Discovery in Astrophysics

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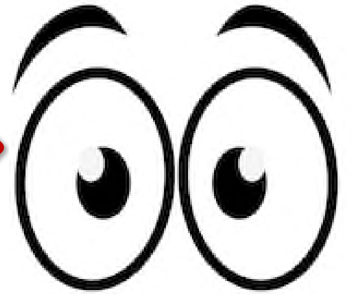
Two approaches

Question / Hypothesis Driven

Knowledge → ?

NASA WMAP
(Wilkinson Microwave Anisotropy Probe)
"…reveal conditions as they existed in the early universe by measuring the properties of the cosmic microwave background radiation over the full sky."

Exploration

Instrument → 

The question-driven approach

- Formulates the most important open questions
  - Theoretical/physics hypotheses
- Seeks answers to these questions

Favored by the Funding Agencies and Review Committees

The question-driven approach

- Focused
- Widely used in our discipline
    - New instruments
    - Telescopes
    - Observing proposals
- This is how we teach our students to do research

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The question-driven approach

….. addresses only the *known unknowns*

….. *c*an bias our knowledge

"the key is to make sure that science policy permits discovery for the sake of discovery and not for finding Earth-like planets, which we have prejudiced to be of greatest interest"
(D. J. Stevenson, CalTech, Physics Today, Nov. 2018)

Similar considerations can be applied to other fields of astrophysics

The question-driven approach

….. does not address the *'unknown unknowns'*

….. they cannot be well-defined 'important questions'

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…but unknown unknowns are important

'Discovery Space' – Harwit, 1984

'Ignorance: How it Drives Science' - S. Firestein, 2012

The only way to address the *unknown-unknowns* *is*

Exploration

Astronomy is first and foremost exploratory

Unforeseen views of the universe have followed new approaches that ***opened up the discovery space***

- new telescopes and instruments (both hardware and software)
- unanticipated data repurposing

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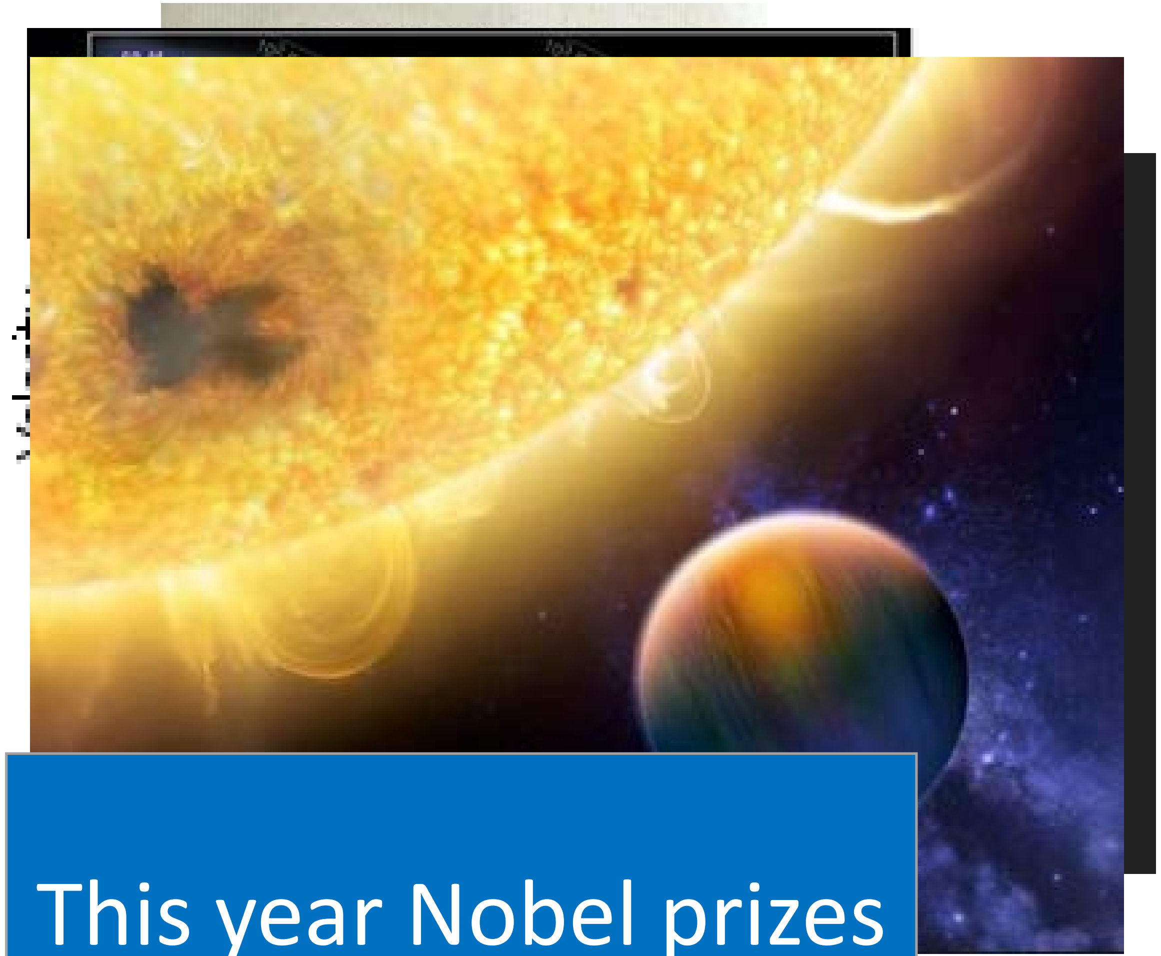
Improvements in optical telescopes and spectrographs

