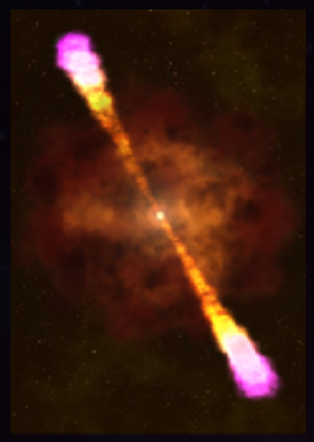
Strategies, challenges and perspectives of the EM follow-up of gravitational sources:

the ENGRAVE and SVOM collaborations

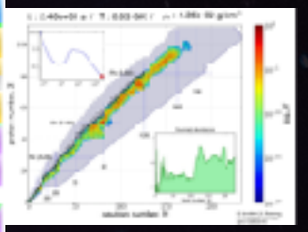
S.D. Vergani

Relativistic astrophysics

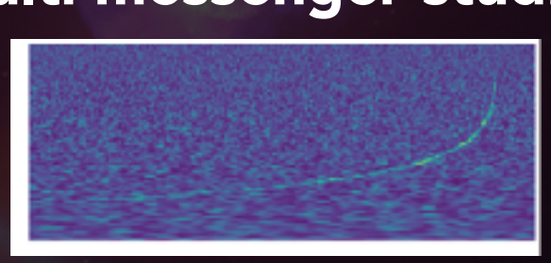


Radioactively powered transients

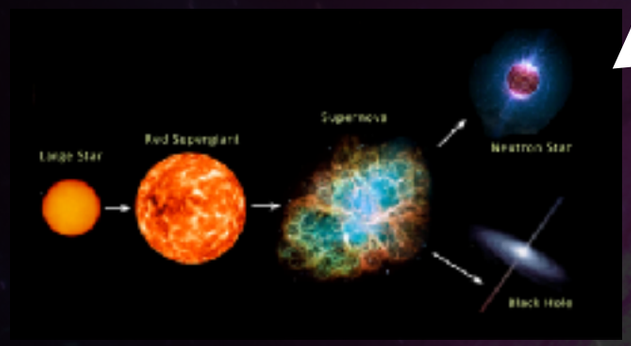
Nucleosynthesis and enrichment of the Universe



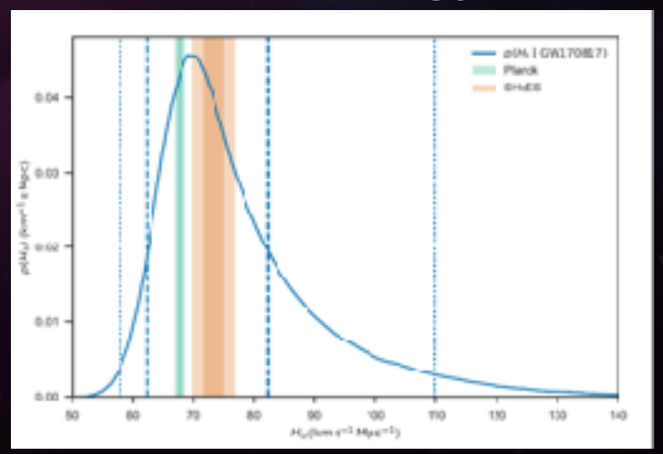
GW170817
Multi-messenger studies



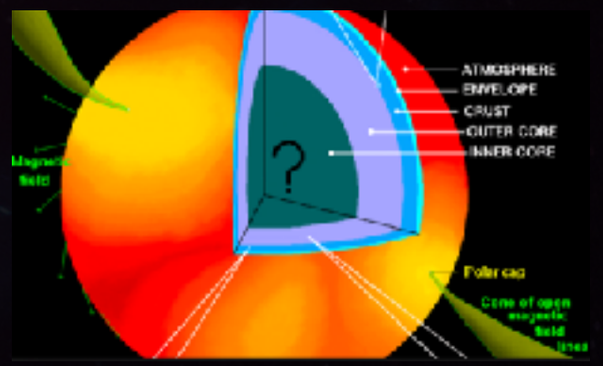
Compact object formation and evolution



Cosmology



Nuclear matter physics



Courtesy of M. Branchesi

- Are all BNS similar to GW170817 (EM side)?
- Rate?
- Population?
- Are all BNS associated with SGRB?
- Are all SGRB associated with BNS?
- NSBH ?
- r-process heavy element production

GW170817/GRB170817

Worldwide, long-term effort is needed

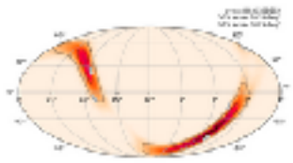
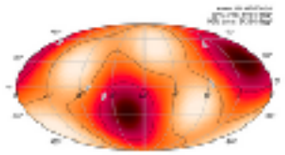
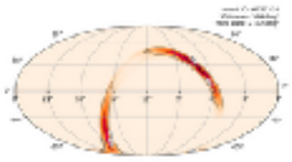
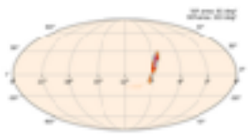
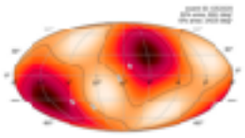
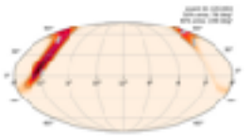
We were lucky

O3

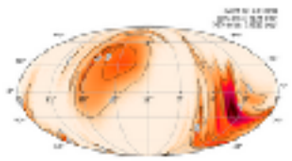
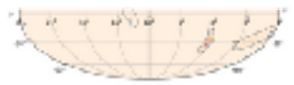
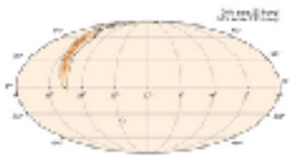
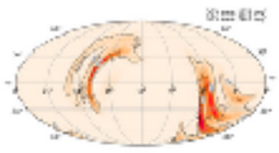
O3 Range: aLIGO 110–130 Mpc, AdV 50 Mpc, KAGRA 8–25 Mpc

LVC Observing scenario paper
https://arxiv.org/pdf/1304.0670.pdf

O3a

Event ID	Possible Source (Probability)	UTC	GCN	Location	FAR	Distance (Mpc)
S190910d	NSBH (98%), Terrestrial (2%)	Sept. 10, 2019 01:26:19 UTC	GCN Circulars Notices | VOE		1 per 8.5248 years	606+/-197
S190910h	BNS (61%), Terrestrial (39%)	Sept. 10, 2019 08:29:58 UTC	GCN Circulars Notices | VOE		1 per 0.88 years	241+/-89
S190923y	NSBH (68%), Terrestrial (32%)	Sept. 23, 2019 12:55:59 UTC	GCN Circulars Notices | VOE		1.5094 per year	438+/-133
S190924h	MassGap (>99%)	Sept. 24, 2019 02:18:46 UTC	GCN Circulars Notices | VOE		1 per 3.5493e+10 years	548+/-112
S190930t	NSBH (74%), Terrestrial (26%)	Sept. 30, 2019 14:34:07 UTC	GCN Circulars Notices | VOE		1 per 2.0536 years	709+/-191
S190930s	MassGap (95%), Terrestrial (5%)	Sept. 30, 2019 13:35:41 UTC	GCN Circulars Notices | VOE		1 per 10.534 years	108+/-38

