

# Statistics from O3 and Instrumentation for GW follow-up

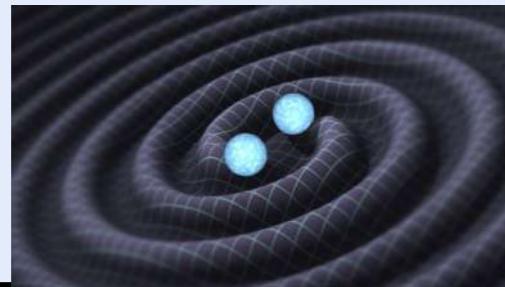
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IAA-CSIC  
DARK/NBI

25 February 2020

# Introduction

Why are EM counterpart  
observations of GWs important?

# Why EM counterparts?



**GW**

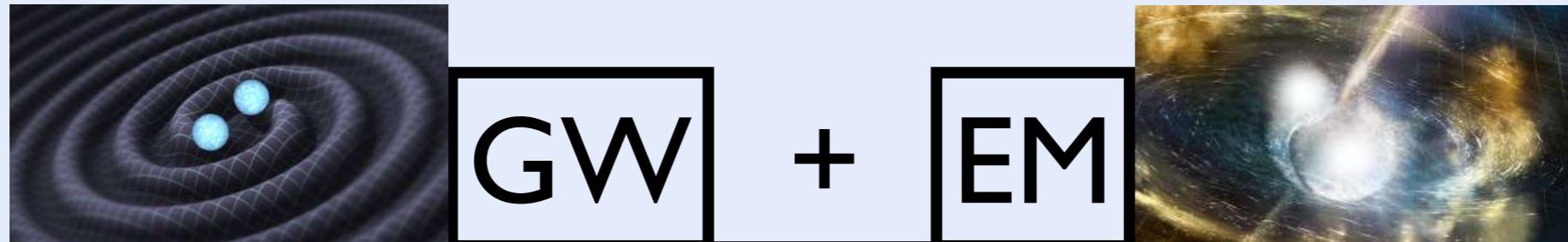


**EM**

- Information on the binary
- Masses
- Spins
- Tidal deformability
- Orientation
- Eccentricity
- Exact time of merger
- Distance

- Precise localisation
- Astrophysical context
- Redshift
- Host galaxy
- Environment of the progenitor
- Outflow properties
  - ▶ Composition
  - ▶ Velocity
  - ▶ geometry

# Why EM counterparts?



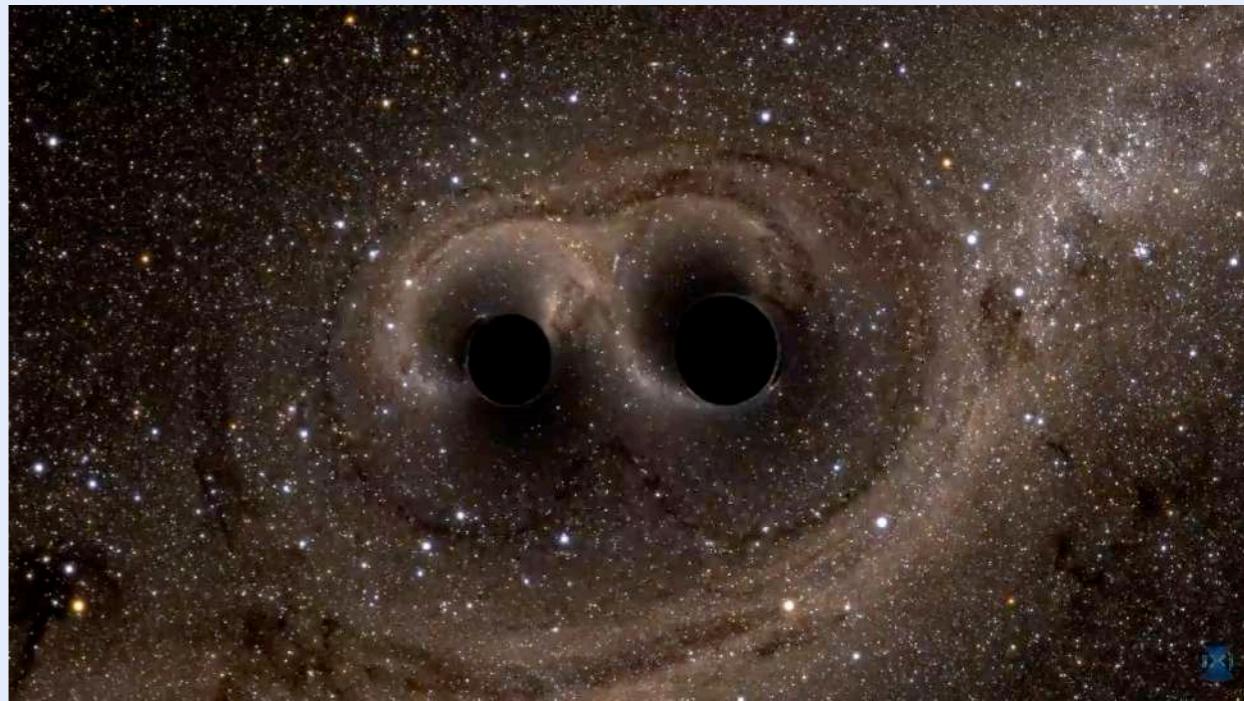
- Nature of gravity
- Cosmological constraints
- Origin of the heaviest elements
- Equation of state at supranuclear densities
- Identification of short GRB progenitors



# EM counterparts of compact binary mergers

# Types of compact binary mergers

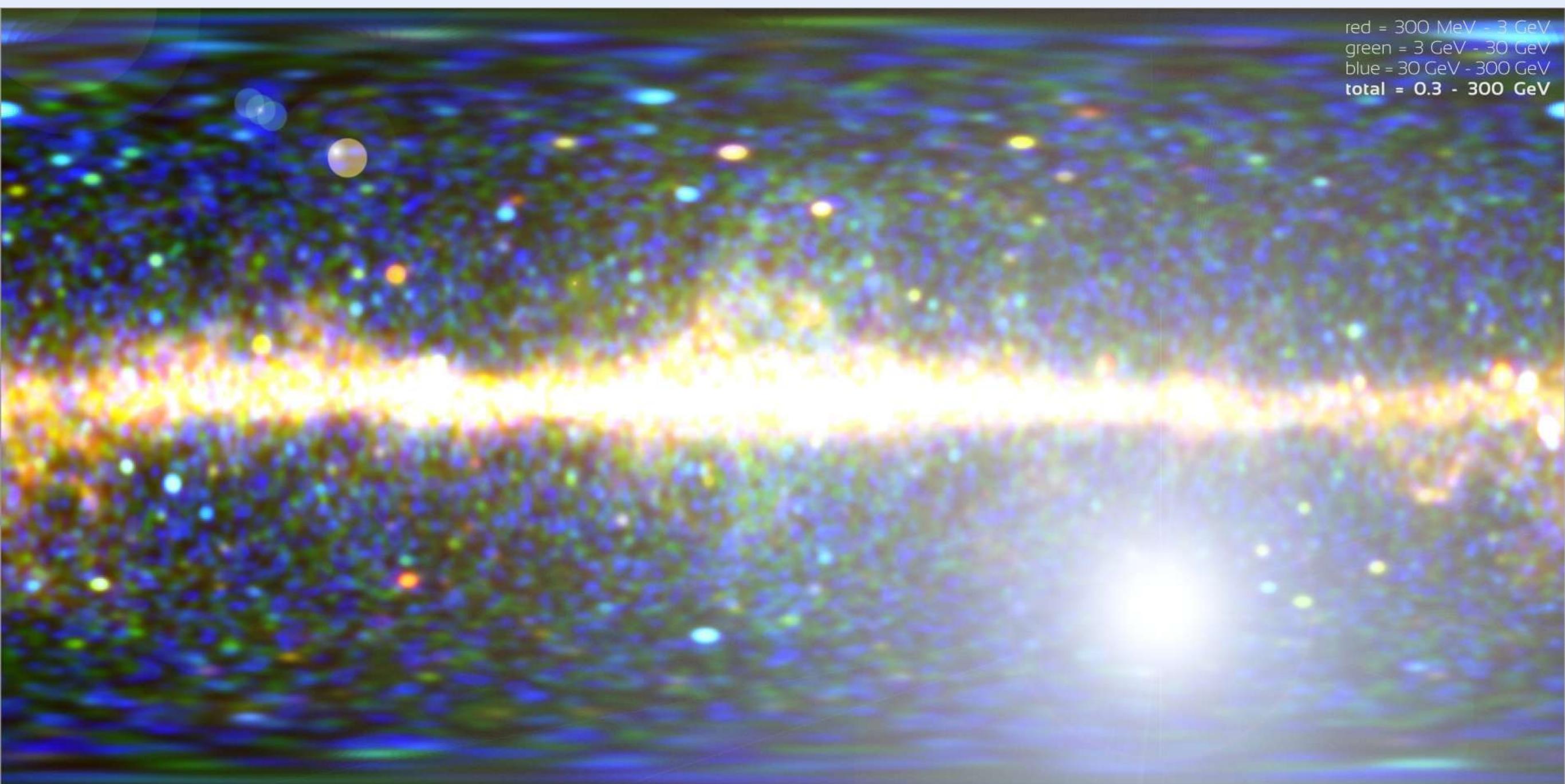
- Binary Black Hole  
BBH
  - Binary Neutron Star  
BNS
  - Neutron Star-Black Hole  
NSBH
  - Mass gap  
( $3\text{-}5 M_{\odot}$ )
- } GRBs



# Gamma-ray bursts

# Gamma Ray Bursts

Long GRB GRB191219A

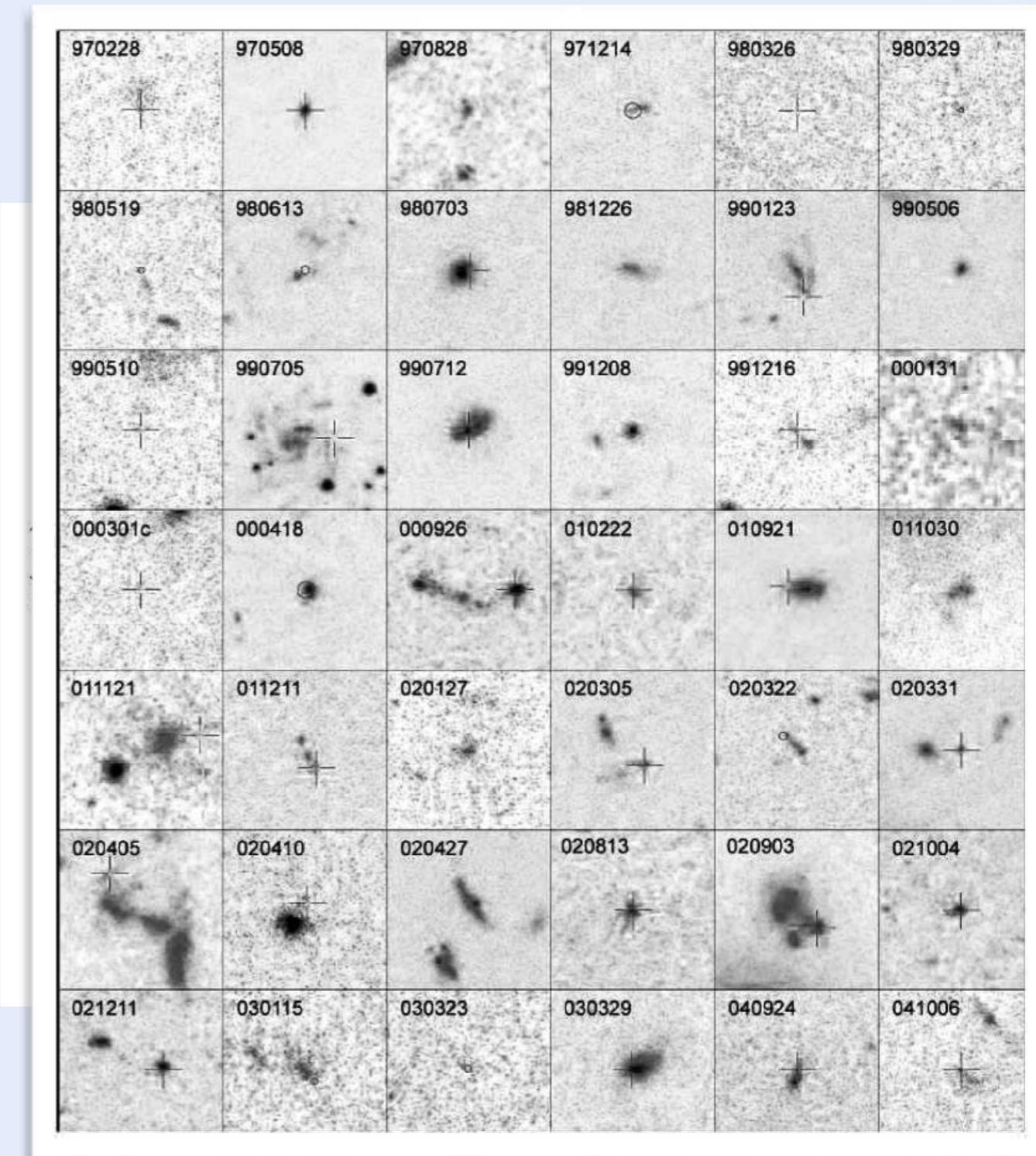


# Naming of GWs

- In a similar way as GRBs: **GW191219** (without the letter)
- Before they are confirmed (published): **S191219az**
  - Superevent**
  - Unique identifier**

