WHITE DWARF BINARIES AND GRAVITATIONAL WAVES

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CONCLUSIONS:

- Close white dwarf binaries in the Galaxy will dominate the gravitational wave spectrum between 10 and 1000 microhertz.
- High-mass and high-frequency binaries will be individually resolvable throughout the Galaxy.
- These observations will be complementary with optical observations of local systems.

BASICS OF GRAVITATIONAL RADIATION

- Gravitational radiation is propagating perturbation of spacetime curvature.
- It manifests itself as a variation in the distance between inertial masses.
- It is measured as a strain $h(t) = dL/L$
- Comes in two polarizations.

MATHEMATICAL INTERLUDE

Invariant distances are measured in spacetime using the metric:

Infinitessimal coordinate displacement

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu$$

Coordinate-dependent metric

Coordinate-independent invariant distance

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

Background metric

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Background metric

Gravitational wave perturbation

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Gravitational wave perturbation

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Choose very specific coordinates so that the perturbation is traceless, and with wave propagation along z-axis. (Transverse Traceless Gauge)

Background metric

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$$h_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} e^{i\omega t}$$

Background metric

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Plus Polarization

Background metric

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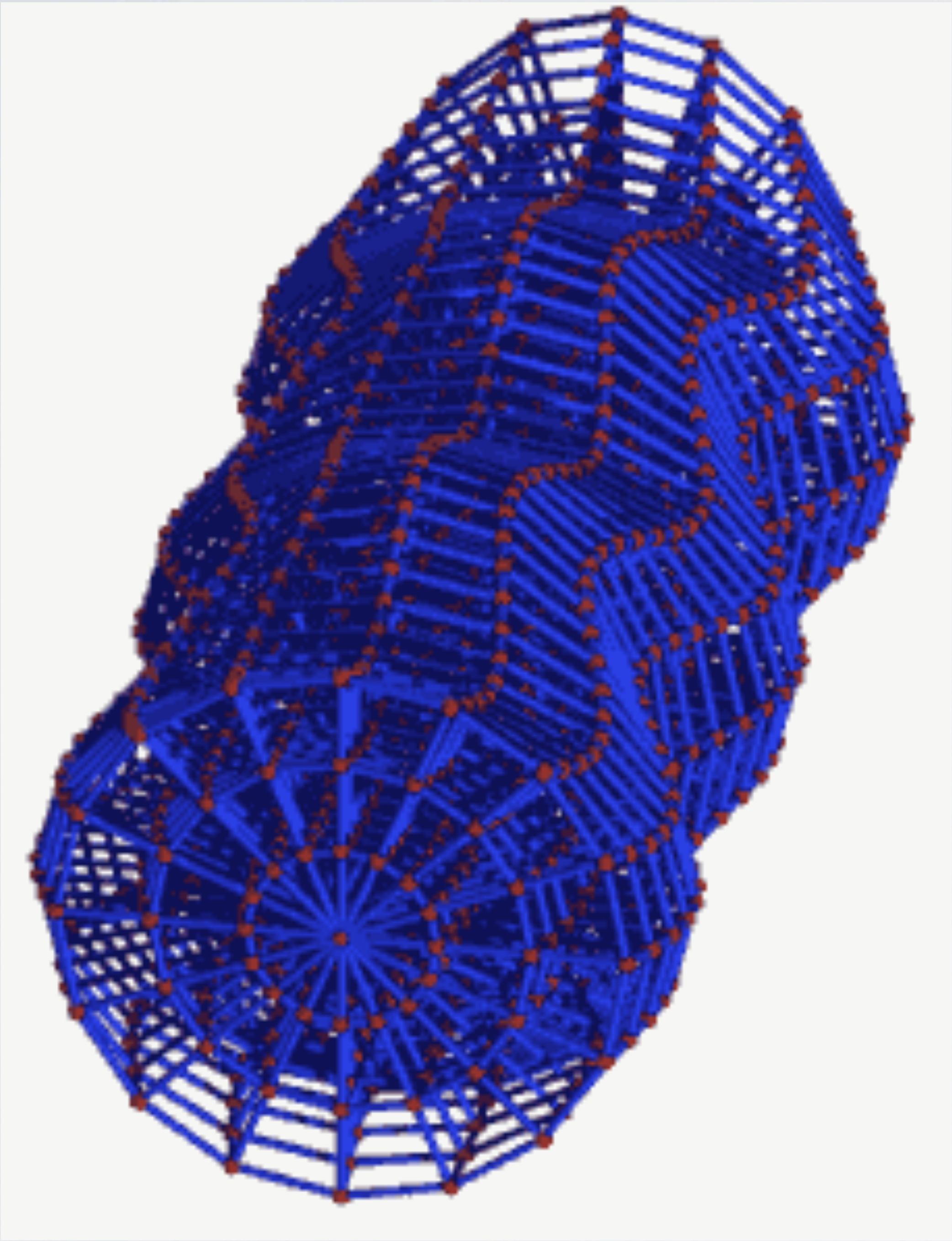
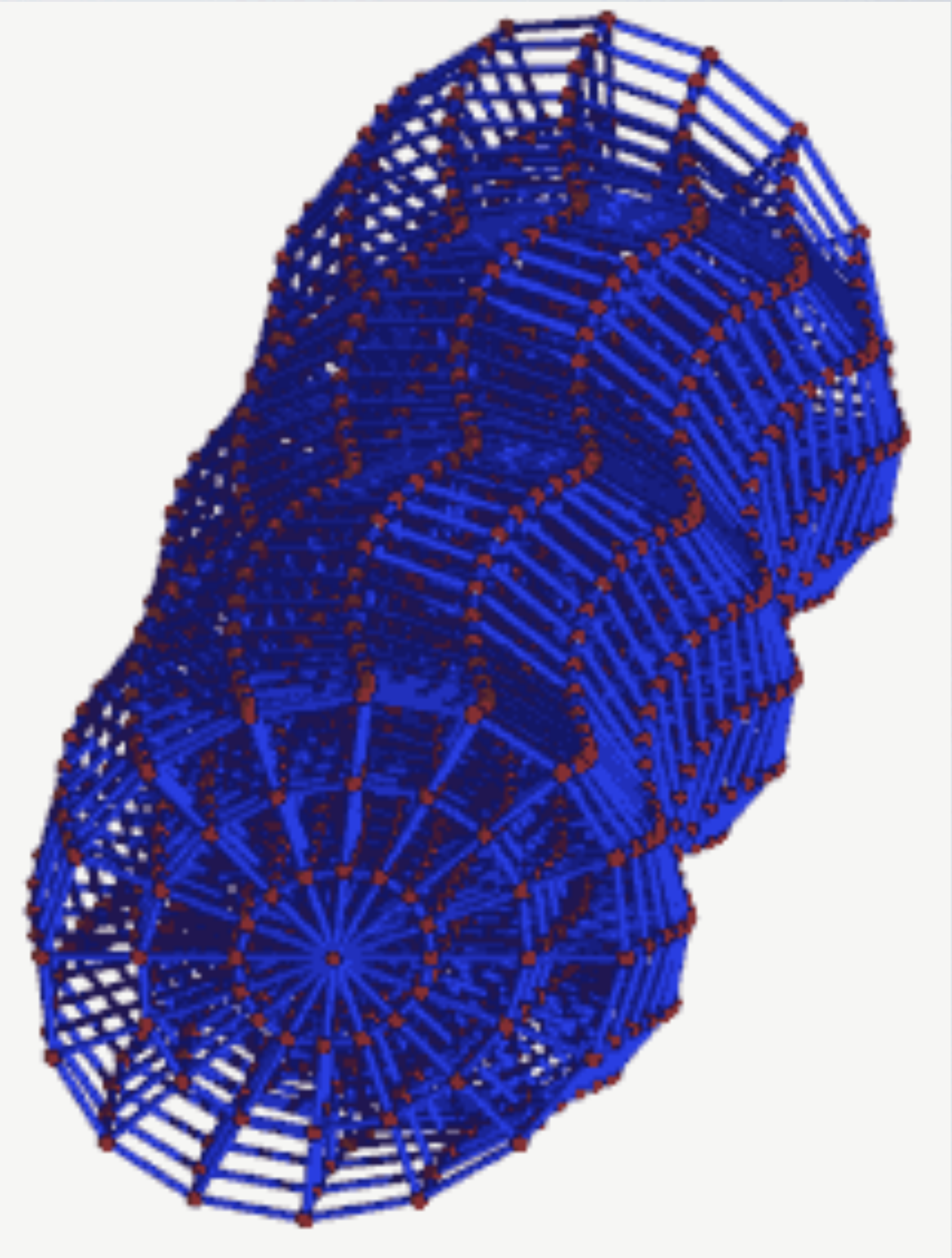
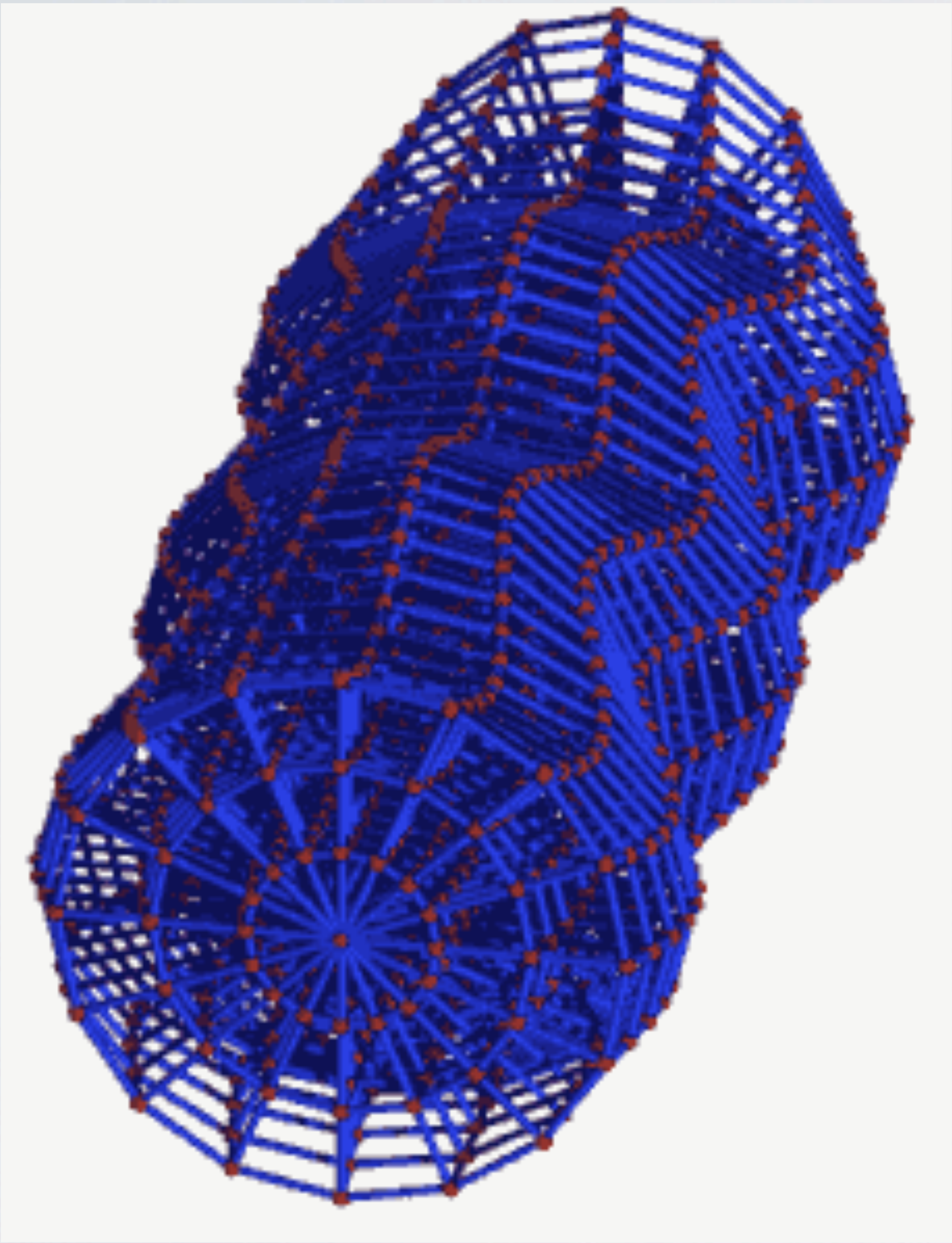
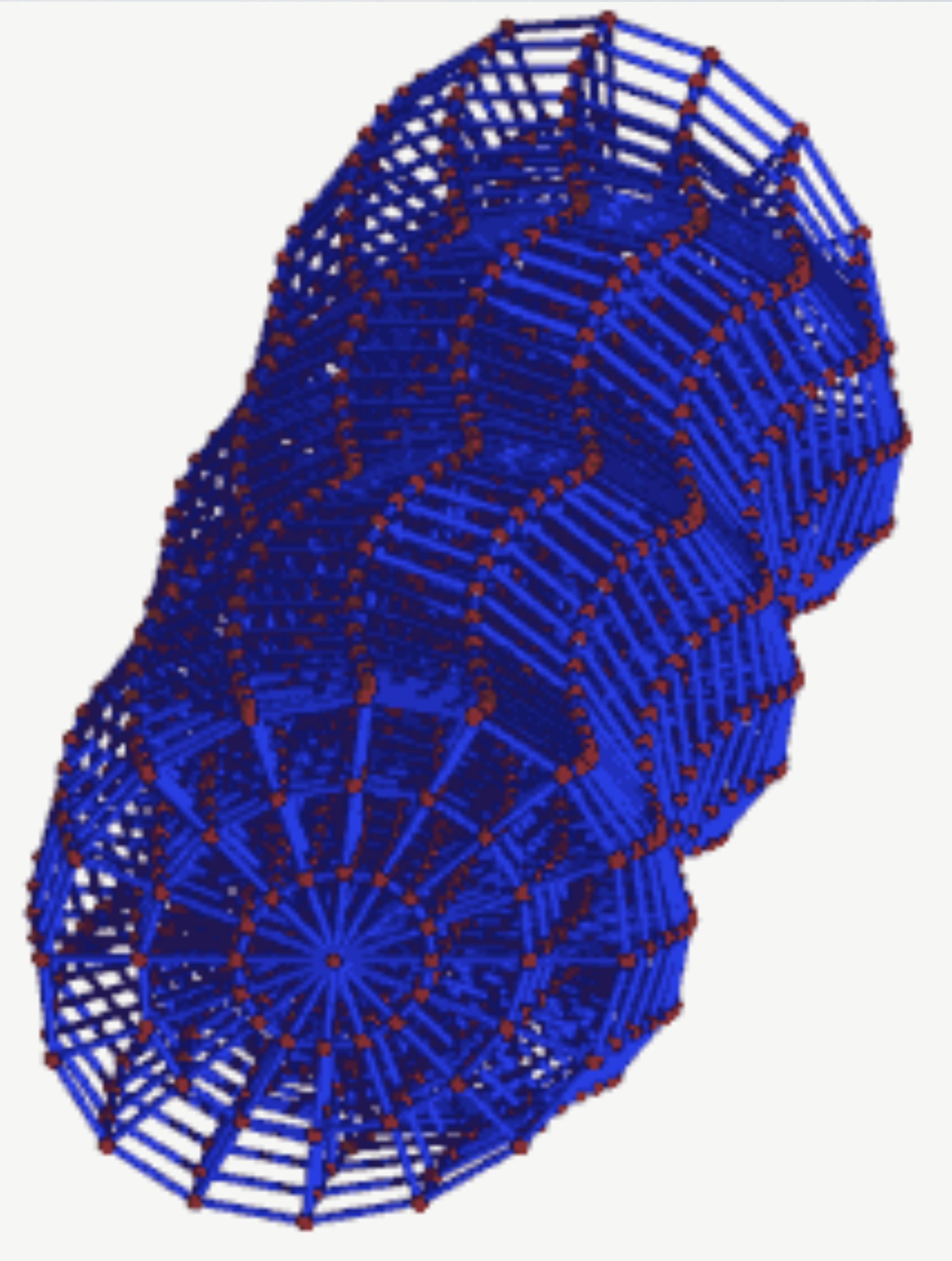
Cross Polarization



