# Multi-Messenger Astronomy: Recent Progress and Future Outlook

Masaomi Tanaka (Tohoku U.)

# History of astronomy

"Visible" light

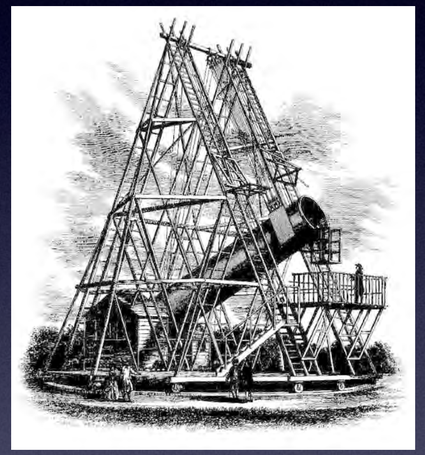
"Multi-wavelength" astronomy

1610-



(C) Astroarts

1789-



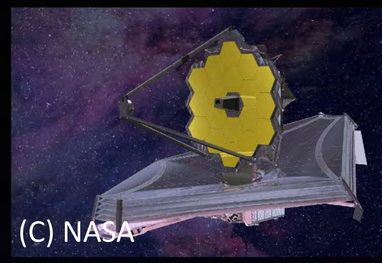
1999-



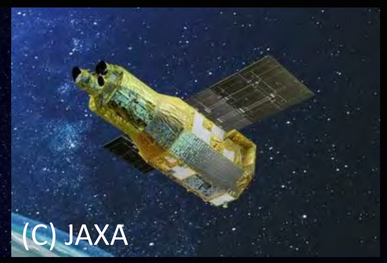

2013-




2021-




2023-




1600

1700

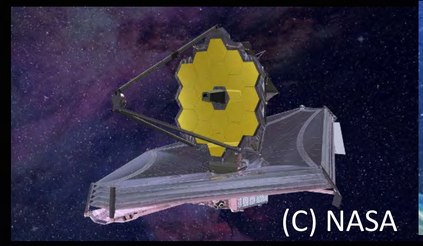
1800

1900

2000

1960s-
Neutrino

2015-
Gravitational wave









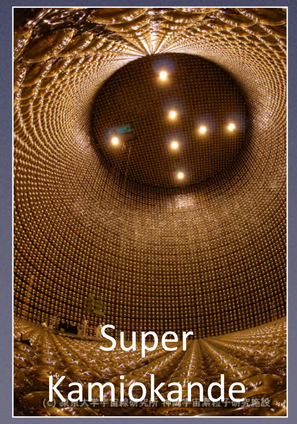


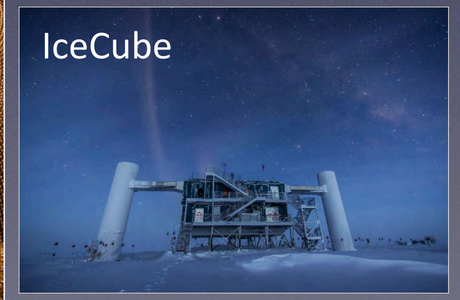


Electromagnetic wave

# Multi-messenger astronomy

## Neutrino




## Gravitational wave







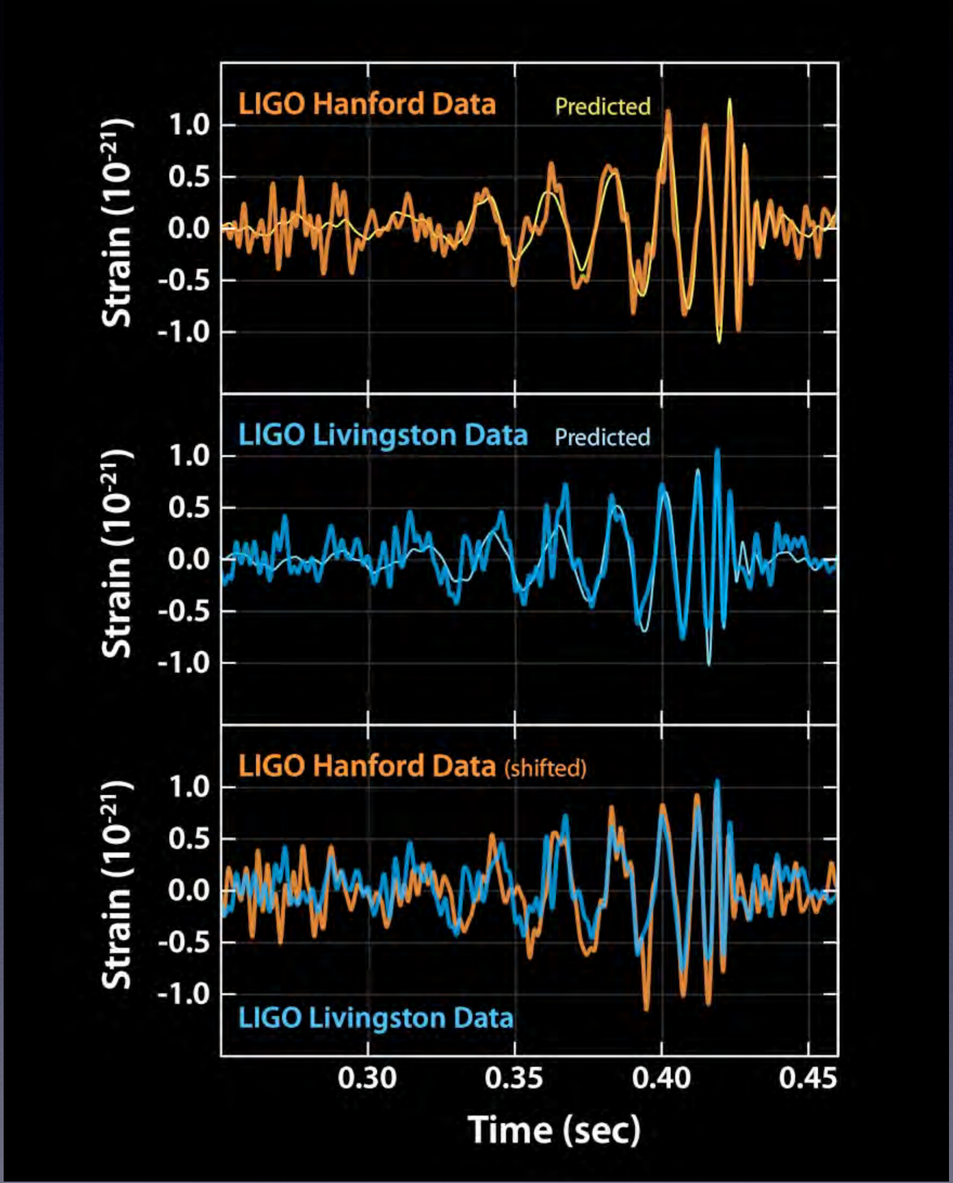




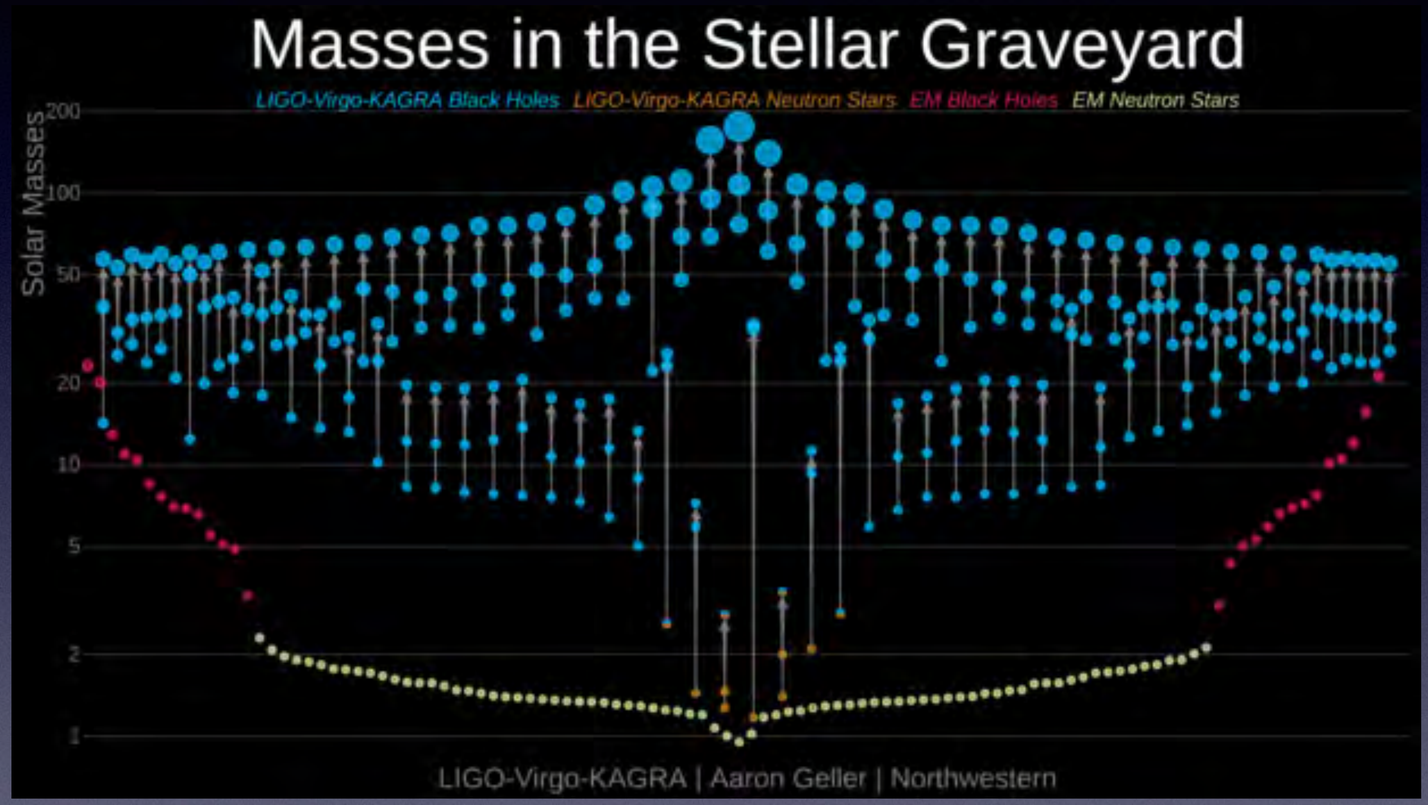

# Multi-Messenger Astronomy:
# Recent Progress and Future Outlook

- **Gravitational wave + Electromagnetic wave**
- **Neutrino + Electromagnetic wave**
- **Future**

