On the Search of the optical counterpart of binary neutron star merge with LSST – The Large Synoptic Survey Telescope

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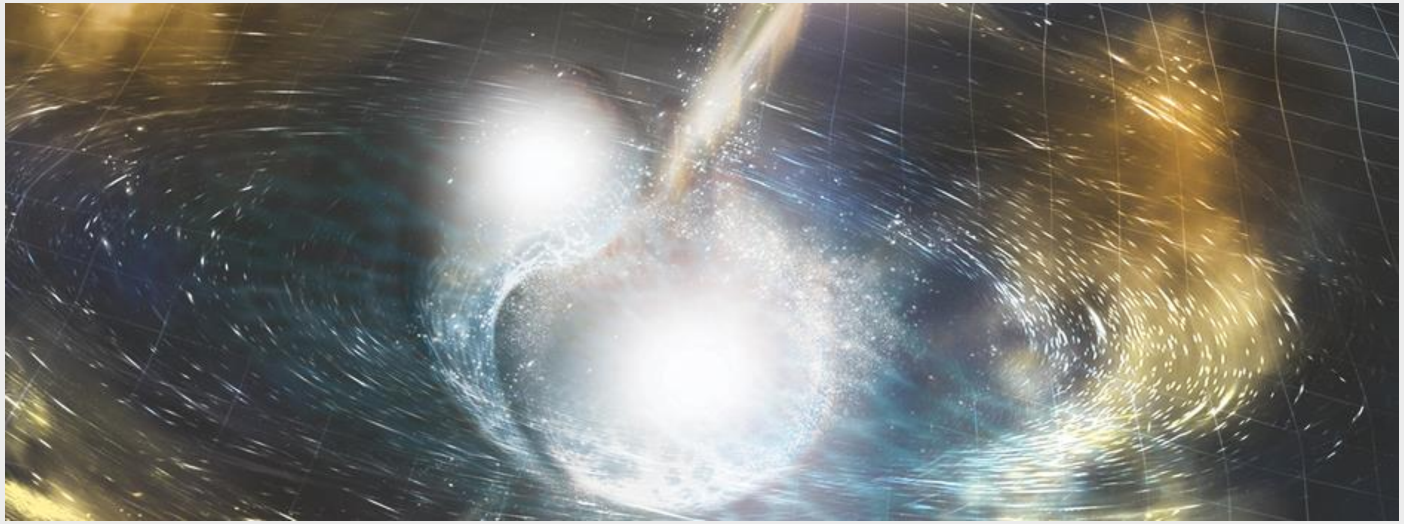
GW170817—Where the story begins