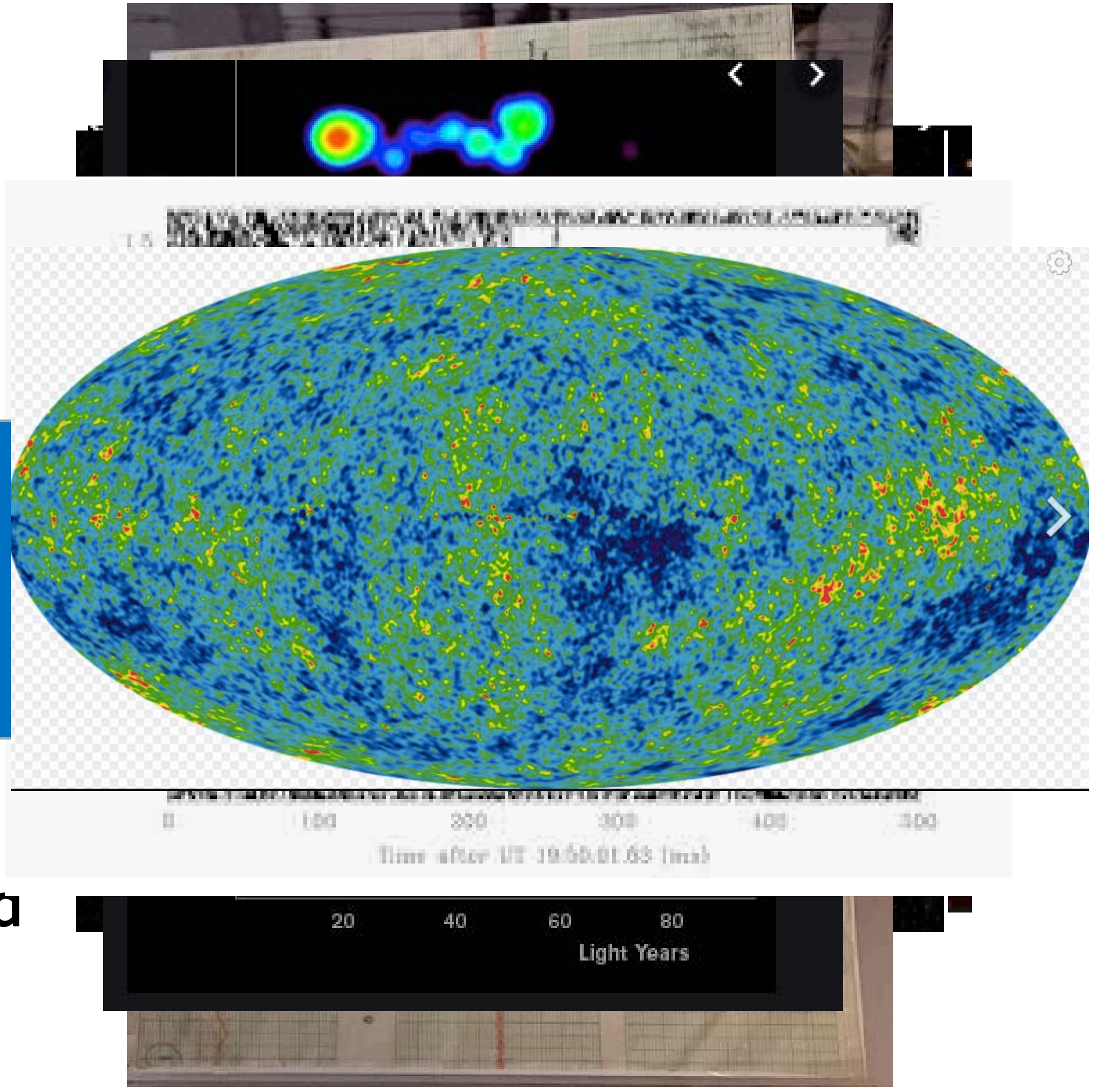
- Galilean Moons of Jupiter
  – Galilei 1610
- Cepheid period-luminosity (LMC)
  – Henrietta Leavitt 1908
- H-R diagram
  – Russel ~1911
- Metal composition of the Sun and stars
  - Cecilia Payne-Gaposchkin 1925
- Expansion of the Universe
  – Hubble+Humason 1929, Lemaitre 1927
- Dark Matter
  – Vera Rubin + 1970
- Large scale structure
  – e.g., Peebles; Geller+Huchra 1989
- Hot Jupiters
  – Mayor + Queloz 1995



