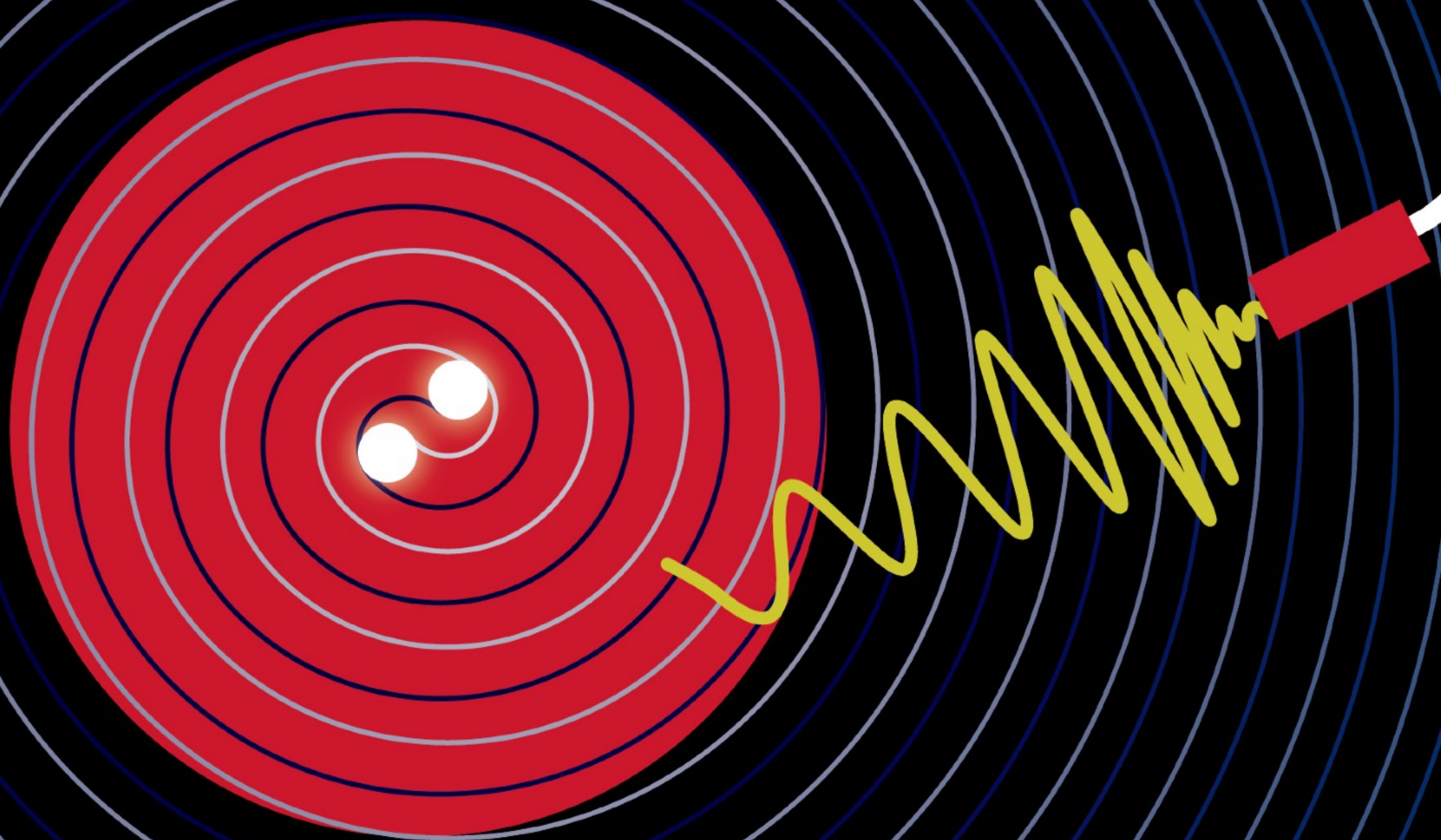
Image credit: S.W. Angela Chen

Gravitational-wave standard sirens with electromagnetic counterparts

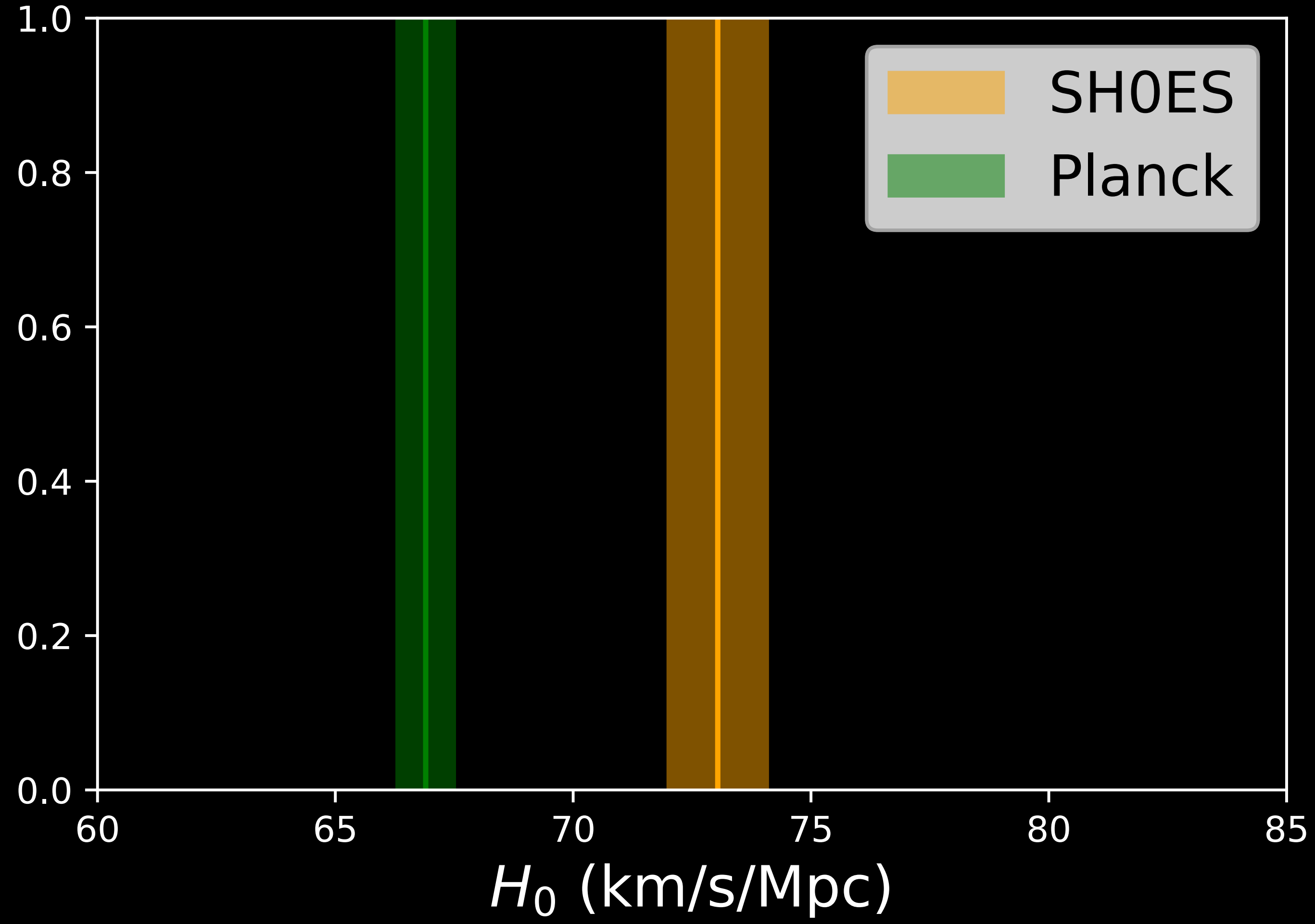


Hsin-Yu Chen

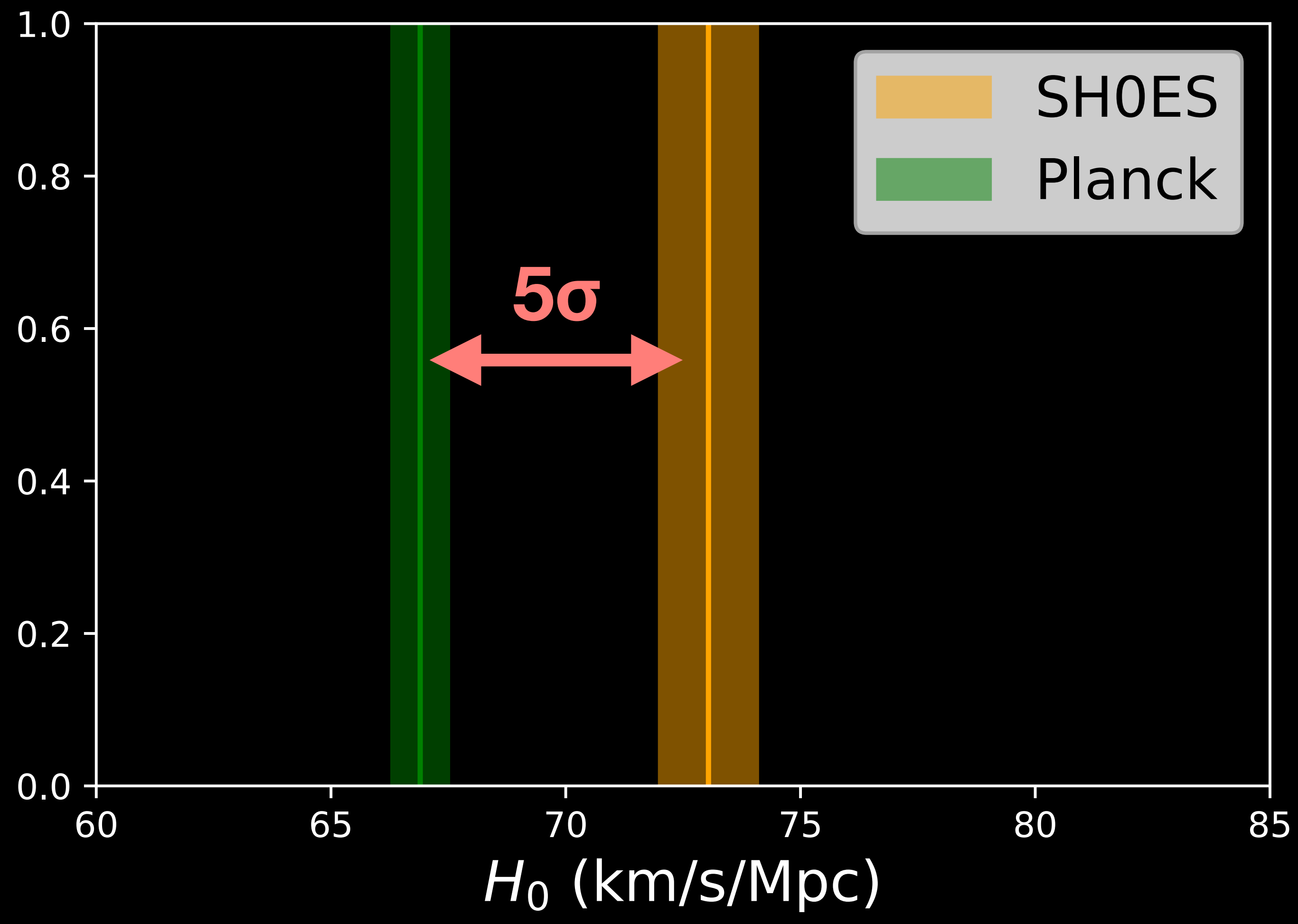
TEXAS
The University of Texas at Austin

ModIC 2024, May 2024

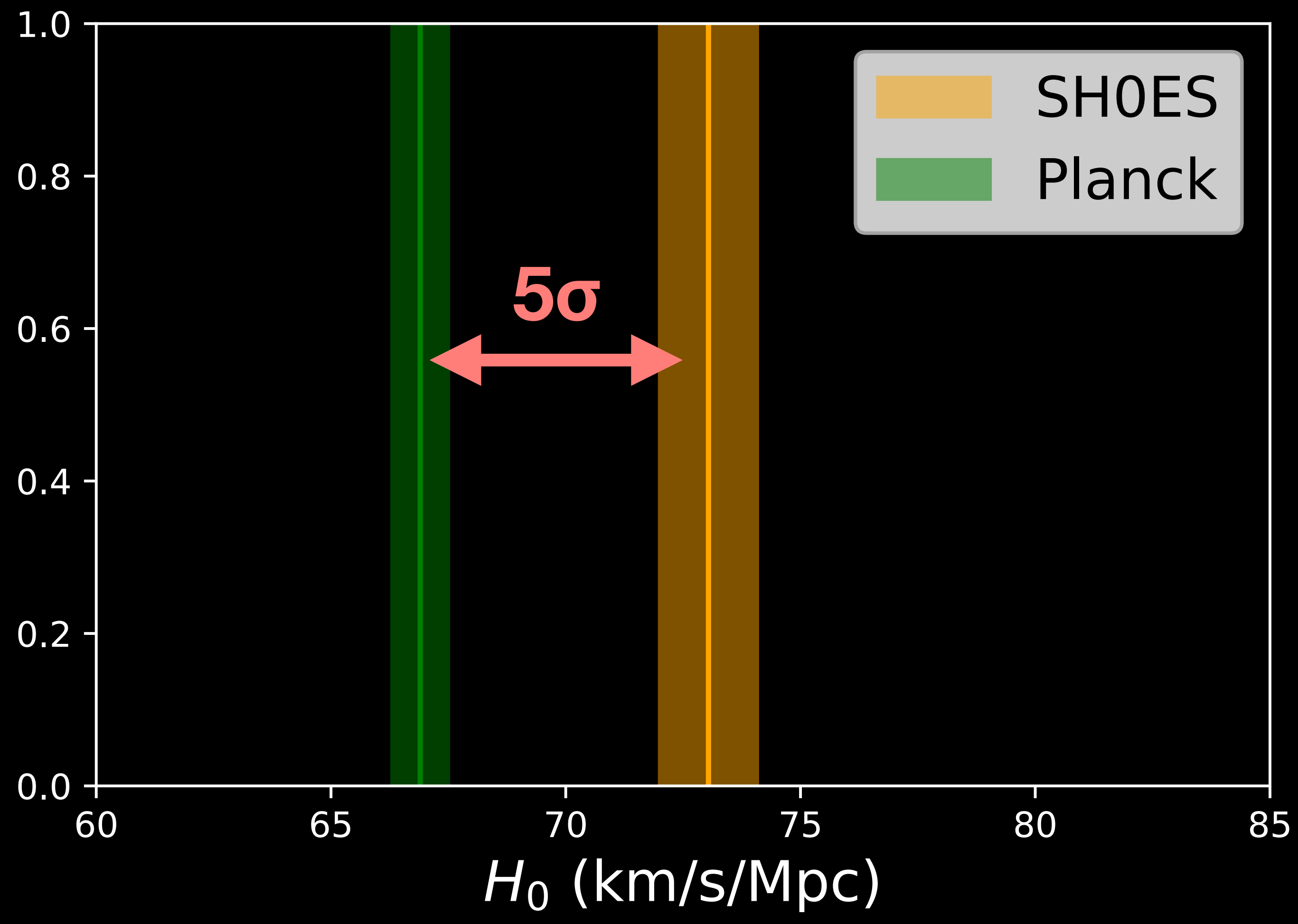
Tension in the Hubble constant measurement



Tension in the Hubble constant measurement

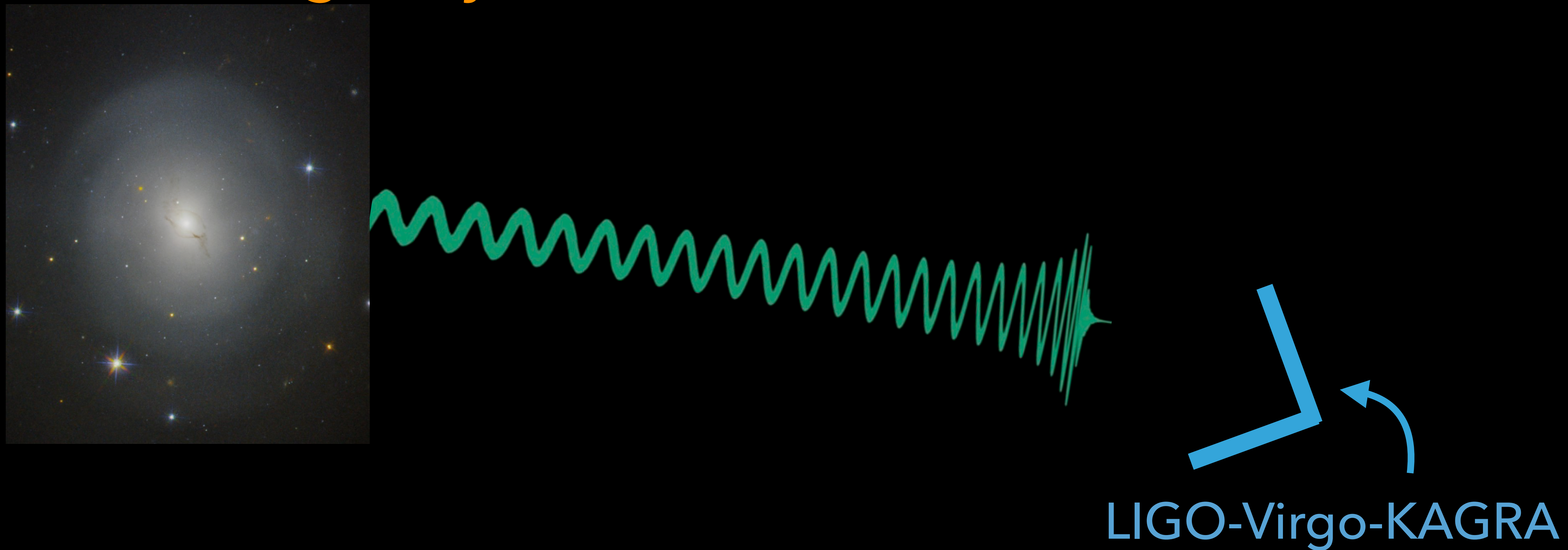


Tension in the Hubble constant measurement



Independent measurement of the cosmological parameters— Standard siren method

Standard siren with electromagnetic counterparts: Determine the redshift of gravitational-wave source with the host galaxy



Schutz, Nature (1986) / Holz & Hughes, ApJ (2005)

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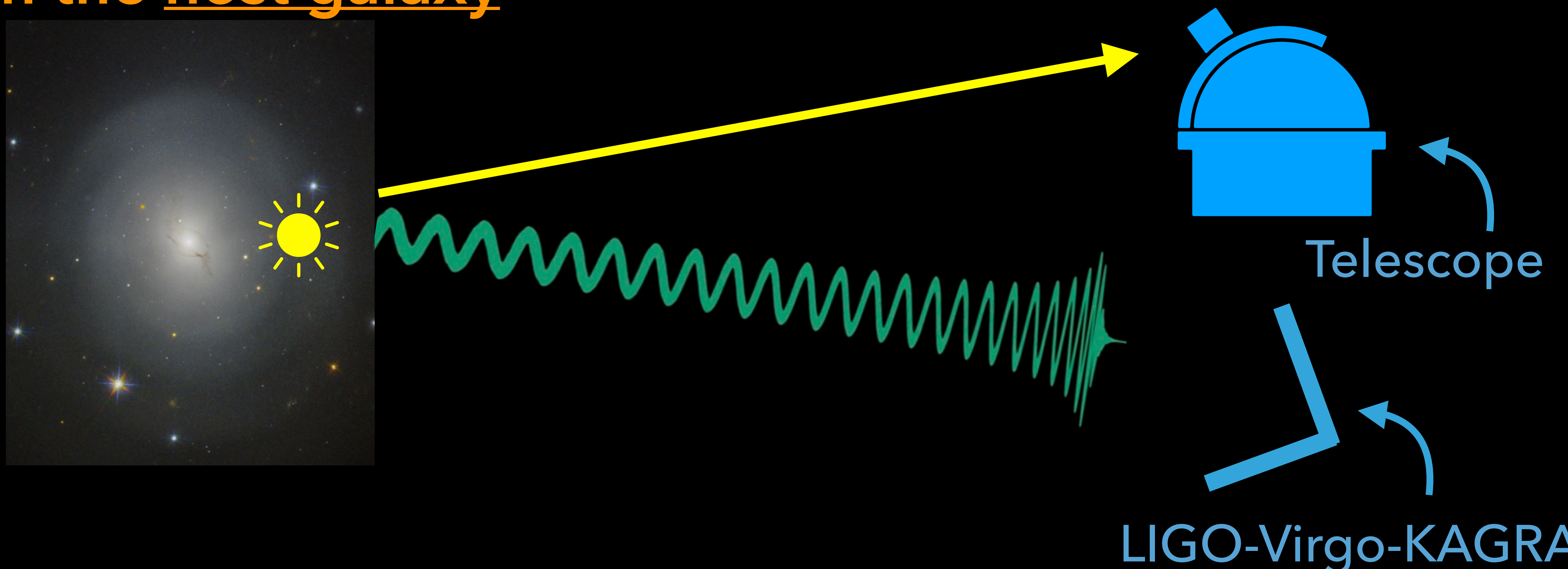

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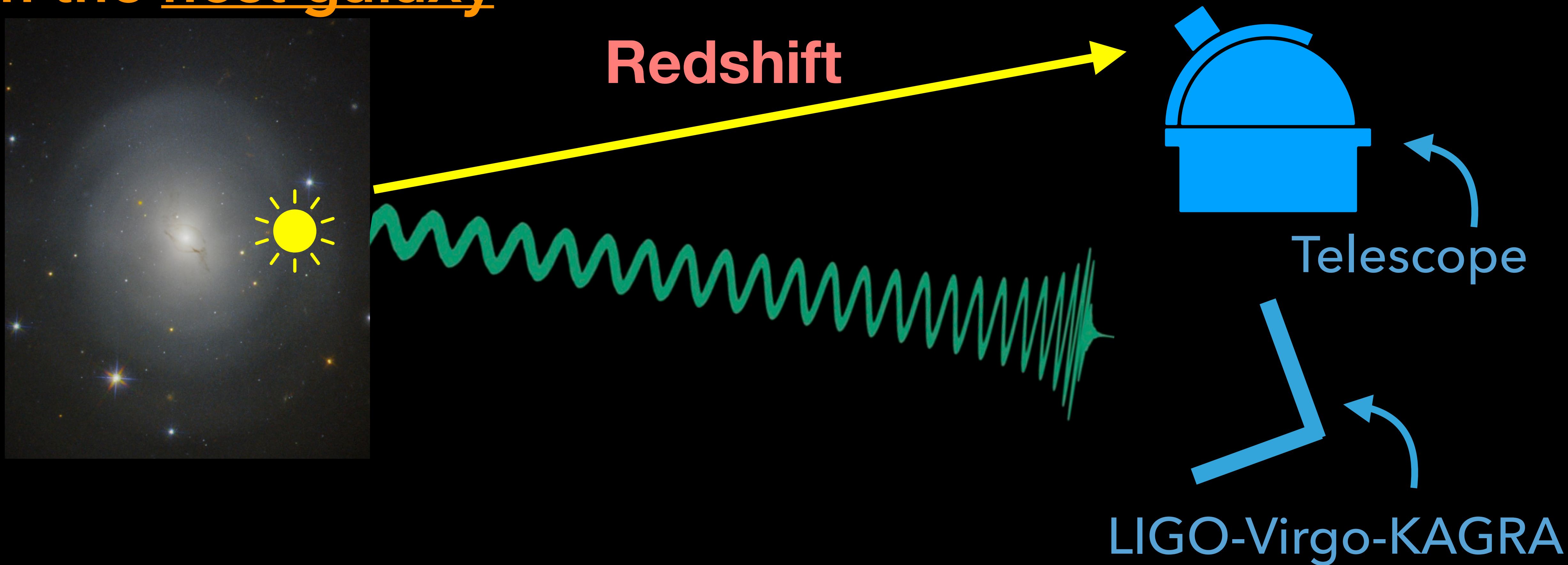

