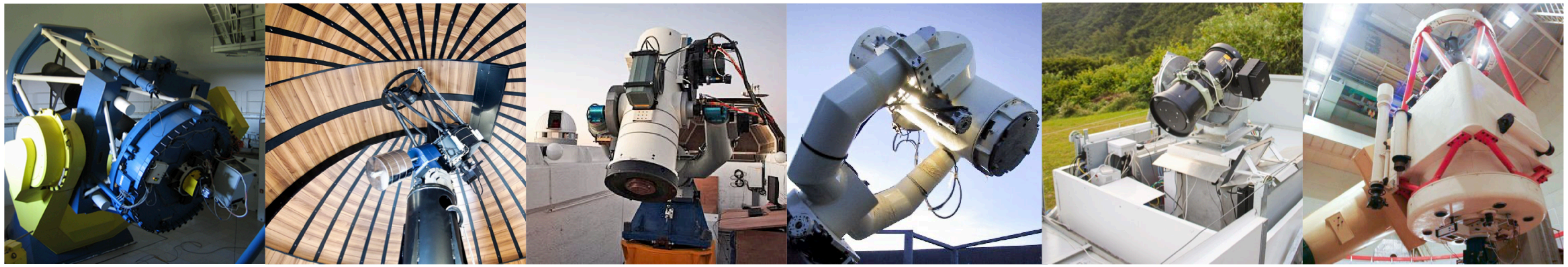
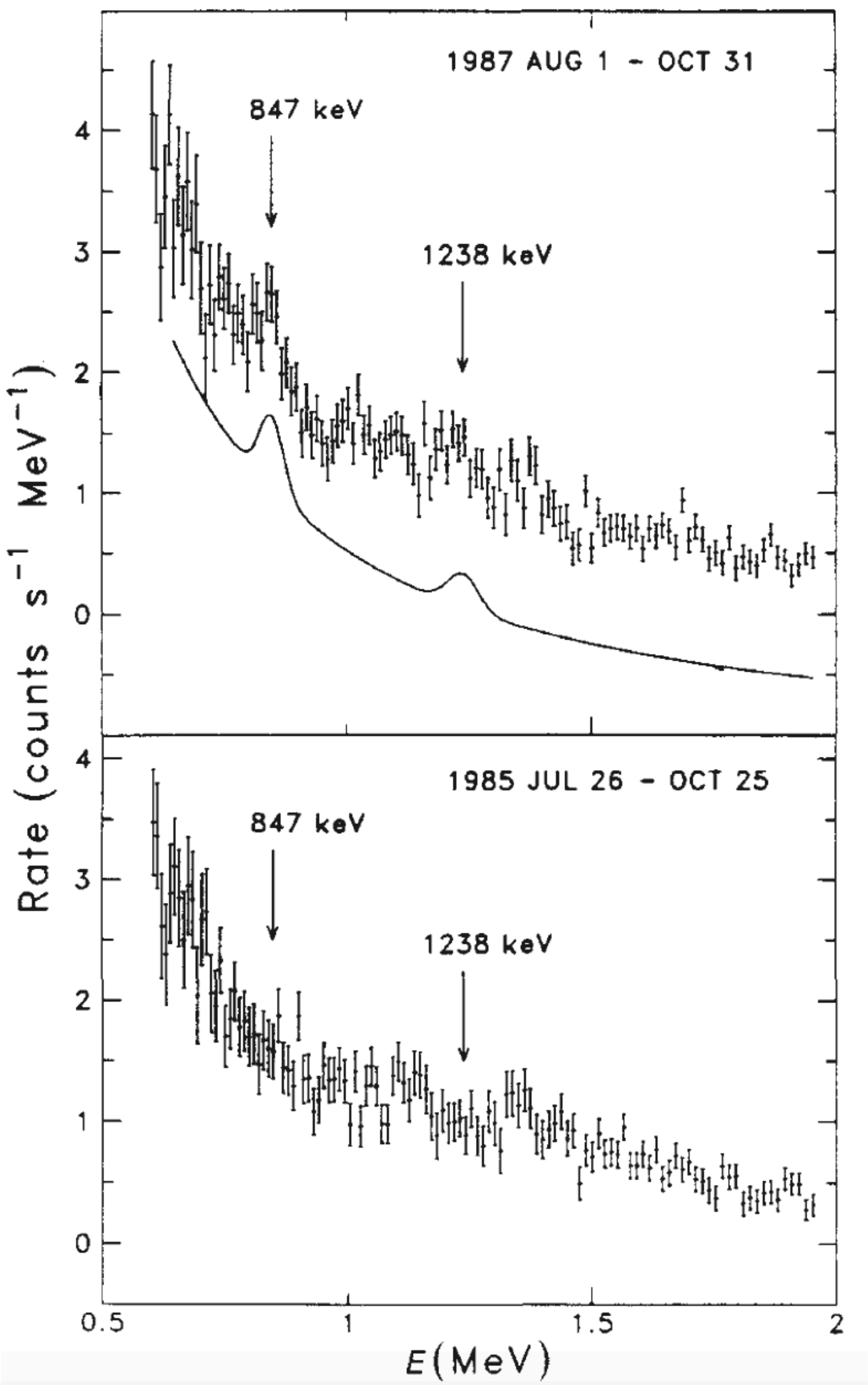
Multi-messenger follow-up of Galactic CCSNe

Alexis Coleiro / APC - Université Paris Cité (alexis.coleiro@u-paris.fr)
On behalf of the GRANDMA collaboration



Galactic CCSN: probe of the explosion mechanism

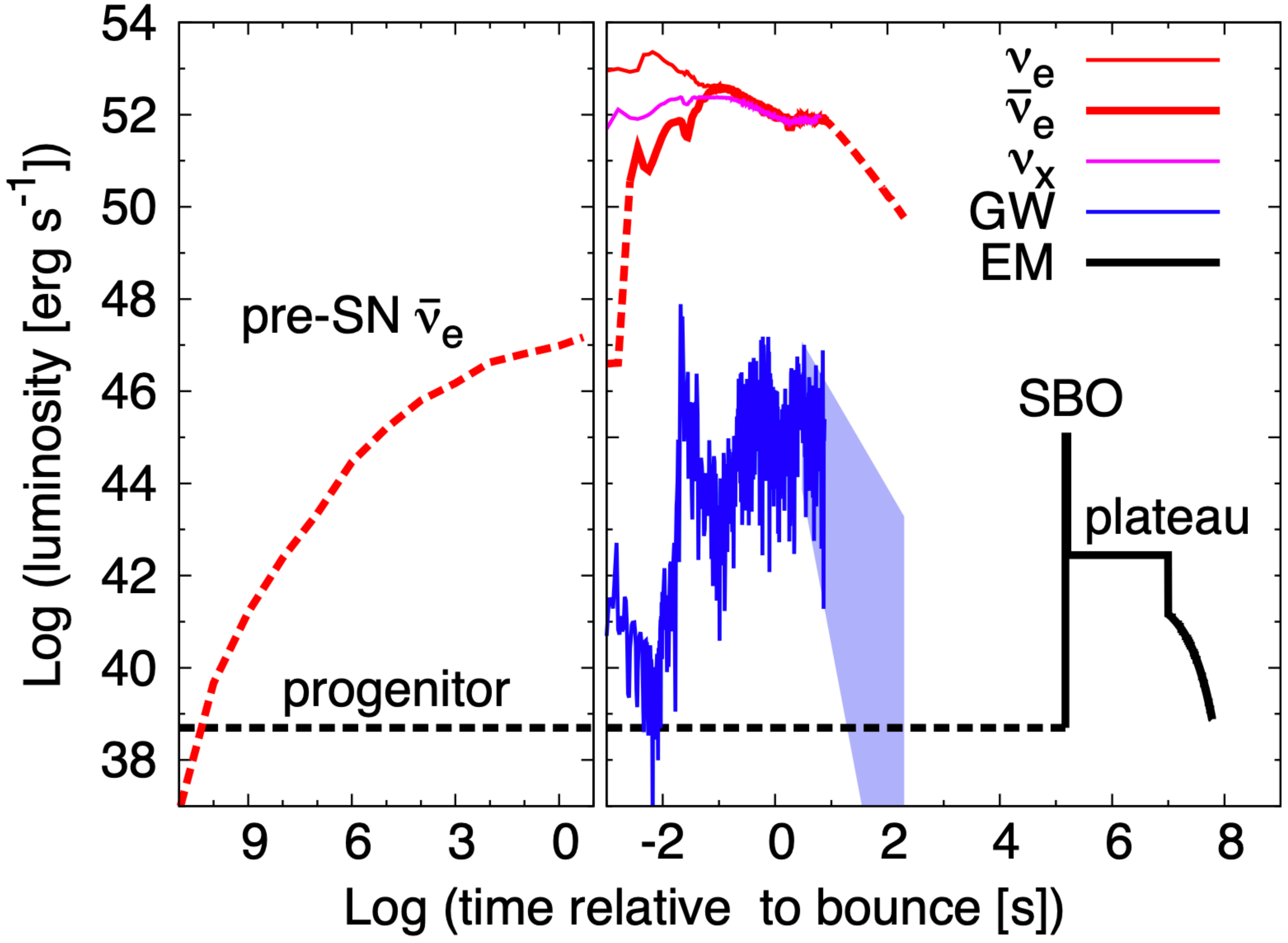
- **Extragalactic CCSNe** regularly observed but very indirect probes of the CCSN mechanism
- **Close-by CCSN**: Muti-messenger signal might be detected
- **SN1987A**: neutrinos and gamma-rays
- **Fast multi-messenger monitoring ⇒ crucial studies including:**
    - Shock breakout
    - Nature of the progenitor
    - Physics of the CCSN explosion
    - …



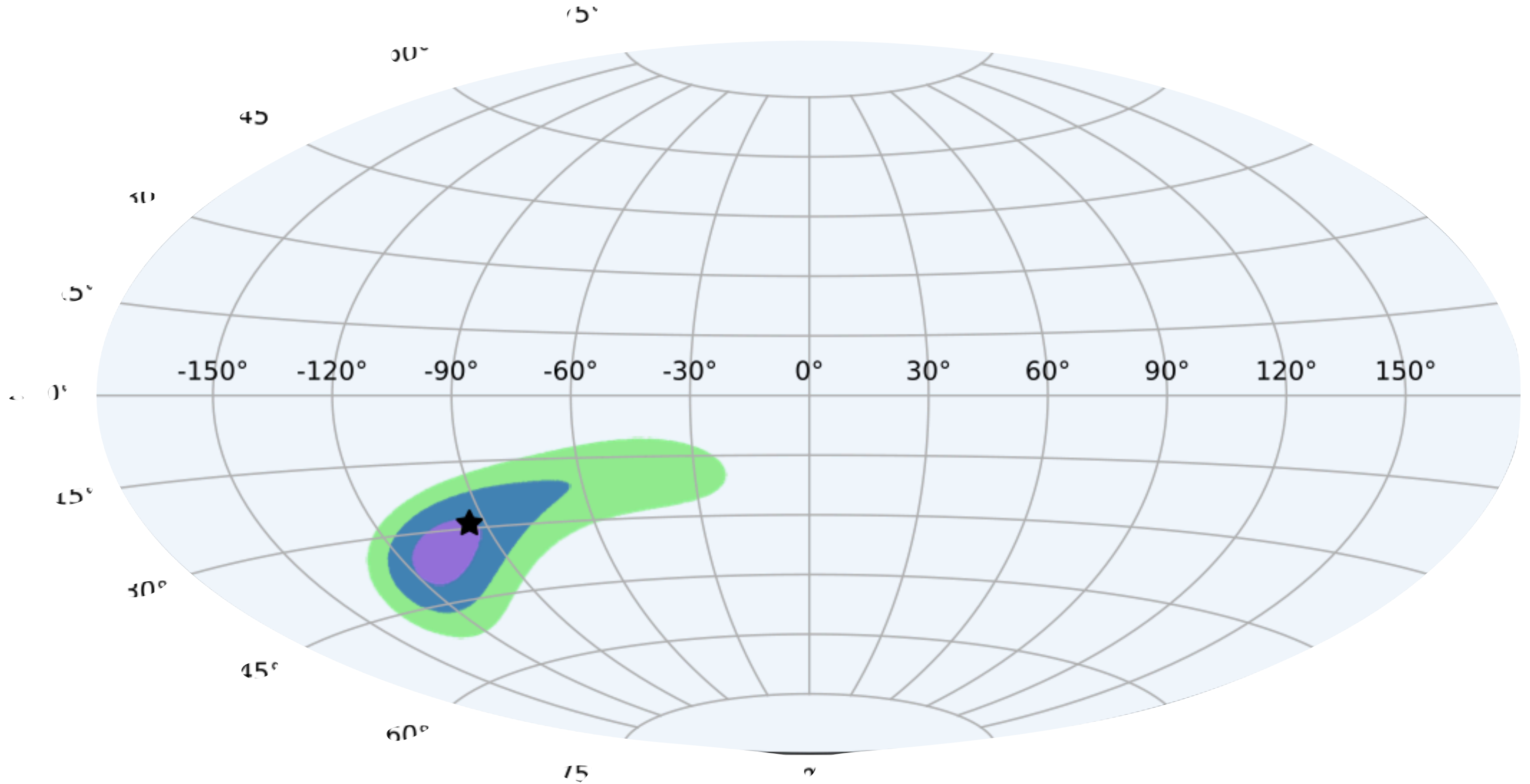
Matz et al., 1888

Neutrino detection is crucial

- **Neutrinos are crucial** to answer **WHERE** and **WHEN** to look
- **Delay between neutrinos and EM emission** ⇒ organize coordinated EM follow-up
- Scientific opportunities may be lost without world-wide multi-messenger coordination

