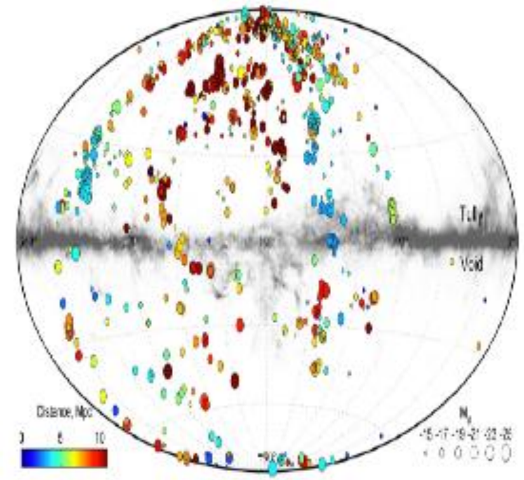
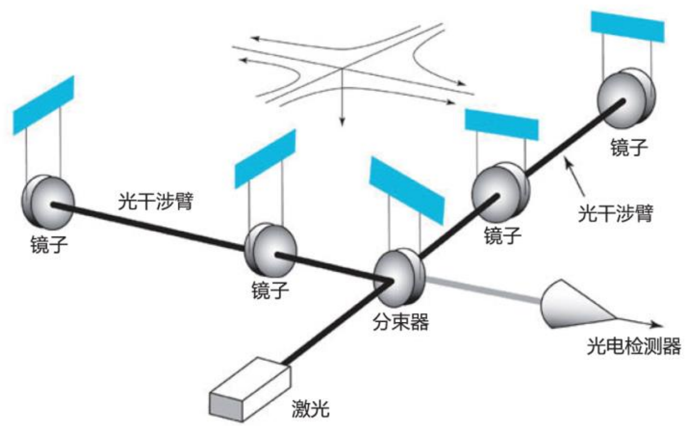
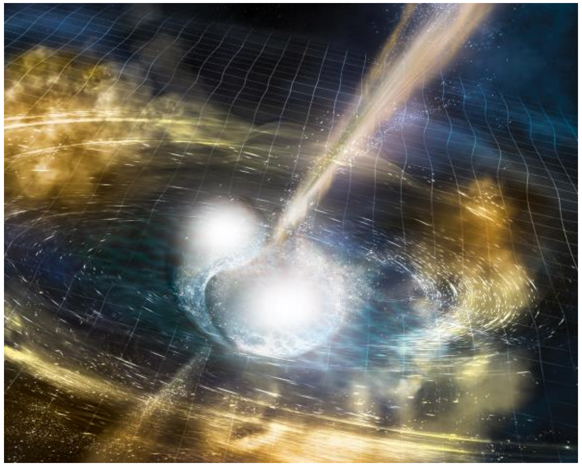
A Bayesian approach to multi-messenger astronomy







范锡龙 武汉大学

Collaborators: Chris Messenger & Ik Siong Heng

University of Glasgow

Google

the most beautiful university in china

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找到约 163,000,000 条结果 （用时 0.90 秒）

Here presents its selection of the top 10 most beautiful college campuses in China.

- **Wuhan University**. ...
- **Peking University**. ...
- Shenzhen University. ...

武漢大學
WUHAN UNIVERSITY

学校概况 机构设置 师资队伍 人才培养 科学研究 社会服务 交流合作 文化生活

- A new center promote multi-disciplinary researches
  - GW data analysis
  - GW astrophysics / cosmology
  - Multi-messenger astronomy (X-ray…)
  - Theory & Phenomenology of Gravity
  - GW experiment
- **Positions at all levels open now**
  - Ph.D   (~10/year)
  - Post doc (~ 10)
  - Junior/ Senior Researcher   (~10)
  - Associate / Full Professor (~ 10)
  - Long term visitors

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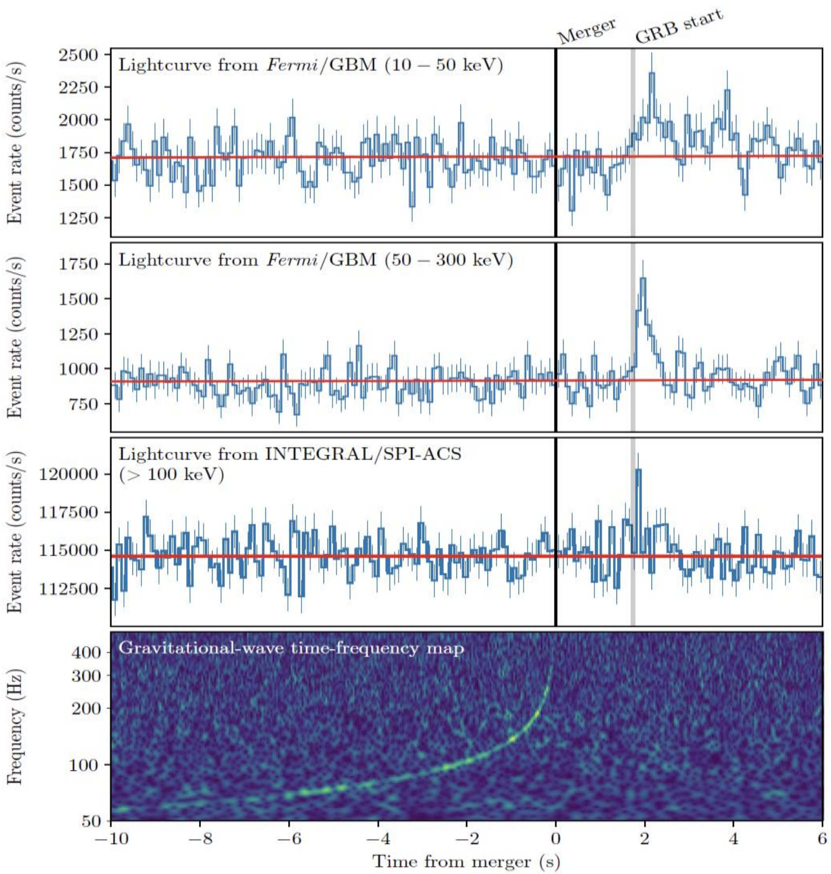
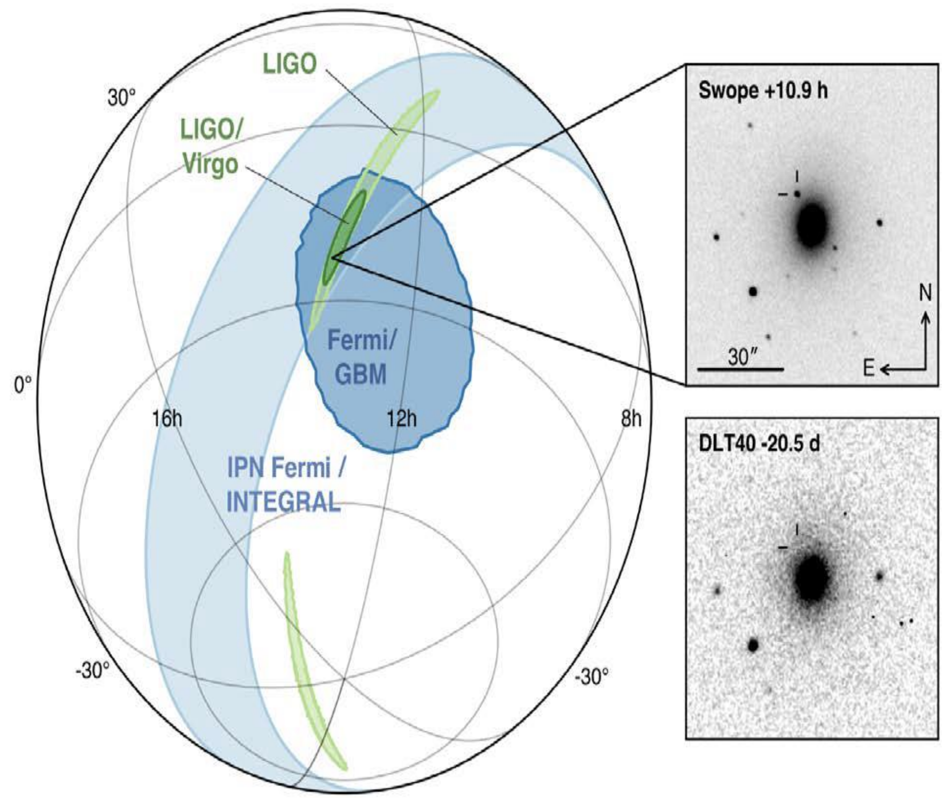
GW170817-GRB170817A-NGC 4993