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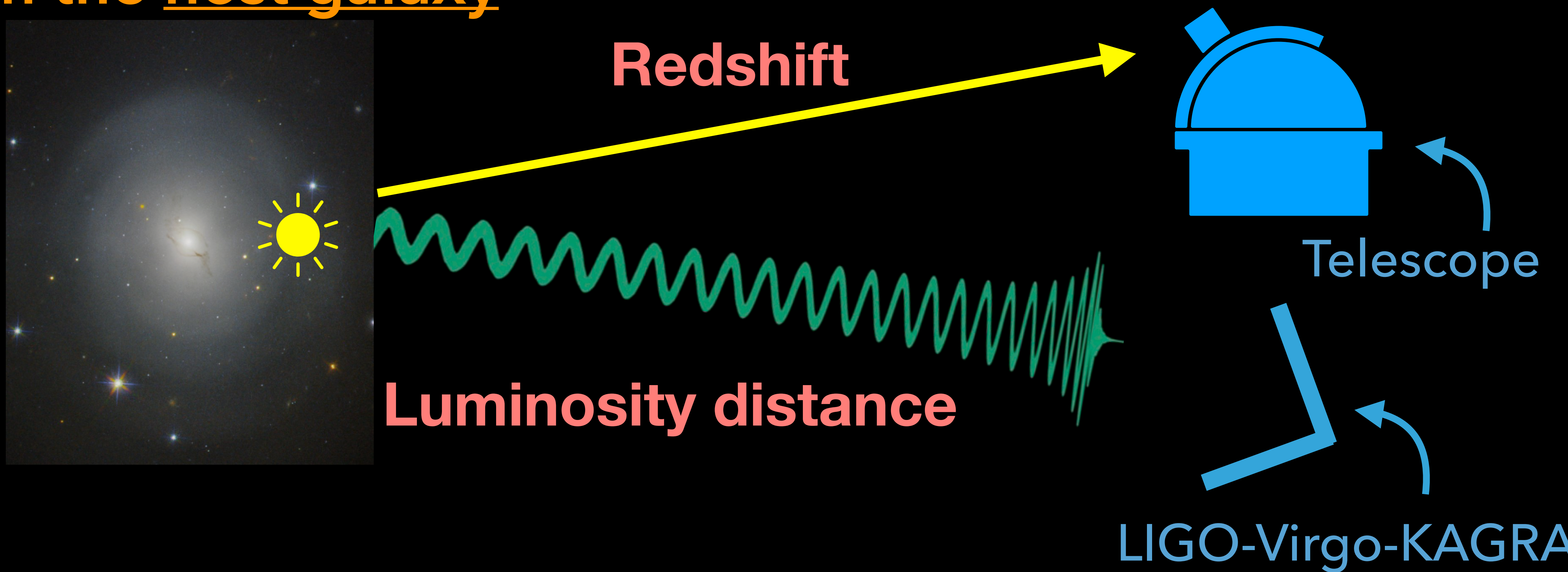

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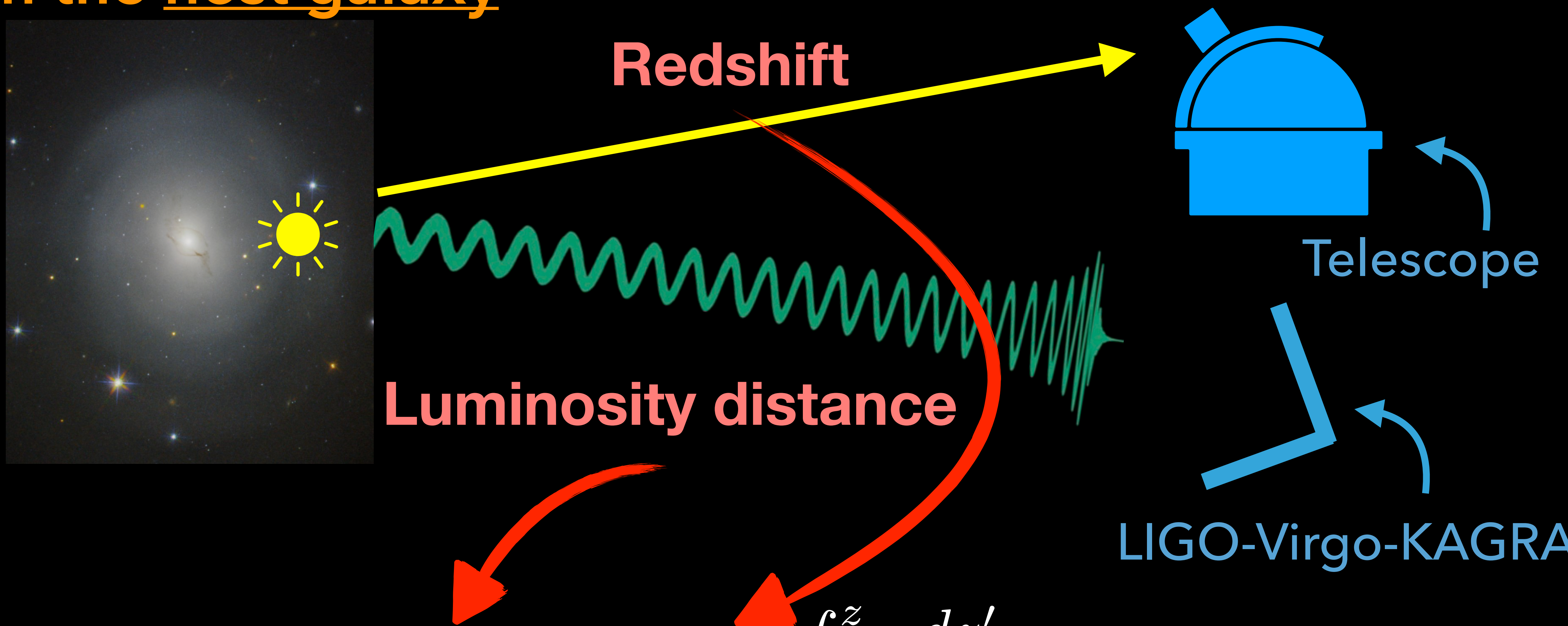


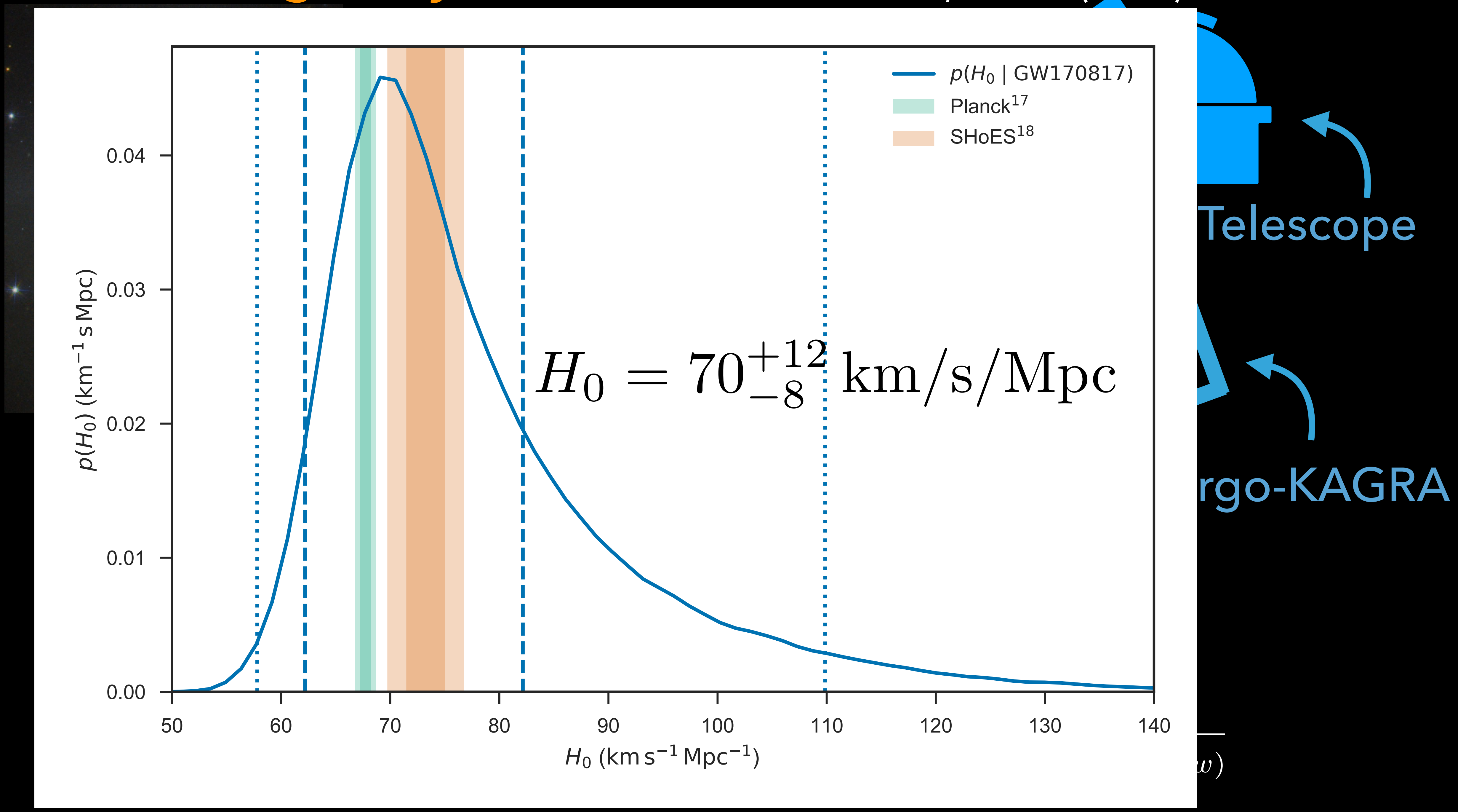
$$D_L = c(1+z)\int_0^z \frac{dz'}{H(z')}$$

$$H(z) = H_0\sqrt{\Omega_M(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda(1+z)^{3(1+w)}}$$

Schutz, Nature (1986) / Holz & Hughes, ApJ (2005)

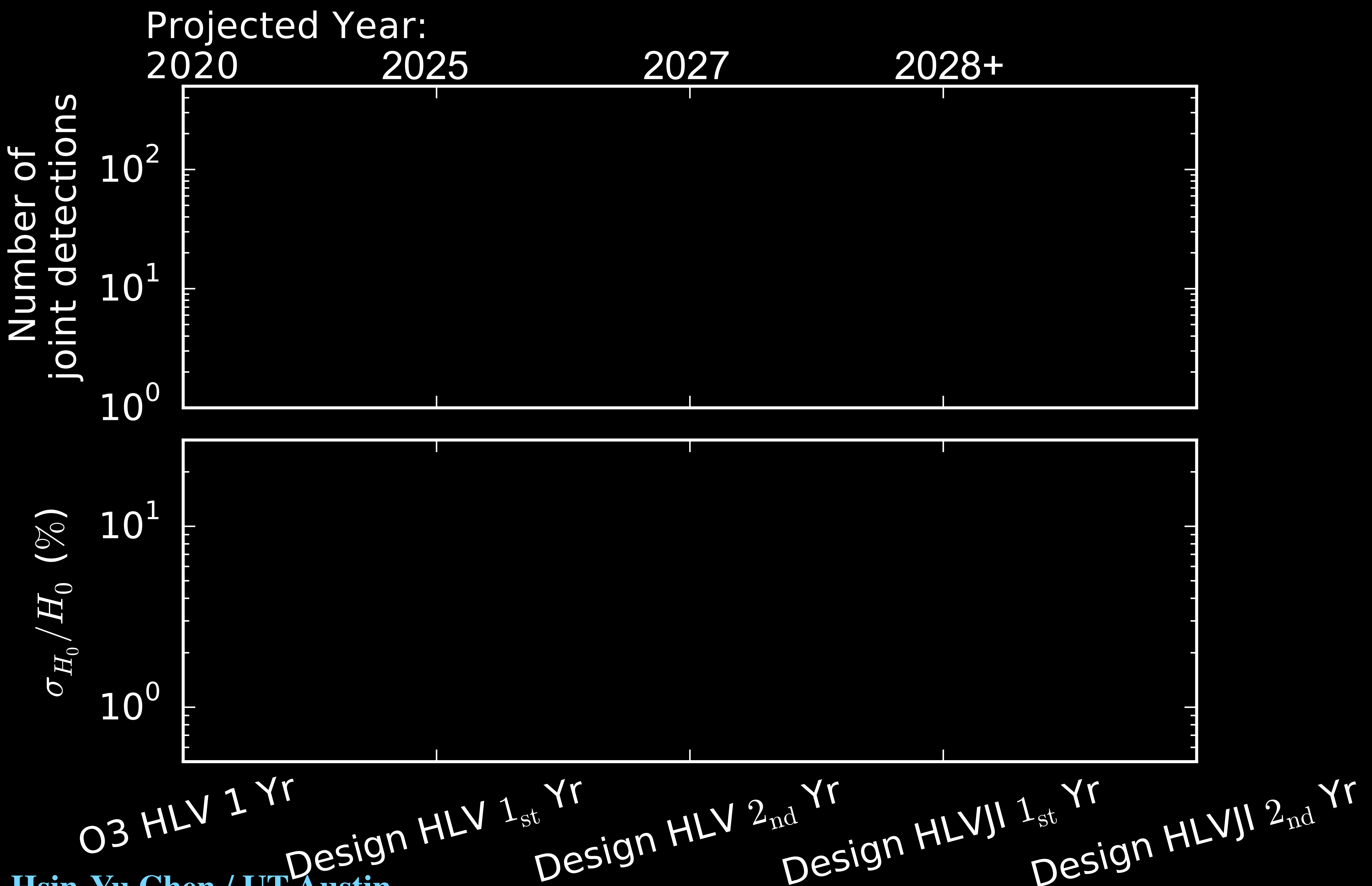
Standard siren with electromagnetic counterparts: Determine the redshift of gravitational-wave source with the host galaxy

Abbott et al., Nature (2017)



Schutz, Nature (1986) / Holz & Hughes, ApJ (2005)

Percent-level Hubble constant measurement within a few years



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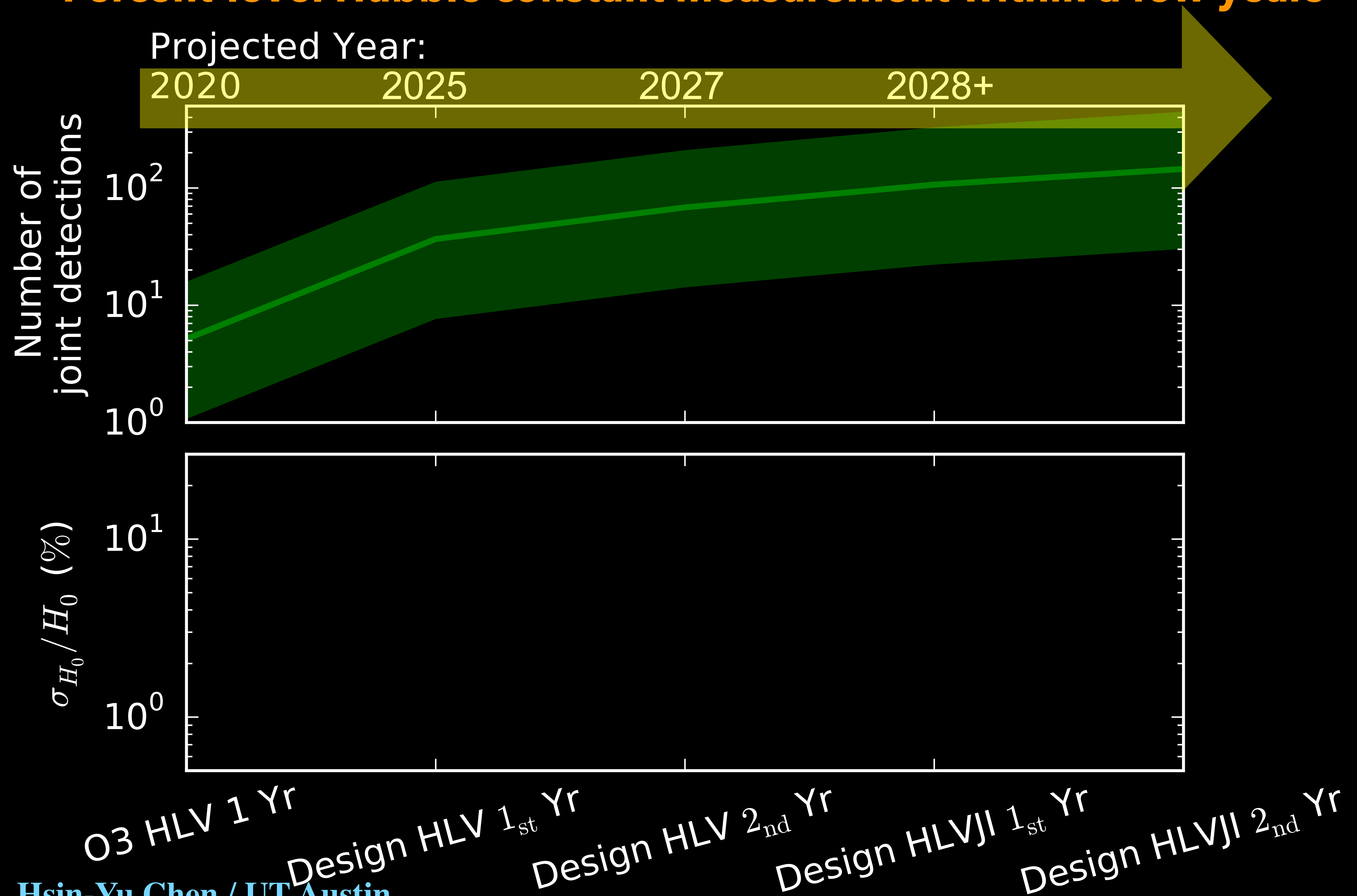

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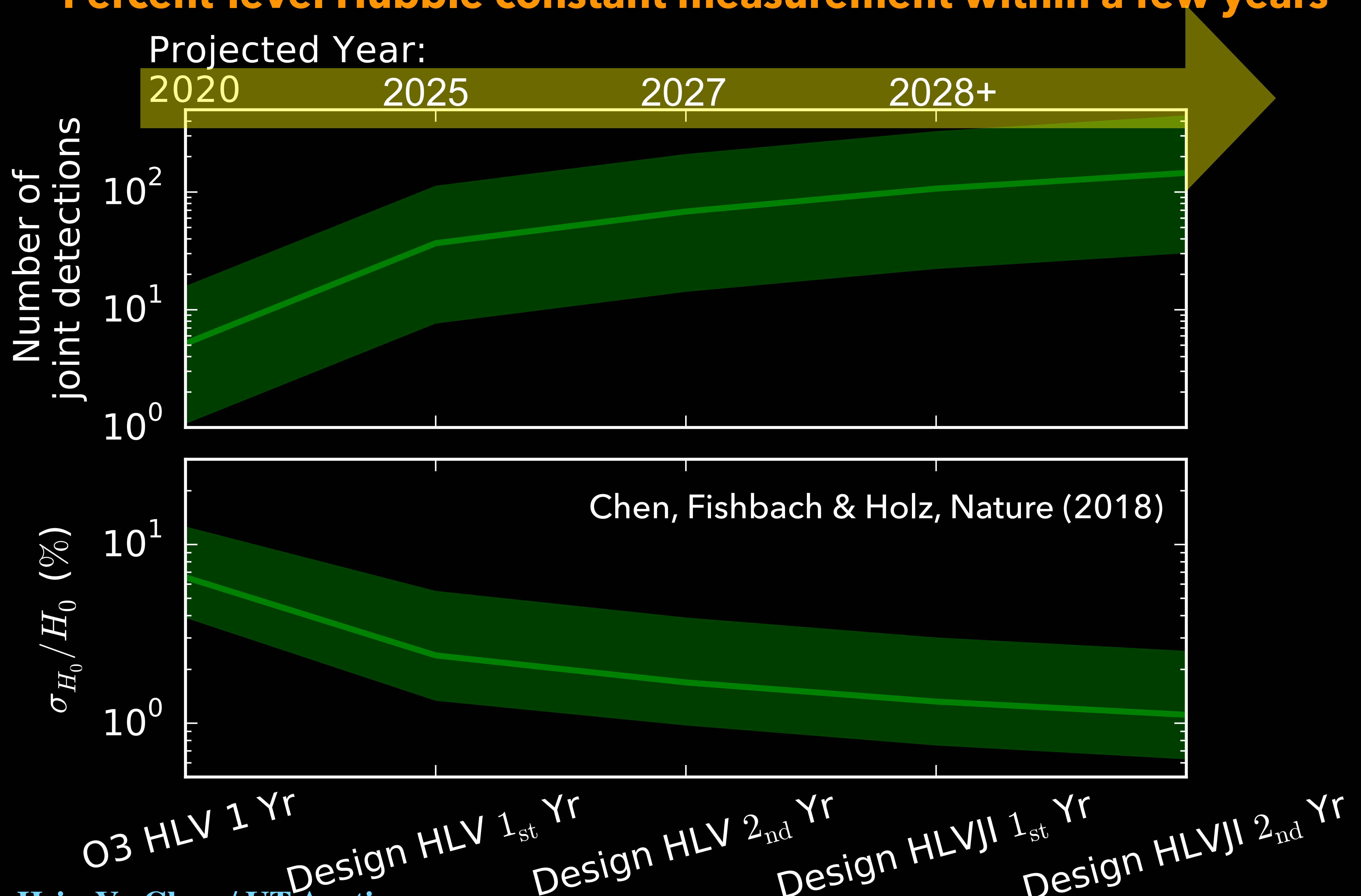

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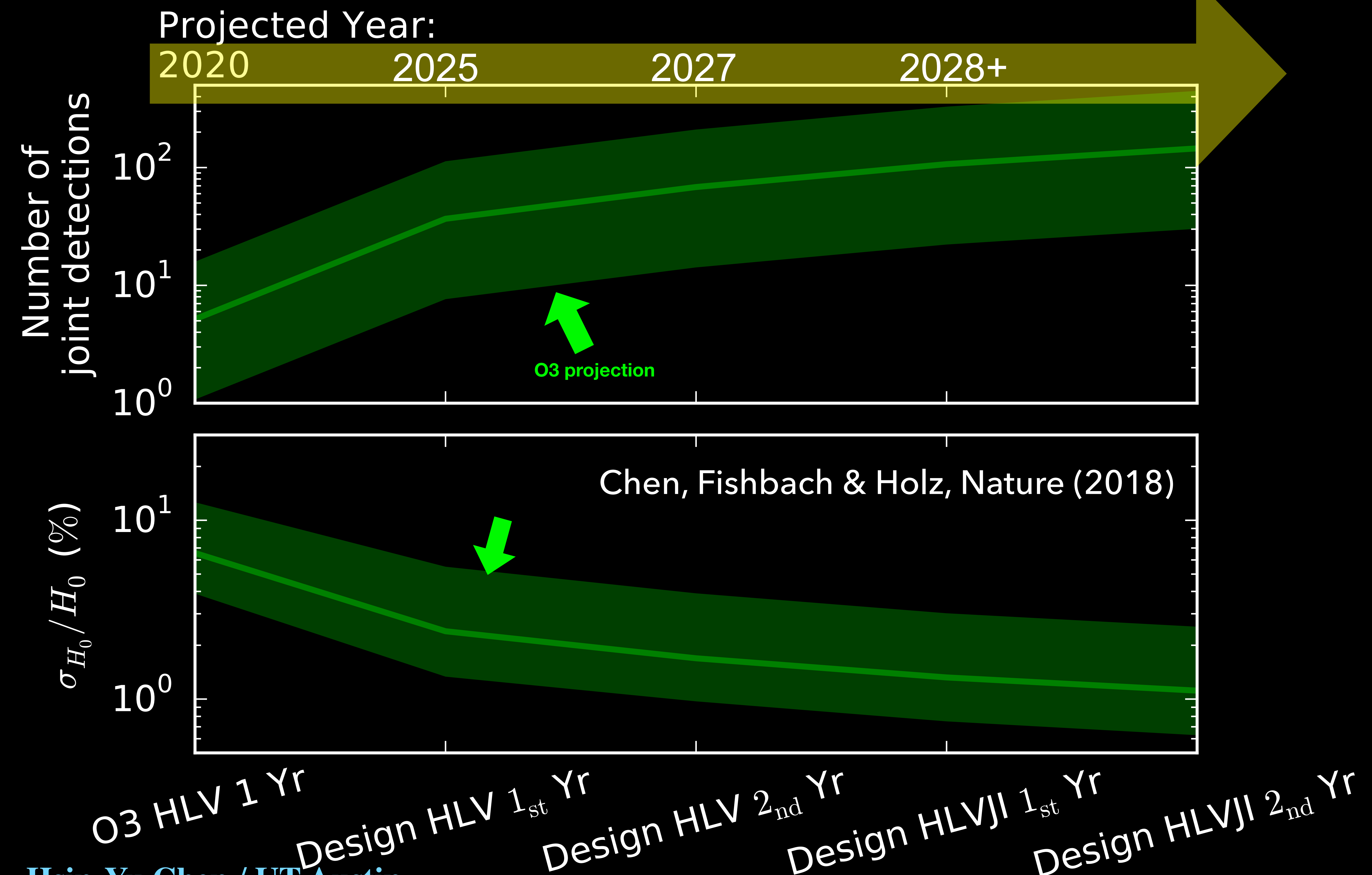

