# Detection of gravitational waves with Virgo: status, recent results and multimessenger astronomy

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# Outline

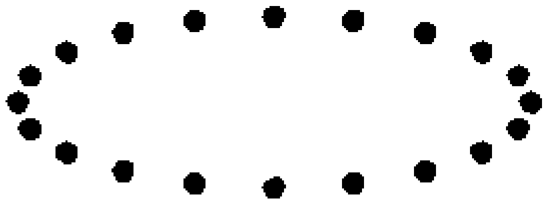
- Introduction
  - Direct detection of gravitational waves (GW)
  - Historical perspective
- Large-scale interferometric detectors: LIGO and Virgo
  - Detection principle and instrument design
  - GW sources
  - Searches for GW transients: sensitivities and methodologies
- Multimessenger astrophysics with GWs
  - Motivations and strategies
  - Externally triggered searchs and electromagnetic follow-ups
- Future perspectives

# Introduction

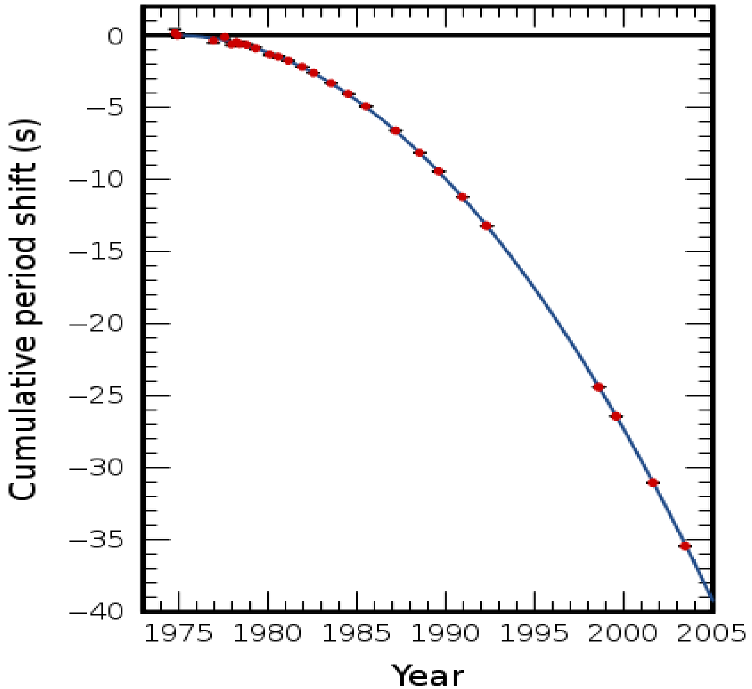
## A primer on gravitational waves and their detection

# Gravitational waves GW

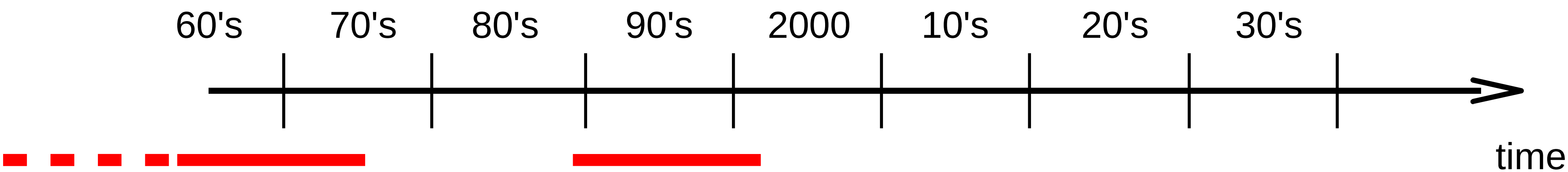
- Propagating distorsion in space-time metric
  - Predicted by General Relativity
  - Propate at the speed of light
  - Transverse and quadrupolar
  - Two polarizations (+ and x)
- Sources of GW
  - Produced by accelerated mass
  - Large mass and density, relativistic motion → astrophysical sources
- Indirect proof of existence
  - Orbital decay of PSR B1913+16
  - Agreement with GR (energy loss due to GW)
  - Hulse & Taylor's Nobel prize



*effect of + polarization (normal incidence) on a circle of free falling masses*

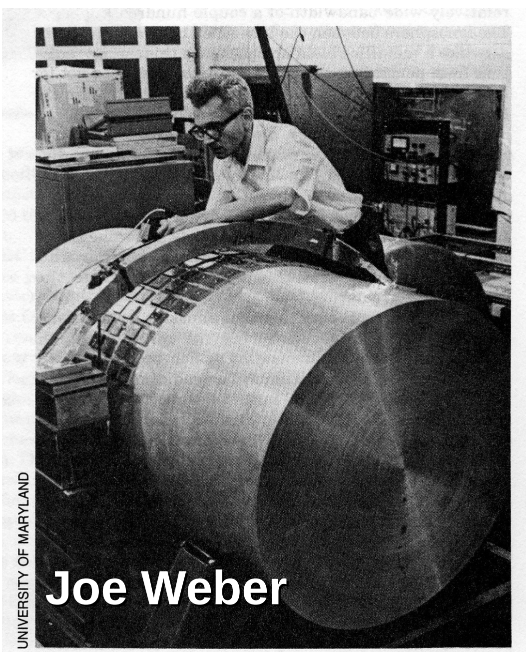


# Direct detection of GW
# Historical perspective: past (1)

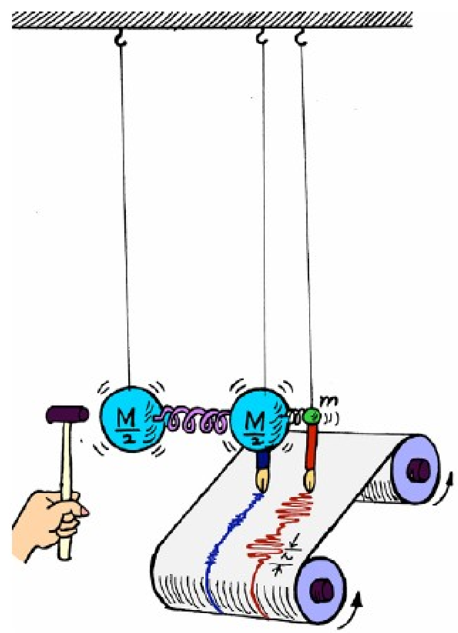


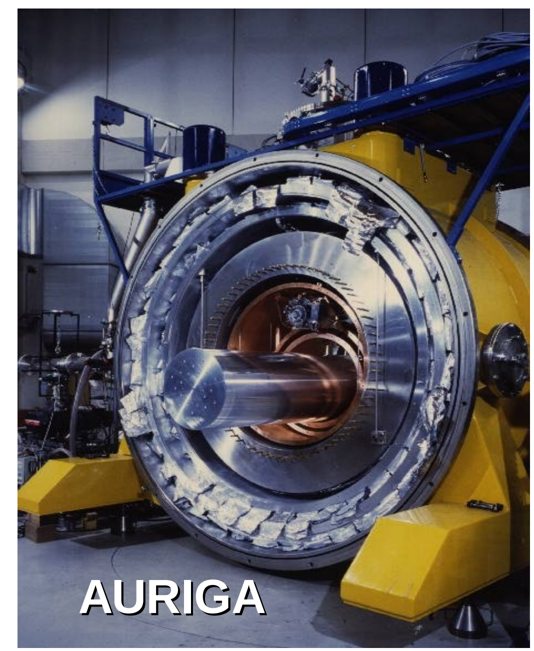

pioneering works

cryogenic bars

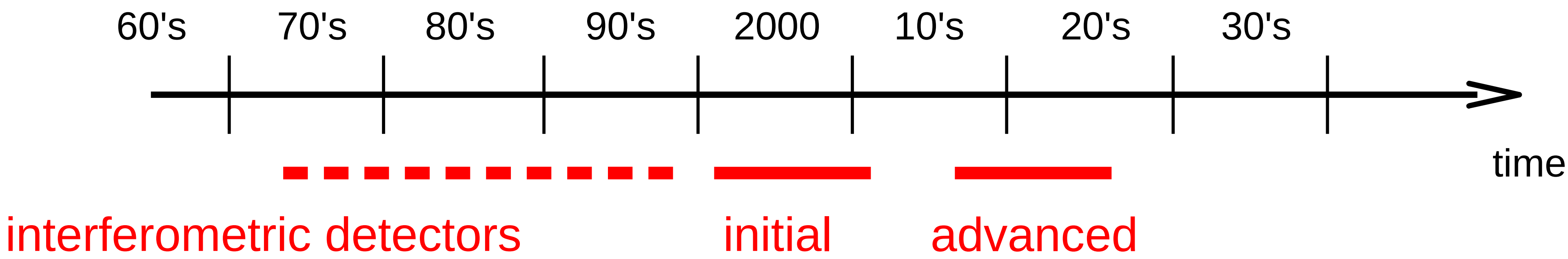


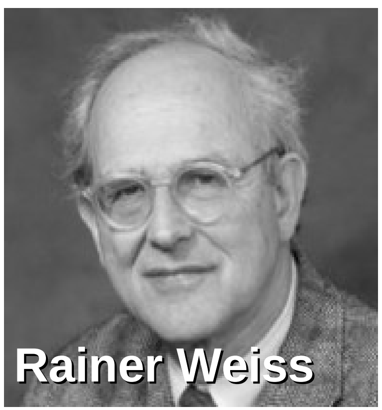




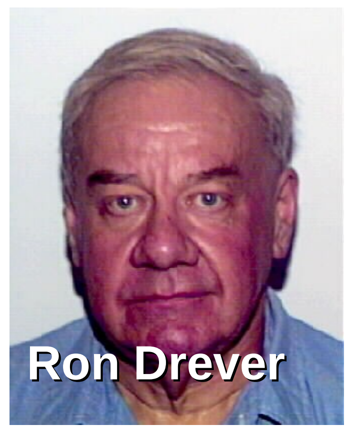


# Direct detection of GW
# Historical perspective: present (2)

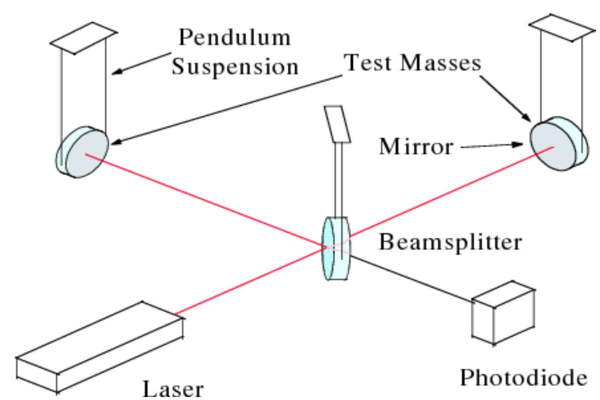


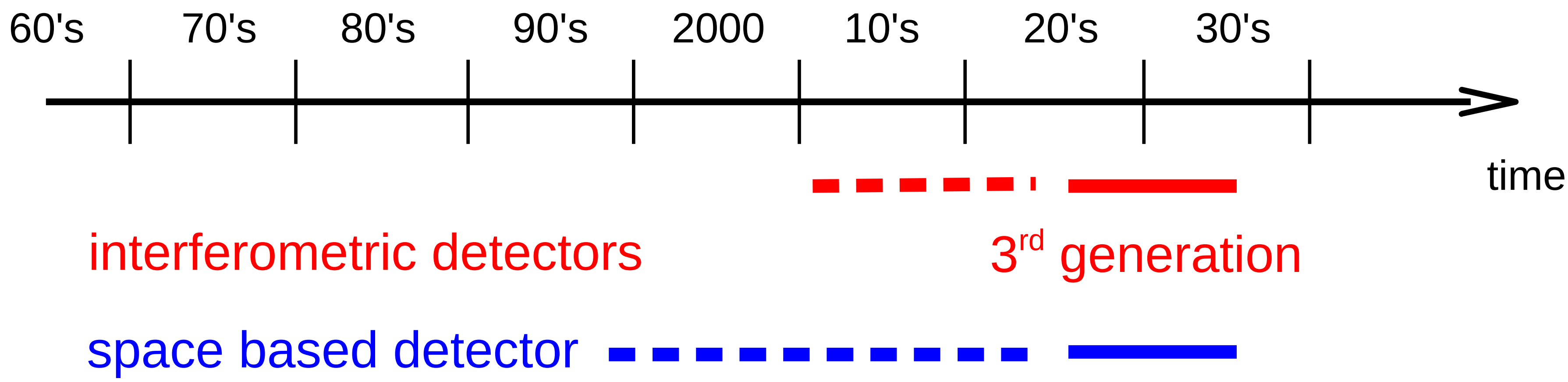


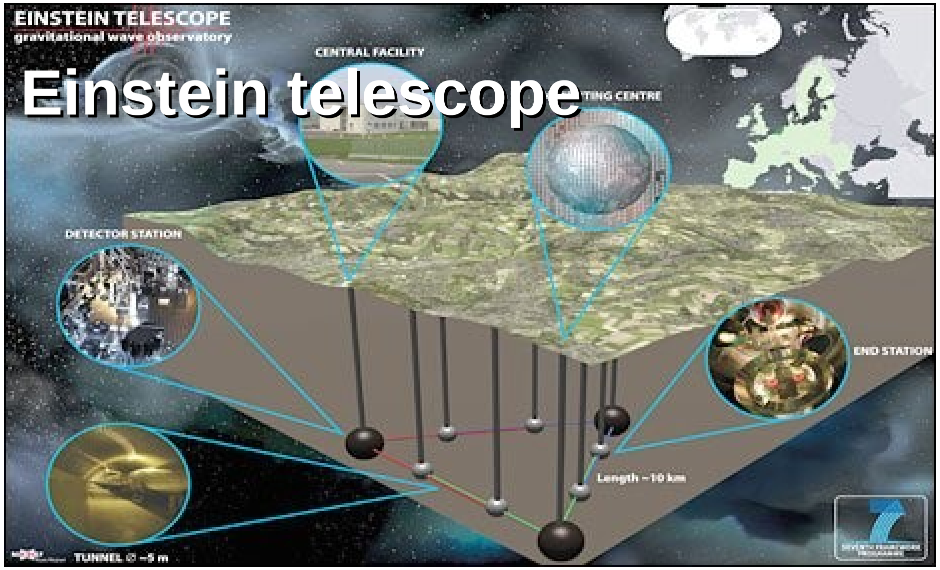


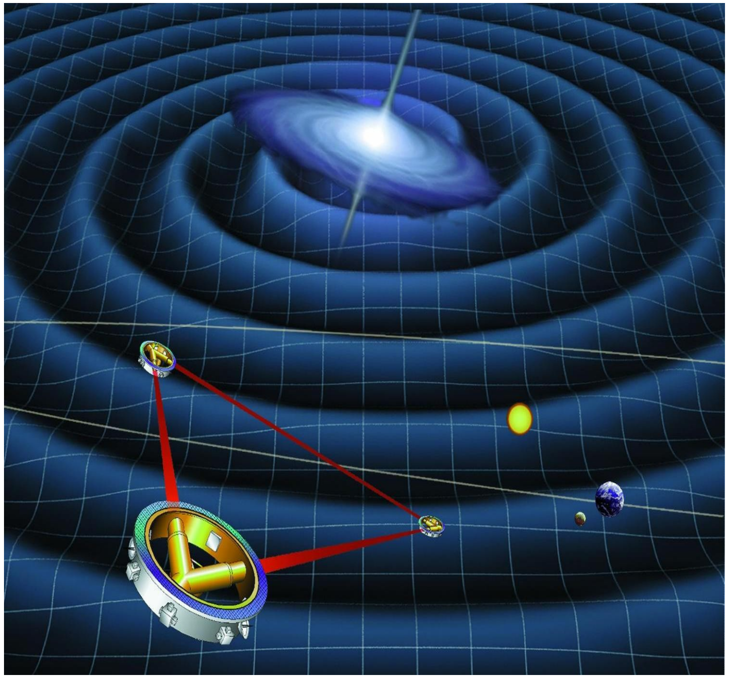




# Direct detection of GW
# Historical perspective: future (3)



# Large scale interfometric GW detectors

# From detection principles to measurement sensitivity

# Direct detection of GW with Virgo

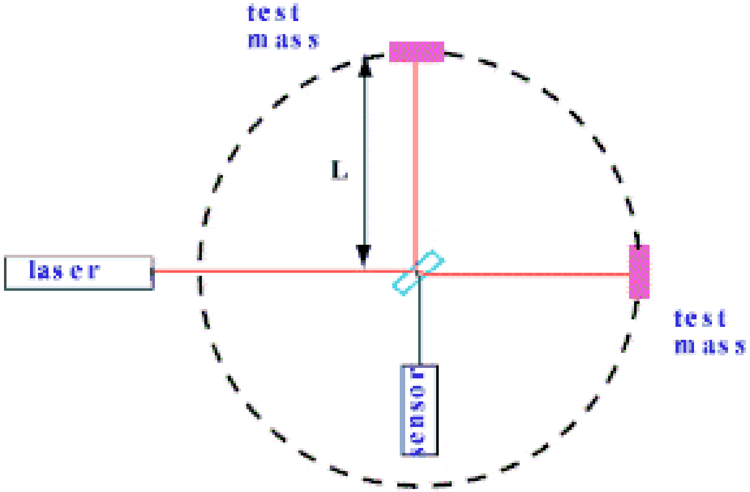
- Michelson interferometer
  - test mass displacement due to GW → phase shift measurement

$$h(t) = \frac{\delta L(t)}{L} \propto \delta\Phi(t)$$

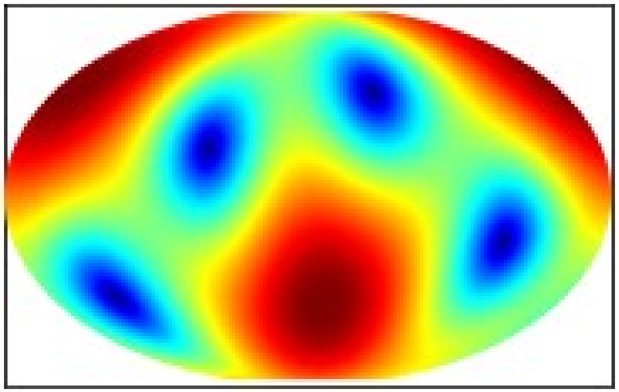
- Sees mixture of both polarizations

$$h(t) = F_+ h_+(t) + F_\times h_\times(t)$$

- Large aperture: not directional
  - more like a ear than an eye!
  - 1D time series (not a 2D image)




