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BLUE WATERS

Deep Learning at Scale: A Paradigm Shift for Multi-Messenger Astrophysics

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NCSA Blue Waters Symposium for Petascale Science and Beyond
June 4th 2019

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Masses in the Stellar Graveyard
in Solar Masses
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
LIGO-Virgo | Frank Elavsky | Northwestern

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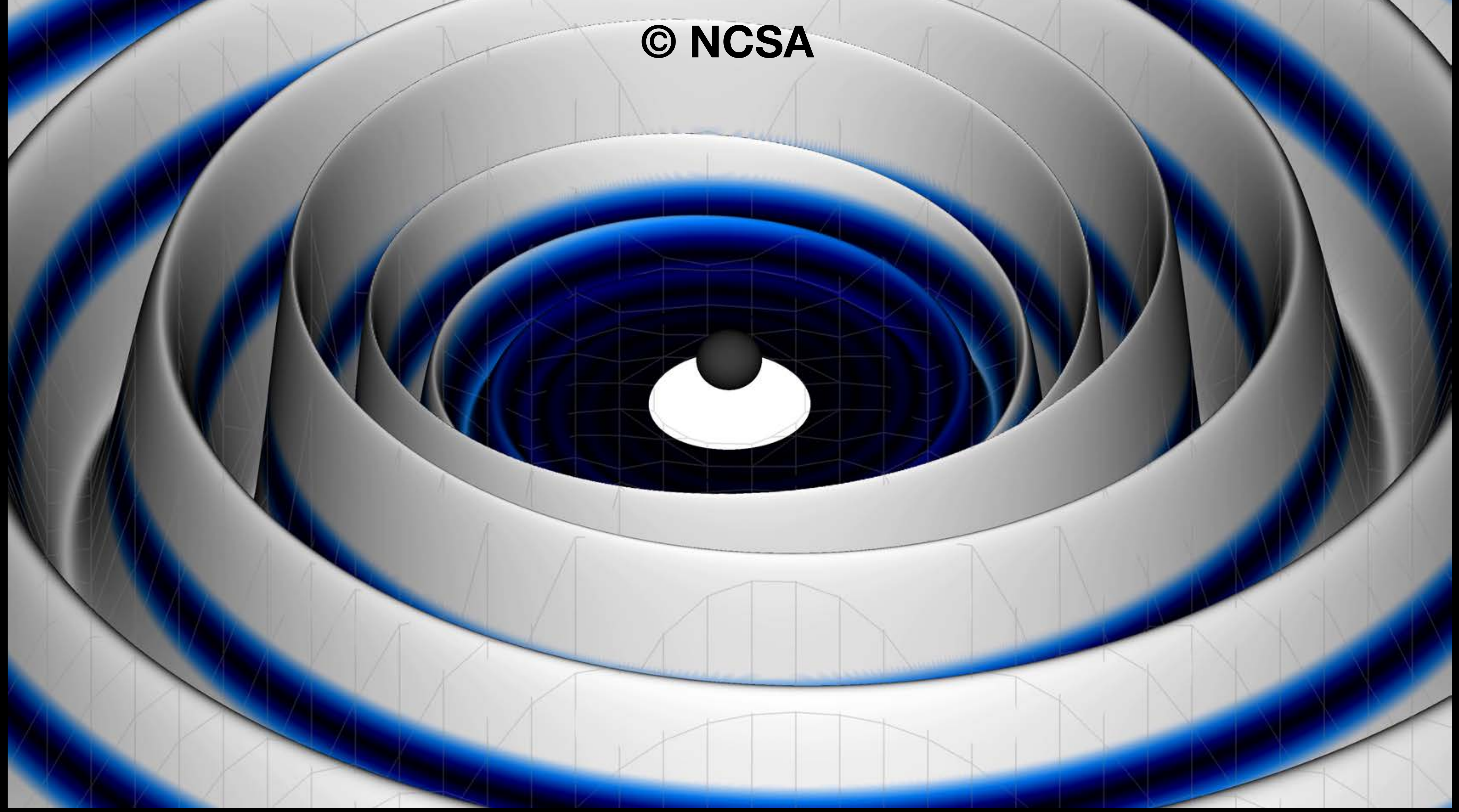
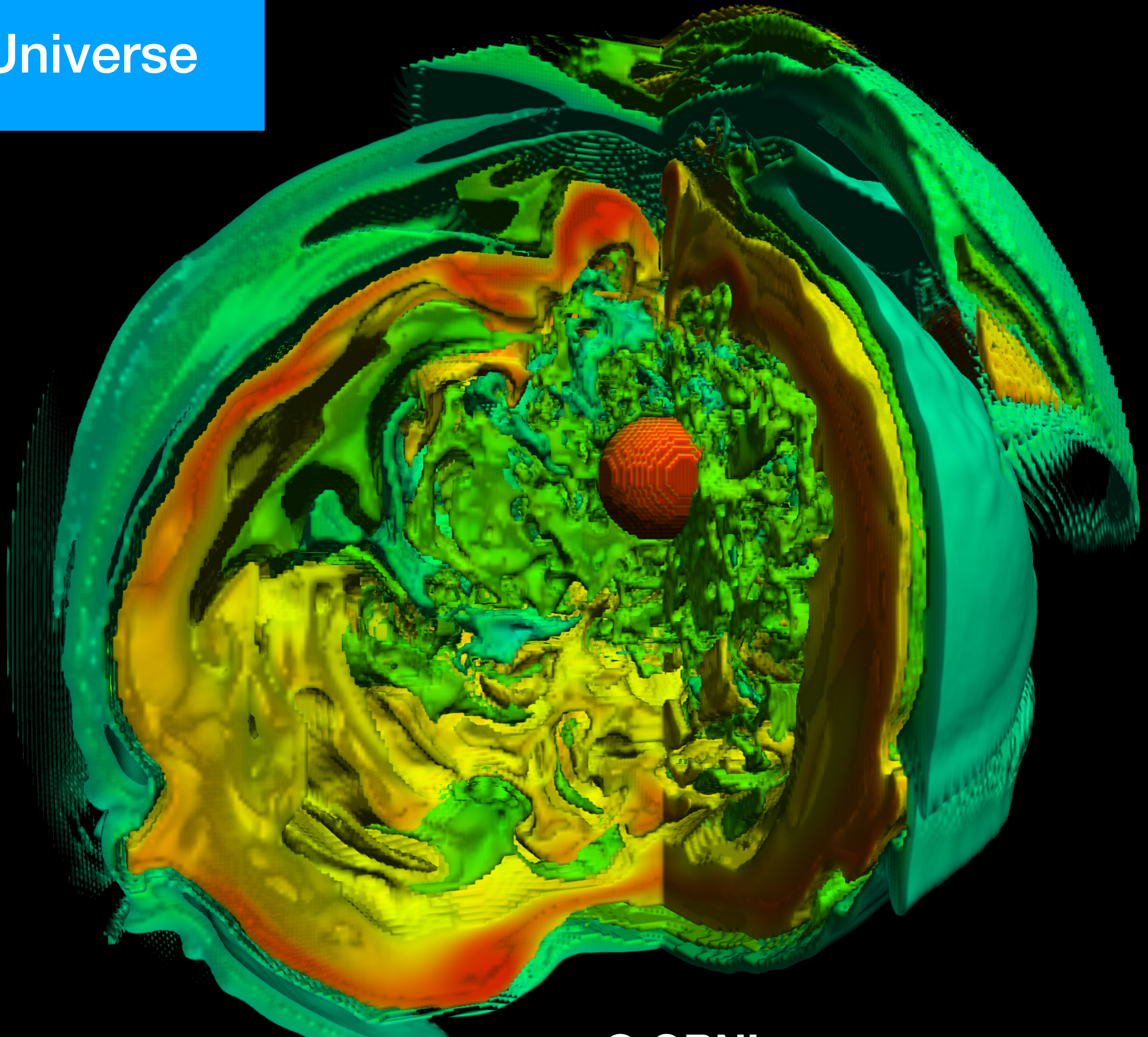


Listen to the Dark Sector of the Universe

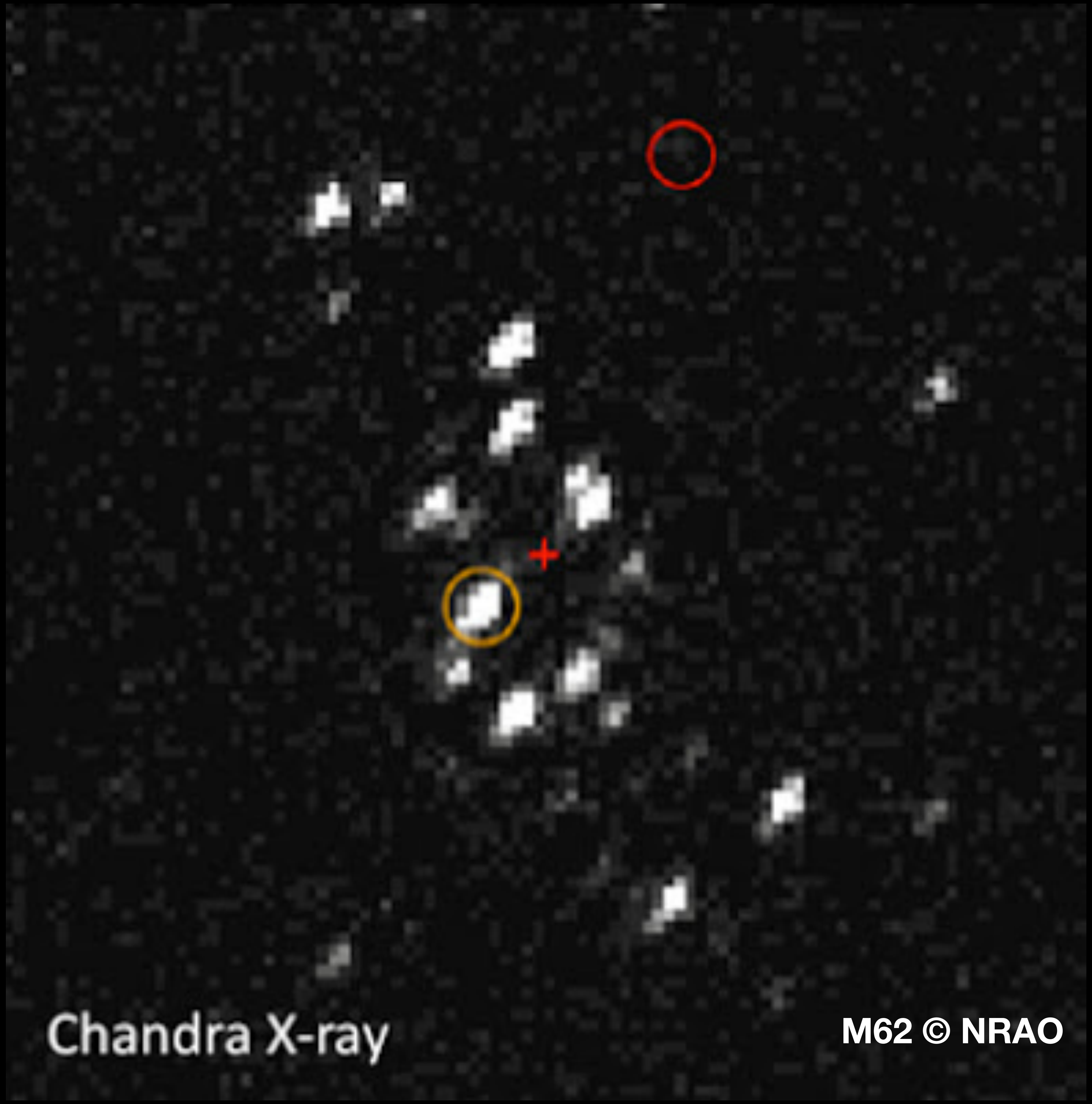
Listen to and observe cosmic mergers



Listen to, observe and feel cosmic explosions in the nearby Universe

Gravitational Wave Astrophysics

- Dynamical assembly of black hole and neutron star binaries in dense stellar environments
- Use gravitational waves to probe the existence of these sources
- Can we actually detect these signals with available algorithms?
- What can we learn from the observation of dynamically assembled compact binaries?

