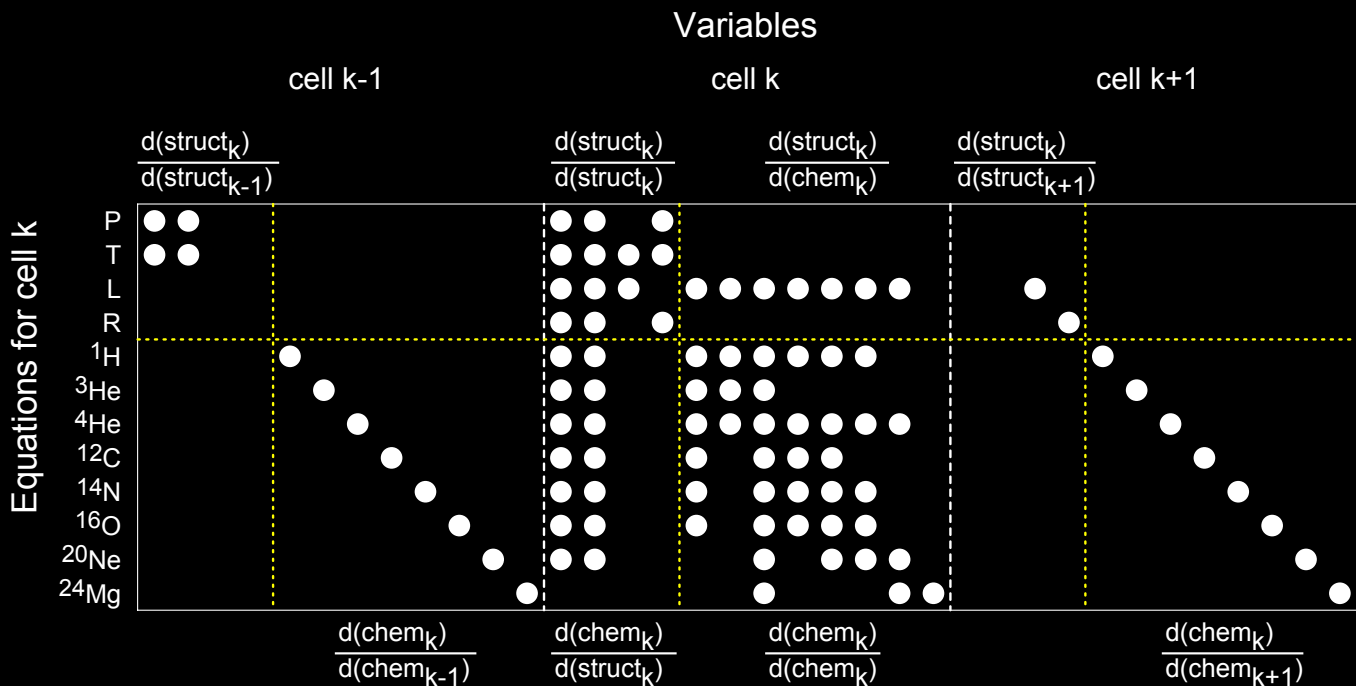# The Modules for Experiments in Stellar Astrophysics (MESA) Project

Frank Timmes
School of Earth and Space Exploration
Arizona State University

The M⊂SA source code is a set of software modules for stellar astrophysics that can be used on their own, or combined to solve the coupled equations governing 1D stellar evolution with an implicit finite volume scheme.

Variables

cell k-1 cell k cell k+1

$\dfrac{d(struct_k)}{d(struct_{k-1})}$ $\dfrac{d(struct_k)}{d(struct_k)}$ $\dfrac{d(struct_k)}{d(chem_k)}$ $\dfrac{d(struct_k)}{d(struct_{k+1})}$

Equations for cell k

P
T
L
R
^{1}H
^{3}He
^{4}He
^{12}C
^{14}N
^{16}O
^{20}Ne
^{24}Mg

$\dfrac{d(chem_k)}{d(chem_{k-1})}$ $\dfrac{d(chem_k)}{d(struct_k)}$ $\dfrac{d(chem_k)}{d(chem_k)}$ $\dfrac{d(chem_k)}{d(chem_{k+1})}$

"Mother of All Demos"
December 8, 1968

"The 90-minute presentation demonstrated almost all the fundamental elements of modern personal computing: windows, hypertext, graphics, efficient navigation and command input, video conferencing, the computer mouse, word processing, dynamic file linking, revision control, and a collaborative real-time editor."