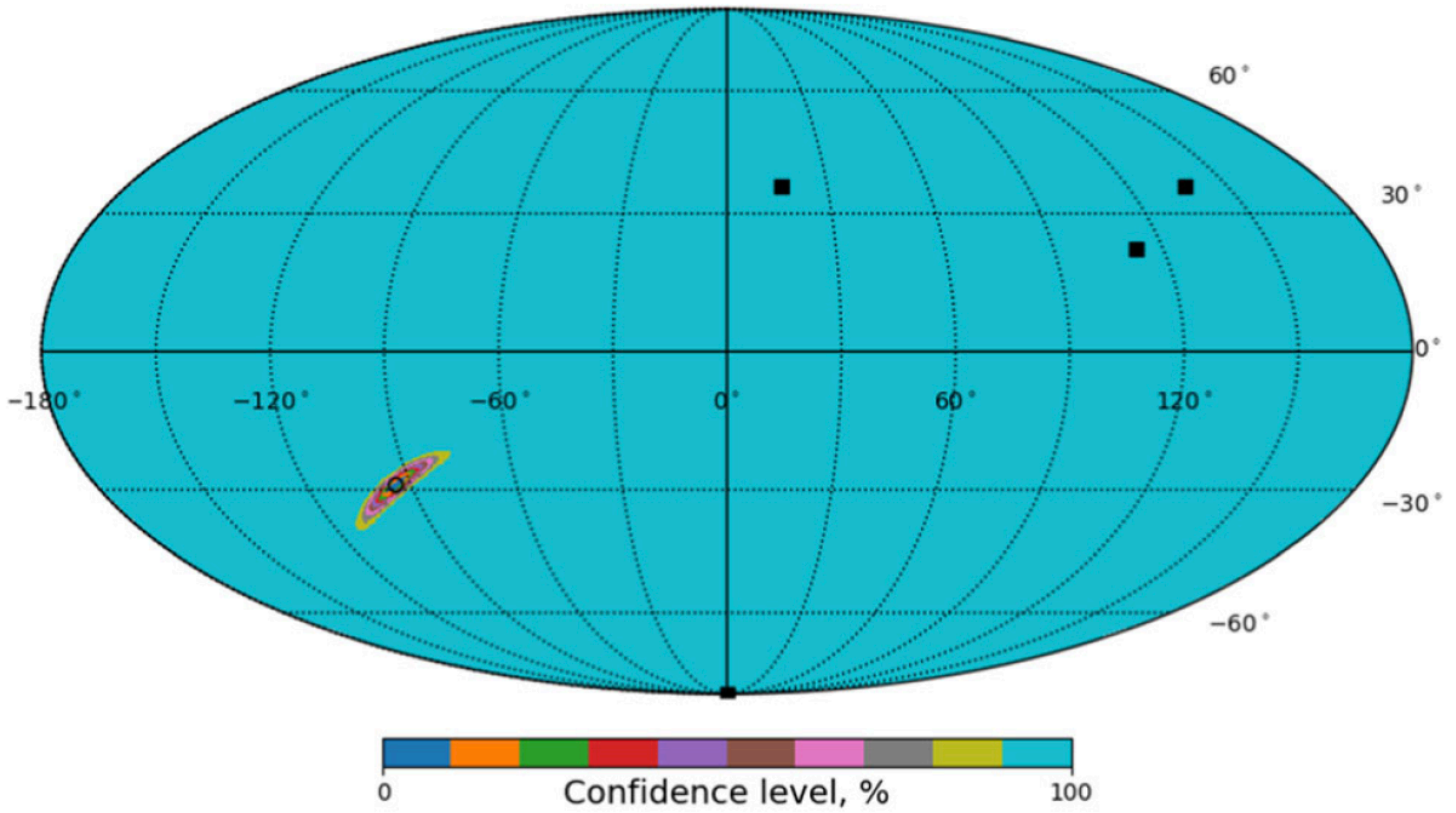


Nakamura et al., 2016



Linzer & Scholberg, 2019

Tens to thousands of sq. degrees

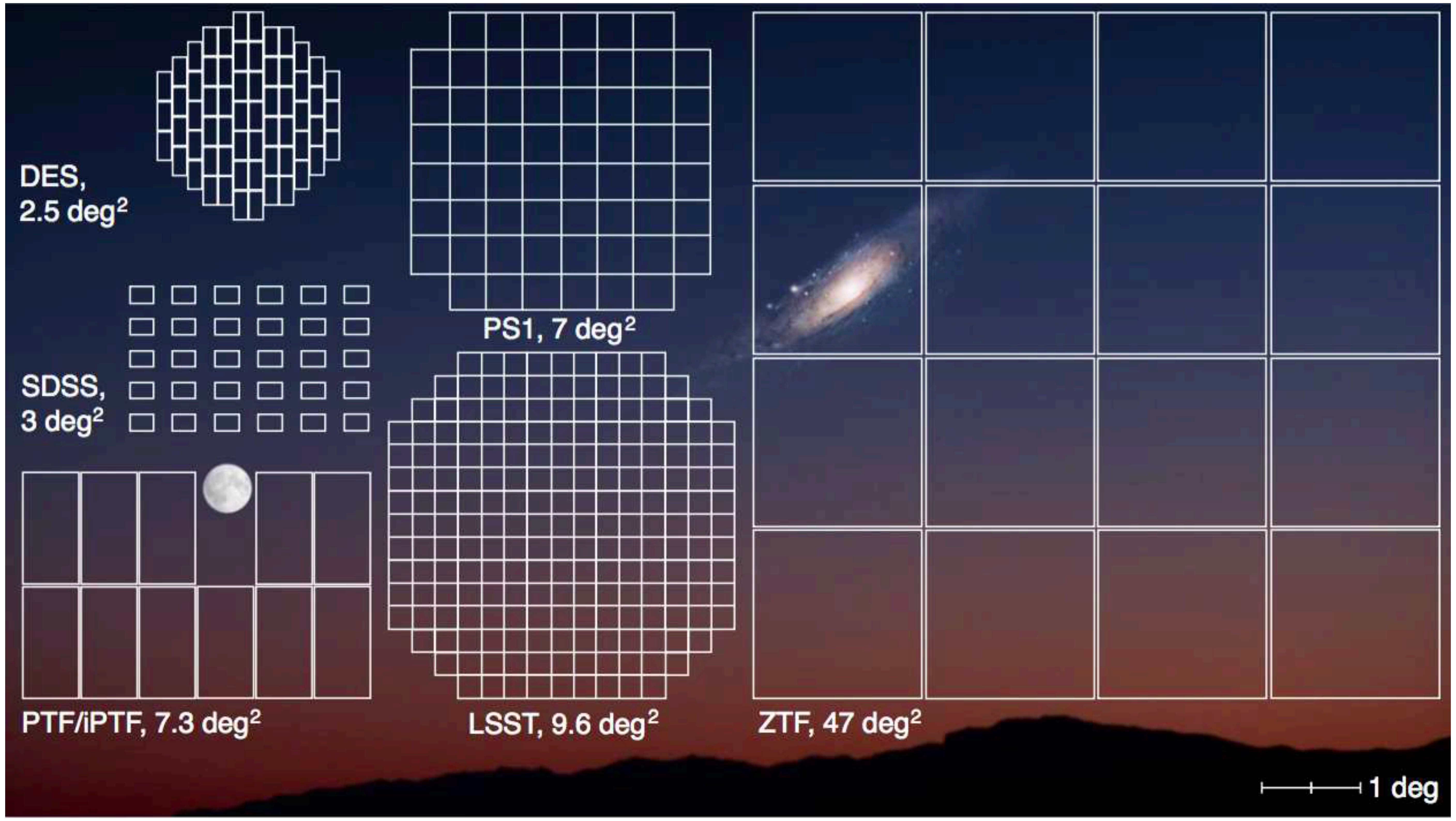


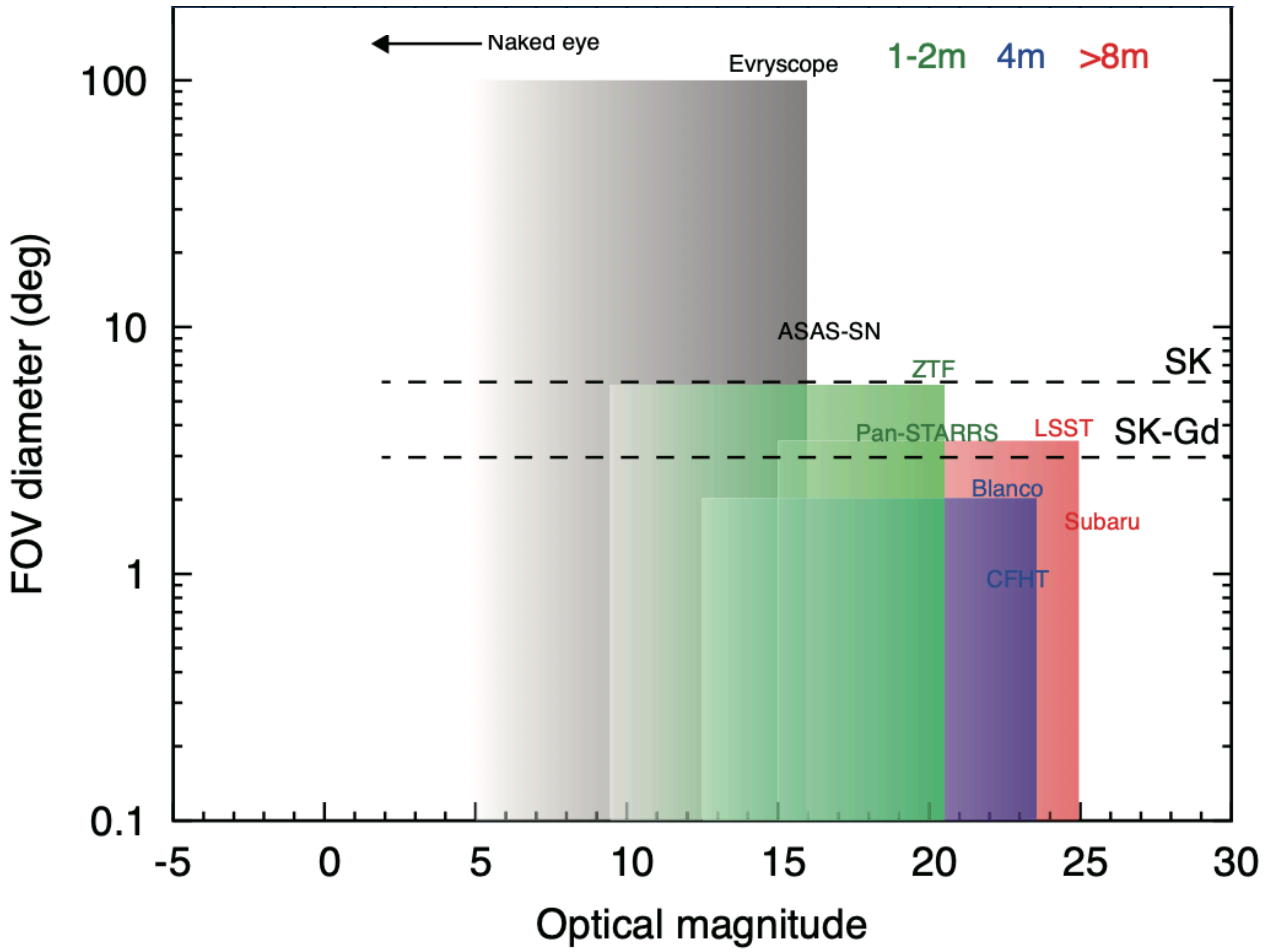
Coleiro et al., 2020

Electromagnetic observing strategies

Two approaches (based on GW follow-up):

