Electromagnetic counterparts of gravitational wave transients

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LIGO-DCC G1300486
**Expected “transient” GW sources detectable by LIGO/Virgo**

“Transient GW signal”: signal with duration in the detector sensitive band significantly shorter than the observation time and that cannot be re-observed.

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**Coalescence of Compact Objects**

**Neutron-Stars and/or Black-Holes**

Binary containing a NS:
- **Inspiral** dominant phase
- **GW emission** enters sensitive band (> 50 Hz)
- < 20 s before merger
- **Energy emitted in GW**: \( \sim 10^{-2}M_\odot c^2 \)

**Core-collapse of Massive Stars**

Energy emitted in GW uncertain:
- Likely \( 10^{-8}M_\odot c^2 \)
- Optimistic \( 10^{-4}M_\odot c^2 \)

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**Initial LIGO/Virgo**

Binary containing a NS detectable to \( \sim 50 \) Mpc likely rate \( 0.02 \) yr\(^{-1} \)

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Ott, C. 2009, CQG, 26

These energetic astrophysical events are expected to emit EM radiation

**Merger of NS-NS / NS-BH**

**Core collapse of massive star**

**Gamma-Ray Burst:** intense flashes of gamma-rays isotropic-equivalent energy up to $10^{53}$ erg

**Short Hard GRB**

**Long Soft GRB**

**Progenitor indications:**
- lack of observed SN
- association with older stellar population
- larger distance from the host galaxy center (~ 5-10 kpc)

**Optical Kilonovae**

**Radio Remnant**

**Supernovae**

Type II, Ib/c

Progenitor strong evidence: observed Type Ic SN spectrum

*Metzger & Berger 2011*
### Advanced era GW-detectors (ADE)

**LIGO and Virgo detectors are currently being upgraded**

- Boost of sensitivity by a factor of ten
- (of $10^3$ in number of detectable sources)
- in the 10-1000Hz range

### Advanced era Detection rates of compact binary coalescences

<table>
<thead>
<tr>
<th>Source</th>
<th>Low yr$^{-1}$</th>
<th>Real yr$^{-1}$</th>
<th>High yr$^{-1}$</th>
<th>Max yr$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NS-NS</td>
<td>0.4</td>
<td>40</td>
<td>400</td>
<td>1000</td>
</tr>
<tr>
<td>NS-BH</td>
<td>0.2</td>
<td>10</td>
<td>300</td>
<td></td>
</tr>
<tr>
<td>BH-BH</td>
<td>0.4</td>
<td>20</td>
<td>1000</td>
<td></td>
</tr>
</tbody>
</table>

(Abadie et al. 2010, CQG 27)

### Mass:
- NS = 1.4 Mo
- BH = 10 Mo

### Sky location and orientation averaged range
- 197 Mpc for NS-NS
- 410 Mpc for NS-BH
- 968 Mpc for BH-BH

### Core-Collapse Supernovae
- 2-4 yr$^{-1}$ EM-observed within 20 Mpc
- GW-signal detectable < Milky Way few Mpc
- LONG-GRB core-collapse - 10 Mpc (?)
Main motivations for joint GW/EM observations

- Consider the GW signal in its astrophysical context
- Give a precise (arcsecond) localization, identify host galaxy
- Multi-messenger picture for a complete knowledge of the most energetic events in the Universe
- GW and EM provide insight into the physics of the progenitors (mass, spin, distance..) and their environment (temperature, density, redshift..)
- Start the GW astronomy to answer a plethora of open questions on:
  - connection between short GRBs and compact object mergers
  - the birth and evolution of black holes
  - equation of state of nuclear matter
  - in the long term cosmology

.........
EM emission from transient GW sources
GRBs emission - Fireball Model

Cataclysmic event
NS-NS NS-BH merger

Central engine
Black Hole + accretion disk

“Magnetar” millisecond magnetized (B > 10^{11} T)
Neutron Star

Surrounding medium

Relativistic Outflow
Internal shocks
External Shocks

Prompt emission
\( \gamma \)-ray - within seconds
Afterglow emission
Optical, X-ray, radio
hours, days, months

Jet temporal evolution
Light curve (Flux vs time)