Hsin-Yu Chen / UT Austin

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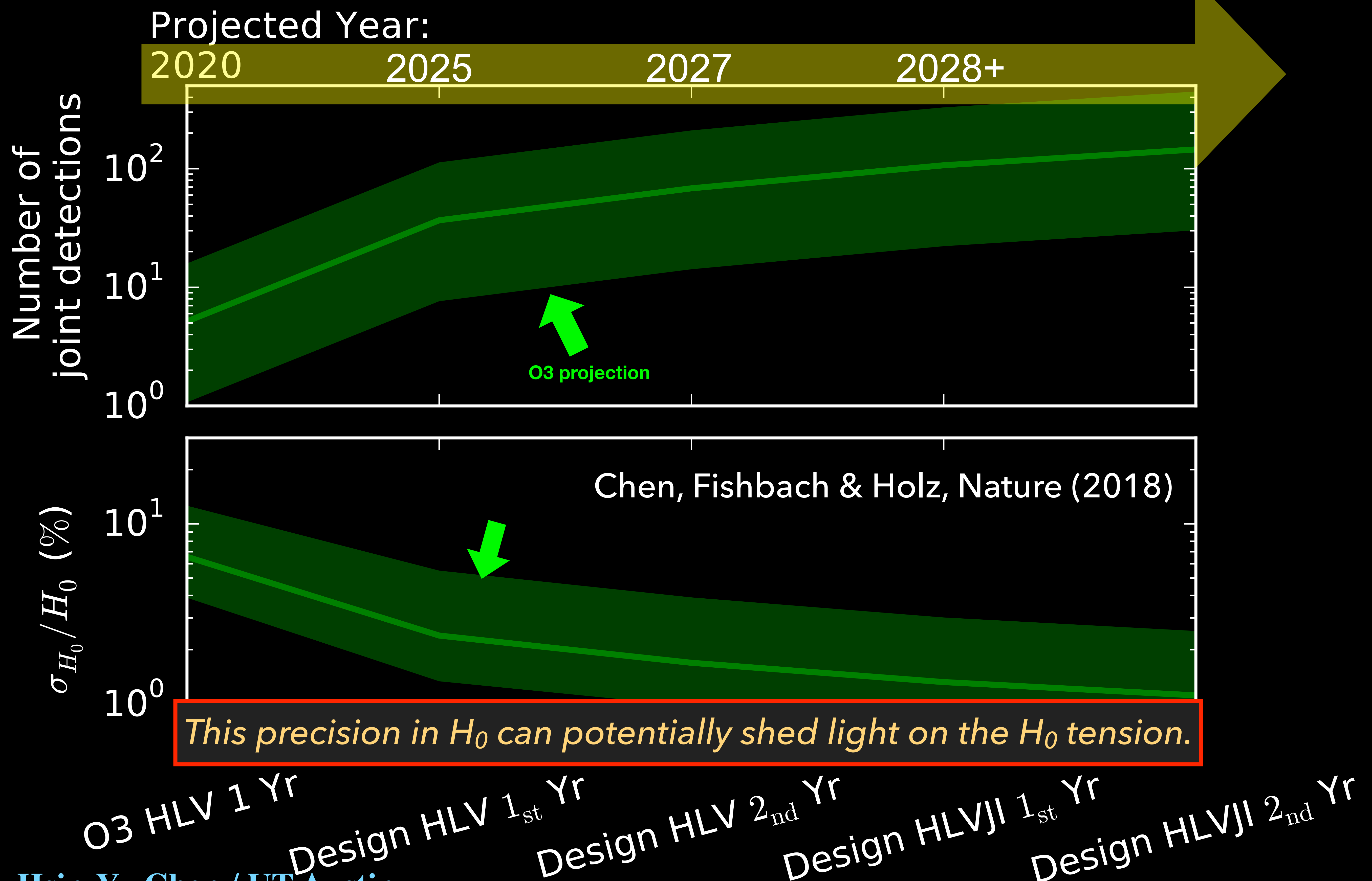
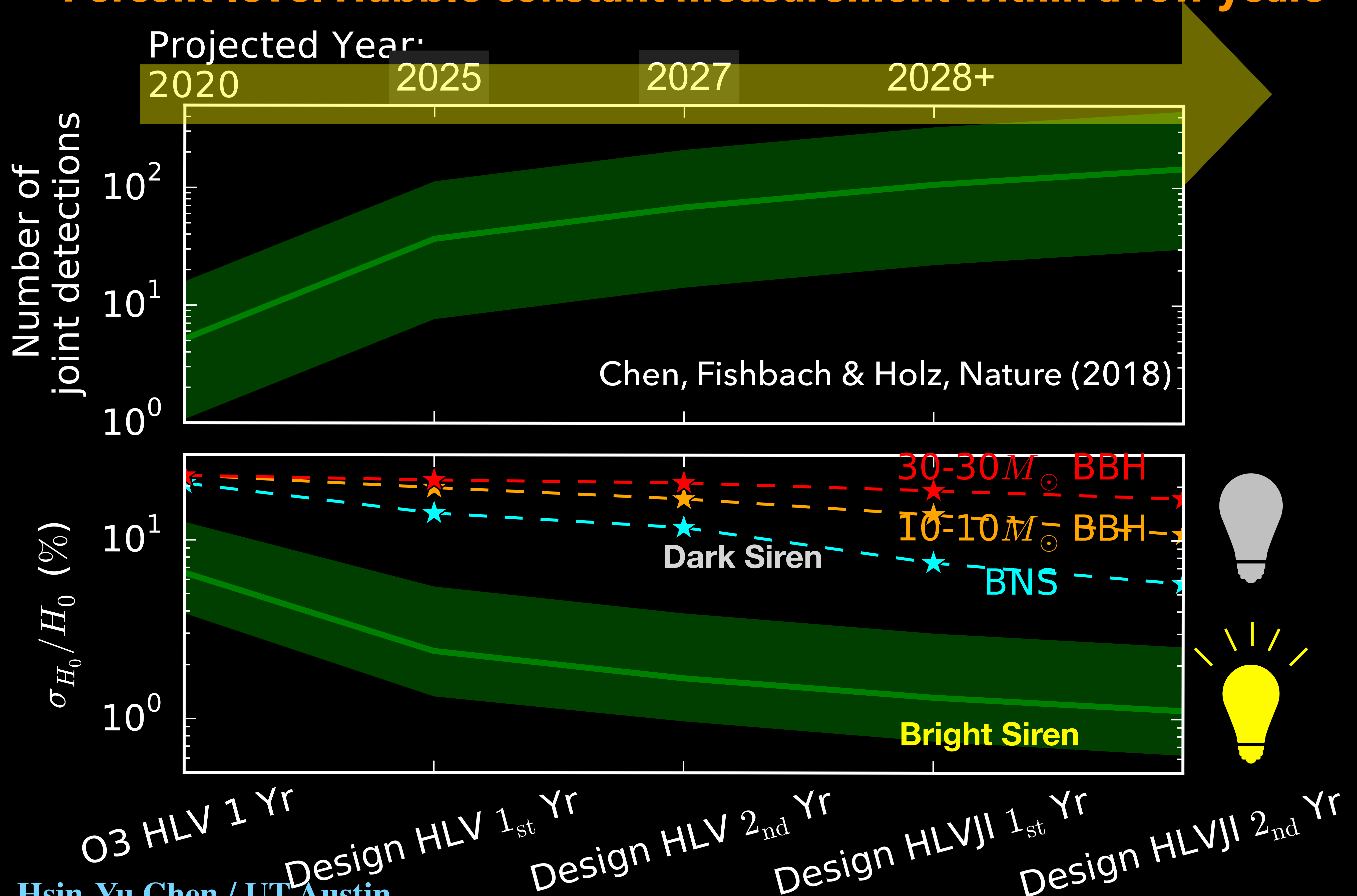


This precision in H_0 can potentially shed light on the H_0 tension.

Percent-level Hubble constant measurement within a few years



How do we improve the precision of the standard siren measurements?

How do we improve the precision of the standard siren measurements?

Distance-inclination degeneracy.

Binary distance and viewing angle are degenerated

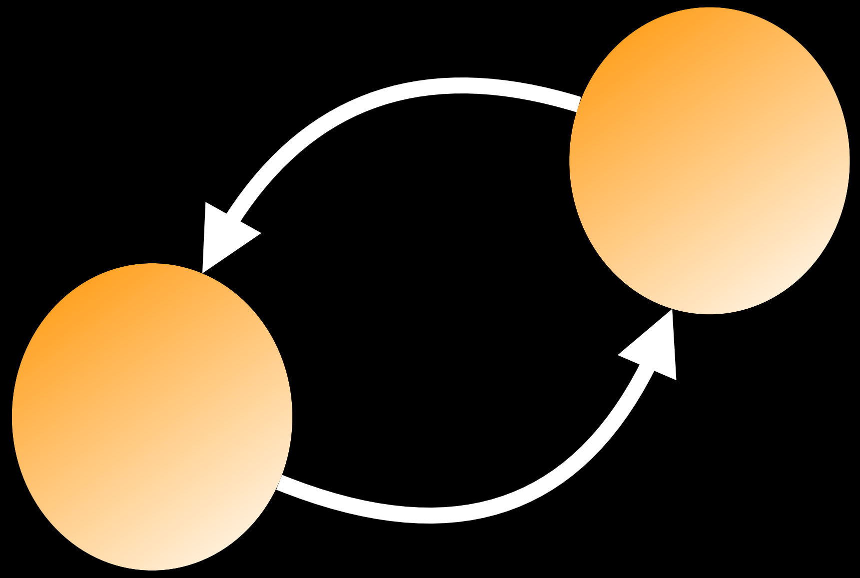
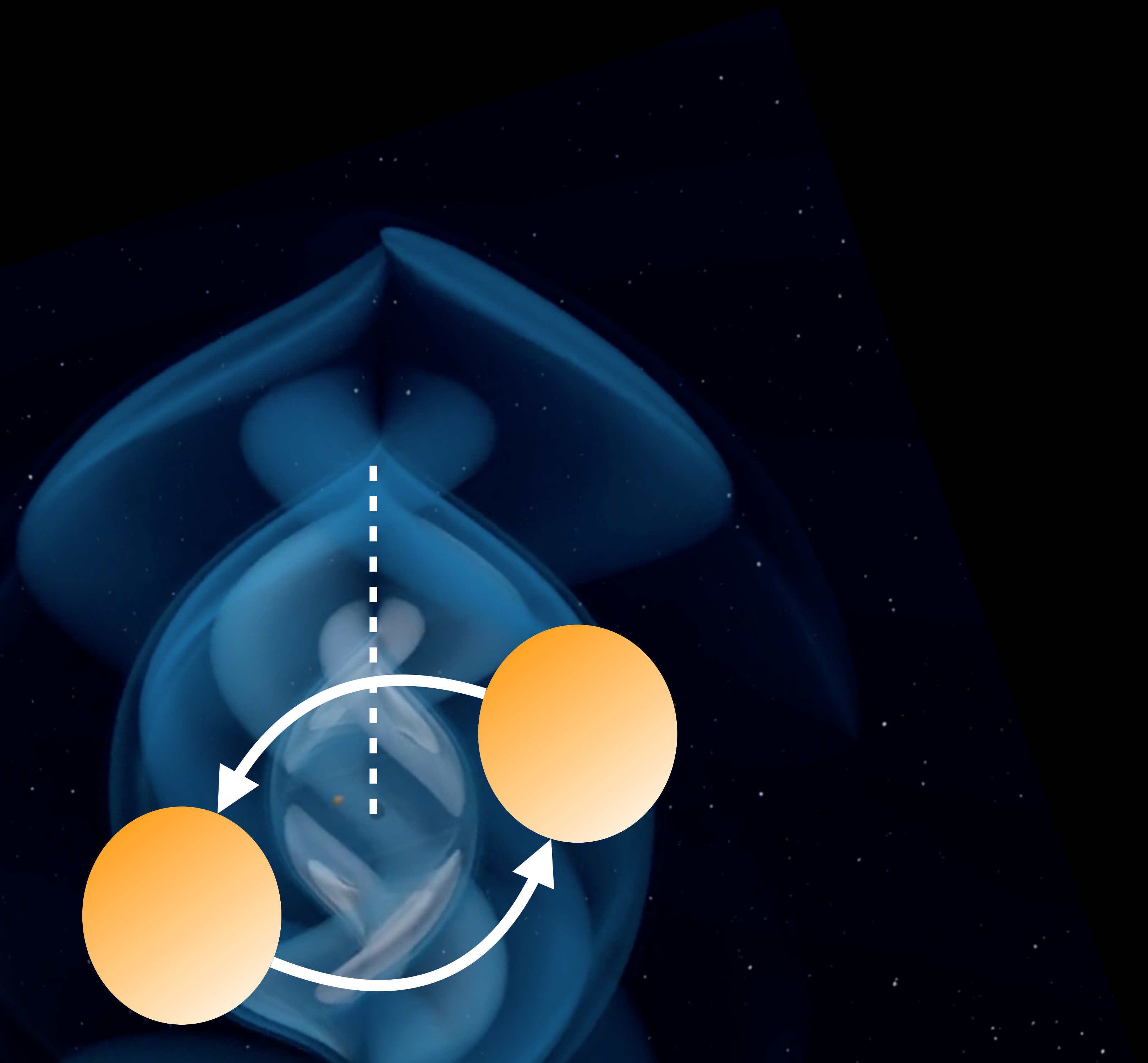


Image credit: S.V. Chaurasia & T. Dietrich

Binary distance and viewing angle are degenerated



Hsin-Yu Chen / UT Austin

Image credit: S.V. Chaurasia & T. Dietrich

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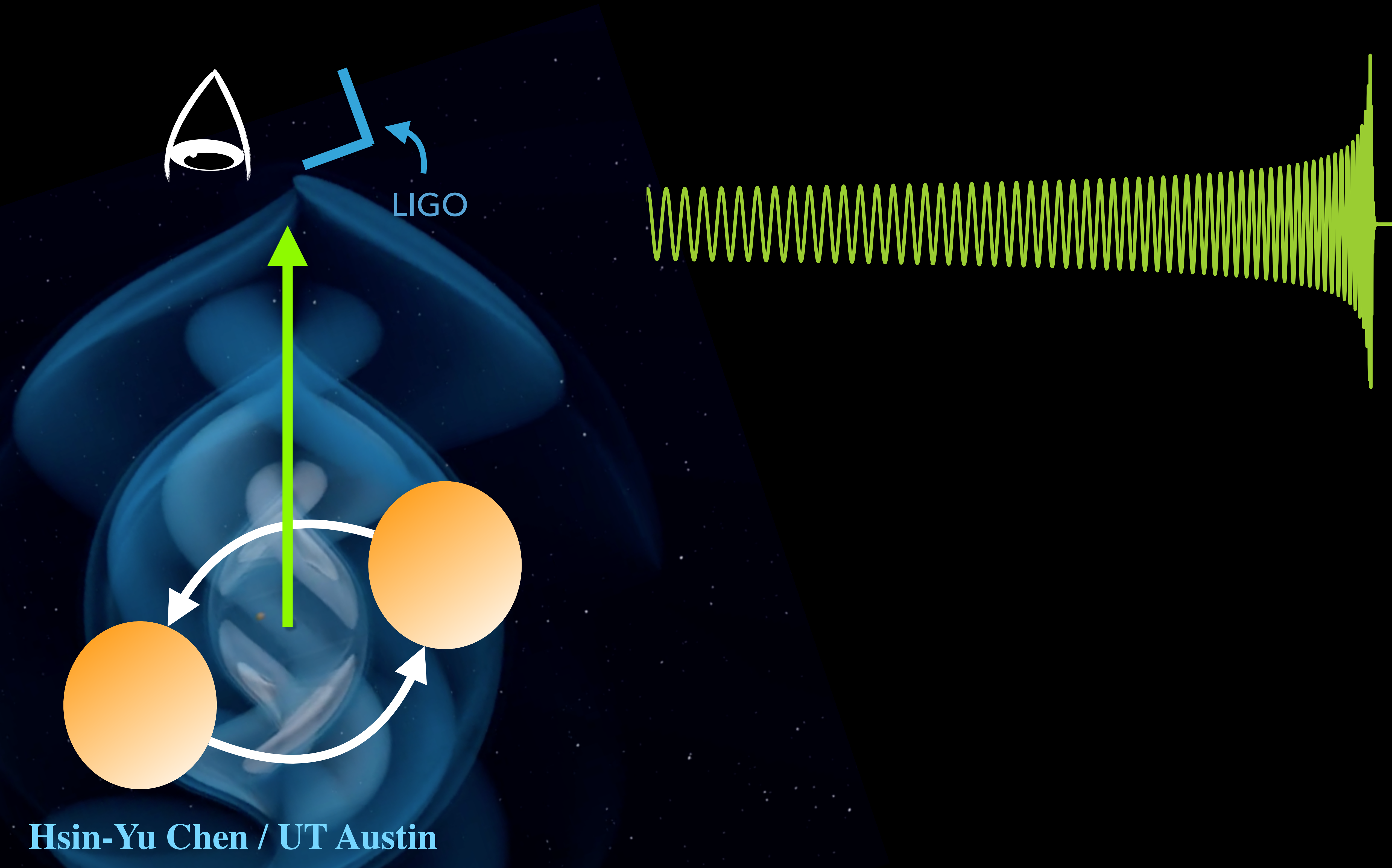

Image credit: S.V. Chaurasia & T. Dietrich

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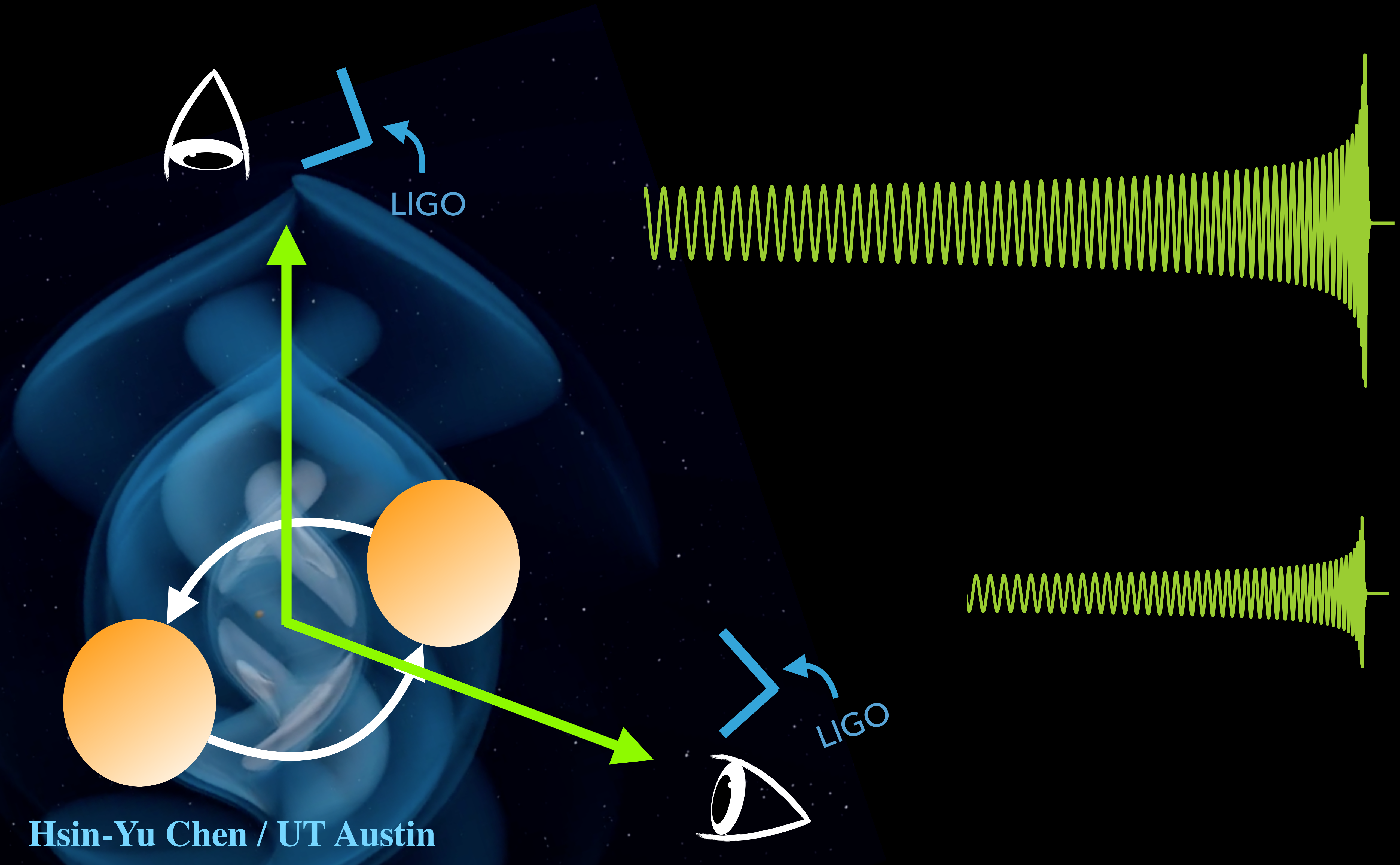

Image credit: S.V. Chaurasia & T. Dietrich

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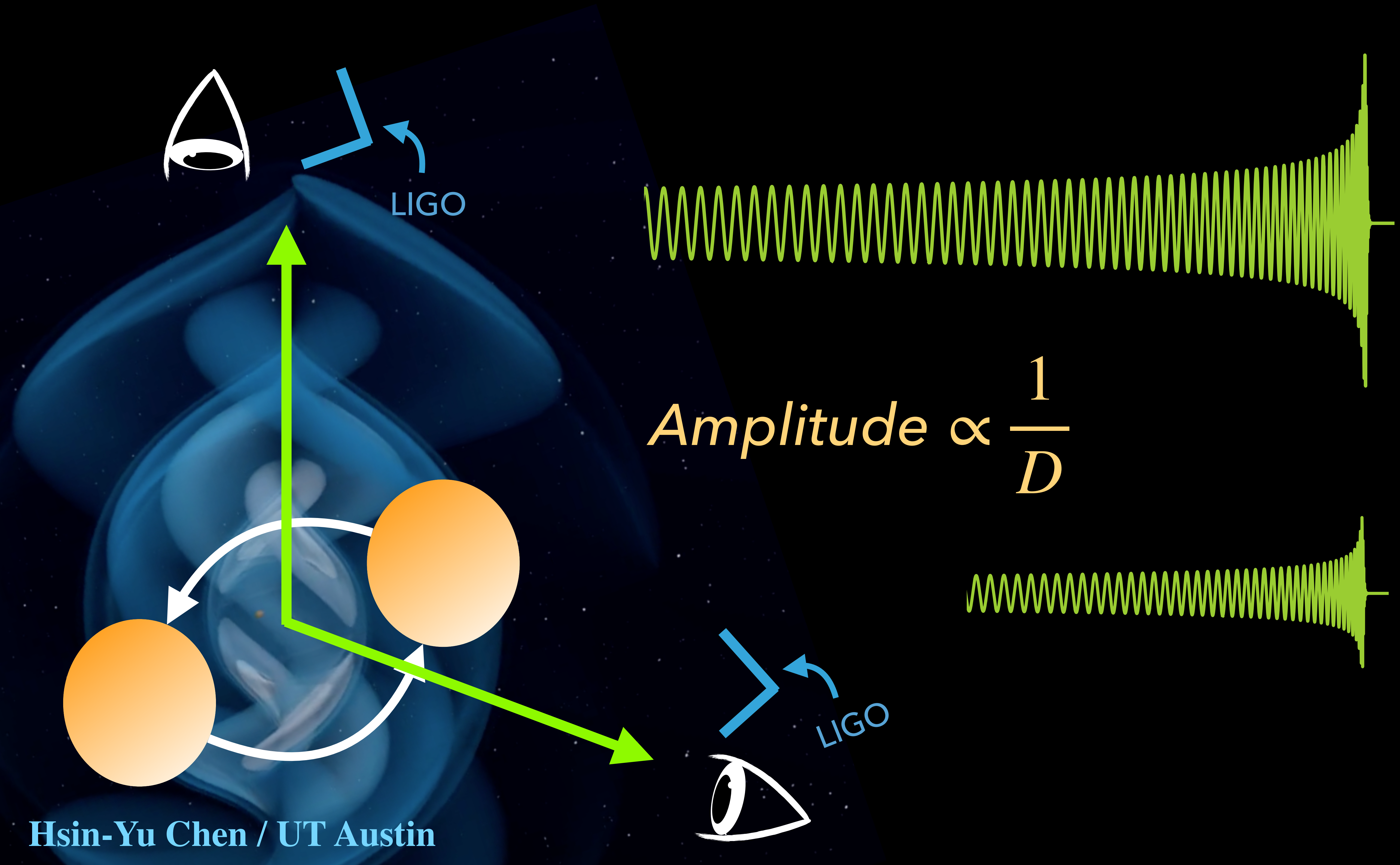