# First observations of gravitational waves (2015)

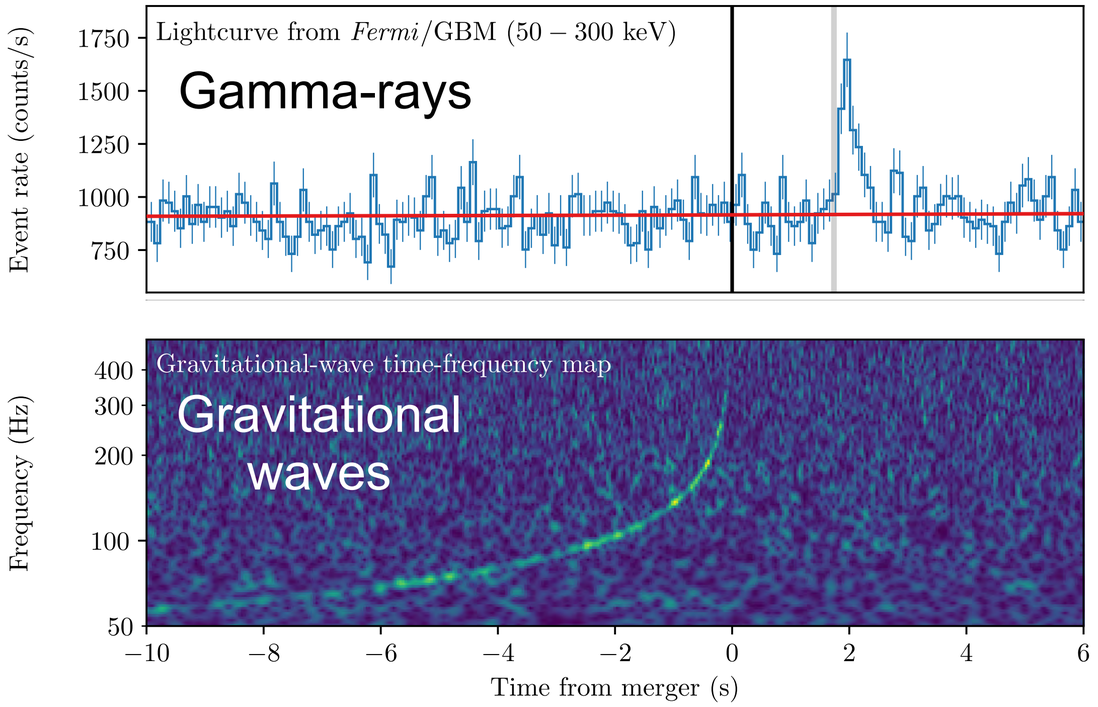



(C) LIGO

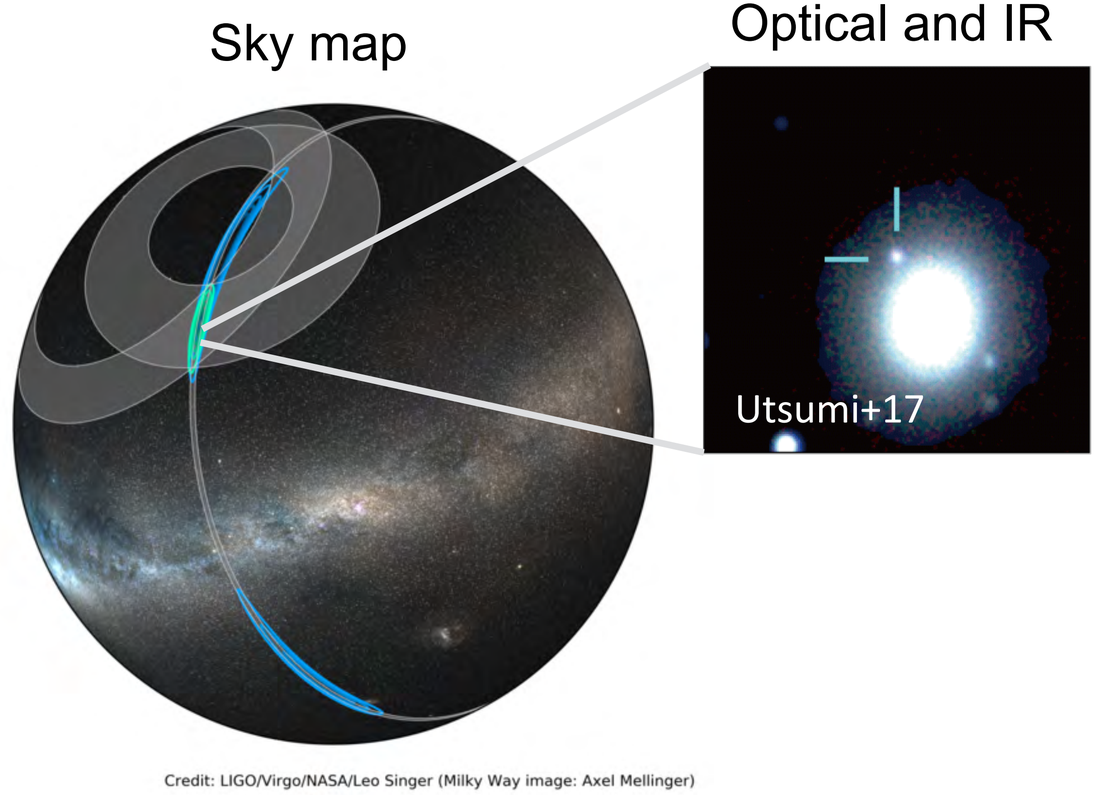



**Merging black holes**

# First observations of neutron star merger (2017)

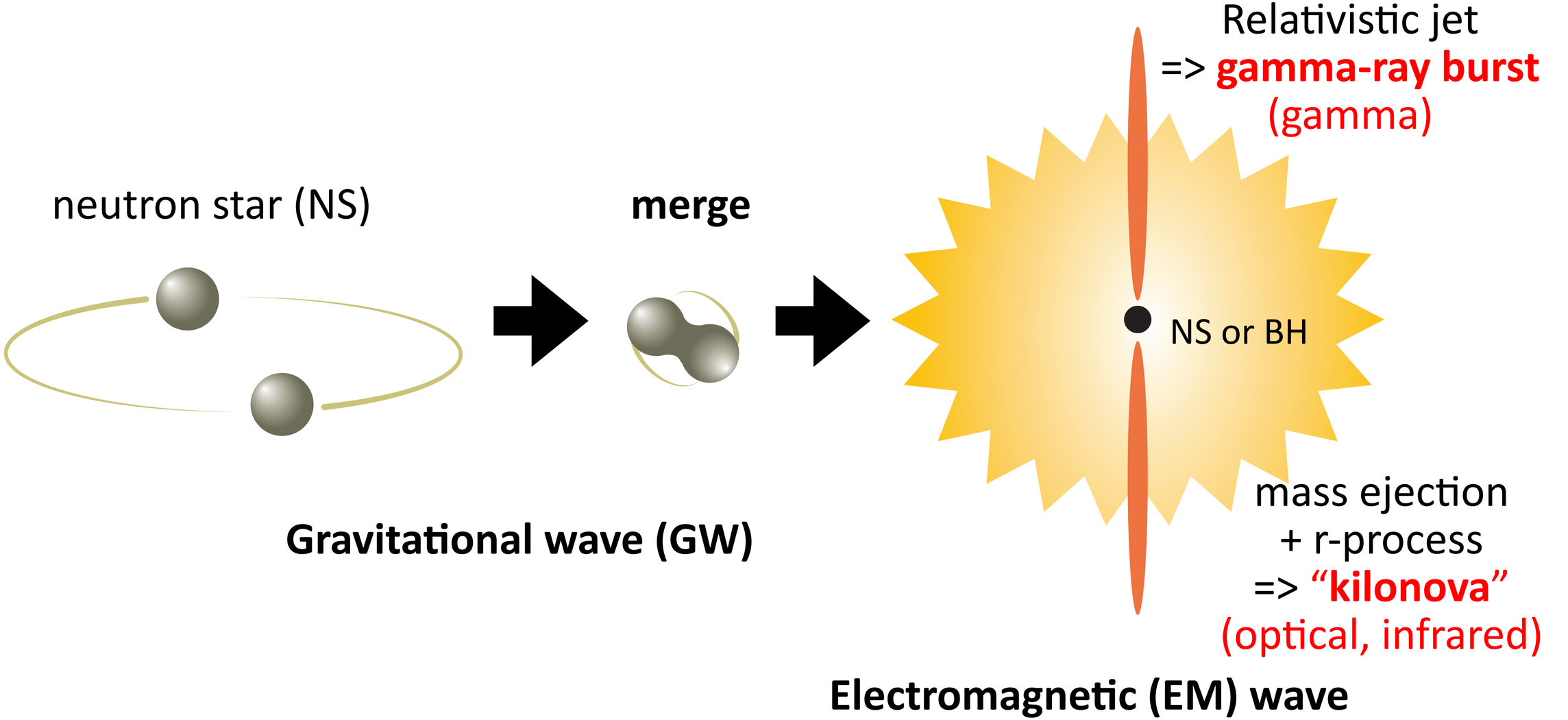



Abbott+2017



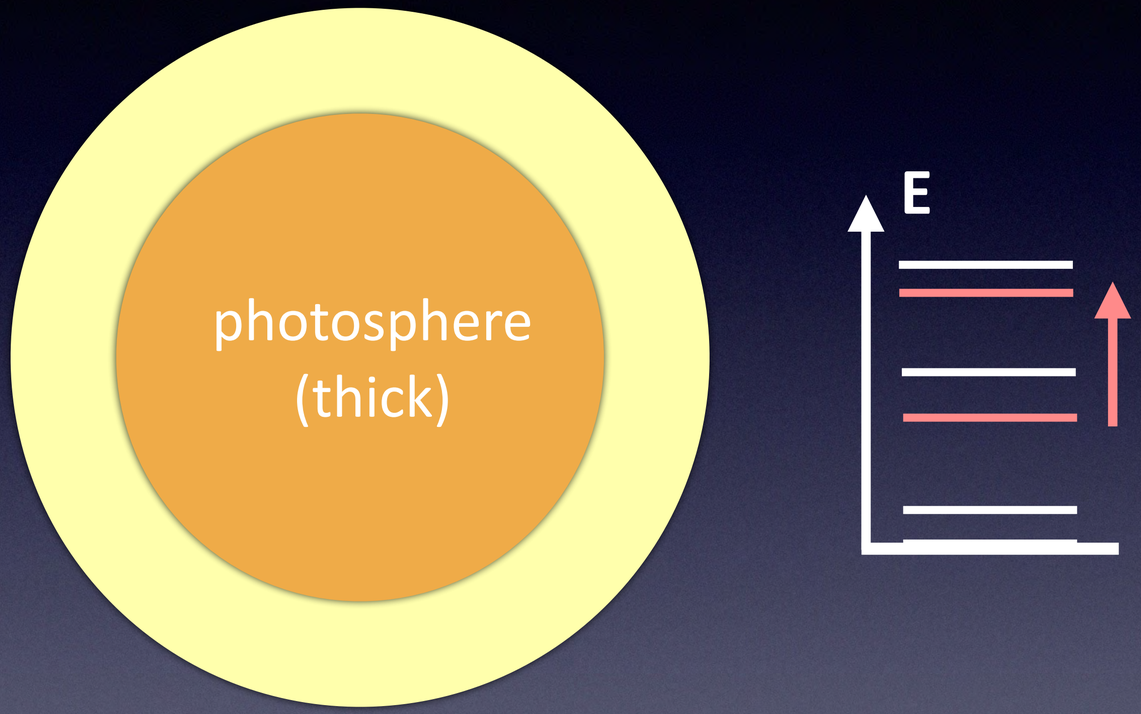

**“Multi-messenger” observations**

# Multi-messenger signals from neutron star merger



# Heavy elements in kilonova spectra?

absorption feature

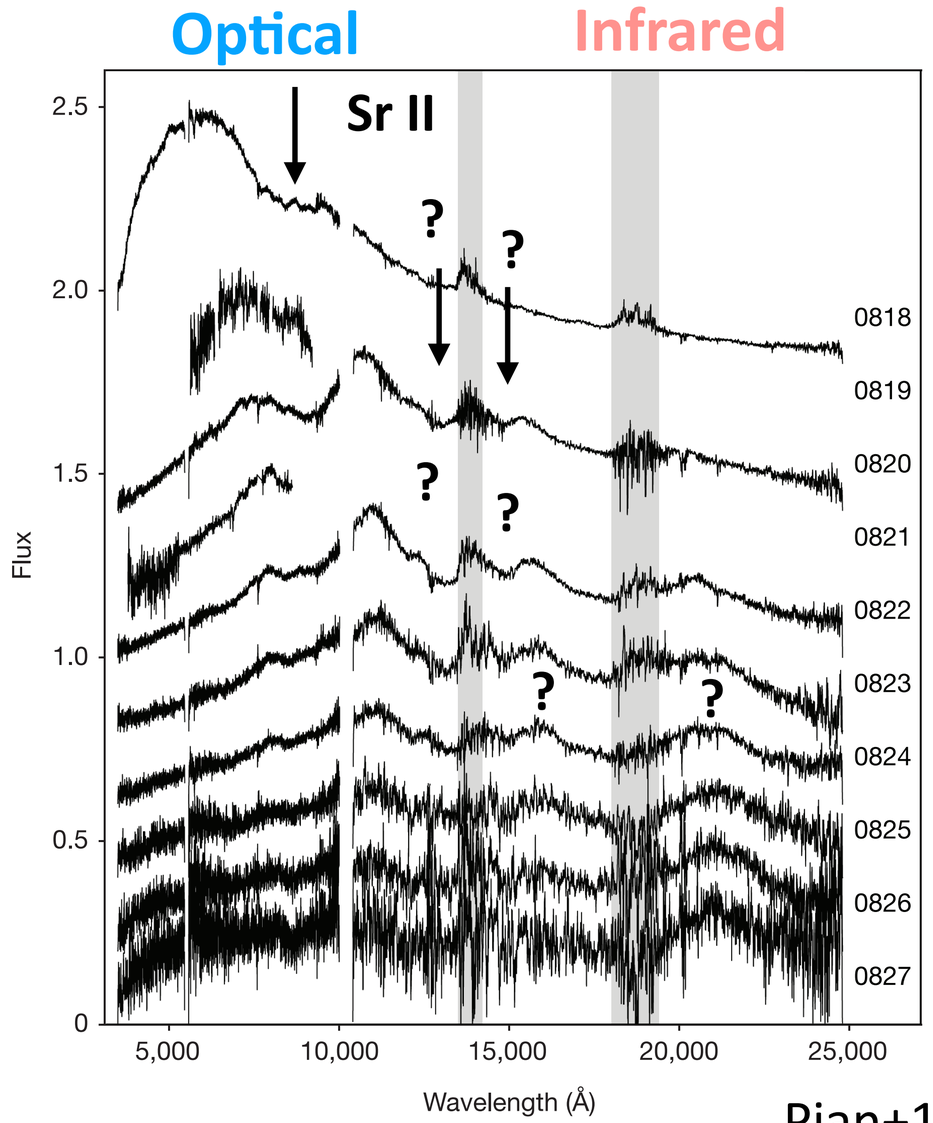