Nakar & Piran 2003
Optical afterglow ON-AXIS GRB

Source at distance of 200 Mpc

Power-law luminosity decay with time $t^{-\beta} \rightarrow \beta = 1 \div 1.5$

Observer along the jet axis

$\theta_{\text{obs}} < \theta_{\text{Jet}}$
Optical afterglow “Orphan GRB”

Source at distance of 200 Mpc

Synthetic afterglow light curves

http://cosmo.nyu.edu/afterglowlibrary/index.html
By van Eerten & MacFadyen
X-RAY: GRB at distance of 200 Mpc

Swift-XRT FoV = 0.16 sq. degree

Observed
On-Axis sGRB

Synthetic
off-axis GRB


Short GRB 050709:

radio

optical

X-ray

Fox et al. 2005, Nature 437
Significant mass \((0.01-0.1 \text{ } m_\odot)\) is dynamically ejected during NS-NS NS-BH mergers at sub-relativistic velocity \((0.1-0.2 \text{ } c)\)


**Macronova – Kilonova**

short lived IR-UV signal \((\text{days})\) powered by the radioactive decay of heavy elements synthesized in the ejected outflow


**RADIO REMNANT**

long lasting radio signals \((\text{years})\) produced by interaction of ejected sub-relativistic outflow with surrounding matter

Kilonovae Light Curves

Source at distance of 200 Mpc

**Kilonova model afterglow** peaks about a day after the merger/GW event

Major uncertainty OPACITY of “heavy r-process elements”

New simulations including lanthanides opacities show:

- broader light curve
- suppression of UV/O emission and shift to infrared bands

Barnes & Kasen 2013, arXiv:1303.5787

Possible HST kilonova detection for short GRB 130603B after 9.4 days

Radio Flare Light Curves

Source at distance of 300

External ambient density $n = 1 \text{cm}^{-3}$

150 MHz

$F_{\text{peak}} \sim 0.2 - 1 \text{ mJy}$

$t_{\text{peak}} \sim 2 - 5 \text{ years}$

1.4 GHz

$F_{\text{peak}} \sim 0.04 - 0.3 \text{ mJy}$

$t_{\text{peak}} \sim 1.5 - 5 \text{ years}$


Dominated by mildly relativistic outflow $v > 0.3c$ not included in the simulation expected brighter emission

External ambient density critical parameter $n = 0.1 \text{ cm}^{-3}$ an order of magnitude fainter signals
EM signals from NS-NS/NS-BH merger and massive star core-collapse

- **Prompt γ-ray emission (beamed):**
  - GRB → GW search
  - "Triggered off-line analysis"

- **GRB afterglow emission, kilonovae:**
  - GW trigger → EM search
  - "Low-latency EM follow-up"

- **Radio flares:**
  - GW trigger → radio search
  - "High-latency follow-up"

  - Blind radio search → GW search
  - "Triggered off-line analysis"

- On-axis sGRB
  - Ultra-relativistic $\Gamma>100$ outflow
  - dynamic ejecta $\langle v \rangle \approx 0.1c$

- Orphan GRB

- Kilonovae
  - Late Radio Flares

- Source distance = 200 Mpc

- Red magnitude vs. Time (days)
Triggered analysis
EM observations → GW analysis
**GRB prompt emission - TRIGGERED SEARCH**

**EM observations guide GW analysis**

Known **GRB event time** and **sky position**:  
→ **reduction in search parameter space**  
→ **gain in search sensitivity**

**Analyzed 154 GRBs** detected by gamma-ray satellites (most from Fermi GBM and Swift BAT) during **2009-2010** while 2 or 3 LIGO/Virgo detectors were taken good data

**Unmodeled GW burst search**

-1.5 h off-source  -600 s on-source  +max(T90,60s) off-source +1.5 h

**Binary system coalescence search**

-5 +1 s

**No evidence for gravitational-wave counterparts**  
Non GW-detection result: **lower bounds on the progenitor distance**


Unmodeled GW burst (150 GRBs) with $10^{-2}$ Moc$^2$ energy in GW (optimistic)

Binary system coalescence (26 short GRBs)

**Median distances:**
- Unmodeled GW burst: 7, 17 Mpc
- Binary system coalescence: 16, 28 Mpc
GRB prompt emission - TRIGGERED SEARCH

