Multimessenger Astronomy with the Einstein Telescope

Martin Hendry

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SUPA, Dept of Physics and Astronomy, University of Glasgow

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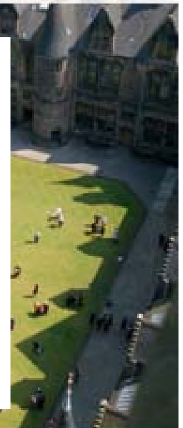
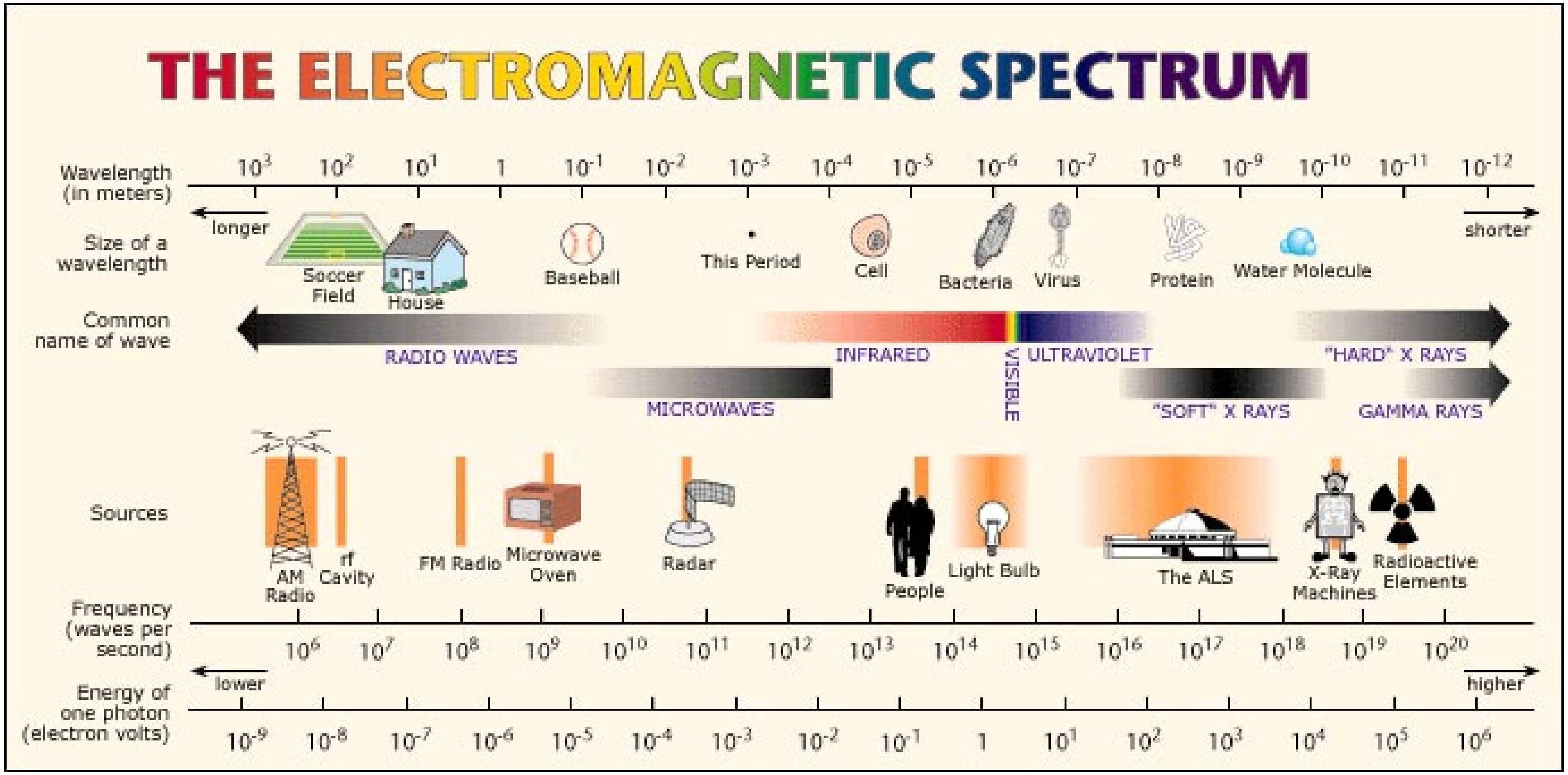
With thanks to:

Eric-Chassande Mottin, APC, Paris
Patrick Sutton, Cardiff University
Szabolcs Marka, Columbia University

See also: gr-qc/1004.1964, GRG in press





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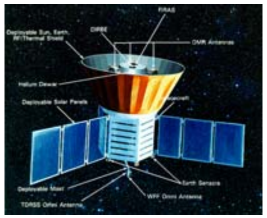

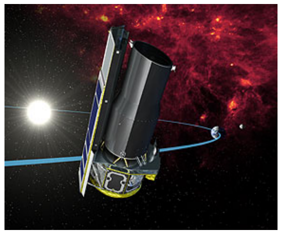

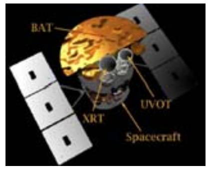

BAT
XRT
UVOT
Spacecraft

Why Multi-messenger Astronomy?

A multi-messenger approach is very important for GW astronomy, and can:

- increase confidence in GW detections and optimise search strategies
- answer specific questions about emission mechanisms, as well as harness sources as astrophysical probes.

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Aim of this talk:

Brief preview of multi-messenger science opportunities, in the ET era, assuming "ET-B" spec. (Punturo et al 2010)

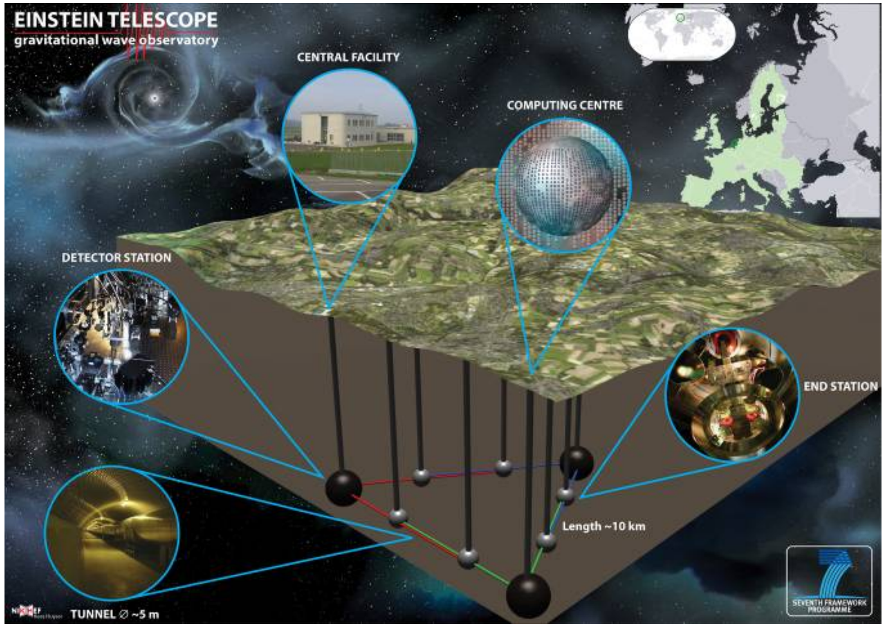
Prospects for the Einstein Telescope…

Third Generation Network — Incorporating Low Frequency Detectors

- Third-generation underground facilities are aimed at having excellent sensitivity from ~1 Hz to ~10^4 Hz.
- This will greatly expand the new frontier of gravitational wave astrophysics.

FP7 European design study, with EU funding, underway for a 3rd-generation gravitational wave facility, the **Einstein Telescope** (ET).

Goal: **100 times** better sensitivity than first generation instruments.



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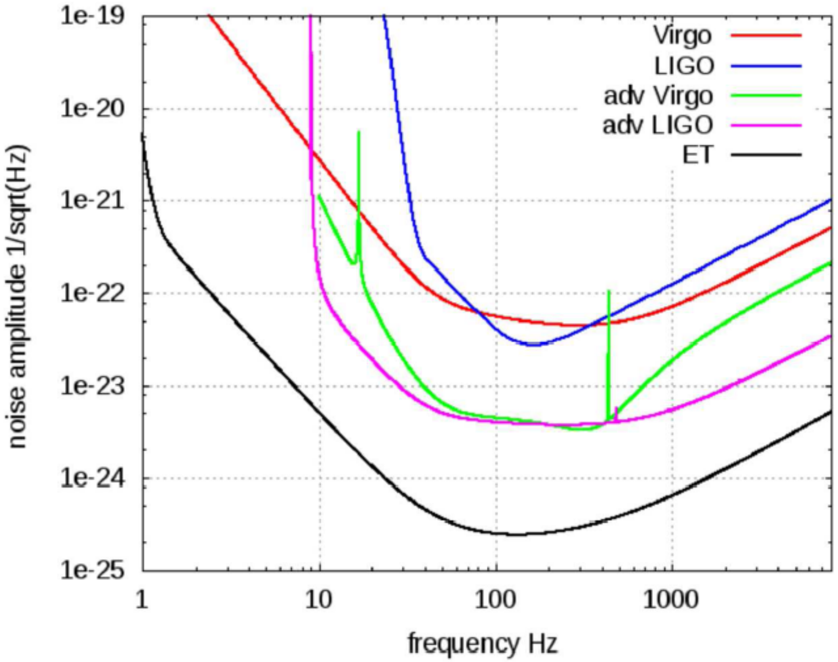


Current multi-messenger approach

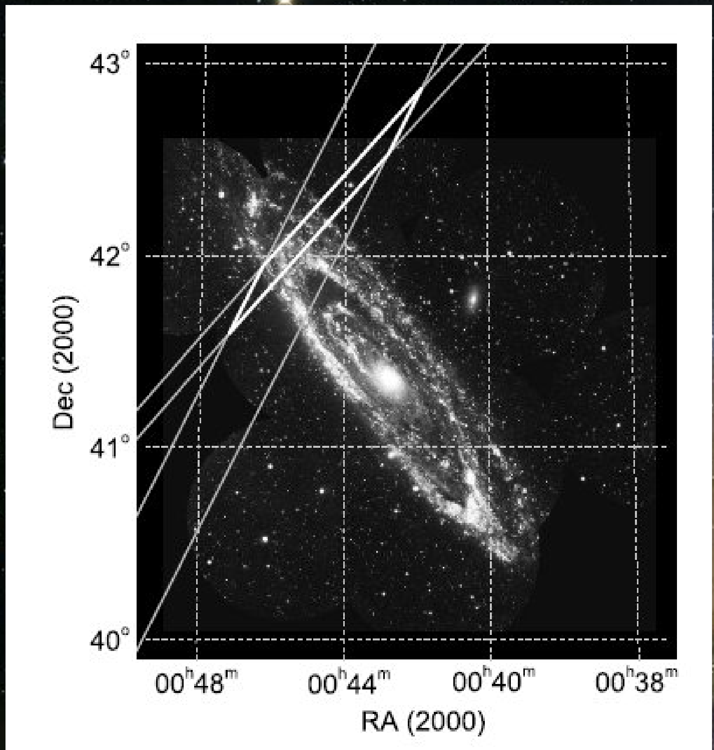
Mode of interaction: **E-M** observation triggers GW search

(see e.g. Abbott et al 2008)

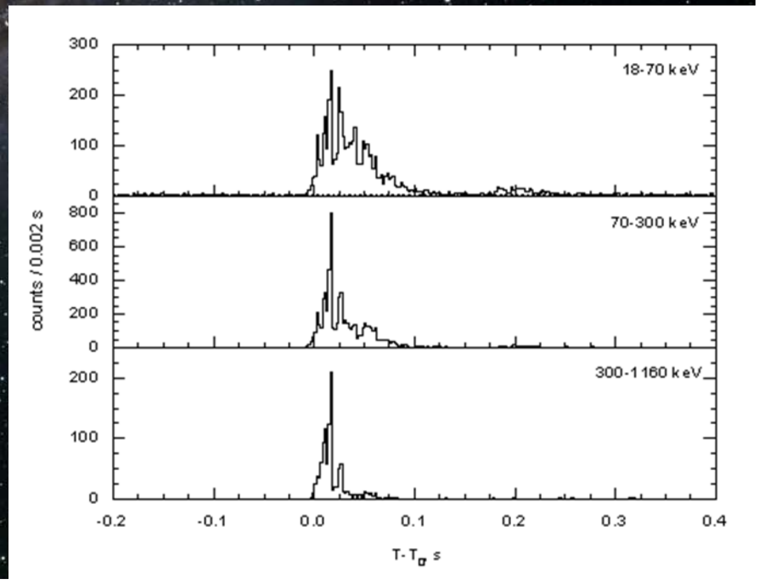
Approach adopted in many searches by ground-based detectors, particularly resulting from gamma-ray and/or x-ray observations.