This year Nobel prizes

Invention of radio telescopes, VLBI

- Radio galaxies
  - Cen A: Bolton + 1949
  - Fanaroff & Riley 1974 Cambridge Catalog
- Quasars
  - 1960's radio surveys
  - 3C 273, Maarten Schmidt 1963
- Cosmic microwave background
  - Penzias + Wilson 1964
- Pulsars
  - Bell-Burnell + Hewish 1967
- Superluminal motion
  - VLBI, Gubbay + 1969
- Fast (msec) radio bursts
  - The first, Lorimer Burst FRB 010724 **detected in 2007 in archived data** recorded by the Parkes Observatory on 24 July 2001



X-ray Astronomy

From rocket science to XMM-Newton and Chandra

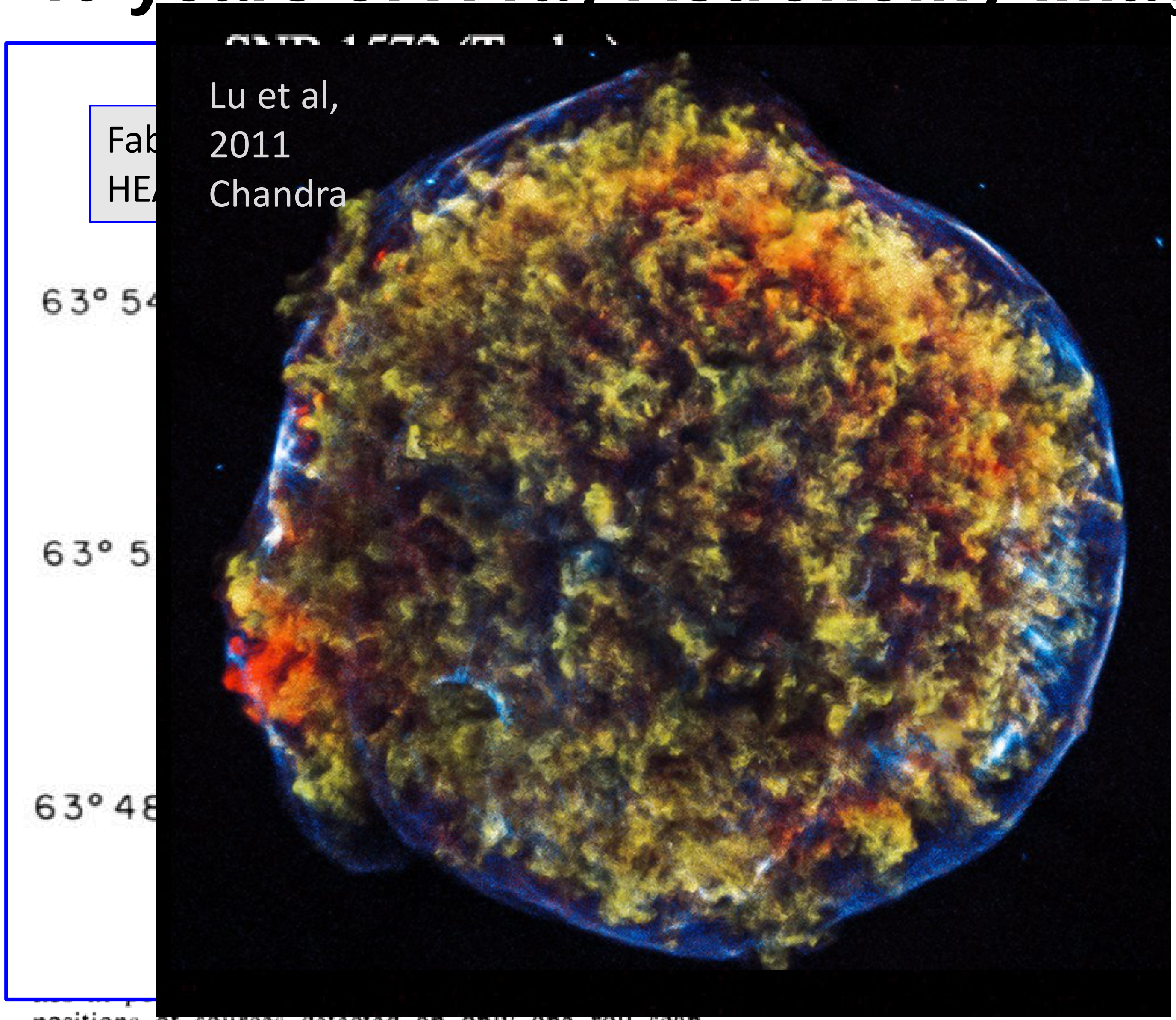
X-ray emission is a critical component of our multiwavelength view of the Universe

~10 million degree plasmas

- *Strong shocks*
- *Accretion*
- *Outflows*
- *Hot halos*
- *Galaxy and cluster interaction and merging*

