Compact binaries

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&
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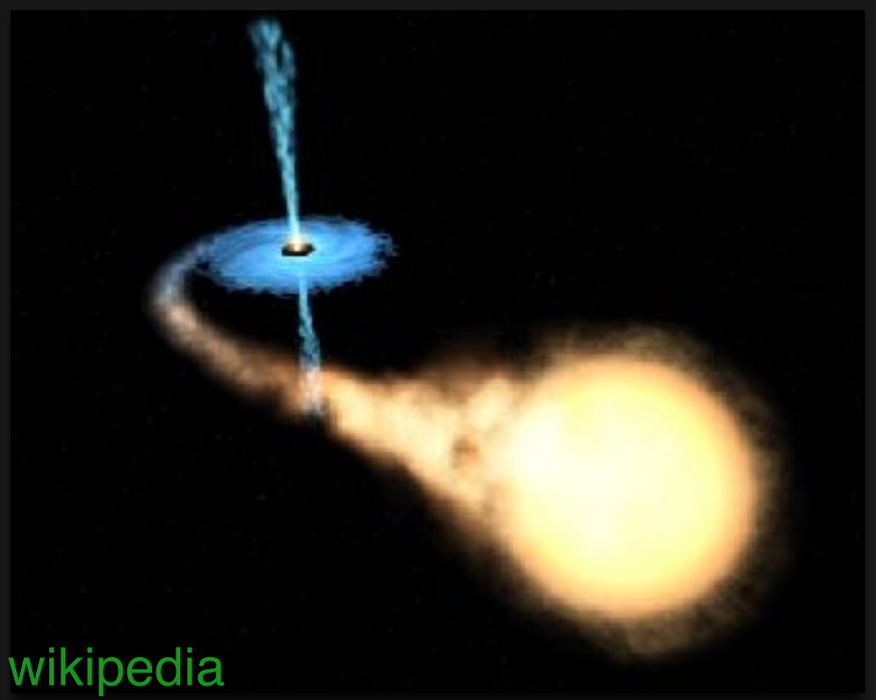
Why compact binaries?

- We have detected 3+1 types of gravitational-wave sources:
  - BNS, NSBH, BBH
  - Stochastic background (probably; and probably from binaries)
- How does the Universe make these sources?
- What do they teach us about astrophysics and cosmology?

A brief history of compact binary histories

How are compact binaries formed? Pick one!



wikipedia

Isolated

- Progenitors stars form in b
- Mass transfer … mon-envelope … us evolution? Por…