O3a

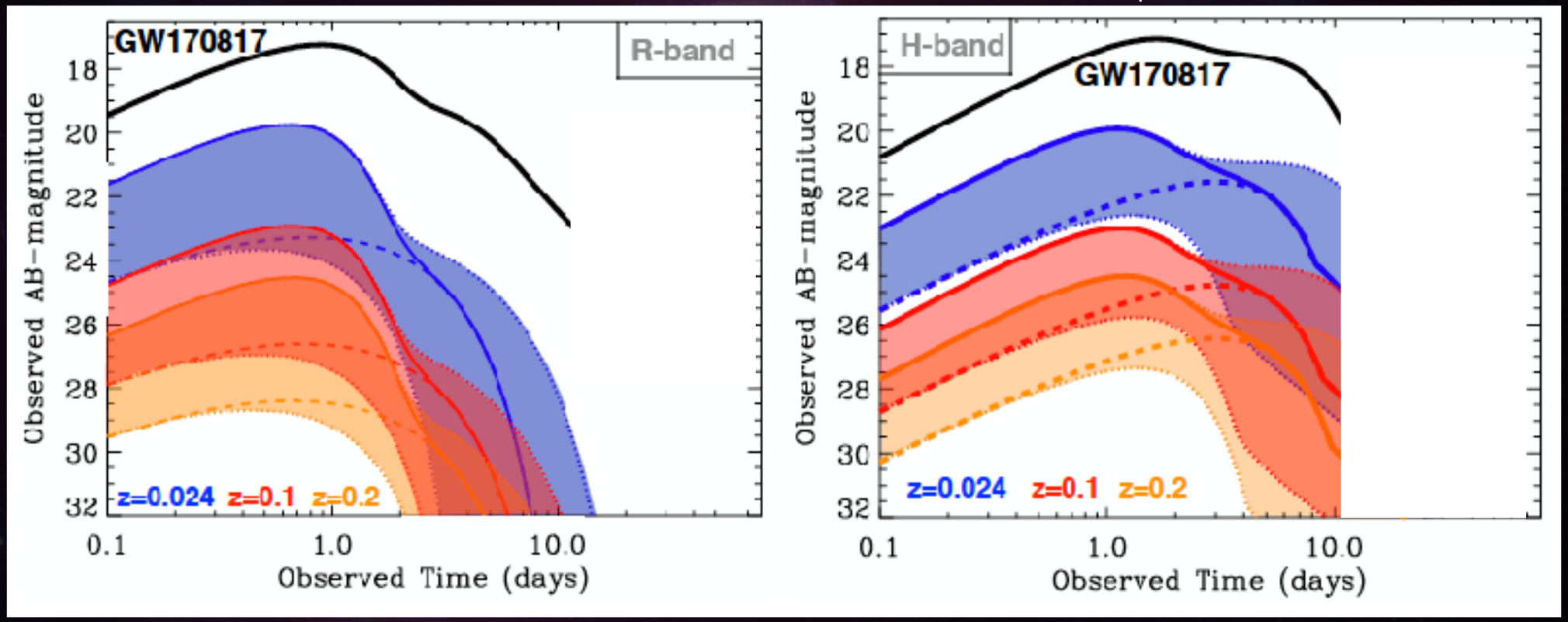
Event ID	Possible Source (Probability)	UTC	GCN	Location	FAR	Distance (Mpc)
S190901ap	BNS (86%), Terrestrial (14%)	Sept. 1, 2019 23:31:01 UTC	GCN Circulars Notices | VOE		1 per 4.5093 years	242+/-81
S190814bv	NSBH (>99%)	Aug. 14, 2019 21:10:39 UTC	GCN Circulars Notices | VOE	50% area: 5 deg² 90% area: 23 deg² 	1 per 1.559e+25 years	267+/-52
S190510g	Terrestrial (58%), BNS (42%)	May 10, 2019 02:59:39 UTC	GCN Circulars Notices | VOE	50% area: 31 deg² 90% area: 1166 deg² 	1 per 3.5872 years	227+/-92
S190426c	BNS (49%), MassGap (24%), Terrestrial (14%), NSBH (13%)	April 26, 2019 15:21:55 UTC	GCN Circulars Notices | VOE		1 per 1.6276 years	377+/-100
S190425z	BNS (>99%)	April 25, 2019 08:18:05 UTC	GCN Circulars Notices | VOE		1 per 69834 years	156+/-41

Extremely rare to have a nearby event as GW170817

Research based on galaxy catalogues, challenging at larger distances
Faint EM counterparts

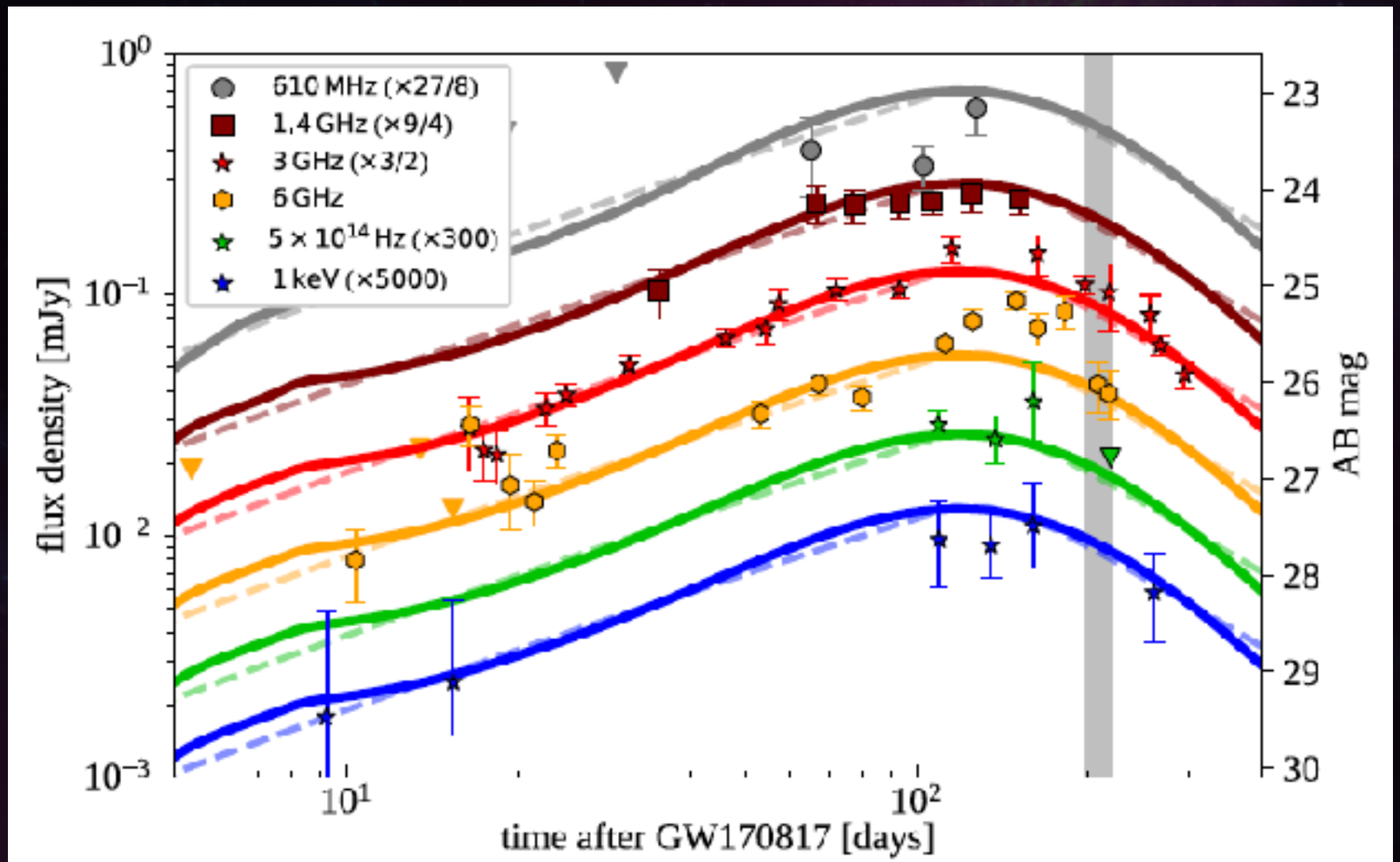
VLT and good coordination btw search and follow-up teams are fundamental