Virgo



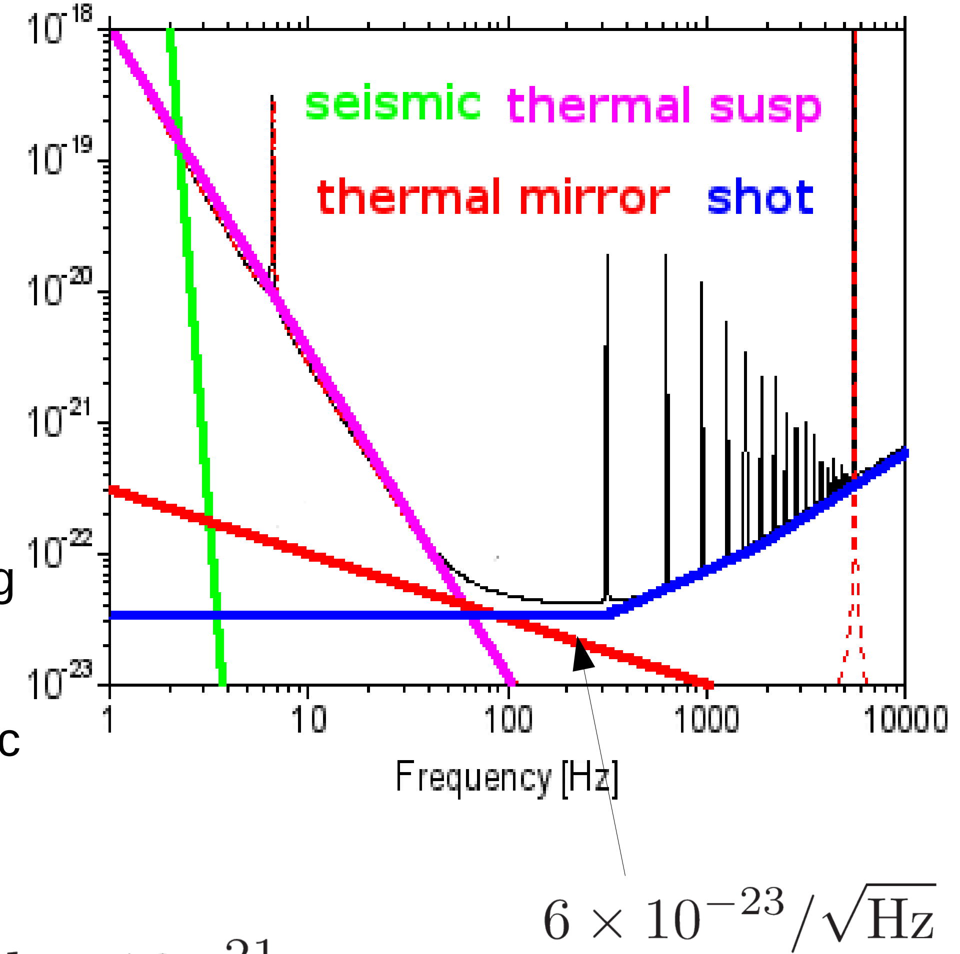
$$(F_+^2 + F_\times^2)^{1/2}$$

# Virgo sensitivity

- Measurement limitations
  - Fundamental sensing and displacement noises
  - Many "technical" noises (control, electronics, acoustic, …)

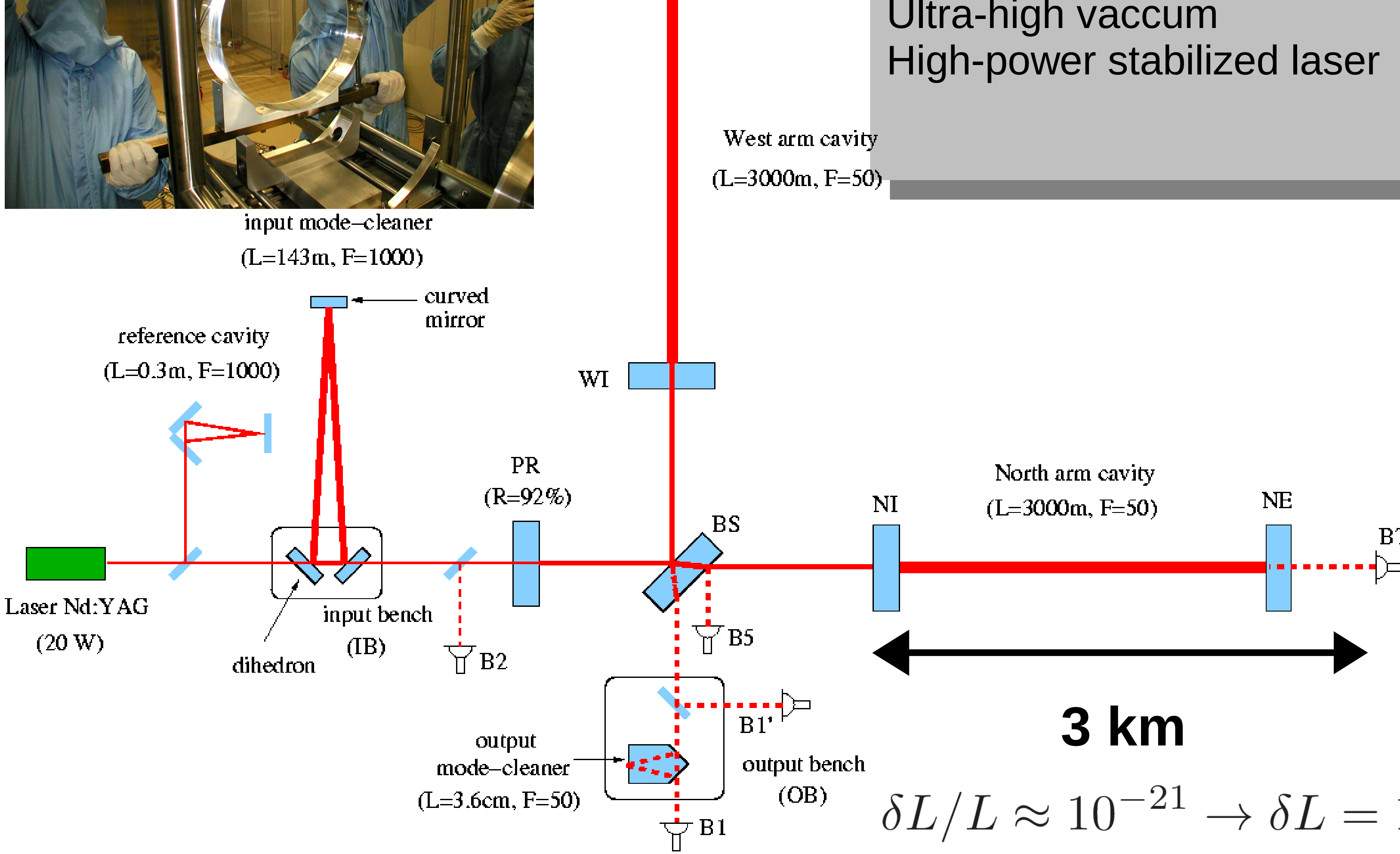
$$h_{noise} \approx 10^{-21}$$

- Expected GW amplitude from a coalescing binary system
  "quadrupole" formula
  R=20 km, M=1.4 $M_{sun}$, f=400 Hz, d=15 Mpc

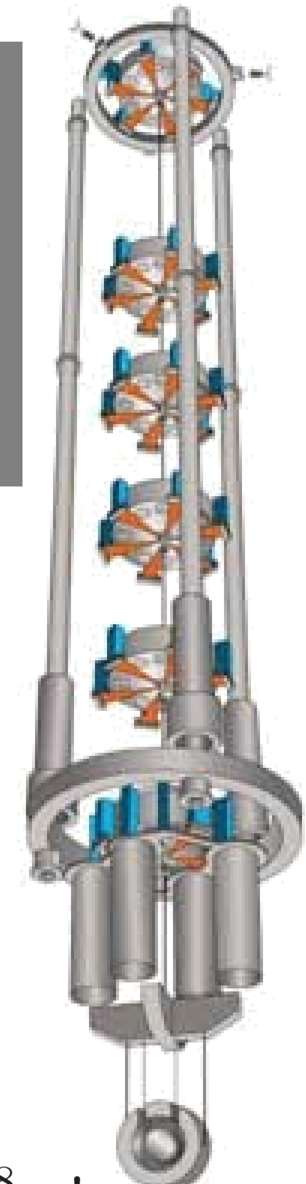



$$h_{expected} \sim G/c^4\, \ddot{Q}/d \propto MR^2 f^2/d \approx 10^{-21}$$

# Virgo: detector highlights




Long folded arms using Fabry-Perot cavities
Suspended instrument
High-Q material
Ultra-high vaccum
High-power stabilized laser



**3 km**

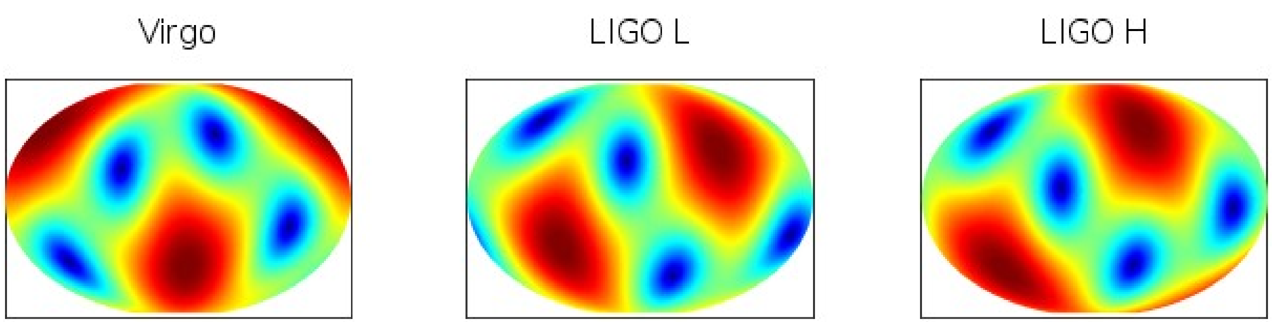
$$\delta L/L \approx 10^{-21} \rightarrow \delta L = 10^{-18} m!$$

# Worldwide network of GW detectors

GEO 600
Germany

LIGO
US

Virgo
Italy



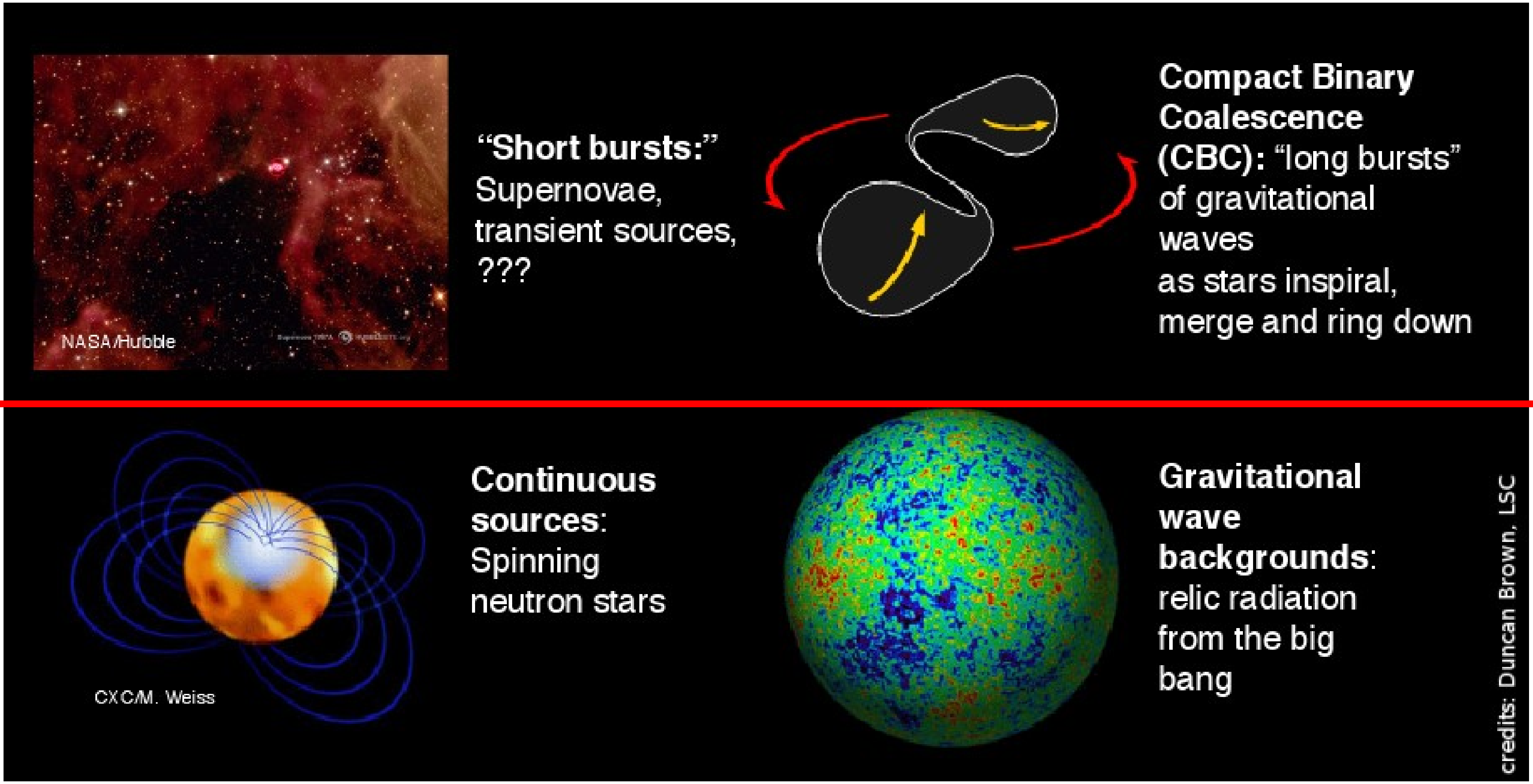

Since 2007, partnership and data exchange agreement

# Large scale interfometric GW detectors

## Source and science reach

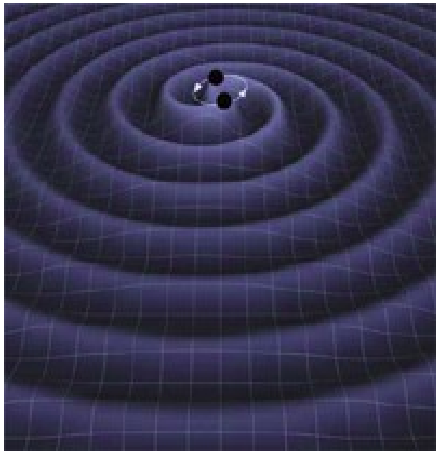
# Sources of gravitational waves

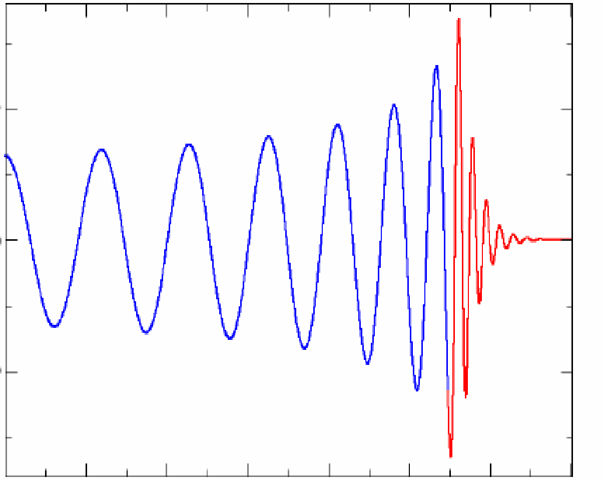
We will be interested in transient sources in this presentation

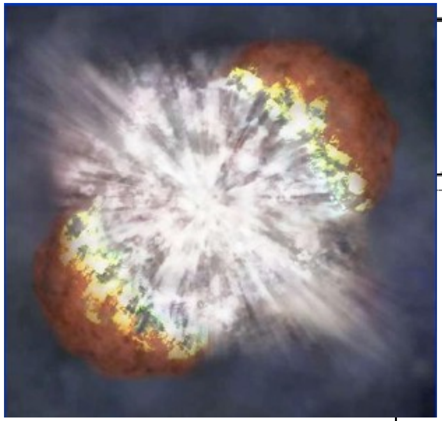


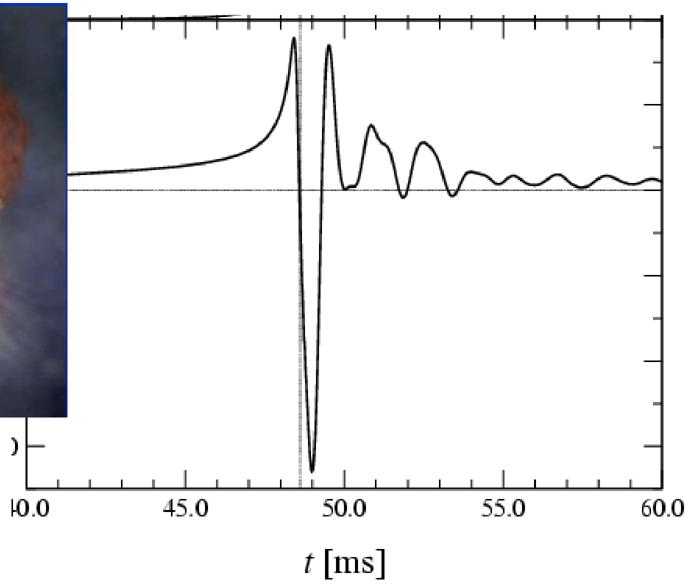
# Sources of gravitational wave transients

- Catastrophic astrophysical events
  the "violent Universe"
- Efficient production of GWs
  - compact objects: neutron stars (NS) or black holes (BH)
  - bulk motion at relativistic velocities
  - Some degree of asymmetry
- Binary mergers (BBH, BNS)
  - post-Newtonian chirps + numerical relativity
- Supernova core collapses
  - numerical simulations. no comprehensive view of the collapse. few predictions, robustness?