Example: GRB070201, *Not a Binary Merger in M31*

Refs:
GCN: http://gcn.gsfc.nasa.gov/gcn3/6103.gcn3



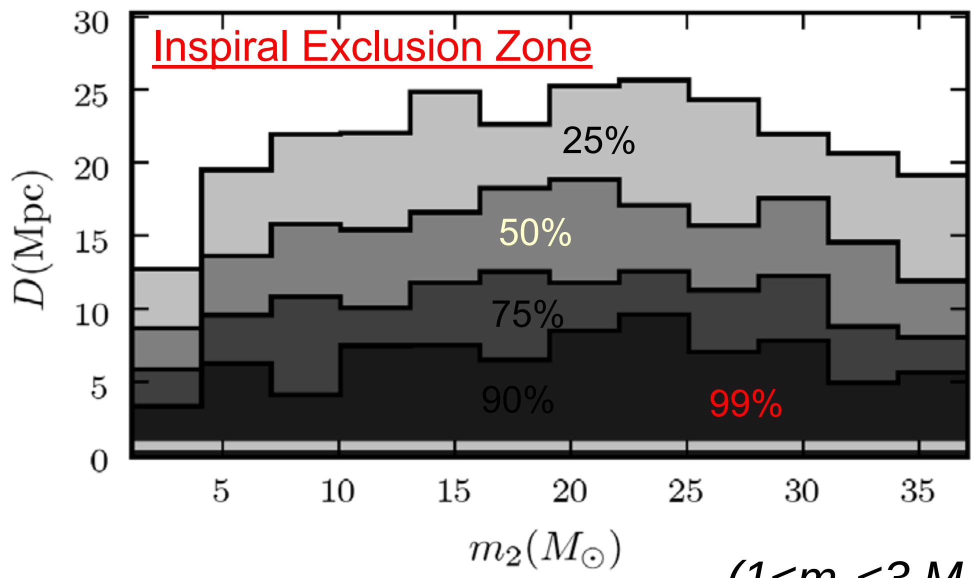
X-ray emission curves (IPN)



Example: GRB070201, *Not a Binary Merger in M31*

- **Inspiral (matched filter search:**
  - **Binary merger in M31 scenario excluded at >99% level**
  - **Exclusion of merger at larger distances**

Abbott, et al. "Implications for the Origin of GRB 070201 from LIGO Observations", Ap. J., 681:1419–1430 (2008).



($1<m_1<3\ M_{sun}$)

- **Burst search:**
  - **Cannot exclude an SGR in M31**

SGR in M31 is the current best explanation for this emission

Current multi-messenger approach

Mode of interaction: **E-M** observation triggers GW search

(see e.g. Abbott et al 2008)

Approach adopted in many searches by ground-based detectors, particularly resulting from gamma-ray and/or x-ray observations.

E-M trigger mode natural:

- GW detector networks all-sky monitors, low angular resolution
- GW detectors operate at **low data rate**, O(10^4 samples/sec).
  → all data archived. (c.f. LOFAR, SKA)
- EM observations highly directional, with FOV of arcminutes or less

Future multi-messenger approach?

Nascent efforts towards GW triggers:

Bloom et al (2009)

Kanner et al. (2008)

arXiv:0902.1527v1 [astro-ph.CO] 10 Feb 2009

Coordinated Science in the Gravitational and Electromagnetic Skies

A Whitepaper Submitted to the Decadal Survey Committee

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Science Frontier Panels:

PRIMARY: Cosmology and Fundamental Physics (CFP)
SECONDARY: Stars and Stellar Evolution (SSE)
Galaxies across Cosmic Time (GCT)

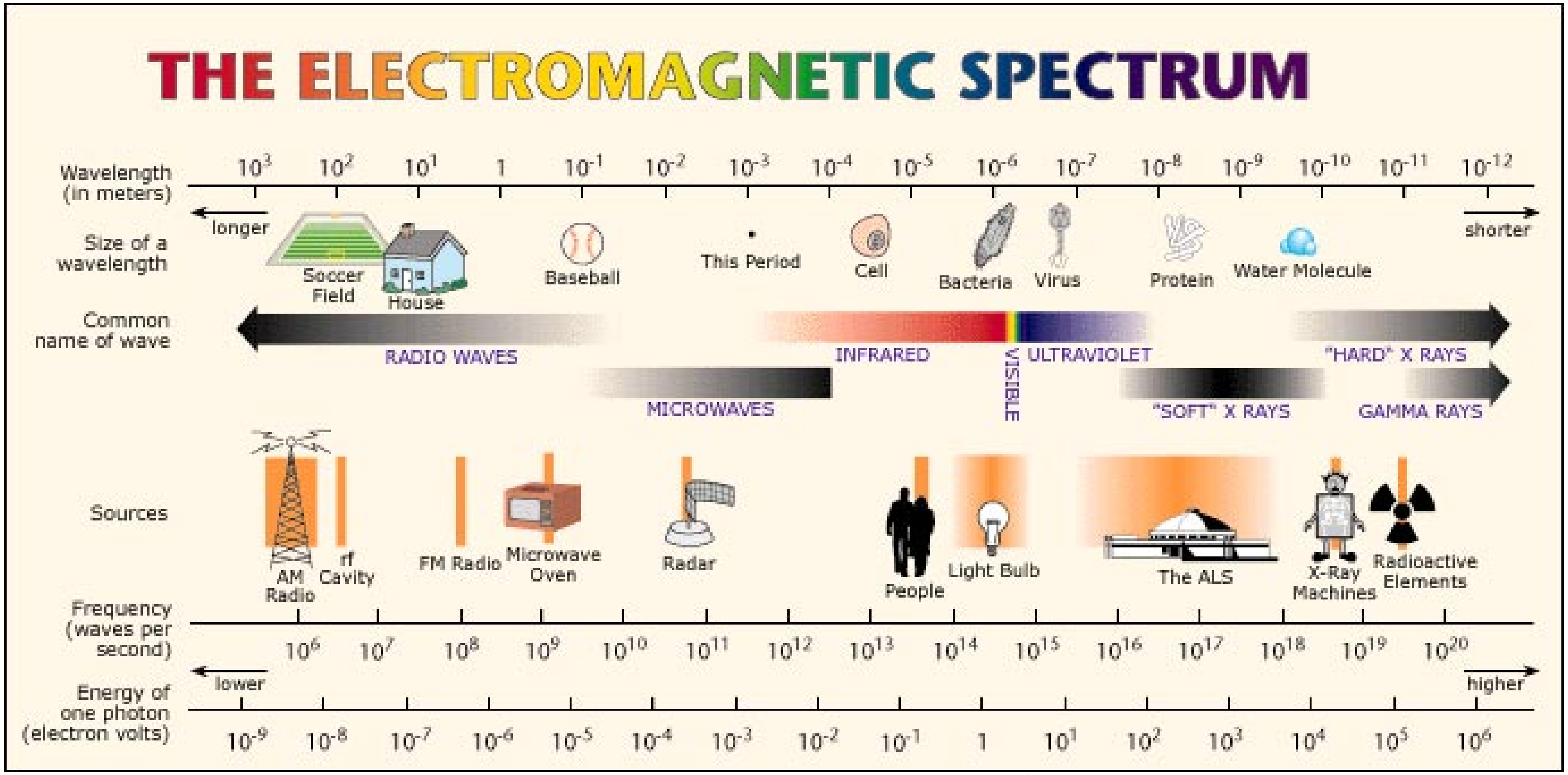
Projects/Programs Emphasized:

1. The Energetic X-ray Imaging Survey Telescope (EXIST); http://exist.gsfc.nasa.gov
2. The Synoptic All-Sky Infrared Imaging Survey (SASIR); http://sasir.org
3. The Large Synoptic Survey Telescope (LSST); http://lsst.org
4. The Laser Interferometer Space Antenna (*LISA*); http://lisa.nasa.gov

In the ET era, we can expect GW detections as a routine occurrence

⇒ *both* ***E-M*** → ***GW***

and ***GW*** → ***E-M***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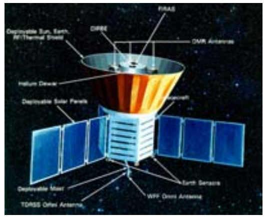

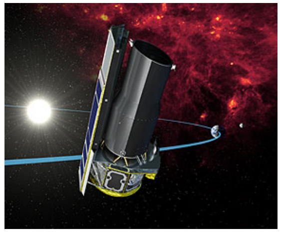

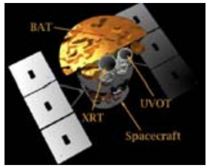
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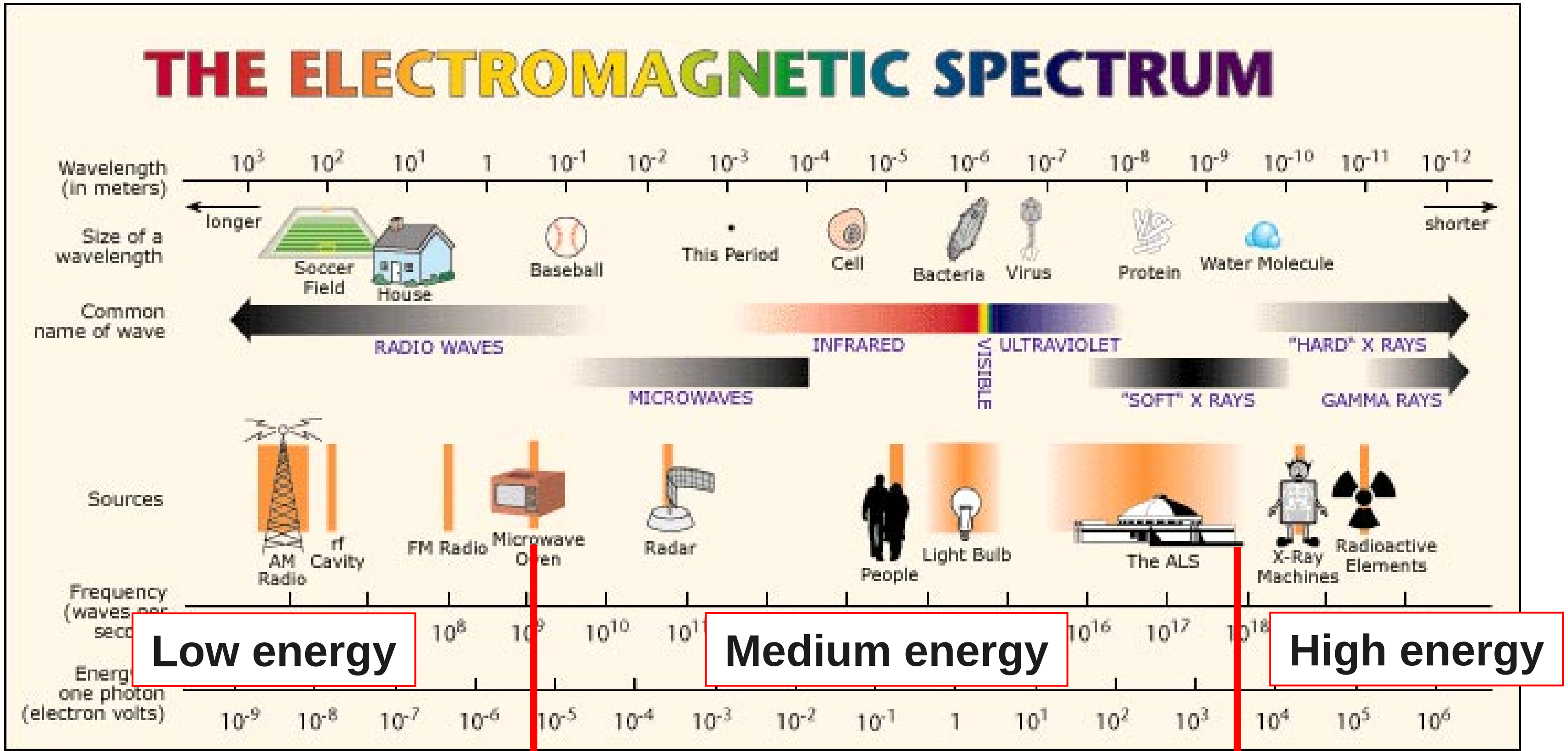
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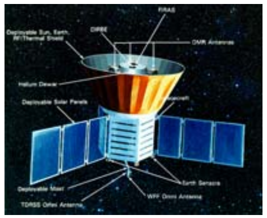
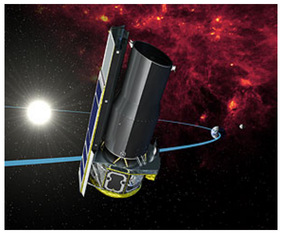
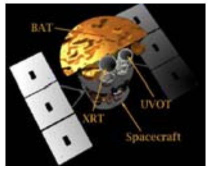