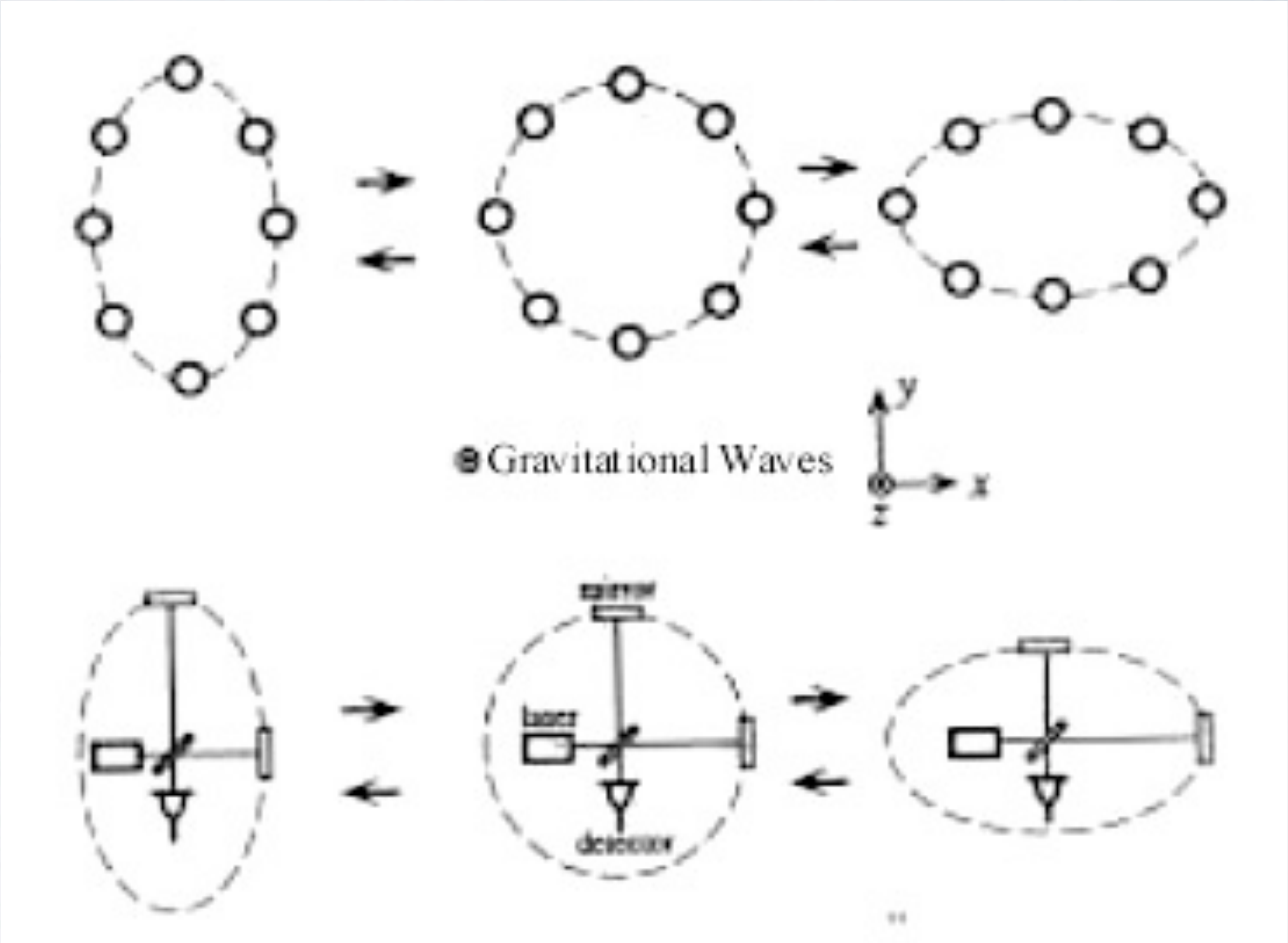




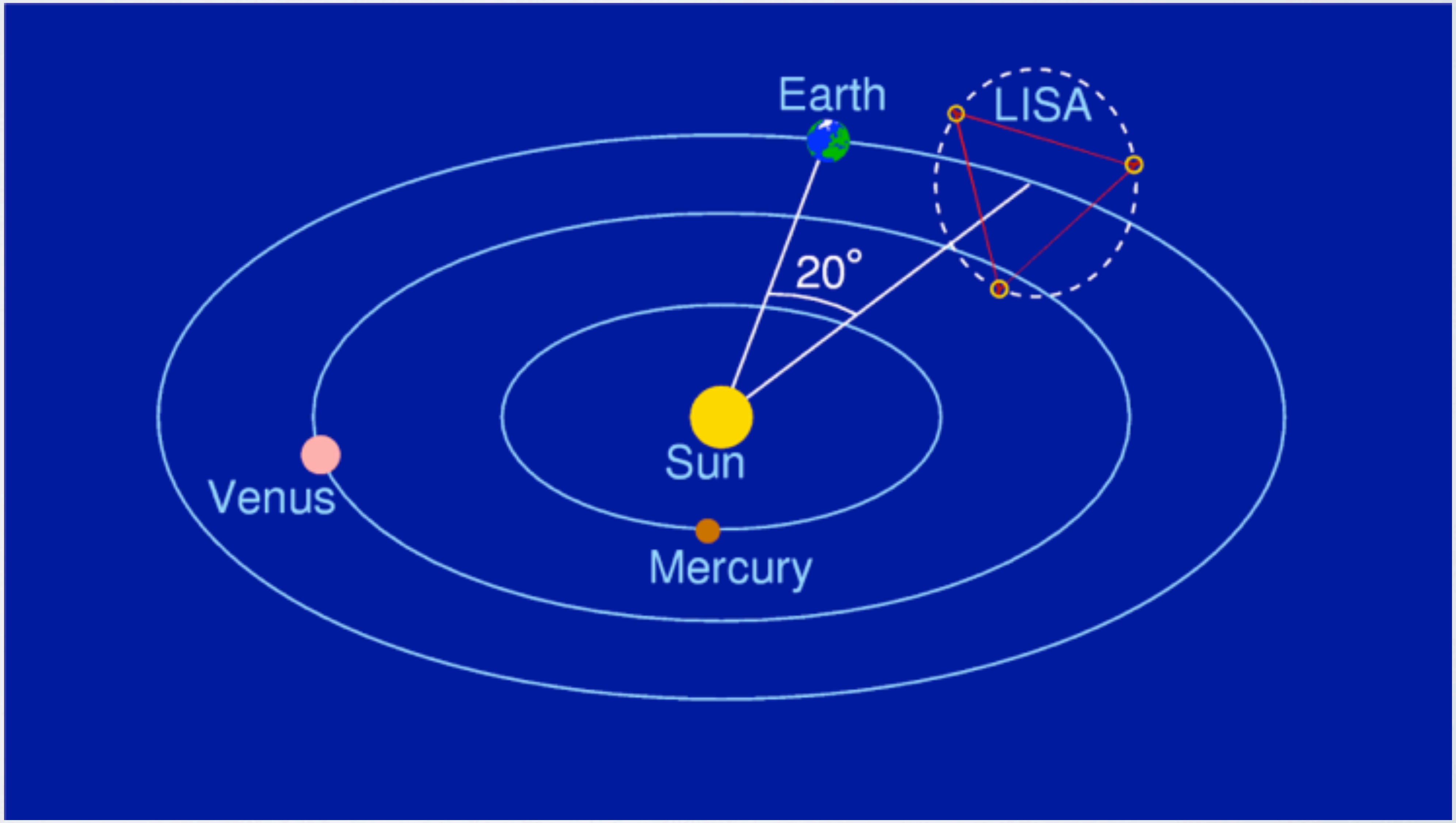


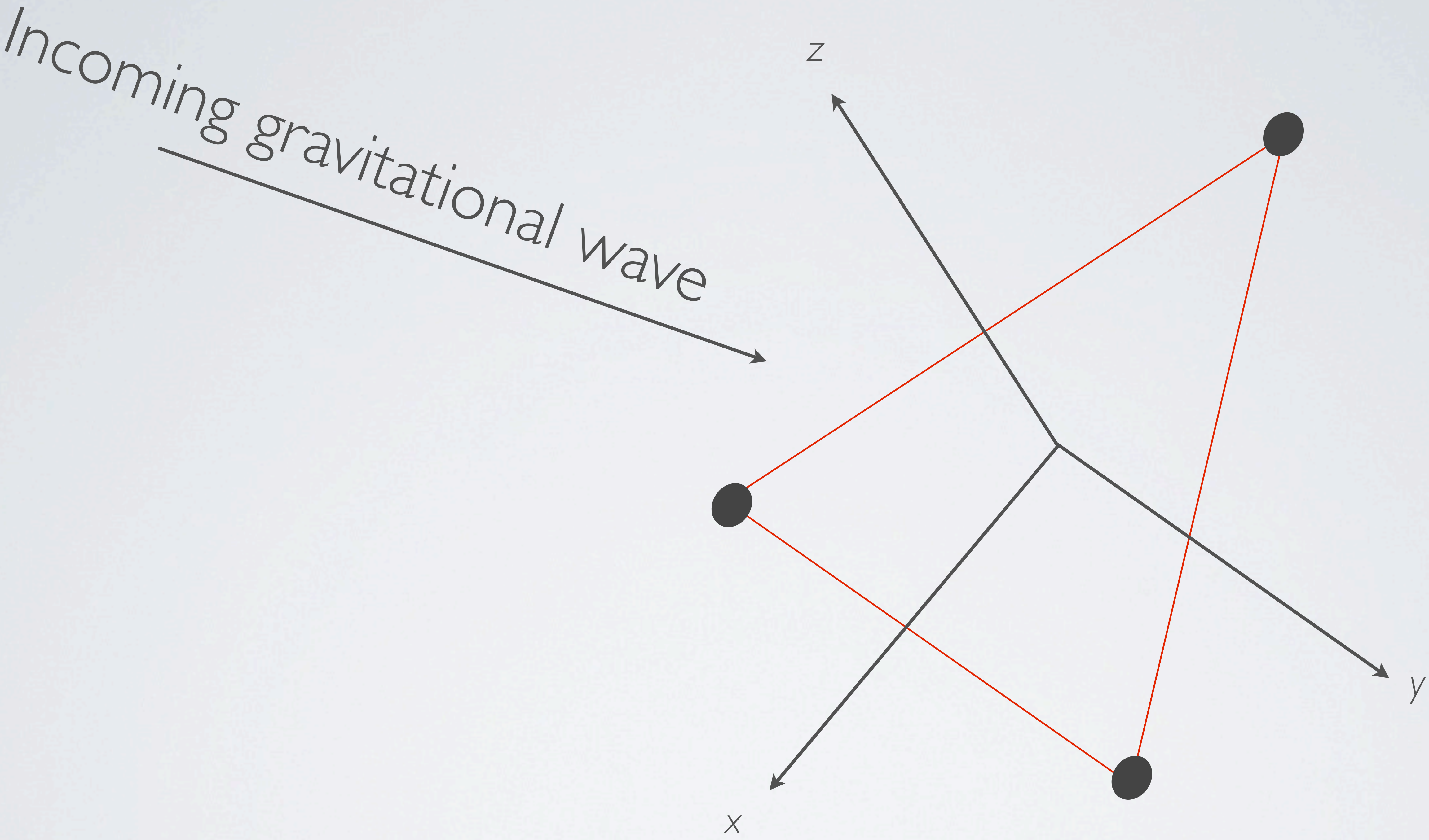
INTERFEROMETRIC DETECTION

- Isolate test masses from external forces.
- Carefully measure the distance/light travel time between two test masses.
- Simple interferometry detects the variation in armlengths.
- Polarization states are usually defined in terms of the arms.



- Space-based inteferometers rely on constellations flying in orbit.
- One-way laser and laser-transponders connect each arm.





Polarization states determined by x, y

- Motion of the detector influences sensitivity to direction of the sources.
  - Rotation of the detector within its plane.
  - Precession of the plane.
  - Motion of the guiding center of the detector plane relative to the stars.

The "Peanut"

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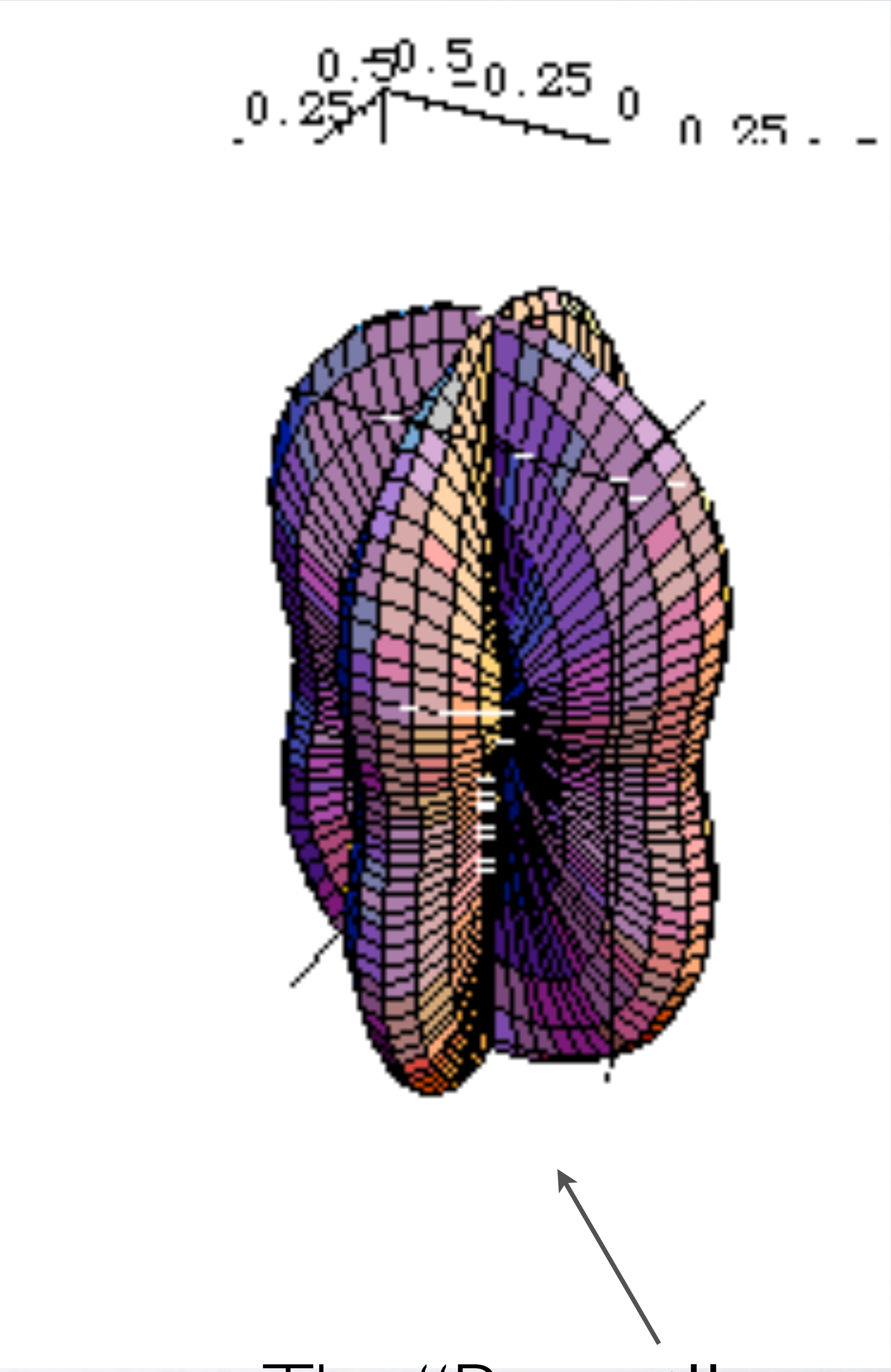


The "Peanut"

- Tumbling motion of the plane of the detector and the orientation of the triangle introduces varying responses to each polarization.
- It also introduces sensitivity variations due to sky location.
- Orbital motion about the sun introduces frequency (or phase) variation due to sky location.
- All this variability permits the estimation of sky location and orientation of the source.

BASICS OF GRAVITATIONAL RADIATION EMISSION

- Accelerating masses emit gravitational waves.
- Analogous to accelerating charges and EM radiation.
- Conservation of mass/energy implies no monopole emission.
- Conservation of momentum implies no dipole emission.
- Quadrupoles can emit!
- Binary systems have time-varying quadrupole moments.

WHY I LIKE WHITE DWARFS

- Because gravitational waves influence the spacetime through which they travel, emission from highly relativistic, strong field sources is difficult to calculate.

- White dwarfs are low mass systems that come into contact before the orbital speeds become relativistic.

- The quadrupole moment is the dominant source of radiation.

- Radiation reaction is easy to compute, using the adiabatic approximation.

- The frequency shift due to radiation reaction is linear for all reasonable observation times.

