Division 3, Population Studies

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September 21 2021, Kick Off Workshop of the ET OSB

OUTLINE: What do we mean for population studies?

- Astrophysical sources:
  - Compact binary mergers: binary neutron stars (BNSs), binary black holes (BBHs), neutron star - black hole (NSBH) binaries;
  - Core-collapse supernovae;
  - Sources of continuous gravitational waves (GWs), e.g. isolated neutron stars (NSs), accreting NSs;
  - NS flares and glitches;
- Primordial black holes (BHs);
- Stochastic backgrounds of astrophysical origin.

What is the merger rate evolution with redshift?

Adv LIGO - Virgo - KAGRA:

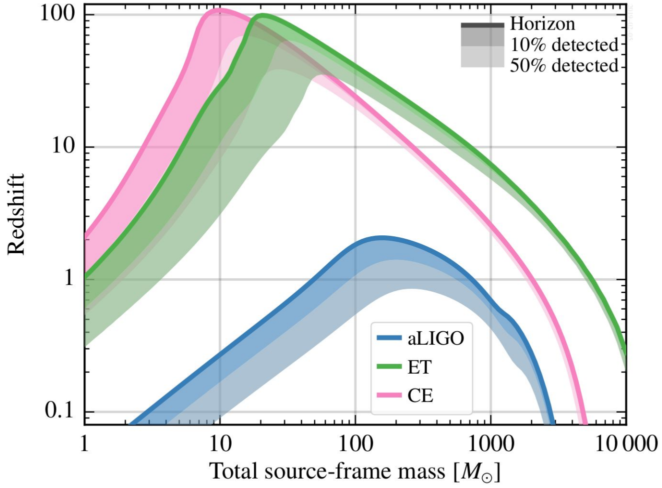
BBHs only up to z~1

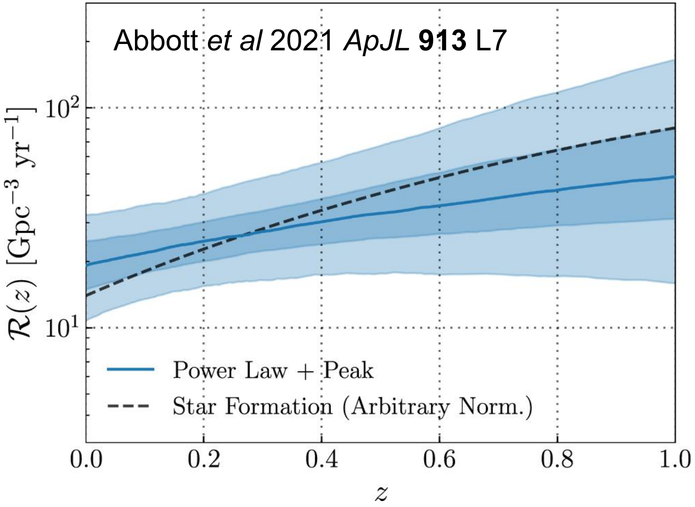
BNSs in the very local Universe

Einstein Telescope:

BBHs up to cosmic Dark Ages (z > 30)

BNSs up to cosmic Noon (z~2)





Connected fundamental questions:

- delay time distribution?
- cosmic star formation rate / metallicity?
- uncertainties on binary evolution?
- primordial / astrophysical BBHs?

What is the mass function of BHs across cosmic time? Are there mass gaps?

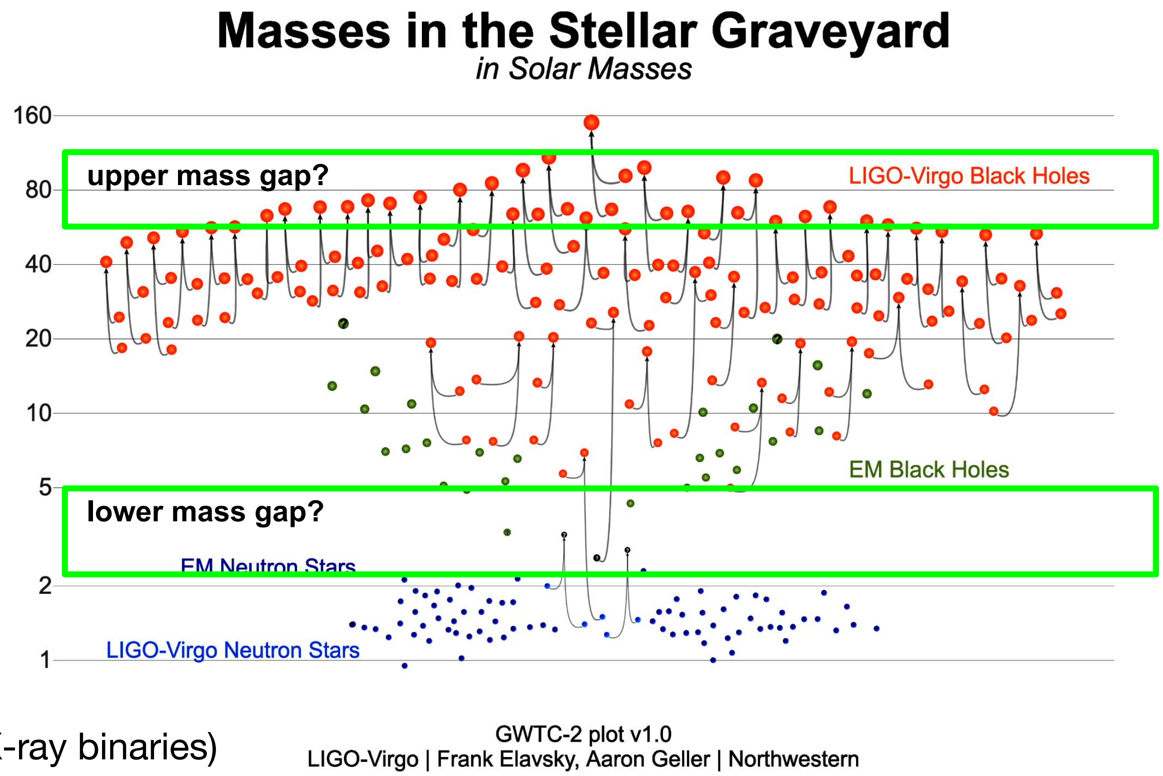
Adv LIGO - Virgo - KAGRA
draw the first “sketch”
of BH mass function

Abbott *et al* 2021 Phys. Rev. X **11** 021053

Abbott *et al* 2021 *ApJL* **913** L7

Einstein Telescope will probe their redshift evolution (if any)