$$Amplitude \propto \frac{1}{D}$$

Image credit: S.V. Chaurasia & T. Dietrich

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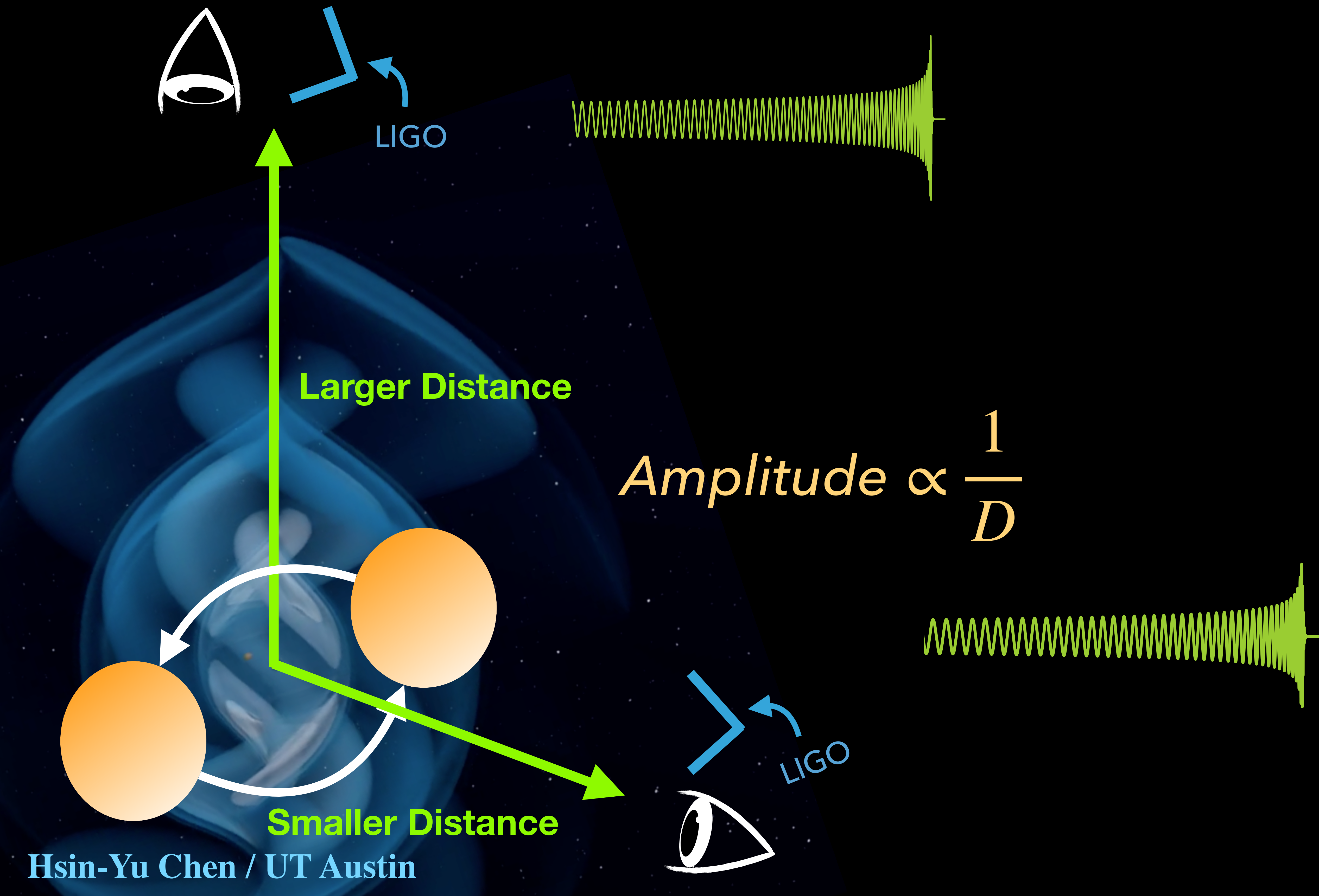

$$Amplitude \propto \frac{1}{D}$$

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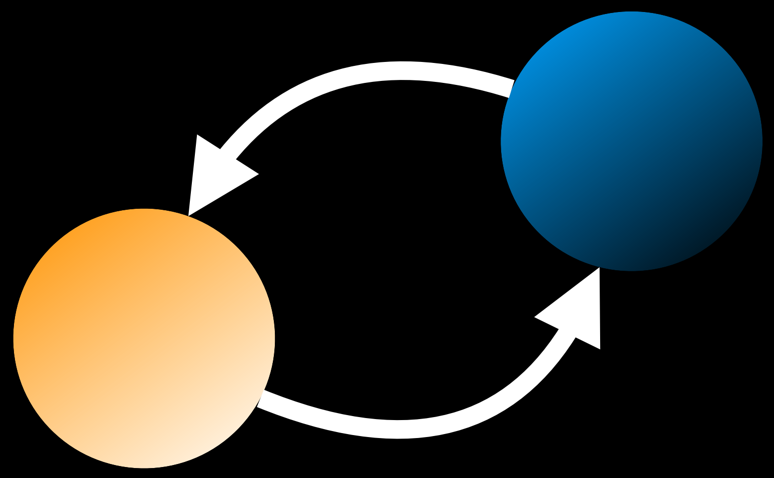
Break the distance-inclination degeneracy

A) ***Neutron star-black hole*** *mergers with precession.*

Vitale & Chen, PRL (2018)



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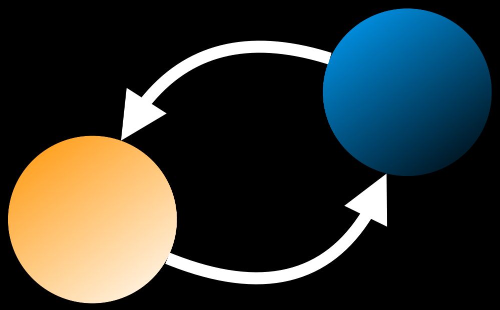
-Electromagnetic emissions could be powered by tidal disruption of the neutron star and the resulting accretion disk.



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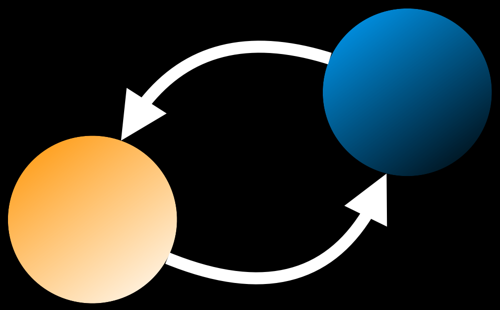
-Electromagnetic emissions could be powered by tidal disruption of the neutron star and the resulting accretion disk.

-The distance-inclination degeneracy can be broken by the observation of ***precession****.*



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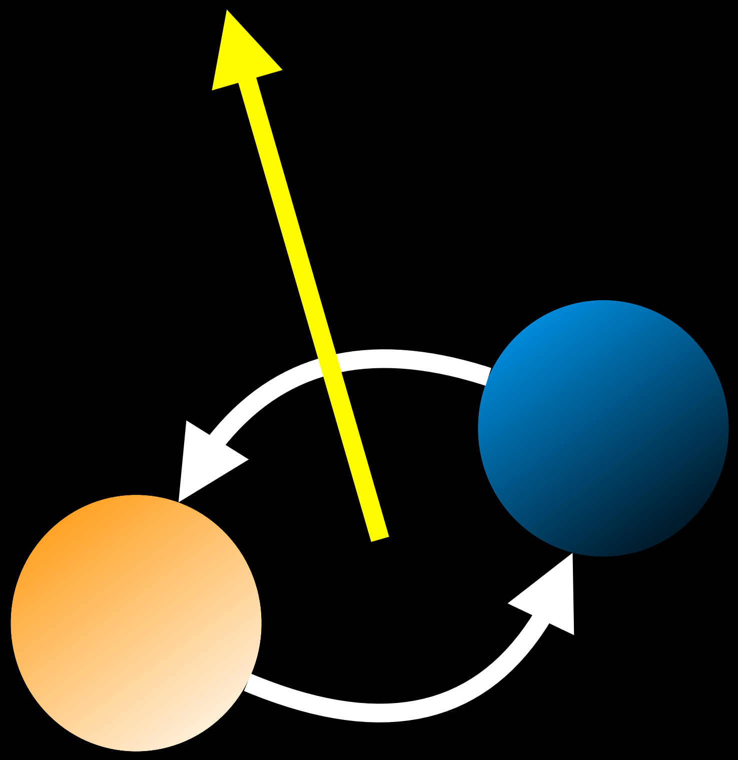

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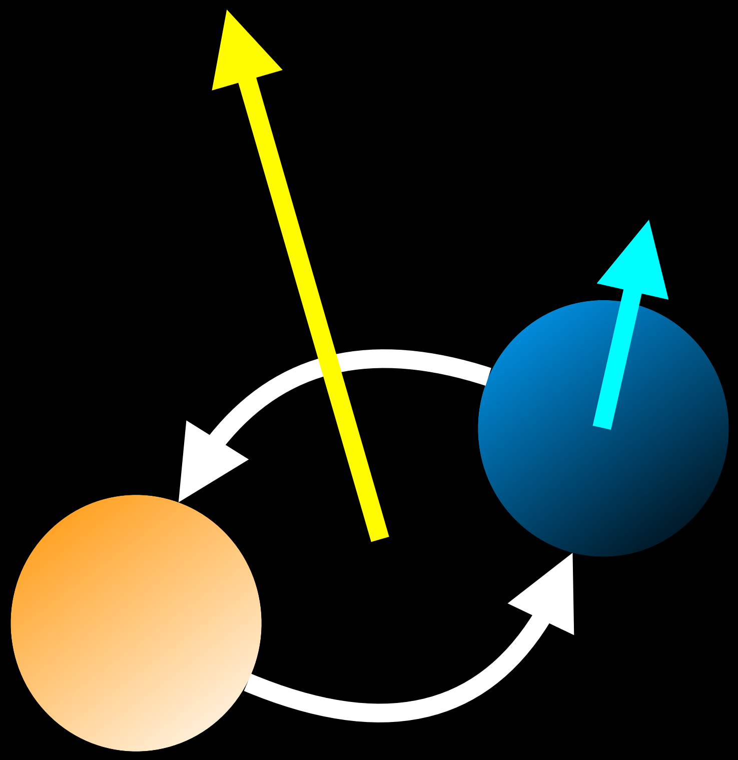

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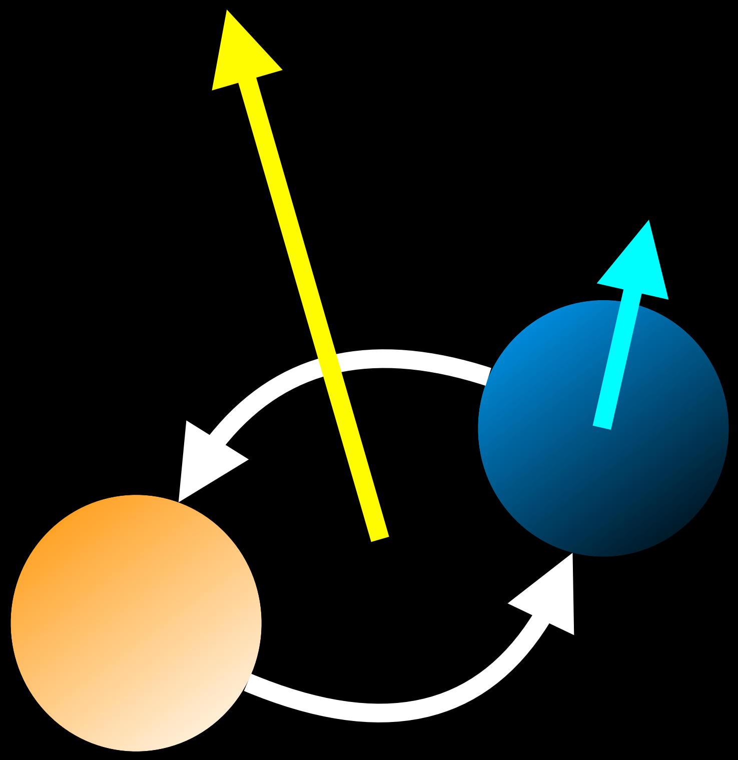

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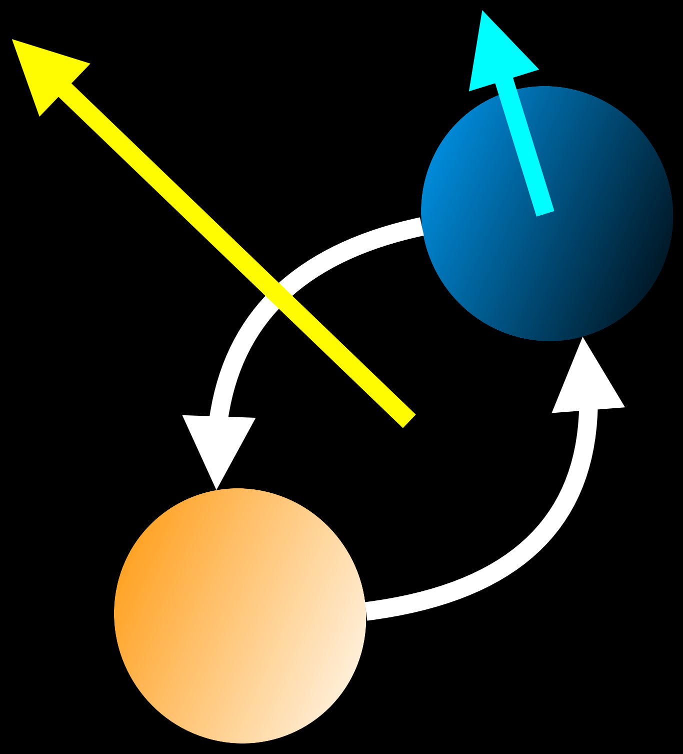

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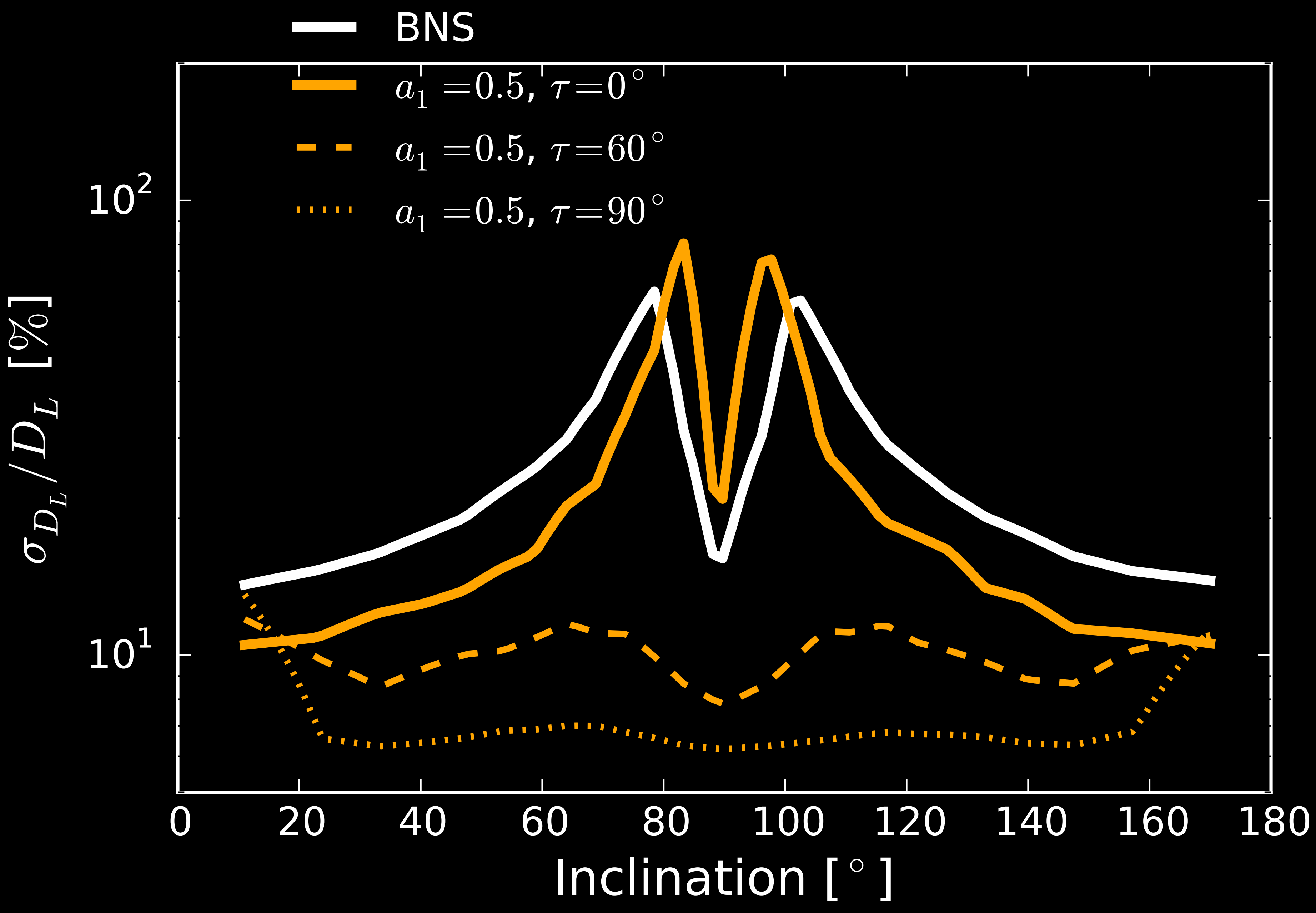
Vitale & Chen, PRL (2018)

Can be viewed as **H$_0$ uncertainty**



Break the distance-inclination degeneracy

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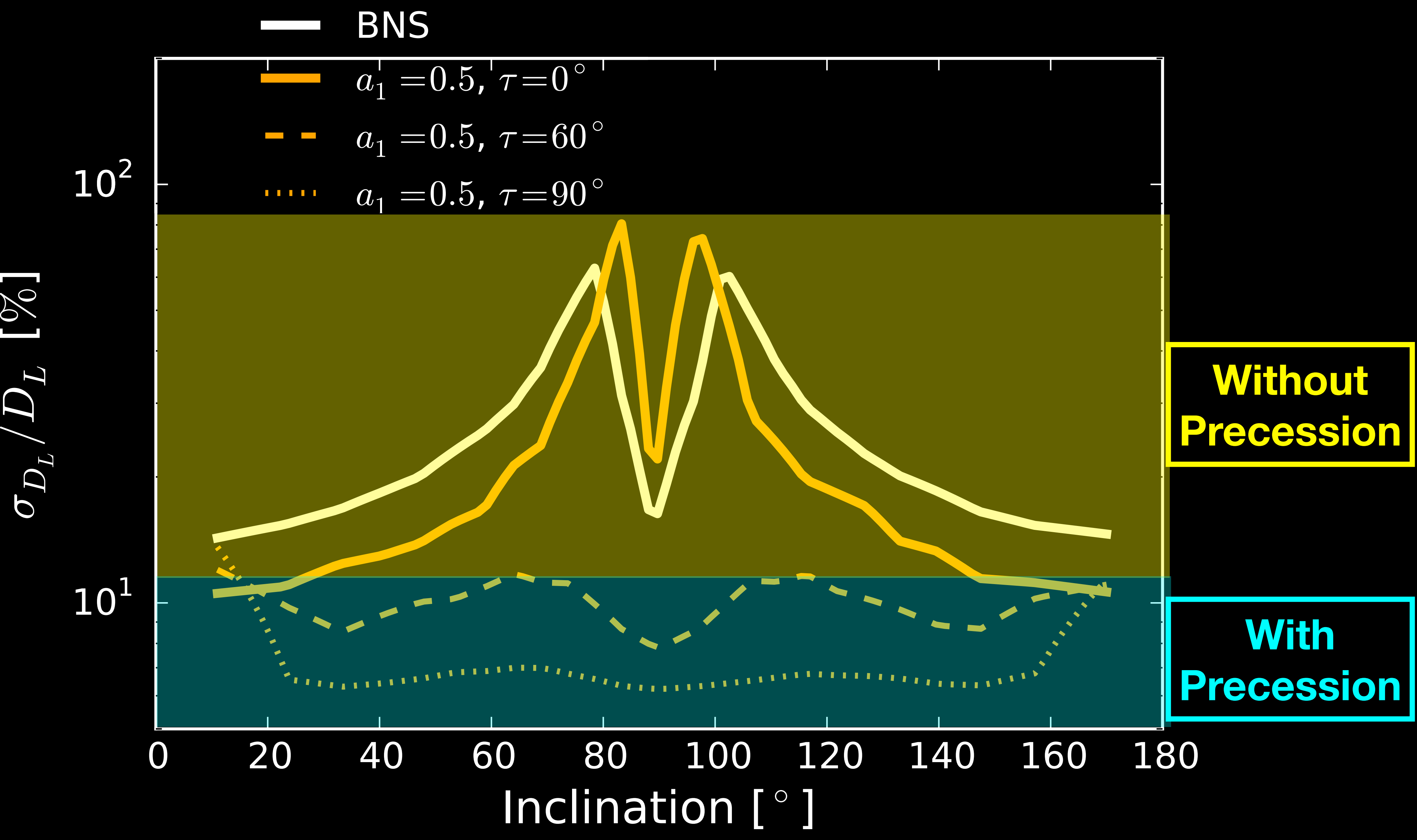