GRAVITATIONAL WAVES

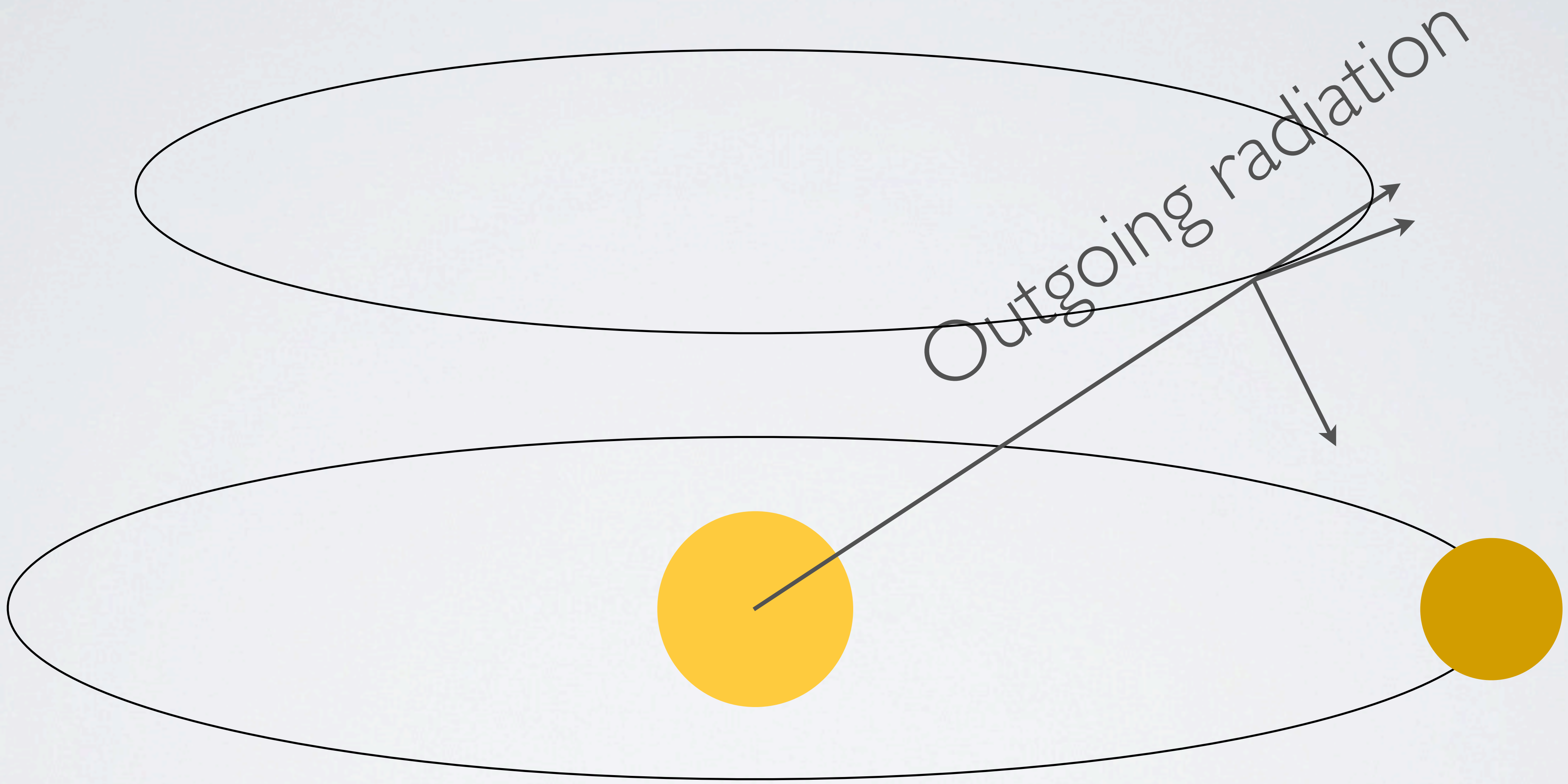
- Quadrupole Formula

$$h_+ = 2\frac{G^{5/3}\mathcal{M}^{5/3}}{c^4 d}\left(2\pi f\right)^{2/3}\left(1+\cos^2\iota\right)\cos\left(2\pi f t\right)$$

$$h_\times = -4\frac{G^{5/3}\mathcal{M}^{5/3}}{c^4 d}\left(2\pi f\right)^{2/3}\cos\iota\sin\left(2\pi f t\right)$$

- Chirp mass $\mathcal{M} = \left(M_1 M_2\right)^{3/5}\left(M_1+M_2\right)^{1/5} = \mu^{3/5}M^{2/5}$

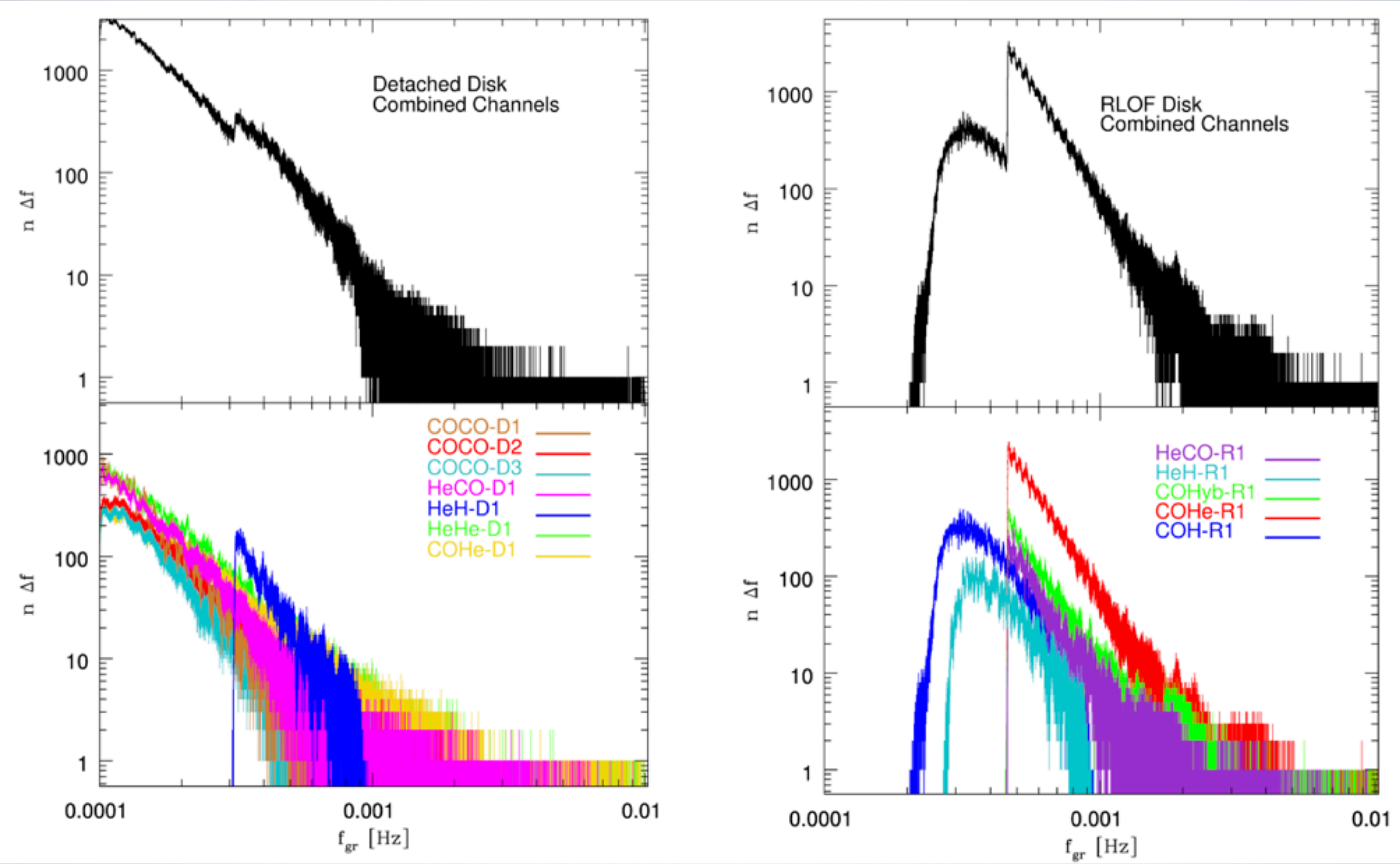
- Inspiral $\dot{f} = \frac{96}{5}\frac{G^{5/3}\mathcal{M}^{5/3}}{c^5}f^{11/3}$


Outgoing radiation

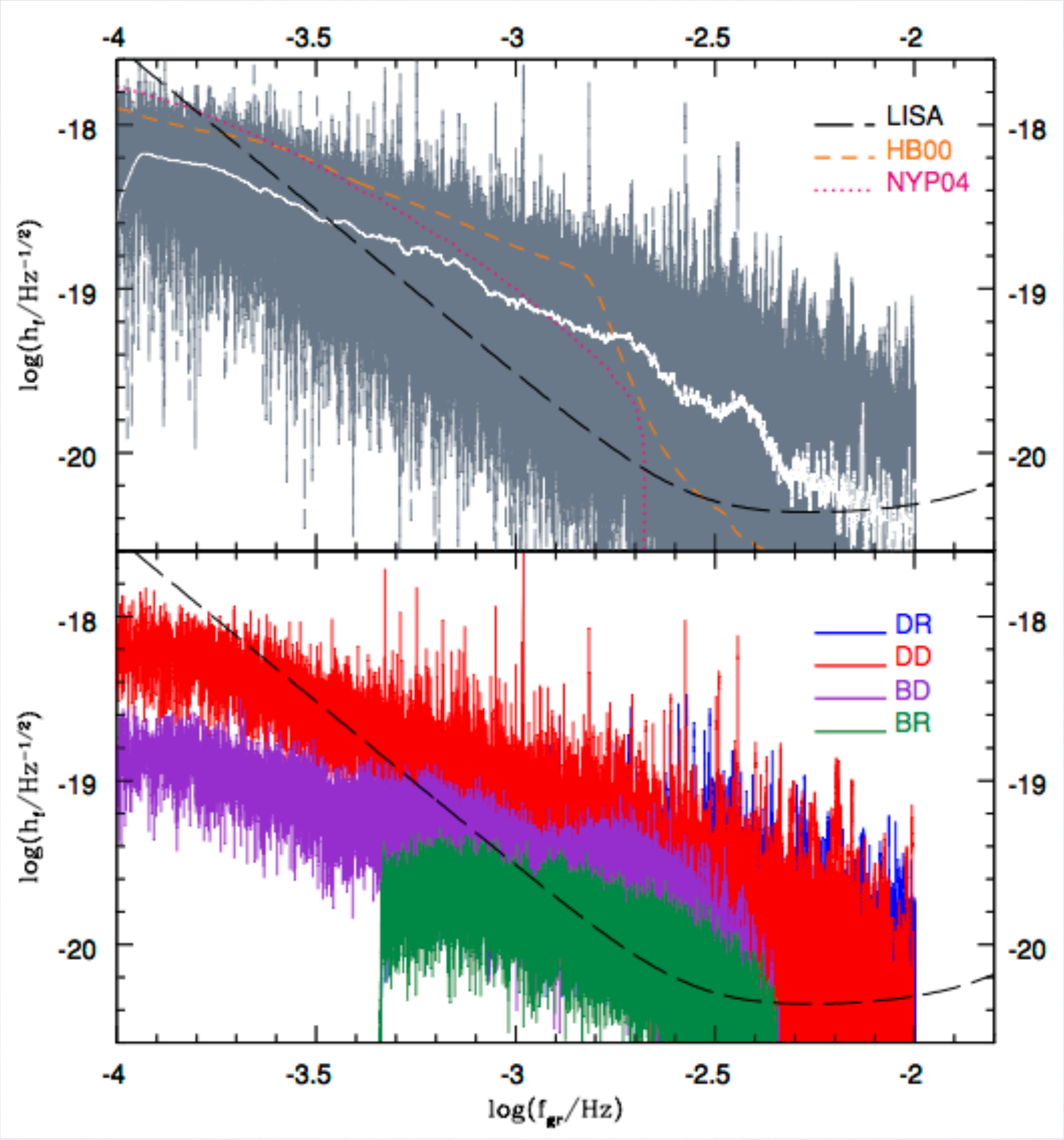
THE GALACTIC POPULATION IN GRAVITATIONAL WAVES

- We can estimate the Galactic population of double white dwarfs in the frequency band of interest.
- Population Synthesis:
  - Belczynski
  - Nelemans
  - Jeffrey
  - …