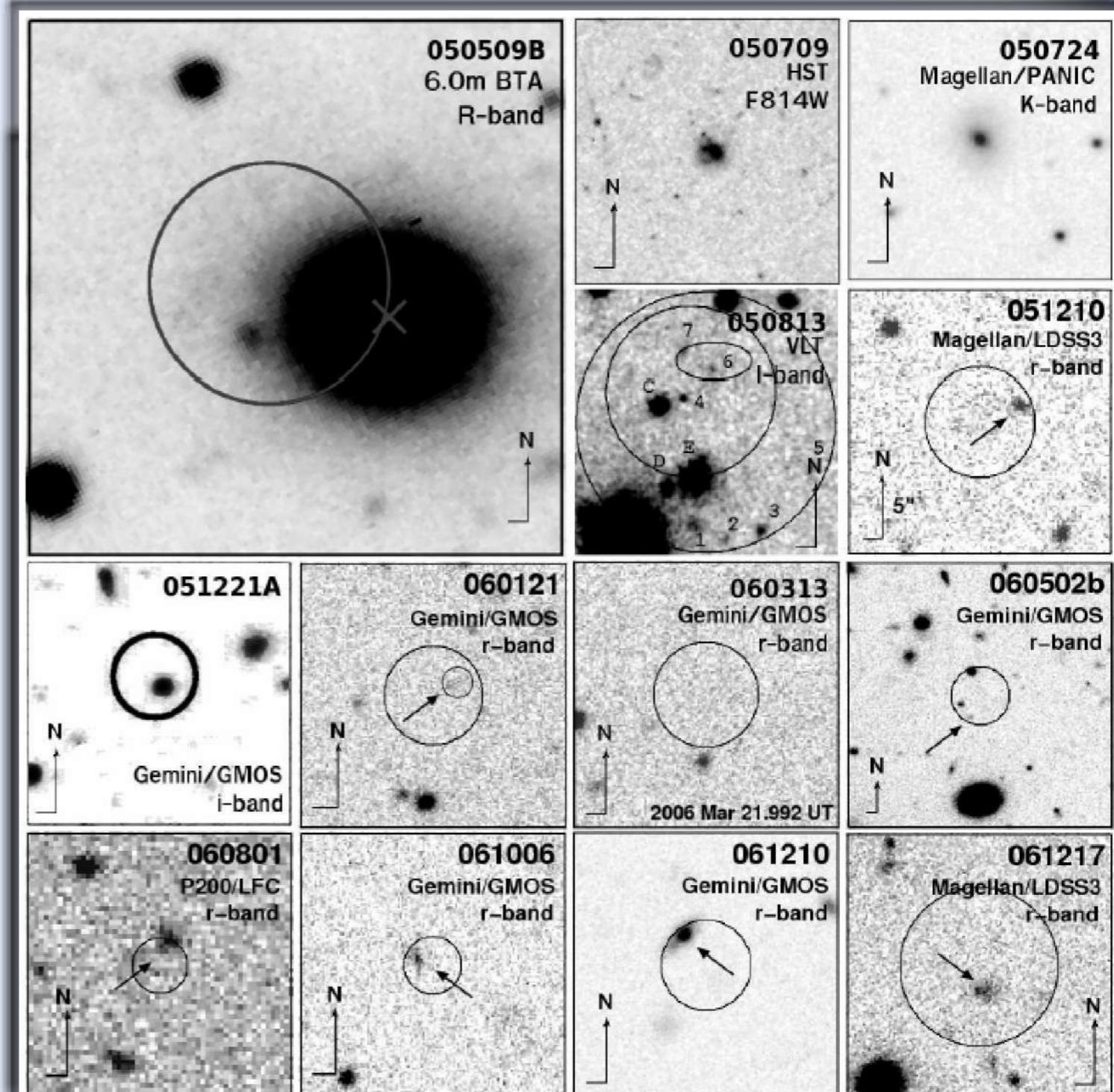
# Long GRBs

- Most luminous explosions in the Universe ( $E_{\text{iso}} = 10^{51-54}$  erg)
- Detected at all redshifts  $0.08 < z < 9.4$ , 99% of the Universe's history (Tanvir et al. 2009, Cucchiara et al. 2011)
- Average  $z \sim 2$  (Jakobsson et al. 2006)
- Associated with broad-line SN Ic (Galama et al. 1998)
- Located in star forming galaxies (Christensen et al. 2004)
- Collapsars are the most probable progenitors

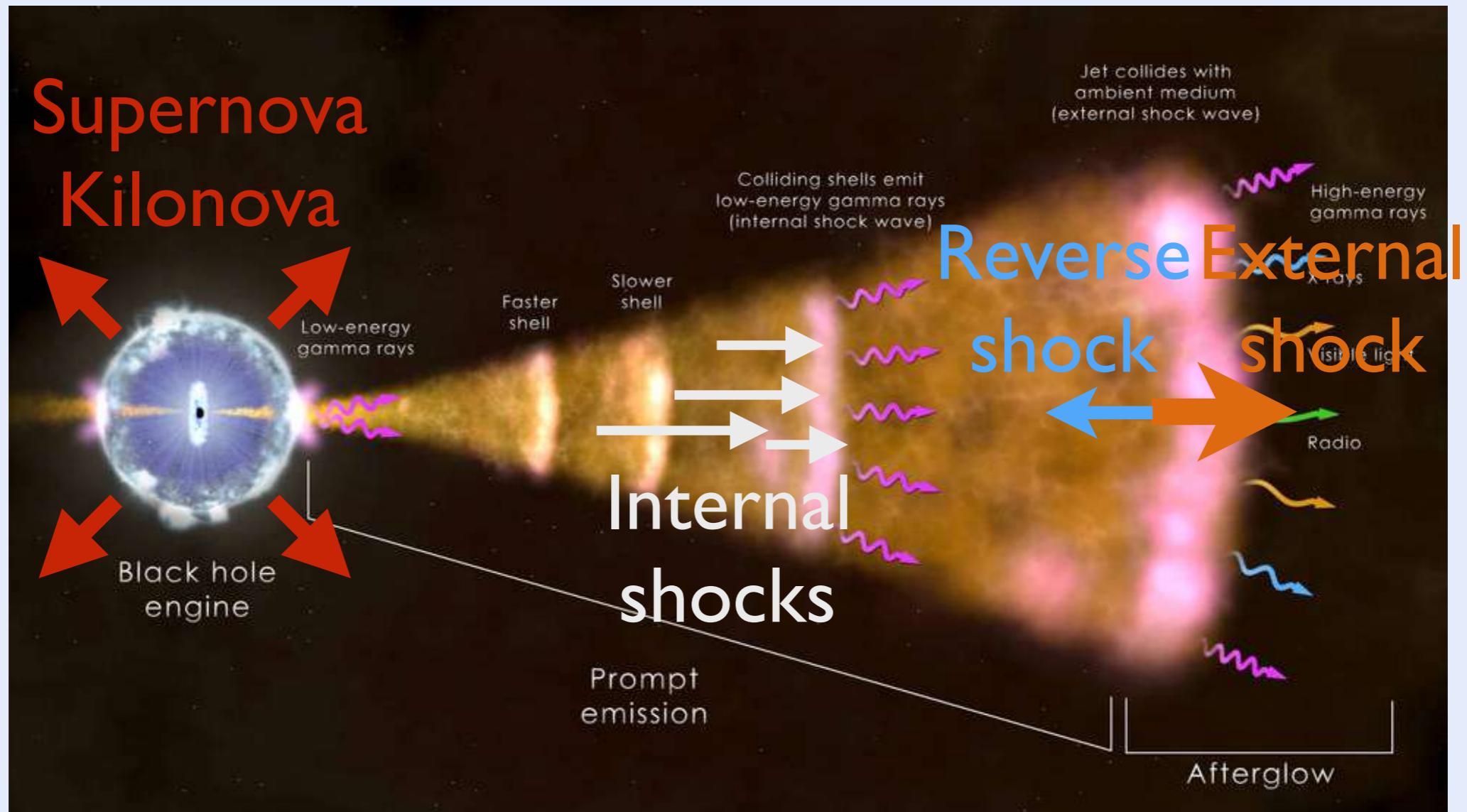


# Short GRBs

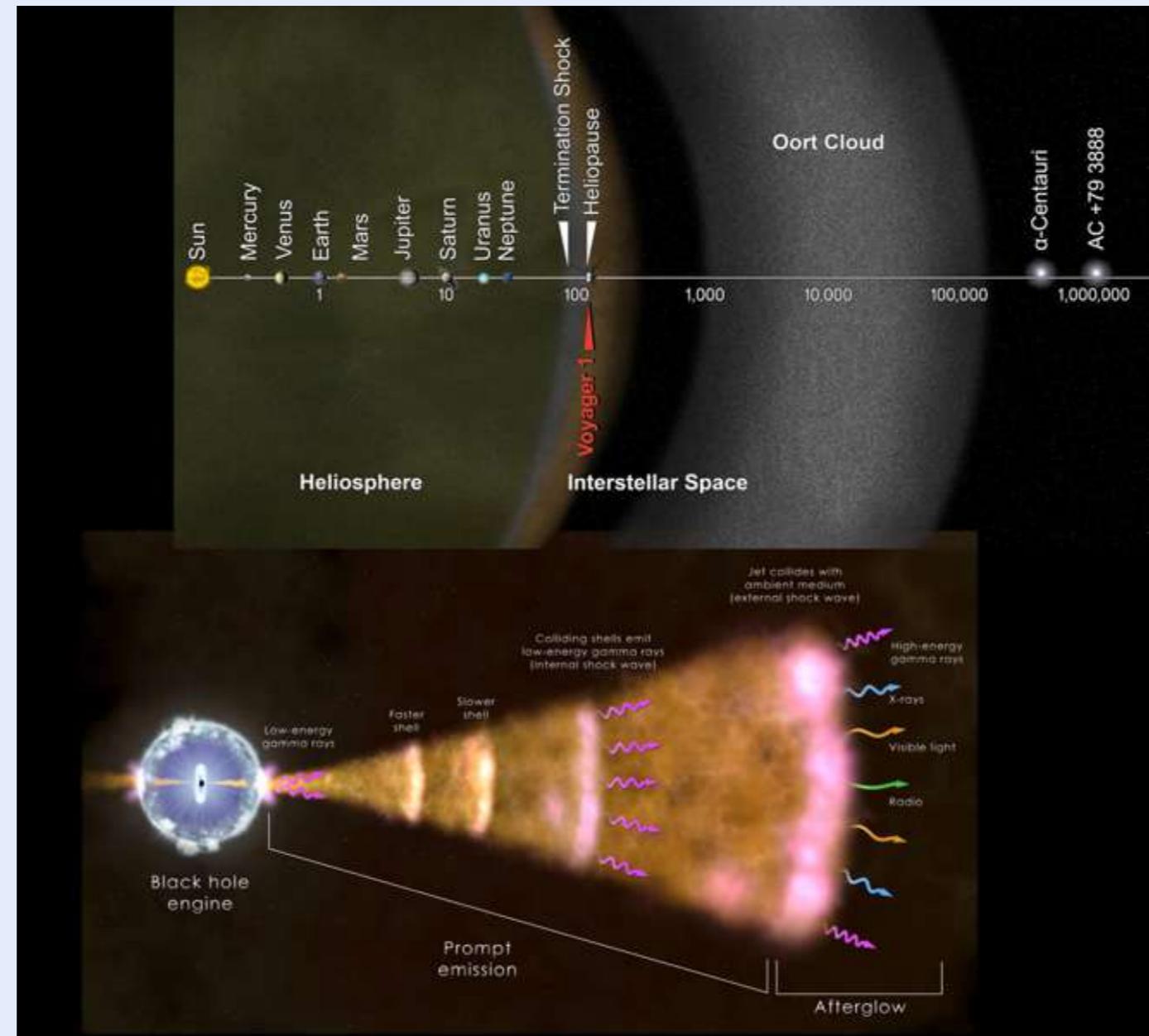
- Fainter and very elusive!
- Varied types of host galaxies
- Only spectroscopy of 1 SGRB afterglow published until now (GRB130603B, de Ugarte Postigo et al. 2013)
- No SN, but an associated kilonova (Tanvir et al. 2013, Berger et al. 2013)
- Associated to GW signals (GRB170817A)
- Produced by the merger of compact objects