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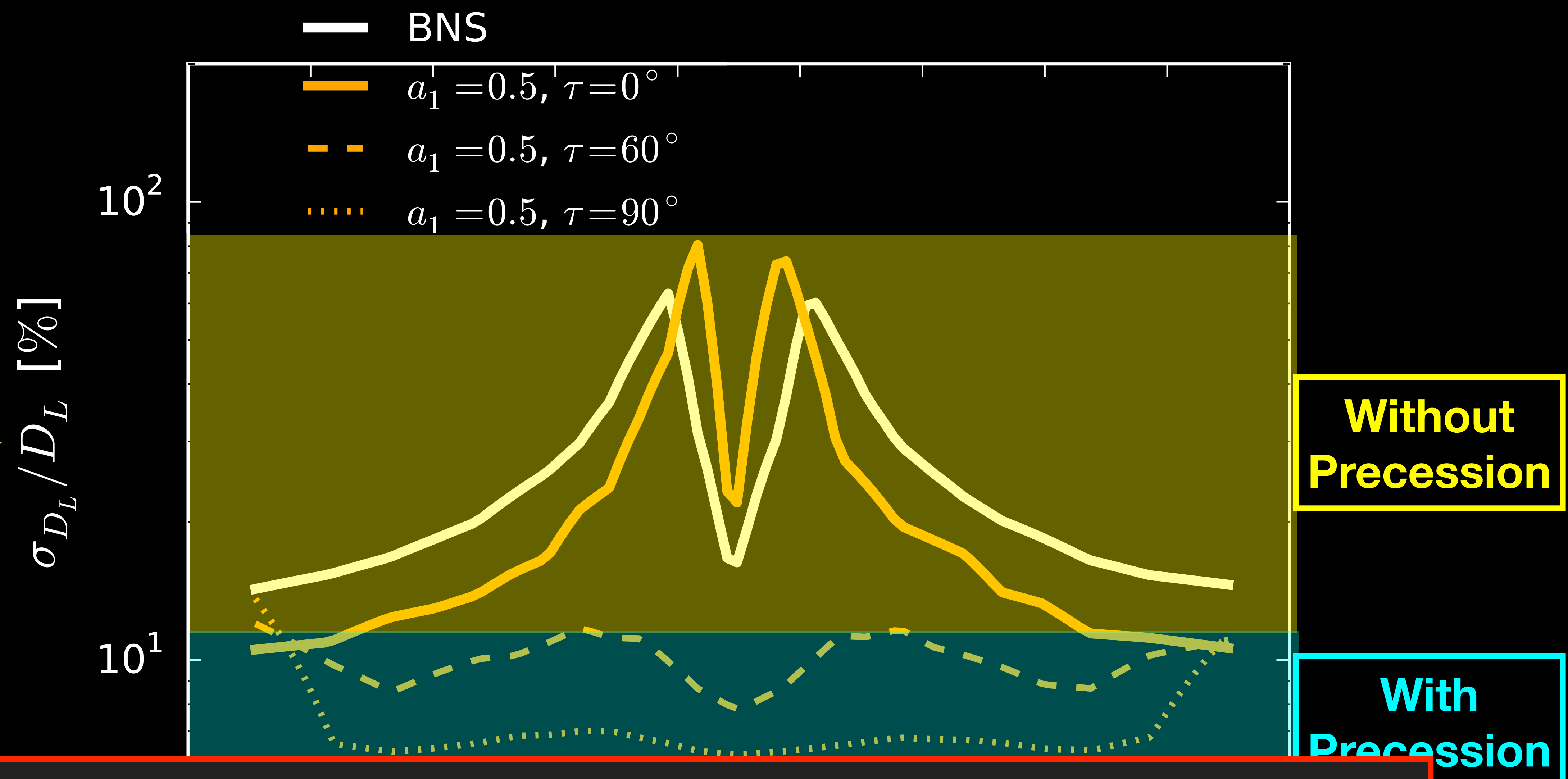
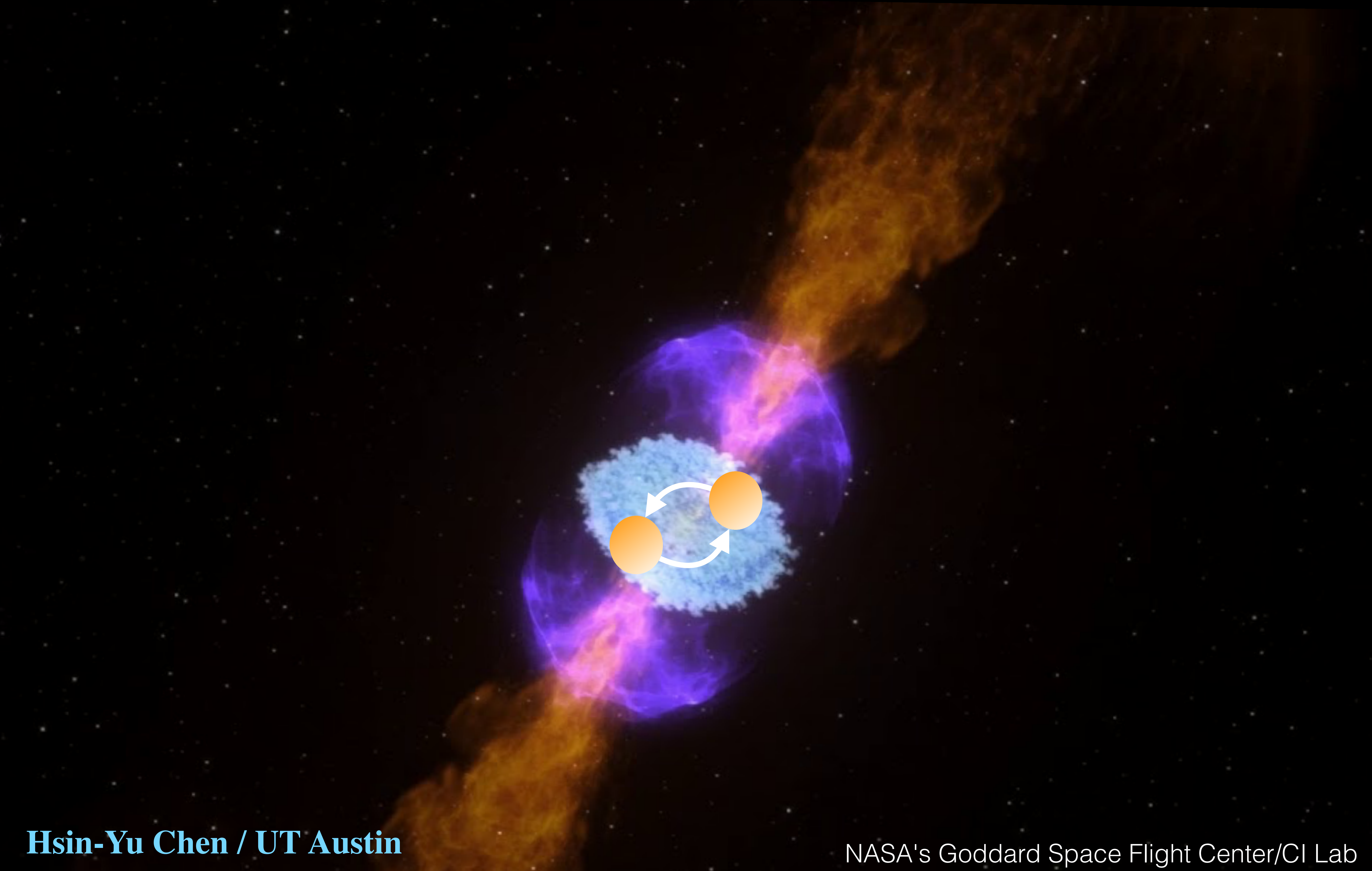


Neutron star-black hole mergers can provide more precise Hubble constant measurement if their astrophysical rate is larger than 1/10 of binary neutron star mergers.

Hsin-

The electromagnetic emissions are not isotropic



NASA's Goddard Space Flight Center/CI Lab

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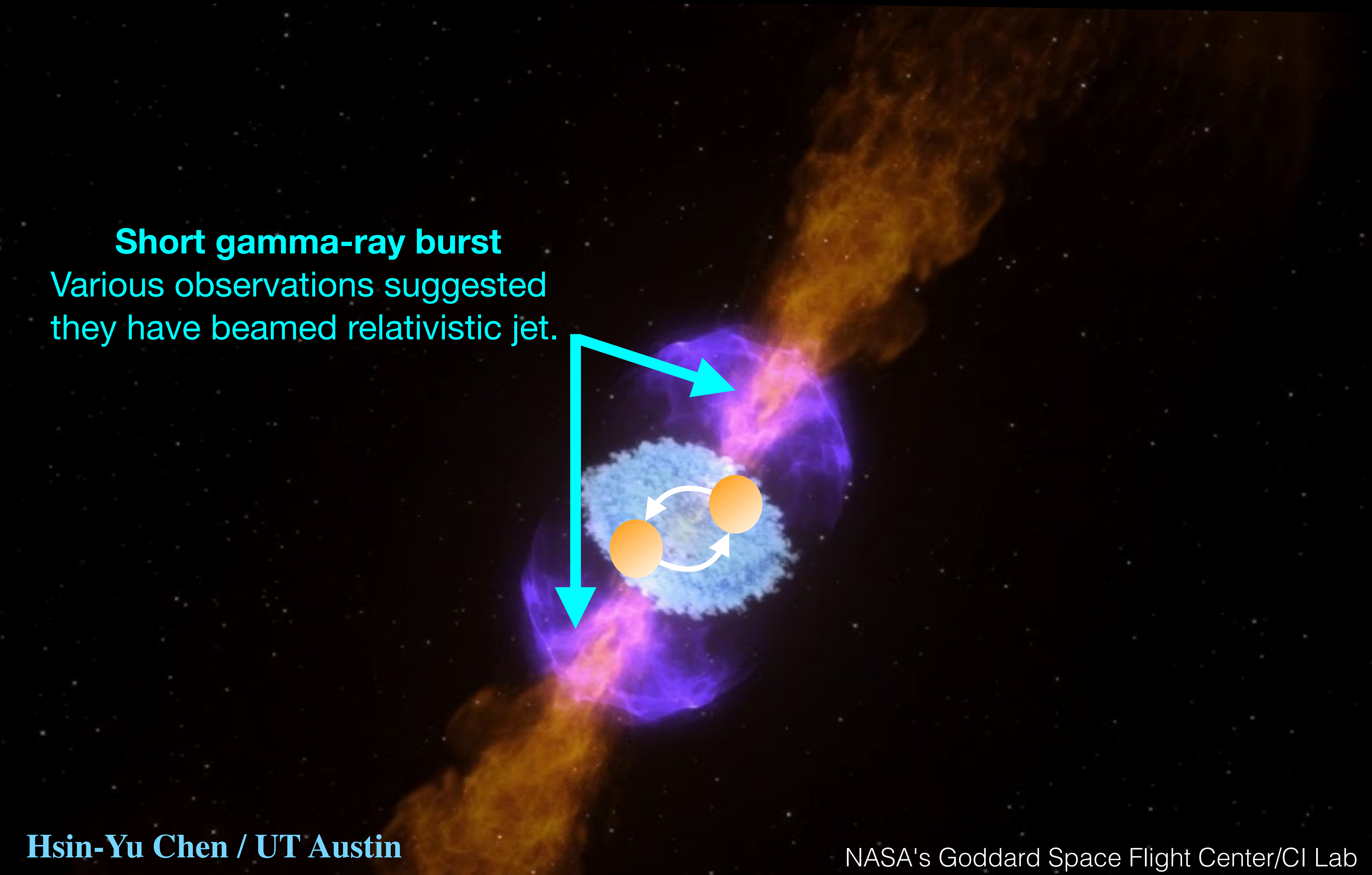

Short gamma-ray burst
Various observations suggested they have beamed relativistic jet.

NASA's Goddard Space Flight Center/CI Lab

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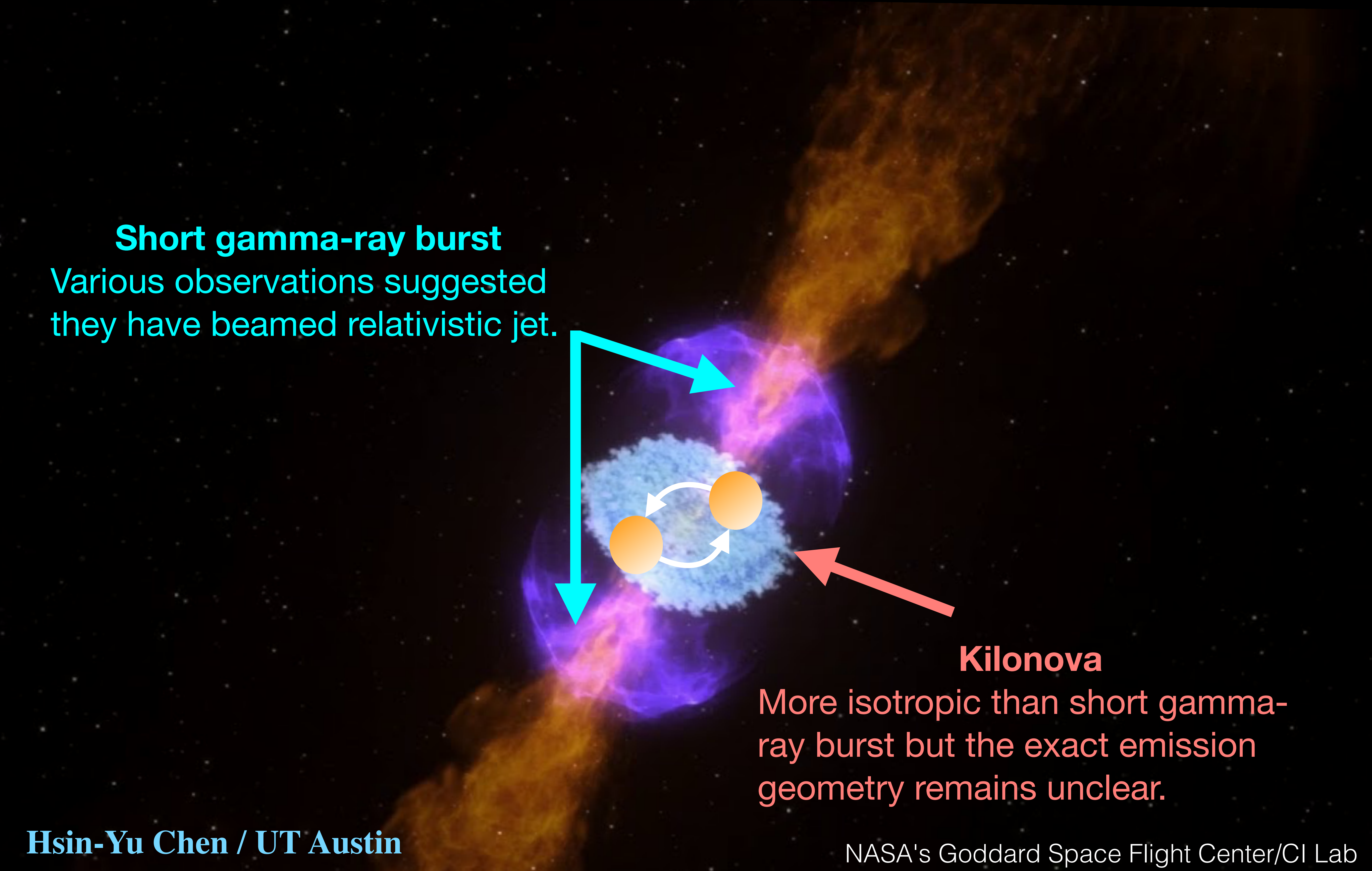
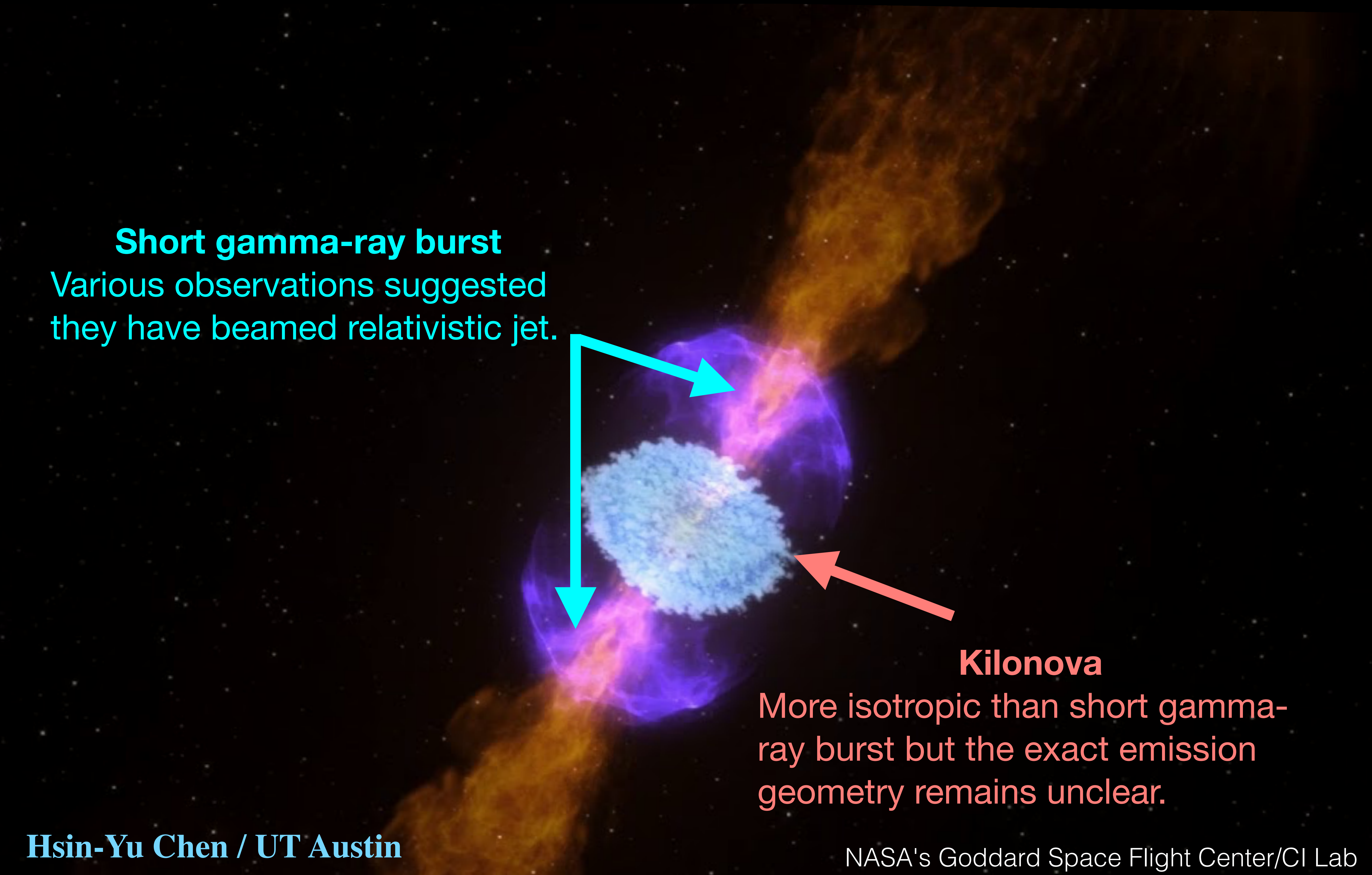


Hsin-Yu Chen / UT Austin



NASA's Goddard Space Flight Center/CI Lab

Break the distance-inclination degeneracy

B) Neutron star mergers with ***viewing angles constrained by electromagnetic emission****.*

Chen, Vitale & Narayan, PRX (2019)

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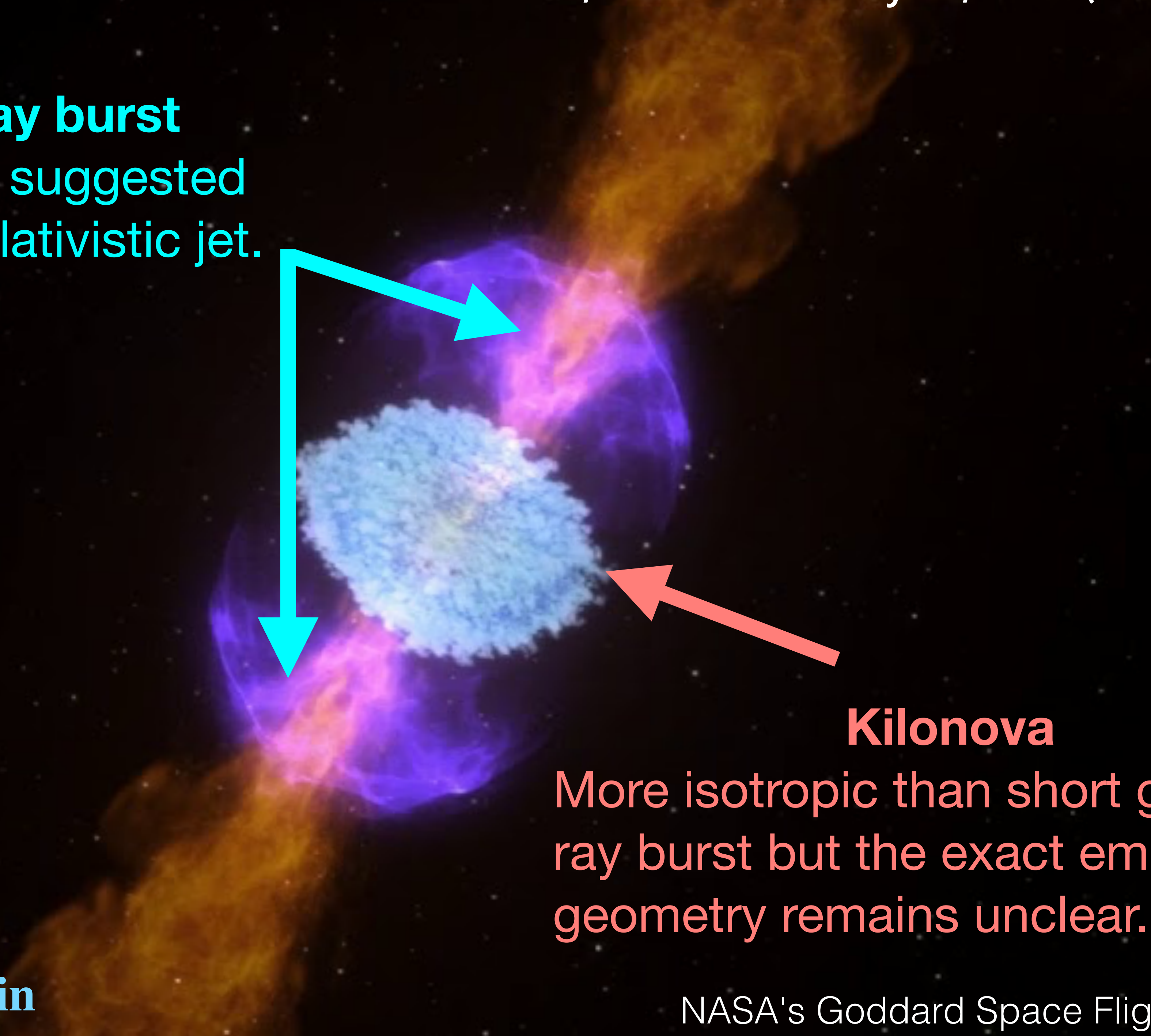

Kilonova
More isotropic than short gamma-ray burst but the exact emission geometry remains unclear.

NASA's Goddard Space Flight Center/CI Lab

Break the distance-inclination degeneracy

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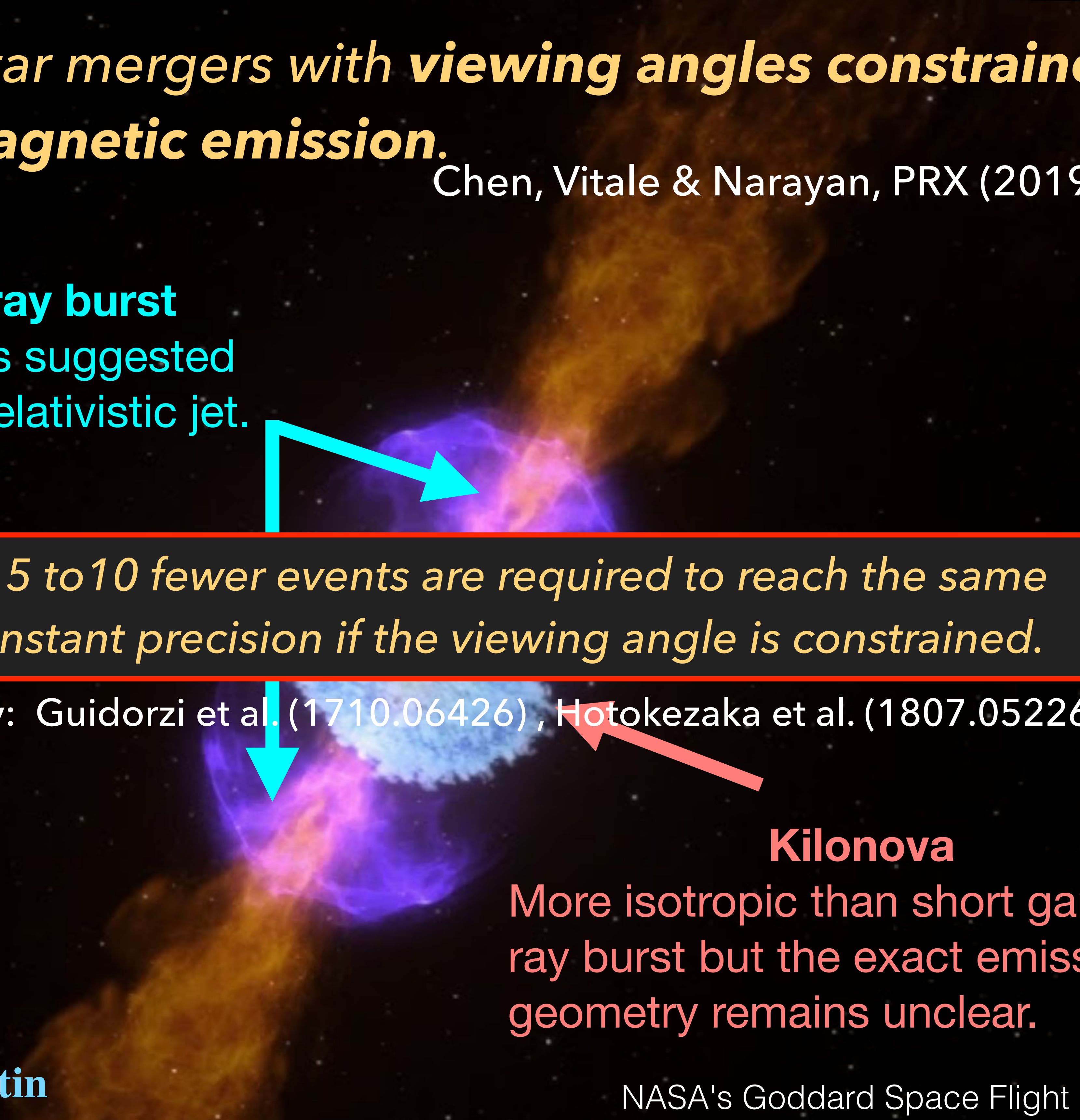


Short gamma-ray burst
Various observations suggested they have beamed relativistic jet.

A factor of 5 to10 fewer events are required to reach the same Hubble constant precision if the viewing angle is constrained.

Observationally: Guidorzi et al. (1710.06426) , Hotokezaka et al. (1807.05226)

Kilonova
More isotropic than short gamma-ray burst but the exact emission geometry remains unclear.