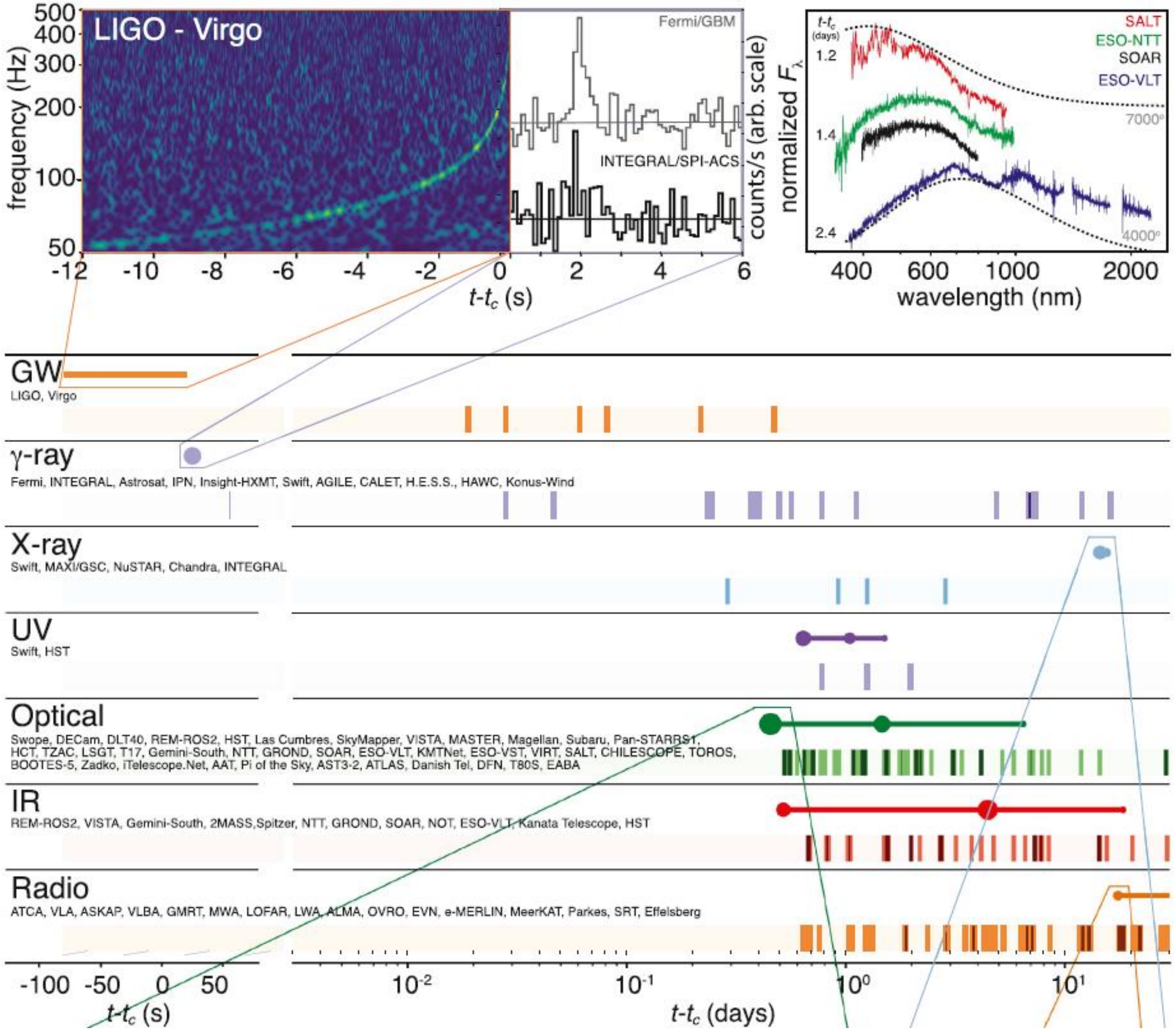
GW170817 – Where the story begins

- On 17th August, a gamma ray burst(GRB) was detected by Fermi Gamma-ray Burst Monitor
- After 6 minutes, LIGO and Virgo identified a signal which corresponded to a coalescence event 2 seconds before the GRB and a luminosity distance of 40Mpc from Earth
- With quick analysis, masses of the component were estimated to be 1.36–2.26 and 0.86-1.36 solar mass respectively
- This mass range implies a binary neutron star system
- Various follow-up on electromagnetic spectrum was then made in the following 24 hours in order to find the theory-suggested EM counterpart
- An optical transient was eventually found in NGC4993 11 hours later
- The first success in multi-messenger astronomy

What makes an EM follow-up possible?

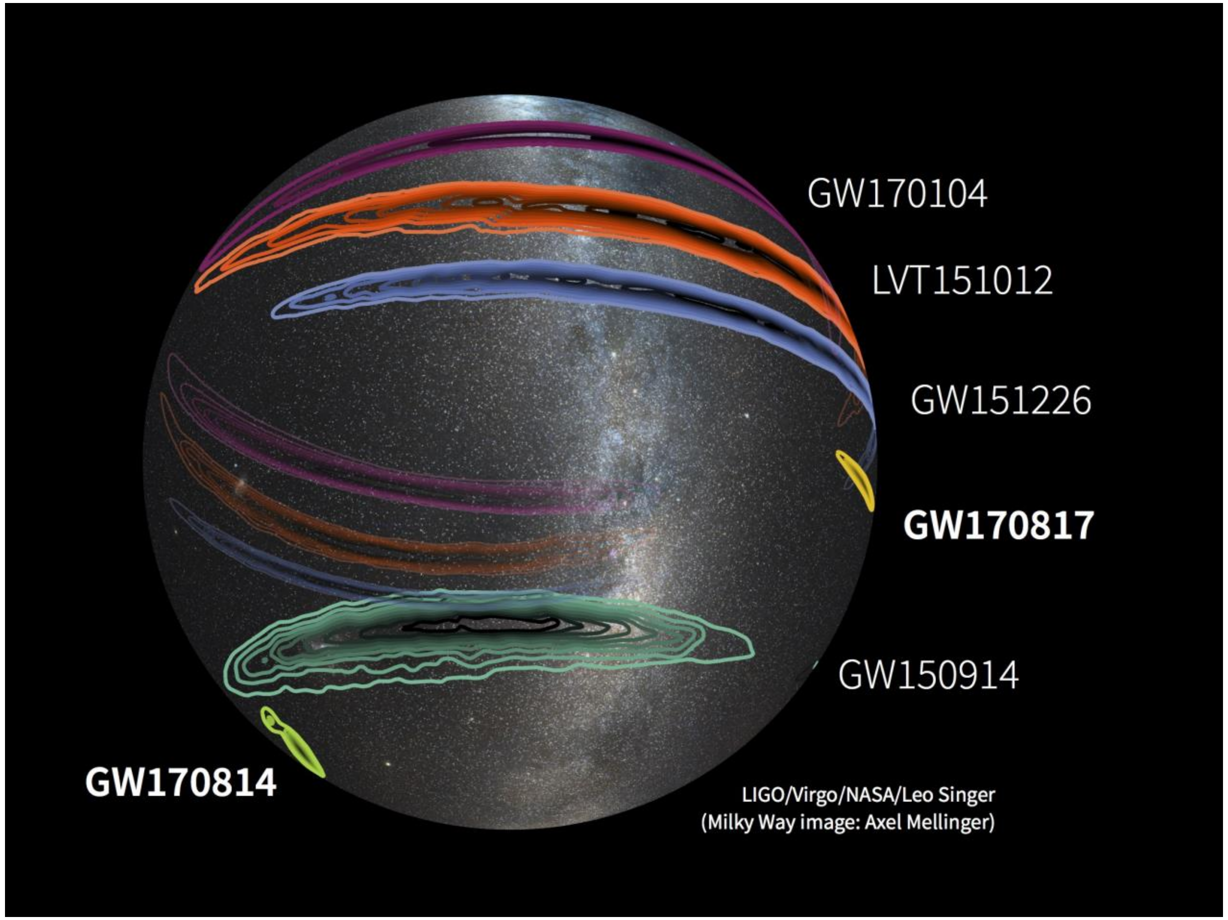
- ✓ Close enough to the Earth (~40 Mpc)
- ✓ Small enough localization (~localization of 31 square degrees)
- ✓ Environmental configuration(observation angle, galactic plane)
- ✓ Posterior status(Not a rapid collapse into a blackhole)
- ✓ Luck (as long as you talk about the optical signal)

Even so………



LIGO et al., AJL, 848:L12

It’s never an easy task…



LIGO/Virgo/NASA/Leo Singer
(Milky Way image: Axel Mellinger)

LSST—
an ‘eye’ for multi-messenger astronomy

LSST—an ‘eye’ for multi-messenger astronomy

- A ground based telescope in Chile
- Wide field of view(9.6 square degrees)
- Large diameter(8.4 meter)
- Unprecedent camera resolution(3.2 Gpix)
- Massive data flow with quick alert
- Operation is expected to begin in 2022
- A 10-year survey over ¼ region of the whole sky

Equipped with various observation strategies

- The Wide-Fast, Deep(WFD) proposal
  - ~85% of the time
  - Repeated visits over 10 years
  - short and constant exposure interval
- The Deep-Drilling Field(DDF) proposal
  - 10-12% of the time
  - Few selected fields
  - Long exposure interval
- Other proposals
  - Up to a few % of the time
  - Targeted to specified events