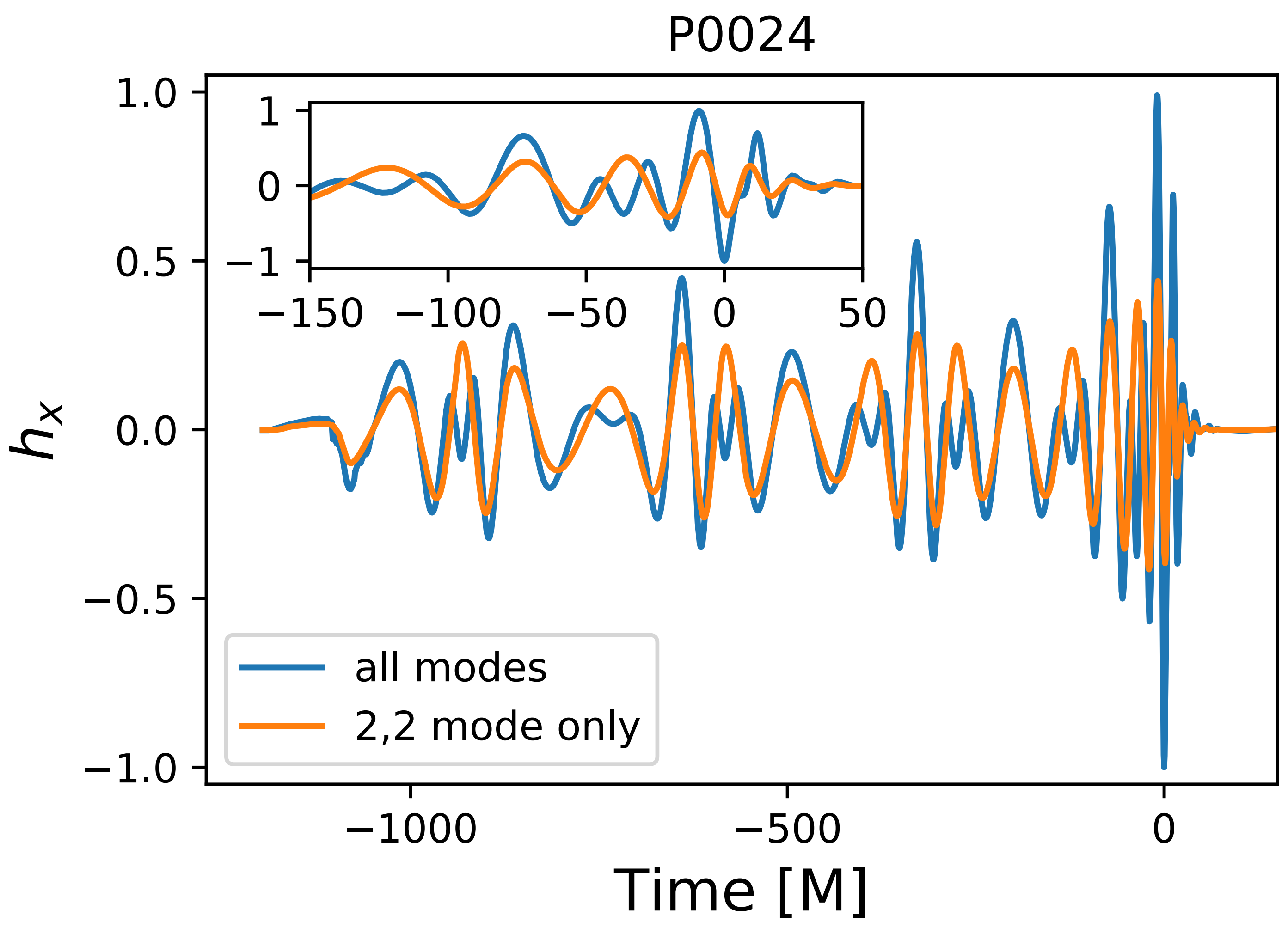


Physics of Eccentric Binary Black Hole Mergers

Huerta *et al.*, arXiv:1901.07038

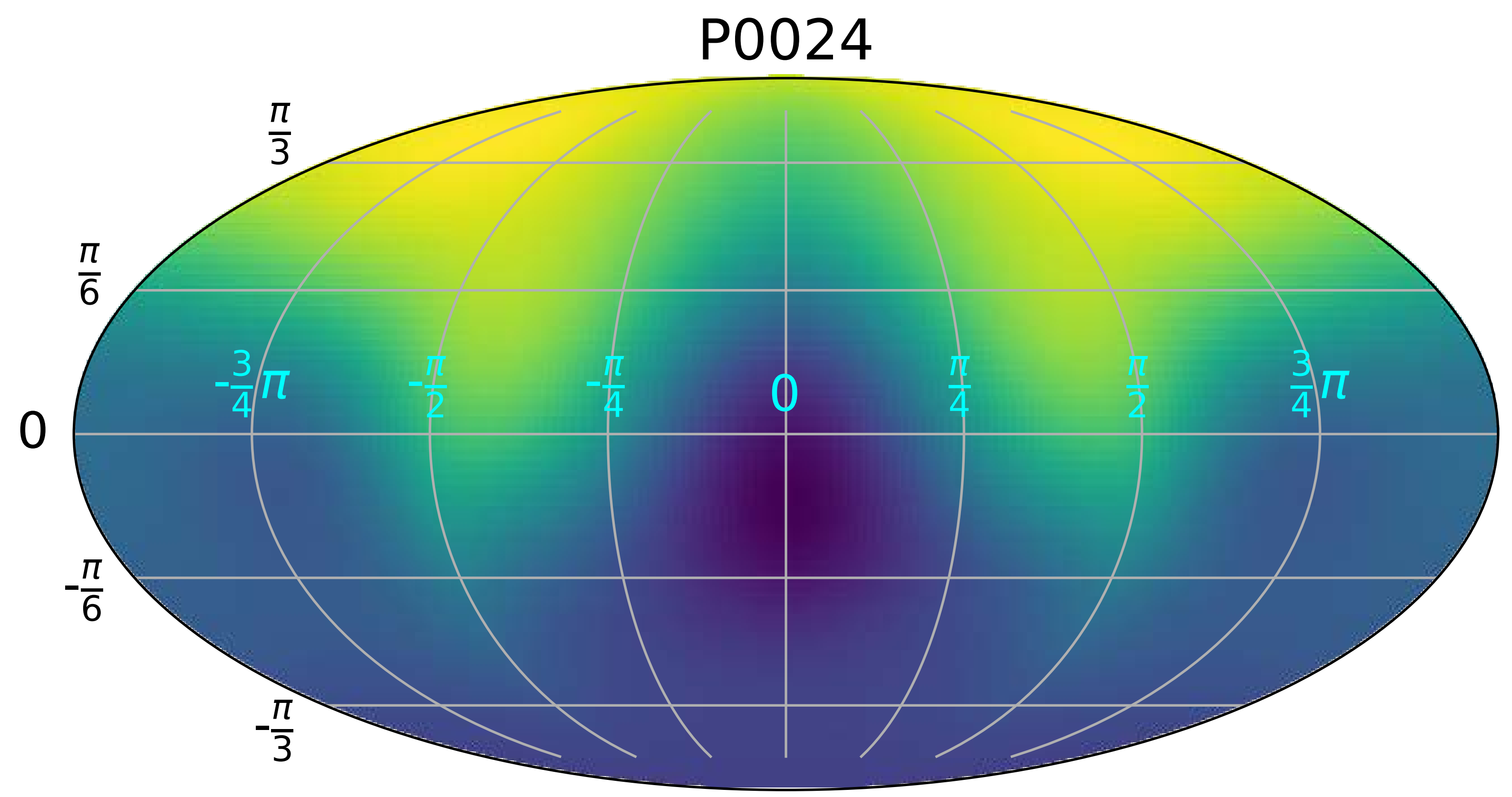
Gravitational Wave Astrophysics

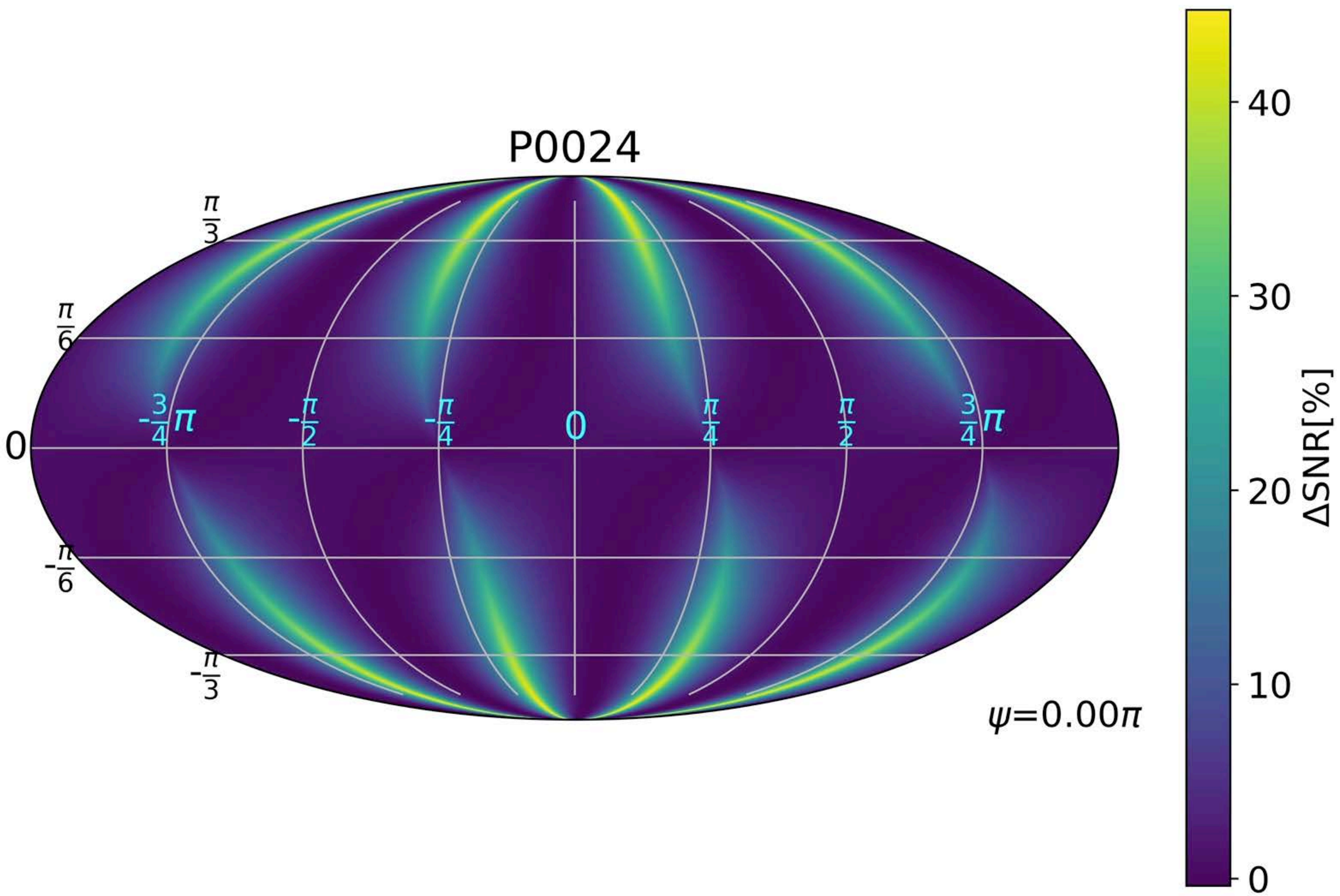
Rebei, Huerta, Wang, *et al.*, arXiv:1807.09787