High Energy Photons

Several types of potential source:

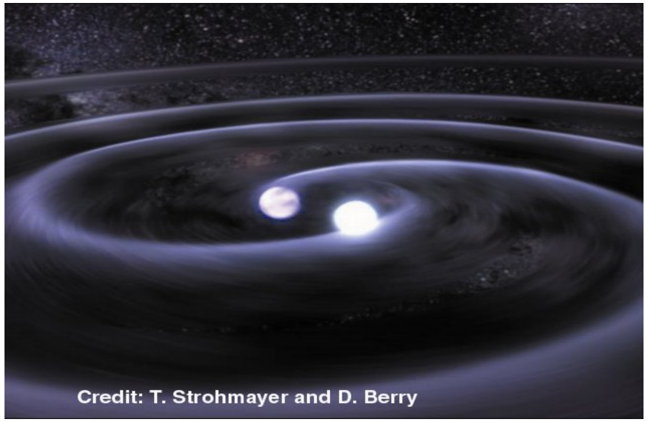
- Gamma ray bursts
- Soft gamma repeaters
- Ultra-luminous X-ray sources
- Micro-quasar flares

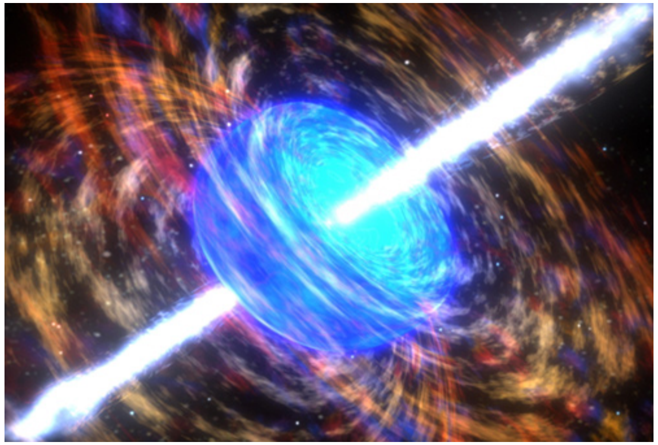
Wide range of relevant astrophysical questions

Science goals of the gravitational wave field

Astronomy and astrophysics

- How abundant are stellar-mass black holes?
- What is the central engine that powers GRBs?
- Do intermediate mass black holes exist?
- Where and when do massive black holes form and how are they connected to galaxy formation?
- What happens when a massive star collapses?
- Do spinning neutron stars emit gravitational waves?
- What is the distribution of white dwarf and neutron star binaries in the galaxy?
- How massive can a neutron star be?
- What makes a pulsar glitch?
- What causes intense flashes of X- and gamma-ray radiation in magnetars?
- What is the star formation history of the Universe?



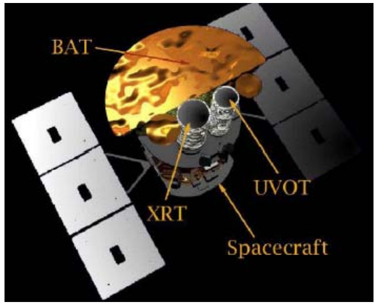


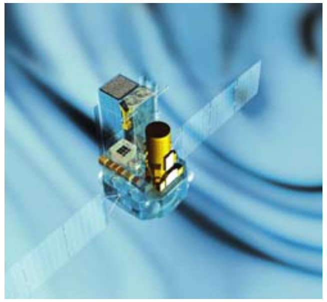
High Energy Photons

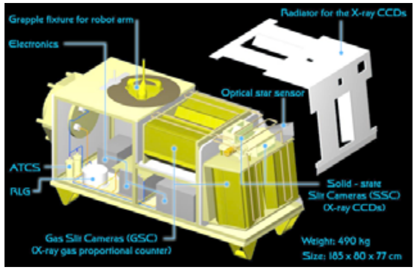
Key requirement:

All-sky high energy burst monitoring satellite operational during the ET era

Current: SWIFT INTEGRAL FERMI MAXI (Japan)







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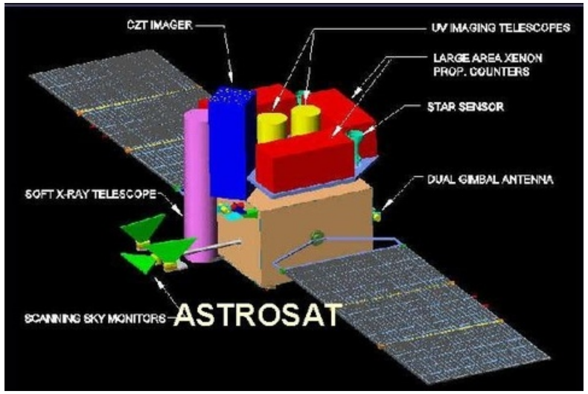
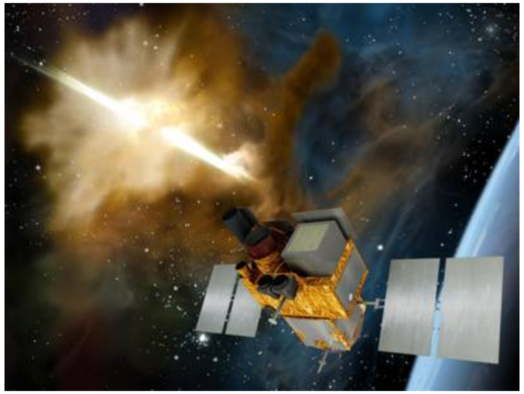
Planned: ASTROSAT (India) SVOM (France/China)





High Energy Photons

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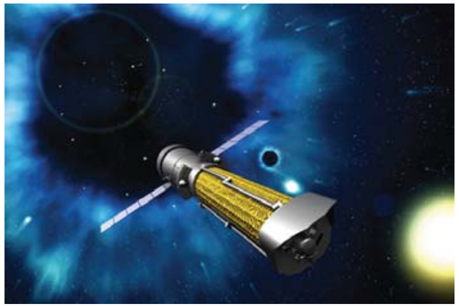
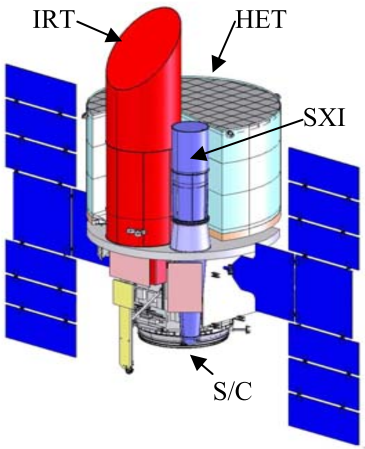
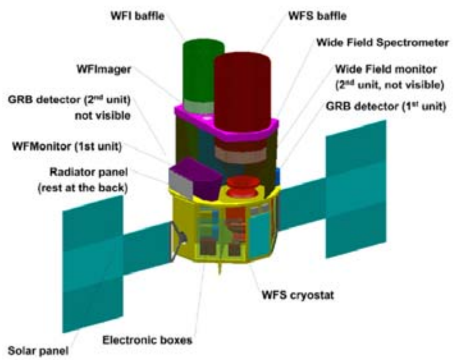
Drawing board: IXO EXIST XENIA / EDGE





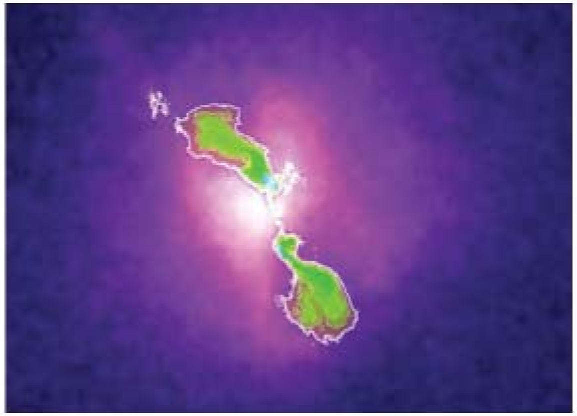


From Lumb & Bookbinder, IXO Mission Overview, Paris, April 2010

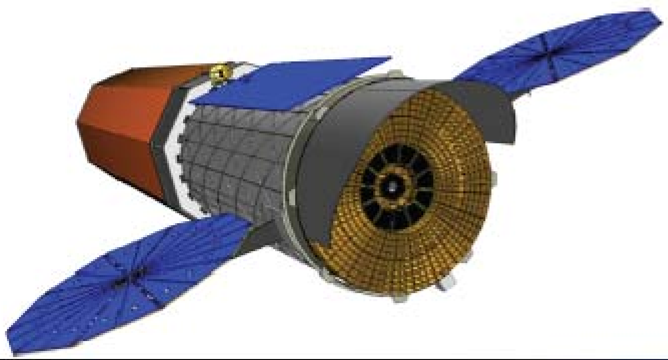
The International X-Ray Observatory

- What happens close to a black hole?
- When and how did super-massive black holes grow?
- How does large scale structure evolve?
- What is the connection between these processes?

Decadal Survey key points



Hydra A Galaxy Cluster



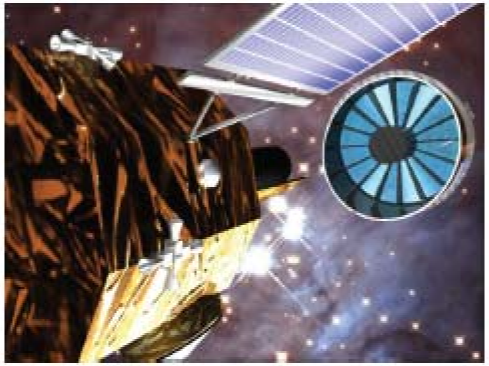
- 20m focal length
- Mass 5900 kg (incl. system margin)
- NASA EELV or ESA Ariane V
- L2 orbit
- 5 year lifetime; 10 year consumables

International X-ray Observatory [IXO]

From Lumb & Bookbinder, IXO Mission Overview, Paris, April 2010

Mission History

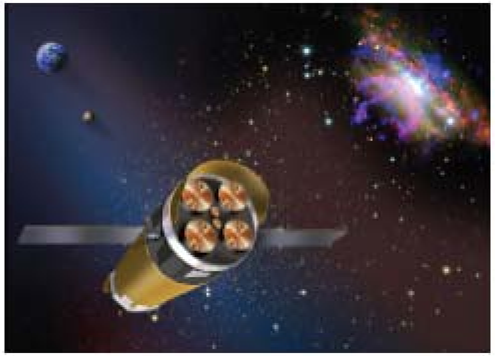
NASA JAXA esa



The well recognized science case for a large-area X-ray Observatory led to:

- Con-X: NASA concept, number two large mission after JWST in 2000 Decadal survey
- XEUS: ESA with JAXA candidate as large Cosmic Vision mission

Similar science goals, but different implementations



Merger of XEUS and Con-X in 2008

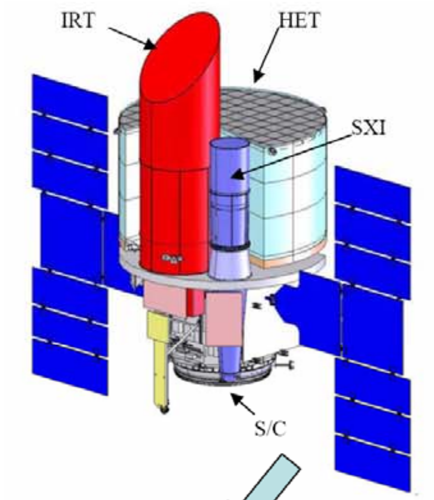
- Formation of Study Coordination Group (SCG) and advisory groups – co-chairs by 3 agencies: SDT, IWG, TWG

Await prioritization by Astro2010 Committee & ESA Cosmic Visions L-Class mission down selection

International X-ray Observatory [IXO]

From Josh Grindlay and the EXIST team, APS Meeting, May 2009

A Hard X-ray, full-sky, deep imaging Survey and IR/X-ray followup is required for the Black Hole Finder Probe to *EXIST*