Doug Engelbart

Bill Paxton

After a PhD in computer science at Stanford and a stint at Xerox Palo Alto Research Center, Bill became one of Adobe's creators in 1983.

Bill helped invent scalable font technology.

The public facing part of this invention was Postscript, which evolved into today's PDF.

Bill retired from Adobe in 1990.

"Hello, my name is Bill Paxton. My I please
use the tools posted on your website?"
January 8, 2005

Bill is M∈SA's First Author
and
a Senior Fellow in Computational Astrophysics
at the KITP.

Recognizing Opportunity

In 2010 stellar evolution software instruments were usually closed source, closed knowledge, secret handshake, and concentrated in ~10 locations around the world.

Yet, stellar astronomy was (and still is) booming with new telescopes, missions, puzzles, and science.
There was a large pent-up demand for new stellar models.

In 2010 M⊏⊐A as an instrument was ready for release.
Time was spent planning for M⊏⊐A's possible future …

APPENDIX A

MANIFESTO

`MESA` was developed through the concerted efforts of the lead author over a six year period with the engagement and deep involvement of many theoretical and computational astrophysicists. The public availability of `MESA` will serve education, scientific research, and outreach. This appendix describes the scientific motivation for `MESA`, the philosophy and rules of use for `MESA`, and the path forward on stewardship of `MESA`, and advanced development of future research and education tools. We make `MESA` openly available with the hope that it will grow into a community resource. We therefore consider it important to explain the guiding principles for using and contributing to MESA. Our goal is to assure the greatest usefulness for the largest number of research and educational projects.