Dynamic…

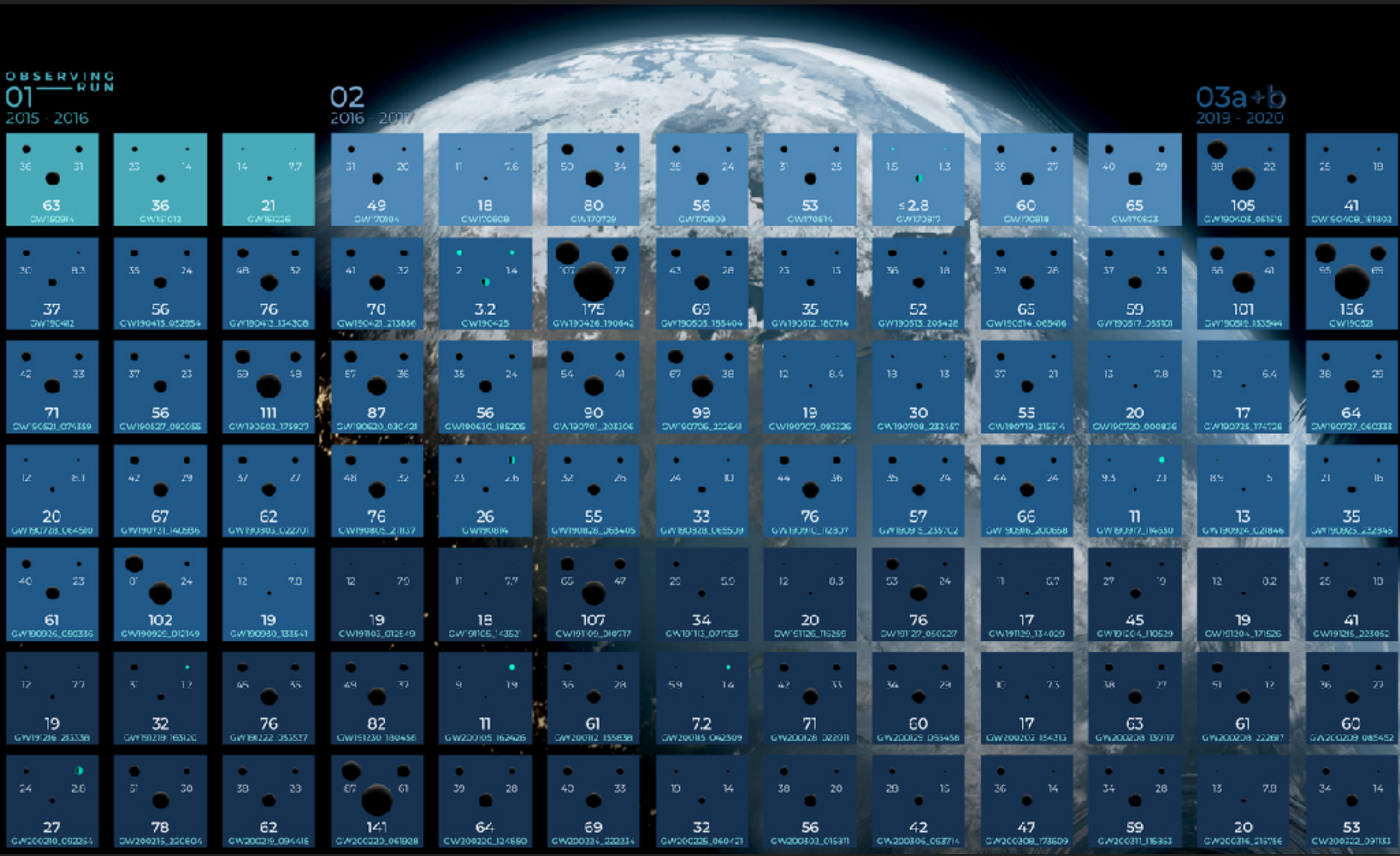
- … segregate towards …

- Dynamical interaction: black holes form binaries, three body interactions harden and (sometimes) eject binaries

Easily distinguish with ~100 observations!

AURA/STSci/NASA

Reality intrudes



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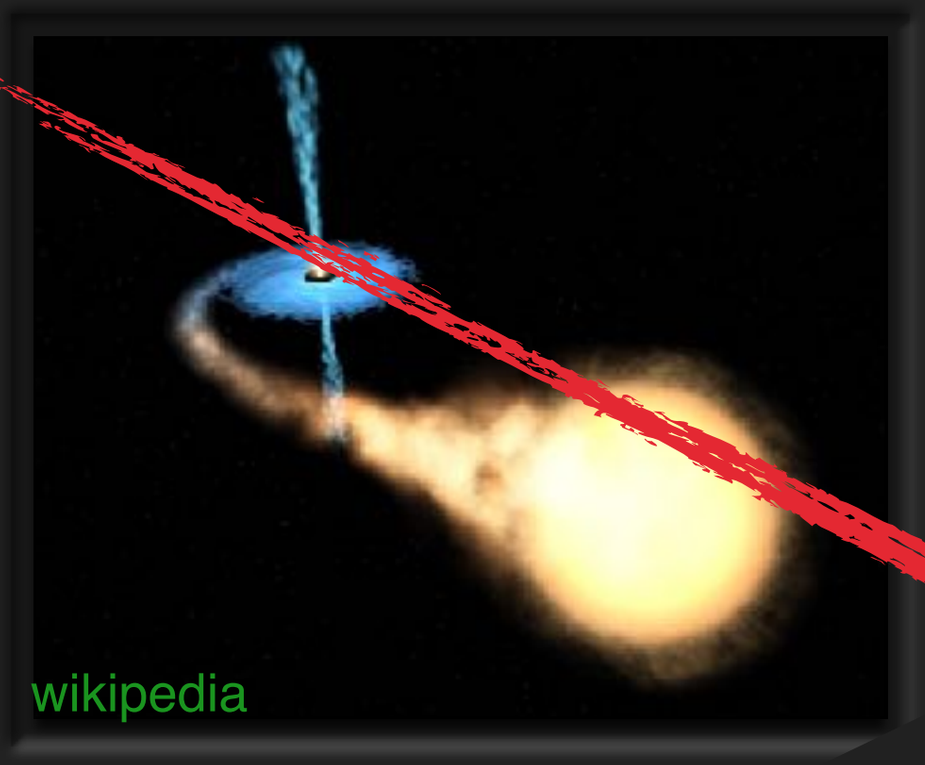

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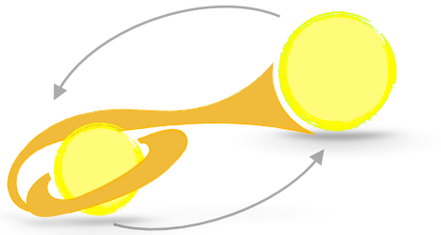
~~100 observations!~~

~~Easily distinguishable~~

Many different formation channels

Isolated binary evolution



Chemically-homogeneous evolution

Pop-III stars

Stable mass transfer

Common envelope

Young clusters

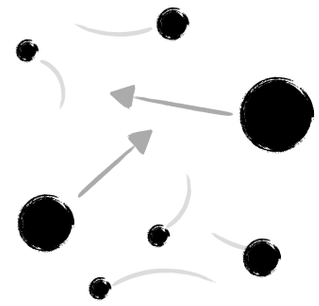
Globular clusters

Triples/ quadruples

Nuclear clusters

Active galactic nuclei

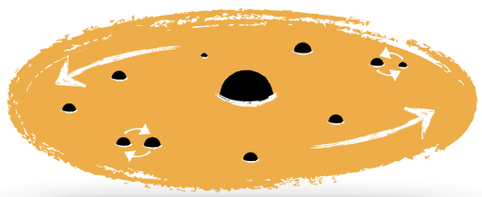
Dynamical assembly



Primordial black holes

Dark matter

Your favorite channel here!!