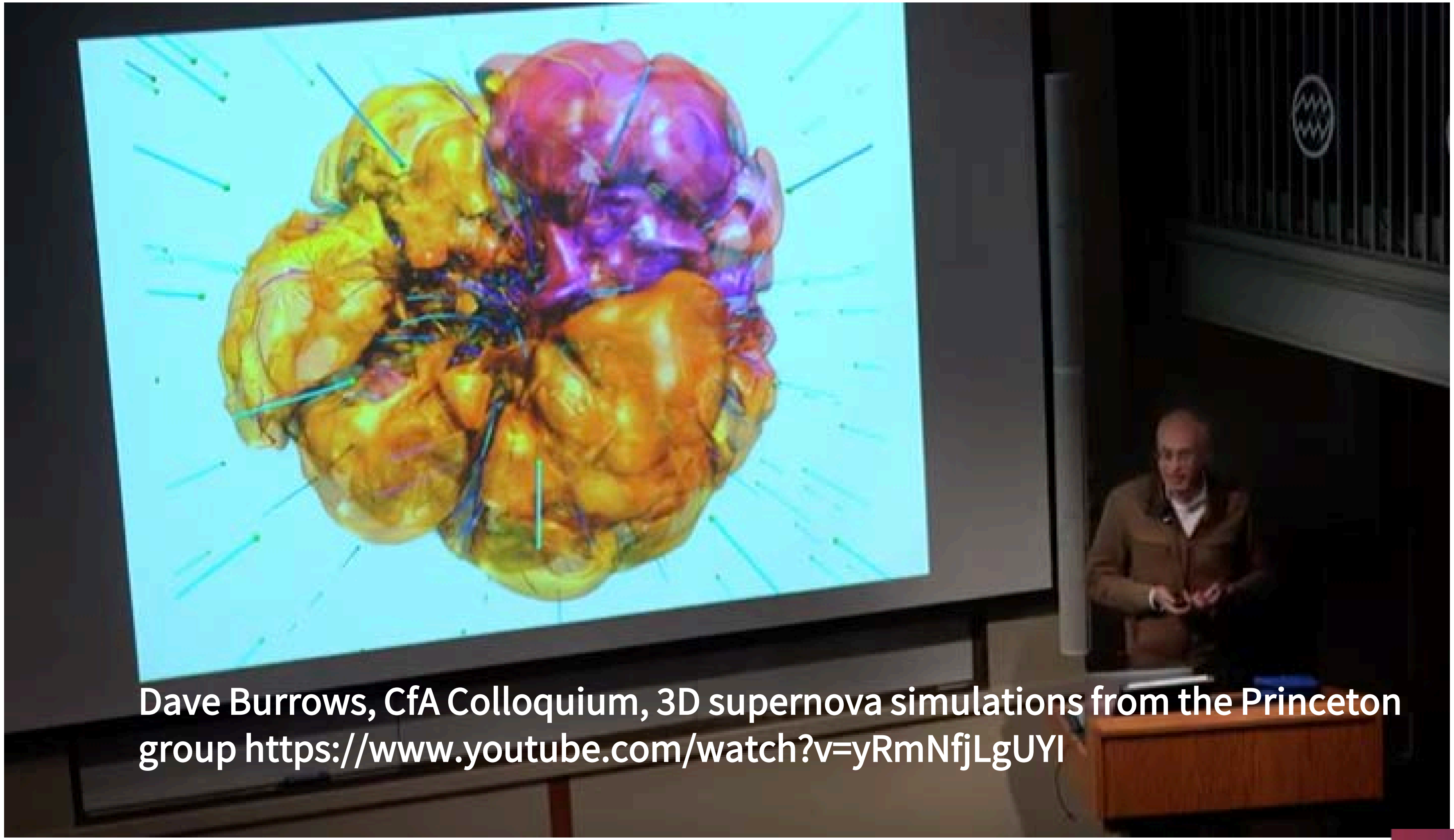
Nobel prize

40 years of X-ray Astronomy image



positions of sources detected on only one roll scan.