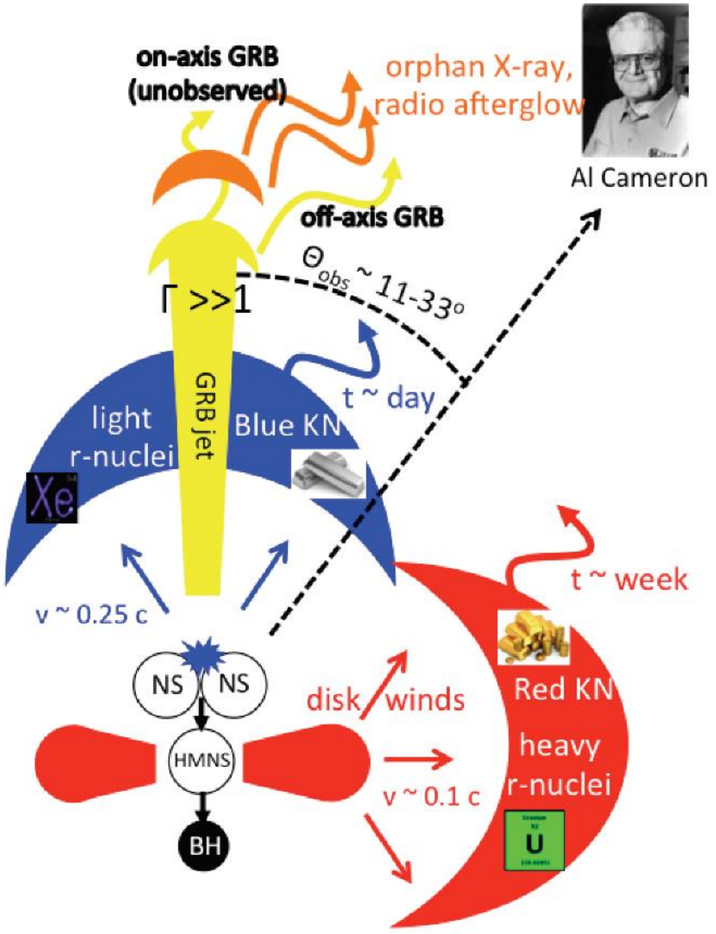

STOP
WHY DO WE NEED THAT

Theory

$$\tau_l = \frac{\pi e^2}{m_e c}\left(\frac{n_{i,j}\lambda_l t}{g_0}\right) g_l f_l \exp^{-E_l/kT}$$

Origin of the optical counterpart

- From near ultraviolet to near infra-red region
- Binary neutron star merger itself don’t emit EM radiation at this band
- Ejecta created along with the merge process would be a promising guess
- Three kinds of ejecta
    - Tidal ejecta – some NS materials are teared away due to strong tidal force (pre-merger)
    - Dynamical ejecta – NS materials being pushed away due to the shockwave of the merge event (during merge)
    - Disk wind – some NS material accretes around the merger, they are heated up and blown away by the accretion disk wind(after merge)



Origin of the optical counterpart

- These ejecta, although processes with different electron fraction, are neutron rich
- The high density flavours a process called rapid neutron capture(r-process)

$$ {}_{0}^{1}n + {}_{b}^{a}X \rightarrow {}_{b}^{a+1}X^{*} \rightarrow {}_{b}^{a+1}X + \gamma $$

- Upon the process, extensive gamma ray and radioactive lanthanide nucleus are formed
- Getting more stable by beta decay
- Photons then propagate along the ejecta, scattering and absorption event occurs(Thermalization)
- The famous two-level transition (Students who have studied PHYS3022 should be familiar with it)
- Eventually escape the ejecta with optical wavelength/Produced a SED which peaks at optical band

Two important parameters

- Starting from 1st Law of thermodynamics(Arnett 1982):

$$\dot{E} + P\dot{V} = -\frac{\partial L}{\partial m} + \varepsilon - (1)$$

- Where $\dot{E}$ is rate of internal energy change per unit mass, P is pressure, $\dot{V}$ is volume, L is luminosity, m is mass and ε is the decay heating energy rate per unit mass
- Then, by assuming a homologous expansion

$$R(t) = R(0) + v_{sc}t - (2)$$

- Where $R(t)$ is the outermost radius of the ejecta at time t and v_{sc} is the expansion velocity. Together with parametrization on temperature and Volume

$$V(r,t) = V(0,0)[\frac{R(t)}{R(0)}]^3 - (3) \text{ and } T(r,t)^4 = \psi(r)\phi(t)T(0,0)^4(\frac{R(0)}{R(t)})^4 - (4)$$

- After a long manipulation, we will obtain the typical photon diffusion timescale τ_0

$$\tau_0 = \frac{\kappa M}{\beta c R(0)} - (5)$$

- Where κ is the mean opacity of the ejecta, M is the total mass and β is a constant

Two important parameters

- With the diffusion time scale, we can estimate the time for the optical transient to reach its peak
- Inserting typical velocity = 0.1c, typical mass = 0.01 solar mass, $\kappa = 0.1 cm^2 g^{-1}$, $\beta = 0.07$ and the relation $R = vt$, we have peak time scale t_p(Metzger 2010):

$$t_p = 0.5 \text{ days}$$

- It is assumed that at t_p, the released energy Q is simply a tiny fraction of rest mass energy of the ejecta, so

