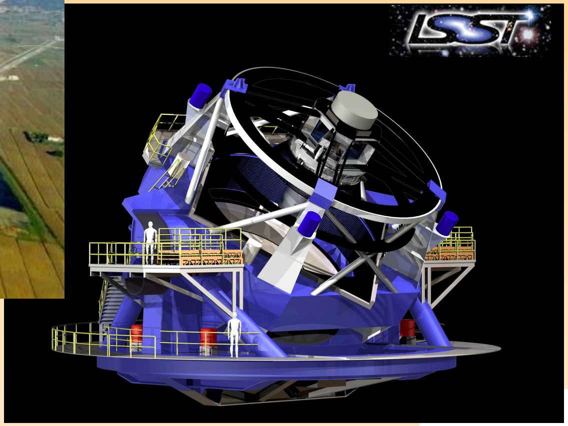
Experiments on Gravitation

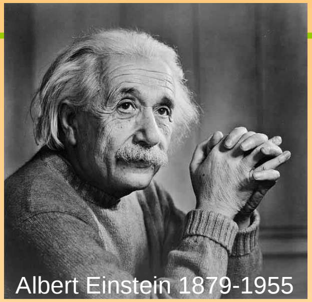
Loïc Rolland, Jean-Stéphane Ricol, Guillaume Pignol



Granit
Gravitational Neutron Induced Transitions

- → **Virgo: the gravitational waves**
- → **LSST: the deep optical sky in time domain**
- → **Granit: the neutron fall**

Gravitational waves (GW)


Albert Einstein 1879-1955

What is a gravitational wave ?

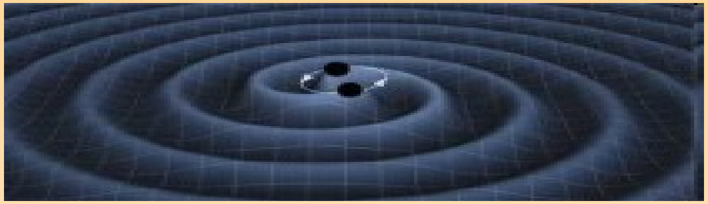
Moving mass

↓

Deformation/perturbation of space-time

↓

Propagation in space-time



Effect is measurable on free masses

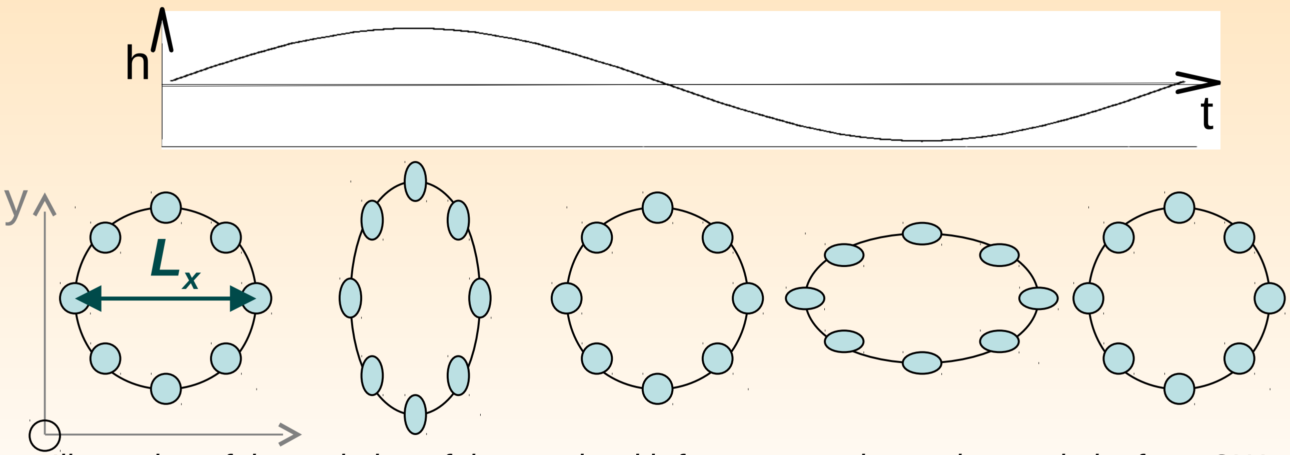
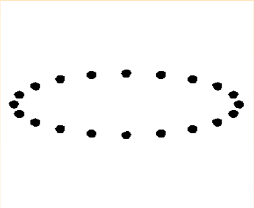


Illustration of the variation of the metric with free masses located on a circle, for a GW with + polarization propagating along z



$\Delta L_x(t) \sim h(t)\, L_x$

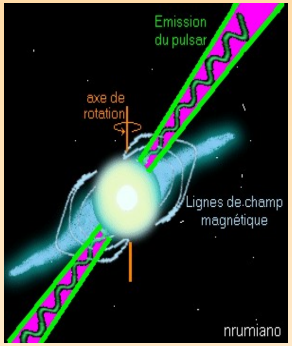
h(t) : GW amplitude

Gravitational wave sources

Supernova

- star collapse
- expected rate: ~2/century in the Milky Way
- GW emitted during **few milliseconds**

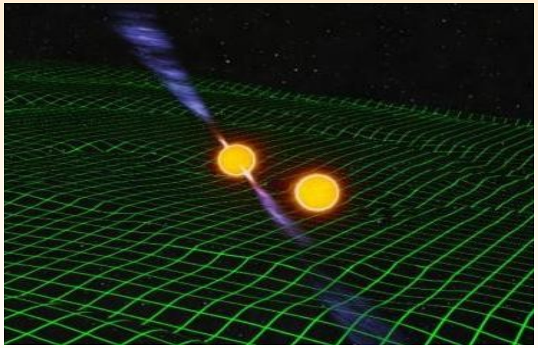

Crab Nebula
(observations of Hubble, Spitzer, Chandra)



Neutron stars

- radius ~10 km
- rotation period: ~ 1 ms to 1 s
- Milky Way: 10^9 expected (1000 known pulsars)
- periodic GW emitted **continuously**