1) Wide field-of-view instruments (with smaller aperture / sensitivity):



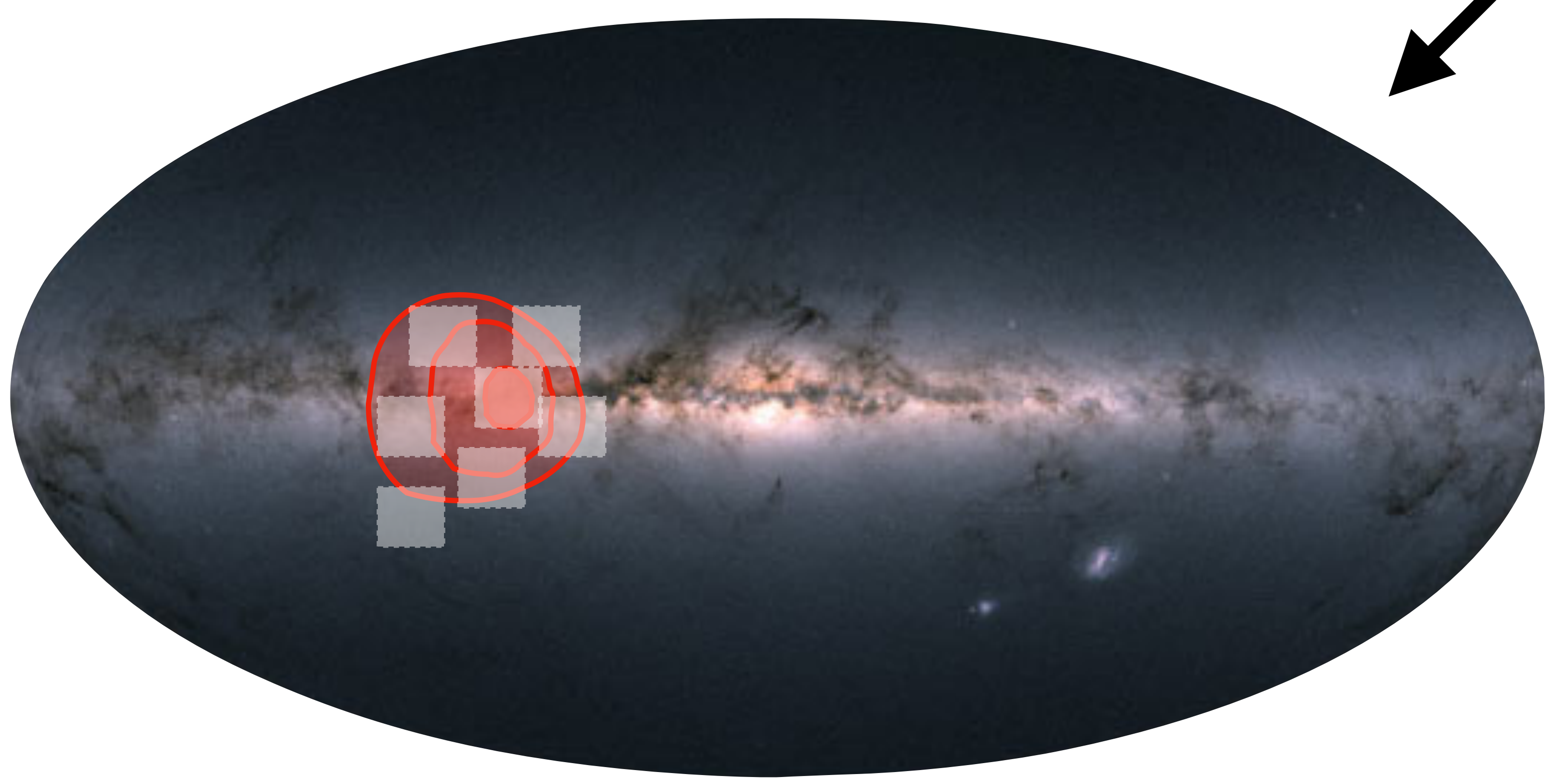


Nakamura et al., 2016

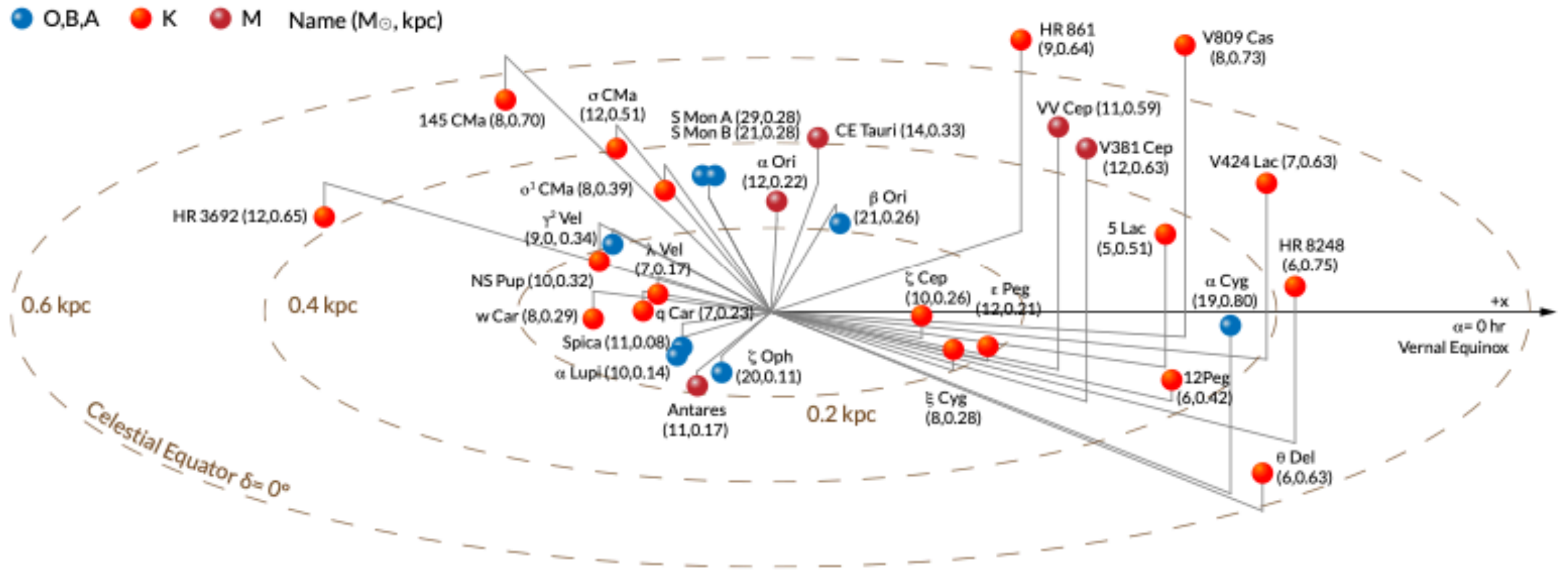
Electromagnetic observing strategies

Two approaches (based on GW follow-up):

2) Small field-of-view telescopes (larger aperture / better sensitivity):



Tiling of the location error box with optimized prioritization



Catalogue targeting (supports target selection)

Mukhopadhyay et al., 2020

- Smaller FoV telescopes might ensure longer timescale monitoring
- Requires good coordination and telescope networks