- Fermi GBM: 90% of the burst fluence observed over T_{90} = 2.0 ±0.5 s.
- Swope telescope : i-band = 17.057 ± 0.018 Mag, 10.6’ ’ from the center of NGC 4993, ~40 Mpc



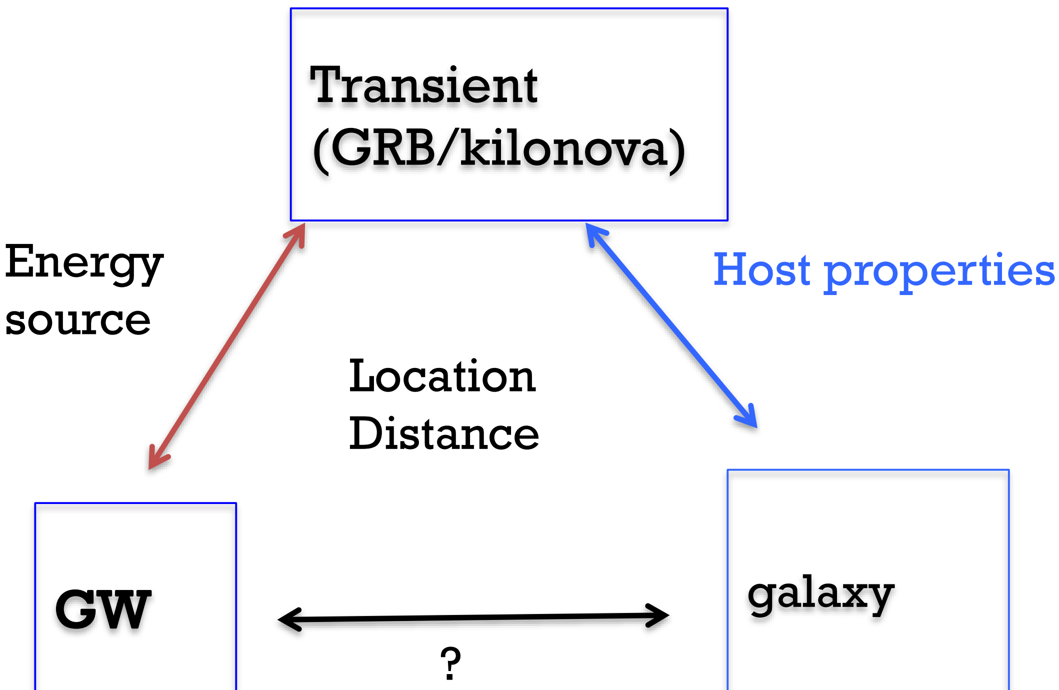


Multimessenger astronomy in mine mind

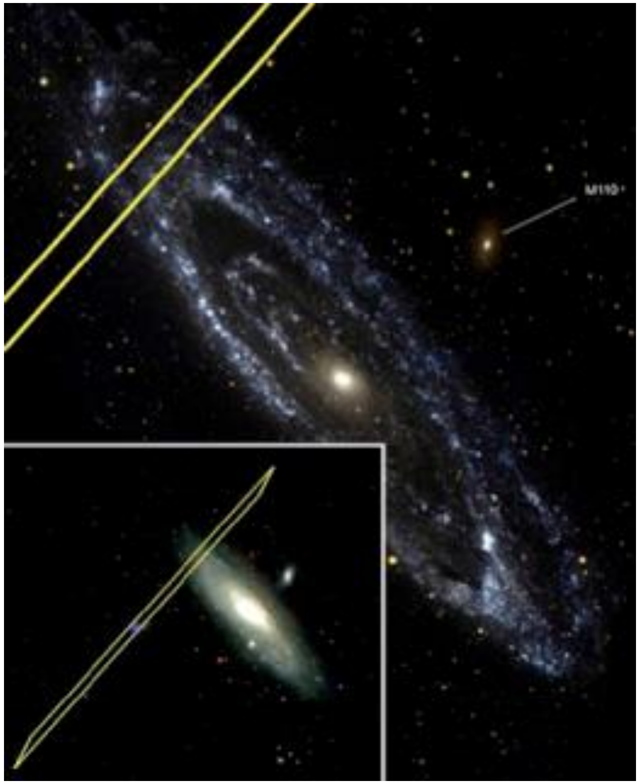
- How to confirm the joint detection by two sets of data (GW and EM)?
  - Do these data respond to one physical relation?
- What can we learn from this joint detection?
  - Beyond confirming detection, what is the new knowledge for both research fields?