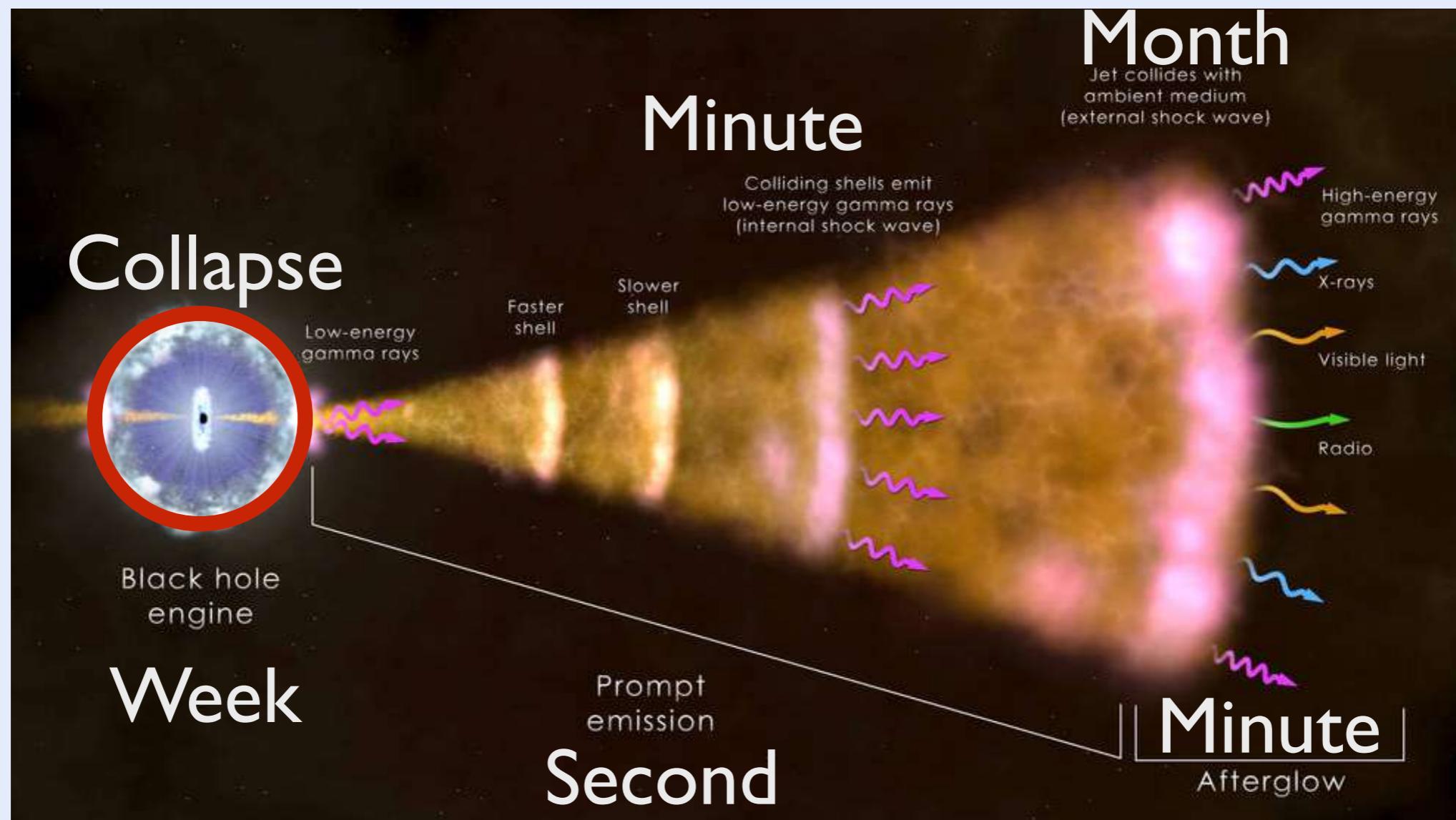
# Ultrarelativistic jets



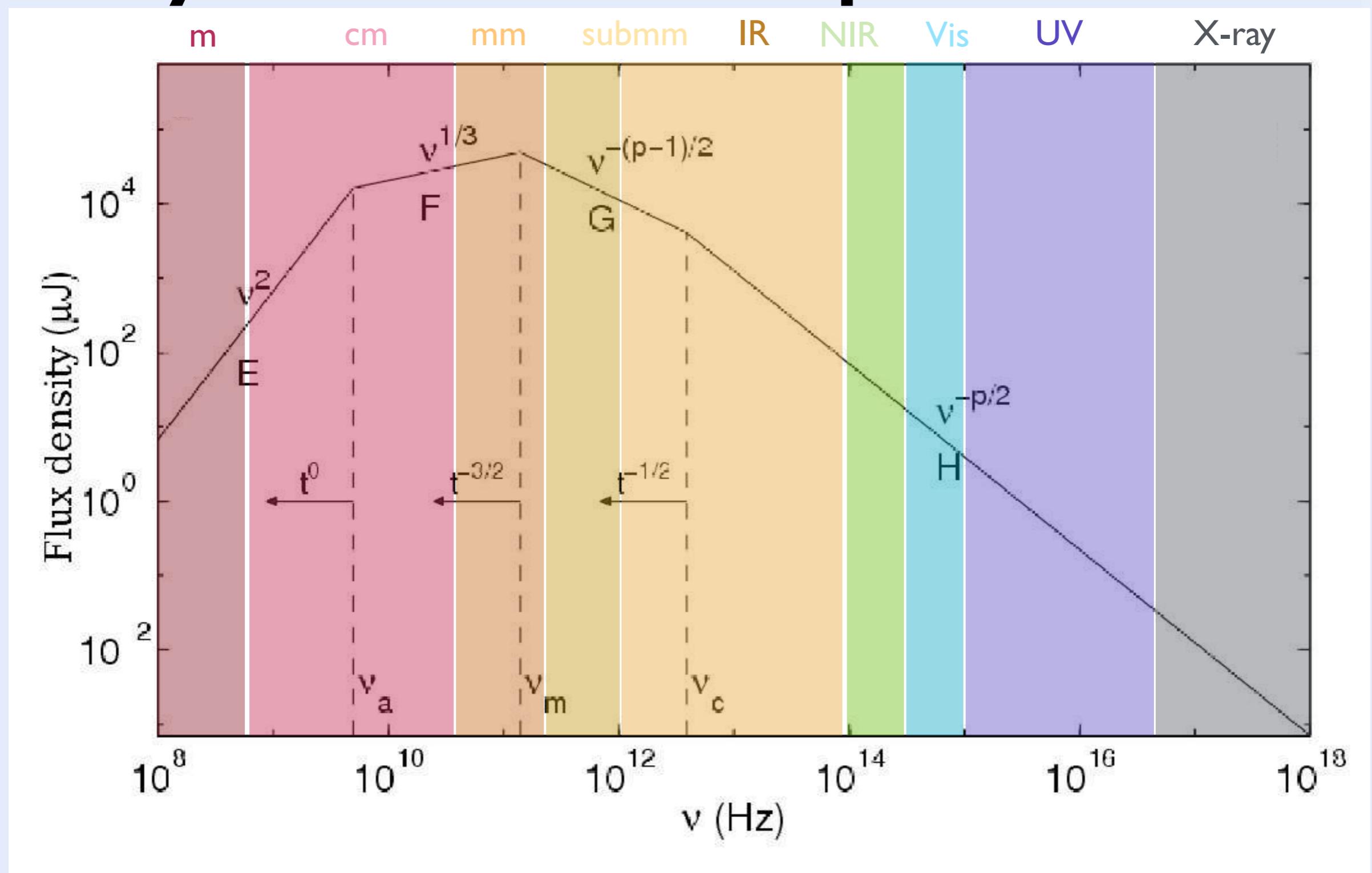
# Physical scale of a GRB



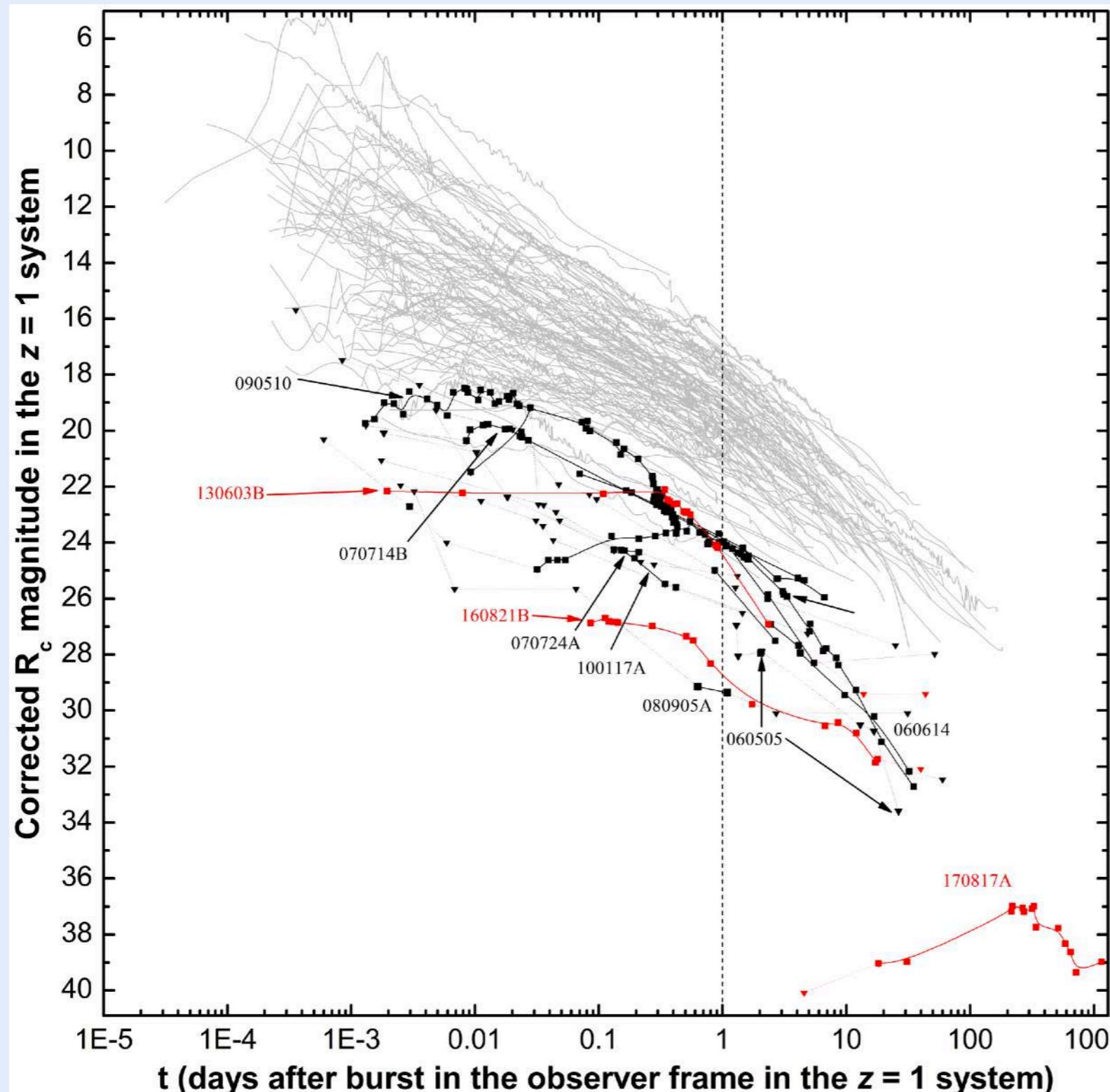
# Temporal scale of GRBs



# Synchrotron spectrum



# SGRBs vs LGRBs



SGRBs are  
 $\sim 250$  times  
 fainter  
 than LGRBs  
 (6 mags)

Adapted from  
 Kann et al. 2011

# Other sources of GWs

# Long GRBs

- GWs from:
  - GRB jets [wrong freq.]
  - Collapsar [ $\sim 1$  Mpc]
  - Neutrino Dominated Accretion Flow (NDAF) [ $\sim 10$  kpc]
- Much brighter EM counterpart:
  - Afterglow if on axis
  - SN independent of the orientation