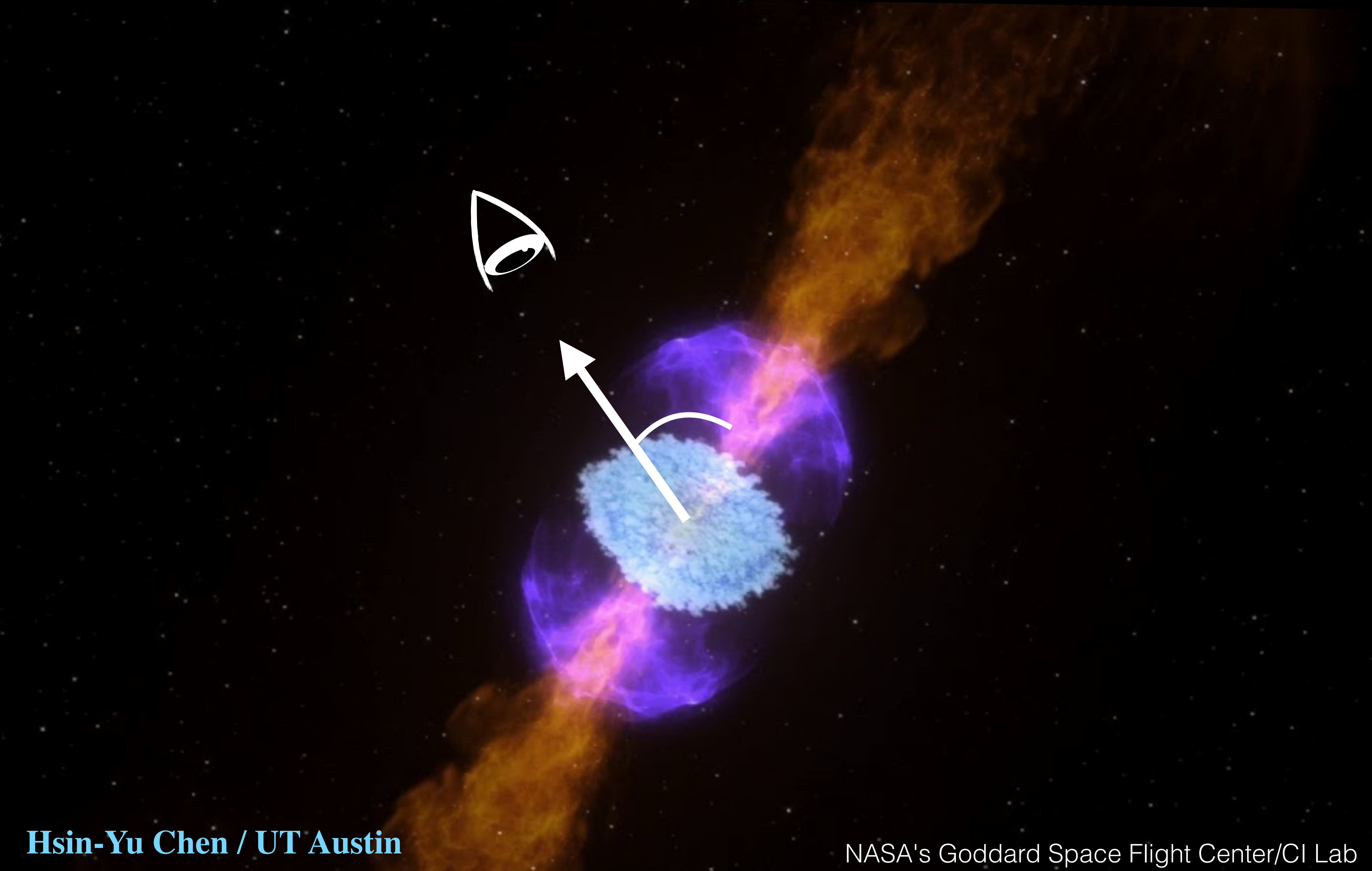
NASA's Goddard Space Flight Center/CI Lab

What if the viewing angle estimated from electromagnetic observations is not accurate enough?

What if the viewing angle estimated from electromagnetic observations is not accurate enough?

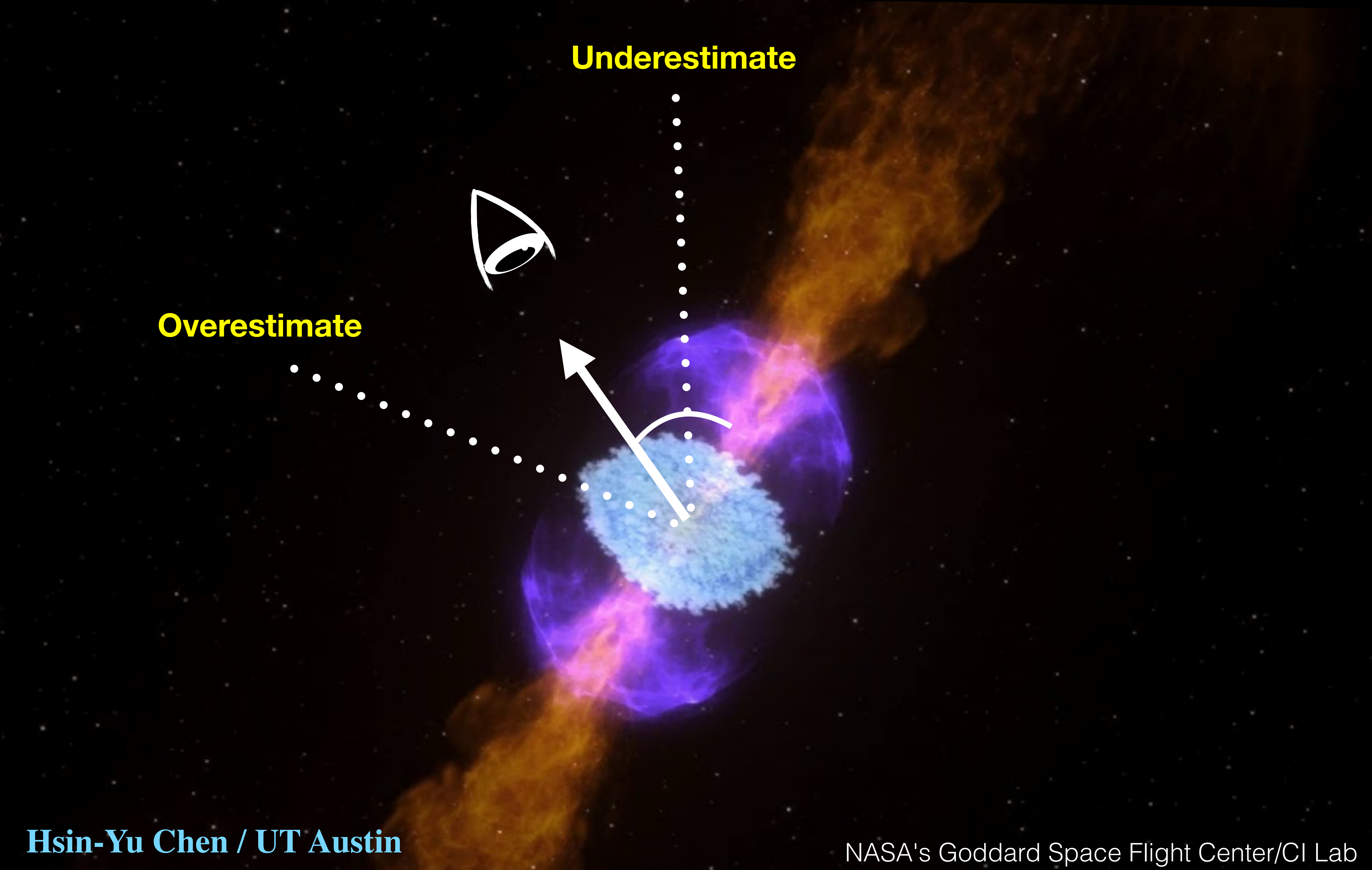
The bias propagates to the Hubble constant measurement.

If the inferred viewing angle is biased



NASA's Goddard Space Flight Center/CI Lab

If the inferred viewing angle is biased



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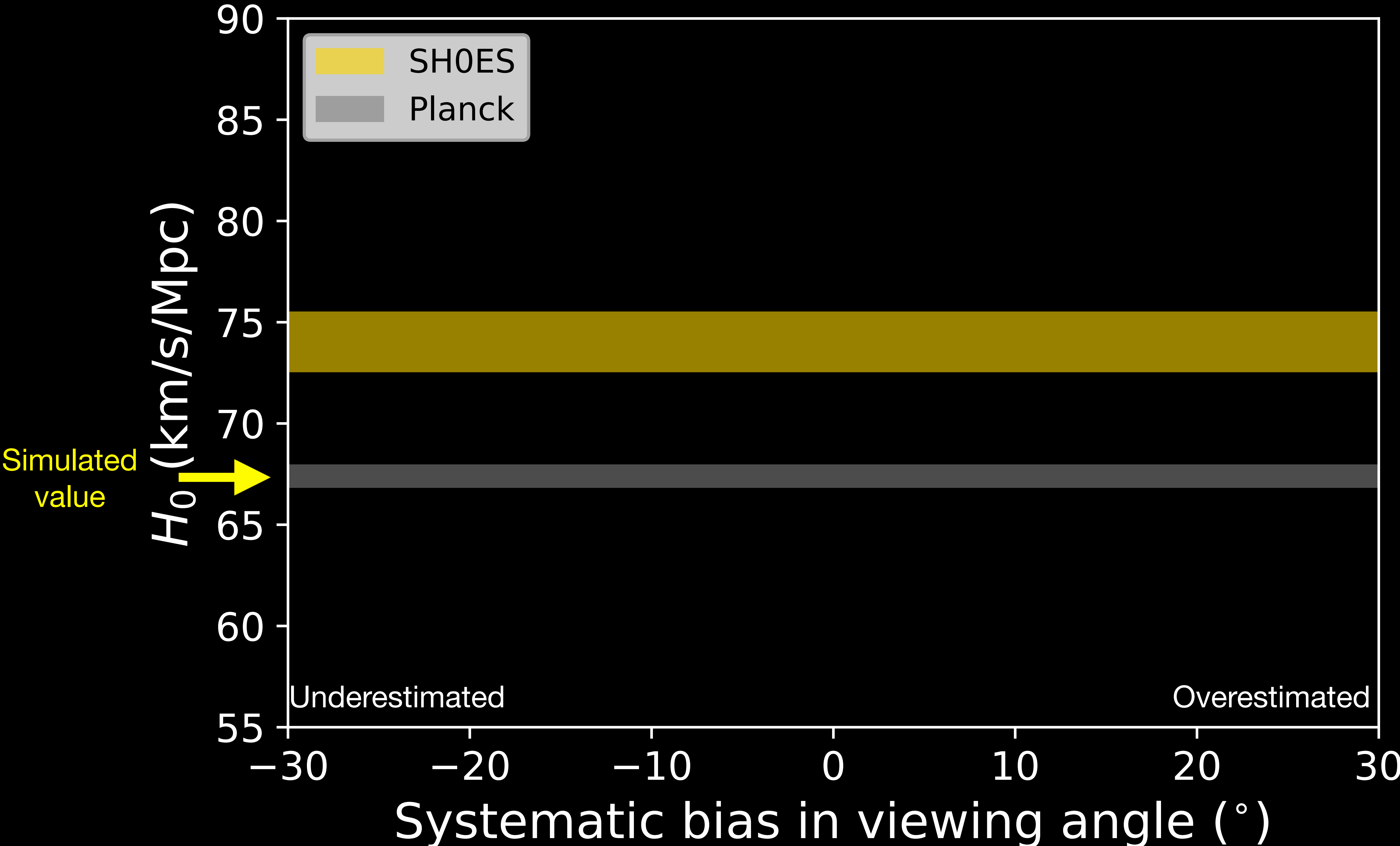
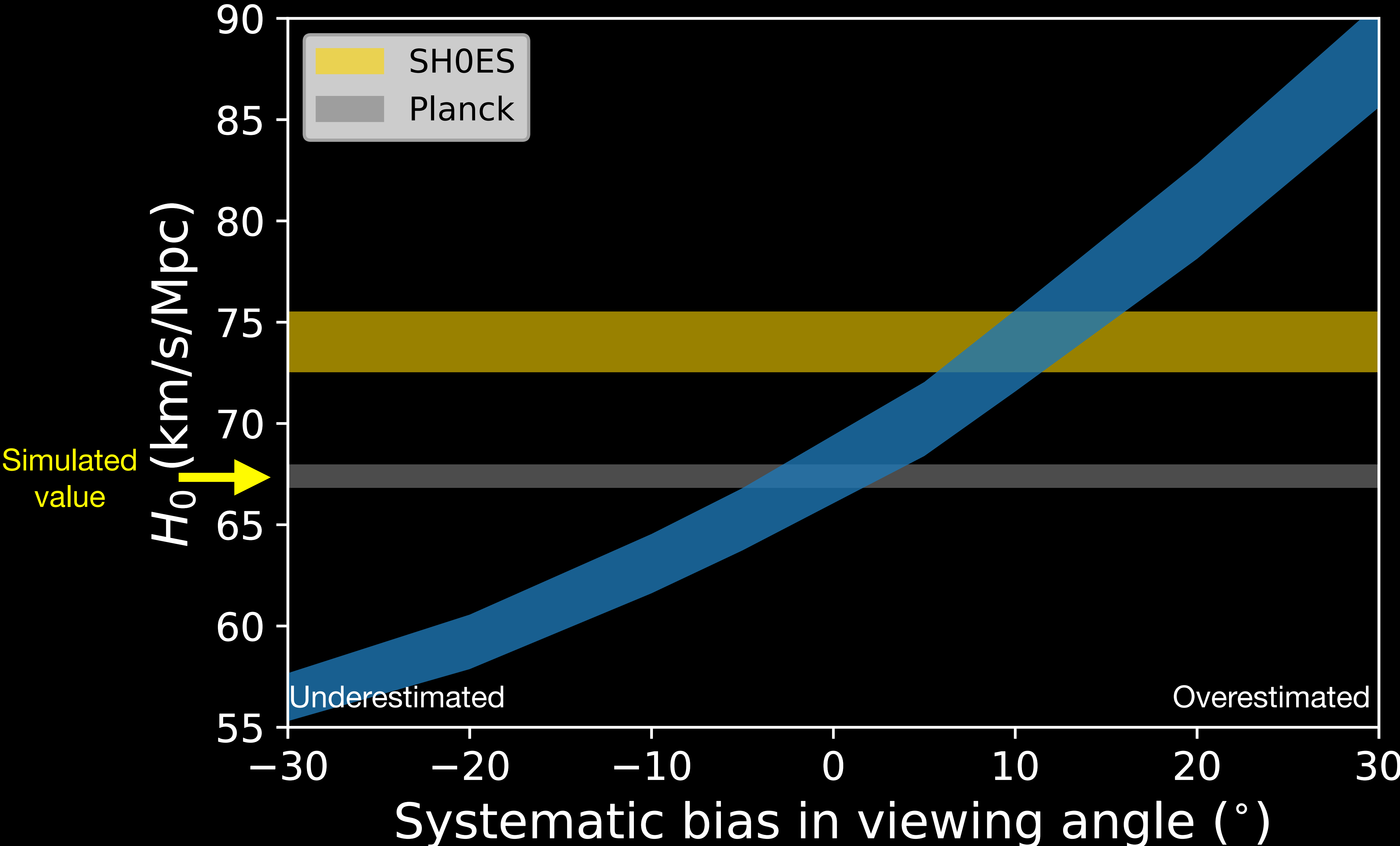
Assuming different bias in viewing angle



Hsin-Yu Chen / UT Austin

Chen, PRL (2020)

Assuming different bias in viewing angle



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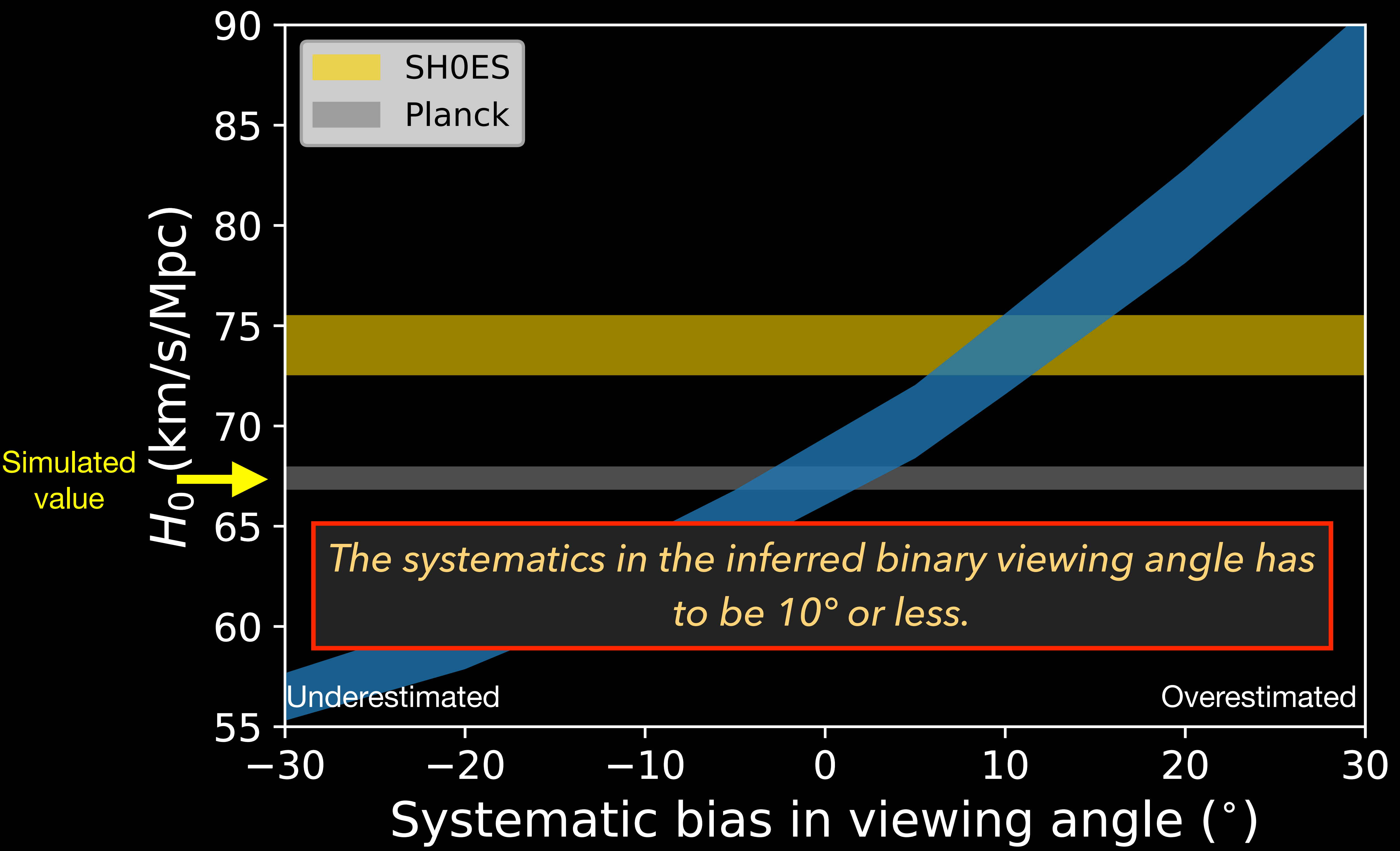

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Chen, PRL (2020)

The electromagnetic emission model is highly uncertain.

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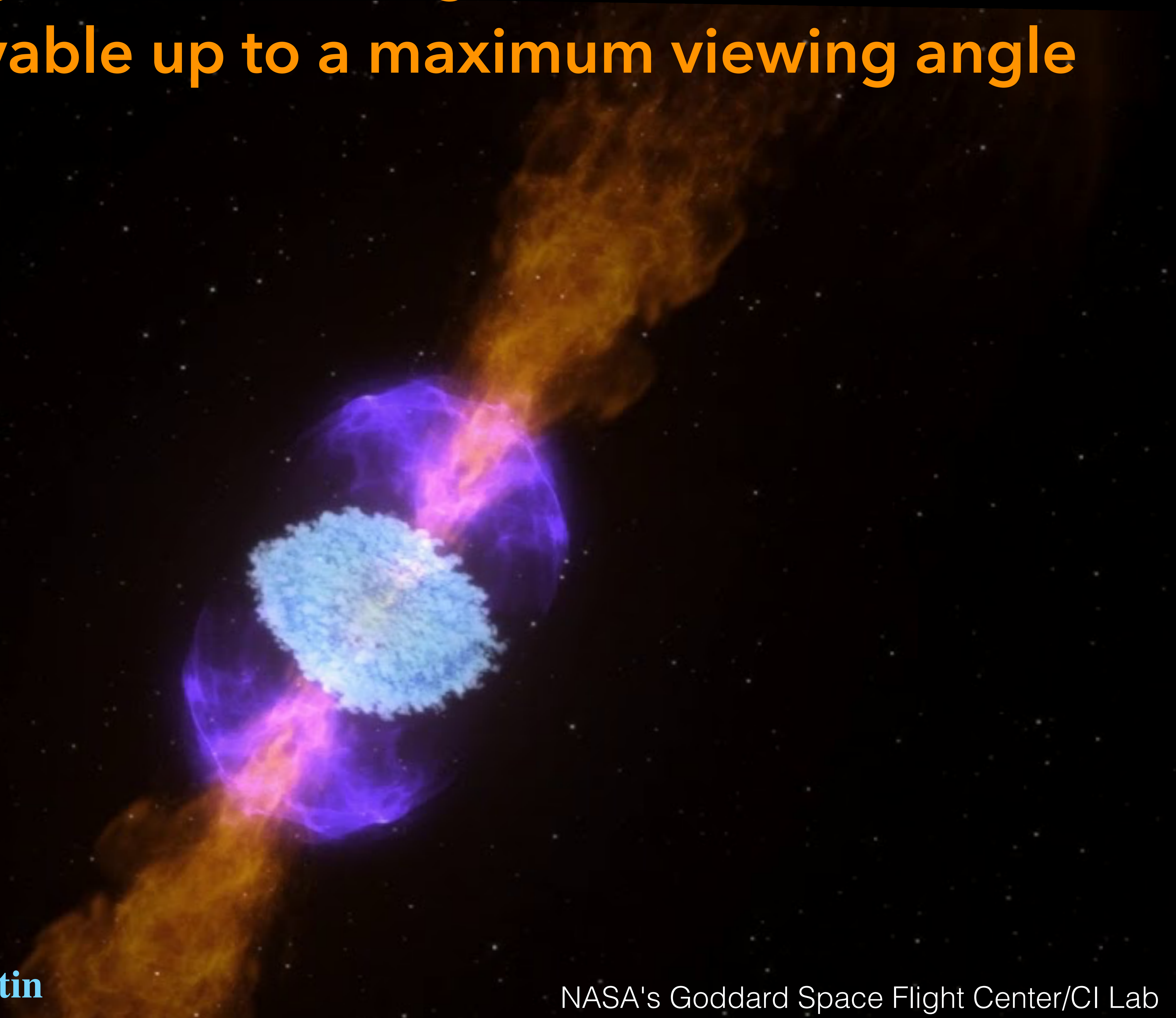
The probability to capture an electromagnetic counterpart could depend on the binary physical parameters in an unknown manner→ unknown selection effect

Assuming the electromagnetic emissions are only observable up to a maximum viewing angle



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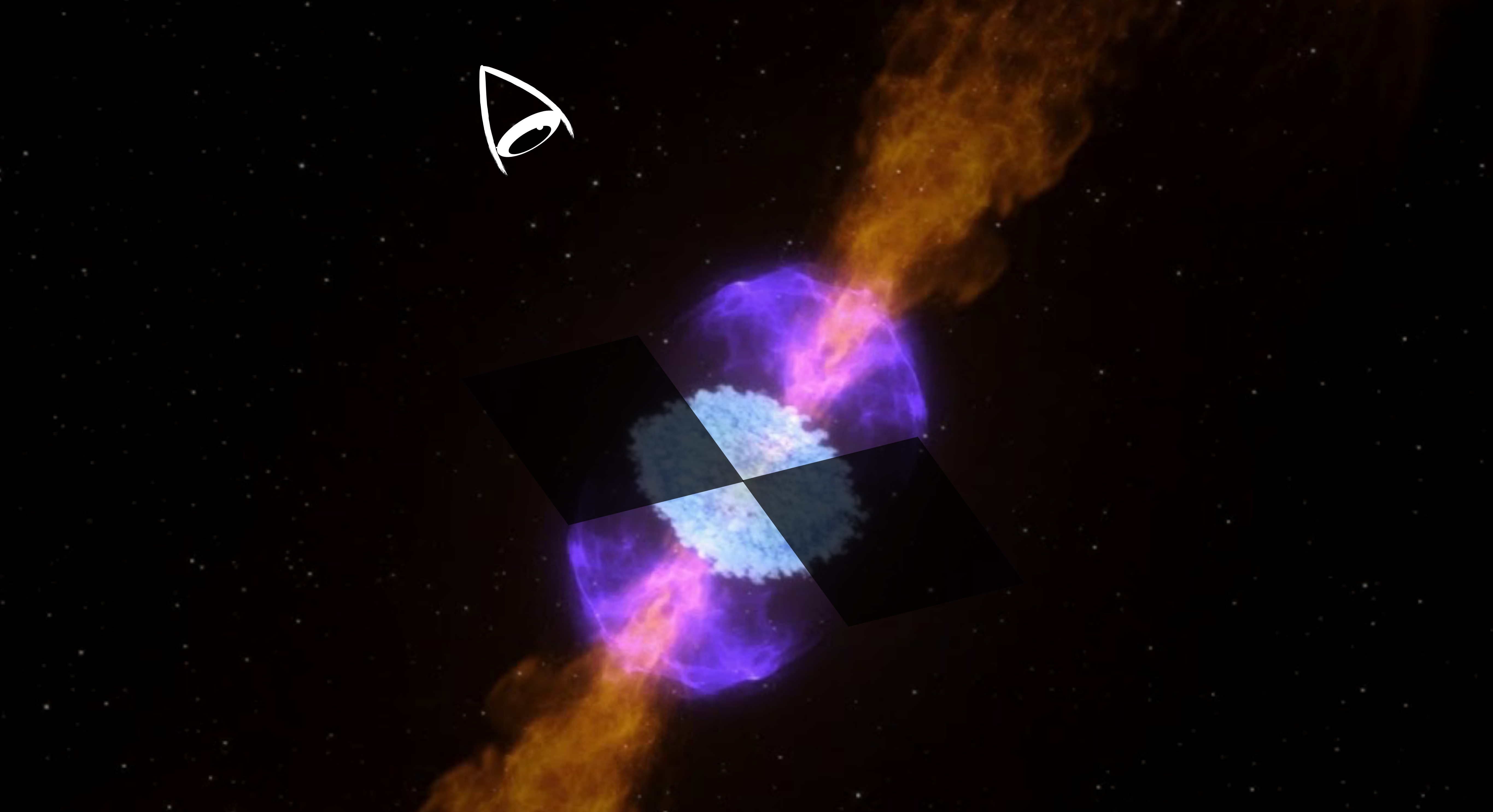

