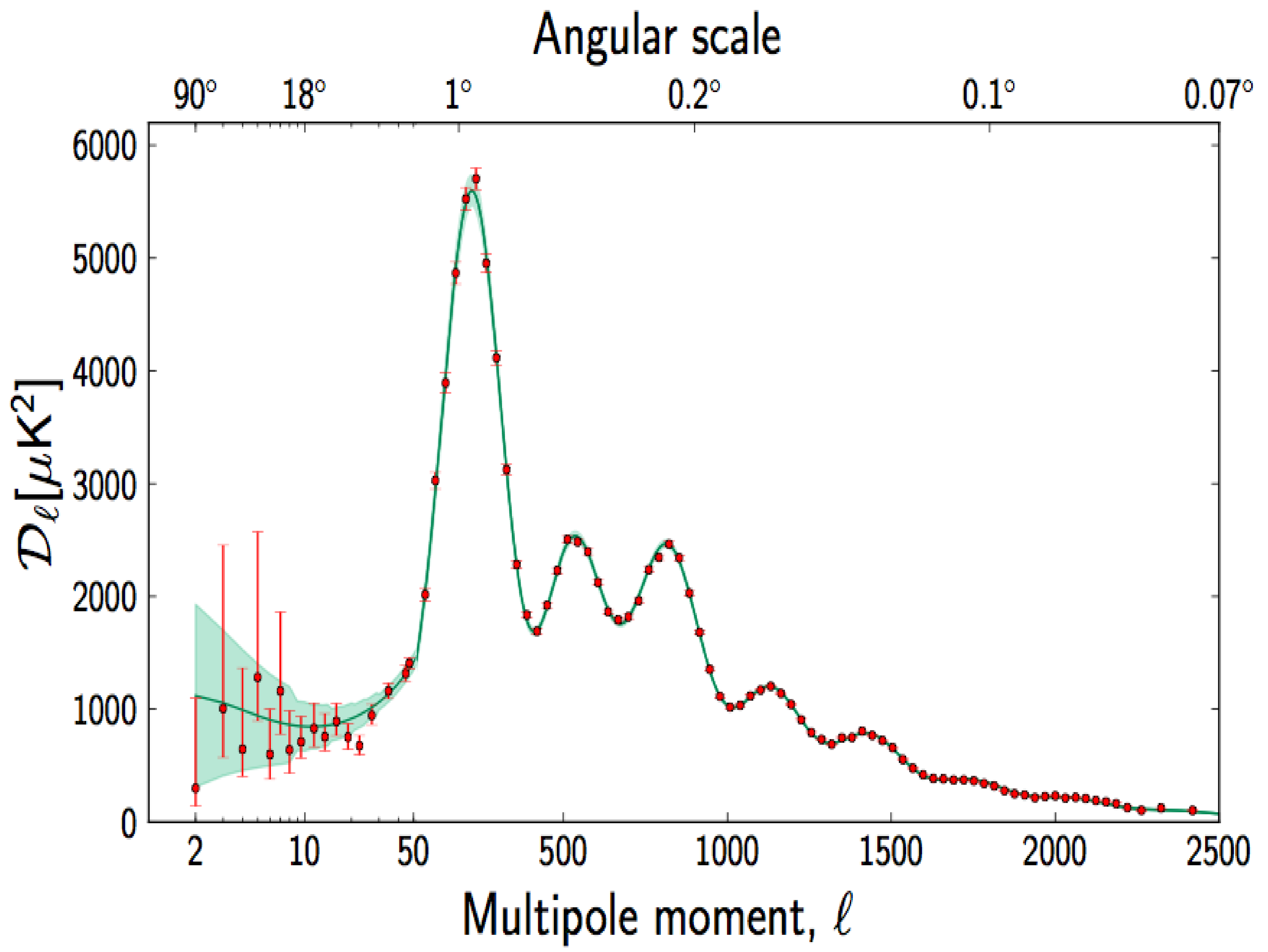
Scientists were joined by First Minister Rhodri Morgan to celebrate

The rocket carried the satellites for half an hour before they separated

(Planck launched in 14, May, 2009)

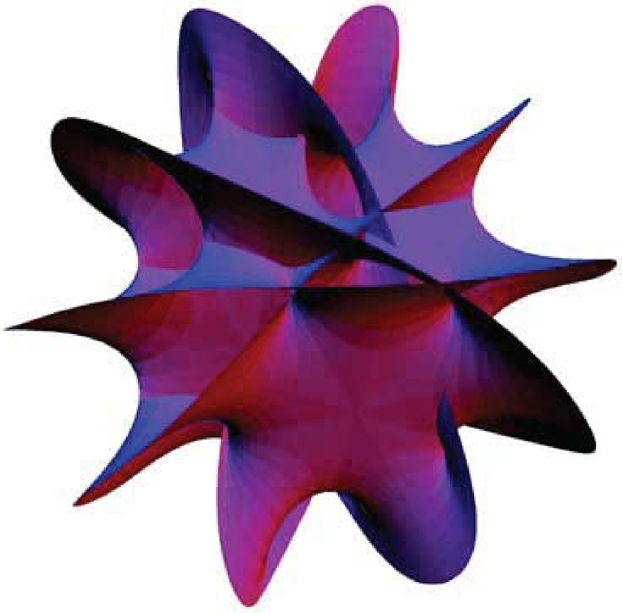
From BBC NEWS CHANNEL





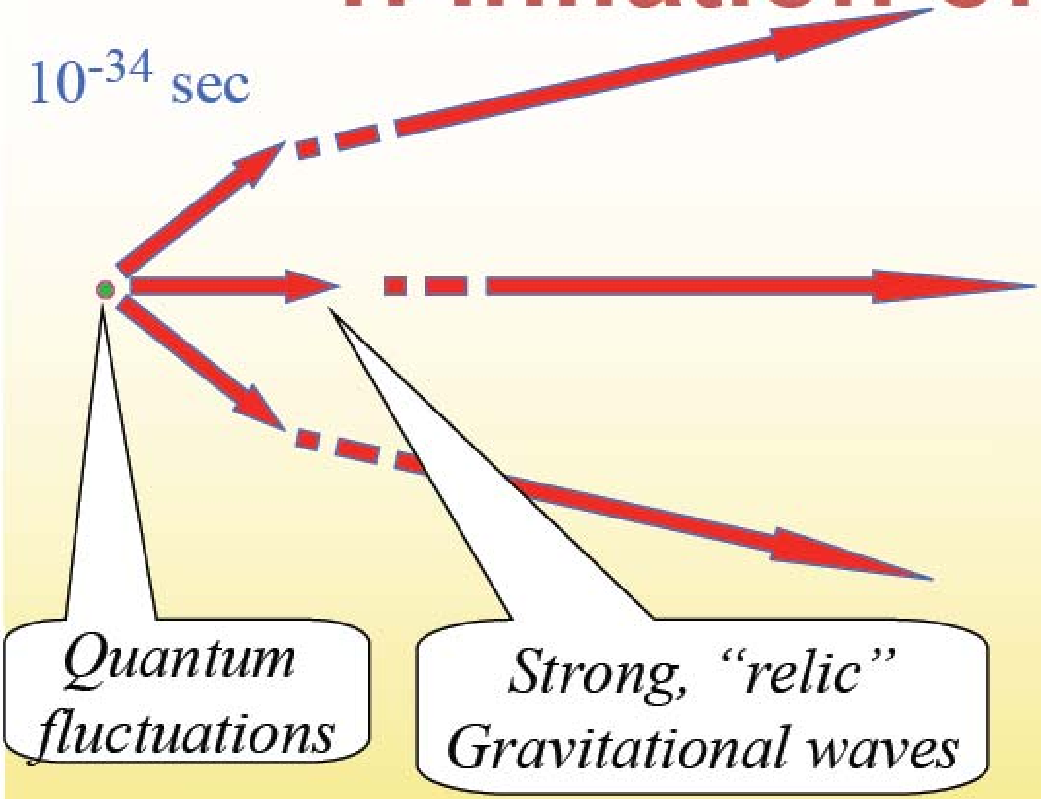
Angular scale
90°
18°
1°
0.2°
0.1°
0.07°
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell [\mu K^2]$
2
10
50
500
1000
1500
2000
2500
Multipole moment, ℓ

暴 涨 的 物 理 机 制 是什么？
------“终极理论”的希望所在

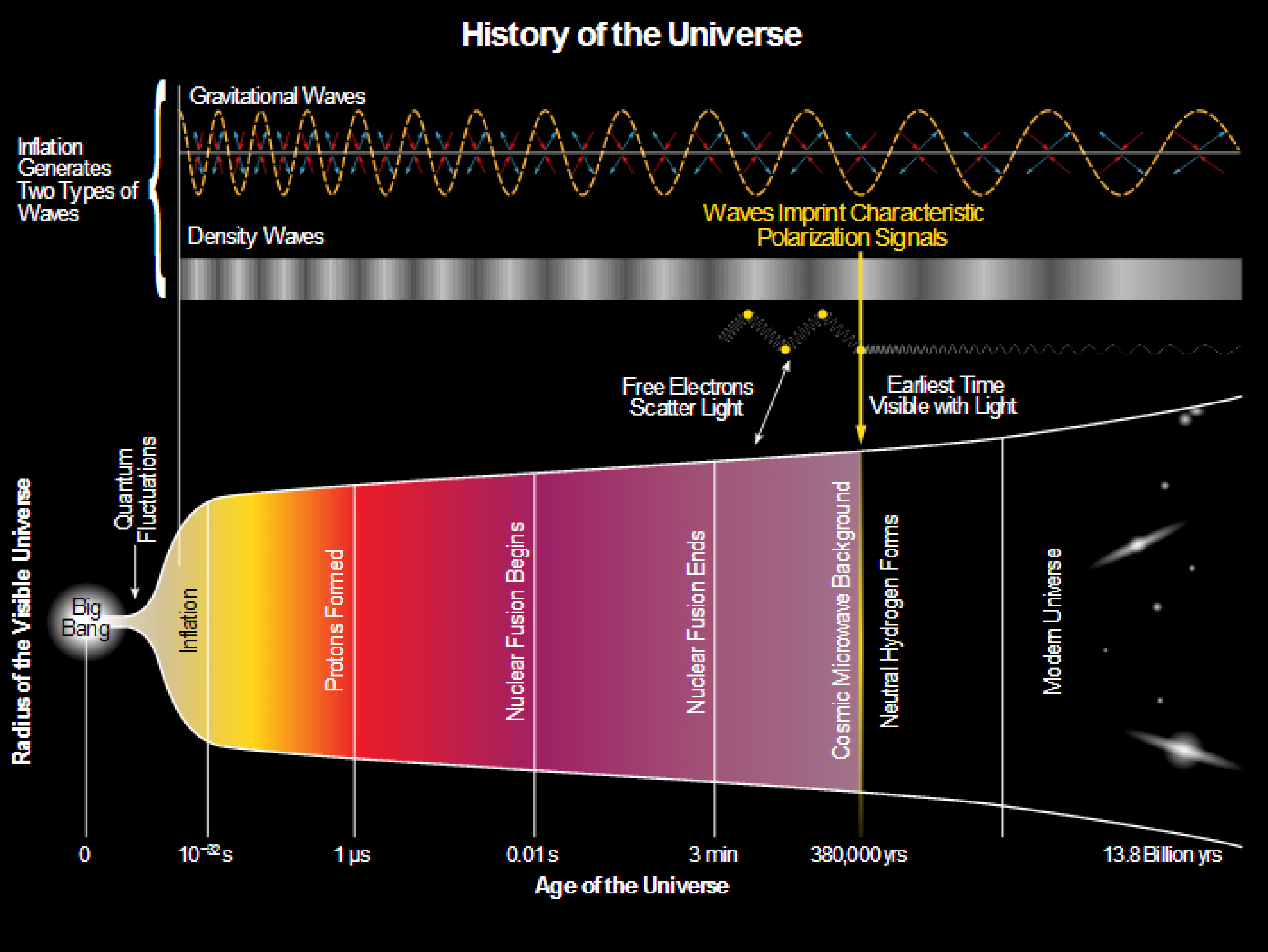


- 高能物理
- 引力物理
- 量子物理
- 通往“大统一”与“终极理论”唯一通道
- 有待进一步观测认证！

1. Inflation of Universe

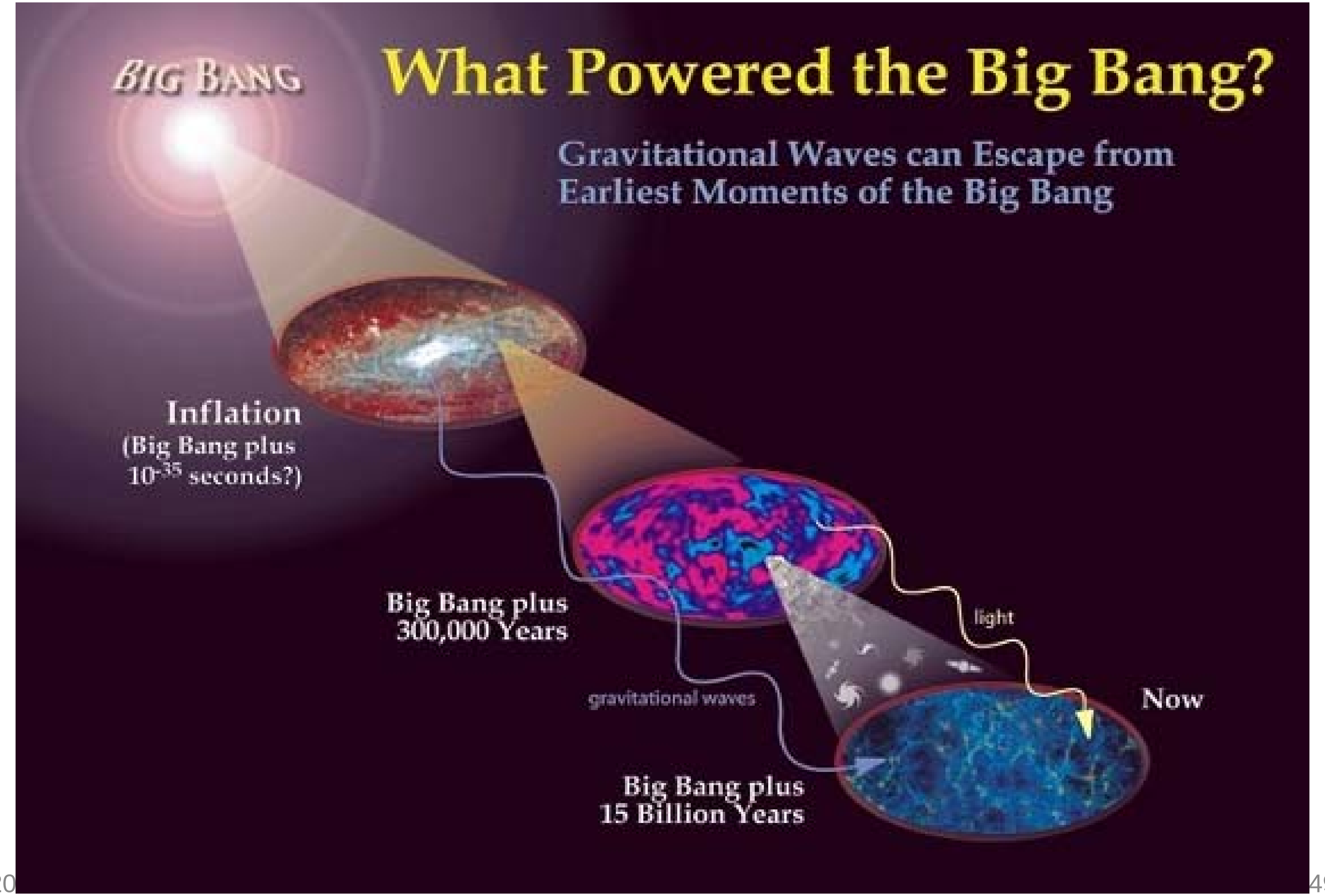


Leonid Grishchuk



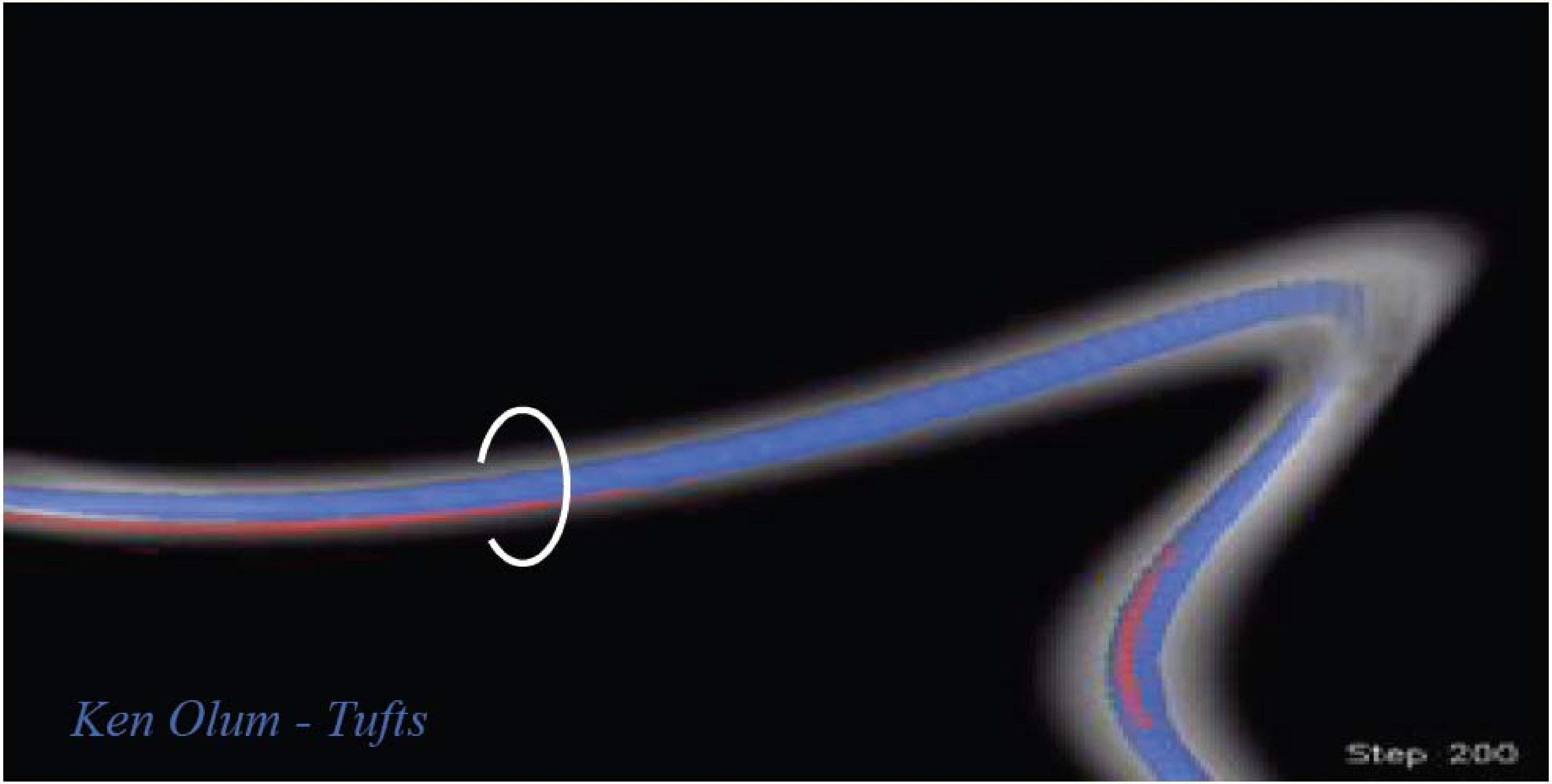
History of the Universe
Inflation Generates Two Types of Waves
Gravitational Waves
Density Waves
Waves Imprint Characteristic Polarization Signals
Free Electrons Scatter Light
Earliest Time Visible with Light
Radius of the Visible Universe
Quantum Fluctuations
Big Bang
Inflation
Protons Formed
Nuclear Fusion Begins
Nuclear Fusion Ends
Cosmic Microwave Background
Neutral Hydrogen Forms
Modern Universe
0
10^{-32} s
1 µs
0.01 s
3 min
380,000 yrs
13.8 Billion yrs
Age of the Universe

宇宙婴儿的第一声"啼哭"
------ 原初引力波



2. Cosmic Strings

- ***Inflation*** enlarges some superstrings to cosmic size
- Kinks and waves on cosmic strings produce gravitational waves



Why important?

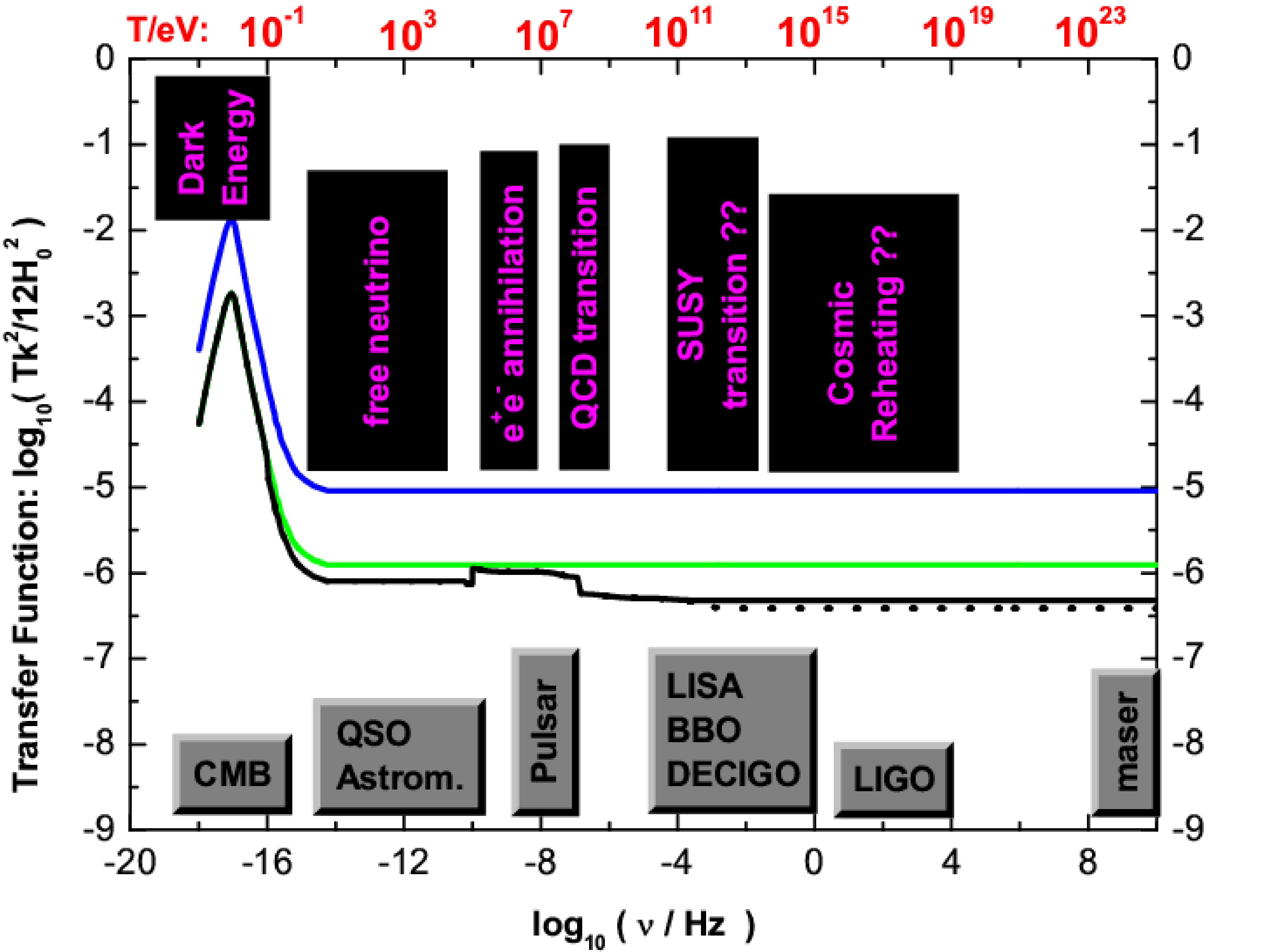
❖ For Physics:

* Gravitational wave detection
* Gravity at high energy scale, Quantum Gravity

❖ For Cosmology:

------unique way for pre-recombination stage

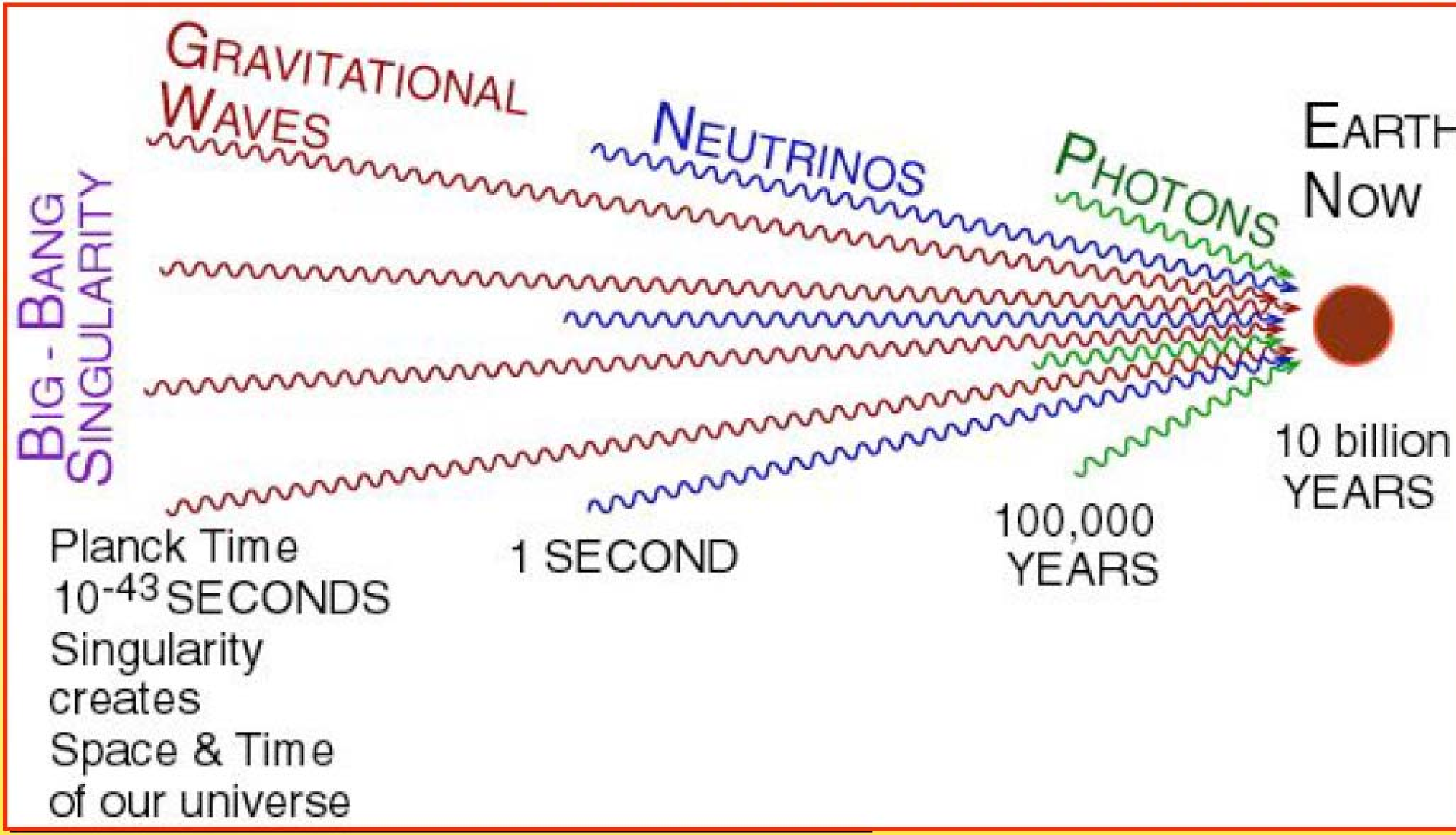
* Pre-inflationary stage,
* Birth of Universe
* Inflation physics (energy scale, evolution, et al.)
* Phase transitions in early Universe (QCD, e+e-, supersymmetry, et al.)
* Cosmic strings, cosmic walls, et al.