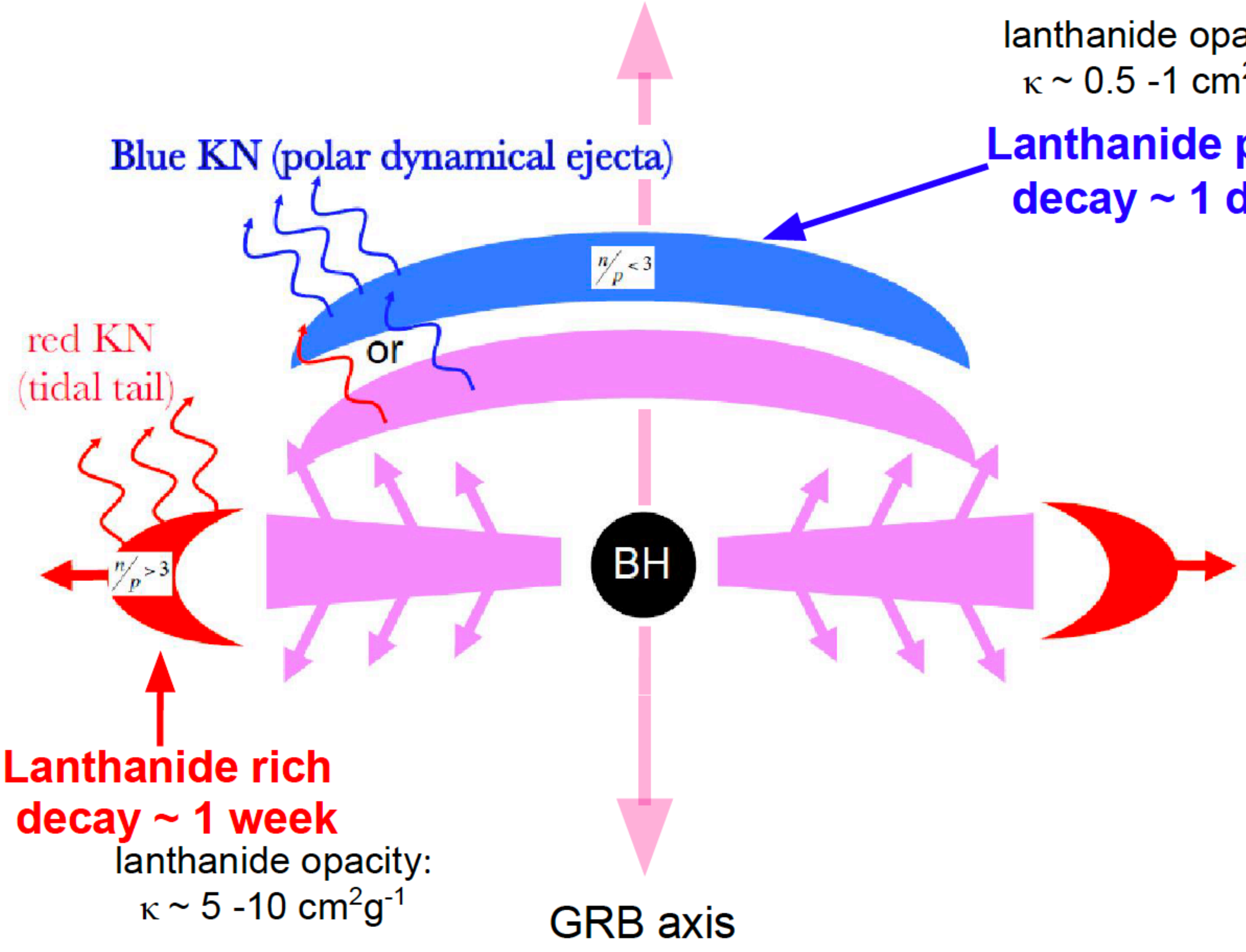
GRANDMA Network

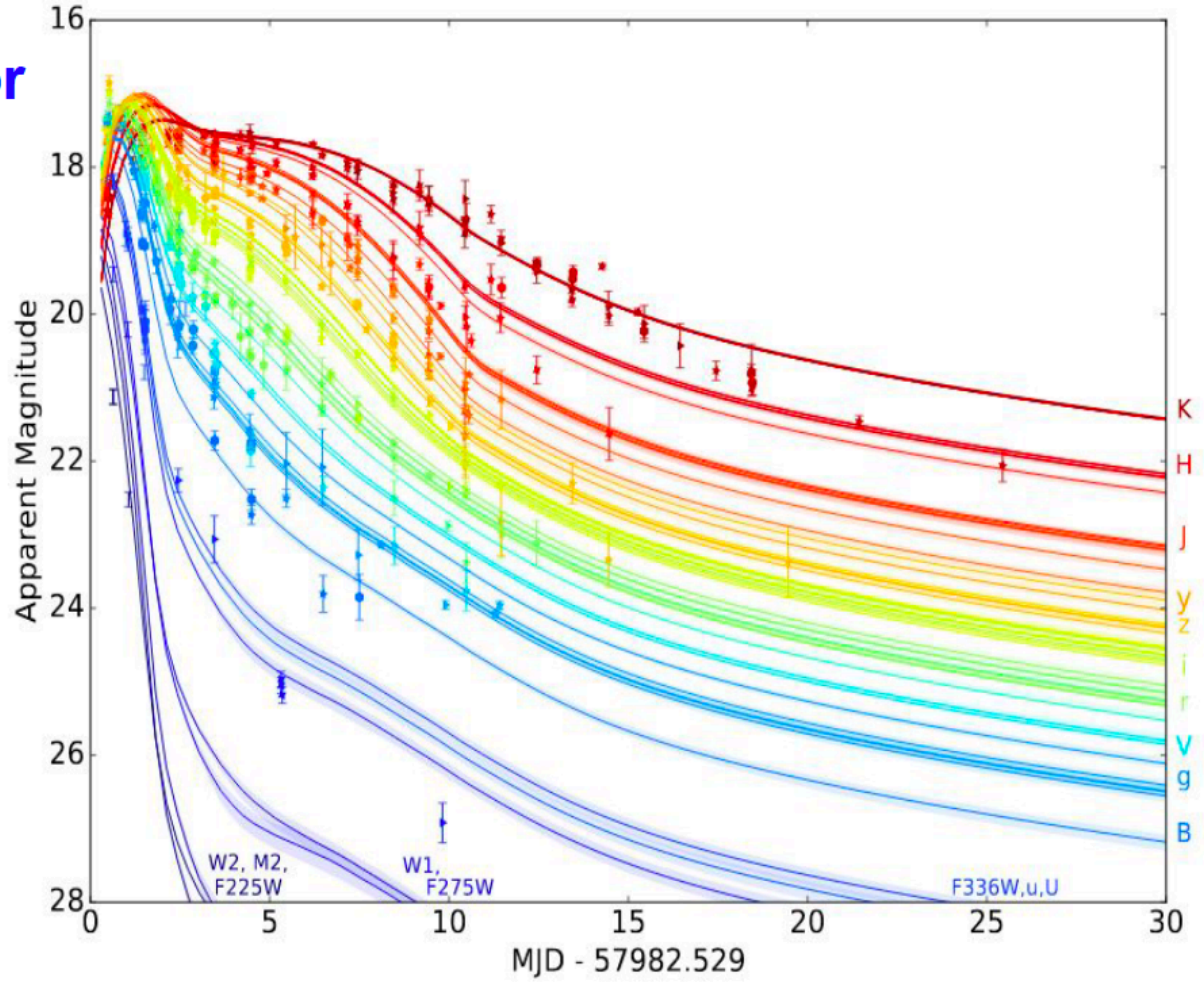
- **GRANDMA**: **network** of telescopes built in 2018 for multi-messenger & transient astronomy
- 18 countries - 23 observatories - **35 telescopes (optical + NIR)**
- Wide-fields down to **20 mag**
- EM candidates **~23 mag** in photometry and 22 mag in spectroscopy
- **Citizen science program** involving >100 amateur astronomers

Kilonova observation

lanthanide opacity:
κ ~ 0.5 -1 cm^2g^{-1}

Lanthanide poor
decay ~ 1 day





Lightcurves AT2017gfo - GW170817 kilonova
Villar et al., 2017, APJL

Kilonova observation

- **Detecting EM emission associated to a kilonova is challenging**

Kilonova Challenge	Possible solution
Short lived - Hours up to days	Quick reaction
Faint - Peak at 20.5 mag at 200 Mpc	Deep observations
Rapid Color Evolution	Multi-wavelength observations
Large localisation uncertainty	Coordination of observations

Requires a Network of **telescopes** and **people** with **different expertises** (electromagnetic, GW, neutrino emission)

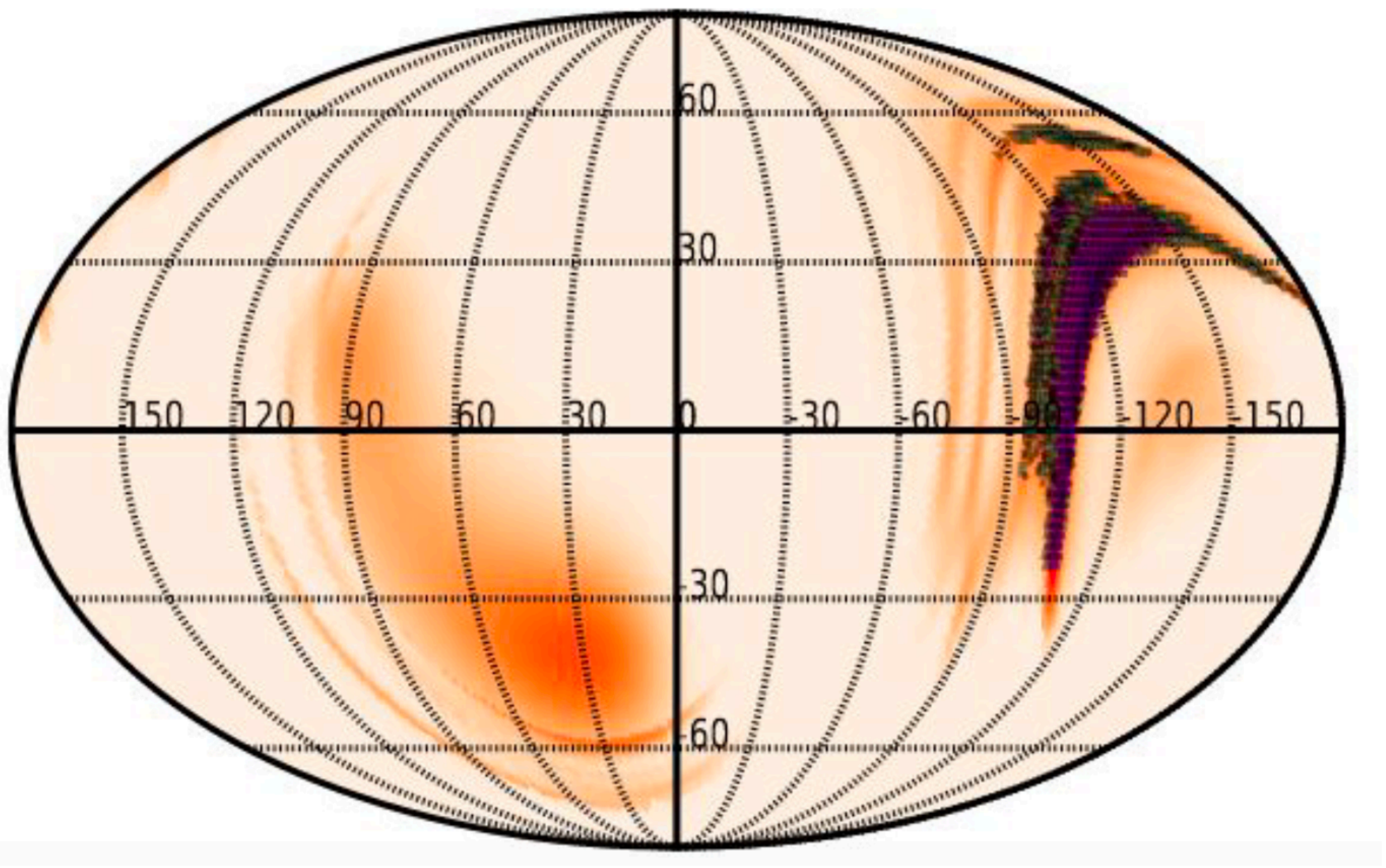
GRANDMA observing strategies

Tiling

Cover the sky localisation map of GW:

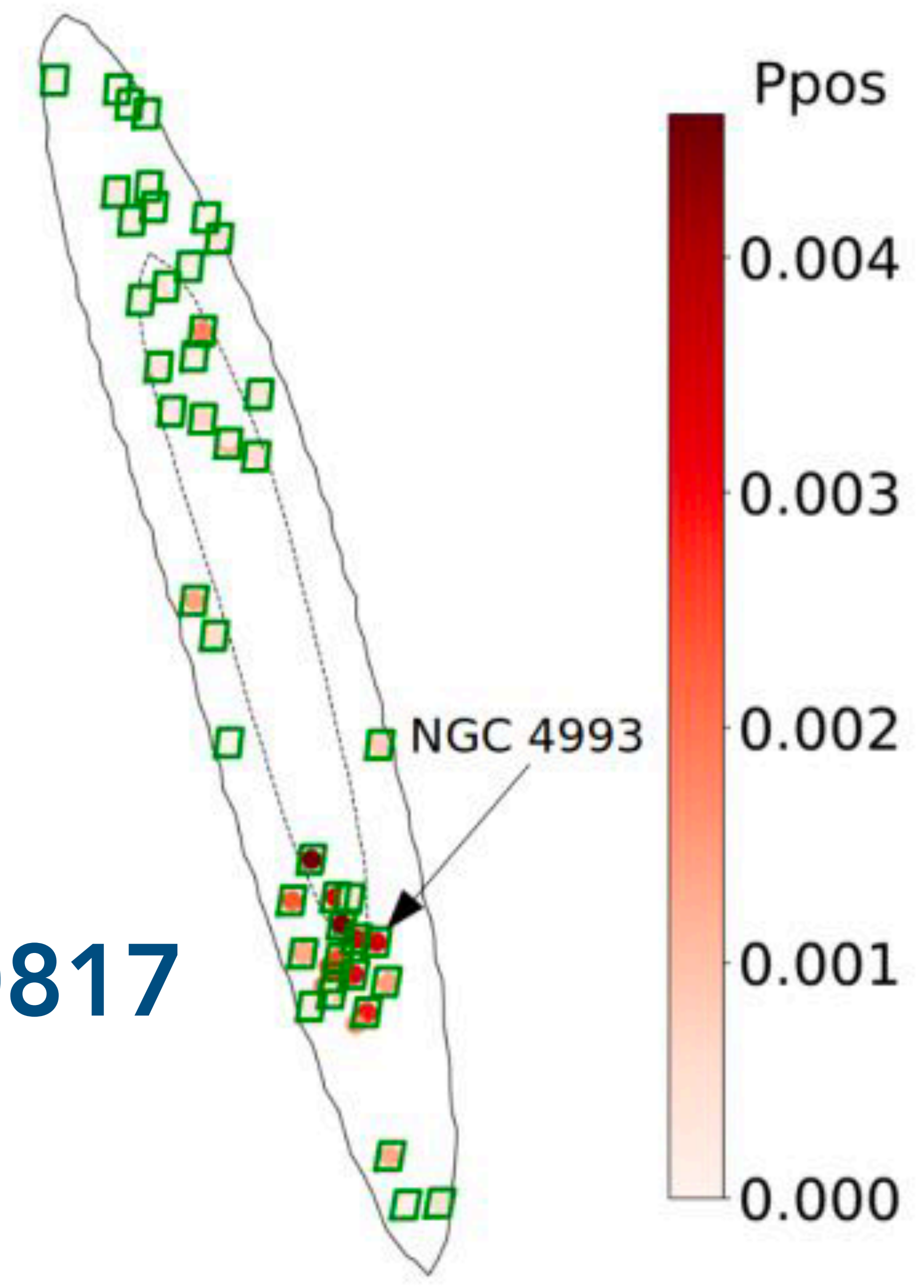
- Look for new object that are related to the GW
- **Best suited for large FoV (>1deg²) instruments**
- Widely used by current surveys (PAN-STARRS, ZTF, TAROT,...)

