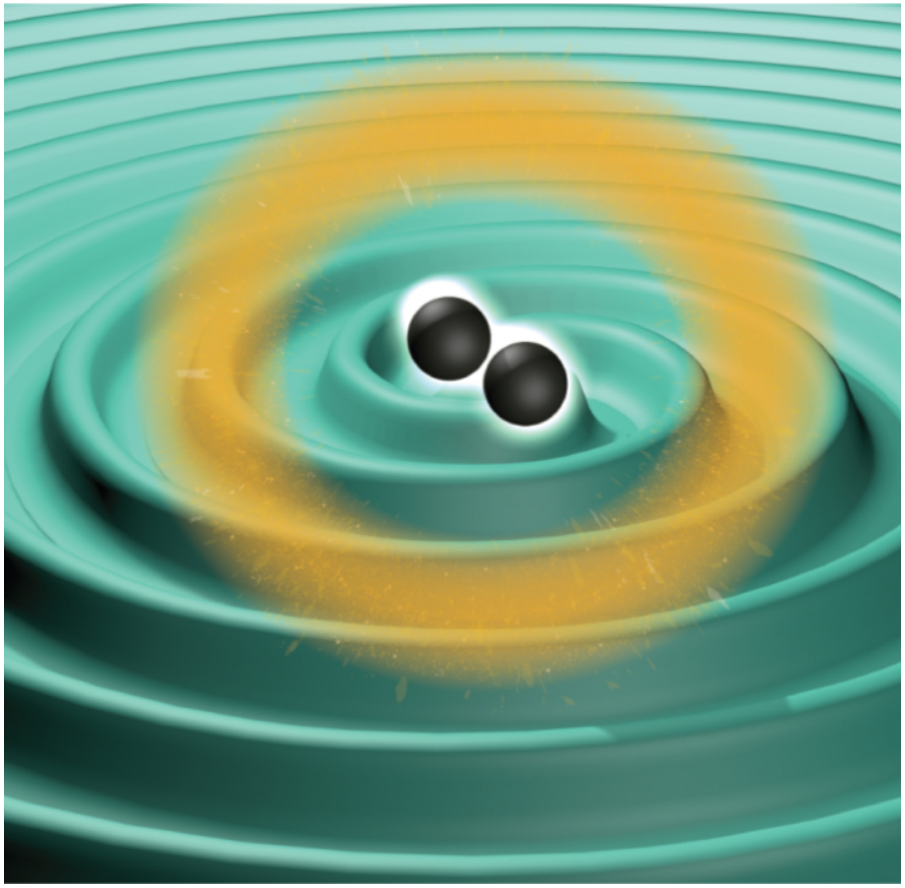
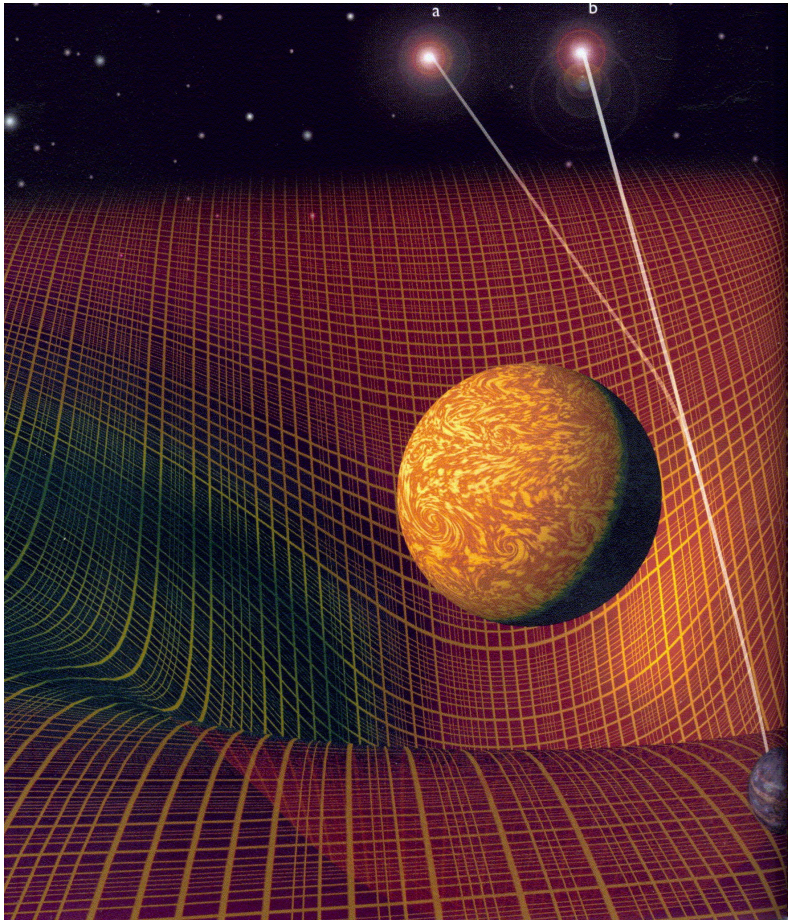


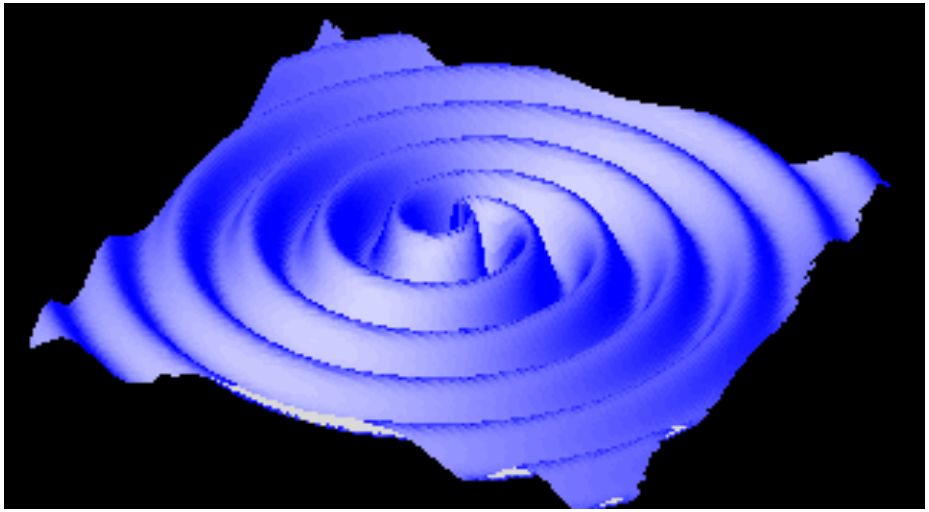
Gravitational wave sources and the hunt for their electromagnetic counterparts using the BlackGEM array

Radboud Universiteit Nijmegen

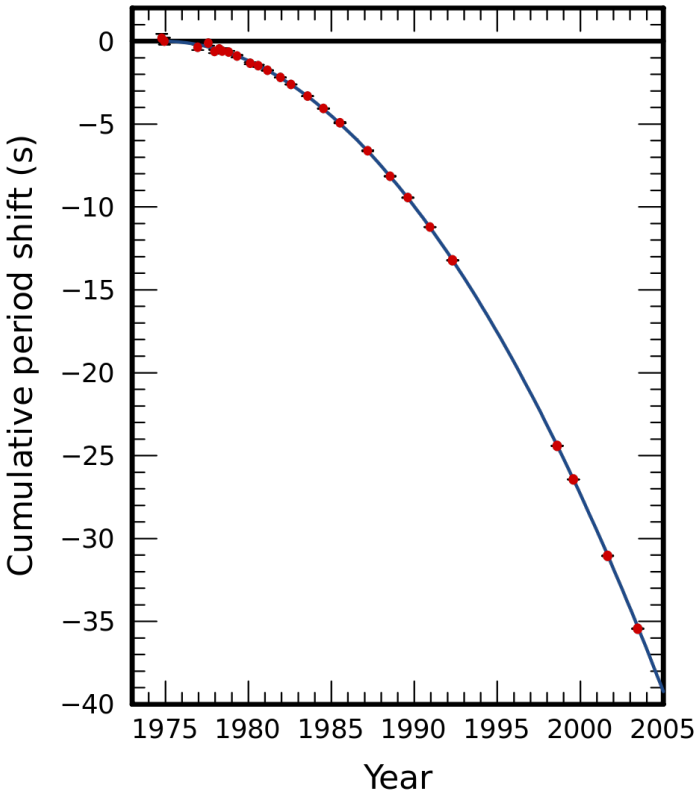
Steven Bloemen
and RU Nijmegen (NL) BlackGEM team: **Paul Groot, Gijs Nelemans, Marc Klein-Wolt**