T/eV: 10^{-1} 10^{3} 10^{7} 10^{11} 10^{15} 10^{19} 10^{23}
Dark Energy
free neutrino
e^+e^- annihilation
QCD transition
SUSY transition ??
Cosmic Reheating ??
CMB
QSO Astrom.
Pulsar
LISA BBO DECIGO
LIGO
maser
Transfer Function: $\log_{10}(Tk^2/12H_0^2)$
$\log_{10}(\nu / Hz)$
0 -1 -2 -3 -4 -5 -6 -7 -8 -9
-20 -16 -12 -8 -4 0 4 8

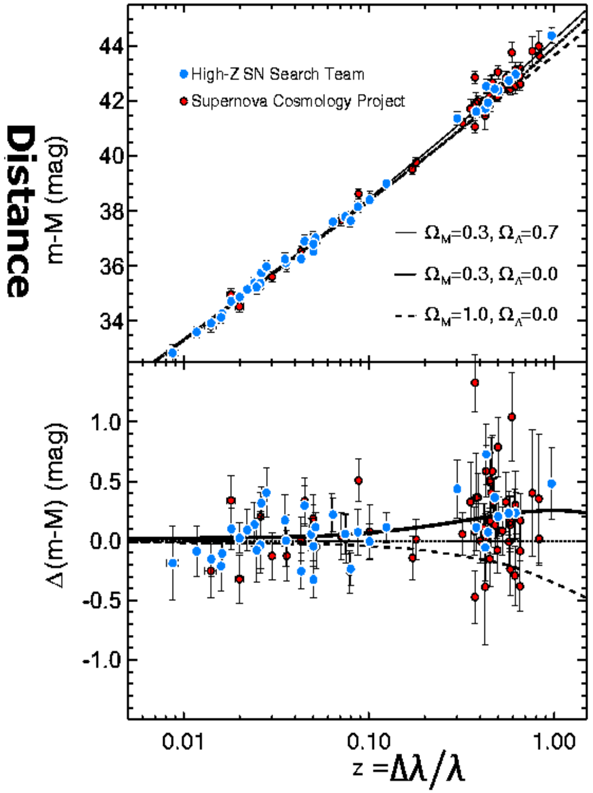
Over the Next 40 Years

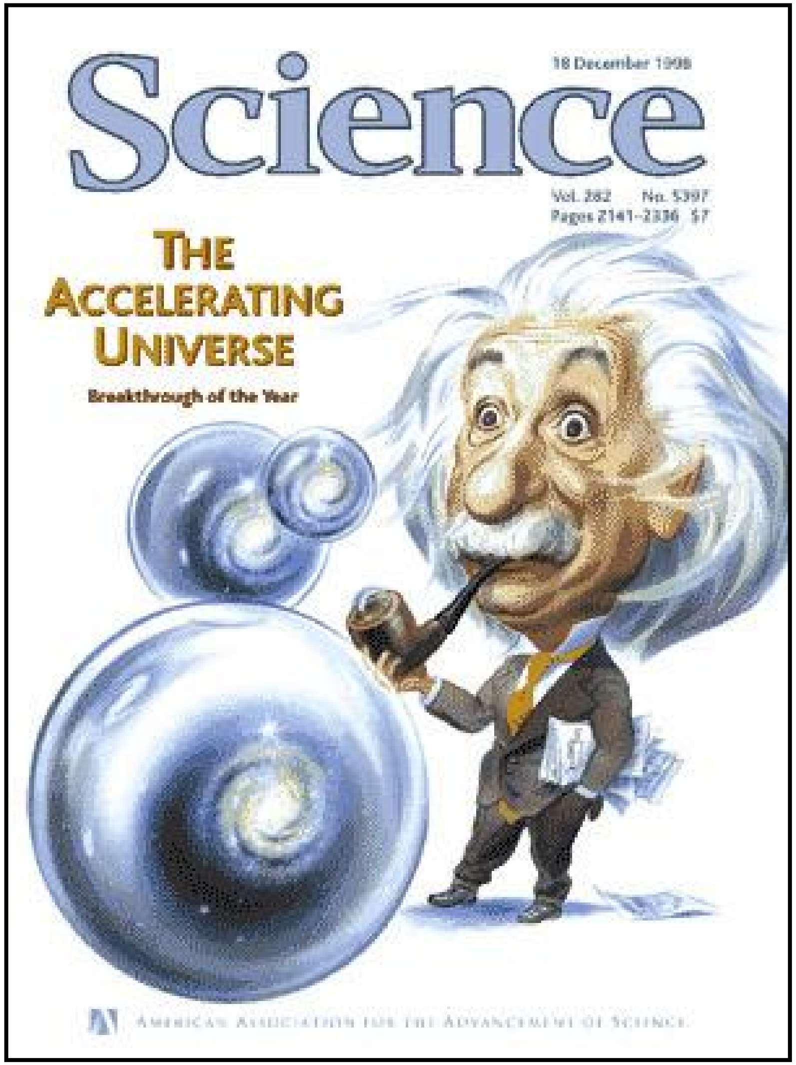
Probe the Initial Second of Universe's Life



Rich Violence in First Second -- Four Examples

引力波源作为“标准铃声”


Distance
m-M (mag)
High-Z SN Search Team
Supernova Cosmology Project
Ω_M=0.3, Ω_Λ=0.7
Ω_M=0.3, Ω_Λ=0.0
Ω_M=1.0, Ω_Λ=0.0
44
42
40
38
36
34
Δ(m-M) (mag)
1.0
0.5
0.0
-0.5
-1.0
0.01
0.10
1.00
z =Δλ/λ


Science
18 December 1998
Vol. 282 No. 5397
Pages 2141-2336 $7
THE ACCELERATING UNIVERSE
Breakthrough of the Year

引力波源作为“标准铃声”

- **In 1986, Schutz found that the luminosity distance of the binary neutron stars (or black hole) can be independently determined by observing the G.W. generated by this system. If we can also find the EM counterpart, the redshift can also be determined. Thus the dL-z relation can be used to study the evolution of universe. This is the so-called: standard sirens.**
  (Schutz,Nature,1986)

characters：1. non-EM method to study the cosmology

2. independent of “cosmic distance ladder”

* 测量哈勃常数

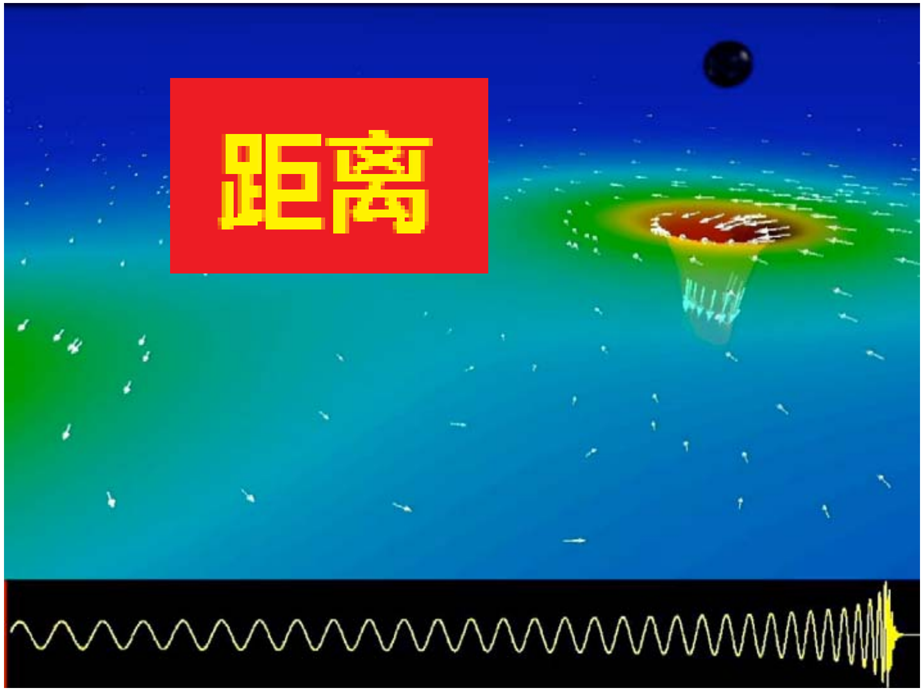
  地面的Adv.LIGO，Adv.VIRGO (BNS, NSBH)

* 测量宇宙暗能量

  地面的Einstein Telescope (BNS, NSBH)

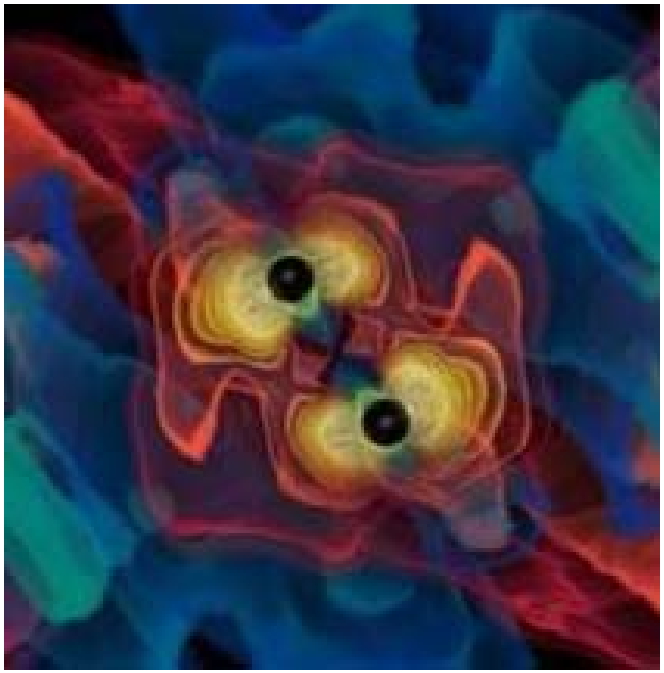
  空间的LISA (SMBBH)

  空间的BBO (BNS, NSBH)

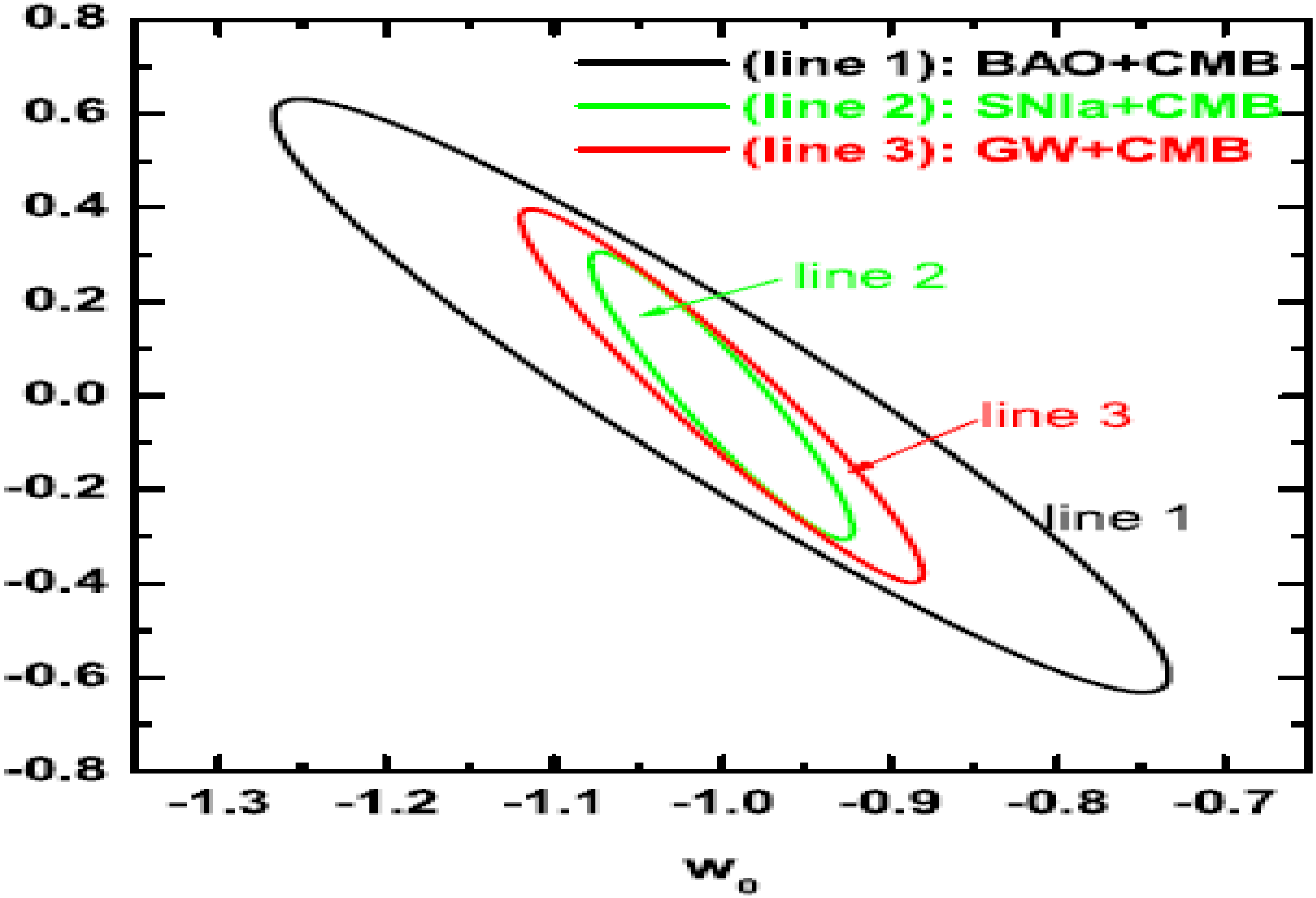


红移 ？

引力波源的多通道观测



ET (GW) & JDEM (BAO) & SNAP (SNIa)



爱因斯坦探针卫星项目

Einstein Probe Satellite Project

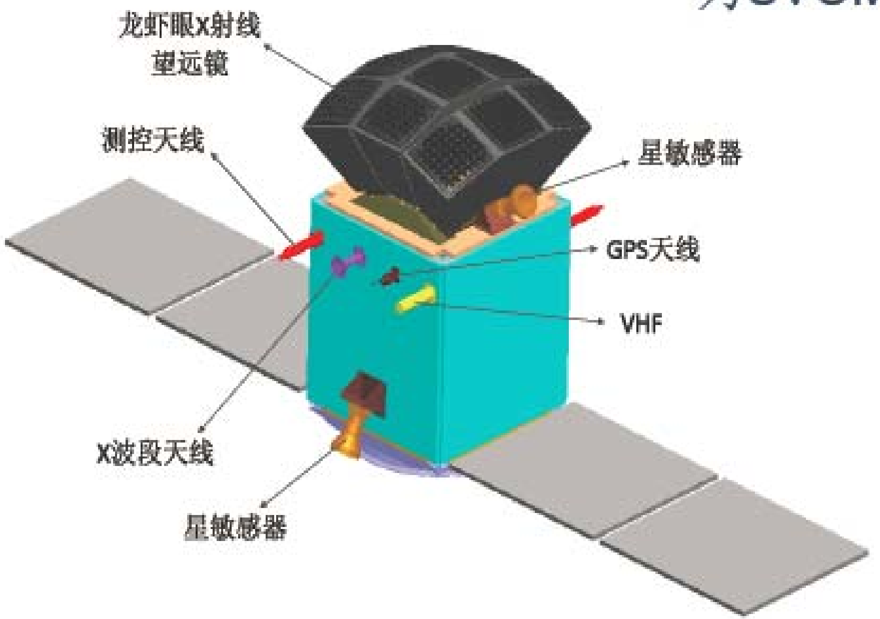
摘要

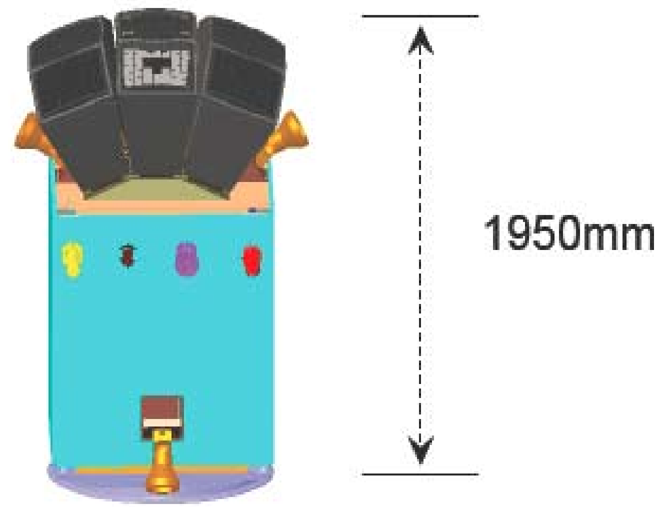
爱因斯坦探针（Einstein Probe，或EP）计划是一台面向未来时域天文学和高能天体物理的小型科学探测卫星。其主要目标是在软X射线（0.5~4keV）波段发现X射线暂现源/剧变源和监测X射线源的变化。为此它具有非常大瞬时视场（60°×60°,约为1球面度即全天立体角的十二分之一），并具有中等空间分辨率（半高全宽约5角分）和一定的光谱分辨率（约20%）。由于其监视器首次采用了先进的、基于MPO龙虾眼技术的X射线聚焦成像光学系统，探测灵敏度和巡天捕获能力Grasp（探测有效面积与视场的乘积）比以往和现有设备高一到两个数量级，为国际领先水平。卫星在每个97分钟的轨道内指向5个反太阳方向的观测天区，每个天区曝光11分钟。每三个轨道可几乎完全覆盖半个天球。大部分天区的观测覆盖次数约在每天5~25次之间。卫星上还搭载一台与大视场监视器能力互补的小视场（约1°×1°）的深度后随观测望远镜，用于对发现的暂现源/剧变源进行深度后随观测。卫星可以发布警报以引导国际上其它空间及地面望远镜进行后随观测。

爱因斯坦探针卫星的主要科学目标是：1）通过捕捉黑洞偶或产生的X射线暂现信号，发现和探测几乎所有尺度上的沉寂的黑洞，它们是宇宙黑洞的主要存在形式。特别是发现星系中心黑洞潮汐摧毁并吞噬恒星产生的X射线暂现爆发；2）与国际上第二代引力波探测设备相配合，探测引力波爆发源的电磁波对应体并对其精确定位。3）开展最深灵敏度的、高监测频度的大视场时域X射线监测，实现对暗弱和遥远的高能暂现源的全天普查监测，开展大样本X射线源的时变的巡天监测。这些科学目标涉及的天体包括：几乎所有尺度的黑洞、引力波源的电磁波对应体、超新星激波暴、活动星系核、中子星、X射线闪、伽马暴、恒星冕活动等。通过卫星的数据分析，将探究黑洞在宇宙中是否普遍存在，证认引力波暴的天体物理起源并理解其产生的物理过程，揭示

卫星构型

采用上海微小卫星中心
为SVOM和炭星设计的卫星平台





卫星总质量 380kg：

平台200kg、龙虾眼150kg、

数传10kg、余量20kg

平台包络尺寸：

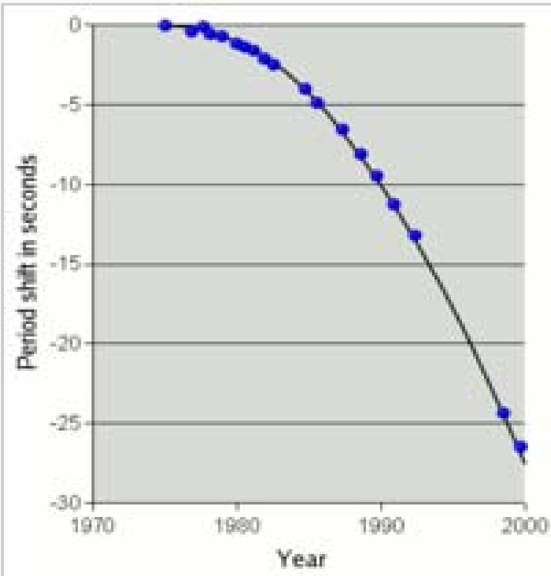
900mm×900mm×1000mm

引力波探测

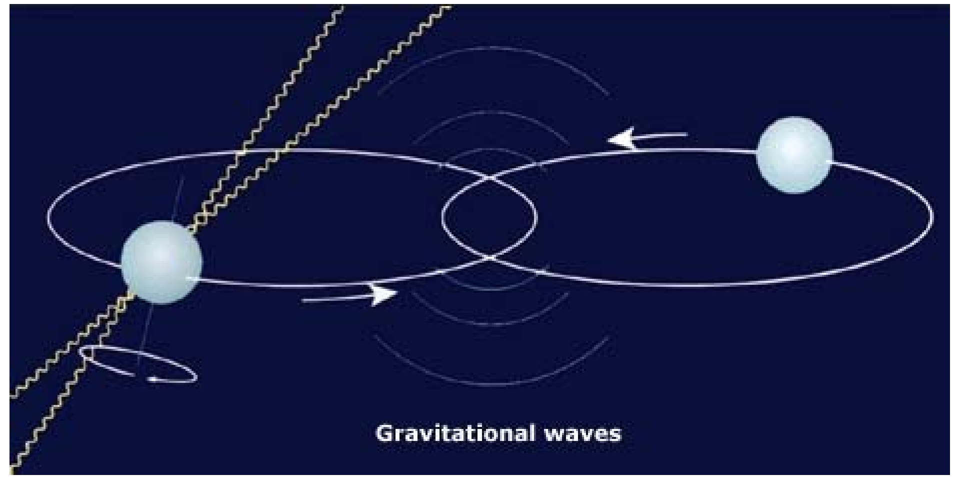
- 早期的探测
- 目前的重要探测方法之一：激光干涉仪
- 目前的主要探测方法之二：脉冲星计时阵列
- 目前的主要探测方法之三：宇宙微波背景辐射
- 引力波天文学

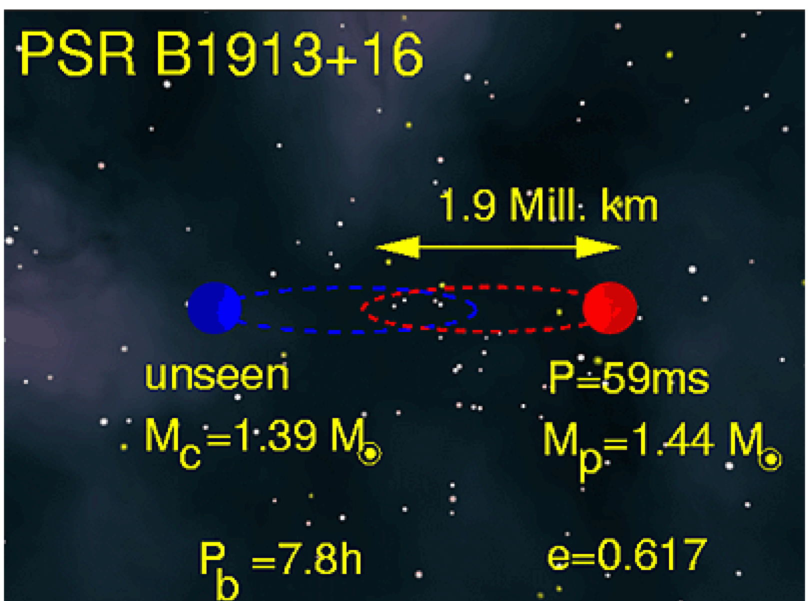
引力波的间接证据

------ 1993诺贝尔物理学奖



实验上观测到的脉冲双星PSR B1913+16的轨道周期变化（图中蓝色的点）和广义相对论的理论预测（图中黑色的曲线）完全吻合





(Indirect) Evidence of GWs

- PSR B1913+16 was the first binary pulsar to be discovered (Hulse & Taylor 1975).
- Observed for over 30 years.
- Weak radio source (1 mJy at 1400 MHz).
- Joseph H. Taylor Jr. and Russell A. Hulse shared the Nobel Prize in Physics in 1993:

c. 1993, Nobel Foundation

"for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation."

c. 1993, Nobel Foundation

GWs Are Out There!