See 1909.01244 for the figure



Galaxy targeting

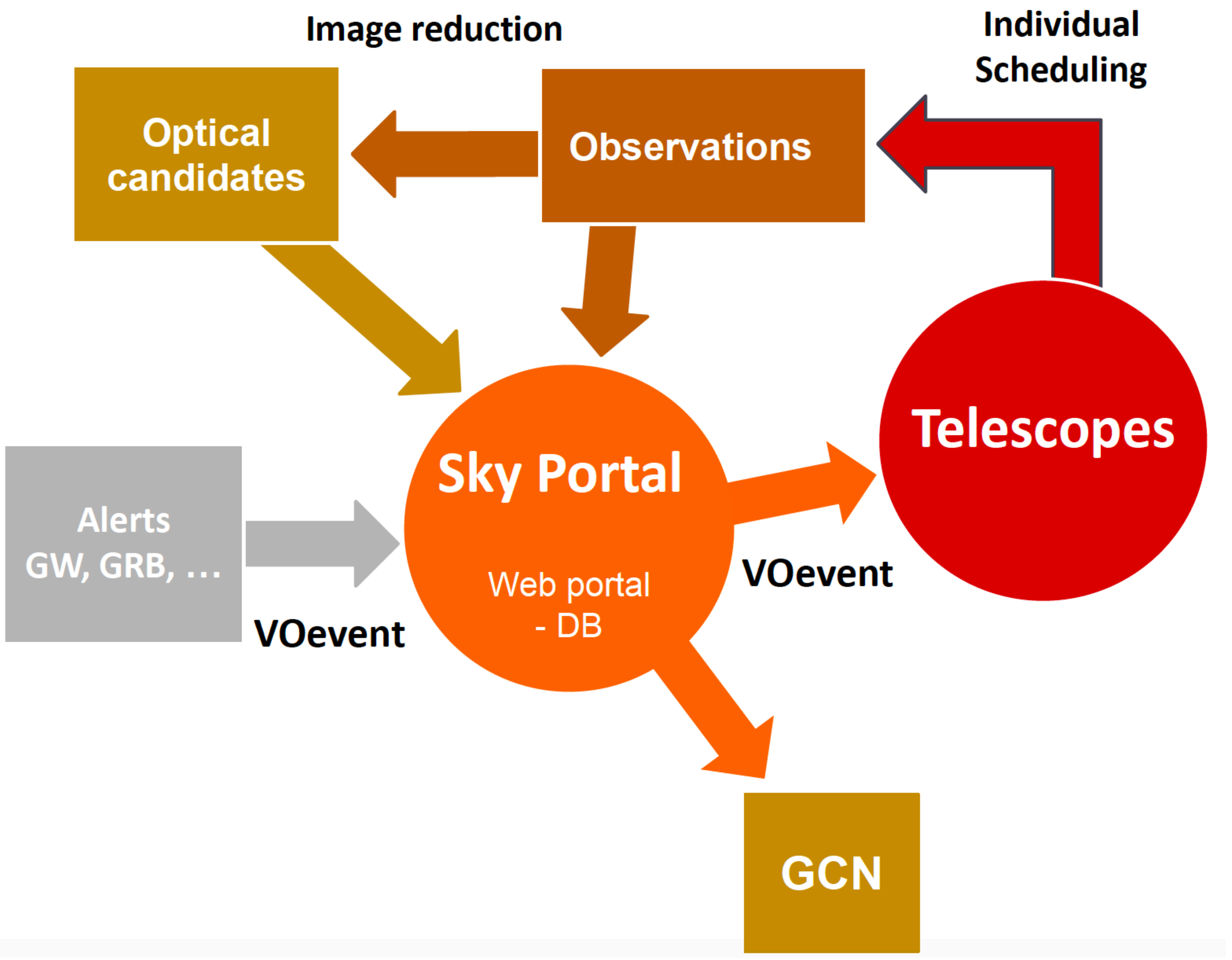
- Observe galaxies compatible with the GW error box
- Galaxies classified with
  - spatial information
  - stellar mass estimation
  - (distance)
- MANGROVE catalog
- **Best suited for small FoV instruments**
- **Technique used for GW170817 detection**



GW170817 localisation and compatible galaxies (1911.05432 and 1909.01244)

GRANDMA Orchestration

- Listening to **external alerts**: GW, GRB, SNe
- GRANDMA operates with a **central database** SkyPortal
- Individual **observation plans** to GRANDMA instruments (GWEMOPT)
- 2 observation strategies : **Galaxy targeting** & **Tilling**
- Homogeneous **data reduction** (STDpipe & Muphoten) and **transient classification**
- Distribution of the **low latency analysis** via GCN circulars
- **Off-line analysis + Modelisation**
- **All our tools are public**



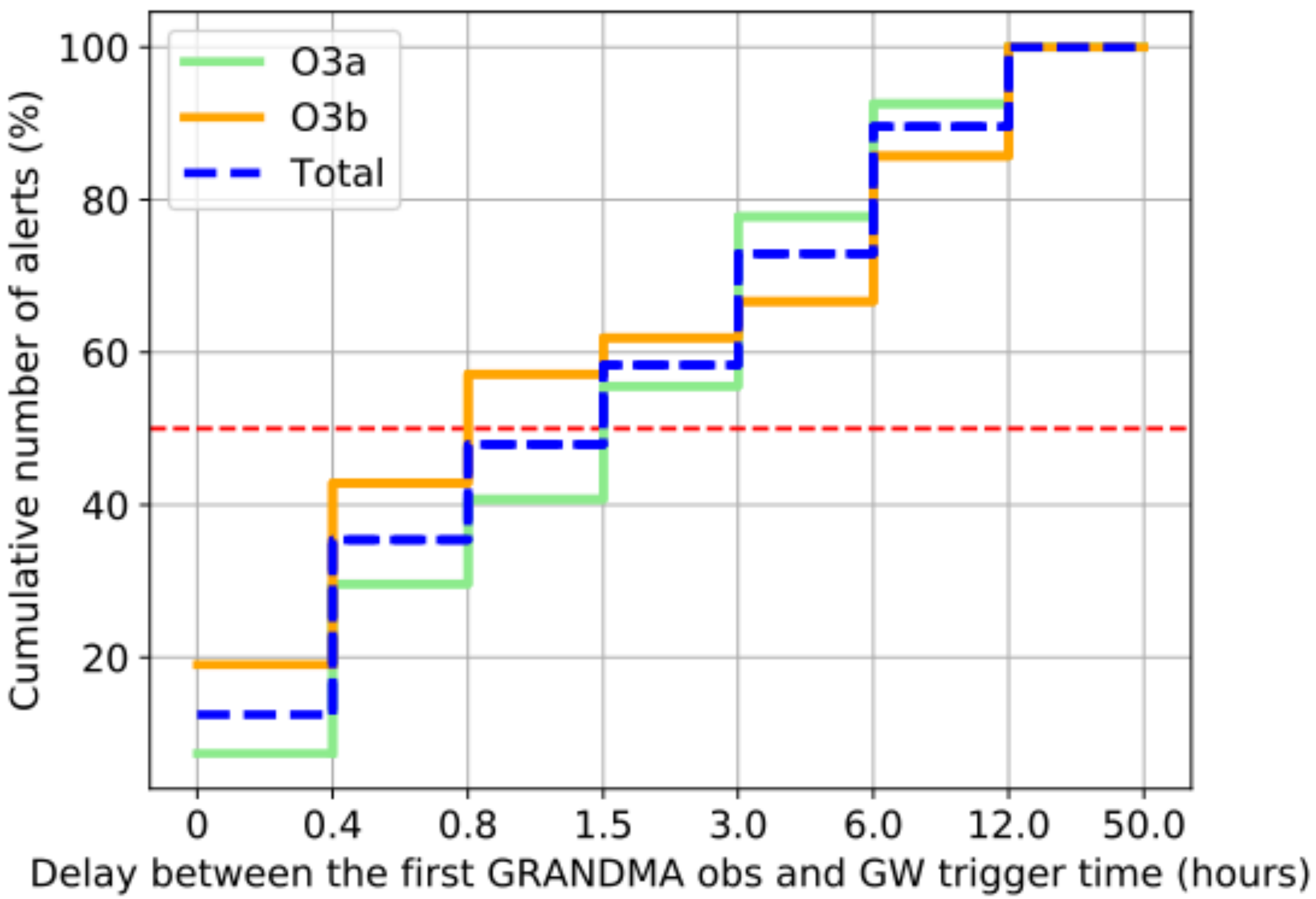
LVC 3rd observing run with GRANDMA

- 49/56 alerts were followed by GRANDMA

- 15 min for the first observation after the GW trigger
- 1.5 h delay for 50% of alerts

- ~200 deg^2 covered in each alert at 18 mag
  11 alerts covered above 90% confidence level

- No EM GW counterpart found but upper limits on ejecta properties



- **O3b and global summary of O3:** GRANDMA Observations of O3 Observational Campaign, MNRAS, 2020
- **O3a and presentation of the collaboration:** The first six months of O3 with GRANDMA, MNRAS, 2020