HET at ~zenith ***scans*** at orbital rate & ***points*** IRT/XRT/HET to GRBs within ~100s

HET: CZT detector arrays + mask: 5-600 keV **$4.5m^2$ tiled CZT**, **coded mask** images 90° diam. FoV, 2' resol. & <20" positions; BGO rear shield (0.2-2MeV)

IRT: 1.1m; cooled (-30C) (dichroic: 0.3-0.9μm (HyViSI) and 0.9–2.3 μm (NIRSPEC)

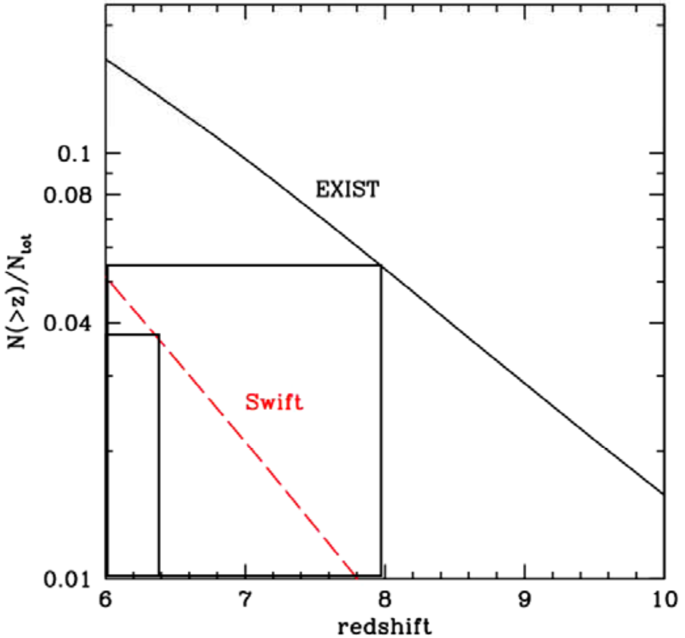
SXI: 0.6m; Italy/ASI contributes upgrade of *Swift/XRT*: *Soft X-ray Imager* (0.1-10keV (CCD))

The *New EXIST* mission:

- ***2y full sky survey:*** ±20deg *Zenith-pointed* **scanning**, 2sr FoV, *full-sky ea. 3h*.
- ***3y followup IDs:*** **IRT/XRT/HET pointings** for IDs, redshifts, spectra & timing

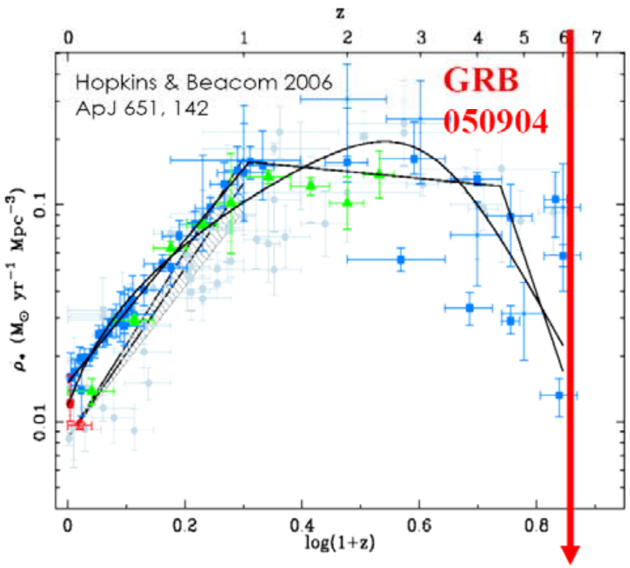
From Josh Grindlay and the EXIST team, APS Meeting, May 2009

P1: *EXIST* GRBs *probe stellar universe to z ≥ 10*



Predicted *fractional* GRB rates *above* z vs. z for *EXIST* vs. Swift/BAT based on Salvaterra (2009). *EXIST will detect ~600 GRBs/y and thus ~90/y at Z > 6 and thus ~0.055 x 600 =* ***33 at z >8 per year!***

Swift detects ~100 GRBs/y and now ~450 GRBs. It Should detect ~0.04 x 450 = 18 at z >6 and has now detected 3, suggesting most are missed.



EXIST GRBs vs. z will probe the star formation rate (SFR) vs. z at highest redshifts, and constrain/measure Pop III.

EXIST will probe:

High Energy Photons

Several types of potential source:

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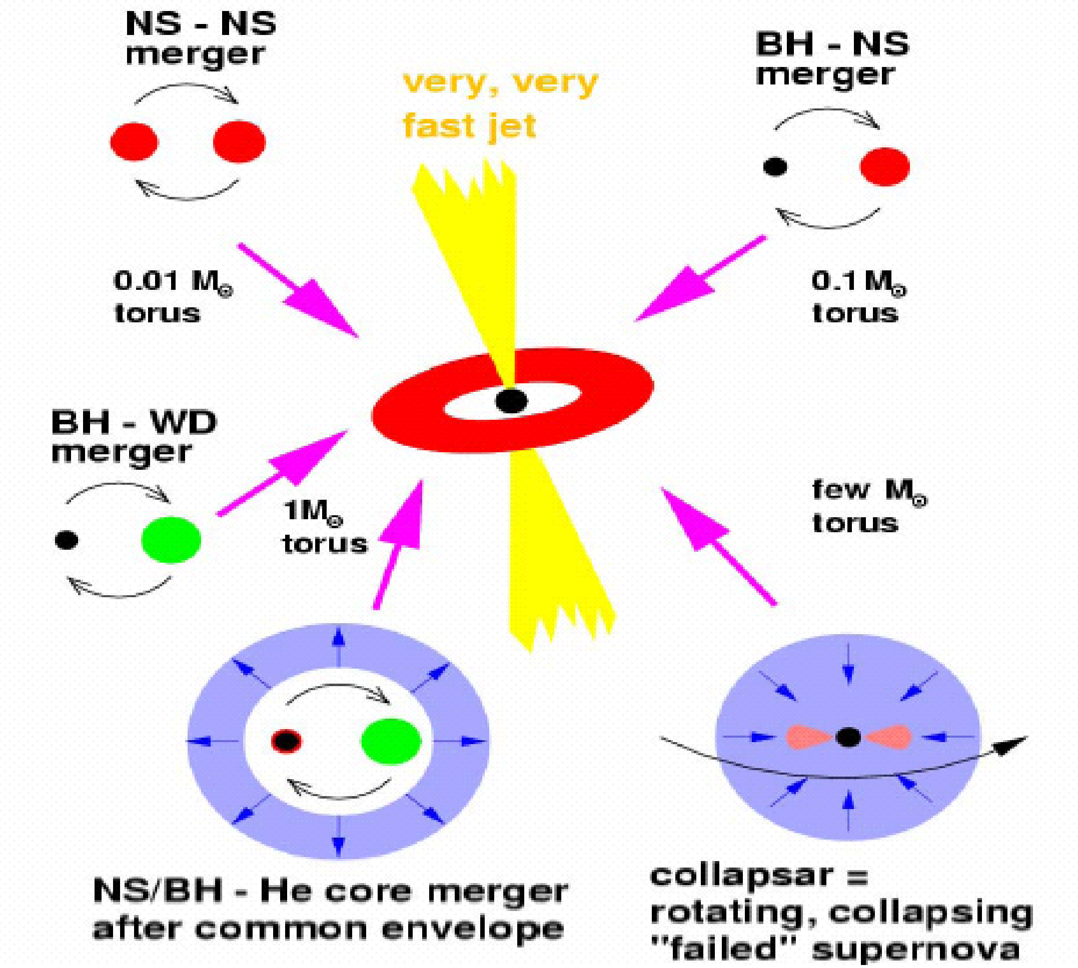
Gamma ray bursts: current paradigm

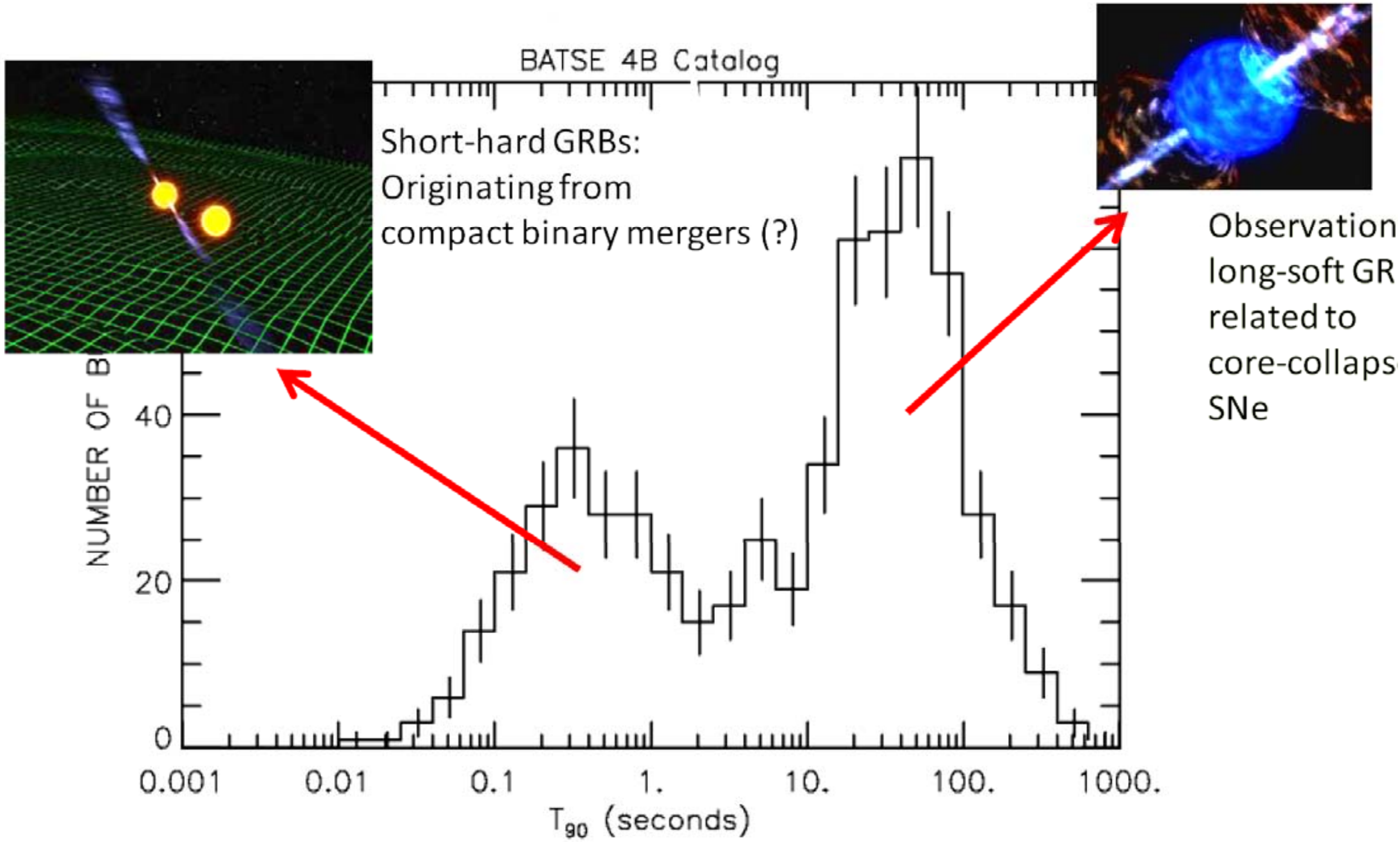


Short
($t_\gamma \lesssim 2$ s)

Long
($t_\gamma \gtrsim 2$ s)

Credit: P. Mészáros

Gamma ray bursts: current paradigm



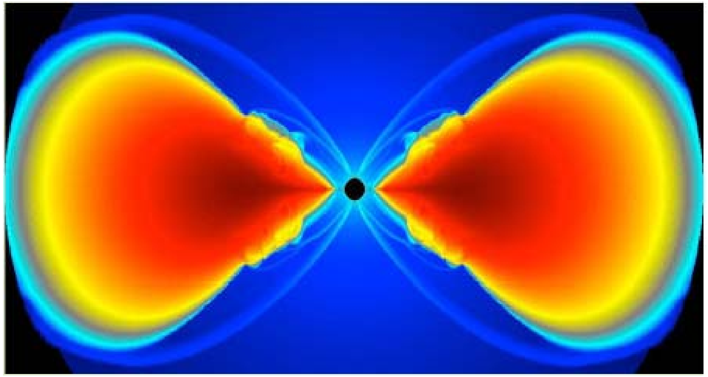
Following C. Ott

High Energy Photons

Long Duration GRBs

Progenitor – Wolf-Rayet star $> 25\mathrm{M}_\odot$

Rate ~ $0.5\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$



Credit: J. McKinney

Details of progenitor model uncertain (see Ott 2009):

