Many thanks to the experimenters and all the great colleagues from the LIGO and Virgo collaborations! Without their hard work neither the data nor the discussion would be possible.









# Impacts of Comprehensive

# Multimessenger Astronomy





Szabolcs Márka

Columbia University in the City of New York

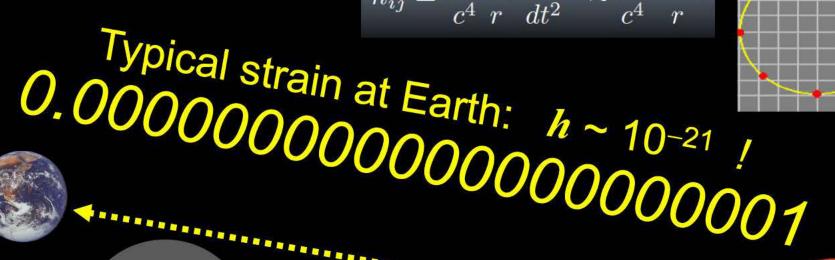


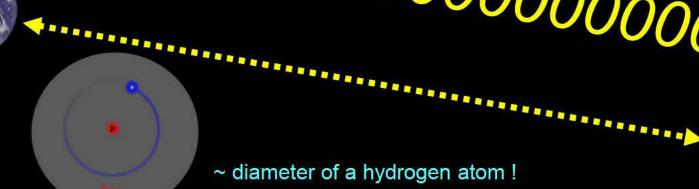
### Gravitational Wave Astronomy

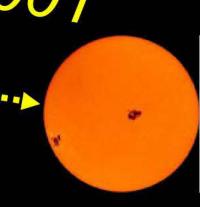
Gravitational waves can carry unique information about black holes, neutron stars, supernovae, the early evolution of the universe, and gravity itself...

However, they are either extremely weak or extremely rare...

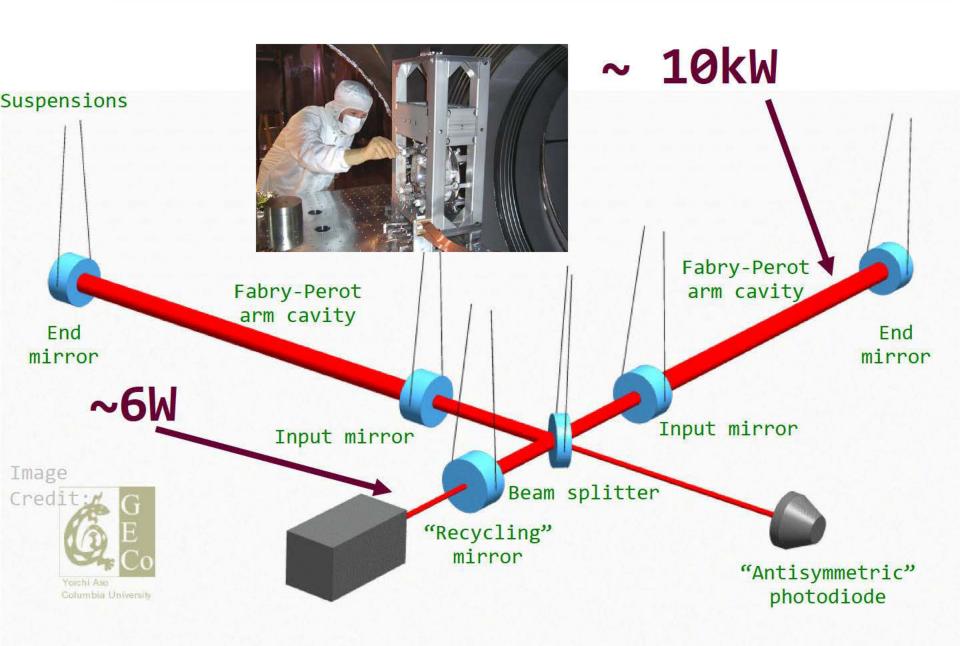
$$h_{ij} = \frac{2G}{c^4} \frac{1}{r} \frac{d^2 Q_{ij}}{dt^2} \sim \frac{G}{c^4} \frac{mv^2}{r}$$