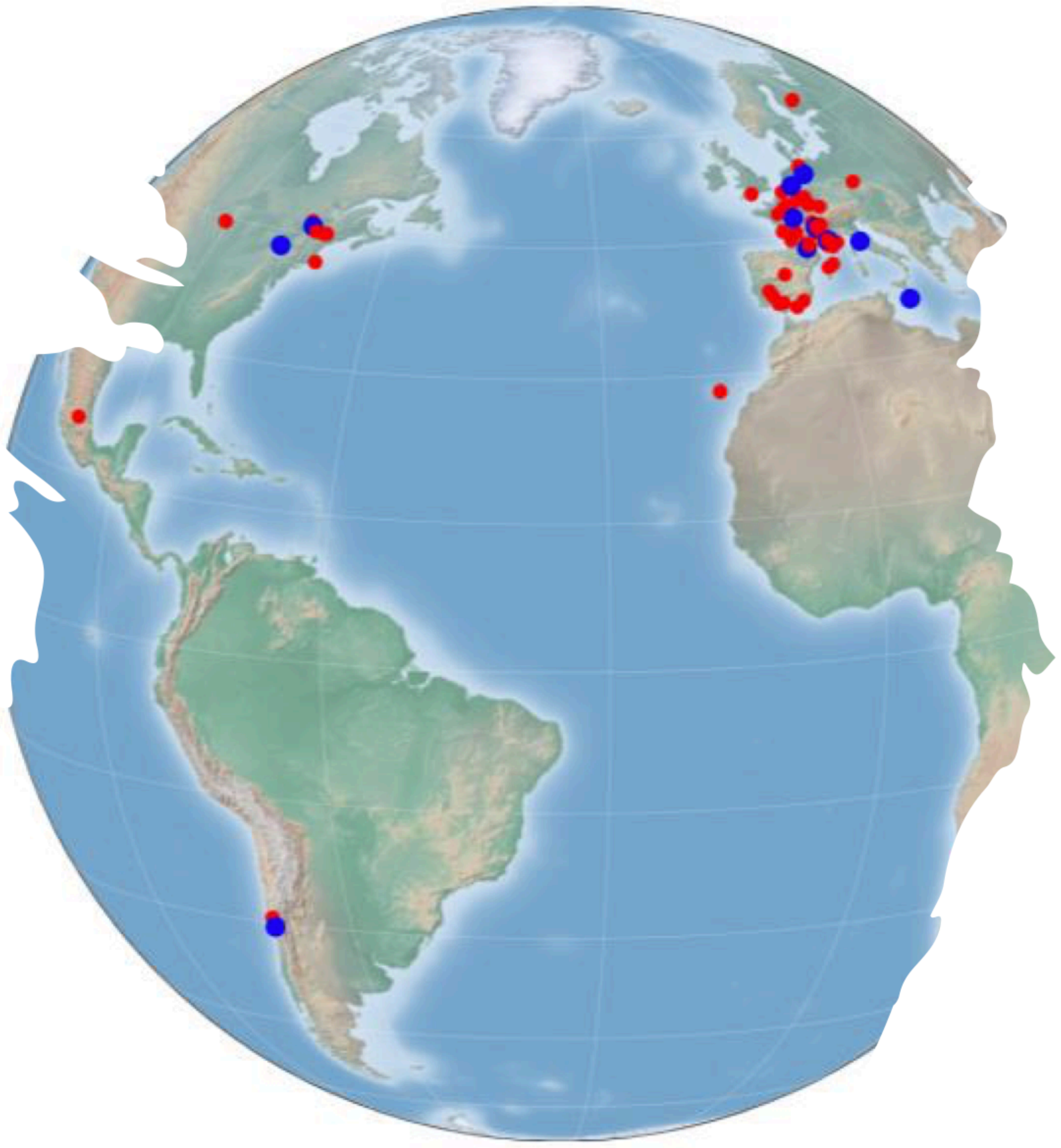
Kilonova-Catcher

KILONOVA CATCHER

http://kilonovacatcher.in2p3.fr

Connecting amateur astronomers to GRANDMA network

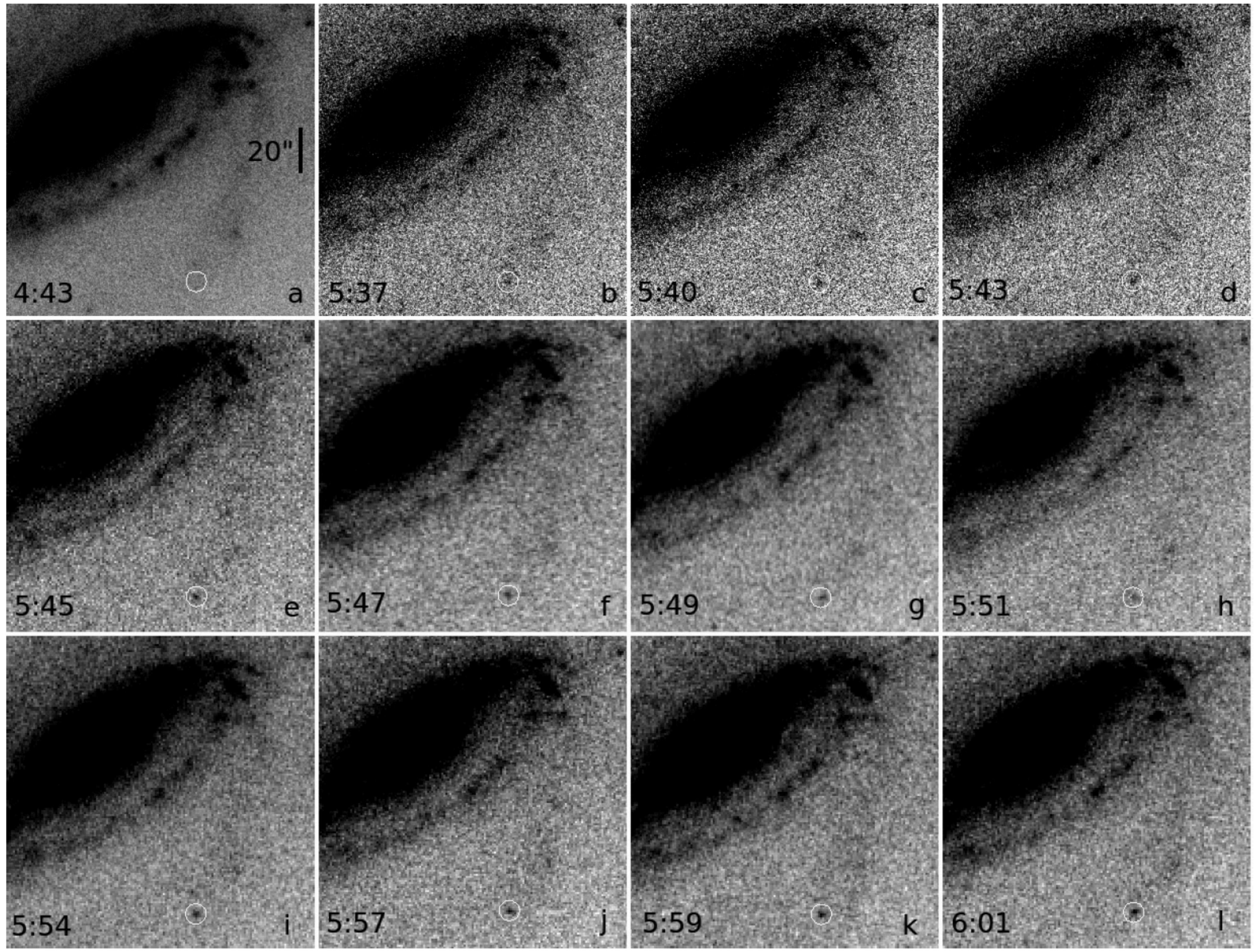
- **Observation of transient events with poorly known location by amateur astronomers**
- **More than 130 participants** with telescopes from 15-60 cm diameter
- **Example**: search for kilonovae:
  - GRANDMA provides **observing plans** optimized for the identification of the galaxy
  - Amateurs perform **observations**
  - **Automatic data analysis** to identify transients on GRANDMA database

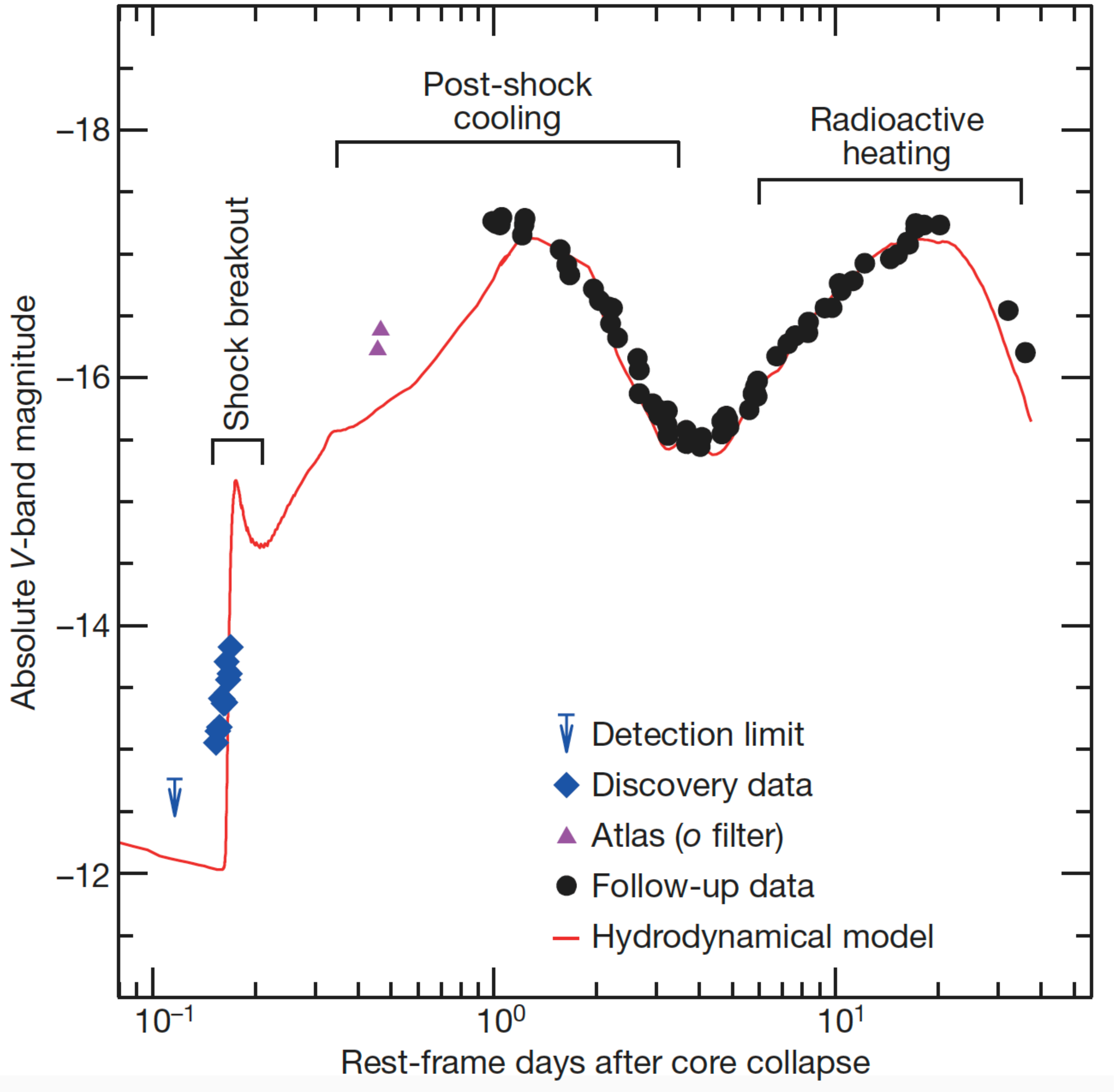


⇒ *First campaign demonstrated ability of amateur astronomers to reach required sensitivity to detect kilonova at ≤ 150 Mpc.*

Kilonova-Catcher

- **Same approach can be used for (Galactic) CCSN search.**
- **An example:**
  - SN 2016gkg was observed serendipitously by an amateur astronomer Victor Buso in NGC 613
  - Core-collapse (type IIb CCSN) and observation of the shock breakout.