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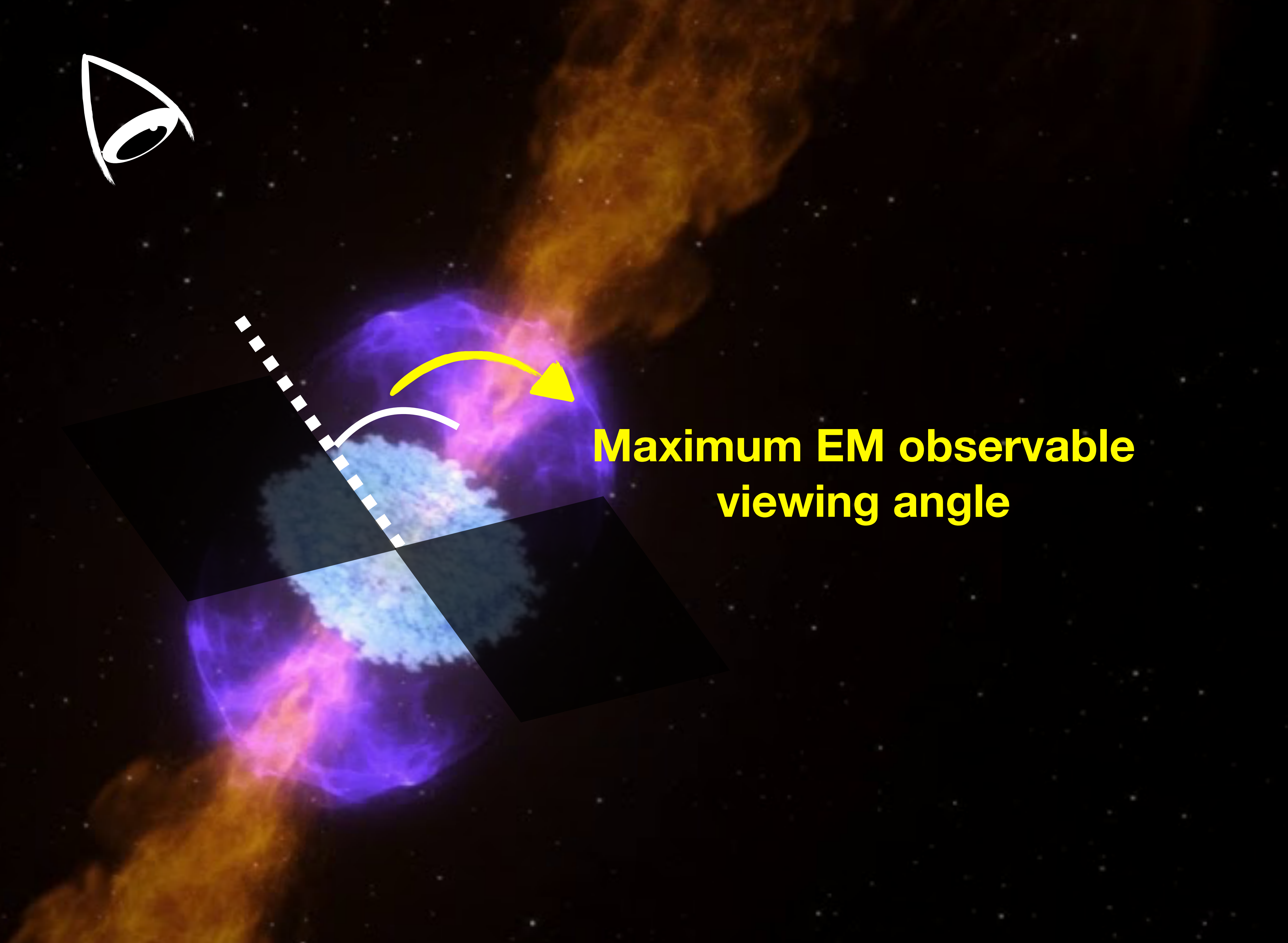

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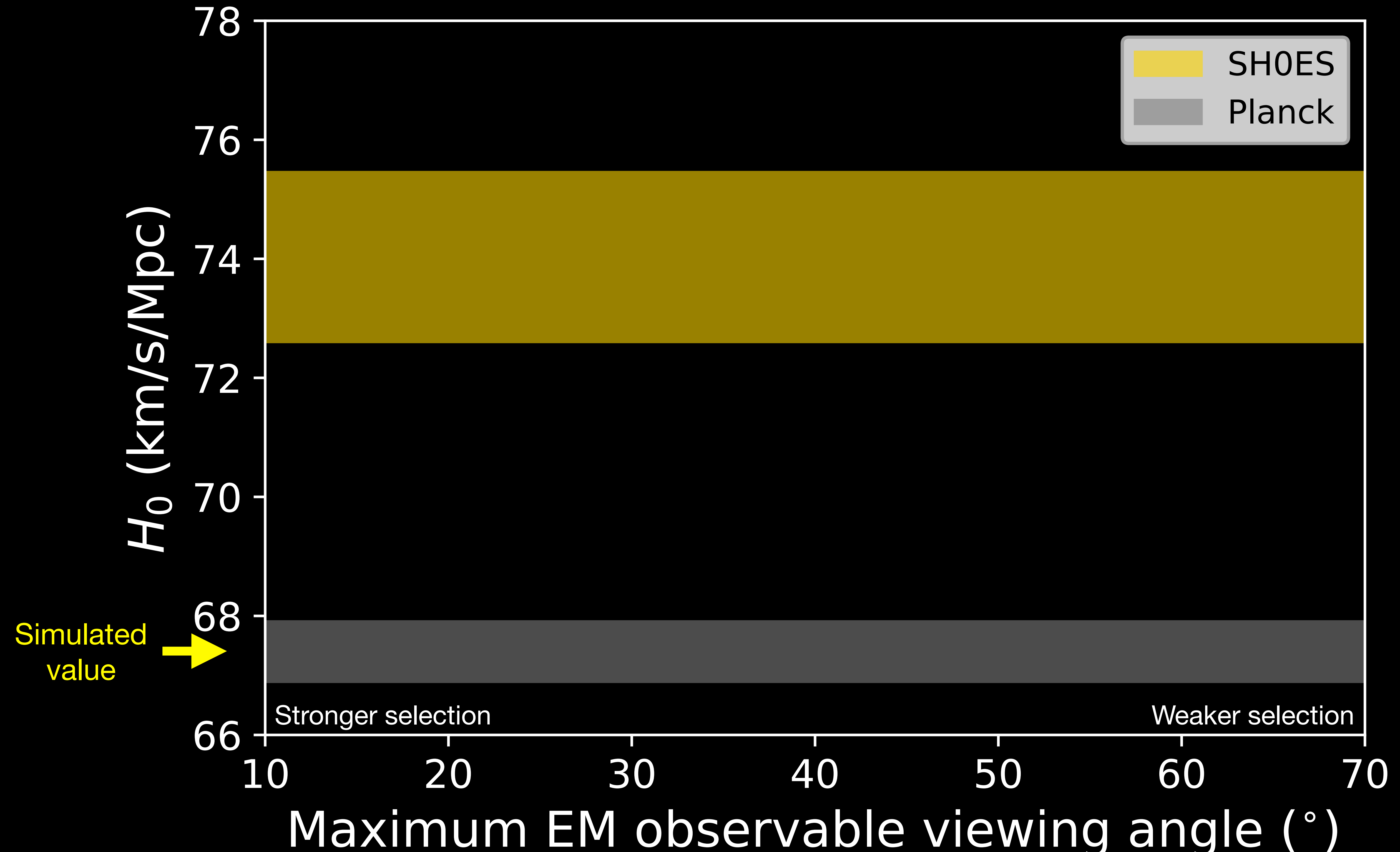

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Chen, PRL (2020)

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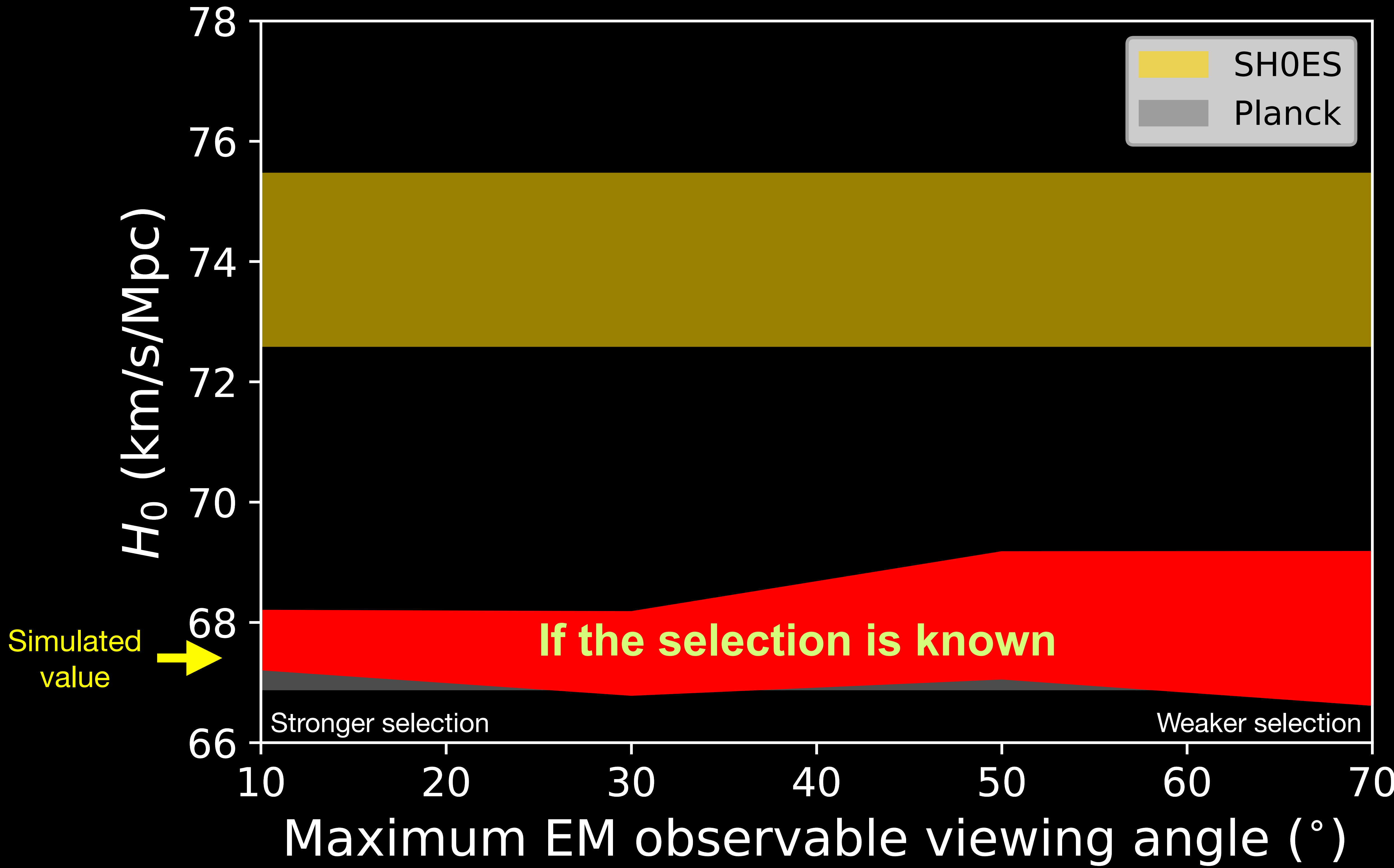

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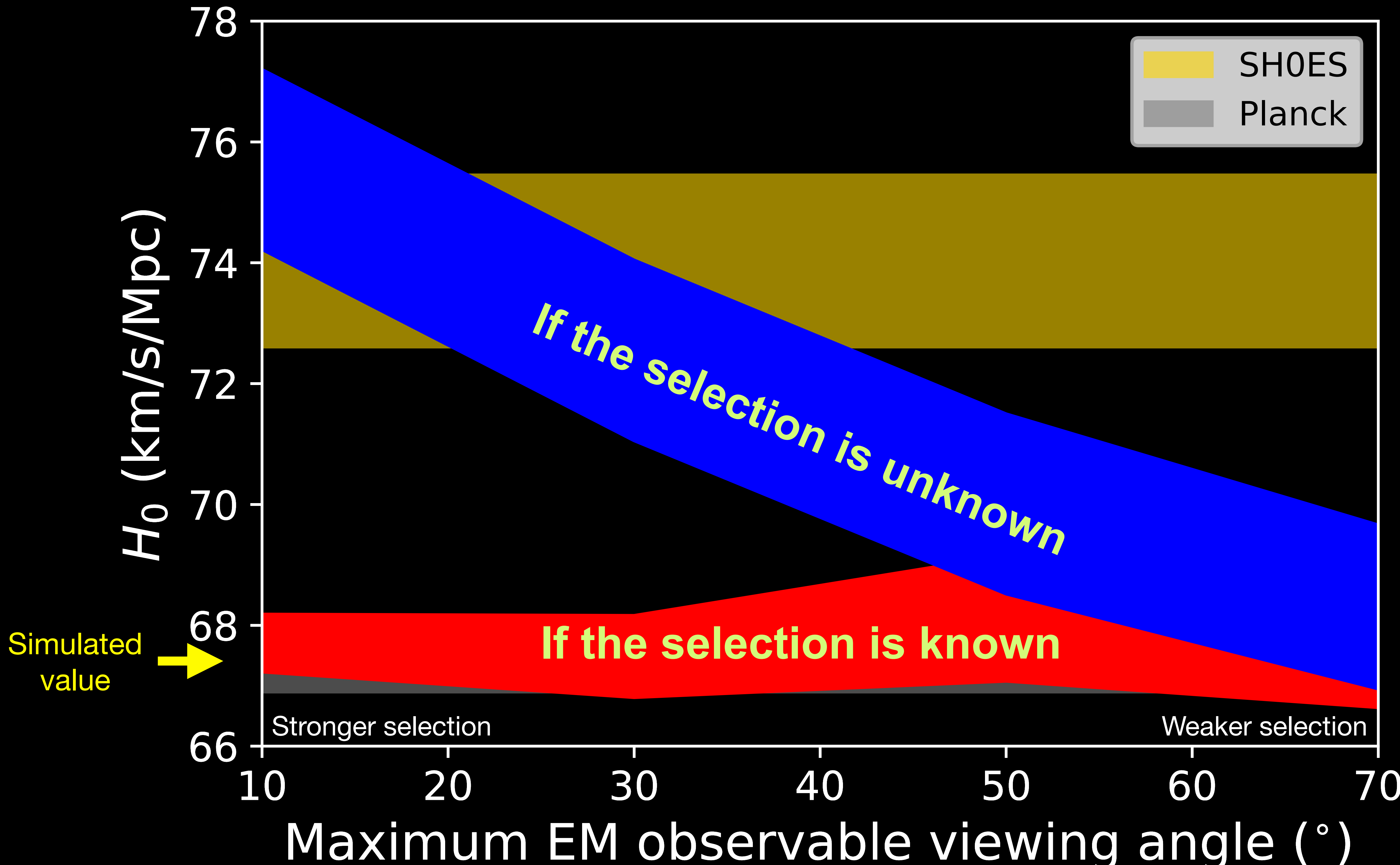

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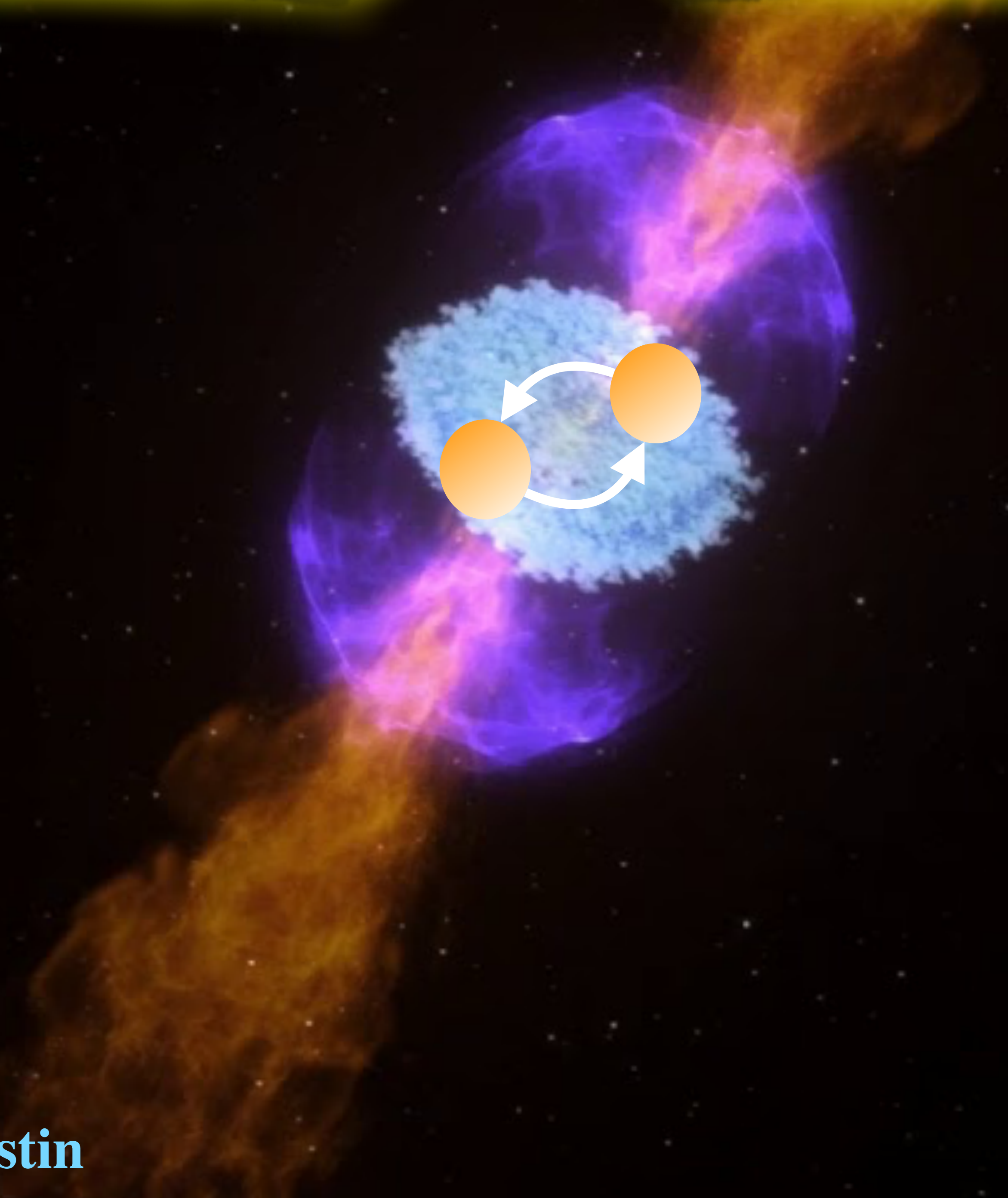
Chen, PRL (2020)

Image credit: NASA's Goddard Space Flight Center/ CI Lab, Caltech/MIT/LIGO Lab/Virgo, NRAO

Mitigating the counterpart selection effect: Combine the GW-EM information

Gravitational Waves

Electromagnetic Waves



Chen et al., PRL (2024)

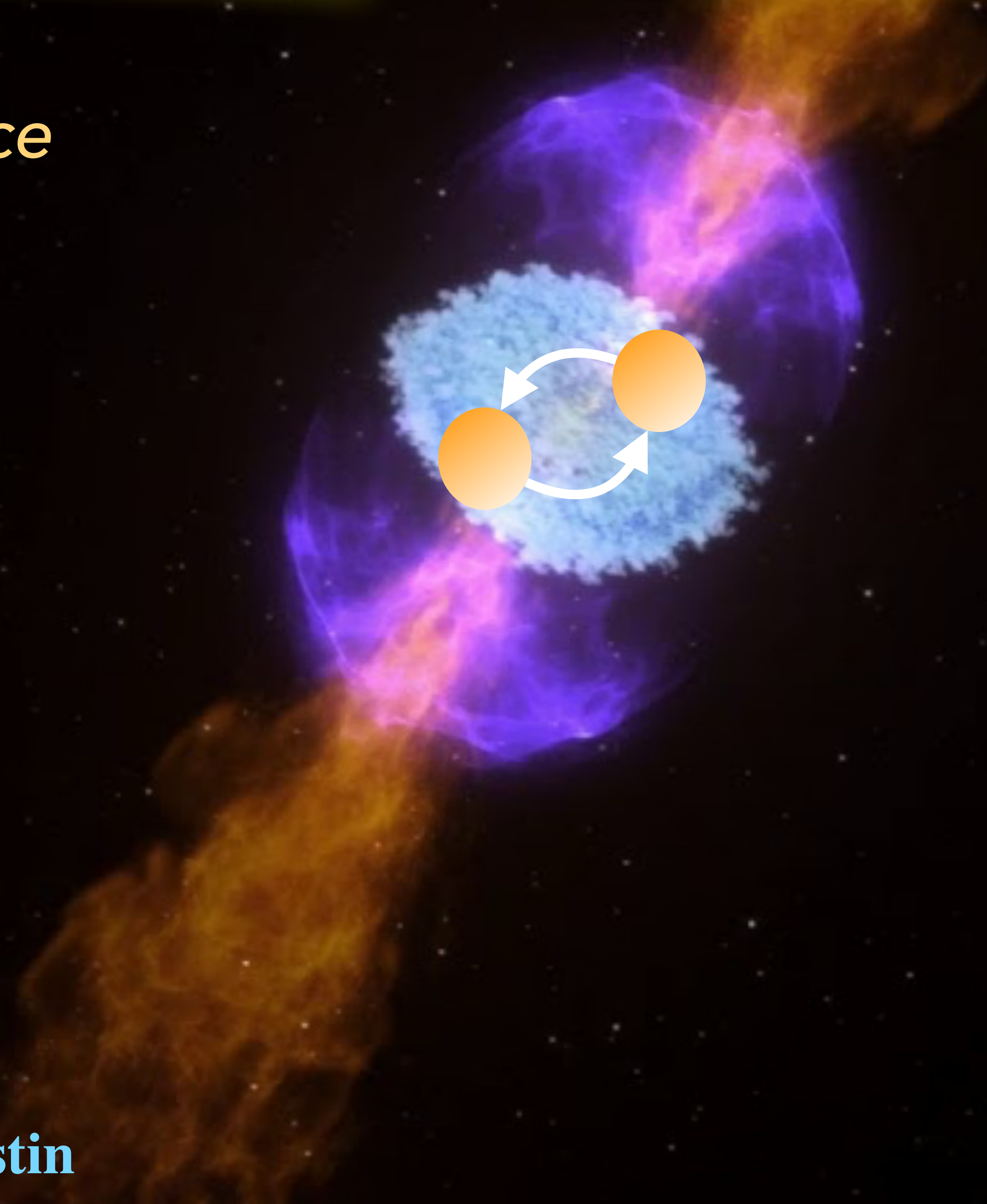
Mitigating the counterpart selection effect: Combine the GW-EM information

Gravitational Waves

Distance

Electromagnetic Waves

Redshift



Chen et al., PRL (2024)

Image credit: NASA's Goddard Space Flight Center/
CI Lab, Caltech/MIT/LIGO Lab/Virgo, NRAO