General picture

- Observational triangle



Fan, Messenger & Heng, ASSP, 2015



GRB 070201, M31 and
no Ns-Ns Merger in M31
Abbott et al. 2008

Our Bayesian approach

- Combine GW observations with non-GW (EM, neutrinos, others…) information/observations
  - Gives the posterior probability on desired parameters from joint observations
  - Model selection (on-going project)

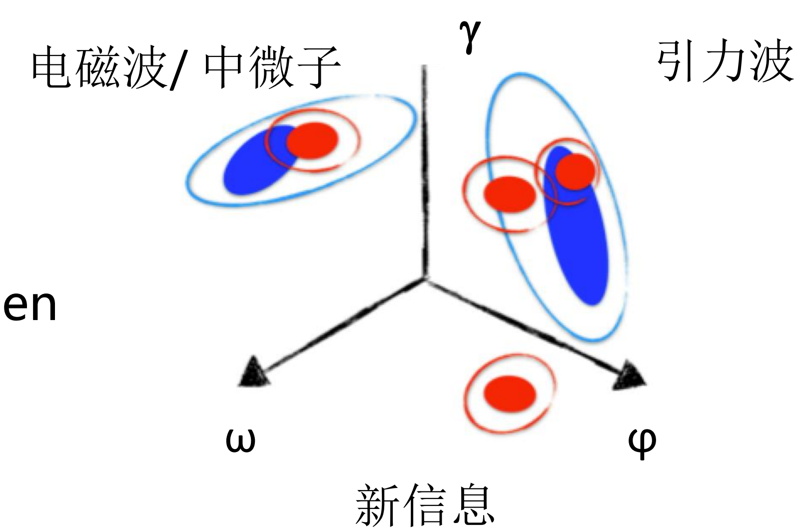
- CBC sources , nicer error regions and a distance estimate

- Which EM information/ observations?
  - Applicable to joint observations with many kinds of EM data
  - Other applications (e.g. Cosmology)

A Bayesian approach :Joint observations with GW

- **Data** γ
  - **D** : the gravitational wave data
  - **S** : the non-GW observations
- Parameters:
  - γ : the common parameters between

    the **D** and **S** data
  - ω: non-common EM parameters
    - not well defined
  - ϕ: non-common GW parameters
  - M : model



From non-GW data analysis

From GW data analysis

$$p(\boldsymbol{\gamma}, \boldsymbol{\phi}, \omega | \mathbf{S}, \mathbf{D}, M, I) = \frac{p(\mathbf{D}|M, I)\, p(\boldsymbol{\gamma}, \boldsymbol{\phi} | \mathbf{S}, M, I)\, p(\boldsymbol{\gamma}, \omega | \mathbf{D}, M, I)}{p(\mathbf{D}|\mathbf{S}, M, I)\, p(\boldsymbol{\gamma}|M, I)}$$

The prior of γ used in GW or non-GW data analysis

Do not need to re-analyze all data

A Bayesian approach (i) :Joint galaxy observations with GW

The final posterior probability of common parameters (location and distance):

$$p(\gamma|\mathbf{S},\mathbf{D},I) = \frac{p(\gamma|\mathbf{S},I)}{p(\mathbf{D}|I)} \frac{p(\gamma|\mathbf{D},I)p(\mathbf{D}|I)}{p(\gamma|I)}$$

$$= \frac{p(\gamma|\mathbf{S},I)p(\gamma|\mathbf{D},I)}{p(\gamma|I)}$$

$$= f(\gamma)\frac{p(\gamma|\mathbf{D},I)}{p(\gamma|I)}$$

prior on sky location and distance with your favorite galaxy catalogue and model

inference on sky location from GW parameter estimation with your favorite pipeline