# Sensitivity estimate
# GW transients

## Strain amplitude

$$h_{rss}^2 = \int dt \, h_+^2(t) + h_\times^2(t)$$

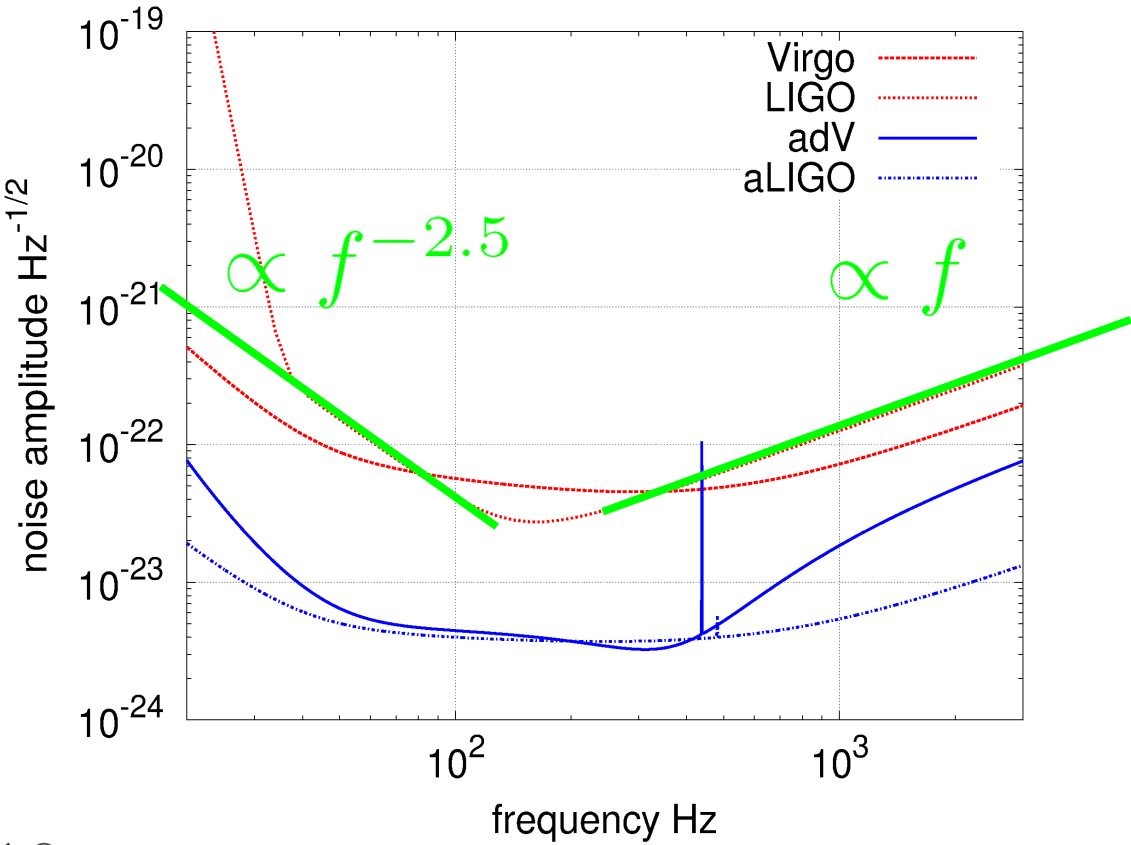
## Signal-to-noise ratio (SNR)

monochromatic signal of freq *f*

$$\rho \propto \frac{h_{rss}}{S^{1/2}(f)}$$

factor of ~½ for polar./orient.

SNR of detectable events is $\rho \approx 10$



# Detectable GW radiated energy

**Energy fluence** J/m²

$$\mathcal{F}_{GW} = \frac{dE}{dA} = \frac{c^3}{16\pi G}\int dt\,\langle \dot{h}_+^2 + \dot{h}_\times^2 \rangle$$

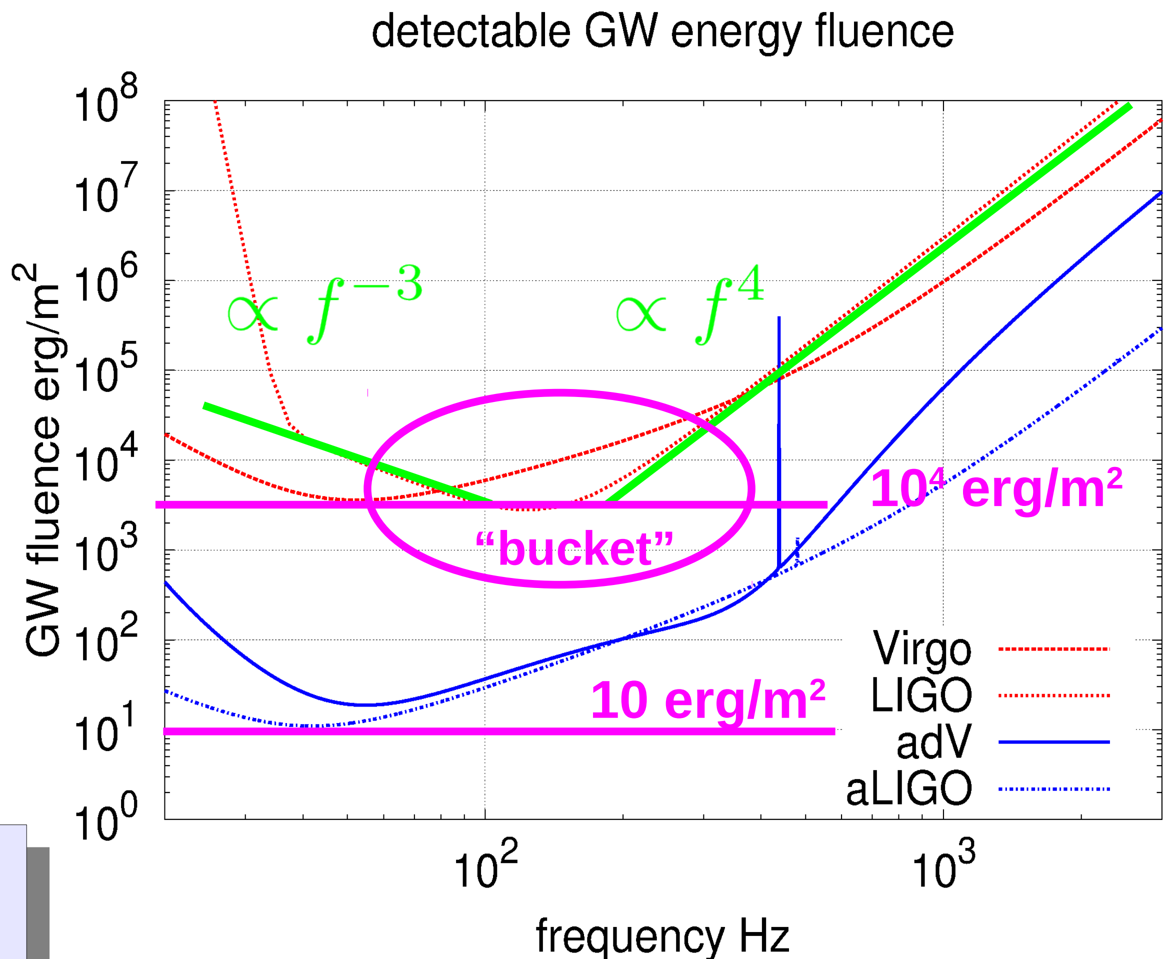
monochromatic signal of freq *f*

$$\mathcal{F}_{GW} \approx \frac{c^3}{4\pi G} f^2 h_{rss}^2$$

assuming isotropic emission

$$E_{GW}^{iso} = 4\pi D_L^2 \mathcal{F}_{GW}$$

$$E_{GW}^{iso} \approx \frac{c^3}{G} D_L^2 f^2 h_{rss}^2$$




**Note on energy units**
1 Joule (SI) = $10^7$ erg (CGS)

# GW “horizon”

## “back of the envelope” estimates

- Best case estimate

Assume monochromatic source emitting “in the bucket” and require SNR=10

Compute necessary GW energy as a function of distance

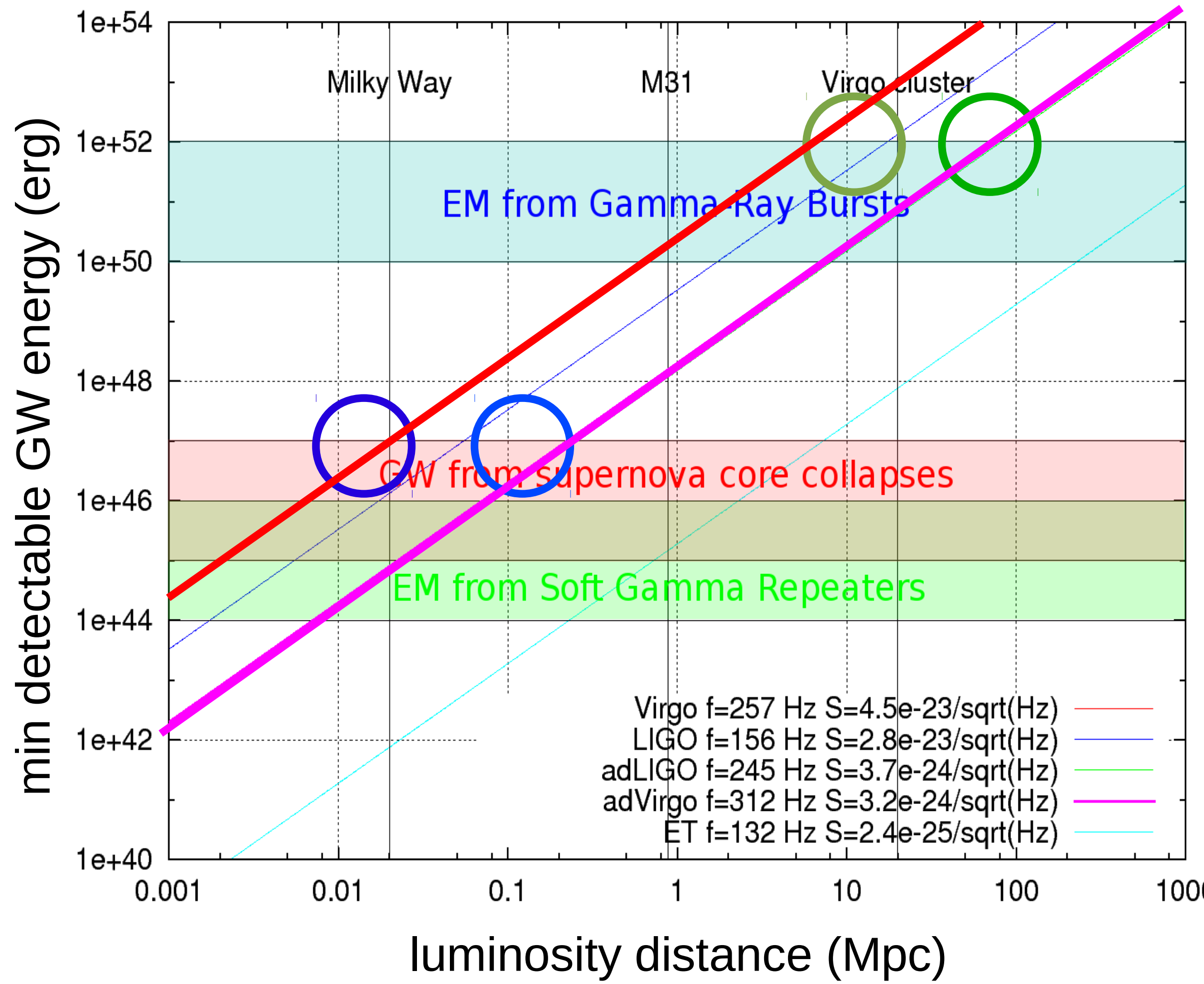
Compare with typical orders of mag. for considered astrophysical sources

- BNS, BBH coalescences

~10 Mpc with **initial** detectors
~100 Mpc with **advanced** detectors

- SN core collapses

Galactic only, O(10) kpc

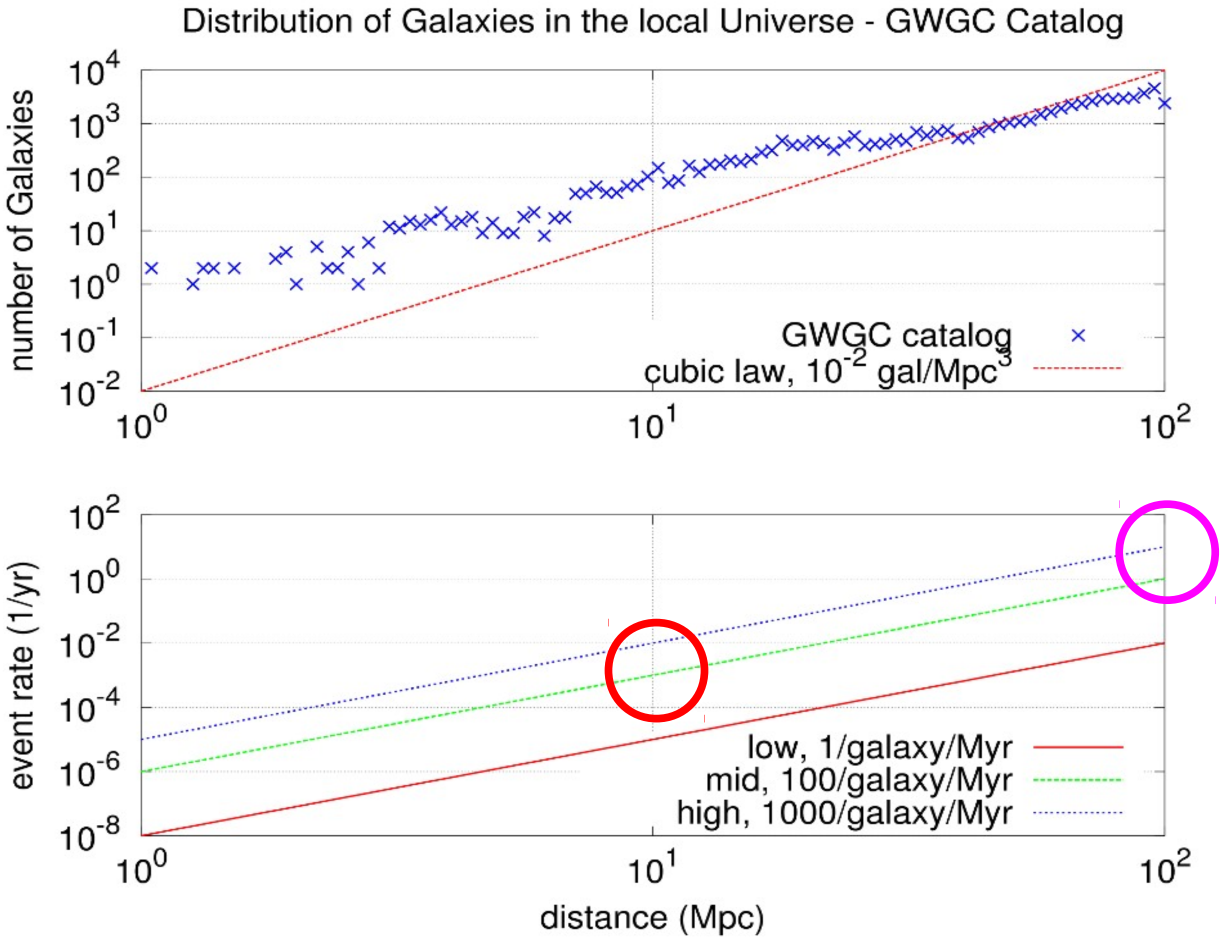



**Energy units**

$M_{sun} c^2 = 1.8 \times 10^{47}$ J $= 1.8 \times 10^{54}$ erg
binary mergers, $E_{GW}$ is < 5 % of rest mass

# Event rate

## "back of the envelope" estimates




- Horizon ~ 10 Mpc, **initial** detectors
Need to get lucky!