→ key to understand
BBH formation channels:
isolated vs dynamical
vs primordial



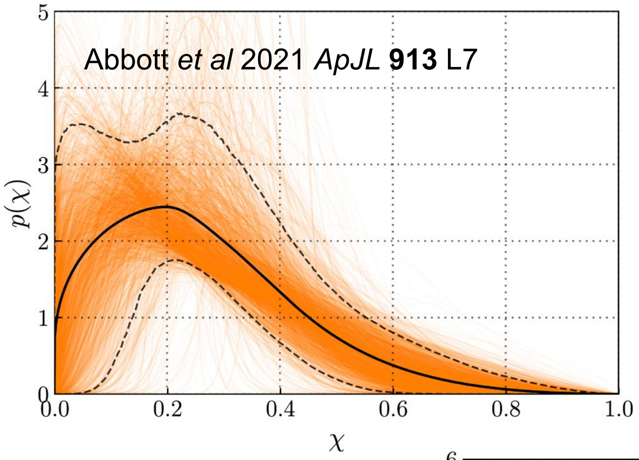
- lower mass gap ~ 2 - 5 $M_\odot$ (from X-ray binaries)
- upper mass gap ~ 60 - 120 $M_\odot$ (from theory of pair instability)

What is the spin distribution of BHs across cosmic time?

Adv LIGO - Virgo - KAGRA draw the first "sketch" of BH spins

Abbott *et al* 2021 Phys. Rev. X **11** 021053

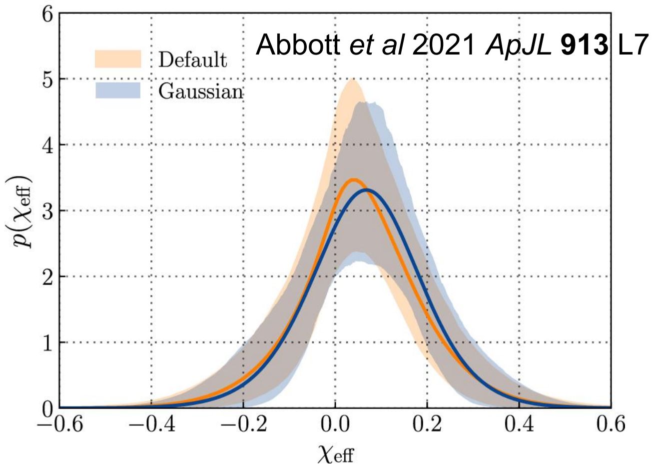
Abbott *et al* 2021 *ApJL* **913** L7



Einstein Telescope will probe spins and their redshift evolution

→ key to understand BBH formation channels

$$\chi_{\rm eff} \equiv \frac{m_1\,\vec{\chi}_1 + m_2\,\vec{\chi}_2}{m_1 + m_2} \cdot \hat{L}$$



Current open issue on spins:

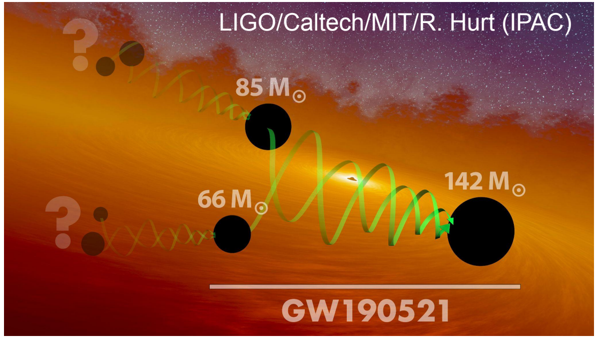
- **LVK favor low spins for most BHs**
- **high-mass X-ray binaries favor high spins**

(e.g. Reynolds 2021 arXiv:2011.08948)

Where are the intermediate-mass BHs (IMBHs)?

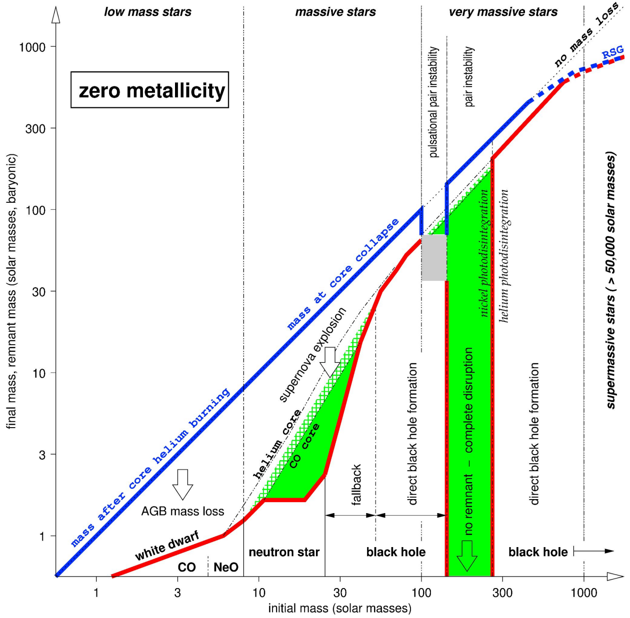
Mass 10^2 - 10^5 $M_\odot$ → bridge gap between stellar-sized and supermassive BHs

- When do they form?
- What is their merger rate across cosmic time?
- What are their formation channels?
- Are they seed of supermassive BHs?



Is it possible to infer the properties of population III stars from their compact remnants?

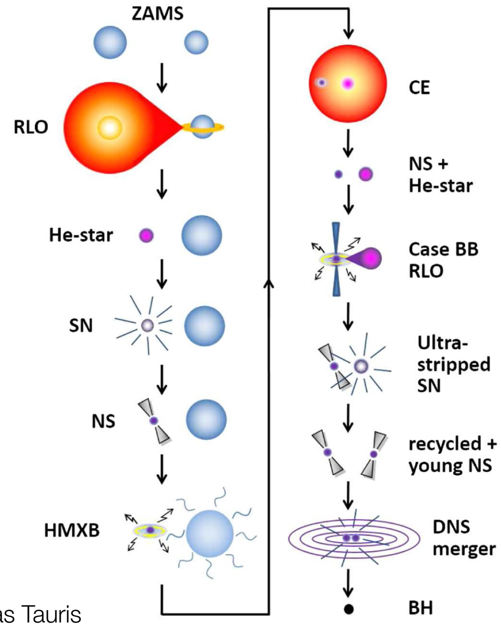
- When did they form?
- What is their mass function?
- What is their binary fraction?
- What is their delay time?