Deformation of space-time by massive objects





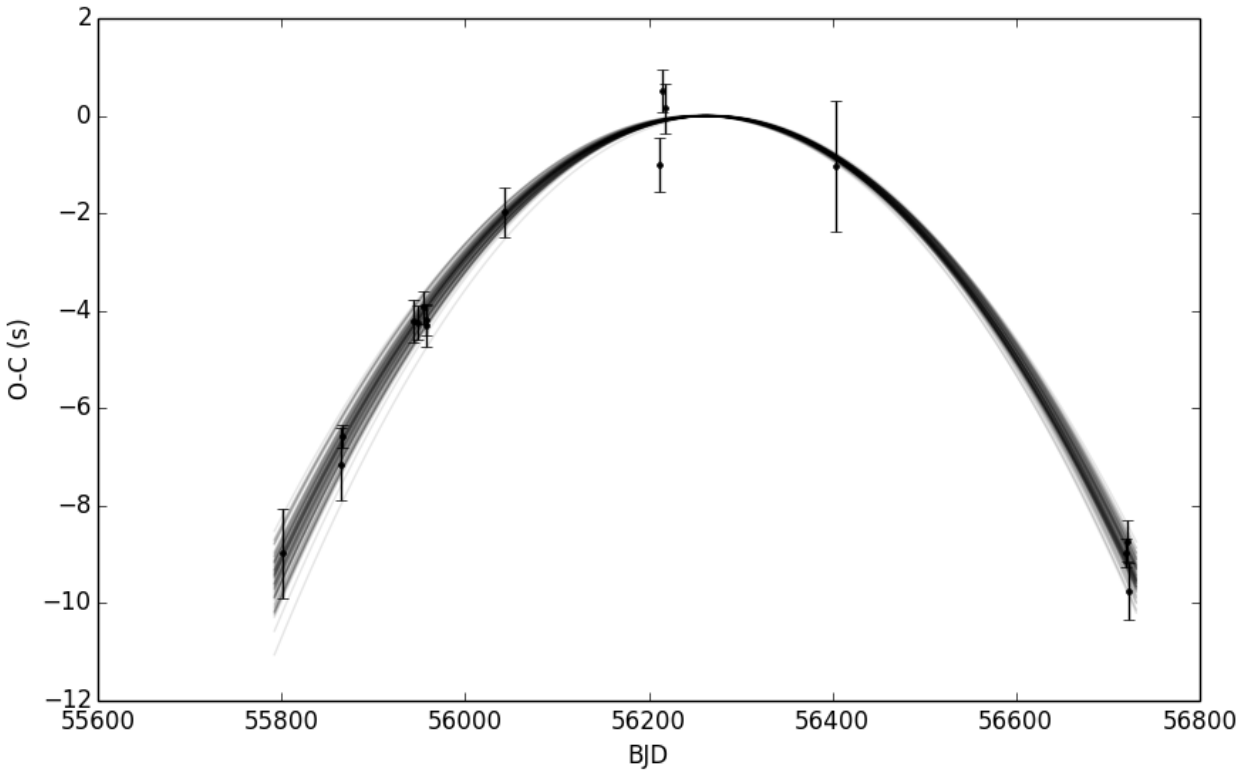
Indirect proof of existence of GW



Hulse-Taylor pulsar (Nobel Prize 1993)

- Orbital period NS+NS: 7h45
- Reduces by 77 microseconds/yr
- Merger in 300 Myr

Indirect proof of existence of GW



3 yr Ultracam @ WHT

[Bloemen et al, in prep.]

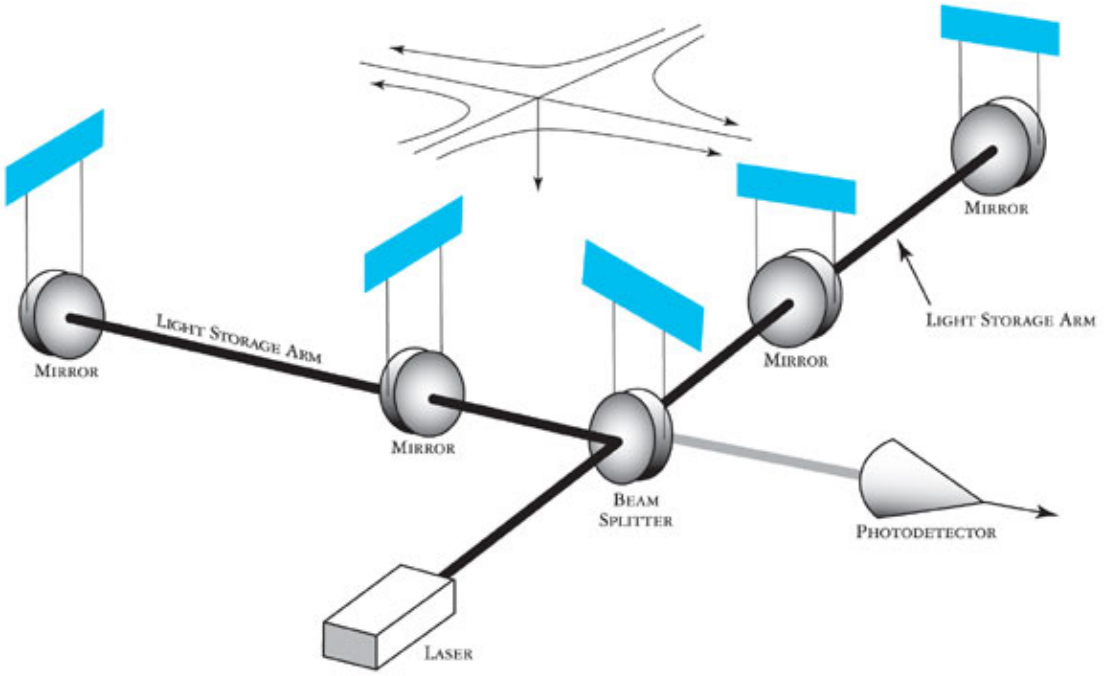
SDSS J0651+2844 [Brown+ 2011, Hermes+ 2012]

- Eclipsing double white dwarf binary
- P_{orb}= 12.75 min, merger in 1 Myr
- Now more precise orbital decay measurement than GR prediction!

Direct detections: interferometers

Distance changes of order 10^{-22}

2016-2017: Advanced LIGO/VIRGO → 10x more sensitive



What will (hopefully) be detected by LIGO/Virgo?

GW freq. in range 10 Hz to few kHz

Mergers (inspiral) of

- Neutron star + neutron star (13 known)
- Neutron star + black hole (0 known)
- Black hole + black hole (0 known)

We have to find the electromagnetic counterparts…

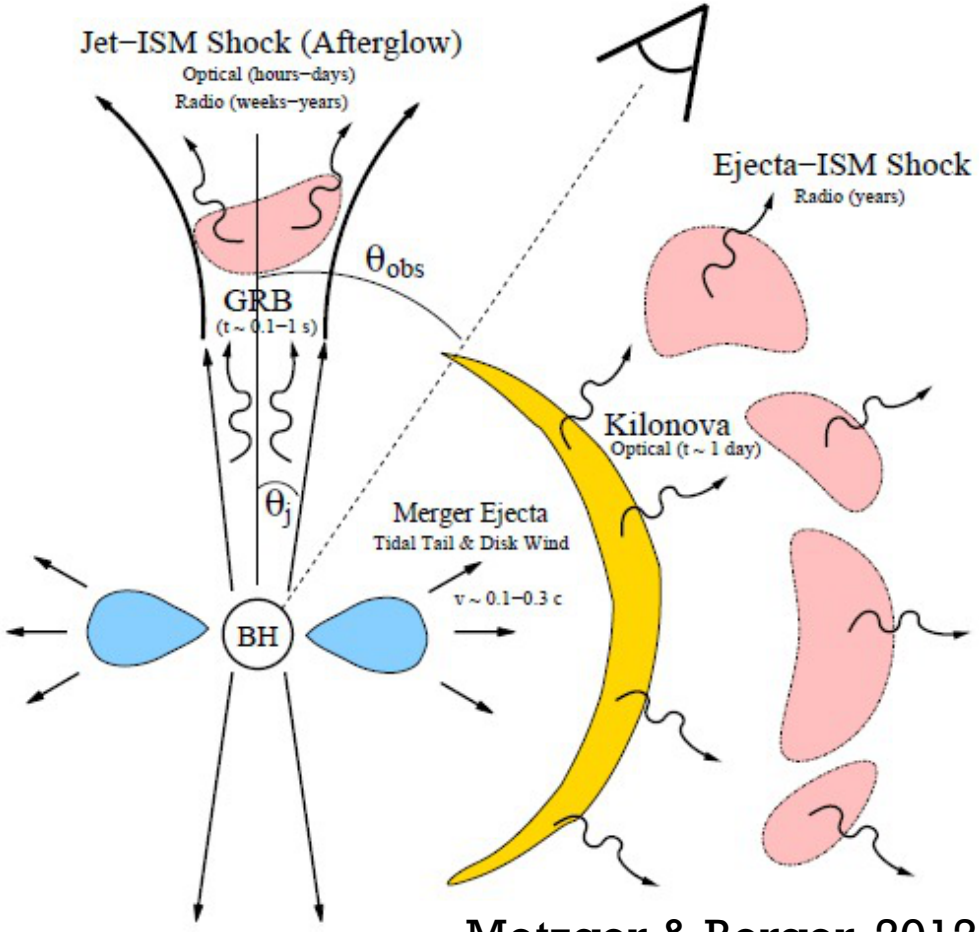
Need for **identification** and **follow-up**

