Gravitational Waves

Listening to the Universe

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Summary

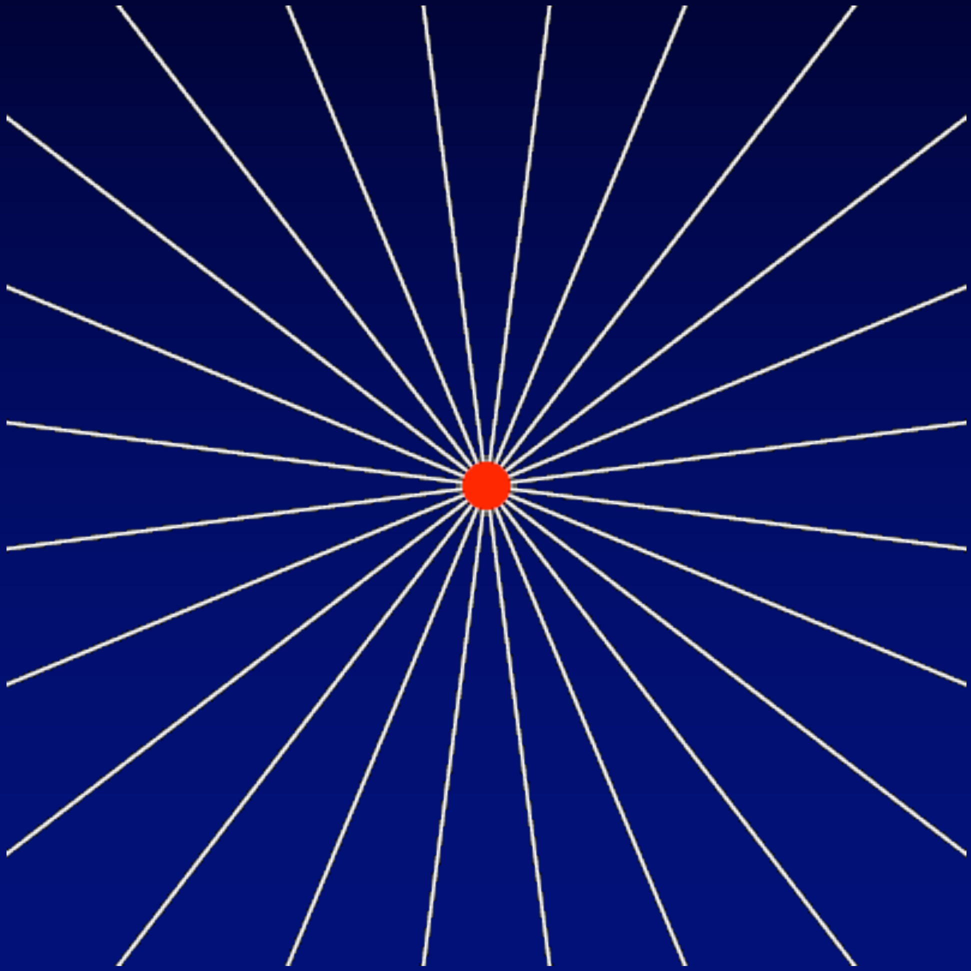
- So far, nearly all our knowledge of the Universe comes from electromagnetic radiation.
- This will soon change, as new detectors begin to observe gravitational radiation.
- Gravitational radiation offers a complementary image of the universe:
  - » "Listening" rather than "looking"
  - » Sensitive to different types of phenomena
- Unprecedented potential for new discoveries!

Outline

- The view with electromagnetic radiation
  - » Past revolutions in astronomy
- The view with gravitational radiation
  - » Similarities and differences
- Sources of gravitational radiation
  - » Tones, chirps, backgrounds, and bursts
- Gravitational-wave detectors
  - » Bars, interferometers, and space antennae

Electromagnetic waves

- Time-varying disturbance in electromagnetic field
- Arise as a direct consequence of relativity (causality)