Berstein et al., 2018

Kilonova-Catcher

- Same approac
- An example:
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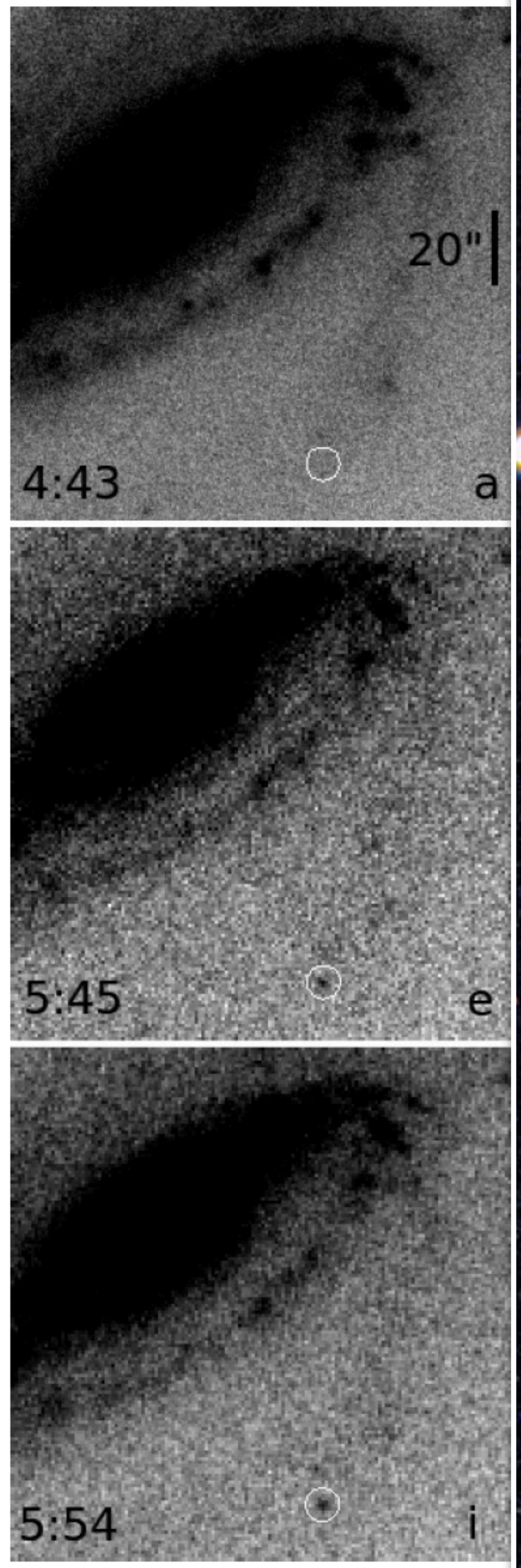
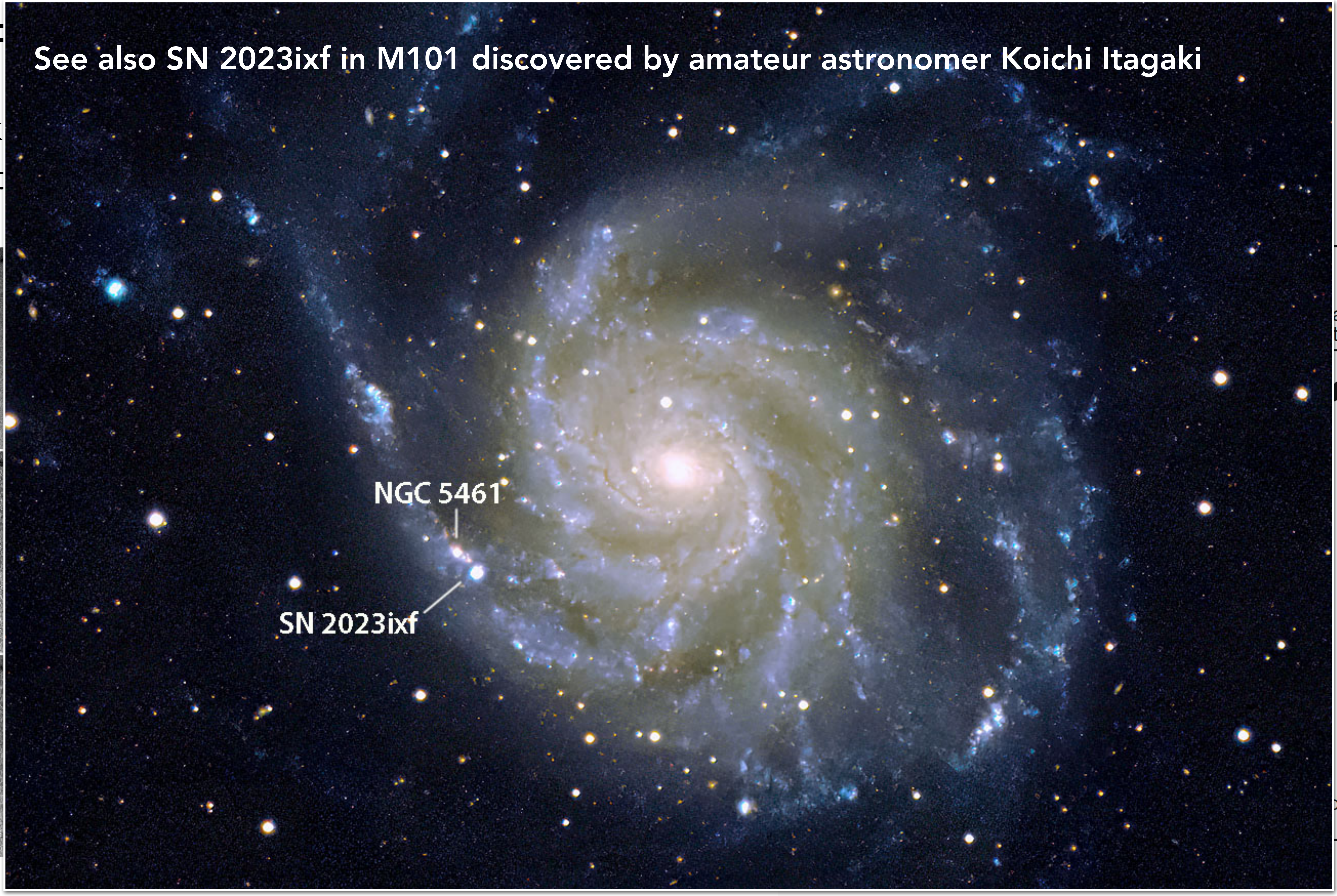
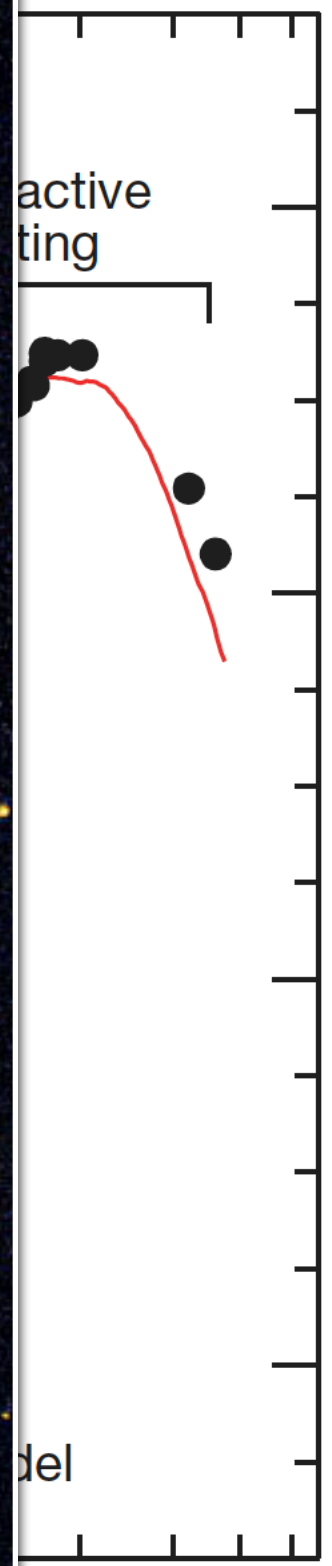




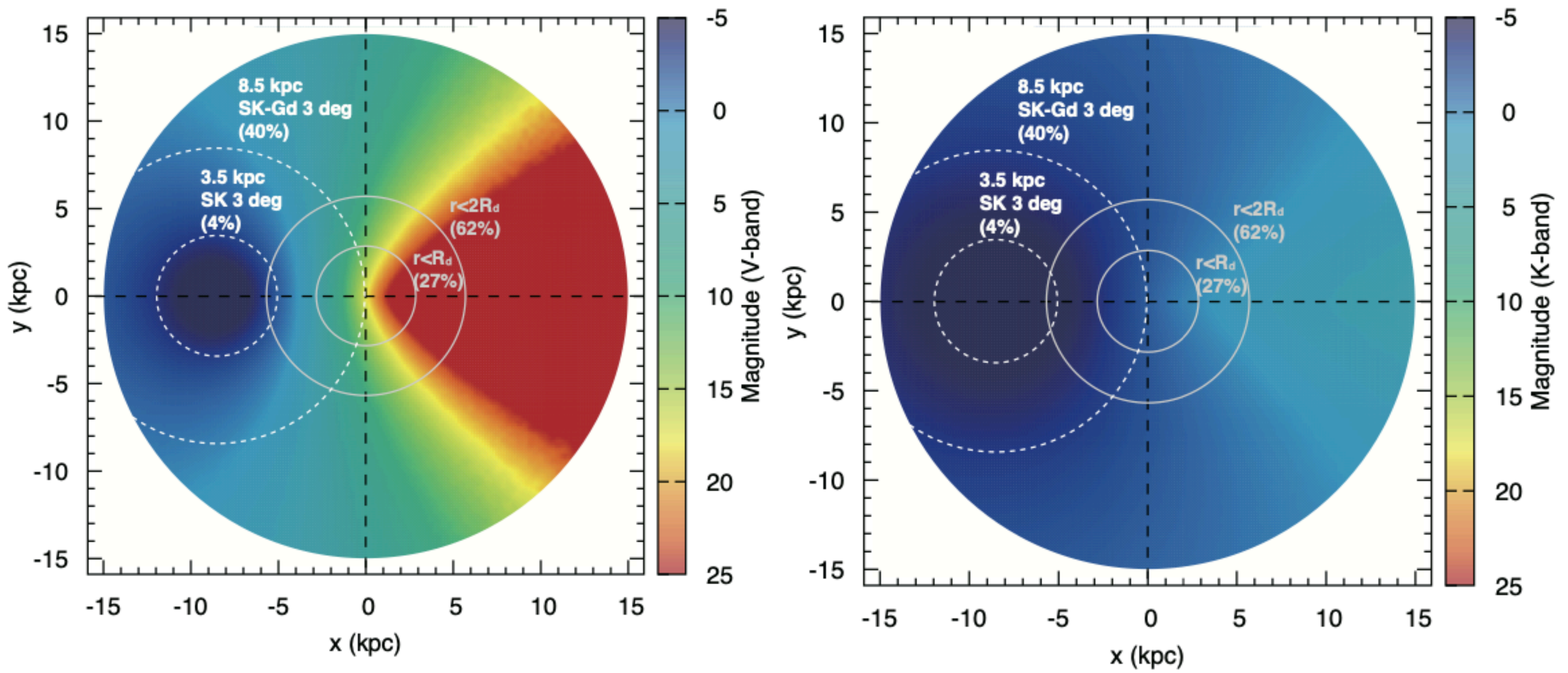


Berstein et al., 2018

CCSN follow-up: observing strategies

- **Main objective:** locate progenitor star **from** the shock breakout: intense multi-wavelength monitoring needed
  - Wide FoV instruments (X-ray + optical + NIR)
  - + Smaller FoV instruments: tilling or star catalogue targeting.
  - **Near-infrared is crucial to avoid extinction**

- Other considerations:
  - **Failed CCSN:** weak SBO signal to be expected
  - **Spectropolarimetry:** early polarization data might reveal asymmetry of the explosion.



Nakamura et al., 2016

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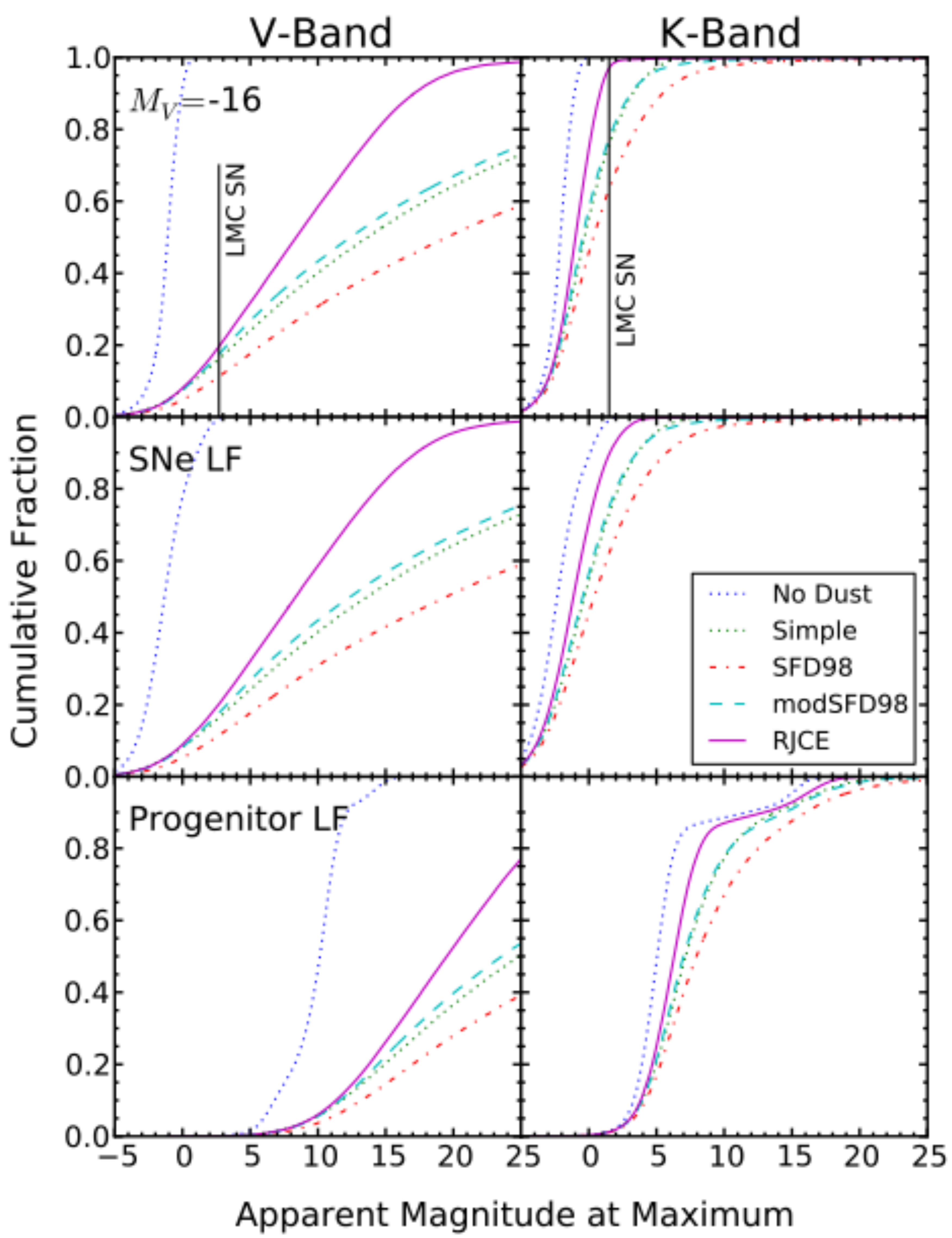