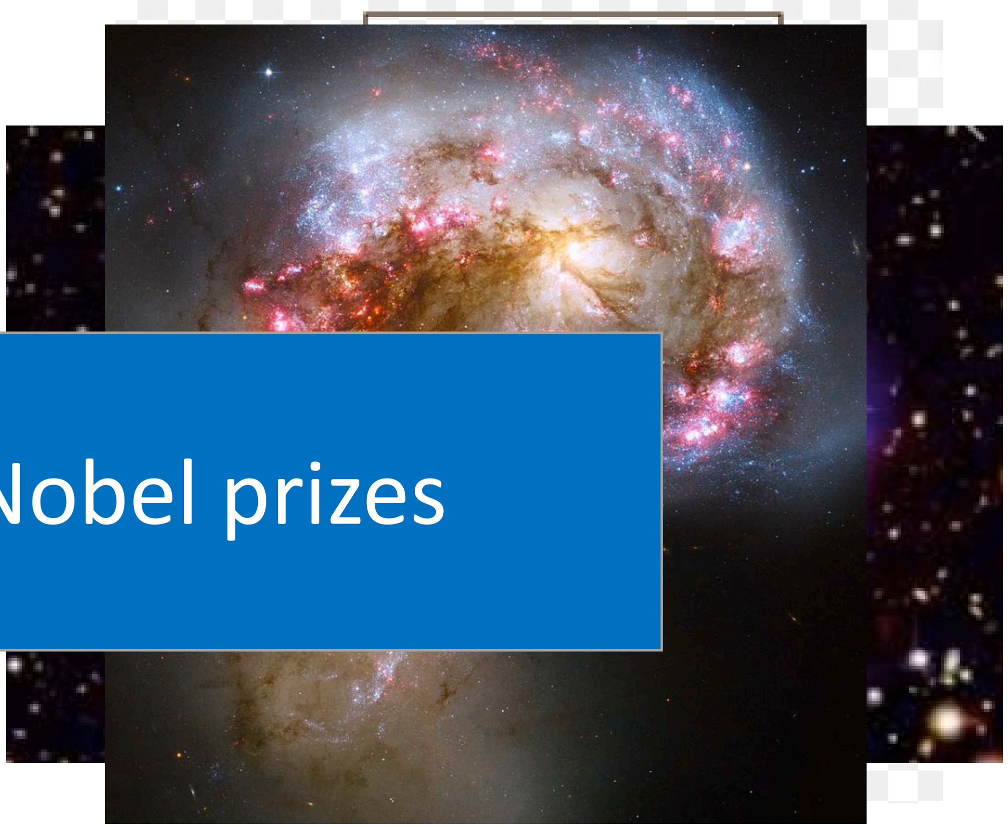
..and now data are driving theory



Dave Burrows, CfA Colloquium, 3D supernova simulations from the Princeton group https://www.youtube.com/watch?v=yRmNfjLgUYI

Multi-wavelength space observations
e.g., Hubble, Chandra, Spitzer, XMM-Newton

- Black holes and their mass range
  - X-ray accretion sources
  - End-product of massive star evolution
  - Ubiquitous in galaxy nuclei
  - Now imaged with EHT (question-driven)
