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Gravitational wave probes of dark matter

Challenges and Opportunities

Presented by
Giada Selva

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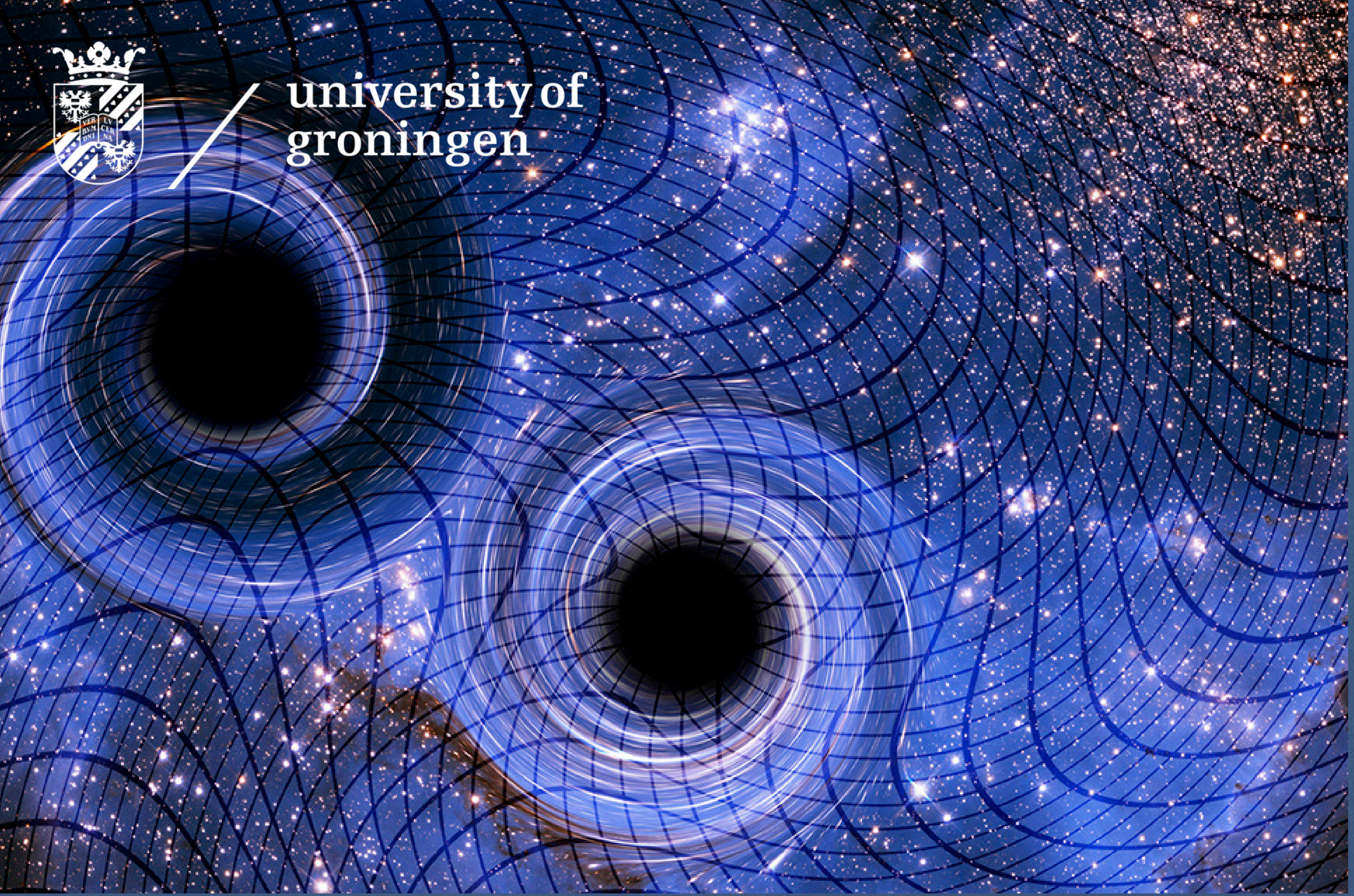

adapted by BBC skyatnightmagazine

adapted by UC Riverside

A New Era: Gravitational Waves as DM Probes

- Gravitational waves opened a new window on the Universe
- Reveal black holes, neutron stars, and their environments in detail
- Extend beyond astrophysics → probing Dark Matter
- LIGO, Virgo, ET, LISA, PTAs: unmatched sensitivity to the unseen Universe

The Six Pillars of GW Dark Matter Research

GW probes cover nearly 90 orders of magnitude in dark matter mass

Adapted by: Bertone et all

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Testing a Compact DM Candidate

Early-Universe Origin:

Formed <1 second after the Big Bang, PBHs remain a leading dark matter (DM) candidate

Gravitational Wave Evidence:

- Sub-solar mergers ($<1.4\ M_\odot$) → would indicate non-astrophysical origin
- High-redshift mergers ($z \gtrsim 40$) → detectable with Einstein Telescope / Cosmic Explorer