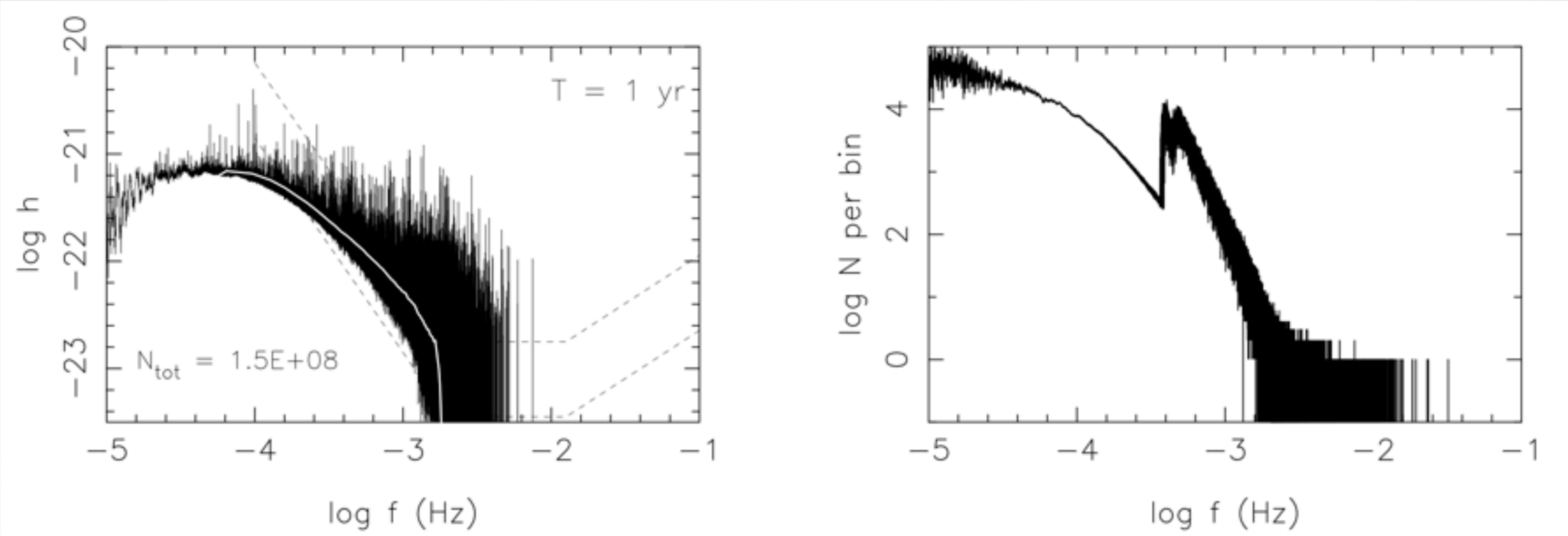
- ~ 30 million binaries within 0.01 and 100 mHz
- Crowding in frequency-space for frequencies below about 3 mHz
- Mass-transferring and Detached systems within the band.



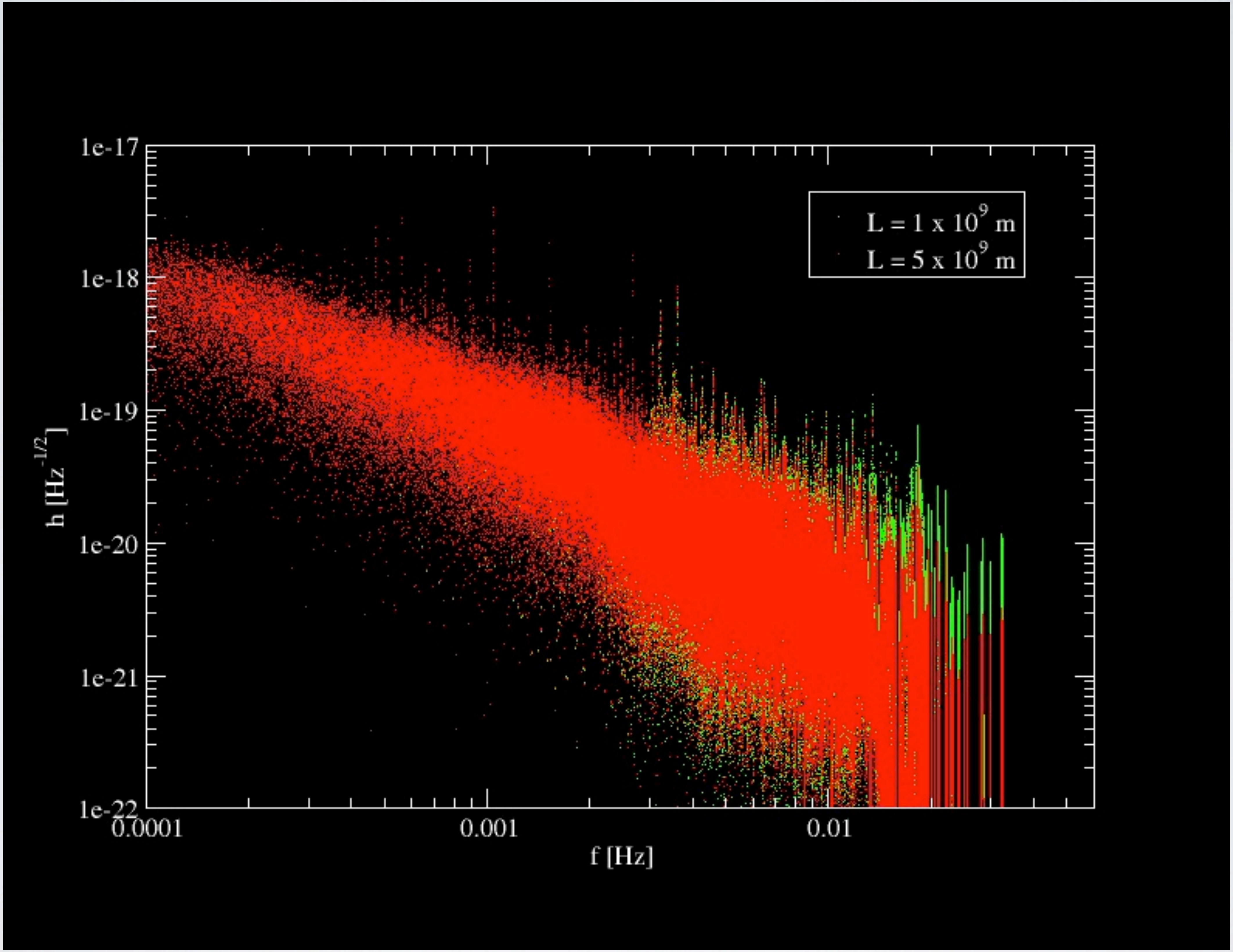
Ruiter et al. 2010



-4
-3.5
-3
-2.5
-2
LISA
HB00
NYP04
DR
DD
BD
BR
-18
-19
-20
log(h_f/Hz^-1/2)
log(f_gr/Hz)

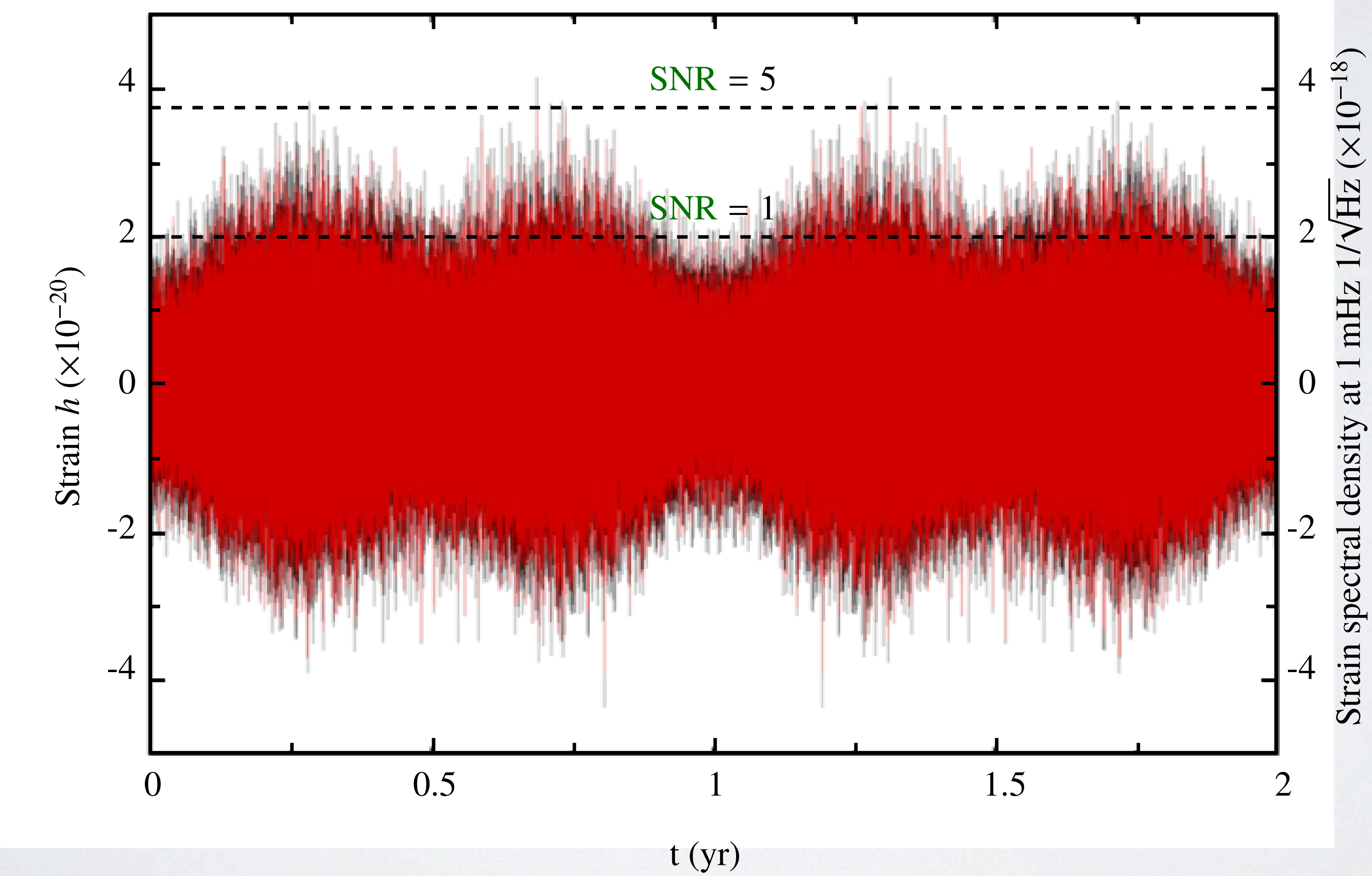


Nelemans et al. 2004



L = 1 x 10^9 m
L = 5 x 10^9 m
1e-17
1e-18
1e-19
1e-20
1e-21
1e-22
h [Hz$^{-1/2}$]
0.0001
0.001
0.01
f [Hz]

- Parameter Estimation of Resolvable Systems:
  - Add annual rotation of the "peanut"
  - Annual variation of polarization phase
  - Annual variation of Doppler phase