Gaseous environments

Adapted from **Tom Callister**'s adaptation of **Mike Zevin**'s adaptation of **Selma de Mink**'s slide

Uncertainties in channels

- Metallicity
- Star formation rate
- CE efficiency
- RLOF processes
- Globular cluster formation rates
- Initial mass function
- Galaxy formation/merger histories
- Nuclear reaction rates
- Pop III
- Delay time distribution
- Etc. etc. etc. etc. etc.

Formation of GW systems is muddled and confused

Half empty: We don't know anything

Half full: There is so much physics and astrophysics to learn!

This is one of the reasons that Cosmic Explorer is awesome!

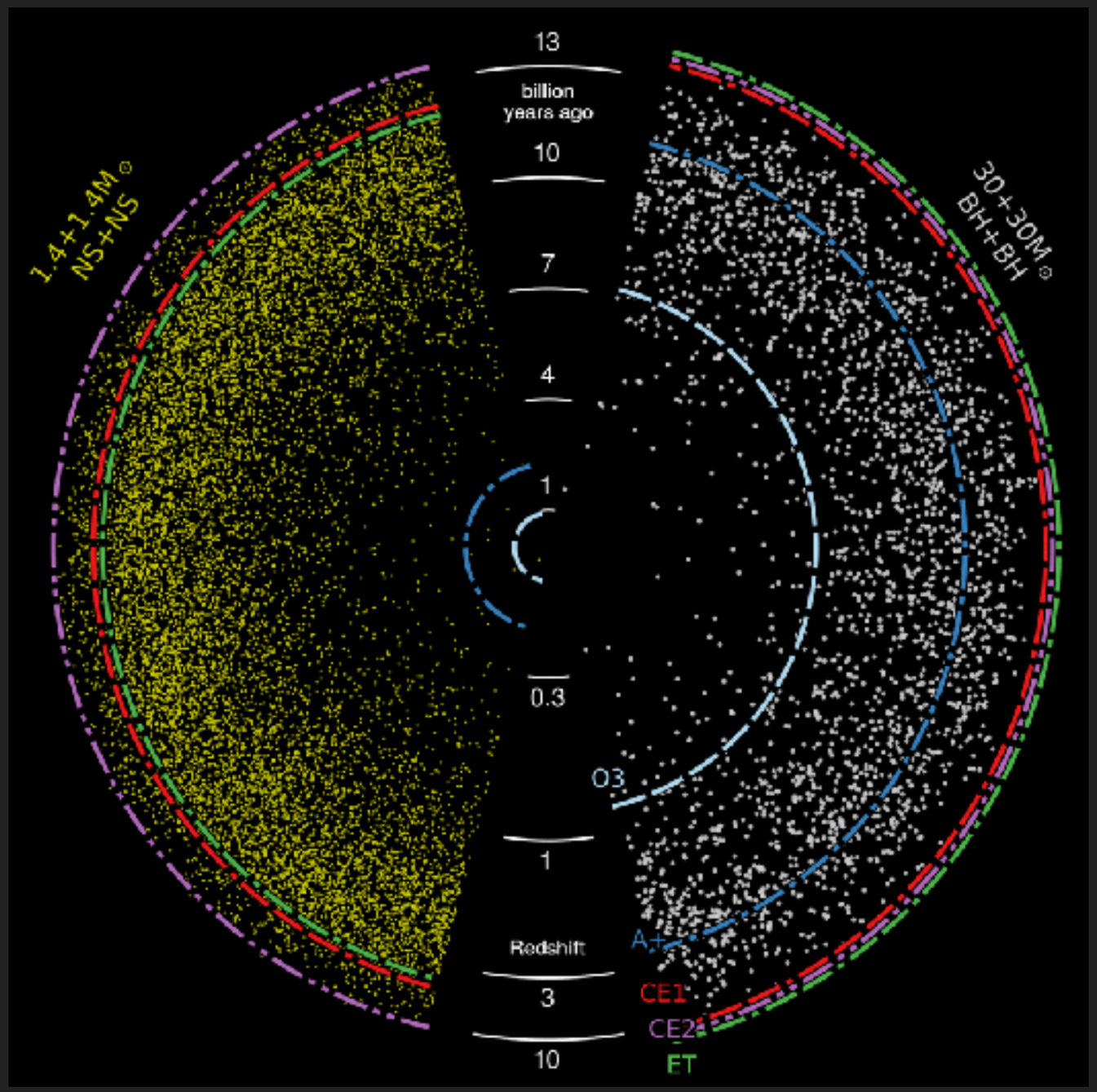
Cosmic Explorer to the rescue!