MESA + GYRE RSP MIST STELLA

MESA : Community of ~1000, Jan 2019

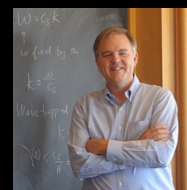Josiah Schwab, Adam Jermyn, Radek Smolec, Anne Thoul, Evan Bauer, Bill Wolf, Rob Farmer, Pablo Marchant, Warrick Ball, Aaron Dotter, Rich Townsend, Frank Timmes, Bill Paxton, Lars Bildsten, Matteo Cantiello
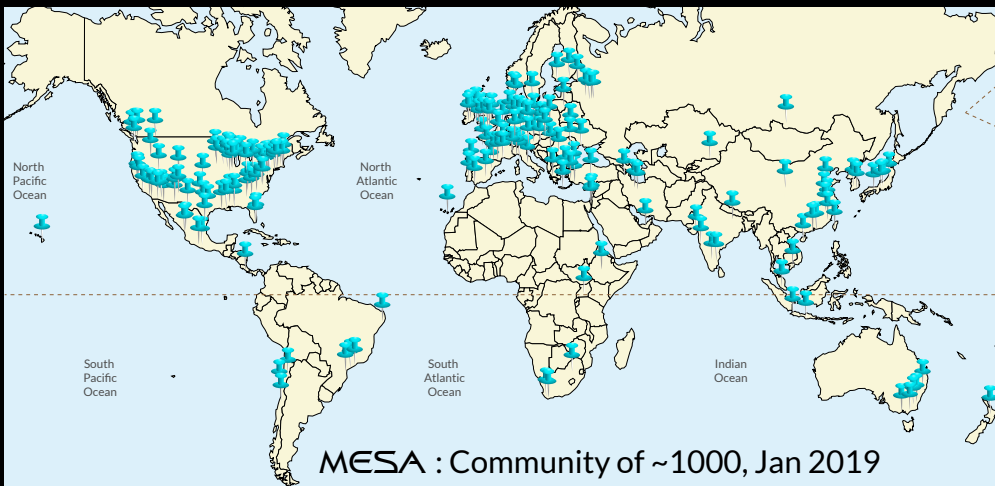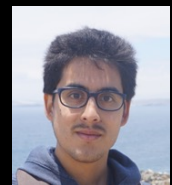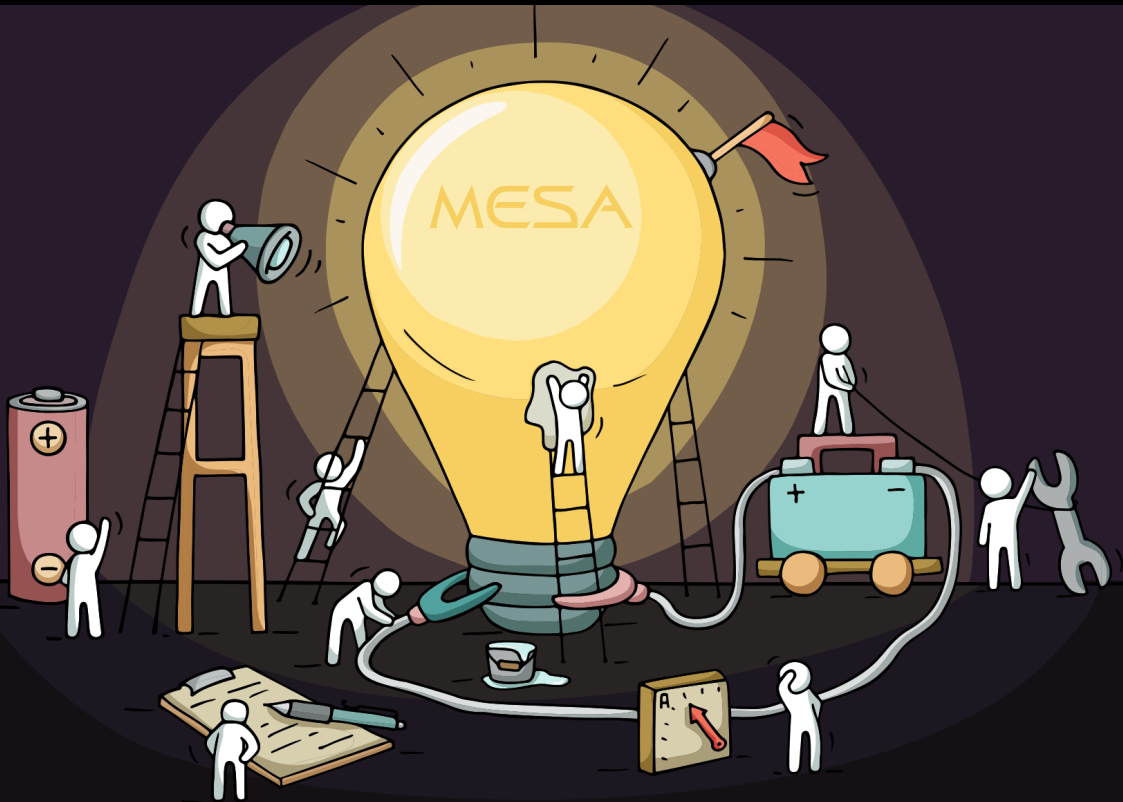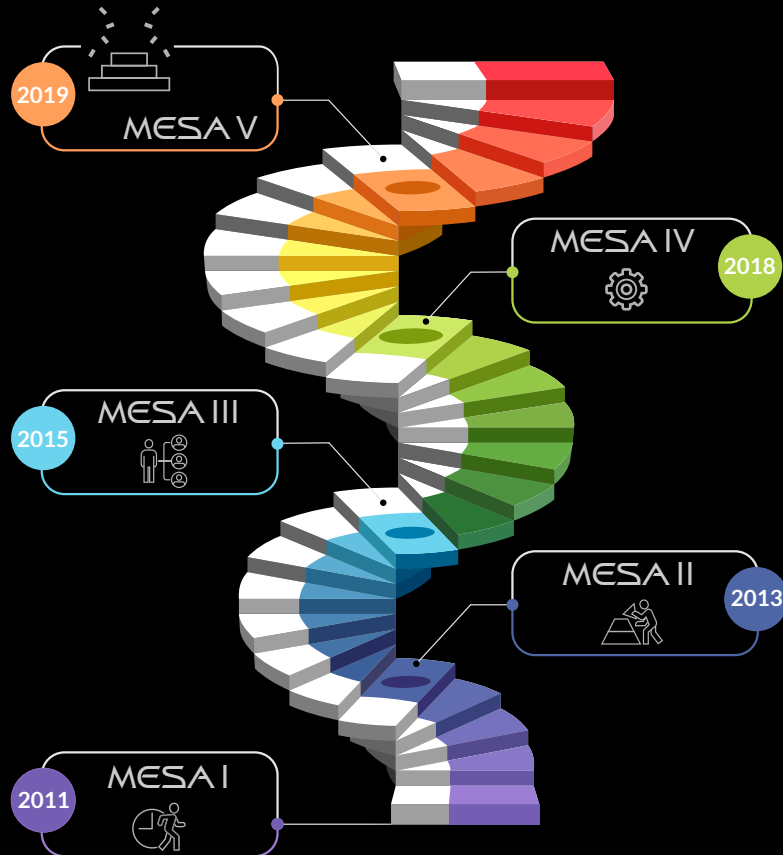
A thriving open-knowledge software project takes a village.