MODEL GALAXY AND DETECTION EXAMPLE: SNE IA PROGENITORS

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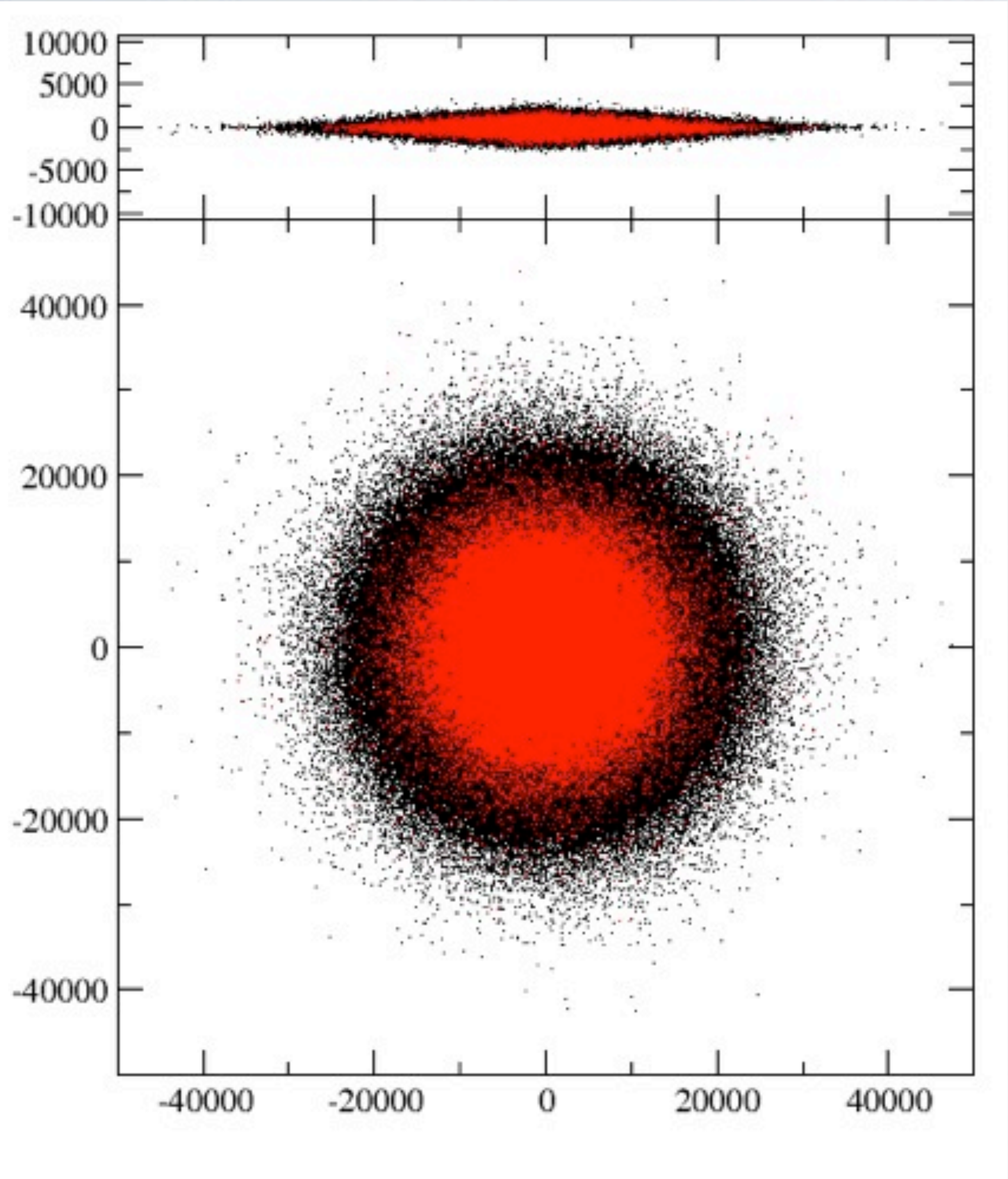
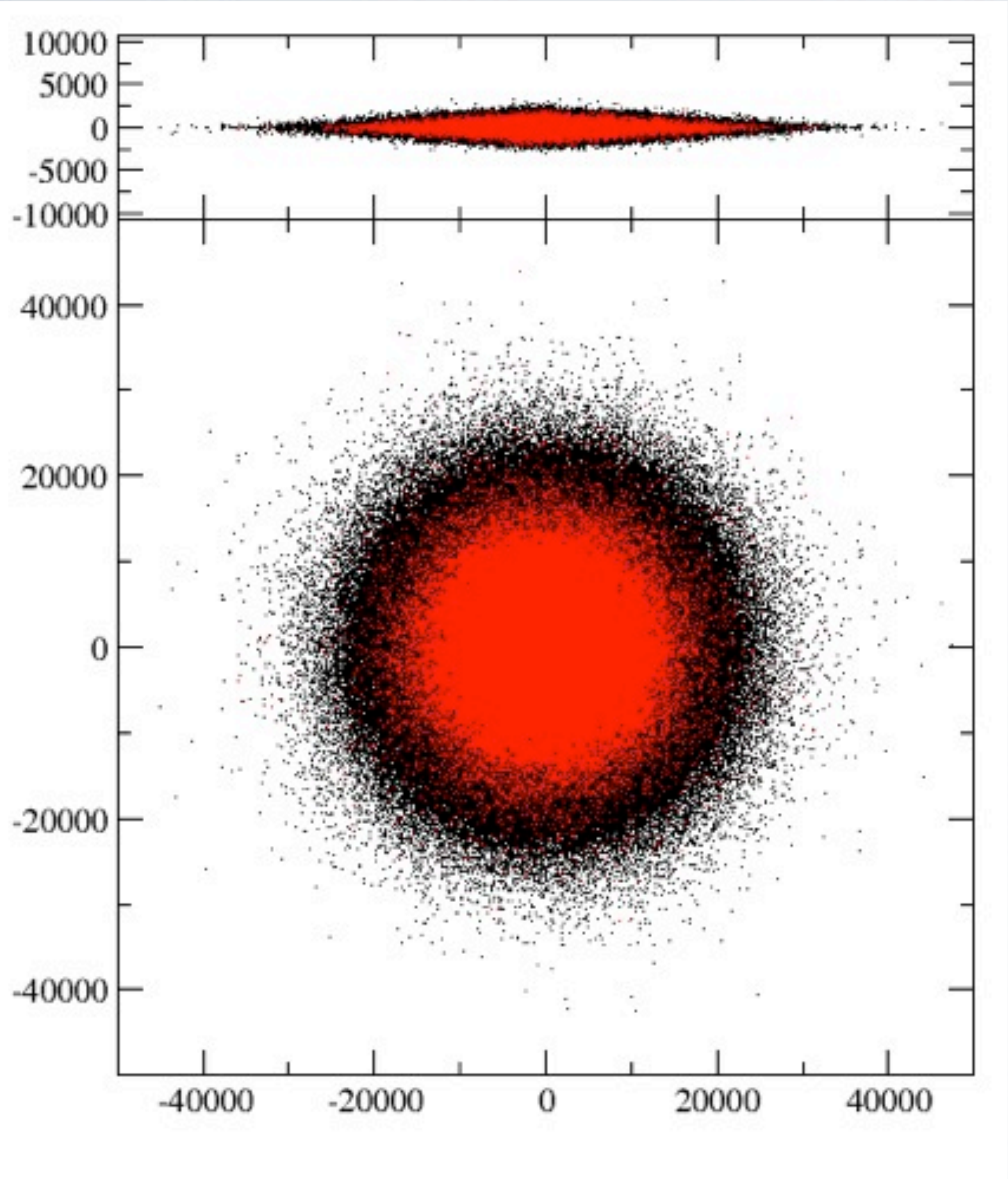
Full
Galaxy
model
with bulge