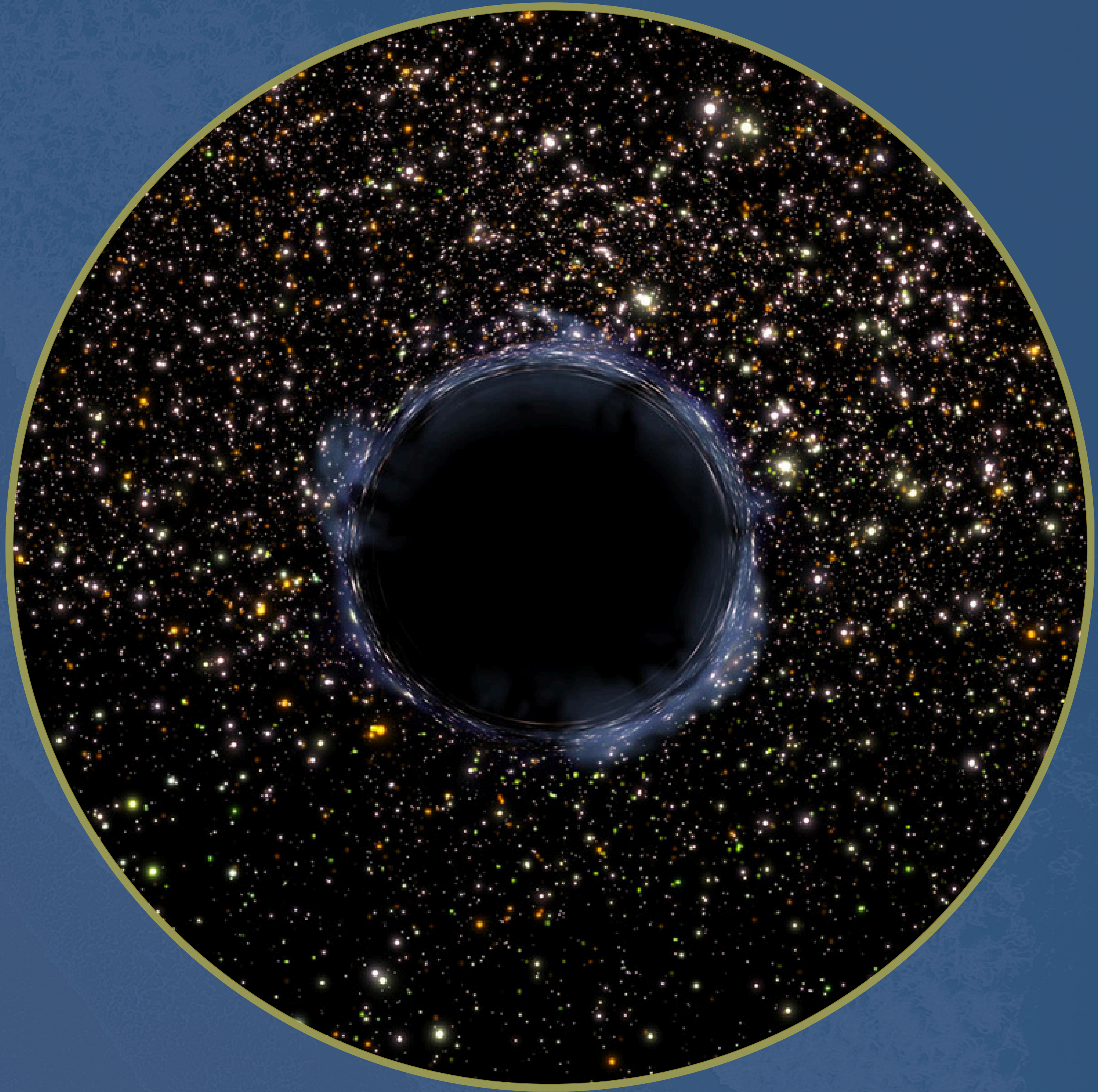
How to Tell PBHs Apart:

Compare merger rates, spins, mass & eccentricity distributions

Big Implication:

Detecting PBHs via GWs could rule out many WIMP models, reshaping dark matter theory

Adapted by:NASA/ESA and G. Bacon (STScI)



Primordial Black Holes (PBHs)

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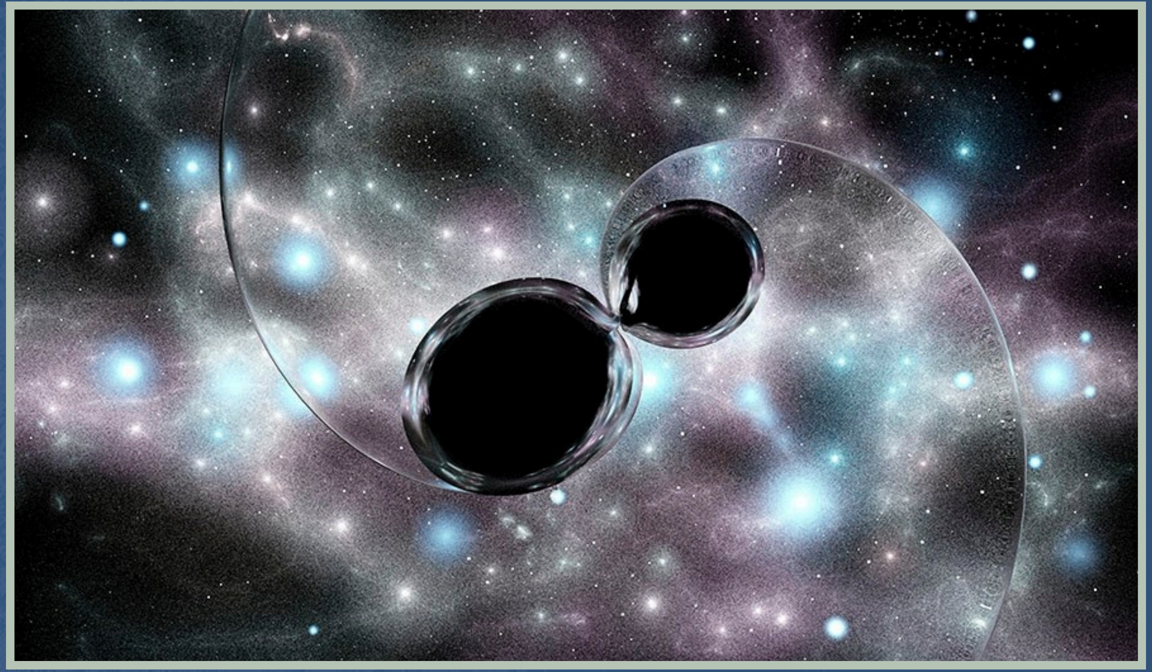
Environmental Effects