- Horizon ~ 100 Mpc, **advanced** detectors
O(1) to O(10) BNS events/year

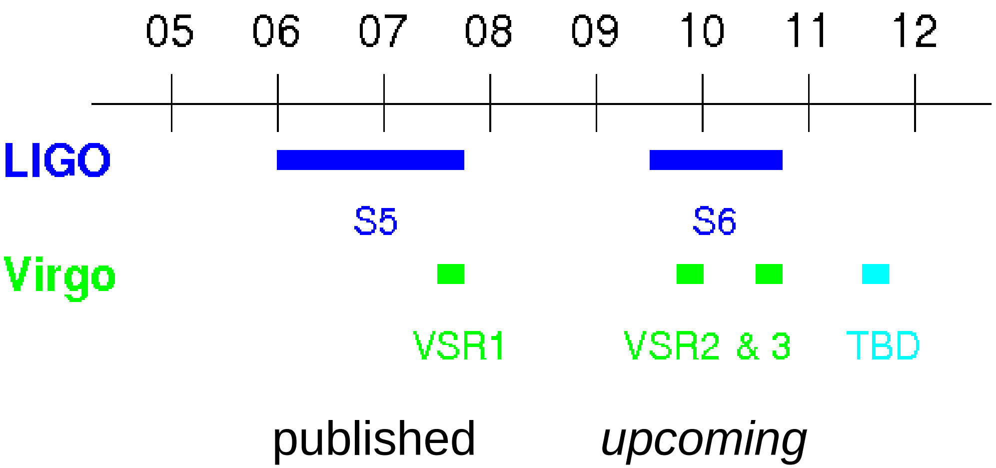
**Note on event rate**

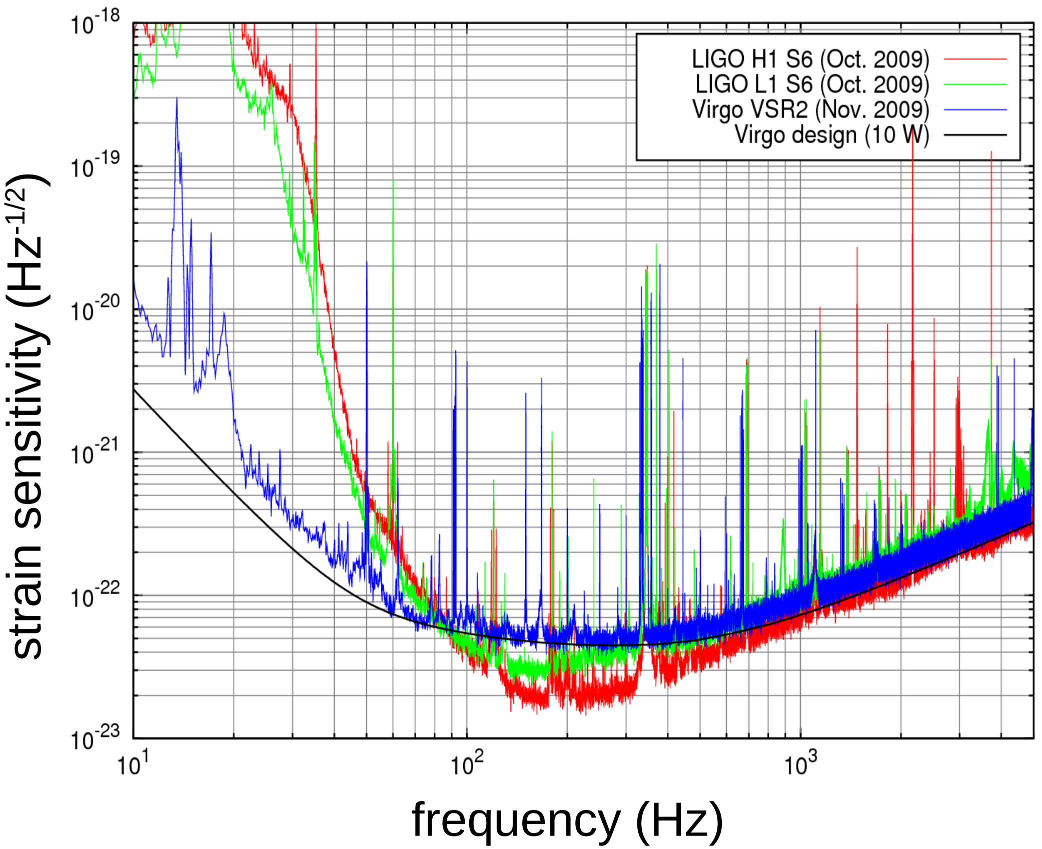
SN = $10^4$/MWEG/Myr
BNS=1 – 100 – 1000 MWEG/Myr

# Large scale interfometric GW detectors

# Data analysis

# Data takings as of 2011



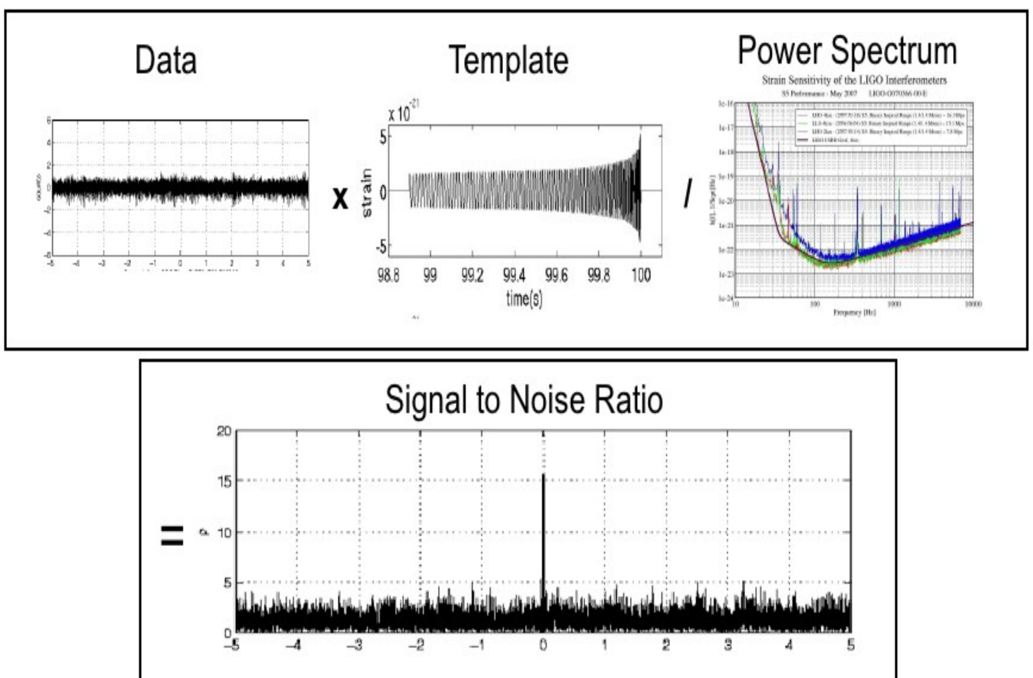




- 3 science data taking completed (total of 12 months)
  - VSR1: horizon BNS 4 Mpc, 80 % duty cycle
  - VSR2/3: horizon BNS ~8 Mpc (reached 10 Mpc), comparable duty cycle
- Major upgrade performed during first half of 2010
  - Monolythic suspension (fused silica fiber) installed

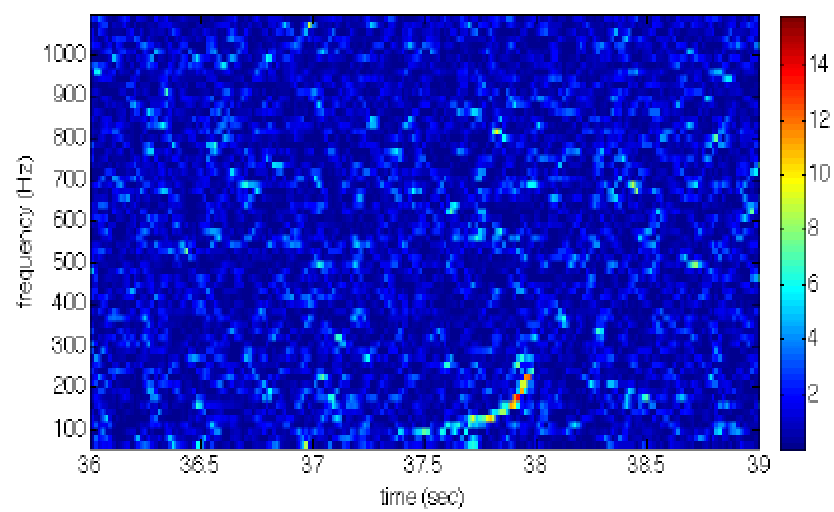
# Searches for GW transients: basic ideas

## Time series analysis
## rare transients with low signal to noise ratio

Expected signal is **known**
(inspiralling binaries)
Matched filtering




Expected signal is **unknown**
Excess in time-frequency maps
(wavelets)



# Searches for GW transients: cruel real world

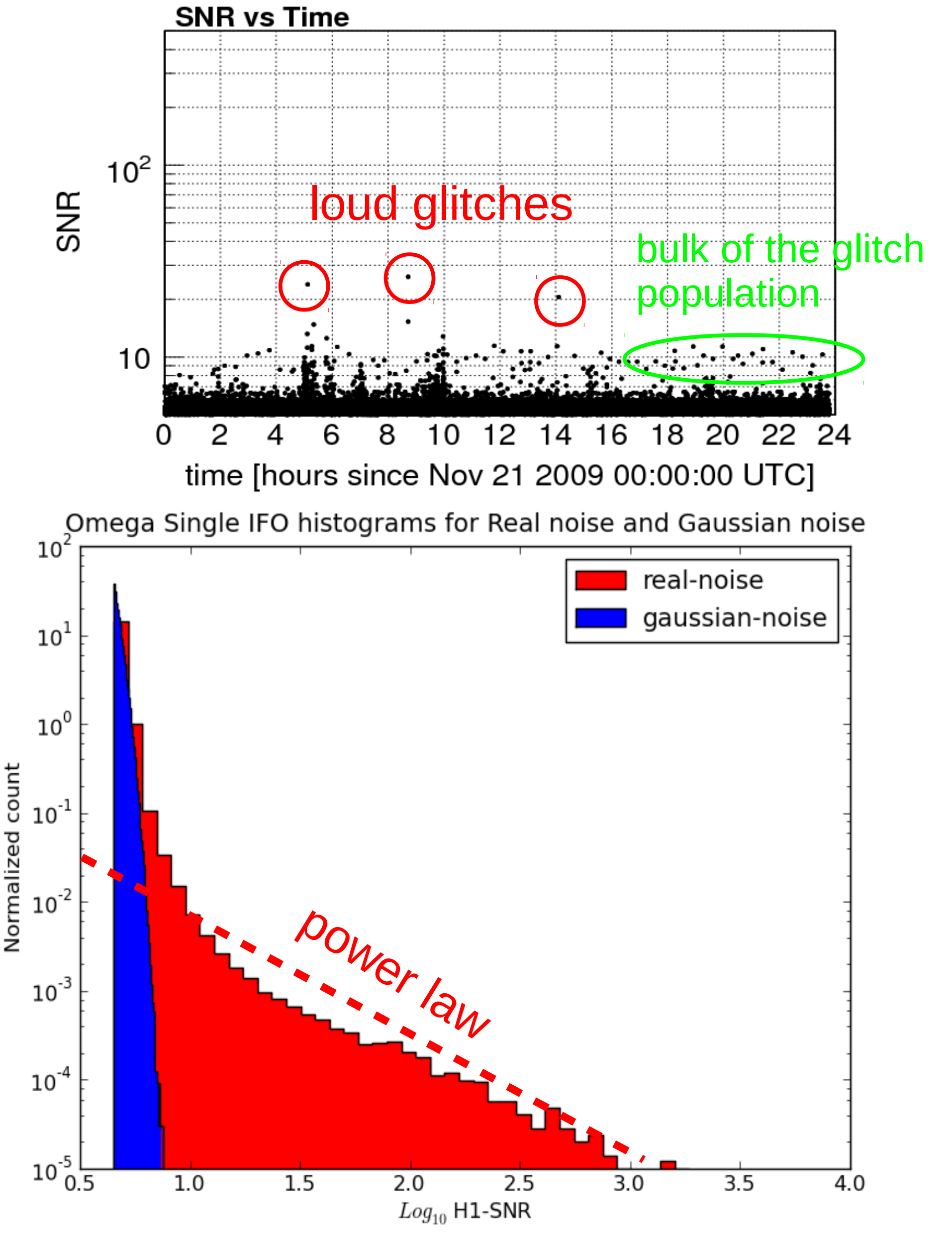
- Noise is non-stationary and non-Gaussian
- A zoo of instrumental glitches which mimics GW

Background has **heavy tails**

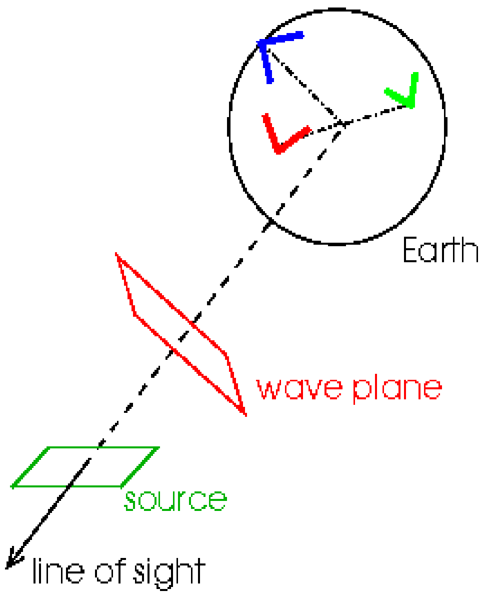
- Comprehensive modelling is out of reach

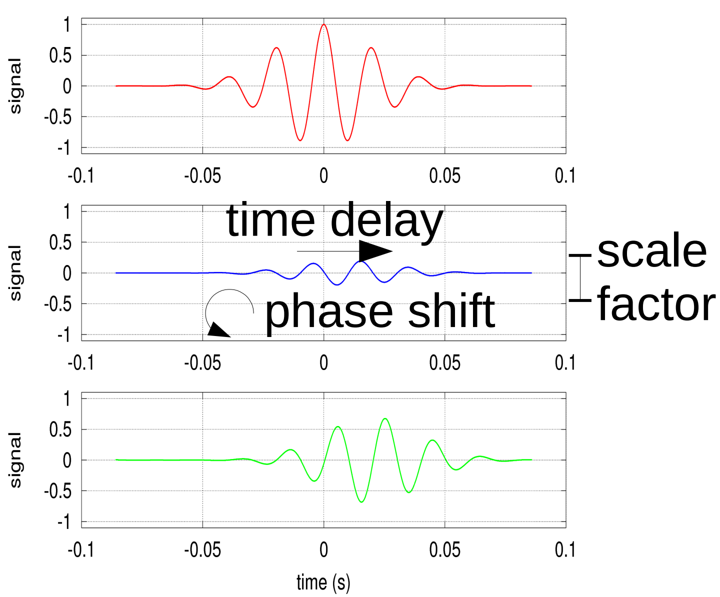
GW detectors are **very complex** instruments

**Data quality** and **background estimation** are a key issue



# Worldwide network of GW detectors




- Network of GW "receivers"

all detectors receive the same polarizations but couples differently according to their antenna patterns

$$s(t) = F_+ h_+(t-\tau) + F_\times h_\times(t-\tau)$$

orientation

phase shift – scaling (antenna patterns)

position

time delay (propagation)

**Note on time delay**

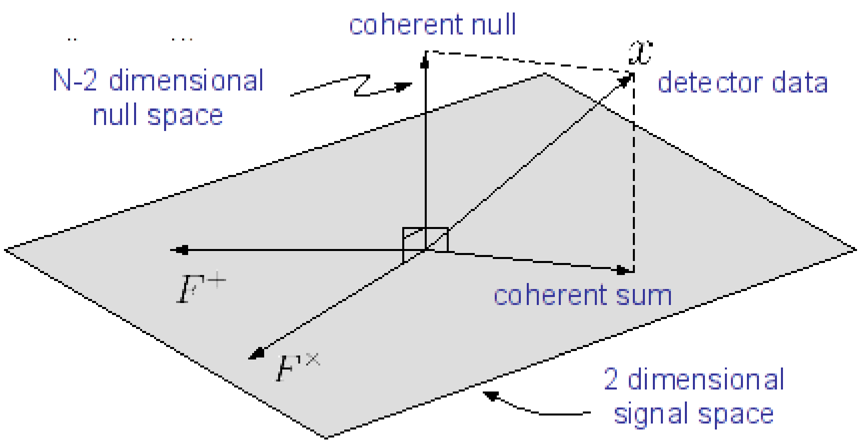
$$2R_\oplus/c \approx 42.5\text{ms}$$

max. LV time delay = few 10 ms

# Search for GW transients: Multiple detectors

$$\begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_N \end{bmatrix} = \begin{bmatrix} F_1^+ & F_1^\times \\ F_2^+ & F_2^\times \\ \vdots & \vdots \\ F_N^+ & F_N^\times \end{bmatrix} \begin{bmatrix} h_+ \\ h_\times \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_N \end{bmatrix}$$

*data* = *response* x *signal* + *noise*




signal space is a 2D plane!