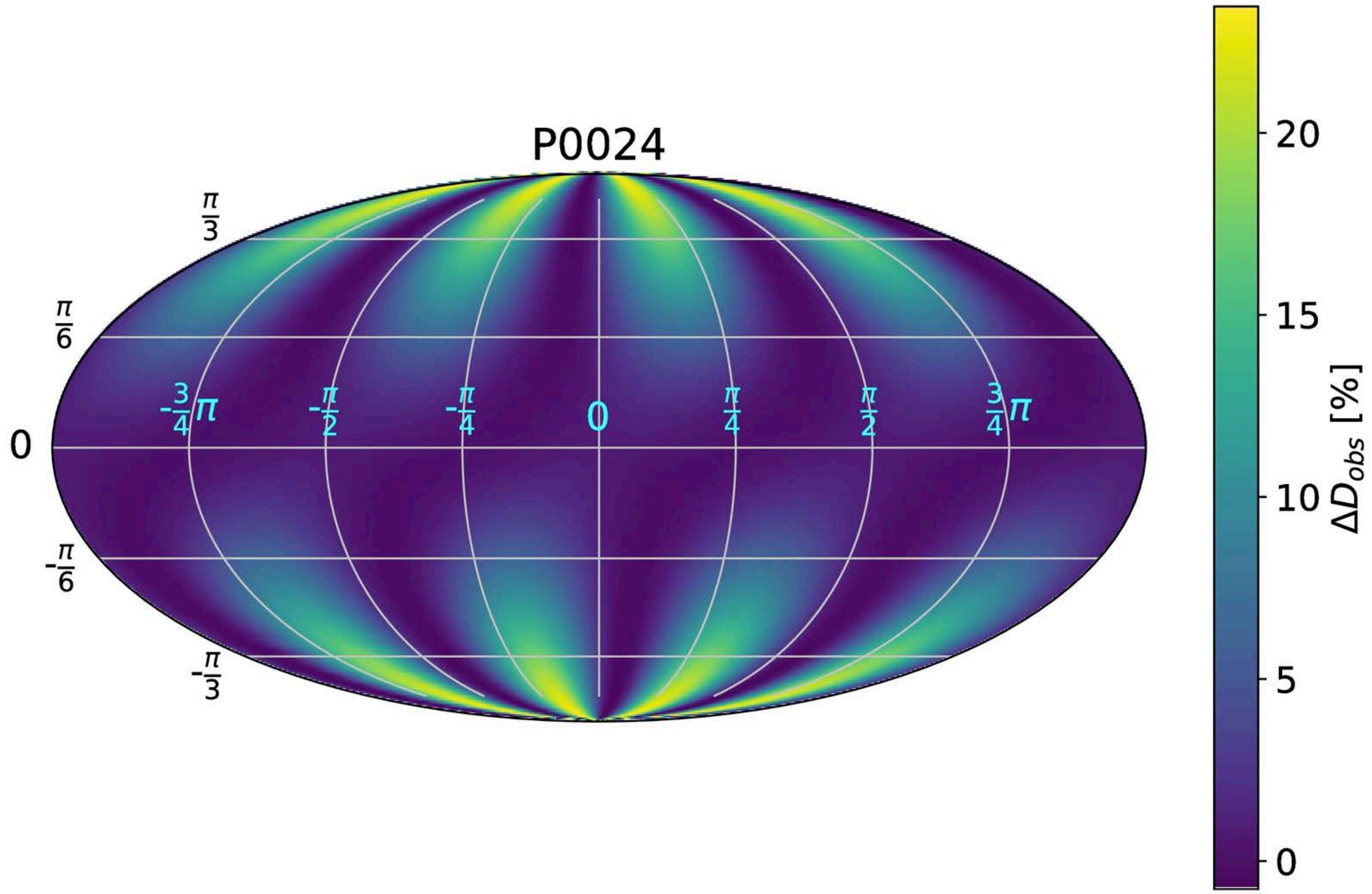


$$h(t) = \sum_{i=\{+,\times\}} h_i\left(\theta,\phi\right) F_i\left(\alpha,\beta,\psi\right)$$

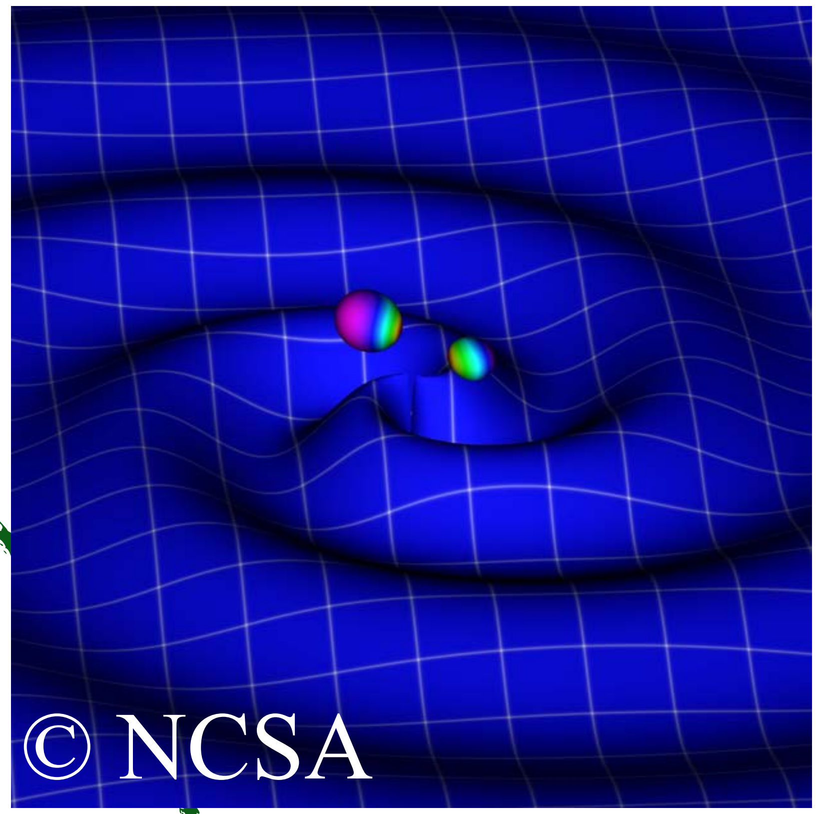
$$\mathrm{SNR}^2 = 4\Re \int_{f_0}^{f_{\max}} \frac{\tilde{h}\tilde{h}^*}{S_n(f)} \mathrm{d}f$$