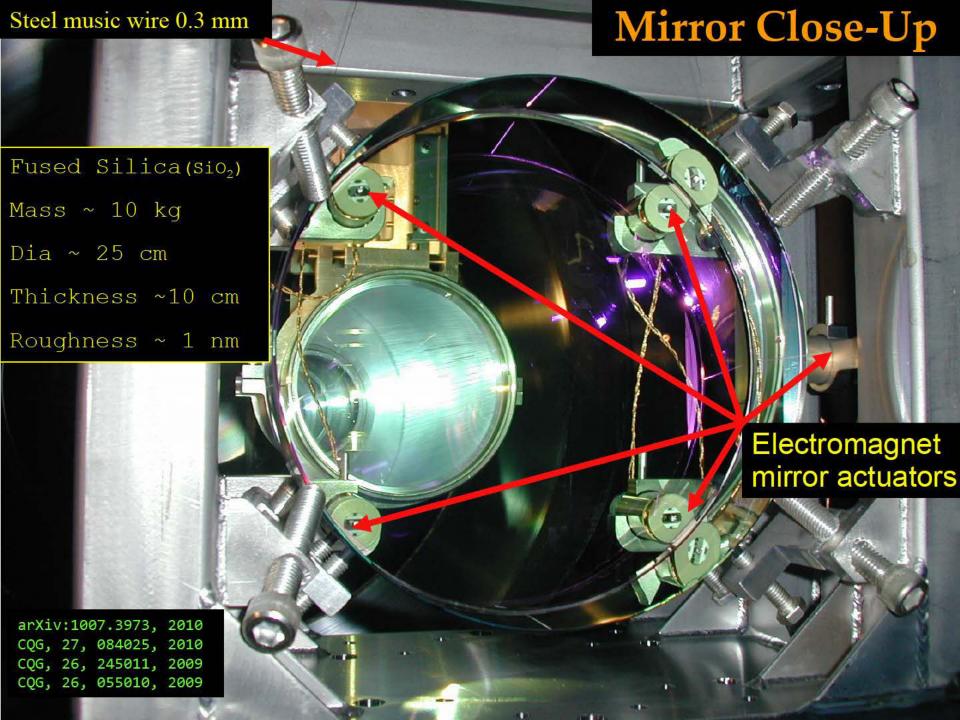






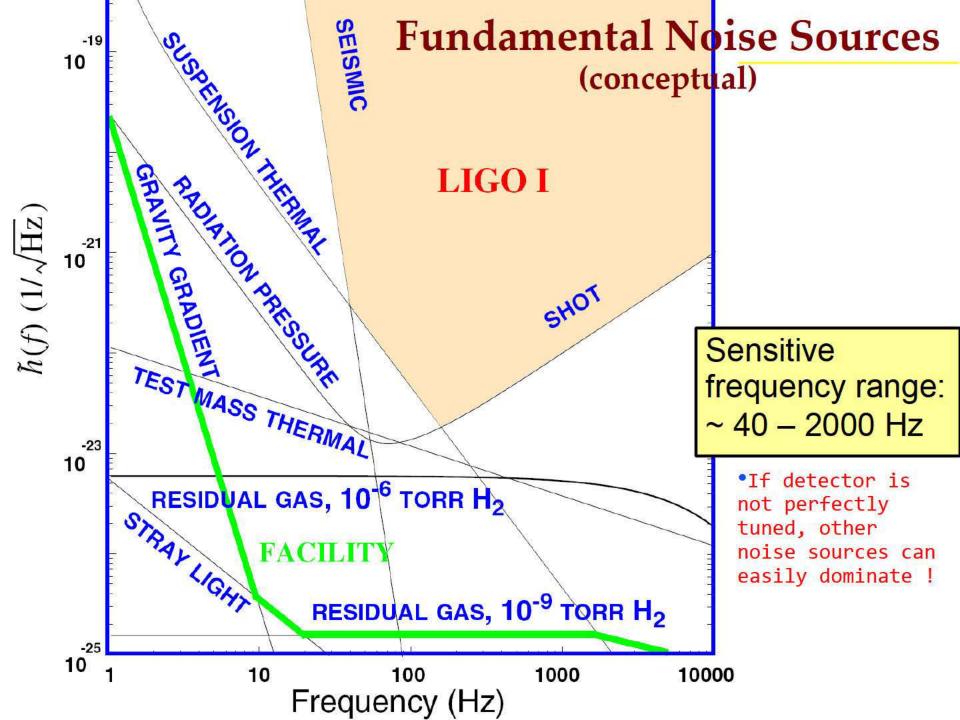
### iLIGO Optical Layout (not to scale)