Rejection of non-Gaussian background

- require coincidence
- consistency of the observations

coherent analysis & veto: signal vs null

Measure the two wave polarizations

- 5—10 % of the LIGO-Virgo sky is degenerate (see one polar. only)

- Increase sky coverage
- Source direction reconstruction

# Search for GW transients: procedure

- Background estimate
  - “time slides”: generate noise only data set using non physical time shifting
  - On source – Off source (exttrig)
- Detection
  - Estimate significance of GW candidate events by comparing to background
- Upper-limit
  - Estimate minimum detectable signal amplitude by adding fake GWs and re-analysing

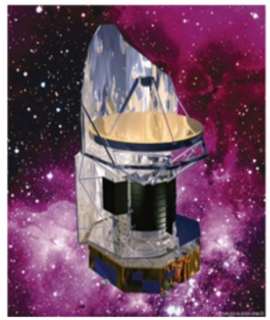
# Multimessenger astrophysics with GW

# Connection to high-energy astrophysics

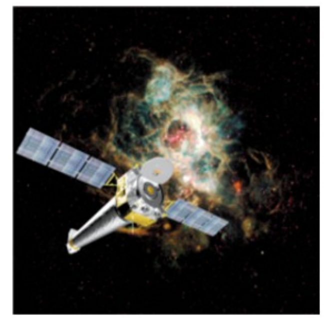
electromagnetic

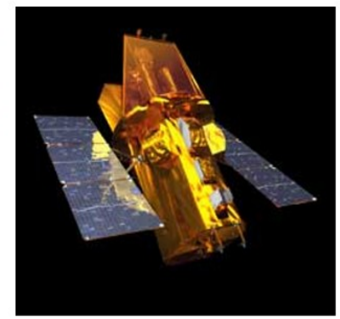
*low* | *medium* | *high* — *energy range*


radio


infrared


visible


X-rays


gamma-rays (keV)

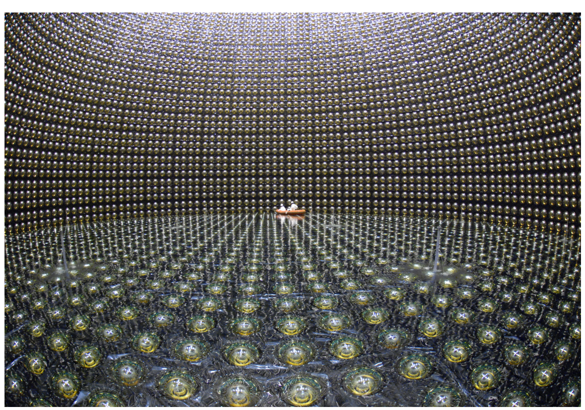

gamma-rays (MeV)

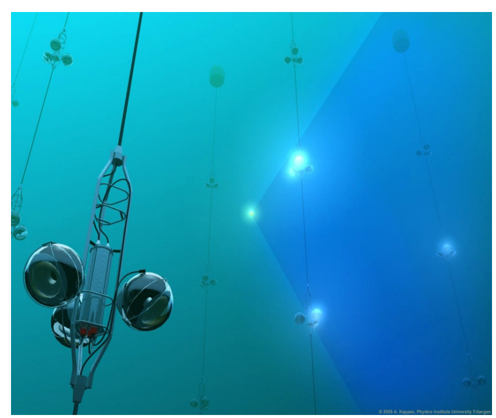
Gamma-ray burst and their afterglow
Anomalous X-ray pulsars

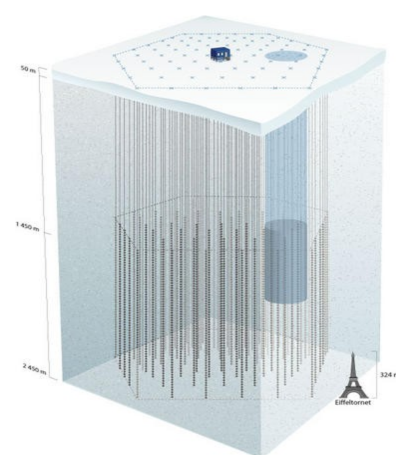
Soft-gamma repeaters
Pulsar glitches

neutrino

*low* | *high* — *energy range*







# Rationale for multimessenger astronomy

- Sensitivities to EM and GW differs by many orders of magnitude
- Assume GW fixes the size of the energy reservoir: A tiny fraction of this reservoir converted into EM suffices to produce a detectable signal
- This sounds quite likely
- Relies on the existence of a mechanism that makes this conversion
- Caveat: source compactness (e.g., black hole) may be an obstacle to EM radiation

# Detectable energy fluence at Earth
# EM *vs* GW

*order-of-magnitude estimate*

EM observatories have a much longer history !
Sensitivity is better by orders-of-magnitude

## Radio

1 mJy (for LOFAR) $\mathcal{F}_{radio}$ ~ $10^{-22}$ **erg/m²**

## Optical [*limit magnitude*]

25 cm aperture $\mathcal{F}_{V}$ ~ **5 x $10^{-7}$ erg/m²**

## X and gamma-ray

1 photon/cm²/s,100keV $\mathcal{F}_{\gamma}$ ~ **$10^{-3}$ erg/m²**

note: numbers in this column are **not** 5-sigma detection level

*Approximation here!* Noise property affect similarly the detection of short and long signals

## Initial GW detectors [*f=200 Hz*]

$h_{rss}$ ~2.5 x $10^{-21}$ Hz$^{-1/2}$ $\mathcal{F}_{GW}$ **= $10^{3}$ erg/m²**

## Advanced GW detectors

$h_{rss}$ ~ 2.5 x $10^{-22}$ Hz$^{-1/2}$ $\mathcal{F}_{GW}$ **= 10 erg/m²**

## 3rd generation detectors

$h_{rss}$ ~$10^{-23}$ Hz$^{-1/2}$ $\mathcal{F}_{GW}$ **= 1.5 $10^{-2}$ erg/m²**

# Extract more physics

## GW radiated energy estimate

$$E_{GW}^{iso} \approx \frac{c^3}{G} {D_L}^2 f^2 {h_{rss}}^2$$

- GW strength and freq.
- Locate host galaxy from counterpart → redshift / luminosity dist

  → GW radiated energy

Missing ingredient in the energy accounting of the source

To be compared with the radiated energy in EM obs and available energy reservoir

*note*: used average antenna pattern (real value can be obtained from accurate sky position of the EM counterpart) and isotropic emission

# Multimessenger astronomy with GW: observation strategies

*field of view, causality, reliability of the observations,*

*data storage capacity*

- The “exttrig” approach: other observatories → GW

    search GW data where indicated by “**EXT**ernal **TRIG**gers” (e.g., GRB alerts)

- The “looc-up” approach: GW → other observatories

    send alerts to partner observatories (e.g., robotic telescopes)

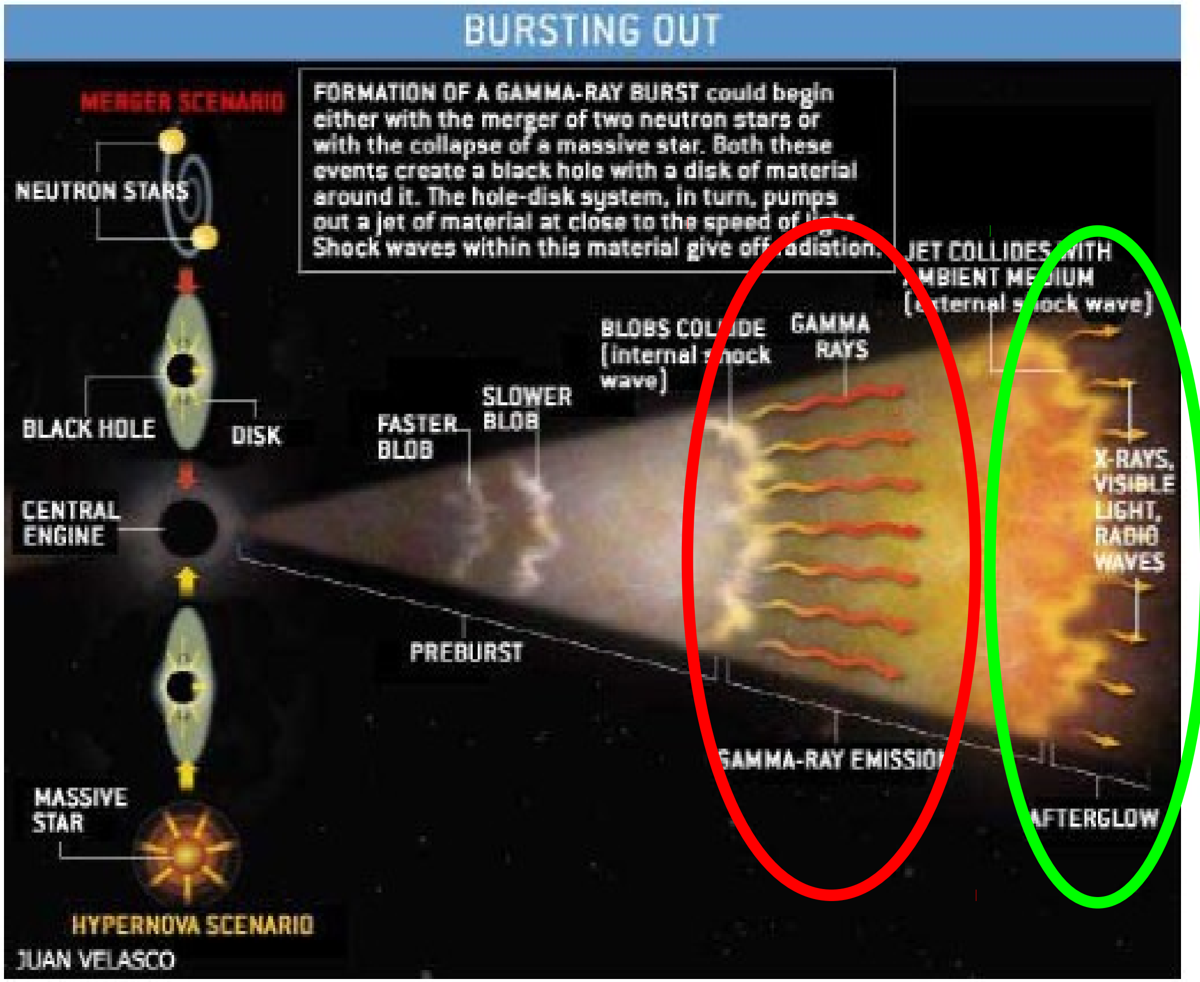
    termed after the “LOOC-UP project” we will present later

- Joint analysis: GW ↔ other observatories

# Multimessenger astrophysics with GWs

## 1. the exttrig approach: GRBs

# Relativistic jets and γ-ray bursts




- GRB phenomenology

very energetic burst of gamma-rays

$E_{EM}^{ISO} > 10^{50}$ erg

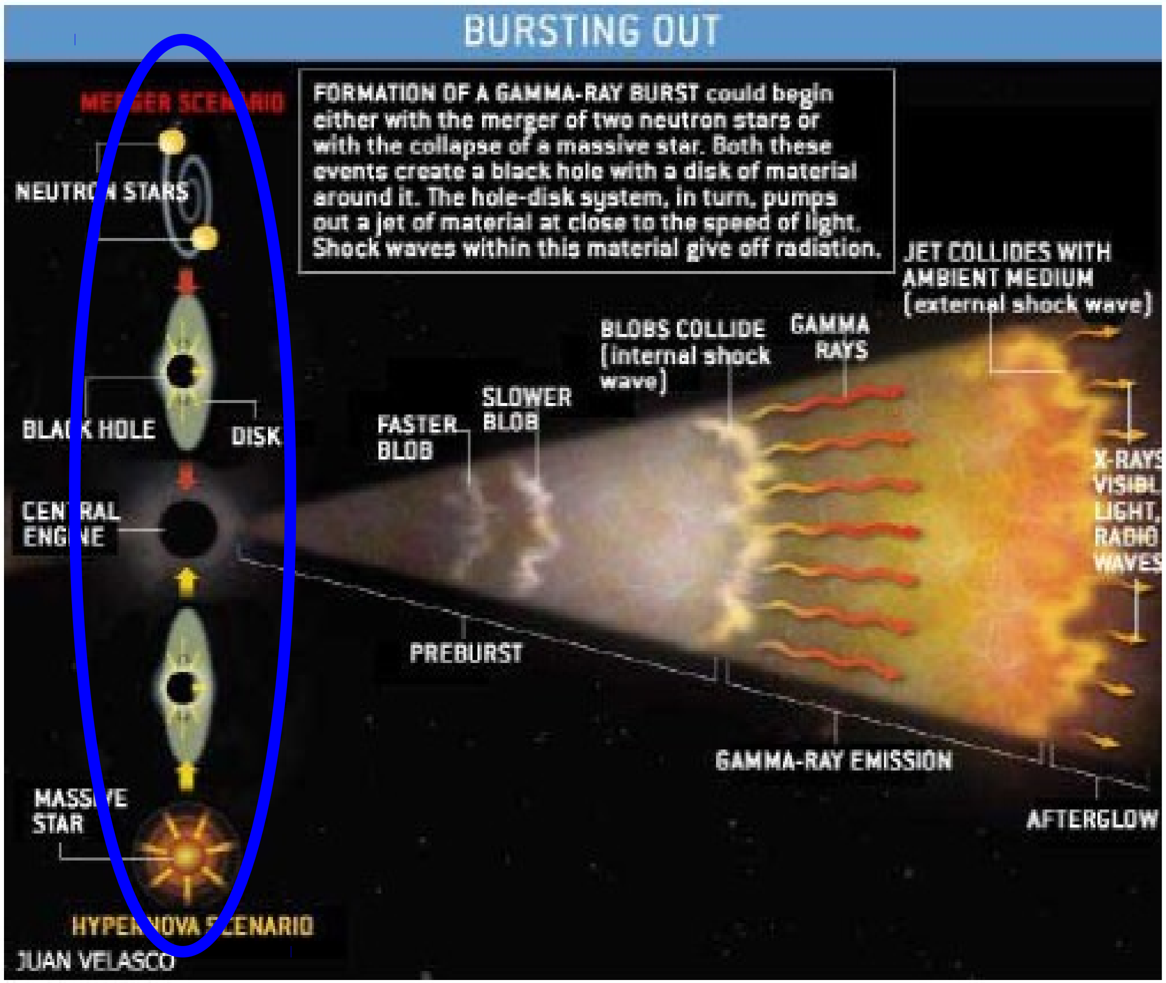
**“fireball model”**

- ultra-relativistic jet of plasma
- inhomogeneities at different speeds → shocks
- shock accelerated $e^-$ → synchrotron/inverse Compton radiation → **prompt γ**
- jet encounter with interstellar medium → **afterglow**

**prompt emission**
**γ-rays**

**afterglow**
**radio, visible, X-rays**

# Relativistic jets and $\gamma$-ray bursts




GW ?

- short/long GRBs (T<>2s)

*short*: BNS or NS-BH coal.

→ **GW “inspiral” chirp**

*long*: collapse of massive star to a BH

→ **GW burst**

**GRB are possibly associated to GW emission**

- GRB population

long: cosmological (typ. ~ Gpc)

hints of a local low-lumin. pop. (~100 Mpc)

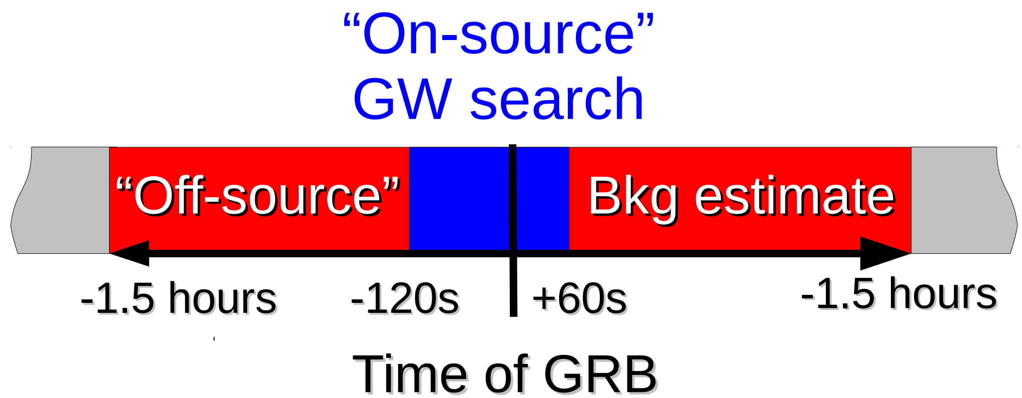
short: closer population (typ. few 100 Mpc)

# Search for GWs associated with GRBs (1)

- S5/VSR1

212 GRBs reported by the GCN (SWIFT, INTEGRAL,HETE2,...)

**137** in livetime and analyzed (21 short)

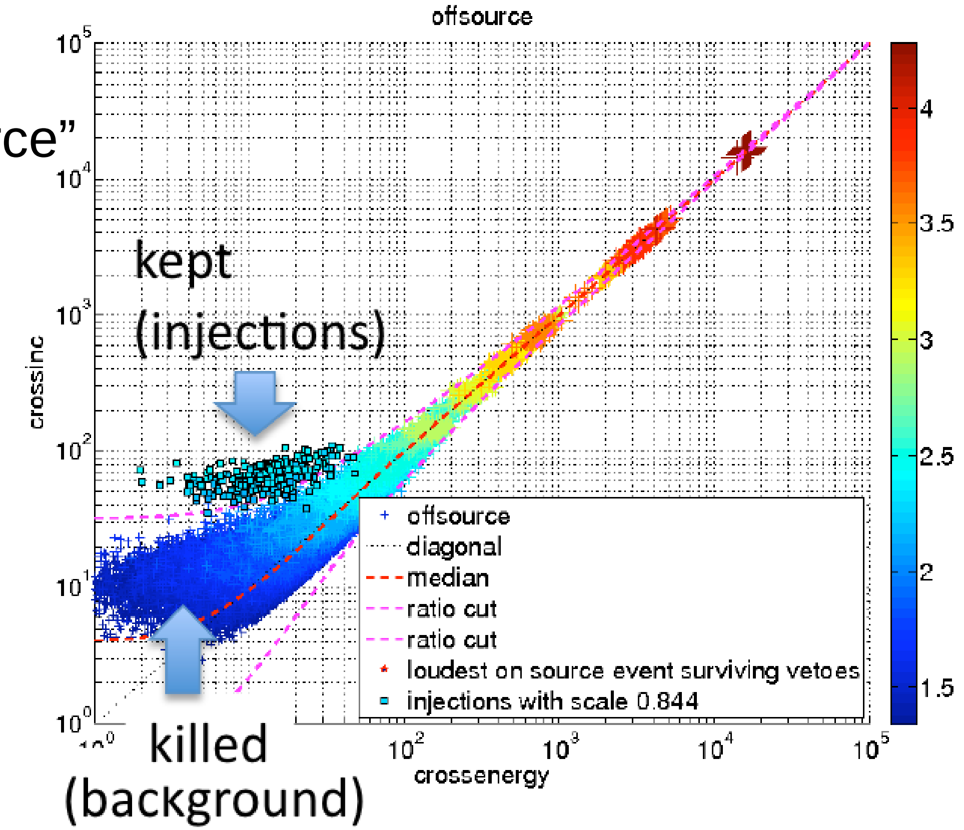



- Methodology: “X pipeline”

conservative time coinc. window → “on source”