- Orbital parameters for PSR B1913+16 are known to extremely high accuracy (both relativistic and non-relativistic measurables).
- Binary should emit energy as GWs
  → system loses energy
  → orbit should shrink
  → the period should decrease
- GR says the rate of period decrease is:

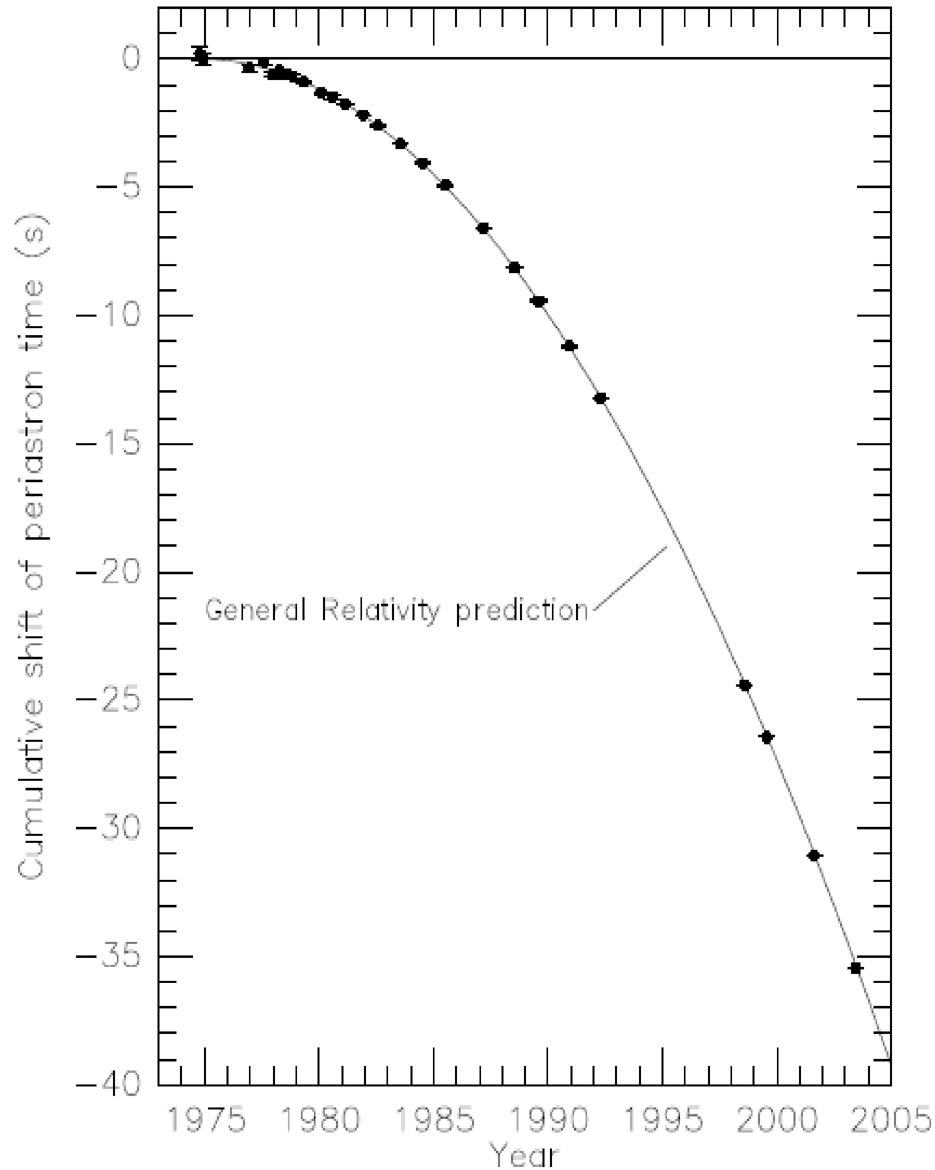
$$\dot{P}_{b,GR} = -\frac{192\ \pi\ G^{5/3}}{5\ c^5}\ \left(\frac{P_b}{2\pi}\right)^{-5/3}\ (1-e^2)^{-7/2}\ \times$$
$$\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)\ m_p\ m_c\ (m_p+m_c)^{-1/3}.$$

(Weisberg & Taylor 2004)

- Using the measured values and correcting for the relative acceleration between the solar system and the binary:

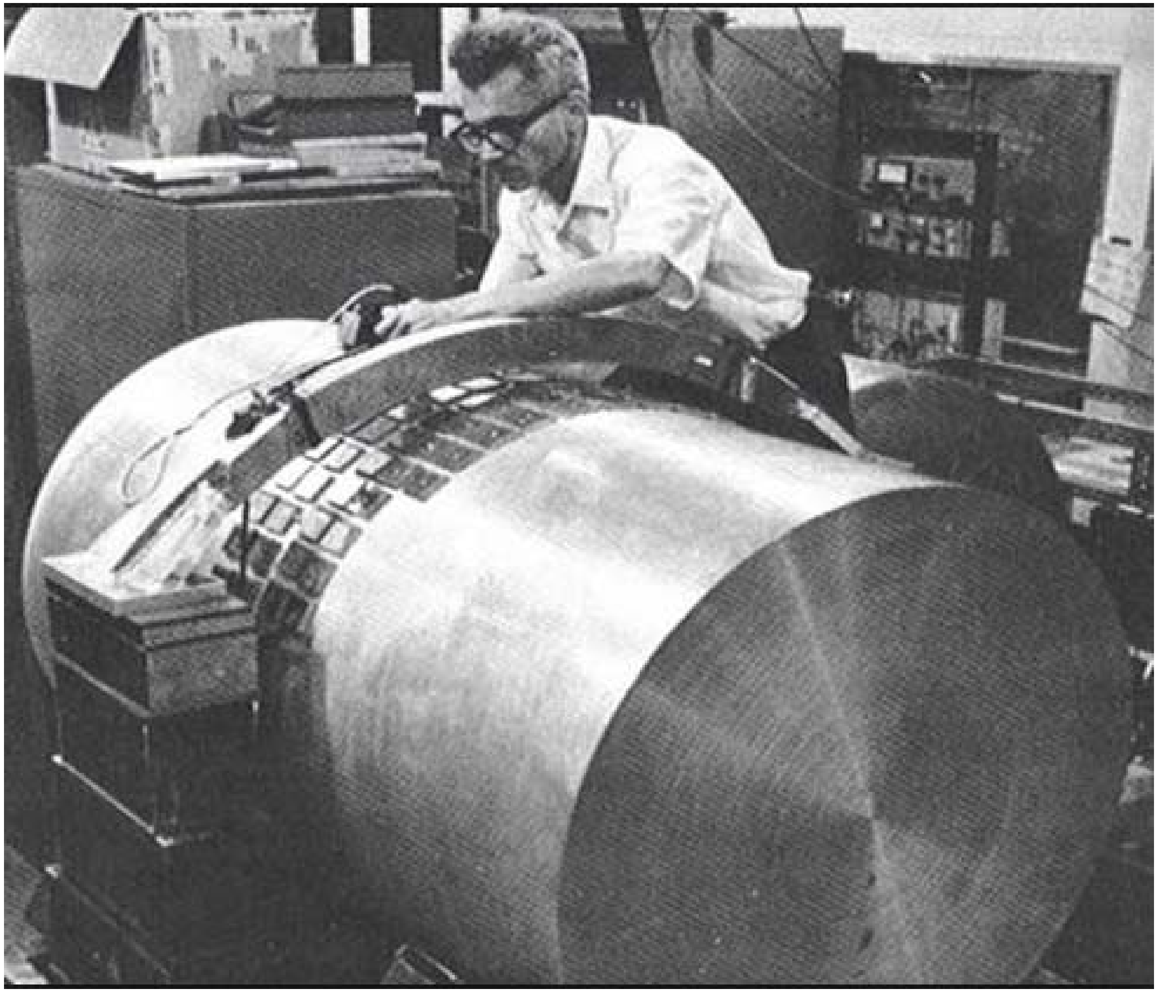
Building Up Our Confidence

- The dominant dissipation in the binary is energy loss by GWs (not mass loss or tidal drag).
- No GWs directly detected yet.
- However, the Hulse-Taylor PSR has convinced us they exist (and that we understand them relatively well).

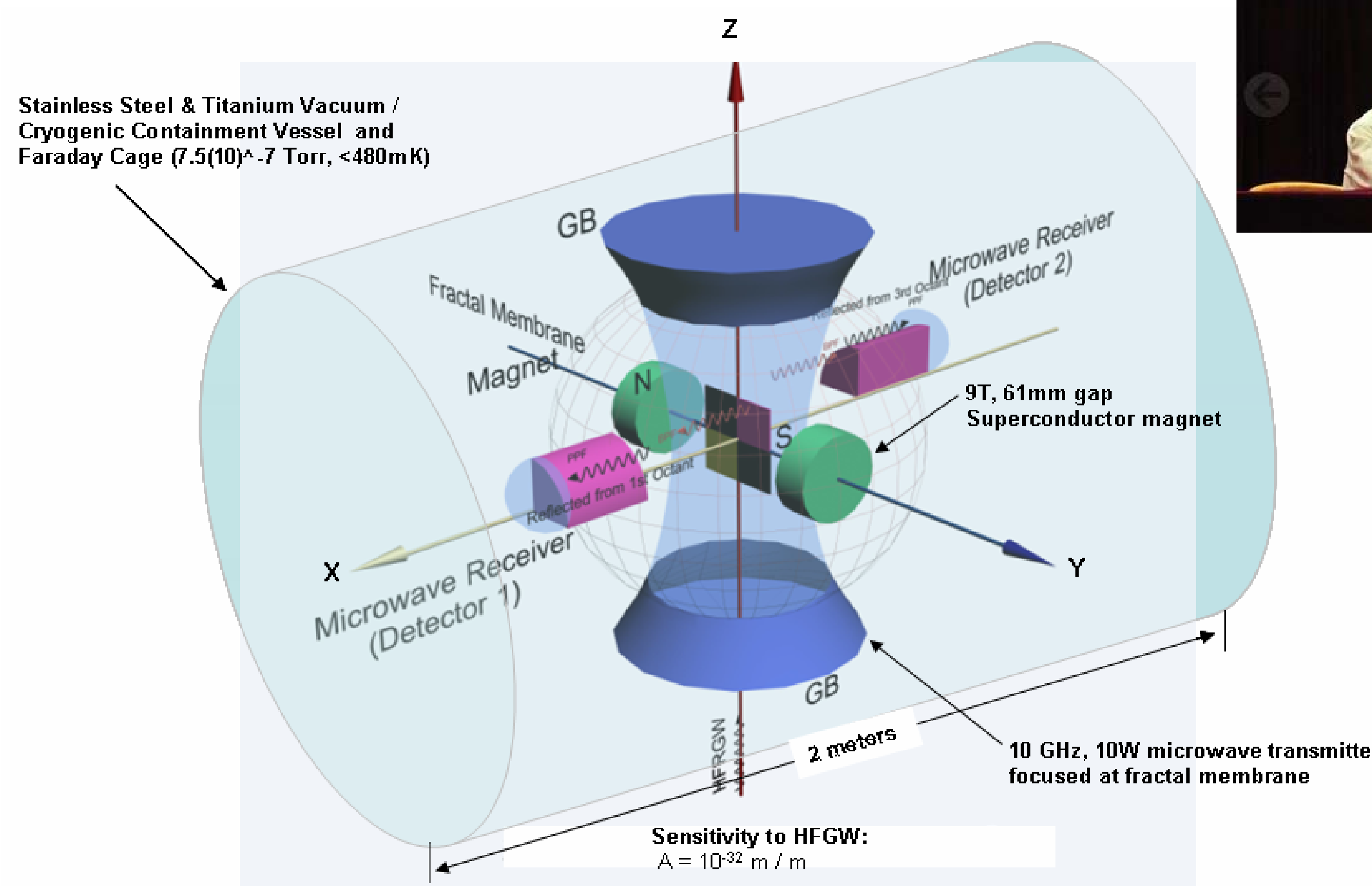


Weisberg & Taylor 2004

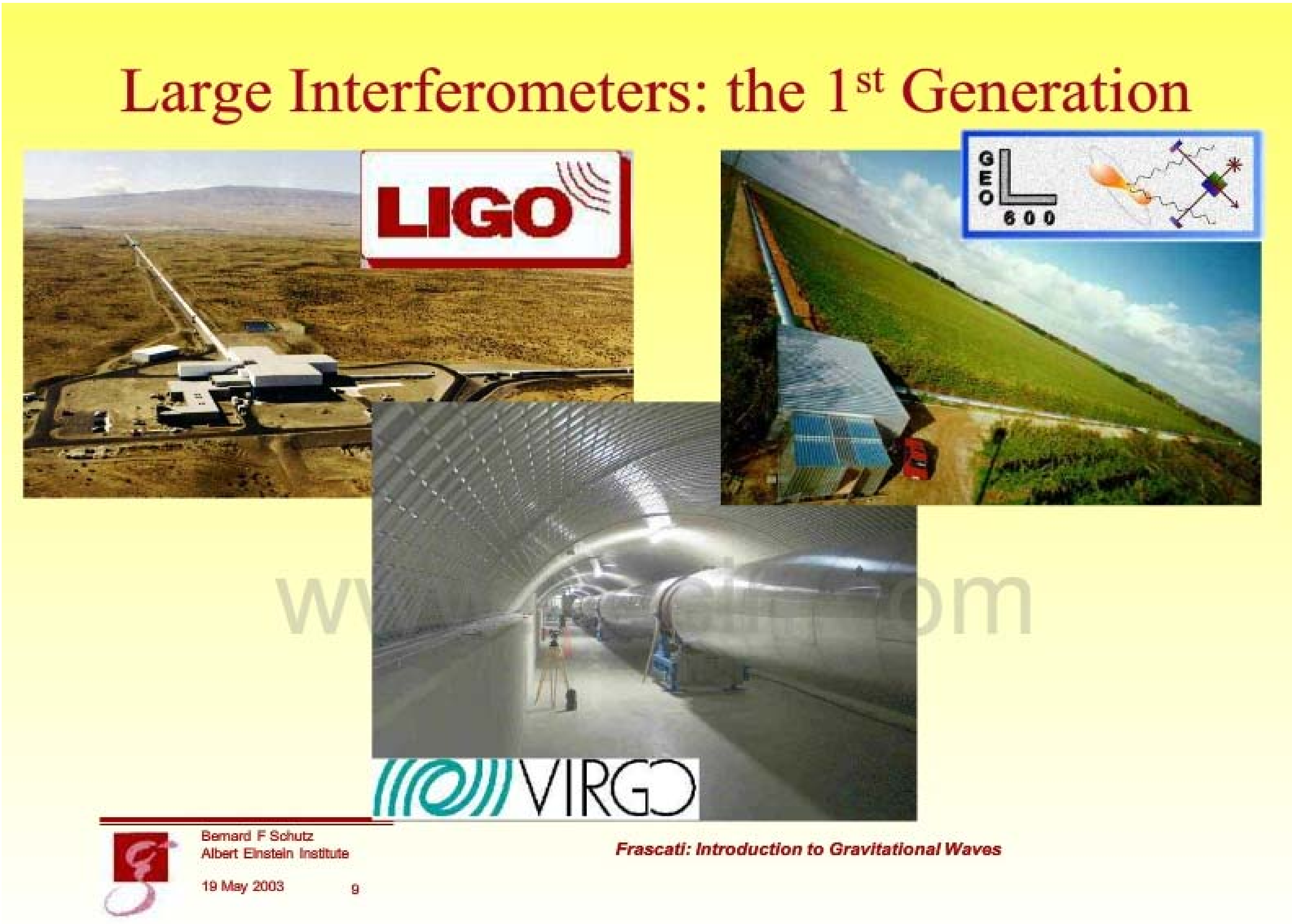
早期的引力波探测器



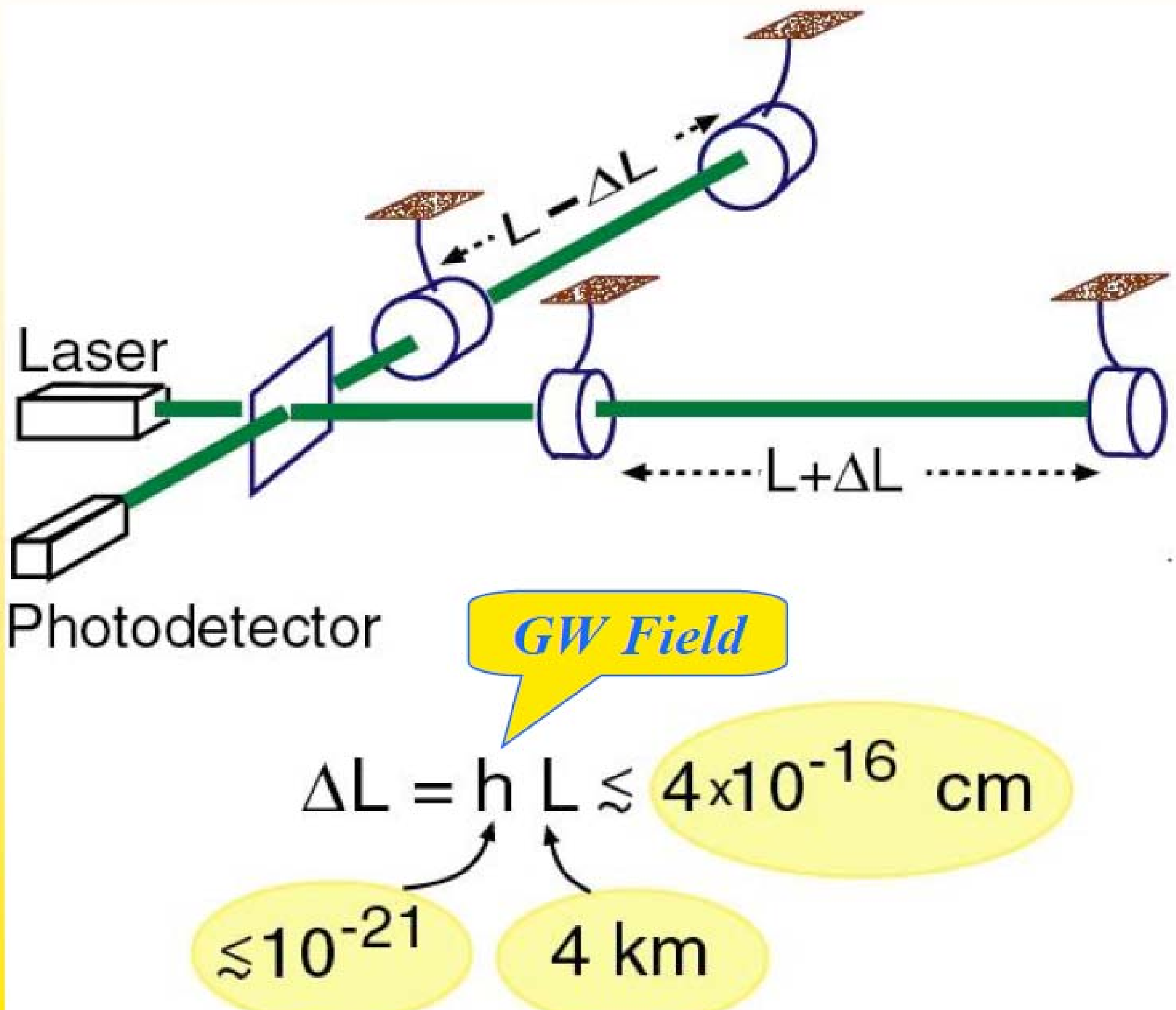
Li-Baker Detector



引力波探测之一: 激光干涉仪



Laser Interferometer Gravitational-Wave Detector - "GW Interferometer"

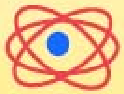


How Small is 10^{-16} Centimeters?

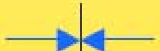
One centimeter ~ 1/2 inch

÷100  Human hair ~ 100 microns

÷100  Wavelength of light ~ 1 micron

÷10,000  Atomic diameter 10^{-8} cm

÷100,000  Nuclear diameter 10^{-13} cm

÷1,000  LIGO sensitivity 10^{-16} cm

LIGO Livingston

Hanford Observatory | LIGO Caltech | LIGO MIT

Search LIGO Lab

LIGO

Laser Interferometer
Gravitational-Wave Observatory
Supported by the National Science Foundation
Operated by Caltech and MIT

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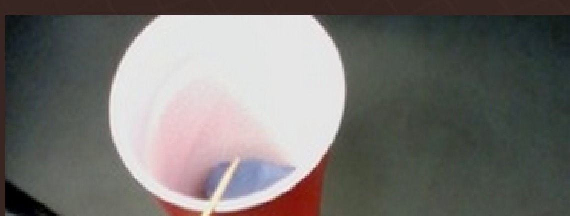
What are gravitational waves?

Why are we looking for them?

How does it affect us?

Virtual Tour



LATEST HEADLINES

Super Science Saturday at LSU

News Release • October 21, 2015

RESEARCHERS

- LIGO Scientific Collaboration
- LIGO Open Science Center

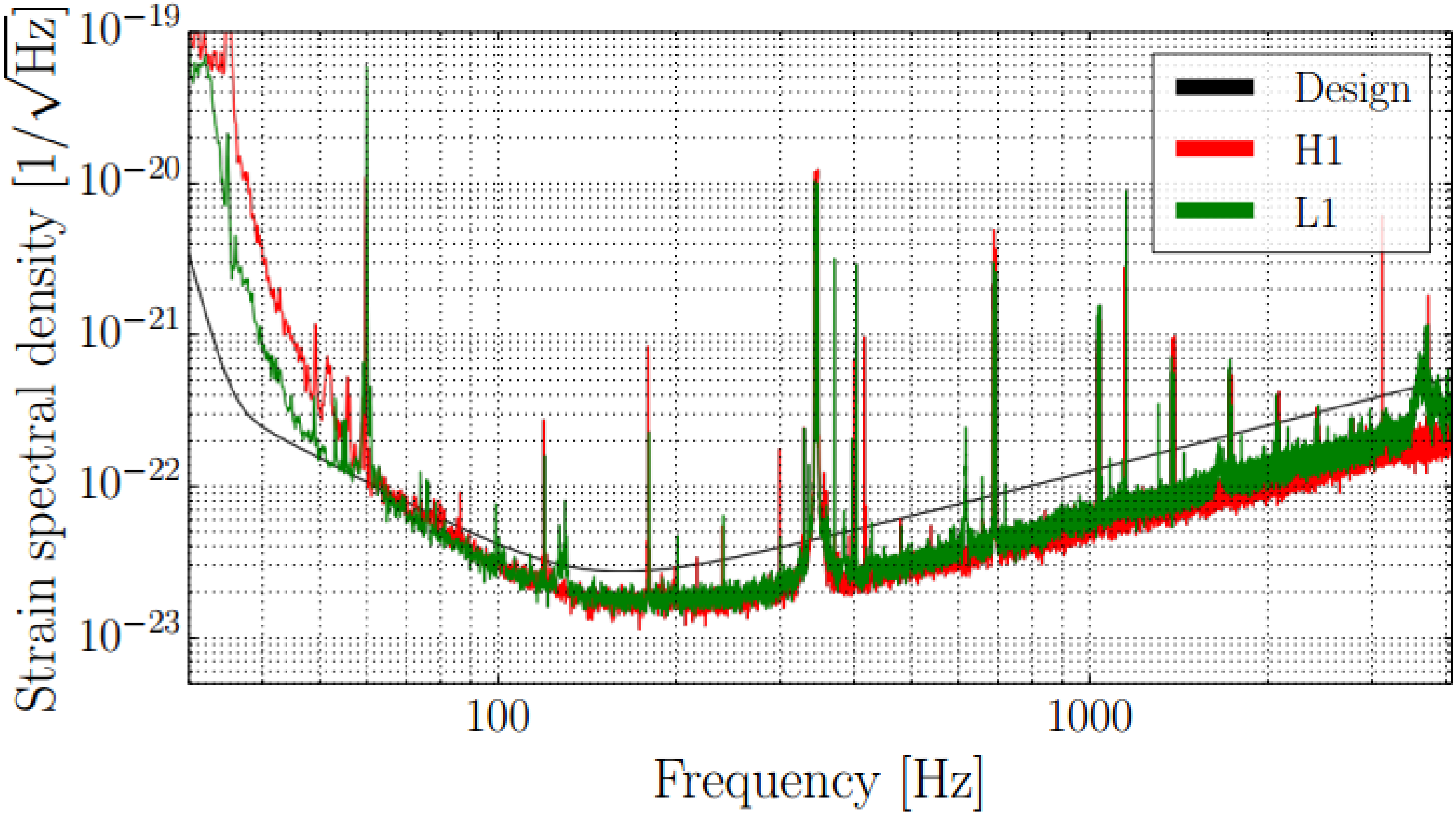
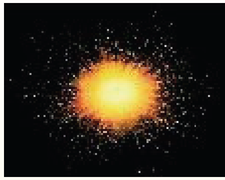


Figure 3: Typical strain amplitude sensitivity of the LIGO detectors during S6.