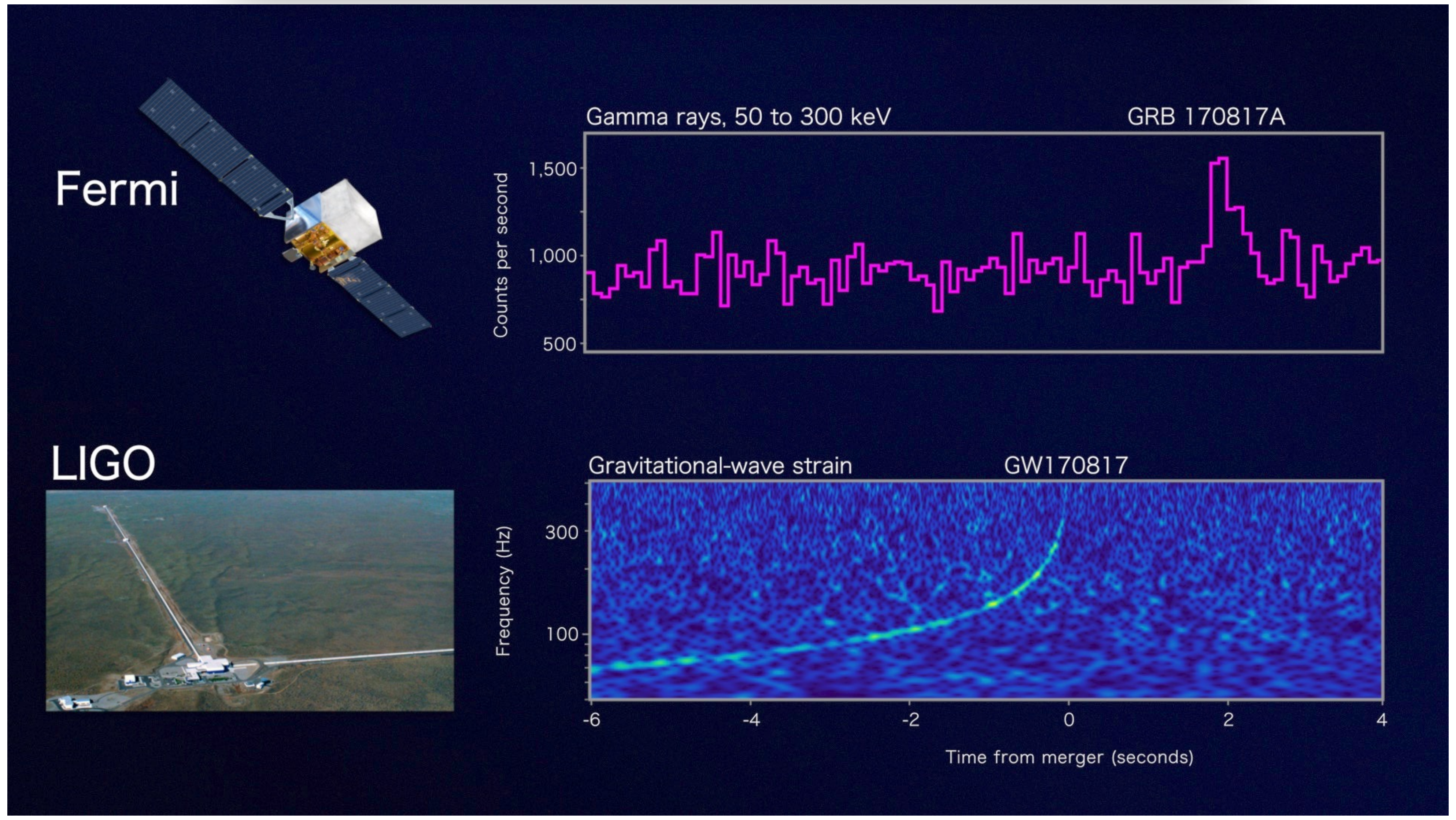




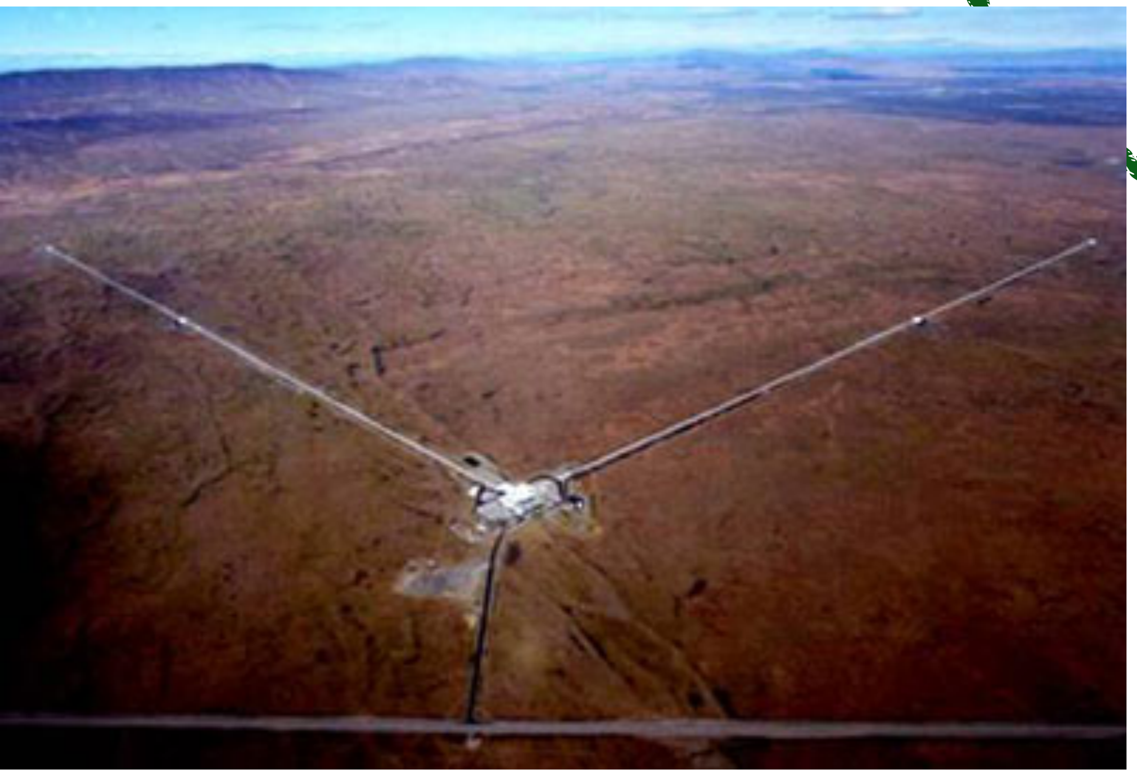
Models and simulations



Scientific Discovery



Observations



Theory

$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

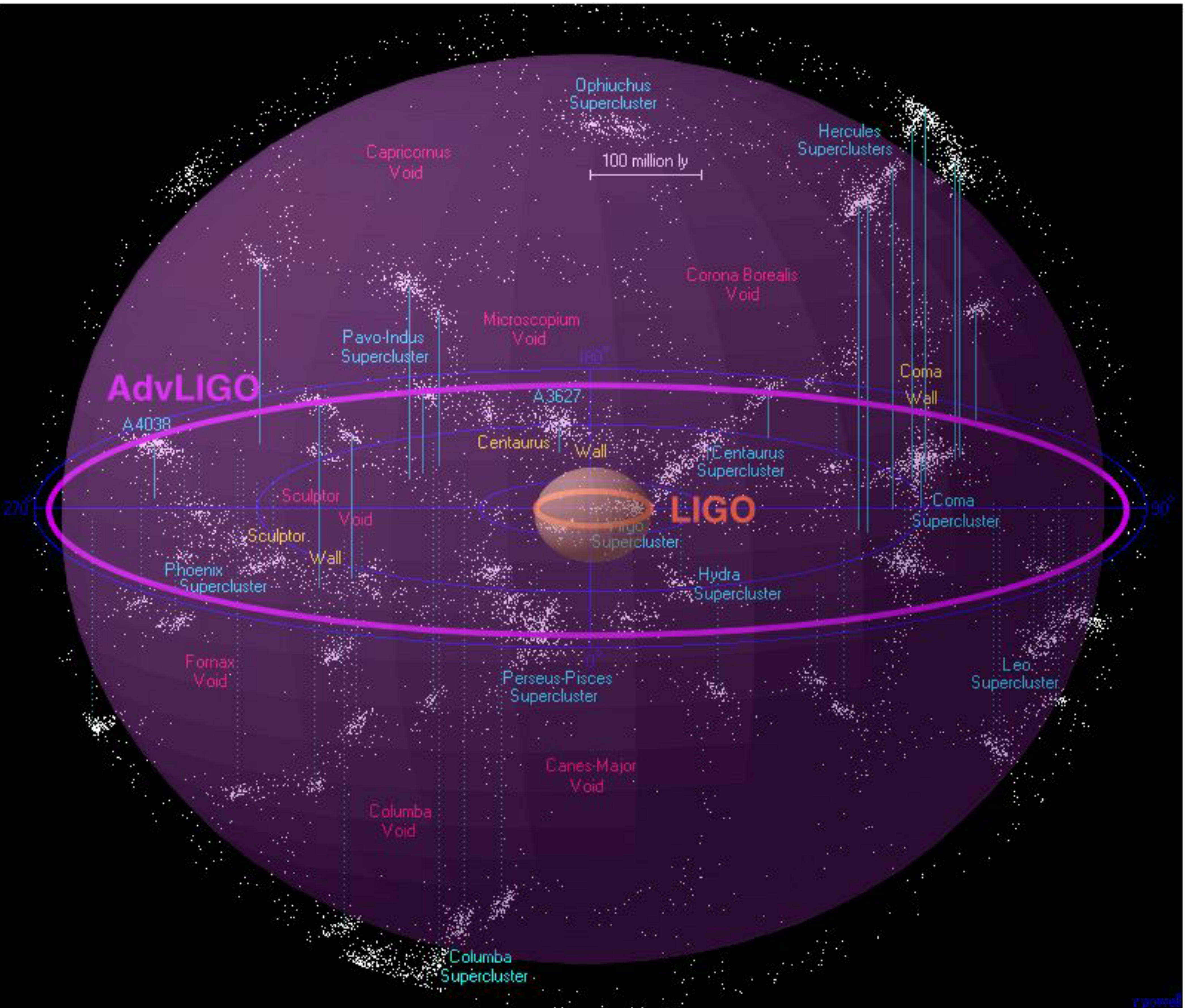
Routine: black hole and neutron star collisions

Future: supernovae, oscillating neutron stars….

Sources, Signals and *Searches*

Number of observations increases with the detectors' sensitivity

Localization improves with a global detector network



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Thomas Kuhn, The Structure of Scientific Revolution

Multi-Messenger Astronomy has taken off!

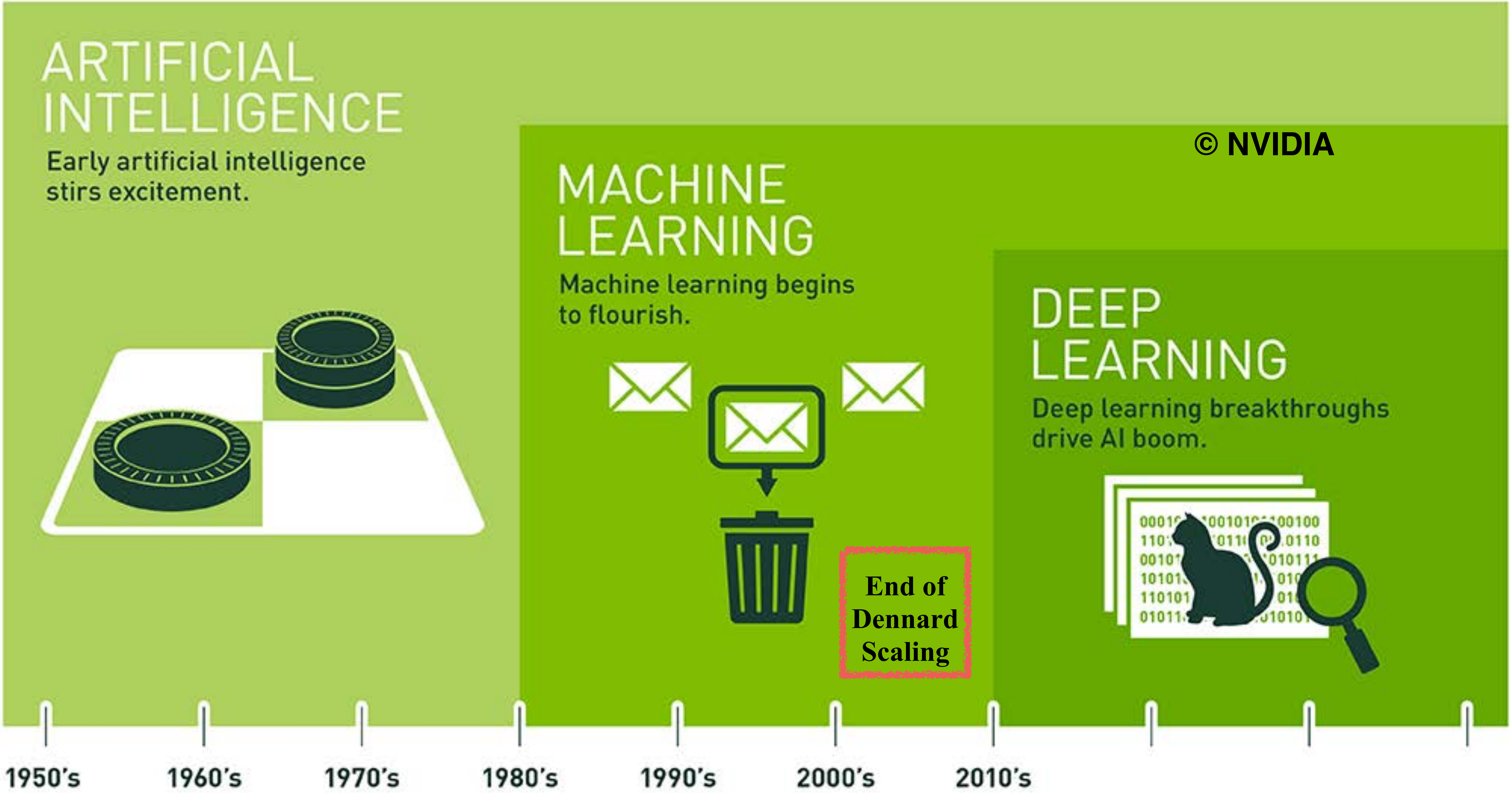
Swift transition from “first detection era”
to discovery at scale

Binary black holes observations are now routine!

Several Multi-Messenger observations may take place in
LIGO-Virgo third observing run