search for an excess of “coherent” power

coherent veto to reject glitch




The LVC, ApJ, 715:1438–1452, 2010

# Search for GWs associated with GRBs (2)

- Results

**no GW found**.

UL $h_{rss}$ = 1.75 x $10^{-22}$ $Hz^{-1/2}$ @ 150 Hz 90% conf

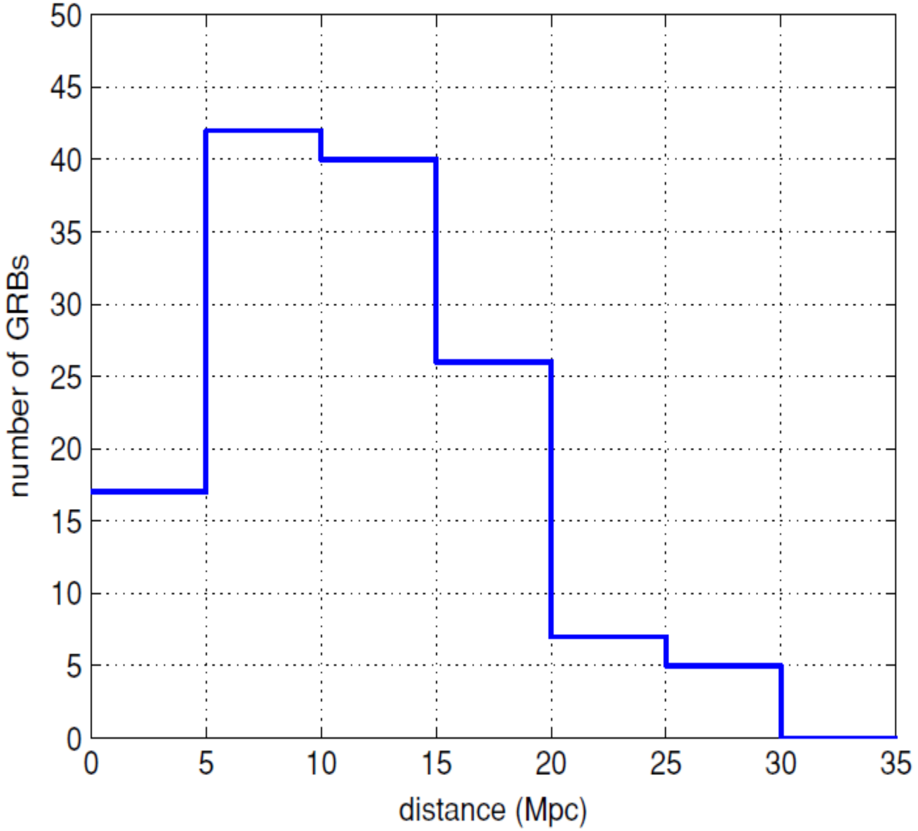
- Astrophysical interpretation

assuming "standard candle", $E_{GW}=10^{-2}$ $M_{sun}$ $c^2$

lower-limit on source distance $D_L$ > 26.2 Mpc

smallest known distance in the GRB set is ~500 Mpc

note: GRB 060218 at $z=0.0331$ (143 Mpc)




$$E_{GW}^{iso} \approx \frac{\pi^2 c^3}{G} D_L^2 f_0^2 h_{rss}^2$$

The LVC, ApJ, 715:1438–1452, 2010

# GRB070201

- Short GRB detected by Konus-wind, INTEGRAL, Swift, MESSENGER
- Error box overlap with M31 (700 kpc)

  from received flux, $E_{EM}^{ISO} \sim 10^{45}$ erg if in M31

  → too weak for a GRB, more likely SGR flare

  if typical GRB, $E_{EM}^{ISO} \sim 10^{50}$ erg → $D_L > 23$ Mpc

- LIGO H was in operation. **no GW detected**
- Is it an inspiral in Andromeda?

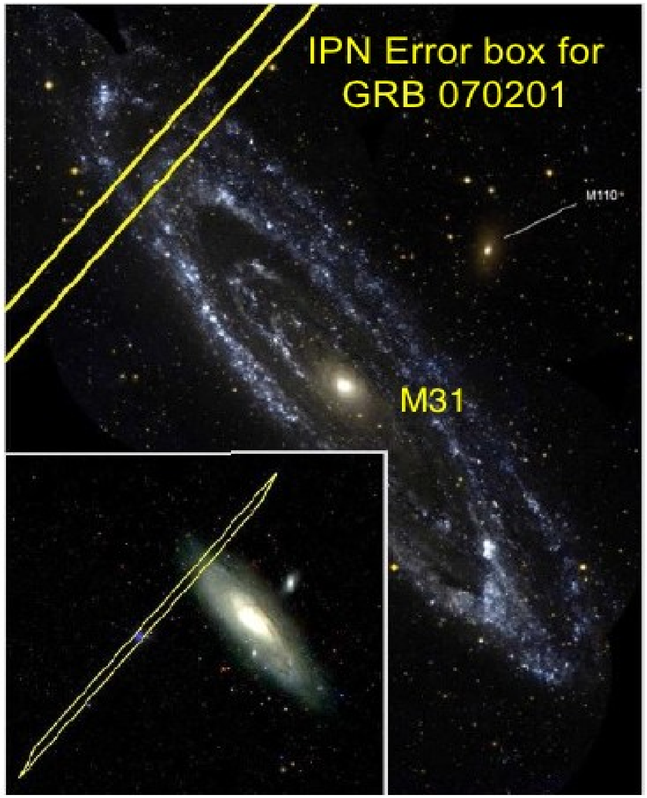
  $1 < m_1 < 3.0\ M_{sun}$ & $1 < m_2 < 40\ M_{sun}$ is excluded

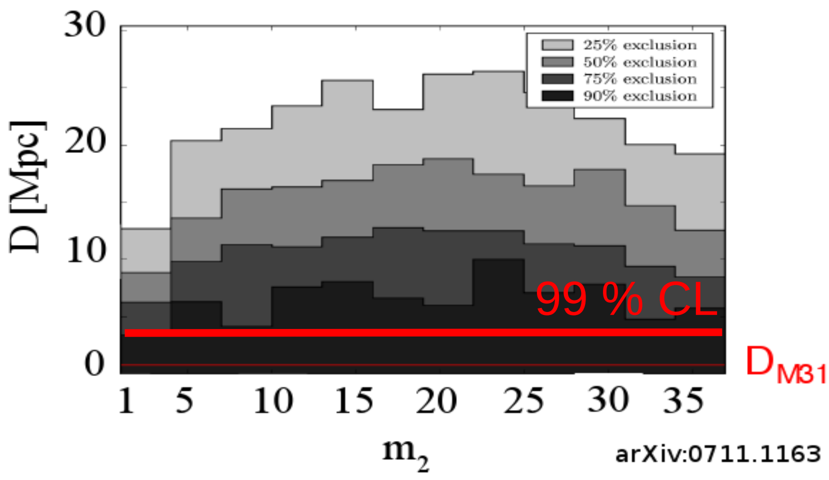
- GW energy release if in Andromeda?

  $E_{GW}$ *is* $< 8\ 10^{50}$ erg

  UL is comparable to $E_{EM}$ for typical GRB

  but much higher than expected for SGR ($< 10^{46}$ erg)



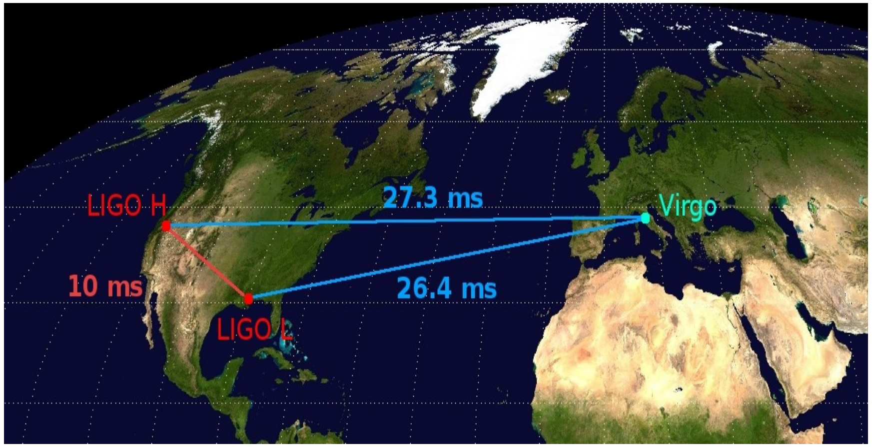




arXiv:0711.1163

# Multimessenger astrophysics with GWs

## 2. the looc-up approach: EM follow-ups

# Source direction reconstruction (1)




Diffraction : $\theta \sim \frac{\text{wavelength}}{\text{aperture}} = \frac{1}{fT}$

*f*=200 Hz → 10 x 30 degrees

---

Error box $\delta\Omega \approx 2c^2 \frac{\delta\tau_{12}\delta\tau_{13}}{A\cos\theta}$

- "Triangulate" the source direction

  from arrival time at each detectors

- Size of the error box
  - Order-of-magnitude estimate from diffraction limit
  - Statistical timing error ($\rho$ = 10)

$$\sigma_t \approx (2\pi\Delta_f\rho)^{-1} \sim 0.2\ \text{ms}$$

$$\Delta_f^2 = \langle (f - \bar{f})^2 \rangle \sim 150\ \text{Hz}$$

  - Systematics (calib. uncertainties)

$$\delta_t \approx \delta\phi_{max}/(2\pi\Delta_f)$$

$$\sigma_t \equiv \delta_t \text{ when } \delta\phi_{max} \sim 5^\circ$$

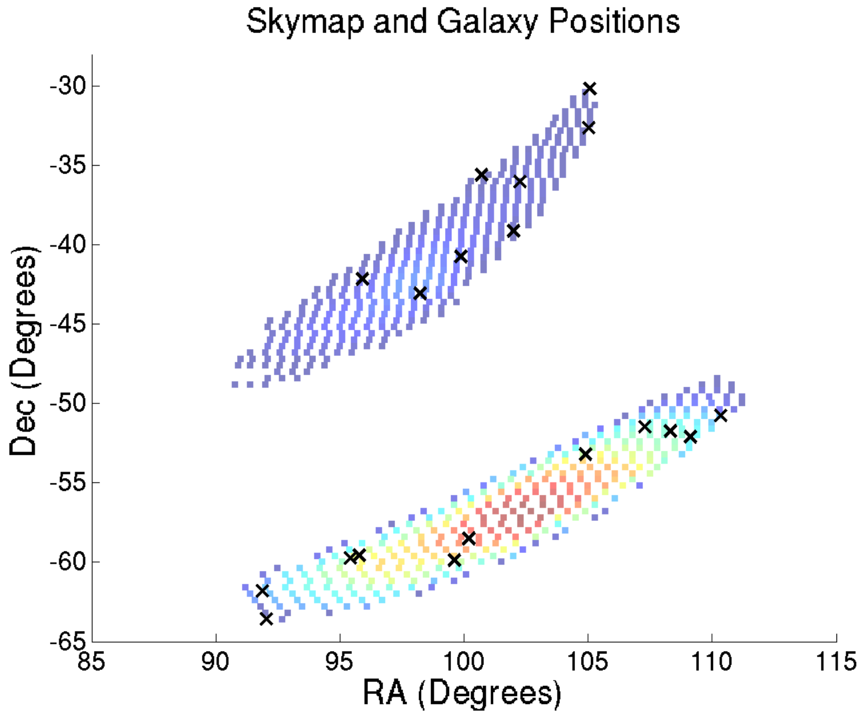
Searle (unpublished), Steve Fairhurst arXiv:0908.2356, Linquin Chen arXiv:1003.2504, Guersel & Tinto (1989)

Cavalier et al, gr-qc/0609118

# Source direction reconstruction (2)

- Error box geometry is non trivial!

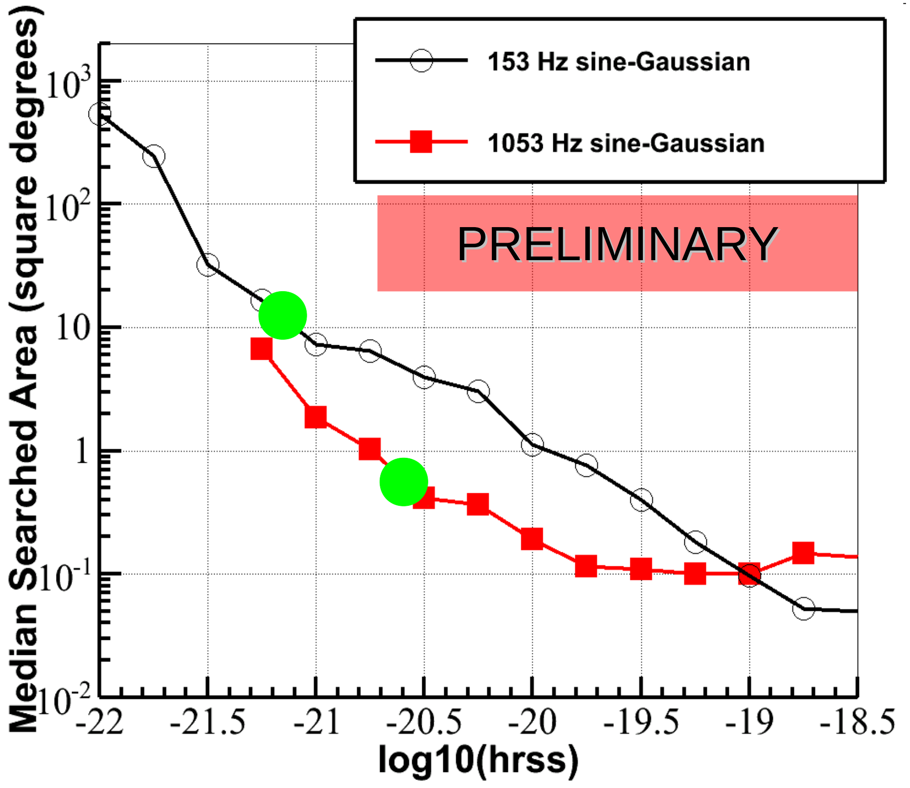
"search window" has a complicated shape made of disconnected "islands"




Kanner et al 2008 Class. Quantum Grav. 25 184034

- Typical angular resolution

10 sq degrees for a detectable signal in the bucket



# Low-latency analysis chain

**LIGO H** | **LIGO L** | **Virgo**

**Omega & cWB**
for unmodeled GW Bursts

**MBTA**
for signals from Compact Binary Coalescences

Search algorithms
Source position reconstruction

**Database**
**GraceDB**

**LUMIN**
for optical telescopes

**GEM**
for Swift

Select Significant Triggers
Determine Pointing Locations

**10 min.**

**Event validation**

**30 min.**

**Send alert to telescopes**

# Robotic telescopes and other follow-up observatories

"**Target of Opportunity**" program

with automatic telescopes

rapid slew rate (seconds to mins) and governed by a scheduler (initially conceived for GRB follow-up)

many partners: good sky coverage, robustness to weather conditions

- Wide-field telescopes

**Pi of the Sky (camera) 20 degrees x 20 degrees**

**PTF: P48 ~ 8 degrees**

**QUEST/ESO Schmidt 4.1 degrees x 4.6 degrees**

**ROTSE & TAROT 1.85 degree x 1.85 degree**

**SkyMapper 5.6 sq degrees**

- Narrow-field telescopes

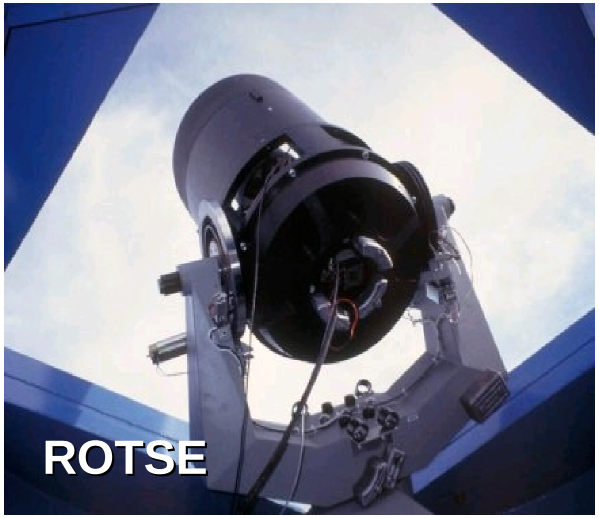
**Liverpool telescope .1 degree x .1 degree**