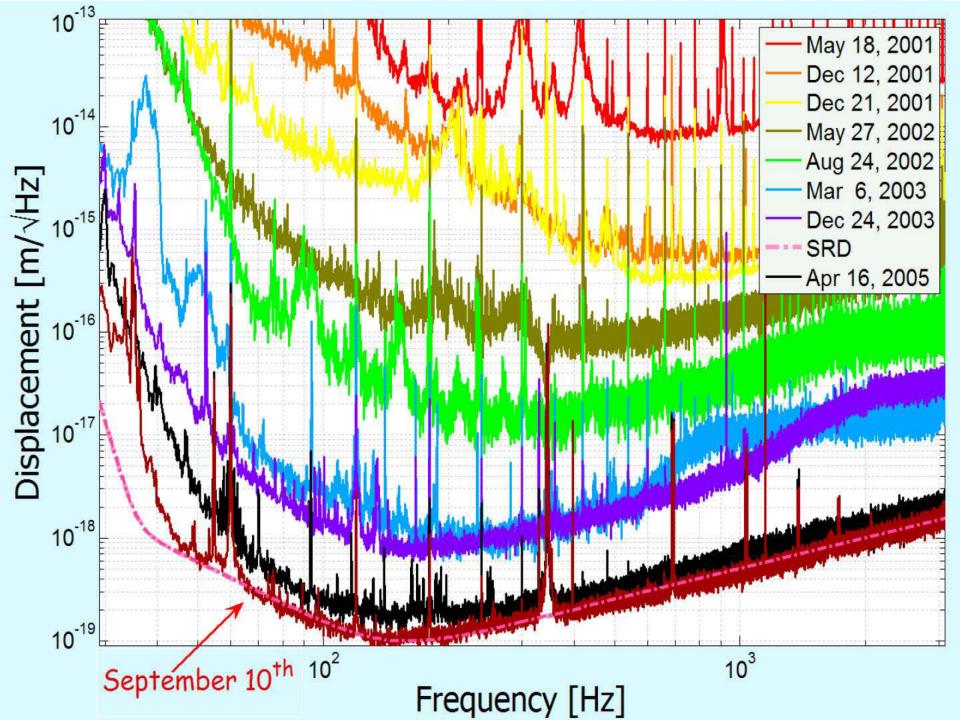




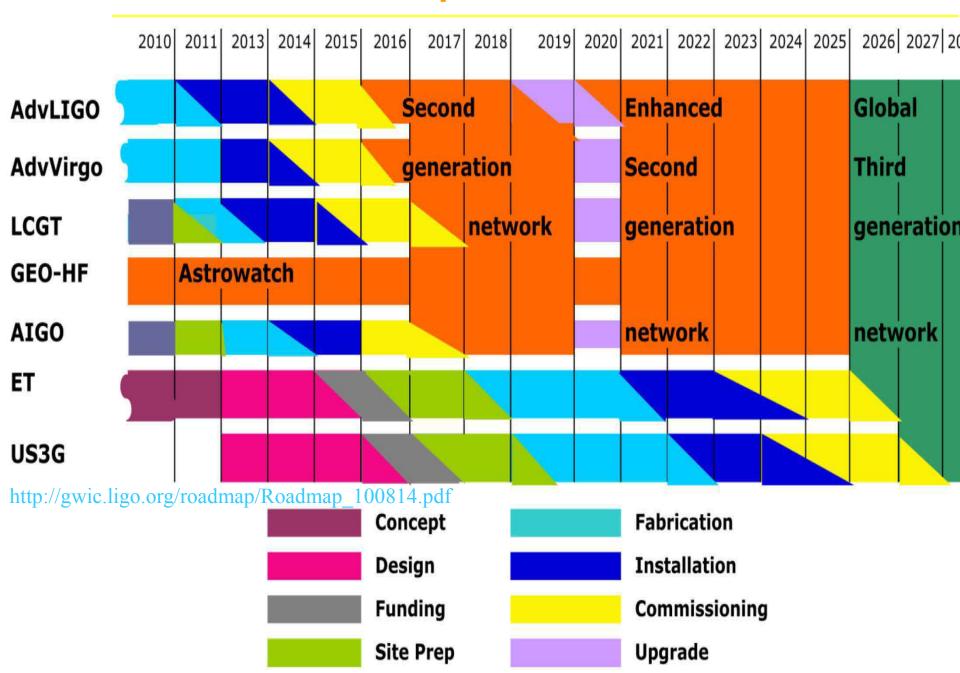
## Vacuum System

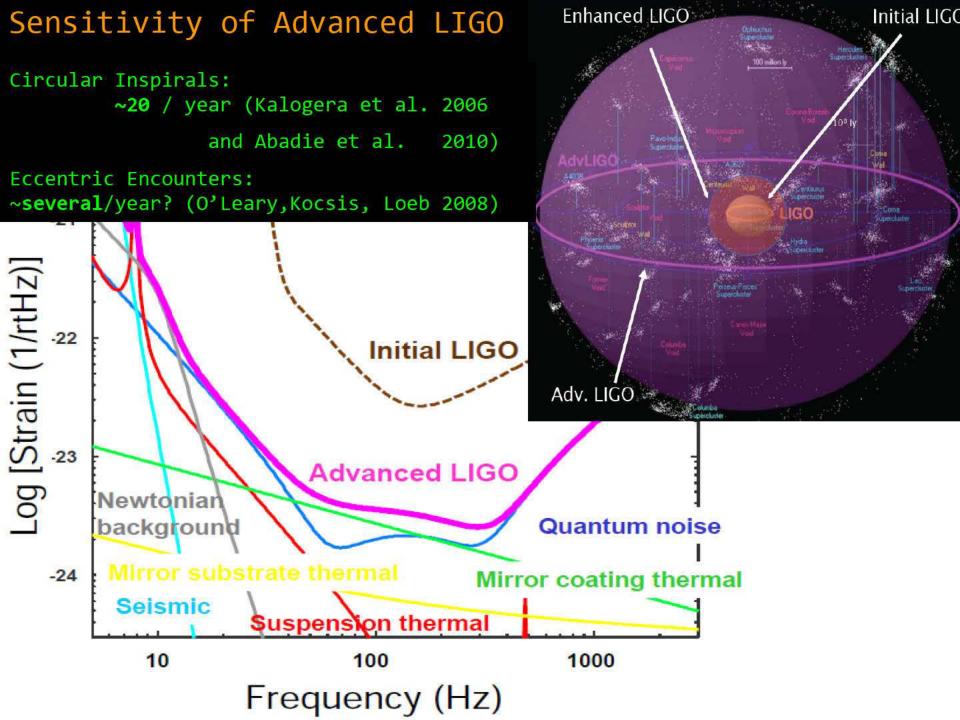






### Roadmap... Realistic...





#### Advanced LIGO

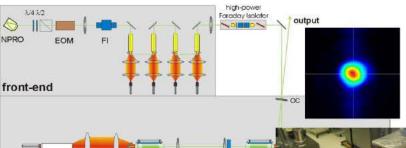
- Major upgrade of LIGO interferometers
- A factor of  $> \times 10$  improvement in strain sensitivity:  $> \times 10^3$  in detectable volume
- <1 day of AdvLIGO observation ≈ 1 year of current LIGO observation</p>
- Detect gravitational waves regularly... hope so!
- Installation: planned to start in 2010, Observation: planned to start in 2015

### Data Acquisition / Timing

http://iopscience.iop.org/0264-9381/27/8/084006

#### 180 W laser

high-power oscillator



Seismic isolation

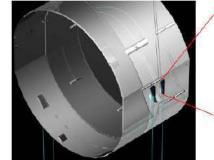


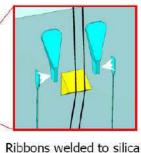




Mirror Suspensions

#### **Mirrors**

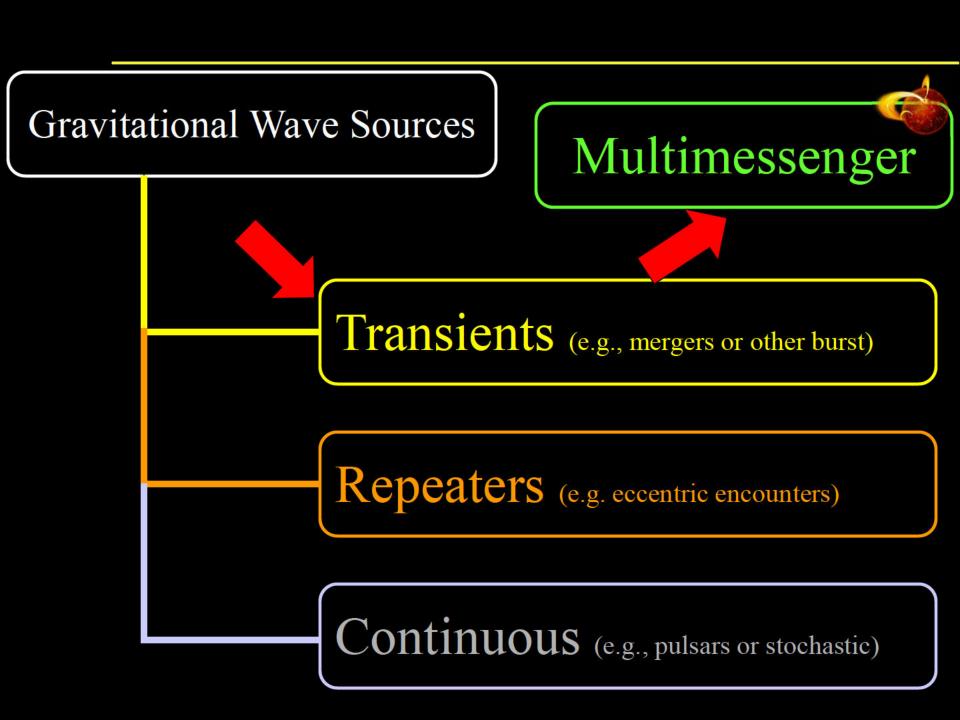




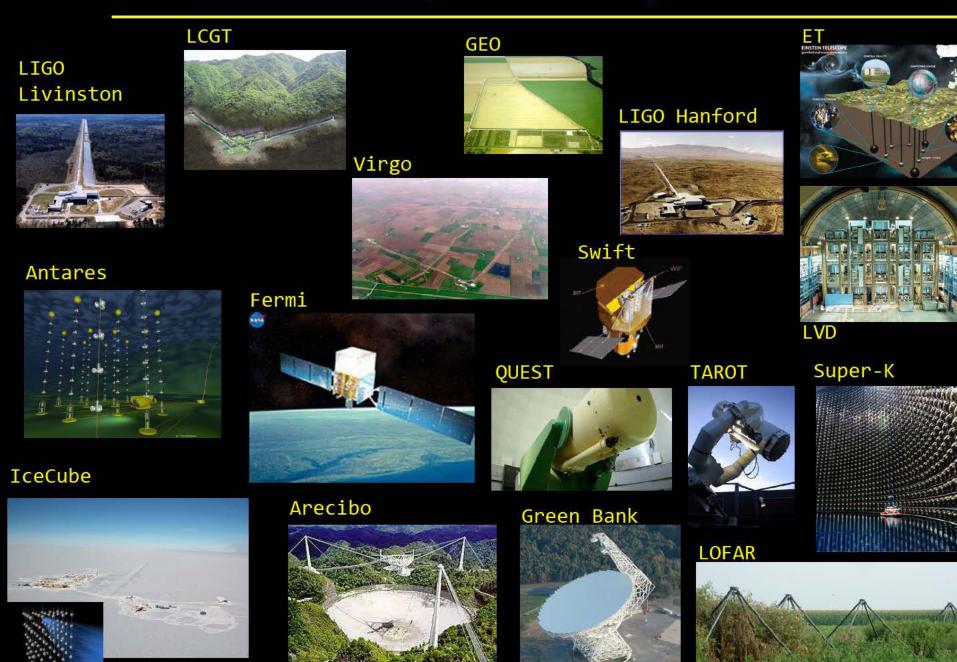
ears bonded to mass



 $\sqrt{\frac{3G\left(1+z\right)E_{\mathrm{GW}}}{\pi^{2}c^{3}\,S(f)}}\,\,rac{F_{\mathrm{rms}}}{
ho_{\mathrm{det}}f}$  Future Detectors-Rule of Thumb?  $D_{\rm L} \simeq$  $\approx$  5 Gpc  $(1+z)^{1/2} \frac{10}{\rho_{\text{det}}} \frac{100 \,\text{Hz}}{f} \left(\frac{E_{\text{GW}}}{10^{-2} M_{\odot} c^2}\right)^{1/2} \frac{2.5 \times 10^{-25} / \sqrt{\text{Hz}}}{S(f)^{1/2}}$ Virgo LIGO adv Virgo 1e-20 adv LIGO 1e-21 LCGT Amplitude 1e-22 Noise 1e-24 1e-25 100 1000 10 Kuroda et al, CQG, 2010 Frequency Eric Chassande-Mottin, GRG, 2010