$$Q \approx fMc^2 - (6)$$

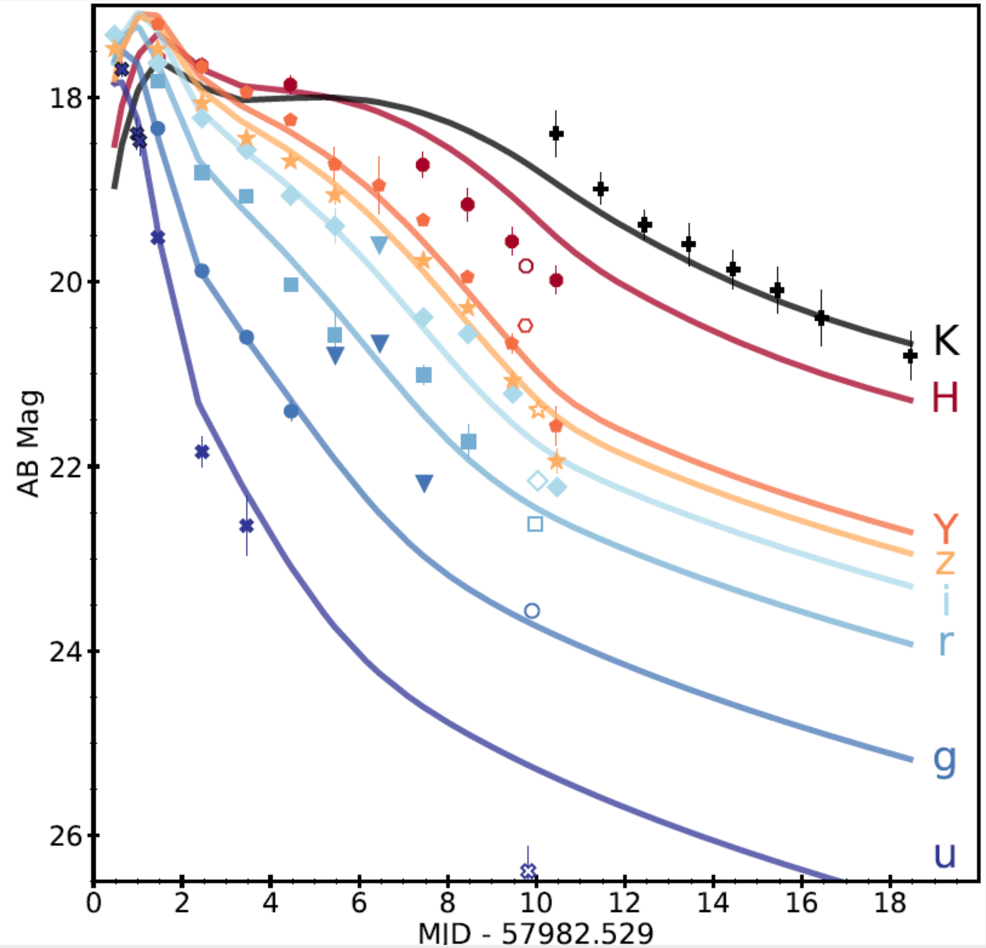
- And $f = 10^{-6}$, the peak luminosity L_p can then be estimated

$$L_p = \frac{Q}{t_p} \approx 5 \times 10^{41} erg s^{-1}$$

That’s why we study them with LSST

- A Nova has a typical luminosity of $1 \times 10^{38} ergs^{-1}$
- The optical transient is often called a “Kilonova”(KN)
- In general, KN’s luminosity varies rapidly across time(0.5 days)
- The composition of the ejecta affects both the time scale and peak luminosity(opacity)
- Obvious reasons to study kilonova:
  - ➢ Understanding the r-process
  - ➢ Find out whether KN is a birthplace of heavy element
- Subtle reasons to study kilonova:
  - ➢ Inferring Hubble and cosmological constants from the intrinsic luminosity of KN
  - ➢ Providing hints for the EOS of neutron star(early stage of the ejecta)

Project



Cowperthwaite et al., ApJ, 848:2

To search for kilonova, we have to…

- Realise that baseline proposals are not able to capture kilonova, they just evolve too fast
- Think of a strategy that can effectively follow up LIGO signal
- We already have one! → the Target-of-Opportunity (ToO) strategy
- Repeated visits within few nights
- Balanced exposure time
- Logarithmic epoch
- Next, we have to put it into test
- Check the lightcurves and make comparison between different strategies
  - If more observations on a KN lightcurve can be found in ToO than WFD → Success!