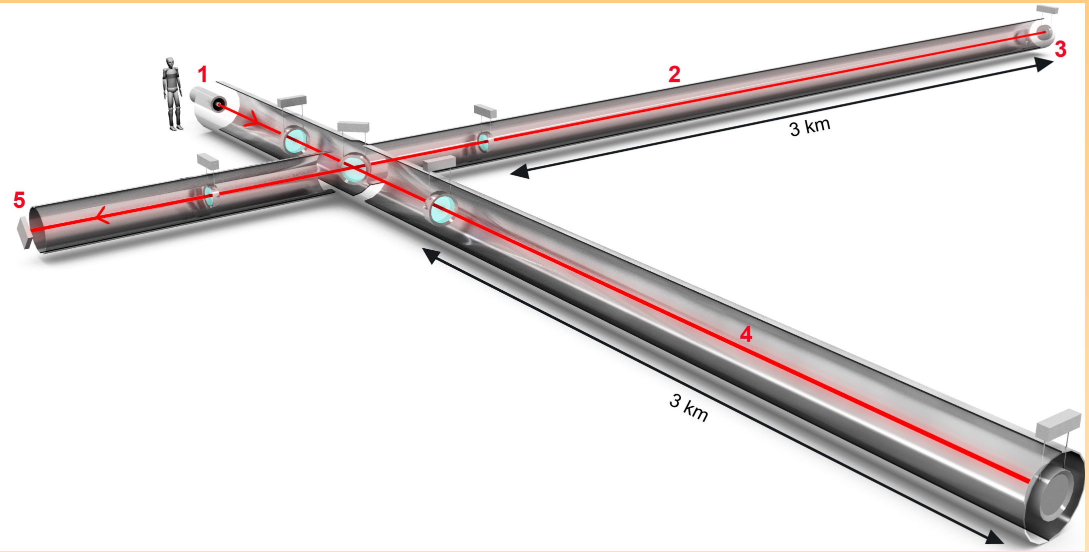

(Chandra)

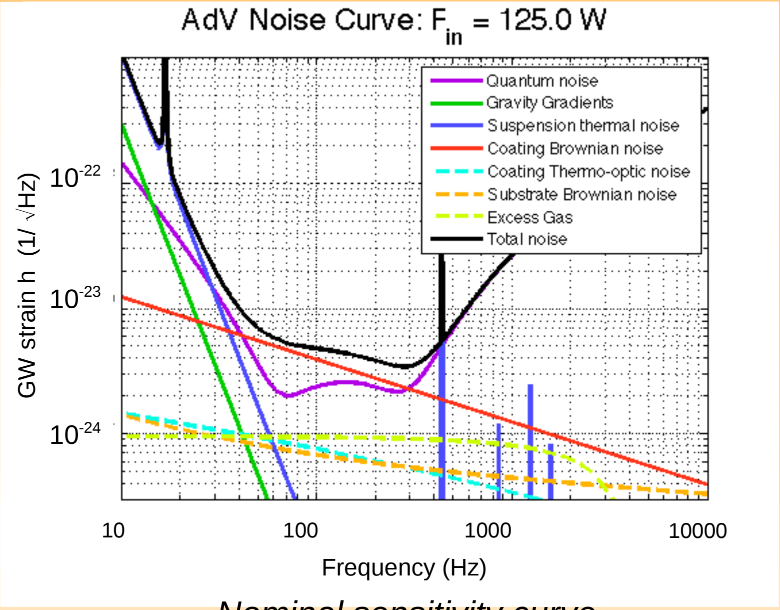


Compact binary objects

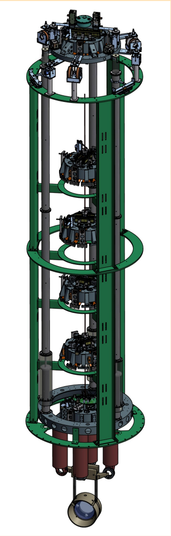
- systems with two neutrons stars and/or black holes
- end of life: coalescence of the two objects (CBC)
- expected rates: 0.4 to 200/year in a radius of 200 Mpc
- GW received during **few seconds**

Interferometric GW detection

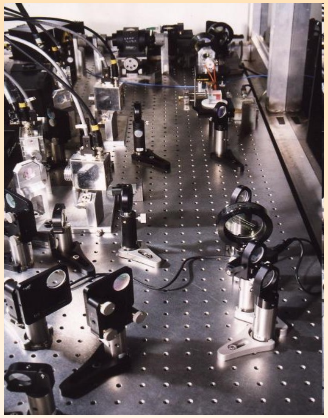




Nominal sensitivity curve of Advanced Virgo



Suspended mirror



Beam power measurement

GW in the range **10 Hz – 10 kHz**
Amplitudes **h ~ 10^{-23}**

Orders of magnitudes:
– variation of the Earth-Sun distance by an atom
– variation of a 3-km long arm by 1/1000 of a proton

A world-wide network of interferometers

Evolution of ground-based GW detectors

2004
2008
2012
2016
2020

1st generation

Initial LIGO, Virgo, GEO600

Enhanced LIGO, Virgo+

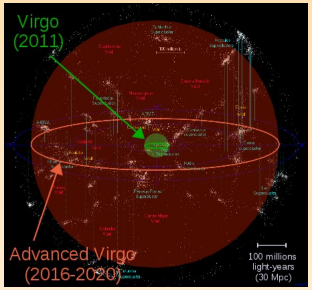
Unlikely detection

Science data taking
Setup network observation

Plausible detection

Lay ground for multi-messenger astronomy

2nd generation



Advanced LIGO, Advanced Virgo, GEO-HF
+ KAGRA, LIGO-India

Likely detection

Routine observation
→ GW astronomy

3rd generation

Einstein telescope, ...