Mitigating the counterpart selection effect: Combine the GW-EM information

Gravitational Waves

Distance

Mass

Electromagnetic Waves

Redshift

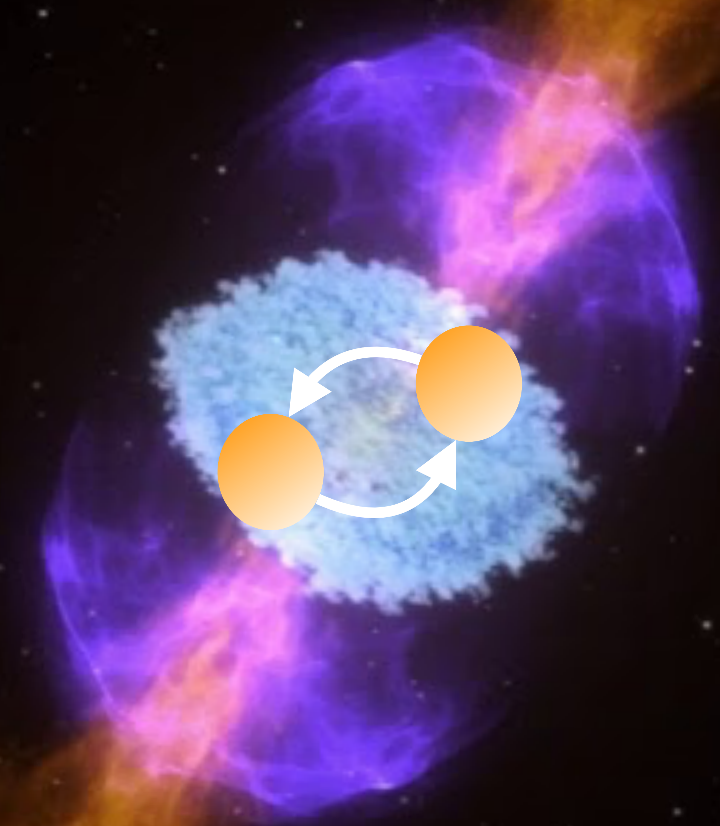
Matter

Chen et al., PRL (2024)

Image credit: NASA's Goddard Space Flight Center/
CI Lab, Caltech/MIT/LIGO Lab/Virgo, NRAO

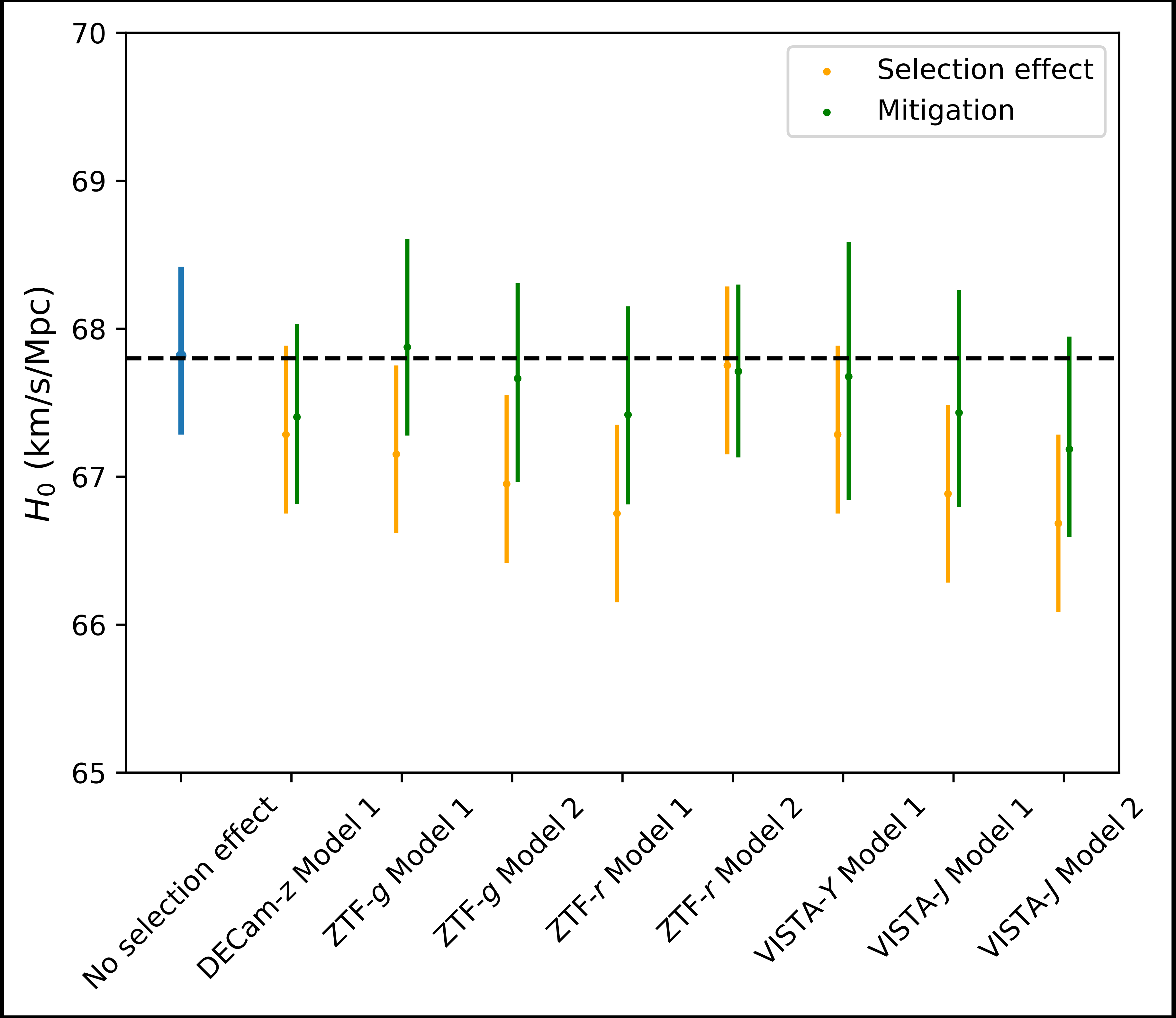
Mitigating the counterpart selection effect: Combine the GW-EM information

Gravitational Waves	Electromagnetic Waves
Distance	*Redshift*
Mass	*Matter*
Viewing angle	*Viewing angle*



Chen et al., PRL (2024)

Mitigating the counterpart selection effect



Chen et al., PRL (2024)

Potential sources of systematic for standard sirens

Distance

Waveform

Non-stationary Noise

Calibration

Viewing angle

Redshift

Peculiar motion

Wrong counterpart

Population

Population distribution

Counterpart selection

Hsin-Yu Chen / UT Austin

Potential sources of systematic for standard sirens

Distance

- Waveform
- Non-stationary Noise
- Calibration
- Viewing angle

Redshift

- Peculiar motion
- Wrong counterpart

Population

- Population distribution
- Counterpart selection

Hsin-Yu Chen / UT Austin

Potential sources of systematic for standard sirens

Distance

- Waveform
- Non-stationary Noise
- Calibration
- Viewing angle

Redshift

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- Wrong counterpart

Population

- Population distribution
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Hsin-Yu Chen / UT Austin

Potential sources of systematic for standard sirens

Distance

Waveform

Non-stationary Noise

Calibration

Viewing angle

Redshift

Peculiar motion

Wrong counterpart

Precise and accurate gravitational-wave cosmological measurements are possible in the upcoming years.

Population distribution

Counterpart selection

Image credit: Eddie Anaya, M Kraan, Astrium, NASA E/PO, Aurore Simonnet, ESA/IRAP/CNRS/UT3/CNES/Fab&Fab, Caltech, NRAO, SPDO/TDP/DRAO/Swinburne Astronomy Productions, LSST Project Office, STROBE-X, C. Carter

Future gravitational-wave and electromagnetic-wave observatories

Ground-based gravitational-wave observatory

2024

O4

Image credit: Eddie Anaya, M Kraan, Astrium, NASA E/PO, Aurore Simonnet, ESA/IRAP/CNRS/UT3/CNES/Fab&Fab, Caltech, NRAO, SPDO/TDP/DRAO/Swinburne Astronomy Productions, LSST Project Office, STROBE-X, C. Carter

Future gravitational-wave and electromagnetic-wave observatories

Ground-based gravitational-wave observatory

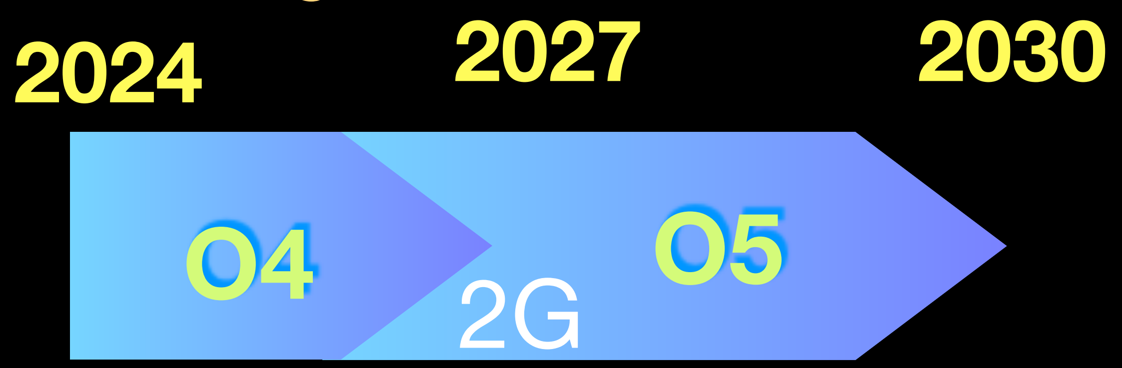

Image credit: Eddie Anaya, M Kraan, Astrium, NASA E/PO, Aurore Simonnet, ESA/IRAP/CNRS/UT3/CNES/Fab&Fab, Caltech, NRAO, SPDO/TDP/DRAO/Swinburne Astronomy Productions, LSST Project Office, STROBE-X, C. Carter

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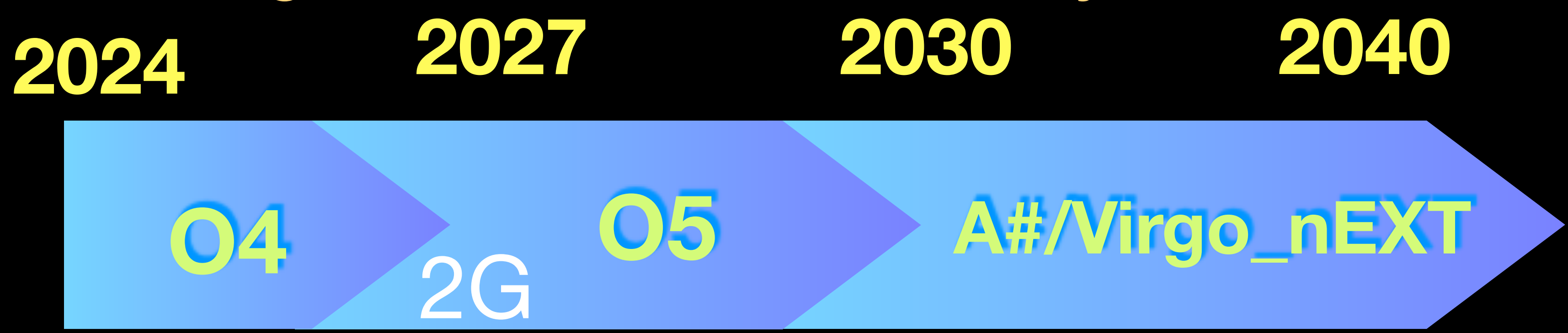

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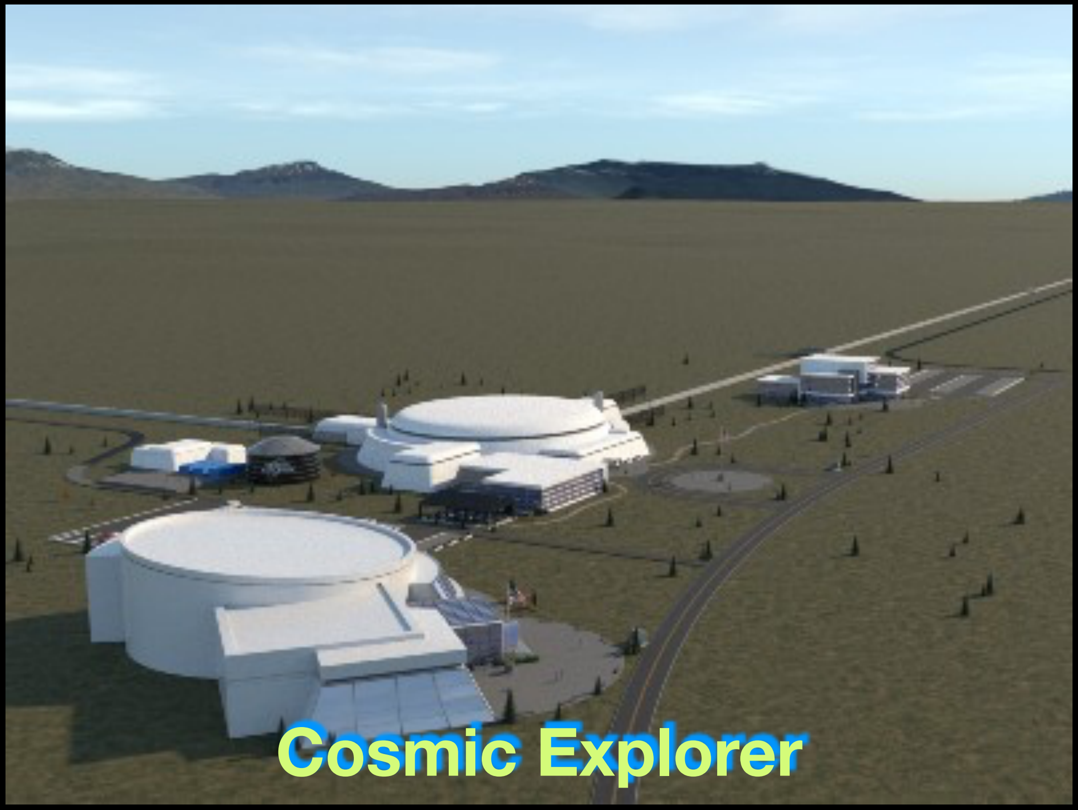
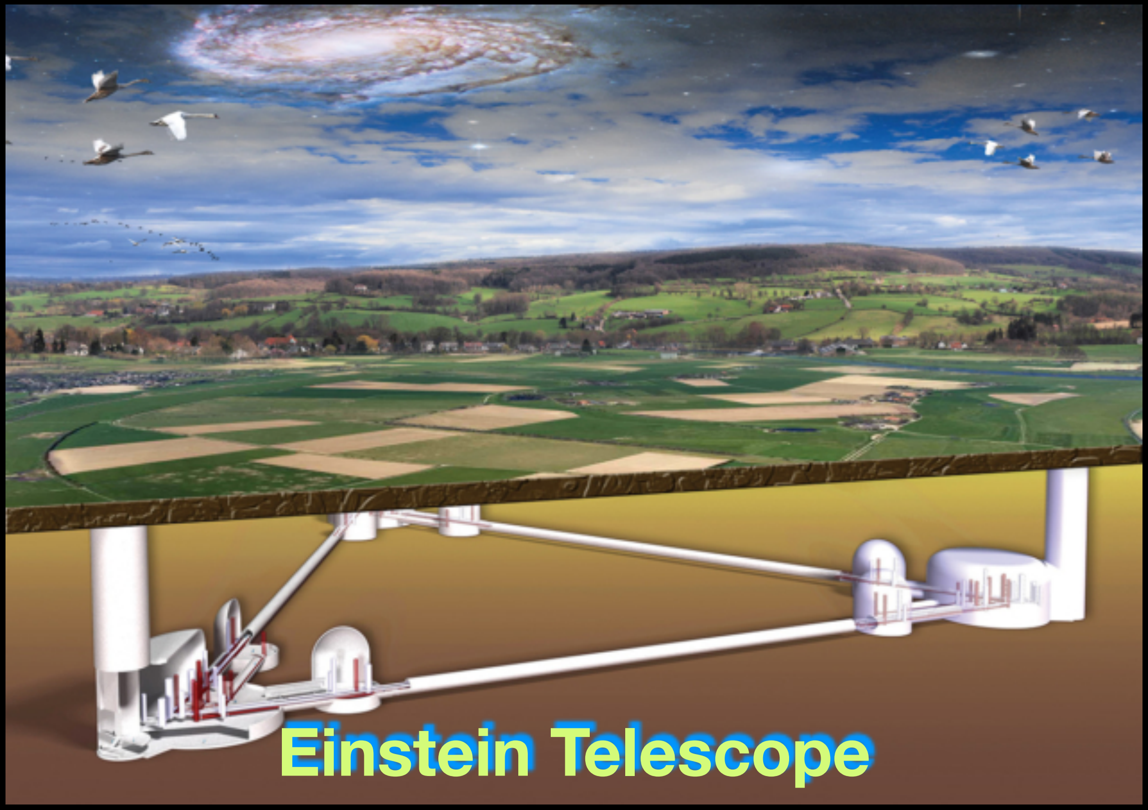
Future gravitational-wave and electromagnetic-wave observatories

Ground-based gravitational-wave observatory

2024 | 2027 | 2030 | 2040

O4 → 2G O5 → A#/Virgo_nEXT → XG Cosmic Explorer/ Einstein Telescope





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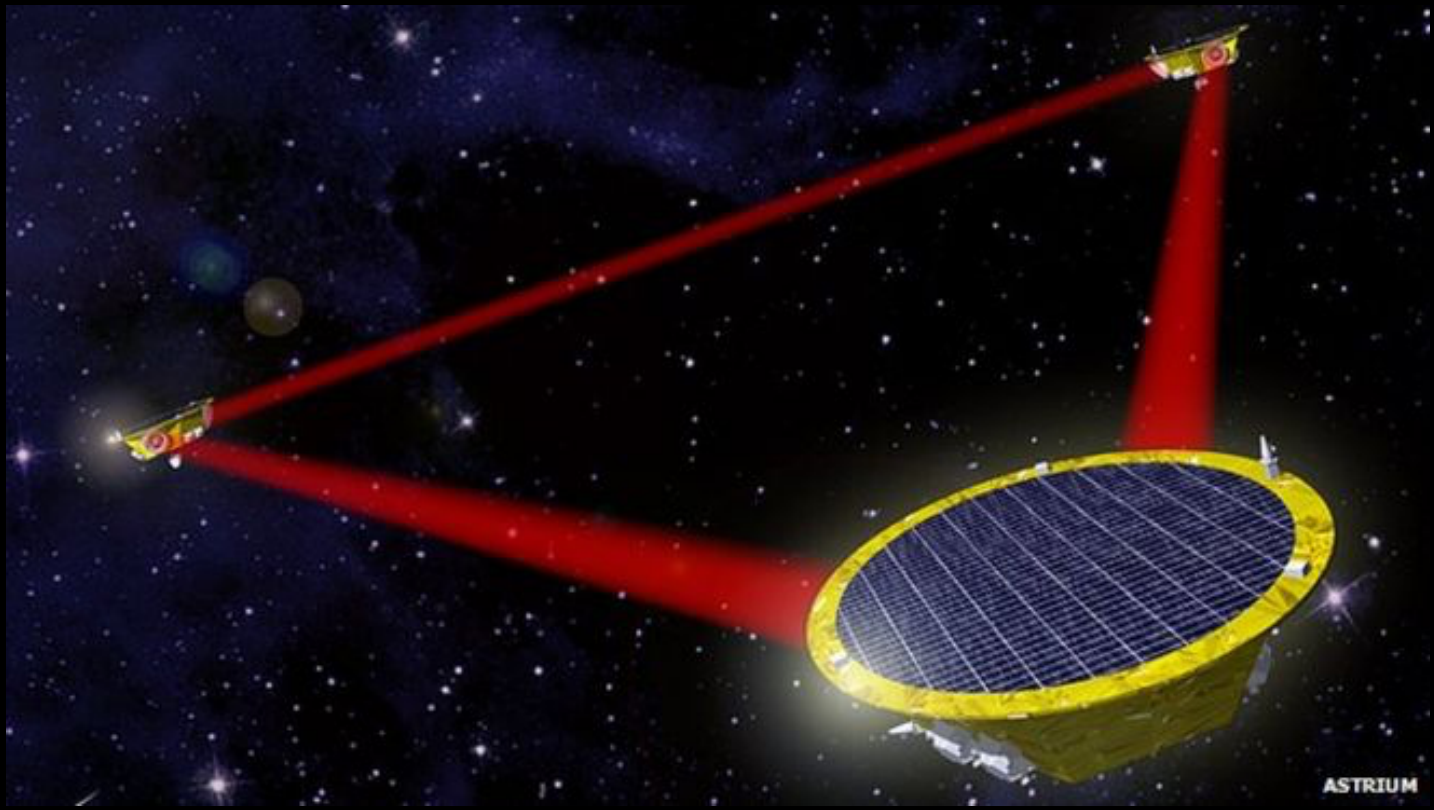
Future gravitational-wave and electromagnetic-wave observatories

Ground-based gravitational-wave observatory

Space-based gravitational-wave observatory



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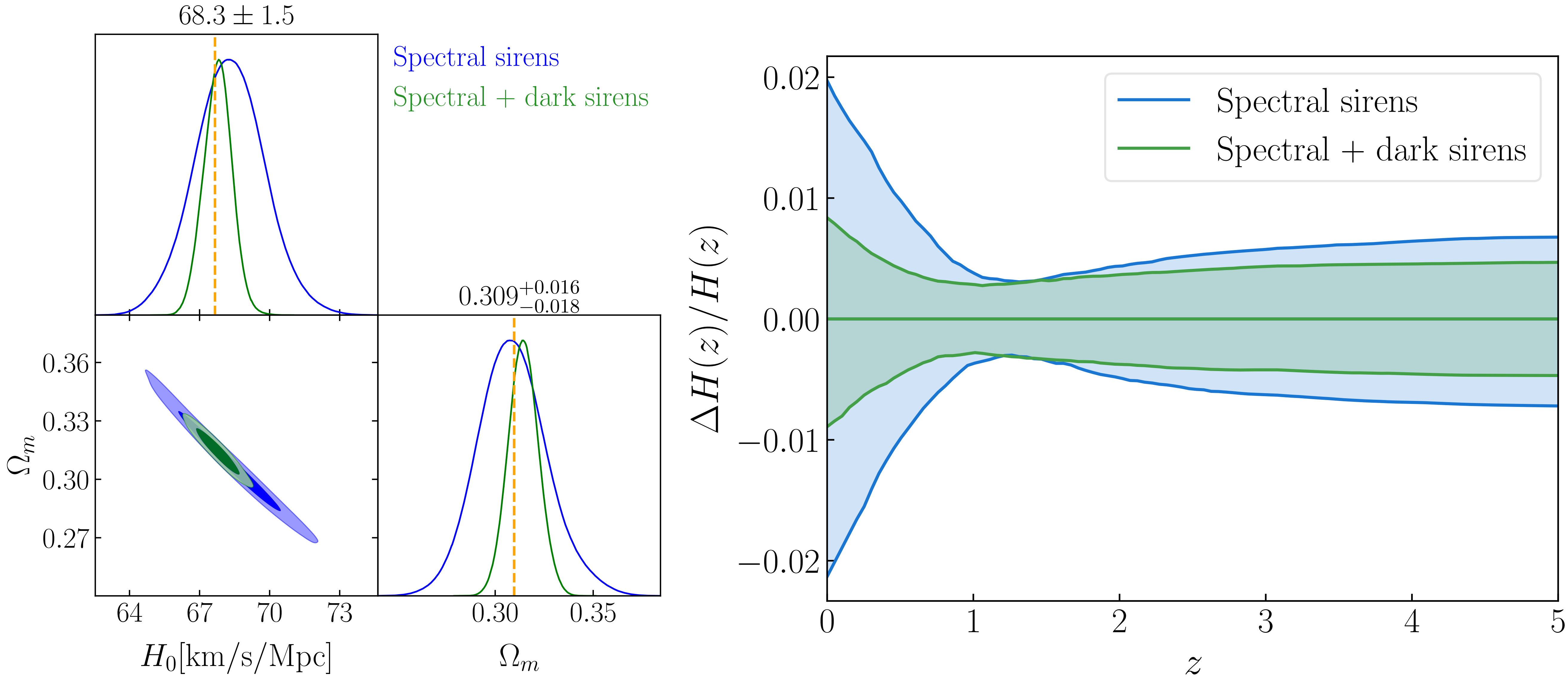
Future gravitational-wave and electromagnetic-wave observatories

Future gravitational-wave and electromagnetic-wave observatories



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Chen, Ezquiaga & Gupta, CQG Special Issue (2024)

Thank you!