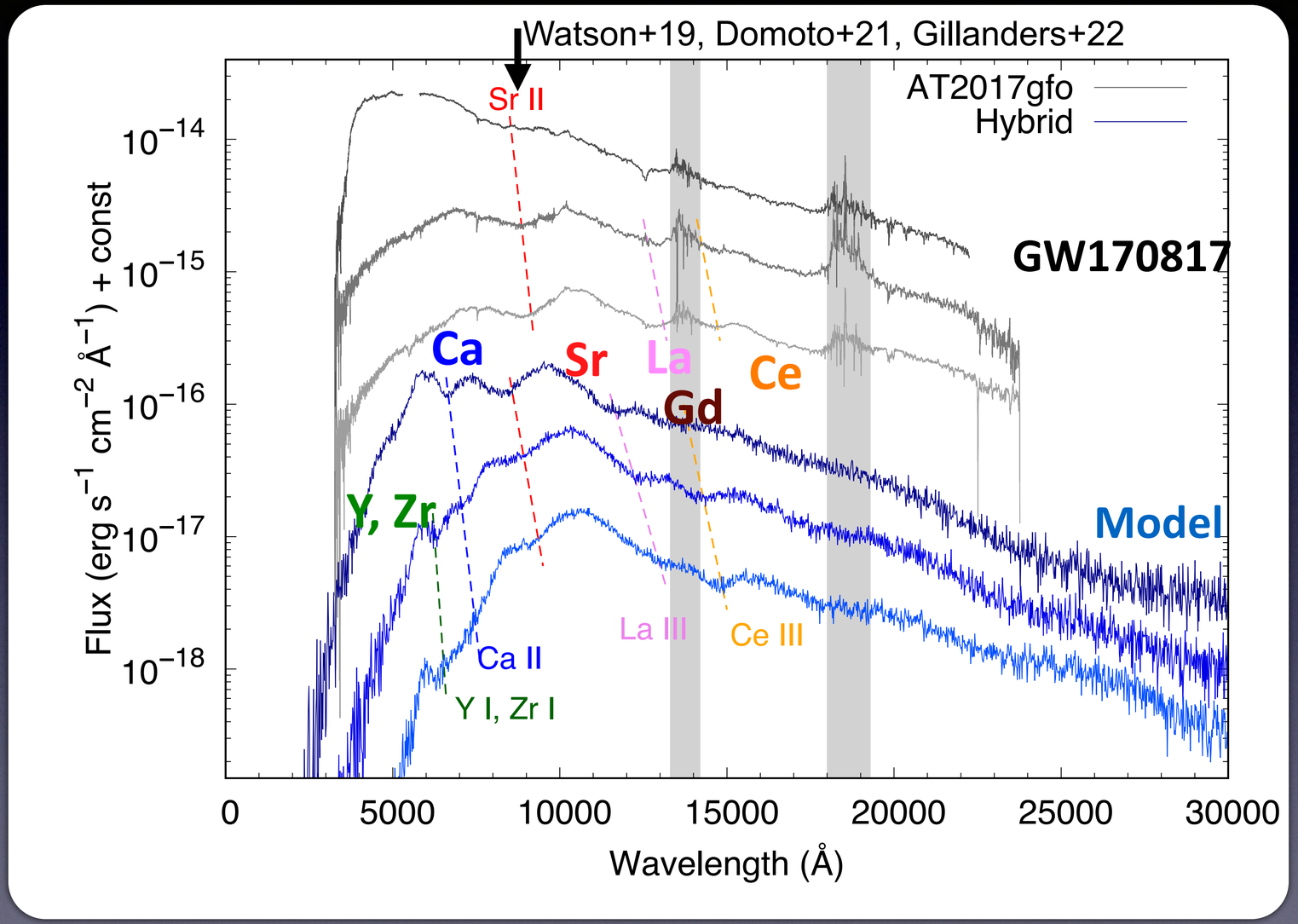
**Element identification has been challenging**
**- large Doppler shift**
**- Incomplete atomic data (in particular IR)**

**GW170817/AT2017gfo**

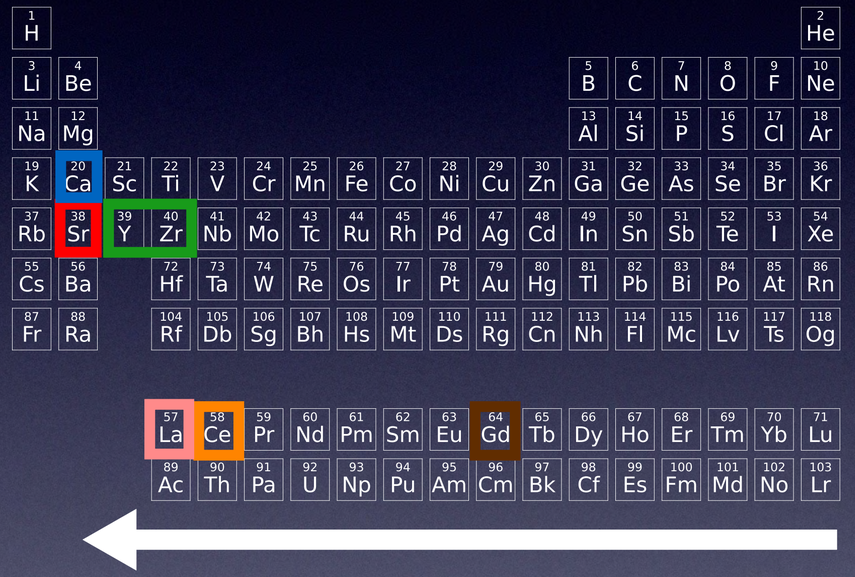



Pian+17

# Progress: identification of heavy elements




Domoto,+22, 23, MT+23, Rahmouni+25

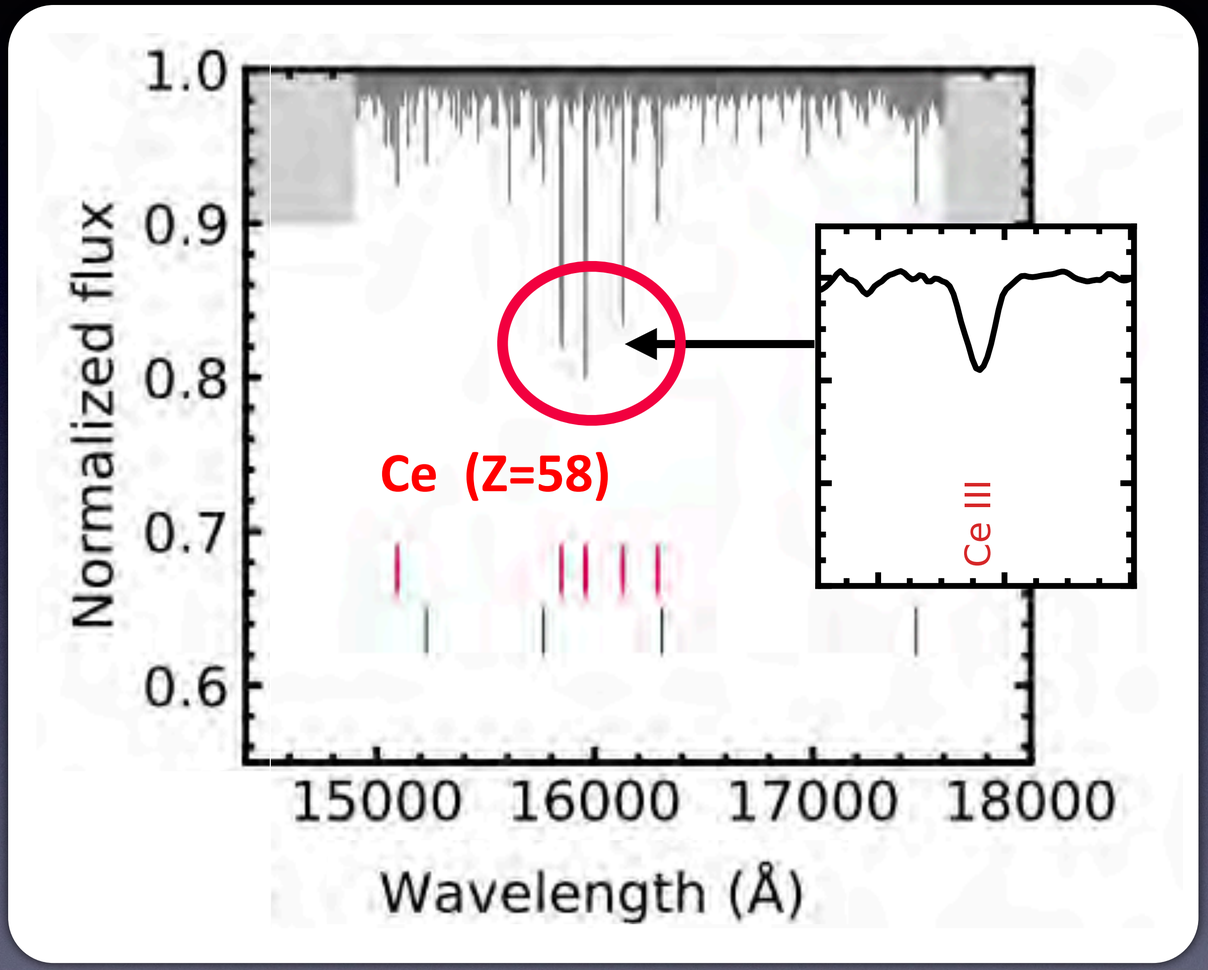



See S. Rahmouni's talk

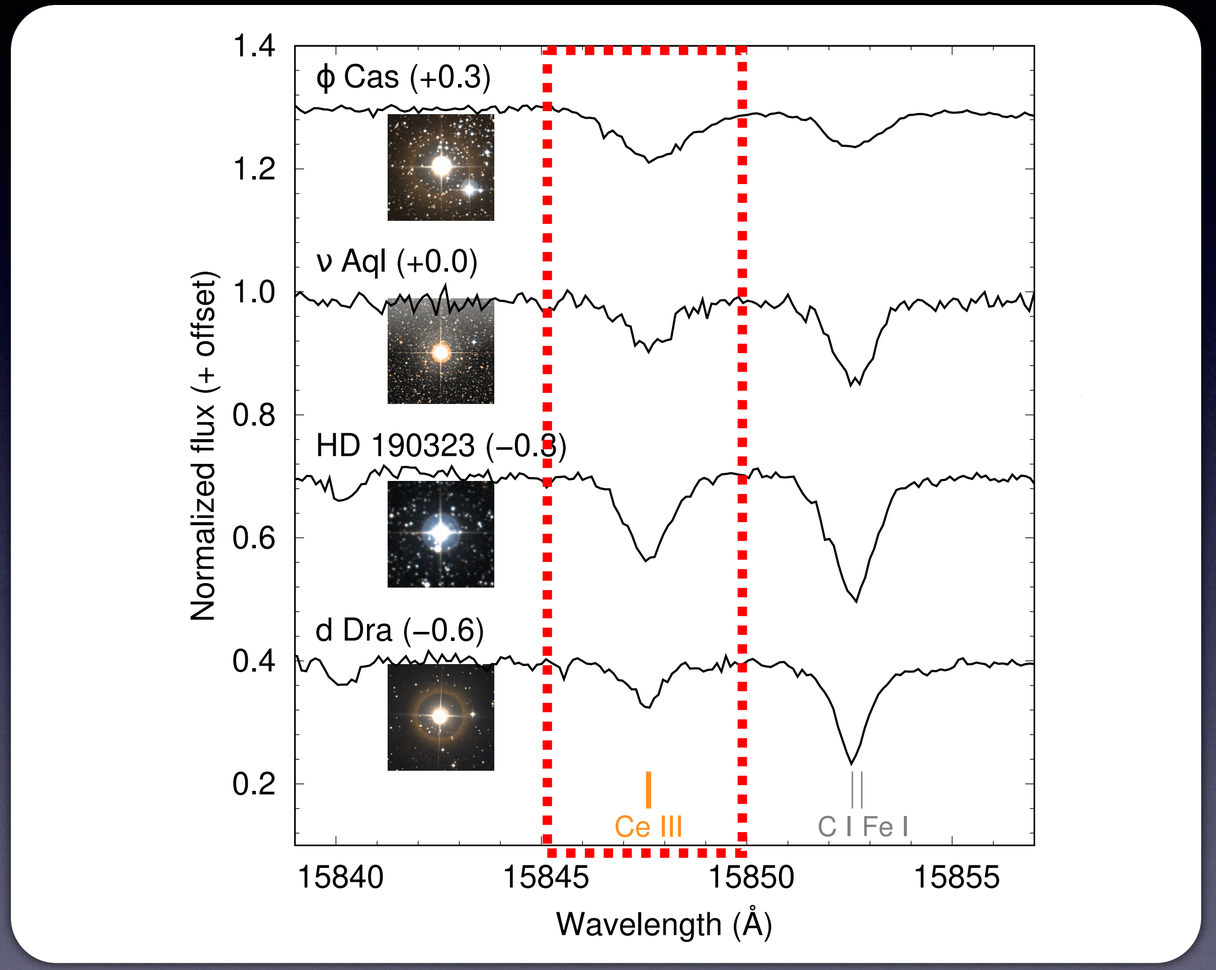
**Direct evidence of heavy element production**