Thorough observation of Universe with GW

Main Advanced Virgo goals

Participate to the **1st detections of GW !**

General Relativity studies

Check the GW properties
Study GR in strong fields

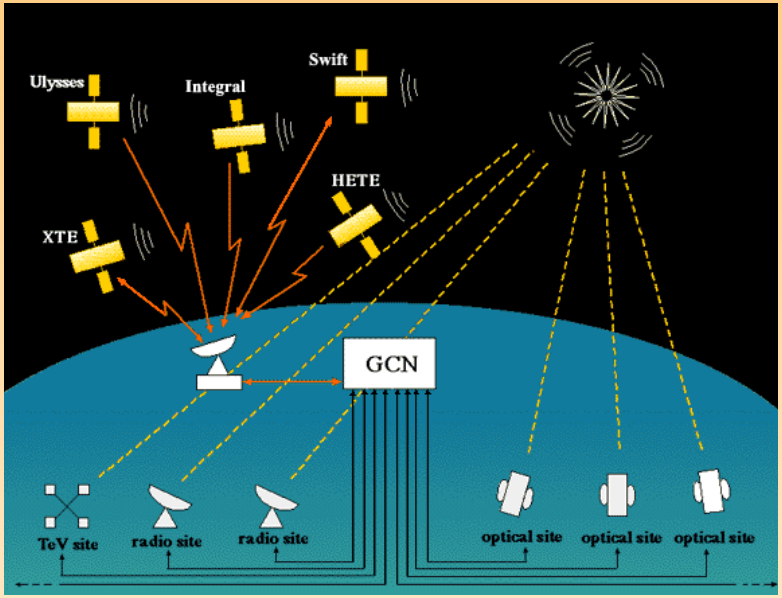
Understand the GW source astrophysics

Link the short gamma-ray bursts (GRBs) to compact binary coalescences ?
Observe the formation of black holes during supernovae
Get information on neutron star internal structure
→ study the sources within a (real-time) multi-messenger framework

Cosmology

Constrain the Hubble parameter with GRBs
Search for the cosmic background of GW

AdV goals: multi-messenger astronomy



Astrophysical events (GCN, SNEWS)

→ Alerts received in LIGO-Virgo control rooms
Specific analysis (online and offline)

GW online candidates (LIGO-Virgo)

→ Alerts sent to observatories

July 2009 – October 2010: 14 GW alerts → 8 observations

Radio and optical telescopes:
ROTSE, TAROT, SkyMapper, QUEST, Pi of the Sky, Zadko, Liverpool Telescope, LOFAR

X-ray Satellite
Swift/XRT

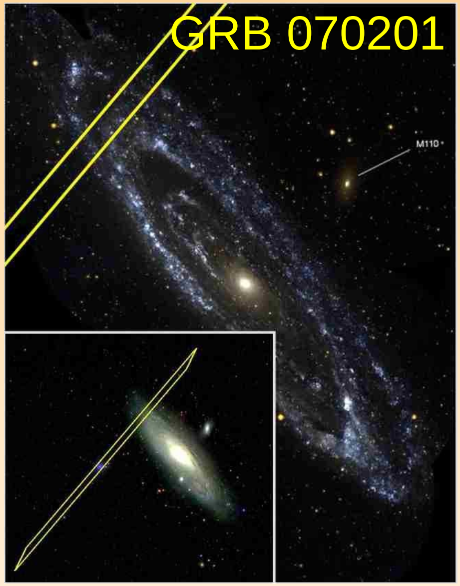
LSST

Lay ground for multi-messenger astronomy

- Increase the significance of the GW events
- Better understand the **astrophysical** events

AdV goals: linking short GRBs and compact binary object coalescences ?

External trigger: look for GW at the time and in the direction of GRBs
→reduce background level
→improve analysis sensitivity



D > 3.5 Mpc
→ this GRB was not in the Andromeda Galaxy !

B. Abbot et al, Astrophys.J.681 (2008) 1419

Expected rates for nominal Advanced LIGO-Virgo

2 neutron stars:	0.4 →	400 /year	(up to ~200 Mpc)
2 black holes:	0.4 →	1000 /year	(up to ~1 Gpc)

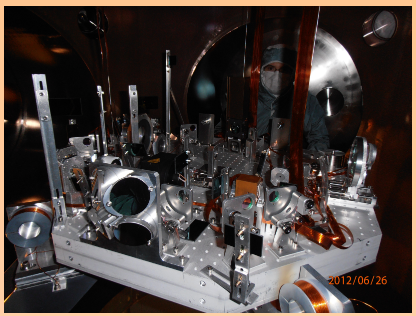
J. Abadie et al. Class. Quantum Grav. 27 (2010) 173001

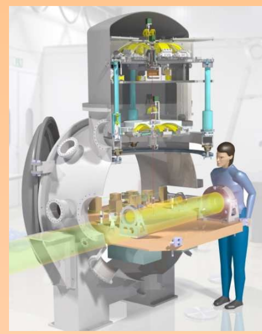
Main LAPP activities in Advanced Virgo

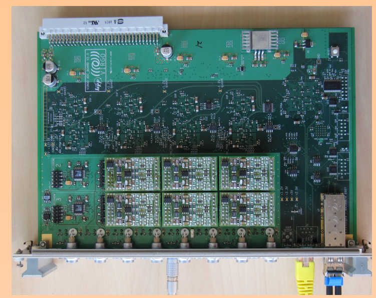
Instrumentation

Sensing of the power of laser beams of the interferometer
(optical components and mounts, photodiodes, front-end electronics, vacuum tanks, suspended benches, in-vacuum compatibility, ...)

General digital electronics and data acquisition system
(timing synchronization, ADC and DAC channels, cameras, online data collection/distribution, data visualization tools, ...)