Gravitational Wave information	**Electromagnetic Wave information**
- Merger time T_0	- Outflow velocities and energetics
- Chirp mass of components	- Delay times
- Inclination of the binary system	- Nucleosynthesis in merger material
	- Remnant geometry: information on mass ratio
- Rough sky location (~100 sqd)	**- Accurate position (1")**
- Distance	**- Redshift**
- Neutron star internal structure	**- Position in/near a galaxy**
	- Correlation with stellar populations
	- Magnetic field strength
- Rates of BH/NS mergers	- Previous evolution: mass ejection, binary evolution

Predicted electromagnetic signals (NS + NS → BH)

- First <1s:
  gamma/X-ray; beamed
- Up to hours/days:
  optical and IR; ***kilonova*** **due to decay of r-process elements** in neutrino-driven wind + *jet-ISM shock*
- After weeks to months:
  radio; *ejecta-ISM shock*

Optical and IR are ideal:
- isotropically emitted
- immediately visible

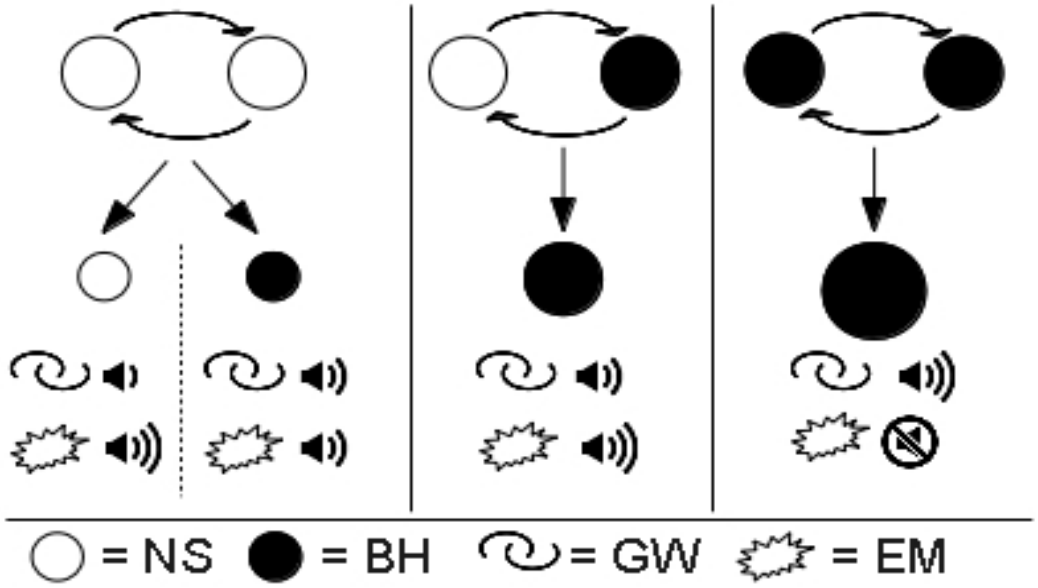


Metzger & Berger, 2012

How many sources are expected?

Unclear how many mergers will be detectable in GW+EM

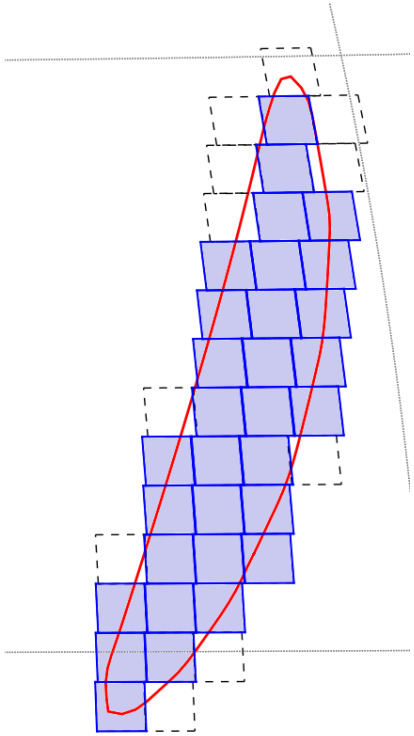
Some realistic estimates for LIGO+VIRGO (Nissanke+ 2013):

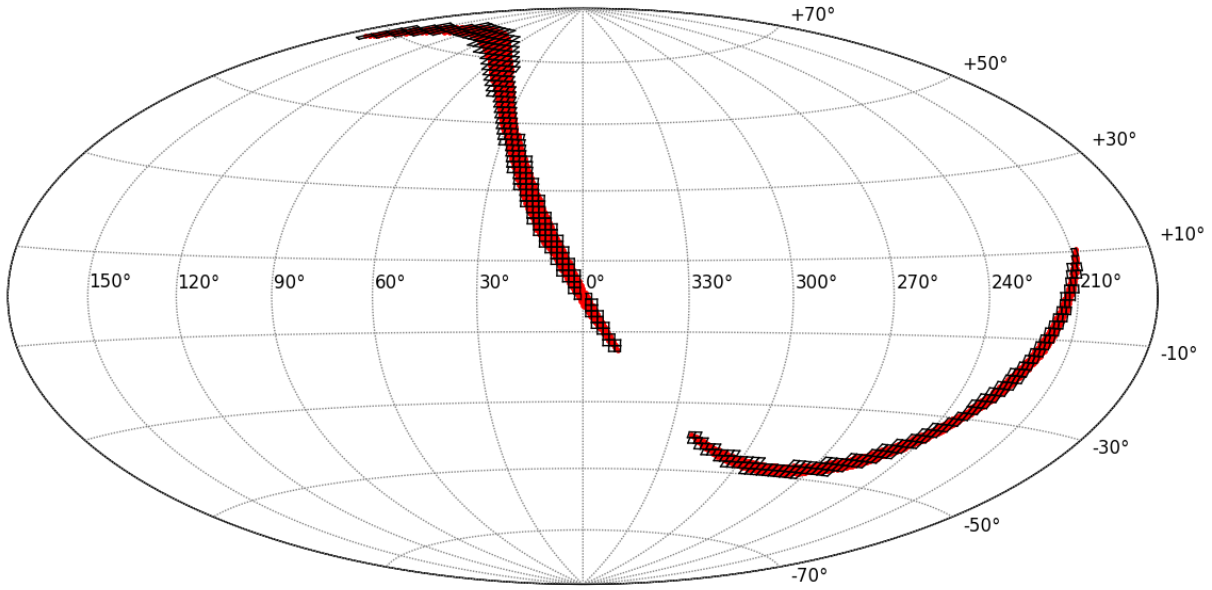


Detection horizon:	220-400 Mpc	350-600 Mpc	no expected
Typical expected event rate:	~20/yr	~3/yr	EM signal