- Cosmic Explorer does three things for CBCs:

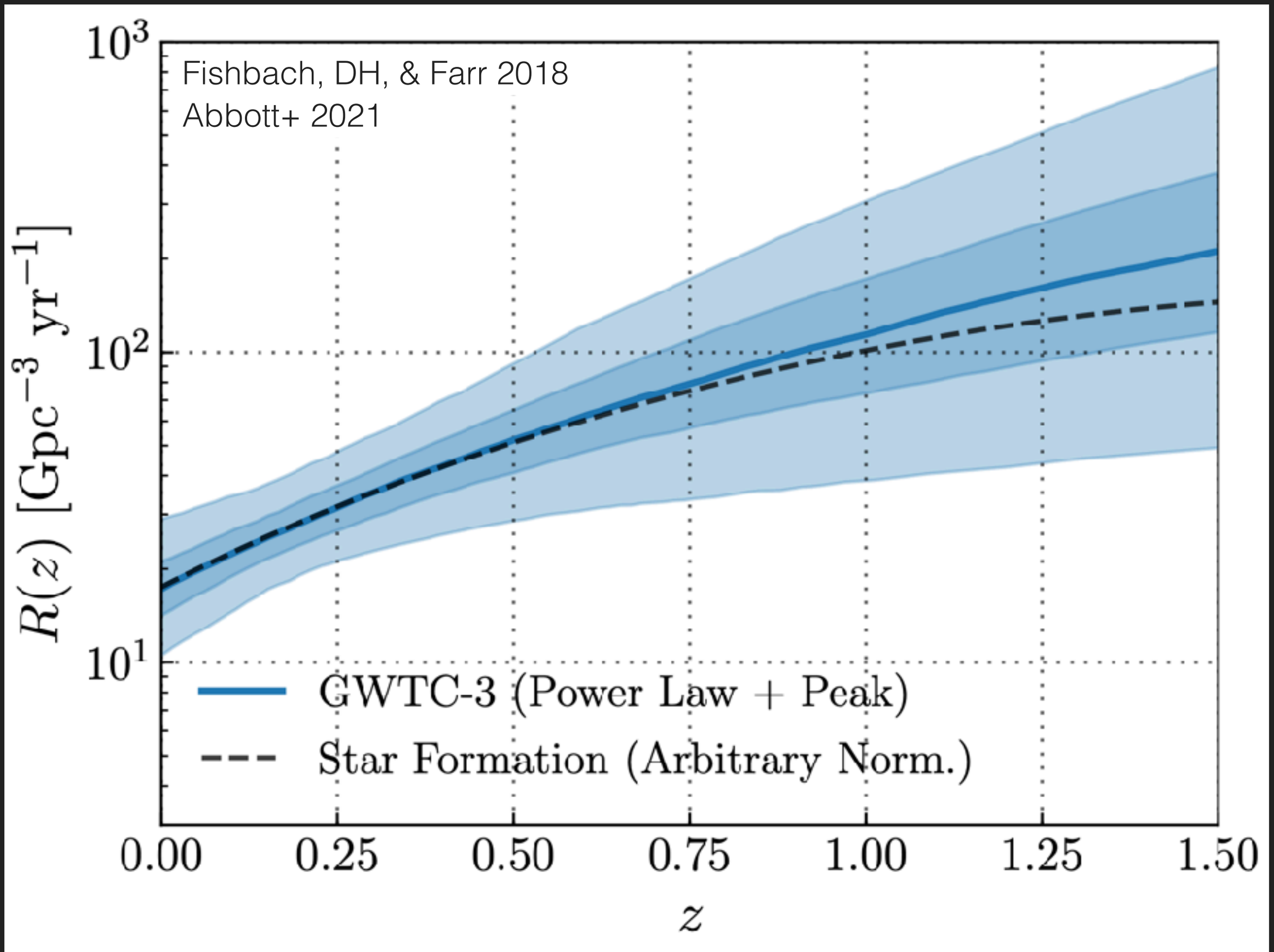
- CE is more sensitive in amplitude: binaries are louder (high SNR!), binaries can be detected farther (probe high redshift!)

- CE is more sensitive at low frequency: probe higher masses and higher redshifted masses