Population exclusion on cumulative redshift distribution

Results 2009-2010 & prospects for Advanced LIGO/Virgo

Unmodeled GW burst

~ 40 Mpc ~ 400 Mpc

x10 sensitivity

x5 GRBs

Observed Swift GRBs (Jakobsson et al. 2012)

Binary system coalescence

~ 40 Mpc ~ 400 Mpc

x10 sensitivity

Observed Swift short GRBs (Dietz 2011)

x5 GRBs

→ Detection is quite possible in the advanced detector era
→ No detection will place relevant constraints on GRB population models
Electromagnetic follow-up

GW $\rightarrow$ prompt EM observations
2009-2010 first EM follow-up of candidate GW events

Low-latency GW data analysis pipelines enabled us to: 1) identify GW candidates in “real time” and 2) obtain prompt EM observations to detect the EM signature of the possible GW source.

“Search Algorithms” to identify the GW-triggers:
• Unmodeled Burst Search
• Matched Filter Search for Compact Binary Coalescence

“Software” to identify GW-trigger for the EM follow-up:
• select statistically significant GW triggers
• determine telescope pointing

ADE latency expected to be improved!

Sky Localization of GW transients

The **sky position of a GW source** is mainly evaluated by “**triangulation**” based on **arrival time delay between detector sites**

low SNR signals were localized into regions of **tens of square degrees** possibly in several disconnected patches

**Necessity of wide field of view EM telescopes**

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Binary coalescence localization in the last science run

\[
\rho_{\text{combined}} \equiv \sqrt{\rho_{H1}^2 + \rho_{L1}^2 + \rho_{V1}^2},
\]

Ground-based and space EM facilities observing the sky in the Optical, X-ray and Radio bands involved in the follow-up program

**Optical Telescopes**

- **TAROT SOUTH/NORTH**
  - FOV: 3.4 deg², Limiting magnitude: 17.5 mag
- **Zadko**
  - FOV: 0.17 deg², Limiting magnitude: 20.5 mag
- **ROTSE**
  - FOV: 3.4 deg², Limiting magnitude: 17.5 mag
- **QUEST**
  - FOV: 9.4 deg², Limiting magnitude: 20.5 mag
- **Pi of the Sky**
- **SkyMapper**
  - FOV: 5.7 deg², Limiting magnitude: 21 mag
- **ROTSE a**
- **ROTSE b**
- **ROTSE d**

**X-ray and UV/Optical Telescope**

- **Swift Satellite**
  - XRT-FOV: 0.16 deg²
  - Flux: 10⁻¹³ ergs/cm²/s
- **Radio Interferometer**
  - **LOFAR**
    - Frequency: 30 - 80 MHz, 110 - 240 MHz
    - Maximum FOV: 25 deg²
  - **EVLNA**
    - Frequency: 5 GHz - 7 arcmin²
Additional priors to improve the localization accuracy and increase the chance to observe the EM counterpart

**Initial LIGO/Virgo horizon:**
a binary inspiral containing a NS detected out to 50 Mpc

EM-observation was restricted to the regions occupied by galaxies within 50 Mpc and Galactic globular clusters

(GWGC catalog White et al. 2011, CQG 28, 085016)

To determine the telescope pointing position:

The probability skymap of each GW trigger was ‘weighted’ taking into account luminosity and distance of nearby galaxies and globular clusters
**Optical telescope**

14 GW alerts ➔ 9 followed by at least one telescope

**Swift Satellite: X-ray and UV/Optical telescope**

2 GW alerts sent and followed


**Radio Interferometers**

**LOFAR**

5 GW alerts sent and followed


**Expanded-VLA**

High-Latency Follow-up ➔ 2 GW alerts followed

Lazio et al., 2012 IAUS, 285

3 weeks, 5 weeks + 8 months later

**GW/EM transient data analysis results:**

- Off-line analysis of the GW data alone ➔ GW candidates show no evidence of an astrophysical origin

- EM transients detected in the images consistent with the EM background (optical analysis results under internal LIGO/Virgo review)
Main steps:

1) Identification of all “Transient Objects” in the images

2) Removal of “Contaminating Transients”

Main challenge due to the “large sky area” to analyze

“Contaminating transients” rejection:

- by limiting the analysis to the regions occupied by the most likely GW source host galaxies
- by a rapid transient discovery and (light curve/color/shape) classification over wide sky areas

3) Multi-wavelength and spectroscopic follow-up to uniquely identify a counterpart of a small number of counterpart candidates to uniquely identify a counterpart

Very promising result: discovery and redshift of optical afterglow for the long GRB 130702 over 71 sq. degree

Singer et al. 2013, arXiv1307.5851
Exploration of the optical transient sky at faint magnitudes and short timescale has started recently.