MODEL GALAXY AND DETECTION EXAMPLE: SNE IA PROGENITORS

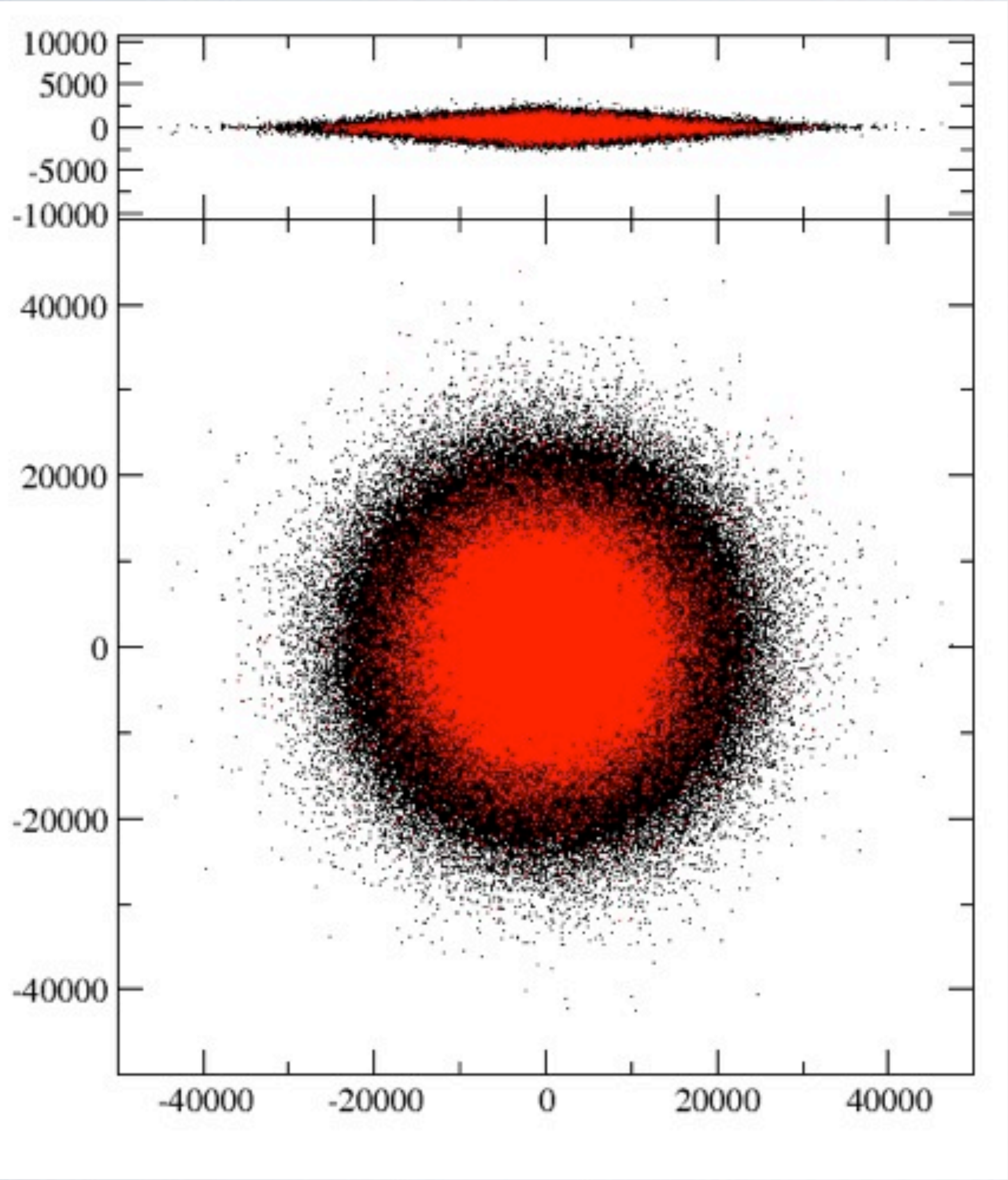


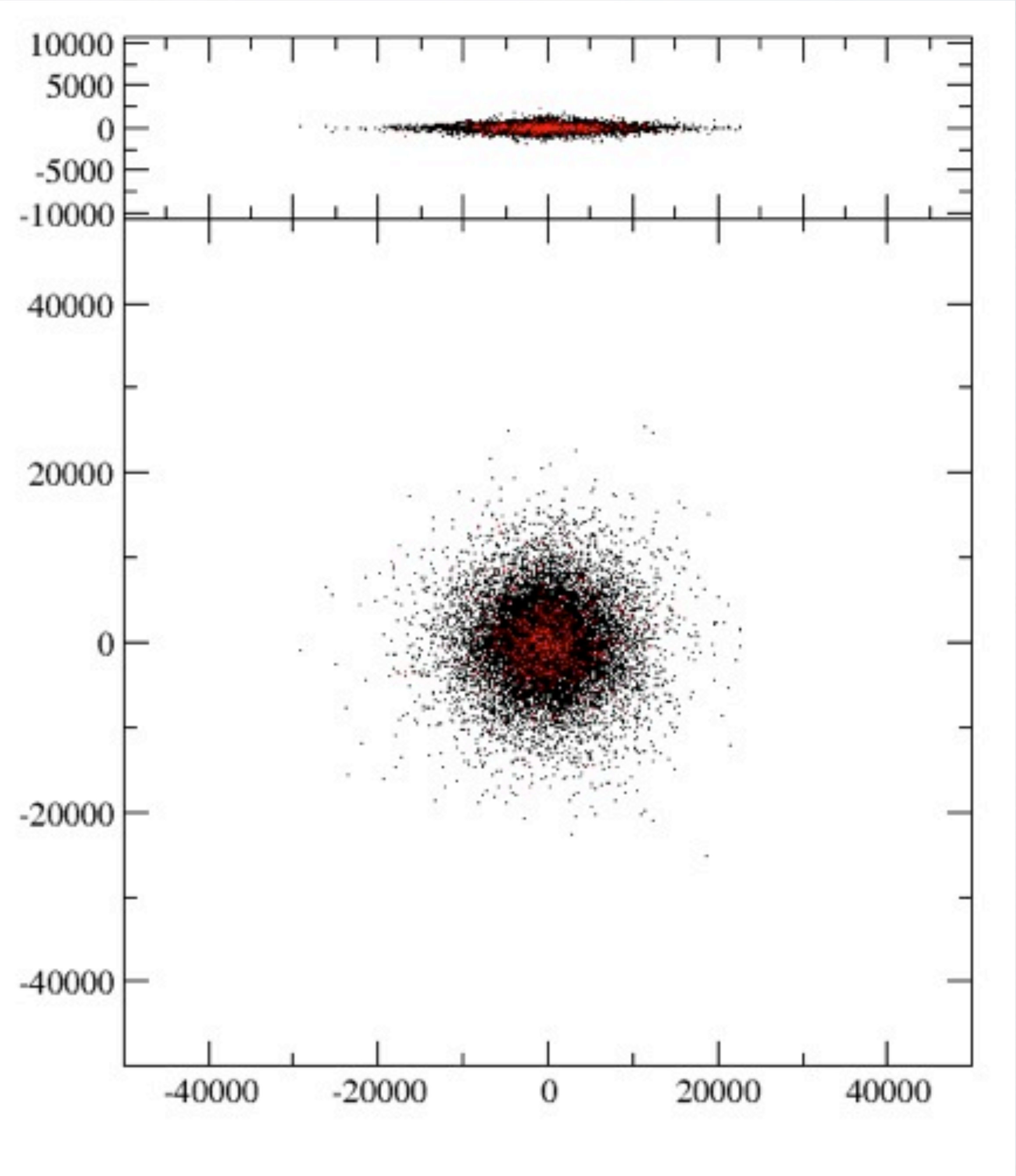
MODEL GALAXY AND DETECTION EXAMPLE: SNE IA PROGENITORS

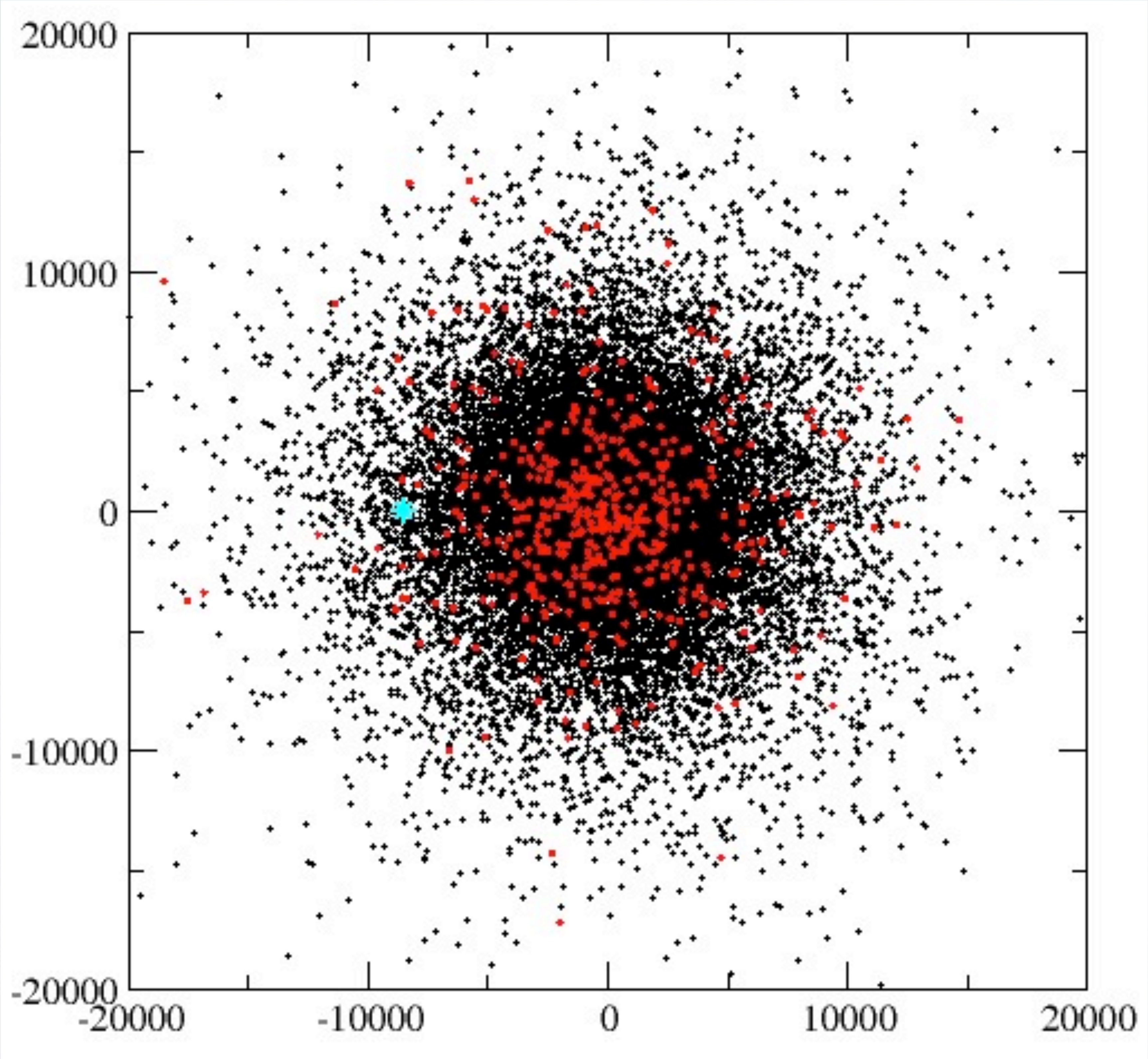


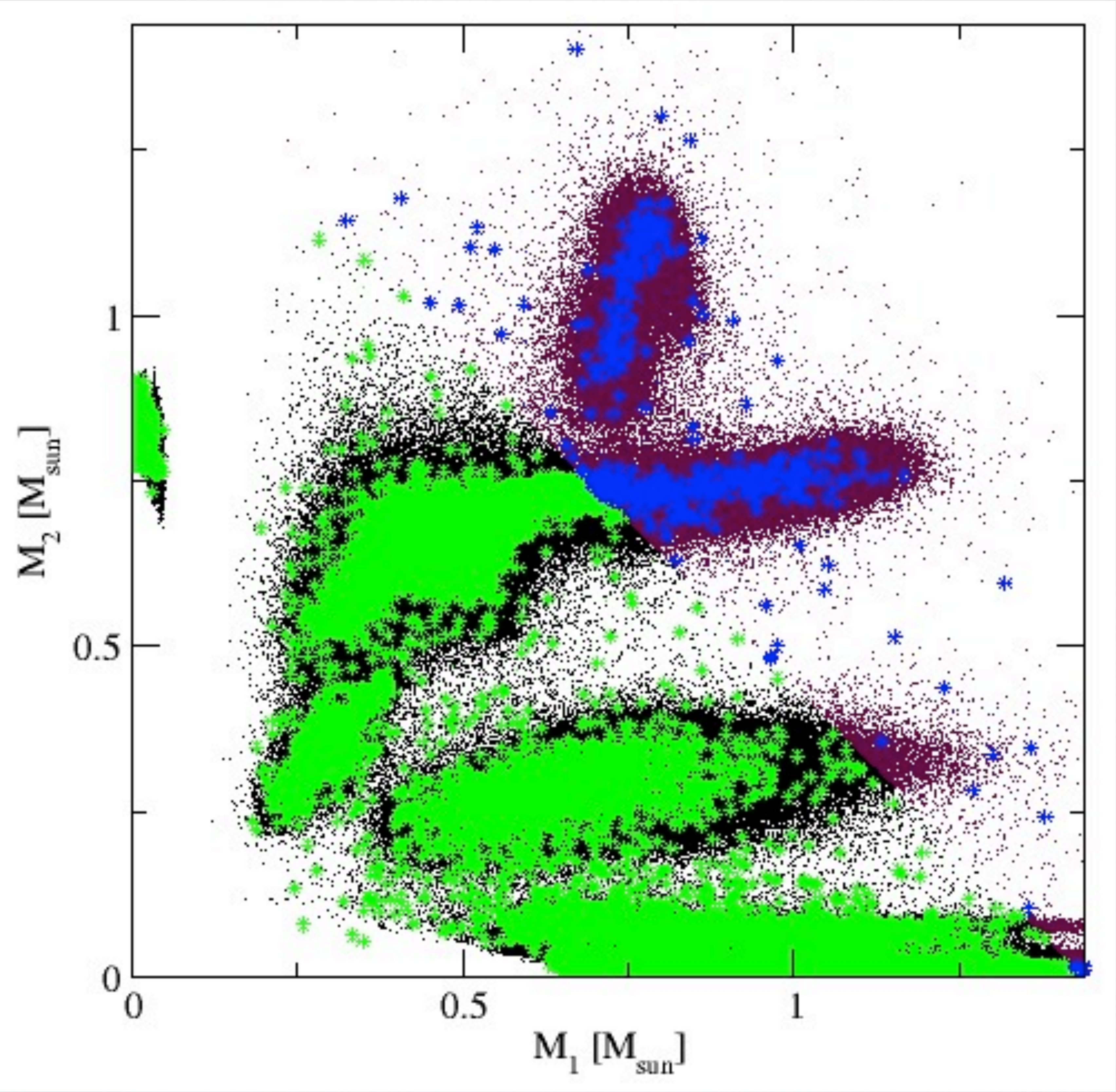
Resolved binaries using matched filtering