**Nearest LGRB at 37 Mpc**



# Supernovae

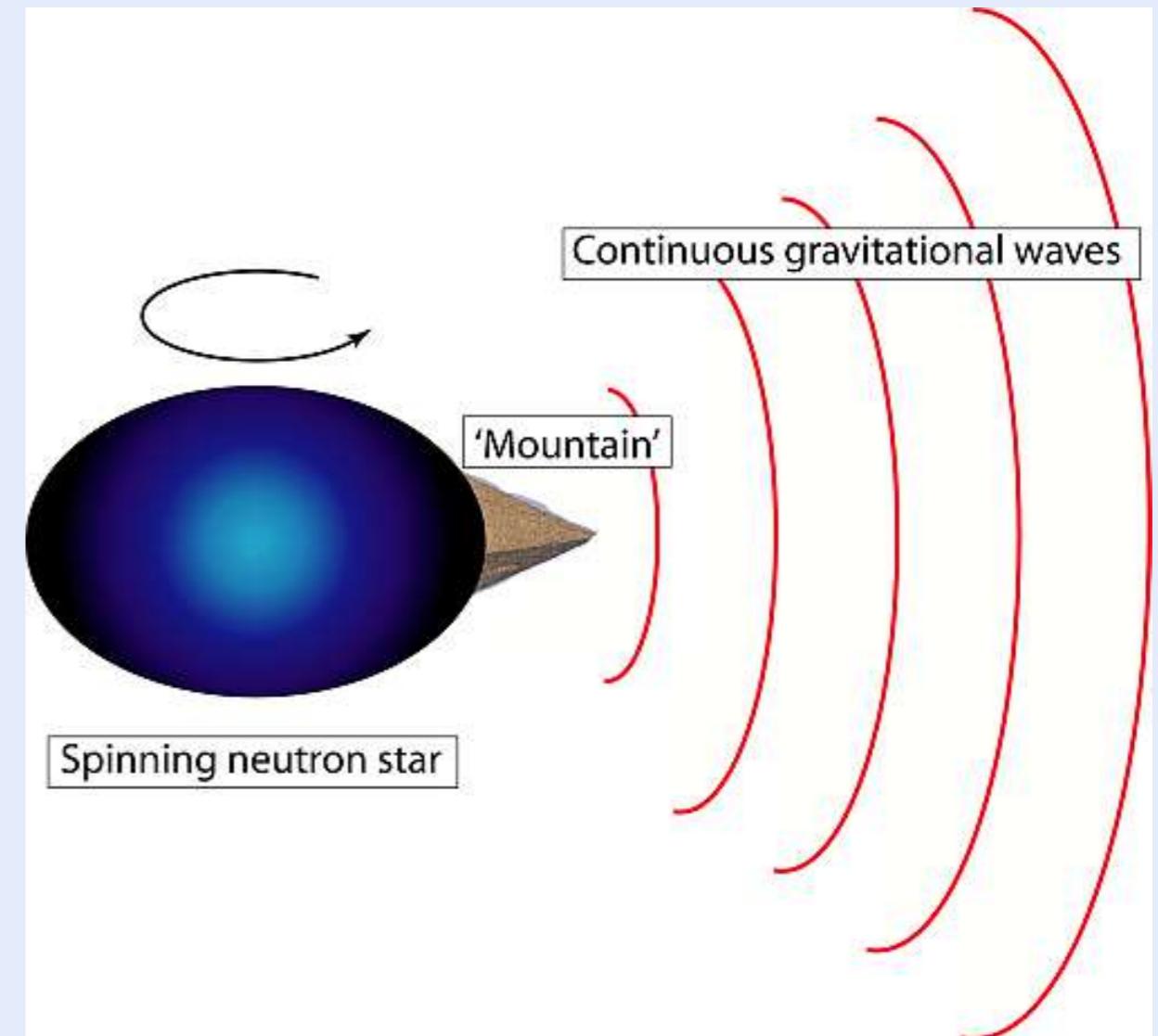
GW  
 $\Sigma$

- Neutrino driven CCSN (99% of all CCSN):  $\sim 5.5$  kpc
- Rapidly rotating CCSN:  $\sim 50$  kpc (LMC)
- Extreme models could expect detections up to a few Mpc
- At  $d < 100$  kpc, neutrinos are expected Gossan et al. 2016
- Easily detectable at those distances with any technique (imaging, spectroscopy, polarimetry, spectropolarimetry, radio, X-rays, etc.)
- At these distances pre-imaging of the progenitor is feasible

We need a Galactic SN  
while the detectors are ON!!!

# Spinning NS

- GW**
- Continuous but weak signal
- EM**
- Slow decline in the periodicity of the pulsar signal



# Results of O3

# Statistics of O3

- OI: 3 GW signals (all BBH)
  - O2: 8 GW signals (7 BBH, 1 BNS) one EM counterpart!
  - O3 started in April 2019 and stopped for a month in November
  - Will go on for a total of at least 1 year
  - 50 triggers in 300 days (one every 6 days)
    - 5 BNS, mean  $D_L = 206 \text{ Mpc}$  ( $0.037 \text{ Gpc}^3 \Rightarrow \sim 167 \text{ BNS/Gpc}^3/\text{yr}$ )
    - 5 NSBH, mean  $D_L = 366 \text{ Mpc}$  ( $0.205 \text{ Gpc}^3 \Rightarrow \sim 30 \text{ BNSBH/Gpc}^3/\text{yr}$ )
    - 4 Mass gap, mean  $D_L = 616 \text{ Mpc}$  ( $0.977 \text{ Gpc}^3 \Rightarrow \sim 5 \text{ MG/Gpc}^3/\text{yr}$ )
    - 33 BBH, mean  $D_L = 1669 \text{ Mpc}$  ( $19.47 \text{ Gpc}^3 \Rightarrow \sim 2.1 \text{ BBH/Gpc}^3/\text{yr}$ )
    - 1 Burst even,  $D_L = ???$
  - No electromagnetic counterpart found yet
- The rest probably terrestrial

# Rate from short GRBs

- Avg distance:

$z \sim 0.5$  (2.8 Gpc)

$z(\text{median}) \sim 0.454$  (2.55 Gpc)

$z(\text{avg}) \sim 0.647$  (3918 Gpc)

- Number:

$\sim 10 \text{ yr}^{-1}$

$\sim 12.5 \text{ yr}^{-1}$

- Rate:

$0.11 \text{ SGRB Gpc}^{-3} \text{ yr}^{-1}$

$0.18 \text{ SGRB Gpc}^{-3} \text{ yr}^{-1}$

$0.05 \text{ SGRB Gpc}^{-3} \text{ yr}^{-1}$

- Correction for sky coverage  $\sim 12.6$  (*Swift/BAT*)

**1.38 SGRB Gpc<sup>-3</sup> yr<sup>-1</sup>**

$2.26 \text{ SGRB Gpc}^{-3} \text{ yr}^{-1}$

$0.63 \text{ SGRB Gpc}^{-3} \text{ yr}^{-1}$

From GWs:  $170 \text{ Gpc}^{-3} \text{ yr}^{-1}$

From SGRBs:  $1.4 \text{ Gpc}^{-3} \text{ yr}^{-1}$

Collimation factor  $\sim 120$

=> half opening angle  $\sim 7.4 \text{ deg}$

# BNS statistics

$z$	dL (Mpc)	KN peak mag	AG peak mag	KN/yr	AG/yr (1/100)
0.01	43	17.2	8.2-16.2	0.06	$4.7 \cdot 10^{-4}$
0.02	88	18.7	9.7-17.7	0.47	$4.0 \cdot 10^{-3}$
0.03	132	19.6	10.6-18.6	1.6	$1.4 \cdot 10^{-2}$
0.04	178	20.2	11.2-19.2	3.9	$3.4 \cdot 10^{-2}$
0.05	224	20.7	11.7-19.7	7.8	$6.7 \cdot 10^{-2}$
0.06	270	21.2	12.2-20.2	14	0.12
0.07	318	21.5	12.5-20.5	22	0.19
0.08	365	21.8	12.8-20.8	34	0.29
0.09	414	22.1	13.1-21.1	50	0.43
0.10	463	22.3	13.3-21.3	69	0.59
0.202	1000	24.0	14.8-23.0	698	6.0