# “Experiments” with stellar spectra (IGRINS)

Collaboration with KASI team



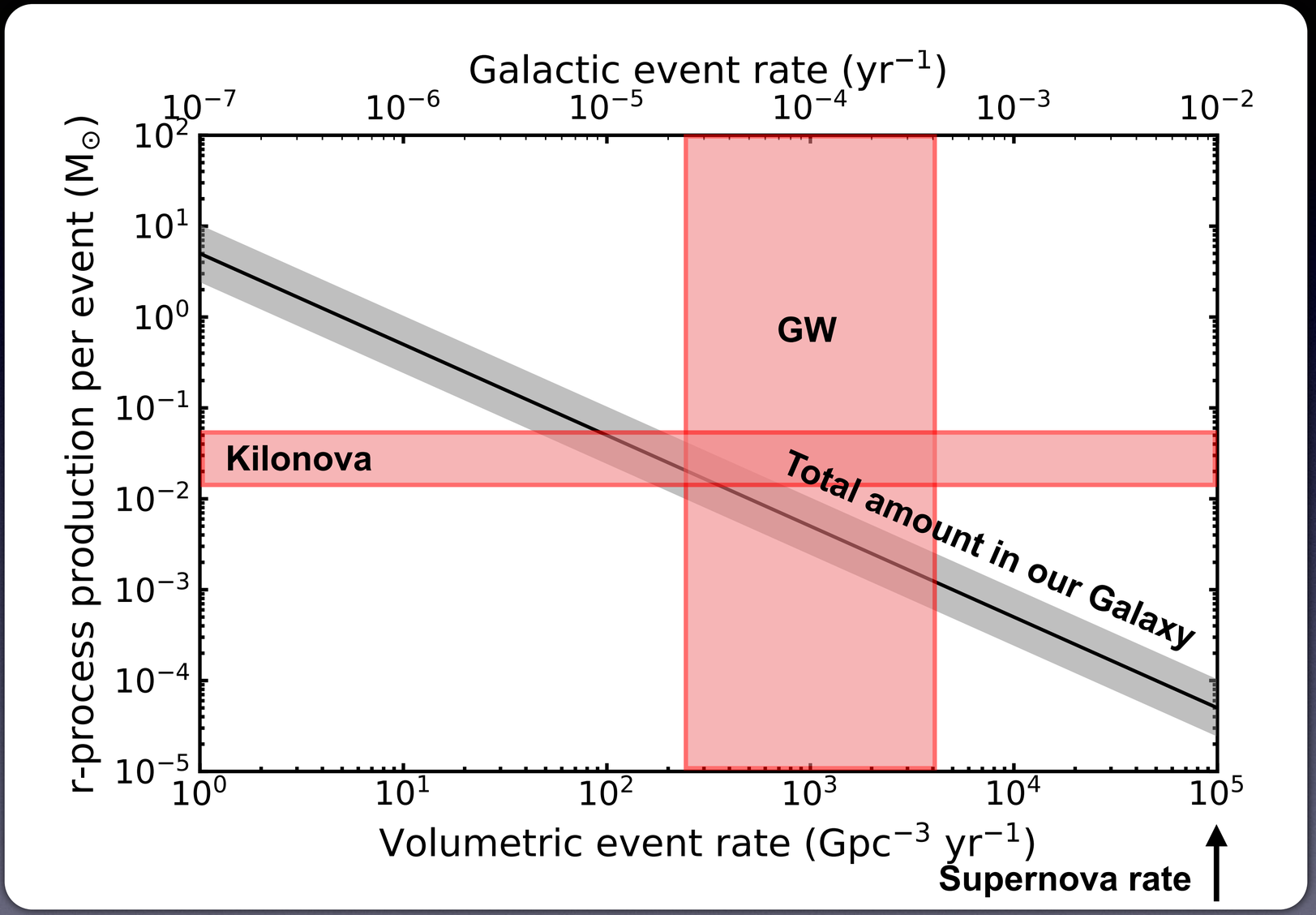

MT, Domoto, Aoki et al. 2023




Domoto, Lee, MT et al. 2023

**Strong support of element identification in kilonova**

# Production rate of heavy elements




Rosswog+17
Hotokezaka+15, 18

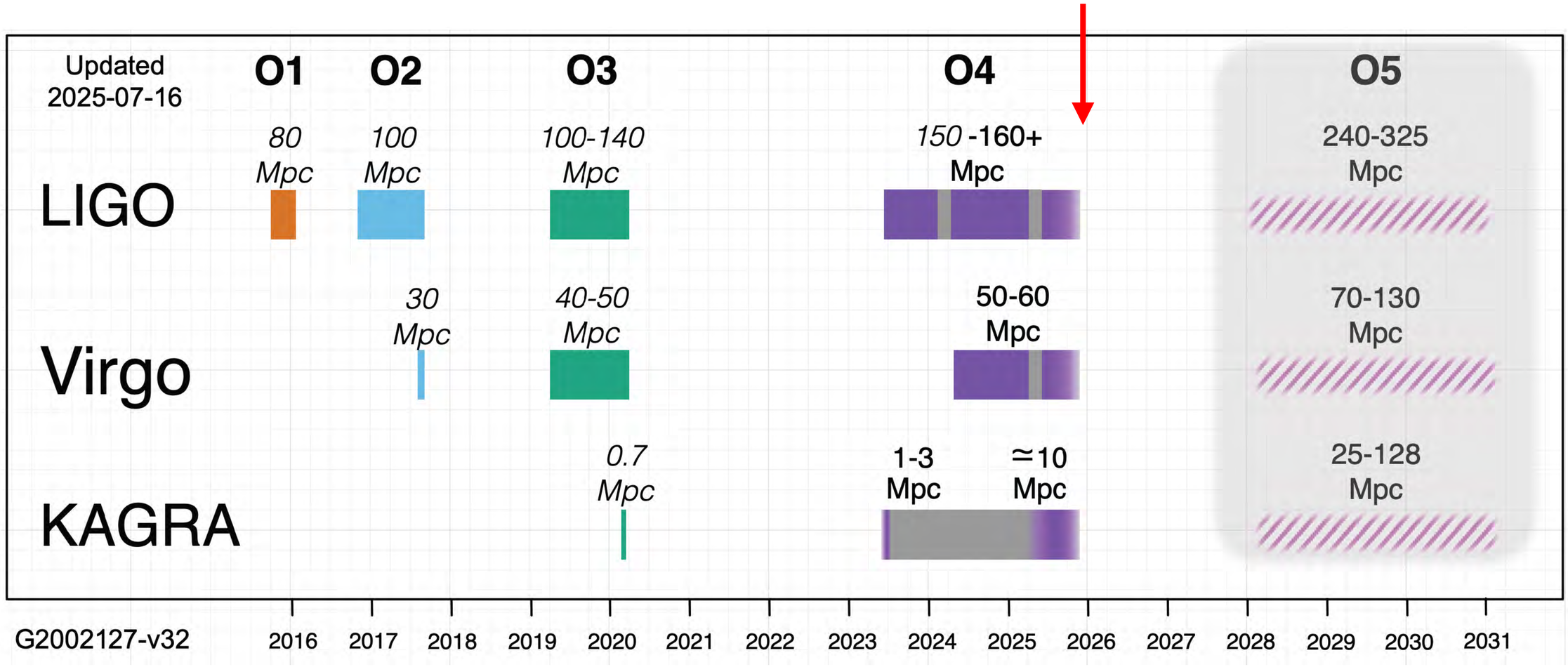
**Neutron star mergers can provide enough amount of heavy elements**

# Power of multi-messenger astronomy

| | GW | EM |
|---|---|---|
| Origin of GRBs | Nature of merging objects | Gamma-ray burst |
| Origin of elements | Nature of merging objects | Kilonova |
| Cosmology | Luminosity distance | Redshift |
| Fundamental physics | Speed of GW | Speed of light |

(C) Tohoku University

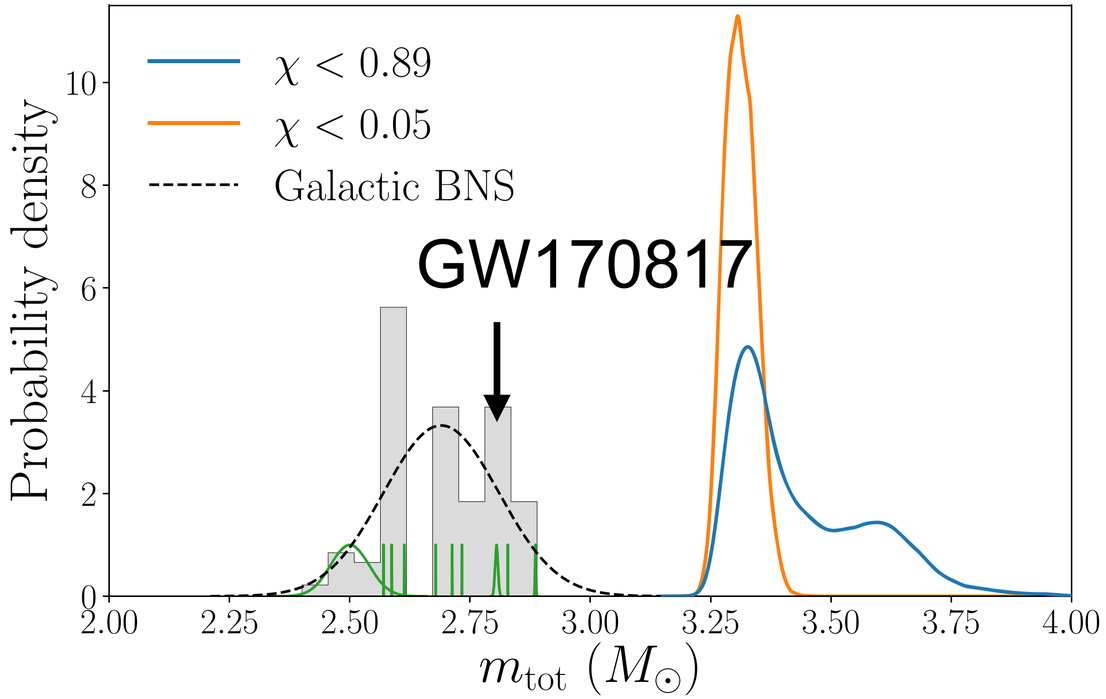
# Status of GW observations




https://observing.docs.ligo.org/plan/

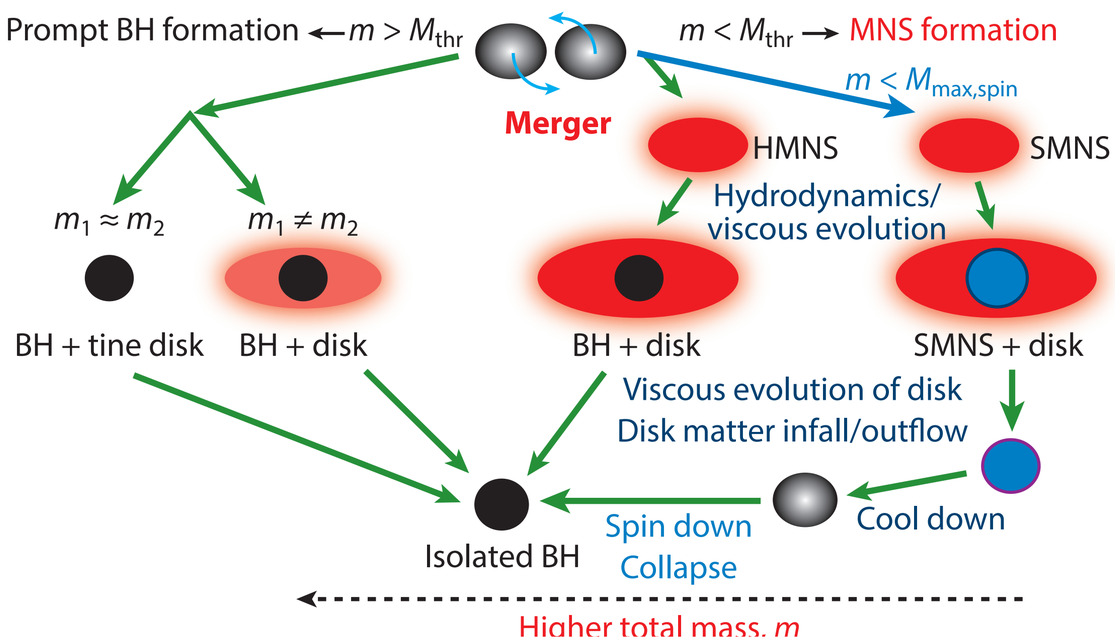
# GW190425: 2nd NS merger event in O3 (no EM counterpart)