Optical counterparts

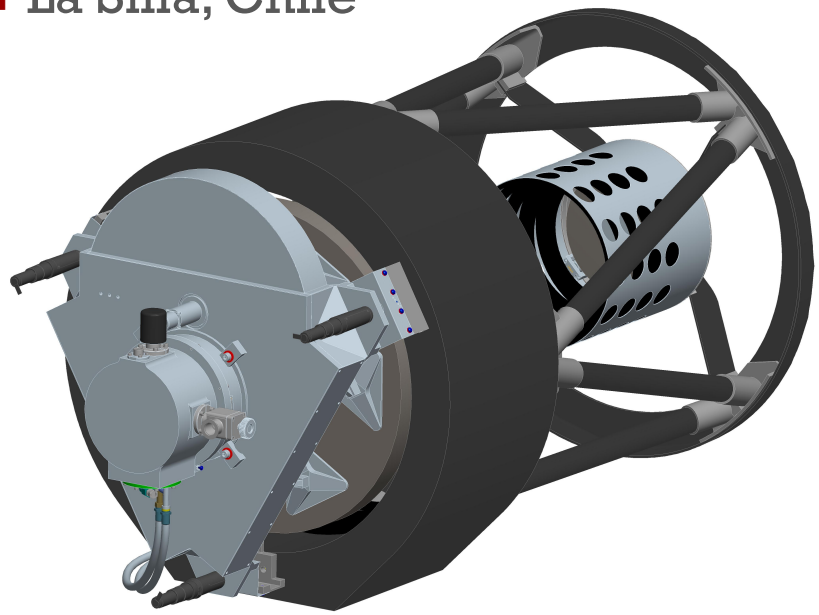
- Challenges:
  - Poor sky localization (~100 sqd)
  - Faint (21st-22nd mag at 200 Mpc)
  - False positives
  - Gone in hours/days
- What do we need?
  - Large field of view
  - Sensitivity
  - Colour information
  - Dedicated facility for rates

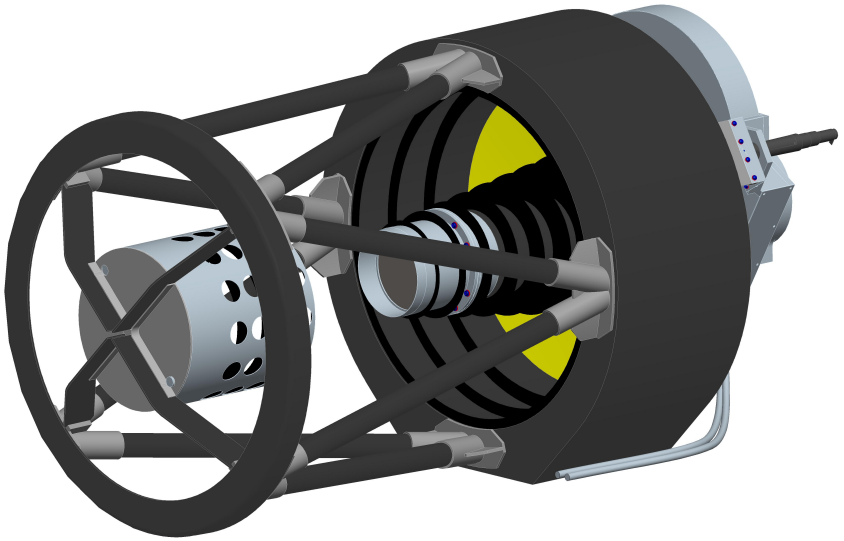




BlackGEM Array

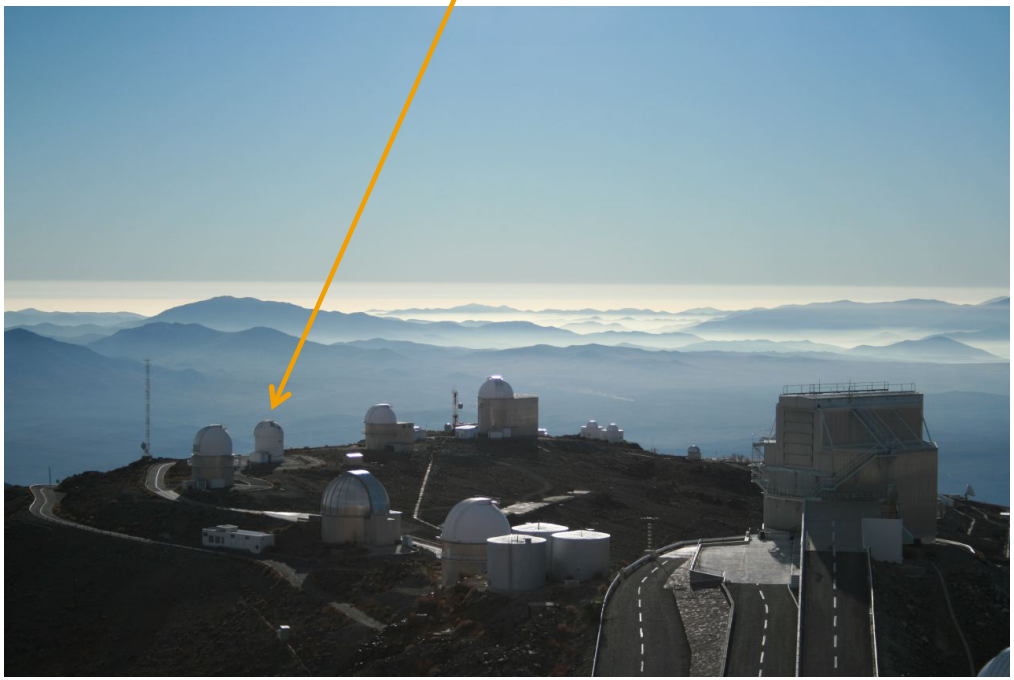
- Phase-I: 4 telescopes
  Funded by Netherlands
  (NOVA, RU, FOM) and KU Leuven
- Phase-II: 15 telescopes
  Not yet funded
- La Silla, Chile

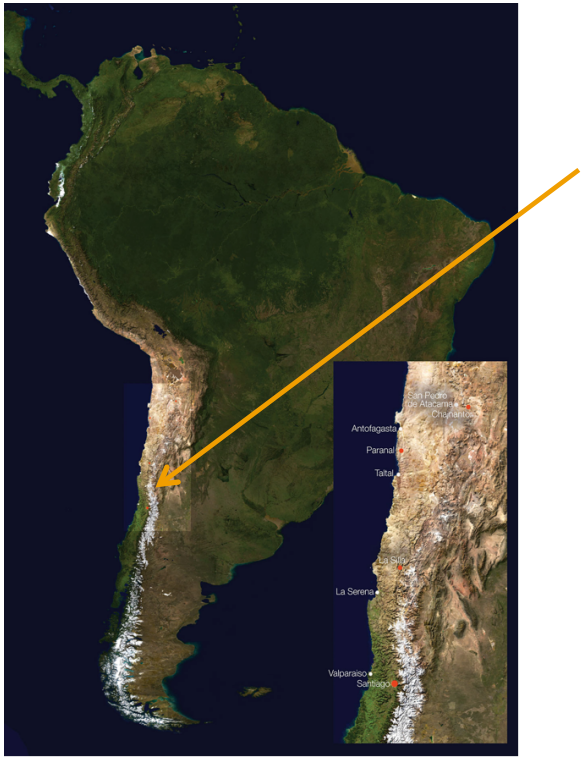




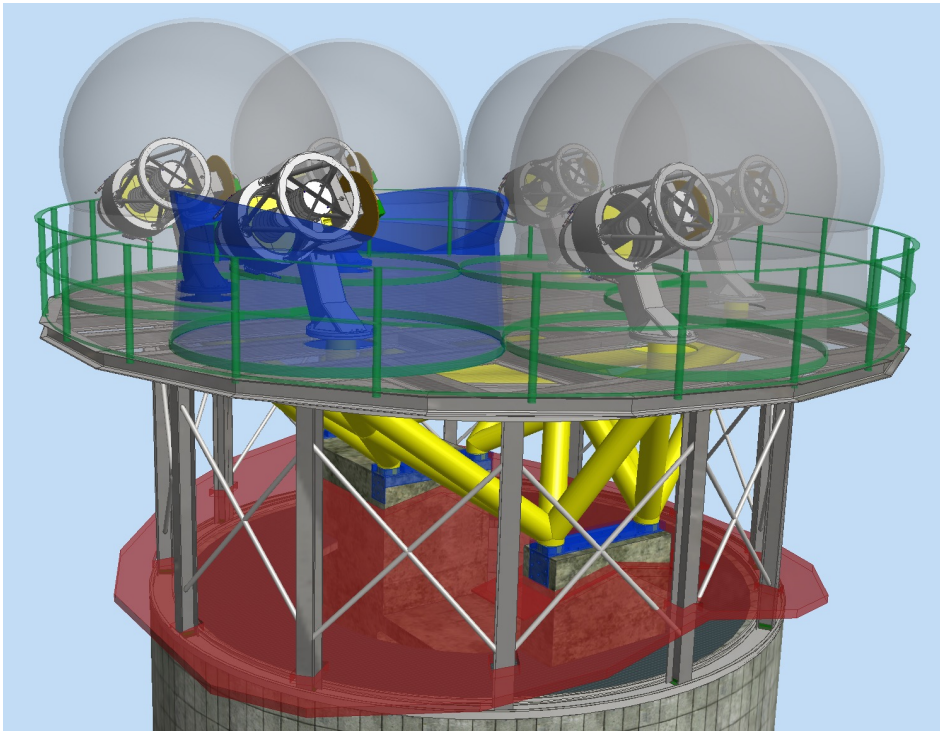
- Cassegrain camera, u'g'r'i'z' filters
- 2.7 sqd FOV
- Single 10k * 10k CCD per telescope
- Thanks to good site:
  ~22nd mag in 5 minutes in g'