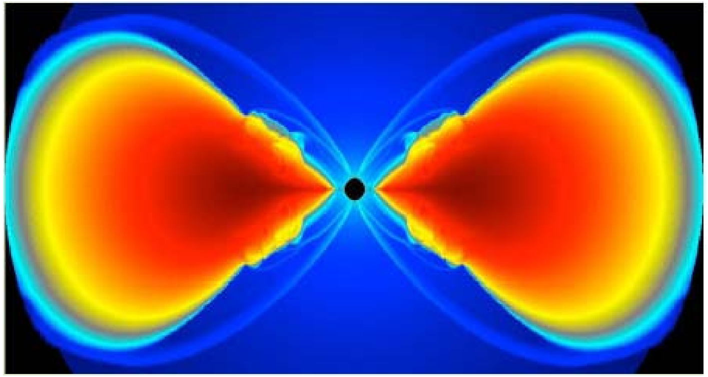
- **Collapsar type I** (no SN explosion; star blown up by GRB)
- **MHD Hypernova + Collapsar** (explosion before BH)
- **MHD Hypernova + Millisecond Magnetar** (Corsi & Meszaros 2009)

High Energy Photons

Long Duration GRBs

Progenitor – Wolf-Rayet star $> 25\mathrm{M}_{\odot}$

Rate ~ $0.5\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$



Credit: J. McKinney

Details of progenitor model uncertain (see Ott 2009):

- Rapidly rotating stellar core; accretion disk centrifugally supported; Non-axisymmetric instabilities $\rightarrow$ GWs (so far only estimates)

e.g. van Putten et al (2008)

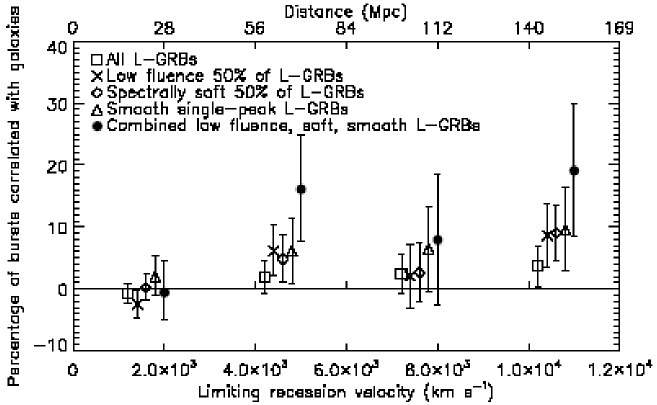
Suspended accretion model

$E_{\mathrm{GW}} \simeq 0.2\mathrm{M}_{\odot}$ at 500 Hz. Observable to **~1Gpc** with ET

High Energy Photons

Sub-class of low-L Long Duration GRBs?

e.g. GRB980425 / SN1998bw,
at $z = 0.0085$



Chapman et al (2007), Liang et al (2007)

Suggestion that local rate up to **1000x** that of the high-L population.

Believed to be associated with particularly energetic core-collapse SN.

Extreme end of a continuum, with the same underlying physical model?...

ET should answer this question

High Energy Photons

Several types of potential source:

- Gamma ray bursts
- **Soft gamma repeaters**
- Ultra-luminous X-ray sources
- Micro-quasar flares

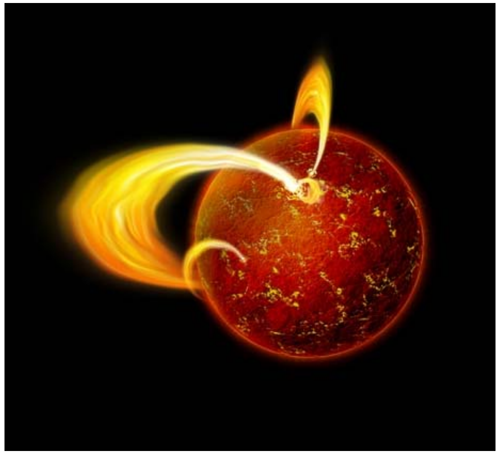
Soft Gamma-ray Repeaters

SGRs = systems emitting brief bursts of soft γ-rays and X-rays at irregular intervals.

Magnetar model:

galactic neutron star with **B ~10^{15} G**.

Flares occur when solid NS crust cracks, due to B-induced deformations.



Credit: M. Weiss

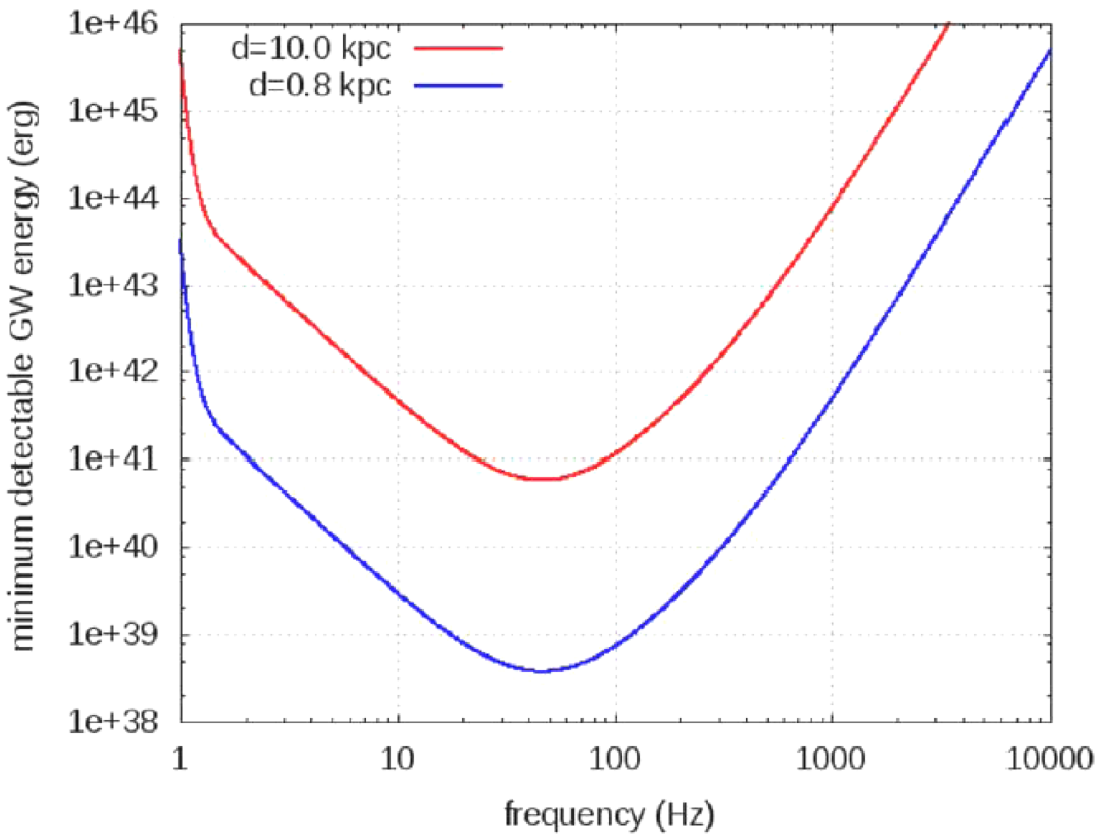
May excite non-radial oscillations, producing GWs.

Available energy reservoir: **10^{45} – 10^{47} erg**

(Corsi & Owen 2009)

Soft Gamma-ray Repeaters

What is the minimum GW energy, detectable by ET, for an SGR
e.g. at 10kpc, at 0.8kpc (SGR 0501+4516) ?



Medium Energy Photons

Here there are two clear opportunities for multi-messenger astronomy:

- Optically selected core-collapse supernovae
- Cosmological 'Standard Sirens'

Optically selected core-collapse SNe

Even 2nd generation detectors only able to detect GWs from galactic SN.

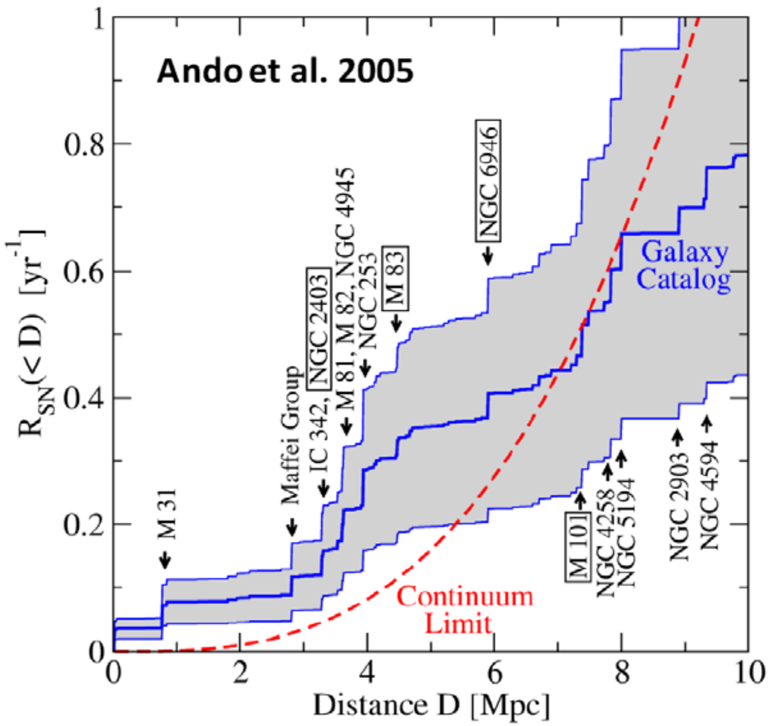
Expected galactic SN rate ~ 0.02 / year.

Nearby core-collapse SNe in the LIGO era

SN	Host Galaxy	Date	Type	Distance
2008iz[1]	M 82	20090515 [2]	II	~ 3.5 [3]
2008bk	NGC 7793	20080325 [4]	II-P	~ 3.9 [5]
2005af	NGC 4945	20050208 [6]	II-P	~ 3.6 [5]
2004dj	NGC 2403	20040731 [7]	II-P	~ 3.3 [5]
2004am	M 82	20040305 [8]	II-P	~ 3.5 [3]
2002kg	NGC 2403	20021026 [9]	IIn	~ 3.3 [5]

[1] Radio supernova, not observed in the optical. Explosion in late January 2008.

Credit: C. Ott



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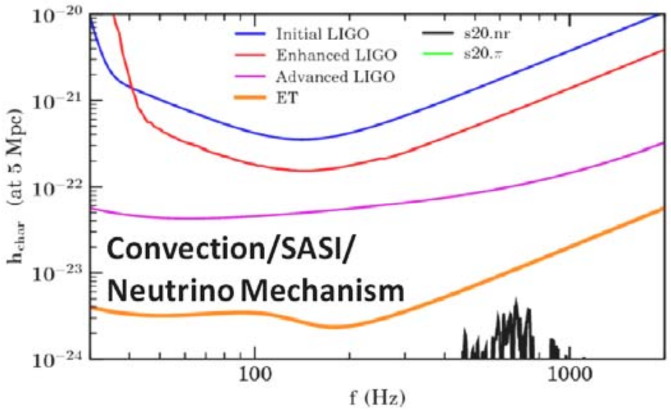
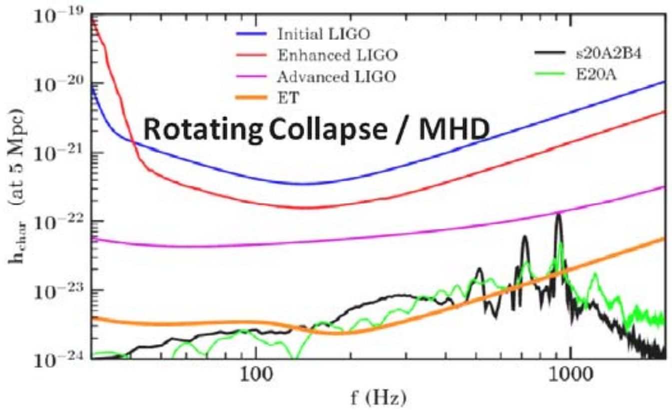
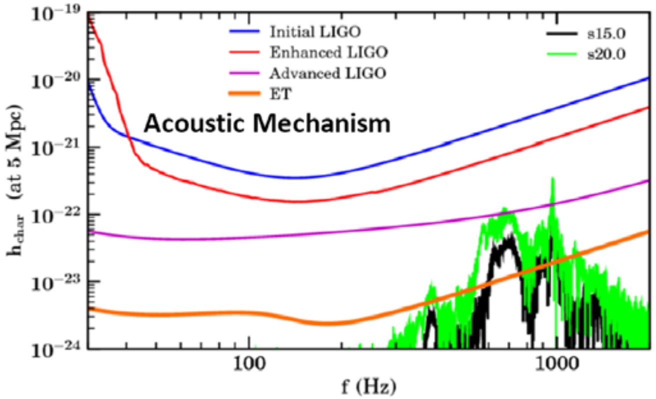
Even 2nd generation detectors only able to detect GWs from galactic SN.