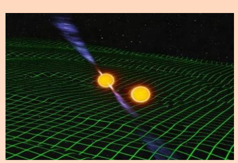


Data analysis

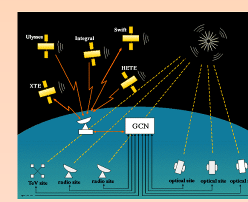
Interferometer calibration and GW signal reconstruction

Data quality

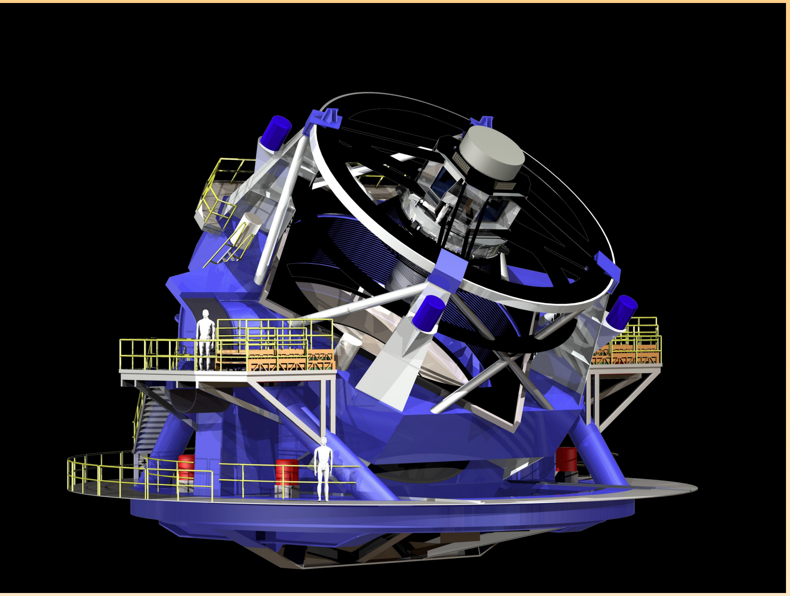
Searches of binary compact object coalescences



LIGO-Virgo online data analysis to provide alerts for other observatories



LSST detector in brief



Large Synoptic Survey Telescope

Location: Northern Chile (Cerro Pachon)
Optical telescope: 6 bands (ugrizy) in 320 nm to 1050 nm
Large field of view: 3.5°
Large collection area: 8.4 m
→ detect faint objects up to magnitude 24 in 15 s

First light: 2020, for 10 years

The main “deep-wide-fast” survey

1 pair images of each sky field every 3 nights
→ 1000 images of each sky field in 10 years

→ deep observation of the time domain optical sky !

Physics with LSST

Cosmology

Dark matter
3D mapping via strong gravitational lensing

Dark energy and accelerated expansion of the Universe
with different independent observables: cosmic shear, BAO, supernovae, ...

Transients

Supernovae, GRBs, AGNs, ..., new variable objects ?
→ **multi-messenger/wavelength observations** with AdVirgo, CTA, ...

Solar System

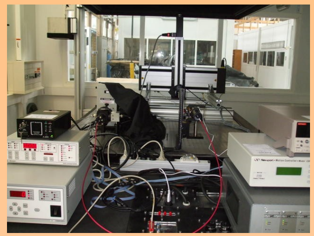
Asteroids, comets, ...

Milky Way

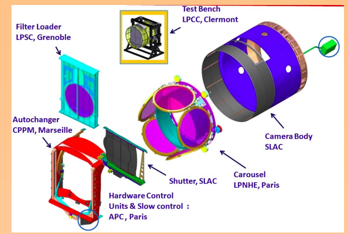
Main LPSC activities in LSST

Instrumentation

Development of a bench for the calibration of the camera



Conception and realization of the camera *filter loader*



Data analysis and simulation

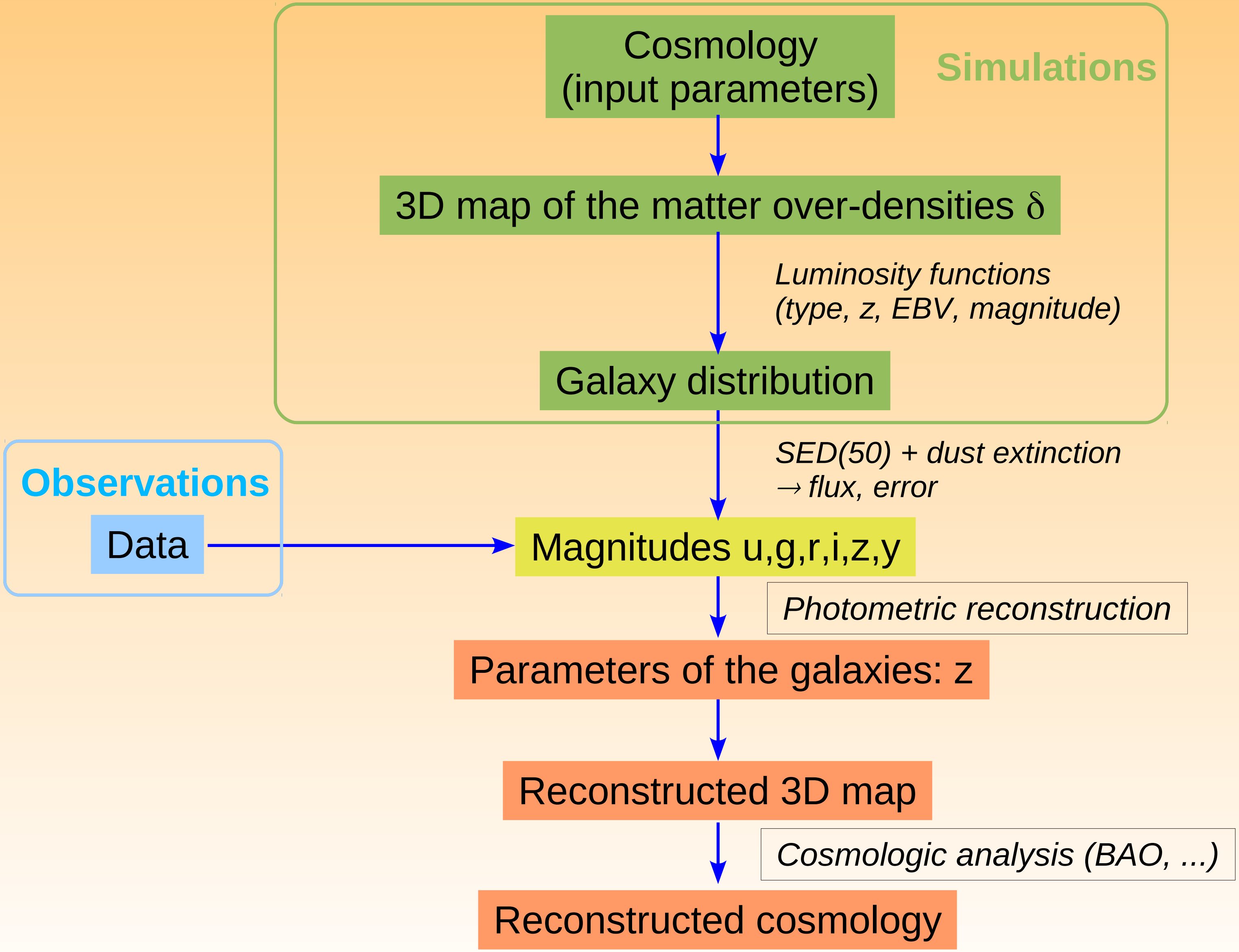
Galaxy redshift estimation
(photometric reconstruction from the six optical bands of the telescope)