Med  
BNS

O4

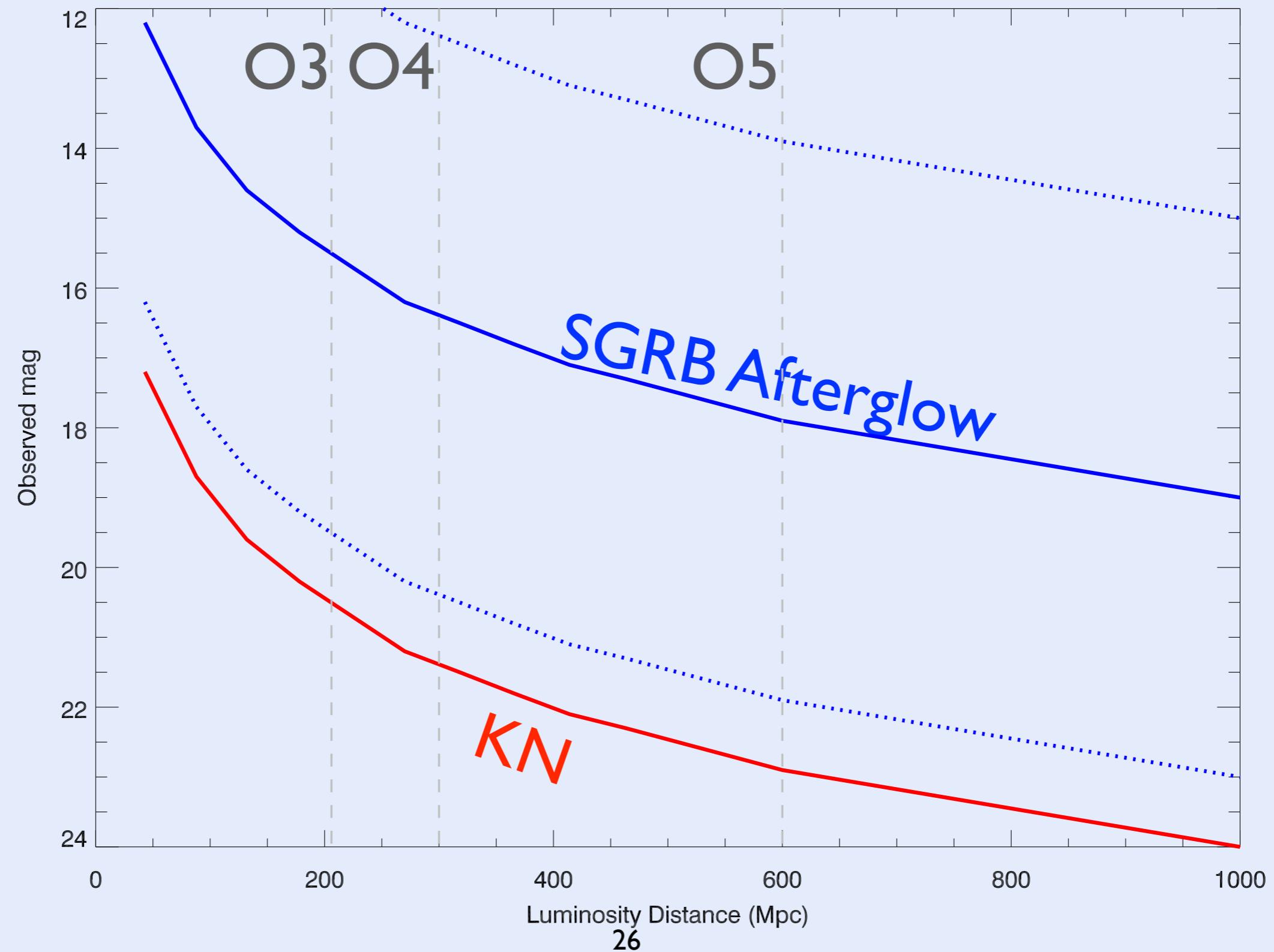
O5

# Current GRANDMA

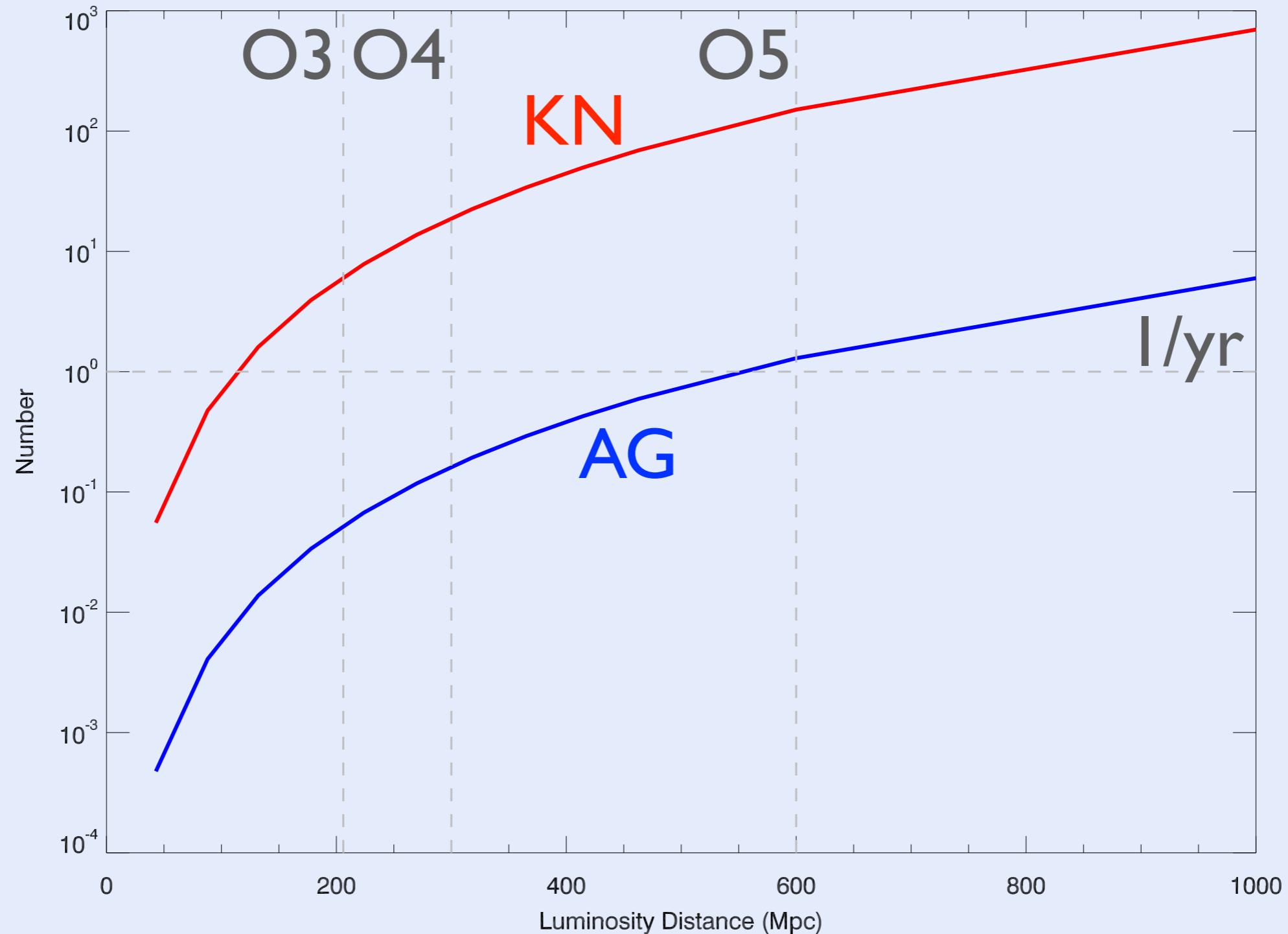


Telescope name	Location	Aperture (m)	FoV (deg)	Filters	$3 - \sigma$ limit (AB mag)	Maximum night slot (UTC) (h)
TAROT/TCH	La Silla Obs.	0.25	$1.85 \times 1.85$	Clear, $g' r' i'$	18.0 in 60 s (Cear)	06–15
CFHT/WIRCAM	CFH Obs.	3.6	$0.35 \times 0.35$	$JH$	22.0 in 200 s ( $J$ )	10–16
CFHT/MEGACAM	CFH Obs.	3.6	$1.0 \times 1.0$	$g' r' i' z'$	23.0 in 200 s ( $r'$ )	10–16
Zadko	Gingin Obs.	1.00	$0.17 \times 0.12$	Clear, $g' r' i' I_C$	20.5 in 40 s (Clear)	12–22
TNT	Xinglong Obs.	0.80	$0.19 \times 0.19$	$BVg' r' i'$	19.0 in 300 s ( $R_C$ )	12–22
Xinglong-2.16	Xinglong Obs.	2.16	$0.15 \times 0.15$	$BVRI$	21.0 in 100 s ( $R_C$ )	12–22
GMG-2.4	Lijiang Obs.	2.4	$0.17 \times 0.17$	$BVRI$	22.0 in 100 s ( $R_C$ )	12–22
UBAI/NT-60	Maidanak Obs.	0.60	$0.18 \times 0.18$	$BVR_CI_C$	18.0 in 180 s ( $R_C$ )	14–00
UBAI/ST-60	Maidanak Obs.	0.60	$0.11 \times 0.11$	$BVR_CI_C$	18.0 in 180 s ( $R_C$ )	14–00
TAROT/TRE	La Reunion	0.18	$4.2 \times 4.2$	Clear	16.0 in 60 s (Clear)	15–01
Les Makes/T60	La Reunion.	0.60	$0.3 \times 0.3$	Clear, $BVR_C$	19.0 in 180 s ( $R_C$ )	15–01
Abastumani/T70	Abastumani Obs.	0.70	$0.5 \times 0.5$	$BVR_CI_C$	18.2 in 60 s ( $R_C$ )	17–03
Abastumani/T48	Abastumani Obs.	0.48	$0.33 \times 0.33$	$UBVRCI_C$	15.0 in 60 s ( $R_C$ )	17–03
ShAO/T60	Shamakhy Obs.	0.60	$0.28 \times 0.28$	$BVR_CI_C$	19.0 in 300 s ( $R_C$ )	17–03
Lisnyky/AZT-8	Kyiv Obs.	0.70	$0.38 \times 0.38$	$UBVRCI_C$	20.0 in 300 s ( $R_C$ )	17–03
TAROT/TCA	Calern Obs.	0.25	$1.85 \times 1.85$	Clear, $g' r' i'$	18.0 in 60 s (Clear)	20–06
IRIS	OHP	0.5	$0.4 \times 0.4$	Clear, $u' g' r' i' z'$	18.5 in 60 s ( $r'$ )	20–06
T120	OHP	1.20	$0.3 \times 0.3$	$BVRI$	20.0 in 60 s ( $R$ )	20–06
OAJ/T80	Javalambre Obs.	0.80	$1.4 \times 1.4$	$r'$	21.0 in 180 s ( $r'$ )	20–06
OSN/T150	Sierra Nevada Obs.	1.50	$0.30 \times 0.22$	$BVR_CI_C$	21.5 in 180 s ( $R_C$ )	20–06
CAHA/2.2m	Calar Alto Obs.	2.20	$0.27\text{D}$	$u' g' r' i' z'$	23.7 in 100 s ( $r'$ )	20–06

# BNS mag vs z



# BNS vs distance



# Error areas in O3

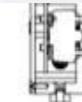
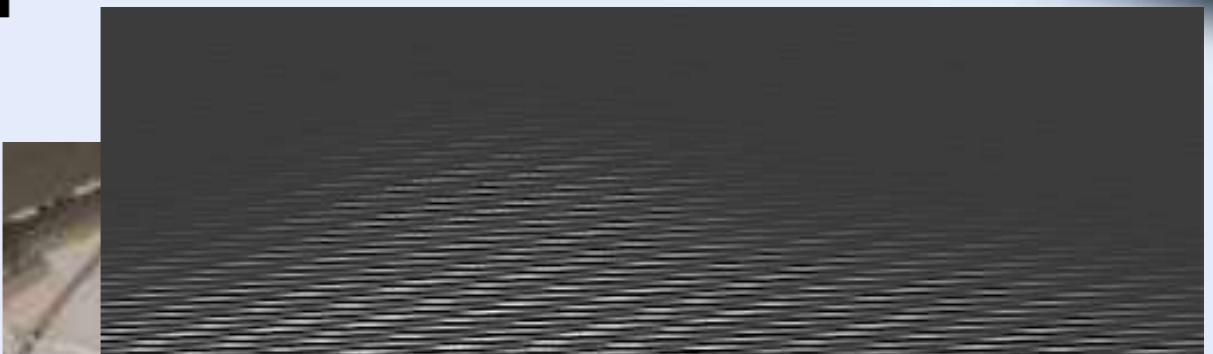
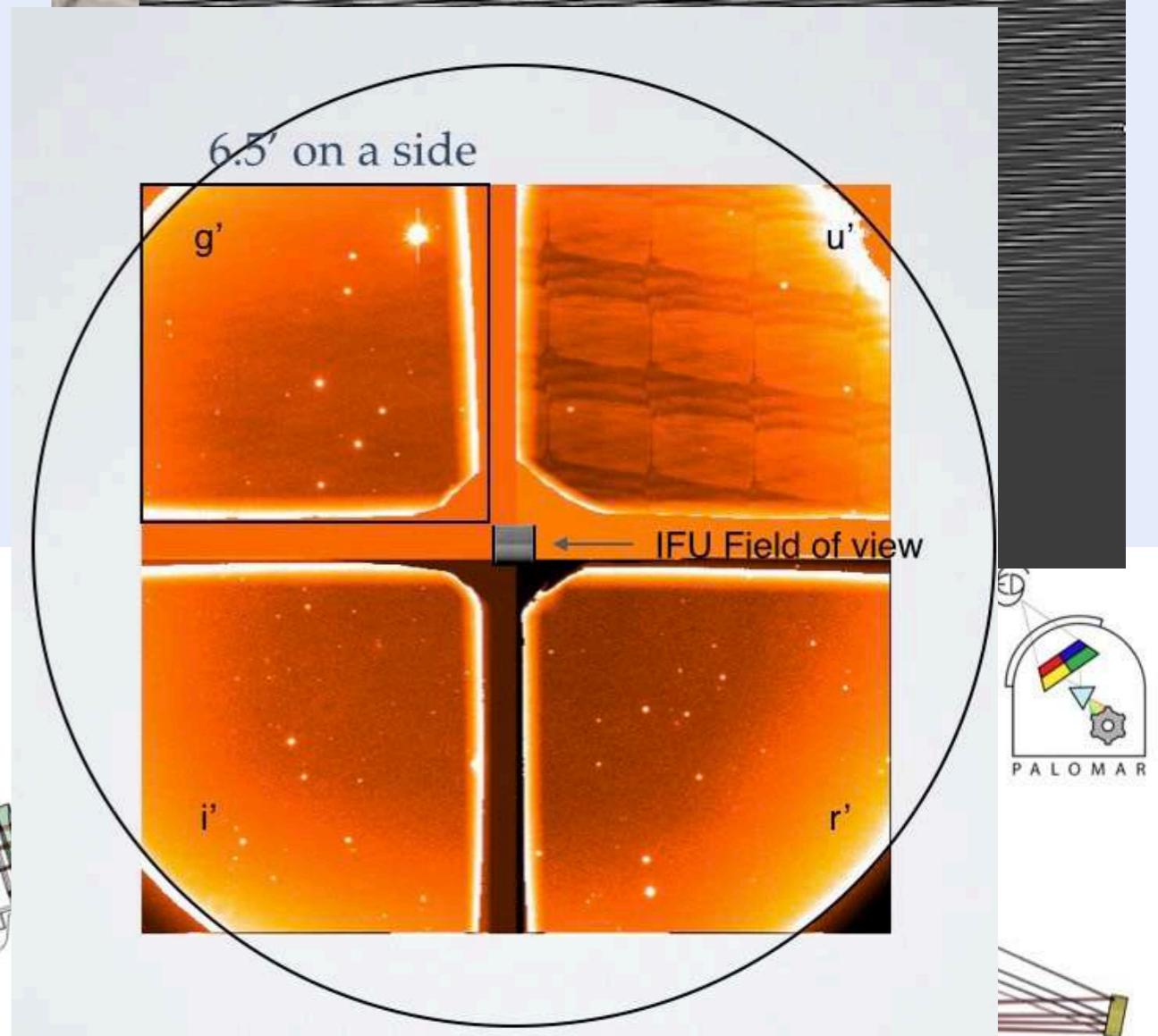
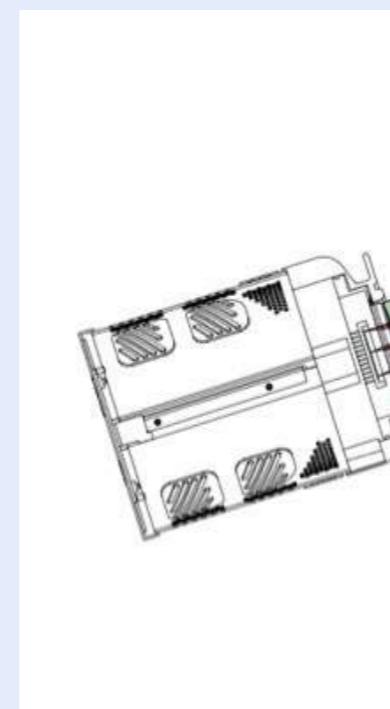
- Mean error area in O3 = 2258 sqdeg
- Median error area in O3 = 765 sqdeg
- How will this improve in O4 and O5?