Expected galactic SN rate ~ 0.02 / year.

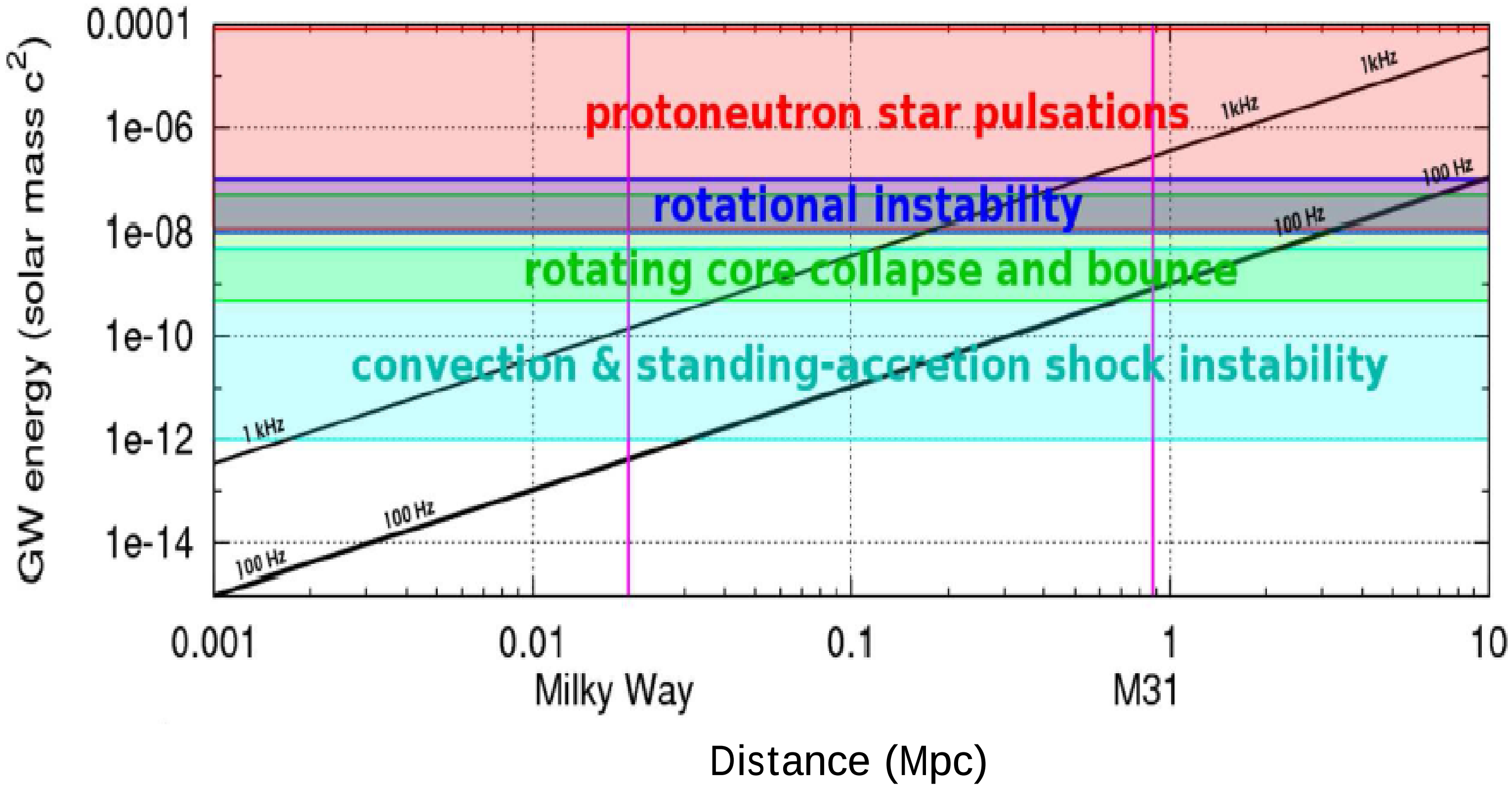
Characteristic strain spectra at 5Mpc (from Ott 2009)







Optically selected core-collapse SNe



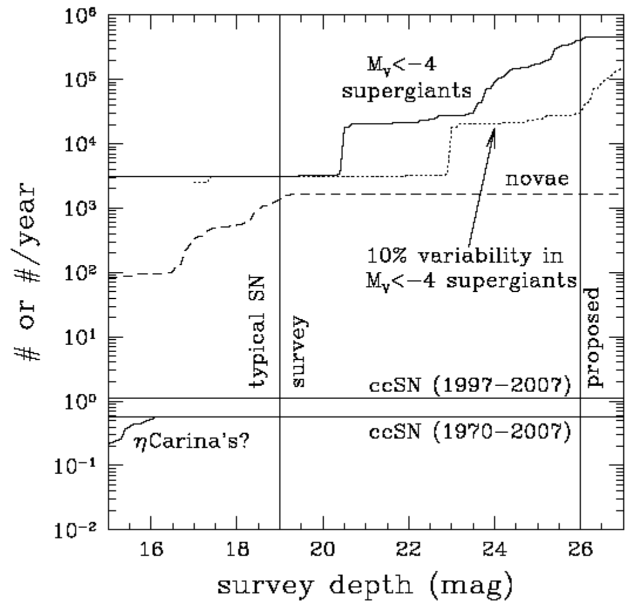
ET virtually guaranteed to see at least **0.5 CCSNe / year**, with some power to discriminate between models.

Searching for Un-novae

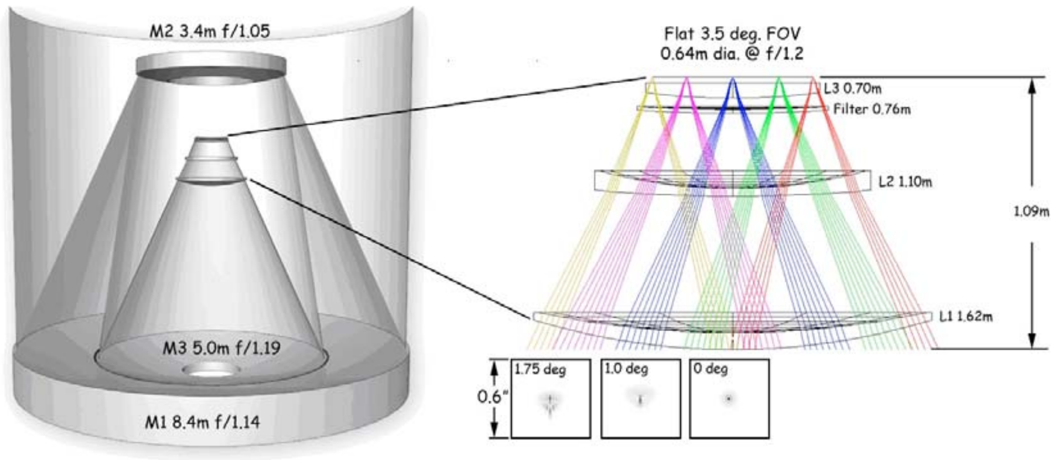
Un-nova = core collapse event that doesn't lead to explosion

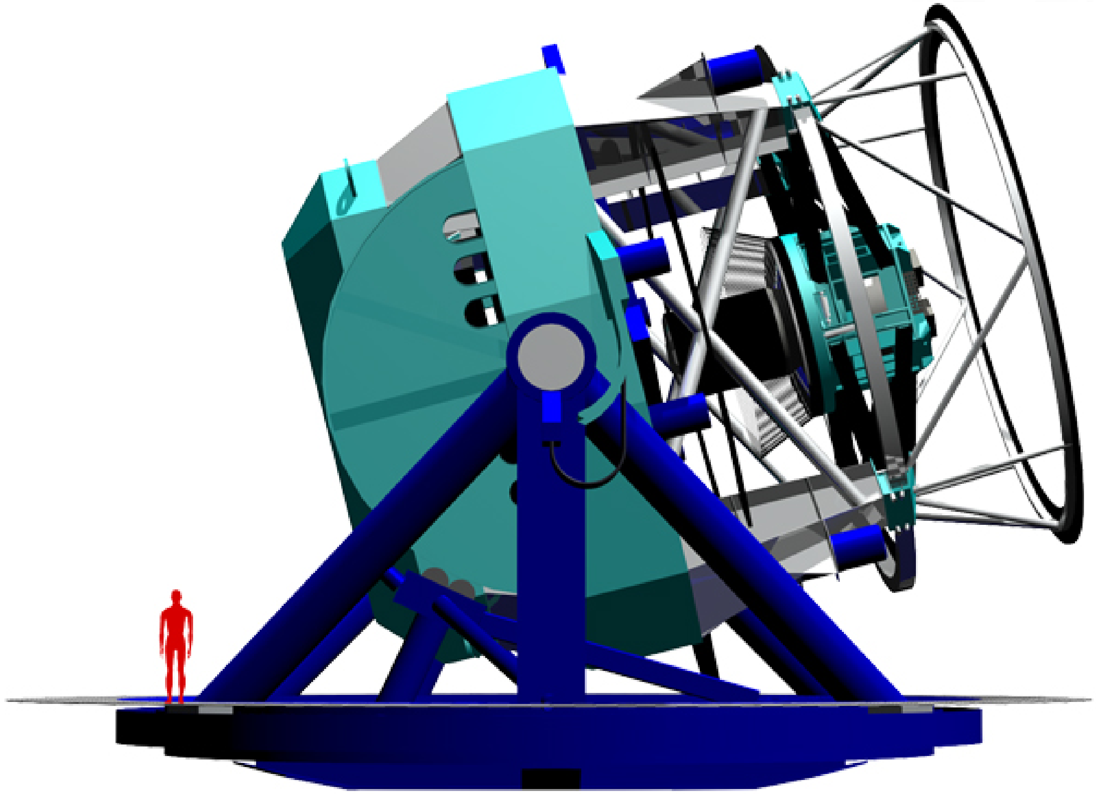
Kochanek et al. (2008):
Use e.g. **LSST** to monitor ~10^6 luminous supergiants, looking for stars that disappear in E-M.

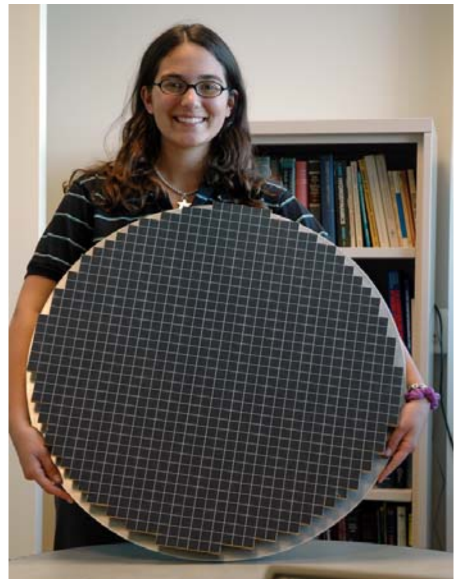
Survey depth ~10 Mpc



LSST – Large Synoptic Survey Telescope







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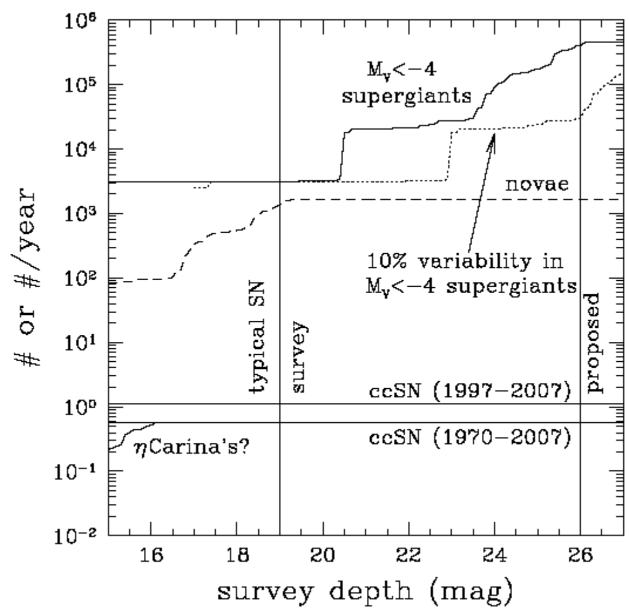


ET should "see" GW signature

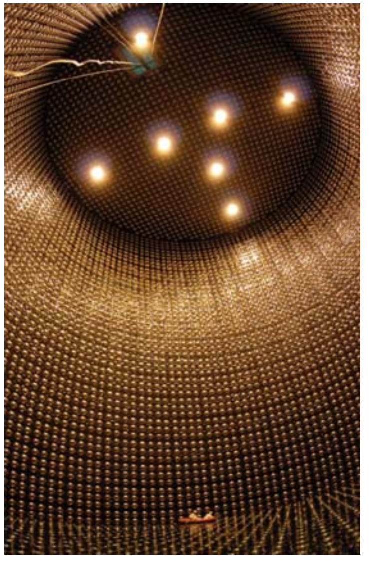
[Also strong neutrino signature]

Neutrinos

Many targets of ET will also be strong neutrino emitters.