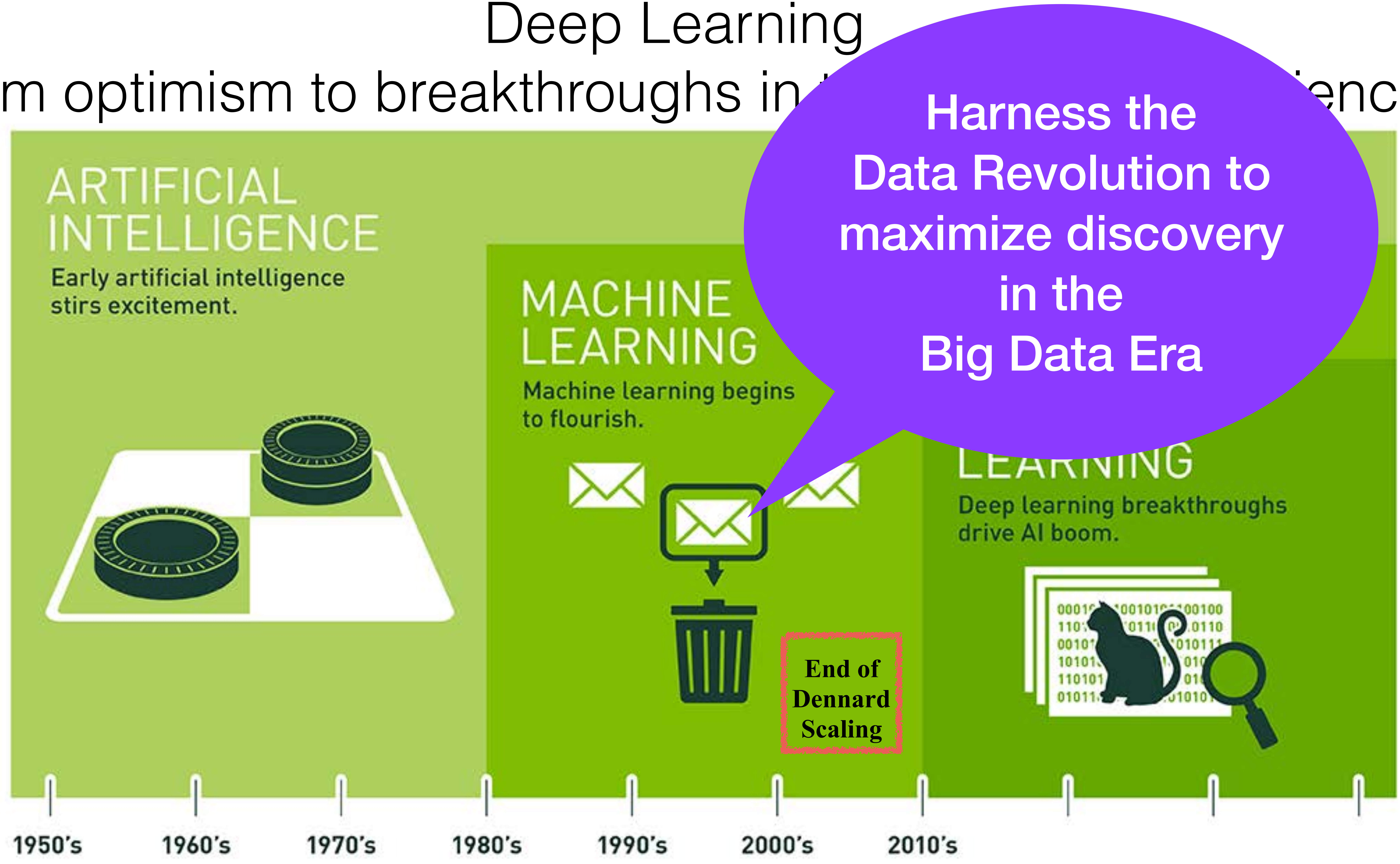
Pressing need to maximize discovery

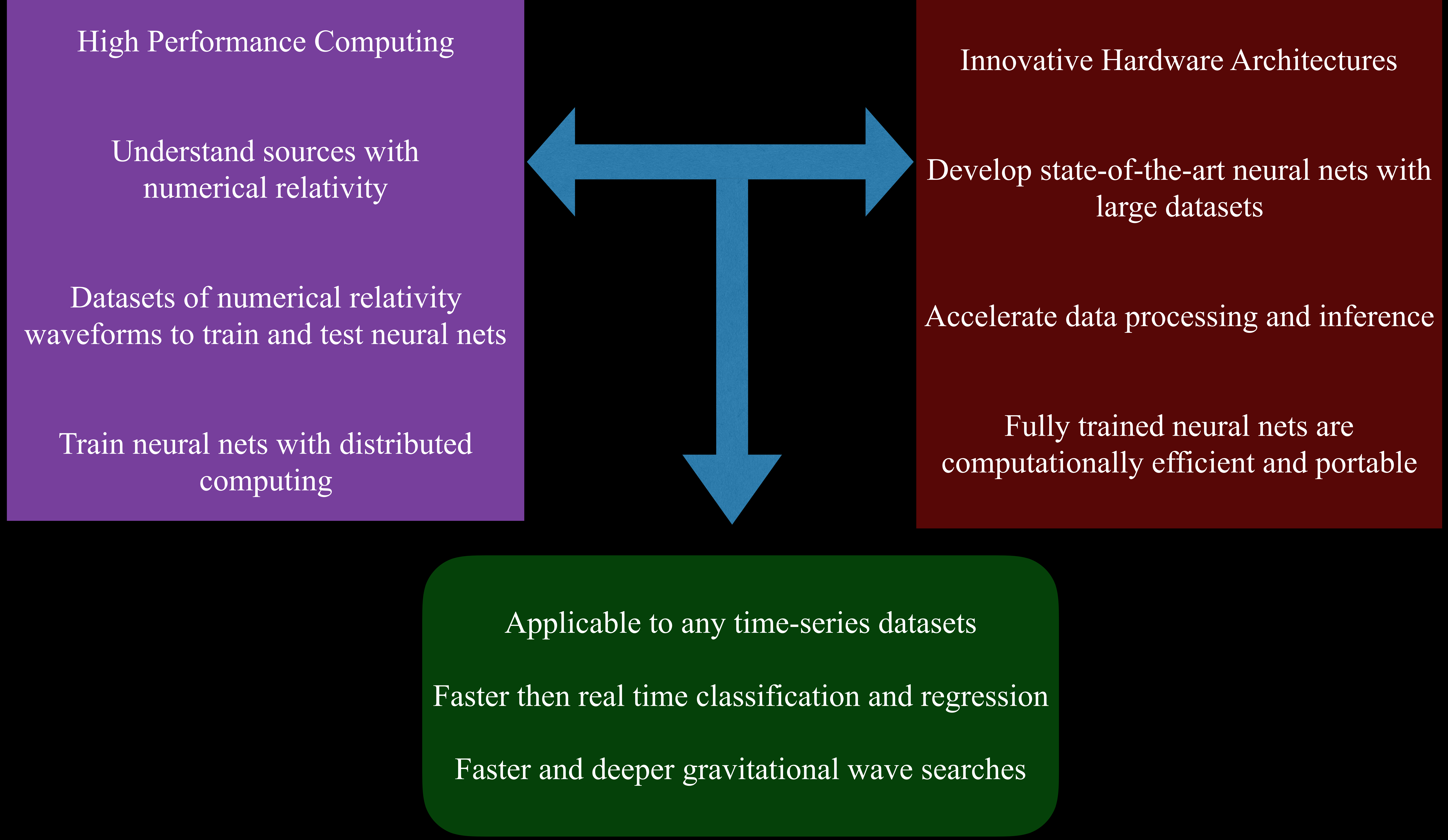
Deep Learning
From optimism to breakthroughs in technology and science



Deep Learning

From optimism to breakthroughs in ... ience




High Performance Computing
Understand sources with numerical relativity
Datasets of numerical relativity waveforms to train and test neural nets
Train neural nets with distributed computing
Innovative Hardware Architectures
Develop state-of-the-art neural nets with large datasets
Accelerate data processing and inference
Fully trained neural nets are computationally efficient and portable
Applicable to any time-series datasets
Faster then real time classification and regression
Faster and deeper gravitational wave searches

The rise of deep learning for gravitational wave astrophysics

First generation of neural network models for gravitational wave detection

Simple architectures 2-D black hole binary signal manifold Small training data sets

George & Huerta, Phys. Rev. D 97, 044039
Classification and regression in simulated LIGO noise

George & Huerta, Physics Letters B, 778 64-70
Classification and regression in real advanced LIGO noise

Follow-up studies a year later:

Classification of 2-D BBH signals in simulated LIGO noise:

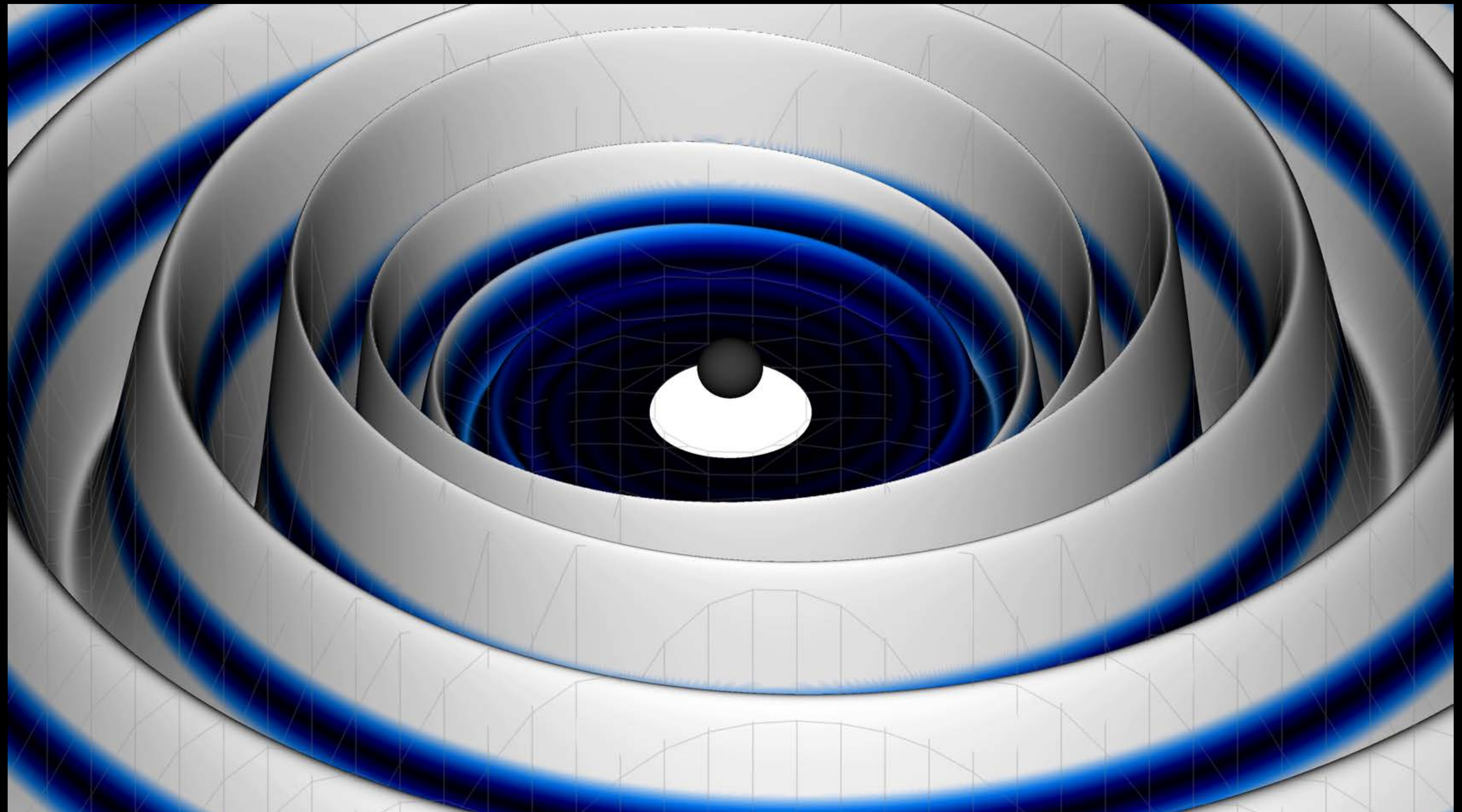
Gabbard *et al.*, PRL **120**, 141103 (2018)

Xilong Fan et al., Sci.China Phys.Mech.Astron. 62 (2019)

From pioneering work to production scale applications

First application of deep learning at scale to characterize a 4-D signal manifold with 10M+ templates
Shen, Huerta and Zhao, arXiv:1903.01998