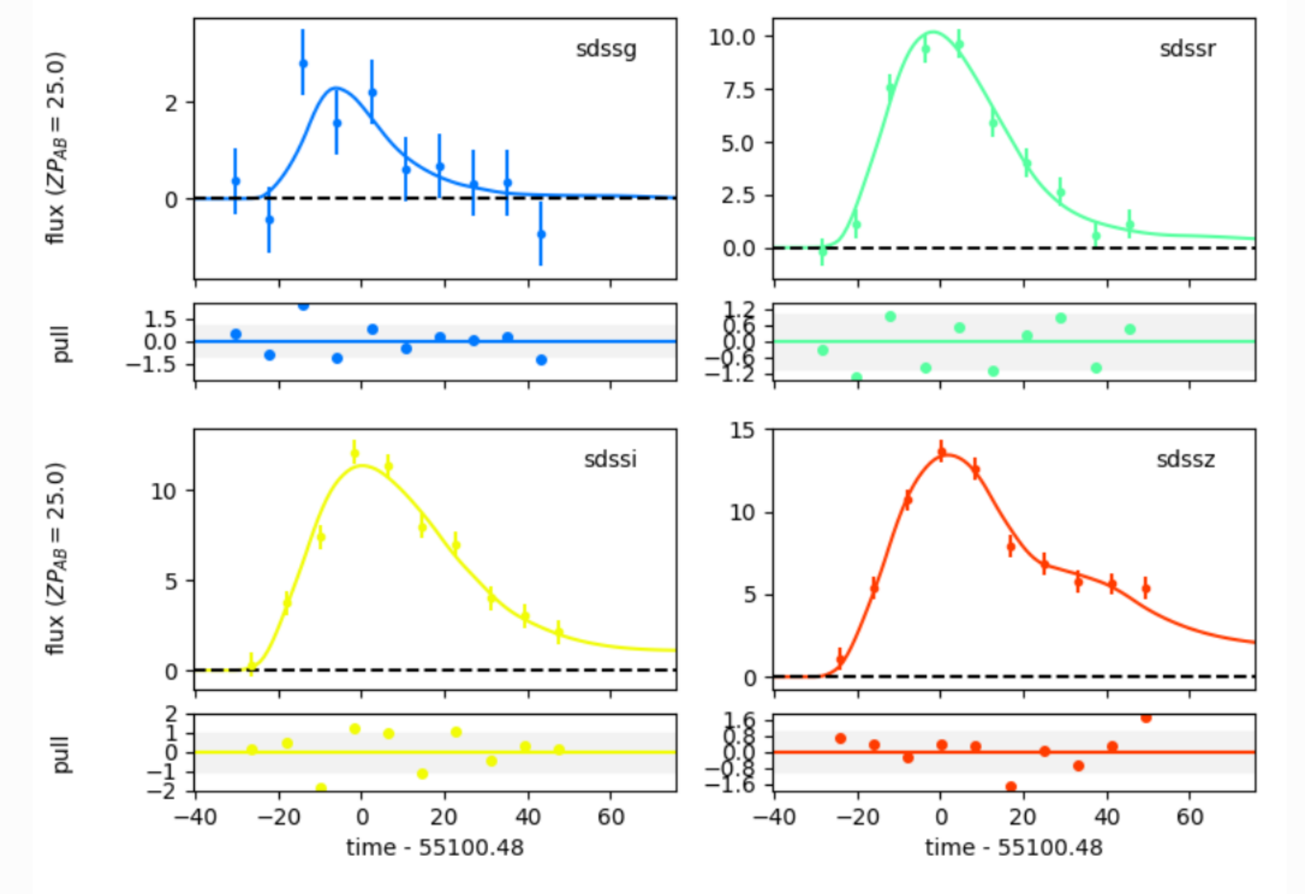
Sounds great, but…

- In the beginning, we want to generate a set of telescope observation using OpSim, a build-in simulator in the LSST pipeline
- It do not support a customize strategy
- We could generate baseline observations only
- Could we make one simulator ourselves? Nearly impossible!
- It is hard to simulate an realistic observation without detailed past sky conditions

- Oh wait! As they only consist of a few% of survey time, maybe it is possible to change WFD observations into a TOO observations only when there is a kilonova
- In that case, we can create an editor instead of a simulator → much easier task!

Alright, what's next?

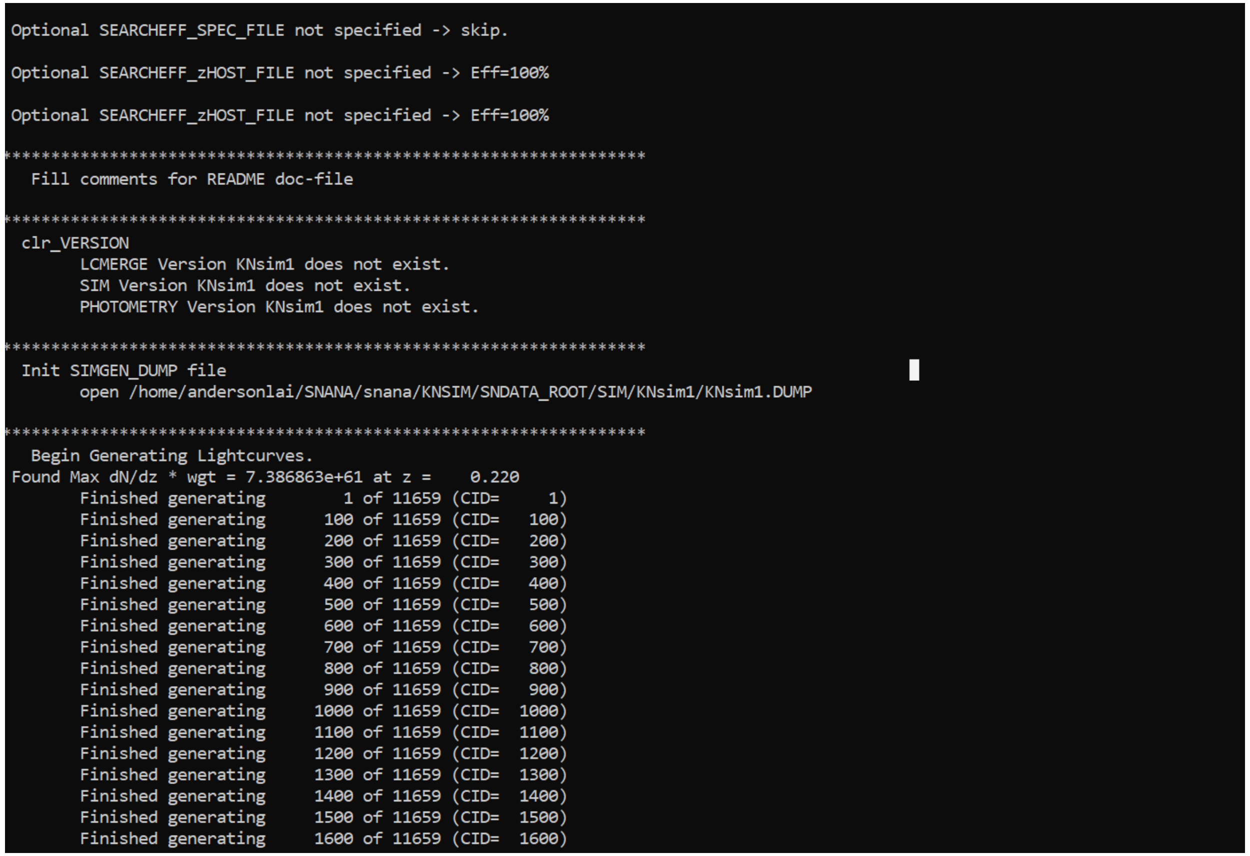
- We need a tool to simulate kilonova, then by piling LSST observations with a software called OpSimSummary and passing them into the tool to generate a set of observations lies on a kilonova event
- There was no existing software for this kind of transient
- Seek for possible candidates that can be modified for our purpose
- Candidate 1: SNcosmo
  - User friendly
  - No strict requirement on user's OS
  - Simulation is time consuming
  - Difficult to add KN model
  - Unable to simulate multiple objects



Alright, what’s next?

- Candidate 2: SNANA
  - Strict requirement on OS and prerequisites
  - Hard to get used with
  - Had to be tested carefully for each configuration
  - Highly compactible with user defined models
  - Support simultaneous simulation on multiple transients

- We decide to use SNANA as our simulator(after a painful jounery)



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  Fill comments for README doc-file

******************************************************************
 clr_VERSION
       LCMERGE Version KNsim1 does not exist.
       SIM Version KNsim1 does not exist.
       PHOTOMETRY Version KNsim1 does not exist.