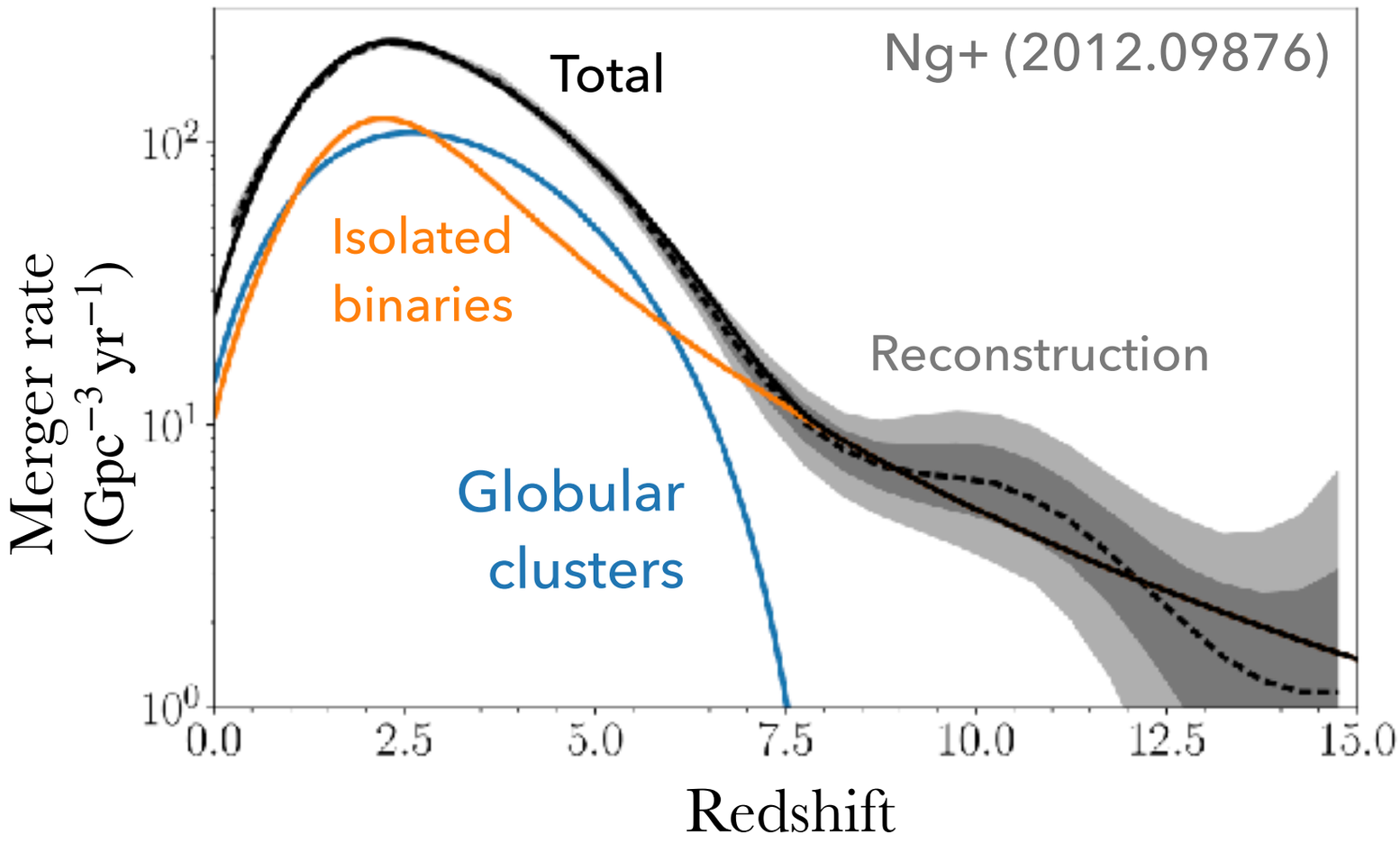
- CE probes a staggeringly large volume: rates are crazy high, rate evolution is inescapable, binary sample is complete (at certain masses; we probe to the beginning of binary existence)



O3: the rate of BBH mergers evolves!



CE: rate evolution to high redshift



Branching ratios

van Son+ (2110.01634)
Ng+ (2012.09876)
Zevin+ (2011.10057)

Evolutionary time delays

Fishbach & Kalogera (2105.06491)
Safarzadeh+ (2004.12999)

Metallicity-dependent star formation rate

Singh+ (2304.01341)
Chruslinska (2206.10622)
Chruslinska+ (1811.03565)
Vitale+ (1808.00901)