Study of the baryonic acoustic oscillations (BAO)
(simulation and reconstruction of the cosmological parameters)

Phenomenology

Loop quantum gravity
→ see next talk by Aurelien Barrau

LSST: global view of the cosmological analysis

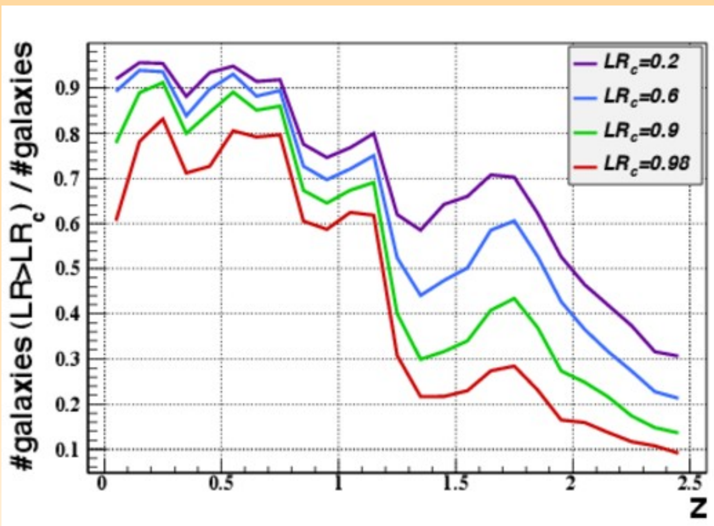


Photometric reconstruction (photoz) in LSST

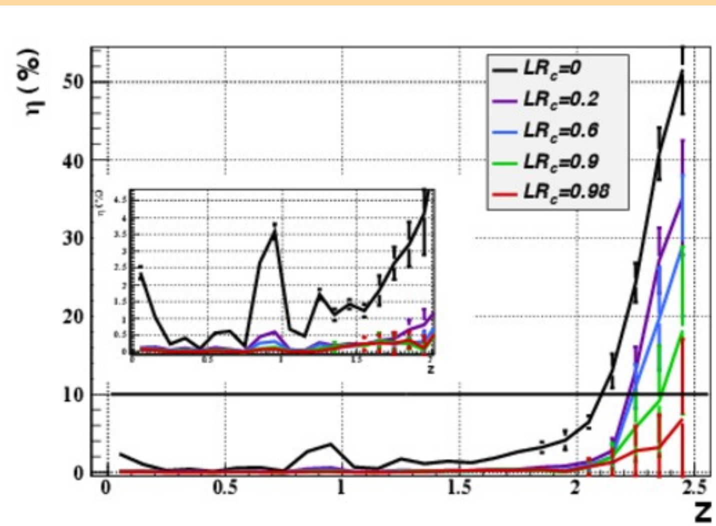
Galaxy images
in 6 bands
(ugrizy)

→ Statistical parameter LR: goodness of the reconstruction

Probability of galaxy parameters:
- galaxy type (spectral energy density)
- **redshift (z)**
- dust extinction (color excess E(B-V))
- magnitude



Efficiency of the selection on LR, vs z



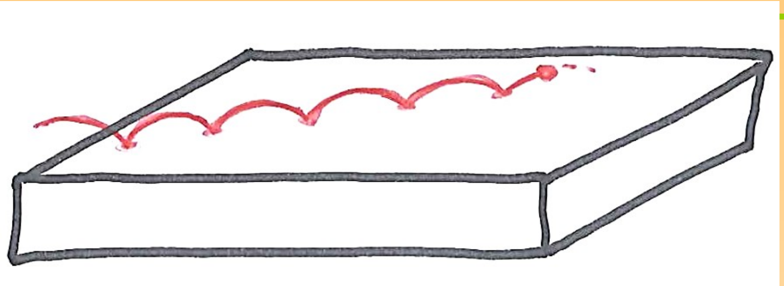
← specif.

Fraction of 'catastrophic' galaxies vs z
(bad reconstructed galaxies among the selected ones)

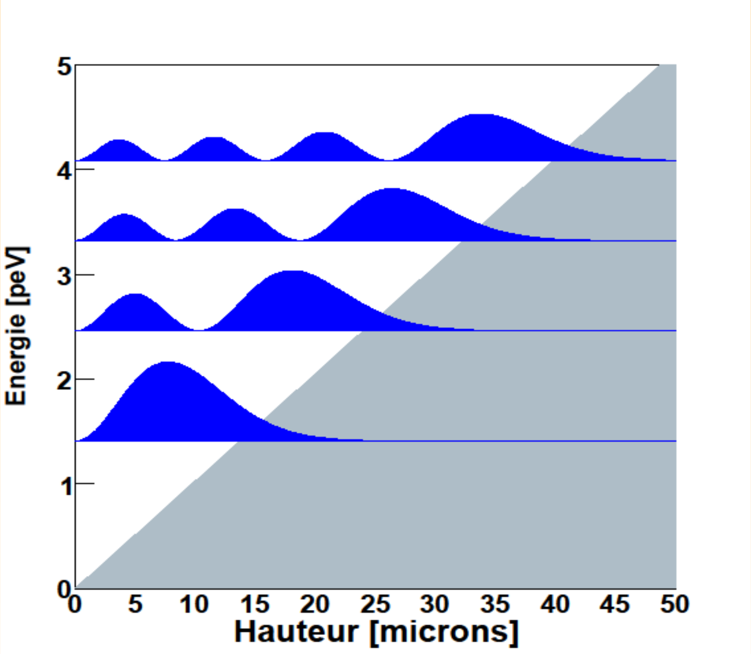
For LR>0.98, the *photoz* reconstruction is within LSST specifications
Correlation with reconstruction using neural network can further reject 'catastrophic' galaxies

Further work: improve simulations, detailed study of the systematics, ...