Inference of the properties of the binary components before and after merger

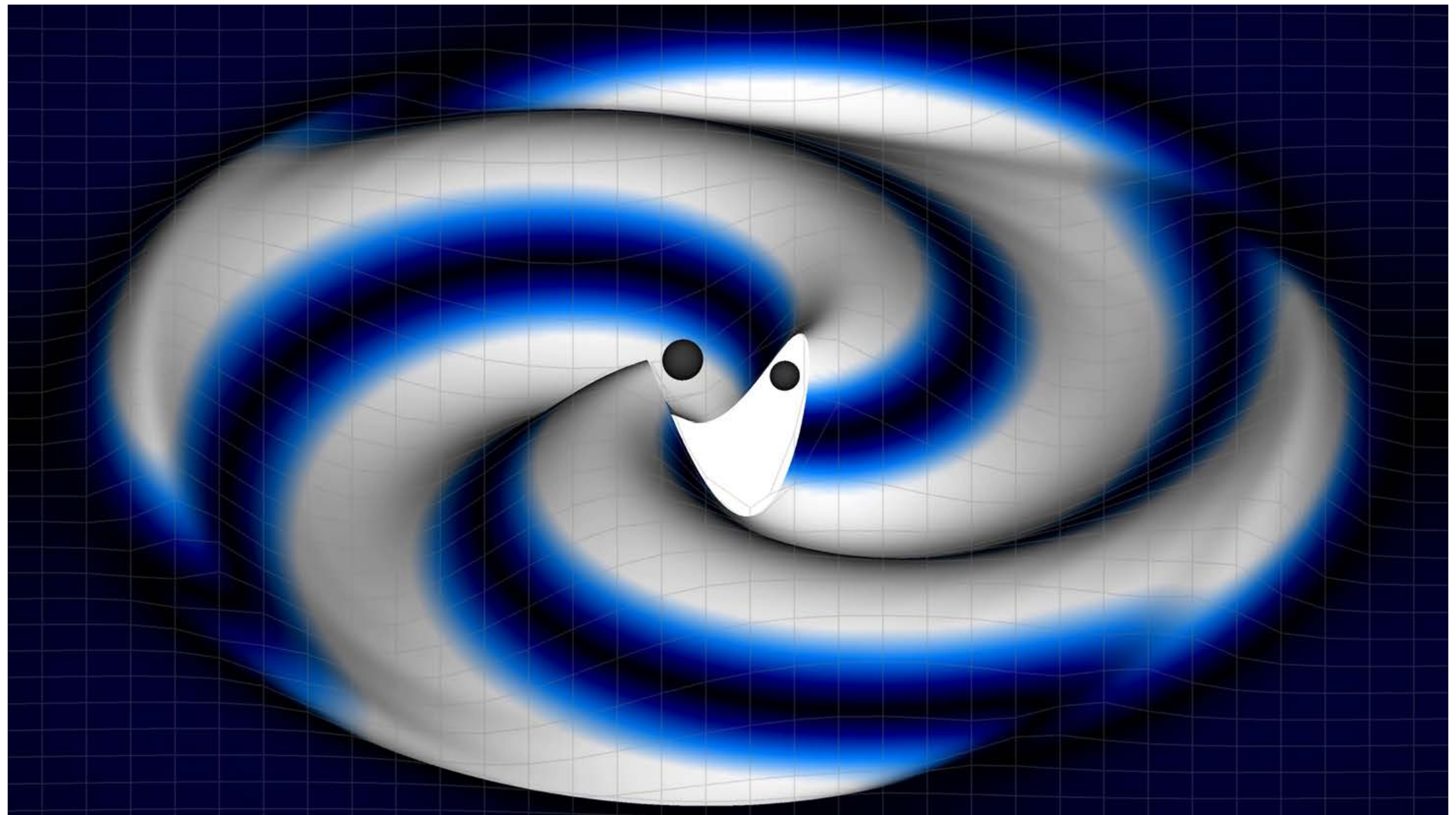


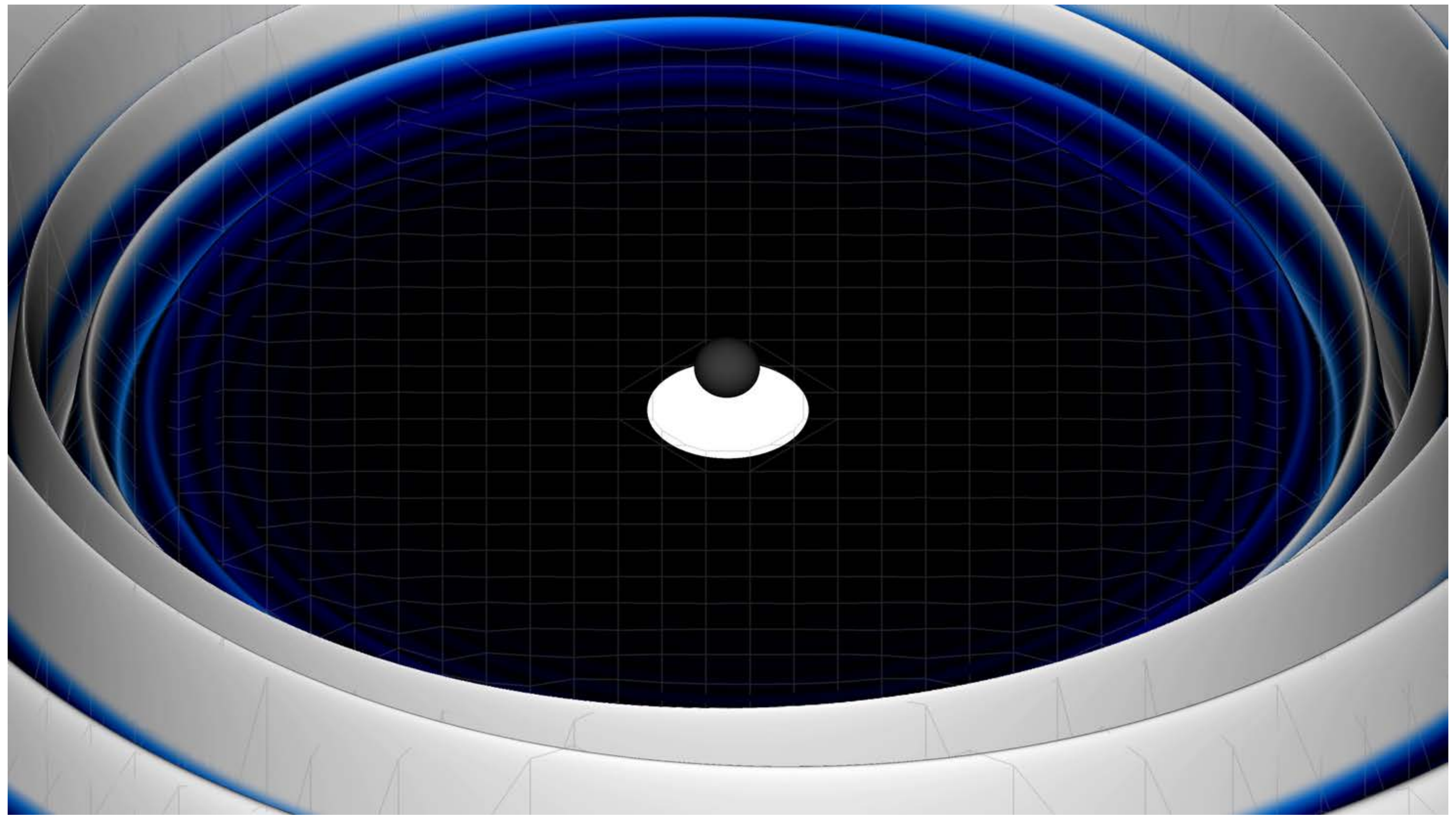
Parameter estimation studies are now endowed with a solid statistical backbone

From pioneering work to production scale applications

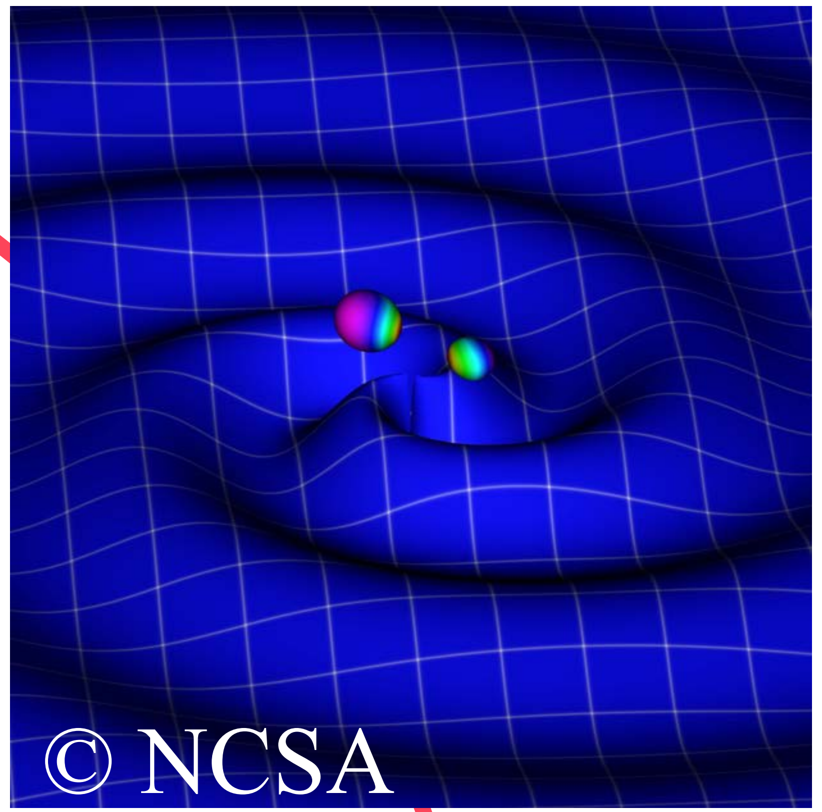
Shen, Huerta and Zhao, arXiv:1903.01998

EVENT NAME	$m_1[M_\odot]$	$m_2[M_\odot]$	a_f	ω_R	ω_I
GW150914	37.46 [4.13| 0.06]	30.80 [0.43|-1.65]	0.689 [0.037| 0.17]	0.5362 [0.0127|-0.20]	0.0798 [0.0011| 0.16]
GW151012	23.89 [0.35| 1.65]	17.34 [0.56| 1.44]	0.653 [0.009| 0.25]	0.5214 [0.0030| 0.15]	0.0810 [0.0003|-0.15]
GW151226	17.60 [2.01| 0.87]	14.14 [2.85| 0.73]	0.646 [0.006| 1.53]	0.5188 [0.0021| 1.51]	0.0812 [0.0001|-1.60]
GW170104	36.45 [1.54|-0.76]	21.83 [3.54|-0.56]	0.661 [0.080|-0.84]	0.5185 [0.0306|-0.48]	0.0816 [0.0029| 0.57]
GW170608	13.96 [1.13| 1.10]	11.96 [1.07| 1.56]	0.697 [0.025|-1.28]	0.5278 [0.0154|-0.95]	0.0809 [0.0011|-0.67]
GW170729	48.61 [1.58|-1.61]	37.69 [1.82|-0.28]	0.694 [0.019|-0.47]	0.5102 [0.0107|-0.50]	0.0812 [0.0019|-0.16]
GW170809	31.01 [3.29| 0.60]	22.42 [4.56| 1.85]	0.698 [0.034|-1.23]	0.5428 [0.0163|-1.15]	0.0779 [0.0016|-1.05]
GW170814	35.07 [1.75| 0.84]	21.50 [0.52| 0.99]	0.718 [0.010|-1.89]	0.5377 [0.0108|-1.38]	0.0794 [0.0003| 1.76]
GW170818	40.05 [1.29|-1.57]	24.08 [0.93|-1.33]	0.656 [0.015| 0.73]	0.5129 [0.0043| 1.21]	0.0816 [0.0005|-1.02]
GW170823	39.56 [1.75|-1.44]	30.14 [0.53|-1.68]	0.740 [0.002|-1.76]	0.5510 [0.0007|-1.74]	0.0782 [0.0001| 1.75]





Training and testing datasets from numerical relativity simulations



Convergence of HPC and HDA

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Observational data to train, validate and test neural network models

Theory to inform the design of deep learning models

$G_{\mu\nu} = 8\pi T_{\mu\nu}$

Routine: black hole and neutron star collisions

Future: supernovae, oscillating neutron stars….