- Dark Energy
  - Riess + 1998, Perlmutter+ 1999
- Non-baryonic Dark Matter
  - Markevitch + 2004
- High-z super-starburst galaxies
  - NASA press release 2008



Nobel prizes

These are **foundational** discoveries
for the understanding of the Universe

Not in any way anticipated

….from *Exploration*
i.e. expansion of the Discovery Space

Increasing the Discovery Space

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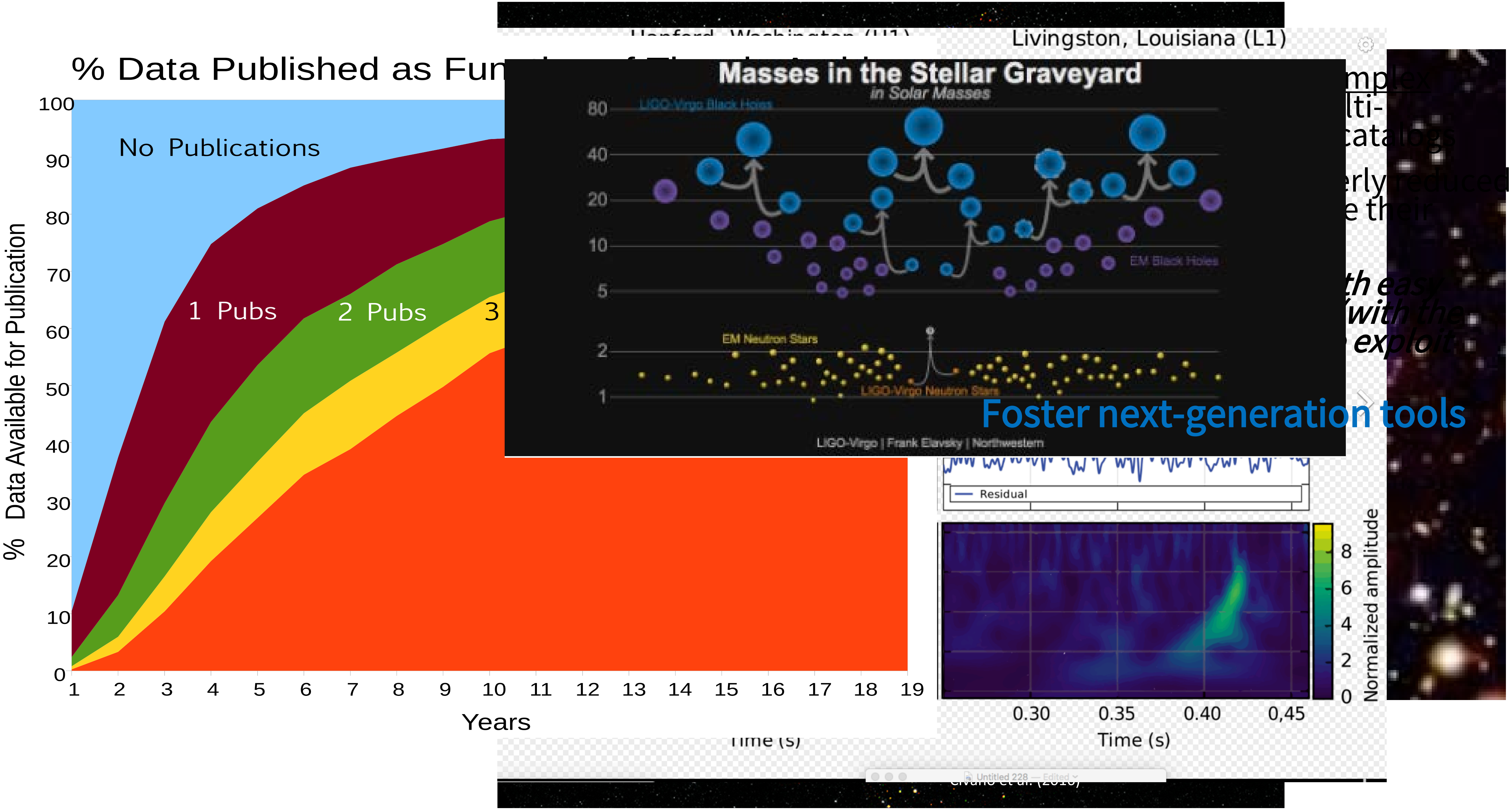