******************************************************************
 Init SIMGEN_DUMP file
       open /home/andersonlai/SNANA/snana/KNSIM/SNDATA_ROOT/SIM/KNsim1/KNsim1.DUMP

******************************************************************
  Begin Generating Lightcurves.
Found Max dN/dz * wgt = 7.386863e+61 at z =    0.220
       Finished generating       1 of 11659 (CID=     1)
       Finished generating     100 of 11659 (CID=   100)
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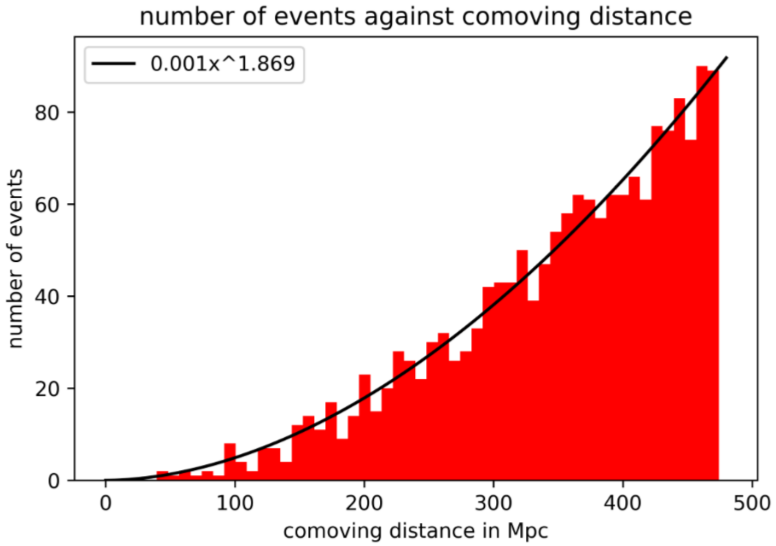
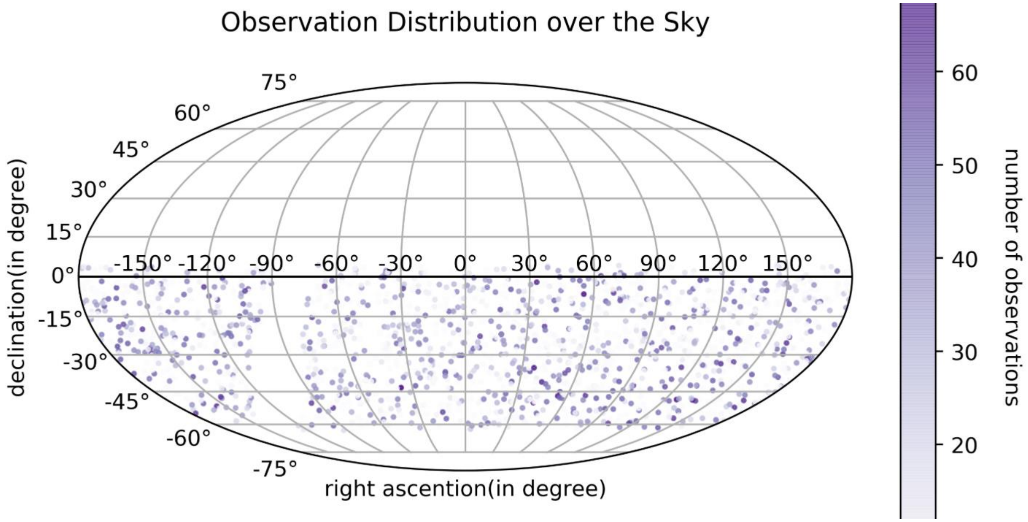
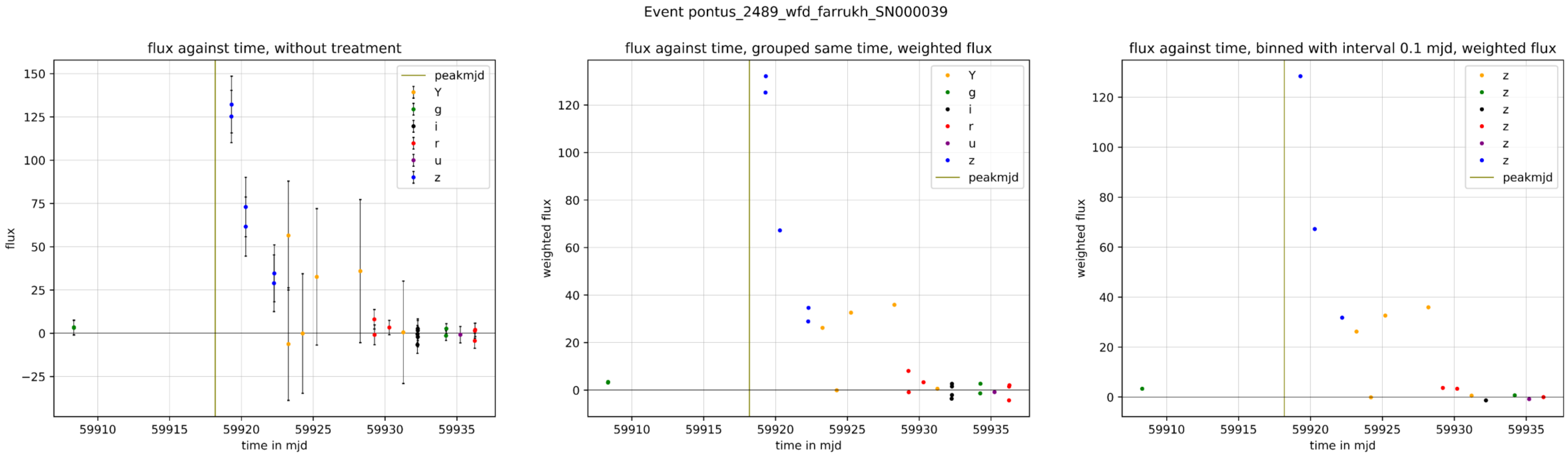
Houston, we have a problem(again)





- Although simulations can be ran smoothly, not all data points can be perfectly generated
- Most of the time, it is because of inputting wrong supplementary file
- However, there are intrinsic errors arisen from the program
- Think of a way to handle them