## Total NS mass ~ 3.4 Msun




Abbott+2020

## Direct collapse to BH?




Shibata & Hotokezaka 19

**Diversity in neutron star masses**
**=> diversity in mass ejection, nucleosynthesis, and kilonova**

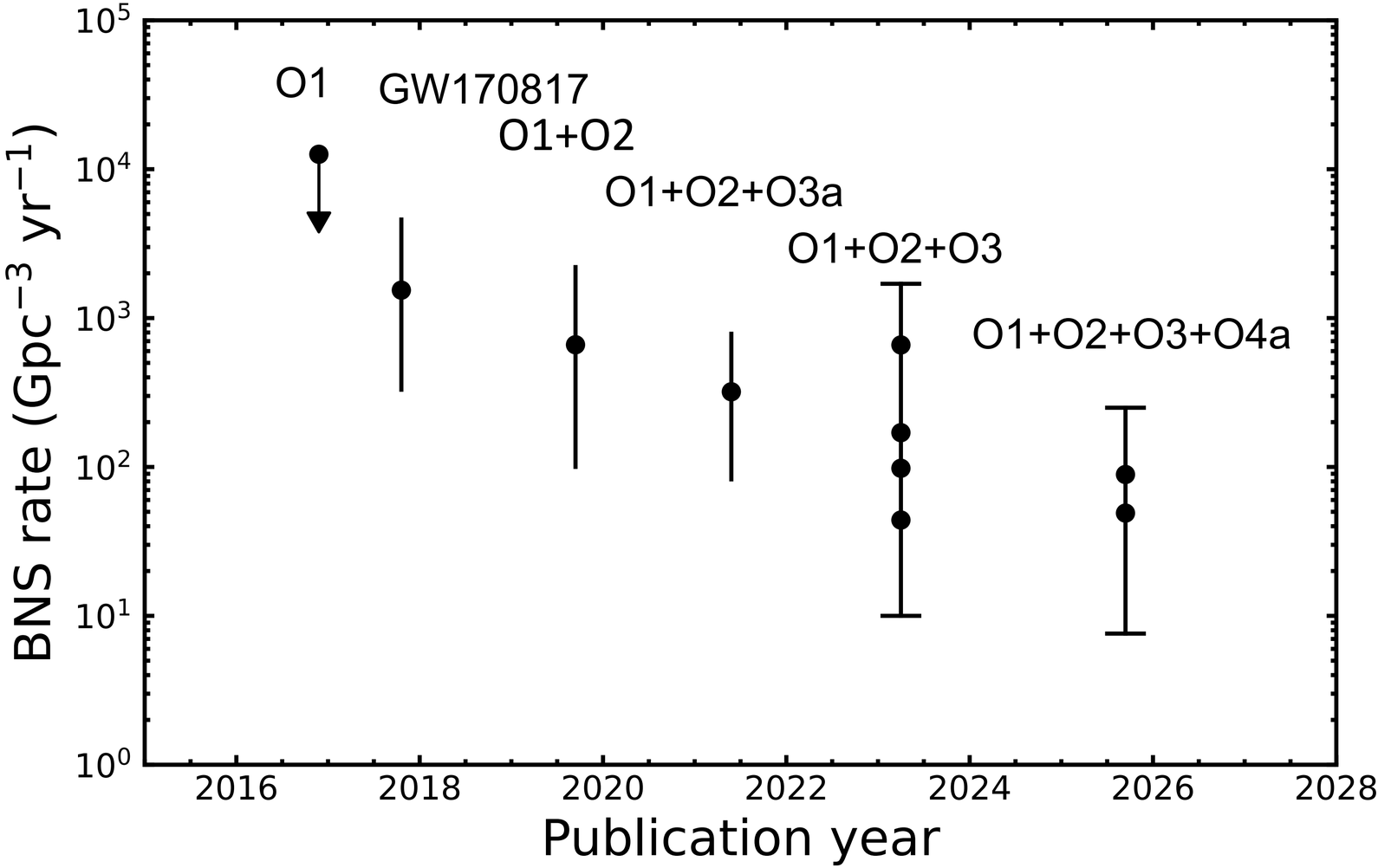
# Event rate of neutron star merger

**# of events within 100 Mpc**

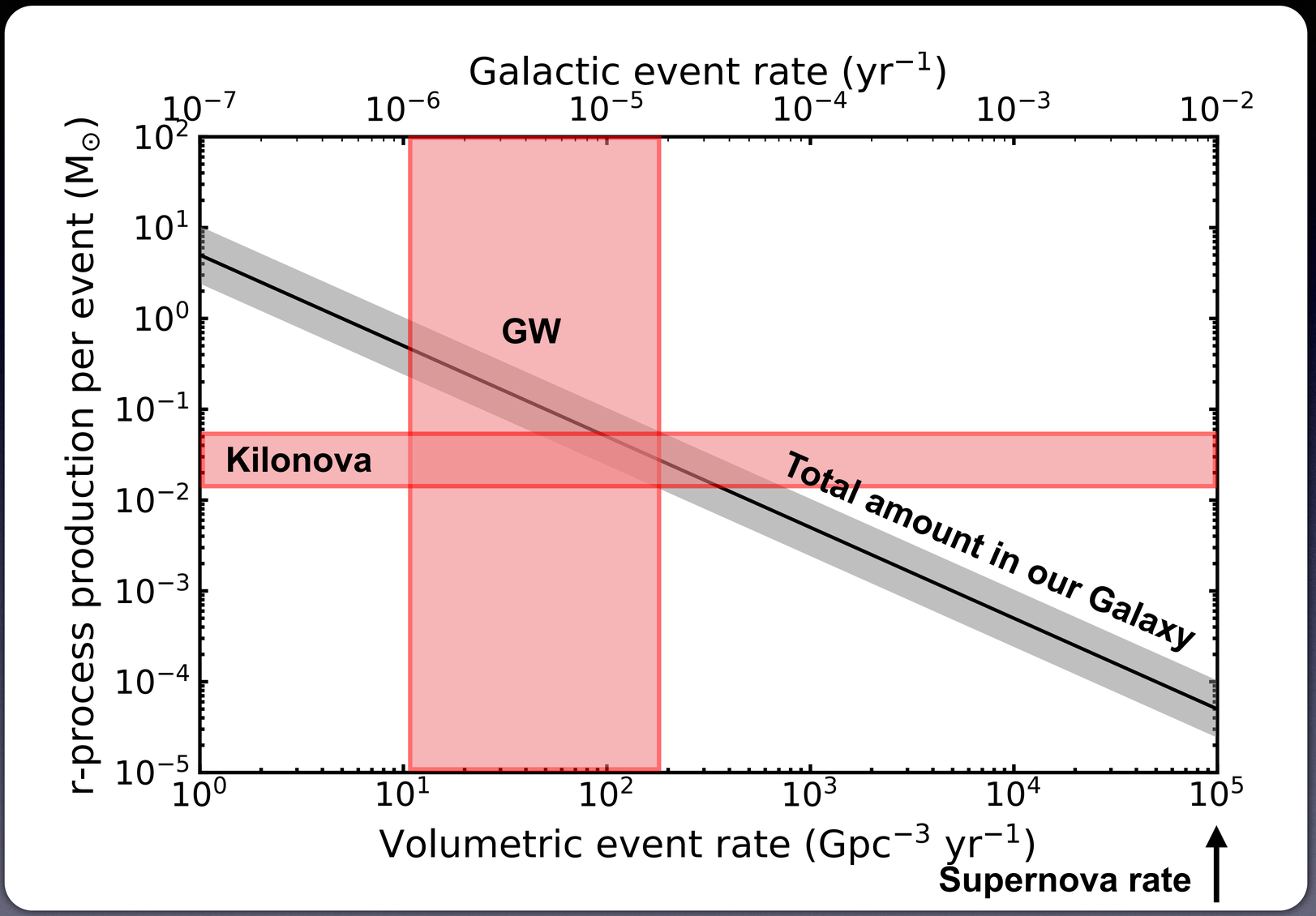
~4 events/yr

~0.4 events/yr

~0.04 events/yr



# Production rate of heavy elements




Rosswog+17
Hotokezaka+15, 18

**Possible tension??**

# Multi-Messenger Astronomy: Recent Progress and Future Outlook

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- Neutrino + Electromagnetic wave
- Future