Finding Dark Matter in the Waveform



Core Idea:

Future GW detectors can spot tiny distortions in waveforms caused by matter near merging compact objects

Itralight Bosons (Axions / Dark Photons):

- Form bound clouds via superradiance around spinning BHs
- Cause BH spin-down and emit monochromatic GWs (detectable by LIGO / LISA)

Cold Dark Matter “Dark Dresses”:

- Dense DM halos may surround black holes
- Dynamical friction → waveform de-phasing
- Measuring this effect could reveal local DM densities

Multimessenger Opportunity:

Combine GW signals (e.g., from LISA) with radio data (Square Kilometre Array) to probe candidates like the QCD axion

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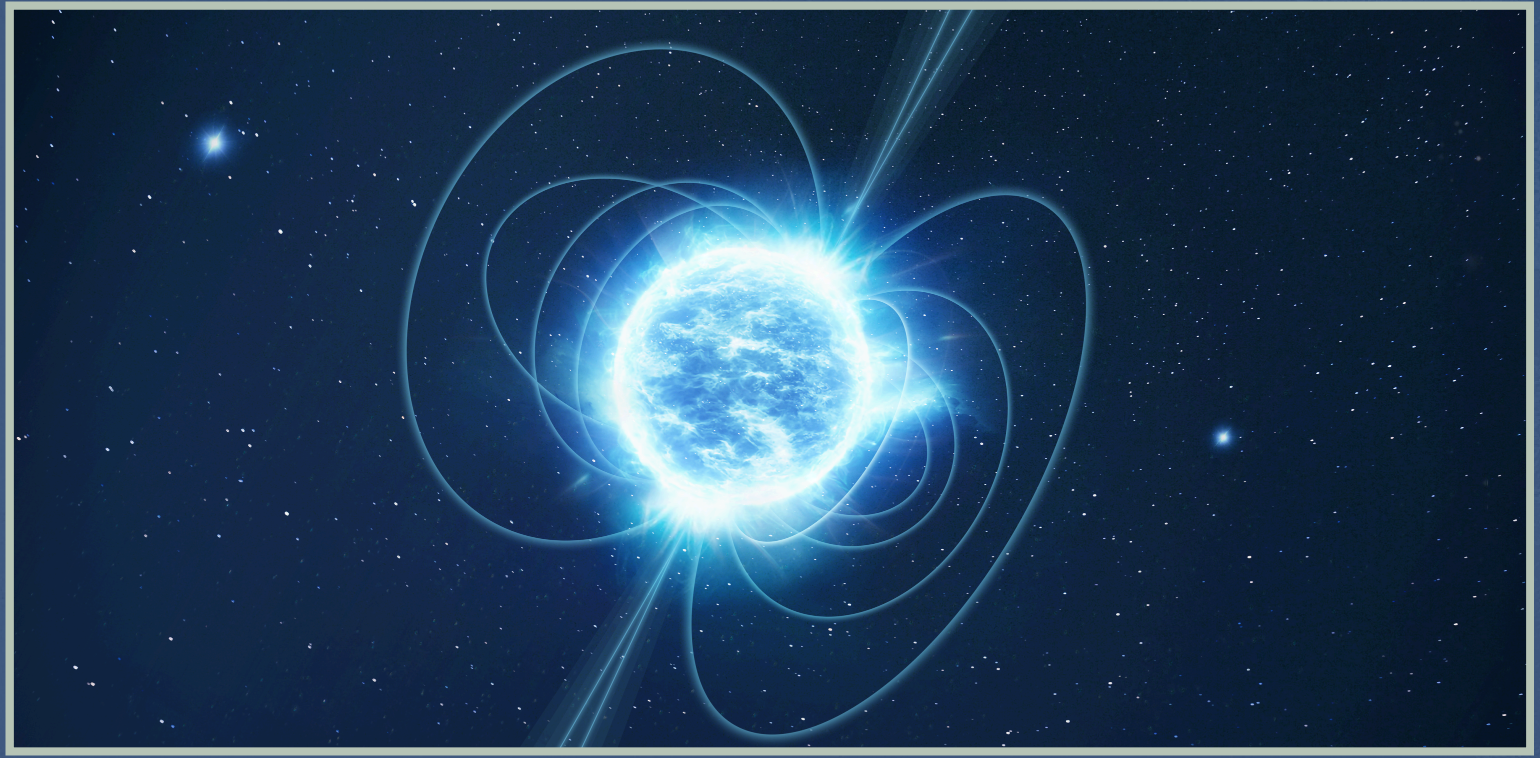
Exotic Compact Objects (ECOs):

Hunting for Dark Structures



Exotic Stars (e.g., Boson Stars):

- Built from scalar fields forming ultra-compact solitons
- Detectable by LIGO/LISA, depending on mass & compactness
- Differ from NSs/BHs by tidal deformability and scalar radiation

Black Hole Mimickers (ClePhOs):

- Horizonless objects (e.g., Gravastars, Wormholes)
- Identified by non-zero tidal Love numbers
- EMRIs can expose deviations in long inspiral waveforms

The main idea:

Dark particles may form Exotic Compact Objects (ECOs): mergers of these or mixed systems emit distinct gravitational waves

Captured DM Effects:

- DM inside neutron stars or captured PBHs can alter NS structure
- Leads to modified tidal deformability or dark-force effects in mergers