### <u>Comprehensive</u> Multimessenger Studies



#### **Basic Glossary: Multimessenger Approaches**

"Multi-messenger astrophysics": connecting different kinds of observations of the same astrophysical event or system



"Looc-Up" strategy:

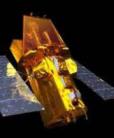


information

Flow of trigger Telescopes, Satellites

or other external entities

"ExtTrig" strategy:



Flow of trigger Telescopes, Satellites or other external entities information



#### Transient Multimessenger Astrophysics with GWs

- » Gamma-ray transients (GRBs, SGRs)
- » Optical transients
- » Neutrino events
- » Radio transients
- » X-ray transients
- »···
- > Correlation in time
- > Correlation in direction
- ➤ Information on the source properties, host galaxy, distance
- > ...
  - ✓ Confident detection of GWs.
  - ✓ Better background rejection ⇒ Higher sensitivity to GW signals.
  - ✓ More information about the source/engine.
  - ✓ Measurements made possible through coincident detection.

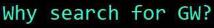


### Soft Gamma Repeaters (SGRs)

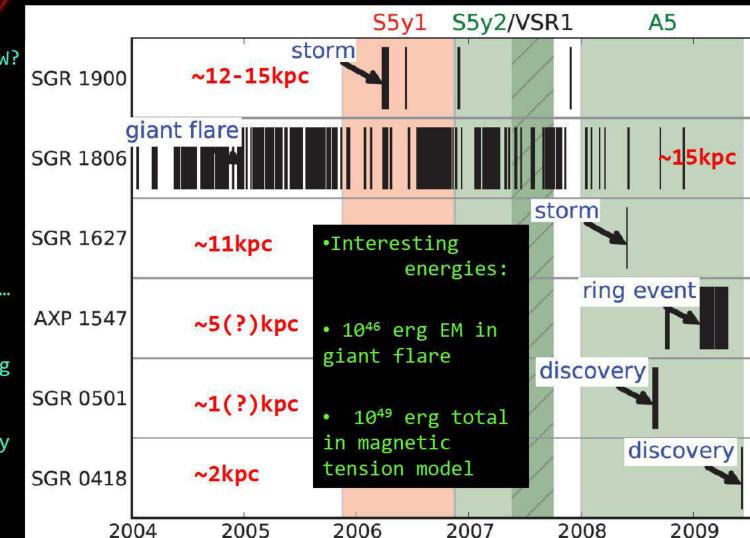
Exciting Models:

Highly magnetized (10 $^{15}$ G) neutron-stars…! Emitting  $\gamma$  flares sporadically…

[1] Ioka MNRAS 327, 639 (2001) [2] Corsi & Owen, LIGO-T0900242 VIR-NOT-ROM-028A-09 [3] Kalmus & Ott, LIGO-G1000046



- Time and direction is known...
- Close-by sources!
- Observed QPOs...
- Some models predict strong GW emission...
- GW sensitivity
   in ~ 10<sup>44</sup>-10<sup>48</sup>
   erg range...



#### **Soft Gamma Repeater - GW results**

PRD, 80, 042001, 2009 CQG, 24, 659, 2007



Long-lived quasiperiodic GWs after giant flare ?

December 2004 giant flare of SGR 1806-20

Searched for GW signals associated with X-ray QPOs

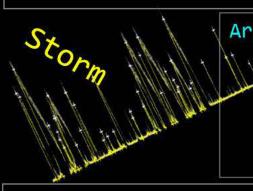
GW energy limits are comparable to total EM energy
emission -> Abbott et al., PRD 76, 062003 (2007)

#### Are there GW bursts at times of SGR flares ?

2004 giant flare plus 188 other flares from SGR 1806-20 and SGR 1900+14 during first calendar year of LIGO S5 run (First search for neutron star f-modes ringing down ( $\sim$ 1.5-3 kHz, 100ms), also for arbitrary lower-frequency transients...) For certain assumed waveforms, GW energy limits are as low as  $3\times10^{45}$ erg, comparable to EM energy emitted in giant flares



-> Abbott et al., PRL 101, 211102 (2008)



Are repeated GW bursts associated with multiple flares?

"Storm" of flares from SGR 1900+14 on 29 March 2006

"Stack" GW signal power around each EM flare. Gives perburst energy limits an order of magnitude lower than the individual flare analysis for the storm events

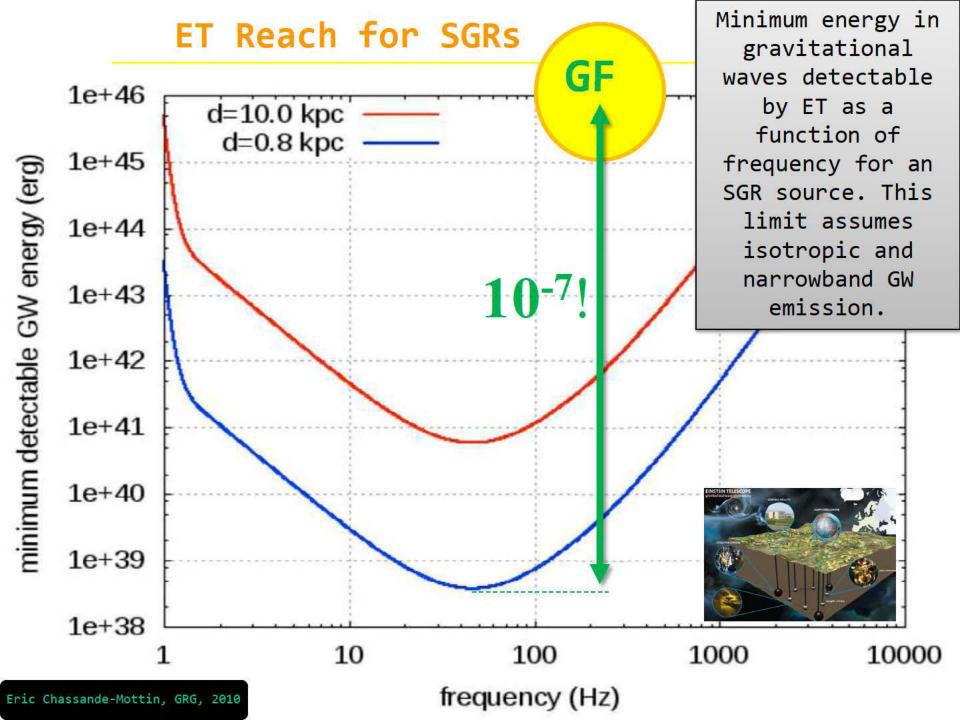
-> Abbott et al., ApJ 701, L68 (2009)

Can we see gravitational waves from newly discovered close-by SGRs ?