GRANIT

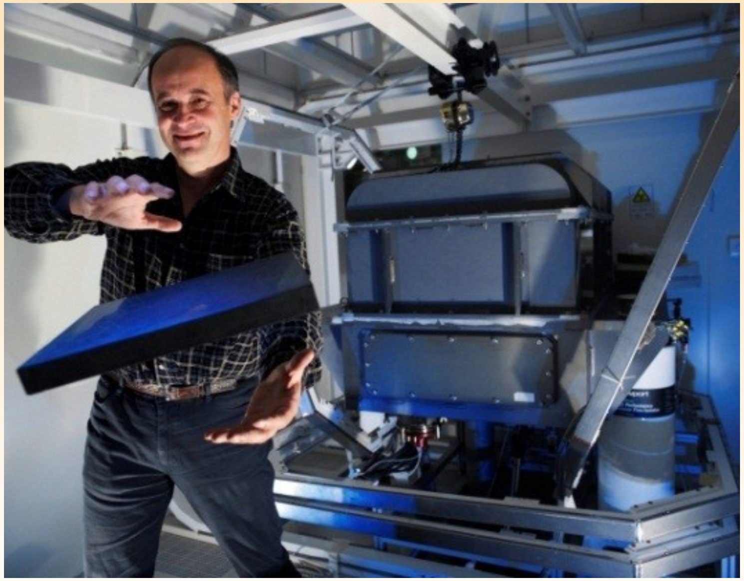


$$-\frac{\hbar^2}{2m}\frac{d^2\psi}{dz^2} + mgz\,\psi = E\,\psi$$



GRAvitational Neutron Induced Transition
→ measure, at the ILL reactor, the discrete energy levels of neutrons bouncing above a mirror

Probing **Dark Energy models** (Chameleons) by searching for a new force close to the mirror.
(see Aurelien Barrau talk)

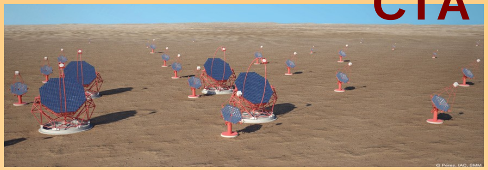


Conclusions

Advanced Virgo

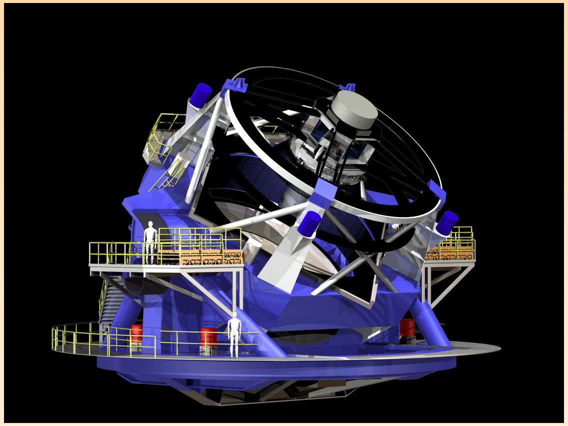
Science data starting in 2015—2016
Going towards nominal sensitivity in few years
→ 1st detections of gravitational waves !

CTA



Multi messenger astronomy

GRBs, supernovae, pulsars, other transients...



LSST

First light in 2020
→ Deep optical sky in the time domain

Independent cosmological measurements

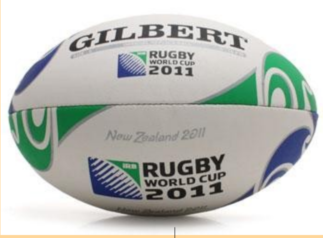
Hubble parameter, dark matter, dark energy, Universe expansion...

Granit

Construction is on-going
→ neutron quantum states in gravity field

Backup

Un résultat choisi : recherche d'étoiles à neutrons



Emission d'ondes gravitationnelles par les étoiles à neutrons
→ non-sphéricité de l'étoile

?

Recherche sur 116 pulsars connus (d<~500 pc)
➢ pas de détection d'OG → ellipticités des étoiles à neutrons < ~ 10^{-7}

→ l'écart à la sphéricité des étoiles à neutrons (r~10 km) est inférieur à ~1 mm !

ApJ 713 (2010) 671-685

Pulsars du Crabe (~30 Hz) et de Vela (~12 Hz)
➢ralentissement de la période de rotation (obs. radio) → perte d'énergie
➢pas de détection d'OG

→ moins de 2% / 35% de cette énergie est émise sous forme d'OG

ApJ 683(2008) L45-L49
ApJ 737 (2011), 93 (16pp)

Advanced Virgo: observing further !