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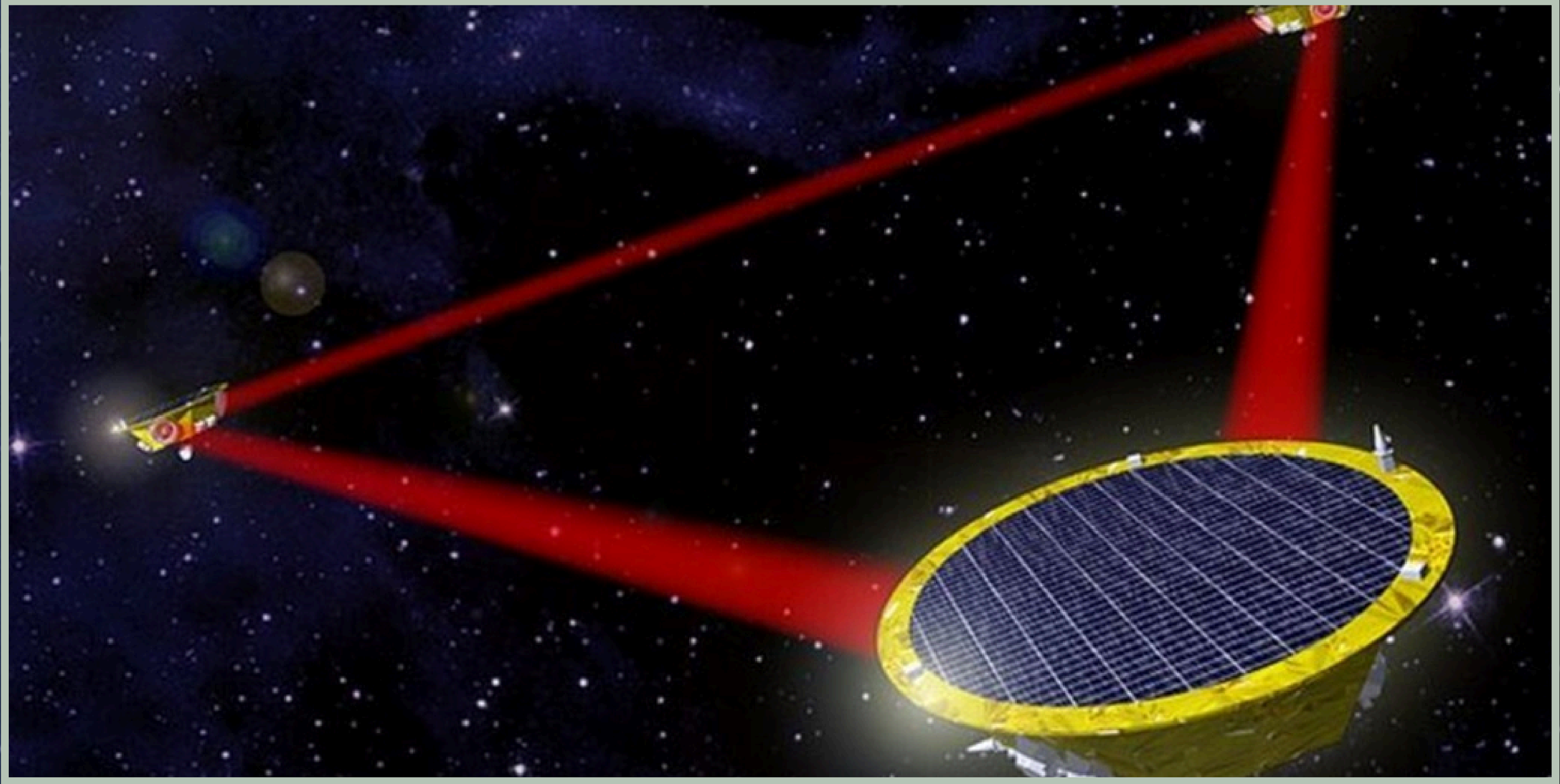
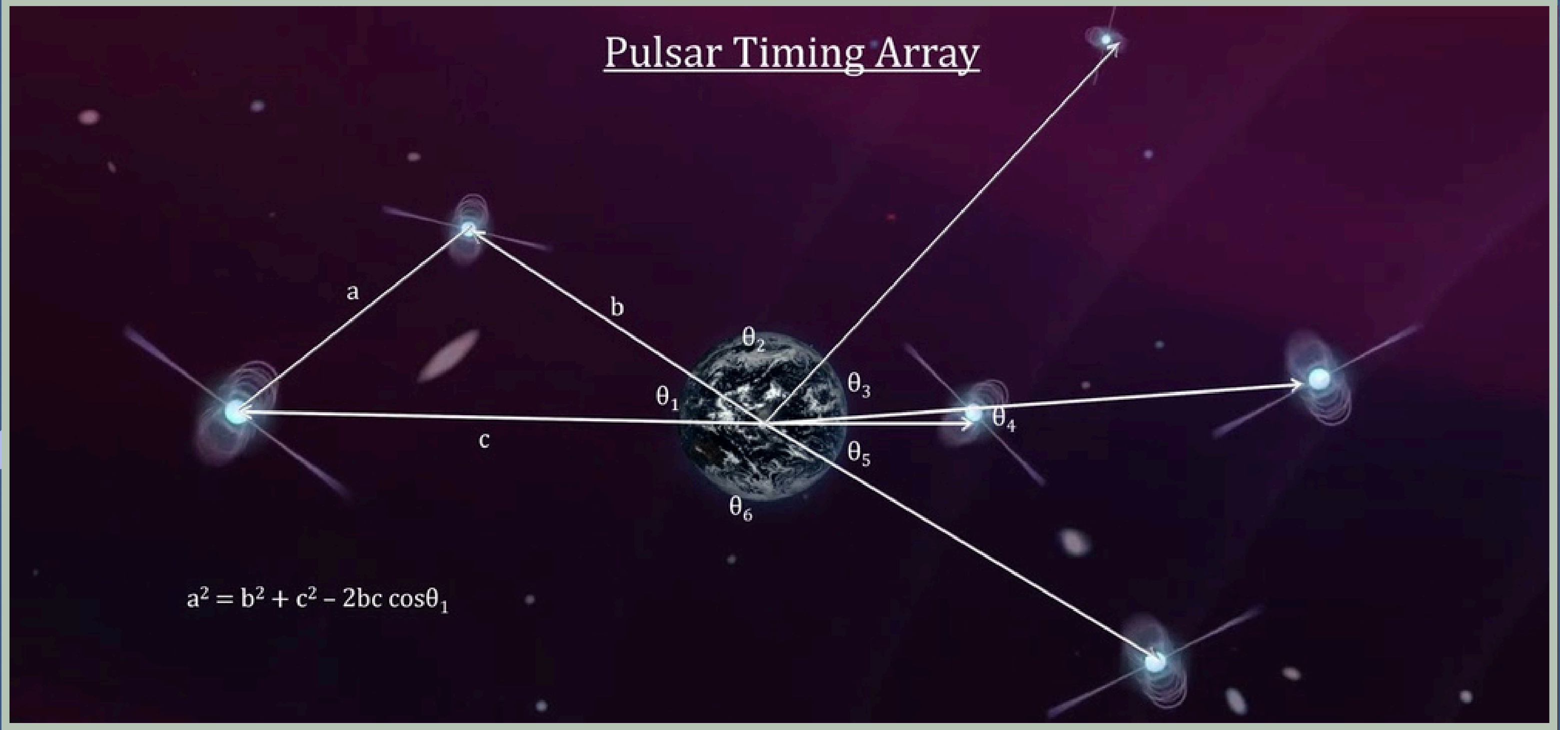
Direct DM Detection with GW Experiments