BlackGEM site: La Silla





Re-use GPO building



end 2016

Three phases in BlackGEM operations

Phase 1: (50% of year 1) **All Sky Survey**

Full Southern Sky in u,g,r,i,z down to ~22nd mag

Phase 2: (50% y1 + when no trigger) **Survey Phase**

Rates : $N_{candidates}(l,b, \tau, mag, colour)$ $(degr^{-2}\, hr^{-1}\, mag^{-1})$

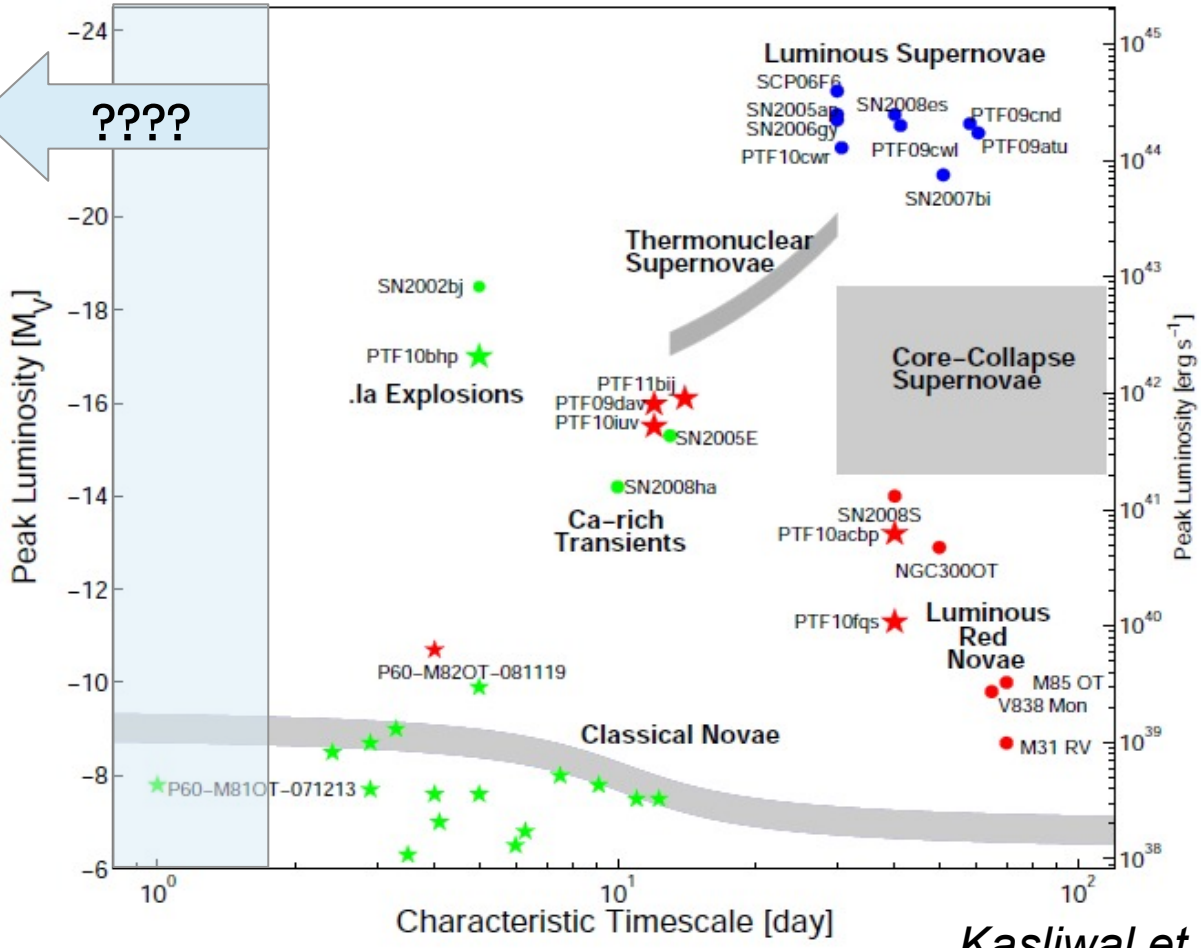
- Number of fiducial fields: ~100 square degrees
- Cadence: once every 2 minutes, in 3 bands (g+r ,r, i)
- Time per field: 14 nights

Phase 3: **Trigger Phase**

GW events

- Follow-up of Virgo/LIGO detections
- Cover the error boxes in a tiling pattern

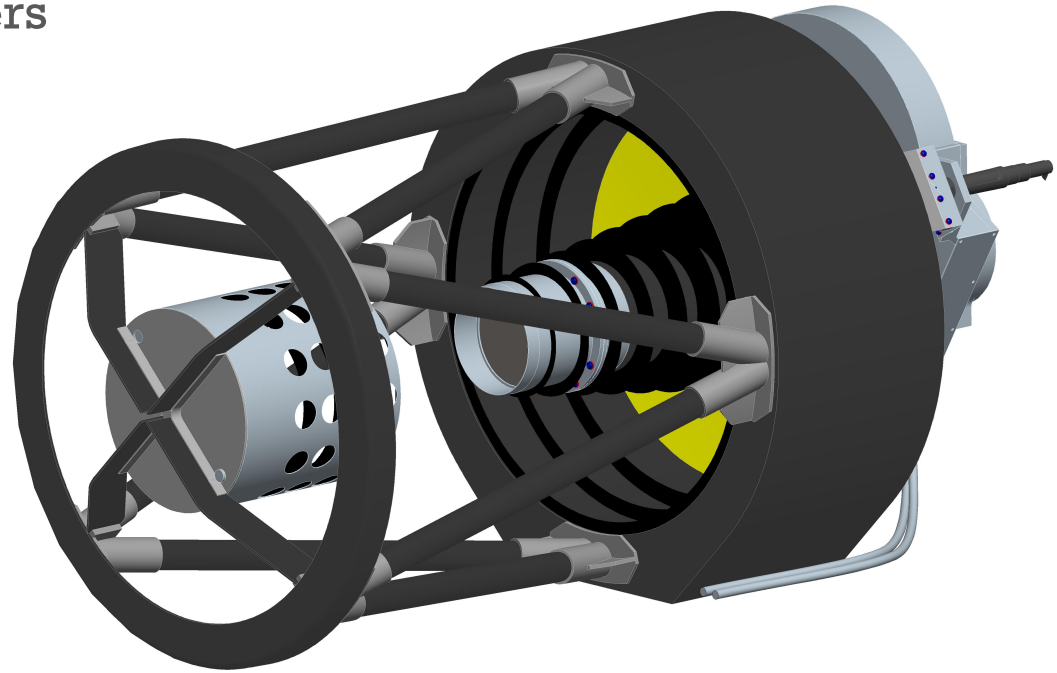
Variability on times scales of minutes/hours is not well studied



Kasliwal et al., 2011

Gravitational wave sources and rates, but also:

- Local Group Dwarf Galaxies
- Extragalactic globular clusters
- NS/BH binaries
- Eclipsing binaries
- Pulsating stars
- Tidal disruptions
- AGN variability
- Extragalactic science
- Supernovae
- GRBs
- CVs, Novae
- Asteroids/NEOs
- Hypervelocity stars
- White dwarfs
- Brown dwarfs
- Stellar populations and star clusters
- …



www.blackgem.eu
@BlackGEM_Array

Discussion

- Many ongoing and upcoming *time-resolved* wide-field surveys

  Gaia, iPTF, Skymapper, Pann-STARS, ZTF, BlackGEM, LSST,…

  → Different setups: cadence, depth, sky coverage, colours,…

  → 'Big data' era in astronomy

  Are we ready to find what we are looking for, as well as the unexpected?