»Field of a stationary charge

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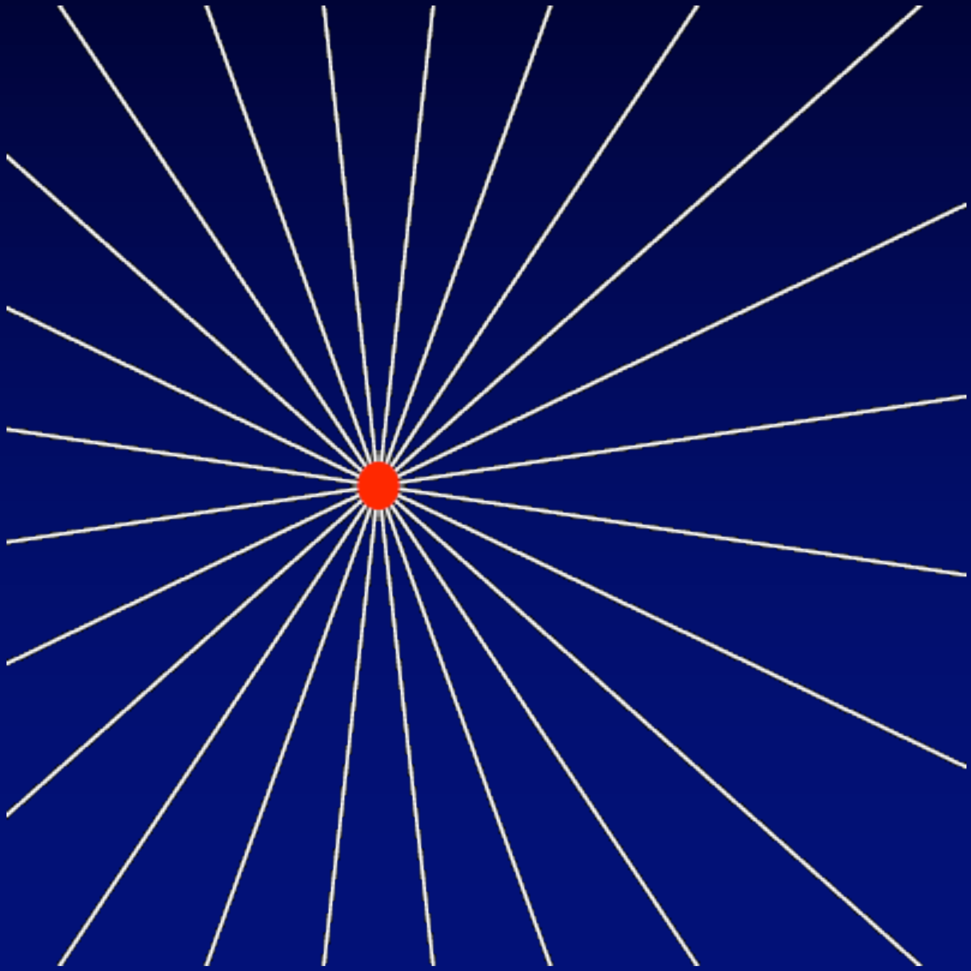

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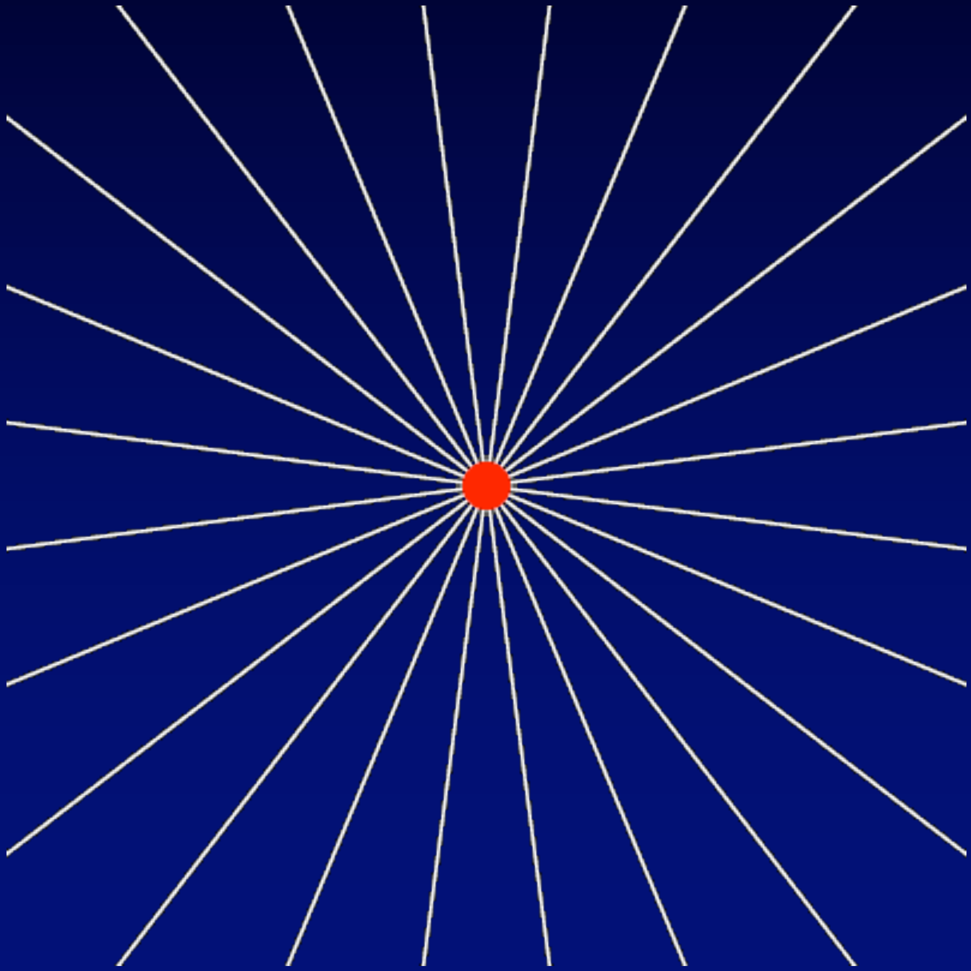