Heger et al. 2003, DOI: 10.1007/10828549_1

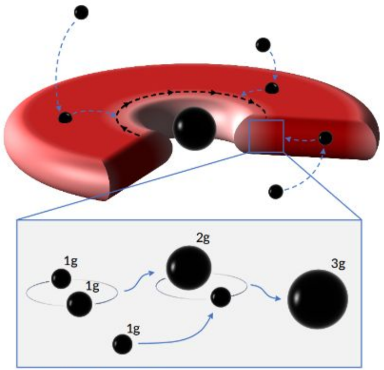
What are the formation channels of binary compact objects?

ISOLATED FORMATION:
Massive binary star evolving through stable mass transfer or common envelope

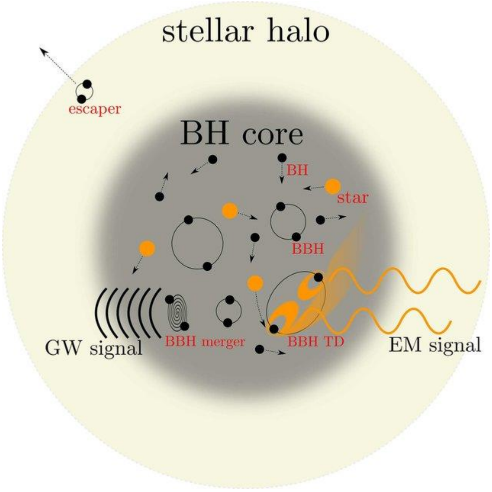


Credit: Thomas Tauris

DYNAMICAL FORMATION
in triple systems,
young and open clusters,
globular clusters,
nuclear star clusters, or AGN disks



Credit: Imre Bartos



Credit: Johan Samsing

What are the formation channels of binary compact objects?

ISSUE: Predictive power of astrophysical models on BHs and NSs is hampered by

- Uncertainties on massive star evolution:
  stellar winds, rotation, ang. mom. transport,
  core/envelope overshooting, nuclear reactions,..
- Uncertainties on binary evolution
  common envelope, mass transfer efficiency..
- Uncertainties on stellar collision products

→ **open questions on stellar and binary evolution**

- Uncertainties on core collapse supernovae
- Uncertainties on natal kicks

→ **open questions on supernovae**

- Uncertainties on star cluster formation / evolution
- Uncertainties on AGN disk physics

→ **open questions on stellar / gas dynamics**

- Uncertainties on cosmic star formation rate
- Uncertainties on cosmic metallicity evolution

→ **open questions on cosmic star formation**

\+ **utterly large parameter space → computational challenge, a lot of work to do**

Primordial Black Holes

- Astrophysical BHs forms from the gravitational collapse of a star. We know they exist. Their mass must be above the Chandrasekhar limit,

$$M > \mathcal{O}(1)\, M_\odot$$

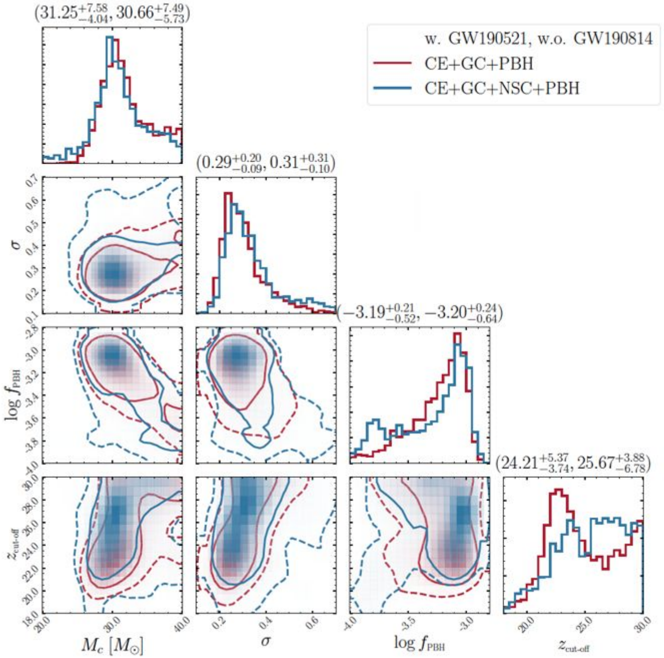
- PBHs are formed in the early universe. Their mass can be small and they can still be around as long as they do not evaporate within the age of the universe

$$M > 10^{-18}\, M_\odot$$

Key Questions on PBHs in the GW era

- Do PBHs contribute to current and future GW signals?
- What are the smoking-gun evidences for PBHs and how to distinguish them from astrophysical sources?
- Can PBHs account for all the dark matter in the universe?

Population posterior distributions



$$\psi(M_{\rm PBH}) = \frac{1}{\sqrt{2\pi} M_{\rm PBH}} \exp\left(-\frac{\ln^2(M_{\rm PBH}/M_c)}{2\sigma^2}\right)$$