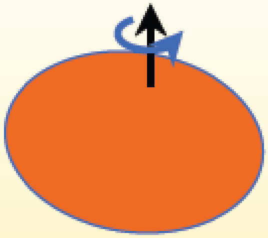
Preliminary Results from 2005-07 Search

- Gravitational waves from big-bang birth of the universe



  » < 5/100,000 of the universe!s total mass, at LIGO frequencies

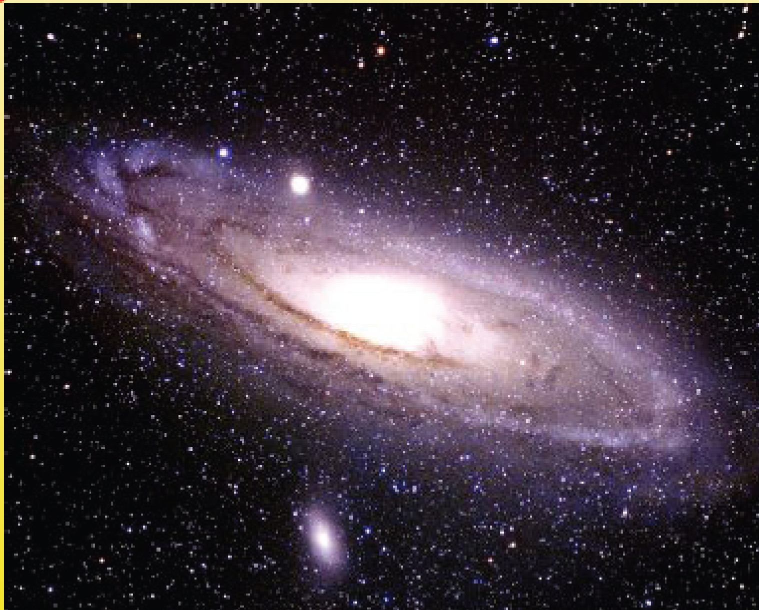
- Gravitational waves from Crab Pulsar

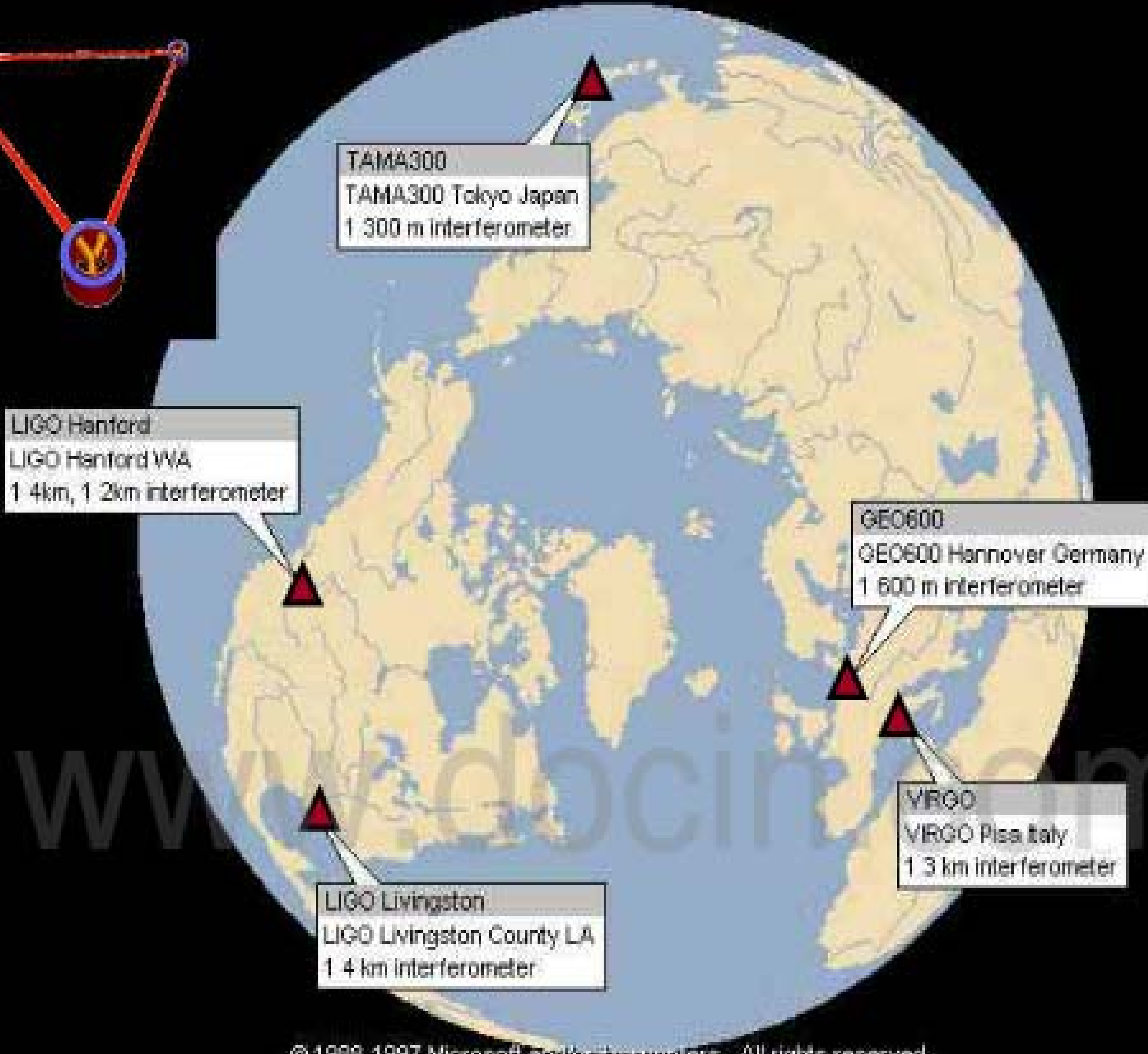


  » < 1/16 as much energy as emitted in EM waves

- Gravitational waves from gamma-ray burst 070201

  » If in Andromeda galaxy: NOT triggered by colliding neutron stars or by a black hole ripping apart a neutron star





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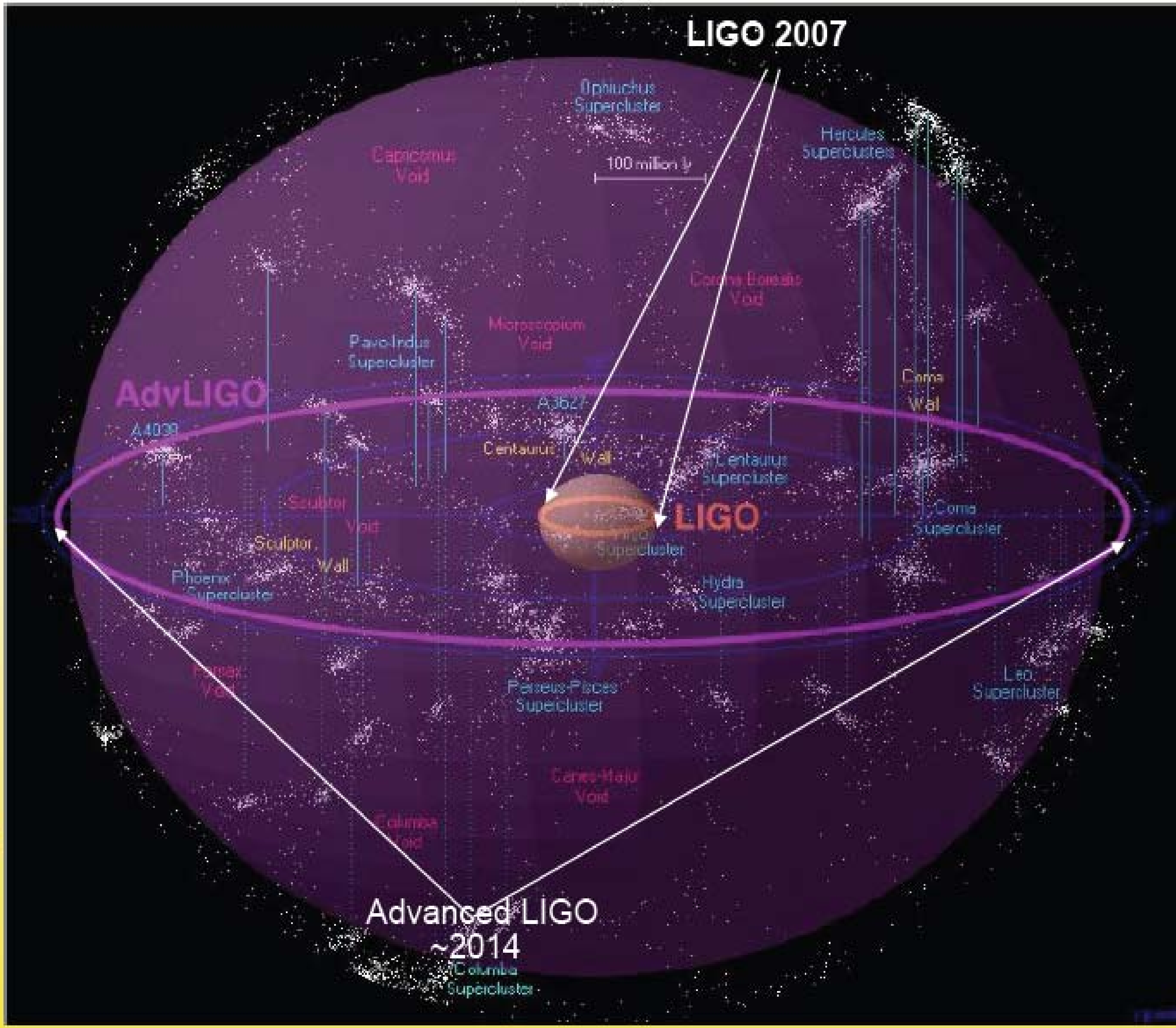
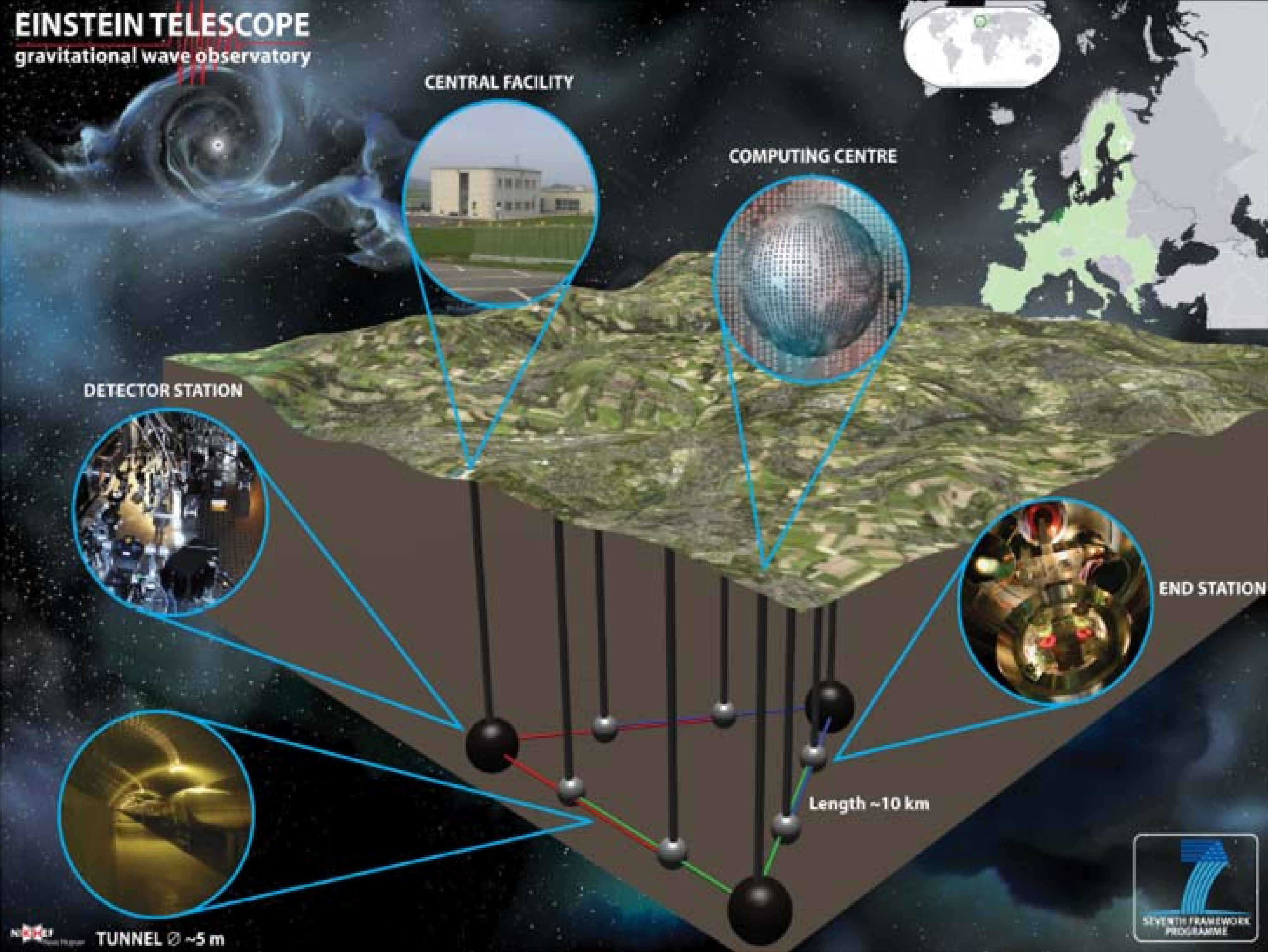
Future Interferometers in LIGO

Initial LIGO, 2007:
BH/BH 300 million light years -
~ 1 BHBH / 10 yrs

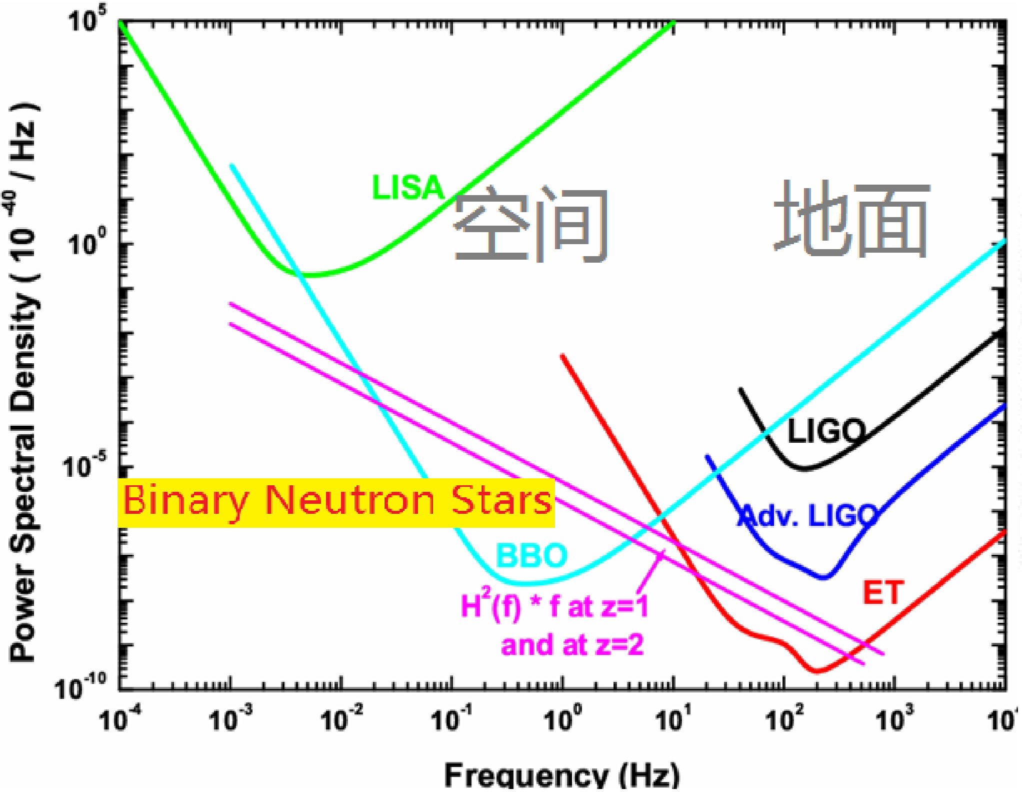
Enhanced: 2009-10
600 million lt yrs
~ 1 BHBH / yr

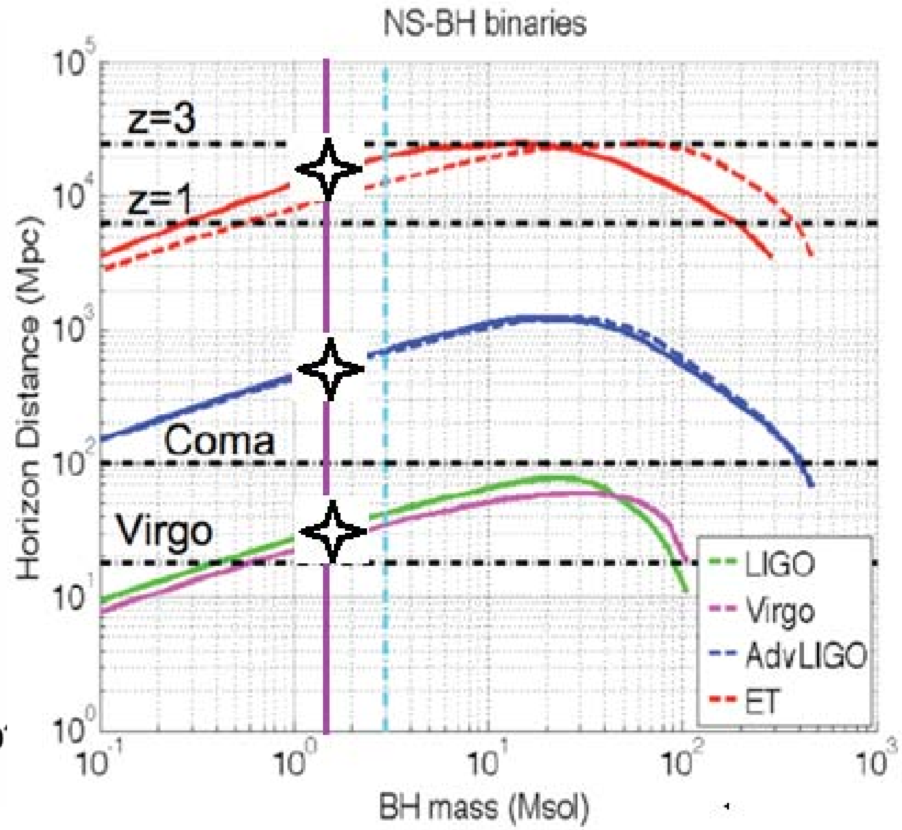
Advanced: 2014-…
5 billion lt yrs
~1 BHBH/day or wk



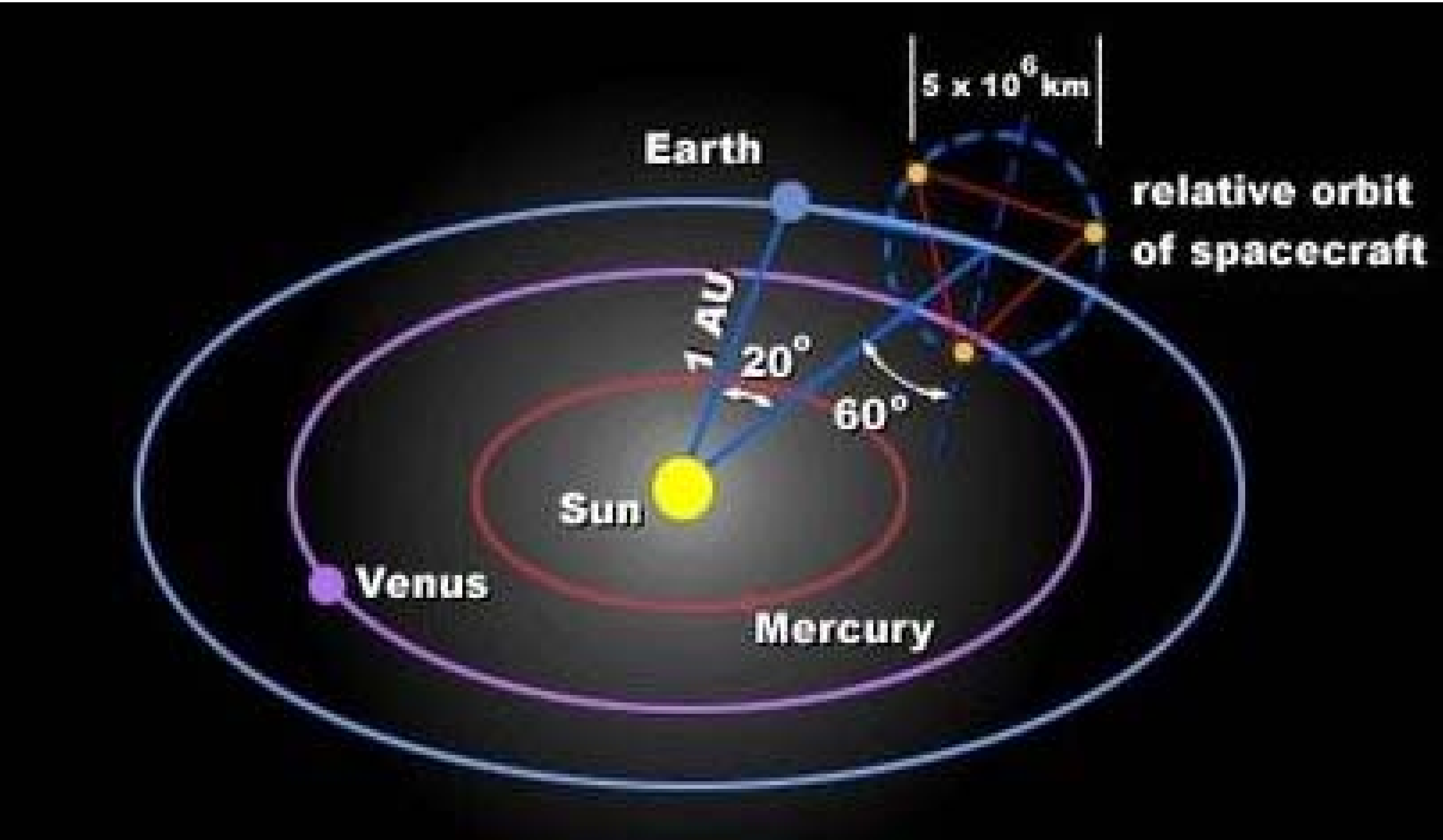

EINSTEIN TELESCOPE
gravitational wave observatory
CENTRAL FACILITY
COMPUTING CENTRE
DETECTOR STATION
END STATION
Length ~10 km
TUNNEL ∅ ~5 m
SEVENTH FRAMEWORK PROGRAMME

引力波源与引力波探测器

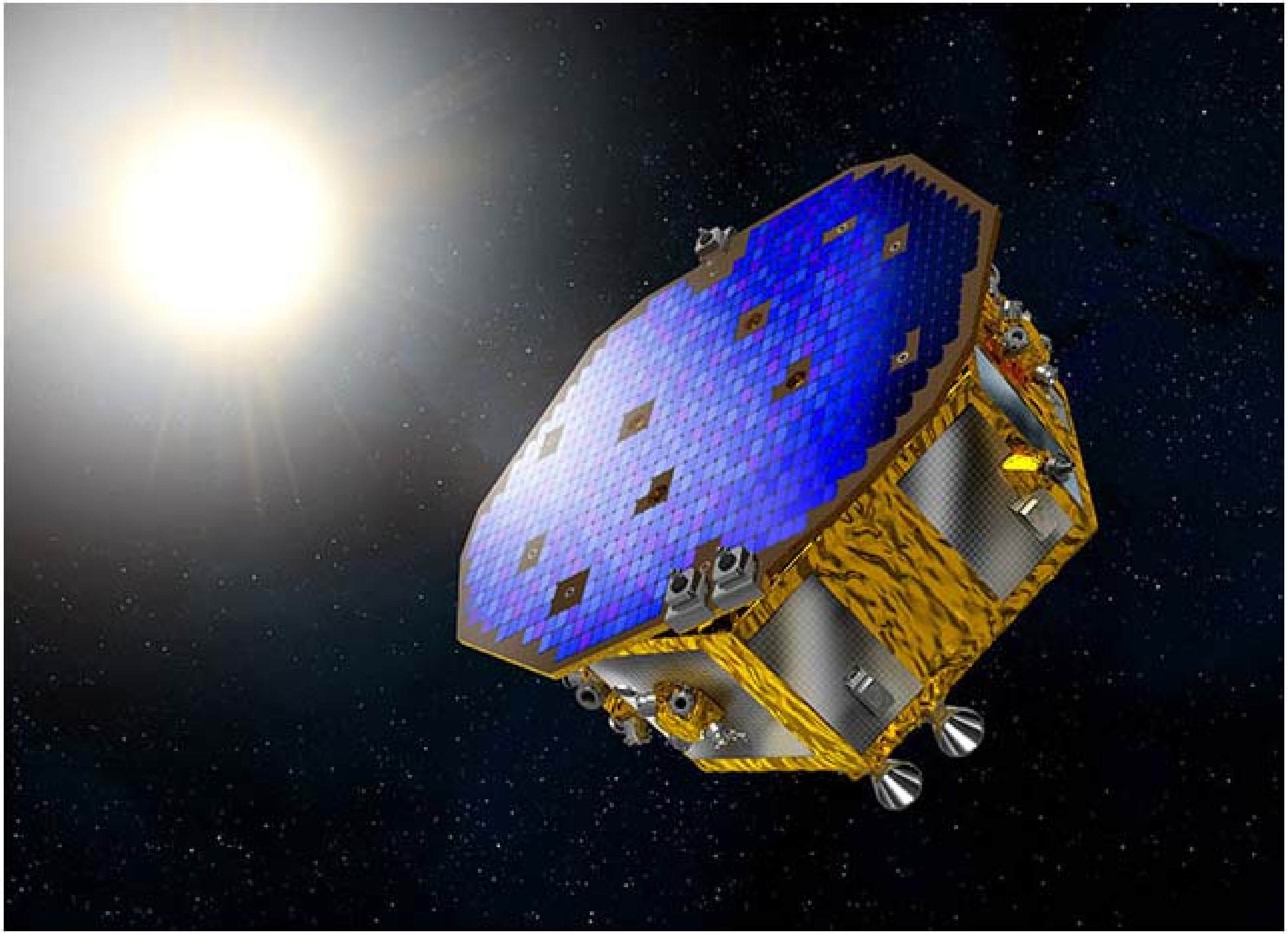




LISA: Laser Interferometer Space Antenna



一路坎坷，LISA探路者艰难启航！



今天天发射的LISA探路者，将为太空引力波探测铺平道路。图片来源：ESA

UPDATE：LISA探路者已于12月3日发射升空，预计将花10周时间转移到最终的轨道。预计此次试验顺利！

收藏 0 0

天琴计划

编辑

本词条缺少**信息栏**、**名片图**，补充相关内容使词条更完整，还能快速升级，赶紧来编辑吧！

天琴计划是中山大学发起的一个科研计划，中山大学正在组建研究小组开展我国空间引力波探测计划任务的预先研究，制定我国空间引力波探测计划的实施方案和路线图，提出"天琴"空间引力波探测计划，并开展关键技术研究。[1]