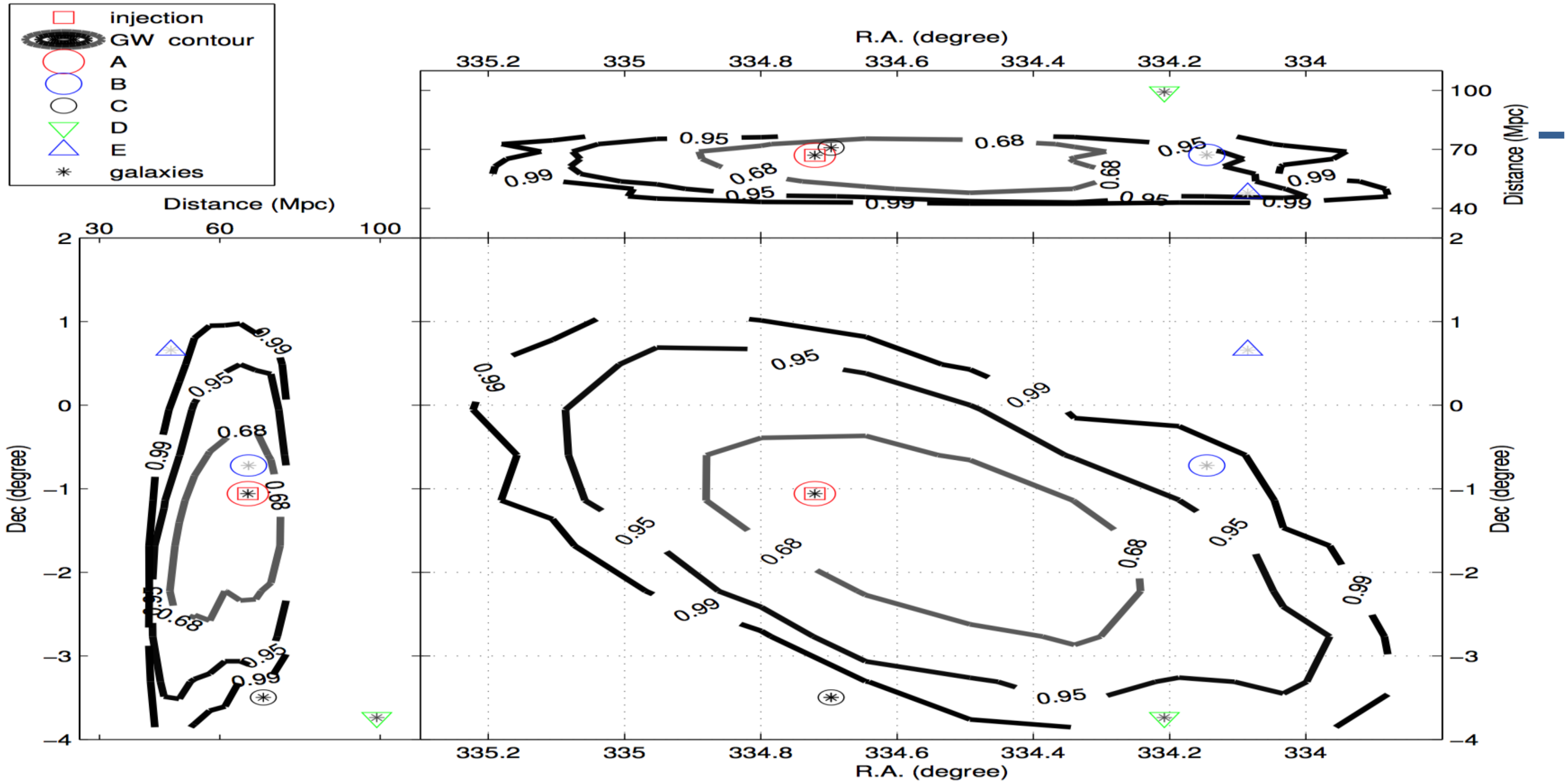
理论天文学家的贡献

- We choose to call the galaxy catalogue prior the *MMPF*
- So, if we have the correct *MMPF* function, the GW is most likely to originate from the host galaxy with the largest value in the posterior probability
  - rank potential GW host galaxies based on this probability

[Fan, Messenger & Heng, arXiv:1406.1544 , ApJ. 2014]

Which (galaxy) information?

- A lot of galaxy properties:
  - Location
  - Distance
  - Stellar mass
  - Luminosity （K , B…)
  - Metallicity
  - Morphology
  - ……　　太多~~（不靠谱）~~理论天文学家。。。
- The current MMPF
  - Model: GW hosted by a galaxy!
    - Based on Gravitation Wave Galaxy Catalog (White et al 2011) ignoring the completeness within 100 Mpc
    - $d^{\wedge 2}$ distribution beyond 100 Mpc
    - Ignore source offset effect
  - Only use location, distance and B band luminosity of galaxies



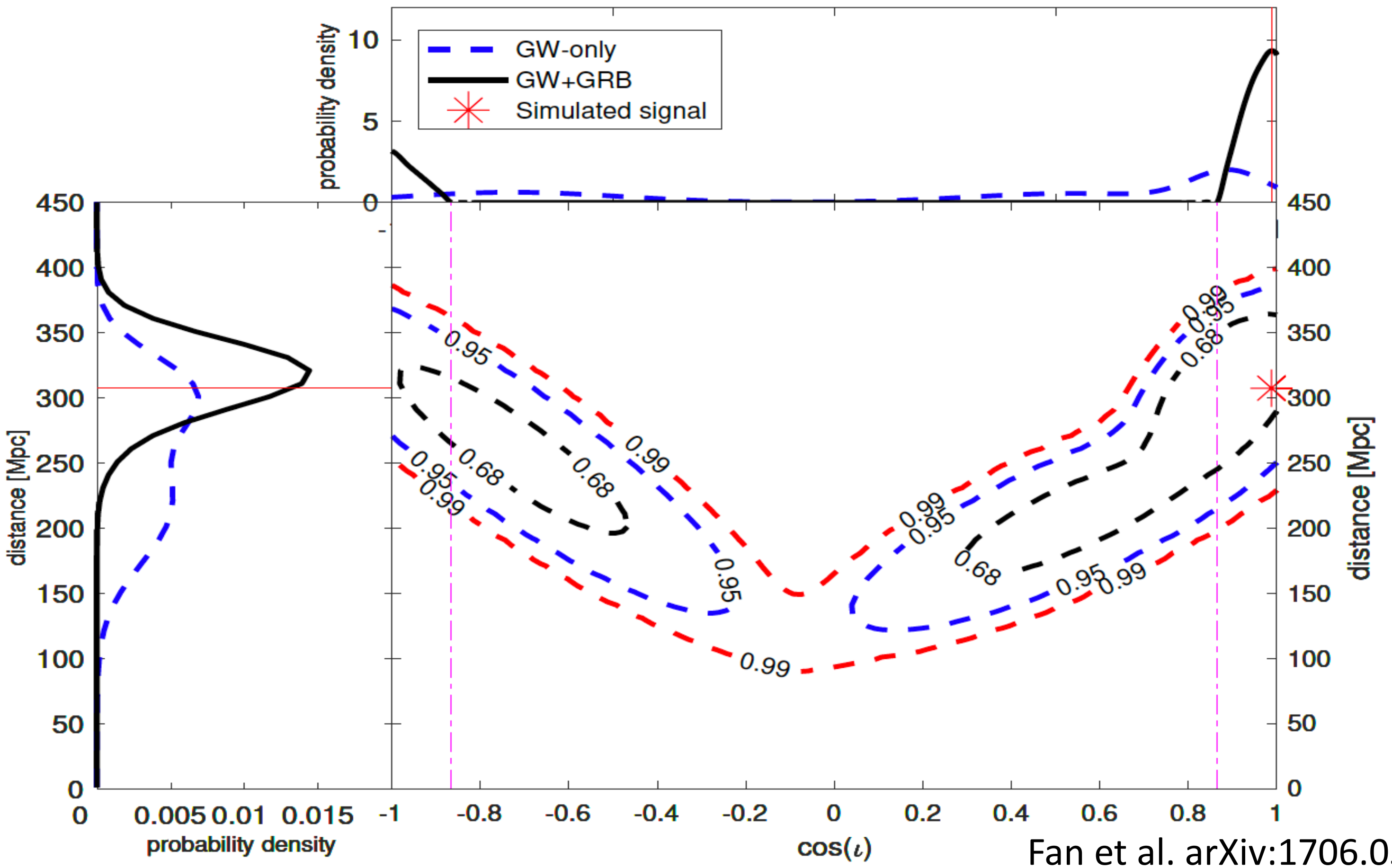
NS-NS injection into Ad-LVC with designe sensitivity

NS-NS rate ~ mass of galaxy ~ L_B ??