Pan-STARRS searching for fast optical transient (0.5 hr – 1d) brighter 22.5 mag:

→ primary contaminants: M-dwarf flares and asteroids (19/19 transient detections)

→ upper limit on extragalactic fast transients (no detection): rate $0.12 \text{ deg}^{-2} \text{ d}^{-1}$ (0.5 hrs)

rate $< 2.4 \times 10^{-3} \text{ deg}^{-2} \text{ d}^{-1}$ (1d)

Berger et al. 2013, arXiv 1307.5324

Transient X-ray and radio sky is emptier than in the optical band

X-ray transients in the Advanced LIGO/VIRGO horizon
Systematic search in the XMM-Newton Slew Survey covering 32800 deg$^2$ above a flux threshold of $3 \times 10^{-12}$ (erg s$^{-1}$cm$^{-2}$)

$4 \times 10^{-4}$ transients per sq. degree

Kanner et al. 2013, arXiv 1305.5874

Radio transients
(1.4 GHz and 150 MHz)
49 epochs of E-CDFS VLA observations on timescale 1 day – 3 months:

→ transient density $< 0.37 \text{ deg}^{-2}$ above 0.21 mJy

Advanced detector era observing scenario

LSC & Virgo Collaborations, arXiv:1304.0670
The advanced LIGO and Virgo will observe the sky (10-1000 Hz) as a single network aiming at the first direct detection of GWs.
Progression of sensitivity and range for Binary Neutron Stars

Larger GW-detectable Universe
Sky Localization of Gravitational-Wave Transients

Follow-ups would need to deal with large position uncertainties with areas of many **tens of sq. degrees**

Burst search “uncertainty region size”

\[ \rho_c \geq 15 \] median region of \(30 \text{ deg}^2 - 200 \text{ deg}^2\)

Network sensitivity /Localization accuracy for Binary Neutron Stars

\[ \rightarrow 90\% \text{ confidence localization areas} \]

\[ \times \rightarrow \text{Regions of the sky where the signal would not be confidently detected} \]
Summary of plausible observing scenario

<table>
<thead>
<tr>
<th>Epoch</th>
<th>Estimated Run Duration</th>
<th>$E_{GW} = 10^{-2}M_\odot c^2$ Burst Range (Mpc)</th>
<th>BNS Range (Mpc)</th>
<th>Number of BNS Detections</th>
<th>% BNS Localized within 5 deg$^2$</th>
<th>% BNS Localized within 20 deg$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>LIGO</td>
<td>Virgo</td>
<td>LIGO</td>
<td>Virgo</td>
<td></td>
</tr>
<tr>
<td>2015</td>
<td>3 months</td>
<td>40 - 60</td>
<td>-</td>
<td>40 - 80</td>
<td>-</td>
<td>0.0004 - 3</td>
</tr>
<tr>
<td>2016-17</td>
<td>6 months</td>
<td>60 - 75</td>
<td>20 - 40</td>
<td>80 - 120</td>
<td>20 - 60</td>
<td>0.006 - 20</td>
</tr>
<tr>
<td>2017-18</td>
<td>9 months</td>
<td>75 - 90</td>
<td>40 - 50</td>
<td>120 - 170</td>
<td>60 - 85</td>
<td>0.04 - 100</td>
</tr>
<tr>
<td>2019+</td>
<td>(per year)</td>
<td>105</td>
<td>40 - 80</td>
<td>200</td>
<td>65 - 130</td>
<td>0.2 - 200</td>
</tr>
<tr>
<td>2022+ (India)</td>
<td>(per year)</td>
<td>105</td>
<td>80</td>
<td>200</td>
<td>130</td>
<td>0.4 - 400</td>
</tr>
</tbody>
</table>

Observational strategies for each epoch..key points:

- **Image the whole GW error box:**
  - Large “etendue surveys” (PTF, Pan-STARRS, LSST)?
  - Wide-medium FOV telescope networks?