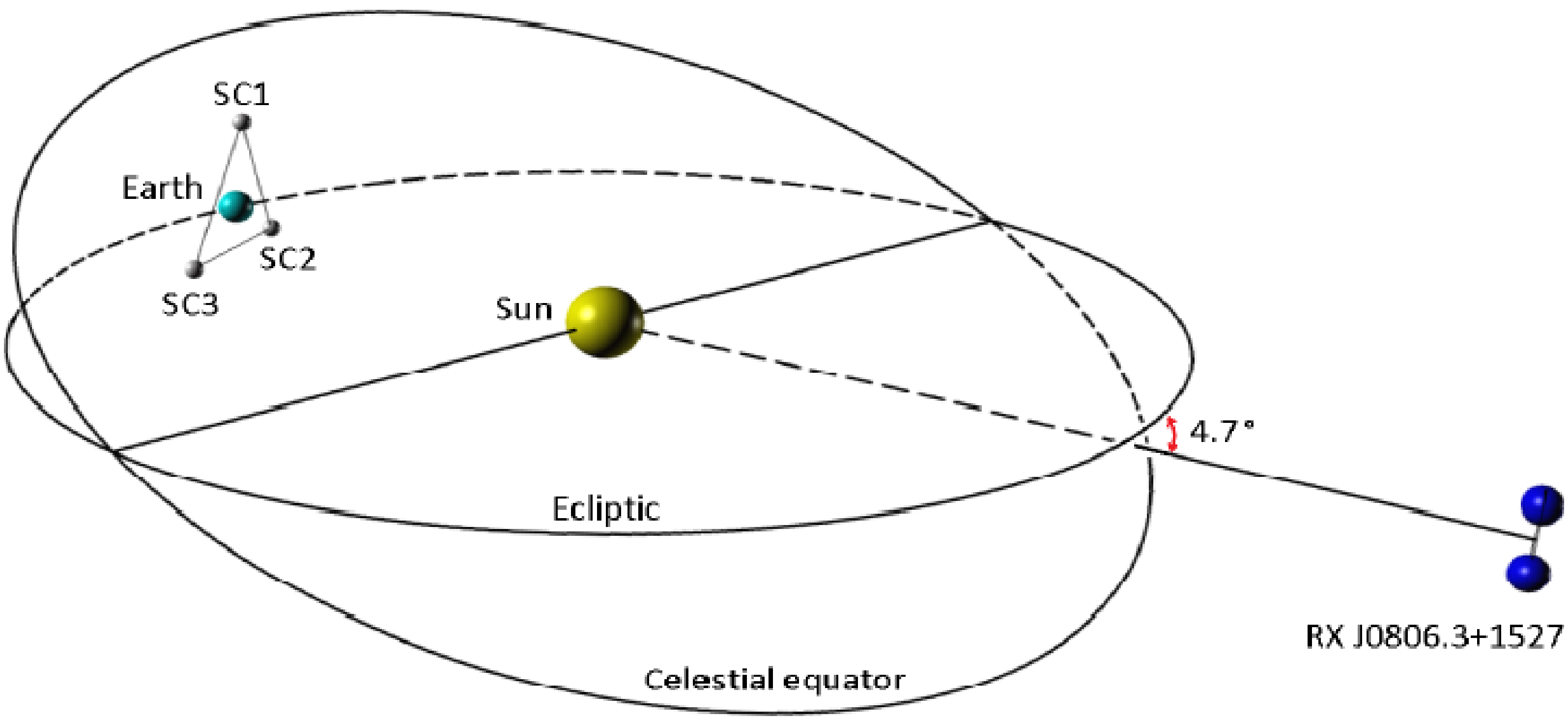
中山大学珠海校区将建设"天琴计划"所需的地面研究基础设施，并以此为基地开展面向国家重大需求和科学基础前沿的国家大科学工程项目。其中山洞超静实验室和激光测距地面台站基础设施建设已经启动，部分关键技术研究也已经有具体进展。天琴计划的推动将使中山大学将成为国际上引力波探测与空间精密测量领域的学术研究重镇之一，并成为推动后续一系列空间精密测量物理实验的研究基地。[1]

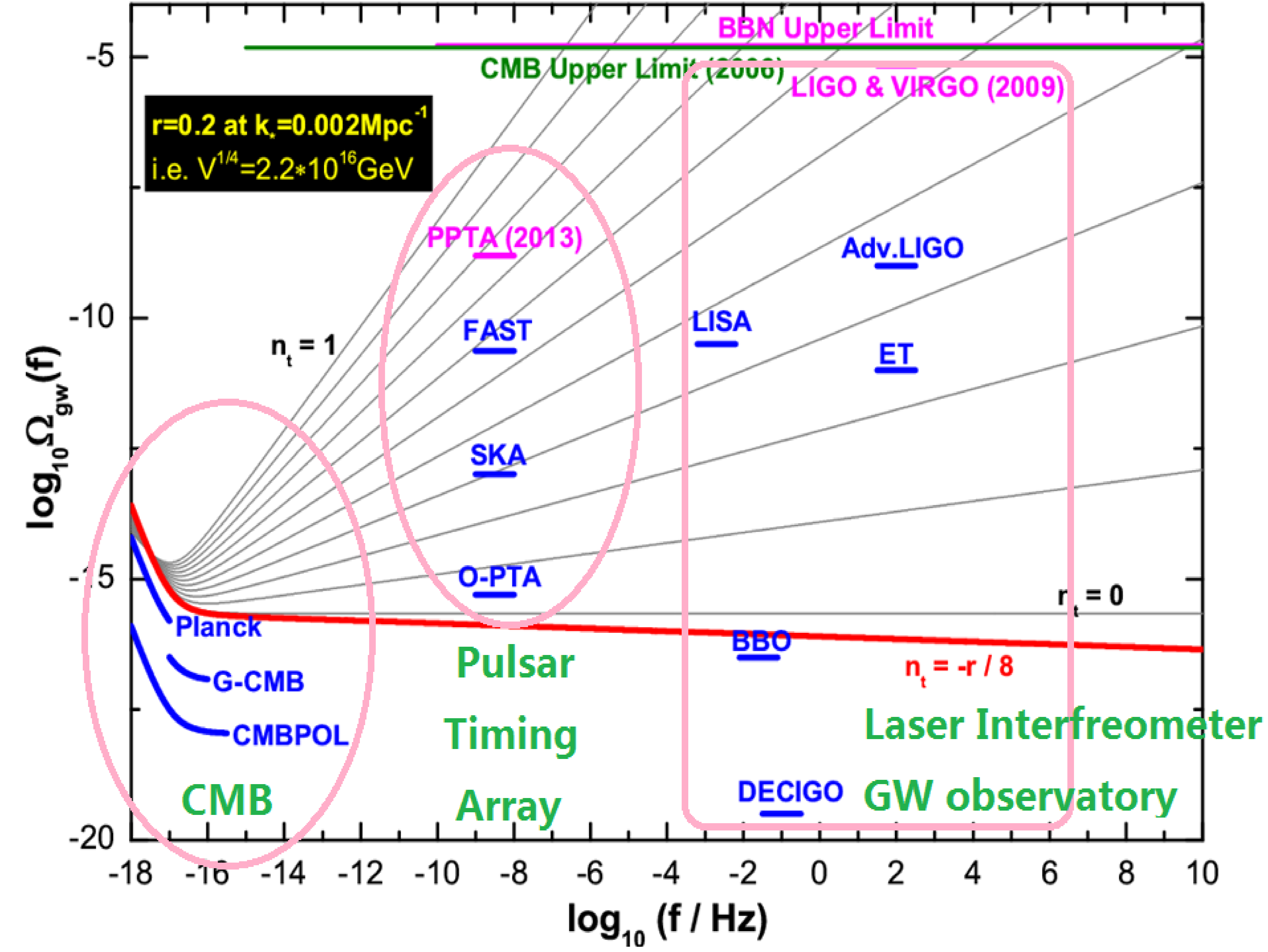
参考资料

1. 中山大学将成立物理与天文学院 . 新浪[引用日期2015-10-10]

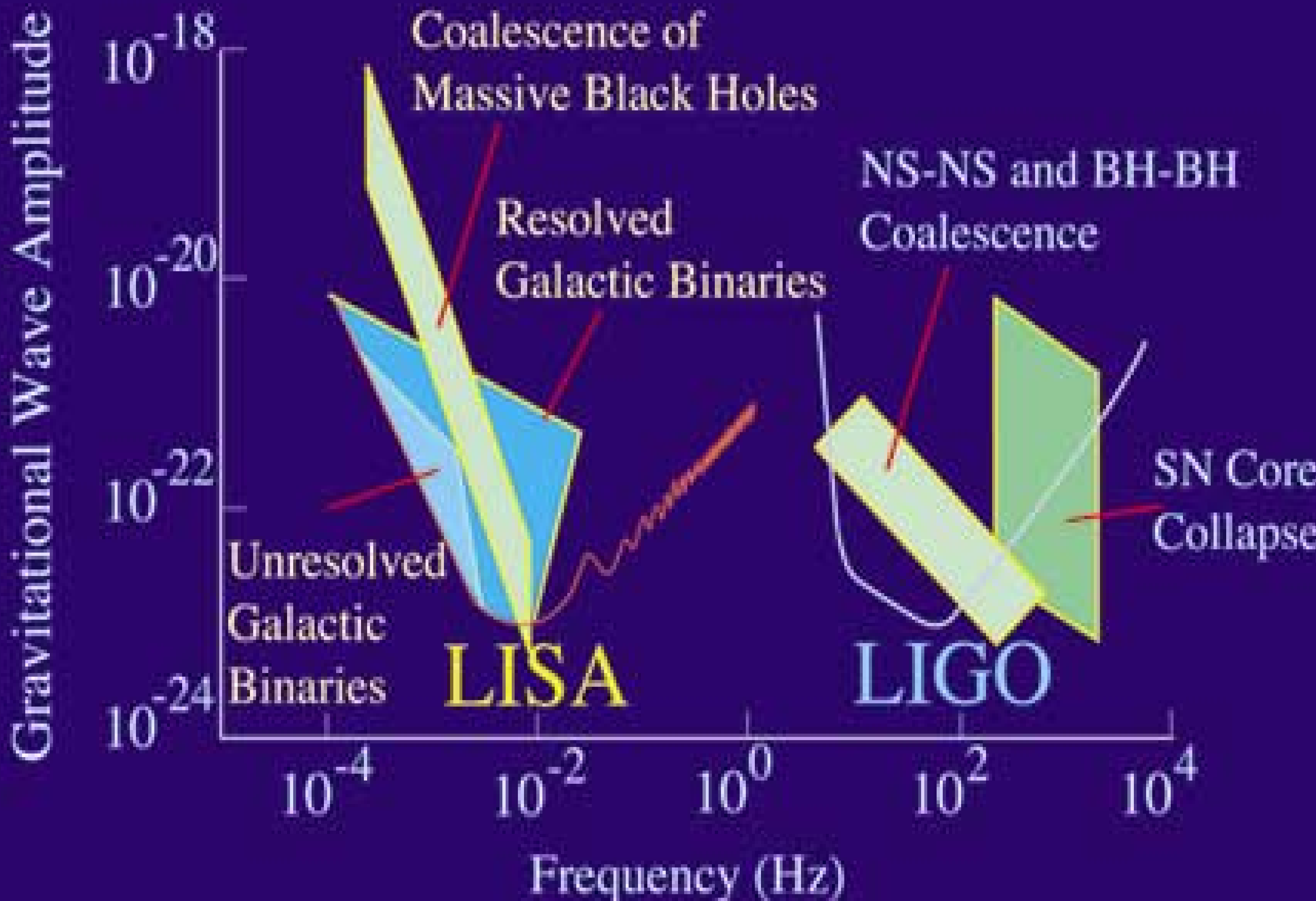
TianQin: a space-borne gravitational wave detector

Jun Luo[1]*, Li-Sheng Chen[4], Hui-Zong Duan[2], Yun-Gui Gong[2], Shoucun Hu[6], Jianghui Ji[6], Qi Liu[2], Jianwei Mei[2], Vadim Milyukov[3], Mikhail Sazhin[3], Cheng-Gang Shao[2], Viktor T. Toth[8], Hai-Bo Tu[5], Yamin Wang[7], Yan Wang[2], Hsien-Chi Yeh[2], Ming-Sheng Zhan[4], Yonghe Zhang[6], Vladimir Zharov[3], Ze-Bing Zhou[2]



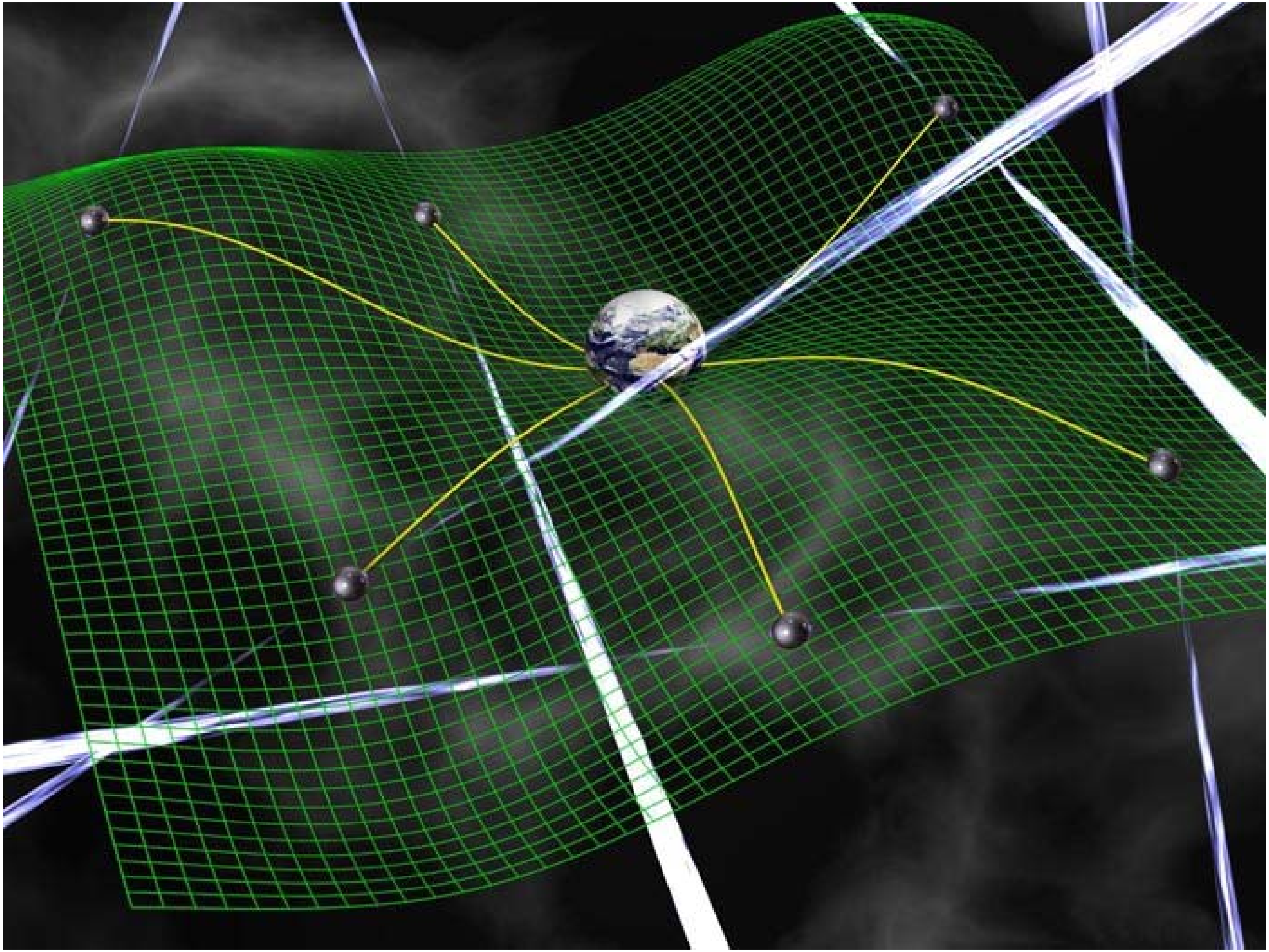


BBN Upper Limit
CMB Upper Limit (2006)
LIGO & VIRGO (2009)
r=0.2 at k*=0.002Mpc-1
i.e. V1/4=2.2*1016GeV
PPTA (2013)
Adv.LIGO
FAST
LISA
ET
nt = 1
SKA
O-PTA
nt = 0
Planck
BBO
G-CMB
nt = -r / 8
Pulsar
Timing
Array
CMBPOL
Laser Interfreometer
GW observatory
CMB
DECIGO
log10Ωgw(f)
log10 (f / Hz)
-5
-10
-15
-20
-18
-16
-14
-12
-10
-8
-6
-4
-2
0
2
4
6
8
10



Gravitational Wave Amplitude
10^-18
10^-20
10^-22
10^-24
Coalescence of
Massive Black Holes
Resolved
Galactic Binaries
NS-NS and BH-BH
Coalescence
SN Core
Collapse
Unresolved
Galactic
Binaries
LISA
LIGO
10^-4
10^-2
10^0
10^2
10^4
Frequency (Hz)

引力波探测之二:脉冲星天线阵



The Parkes Pulsar Timing Array Project

Collaborators:

- Australia Telescope National Facility, CSIRO

  Dick Manchester, George Hobbs, Russell Edwards, John Sarkissian, John Reynolds, Mike Kesteven, Grant Hampson, Andrew Brown

- Swinburne University of Technology

  Matthew Bailes, Ramesh Bhat, Joris Verbiest, Albert Teoh

- University of Texas, Brownsville

  Rick Jenet, Willem van Straten

- University of Sydney

  Steve Ord

- National Observatories of China, Beijing

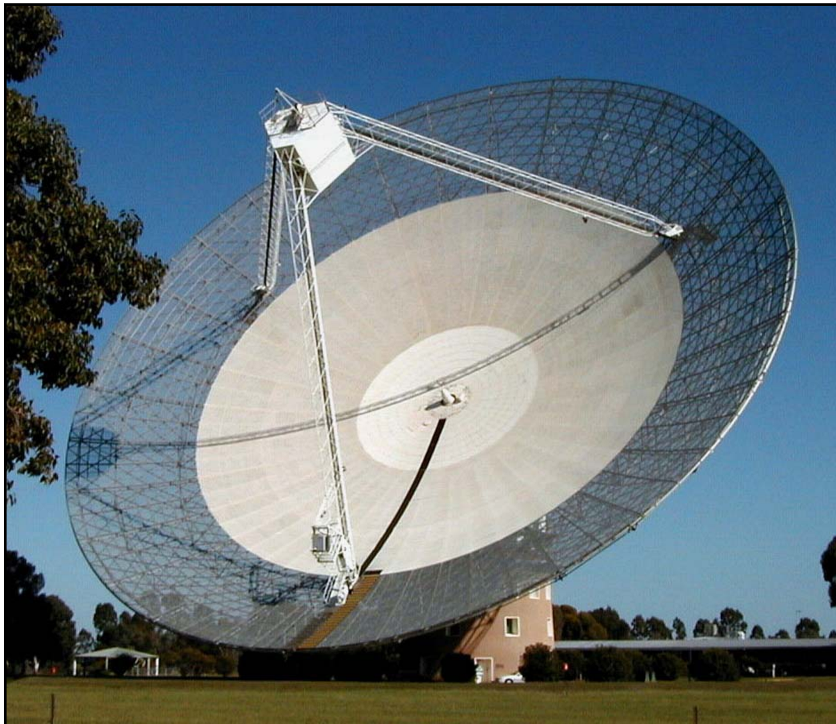
  Xiaopeng You

- Peking University, Beijing

  Kejia Lee

- University of Tasmania

  Aidan Hotan



The PPTA Project: Goals

- To detect gravitational waves of astrophysical origin
- To establish a pulsar-based timescale and to investigate irregularities in terrestrial timescales
- To improve on the Solar System ephemeris used for barycentric correction
- Modelling and detection algorithms for GW signals
- Measurement and correction for interstellar and Solar System propagation effects
- Investigation and implementation of methods for real-time RFI mitigation

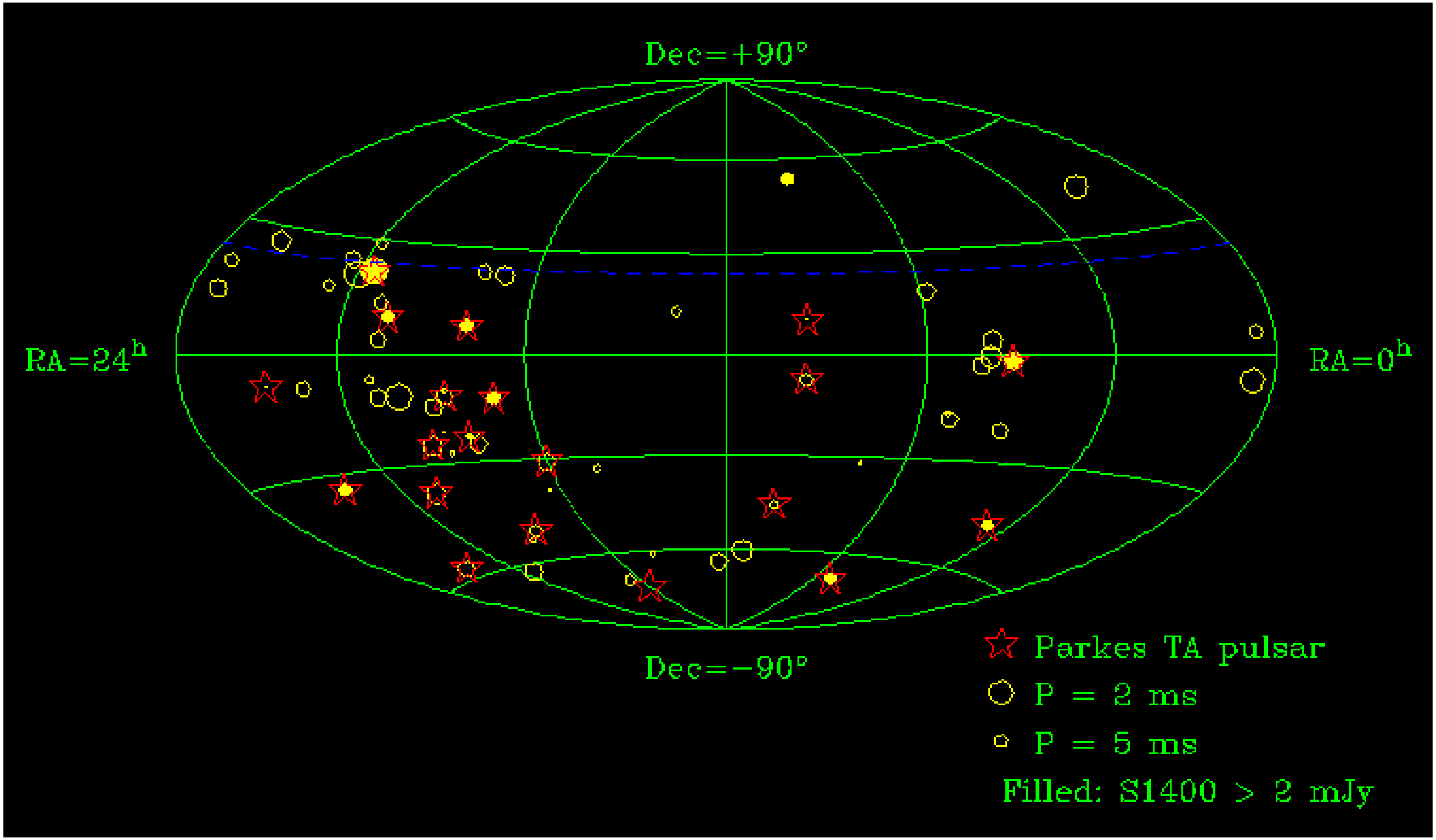
To achieve these goals we need ~weekly observations of ~20 MSPs over at least five years with TOA precisions of ~100 ns for ~10 pulsars and < 1 μs for rest

The PPTA Project: Methods

- Using the Parkes 64-m telescope at three frequencies (680, 1400 and 3100 MHz)
- Digital filterbank system, 256 MHz bandwidth (1 GHz early 2007), 8-bit sampling, polyphase filter
- CPSR2 baseband system 2 x 64 MHz bandwidth, 2-bit sampling, coherent de-dispersion
- Developing APSR with 512 MHz bandwidth and 8-bit sampling
- Implementing real-time RFI mitigation for 50-cm band
- TEMPO2: New timing analysis program, systematic errors in TOA corrections < 1 ns, graphical interfaces, predictions and simulations (Hobbs et al. 2006, Edwards et al. 2006)
- Observing 20 MSPs at 2 - 3 week intervals since mid-2004
- Looking to international co-operation to obtain improved data sampling including pulsars at northern declinations

Sky Distribution of Millisecond Pulsars

P < 20 ms and not in globular clusters

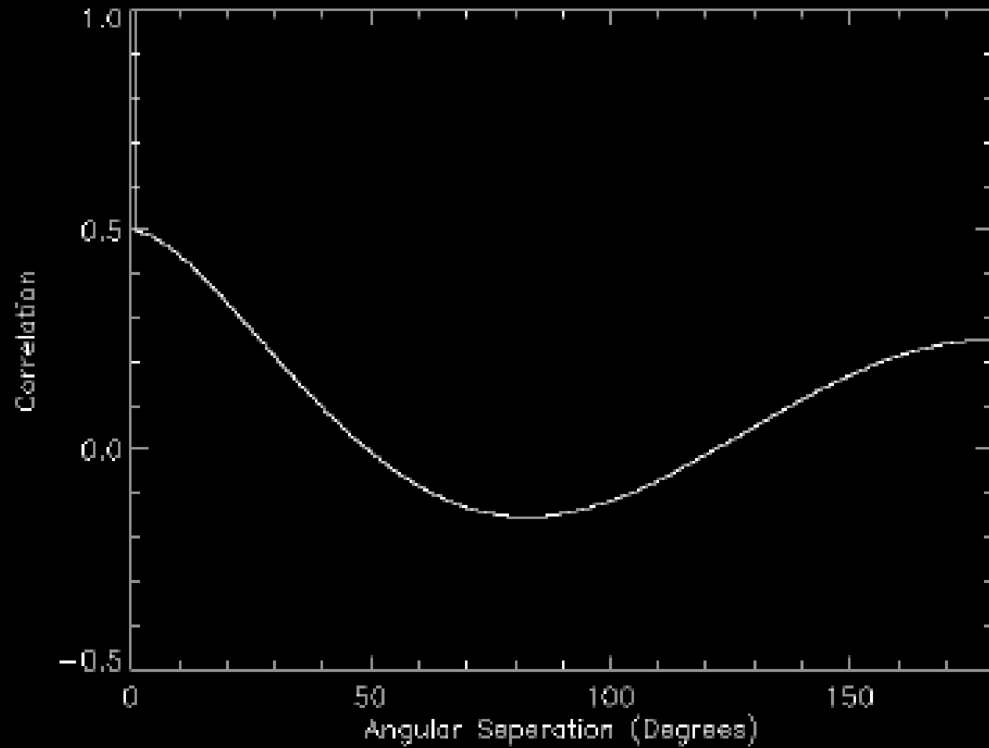


Detecting a Stochastic Background of GWs

Pulse arrival time fluctuations from different pulsars will be correlated:

$$C(\theta_{ij}) = \langle R_i R_j \rangle$$

We will need at least 20 pulsars at 100ns to do this In 5-10 years time.