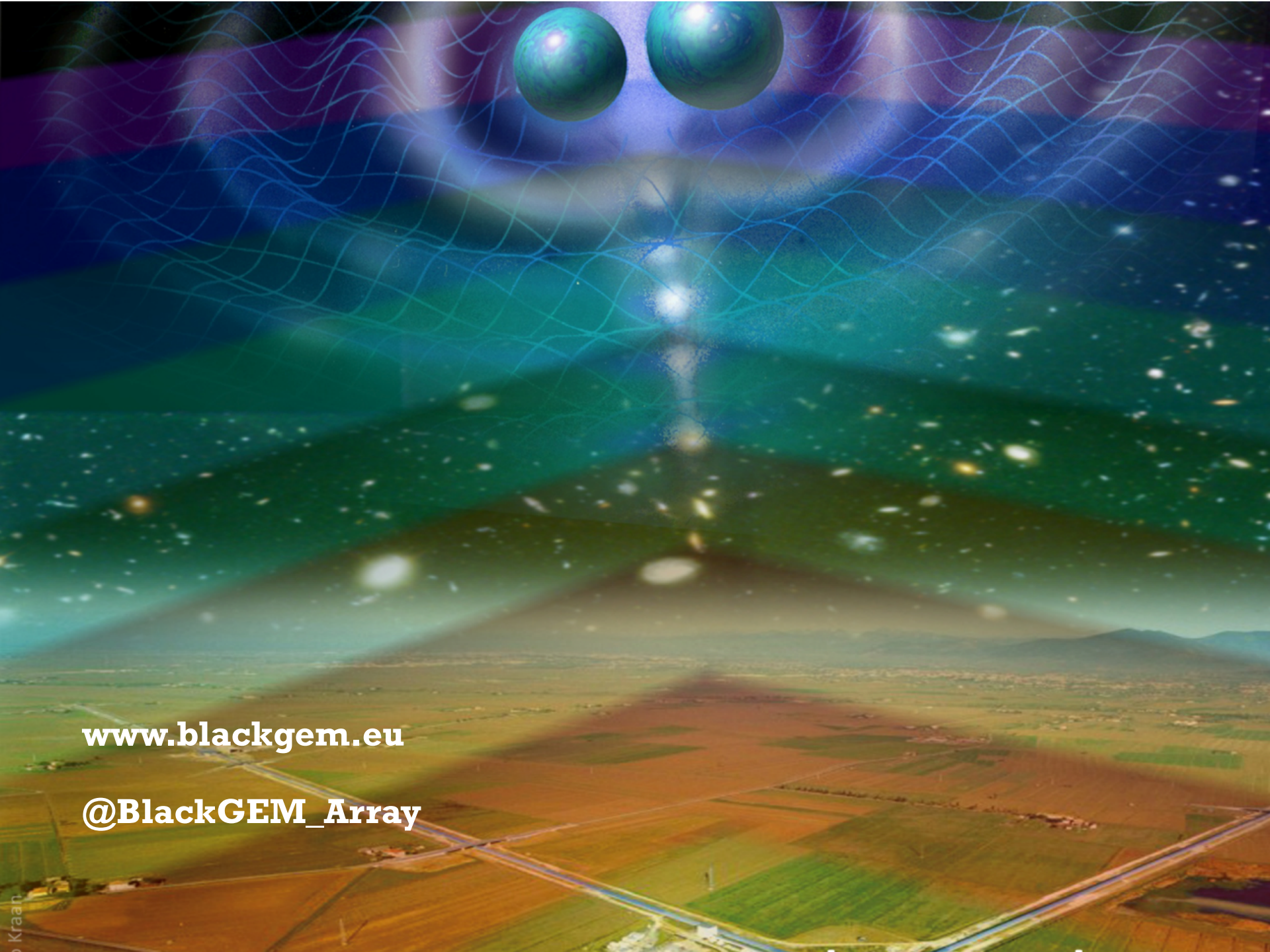
- Gravitational wave astrophysics

  → New window on the sky (LIGO/Virgo, eLISA,…)

  → Probing poorly known population of ultra-compact binaries (rates!)

  → Witness stellar merger events

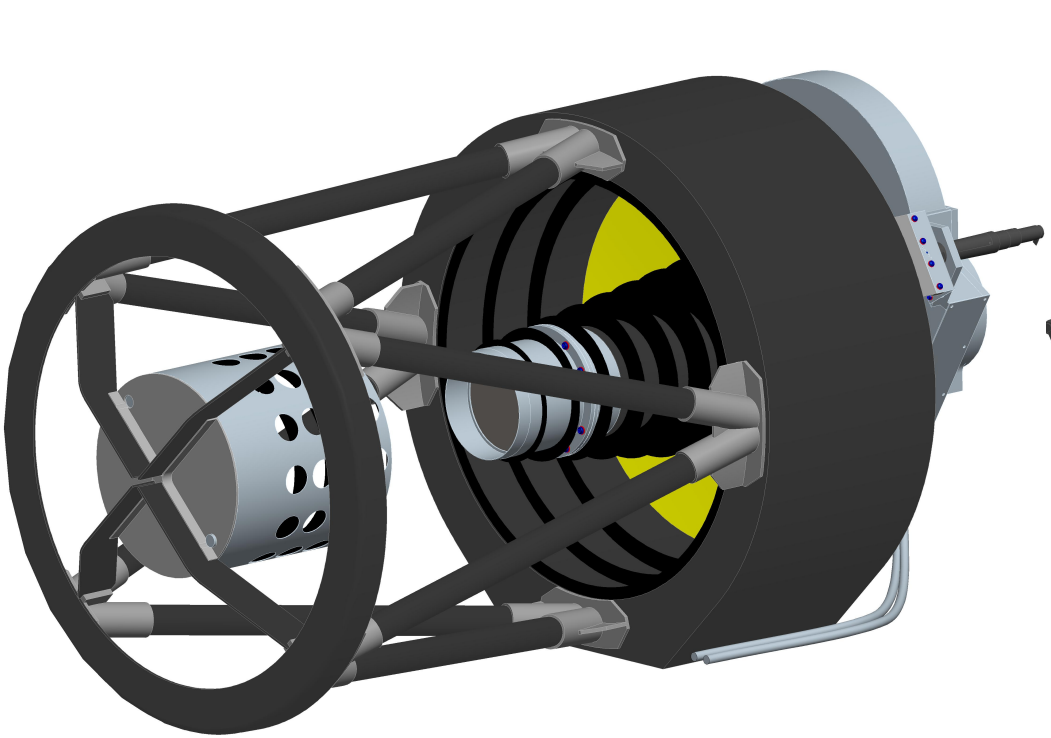
  → Challenging multi-wavelength follow-up

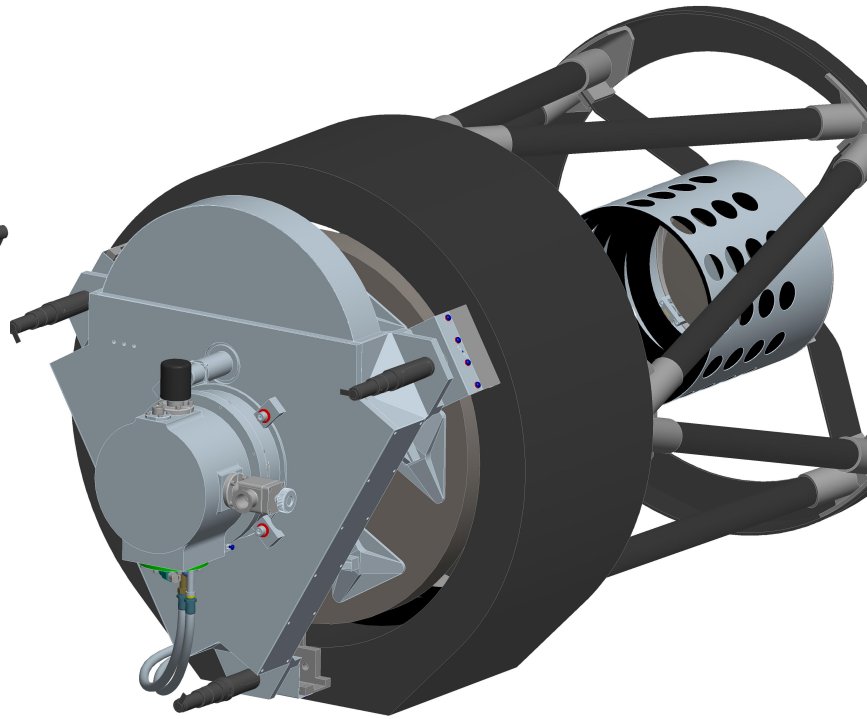

www.blackgem.eu
@BlackGEM_Array

Extra slides – only here for potential use during Q&A

Custom optical, mechanical design

- Cassegrain camera, u'g'r'i'z' filters
- Modified Dall-Kirkham design: 2.7 sqd FOV
- Single 10k * 10k CCD per telescope
- Thanks to good site: ~22nd mag in 5 minutes in g'