- »Field of a stationary charge
- »Field of a moving charge
- »Field of an accelerated charge

Electromagnetic waves

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»Field of a stationary charge

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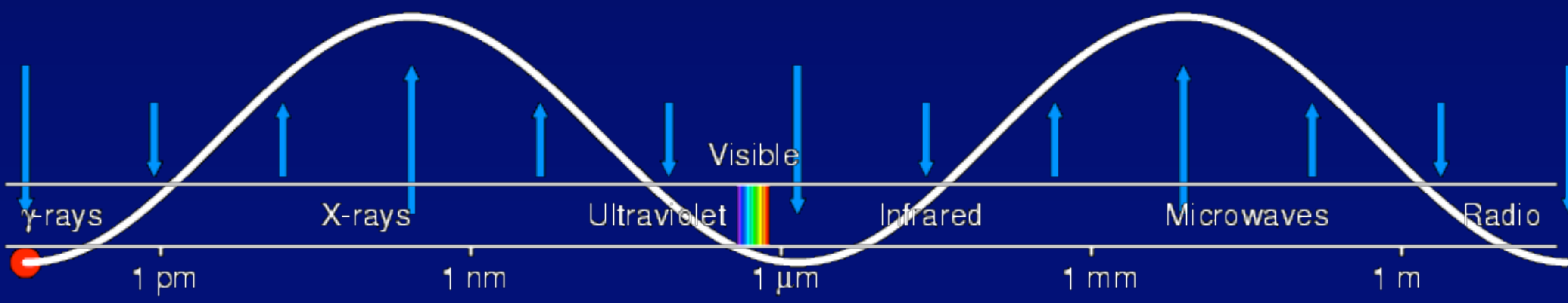
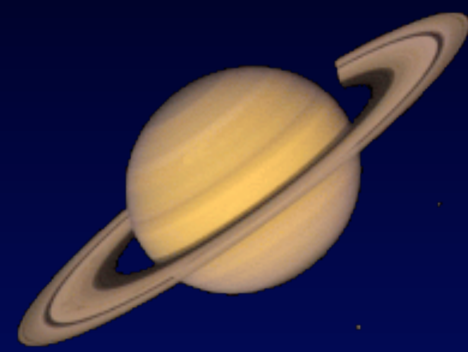
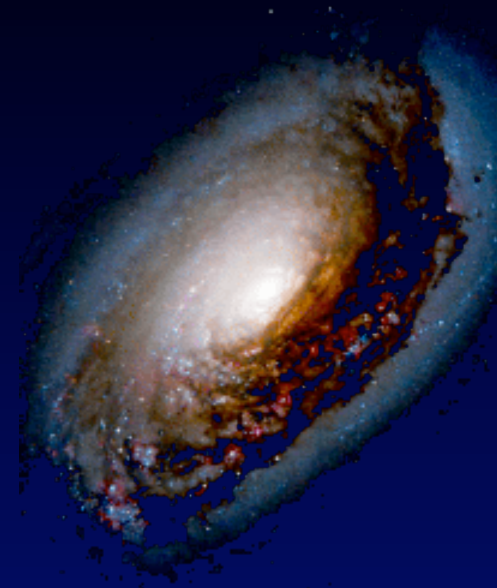
»Field of an accelerated charge

- Oscillating charges → waves with characteristic lengths
- Different wavelengths make up electromagnetic spectrum

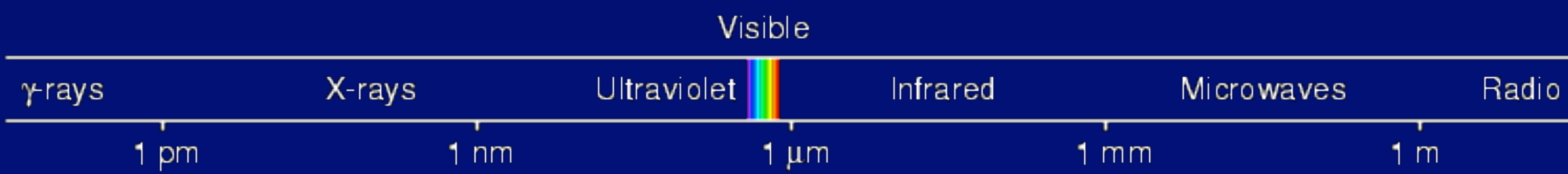


Electromagnetic astronomy





- Visible light: only form of astronomy until 1930s
  - » Powered by steady heat from ordinary stars
  - » Serene view of stars, planets, galaxies