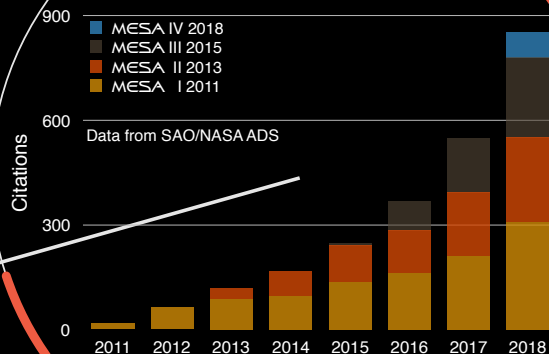How does the MESA project innovate?

Multiple Instrument Papers

Usually there is one software instrument paper, occasionally two separated by decadal timescales.

We update the community with instrument papers describing new science capabilities about every two years.

Larger Science Community

MESA

Influence
Radius ≈15

Citations: 2,456

Citations to papers
that cite MESA: 37,645

MESA I - Top   5 in 2011
MESA II - Top 10 in 2013

MESA III - Top   5 in 2015
MESA IV - Top 30 in 2018

Of the Top 10 most cited astro articles published in 2013, three are represented at our meeting.

| 1 ☐	2013ApJS..208...19H	2013/10	cited: 3308
	Nine-year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Cosmological Parameter Results		
	Hinshaw, G.; Larson, D.; Komatsu, E. *and 18 more*		
2 ☐	2013PASP..125..306F	2013/03	cited: 2617
	emcee: The MCMC Hammer		
	Foreman-Mackey, Daniel; Hogg, David W.; Lang, Dustin *and 1 more*		
3 ☐	2013A&A...558A..33A	2013/10	cited: 1979
	Astropy: A community Python package for astronomy		
	Astropy Collaboration; Robitaille, Thomas P.; Tollerud, Erik J. *and 42 more*		
4 ☐	2013ApJS..208...20B	2013/10	cited: 1447
	Nine-year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Final Maps and Results		
	Bennett, C. L.; Larson, D.; Weiland, J. L. *and 18 more*		
5 ☐	2013ARA&A..51..511K	2013/08	cited: 1286
	Coevolution (Or Not) of Supermassive Black Holes and Host Galaxies		
	Kormendy, John; Ho, Luis C.		
6 ☐	2013ApJ...770...57B	2013/06	cited: 1086
	The Average Star Formation Histories of Galaxies in Dark Matter Halos from z = 0-8		
	Behroozi, Peter S.; Wechsler, Risa H.; Conroy, Charlie		
7 ☐	2013AJ....145...10D	2013/01	cited: 1012
	The Baryon Oscillation Spectroscopic Survey of SDSS-III		
	Dawson, Kyle S.; Schlegel, David J.; Ahn, Christopher P. *and 162 more*		
8 ☐	2013ApJS..208....4P	2013/09	cited: 859
	Modules for Experiments in Stellar Astrophysics (MESA): Planets, Oscillations, Rotation, and Massive Stars		
	Paxton, Bill; Cantiello, Matteo; Arras, Phil *and 8 more*		
9 ☐	2013A&A...556A...2V	2013/08	cited: 834
	LOFAR: The LOw-Frequency ARray		
	van Haarlem, M. P.; Wise, M. W.; Gunst, A. W. *and 198 more*		
10 ☐	2013ApJ...770..103H	2013/06	cited: 813
	The Nuclear Spectroscopic Telescope Array (NuSTAR) High-energy X-Ray Mission		
	Harrison, Fiona A.; Craig, William W.; Christensen, Finn E. *and 78 more*		