Interferometer Searches (LIGO / LISA)

- Ultralight fields (axions, dark photons) cause tiny, periodic distortions in spacetime or light paths
- Appear as monochromatic signals within detector sensitivity
- Cross-detector correlations enhance detection confidence





Pulsar Timing Arrays (PTAs):

- Use pulsars as cosmic clocks
- Detect tiny timing shifts caused by dark matter clumps or waves passing through the galaxy (nano frequencies)

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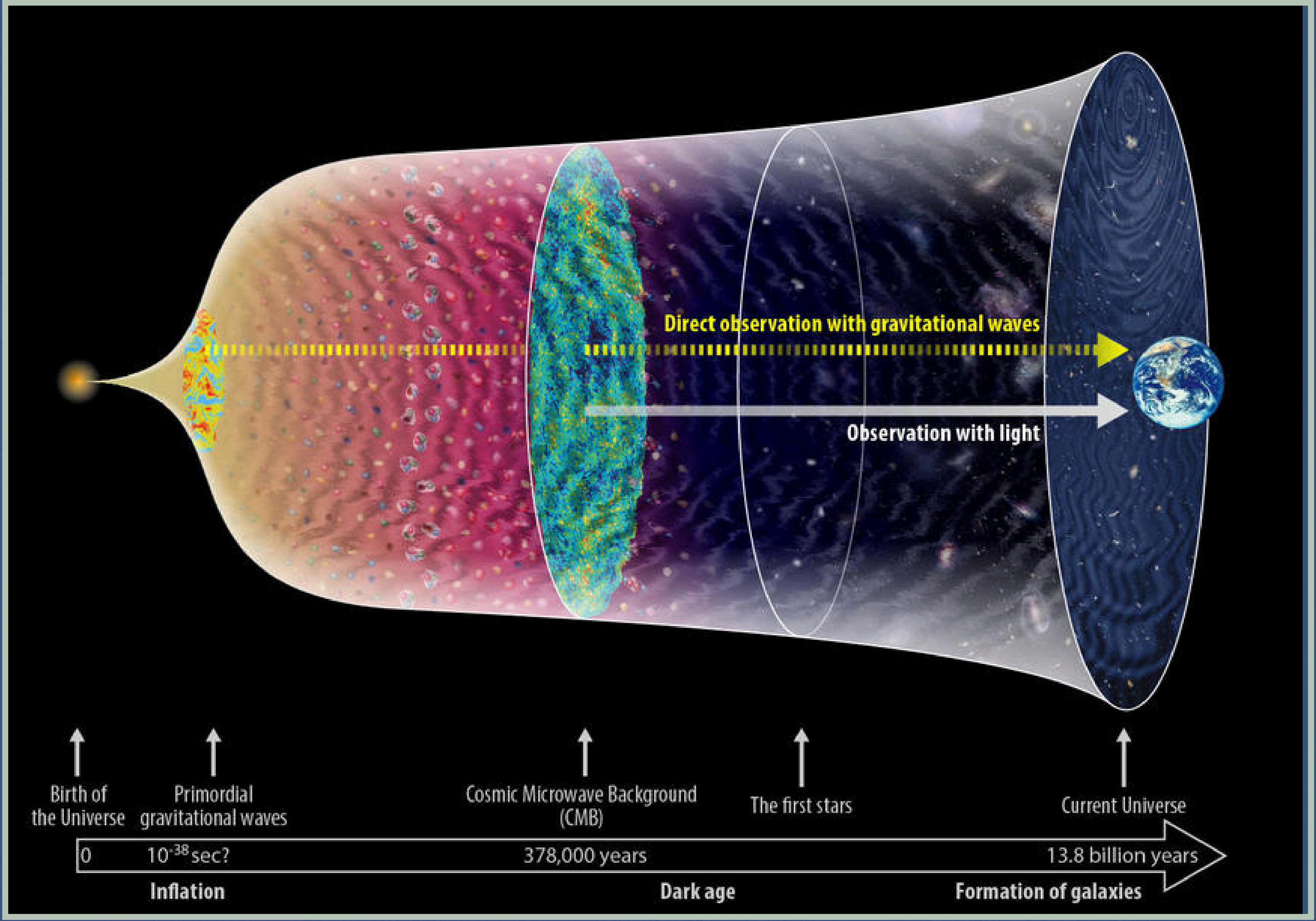
Non-Perturbative DM Dynamics:

Core Idea:

Early-universe dark matter dynamics can produce a stochastic background of gravitational waves

Key Mechanisms:

- **Scalar Fragmentation:**
 Oscillating fields fragment and cluster, sourcing turbulent GWs
- **Non-Perturbative Production:**
Explosive boson production (axions, vectors) creates anisotropic GW bursts



Tracing DM to Cosmic Origins

GW background

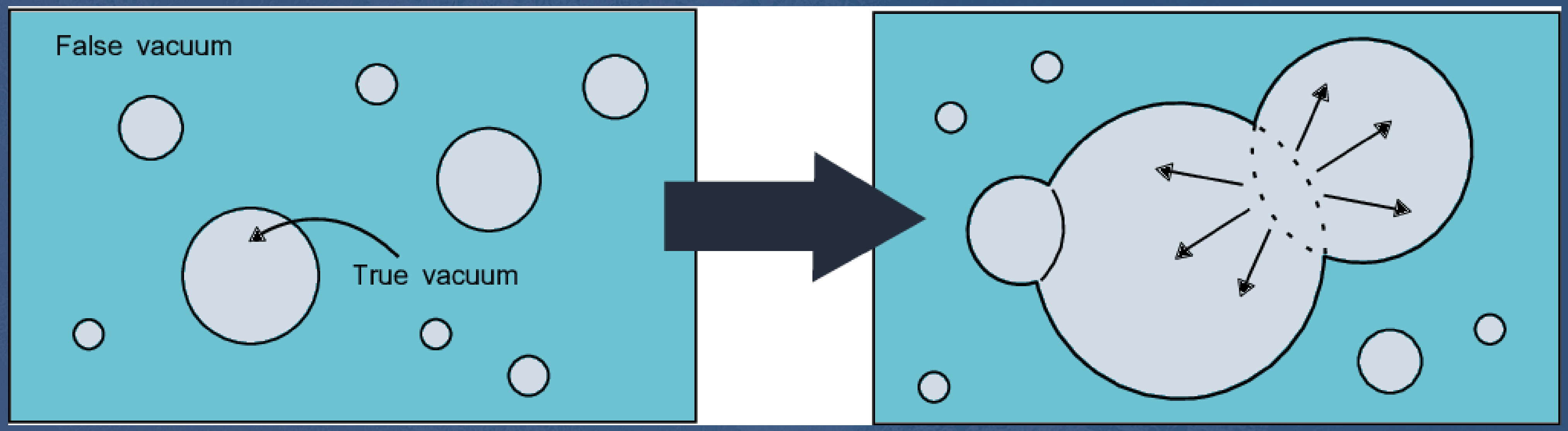
First-order phase transitions in the early Universe create bubble collisions that emit a stochastic GW background

Signature:

- Broken power-law GW spectrum; peak set by nucleation temperature (T_n)
- LISA targets EW-scale transitions ($T_n \approx 10^{-1}$–10^3 GeV)

DM Links:

- New scalars for EW baryogenesis → DM candidates
- Hidden sectors and supercooling alter DM relics or create heavy DM



Phase Transitions:

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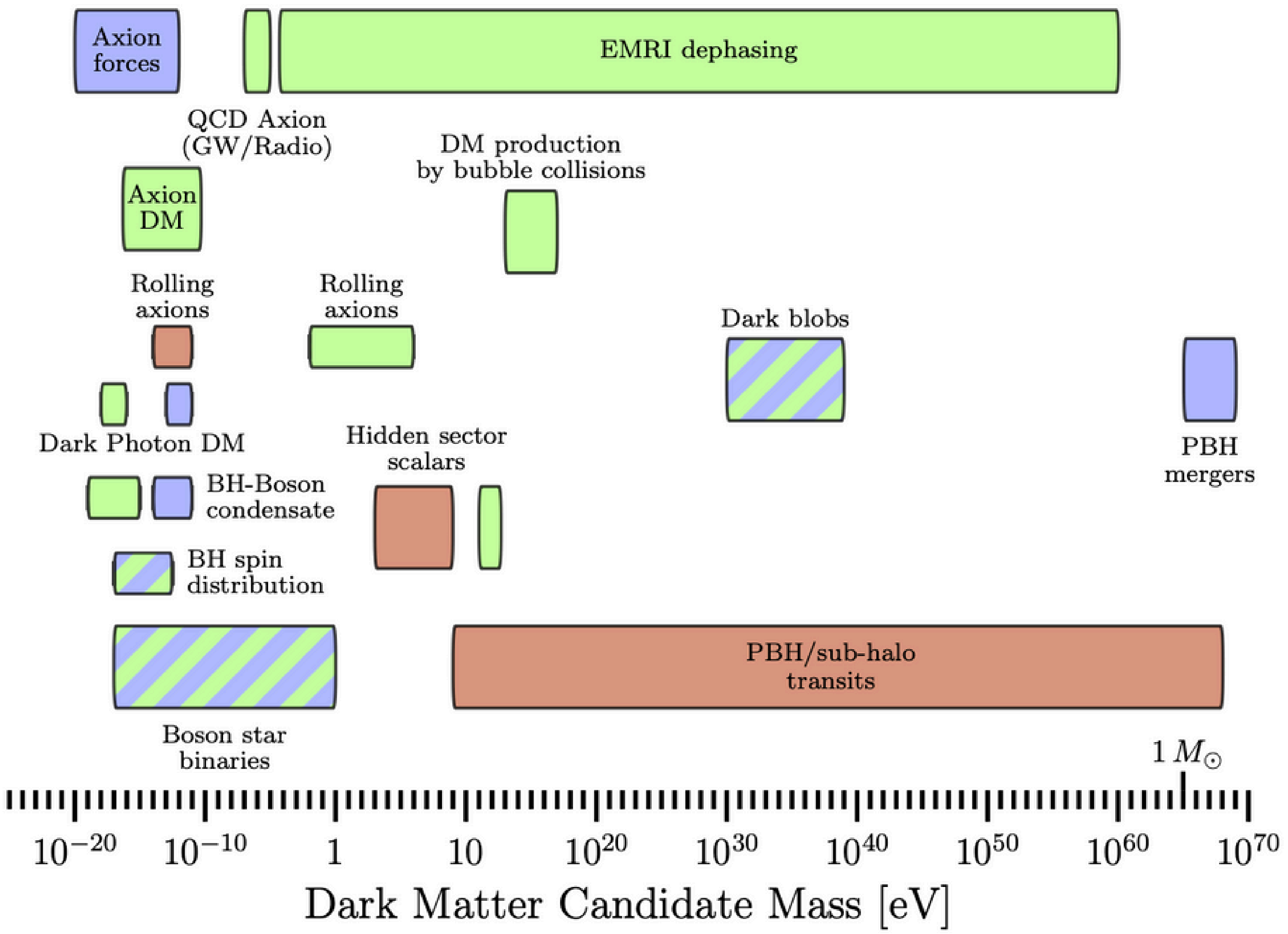
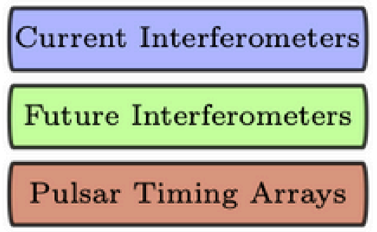
The Broad Scope of GW Constraints