# What do we need?

- Cover a typical area of 765 sqdeg
- Down to 20.5 mag (better +1 mag)
- Within the first night
- Spectroscopic follow-up!

# Instruments for discovery

- Wide field
- Multi-band
- Large area IFS SED machine

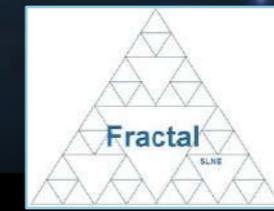


# Instruments for Characterisation

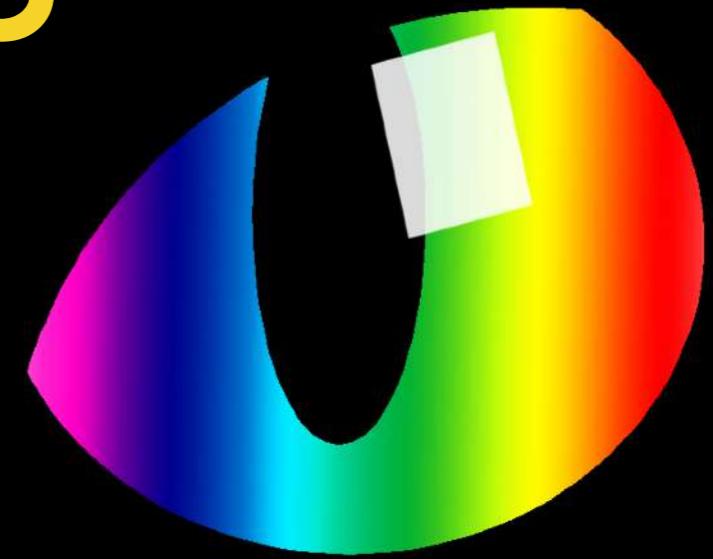
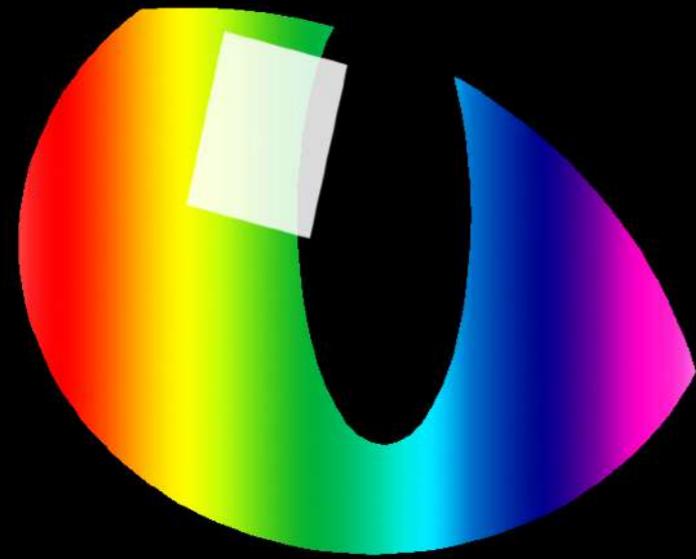
- Multiband Imaging
- Broad wavelength range spectroscopy
- Polarimetry
- Time resolution



cheth



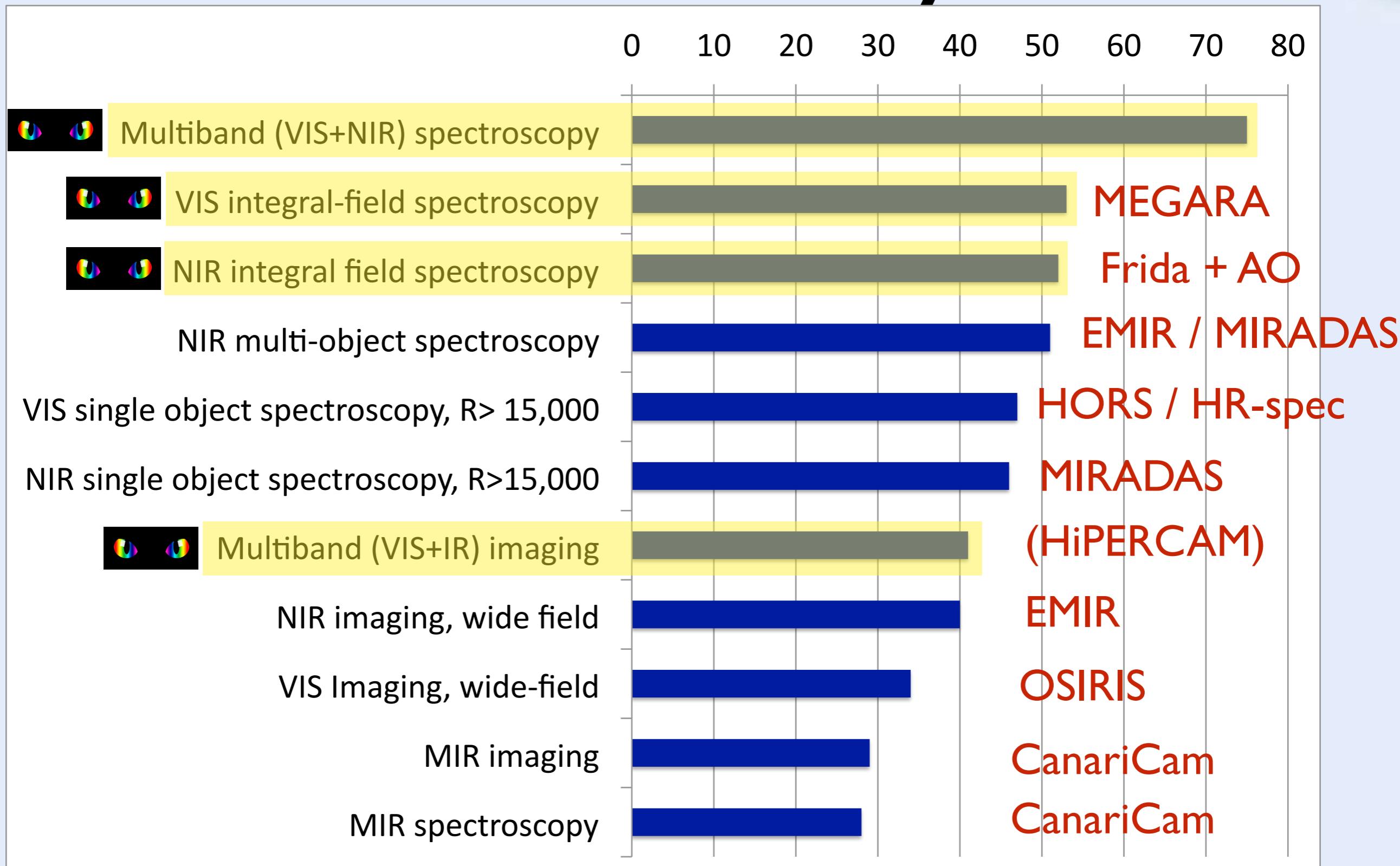
# GATOS



T. Muñoz-Darias<sup>3</sup>, A. Labiano<sup>4</sup>, A. Gil de Paz<sup>5</sup>, M. L. García Vargas<sup>6</sup>, M. Blazek<sup>1</sup>, V. Dhillon<sup>7,3</sup>, L. Izzo<sup>1</sup>, D. A. Kann<sup>1</sup>, A. Perez<sup>6</sup>, J. Piquerias López<sup>4</sup>, A. Alonso Herrero<sup>4</sup>, D. Barrado<sup>4</sup>, J. Casares<sup>3</sup>, M. Fernández<sup>1</sup>, J. García Rojas<sup>3</sup>, A. Gardini<sup>1</sup>, R. Garrido<sup>1</sup>, R. González Delgado<sup>1</sup>, N. Huélamo<sup>4</sup>, J.L. Ortiz<sup>1</sup>, C. Ramos Almeida<sup>4</sup>, S. Simón-Díaz<sup>3</sup>

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# GUC survey

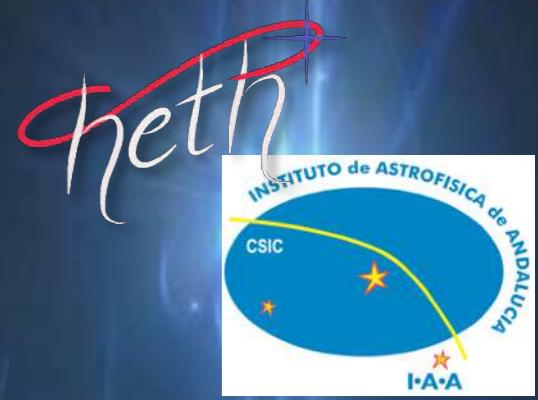


# Science drivers for a workhorse instrument



- Transients
- X-ray binaries/transients
- TDEs
- AGNs
- Lensing
- High-redshift galaxies / intergalactic medium
- Supernovae
- SN remnants
- GRBs
- High-redshift Universe
- Trans-Neptunian objects
- Transiting extrasolar planets
- Asteroseismology
- Low-metallicity stars
- Massive stars / stellar winds
- Low-mass binaries
- Brown dwarfs
- Interacting binaries
- Magnetars
- Isolated Neutron stars
- Gravitational wave follow-up