$$M_c \simeq 30 M_\odot$$

$$\sigma \simeq 0.3$$

$$f_{\rm PBH} \simeq 6 \cdot 10^{-4}$$

$$z_{\rm cut\text{-}off} \simeq 25$$

PBH not the dark matter

Moderate accretion

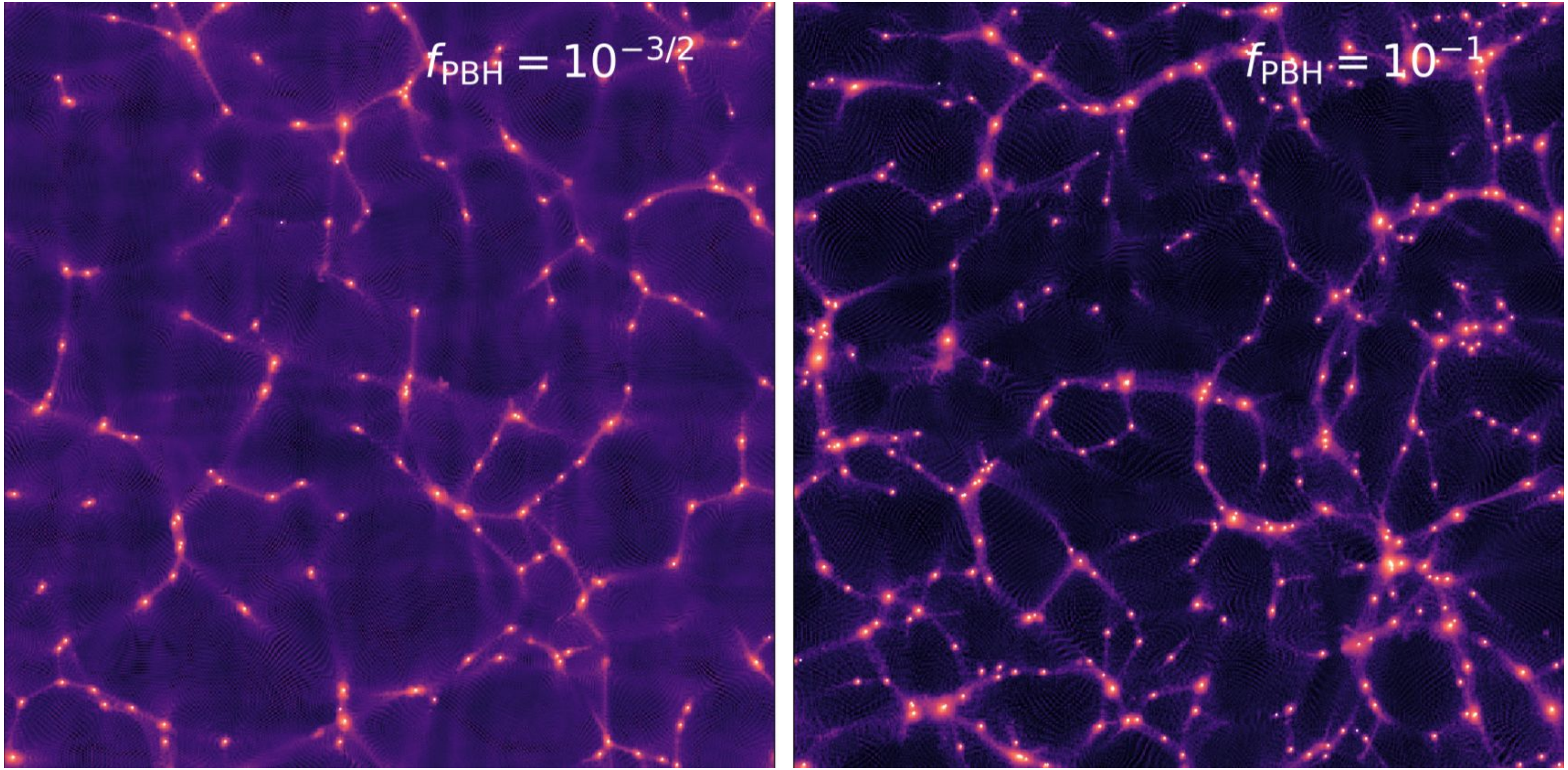
Franciolini et al. (2021)

Do PBHs contribute to current and future GW signals?

- Need to know the PBH merger rate, and therefore the evolution and survival of PBH binaries between formation and merger, effect of clustering (enhance both binary formation and gravitational disruption)?
- Detail knowledge of the astrophysical channels, reduce the uncertainties
- How PBH constraints change with PBH clustering, accretion, mass function?

PBH clustering evolution

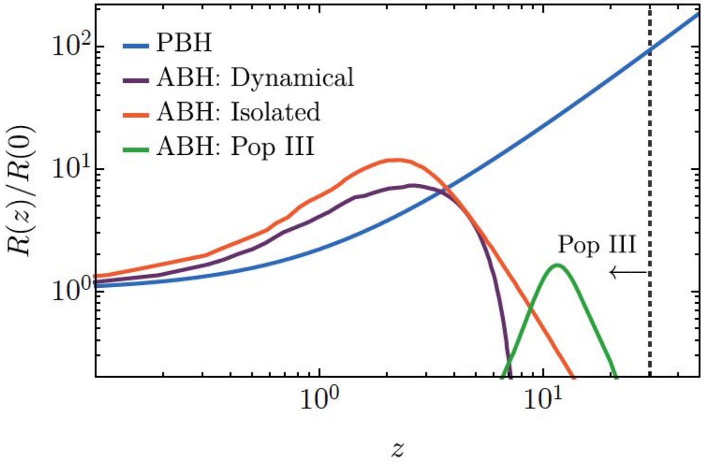
$z = 99$



Inman and Ali-Haïmoud (2019)

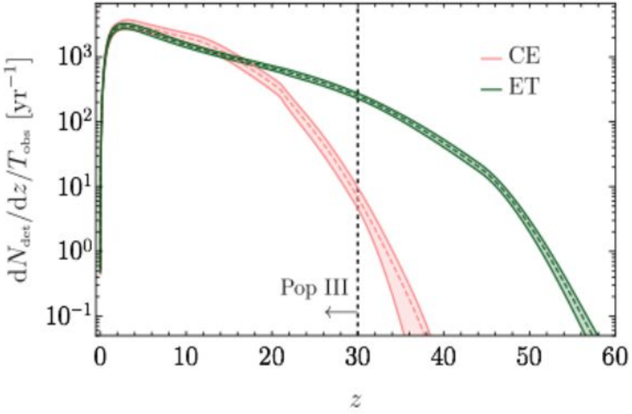
Smoking-gun evidences for PBHs and distinguish them from astrophysical sources

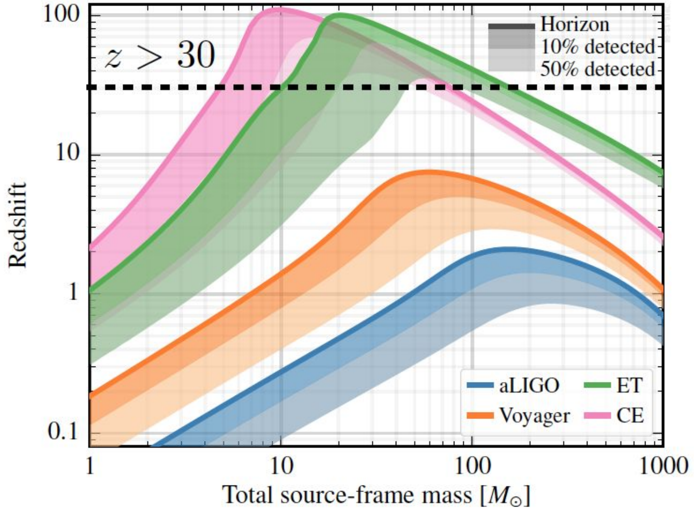
- Sub-solar BHs
- Merger rate time evolution at high redshifts
- Spin of PBHs (tendency of large spins for large masses)
- Stochastic GW background from PBHs at high redshifts