adapted from Chornock+2019



Kilonova

Ghirlanda+2019, Science



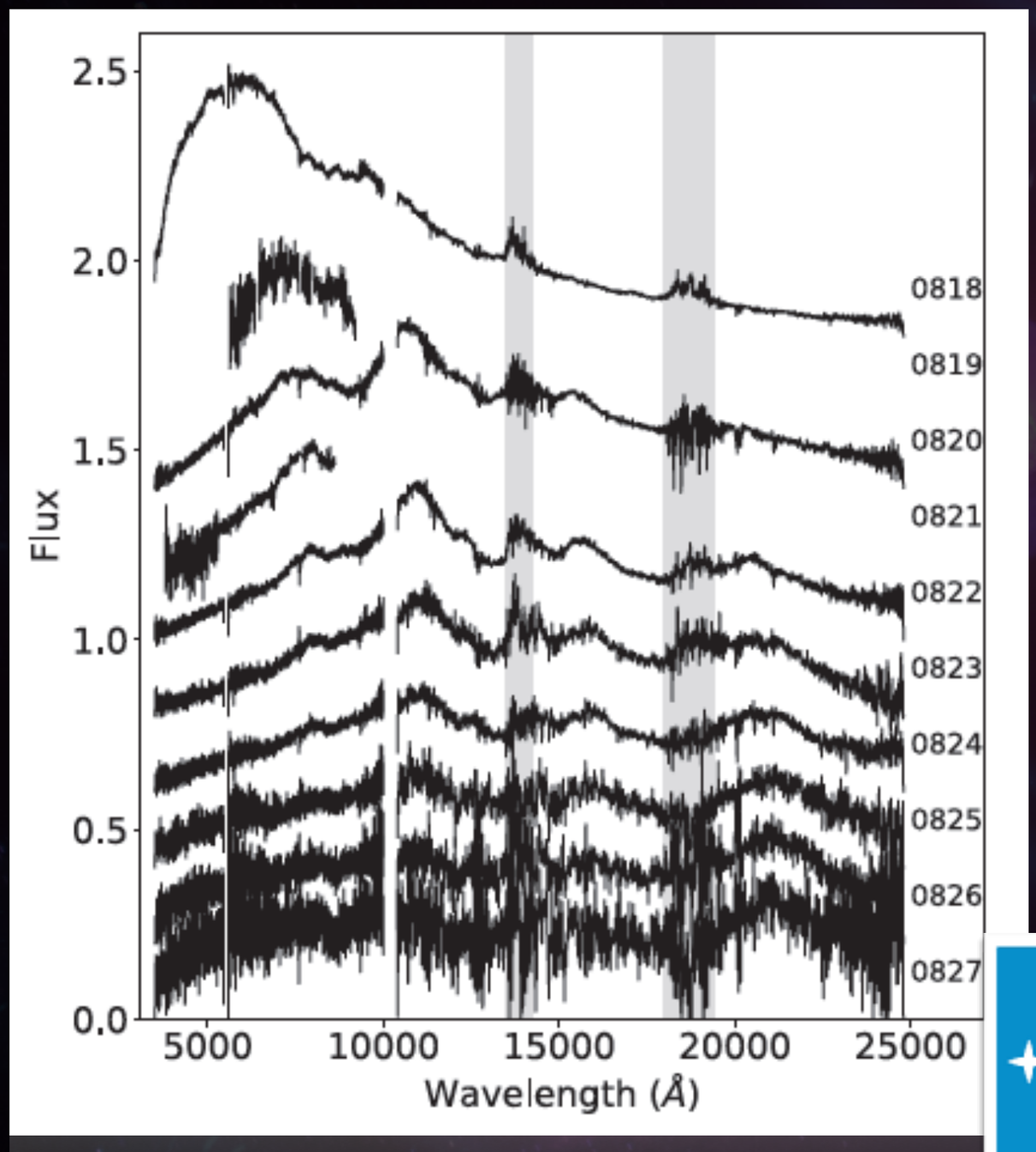
Relativistic jet

> viewing angle —> fainter

let's hope for a denser medium

GW170817/GRB170817: kilonova

ESO-VLT/X-Shooter Pian et al. 2017, Nature

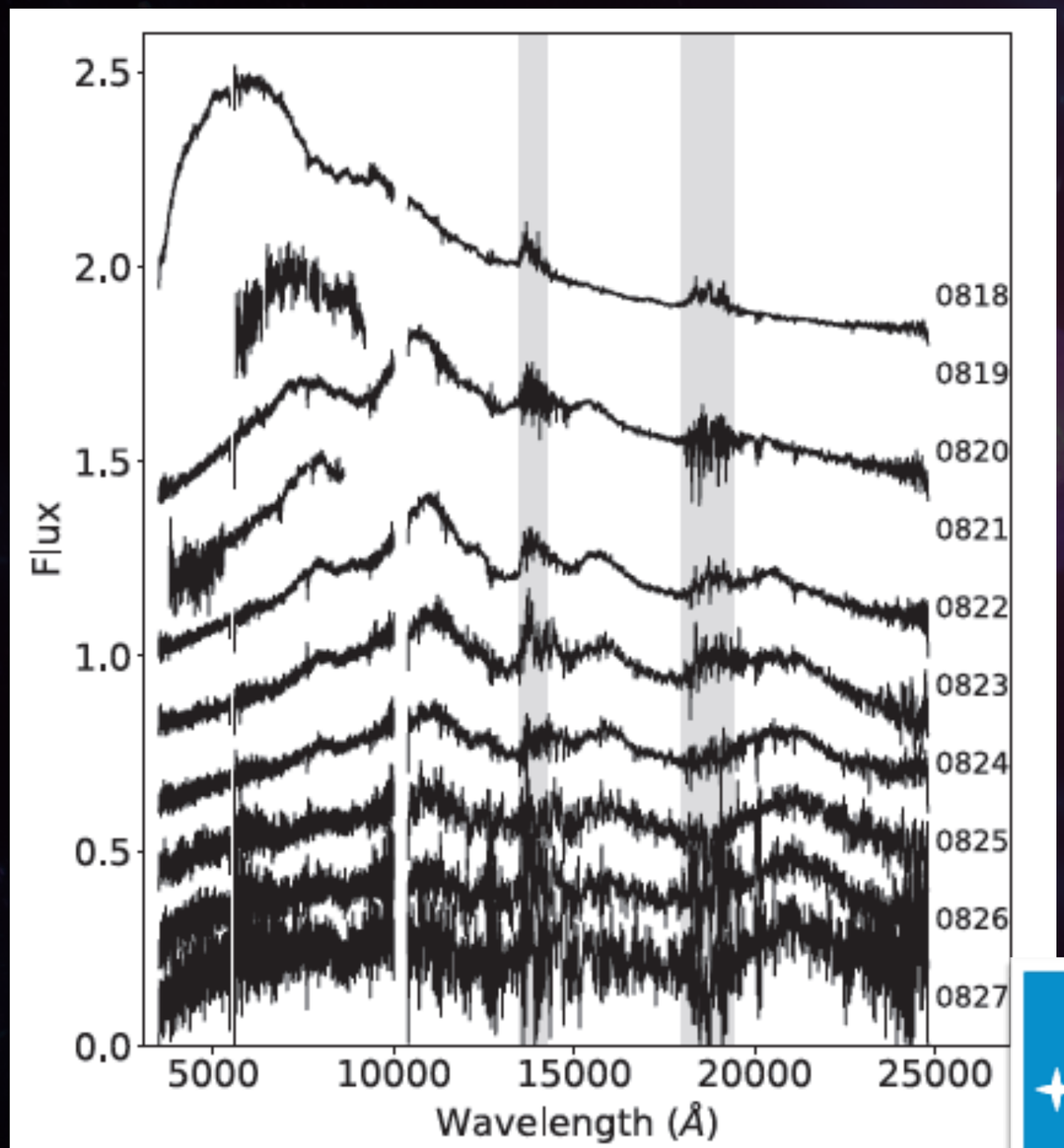


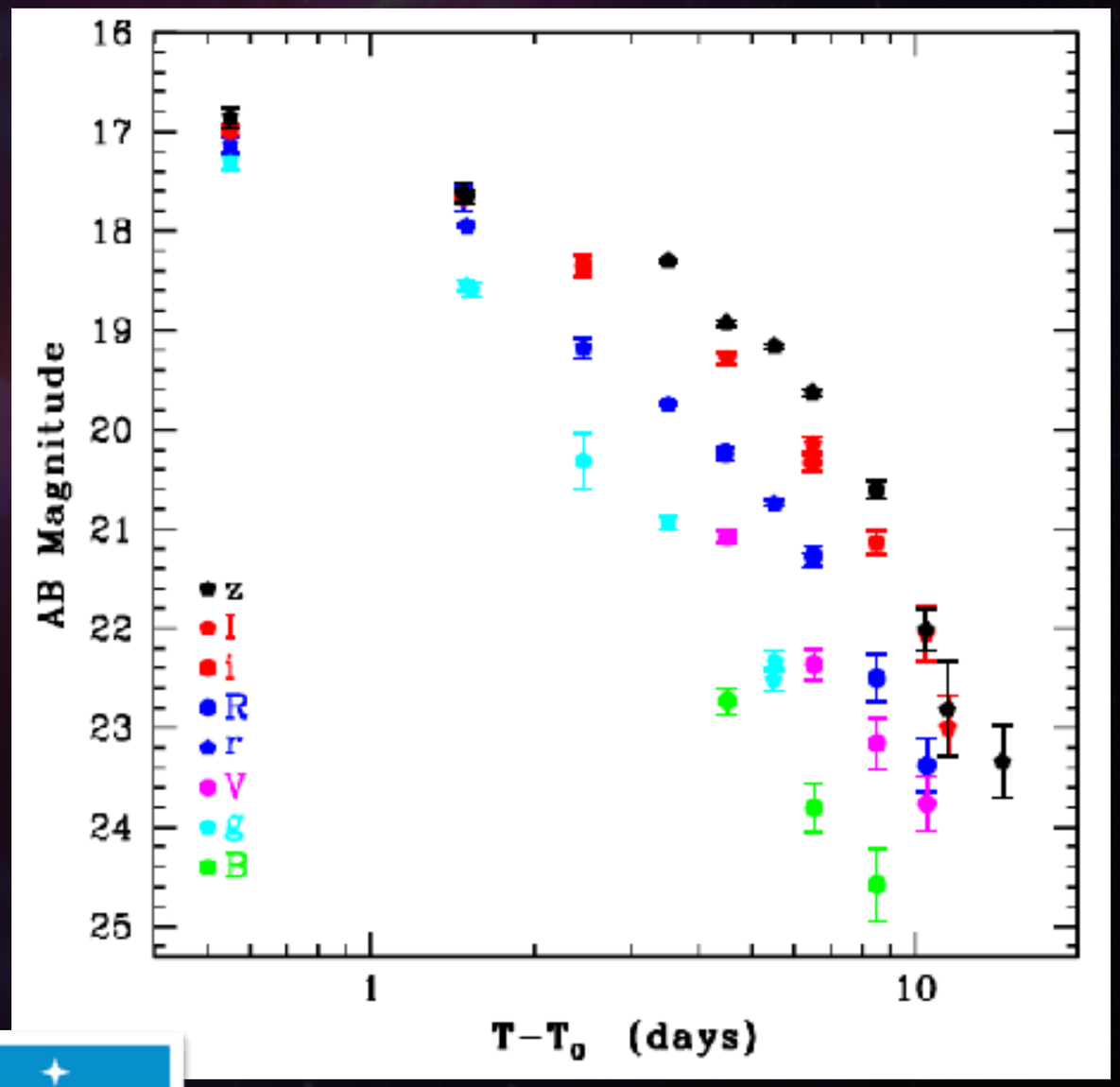
First spectral identification of the kilonova emission

- radioactive decay of **r-process nucleosynthesis** (Pian et al. 2017, Smartt et al. 2017, Watson et al. 2019)
- BNS merger **site for heavy element production in the Universe** (Cote et al. 2018, Rosswog et al. 2017)

GW170817/GRB170817: difficulties

ESO-VLT/X-Shooter Pian et al. 2017, Nature





Engrave

Electromagnetic counterparts of gravitational wave sources
at the Very Large Telescope
http://www.engrave-eso.org/

ESO

Governing Council

- Marica Branchesi
- Enzo Brocato
- Paolo D'Avanzo
- Jens Hjorth
- Peter Jonker
- Elena Pian
- Stephen Smartt (Chair)
- Jesper Sollerman
- Danny Steeghs
- Nial Tanvir

Executive Committee

- Stefano Covino
- Andrew Levan (Chair)
- Kate Maguire
- Daniele Malesani
- Susanna Vergani

274 members

Large Programme @ VLT

~ 230hr to follow-up EM candidate counterparts

photometry, spectroscopy, polarimetry