	Ranking Method		
Ranking	Galaxy L_B	Galaxy L_B and d	GW+MMPF (probability)
1	C	C	A (99.36%)
2	A	A	B (0.37%)
3	D	B	C (0.27%)
4	B	E	...
5	E	...	...

A Bayesian approach (ii) :Joint observations with GRB

- The distance-inclination angle degeneracy in GW

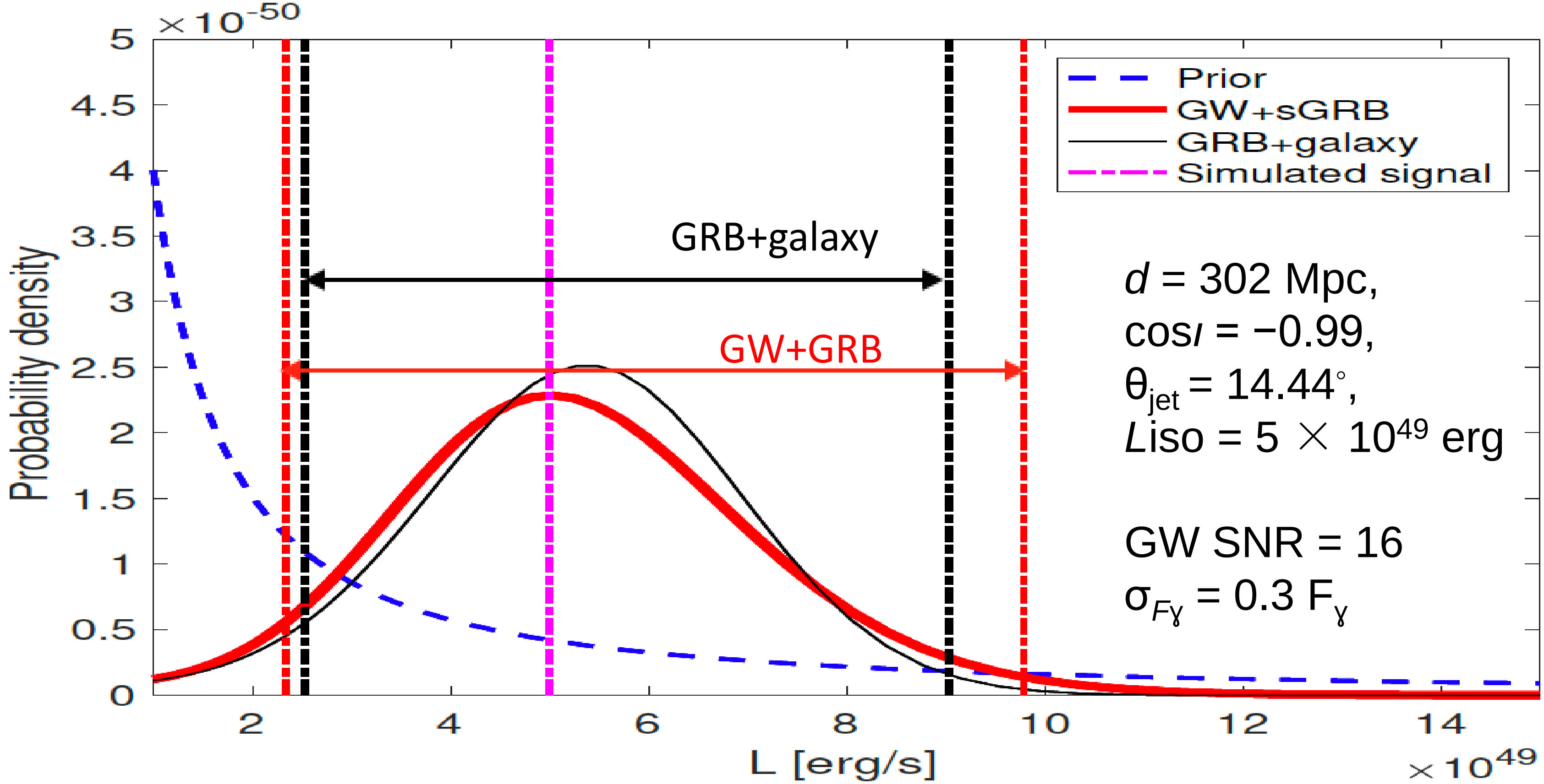


SNR = 14.8
d = 307 Mpc
cos$i$ = 0.97
$\theta_{\rm jet}$ = 19.95°
L_iso = 10^{51} erg

Fan et al. arXiv:1706.05639, PRL 2017

A Bayesian approach (ii) :Joint observations with GRB

■ GW+sGRB: GRB isotropic luminosity



$$f_{\rm th}(d, L_{\rm iso}, \theta_{\rm jet}) = \frac{L_{\rm iso}}{4\pi d^2}.$$

$$p(L|I) = \frac{0.4}{L_{min}}\left(\frac{L}{L_{min}}\right)^{-1.4}.$$

with a lower cut-off luminosity $L_{min} = 10^{49}\,\mathrm{erg\,s^{-1}}$.

GRB 170817A luminosity

- GW170817 and GRB 170817A
  (LVC+ Fermi+ INTEGRAL, APJL, 2017)

estimated using a Bayesian approach proposed by Fan (2017). Assuming a flat prior on isotropic luminosity, we obtain $L_{\mathrm{iso}} = 1.2^{+0.7}_{-0.6} \times 10^{47}$ erg s^{-1}, which is consistent with the standard GBM approach. This Bayesian approach can be used to combine future joint GW-GRB observations to provide a redshift-independent estimate of the GRB luminosity function.

CBC is not the whole story!!