Neutron stars coalescences

1000 galaxies within
Virgo range

~1/century

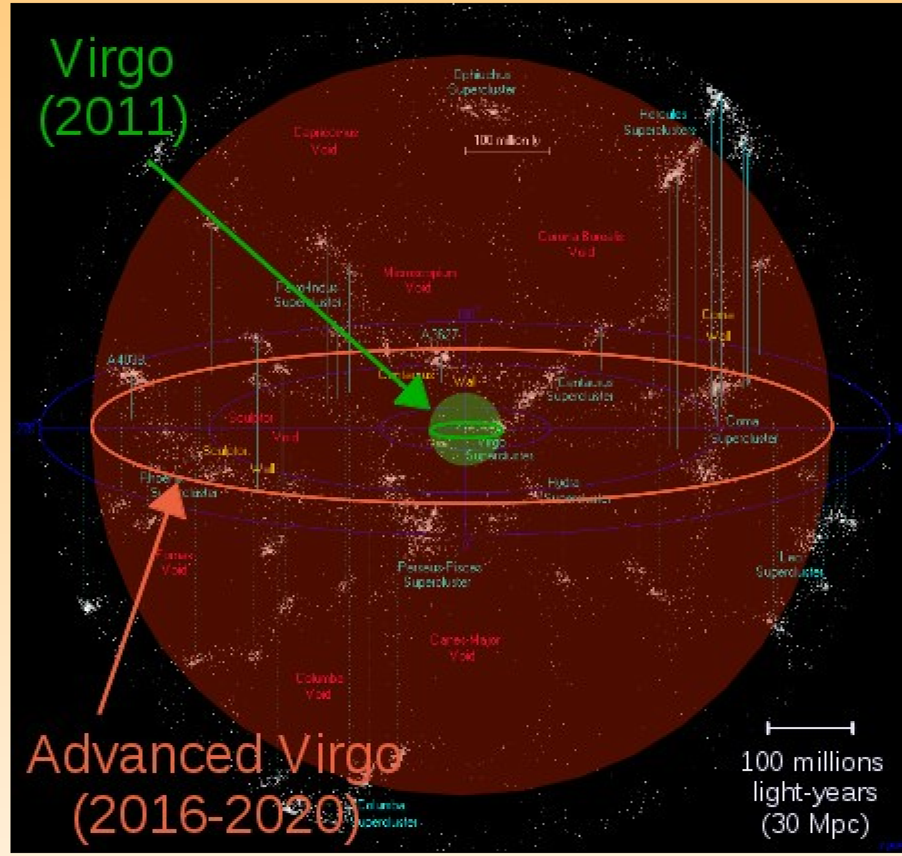
↓

1000000 galaxies within
AdVirgo range

~10/year

Black holes coalescences

→ up to 3 billions of light-years
(1 Gpc)

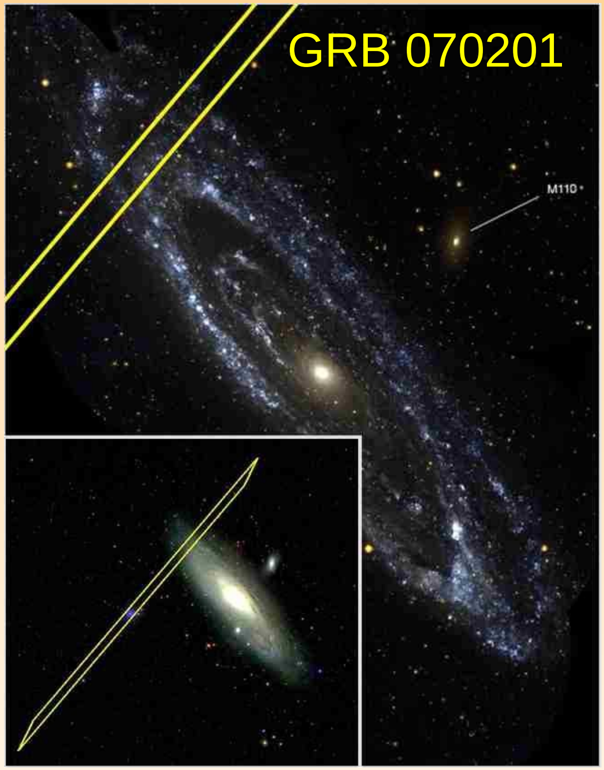


→ Likely detections:
beginning of the gravitational wave astrophysics
in 2015 – 2020 !

See more about the technical challenges in Laurent Derôme talk

AdV goals: linking short GRBs and compact binary object coalescences ?

External trigger: look for GW at the time and in the direction of GRBs
→reduce background level
→improve analysis sensitivity



D > 3.5 Mpc
→ this GRB was not in the Andromeda Galaxy !

GW searches around 22 short GRBs (2005-2007)

→90% CL lower bound on GRB distances:
- neutron star-neutron star: D_{median} ~ 3.3 Mpc
- neutron star-black hole: D_{median} ~ 6.7 Mpc

J. Abadie et al, Astrophys. Journal 715 (2010) 1453

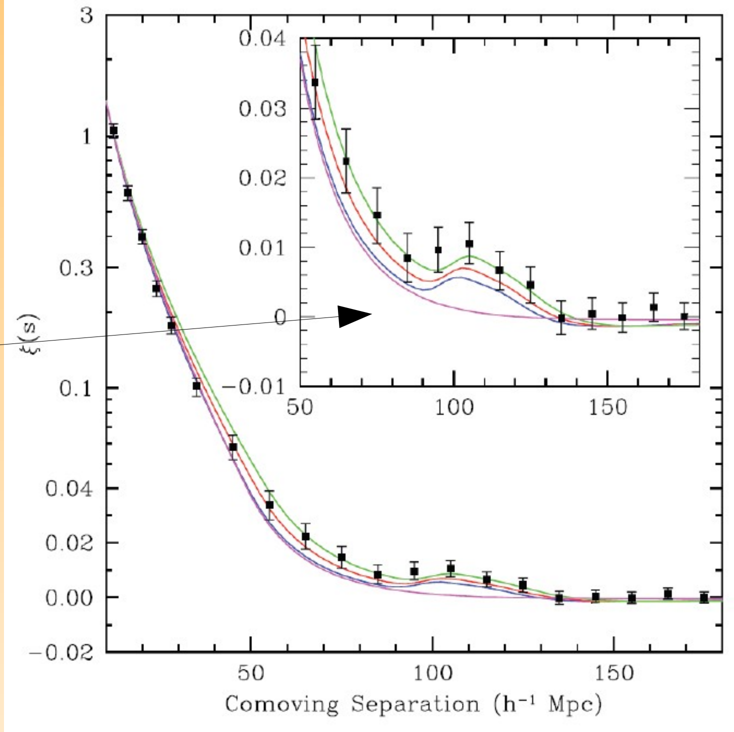
B. Abbot et al, Astrophys.J.681 (2008) 1419