Actively Support the MESA Community

We provide two portals to openly share knowledge.

MESA-Users offers over 10,000 archived and searchable posts on community discussions of stellar astrophysics.
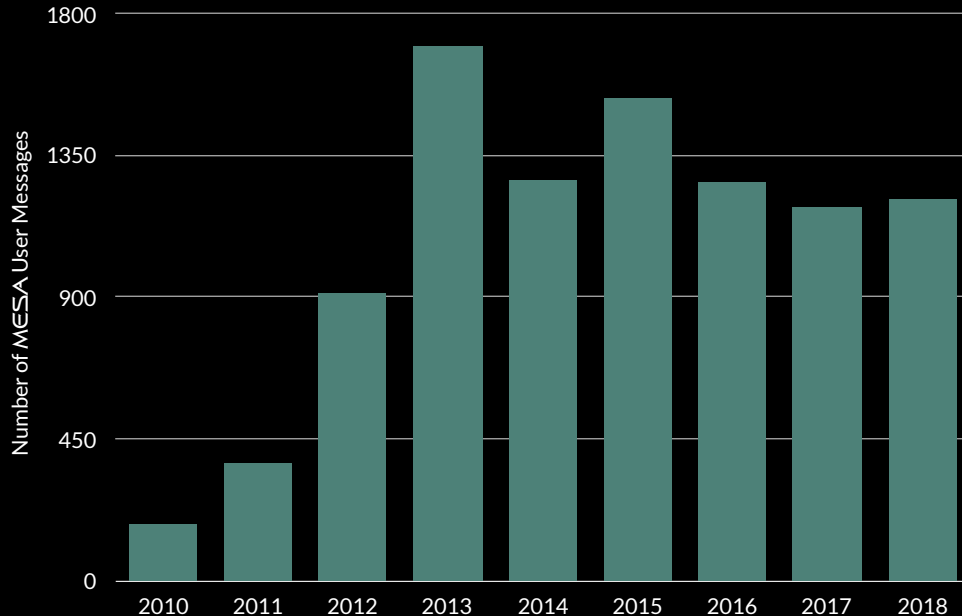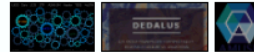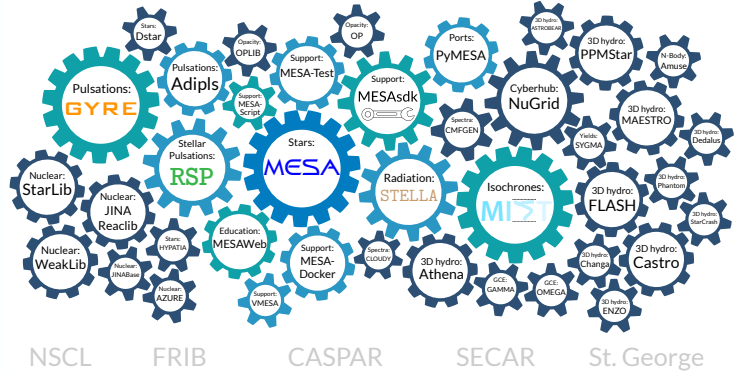
mesastar.org offers a Zenodo backed portal to share tools, inlists, guidance, and to build provenance.