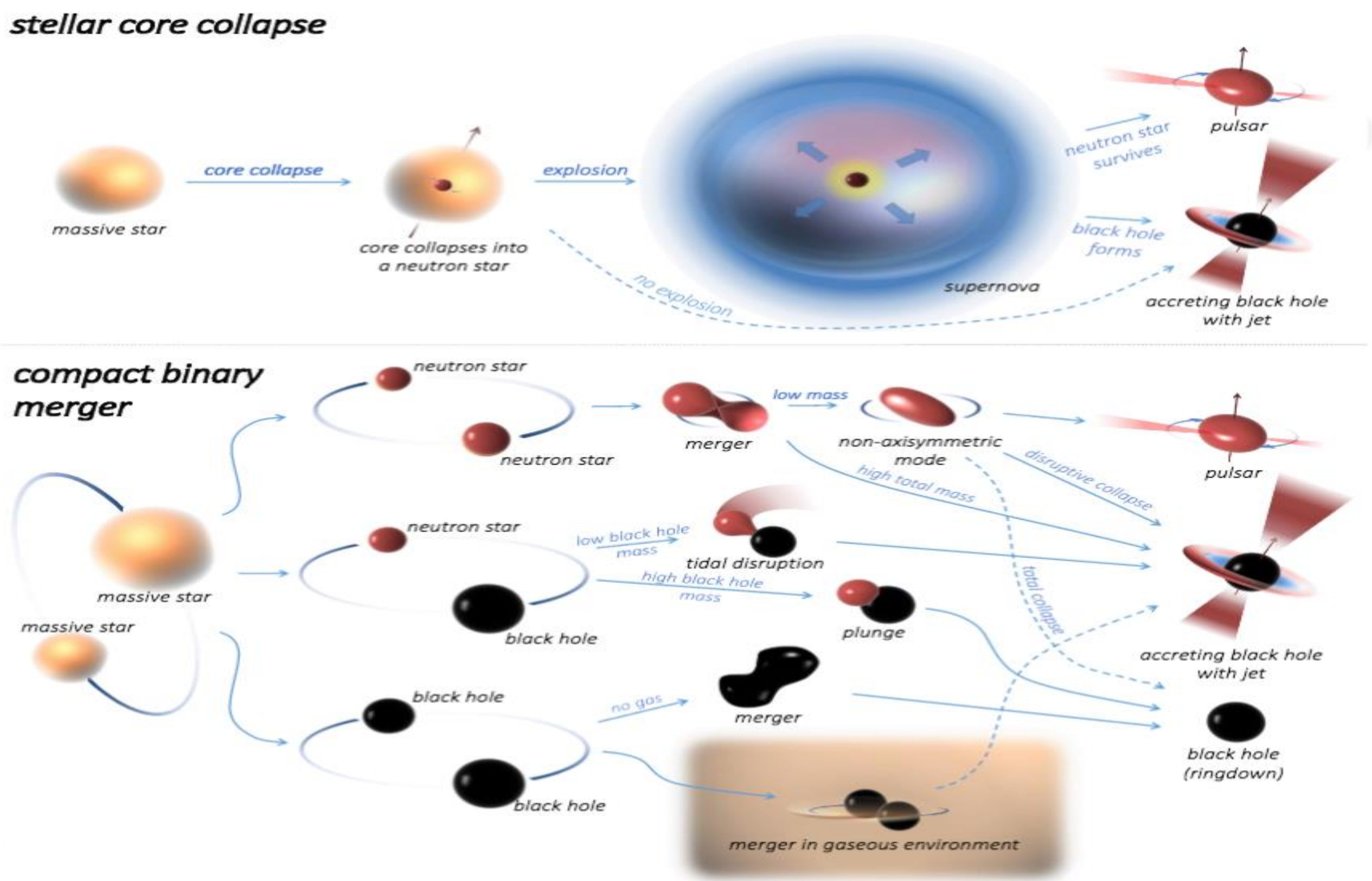
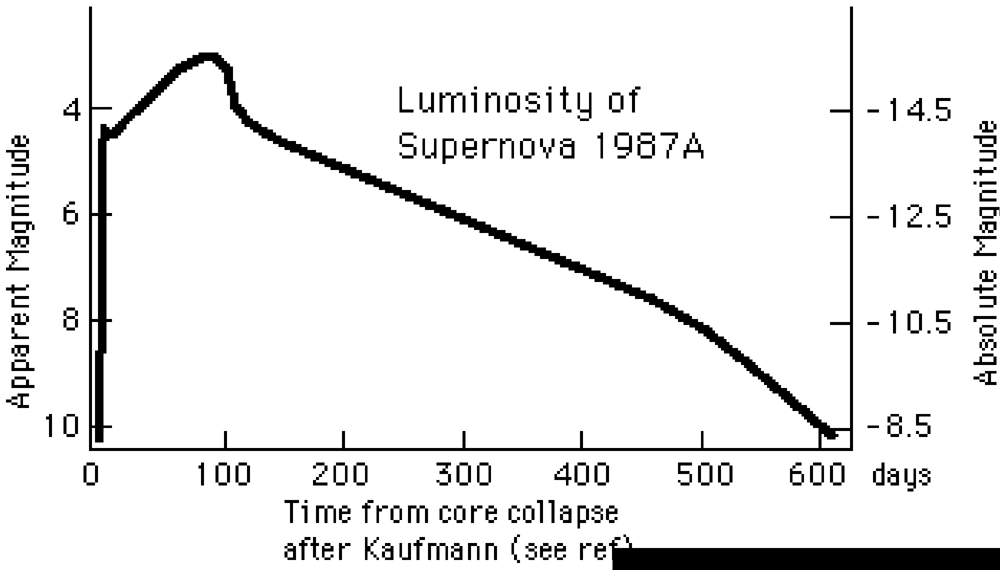


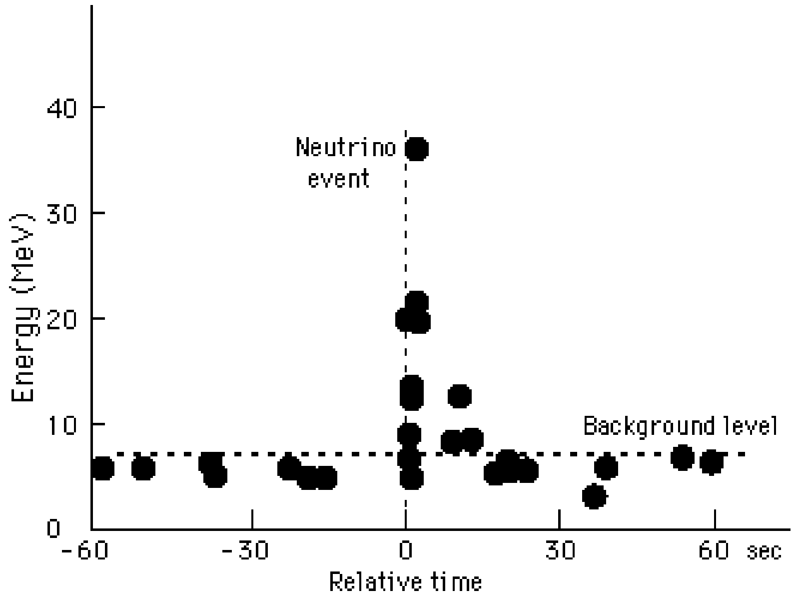
Figure 3: Gravitational wave emission.