Globular cluster evolution

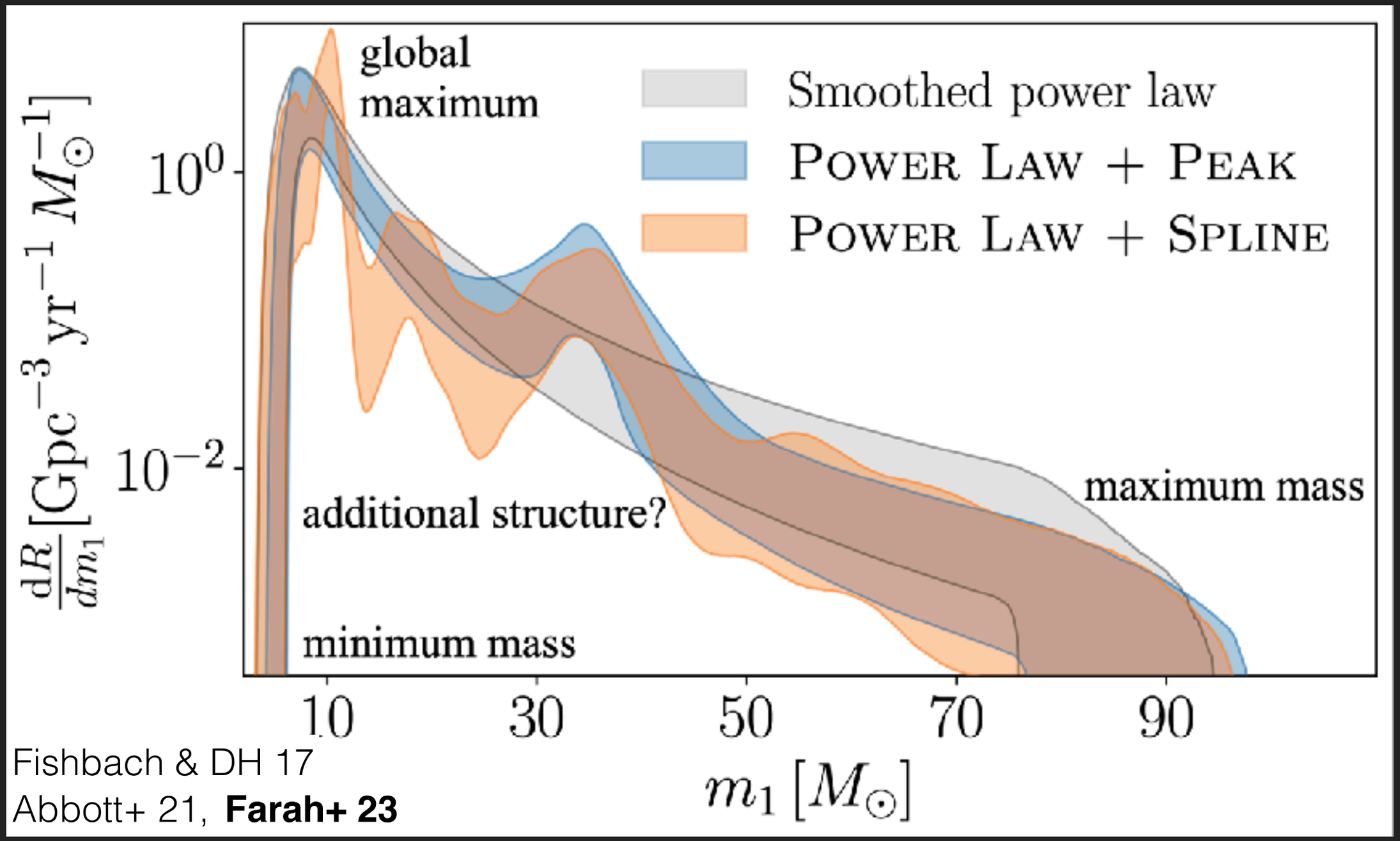
Fishbach & Fragione (2303.02263)
Romero-Shaw+ (2011.14541)
Rodriguez & Loeb (1809.01152)

Primordial black holes

Ng+ (2108.07276; 2204.11864)