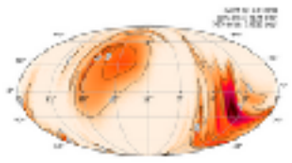
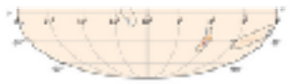
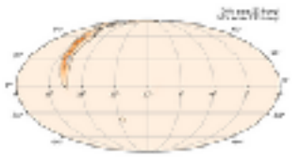
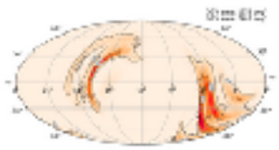
“Spin-off” radio-mm and HST awarded programs

Weekly on-call Operations Team & Writing Team

WG: imaging, spectroscopy, polarimetry, theory, infrastructure, epo, external

Many ENGRAVE members belong to different collaborations searching for the EM counterpart

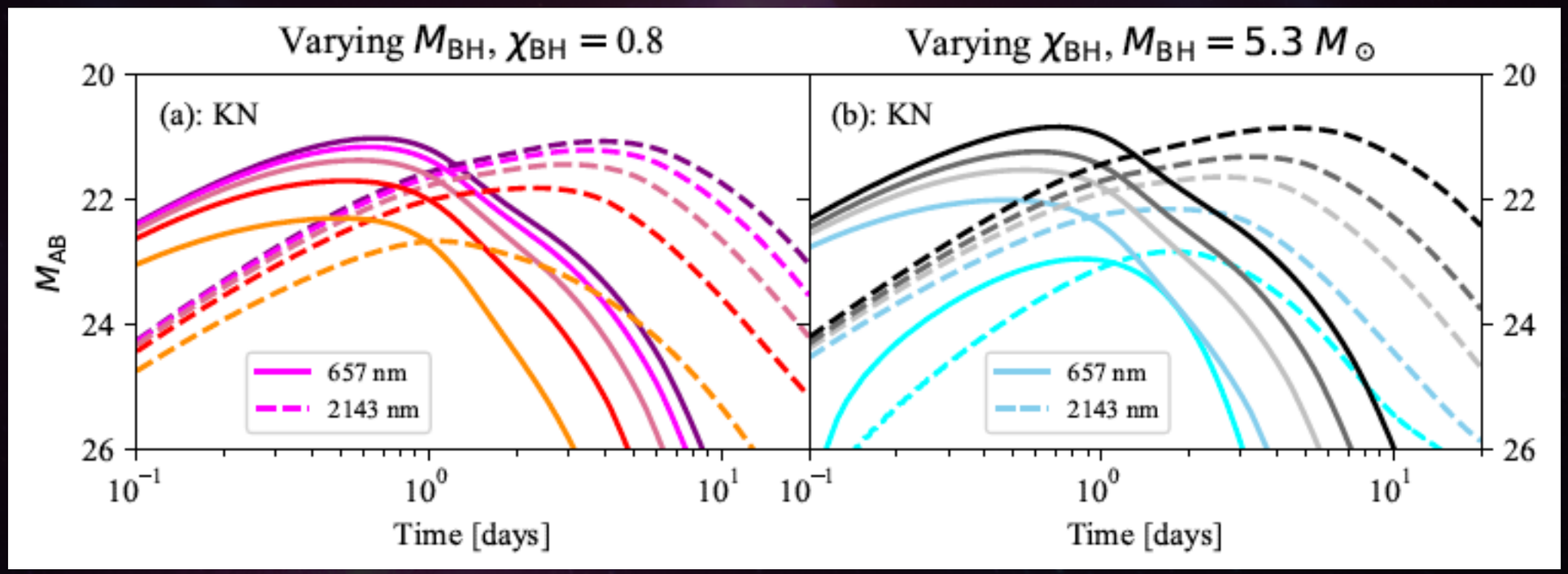
ngraye

Event ID	Possible Source (Probability)	UTC	GCN	Location	FAR	Distance (Mpc)
S190901ap	BNS (86%), Terrestrial (14%)	Sept. 1, 2019 23:31:01 UTC	GCN Circulars Notices | VOE		1 per 4.5093 years	242+/-81
S190814bv	NSBH (>99%)	Aug. 14, 2019 21:10:39 UTC	GCN Circulars Notices | VOE	50% area: 5 deg² 90% area: 23 deg² 	1 per 1.559e+25 years	267+/-52
S190510g	Terrestrial (58%), BNS (42%)	May 10, 2019 02:59:39 UTC	GCN Circulars Notices | VOE	50% area: 31 deg² 90% area: 1166 deg² 	1 per 3.5872 years	227+/-92
S190426c	BNS (49%), MassGap (24%), Terrestrial (14%), NSBH (13%)	April 26, 2019 15:21:55 UTC	GCN Circulars Notices | VOE		1 per 1.6276 years	377+/-100
S190425z	BNS (>99%)	April 25, 2019 08:18:05 UTC	GCN Circulars Notices | VOE		1 per 69834 years	156+/-41