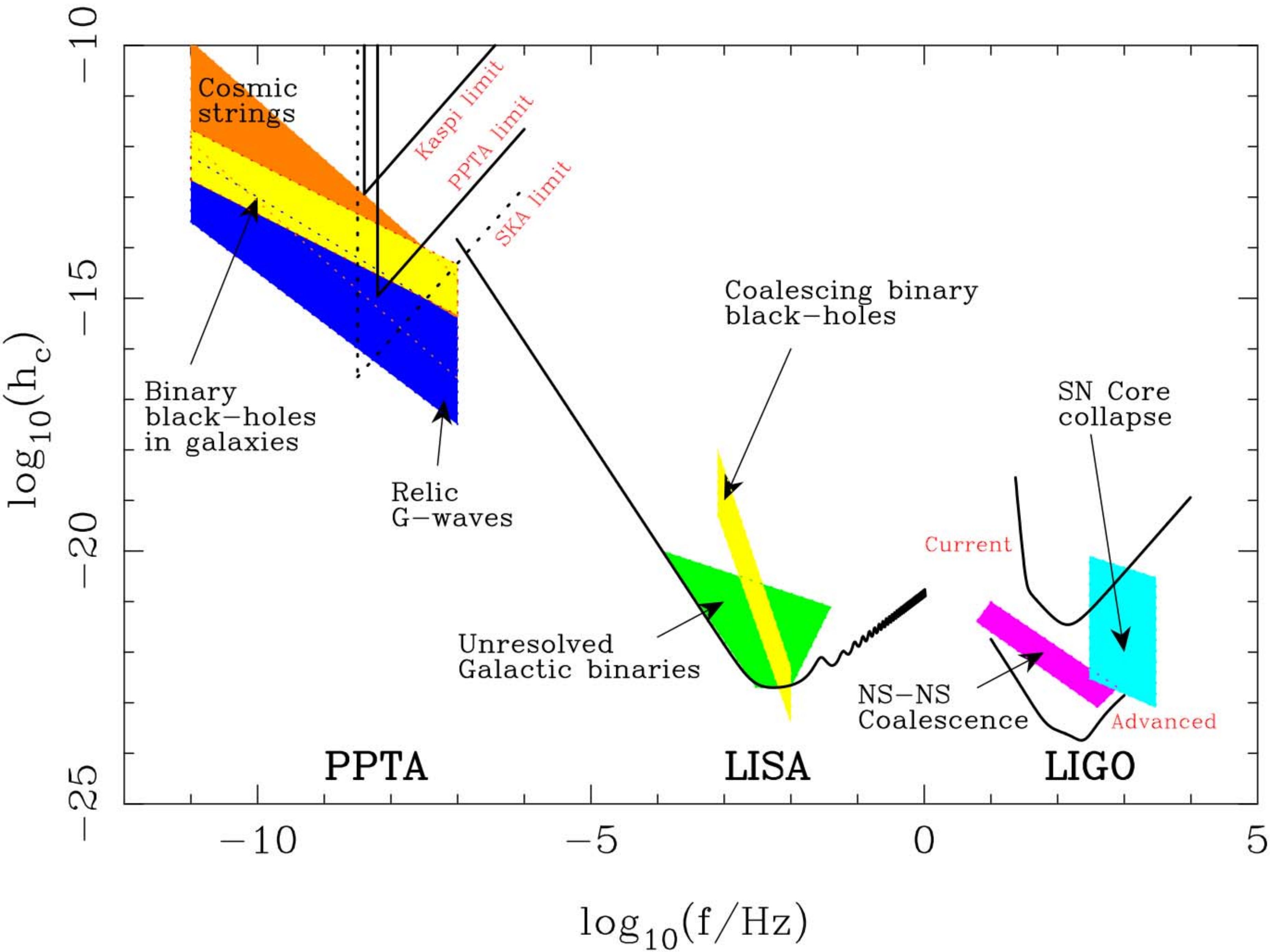


PPTA Pulsars

- 20 MSPs - all in Galactic disk except J1824-2452 (B1821-24) in M28
- Two years of timing data at 2 -3 week intervals and at three frequencies
- Uncorrected for DM variations and polarisation calibration
- Five pulsars with rms timing residuals < 500 ns, all < 2.5 μs
- Best results on J0437-4715 (120 ns) and B1937+21 (170 ns)

Still have a way to go!

Name	Period (ms)	DM (cm^{-3} pc)	Orbital period (d)	Rms Residual (μs)
J0437-4715	5.757	2.65	5.74	0.12
J0613-0200	3.062	38.78	1.20	0.83
J0711-6830	5.491	18.41	-	1.56
J1022+1001	16.453	10.25	7.81	1.11
J1024-0719	5.162	6.49	-	1.20
J1045-4509	7.474	58.15	4.08	1.44
J1600-3053	3.598	52.19	14.34	0.35
J1603-7202	14.842	38.05	6.31	1.34
J1643-1224	4.622	62.41	147.02	2.10
J1713+0747	4.570	15.99	67.83	0.19
J1730-2304	8.123	9.61	-	1.82
J1732-5049	5.313	56.84	5.26	2.40
J1744-1134	4.075	3.14	-	0.65
J1824-2452	3.054	119.86	-	0.88
J1857+0943	5.362	13.31	12.33	2.09
J1909-3744	2.947	10.39	1.53	0.22
J1939+2134	1.558	71.04	-	0.17
J2124-3358	4.931	4.62	-	2.00
J2129-5721	3.726	31.85	6.63	0.91
J2145-0750	16.052	9.00	6.84	1.44



Cosmic strings
Kaspi limit
PPTA limit
SKA limit
Binary black−holes in galaxies
Relic G−waves
Coalescing binary black−holes
Unresolved Galactic binaries
Current
SN Core collapse
NS−NS Coalescence
Advanced
PPTA
LISA
LIGO
$\log_{10}(h_c)$
$\log_{10}(f/\mathrm{Hz})$
−10
−15
−20
−25
−10
−5
0
5

3C 66B:Evidence

Science magazine

Orbital Motion in the Radio Galaxy 3C 66B: Evidence for a Supermassive Black Hole Binary

Hiroshi Sudou,[1*] Satoru Iguchi,[2] Yasuhiro Murata,[3] Yoshiaki Taniguchi[1]

Supermassive black hole binaries may exist in the centers of active galactic nuclei such as quasars and radio galaxies, and mergers between galaxies may result in the formation of supermassive binaries during the course of galactic evolution. Using the very-long-baseline interferometer, we imaged the radio galaxy 3C 66B at radio frequencies and found that the unresolved radio core of 3C 66B shows well-defined elliptical motions with a period of 1.05 ± 0.03 years, which provides a direct detection of a supermassive black hole binary.

Volume 300, Number 5623, Issue of 23 May 2003, pp. 1263-1265.
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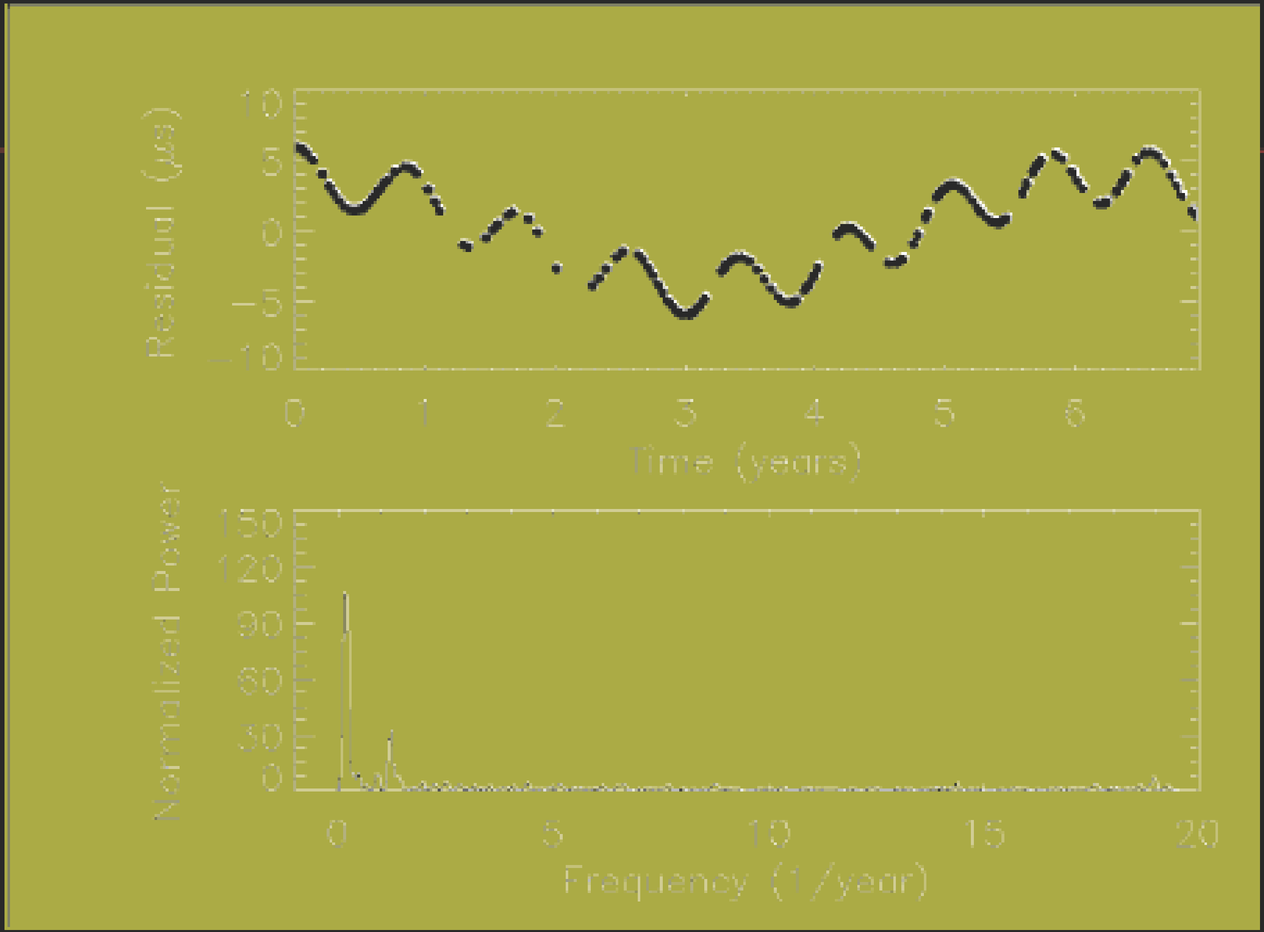
Sudou et al.'s adopted parameters for 3C 66B

- $M_t = 5.4 \times 10^{10}\ M_{solar}$
- Mass ratio = .1
- $M_{chirp} = 1.3\ 10^{10}\ M_{solar}$
- Orbital period = 1.05 ± .03 yrs
- Distance = 85 Mpc (H=75 km/s/Mpc)
- $h \approx M_{chirp}^{5/3}\ \Omega^{2/3}\ /\ D \approx 10^{-12}$
- $R = h/\Omega = 2\ \mu\ s$

The expected signature of GWs from 3C66B on PSRB1855+09



From Jenet, Lommen, Larson, & Wen, ApJ May 10th 2004

Science 25 September 2015:
Vol. 349 no. 6255 pp. 1522-1525
DOI: 10.1126/science.aab1910

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REPORT

Gravitational waves from binary supermassive black holes missing in pulsar observations

R. M. Shannon[1,2,*], V. Ravi[3,*], L. T. Lentati[4], P. D. Lasky[5], G. Hobbs[1], M. Kerr[1], R. N. Manchester[1], W. A. Coles[6], Y. Levin[5], M. Bailes[3], N. D. R. Bhat[2], S. Burke-Spolaor[7], S. Dai[1,8], M. J. Keith[9], S. Osłowski[10,11], D. J. Reardon[5], W. van Straten[3], L. Toomey[1], J.-B. Wang[12], L. Wen[13], J. S. B. Wyithe[14], X.-J. Zhu[13]

+ Author Affiliations

[*]Corresponding author. E-mail: ryan.shannon@csiro.au (R.S.); v.vikram.ravi@gmail.com (V.R.)

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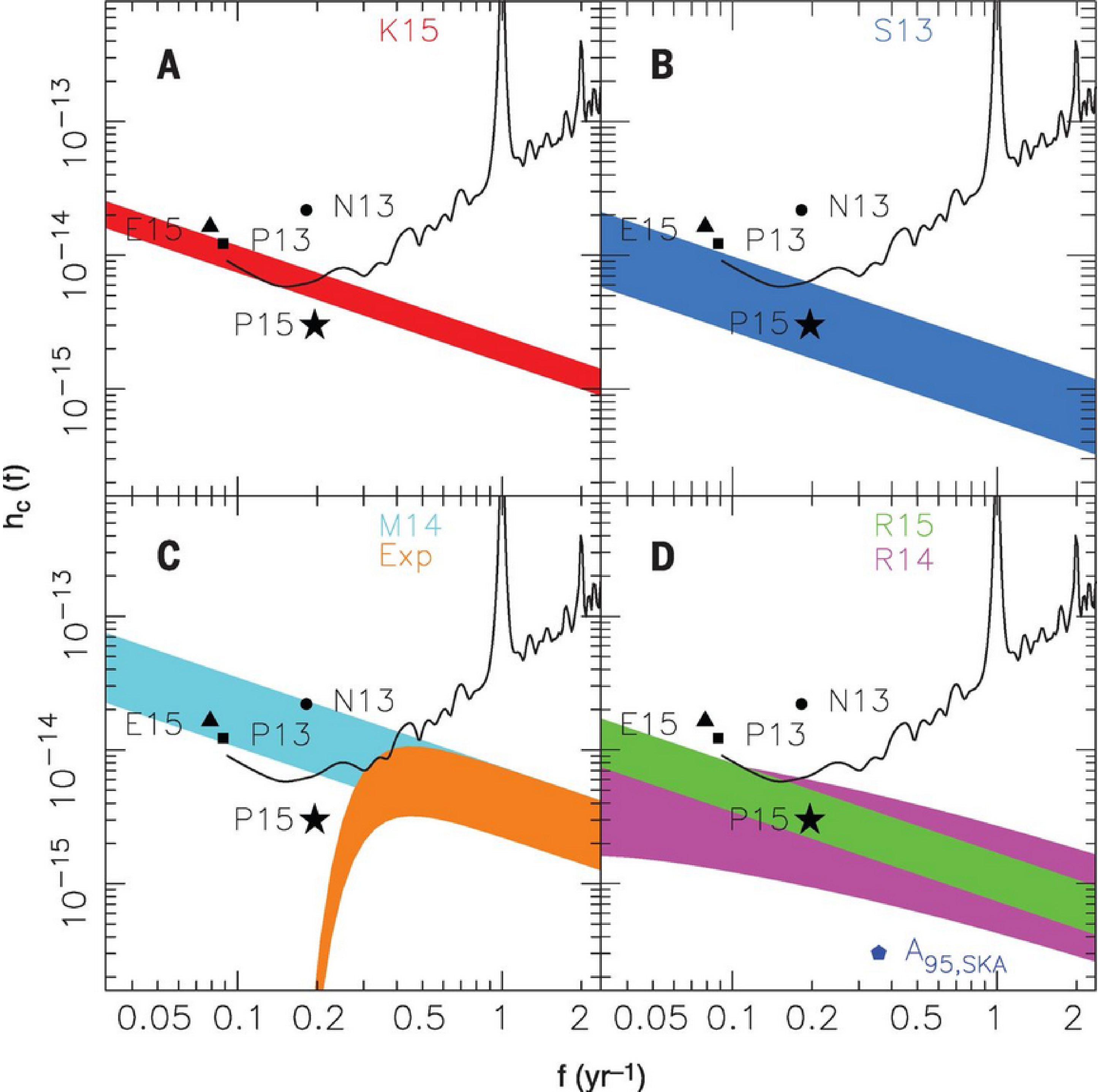
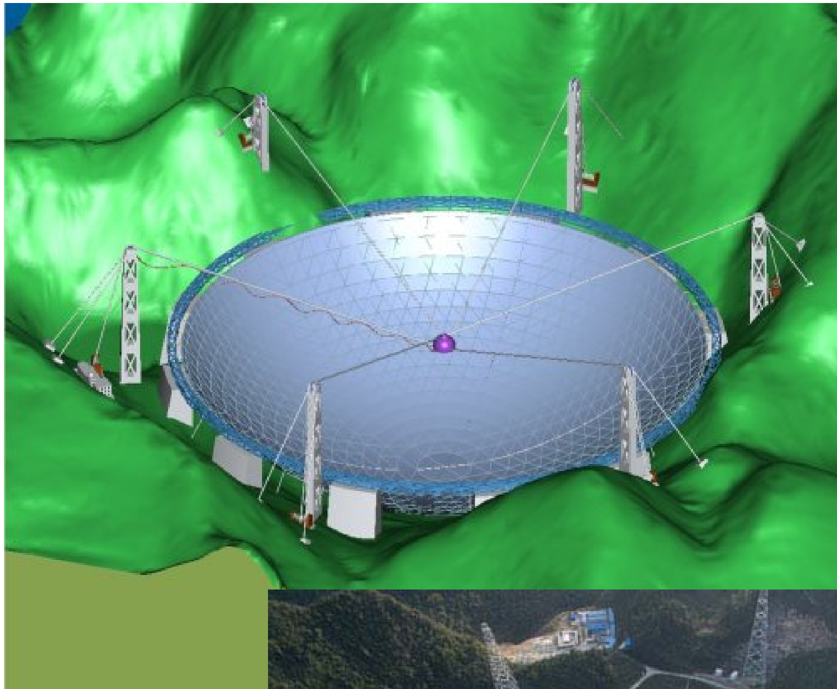
ABSTRACT | EDITOR'S SUMMARY

Gravitational waves are expected to be radiated by supermassive black hole binaries formed during galaxy mergers. A stochastic superposition of gravitational waves from all such binary systems would modulate the arrival times of pulses from radio pulsars. Using observations of millisecond pulsars obtained with the Parkes radio telescope, we constrained the characteristic amplitude of this background, $A_{c,yr}$, to be <1.0×10^{-15} with 95% confidence. This limit excludes predicted ranges for $A_{c,yr}$ from current models with 91 to 99.7% probability. We conclude that binary evolution is either stalled or dramatically accelerated by galactic-center environments and that higher-cadence and shorter-wavelength observations would be more sensitive to gravitational waves.



K15
A
S13
B
M14
Exp
C
R15
R14
D
N13
E15
P13
P15
$A_{95,SKA}$
10^{-13}
10^{-14}
10^{-15}
$h_c(f)$
0.05
0.1
0.2
0.5
1
2
f (yr^{-1})