# Observations of neutrinos

**1960s-**

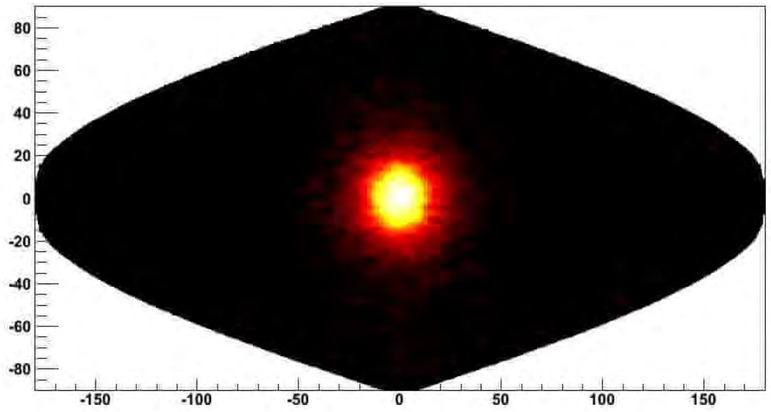
**Sun**
**(MeV)**

**1987**

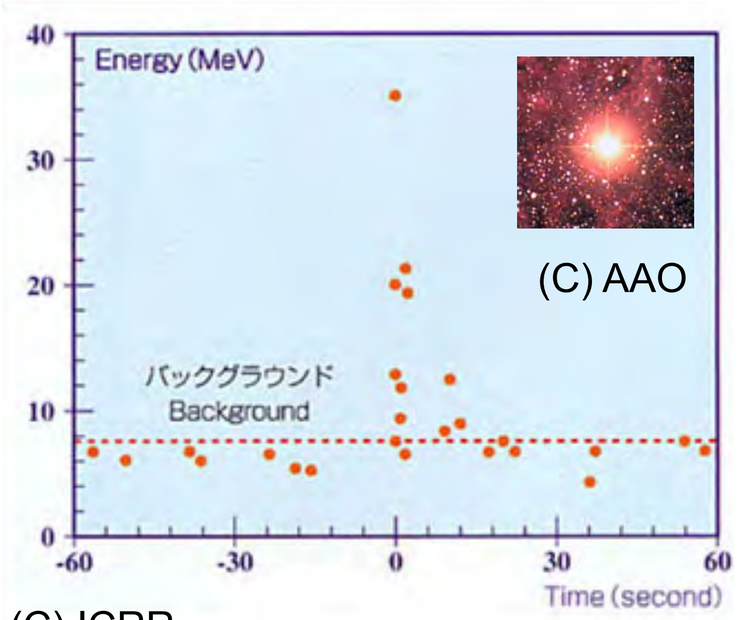
**Supernova**
**(MeV)**

**2012-**

**High-E neutrino**
**(> TeV)**

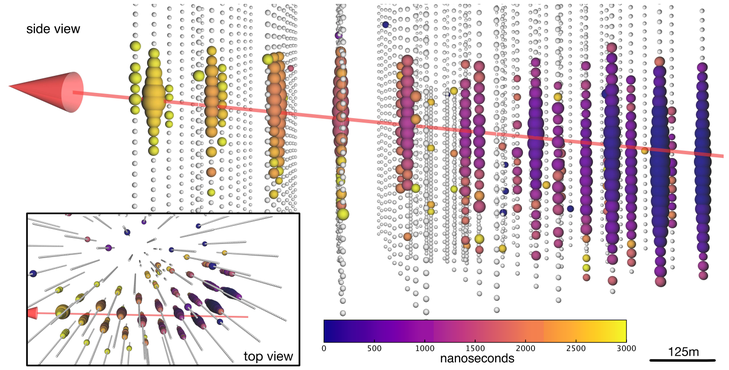



(C) ICRR, Super Kamiokande



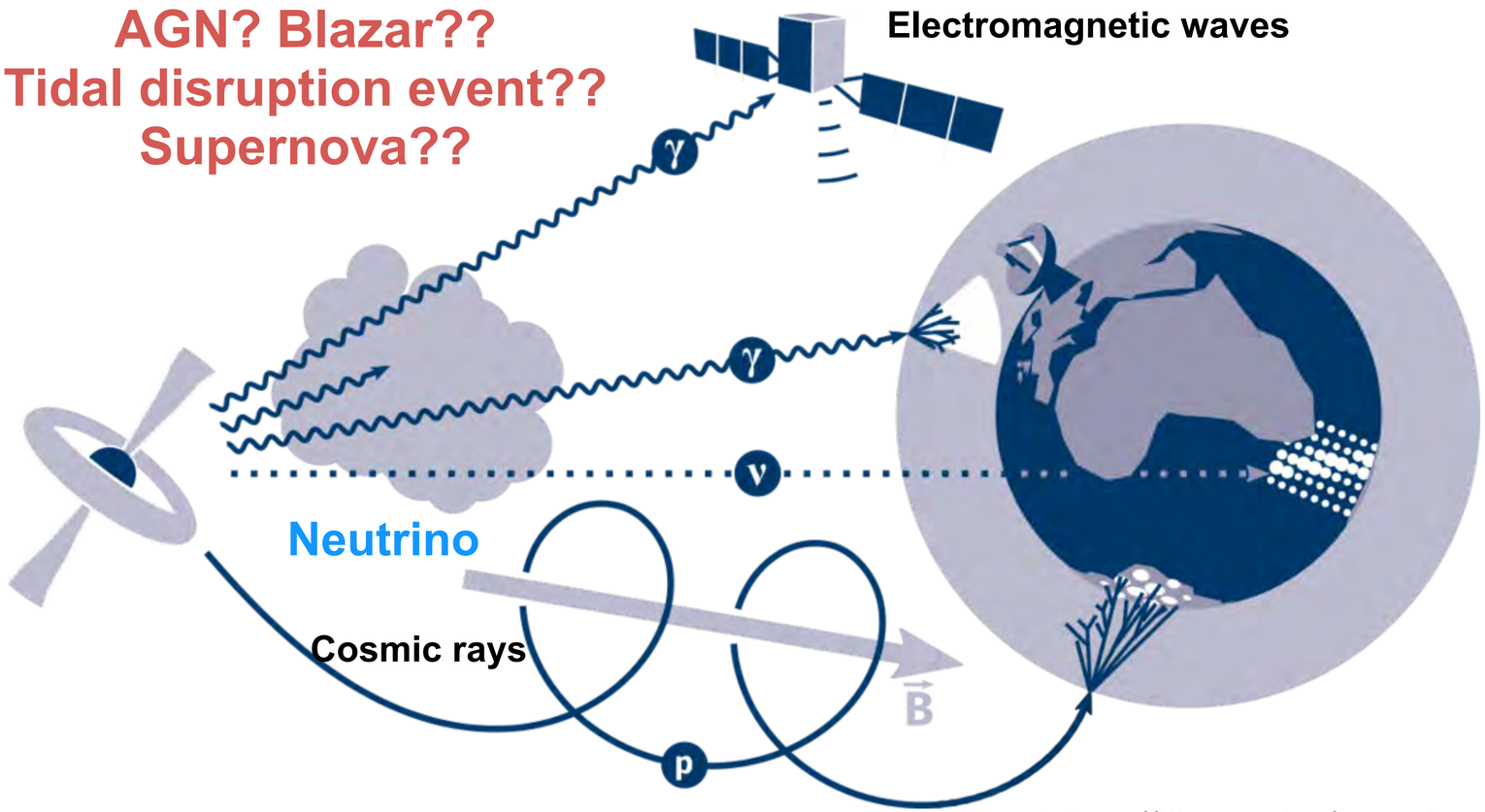

(C) AAO

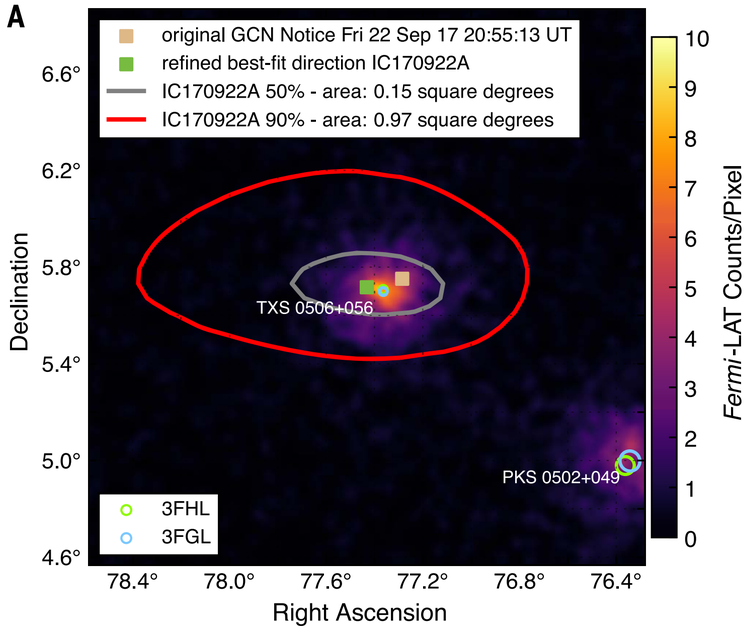
(C) ICRR




IceCube+18

# Power of multi-messenger astronomy




IceCube+18

**Identification of neutrino source**
**Origin of high-energy cosmic rays**

# Challenges in neutrino follow-up

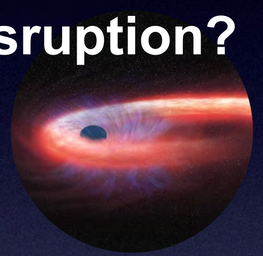
## Unknown source

supernovae ?



(C) NASA/SDO

tidal disruption?



(C) NASA/CXC/M. Weiss

energetic supernovae ??



(C) ESO

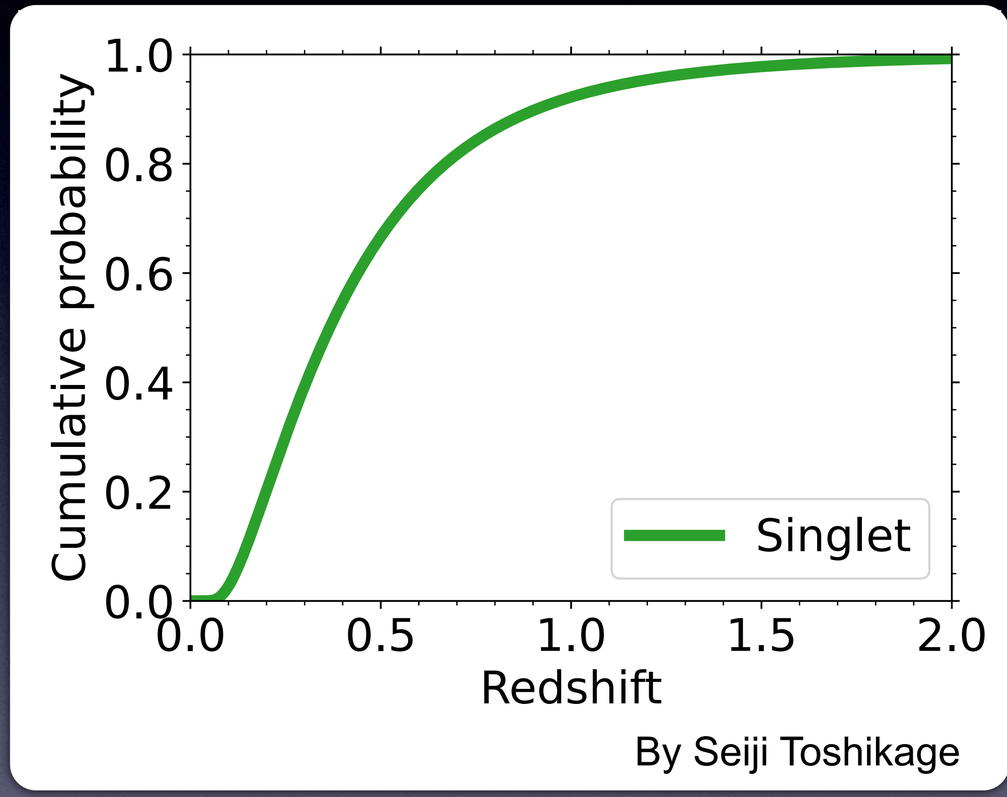
blazars / AGNs??



(C) NASA

c.f. gravitational wave

## Large distance




**Search for “something special”**

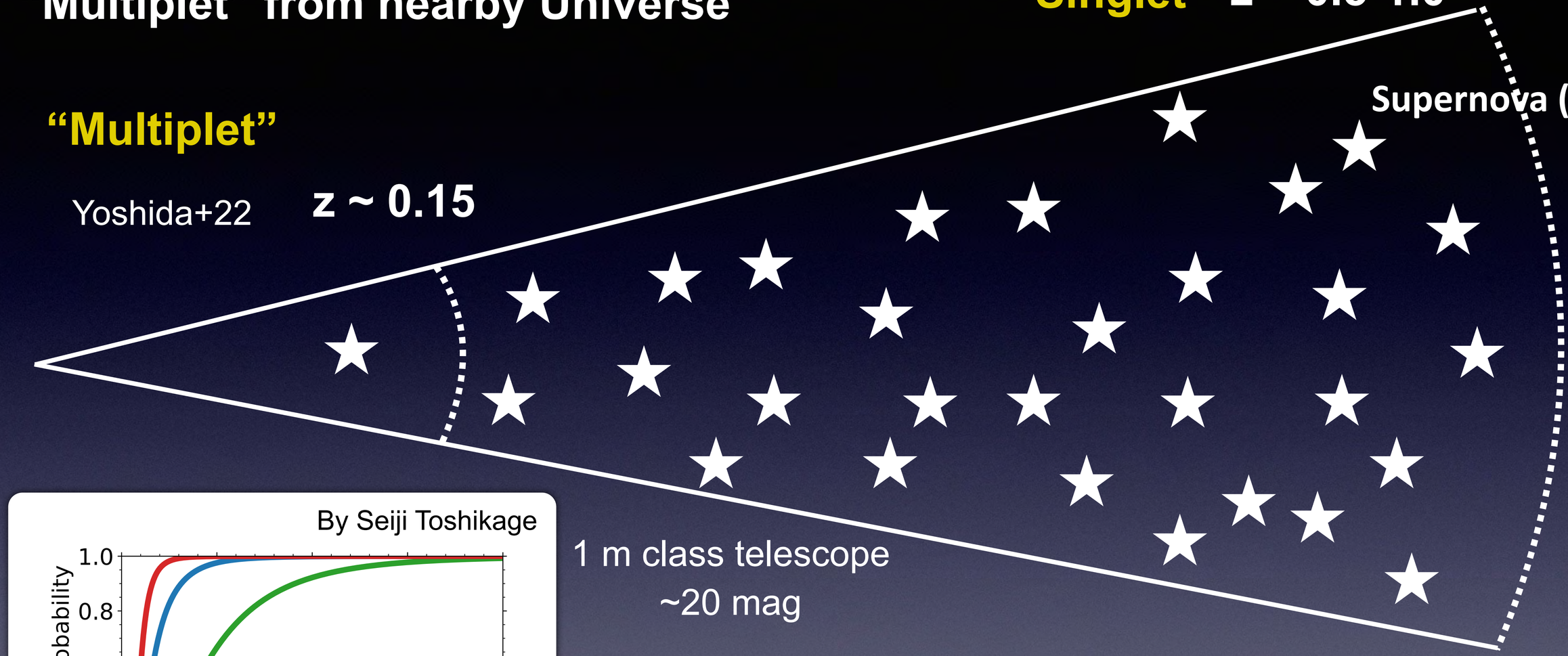
# “Multiplet” from nearby Universe

**Singlet** z ~ 0.5-1.0

Supernova (SN)