NS-BH: EM predictions

z=0.054

n=10^{-3}cm^{-3}



Barbieri+2019

Spectroscopy to characterize selected candidates

TITLE: GCN CIRCULAR
NUMBER: 25384
SUBJECT: LIGO/Virgo S190814bv : ENGRAVE X-shooter spectra of AT2019nqs and AT2019npy
DATE: 19/08/17 16:58:21 GMT
FROM: Andrew Levan at U.of Leicester <a.levan@astro.ru.nl>

S. H. Bruun (DARK/NBI), A. Sagues Carracedo (OKC), T.-W. Chen (MPE), C. Copperwheat (LJMU), P. D'Avanzo (INAF), M. Fraser (UCD), K. E. Heintz (U. Iceland), J. Hjorth (DARK/NBI), J. Japelj (API, Amsterdam), P. Jonker (SRON/Radboud Univ.), G. Leloudas (DTU Space), A. J. Levan (Radboud Univ), D. B. Malesani (DTU Space), T. Mandel (Monash), D. A. Perley (LJMU), N. R. Sabha (Univ. Innsbruck), S. Schulze (Weizmann), S. Smartt (QUB), J. Sollerman (OKC), D. Steeghs (Warwick), S. D. Vergani (Paris Observatory-CNRS) report on behalf of the ENGRAVE collaboration:

We obtained spectroscopy of transients located within the error region of S190814bv (LVC GCN 25333). Observations were taken of desgw-190814e (AT2019nqs: Herner et al., GCN 25373; Dichiara et al., GCN 25374) and DESsevhc (AT2019npy; Andreoni et al., GCN 25352) with the VLT equipped with X-shooter on 17 August 2019.

The spectrum of desgw-190814e (AT2019nqs) exhibits clear emission lines of H-alpha and [N II] at a redshift of z = 0.1263 +/- 0.001. The continuum contains significant host galaxy contamination, but is consistent with an old type Ia or Ibc supernova (around 20-50 days post-maximum) whose sub-type cannot be reliably determined. This classification was determined using DASH (Muthukrishna et al. 2019), redshift of 0.126, and adding host contamination (Sa-type spectrum at roughly 60%). More refined classification will require further work. This redshift corresponds to a distance of almost 500 Mpc and lies >6 sigma from the inferred GW distance. We therefore conclude that desgw-190814e is not associated with S190814bv.

No discrete features are readily identified in the noisy spectrum of DESsevhc (AT2019npy). The source exhibits a red continuum but no obvious broad lines from a transient or narrow emission lines from a host galaxy. The source does not appear spectrally similar to AT2017gfo.

We thank the staff at Paranal for their excellent assistance with these observations.

Based on observations collected by the ENGRAVE collaboration at the European Southern Observatory under ESO programmes 1102.D-0353, 0103.D-0703, 0103.D-0722 (for further information on ENGRAVE see http://www.engrave-eso.org/).

Observations on AT2019osy

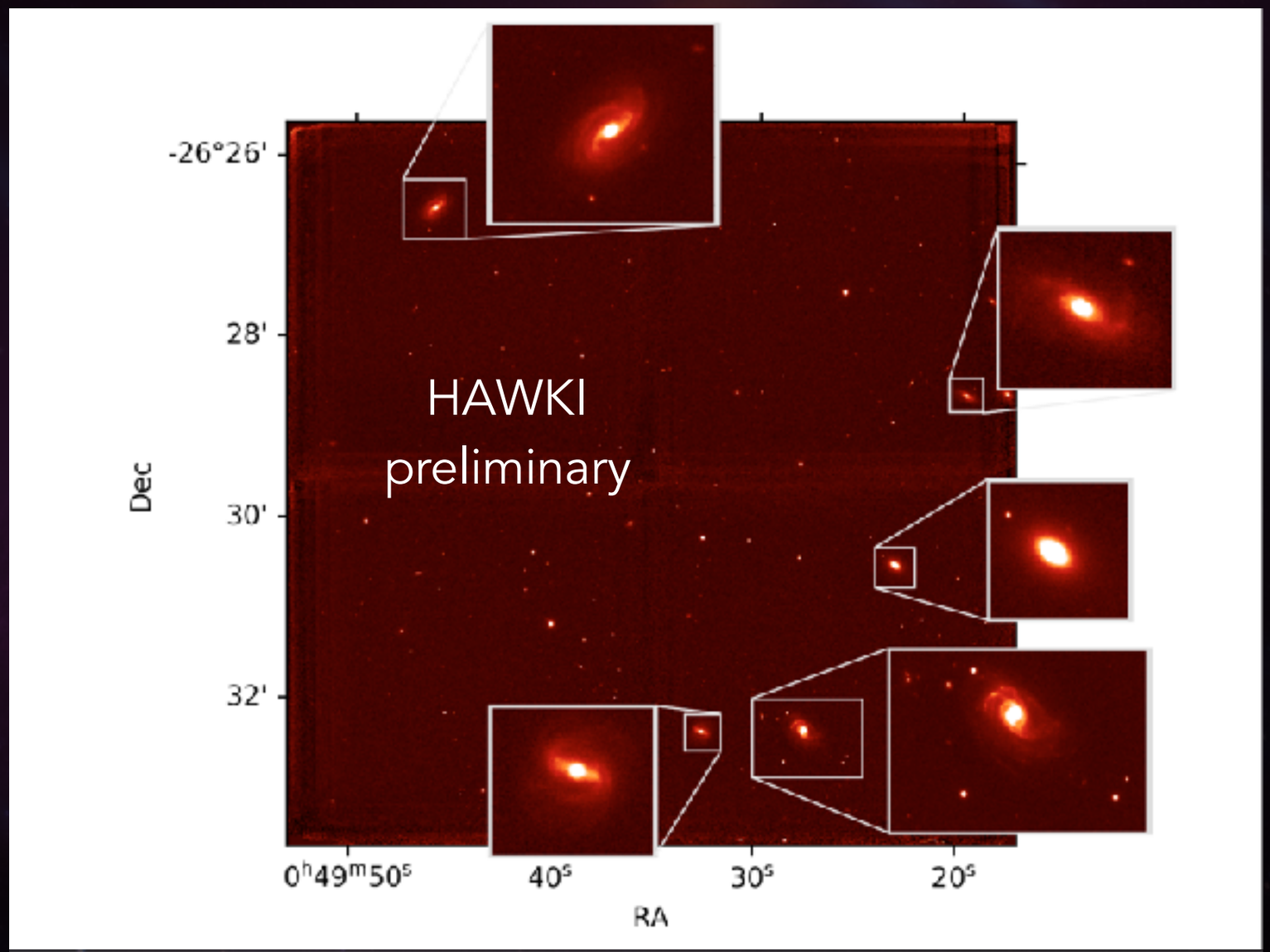
(paper in prep. including HST and ALMA data)

TITLE: GCN CIRCULAR
NUMBER: 25801
SUBJECT: LIGO/Virgo S190814bv: HST and ALMA observations of the host galaxy of ASKAP J005547-270433 / AT 2019osy
DATE: 19/09/21 18:03:22 GMT
FROM: Daniele B Malesani at DTU Space <malesani@space.dtu.dk>

F. E. Bauer (PUC), A. S. Fruchter (STScI), J. Gonzalez Lopez (UDP), J. Hjorth (DARK/NBI), T. Kangas (STScI), S. Kim (PUC), A. J. Levan (Radboud Univ.), D. B. Malesani (DTU Space), M. J. Michalowski (AMU), B. Milvang-Jensen (DAWN/NBI), R. Paladino (INAF/IRA), S. Schulze (WIS), A. de Ugarte Postigo (HETH/IAA-CSIC, DARK/NBI), report on behalf of the ENGRAVE collaboration:

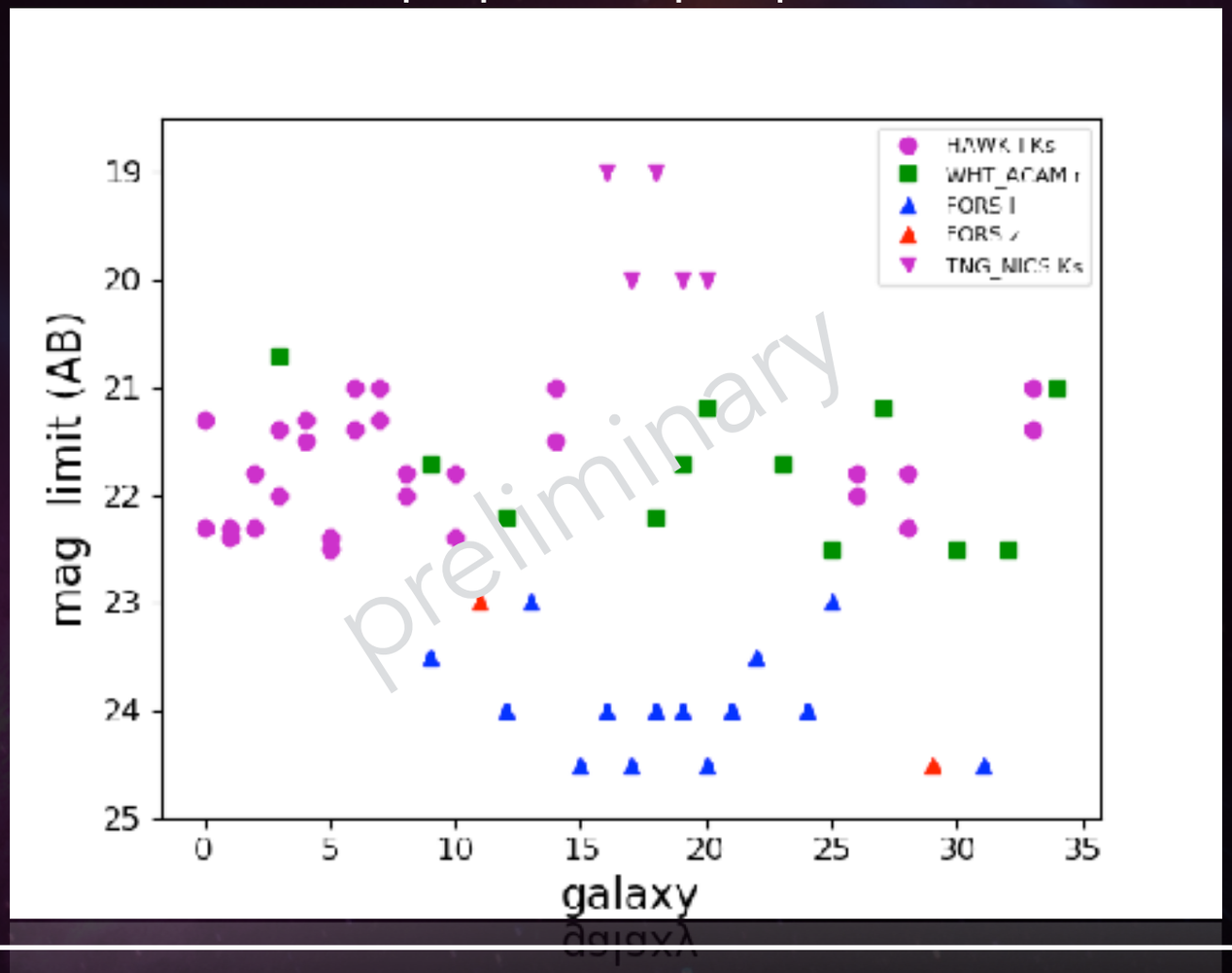
Photometry of targeted galaxies

(paper in prep.)



Photometry of targeted galaxies

(paper in prep.)



No detection in the galaxies we targeted:
If at ~250Mpc —> fainter than AT2017gfo

ngrave

- optimized strategy (time on many VLT instruments)
- advantages of a large collaboration (different expertise, access to *search* collaborations)
- Large Programme

- No flexibility on time split among semesters
- No visitor override
- LVC planning is known too late

O3 & O4 runs

LVC Observing scenario paper
https://arxiv.org/pdf/1304.0670.pdf

O3 Range: aLIGO 110–130 Mpc, AdV 50 Mpc, KAGRA 8–25 Mpc

O4 Range: aLIGO 160–190 Mpc, AdV 90–120 Mpc, KAGRA 25–130 Mpc

Observation Run	Network	Expected BNS Detections	Expected NSBH Detections	Expected BBH Detections
O3	HLV	2^{+8}_{-2}	0^{+19}_{-0}	15^{+19}_{-10}
O4	HLVK	8^{+42}_{-7}	2^{+94}_{-2}	68^{+81}_{-38}
		Area (deg^2) 90% c.r.	Area (deg^2) 90% c.r.	Area (deg^2) 90% c.r.
O3	HLV	250 – 320	310 – 390	250 – 340
O4	HLVK	30 – 48	48 – 69	33 – 47