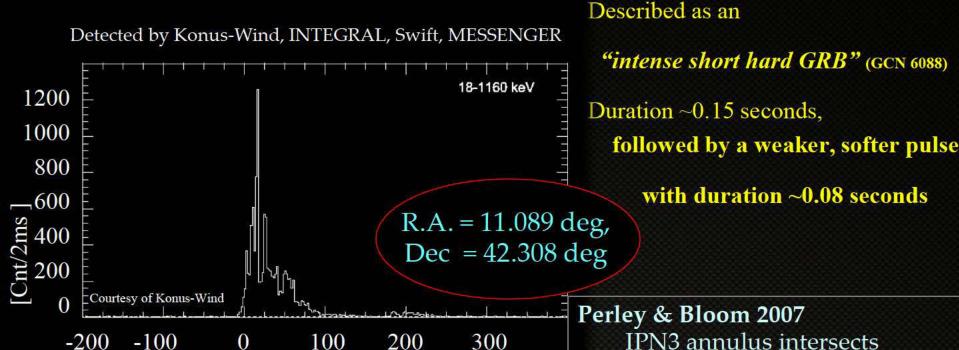
SGR 0501+4516 and SGR 0418+5729 are 5-10x closer than SGR 1806-20

and SGR 1900+14... our GW energy scales as distance<sup>2</sup>... stay tuned!

-> Abadie et al., LIGO-P0900192 TBS(ApJL)



#### EM Observations - GRB 070201



#### Antenna responses of LIGO Hanford:

$$F_{RMS} = \sqrt{F_+^2 + F_\times^2} / \sqrt{2} = 0.304$$

Time  $-T_0$  [ms]

$$h(t) = F_{+}(\theta, \phi, \psi)h_{+}(t) + F_{\times}(\theta, \phi, \psi)h_{\times}(t)$$

IPN3 annulus intersects

spiral arms of the M31

Hurley et al. 2007, Pal'Shin 2007 refined error box, ≈ 1.1° from the center of M31 still overlaps with the spiral arms

Mazets et al. 2007 Final error box still overlaps M31

#### GRB 070201 - Sky Location

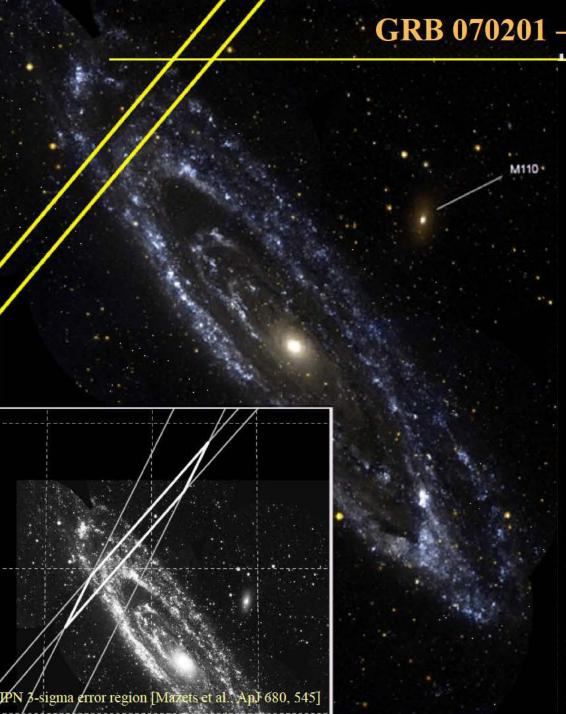
R.A. = 11.089 deg, Dec = 42.308 deg

### $D_{M31} \approx 770 \text{ kpc}$

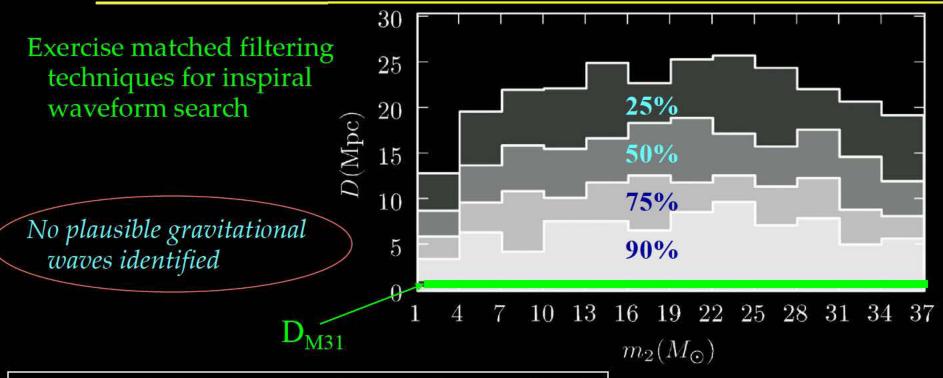
Possible progenitors for short GRBs:

- NS/NS or NS/BH mergers
  Emits strong gravitational waves
- SGR
  May emit GW but weaker

 $E_{iso} \sim 10^{45}$  ergs if at M31 distance



#### Model Based Compact Binary Inspiral Search 070201



Abbott, B. et al. (2008), Astrophysical Journal, 681 . pp. 1419-1430

**Exclude** compact binary progenitor with masses  $1 \text{ M}_{\odot} < \text{m}_1 < 3 \text{ M}_{\odot}$  and  $1 \text{ M}_{\odot} < \text{m}_2 < 40 \text{ M}_{\odot}$  with D < 3.5 Mpc at 90% CL

**Exclude** any compact binary progenitor in our simulation space at the distance of M31 at > 99% confidence level

→ SGR giant flare in M31 ?... (e.g., Mazets et al., ApJ 680, 545; Ofek et al., ApJ 681, 1464)

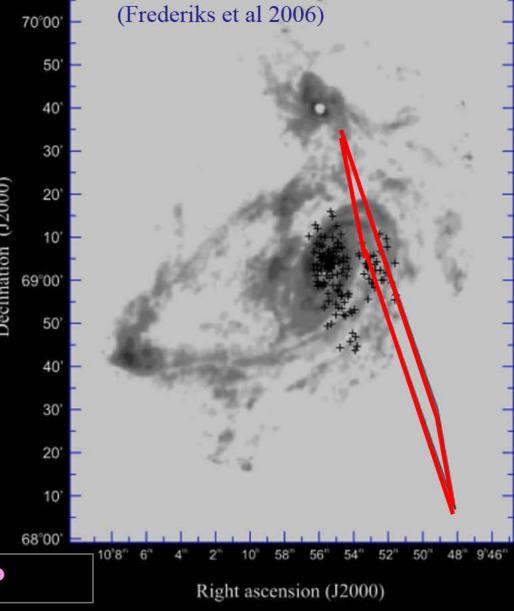
These coincidences do happen from time to time... the 070201 result created a new trend...