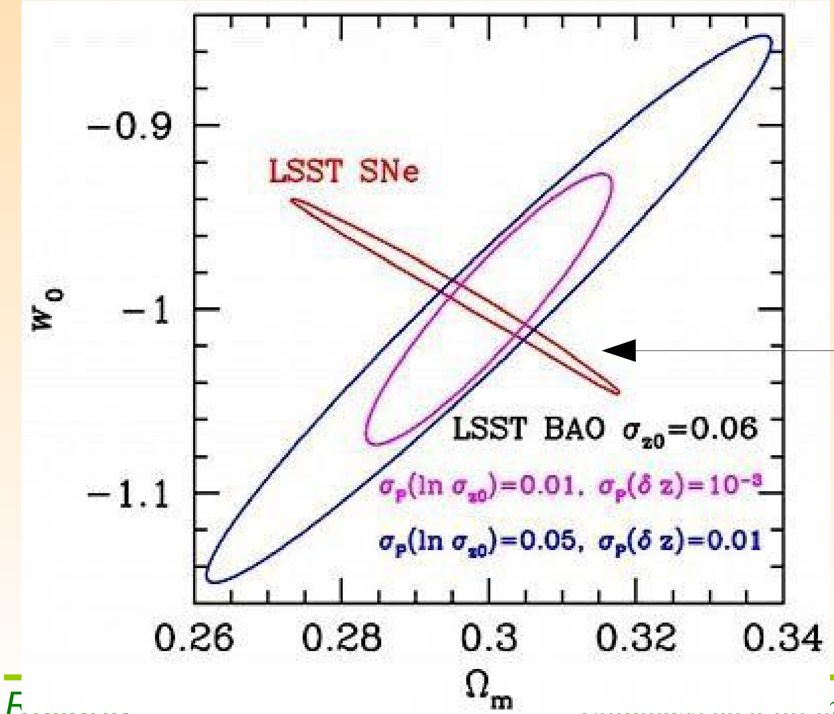
Oscillations acoustique de baryons (BAO)

Univers primordial non homogène, compétition entre la pression de radiation et les forces gravitationnelles : oscillation acoustique de baryons

- Echelle caractéristique dans la distribution des galaxies : étude de la fonction de corrélation entre 2 galaxies

- Ne dépend que de l'expansion de l'Univers



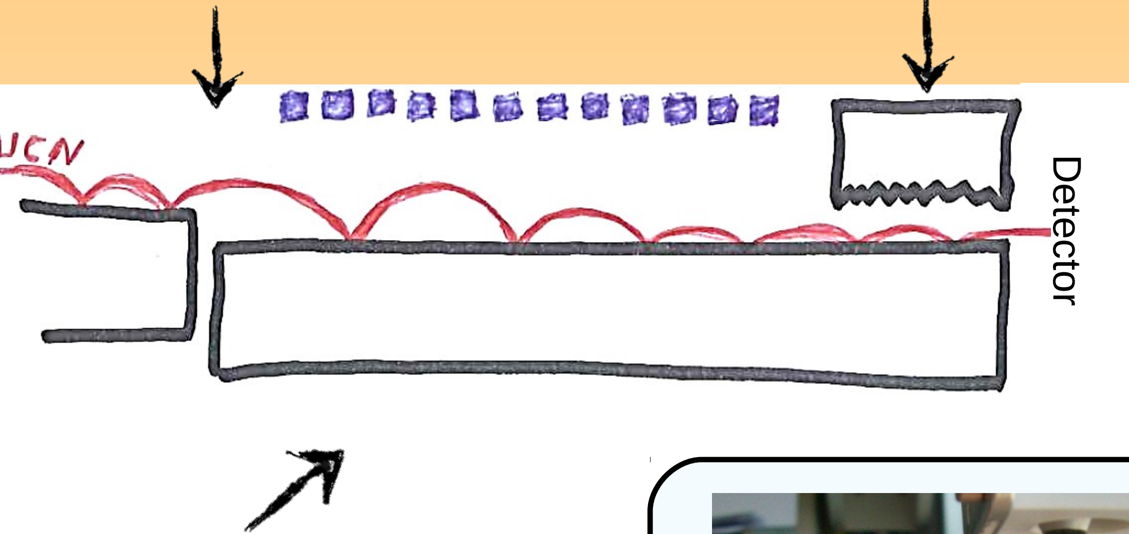


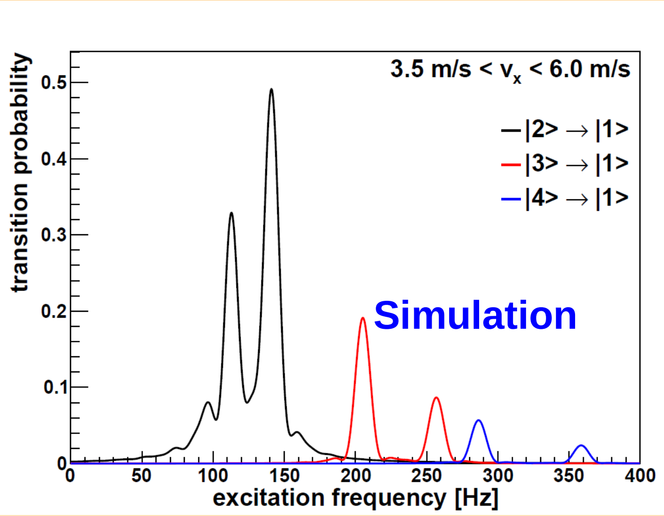
Performances attendues pour LSST
Importance et complémentarité des différentes sondes (BAO, Sne, Weak Lensing, ...)

Excitation of resonant transitions

Prepare an excited level

Select the ground state





Most components needed for this first experiment are ready.
Final implementation is in progress by LPSC group.

Example of development at LPSC: the wire transition system.