Adapted from **Tom Callister**

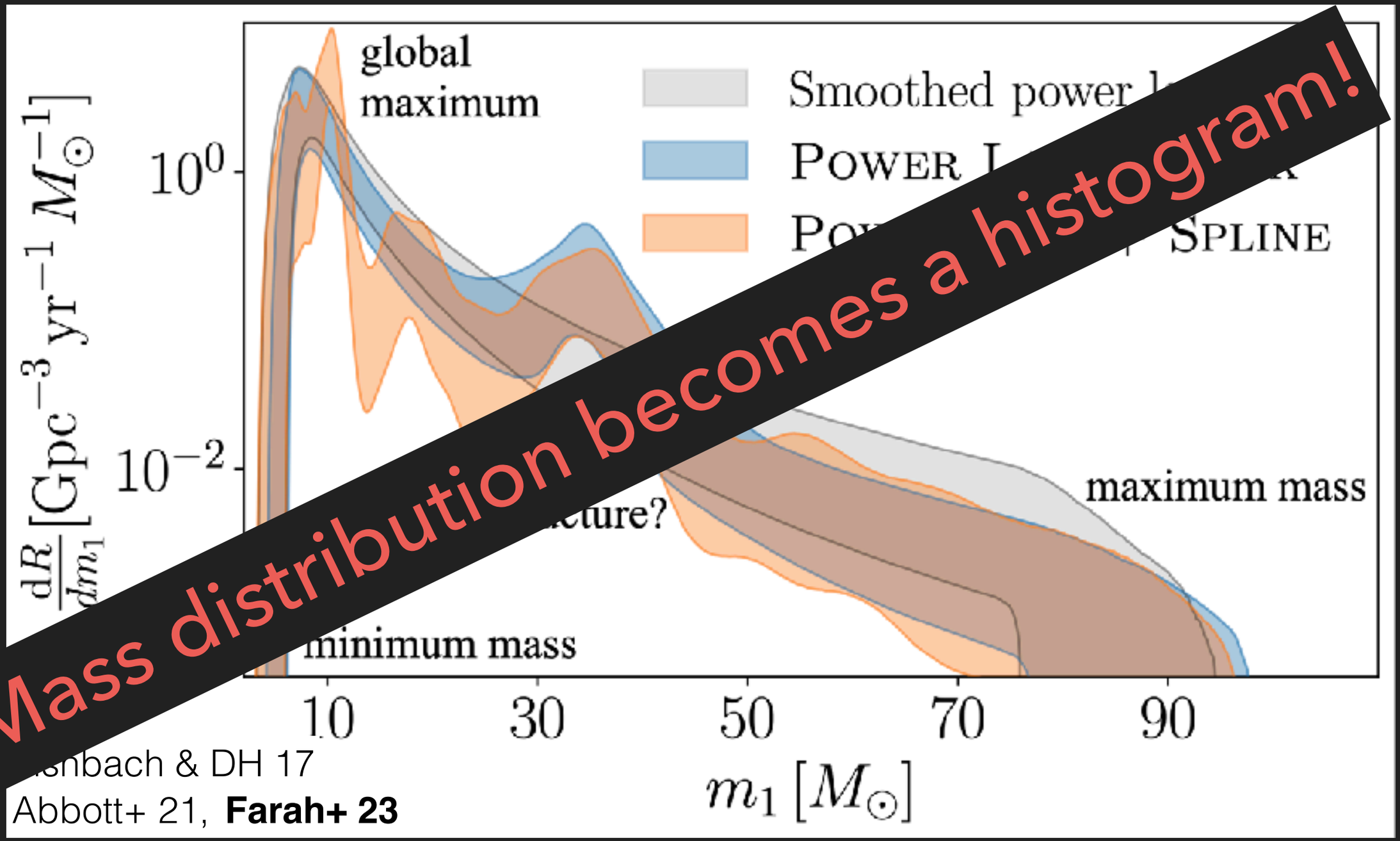
O3: mass distribution at z~0



Fishbach & DH 17
Abbott+ 21, **Farah+ 23**

- There are lower and upper mass gaps! There are bumps!!
- Bayesian inference. Lots of uncertainty/prior dependence

CE: mass distribution at all redshifts!



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- Histograms of evolution, correlations, spins, eccentricity
- No more Bayes?!!

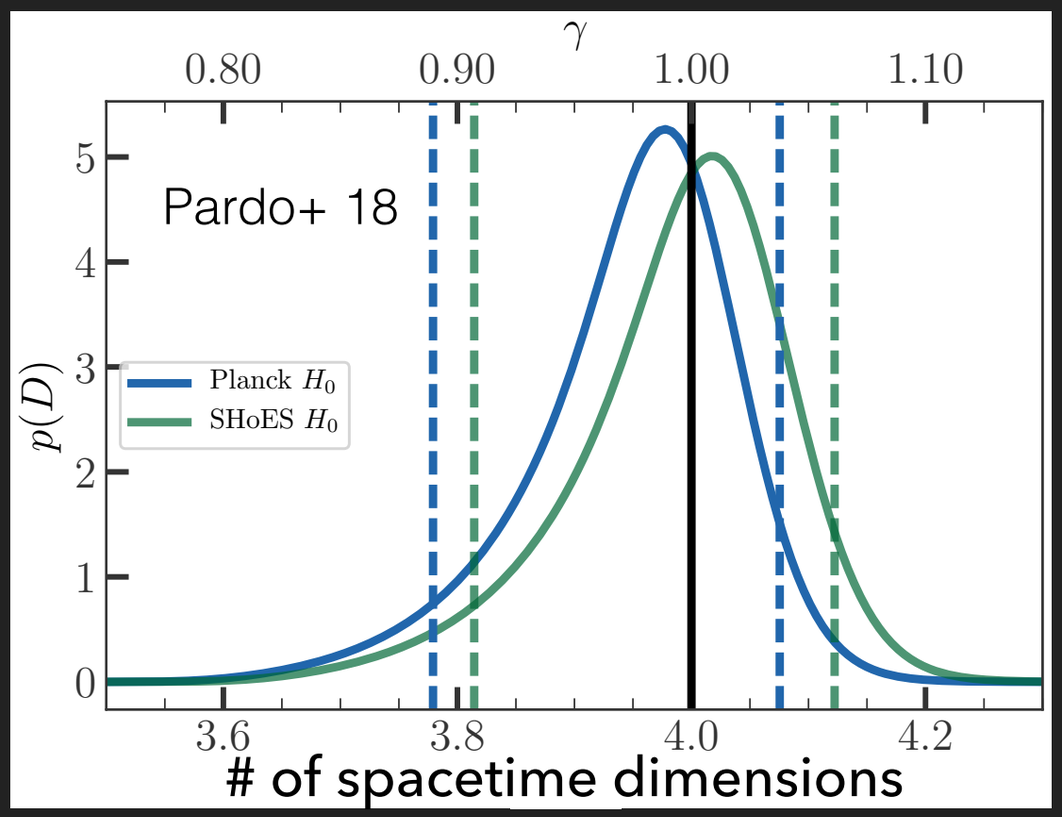
CE untangles GW astrophysics

- Mass gaps? Bumps? BBHs in PISN gap? “Far side” black holes?
- Eccentricity distribution? q<0.1 mass ratio systems?
- Spin amplitudes and alignments? Do spins depend on mass/ratio, metallicity?
- How does the rate evolve? How does everything else evolve? Rates/ properties compared to other explosive transients (X-ray binaries, short GRBs, ...)
- What are the biggest BBHs? Smallest? Most distant? Where does the rate peak?
- Are there EM counterparts to BBHs? NSBHs?
- Host galaxy properties (stellar pops, offsets, metallicity,...)
- Correlations between all parameters? Redshift evolution of correlations?
- Correlations with large-scale structure? BAO features?
- Surprises!! Immense discovery space.....