#### GRB 051103

Sky position error box overlaps with

### M81 group

~3.6 Mpc



#### Extragalactic SGR...?

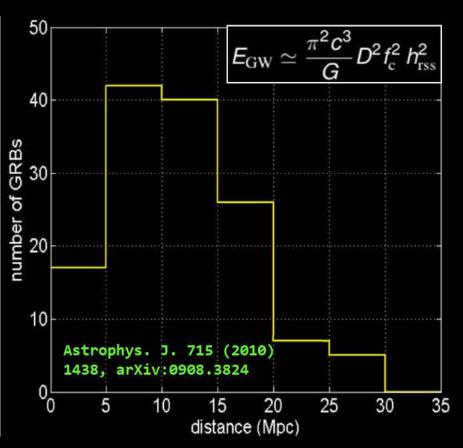
Fig. 4.— The 21 cm HI emission map of the central region of the M81 group of interacting galaxies. M81 at the center; M82 ~ 35' to the north; and NGC 3077 ~ 40' to the east and ~ 20' to the south. X-ray sources (crosses) observed by Chandra, and IPN box of GRB 051103 are superimposed.

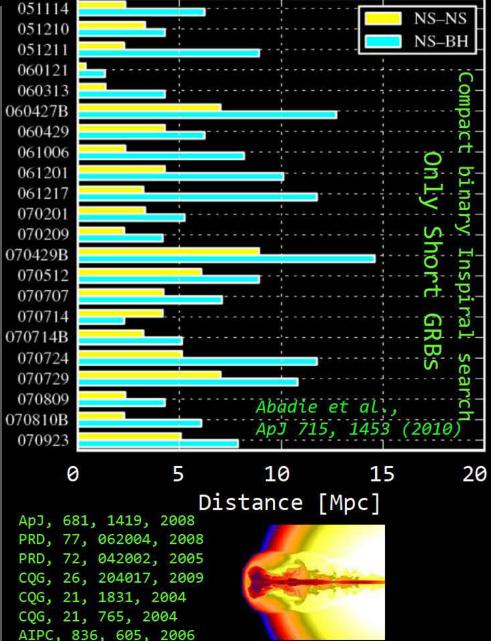
#### Search for Gamma-Ray Bursts during S5/VSR1 Lower Limits on Source distances

# Short Transients Q=8.9, sine-gaussians f=150Hz, $E_{\text{GW}} \equiv 0.01 \text{ M}_{\odot}$

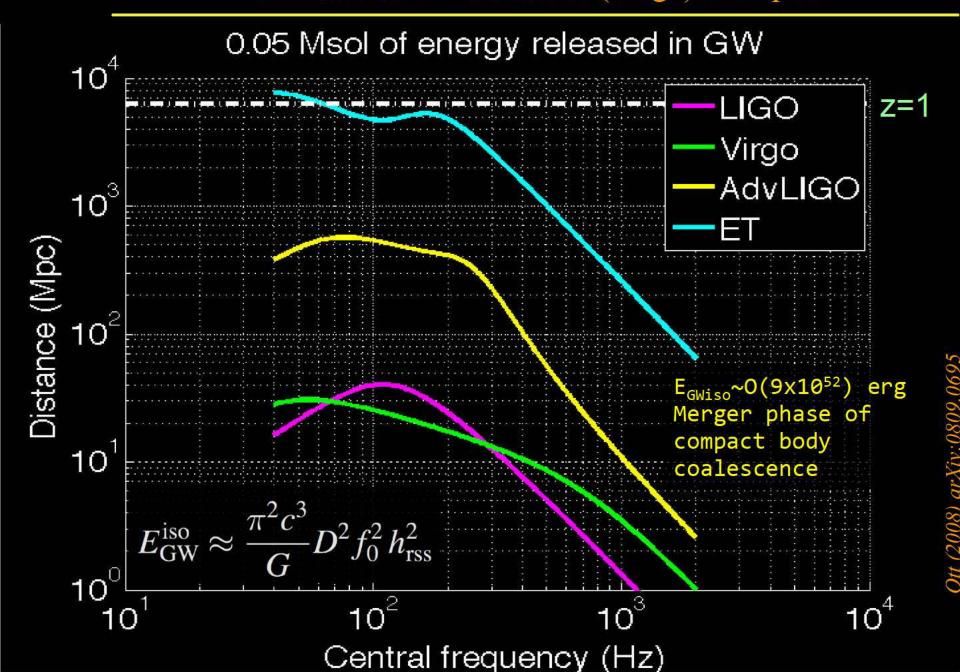
Histogram of lower limits on source distances

- 137 GRBs in the X-Pipeline analysis
- derived from upper limits on GW energy





#### Unmodeled GW transients (rough) examples



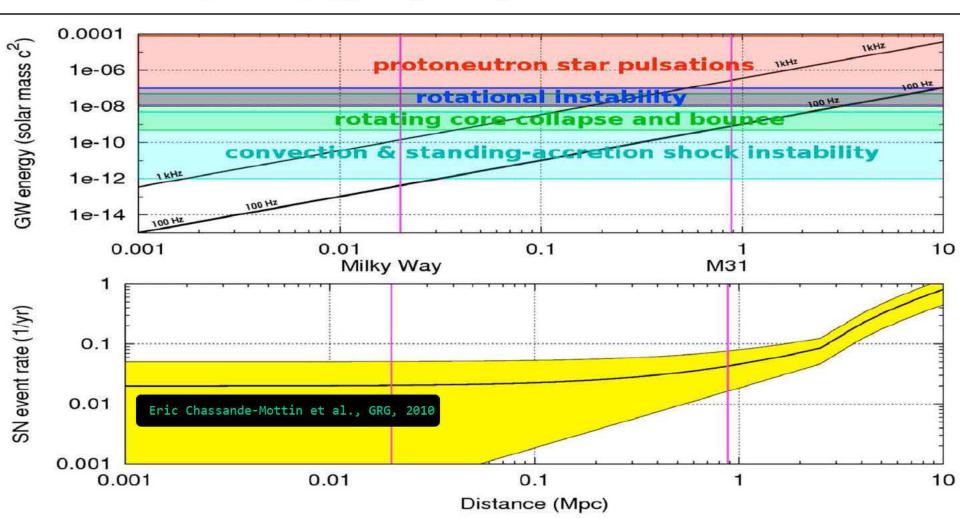
#### Supernovae, GW, Neutrinos and ET?

 $-N \simeq 4.6 \left(\frac{50 \,\mathrm{kpc}}{D}\right)^2 \left(\frac{M}{1 \,\mathrm{kt}}\right)$ 

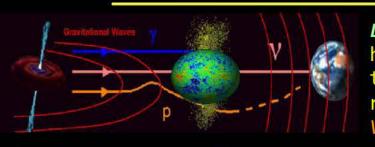
~5 Mt proposed Deep-TITAND neutrino detector:

N ~1 reach is about ~8 Mpc ← Reasonable to expect

**~one** such event during the lifetime of ET.



#### Some GW+HEN source candidates



Long GRBs: In the prompt and afterglow phases, high-energy neutrinos (10<sup>5</sup>-10<sup>10</sup> GeV) are expected to be produced by accelerated protons in relativistic shocks (e.g., Waxman & Bahcall 1997; Vietri 1998; Waxman 2000).