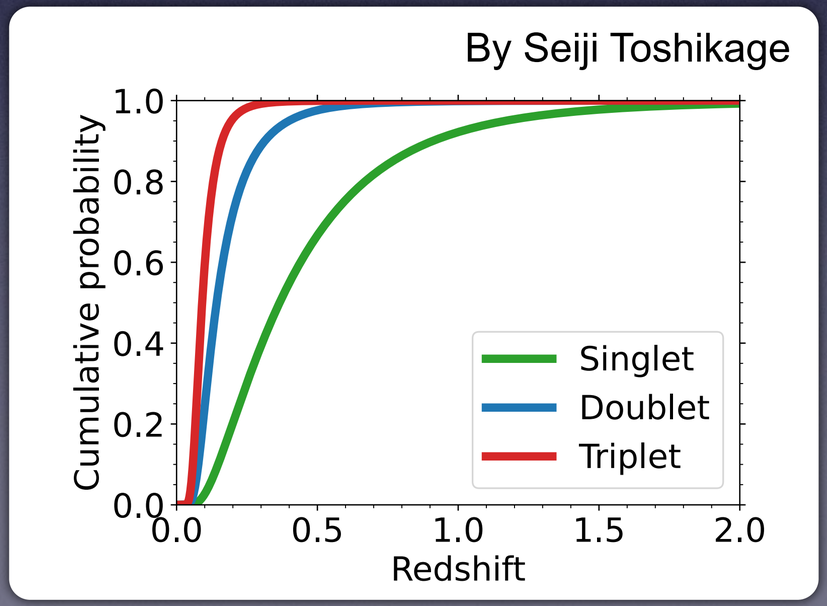
**“Multiplet”**

Yoshida+22 **z ~ 0.15**



1 m class telescope

~20 mg




**8 m class (or space) telescope**

~25 mag

Subaru, Rubin

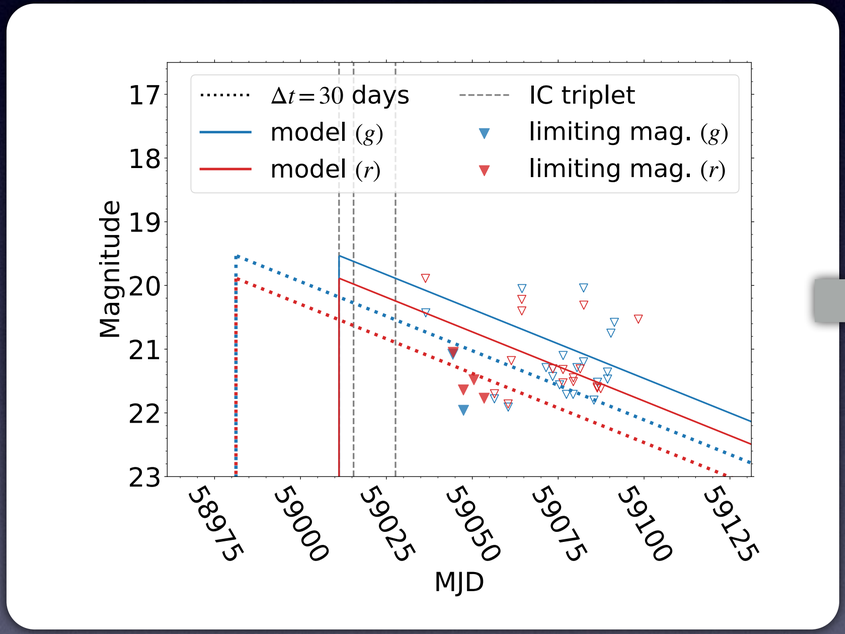
See the talk by L. Hao (CSST)

# Search for optical counterpart of neutrino “multiplet” events

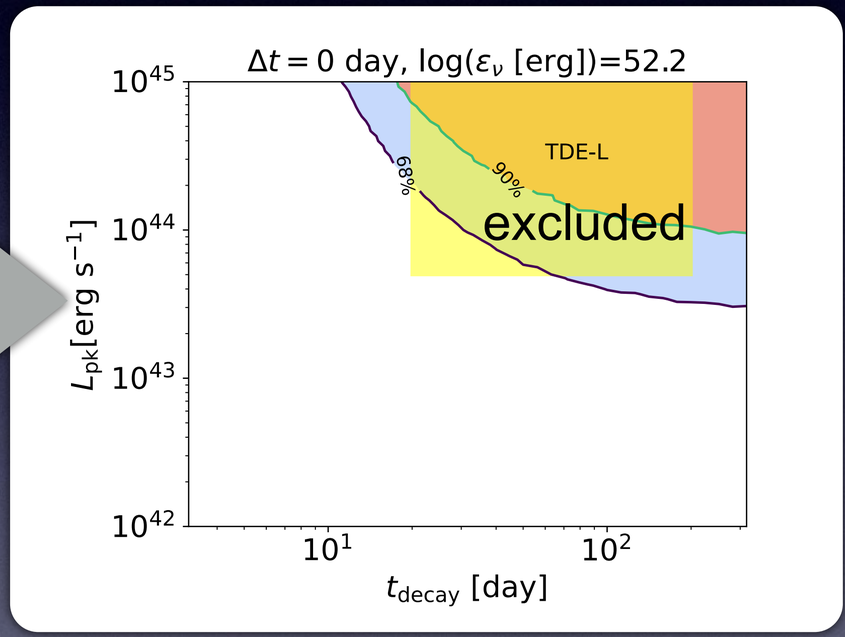
Toshikage+25 See S. Toshikage’s poster



## Transient search with ZTF




## Constraints on transient properties



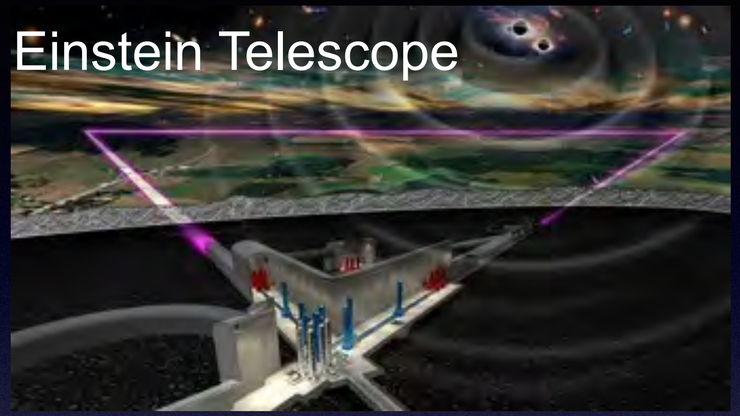

**Future: real-time follow-up: survey (1m class) + spectroscopy**

See the talks by T. Sasaoka (Kiso) and J.H. Kim (7DT)

# Multi-Messenger Astronomy: Recent Progress and Future Outlook

- Gravitational wave + Electromagnetic wave
- Neutrino + Electromagnetic wave
- Future