Testing general relativity

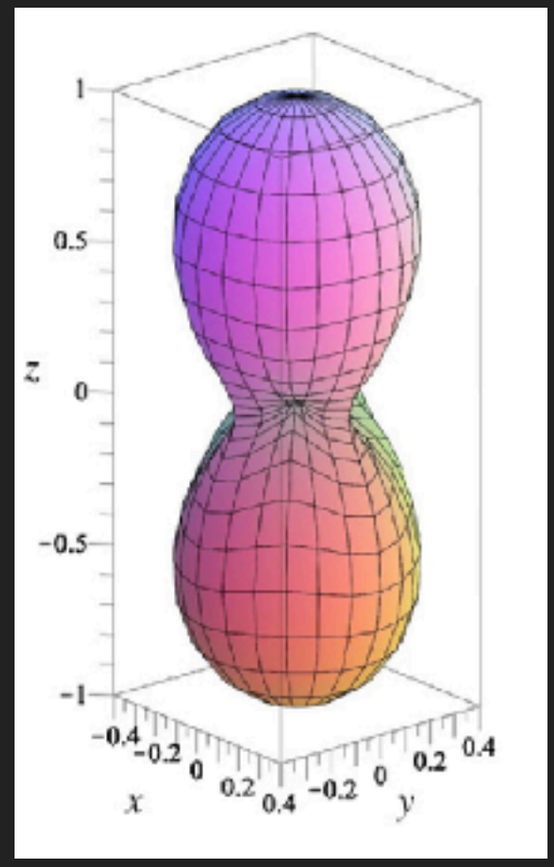
- Residual tests with SNR > 300
- Gravitational-wave memory effect
- EM counterpart: speed of gravity (1000x improvement)
- Standard sirens: bright, dark, spectral (Jose's talk)
- Gravitational lensing of gravitational waves

- Tests of no-hair theorem
- Polarization tests (e.g. birefringence)
- # of spacetime dimensions
- Exotic physics (Masha's talk yesterday)...



Aside: Gravitational-waves are better than EM!

- We understand our sources (from general relativity)
- We understand our selection (from general relativity/statistics)
- Gravitational-waves are never obscured or reddened. Pristine and pure



Thorne 80; Cutler & Flanagan 94; Flanagan & Hughes 98; Schutz 11

$$\frac{dE}{d\Omega dt}=\sum_{l=2}^{\infty}\sum_{l'=2}^{\infty}\frac{1}{4\pi l!\,l'!}\langle {}^{(l+1)}g_{A_l}{}^{(l'+1)}g_{B_{l'}}N_{A_l}N_{B_{l'}}-4\,{}^{(l+1)}g_{jA_{l-1}}{}^{(l'+1)}g_{jB_{l'-1}}N_{A_{l-1}}N_{B_{l'-1}}+2\,{}^{(l+1)}g_{jbA_{l-2}}{}^{(l'+1)}g_{jbB_{l'-2}}N_{A_{l-2}}N_{B_{l'-2}}\rangle$$

$$+\sum_{l=2}^{\infty}\sum_{l'=2}^{\infty}\frac{ll'}{4\pi(l+1)!(l'+1)!}\langle 4\,{}^{(l+1)}g_{A_l}{}^{(l'+1)}g_{B_{l'}}N_{A_l}N_{B_{l'}}-8\,{}^{(l+1)}g_{jA_{l-1}}{}^{(l'+1)}g_{jB_{l'-1}}N_{A_{l-1}}N_{B_{l'-1}}$$

$$+4\,{}^{(l+1)}g_{jbA_{l-2}}{}^{(l'+1)}g_{jbB_{l'-2}}N_{A_{l-2}}N_{B_{l'-2}}-4\epsilon_{cdj}\epsilon_{deb}\,{}^{(l+1)}g_{cdA_{l-2}}{}^{(l'+1)}g_{jbB_{l'-2}}n_pn_qN_{A_{l-2}}N_{B_{l'-2}}\rangle$$

$$+\sum_{l=2}^{\infty}\sum_{l'=2}^{\infty}\frac{8l'}{4\pi l!(l'+1)!}\langle -\epsilon_{jkp}\,{}^{(l+1)}g_{jA_{l-1}}{}^{(l'+1)}g_{kB_{l'-1}}n_pN_{A_{l-1}}N_{B_{l'-1}}+\epsilon_{jkb}\,{}^{(l+1)}g_{jiA_{l-2}}{}^{(l'+1)}g_{kiB_{l'-2}}n_pN_{A_{l-2}}N_{B_{l'-2}}\rangle. \quad (4.14')$$

Cosmic Explorer to the rescue!

- CE will be transformational
- We have trouble even articulating the science which CE will revolutionize
- CE is in some sense complete