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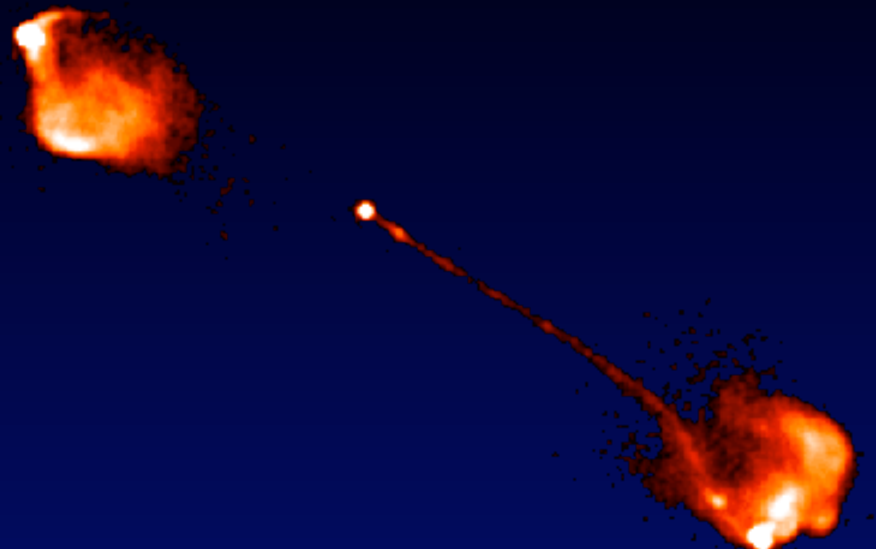
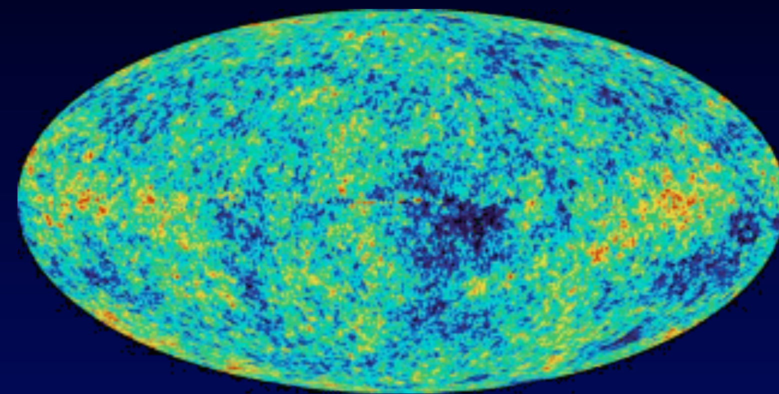
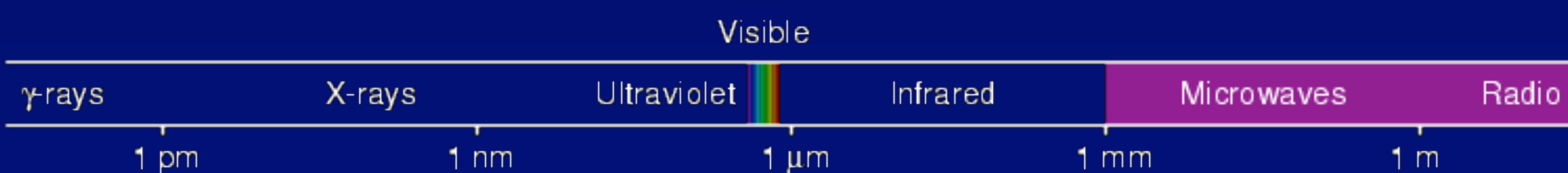
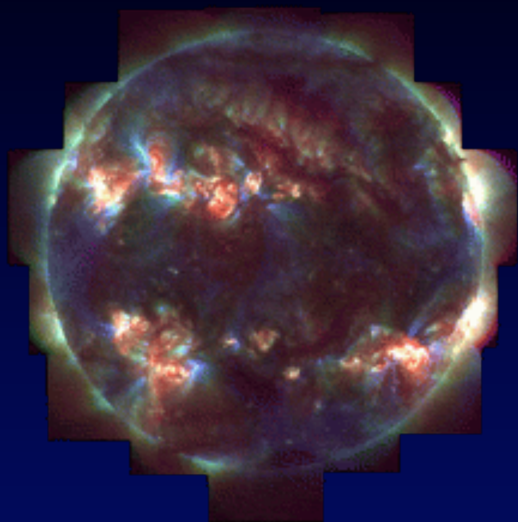
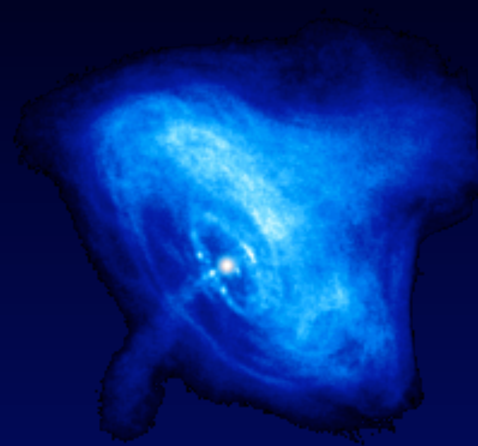
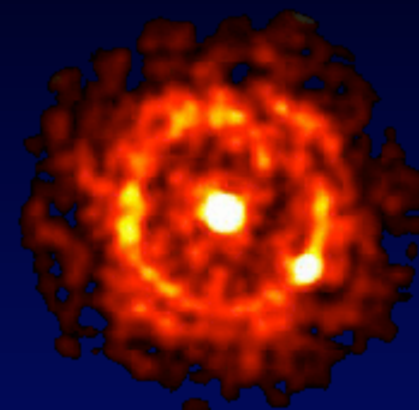