Houston, we have a problem(again)

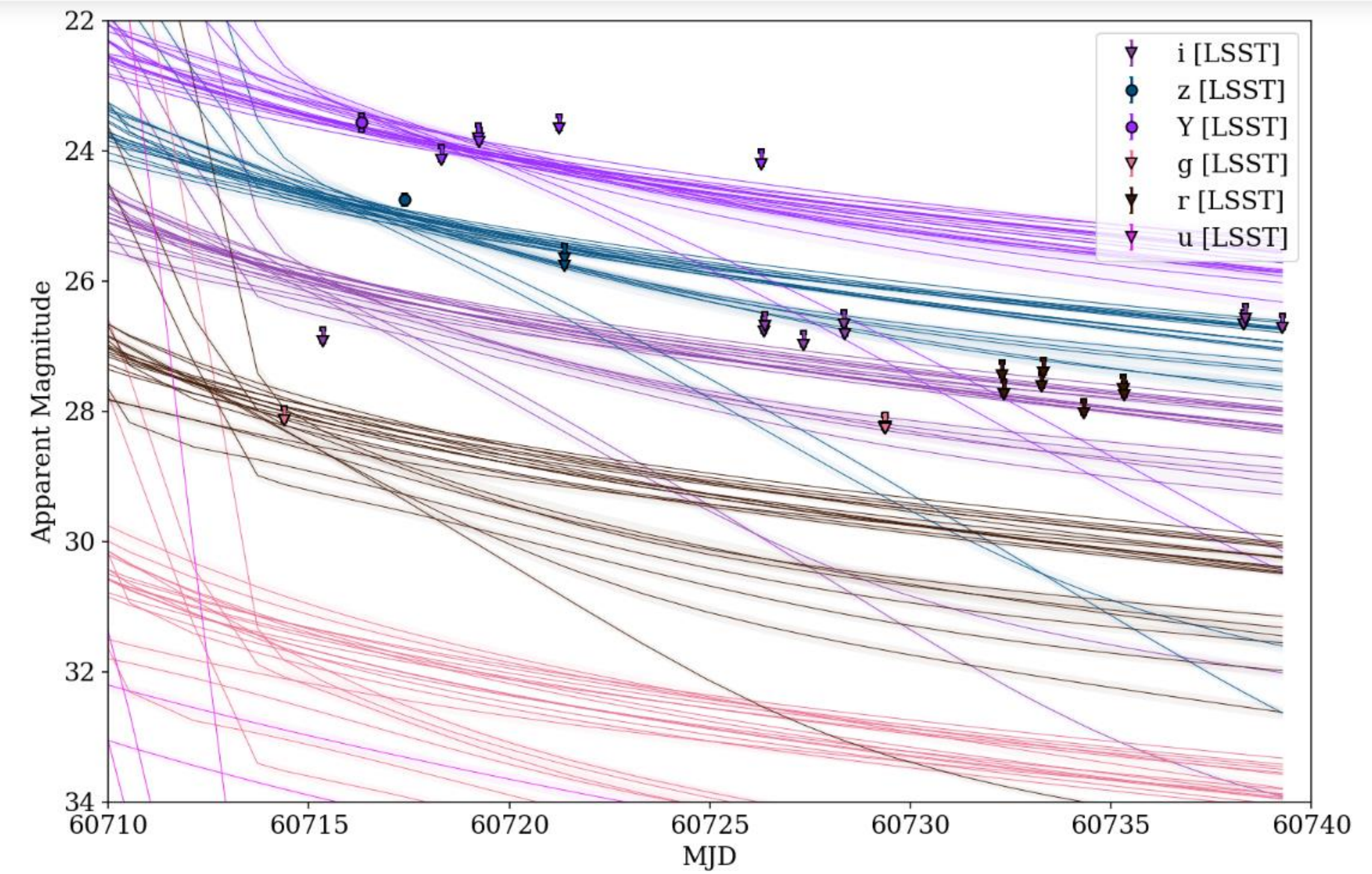


How to ‘see’ kilonova from lightcurves?

- In order to reproduce LSST’s situation, we were simulating a mixture of transients
- The next task would then be picking up a kilonova from millions of transients within a short period
- Equally challenging
- Again we come up with two approachs

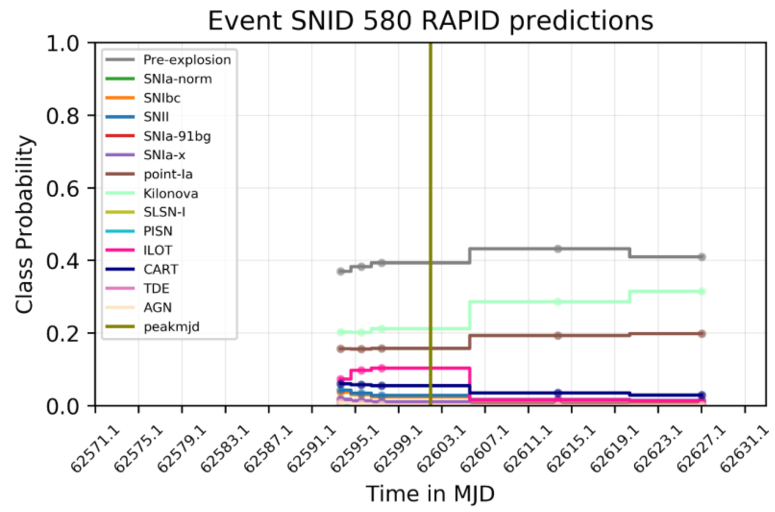
How to ‘see’ kilonova from lightcurves?