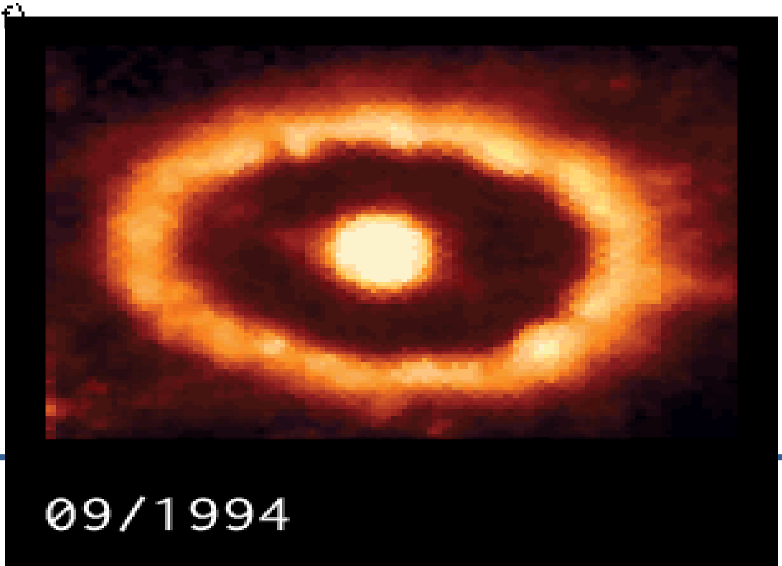
Credits: Bartos & Kowalski

Core-collapse Supernova

SN1987A @ 51.4 kpc

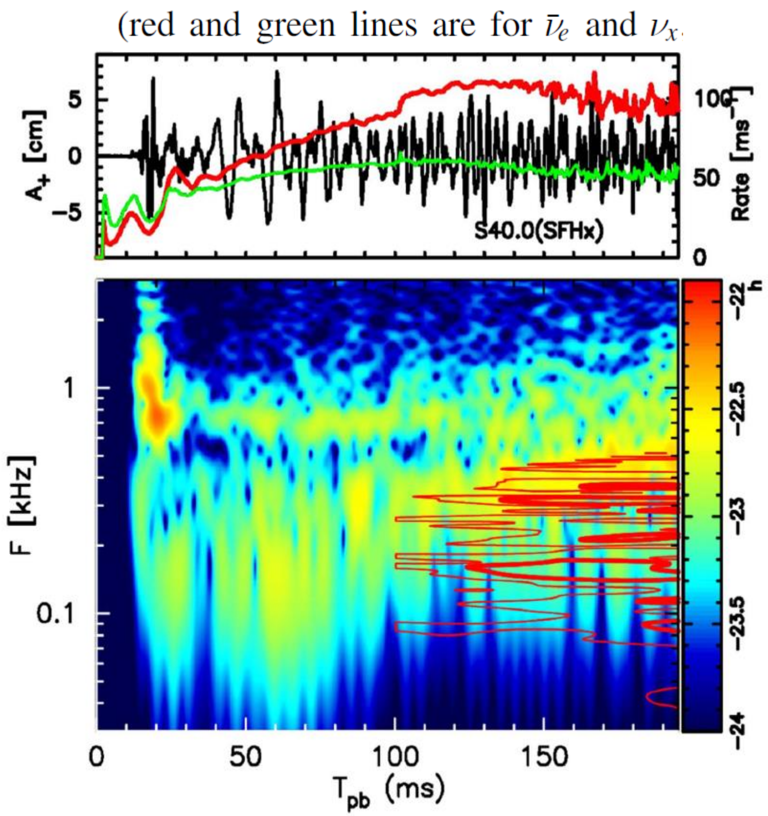


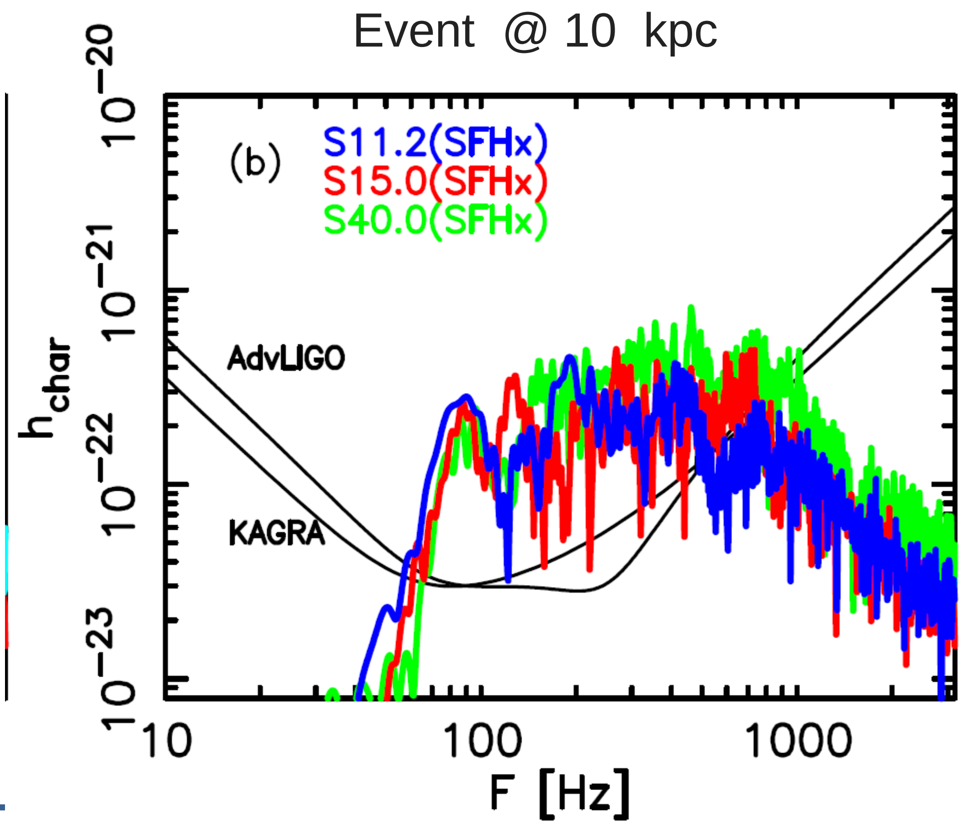




Gravitational-wave and Neutrino Emission

- anti-electron type neutrino spectra and GW spectrum
- GW signals @ 10Kpc

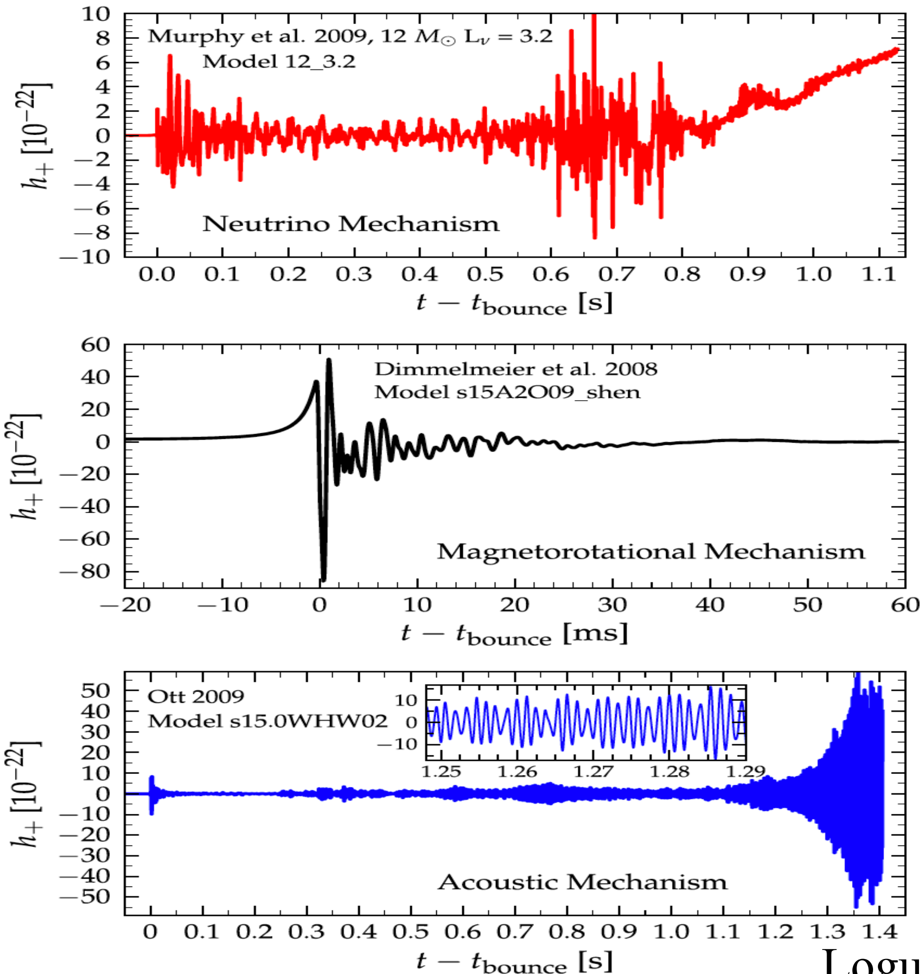


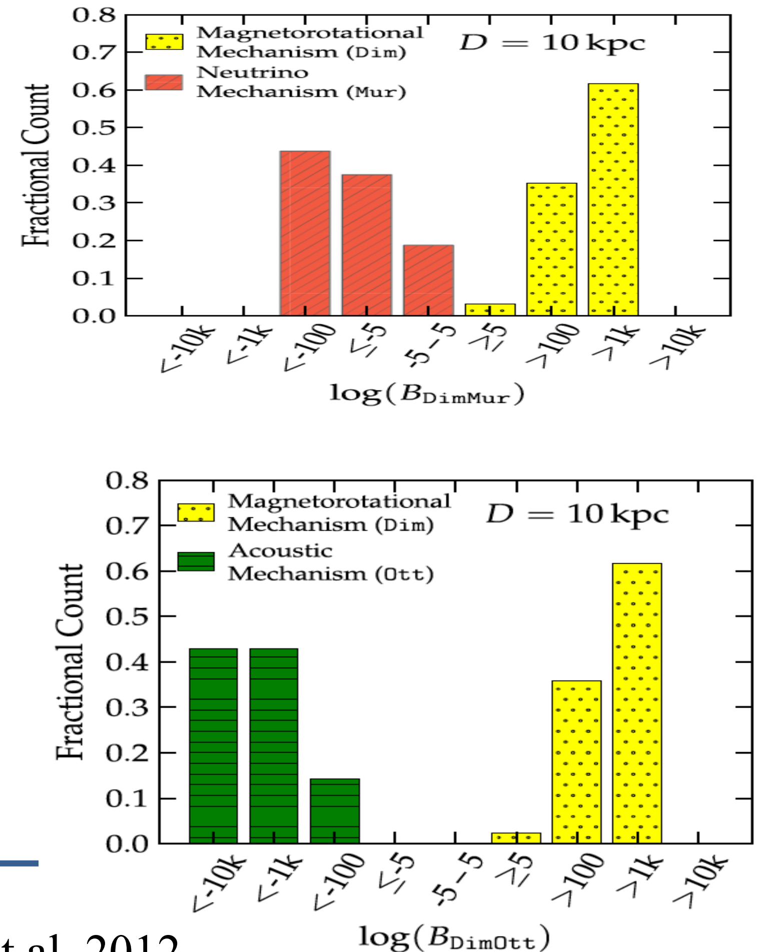


Kuroda et al. ApJ. 2017

GW bursts

- Core-collapse supernova emit GW:
  - mechanisms driving supernovae predict GW waveforms





Logue et al. 2012

Take home message

- The drawing board (our A Bayesian approach) is ready
  - gw-galaxy、 gw-grb
- We just need to wait the model (GW+Neutrinos data)
- 靠谱的painters (GW+Neutrinos experts) enjoy your life ☺
- EM+Neutrinos also works