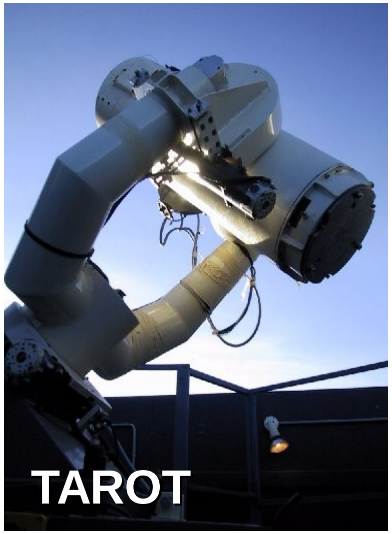
**Zadko .4 degree x .4 degree**

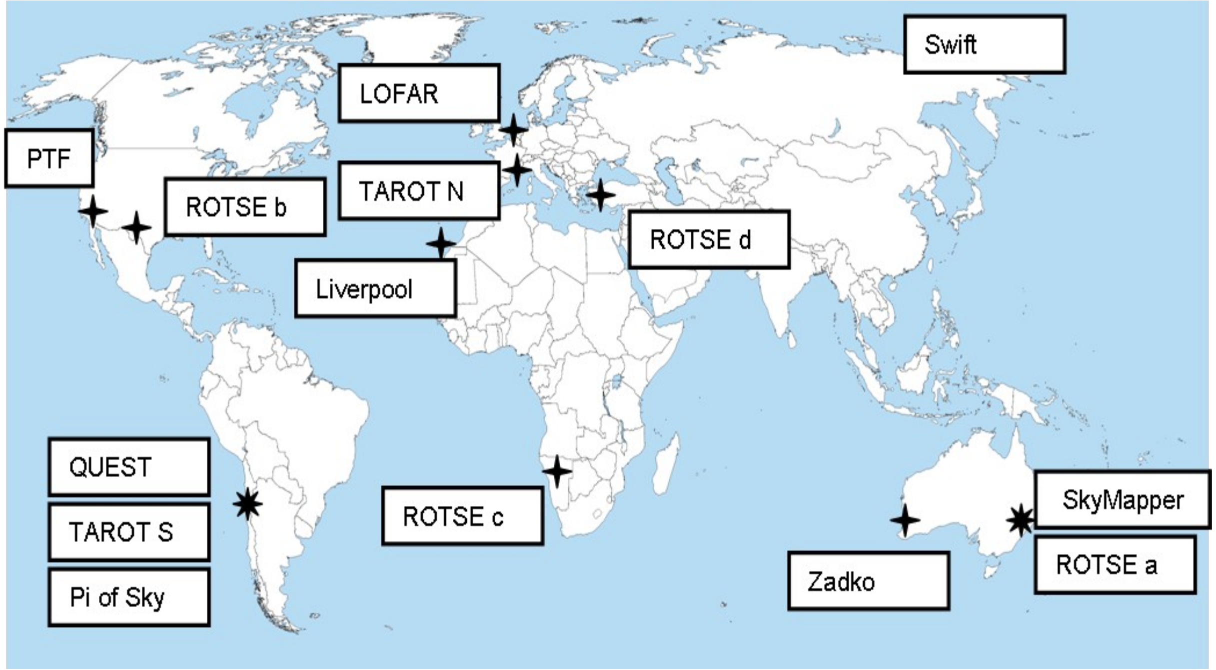
- Other observatories

**Swift (gamma/X-rays, UV) .4 degree x .4 degree**

**LOFAR (radio) 25 degree FOV**



# Pointing strategy (1)

- GW error box vs EM FOV

GW: O(10) sq. deg vs EM: O(1) sq. deg

- Improve pointing using priors

extragalactic sources are most probable

observe as a priority galaxies within 50 Mpc

use GWGC catalog [1]

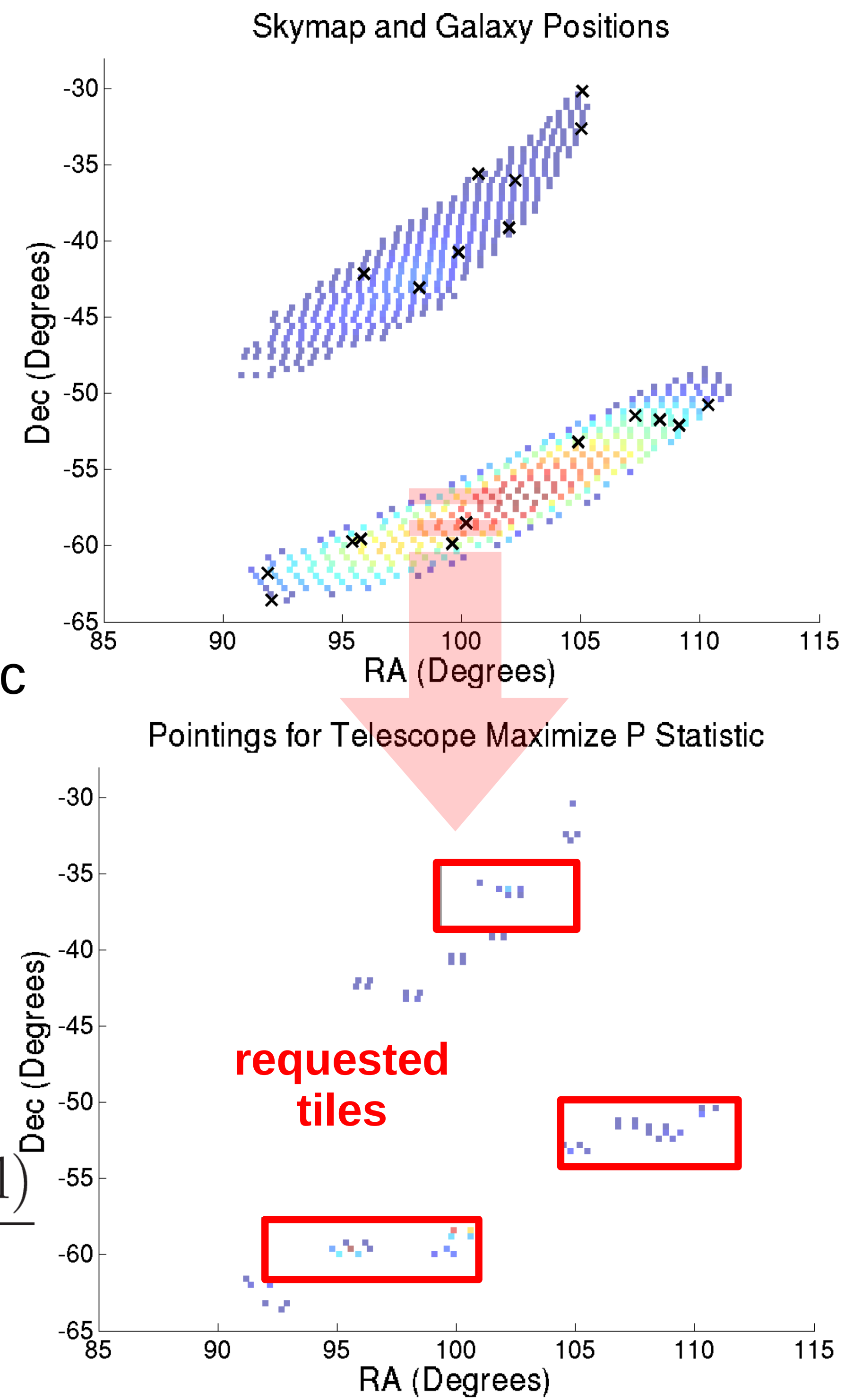
- Mass targetting

use ad-hoc ranking favouring large

mass density and distant galaxies

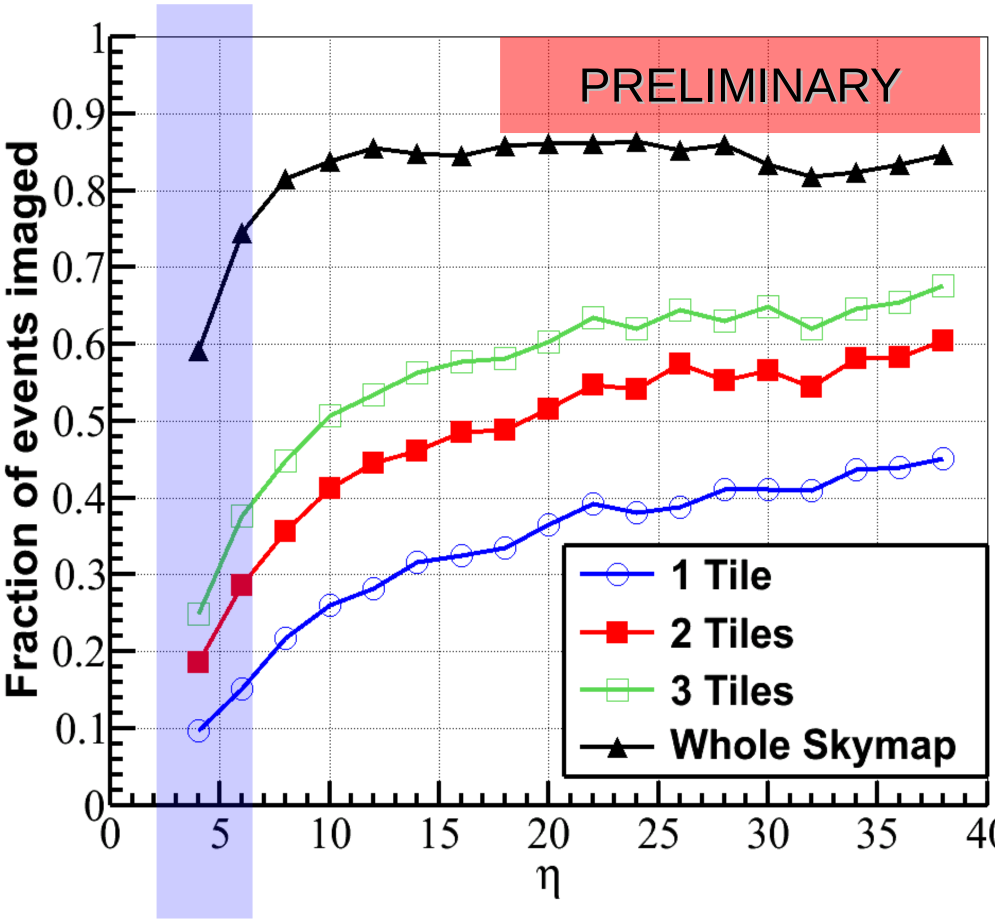
$$P = \sum_{\mathrm{gal} \in \mathrm{pixel}} \frac{\mathrm{mass(gal)\ likelihood\ (pixel)}}{\mathrm{distance(gal)}}$$

[1] Darren J White et al 2011 CQG. 28 085016

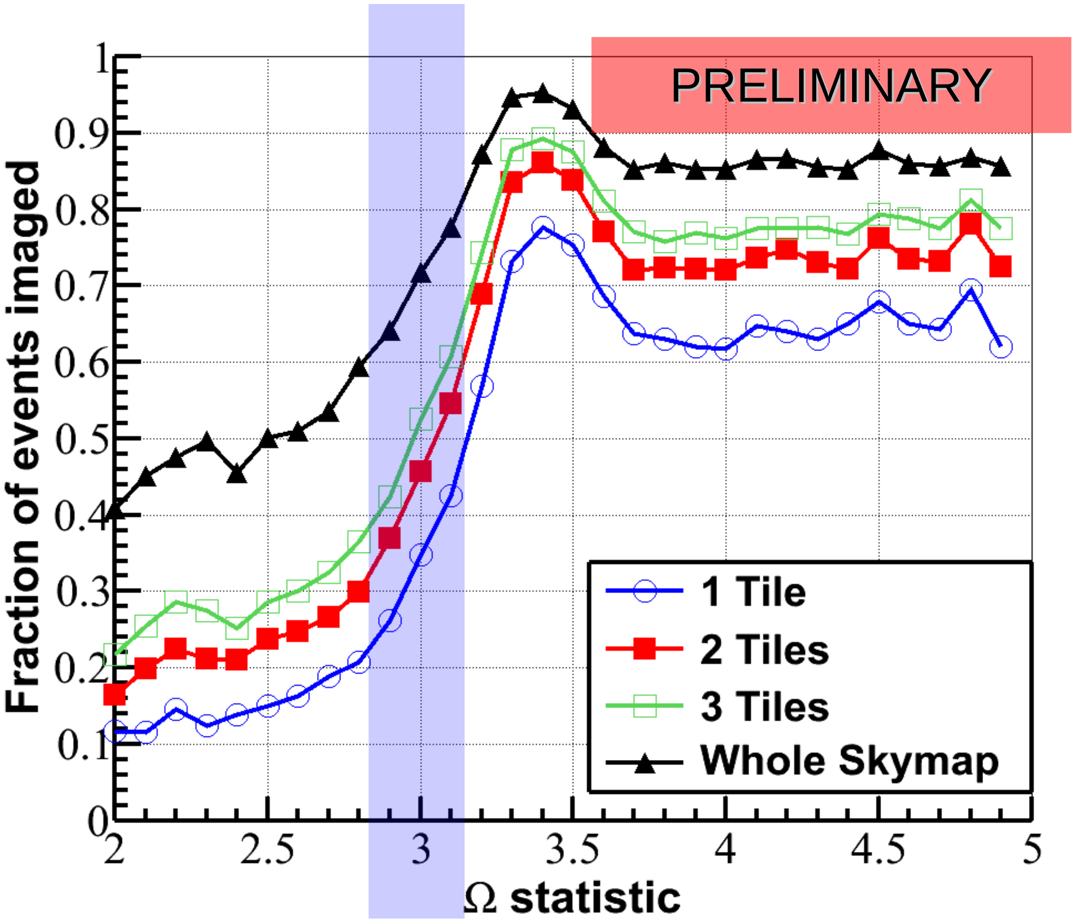


# Pointing strategy (2)

Performance of the pointing strategy used with
coherent Waveburst and Omega
(averaged over many types of injected waveforms)
1 tile = 1.8 deg x 1.8 deg

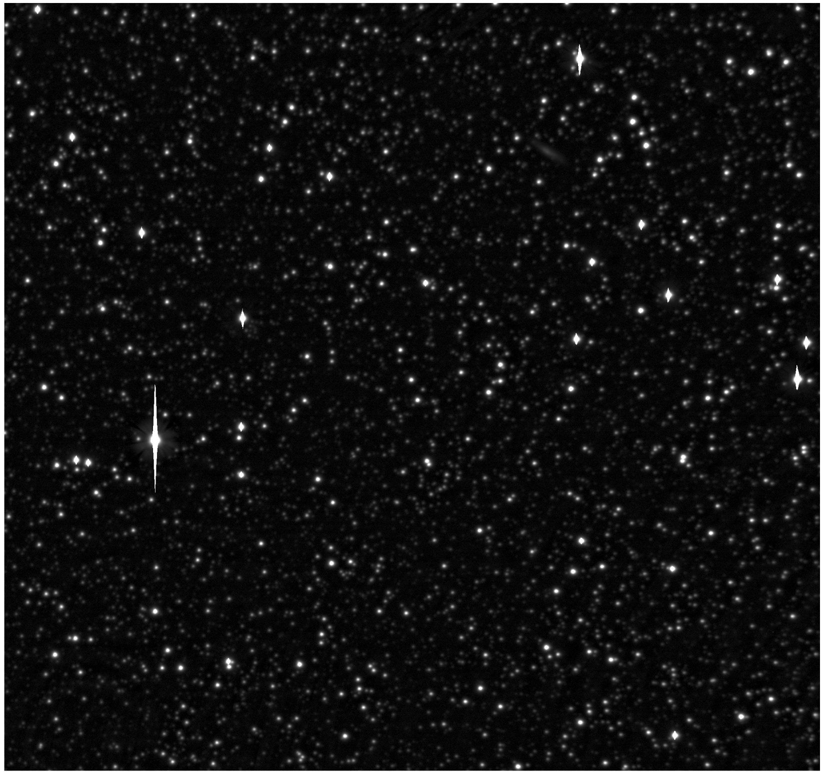



region of interest




region of interest

# Observational data so far



test image taken by the
Zadko telescope

- **EM-follow-up program during S6-VSR2/3**

**“Winter run”,** from dec 17 2009 to jan 8 2010

**8** candidate GW triggers communicated

**4** observed by telescopes

**“Summer run”,** from sep 4 to oct 20 2010

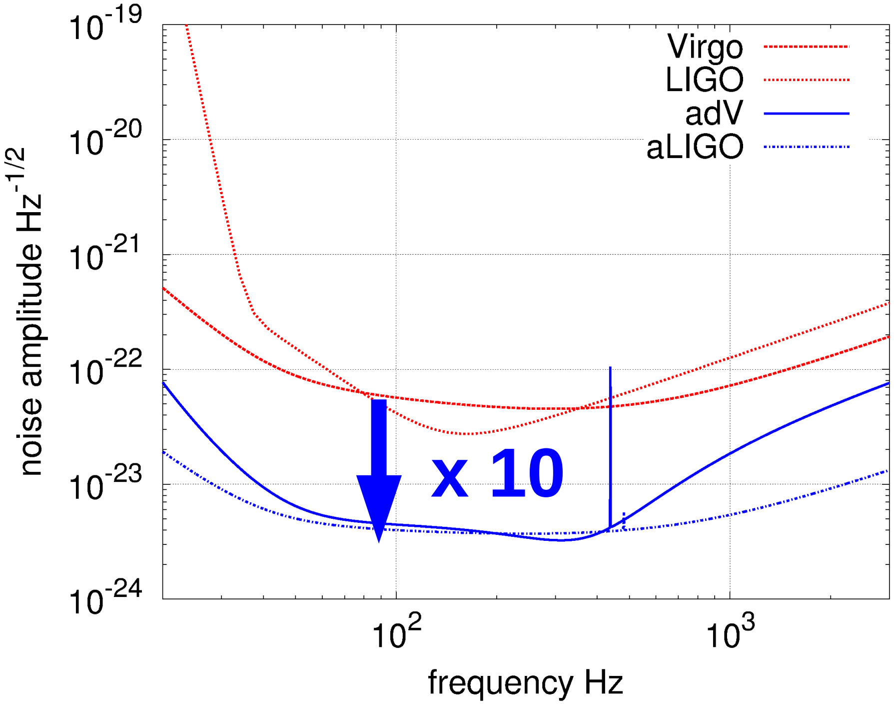
**6** candidate GW triggers communicated

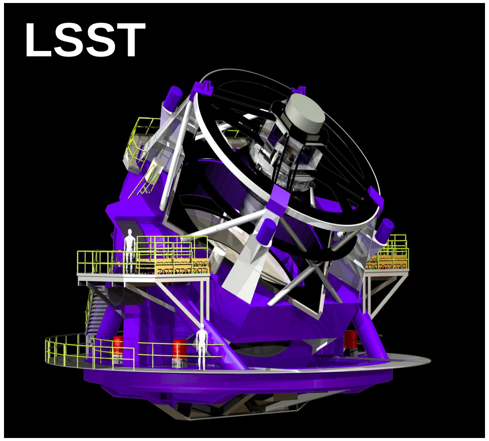
**4** observed by telescopes

Total of O(1000) images collected

Image analysis is on-going

# Perspective : 2$^{nd}$ generation of GW detectors (2015+)





- x 10 sensitivity improvement
  - x $10^3$ observable volume
  - detection is likely
- More detectors around the globe?
  - LCGT (Japan), LIGO Australia, IndIGO (India)
  - x 10 improvement in angular resolution
- Synergy with astroparticle physics
  - “Real-time” astronomy
  - X-ray – Gamma-ray observatories