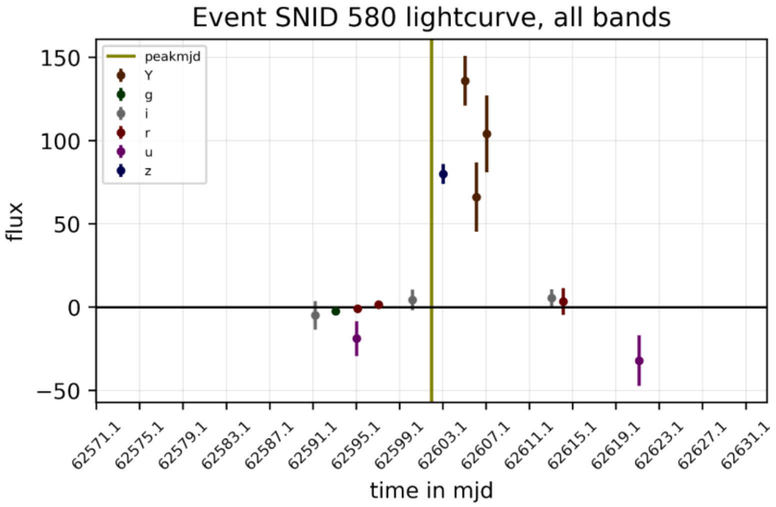
- The first one, also the most traditional one, it to fit the lightcurve with a model directly
- A fitting program MOSFiT can fit the light curve with r-process ejeta model
- Poor results were obtained
  - Too many free parameters(12)
  - Time consuming(30-45mins for each burning)
  - Highly dependent on a single model



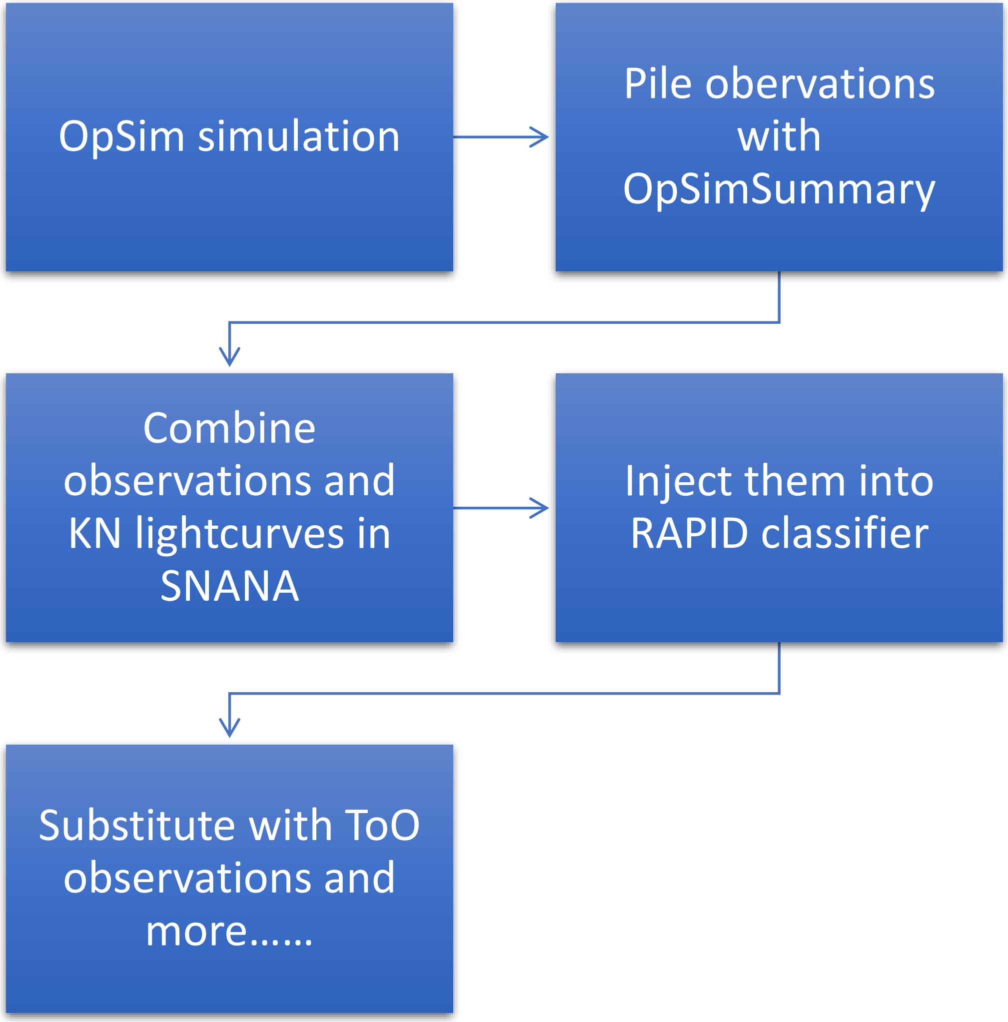
How to ‘see’ kilonova from lightcurves?

- The second one is to classify the transients with deep learning method
- The program RAPID reads a training set and trains a classifier, after that, the classifier can be applied to a lightcurve and gives out result in a few tenth seconds
- It appeared to be more effective as
  - Can handle large injection of lightcurves
  - Extremely short classifying time(as long as being trained)
- Yet drawbacks are obvious as well
  - Hard to sample a good data set
  - Accuracy rapidly drops if observations are obtained in later time
  - It only uses information from two bands instead of all of them





Up to here and we are not going to stop


OpSim simulation

Pile obervations with OpSimSummary

Combine observations and KN lightcurves in SNANA

Inject them into RAPID classifier

Substitute with ToO observations and more……

- We have already tested the software and analysis code for WFD strategy
- The next step will be produce a tool to append ToO observations and run through all of them again
- Ultimate goal: develop a workflow to evaluate the efficiency of an arbitrary strategy in searching for KN
- With the improvement of the instruments(Advance LIGO+, KAGRA, LSST), more detail of kilonova will be revealed
- We are entering the **multimessenger era!**

May I present my profound gratitude to

- Dr. Jeff Tseng for learning with me and helping we on particle physics problems
- Prof. Farrukh Azfar for providing materials and data for my analysis and actively connecting us with FermiLab LSST group
- Dr. Rahul Biswas for solving technical issues and developing analysis code with me
- Josh, Kelvin, Teressa, Esther and another Jeff for staying in the same office with me and all the fruitful discussions between us
- Prof. Ming Chung Chu for all the suggestions about the whole program and the nice whether in Oxford
- My computer for baring my excessive usage in these 3 months

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