Gravitational Wave Cosmology

Gravitational waves can enab [redacted]
siren measurements [redacted]

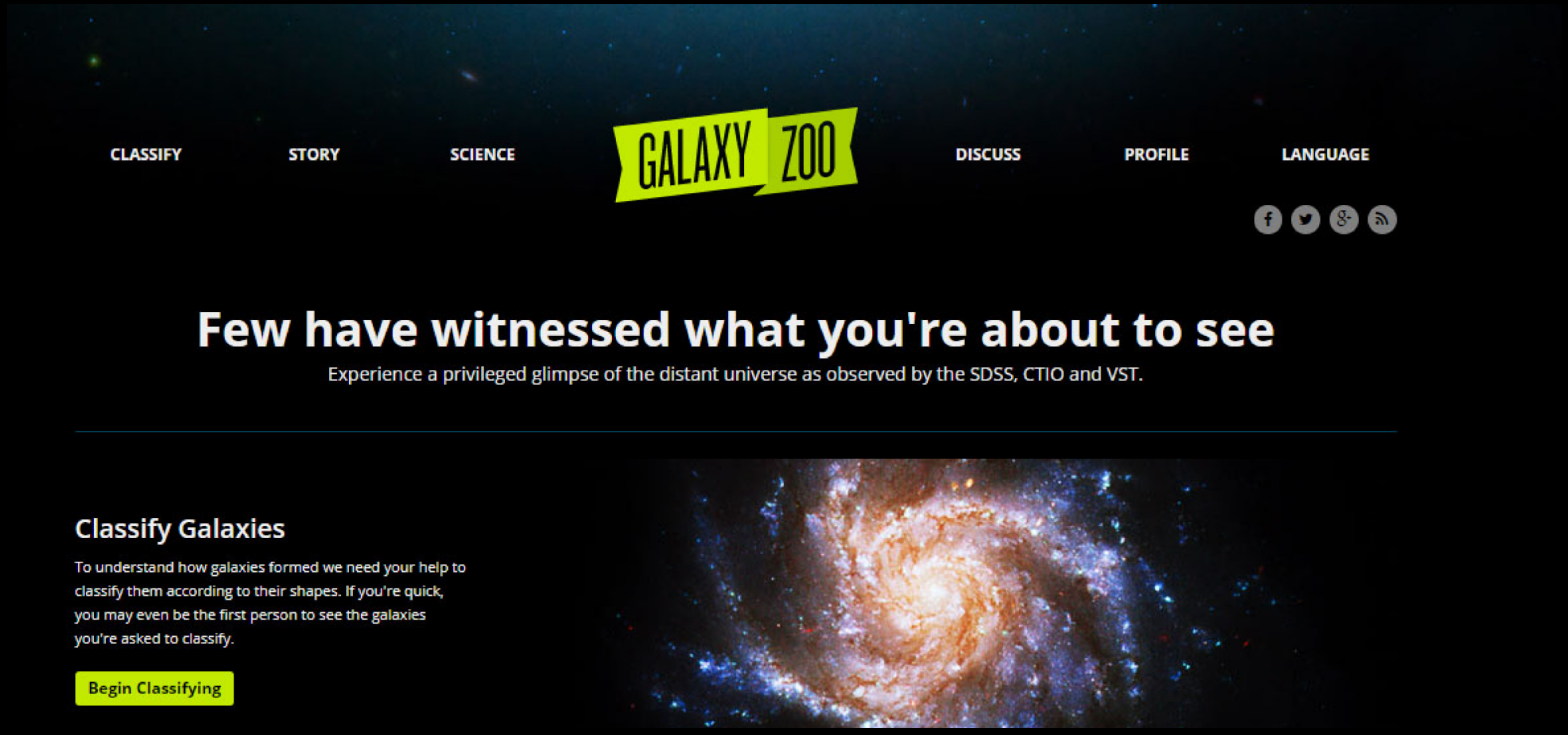
No ele [redacted] eeded

Schutz, N [redacted], Sept. 25, 1986, p. 310, 311

We need galaxy catalogs

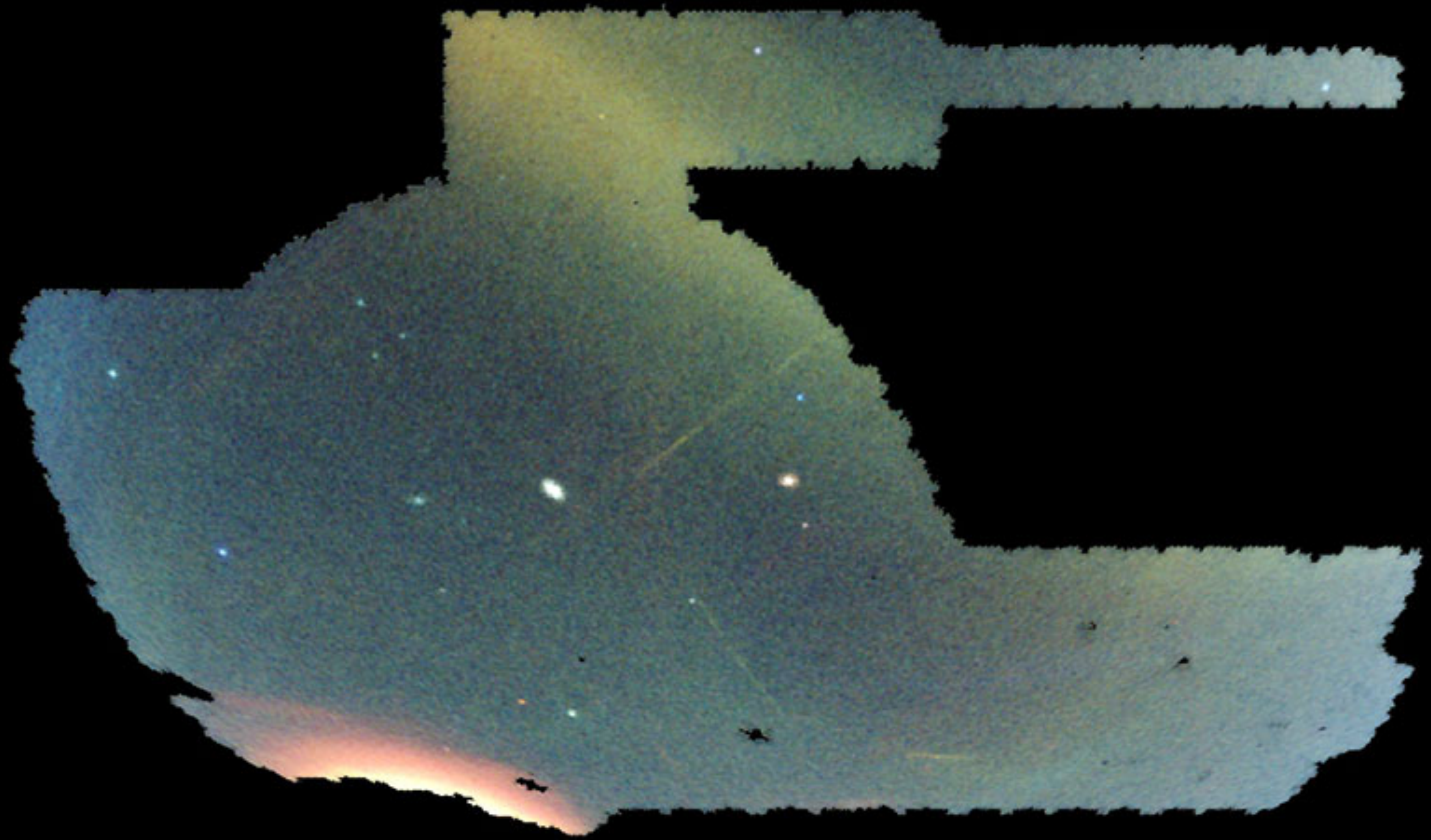
Dark Energy Survey provides ideal case study

Deep Learning for DES data science



From the citizen science revolution using the Sloan Digital Sky Survey…

… to large scale discovery using unlabeled images in the Dark Energy Survey using deep learning



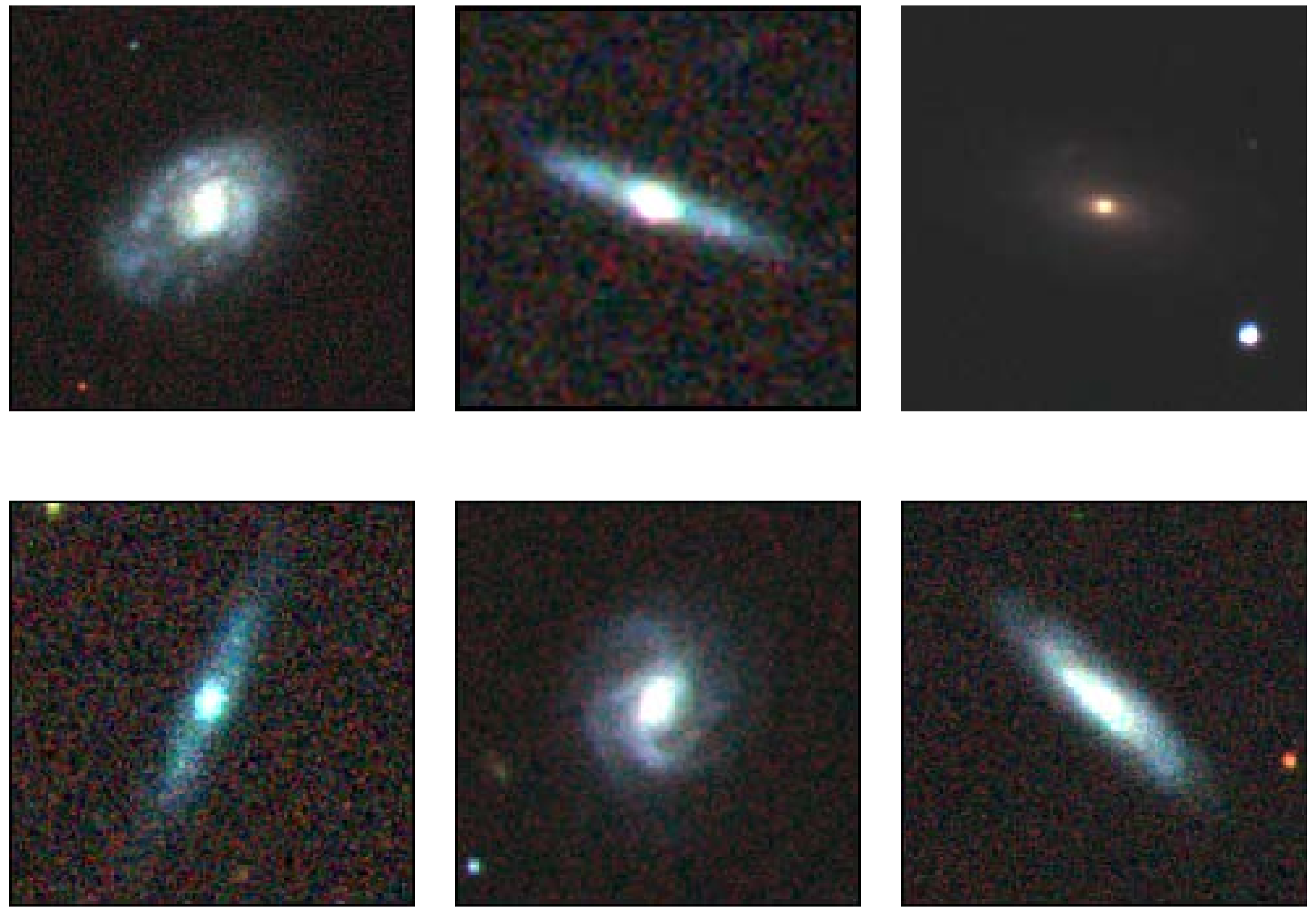
Khan, Huerta, Wang, Gruendl, Jennings and Zheng, arXiv:1812.02183
Accepted to Physics Letters B

Xception neural network model

François Chollet, arXiv:1610.02357

State-of-the-art model for computer vision

Convergence of deep transfer learning, distributed training, data clustering, and recursive training



State-of-the-art galaxy classification

Scalable method for the construction of galaxy catalogs in the Dark Energy Survey