500米口径球面射电望远镜（FAST）

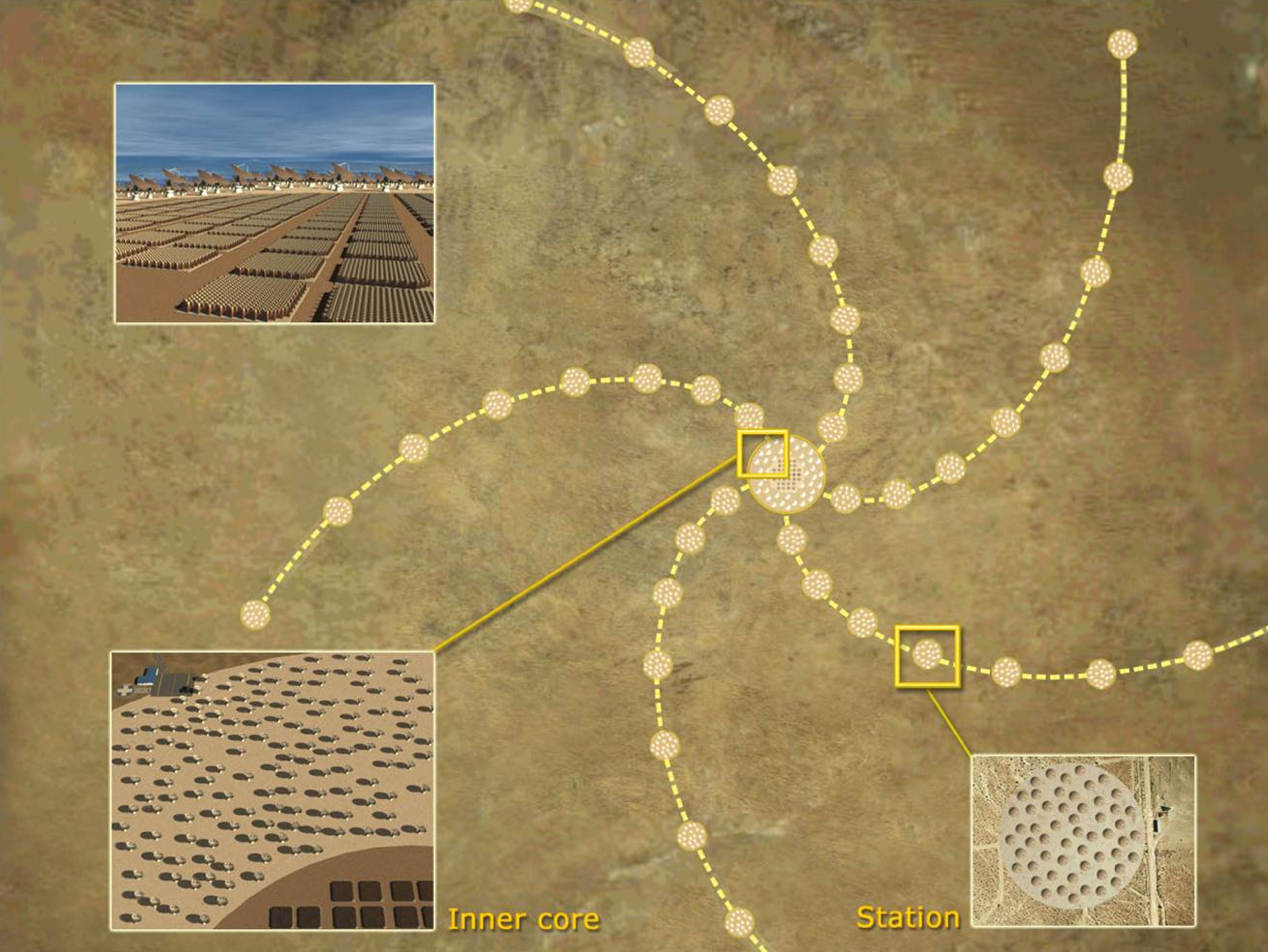


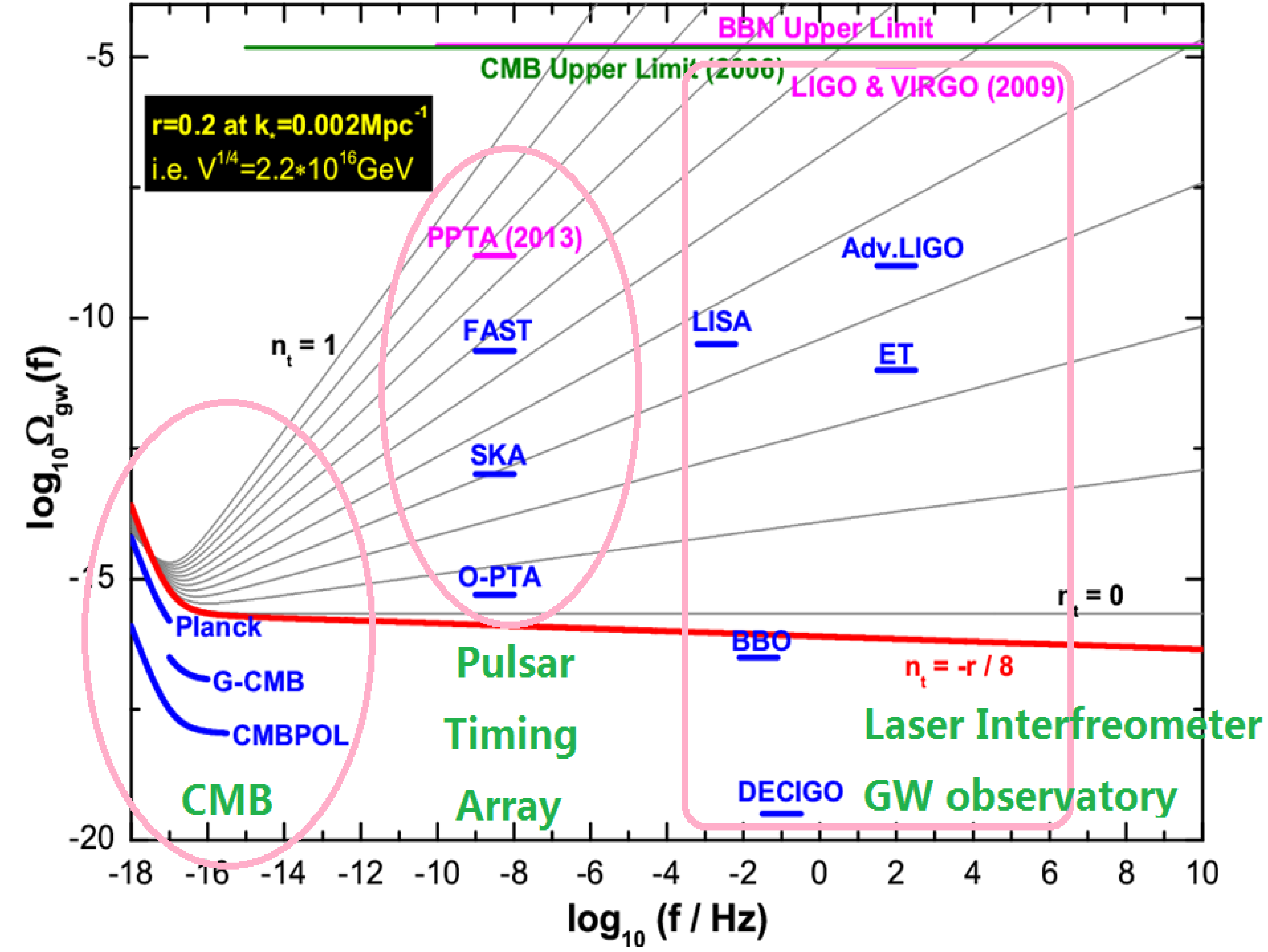
•球面反射面被照明部分实时拟合成一个瞬时抛物面

•反射面由约1800个15米的六边形球面单元拼合而成。

•改正了球差，简化了馈源，克服了球反射面线焦造成的窄带效应。

•利用贵州南部独特的天然喀斯特洼坑可大大降低望远镜工程造价


Inner core
Station



BBN Upper Limit
CMB Upper Limit (2006)
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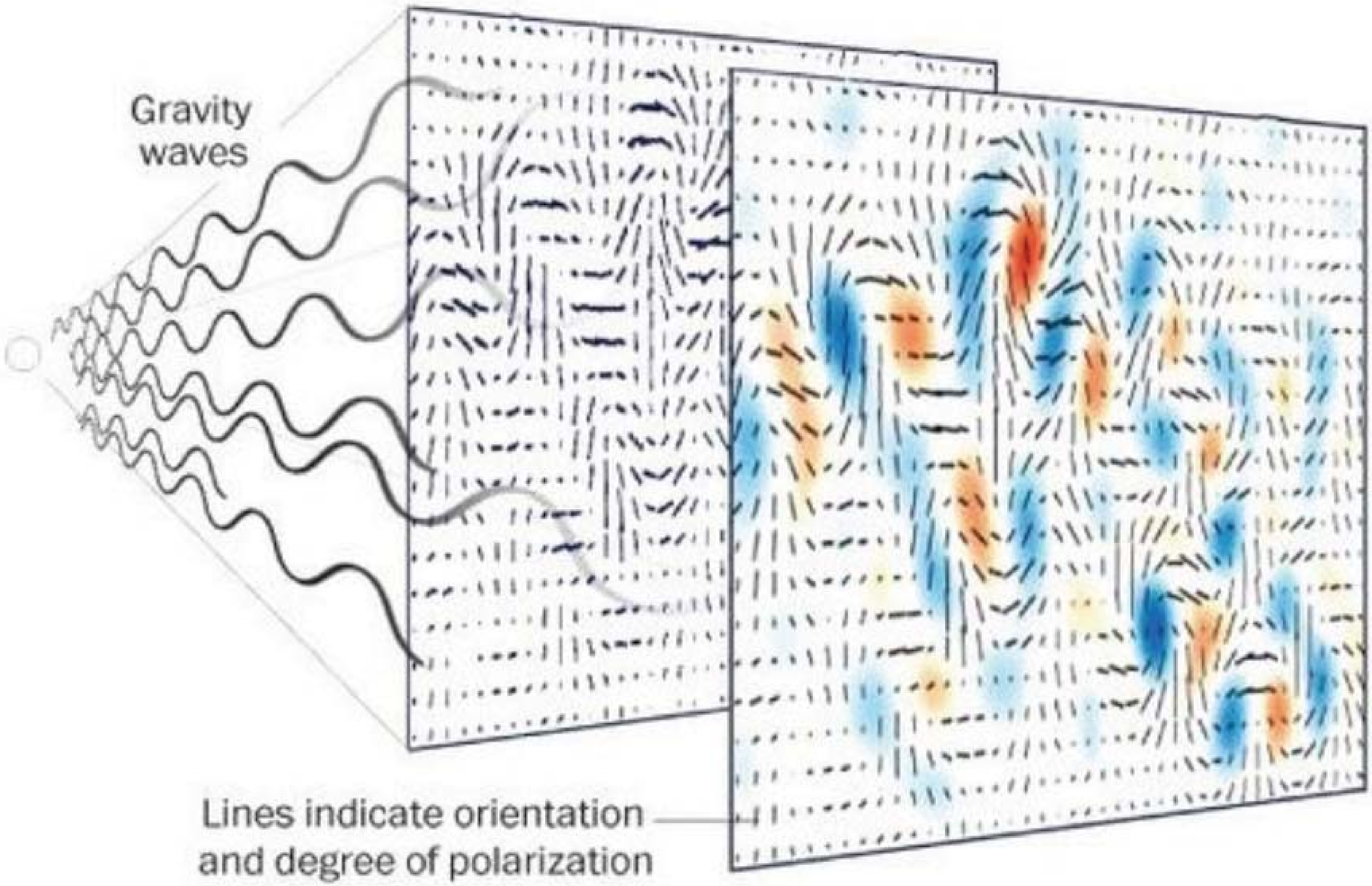
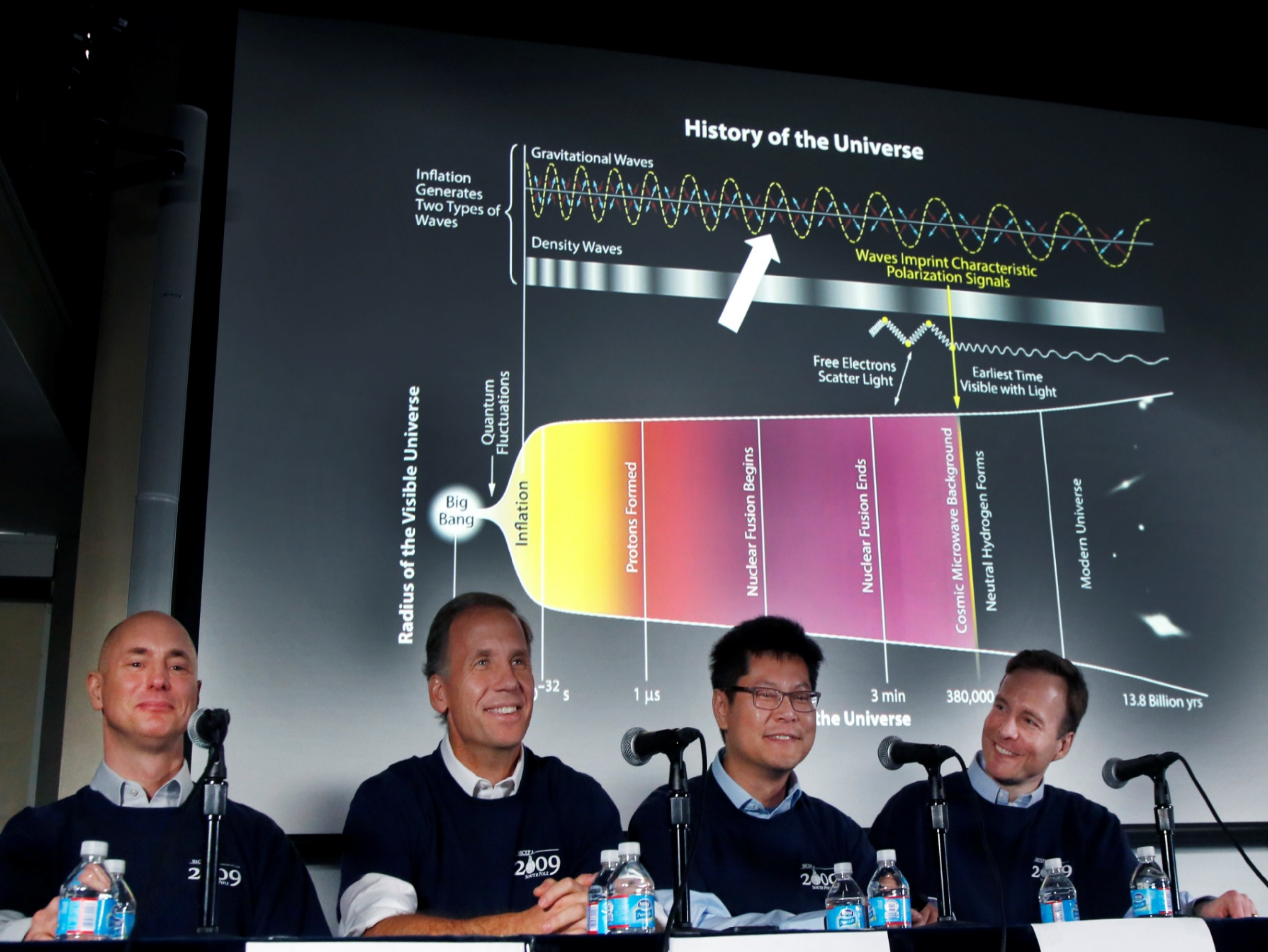
r=0.2 at k*=0.002Mpc-1
i.e. V1/4=2.2*1016GeV
PPTA (2013)
Adv.LIGO
FAST
LISA
ET
nt = 1
SKA
O-PTA
nt = 0
Planck
BBO
Pulsar
Timing
Array
G-CMB
nt = -r / 8
CMBPOL
Laser Interfreometer
GW observatory
CMB
DECIGO
log10Ωgw(f)
log10 (f / Hz)
-5
-10
-15
-20
-18
-16
-14
-12
-10
-8
-6
-4
-2
0
2
4
6
8
10

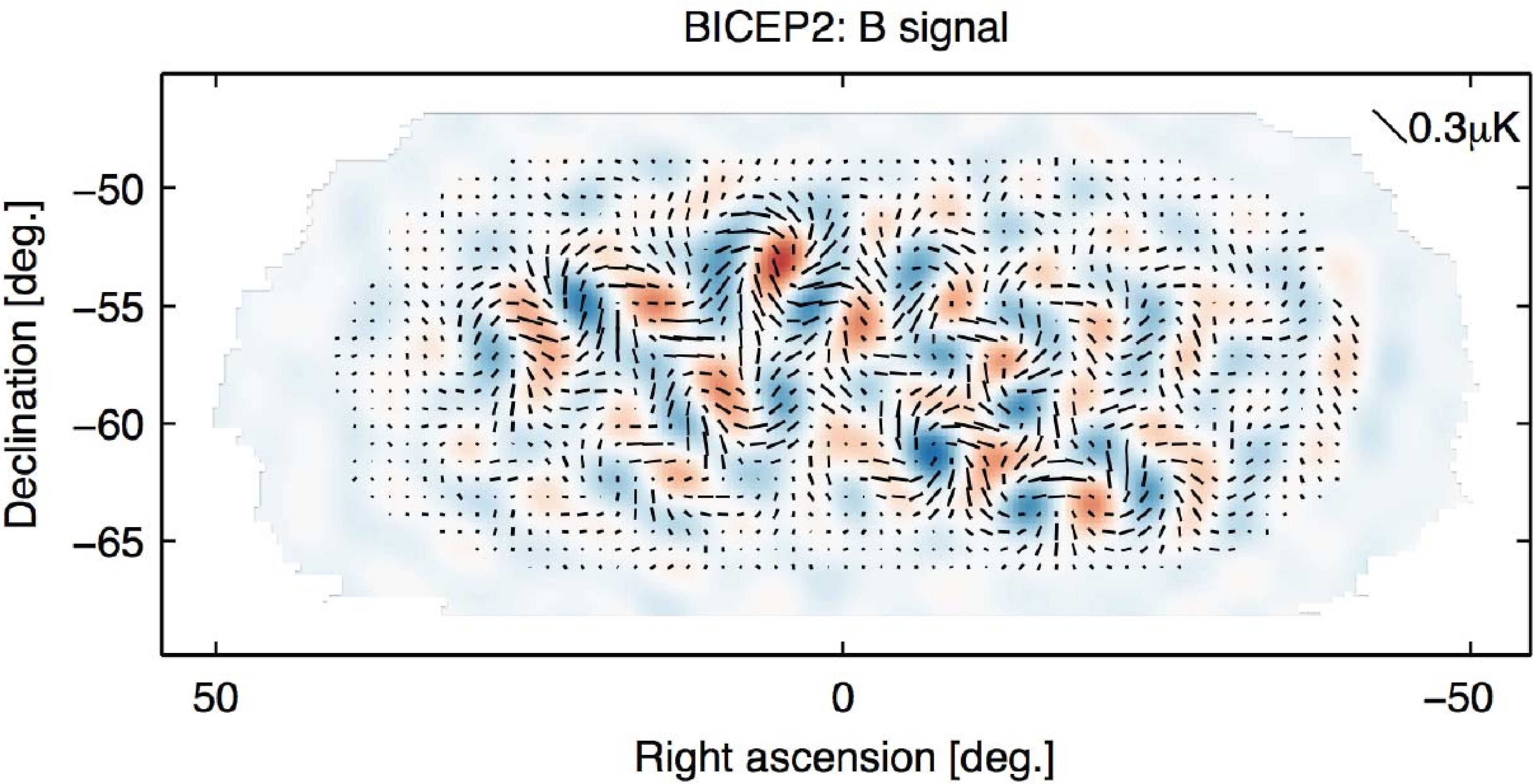
引力波探测之三: 微波背景辐射




History of the Universe
Gravitational Waves
Inflation Generates Two Types of Waves
Density Waves
Waves Imprint Characteristic Polarization Signals
Free Electrons Scatter Light
Earliest Time Visible with Light
Radius of the Visible Universe
Quantum Fluctuations
Big Bang
Inflation
Protons Formed
Nuclear Fusion Begins
Nuclear Fusion Ends
Cosmic Microwave Background
Neutral Hydrogen Forms
Modern Universe
1 µs
3 min
380,000
13.8 Billion yrs
the Universe
2009


BICEP (Background Imaging of
Cosmic Exragalactic Polarization)
宇宙河外偏振背景成像
South Pole Telescope

Gravitational Waves from the Early Universe



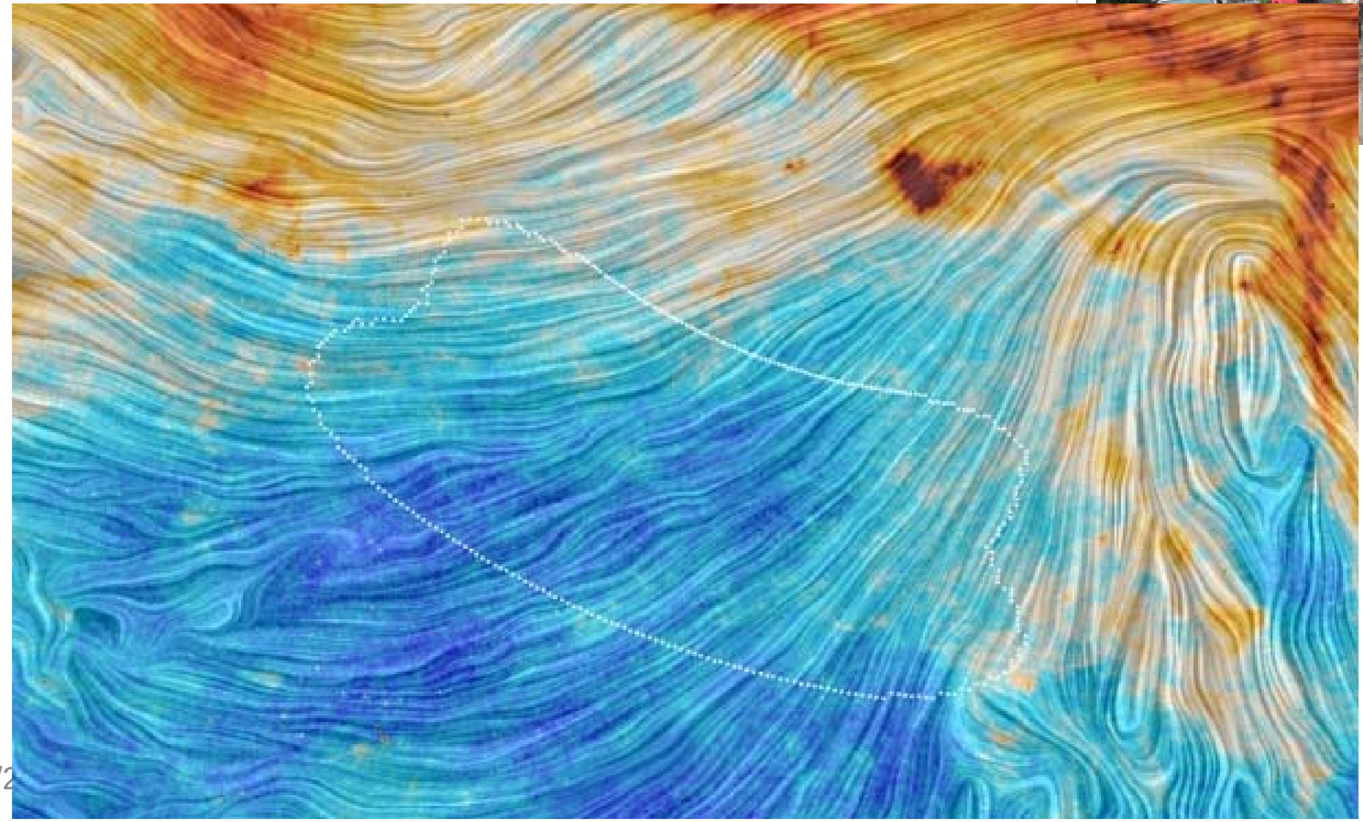
NATURE | NEWS

Gravitational waves discovery now officially dead

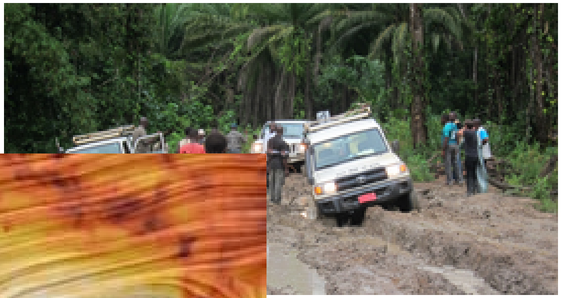
Combined data from South Pole experiment BICEP2 and Planck probe point to Galactic dust as confounding signal.

Ron Cowen

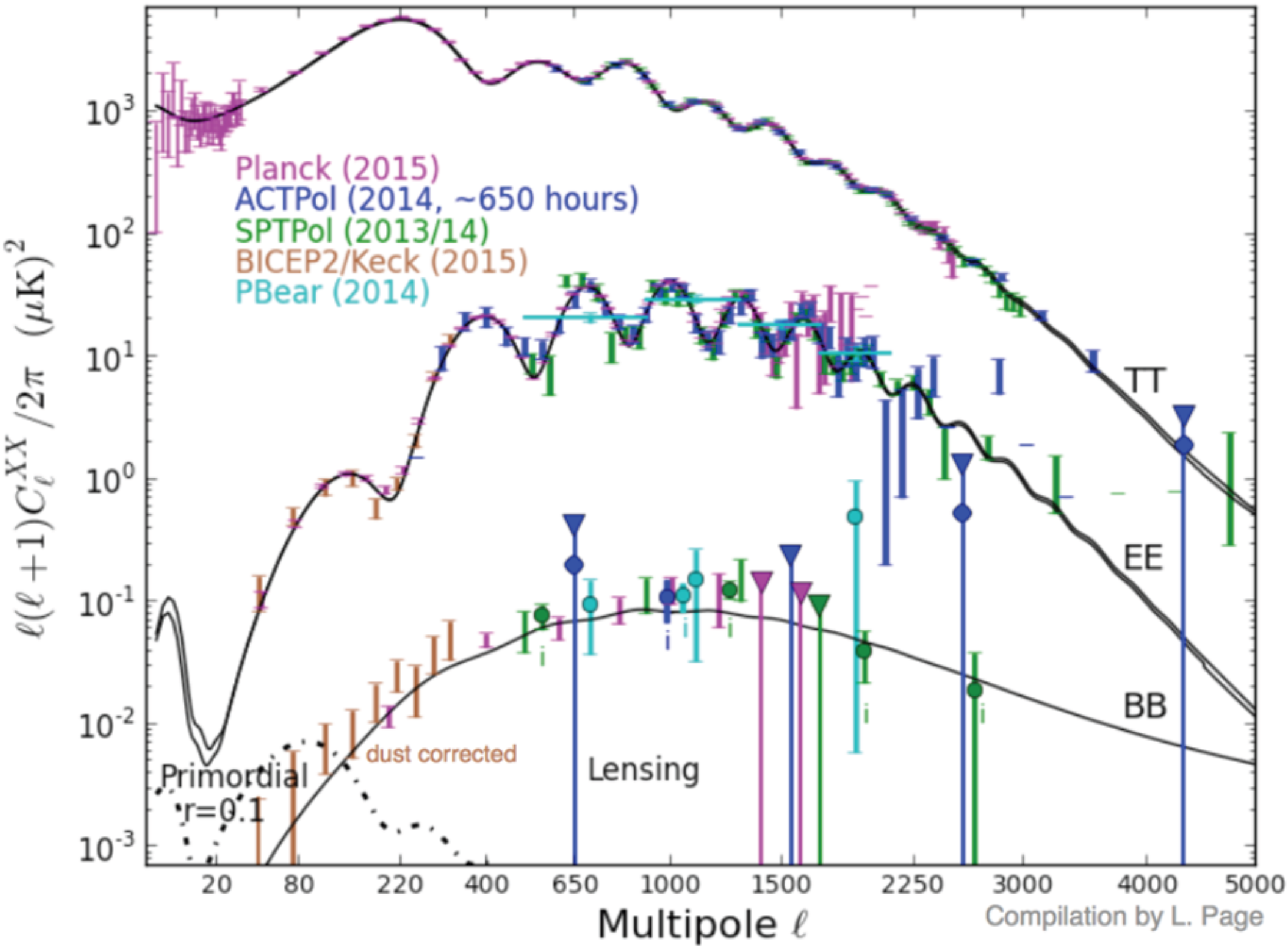
30 January 2015



Top story

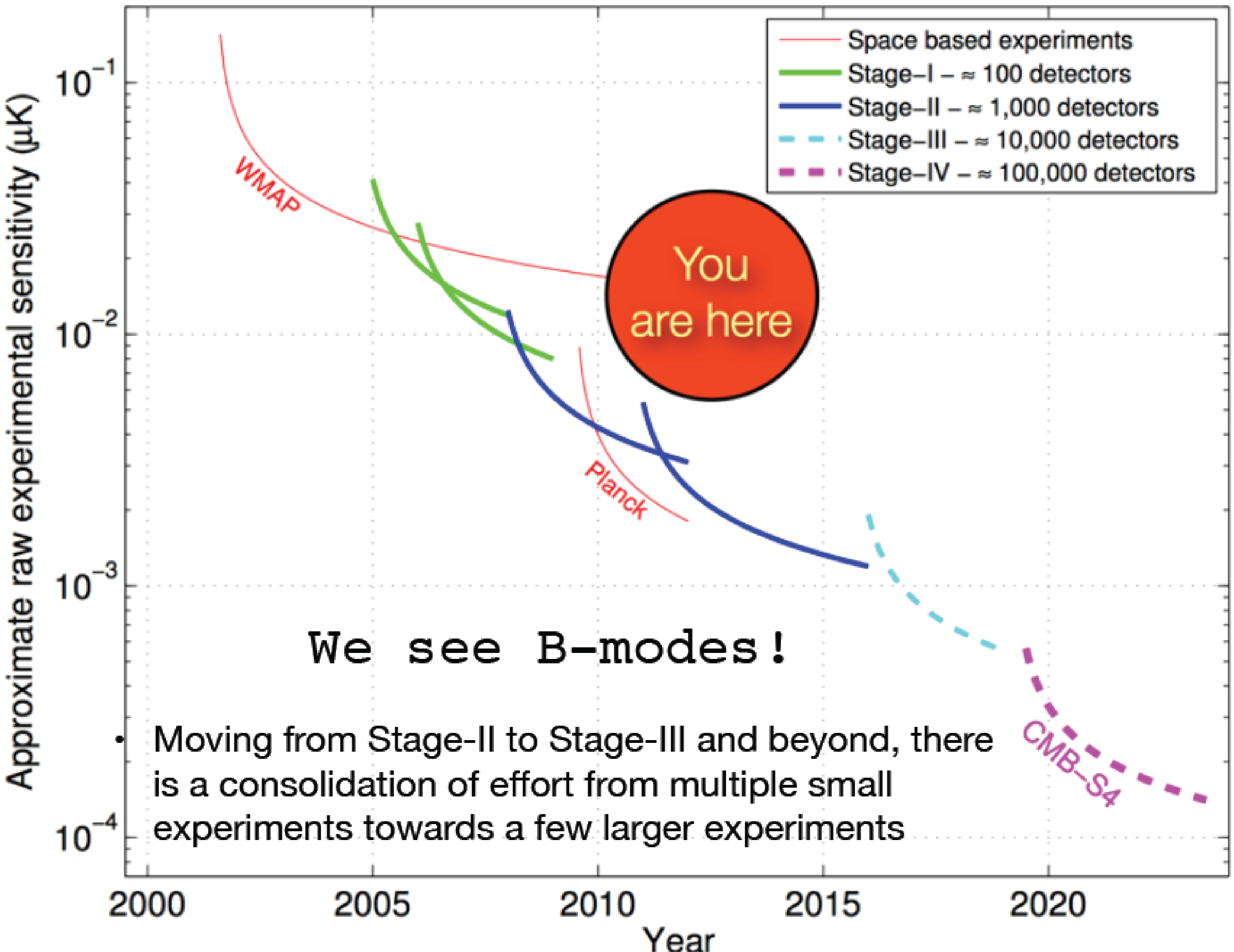


CMB polarization measurements



Rapid progress! All in last ~2 years.