**Breakthrough science  
in many fields**



# Efficiency!

Throughput

Quantum efficiency

Operation

Calibration

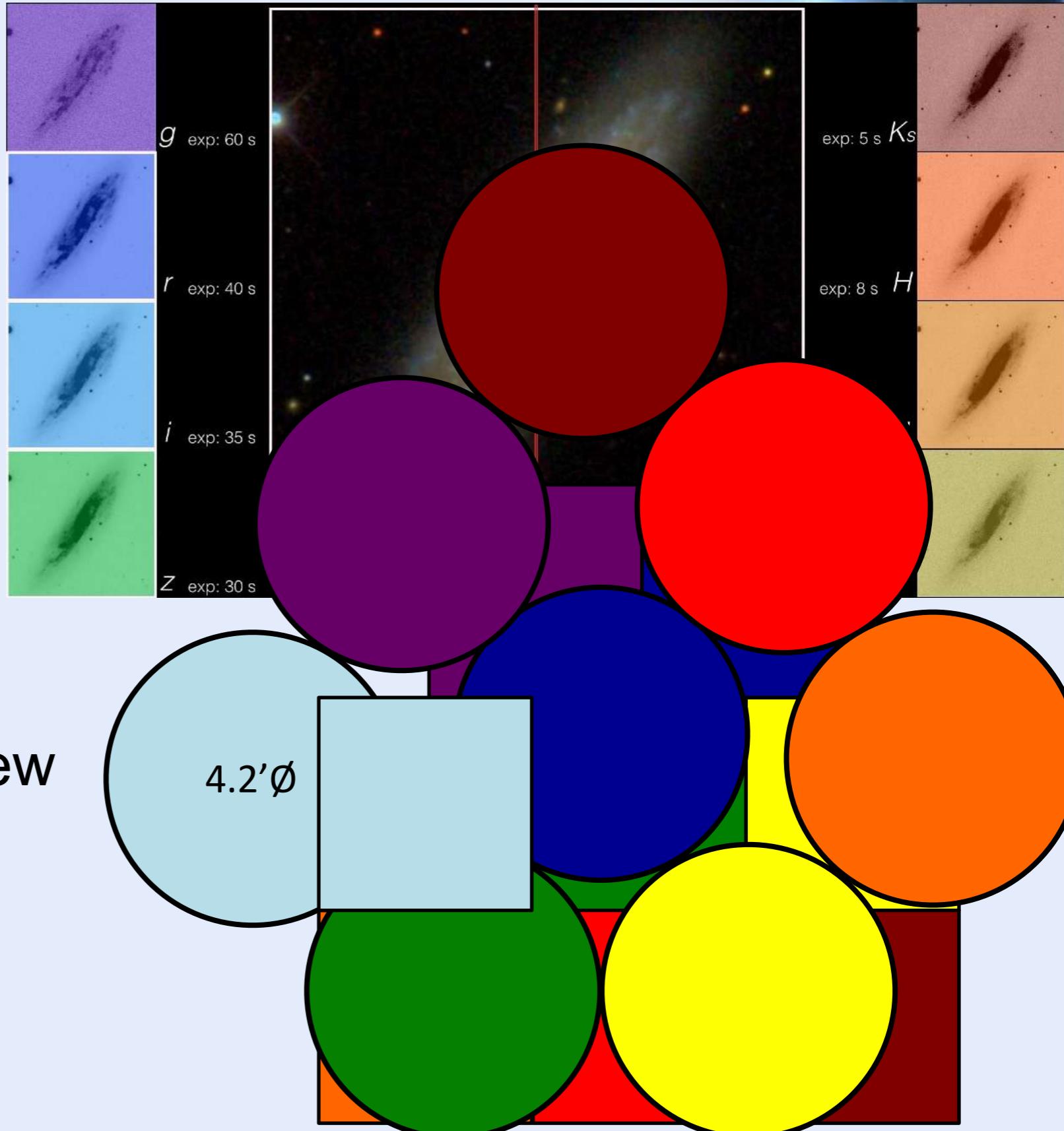
Maintenance

# Simultaneity!



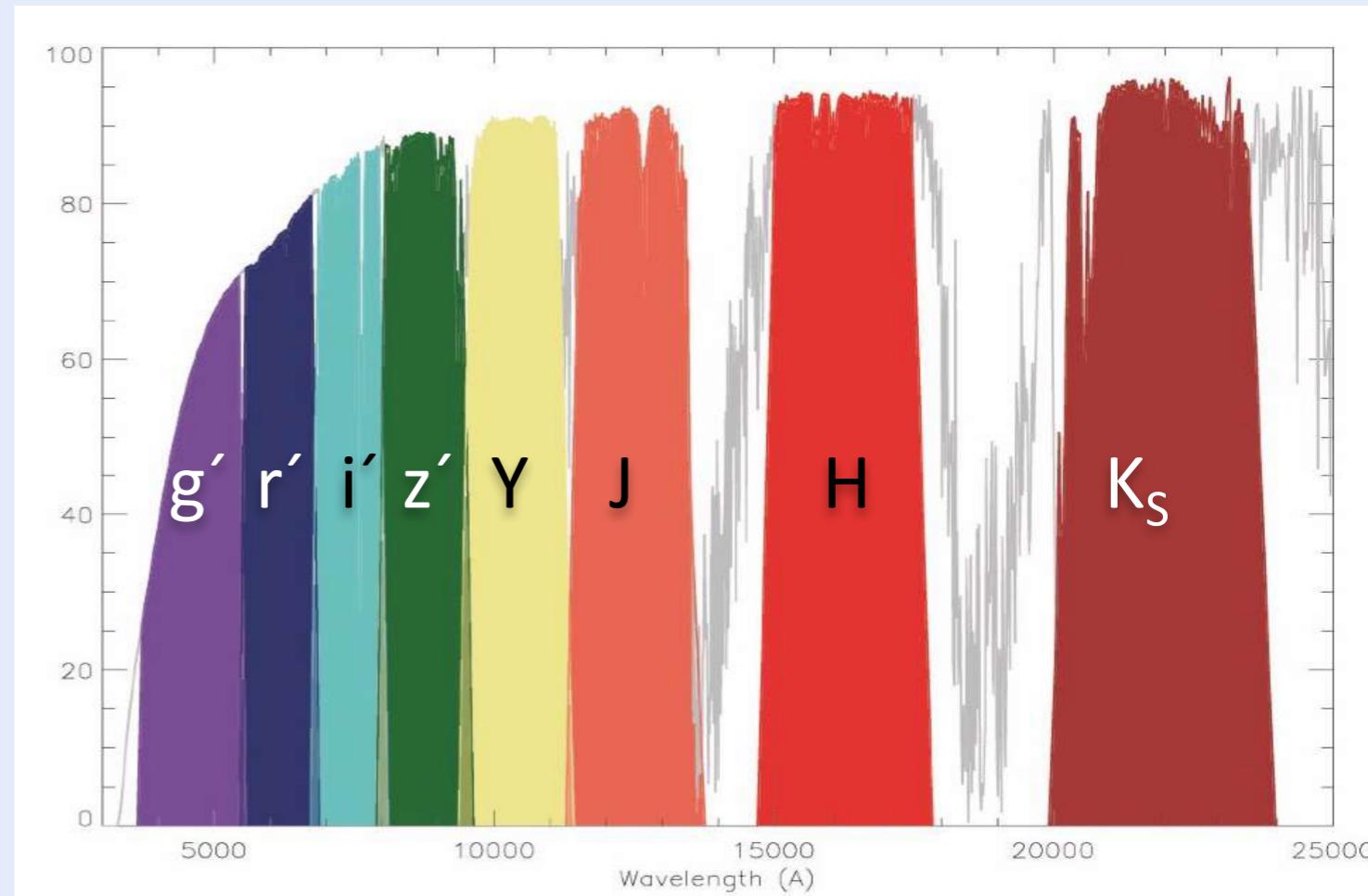
# Imaging

- Simultaneous VIS/NIR  
 $g'$ ,  $r'$ ,  $i'$ ,  $z'$ ,  $Y$ ,  $J$ ,  $H$ ,  $K_S$
- Negligible overheads
  - No filter change time loss
  - No readout time loss
- 3'x3' or 4.2' $\varnothing$  field of view
  - 3'x3'x8 = 72 sqr. Arcmin
  - 4.2' $\varnothing$ x8 = 112 sqr. Arcmin



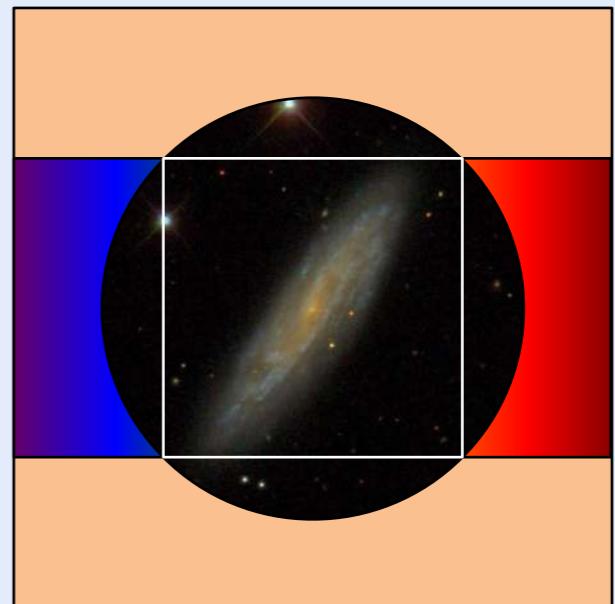
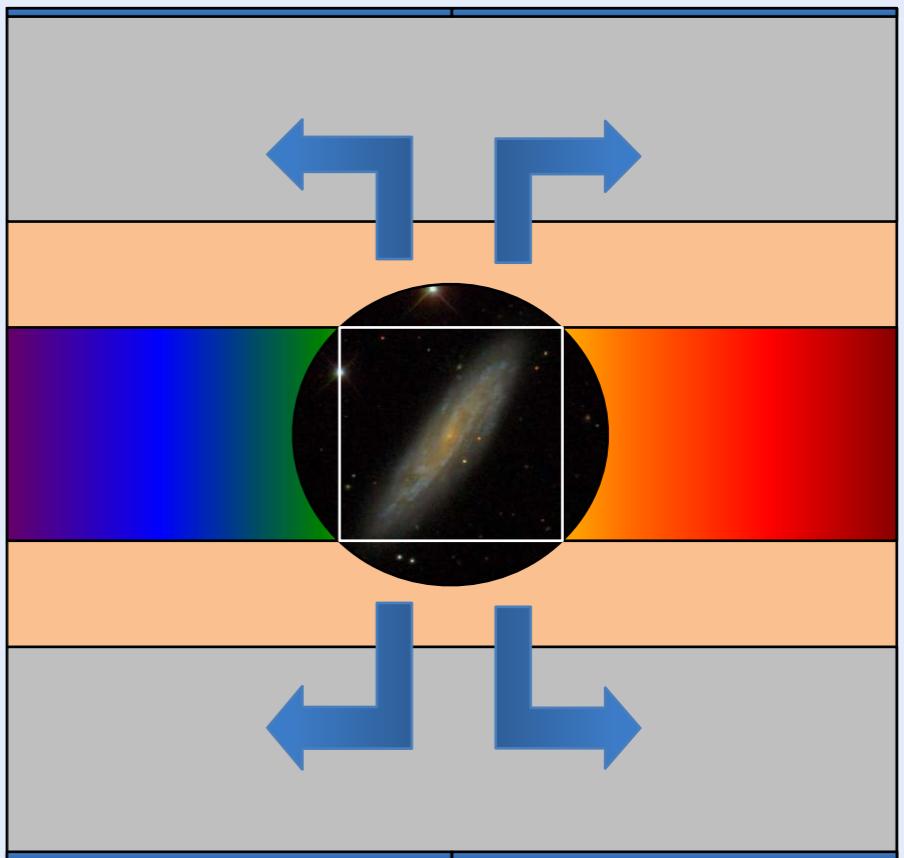
# Spectroscopy

- Wavelength range: 3700 Å to 23,500 Å  
 $[\text{OII}]$  3727/29 Å at  $z = 0$  (blue end),  $\text{H}\alpha$  at  $z = 2.5$  (red end)
- Resolving power  $\sim 4000$ :
  - Look between NIR sky lines
  - Continuum of faint sources
  - Velocity fields of galaxies
- Long slit (180'')



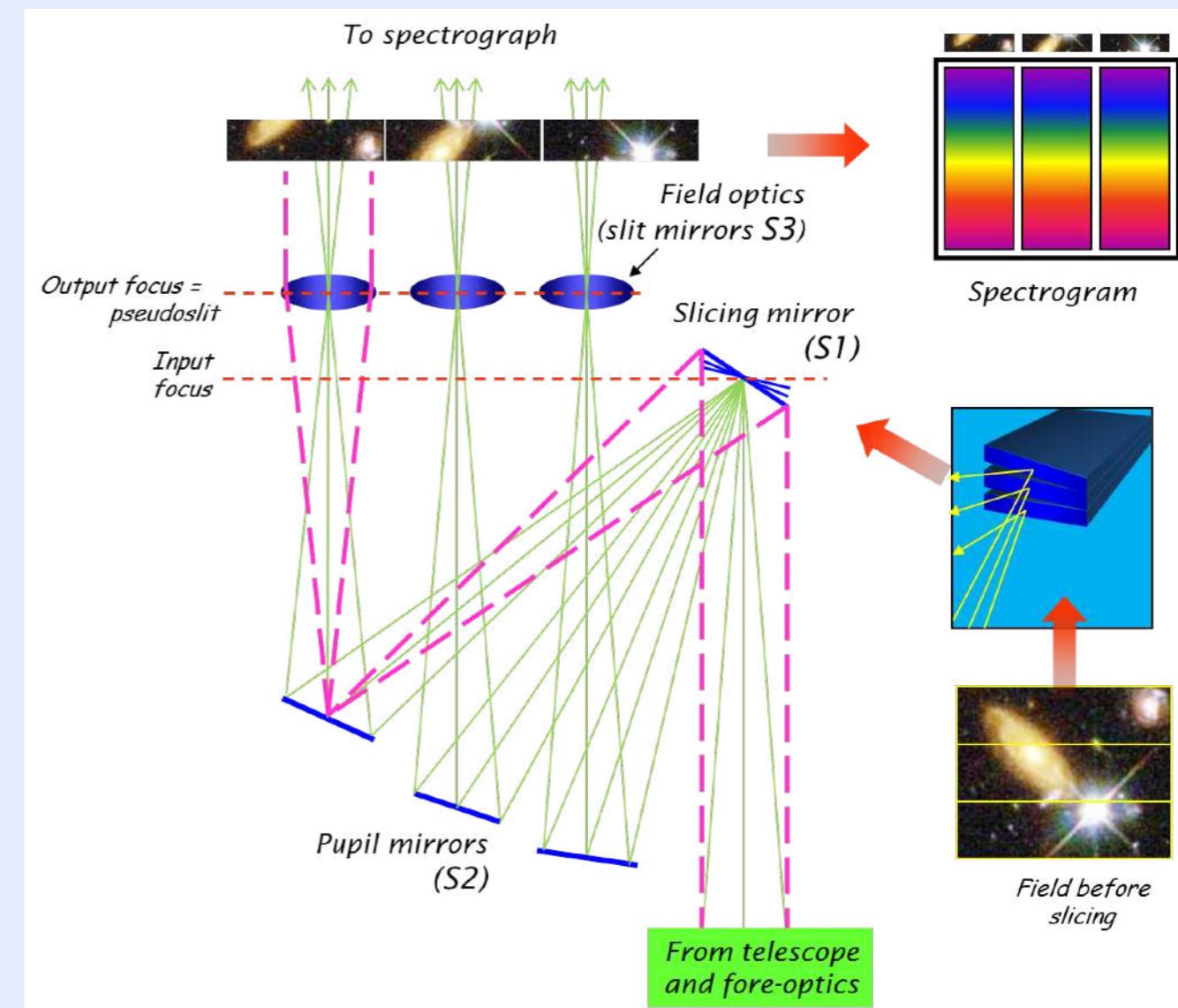
# High time resolution

- Frame transfer in the VIS  
e2v CCD 231-84
  - HAWAII-2RG+SIDECA  
R in the NIR
- \* Full frame > 4Hz
- \* Window > 20 Hz
- \* Drift scan > 100 Hz