10-14 % < 20 deg^2
2-4 % < 5 deg^2

38-44 % < 20 deg^2
11-15 % < 5 deg^2

O4: new actors

Large Synoptic Survey Telescope

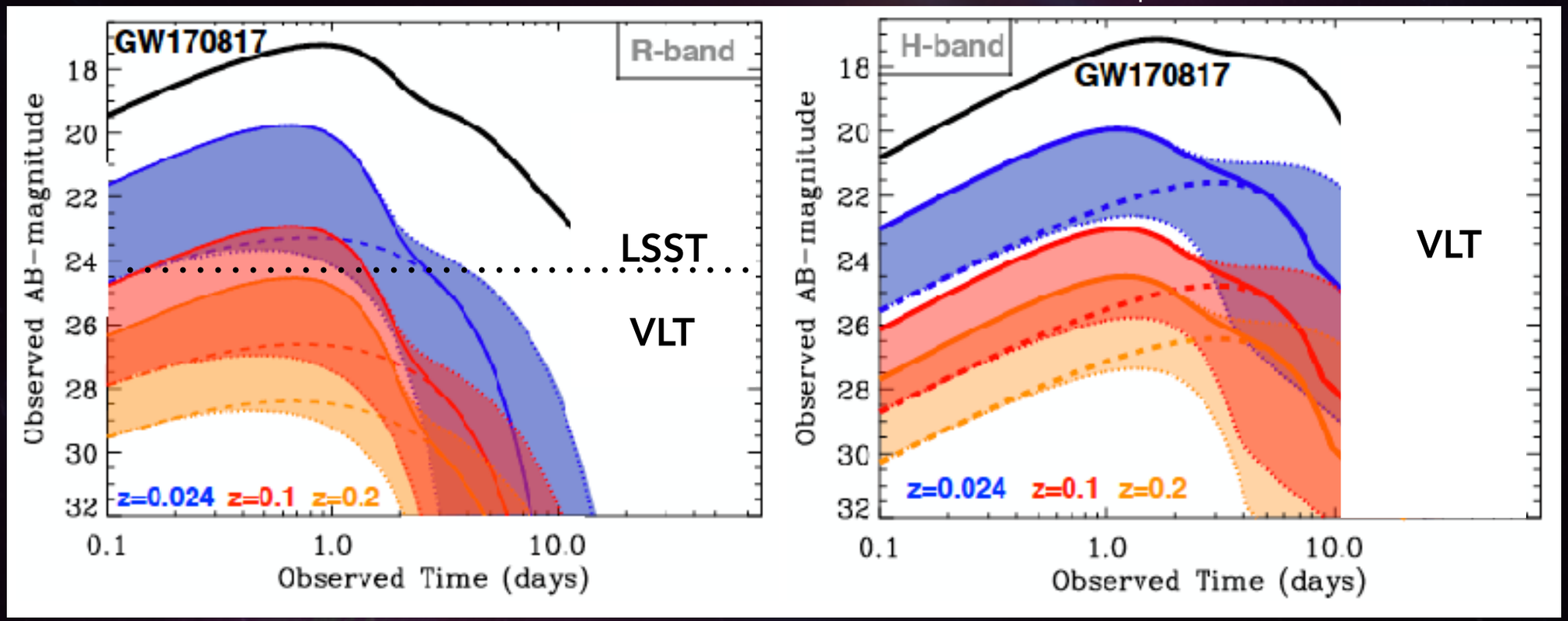
SOXS

James Webb Space Telescope
JWST
NASA • ESA • CSA

SVOM

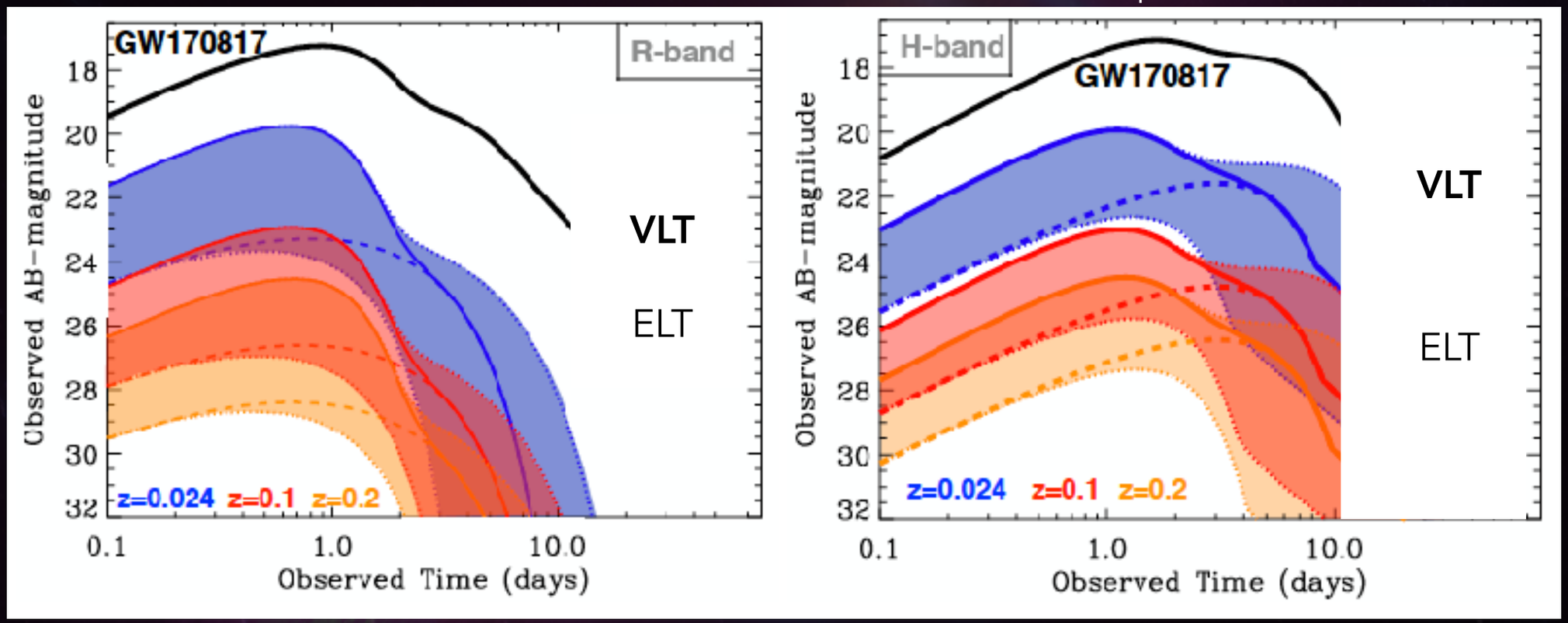
Photometry

adapted from Chornock+2019



Spectroscopy

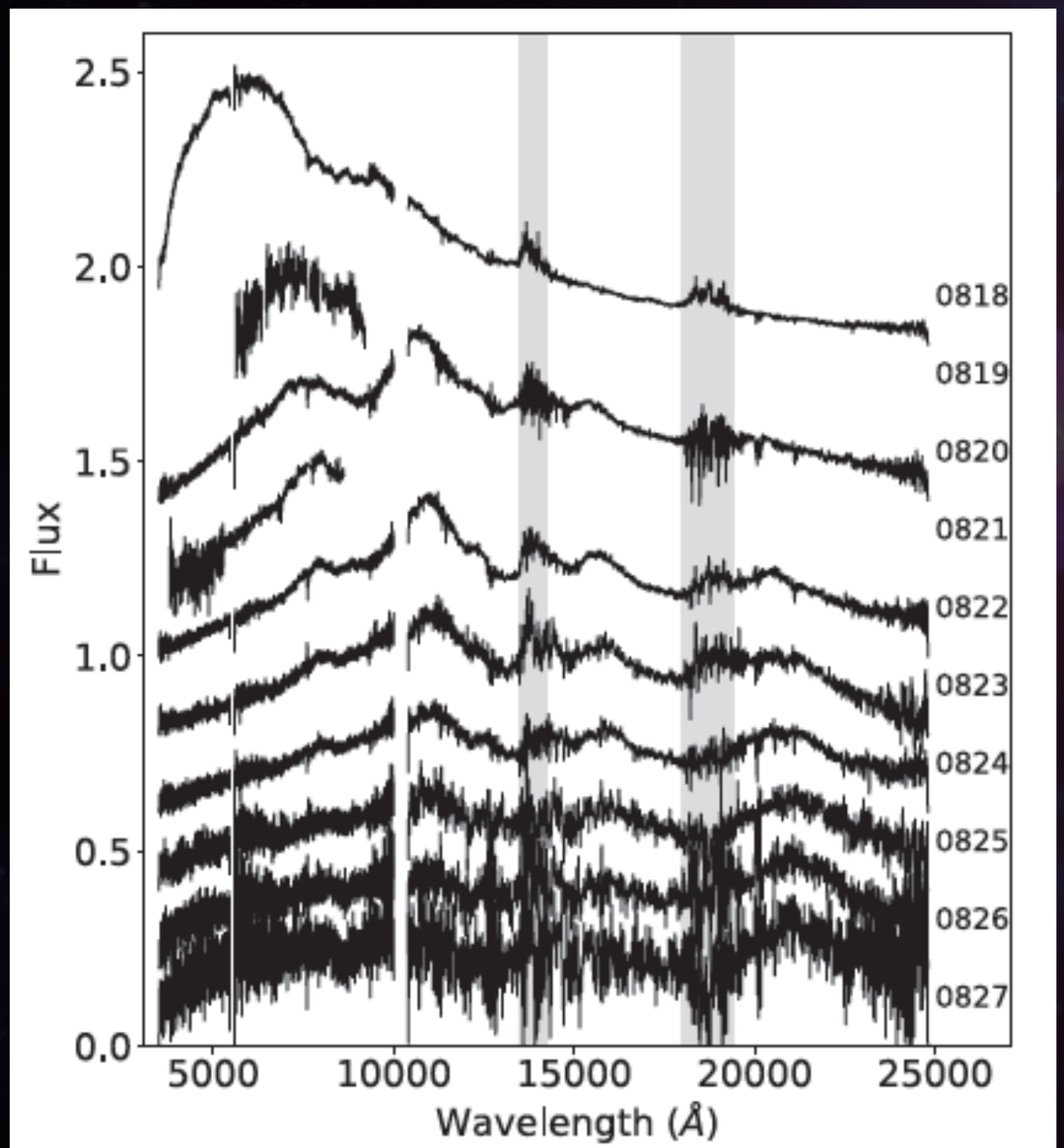
adapted from Chornock+2019



Spectral Resolution

ESO-VLT/X-Shooter

Pian et al. 2017, Nature



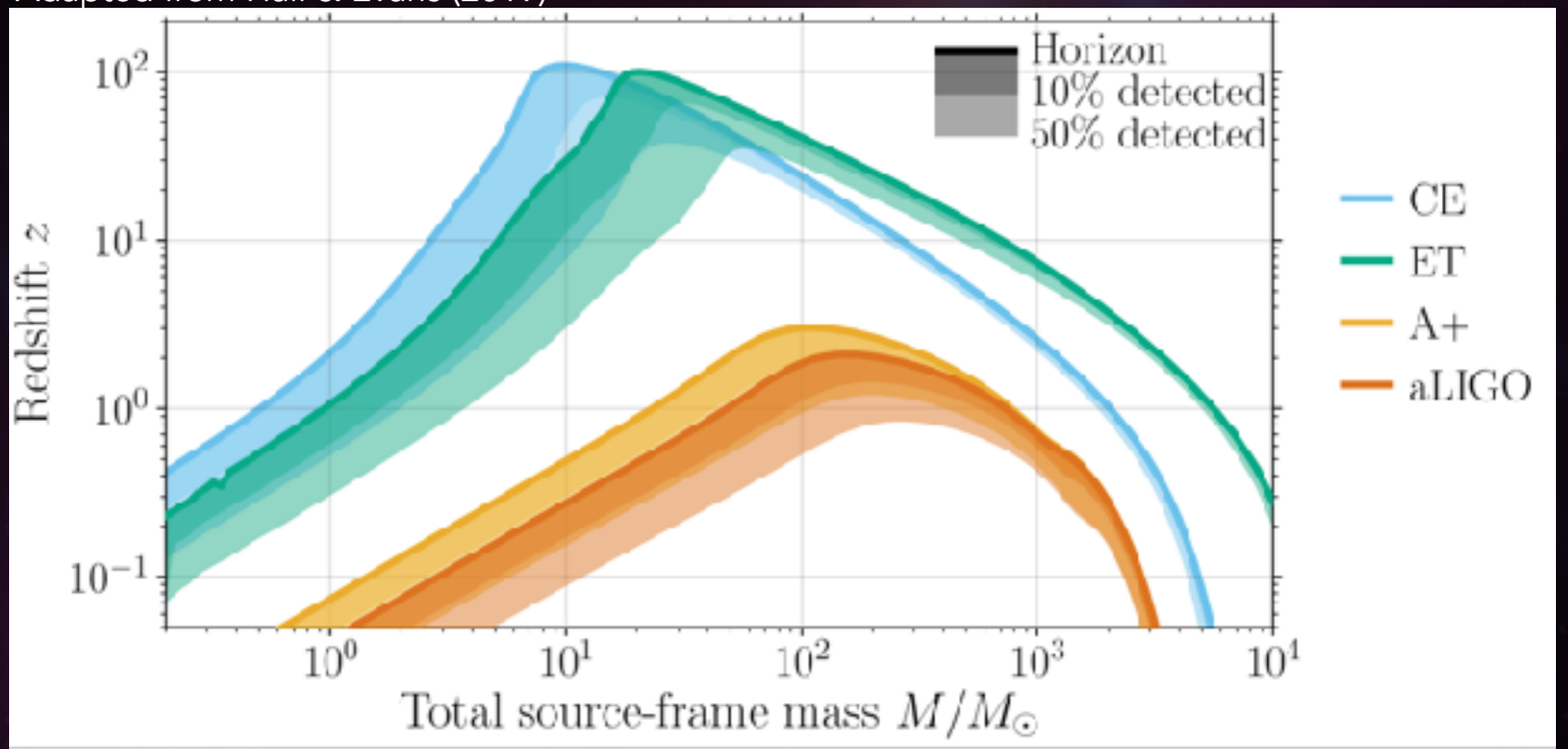
between O3 & O4 runs

Follow-up of potential KN detected by surveys?
Follow-up of peculiar / low-z short GRBs?
coordination with *Stargate* collaboration

Situation in ~2035

3G instruments for GW
EinsteinTelescope & CosmicExplorer

Adapted from Hall & Evans (2019)

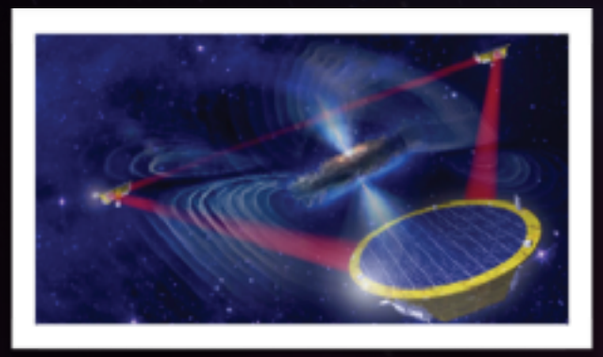


Rely on wide field space missions able to identify high-energy emission with good localization