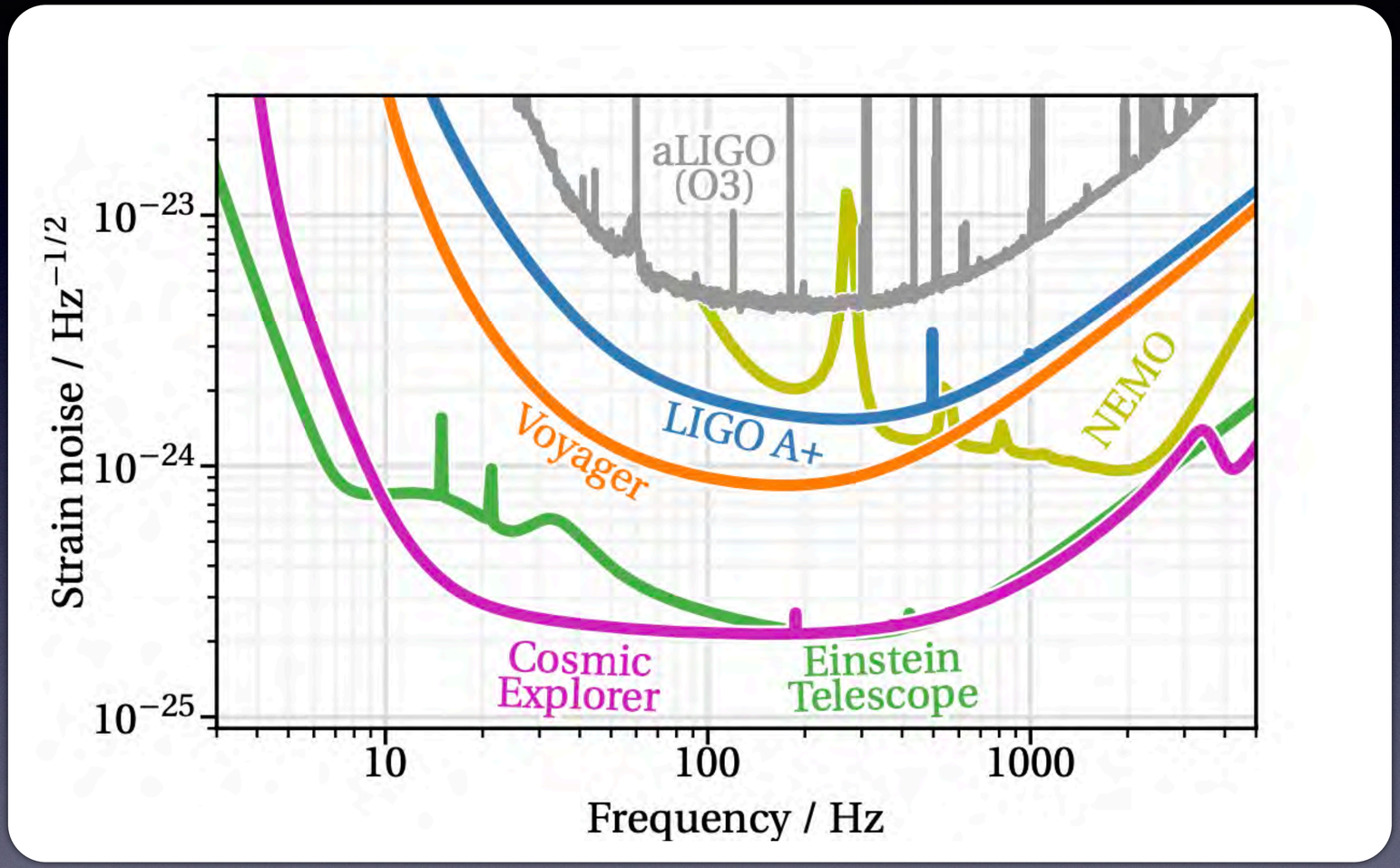
# Future: Gravitational wave




(C) NIKHIF




(C) Eddie Anaya, California State University Fullerton




CE Astro2020

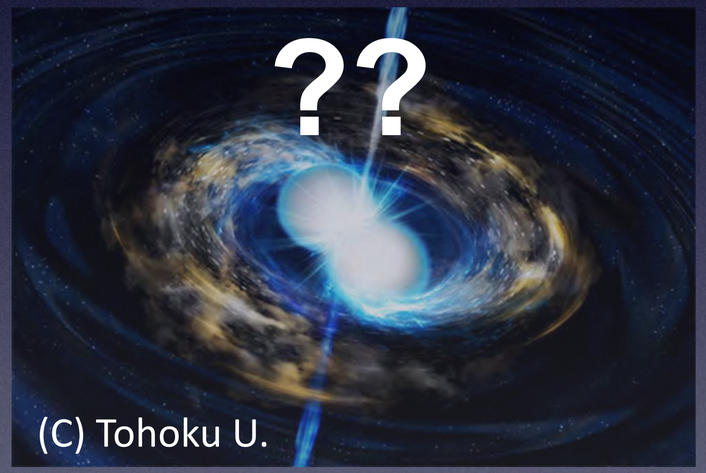
**More and more GW events!**

# “Forecast” of gravitational wave detection

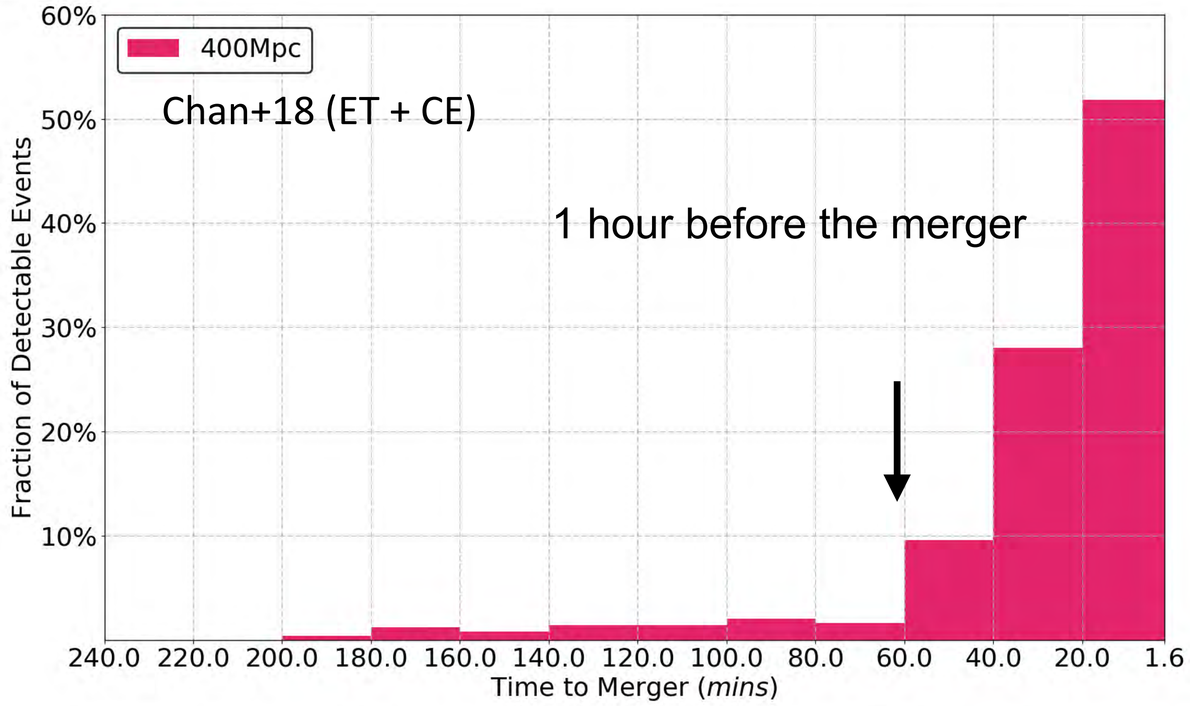
Lower frequency

Higher frequency





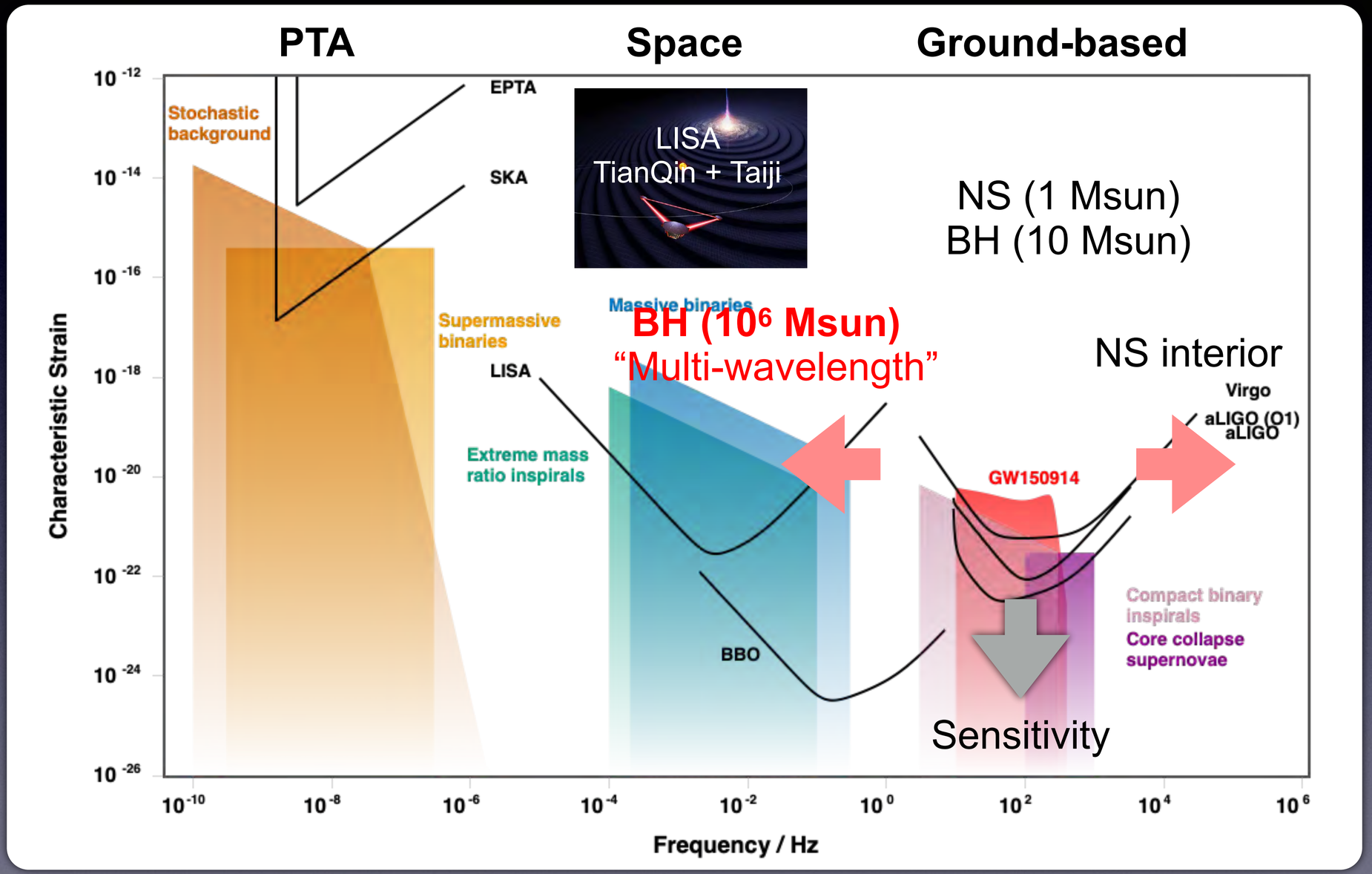

## “Forecast” of neutron star merger




**Electromagnetic observations of the “exact moment” of the merger**

***Time zone in Asia will be unique***

# “Multi-wavelength” gravitational wave observations

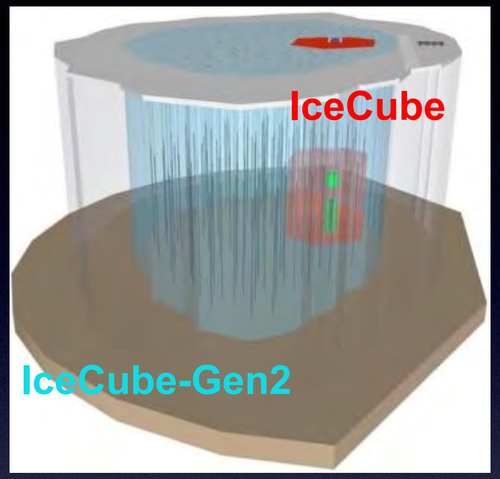



http://www.sr.bham.ac.uk/~cplb/GWplotter/

# Future: High-energy neutrino

arXiv:2008.04323

IceCube collaboration 2017



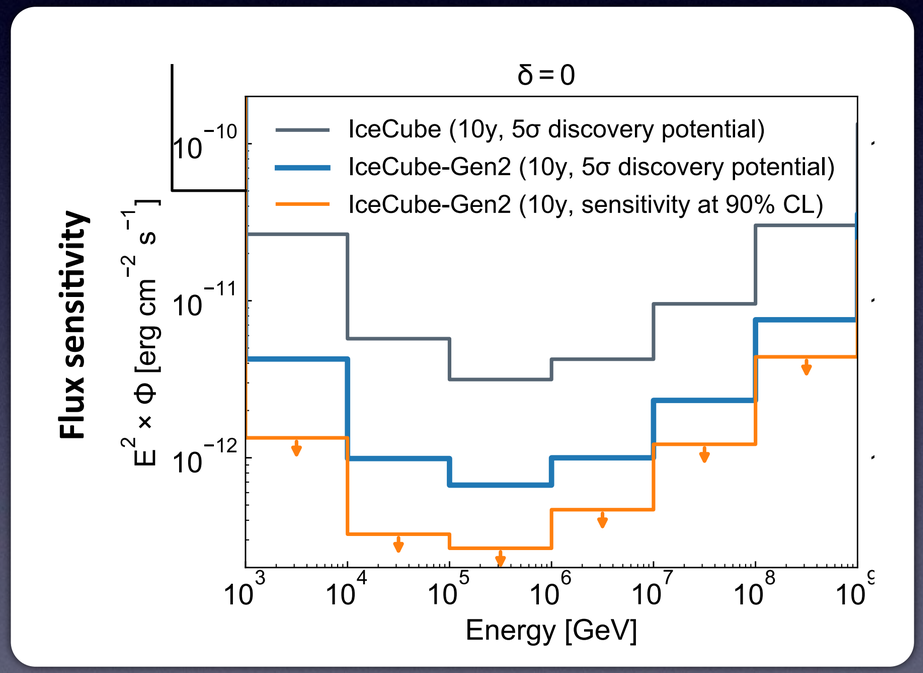




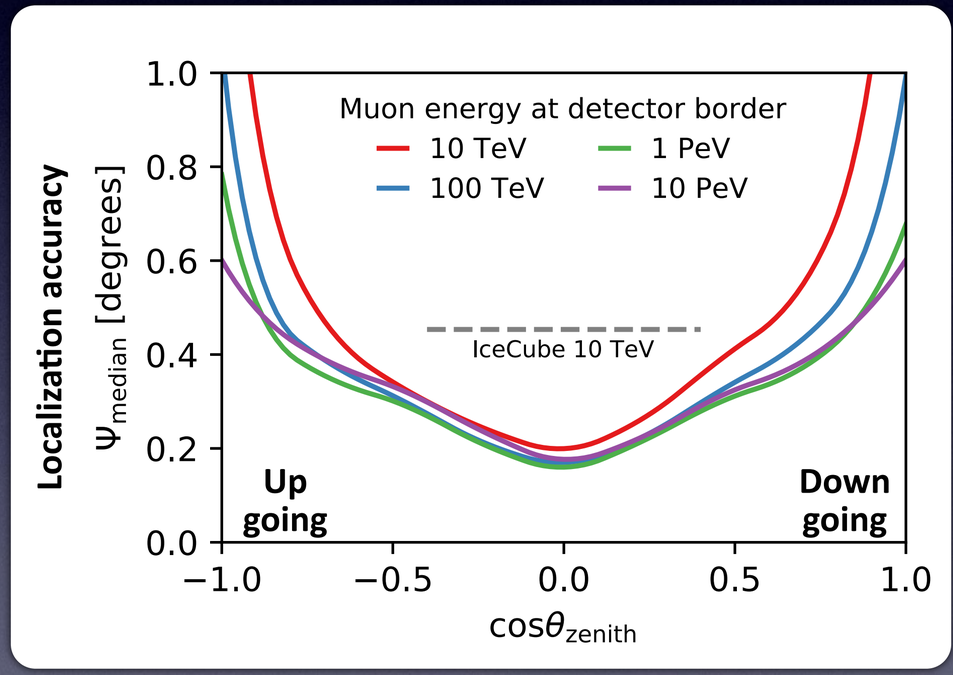



## IceCube-Gen2

### Sensitivity (x ~10)




### Localization (x 3)




**Better sensitivity and localization**
**=> identification of the neutrino sources**

# Summary

"Visible" light

"Multi-wavelength" astronomy

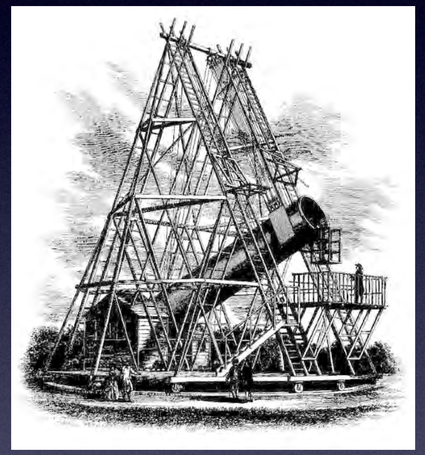
"All-messenger"

1610-



(C) Astroarts

1789-



1999-



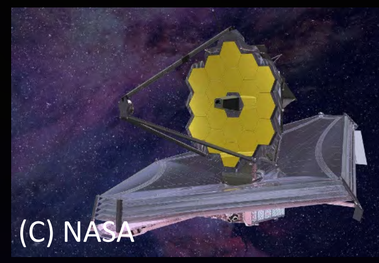
(C) NAOJ

2013-



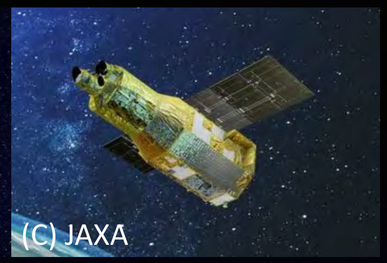
(C) NAOJ

2021-



(C) NASA

2023-



(C) JAXA

1600

1700

1800

1900

2000

2015- Gravitational wave

1960s- Neutrino

Multi-wavelength/energy

More collaboration in east Asia and beyond