Core collapse SNe: ~0.1s pulse of low-energy ν's, up to ~10^{53} erg.

$E_\nu \lesssim 10\,\mathrm{MeV}$ 'Low' energies – vessel filled with water, or liquid scintillator.



Current: e.g. Super-Kamiokande
50 kTon of pure water

LVD, SNO+
1 kTon of liquid scintillator

Future: ASPERA roadmap includes Megaton detector.

Plans for multi-megaton (e.g. **Deep-TITAND**)

Neutrinos

Many targets of ET will also be strong neutrino emitters.

$E_\nu \gtrsim 100\ \mathrm{GeV}.$ 'High' energies – need much larger volume.

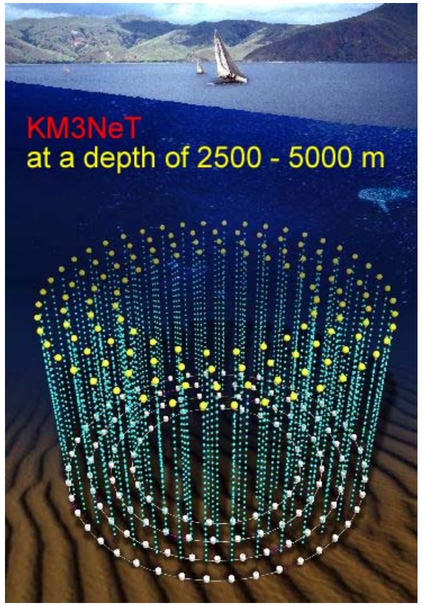
Sources: GRBs, SGRs etc (high energy $\gamma \Rightarrow$ high energy ν)

Current: e.g. IceCube
km^3-scale, at South Pole

ANTARES

0.01 km^3-scale, at 2.5km depth

Future: ASPERA roadmap includes KM3NeT.



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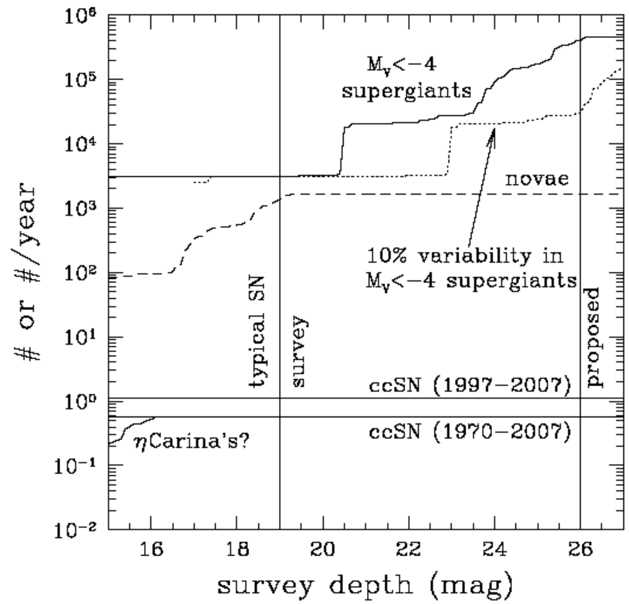
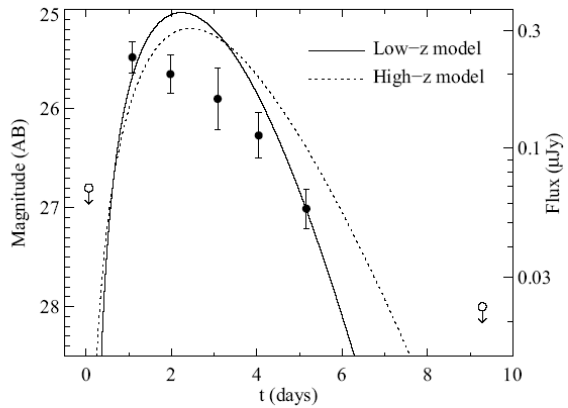


ET should "see" GW signature

Discovery of un-novae ⇒ constraints on SF history; implications for binary inspiral masses and event rates. (c.f. Belcynkski et al 2010)

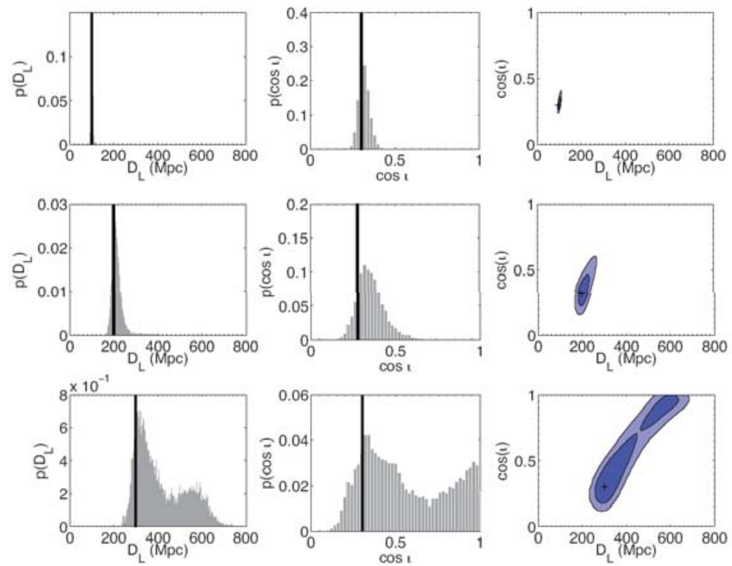
Medium Energy Photons

'Standard Sirens': potential high-precision distance indicators.



First optical observation of a NS-NS merger?

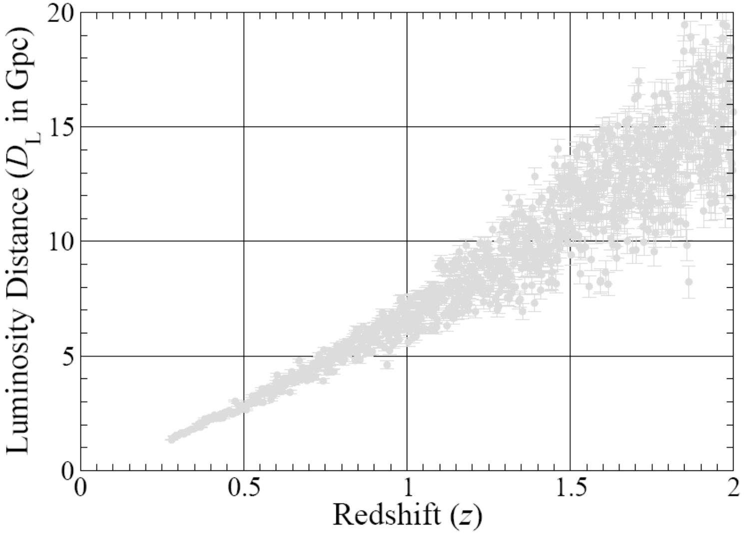
GRB 080503 (Perley et al 2008)



Nissanke et al (2009)

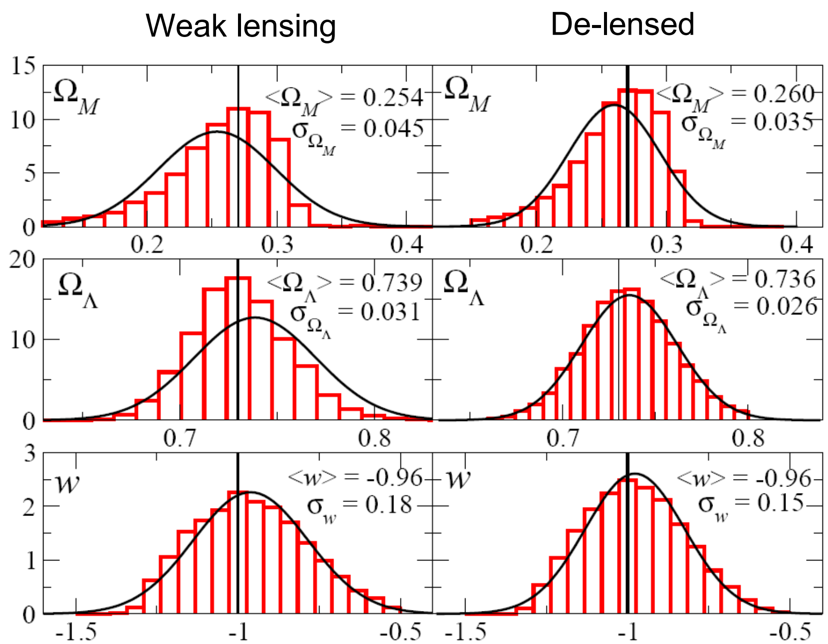
Major challenge: redshift from E-M counterpart

Medium Energy Photons



Sathyaprakash et al. (2009):

~10^6 NS-NS mergers observed by ET. Assume that E-M counterparts observed for ~1000 sources, 0 < z < 2.



Fit $\Omega_M, \Omega_\Lambda, w$

$$\sigma_{\Omega_M} = 0.035$$

$$\sigma_{\Omega_\Lambda} = 0.026$$

$$\sigma_w = 0.15$$

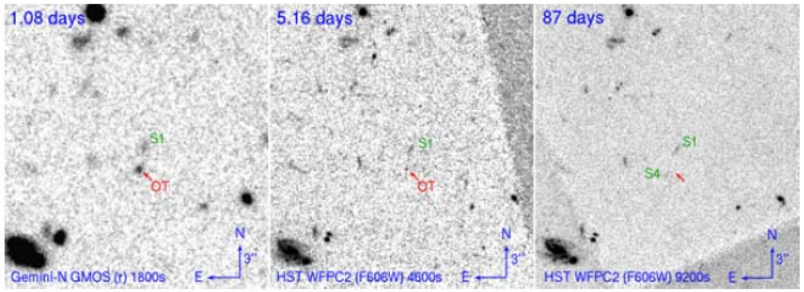
Competitive with 'traditional' methods

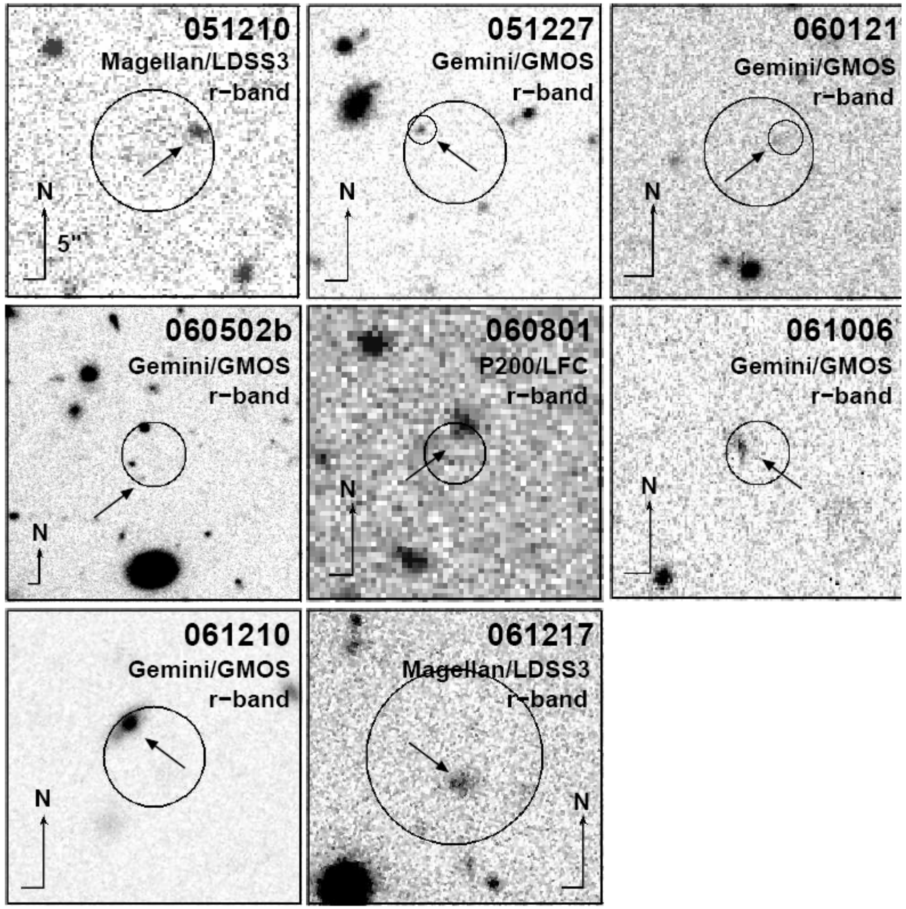
Medium Energy Photons

Berger et al. (2007) present optical observations of 9 short-hard GRBs. Obtained spectrosopic redshifts for 4.