theseus
TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR

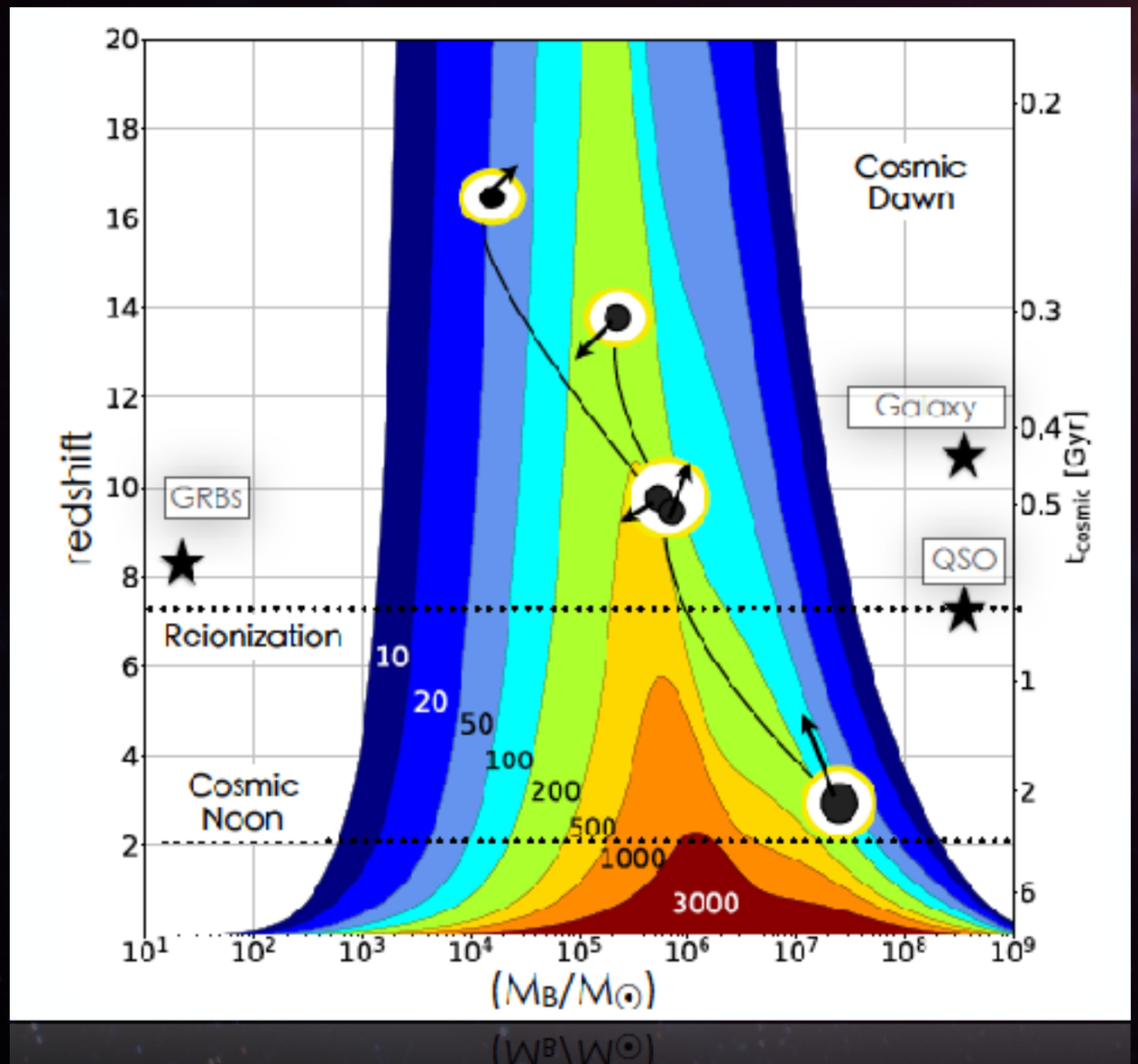
https://www.isdc.unige.ch/theseus/

Situation in ~2035



LISA

Colpi+2019



Merger of galaxies

z=2

1 day before : 100 deg^2

merger time : 1 deg^2

Be ready for the EM follow-up from ground & from space

ATHENA

Conclusions

- Extremely challenging but lots of astrophysics
- The ENGRAVE collaboration is a successful experience at ESO
- Coordination between groups having access at facilities with different capabilities is fundamental
- VLT (and future very sensitive telescopes) play and will play a key role

- No flexibility on time split among semesters
- Astronomers need to plan in advance
- Distant / poorly localized events ????
- Be ready for O4, O5 & ET
- Be ready for LISA

From ground & from space

Thank you!