- **Galaxy targeting:**
  - is still useful to point small-FOV telescope?
  - to reduce the EM FAR?
  - Galaxy priors to sample GW source population?

- **Identify uniquely the EM counterpart:**
  - survey the explore the “transient sky”? multi-wavelength observations? larger telescope and spectroscopic-follow up?

TIGHT LINK is required between GW/EM COMMUNITIES to be ready for the UPCOMING GW-TRANSIENT ASTRONOMY!!
<table>
<thead>
<tr>
<th>EM Band</th>
<th>Sources</th>
<th>Analysis</th>
<th>Strength</th>
<th>Weakness</th>
<th>Example Facilities</th>
</tr>
</thead>
</table>
| γ-rays  | On-axis GRB | EM→GW “off-line” | → strong EM signal  
→ temporal coincidence | → beamed emission/small % of events | Fermi-GBM Swift-BAT |
| X-ray   | On-axis and “orphan” GRB | GW → EM Low-latency | → few false positive | → lack of wide FoV facilities | Swift-XRT ISS-Lobster |
| UV/O/IR | On-axis and “orphan” GRB Kilonova | GW → EM Low-latency | → Transient “survey” facilities  
→ Isotropic | → numerous false positive | PTF, PanStarrs, VISTA, LSST |
| Radio   | GRB Radio flares | GW→EM high-latency EM→GW “Off-line” | → few false positive  
→ isotropic | → long time delay  
→ Dependence on ambient density | ASKAP Apertif LOFAR |
EXTRA SLIDES
Short hard GRB070201 / GRB051103

- **γ-ray emission:**
  - GRB070201 sky position overlaps with M31 (Andromeda, 770 kpc)
  - GRB051103 sky position overlaps with M81 (3.6 Mpc)

- **No binary coalescence GW detection**
  - compact binary progenitor in M31 excluded at 99% c.l.
  - compact binary progenitor in M81 excluded at 98% c.l.

- **No burst GW detection set emitted energy limits compatible with:**
  - soft gamma-repeater giant flare
  - coalescence in galaxy more distant than M31/M81

Useful:
- to define an optimal observational strategy
- to identify the image region to be analyzed

In the 2009/2010 follow up the “blue luminosity” was used to identify the most likely hosts → actual star formation

**EM observational results** vs **GW source population numerical simulation**

- Assuming that the short GRBs trace the binary neutron star mergers:
  
  **Sample: 36 short GRBs**

  ![Pie chart showing distribution of host types](chart.png)

  - Host-less up to mag > 26: 15%
  - Inconclusive: 20%
  - Elliptical: 15%
  - Spiral: 50%


- **Population synthesis models** indicate a relevant fraction (20 – 50%) of elliptical galaxy hosts at z=0
  
Swift Satellite: analysis and results

X-ray and Optical/UV image analysis
1) detection of the sources in the FOV
2) comparison with the number of serendipitous sources
3) variability analysis

RESULTS:
XRT-analysis 20 detections (1.5σ)
UV/OP-analysis 6800 detections

• ALL consistent with EXPECTED SERENDIPITOUS sources
• NO single source with significant variability

Joint GW/X-ray search sensitivity improvement

Figure shows
• an efficiency increase with the X-ray counterpart flux
• an efficiency gain observing with 10 (dashed) wrt 5 (solid) Swift fields

An X-ray telescope with wide FOV increases the chance to observe the counterpart despite the larger serendipitous X-ray background

Expanded Very Large Array: analysis and results

Three epochs (3.5 weeks, 8 months after the GW alert) of 6 cm observations of 6 cm observations

For each of the two GW-candidates observed $\Rightarrow$ 3 most probable host galaxies

Image Analysis:
1) radio source detection
2) variability analysis
3) identification of contaminating transients

variability of AGN emission caused by interstellar medium scintillation of Galaxy

Imaged region ($\approx 30'$) around one galaxy

About 6 sources in the field of each galaxy consistent with number of expected serendipitous sources