Currently there are ~400 contributions by the community, for the community.

Welcome to the **MESA** Marketplace.

This month's featured shareware:

LIGO Gaia LCO LSST ASAS-SN ZTF JWST TESS NuSTAR

Stars: Dstar
Pulsations: Adipls
Opacity: OPLIB
Support: MESA-Test
Opacity: OP
Ports: PyMESA
Stars: ASTROBEAR
3D hydro: PPMStar
N-Body: Amuse
Pulsations: GYRE
Support: MESA-Script
Support: MESAsdk
Cyberhub: NuGrid
3D hydro: MAESTRO
Spectra: CMFGEN
Stellar Pulsations: RSP
Stars: MESA
Radiation: STELLA
Yields: SYGMA
3D hydro: Dedalus
Nuclear: StarLib
Nuclear: JINA Reaclib
Isochrones: MIST
3D hydro: Phantom
Nuclear: WeakLib
Stars: HYPATIA
Education: MESAWeb
Spectra: CLOUDY
3D hydro: FLASH
3D hydro: StarCrash
Nuclear: JINABase
Support: MESA-Docker
3D hydro: Athena
3D hydro: Changa
3D hydro: Castro
Nuclear: AZURE
Support: VMESA
GCE: GAMMA
GCE: OMEGA
3D hydro: ENZO

NSCL   FRIB   CASPAR   SECAR   St. George

Recent Refereed Journal Papers using MESA

Sensitivity of carbon and oxygen yields to the triple-alpha resonance in massive stars
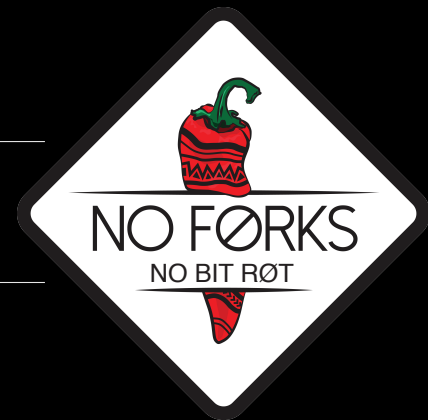Huang, Lillian, Adams, Fred C., and Grohs, Evan

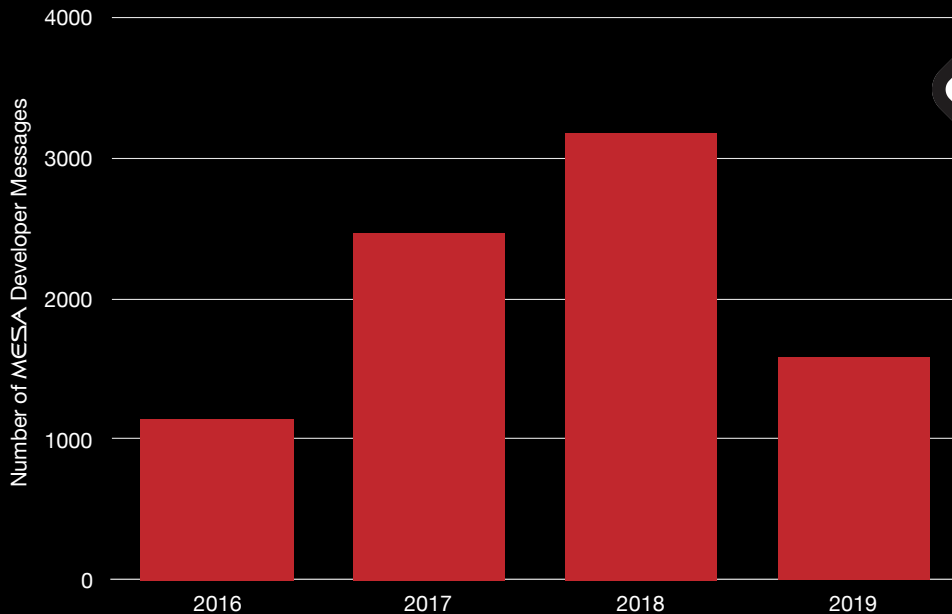Pulsation-triggered dust production by asymptotic giant branch stars
McDonald, I., De Beck, E., Zijlstra, A. A. et al.