In conclusion….

- *Keep multi-wavelength and multi-messenger exploration center stage* in the deliberations of new facilities
  - including consideration for flexible and well-calibrated modes of operation that could foster adaptation for use with new discovery space
- *Recognize the importance of data and their stewardship, and computational services*, as major elements of any new scientific development for the next decade

Innovative observing facilities,
and the state-of-the-art astronomy archives
needed to support these facilities,
will open up the universe to new discovery

If you want to know more….

2019arXiv190306634F 2019/03

Increasing the Discovery Space in Astrophysics - A Collation of Six Submitted White Papers

Fabbiano, G.; Elvis, M.; Accomazzi, A. and 46 more

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Operational (old and new) facility/missions should explicitly include in their scope the proper processing software

- To produce well documented and calibrated data products,
- Have the capability for data recalibration and reprocessing

Data products in well-maintained archives, following the International Virtual Observatory Alliance (IVOA) standards

- To allow a basic level of access and *interoperability*, as well as *repurposing.*
- Much of this is already in place in the major data centers world-wide
- Collaborations are in place to extend and evolve these capabilities to meet the demands of new data types and research methods through the 2020s.
- Data products should be replicable and reproducible, ranging from basic observation data to high-level aggregated data and catalogs.

Ensure that new facilities are adequately supported

- *Future facilities will demand a transformation in the way data are analyzed*.
- The early phases of this transformation are already underway (e.g., the use of *Python* as an environment, cloud computing).
- Resources must be made available for full development
- See, e. g.
  - LSST Science Platform Design document https://ldm-542.lsst.io
  - NASA Big Data Task Force (https://science.nasa.gov/science-committee/subcommittees/big-data-task-force)

Foster next-generation tools

- Interoperable, user-friendly advanced visual interfaces
- Data mining tools
- The ability to construct and implement analysis workflows easily, both via visualization and scripting
- Remote Science Platforms and Server-side analytics
- Implementation of complex fault-tolerant workflows

Support interdisciplinary research in astrostatistics and astroinformatics and the transfer of methods from the statistics, computer science, and machine learning communities

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- For development and application of innovative data analysis methods and algorithms.

Ensure that facilities and archives participate in curation efforts and initiatives to link together datasets, related ancillary data (e.g., atomic and molecular databases), objects, and the literature