Constraints
Axion forces [178]
QCD Axion (GW/Radio) [132]
EMRI dephasing [111, 112]
Axion DM [204]
Bubble collision DM [289]
Rolling axions [246]
Dark Photon DM [202]
Dark blobs [195]
PBH mergers [56, 62]
BH-boson condensate [121, 122]
Hidden-sector scalars [279, 280]
BH spin distribution [121, 122]
Boson stars [157, 158, 163, 166]
PBH/sub-halo transits [228, 229]

almost 90 orders of magnitude in DM candidate mass

Adapted by: Bertone et all.

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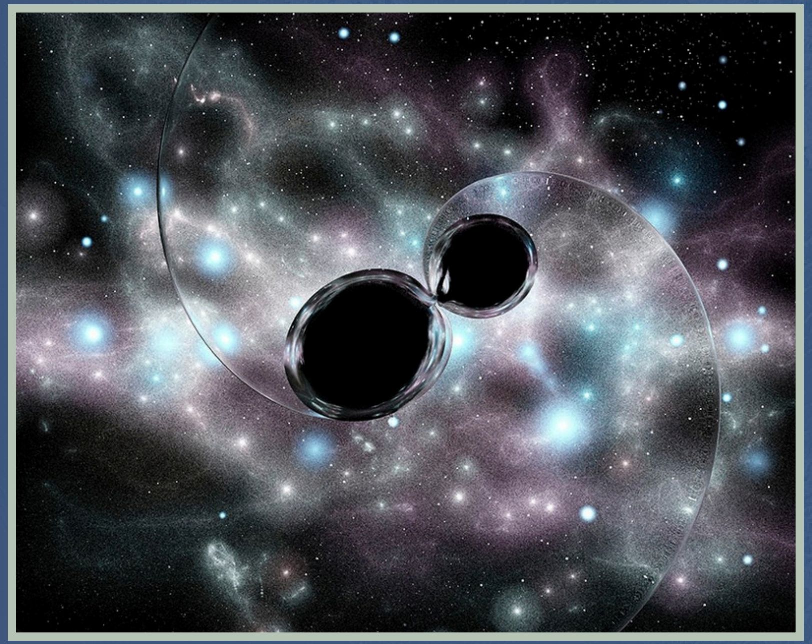
Key Challenges & Open Questions

PBHs

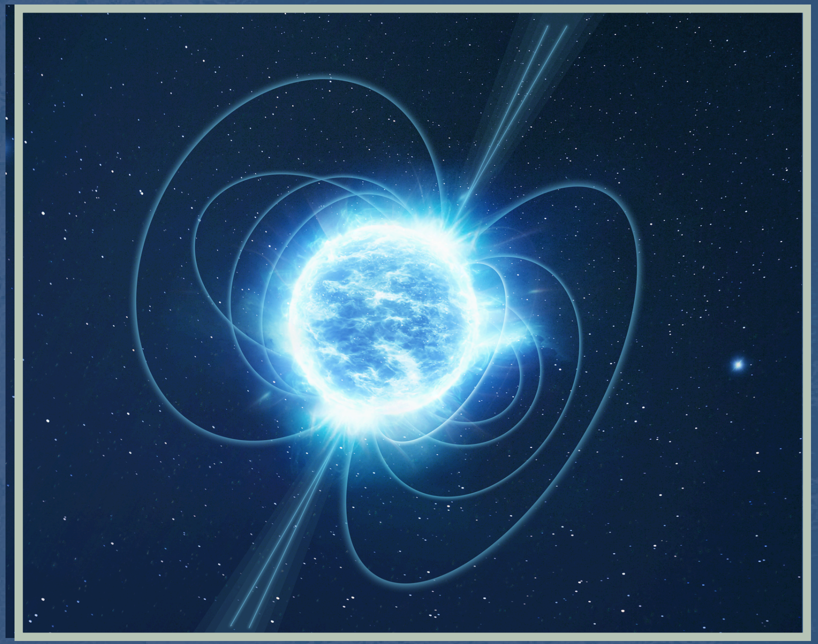
Improve modeling of formation and mass distributions; develop GW methods to distinguish production scenarios