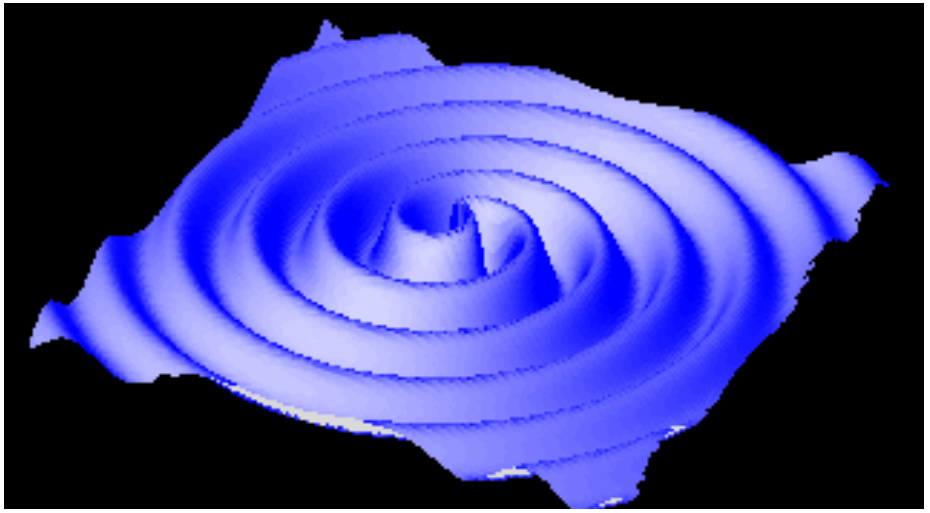




What is available?

Telescope	Hemi-sphere	Oper./Planned	Aperture	Sensitivity (60s)	FOV (sqd)	Spat. Res.
iPTF	WILL BE REPLACED BY ZTF					
PanStarrs	WRONG CADENCE, NOT DEDICATED					
DECam	DARK ENERGY COMMUNITY					
SkyMapper	WRONG CADENCE, NOT DEDICATED					
ZTF	N	2017	1.2m	21	40	2"
LSST	WRONG CADENCE, NOT DEDICATED, TOO LATE					

Deformation of space-time by massive objects

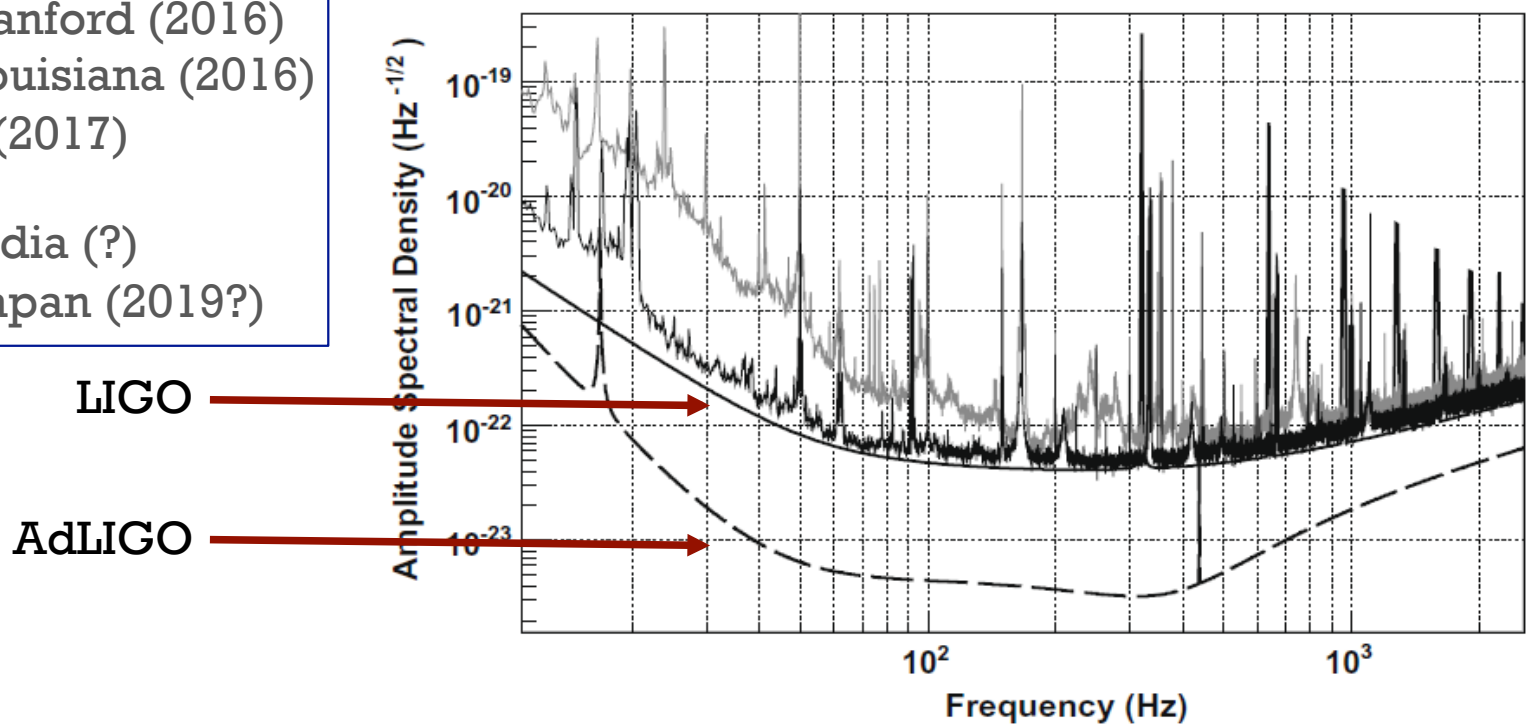


Advanced LIGO and VIRGO

10x more sensitive = 1000 x more volume

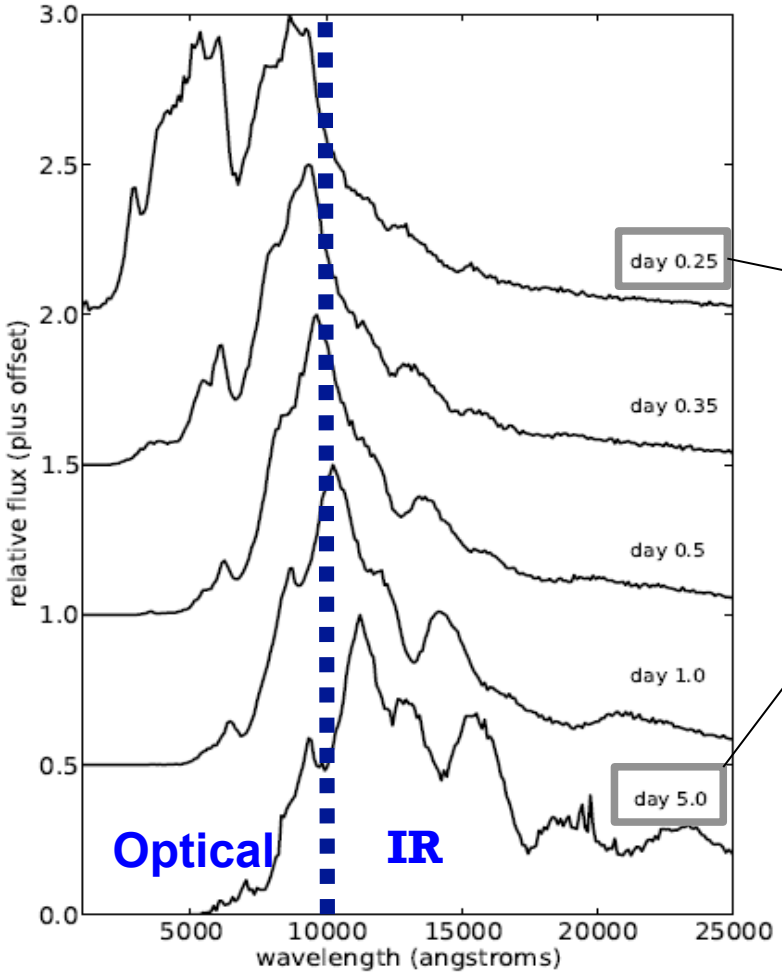
LIGO-Hanford (2016)
LIGO-Louisiana (2016)
VIRGO (2017)

LIGO-India (?)
Kagra-Japan (2019?)