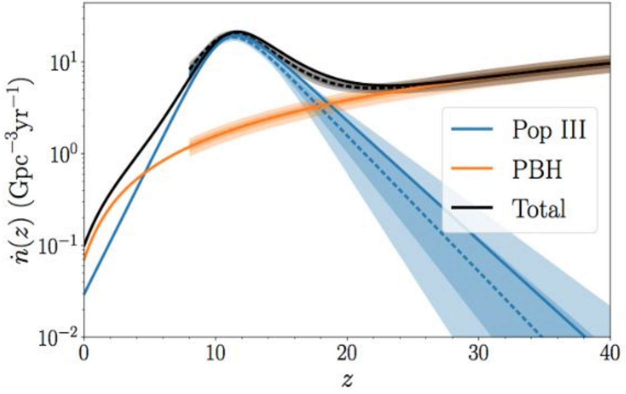
$\sim t^{-34/37}(z)$

V. De Luca et al. (2021)



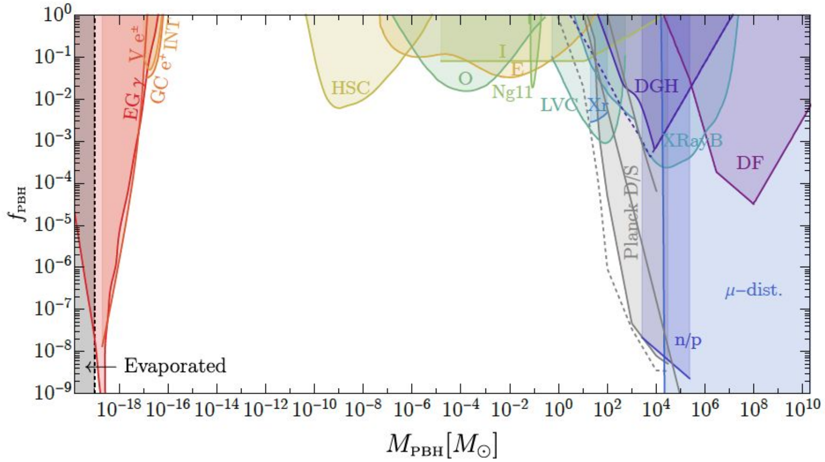


Courtesy of K. Ng



PBHs as dark matter?

- PBH clustering for PBHs as the totality of dark matter
- GWs from the asteroid-mass-like PBHs
- Correlation of nHZ and mHz detectors?



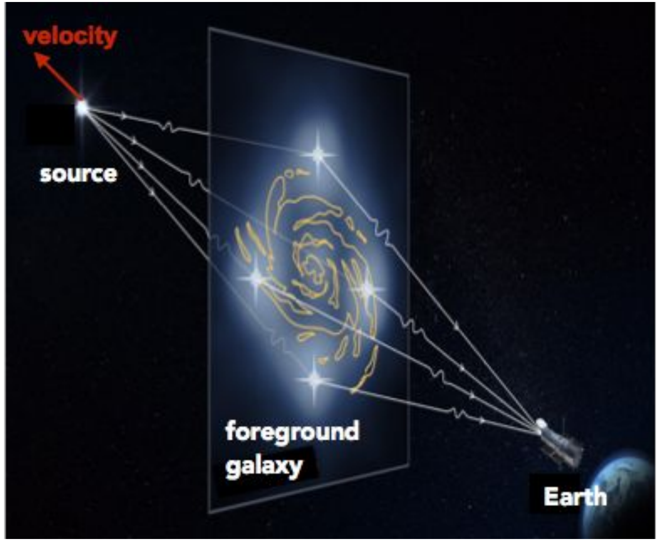
Inclusion of selection effects in population studies

Instrument with finite horizon (SNR cut): we see biased sample of a given population

Lensing: magnified sources are easier to detect than de-magnified ones. Important at high redshift

Peculiar velocities: sources moving toward observer have higher SNR. Important for low redshift population (BNS systems)

Effects particularly important for population “across threshold”, e.g. BNS for ET

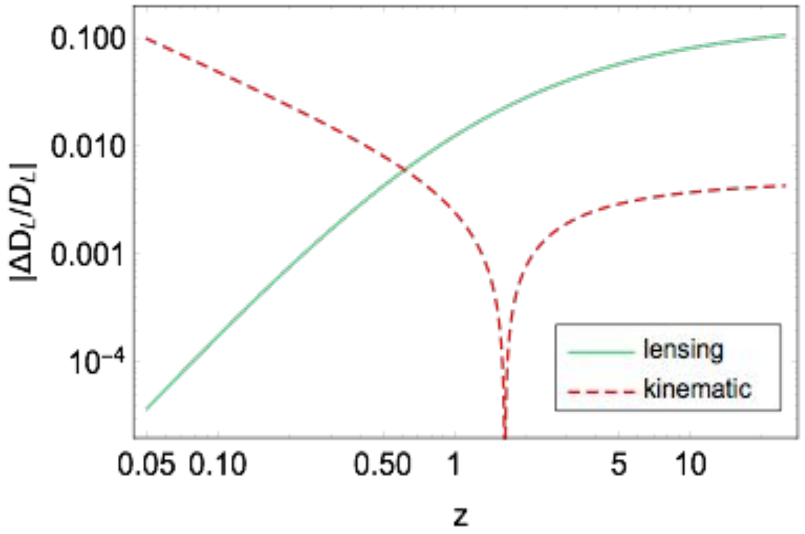


Inclusion of selection effects in population studies

Example: effect on luminosity distance induced by lensing and kinematic effects, as function of redshift