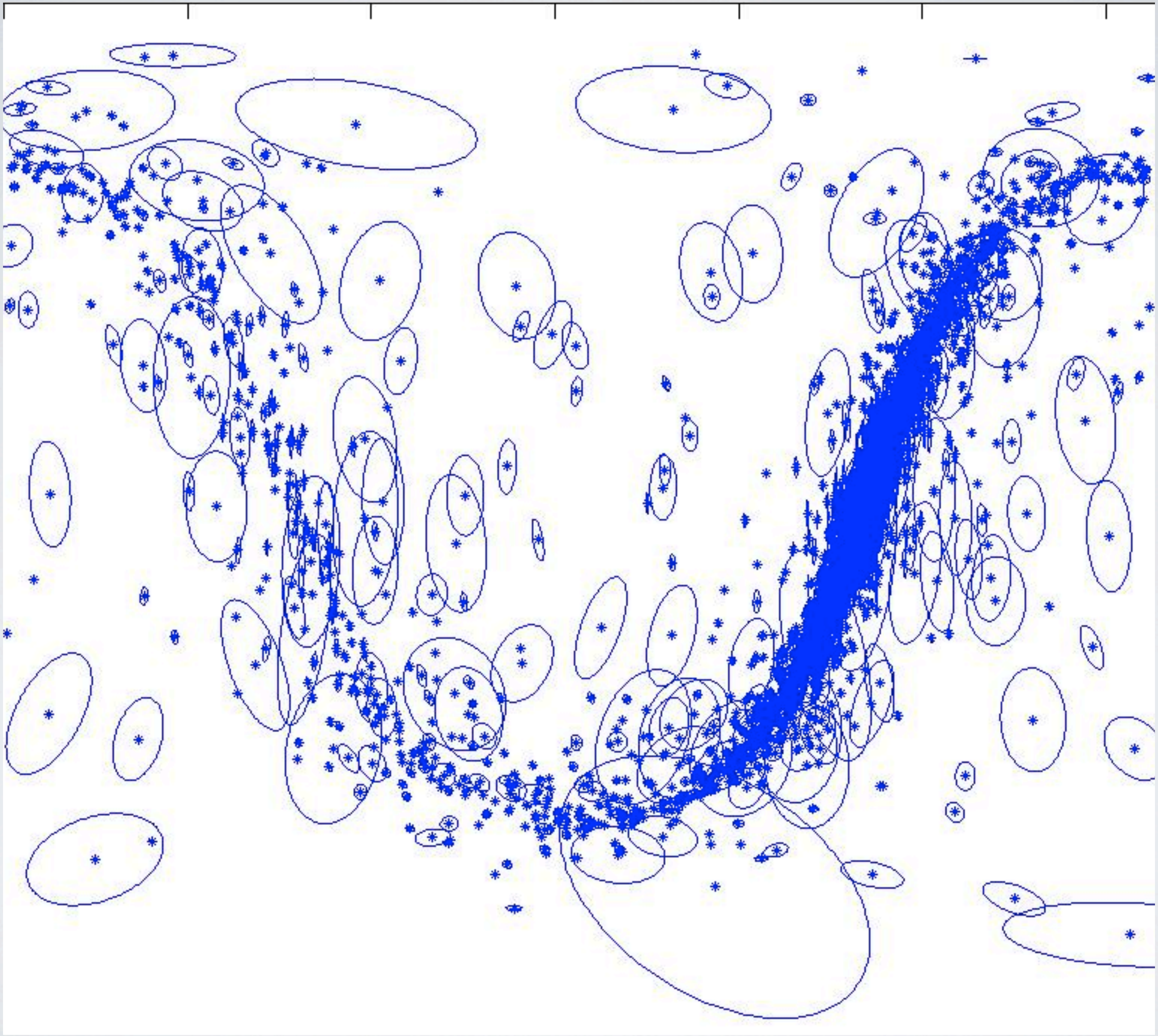
MODEL GALAXY AND DETECTION EXAMPLE: SNE IA PROGENITORS






20000
10000
0
-10000
-20000
-20000
-10000
0
10000
20000


1
0.5
0
0
0.5
1
M_2 [M_{sun}]
M_1 [M_{sun}]

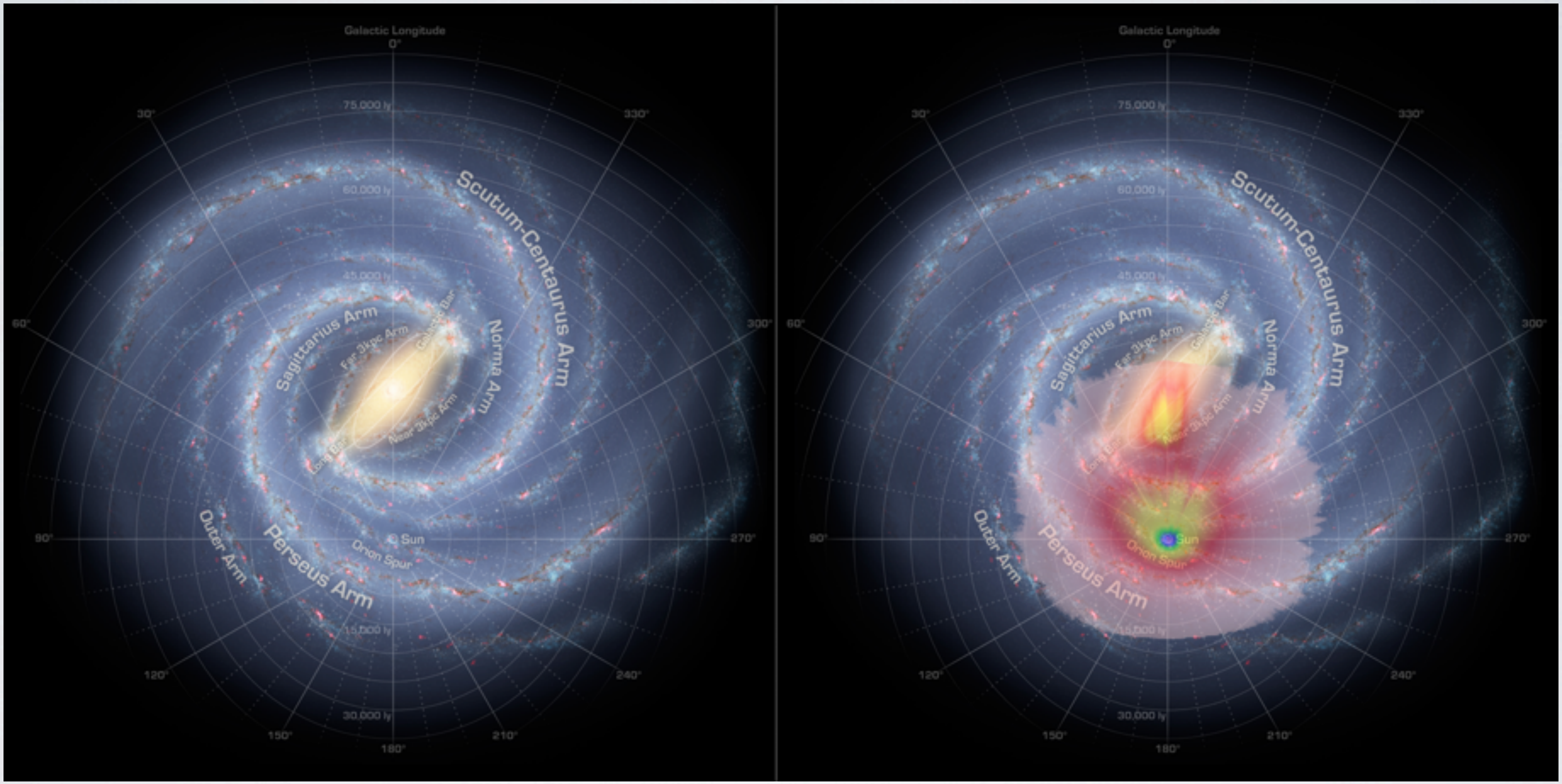


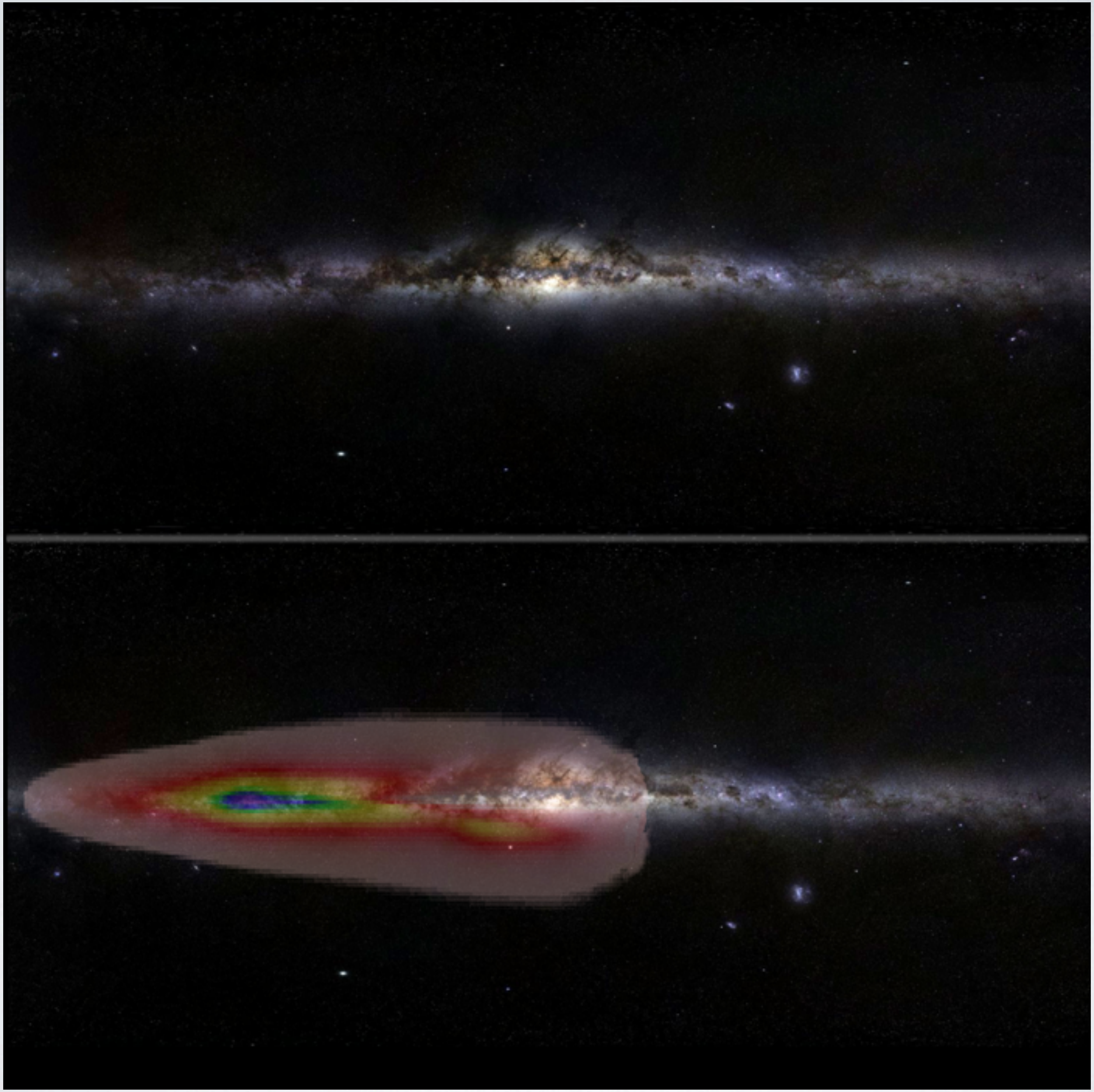
GRAVITATIONAL WAVE OBSERVATIONS OF WHITE DWARF BINARIES

- No extinction in the Galaxy
- Crowding in frequency space—not physical space
- Massive systems are visible throughout the Galaxy
- We get a good census of the entire Galactic population of massive, ultra-compact white dwarf binaries.
- Measure orbital period, inclination, sky location.

GAIA CAPABILITIES

- Limiting magnitude: ~20
- Limiting crowding: ~6 × 10^5 stars/deg^2
- ~ 10^9 stars in the Gaia catalog
- How many will be white dwarf binaries?
- White dwarf absolute magnitude: ~10-15
- Limiting distance: ~ 100-1000 pc


Galactic Longitude
0°
30°
330°
60°
300°
90°
270°
120°
240°
150°
210°
180°
75,000 ly
60,000 ly
45,000 ly
15,000 ly
30,000 ly
Scutum-Centaurus Arm
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Norma Arm
Near 3kpc Arm
Long Bar
Outer Arm
Perseus Arm
Sun
Orion Spur



ELECTROMAGNETIC OBSERVATIONS OF WHITE DWARFS

- Nearby systems are observable.
- Crowding in physical space — not frequency space.
- Extremely accurate sky locations.
- Biased towards young, hot systems.
- Biased towards interacting systems.

COMBINING OBSERVATIONS

- Some of the two observed populations will overlap.

- "Verification Binaries" are known through EM observations and will be used to confirm the GR analysis.

- Many new binaries will be found in GR with accurately known periods and inclination angles.

- Depending on the sky location errors, these can be searched for in the EM observations.

- Complementary observations can be used to identify and correct for the different biases.

ASTROPHYSICS PAYOFF

- Determine SNe Ia progenitor population
- Reveal mass transfer stability criteria
- Explore the far side of the Galaxy
- Reveal common envelope physics

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