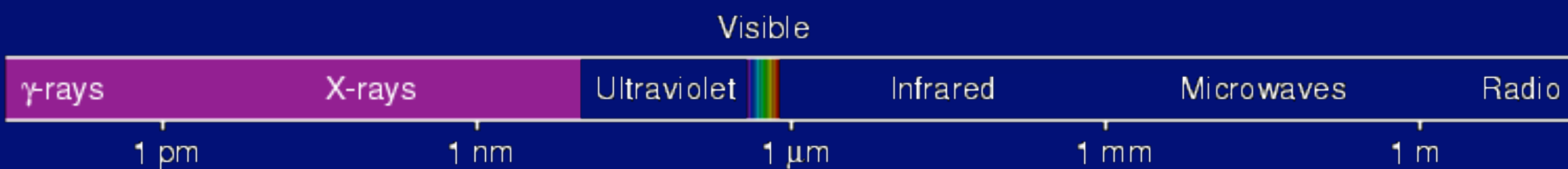
- Radio: revolutionized our view of the Universe!
  - » Powered by electrons blasted to near-light speed
  - » Violent picture of active galaxies, Big Bang



Electromagnetic astronomy

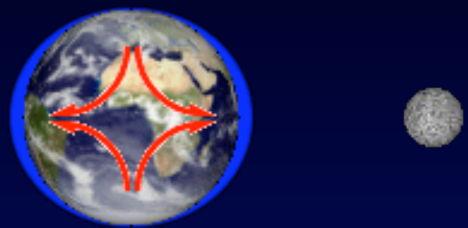
- X and γ rays: Further revealed our violent Universe
  - » Solar flares, stellar remnants (neutron stars, black holes), thermonuclear detonations on stars



If observing new *wavelengths* of light lead to such revolutions in astronomy, what might we expect when we observe an entirely new *spectrum*?

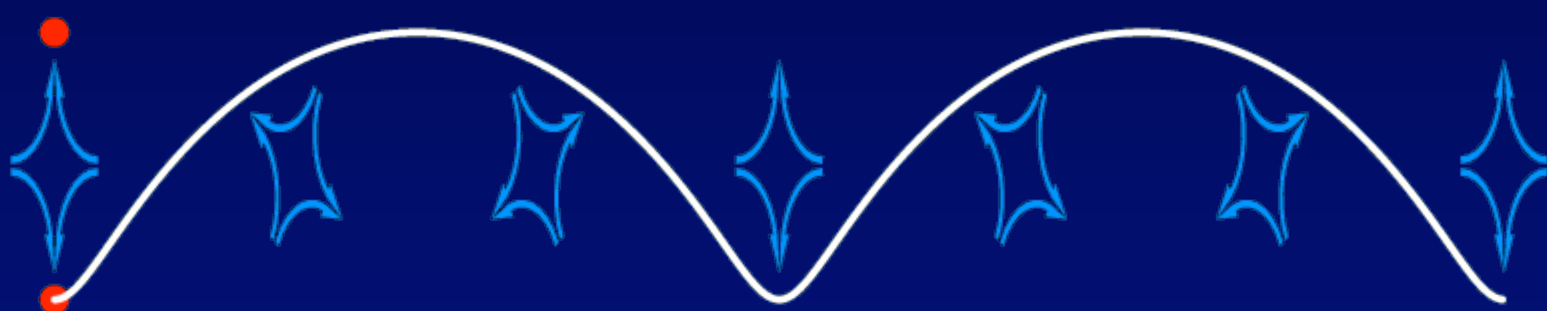
Gravitational waves

- Underlying field is the *gravitational tidal* field (g')