# Toward GW astronomy!

- LIGO/Virgo at/close to target sensitivity
- wealth of scientific data
- interesting results obtained jointly
  - of astrophysical relevance (model exclusion)
- $2^{nd}$ generation/advanced detectors upcoming (2015)
  - x 10 distance reach, x 1000 more sources
  - will see GW
- $3^{rd}$ generation and space-based observatories on the drawing board
- partnership with EM and neutrino observatories
  - multimessenger astronomy!
  - clear synergy with high-energy astrophysics

# Readings

- Philippe Tourenc, Relativité et gravitation, Armand Colin, 1997
- P Saulson, “Fundamentals of Interferometric Gravitational Wave Detectors”, World scientific, 1994
- B Sathyaprakash & B Schutz, “Physics, astrophysics and cosmology with gravitational waves”, Living Reviews 12 (2009)

# Spares

# Soft gamma repeaters (1)

- SGR flares, AXP

series of sporadic X & γ-ray flashes (~0.1 s)

ordinary flares $E^{iso}_{EM} < 10^{42}$ erg

occasionnally, giant flares $E^{iso}_{EM} \sim 10^{46}$ erg (AXP)

possibly connected to some of the GRBs

< 20 known SGRs (galactic and LMC)

- Progenitors? “magnetar”

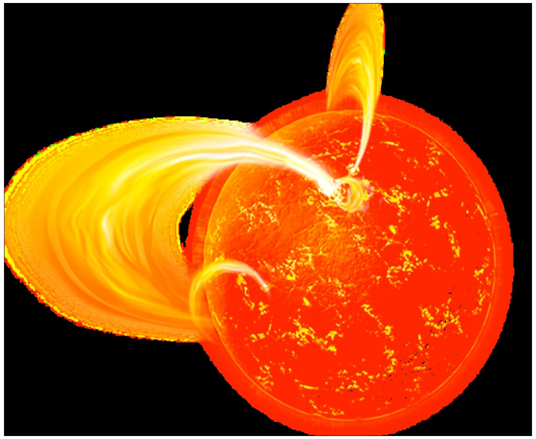
highly magnetized neutron star ($B \sim 10^{15}$ G)

sudden reconfig of the internal magnetic field and cracking of the crust

excite non-radial (f-)modes damped by GW emission

- One of the closest GW burst source (d ~ O(1) kpc)

Search GW data in coincidence with observed flashes



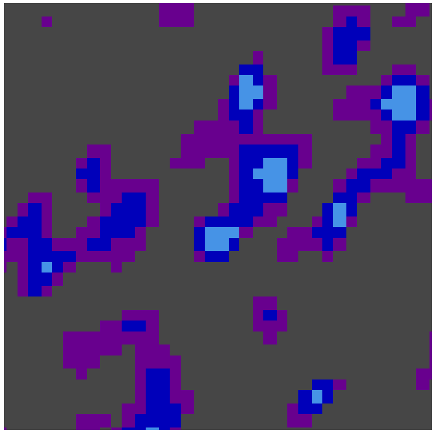
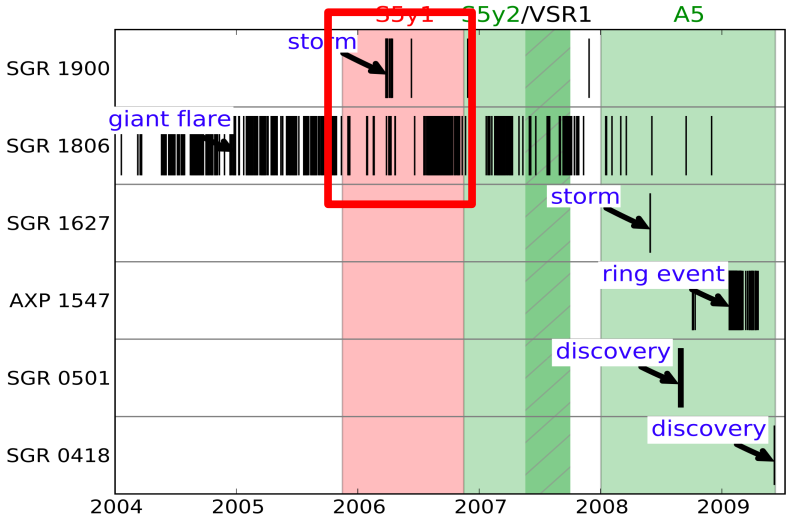


Image: NRAO/VLA



# Soft gamma repeaters (2)

- Most recent data set (LIGO S5)

190 flares during S5 and 1 “storm”

- Methodology: “flare” pipeline

search for 1st f-mode (few kHz) also the “bucket”

extract the time interval from the light curve

excess power statistic ($\mp$ 2 s on-source/off-source)

“stack” triggers (fluence weighted)

- Results

no statistically significant GW signal

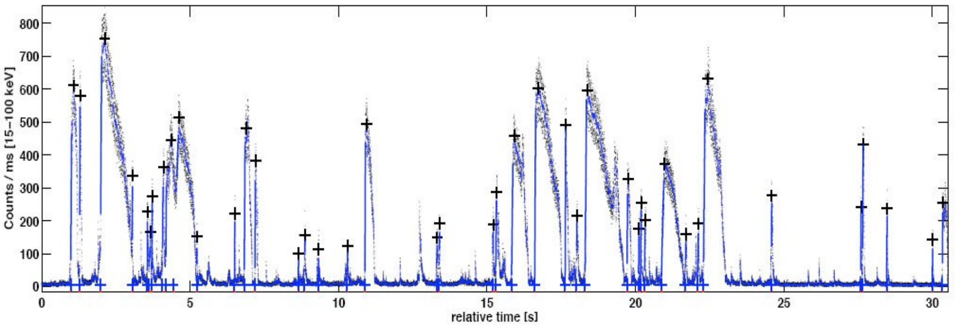
best UL $h_{rss}$=1.3 x $10^{-22}$ $Hz^{-1/2}$

best $E_{GW}$~3 x $10^{45}$ erg (comp. to giant flare EM emission)

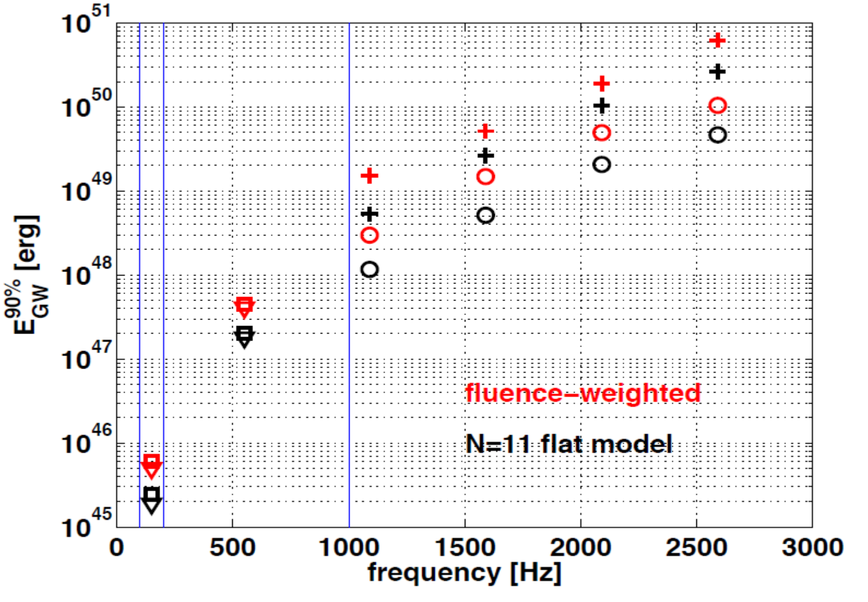
ratio $E_{GW}/E_{EM}$ ~ 3 x $10^4$ (note: best result so far is ~50)

unfortunately, the expected GW strength is yet unknown

- More recent results using S5/VSR1 in the arXiv

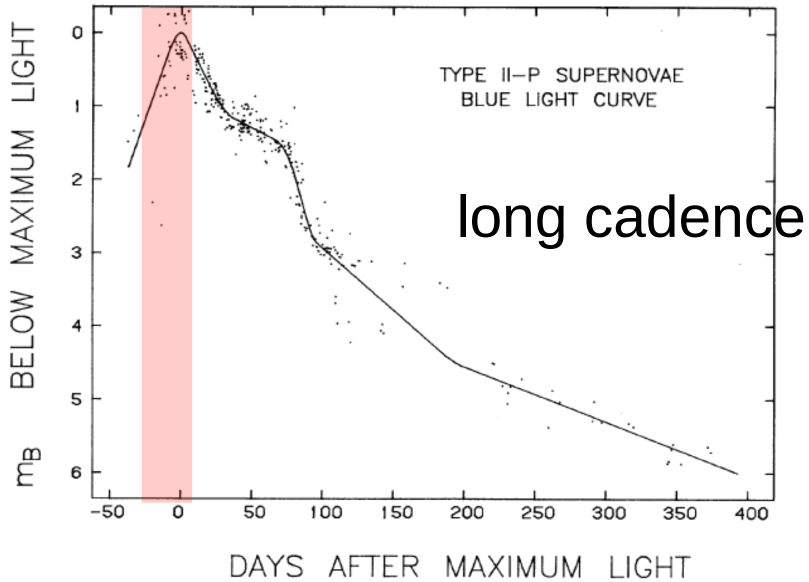


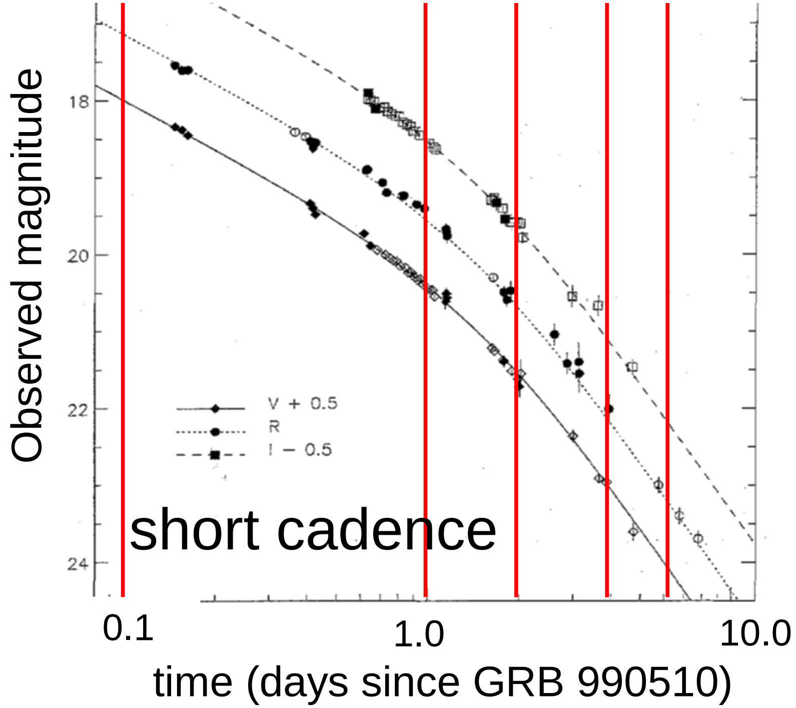

Example of light curve
SGR 1900+14 flare (Mar 29, 2006) seen by Swift-BAT




The LSC, Astrophys. J. 701:L68-L74,2009

# Observational strategy




- Cadence

Proper sampling of the expected light curve

“long” schedule for SN-like event

example: [D+0 +6 +7 +9 +16 +27 +28]

“short” schedule for GRB afterglow-like event

example: [D+0 +1 +2 +4 +6]

- Exposure

Defines limiting magnitude for a given aperture

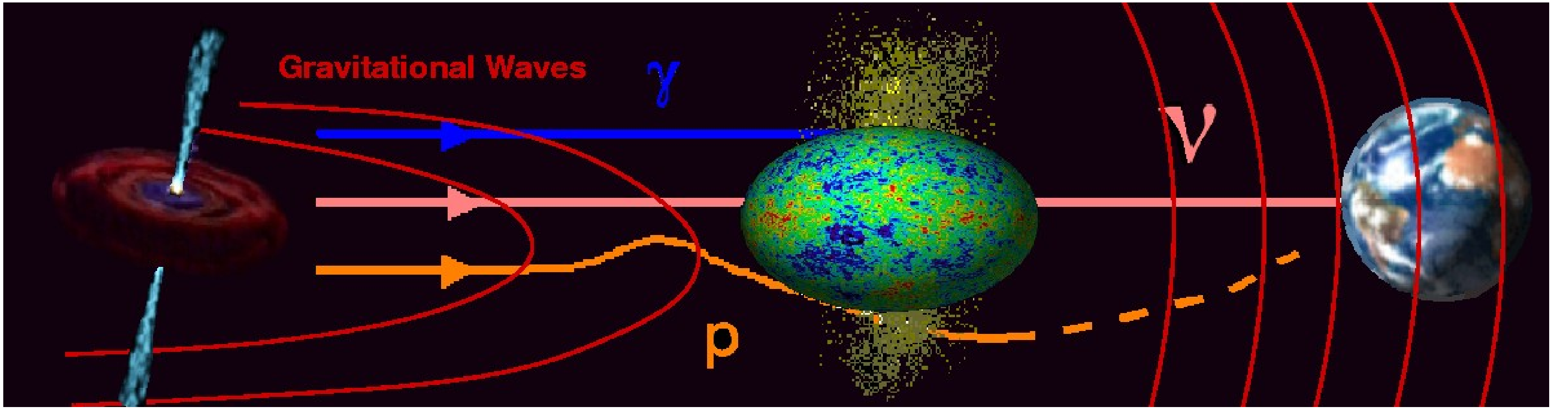
Short exposure < 60 s (→ ~15 mag)

Long exposure > 120 – 180 s (→ ~17 mag)

[more at the hand-on session tomorrow]

- No filtering

# Neutrino spectrum
# Generalities




*no absorption/diffusion*: travel "cosmological" distances

as opposed to photons (dust, gaz, MW or IR background)

*no deflection* by magnetic fields: trace back

(as opposed to charged cosmic rays)

*weakly interacting*: escape from dense objects

# High-energy neutrinos (GeV-TeV)

- **Jet sources (including GRBs)**

accel. proton–$\gamma$ interaction $\longrightarrow \pi^{\pm} \longrightarrow \nu$

choked GRBs (jet not powerful enough to break out the star envelop)

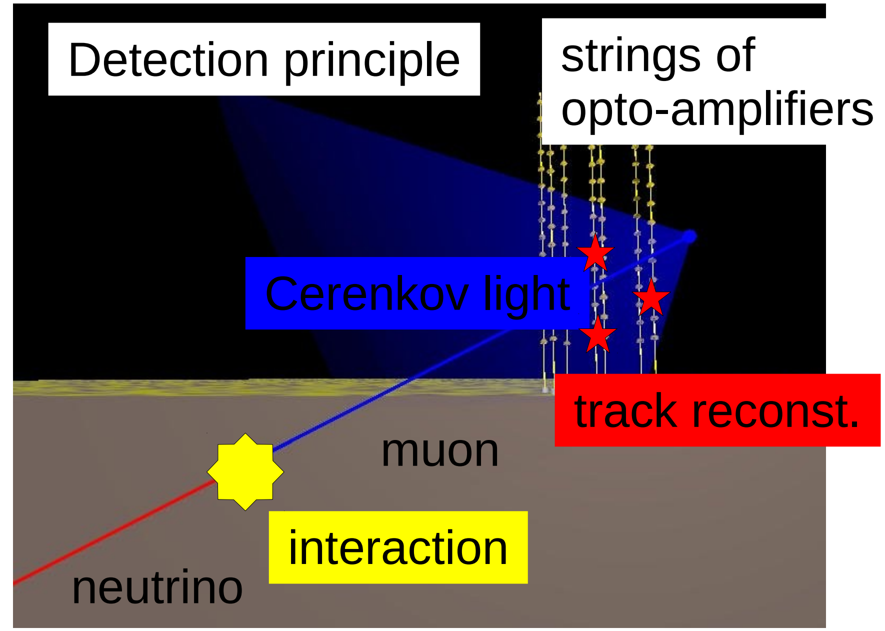
- **ANTARES/IceCube telescopes**

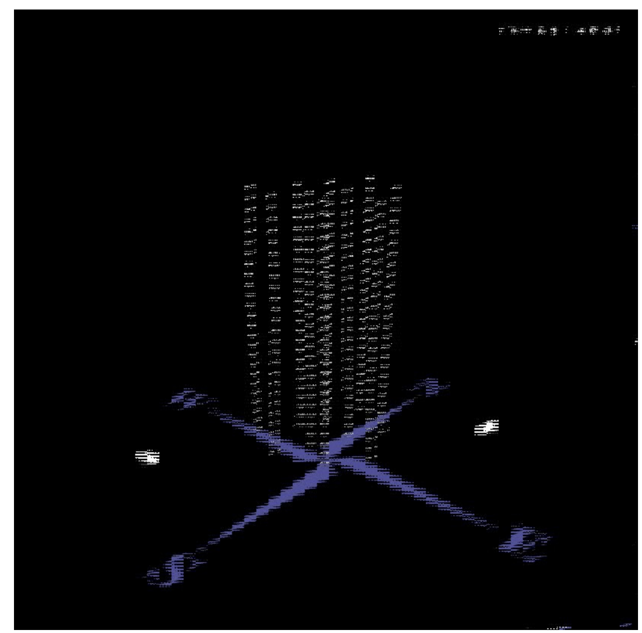
detect Cerenkov light created by the relativistic muon resulting from the interaction of the neutrino with nuclear matter

source direction from muon track reconstruction with typ. error ~1 degree (or better)

large background from atmospheric muons and neutrinos from air shower

detectors observe opposite sky hemispheres



# High-energy neutrinos (GeV-TeV)

- GW and HEN = same search style

few small signal buried in background noise

- Search for an excess of time and spatial coincidence
- Partnership agreement signed, analysis is on-going