Short GRBs: HENs can also be emitted during binary mergers (Nakar 2007; Bloom et al. 2007; Lee & Ramirez-Ruiz 2007).

Low-Luminosity GRBs: Associated with particularly energetic population of core-collapse supernovae (Murase et al. 2006; Gupta & Zhang 2007; Wang et al. 2007). Local event rate can be significantly larger than that of conventional long GRBs (Liang et al. 2007; Soderberg et al. 2006).

"Choked" GRBs: Plausibly from baryon-rich jets. Optically thick, can be hidden from conventional astronomy, neutrinos and GWs might be able to reveal their properties (Ando & Beacom (2005), Razzaque et al. 2004; Horiuchi & Ando 2008).

		SN	"Failed" GRB	GRB
	Energy	10 <sup>51</sup> erg	10 <sup>51</sup> erg	10 <sup>51</sup> erg
F	Rate/gal	~10 <sup>-2</sup> yr <sup>-1</sup>	10 <sup>-5</sup> –10 <sup>-2</sup> yr <sup>-1</sup>	~10 <sup>-5</sup> yr <sup>-1</sup>
	ſ	~	~3–100	~100–103
taken 1	from Ando (2	Barion rich Nonrelativistic Frequent	Similar kinetic energy	Baryon poor Relativistic jets Rare

missing link between SN and GRB?

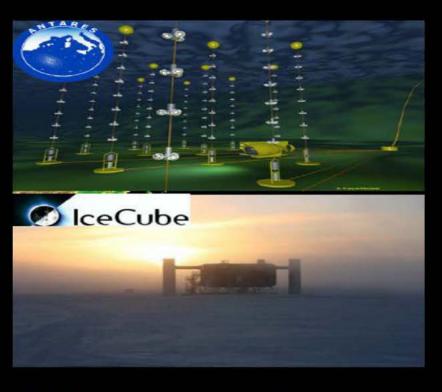
## Event candidate position reconstruction example: LIGO+Virgo vs. IceCube

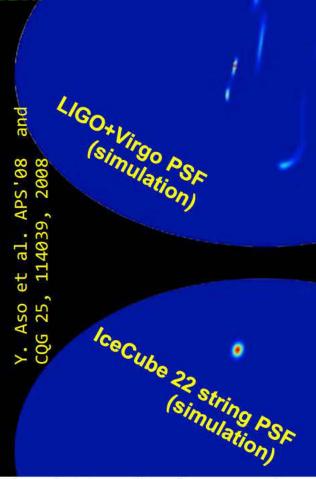
#### LIGO + Virgo:

Triple coincidence

Improved "point" spread function

Reduced coincident noise

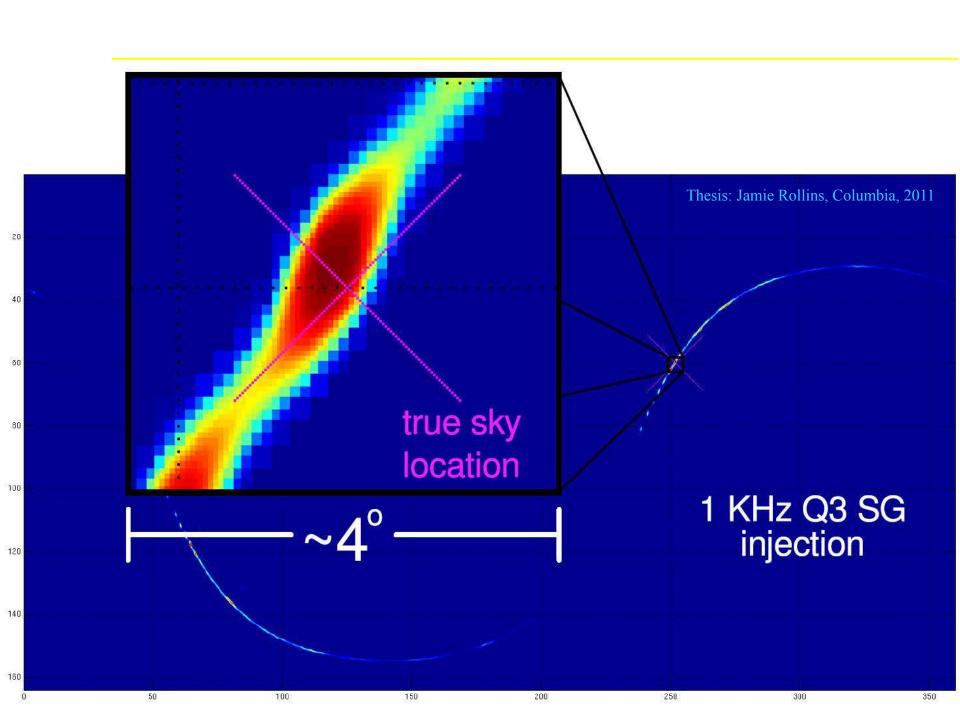




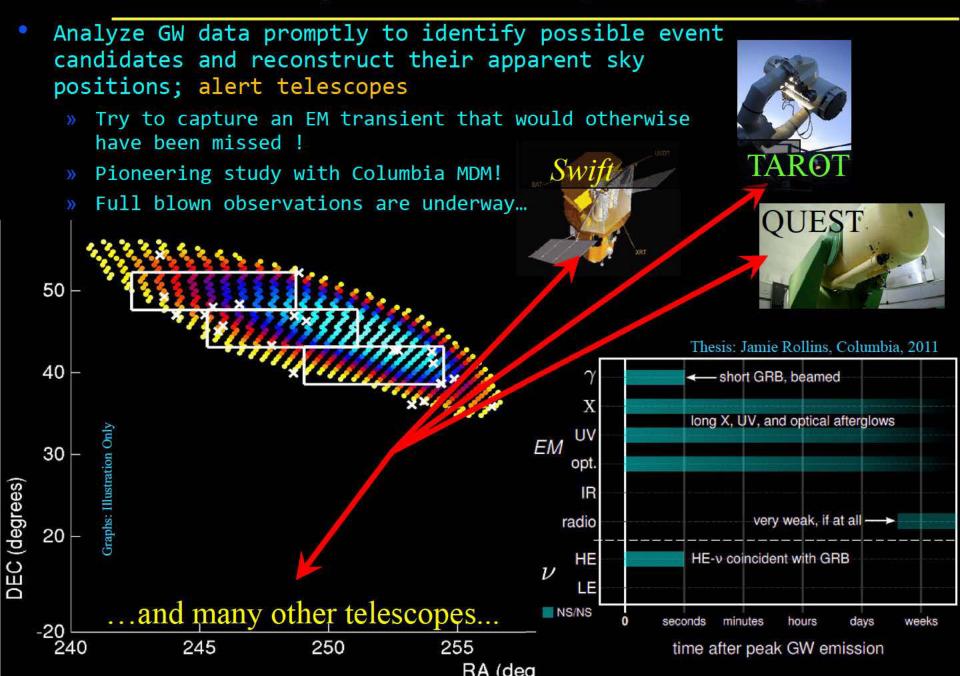
IceCube-Virgo-LIGO May 5, 2010

#### LIGO + Virgo + IceCube:

FalseAlarmRate = 
$$\frac{1}{600} \left( \frac{p}{1\%} \right) \left( \frac{T_{\text{w}}}{1 \text{sec}} \right) \left( \frac{R_{\text{gw}}}{1/\text{day}} \right) \left( \frac{R_{\nu}}{20/\text{day}} \right) \text{ per year}$$