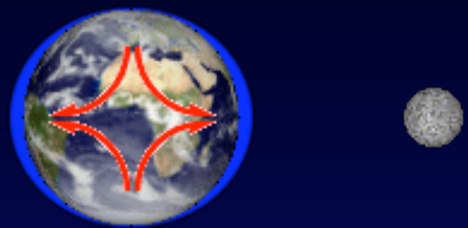
$$g' = \frac{\text{change in relative gravity}}{\text{separation}}$$

- Oscillations produce *gravitational waves* in exactly the same manner as electromagnetic waves



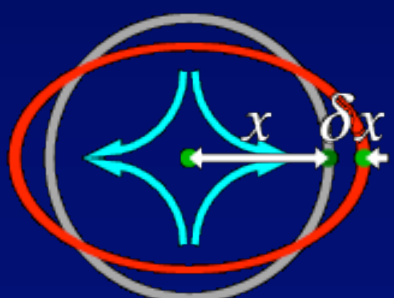
Gravitational waves

- Underlying field is the *gravitational tidal* field (g')



$$g' = \frac{\text{change in relative gravity}}{\text{separation}}$$

- Oscillations produce *gravitational waves* in exactly the same manner as electromagnetic waves
- Strength is given by the *strain amplitude* (h)



$$h = \frac{\delta x}{x} = \frac{\text{change in relative position}}{\text{separation}}$$

» Typically of order 10^{-21} or less!

Gravitational waves: differences from EM

Electromagnetism:

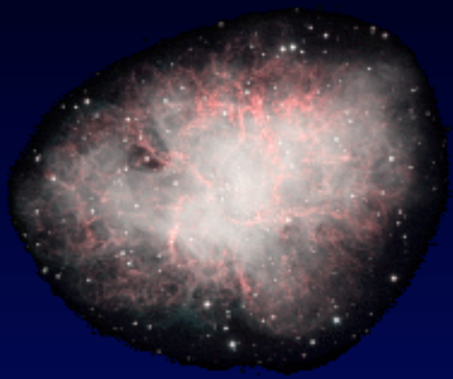
- A strong force, but with opposing charges (+ and –)
- Fields built up incoherently from microscopic charge separations
  - » Wavelengths smaller than the source
- Waves are easy to detect, but easily blocked
  - » Show the surfaces of energetic bodies
- Used to construct *images* of celestial objects

Gravity:

- A weak force, but with only one charge (mass)
- Fields built up coherently from bulk accumulation of matter
  - » Wavelengths larger than the source
- Waves are hard to detect, but pass undisturbed through anything
  - » Reveal the bulk motion of dense matter
- Can be though of as *sounds* emitted by those objects

→ A fundamentally different way of observing the Cosmos!

Sources of gravitational waves

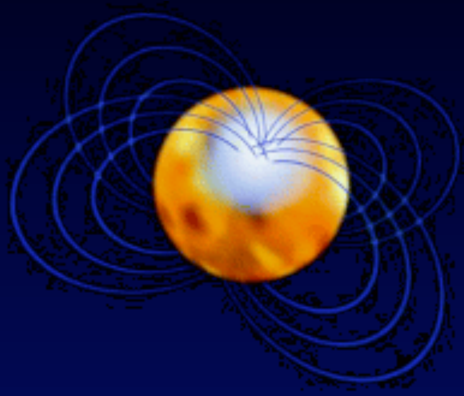


- **Supernova**: Explosion caused by the collapse of an old, burnt-out star
- Produces a burst of gravitational radiation, *if it is non-symmetric!*

- Exact "sound" is difficult to predict theoretically
  - » Challenge is to identify suspicious-sounding bursts in a noisy background

- Leftover core may be a . . .

Sources of gravitational waves

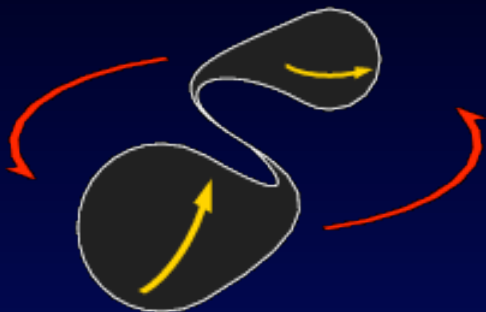


- **Neutron star**: A city-sized atomic nucleus!
- Can spin at up to 600 cycles per second
- Emits continuous gravitational radiation (again, if it is non-symmetric)