Environmental Effects:



Test whether DM halos survive inspiral and if the de-phasing signal remains detectable

ECOs:



Clarify formation history and galactic distribution to predict merger rates

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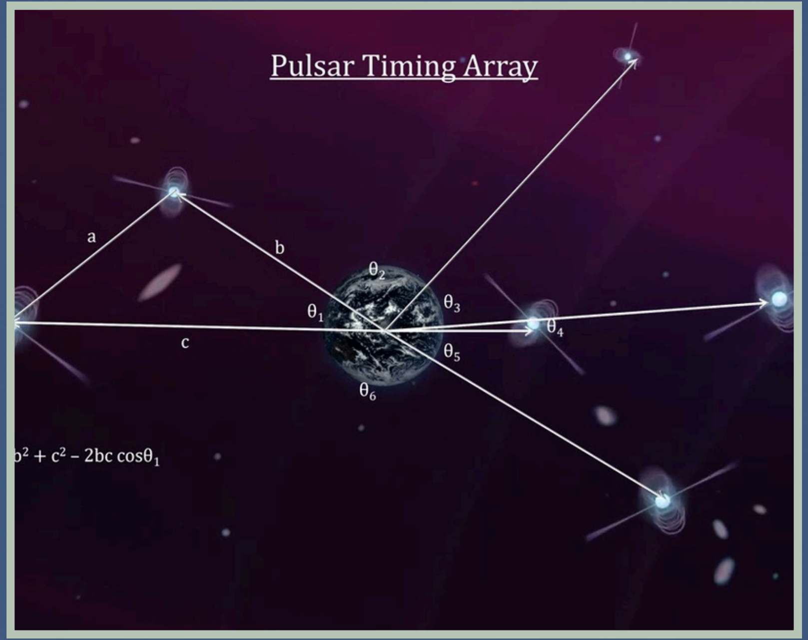
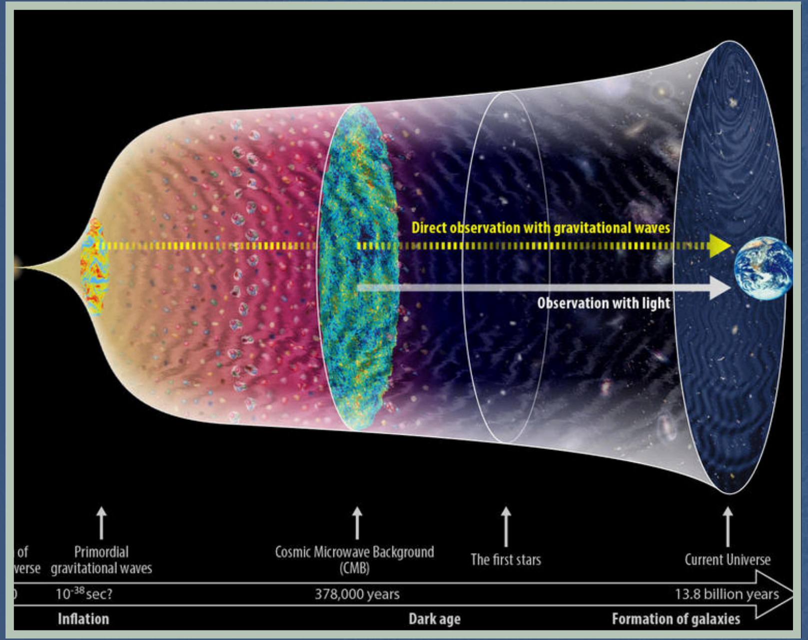
Key Challenges & Open Questions

Direct Detection:



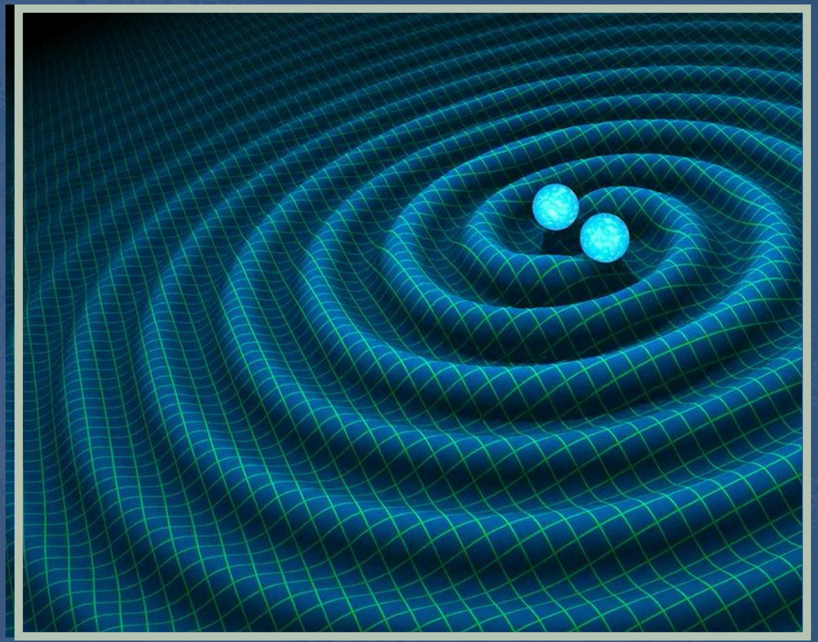
Explore interferometer upgrades that enhance DM sensitivity without impacting GW performance

Stochastic Backgrounds:



Stochastic Backgrounds: Determine if DM dynamics occurred late enough to leave detectable low-frequency GWs

Takaway



The search for dark matter through GWs is still young progress demands coordinated theory, modeling, and technology efforts

Thanks for listening! Any Questions?

Presented by

Giada