(Lazio et al., 2012 IAUS, 285)

Light curves
Rate of False Alarm GW triggers

FAR will depend on the data quality of the advanced detectors “instrumental glitches” will produce an elevated background of loud triggers

2009-2010 LIGO-Virgo data

Compact Binary Coalescence search

Burst search

Modelled-search reduces the background → conservatively, \( \rho_c \) of 12 is required for a FAR \( 10^{-2} \text{ yr}^{-1} \) in aLIGO and aVirgo

Unmodelled search → more difficult to distinguish signal from glitches. At frequencies below 200 Hz significant tails of loud bkg events

LSC & Virgo Collaborations, arXiv:1304.0670
Optical afterglow “Orphan GRB”

Source at distance of 200 Mpc

Synthetic afterglow light curves

http://cosmo.nyu.edu/afterglowlibrary/index.html
By van Eerten & MacFadyen

OFF-AXIS GRB
\( \theta_{\text{obs}} > \theta_{\text{Jet}} \)
\( \theta_{\text{Jet}} = 0.2 \text{ rad} \)

LONG bright GRB
\( \theta_{\text{obs}} = 0.3, 0.6 \text{ rad} \)

LONG low-luminosity GRB
\( \theta_{\text{obs}} = 0.4, 0.8 \text{ rad} \)

SHORT GRB
\( \theta_{\text{obs}} = 0.4, 0.8 \text{ rad} \)
Source at distance of 200 Mpc

Gamma Ray Burst Optical afterglow

Swift - LONG GRB
(Kann et al 2010, Apj 720)

Swift - SHORT GRB
(Kann et al 2011, Apj 734)

Long bright GRB
$\theta_{\text{obs}} = 0.3$ rad

Long low-luminosity GRB
$\theta_{\text{obs}} = 0.4$ rad

Short GRB
$\theta_{\text{obs}} = 0.4$ rad

http://cosmo.nyu.edu/afterglowlibrary/index.html
By van Eerten & MacFadyen
Optical Afterglow Light Curves for GRBs and kilonovae

Source at distance 50 Mpc

Time (days)

Red magnitude

PTF, QUEST, Pi of the Sky, TAROT, ROTSE, Liverpool-Skycam, PTF, QUEST, Liverpool-Skycam, SkyMapper, Zadko, Liverpool-RATcam
Exploration of the optical transient sky at faint magnitudes and short timescale has started recently, but it is still largely unknown.

Pan-STARRS searching for fast optical transient (0.5 hr – 1d) brighter 22.5 mag:
- primary contaminants: M-dwarf flares and asteroids (19/19 transient detections)
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  rate $< 2.4 \times 10^{-3} \text{ deg}^{-2} \text{ d}^{-1}$ (1d)

Berger et al. 2013, arXiv 1307.5324

Extremely valuable
- optical transient survey
- algorithms for a rapid transient discovery and classification over wide sky areas (Bloom et al. 2012, PASP, 124)

→ to select small number of counterpart candidates to be multi-wavelength and spectroscopic followed-up
- to uniquely identify a counterpart of the GW trigger

Very promising result by Singer et al. 2013, arXiv1307.5851
discovery and redshift of optical afterglow of long GRB 130702 over 71 sq. degree
Transient X-ray and radio sky is emptier than the optical at the expected fluxes of the EM counterparts.

X-ray and radio

1. **X-ray Transients**
   - Systematic search in the XMM-Newton Slew Survey covering 32800 sq. deg.
   - 1411 objects above flux $3 \times 10^{-12}$ erg s$^{-1}$cm$^{-2}$
   - 97 transients (> x10 brighter than RASS)
   - 12 transients spatially coincident with known galaxy, after rejecting AGN

   \[ \Rightarrow 4 \times 10^{-4} \text{ transients per square degree} \]

   Kanner et al. 2013, arXiv 1305.5874

2. **Radio Sky**
   - Transient contaminants (1.4 GHz and 150 MHz)
   - 49 epochs of E-CDFS VLA observations

   Observations on timescale 1 day – 3 months show:
   - 1% of unresolved sources show variability above 40 μJy
   - Density of transients is less than 0.37 deg$^{-2}$ above 0.21 mJy