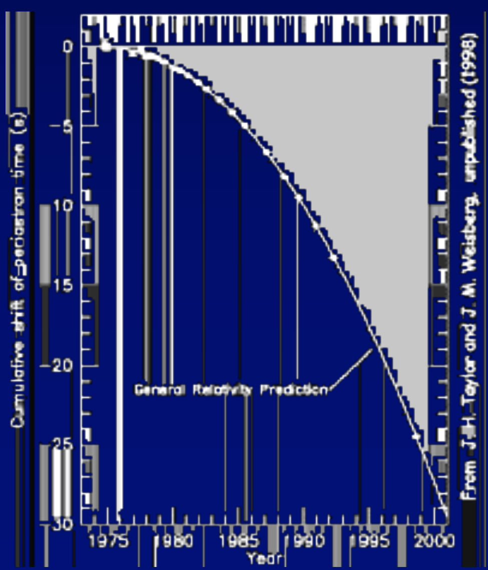
- Signal is very weak, but can be built up through long observation
  - » This is a computationally-intensive process!
  - » Plan to recruit computers from the general public: Einstein@home

- A pair of these could lead to a . . .

Sources of gravitational waves

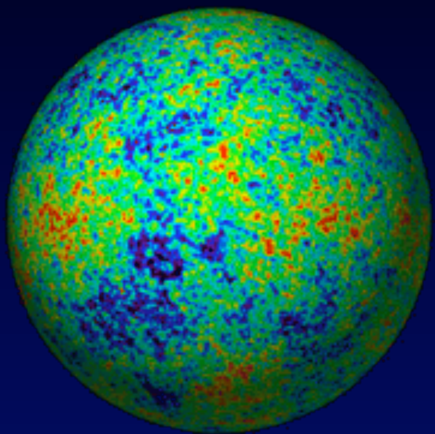


- **Merging compact binary**: Collision of two stellar remnants (neutron stars or *black holes*)
- Produce a sweeping "chirp" as they spiral together



- Already the first *indirect* evidence of gravitational waves
- Our most promising source: strong and easy to model
  » However, event rate is highly uncertain!

Sources of gravitational waves



- **Primordial background**: Leftover radiation from the beginning of the Universe
- Tells us about the state of the Universe at *or before* the Big Bang!
- Sounds like “noise” with a characteristic spectrum
- Difficult to distinguish from instrumental noise
  - » Correlate the data from several *independent* detectors

Sources of gravitational waves

- **Things that go bump in the night**: Sources that are highly speculative, or not predicted at all!
- Could sound like anything
- E.g. a *possible* signal from a folded cosmic string:

- Probably the most exciting of all the sources, but we *don't know what to listen for!*
  - » Again, would need to hear it in several detectors

Detecting gravitational waves

- Strongest sources induce strains less than $h = 10^{-21}$
  - » Exceedingly hard to measure!
  - » Attempts since 1960s, but nothing so far
- Newer instruments are approaching these sensitivities
  - » Some examples . . .

Detecting gravitational waves

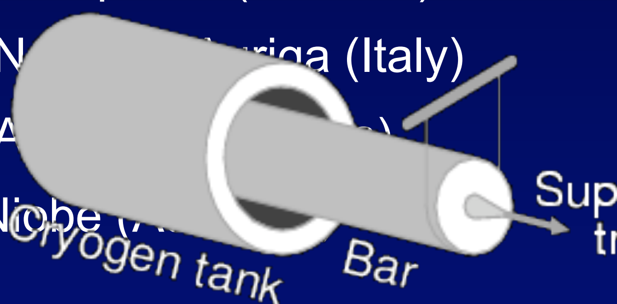
- **Resonant bars**: selectively amplify distortions that are “tuned” to their natural frequency
  - » First detectors built in the 1960s
  - » Respond only to a narrow frequency range

2.3 tonne aluminum bars: Explorer (Geneva)

N … iga (Italy)

A …)

1.5 tonne niobium bar: Niobe (…



Detecting gravitational waves

- **Laser interferometers**: measure relative motions of separate, freely-hanging masses
  - » Masses can be spaced arbitrarily far apart
  - » Respond to all frequencies between 40 and 2000 Hz