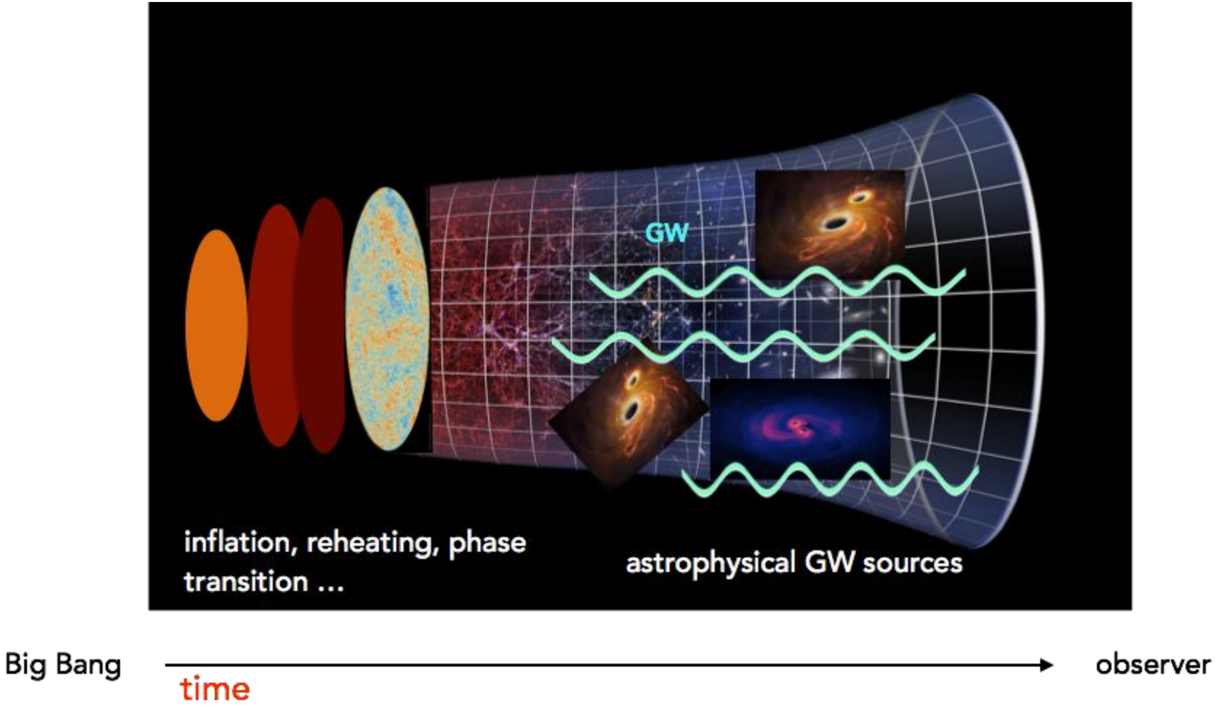
These effects have to be **characterised and included in templates** to have accurate reconstruction astrophysical and cosmological parameters

adapted from Bonvin et al. 2005

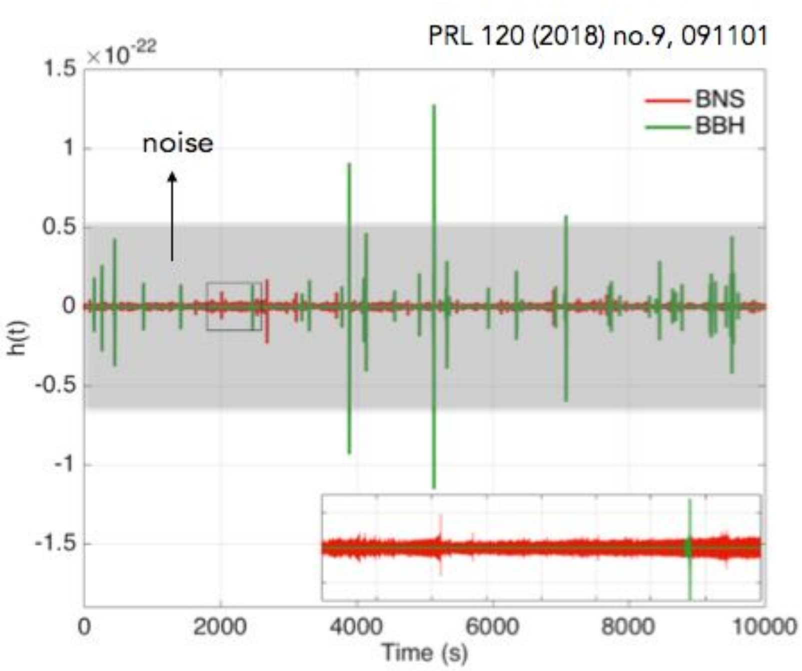


Astrophysical backgrounds

Collect contributions from all sources from the onset of stellar activity on



Popcorn background and overlapping signals

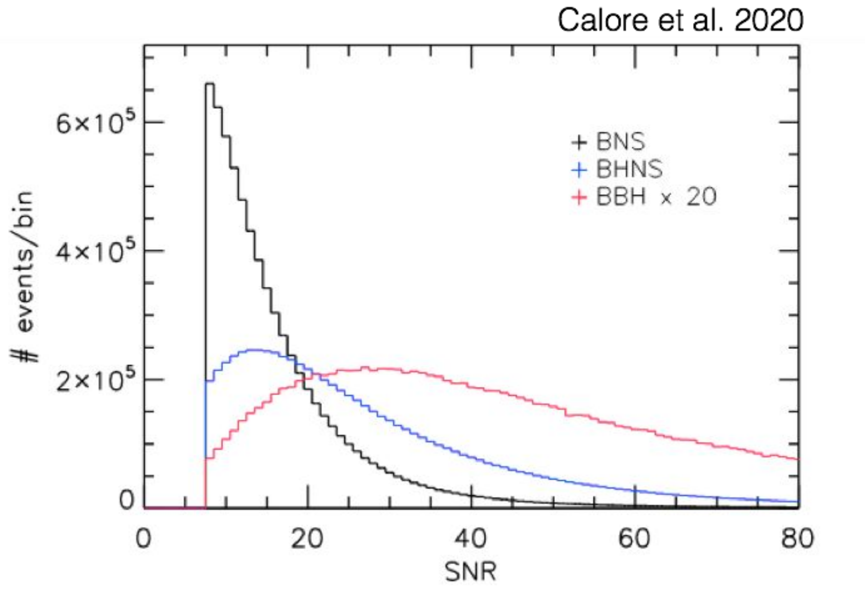


ET sensitive to merger phase of evolution of compact objects: **popcorn background**

BBH separated in time, (almost) no time overlap
BNS do overlap in time

How efficient are current algorithms in discriminating overlapping BNS signals?
(in collaboration with Div. 10)

Complementarity background and catalogue approach

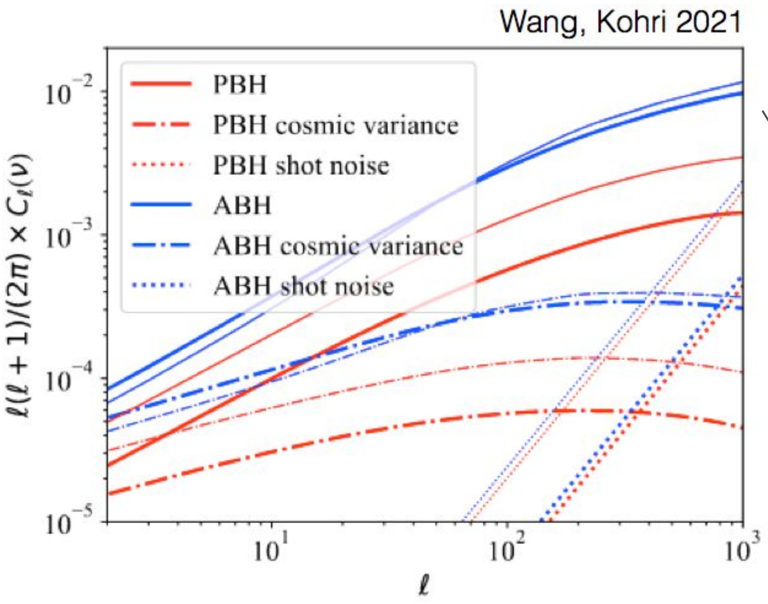


Most of black hole events are detectable individually (catalogue). Peak of BNS distribution below threshold: confusion noise

Combining catalogue and background approach: info on faint and distant population of sources which can not be detected individually

Background as independent tool to investigate multi-channel astrophysical and primordial mergers *(see e.g. Bavera et al. 2021)*

SGWB characterisation: spectral shape, anisotropies, cross-correlations



Reconstruction of **spectral shape** via small band searches. How? Optimal bin size?