#### Electromagnetic Follow-Ups to GW Triggers



## Open Questions for Multimessenger Observations with Gravitational Wave Detectors? Oh... YES!

- 1. What is the speed of gravitational waves, subluminal or superluminal?
- 2. Does Einstein's theory of general relativity remain valid in the strong field regime?
- 3. Does gravity violate parity?
- 4. Is there a new length scale beyond which general relativity is modified?
- 5. Which alternative gravity theories can be excluded experimentally?
- 6. How often can an unidentified electromagnetic transient be explained by a gravitational wave emitter?
- 7. Is there a high redshift population of intermediate mass black holes?
- 8. Can gravitational waves help in explaining the origin of Ultra-Luminous X-ray binaries?
- 9. Can we search for new physics in the ultra-weak field regime?
- 10. Can a massive graviton serve as a cold-dark-matter candidate ?
- 11. What fraction of the cosmic source's energy is emitted in the form of gravitational waves?

## Open Questions for Multimessenger Observations with Gravitational Wave Detectors? Oh... YES !

- 12.Can gravitational wave detectors provide an early warning to electromagnetic observers to allow the detection of early light curves ?
- 13. Do gravitational measurements of distance agree with the concordance cosmology?
- 14. What is the mass spectrum and spin distribution of black holes?
- 15. Are there extra gravitational wave polarizations?
- 16.Is there a significant non-axisymmetric crust or core dynamics associated with SGRs?

## Open Questions for Multimessenger Observations with Gravitational Wave Detectors? Oh... YES!

- 17. What is the precise origin of SGR flares ? (e.g., What is the mechanism for GW and EM emission and how are they correlated?)
- 18. Is there a fundamental difference between giant and common SGRs?
- 19. Do quark stars exist?
- 20. Can we exclude or confirm some of the SGR models?
- 21. What is the origin of pulsar glitches?
- 22. What is the composition and structure of neutron stars and their cores?
- 23. What is the tallest mountain that can be supported by neutron stars?
- 24. Can we use GW-EM observations to guide or EM+null GW results to distinguish the local extragalactic SGR contributions from the short GRB population?

## Open Questions for Multimessenger Observations with Gravitational Wave Detectors? Oh... YES !

- 25. What is the nature of gravitational collapse?
- 26. What is the relationship between the supernova progenitor and remnant (e.g., final mass and spin)?
- 27. If the supernova remnant is not a black hole, how does it behave? (e.g., a transient hypermassive remnant with unstable modes or collapse to a BH?)
- 28. What happens in a core collapse supernova before the light and neutrinos escape?
- 29. What is the delay in between neutrinos and gravitational waves in a core collapse supernovae?
- 30. What is the role of anisotropic neutrino emission in supernovae?
- 31. What is the mass of a neutrino?
- 32. Can we see core collapse supernovae in gravitational waves that are not visible in neutrinos?
- 33. Is there an electromagnetically hidden population of core collapse events?
- 34. How many dynamical scenarios are associated with core collapse supernovae? Can we distinguish between them?
- 35. Can pulsar birth kicks result in detectable gravitational waves?

## Open Questions for Multimessenger Observations with Gravitational Wave Detectors? Oh... YES!

- 25.What is the time delay between the electromagnetic brightening and the core collapse of a supernova?
- 26. What are the properties of the core collapse supernova progenitor?
- 36. What is the role of the rotation and magnetic fields in stellar core collapse?
- 37. What is the origin of long and short GRBs? What is the precise dynamics of each GRB engine?
- 38. Is there any longer-lasting central engine left over from the GRB explosion, and what's its nature?
- 39. Are there electromagnetically hidden populations of GRBs?
- 40. Does the hypothesized low luminosity GRB population exist?
- 41. Can we have direct inferences on the GRB jet parameters from gravitational waves?
- 42. Can we estimate properties of the nuclear equation state using short GRBs?
- 43. Can we relate the luminosity distribution of GRBs to beaming and the central engine mechanism?

## Open Questions for Multimessenger Observations with Gravitational Wave Detectors? Oh... YES !

- 25.What is the relationship between the parameters of a compact binary system and it's electromagnetic and neutrino emission?
- 26. What GRB progenitor models can we confirm or reject?
- 27. Are there other (sub)classes of GRBs? Do choked GRBs exist? What is the origin of choked GRBs? Cosmic population of choked GRBs?
- 44. What are the engines producing high energy neutrino and gravitational wave emission together?
- 45. What is the dynamics/energetics of joint high energy neutrino and gravitational wave emitters?
- 46. What is the electromagnetic emission of binary neutron star coalescence?
- 47. What is the electromagnetic emission of a neutron star-black hole coalescence?
- 48. Is there any electromagnetic emission from binary black hole coalescence?
- 49. What is the nature of XRFs and their relationship to long GRBs?
- 50. Is it possible to construct a competitive Hubble diagram based on gravitational wave standard sirens?
- 51. ...
- ... and dozens(???) of other exciting questions are waiting to be answered by the community!

### Exciting Exploratory Science!

 There is a bold and fruitful effort underway to get a new window on the universe



- Astrophysical results published
  - ☐ SGR1806-20
  - GRB070201
  - and others ...



- Advanced Virgo, aLIGO and GEO-HF are around the corner...
- LCGT received substantial funding!
- ET is being defined...

... the excitement is high!

So much fun and discovery is awaiting us!

#### What about answering the Big Questions ...?

Questions for fundamental physics and general relativity...

Can we detect Shapiro time-delay in the lab for small masses?

What are the properties of gravitational waves?

Is general relativity the correct theory of gravity?

Is general relativity still valid under strong-gravity conditions?

Are Nature's black holes the black holes of general relativity?

How does matter behave under extremes of density and pressure?

#### Questions for astronomy and astrophysics...

How abundant are stellar-mass black holes?
What is the central engine behind gamma-ray bursts?
Do intermediate mass black holes exist?
Where and when do massive black holes form?
What happens when a massive star collapses?
Do spinning neutron stars emit gravitational waves?

What is the distribution of neutron star binaries in the galaxy?

How massive can a neutron star be?

Can we probe neutron star interiors with gravitational waves?

#### Questions for cosmology

What is the history of the accelerating expansion of the Universe? Were there phase transitions in the early Universe?