Shot noise (random photon emissions), photons shake the mirrors, earthquakes,…

Kilonovae (NS+NS): recent models



Large FOV is cheaper in optical than in IR

6 hours after T_0

5 days after T_0

Newest opacities show evolution blue → red

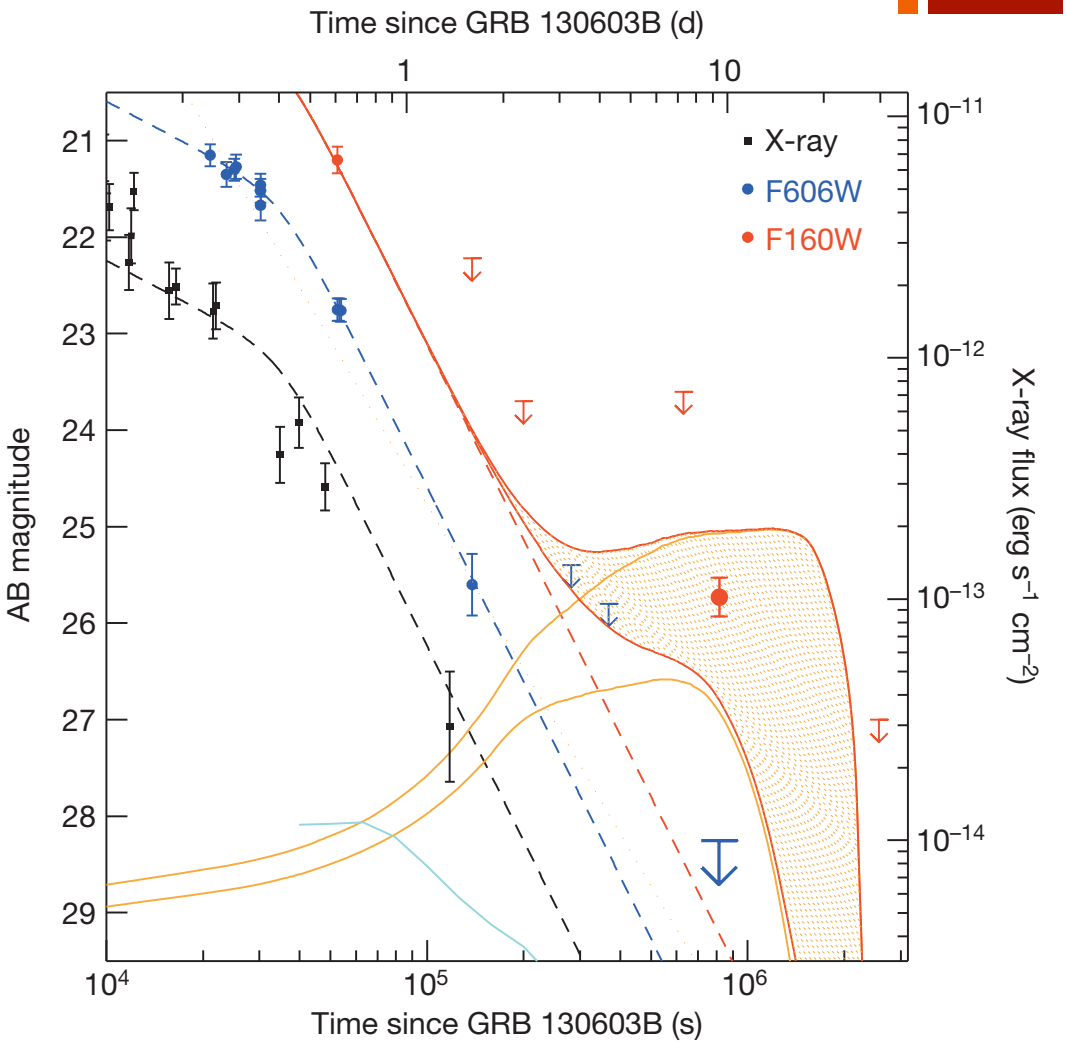
(Kasen et al., 2013)

Gravitational waves – a new window on the sky!

- Strong gravity physics (test for GR)
- Equation of state of ultradence, cold matter (neutron star)
- r-process elements
- NS, BH Merger rates, correlation with environment (galaxies, star forming regions)
- Massive star evolution
- Distance scale in cosmology

First ‘kilonova’ associated with short gamma-ray burst

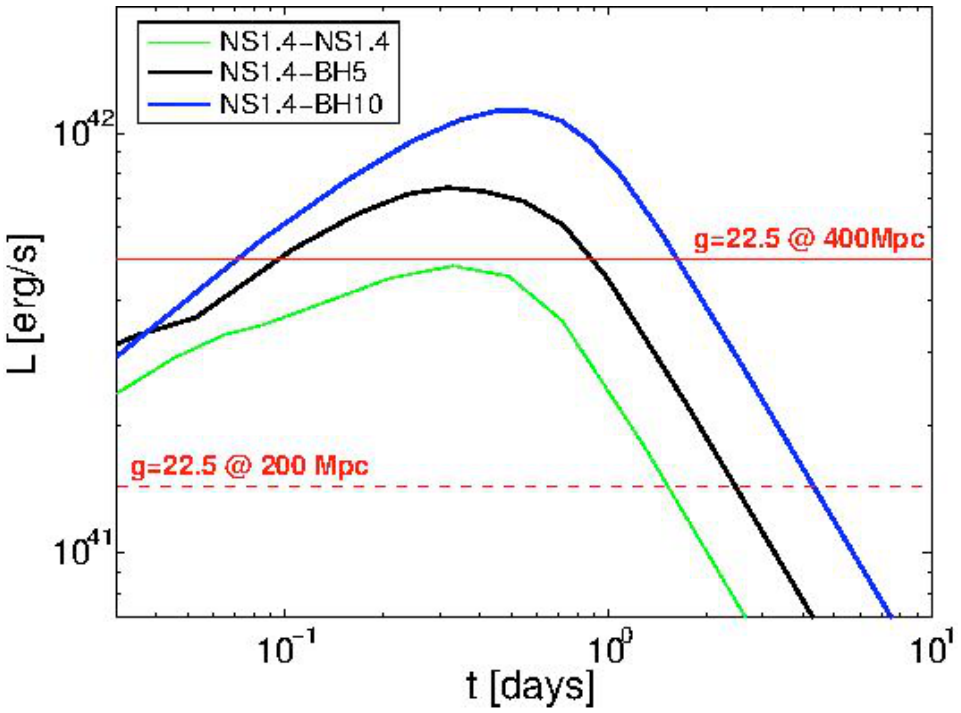
- Tanvir et al. 2013, Nature
- Short GRB (SWIFT, ~0.2s)
- Afterglow:
  X-ray
  optical (WHT, HST)
  near IR (HST)
- IR-excess due to radioactive decay in ejected material
- Redshift z=0.356
  (400 Mpc ~ z=0.1)



Optical signals are weak

Sensitivity needed to detect optical counterparts up to 400 Mpc is ~ 22 mag. → Background limited!

Adapted from Piran et al. 2013



Q1 2016 –

MeerLICHT

Single telescope of BlackGEM type in South Africa

Changing transient science to truly multi-wavelength

Pointing determined by MeerKAT radio telescope

In South Africa: bridge between SALT and SKA/MeerKAT

Nijmegen, NWO (NL);
UCT, SAAO (SA); Oxford (UK)


SKA
MeerKAT
SAAO
MeerLICHT
South Africa
Lesotho
Richtersveld National Park
Aussenkehr Nature Reserve
Richtersveld World Heritage Site
Riemvasmaak Community Conservancy
Namaqua National Park
Tankwa Karoo National Park
Garden Route National Park
Baviaanskloof Nature Reserve
Addo Elephant National Park
Kathu
Upington
Postmasburg
Kimberley
Boshof
Bloemhof
Christiana
Kroonstad
Kutlwanong
Welkom
Virginia
Senekal
Bethlehem
Ficksburg
Bloemfontein
Ladybrand
Botshabelo
Maseru
Springbok
Prieska
Mafeteng
Bethulie
Colesberg
Aliwal North
Burgersdorp
Elliot
Calvinia
Vredendal
Queenstown
Beaufort West
Graaff-Reinet
Cradock
Aberdeen
Somerset East
Stutterheim
King William's Town
East London
Velddrif
Vredenburg
Saldanha
Moorreesburg
Prince Albert
Willowmore
Grahamstown
Malmesbury
Ceres
Oudtshoorn
Port Alfred
Atlantis
Paarl
Worcester
Blouberg
Robertson
Uitenhage
Cape Town
Bellville
Swellendam
George
Riversdale
Mossel Bay
Plettenberg Bay
Humansdorp
Port Elizabeth
Mitchells Plain
Grabouw
Hermanus
Bredasdorp