Adams et al., 2013

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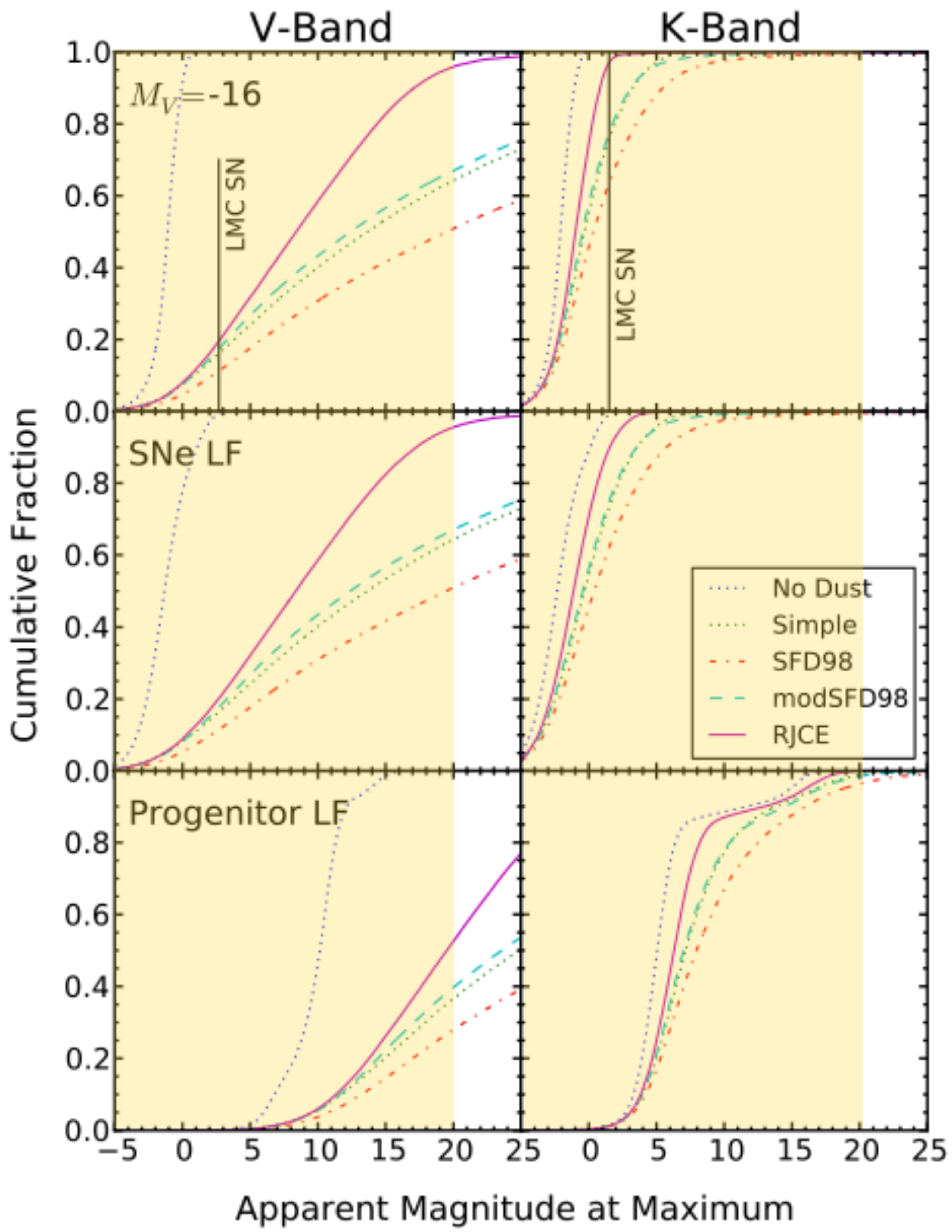
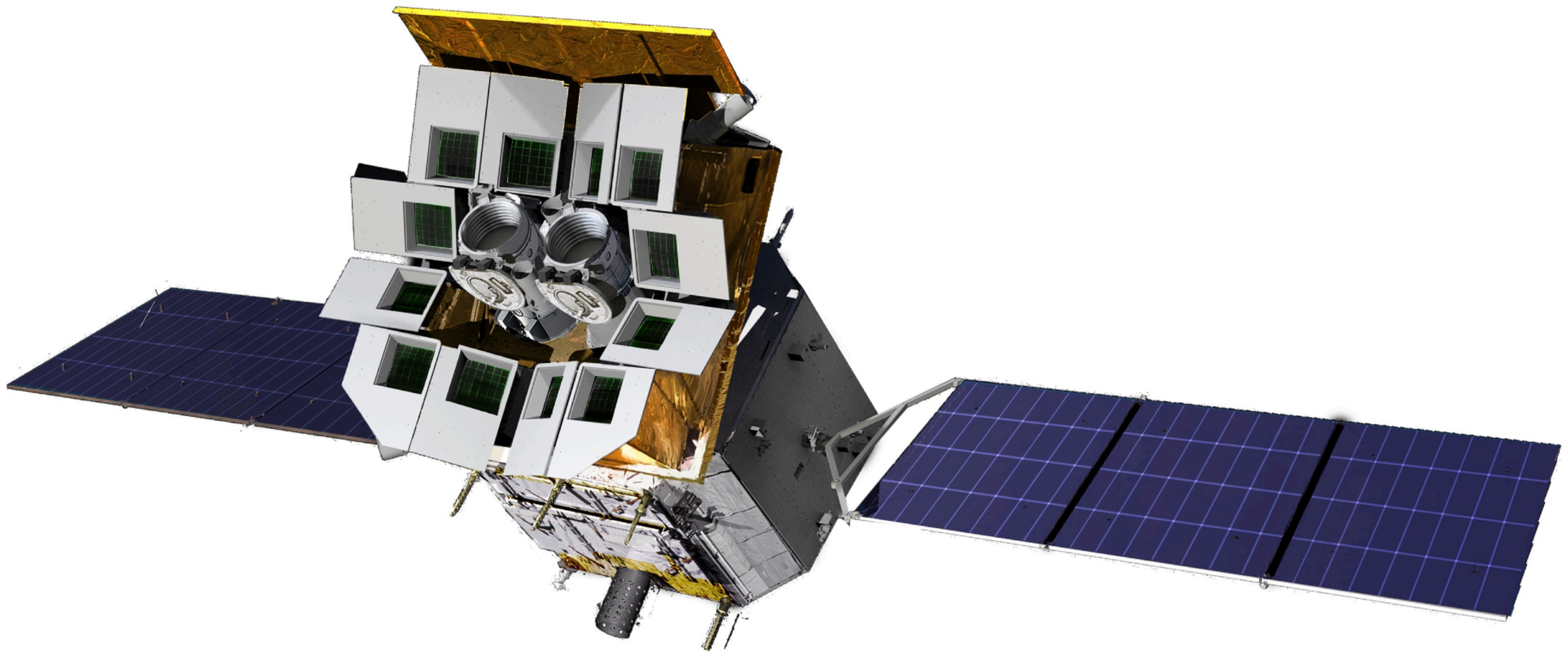
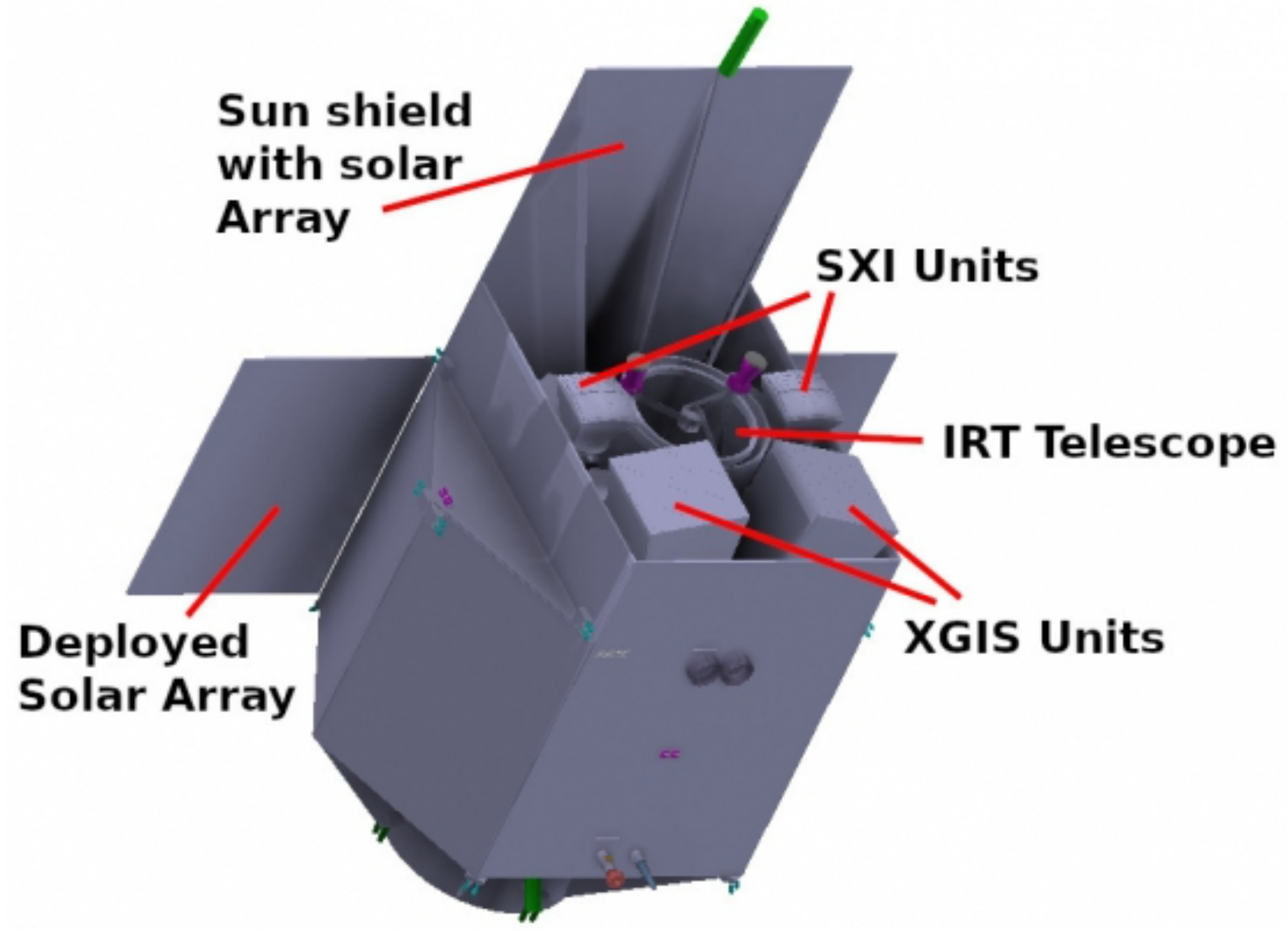
GRANDMA should be able to detect $\gtrsim$ 50% of the cases



Adams et al., 2013

Future X-ray facilities





Einstein Probe: Chinese space mission (with German + EU + Fr contribution)

- **Goal:** discover and characterize transient sources in the soft X-ray.
- To be launched end of 2023.
- WXT: ~3600 deg^2 FoV (5′ angular resolution)
  ⇒ Shock breakout detection

ESA / THESEUS (?): Proposed in response to the ESA call M7

- Launch in ~2037 if selected.
- Dedicated to gamma-ray burst (at high z) + X-ray transients.
- 3 instruments on board including a ˜1000 deg^2 FoV soft X-ray instrument.

How to coordinate ?

- **Network of multi-wavelength observatories** (optical, near-infrared, X-rays)
- **Amateur astronomers** can play a crucial role (if EM counterpart observable in optical)
- Requires an **efficient infrastructure** to coordinate observations + tools (see e.g. SkyPortal / GRANDMA, GROWTH, … feedback)
- **Share observations plans and results** (through GCN, ATel, VOEvent, …) to limit duplication
- GRANDMA: ongoing optimization of the follow-up strategy (tiling + catalog targeting) + detection probability
- Discuss data format + alert dissemination in advance

Conclusions

GW170817 follow-up

Try to optimize multi-messenger follow-up, with **efficient coordination**

Improve the scientific outcome of once-in-a-lifetime opportunity

- **GRANDMA:** an example (among others) of coordinated networks dedicated to multi-messenger astronomy
- Proof-of-concept based on **GW follow-up** and kilonova searches (approach similar to CCSN follow-up)
- Tools, expertise already available.
- **GRANDMA is willing to contribute to this exciting challenge with SNEWS 2.0**