CMB S4



- Moving from Stage-II to Stage-III and beyond, there is a consolidation of effort from multiple small experiments towards a few larger experiments

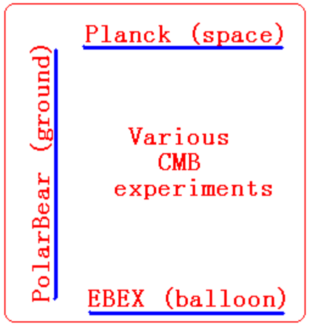
From Clarence Chang

Instrumental parameters for Planck mission

Band center [GHz]	100	143	217	353
N_d	8	8	8	8
NET [μK$\cdot$ sec$^{\frac{1}{2}}$]	50	62	91	277
FWHM [arcmin]	9.5	7.1	5.0	5.0
$f_{\rm sky}$	1			
Integration time	28 months			

Instrumental parameters for PolarBear (II)

Band center [GHz]	90	150	220
N_d	400	600	200
NET [μK$\cdot$ sec$^{\frac{1}{2}}$]	220	244	453
FWHM [arcmin]	6.7	4.0	2.7
$f_{\rm sky}$	0.024		
Integration time	$\sim$ 6 months		

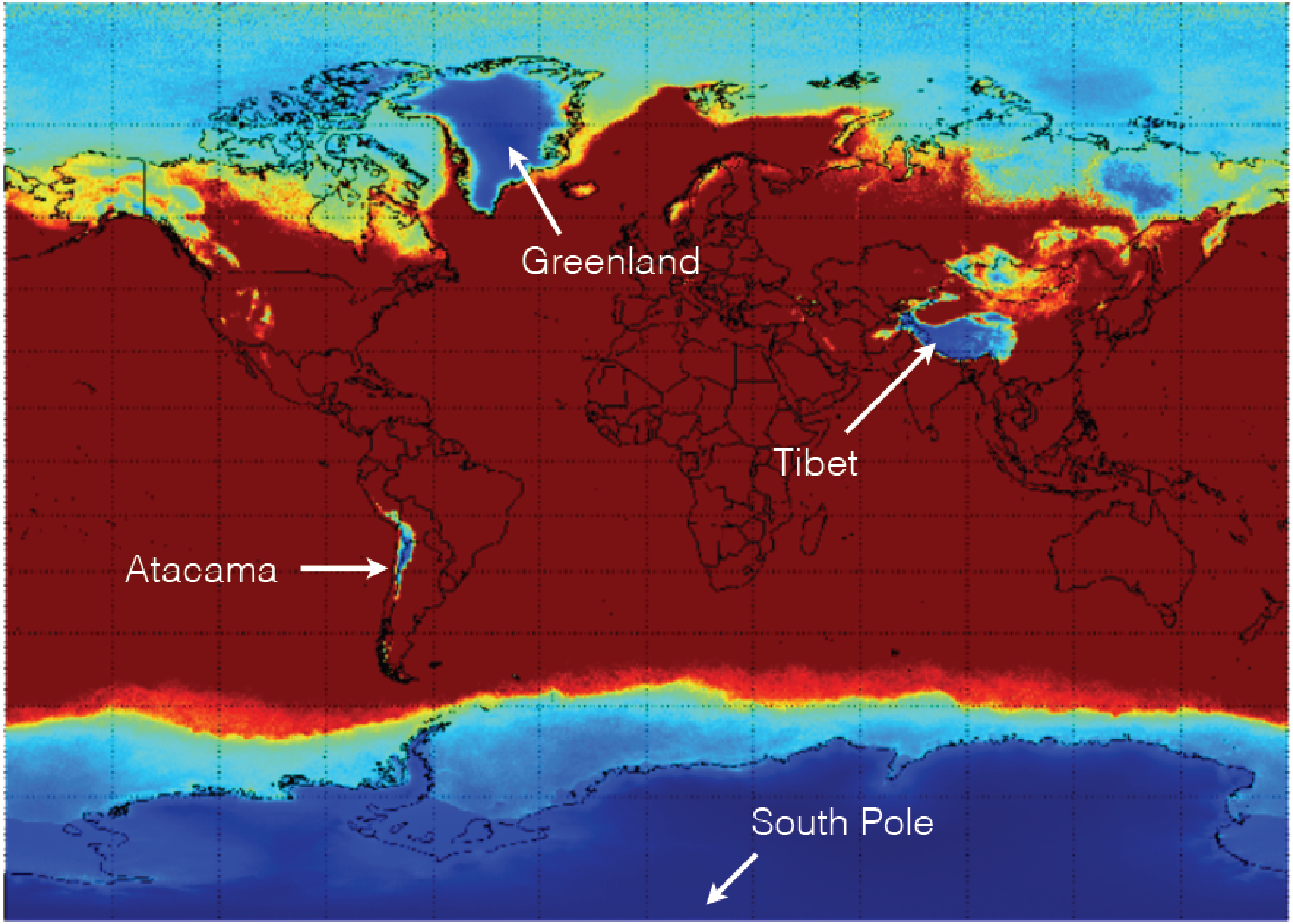


Instrumental parameters for EBEX

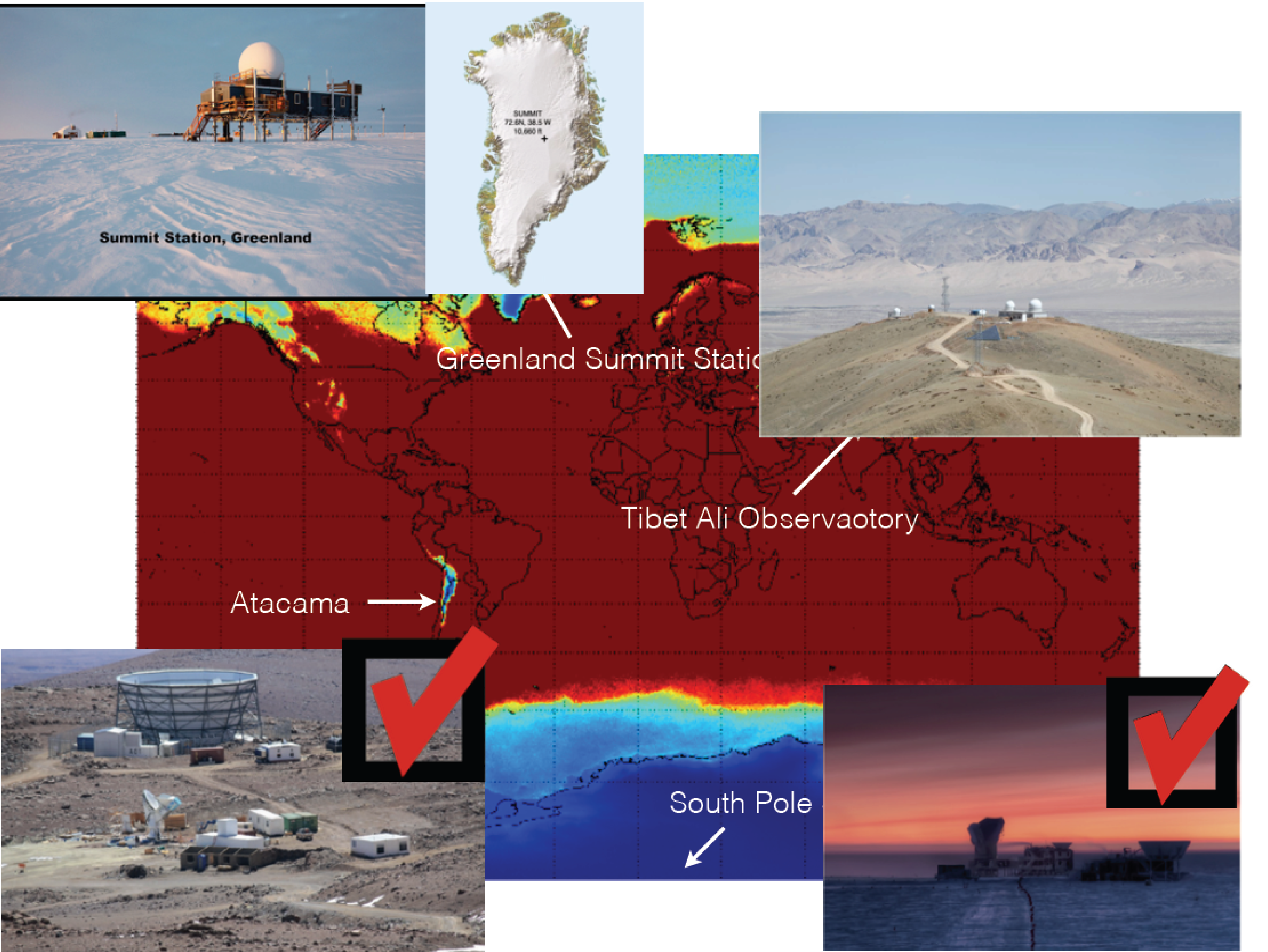
Band center [GHz]	150	250	410
N_d	768	384	280
NET [μK$\cdot$ sec$^{\frac{1}{2}}$]	136	100	85
FWHM [arcmin]	8	8	8
$f_{\rm sky}$	0.01		
Integration time	$\sim$ 14 days		

@ Ground-based experiment can choose the cleanest partial sky to reduce various foreground contaminations.

Atmosphere transmission



Suen et al. 2014, IEEE proceeding on Terahertz Science and Technology



Summit Station, Greenland
SUMMIT
72.6N, 38.5 W
10,660 ft
Greenland Summit Statio
Tibet Ali Observaotory
Atacama
South Pole

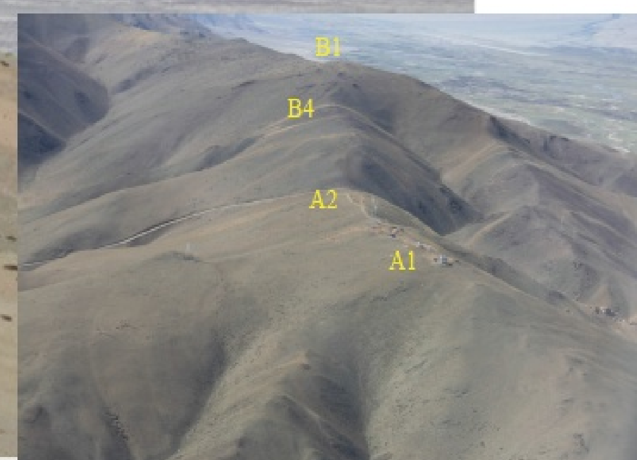
Recent South Pole CMB experiments

Photo credit Cynthia Chiang

Recent Atacama CMB experiments

The Ali Observatory

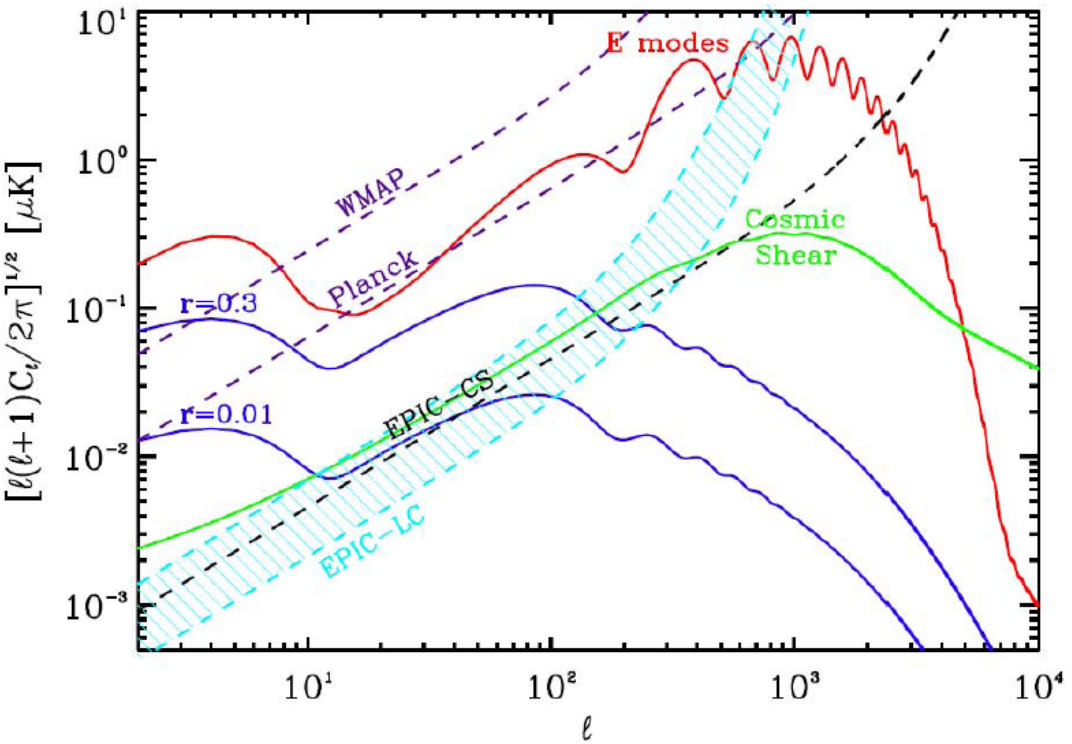
N32 deg, E80 deg, 5100m altitude.
30 km south of the Shiquanhe town
25 km to Kunsha Airport
With a 25 KW solar power station
50 cm telescopes are already in use
Power transmission tower and line is on site

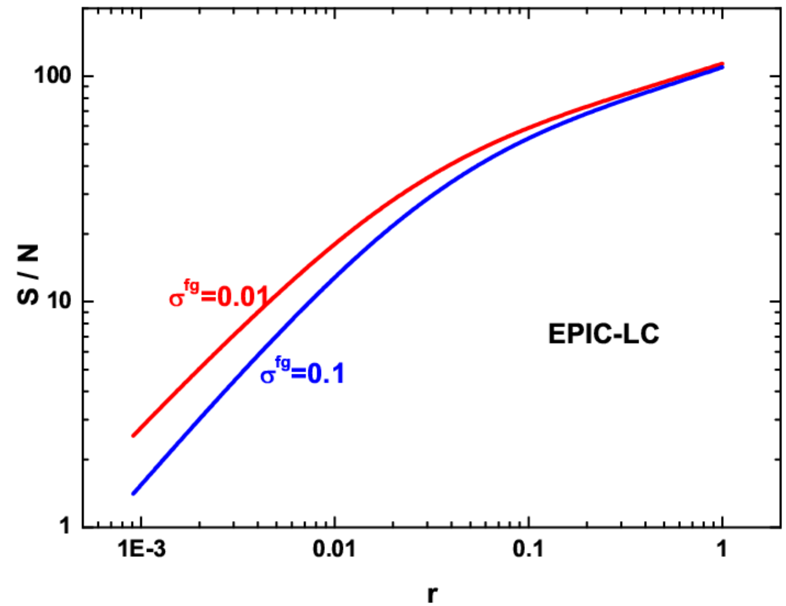


Planned CMBPol experiment

Table 5.5.4 Low-Cost Option TES Focal Plane Design Sensitivity						
Freq [GHz]	θ_{FWHM} [arcmin]	N_{bol}[1] [#]	NET_{bol}[2] [μKcmb$\sqrt{s}$]	NET_{band} [μKcmb$\sqrt{s}$]	$w_p^{-1/2}$[,3] [μK arcmin]	δT_{pix} (2°x2°)[4] [nKrms]
30	155	8	57	20	44	260
40	116	54	50	6.8	15	88
60	77	128	42	3.7	8.1	48
90	52	512	37	1.6	3.5	21
135	34	512	35	1.5	3.3	20
200	23	576	38	1.6	3.5	21
300	16	576	65	2.7	5.9	35
Total[5]		2366		0.8	1.8	11

(see CMBPol white book for details)





When r>0.001 (2 orders smaller than Planck), CMBPol will detect!

Ideal CMB experiment

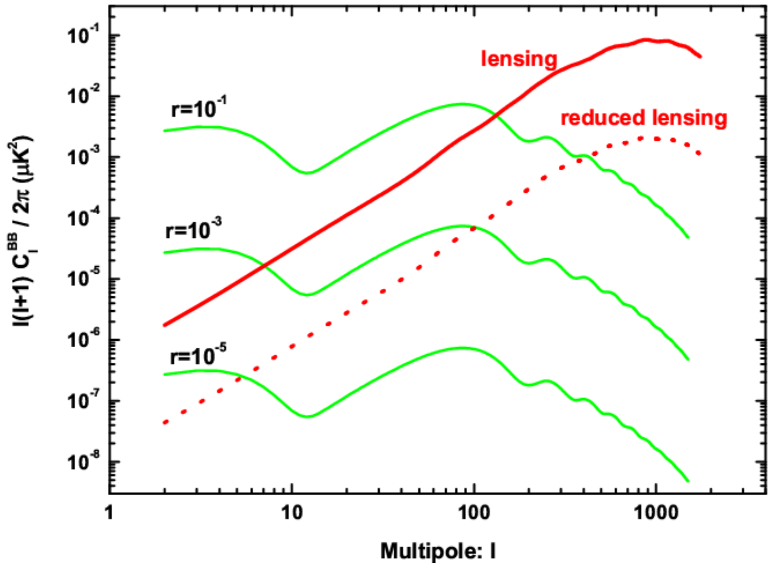
- Cosmic lensing generates the E-B mixtures, and forms a nearly white B-mode spectrum.
- For the ideal experiment, where only the reduced cosmic lensing contamination is considered.
- Detection limit:

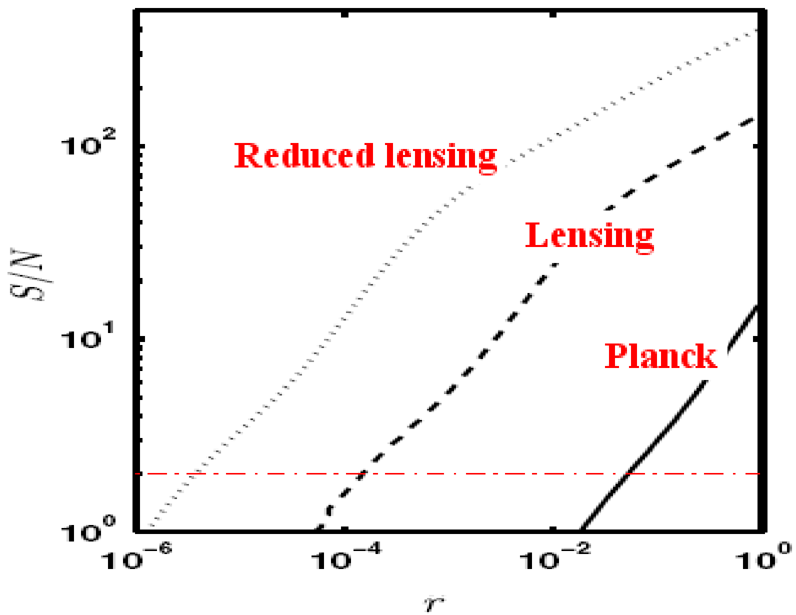
$$r = 3.7 \times 10^{-6}$$

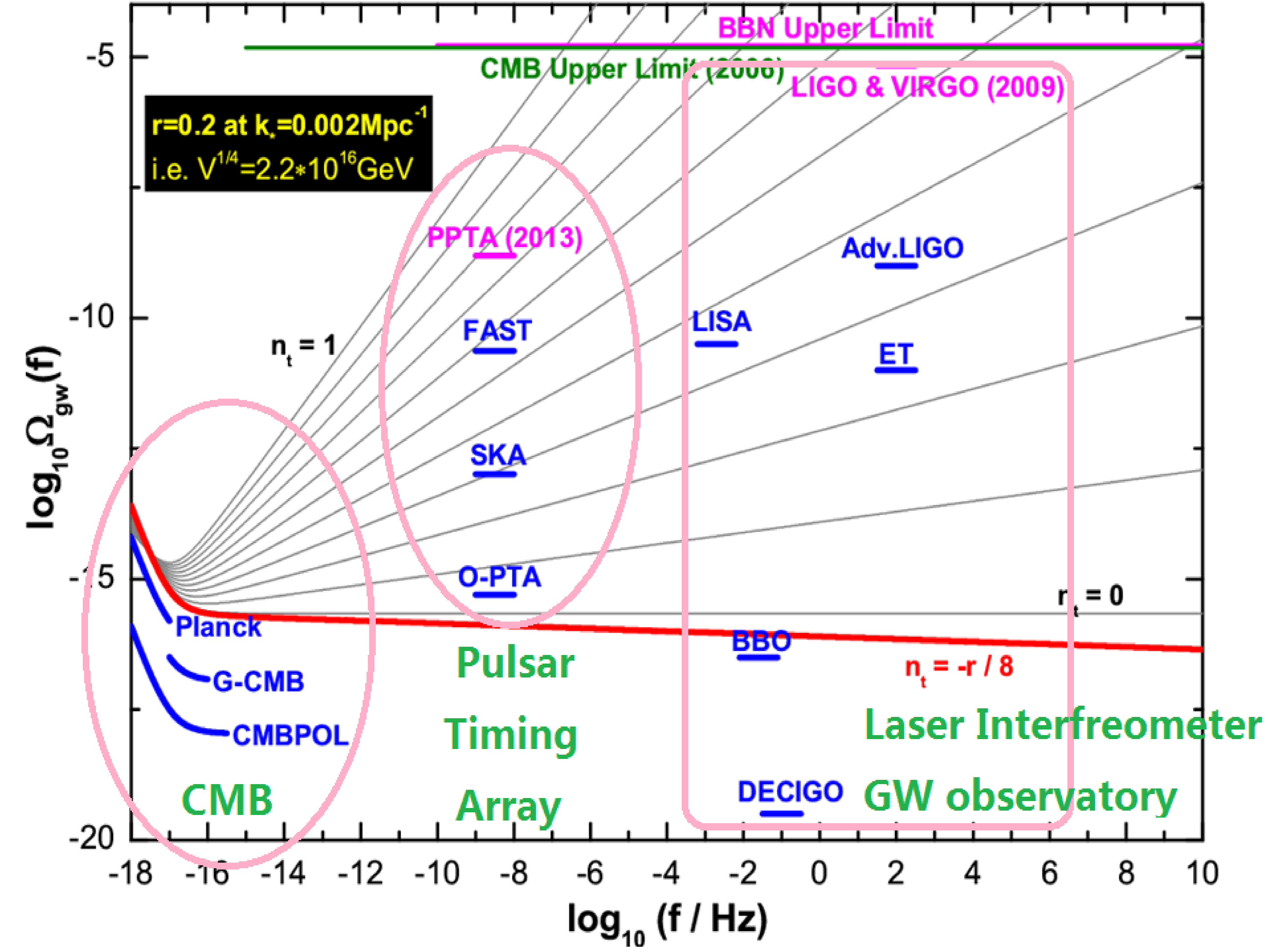
$$H \simeq 3.1 \times 10^{11}\mathrm{GeV}$$

$$V^{1/4} \simeq 1.5 \times 10^{15}\mathrm{GeV}$$

(Knox & Song 2002; Kesdon et al 2002; WZ & Baskaran 2009)

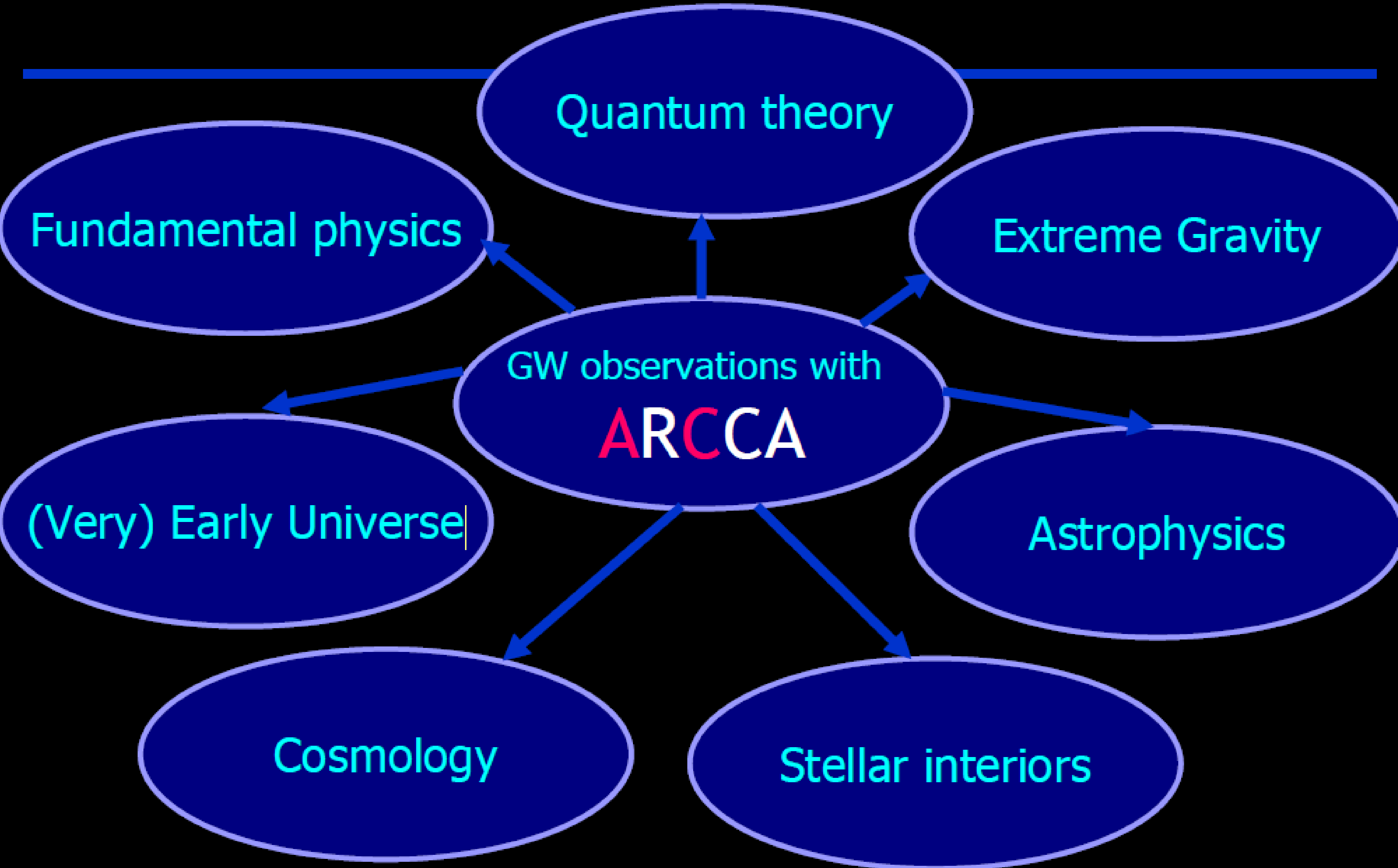






BBN Upper Limit
CMB Upper Limit (2006)
LIGO & VIRGO (2009)
r=0.2 at k*=0.002Mpc-1
i.e. V1/4=2.2*1016GeV
PPTA (2013)
Adv.LIGO
FAST
LISA
ET
nt = 1
SKA
O-PTA
nt = 0
Planck
BBO
G-CMB
nt = -r / 8
Pulsar
Timing
Array
CMBPOL
Laser Interfreometer
GW observatory
CMB
DECIGO
-5
-10
-15
-20
-18
-16
-14
-12
-10
-8
-6
-4
-2
0
2
4
6
8
10
log10Ωgw(f)
log10 (f / Hz)

Gravitational Astronomy



探测不到怎么办?

谢谢！