Study of spectrum of **anisotropies** and **cross-correlation** with cosmological surveys (e.g. Euclid, SKA). Best observable to maximize SNR? *(collaboration with Div. 10)*

OSB-Div.3 organisation

Main goal: stimulate work around questions fundamental for ET science, fostering discussion and cooperation among different groups working on similar subjects in population studies

How: regular telecons, divided by subjects, periodic workshops etc..

You are warmly welcome to join our division if you are interested in these topics.
And don't hesitate to get back to us with feedback and suggestions!

Backup slides

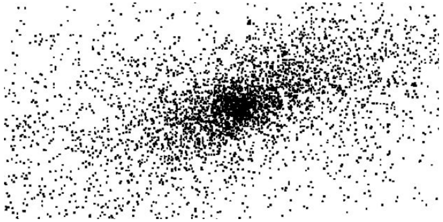
PBH clustering evolution

PBH = discrete objects

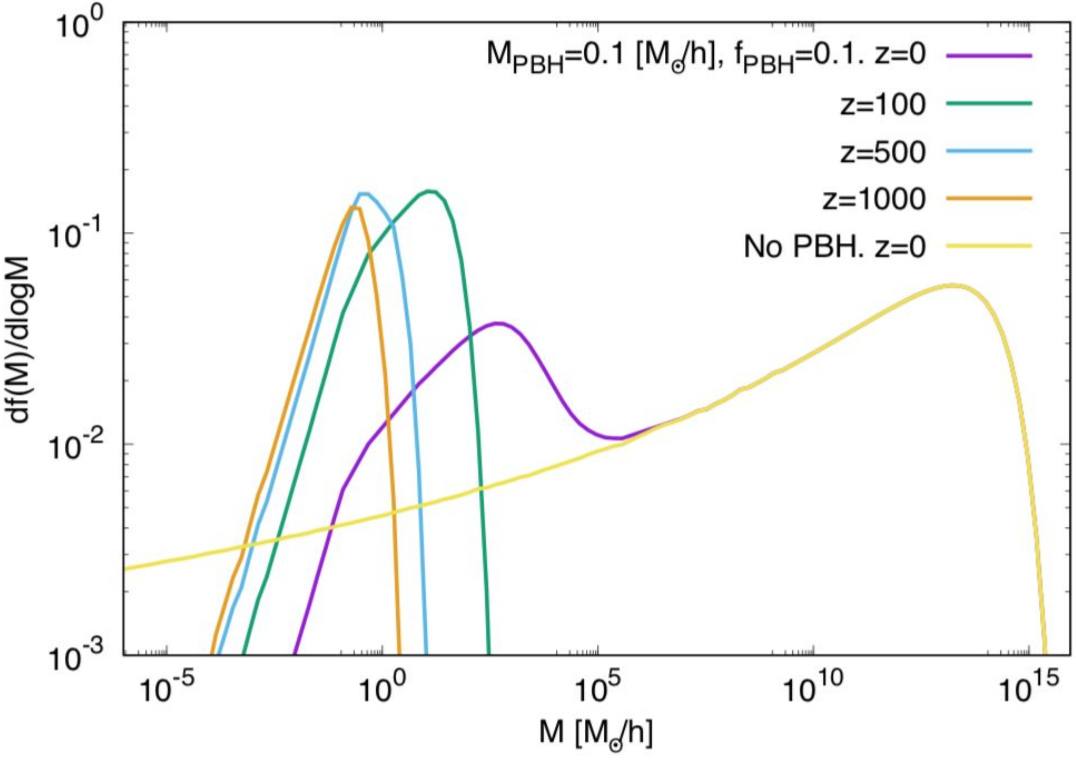
- PBH not clustered at formation (if no primordial NG): with V. Desjaques (2018)

$$\left\langle \frac{\delta\rho_{\rm PBH}(\vec{x},z)}{\bar\rho_{\rm DM}}\frac{\delta\rho_{\rm PBH}(0,z)}{\bar\rho_{\rm DM}}\right\rangle = \frac{f^2_{\rm PBH}}{n_{\rm PBH}}\delta_{\rm D}(\vec{x}) + \xi(x,z).$$

- Shot noise drives early structure formation developing
- PBHs form halos described by the Press-Schechter theory
- PBHs eventually drive other DM component to cluster
- PBH do not cluster for $f_{\rm PBH} \lesssim z \cdot 10^{-4}$



Inman and Ali-Haïmoud (2019)