8/9 host galaxies, with R-band mag. 23 – 26.5

Also, *no* HST optical host galaxy for GRB080503





Medium Energy Photons

By the ET era there should be Extremely Large optical Telescopes operating on the ground.

See e.g. the 42m EELT
http://www.eso.org/sci/facilities/eelt/

EELT will be capable of obtaining high quality spectra at **z ~ 6**.

http://www.eso.org/public/teles-instr/e-elt/index.html

⇒ **Follow-up spectroscopic observations should be straightforward**

Medium Energy Photons

BUT Still strong case for a wide-spectrum high-energy monitoring satellite.

e.g. 5 of the 9 SGBs in Berger et al (2007) had only X-ray positions, but these were measured to ~6 arcseconds.

GW triggers from ET network would locate source to ~10 sq. deg.

With *only* optical afterglows, that leaves ~10^7 galaxies!

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Could this open up entire NS-NS merger population detected by ET?

Low Energy Photons

e.g. Hansen & Lyutikov (2001)

Discuss prospects for detecting radio ***pre-cursor*** of short-hard GRBs, due to magnetospheric interactions of a NS-NS binary.

At 400 MHz

$$F_\nu \sim 2.1\mathrm{mJy}\,\frac{\epsilon}{0.1}\left(\frac{D}{100\mathrm{Mpc}}\right)^{-2} B_{15}^{2/3}\, a_7^{-5/2}$$

Already detectable by largest radio telescopes, out to **few x 100 Mpc**.

Observable with **SKA** to cosmological distances.

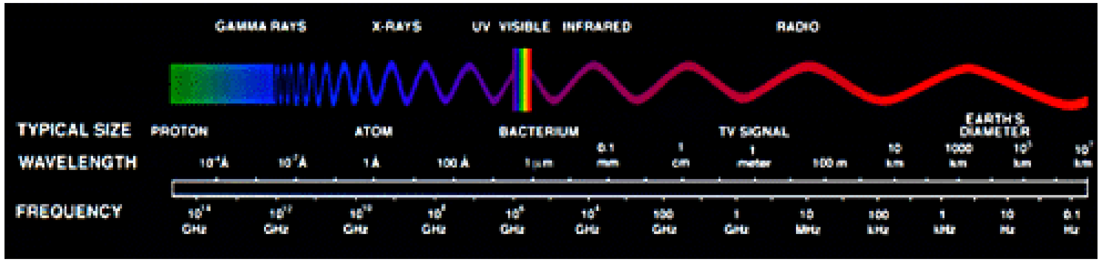
Conclusions

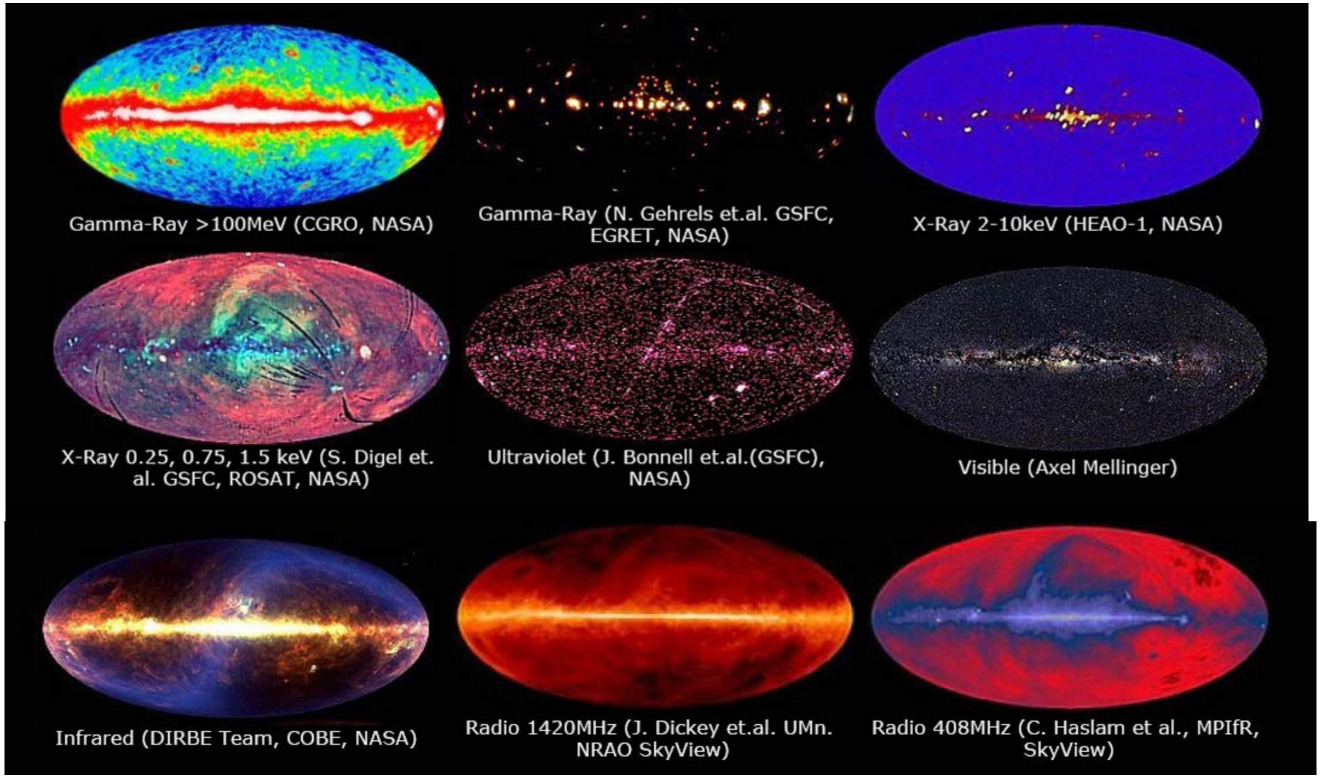
Many and varied MMA science opportunities with ET:

- Long GRBs to ~1Gpc; constraints on low-L population
- SGRs: efficiency constraints in magnetar model
- Coincident GWs and neutrinos from GRBs and **core-collapse SNe**, improving understanding of physical mechanisms
- E-M counterparts of SHB 'standard sirens' (possibly extending to full NS-NS merger population?)

All argues for strong collaboration and synchronicity with other messengers – particularly all-sky high-energy burst monitor

Opening a new window on the Universe





Gamma-Ray >100MeV (CGRO, NASA)

Gamma-Ray (N. Gehrels et.al. GSFC, EGRET, NASA)

X-Ray 2-10keV (HEAO-1, NASA)

X-Ray 0.25, 0.75, 1.5 keV (S. Digel et. al. GSFC, ROSAT, NASA)

Ultraviolet (J. Bonnell et.al.(GSFC), NASA)

Visible (Axel Mellinger)

Infrared (DIRBE Team, COBE, NASA)

Radio 1420MHz (J. Dickey et.al. UMn. NRAO SkyView)

Radio 408MHz (C. Haslam et al., MPIfR, SkyView)

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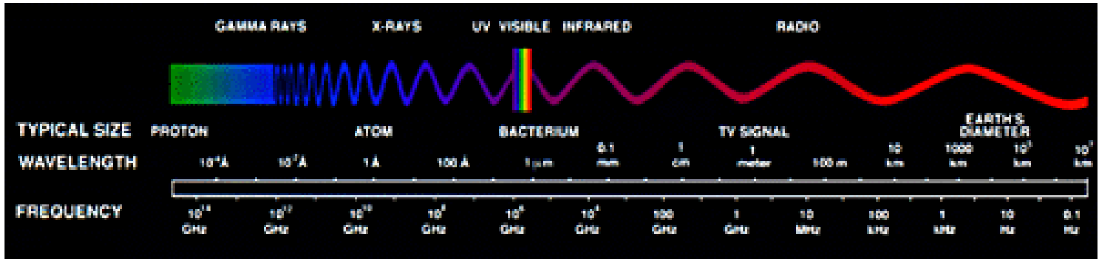

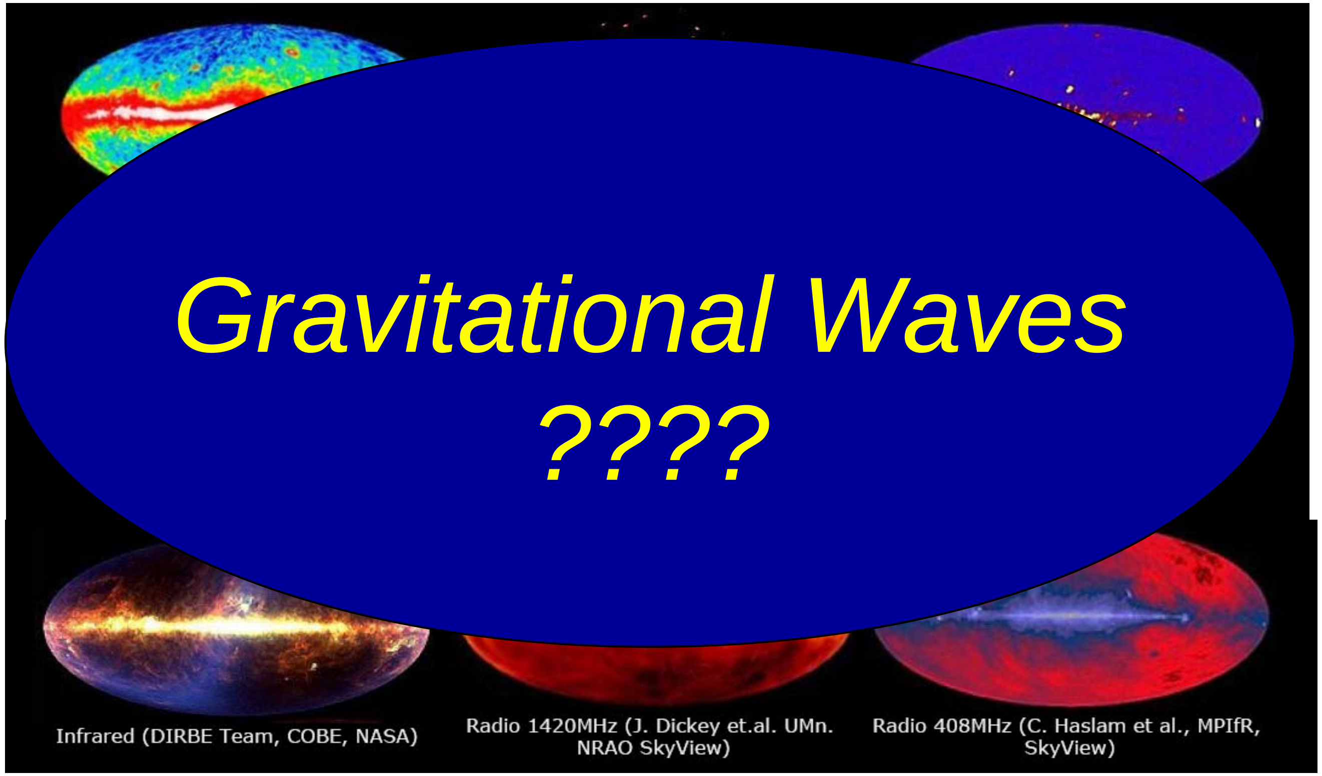

Gravitational Waves

????