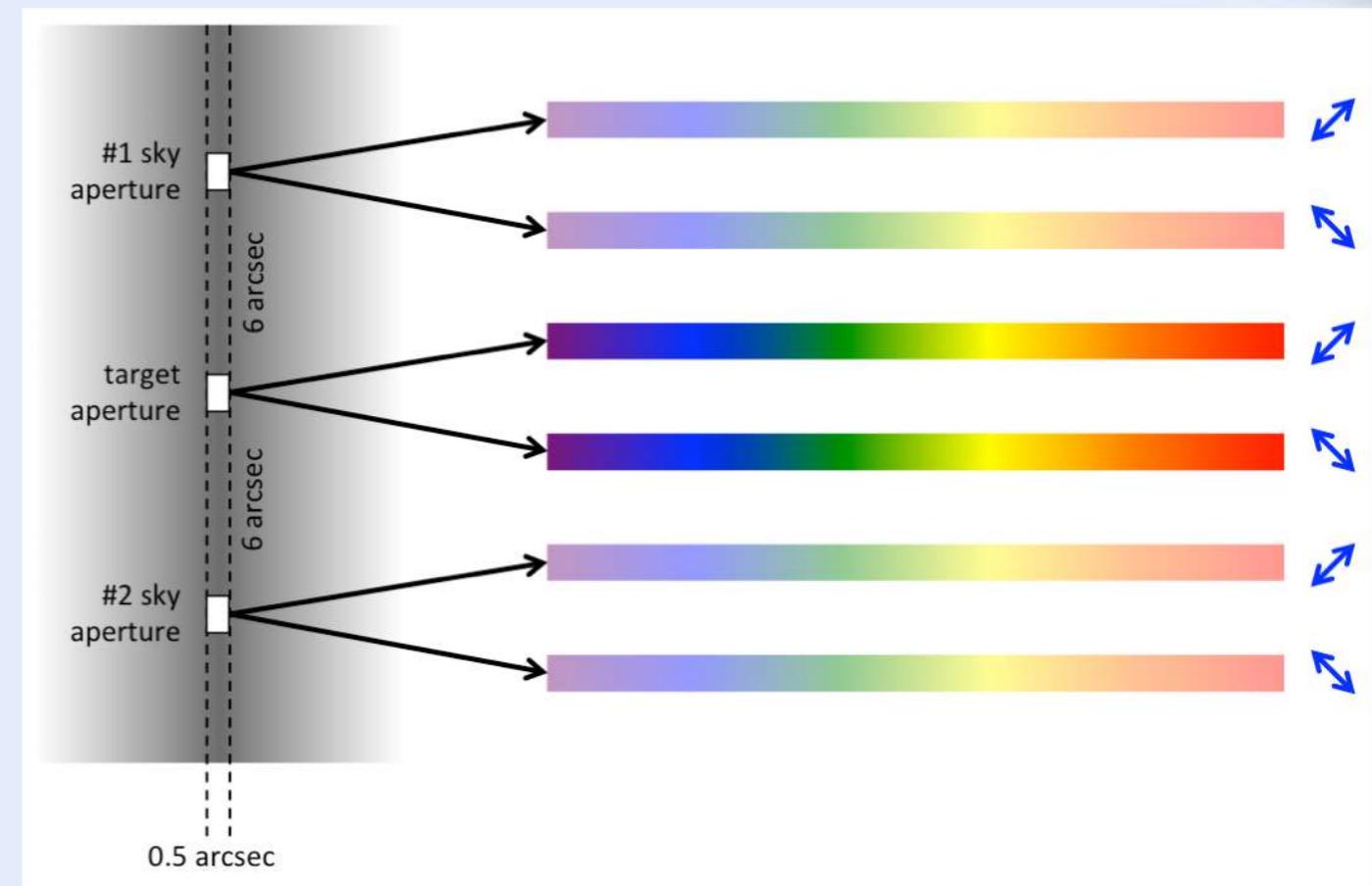
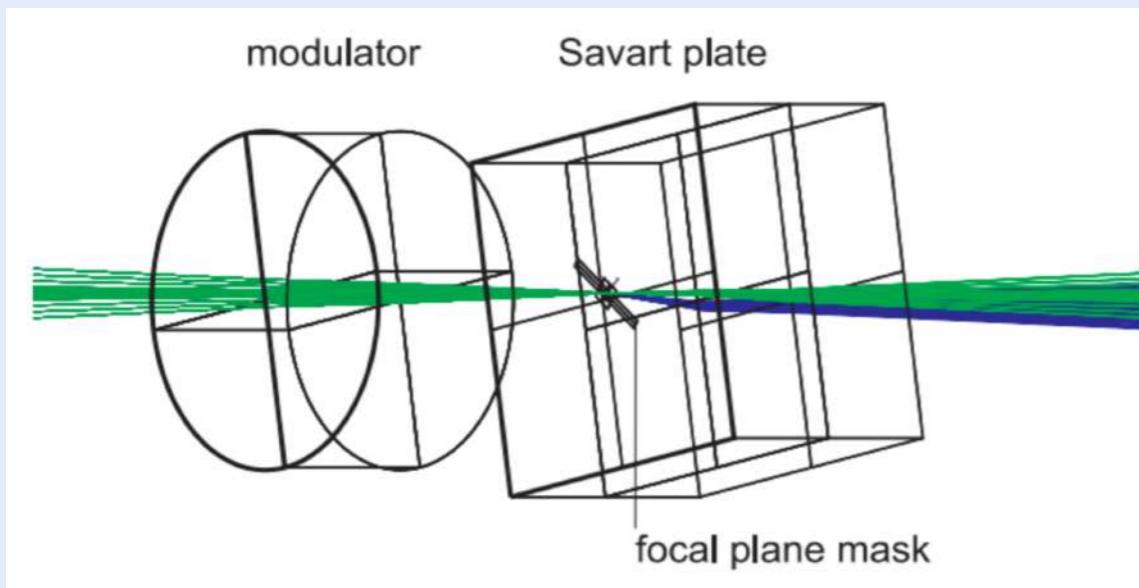


# Integral field spectroscopy

- Image slicer 9.7''x6.8''
- 17 0.4'' resolution elements
- Wavelength coverage UV+IR!
- Full spectral resolution at any seeing
- An additional AO-IFU has been also designed: 3.6''x2.5'' with 0.08'' slitlets



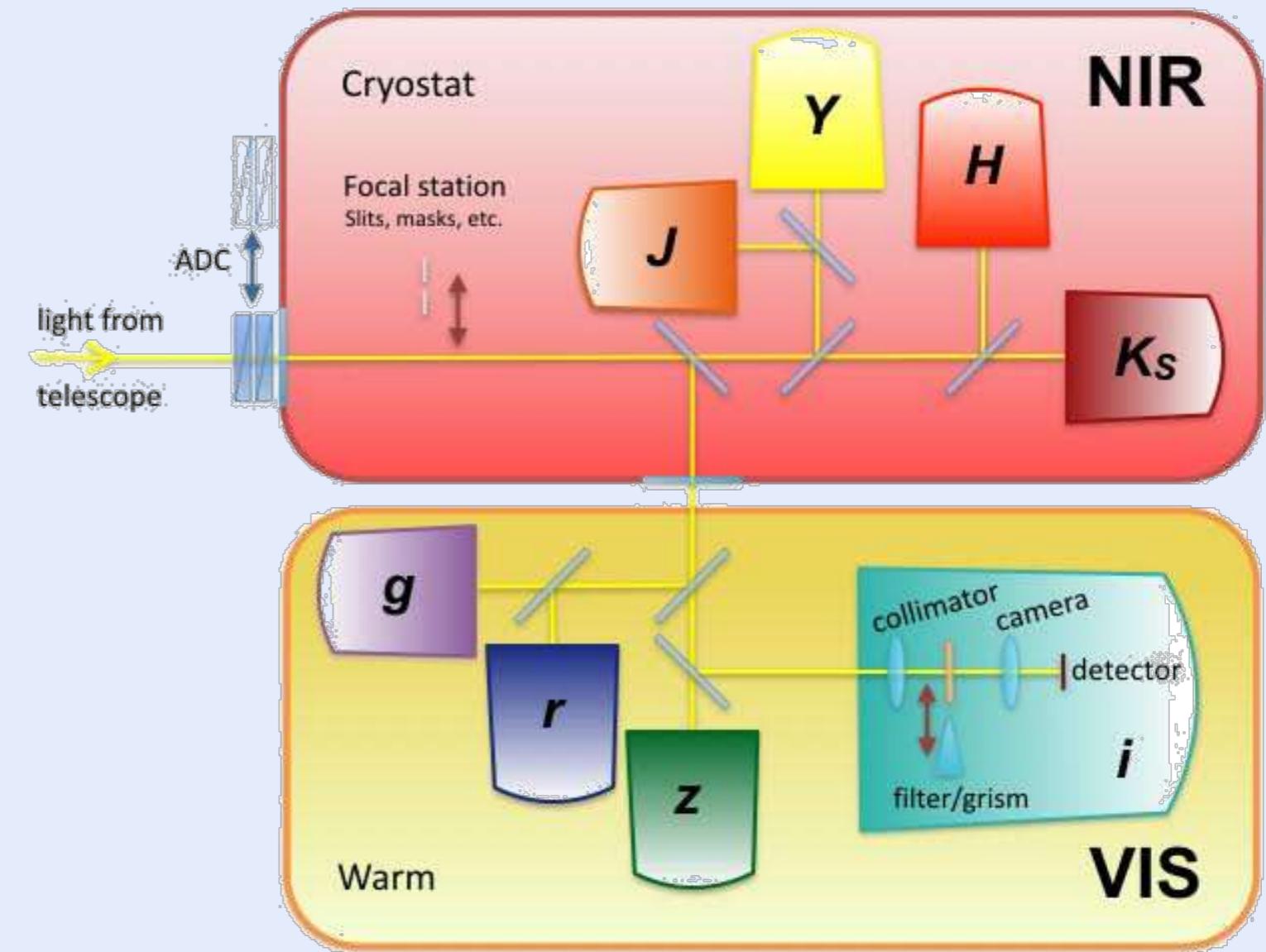
# Spectropolarimeter



- Based on the design by Frans Snik (2012) for X-shooter
  1. Spectropolarimetry of full range
  2. Low resolution single shot spectropolarimetry
    - Structure and magnetism in SNe
    - Stellar physics
    - Characterisation of transients

# Optical design concept

- 8 independent channels
- Common focal plane in cryostat  
(avoid thermal noise)
- Common backbone  
(reduce flexures)
- Retractable ADC
- Different slits  
(0.55'', 0.7'', 0.9'', 1.1'', 5'')
- Allows to include IFU + polarimetry

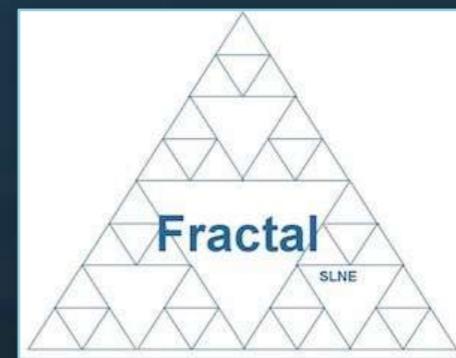




# Consortium



?



# Specifications

<b>Simultaneous spectral range</b>	Photometry: $g'r'i'z'YJHK$ Spectroscopy: 3700-23500 Å
<b>Field of view</b>	3'x3' rectangular, 254" diameter circular 3' long slit 9.7"x6.8" (0.4" slitlets) IFU / 3.6"x2.5" (0.08" slitlets) AO-IFU
<b>Plate scale</b>	0.2"/pixel
<b>Spectral resolution</b>	> 3500 in $g'$ 4100 - 4500 in other bands
<b>Expected efficiency (peak efficiency)</b>	Imaging: > 42 % Spectroscopy: > 35 %
<b>Maximum frame rate</b>	> 4 Hz full frame > 20 Hz for 30x30pix window > 100 Hz drift scan
<b>Observing modes</b>	Multi-band imaging Broad-band spectroscopy (long slit) High time-resolution (img. & spectr.) IFU Spectropolarimetry



# Thank you!