LIGO: 2 detectors (4km & 2km) in WA

1 detector (4km) in Louisiana

VIRGO: 3km detector in Italy

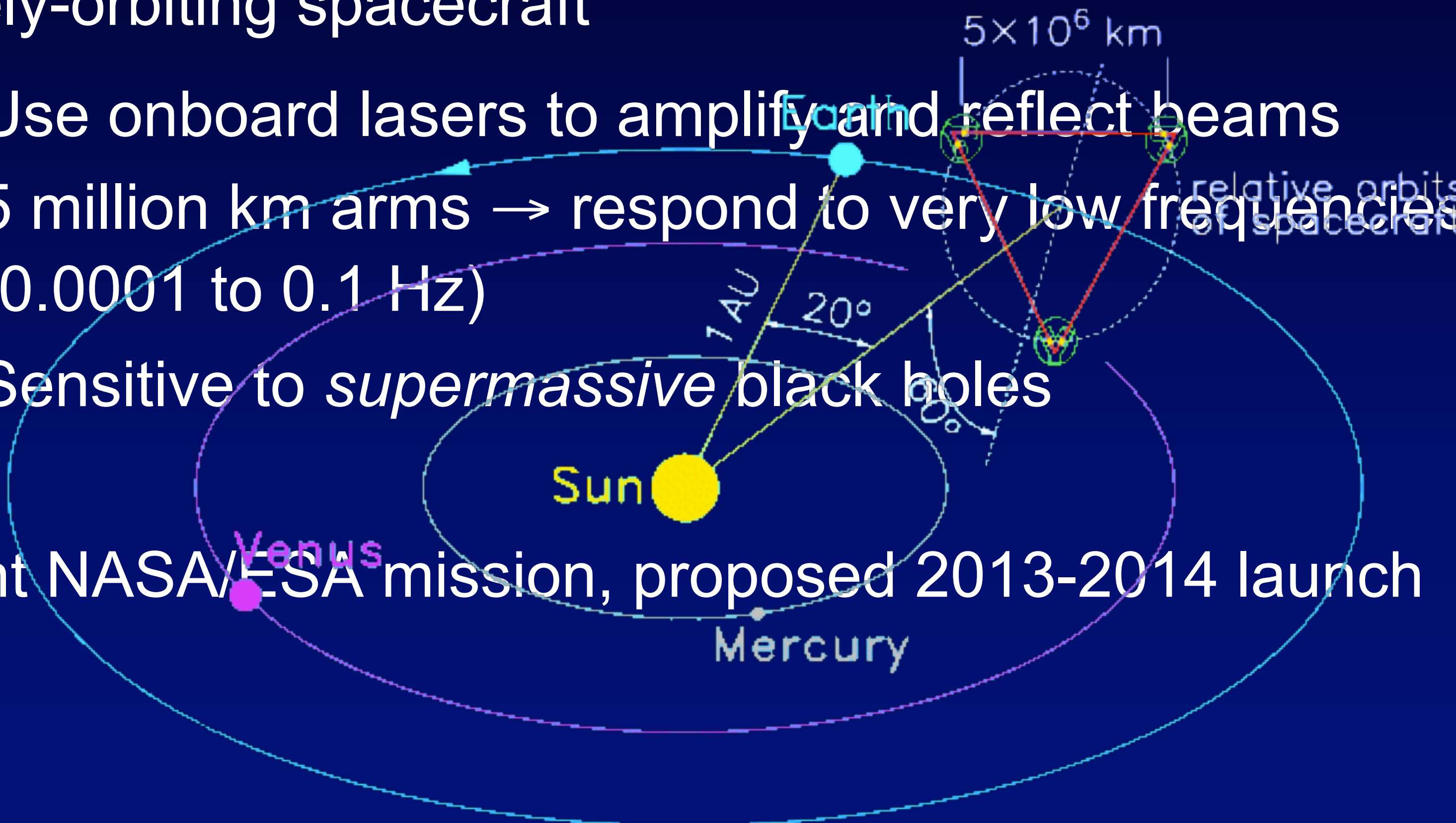
GEO: 600m detector in Germany

TAMA: 300m detector in Japan

- Chinese Academy of Sciences is also supporting a proposal to build an *underground* instrument
  - » Less affected by ground motion

Detecting gravitational waves

- **Laser Interferometer Space Antenna (LISA)**: like ground-based interferometers, but masses are three freely-orbiting spacecraft
  - » Use onboard lasers to amplify and reflect beams
  - » 5 million km arms → respond to very low frequencies (0.0001 to 0.1 Hz)
  - » Sensitive to *supermassive* black holes



- Joint NASA/ESA mission, proposed 2013-2014 launch

Where are we now?

- Half a dozen ground-based detectors (bars and interferometers), with rapidly improving sensitivity
  - » Currently setting upper limits on gravitational waves
- 2005: First long-duration interferometer runs have a good chance at making detections (but not guaranteed!)
- 2011: Improved detectors will almost certainly see colliding neutron stars and black holes, and possibly stranger things!
- 2014: If and when it flies, LISA is guaranteed to see thousands of sources

→ The age of gravitational wave astronomy is upon us!

Photo credits:

M64 galaxy: NASA and the Hubble Heritage Team
Saturn: NASA P-23883C/BW
3C175 active galaxy: NRAO/AUI/NSF
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Sun in X-rays: ESA/NASA Solar and Heliospheric Observatory
X-ray burster: ESA/XMM-Newton
Crab nebula (X-rays): NASA/CXC/ASU/J. Hester et al.
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