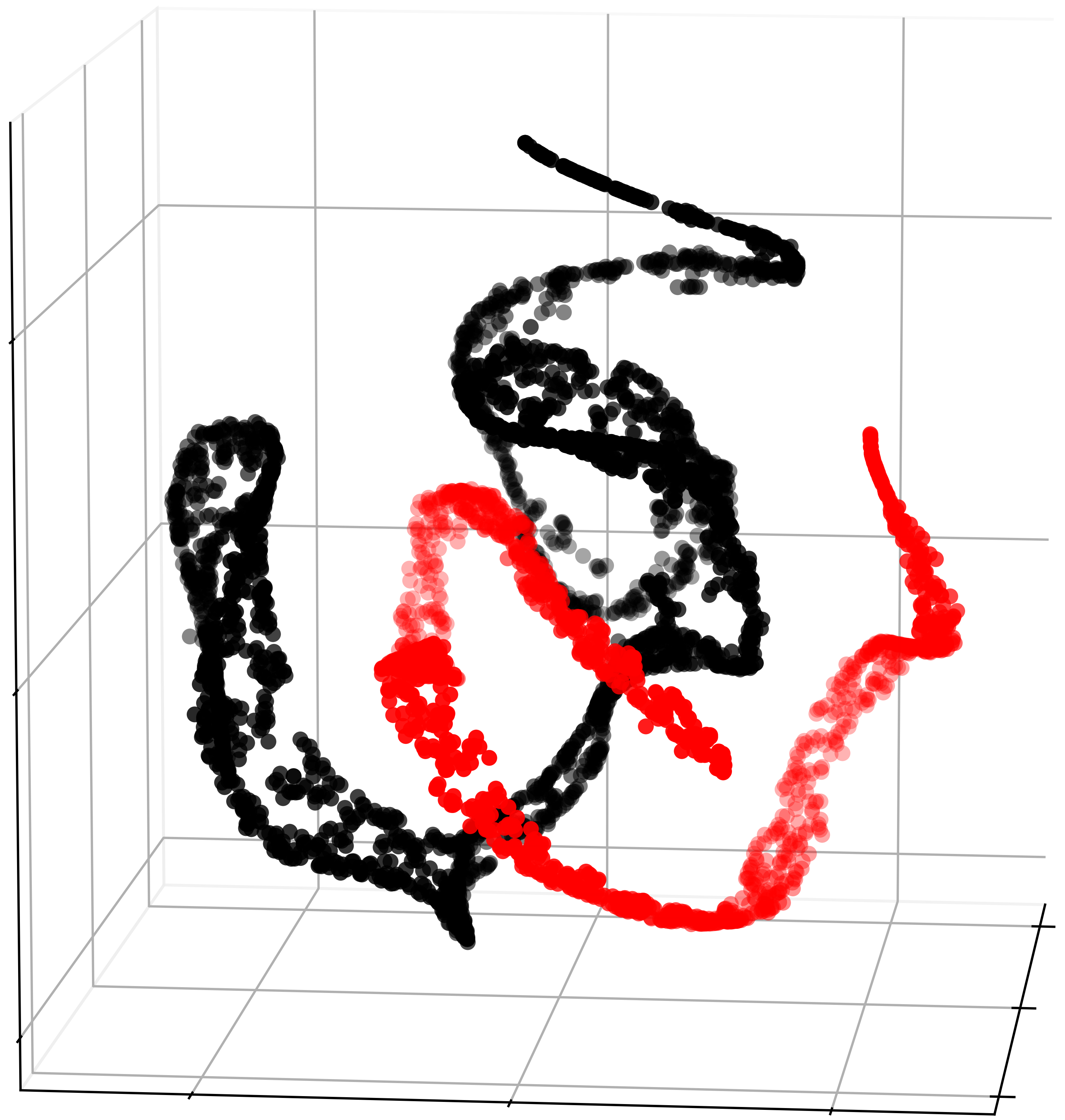
Platform for next-generation electromagnetic surveys

Deep Learning for DES data science

Khan, Huerta, Wang, Gruendl, Jennings and Zheng,
arXiv:1812.02183

NCSA-Argonne Data Science Program

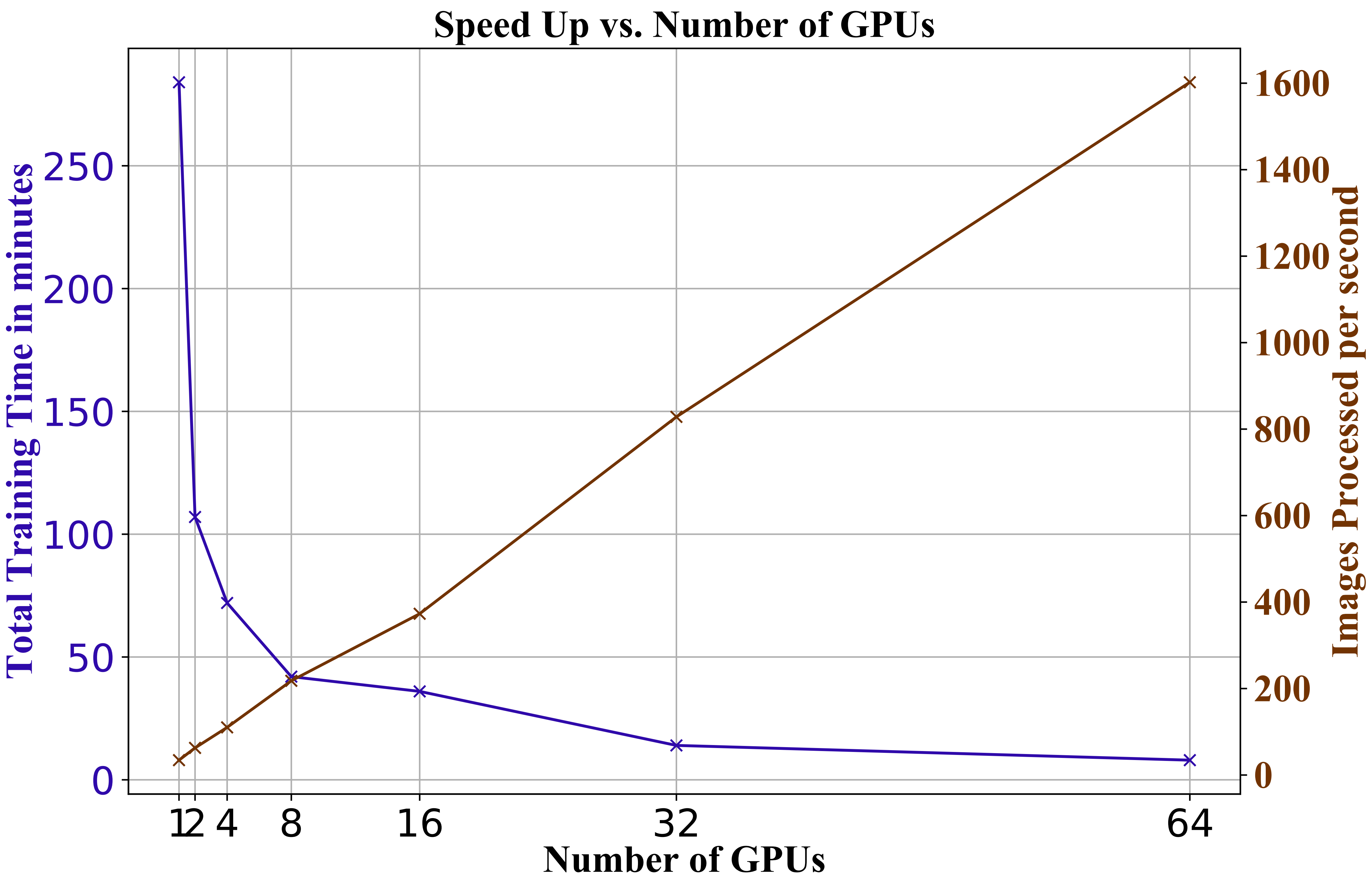
Unlabelled DES



10k+ raw, unlabeled galaxy images from DES clustered according to morphology using RGB filters

Scalable approach to curate datasets, and to construct large-scale galaxy catalogs

See viz at https://www.youtube.com/watch?v=n5rl573i6ws

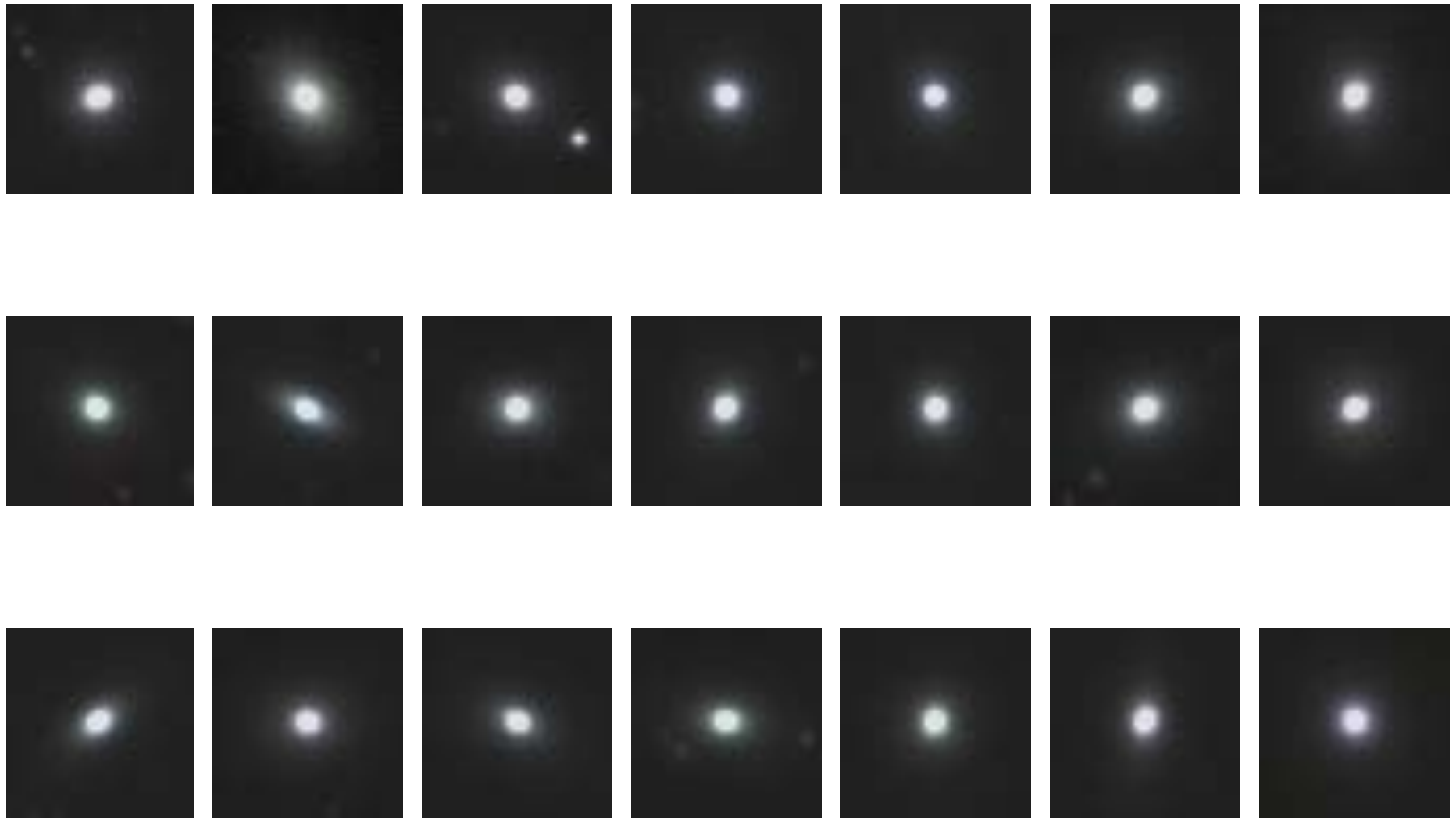


Deep transfer learning combined with distributed training for cosmology

Training is completed within 8 minutes achieving state-of-the-art classification accuracy

Training done at the Cooley supercomputer at Argonne National Lab

Predicted DES elliptical galaxies by our neural network model



Khan, Huerta, Wang, Gruendl, Jennings and Zheng, arXiv:1812.02183

Conclusions

- Deep learning can be seamlessly applied to enhance the science reach of gravitational wave astrophysics and gravitational wave cosmology
- Harnessing the data revolution encompass data fusion, and convergence of deep learning with large scale computing
- Design a new type of deep learning algorithms at scale to characterize 4-D+ signal manifolds
- **Deep learning for Multi-Messenger Astrophysics is just taking off!**

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