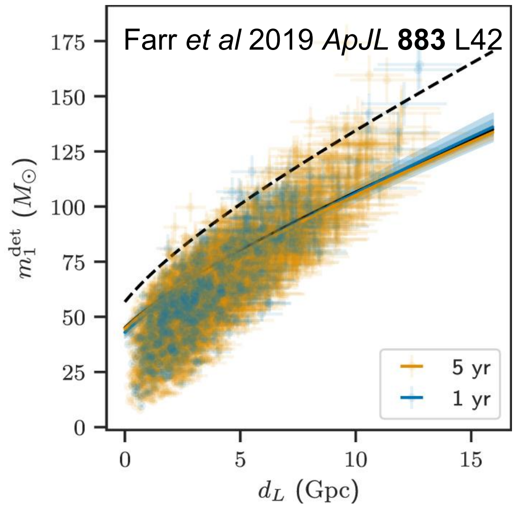


K. Kadota and J. Silk (2012)

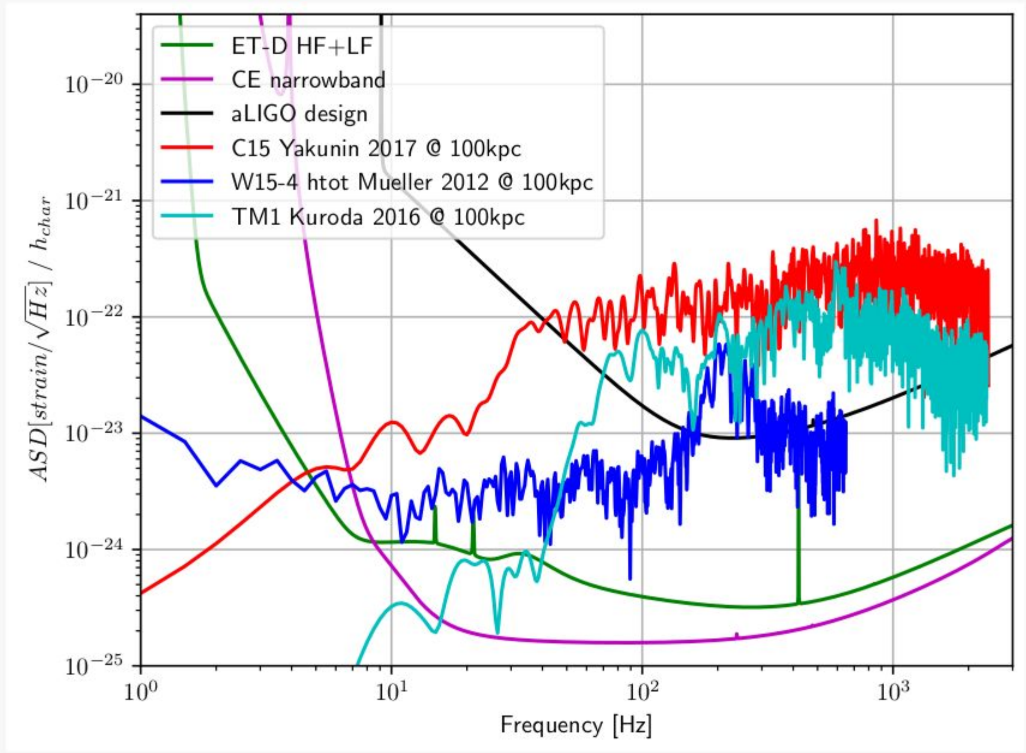
Can we use black holes as standard candles?

If BH mass spectrum has a strong drop at ~ 40 - 50$M_\odot$,
we can use BHs to measure H(z)
without galaxy counterparts

Possible even if mass gap does not exist
but only if the mass spectrum's break
does not change with redshift



Core-collapse supernovae: detectable with ET?



source at 100 kpc

from https://gwic.ligo.org/; red: Yakunin et al. 2017; blue: Mueller & Janka 2012, A&A, 537, A63; cyan: Kuroda et al. 2016, ApJ, 829, L14

Continuous GWs: can we see GWs from NS crust deformation/ellipticity?

Non-axisymmetric, rapidly rotating neutron stars:

- **ISOLATED NSs** with crust deformation / ellipticity

- **ACCRETING NSs**
  e.g., surface magnetic field compressed by infalling material can produce large quadrupolar ellipticity

Current LVK upper limits on ellipticity:

~10^-8 from millisecond pulsars (Abbott *et al* 2020 *ApJL* **902** L21)

~10^-7 from young supernova remnants (Abbott et al. 2021, arXiv:2105.11641)

GW bursts: can we see GW bursts from NS flares / glitches?

- **NS flares** : X-ray flares produced by highly magnetized NSs (magnetars)

  For B~10^15 G at 10 kpc, strain ~ 10^-27

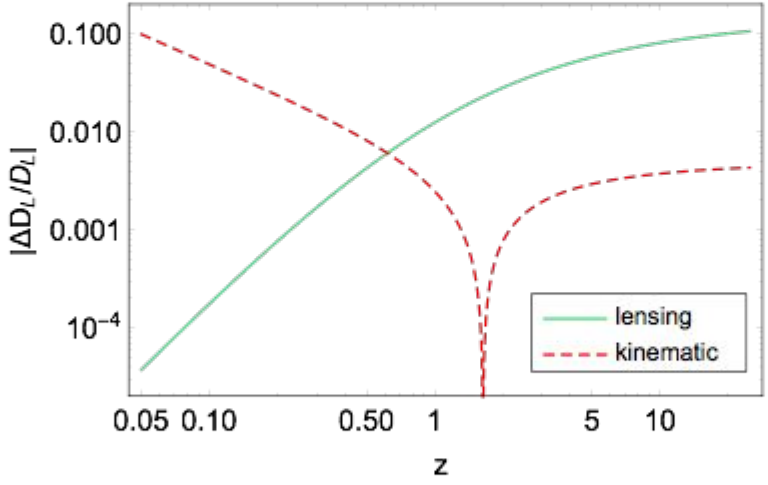
- **pulsar glitches:** sudden spin-up episodes in otherwise stably rotating NSs

  Highly uncertain:
  Maybe detectable already with LVK (Melatos et al. 2015 ApJ, 807, 132)
  Maybe not even with 3G (Sidery et al. 2010, MNRAS, 405, 1061)

Kinematic and lensing effects on distance reconstrcution

kinematic effects dominant: impact on BNS population and standard sirens study with ET

lensing dominant: for high redshift populations



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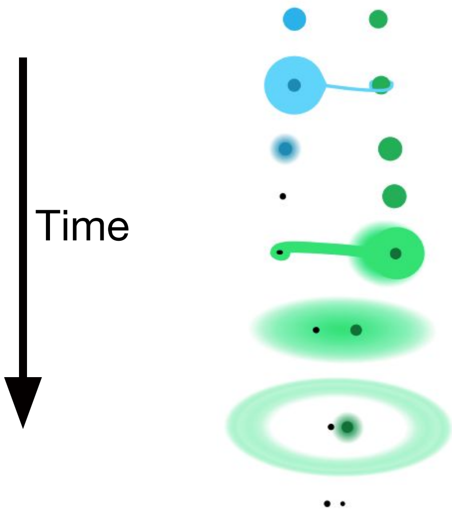
Astrophysical populations

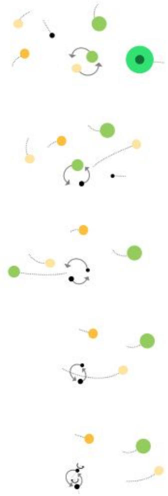
Isolated formation

Binary formation in galactic fields
through a Stable Mass Transfer (SMT)
or Common-Envelope (CE) phase



Dynamical formation

Binary formation in Globular Cluster (GC)
or Nuclear Star Clusters (NCS)
through encounters and GW captures



Large uncertainties