Usually a forked source code is released when people are not getting what they want.

We keep the pace of development high enough that any fork quickly becomes outdated.

We provide a Software Development Kit to build MΞSΛ across a variety of Unix-based platforms.

MESAsdk

MESA-Docker simplifies the requirements for locally running a full installation, with only minor overhead from running in a container. This is useful for new users and Windows users.

Lead: Evan Bauer

MESA-WEB is a web-based cloud resource for education that has served 4000+ models to ~550 unique users in 3 years of operation.
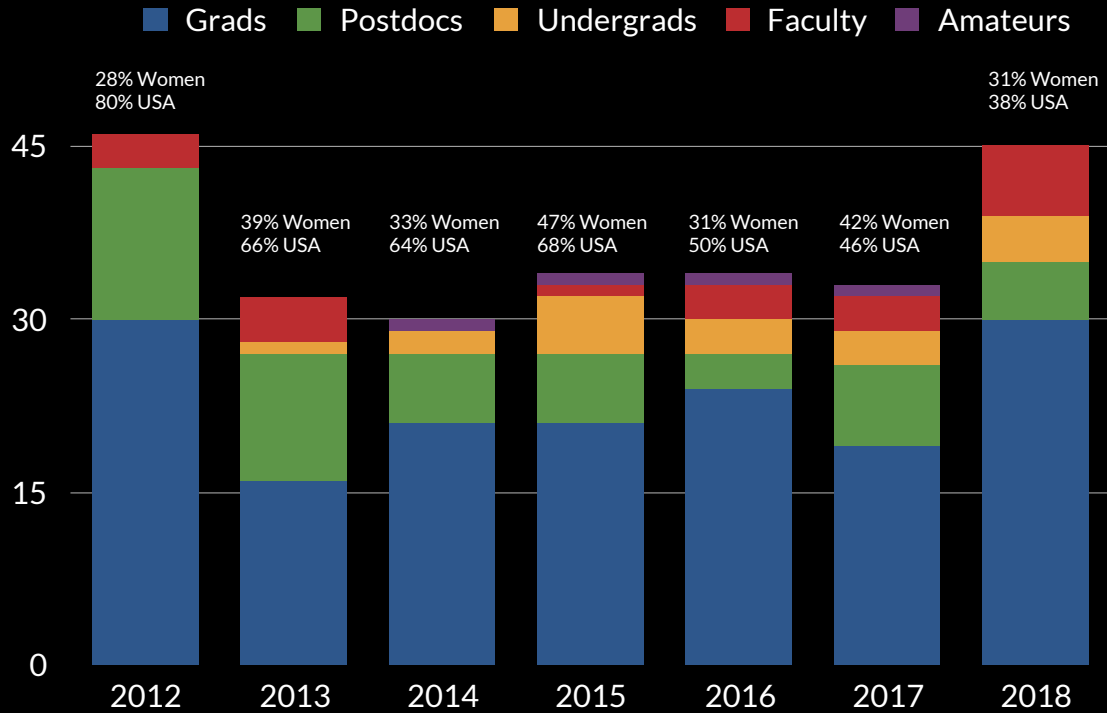

http://mesa-web.asu.edu

Lead: Carl Fields

Building Our Next Generation

The MESA Summer School offers a week of extensive hands-on labs to gain familiarity with MESA and learn how to make better use of MESA in their own research.

The Summer School cadre of instructors, TAs and participants (now over 250) are creating their own MESA user infrastructure at ~40 institutions around the world.

Legend: Grads, Postdocs, Undergrads, Faculty, Amateurs

- 2012: 28% Women, 80% USA
- 2013: 39% Women, 66% USA
- 2014: 33% Women, 64% USA
- 2015: 47% Women, 68% USA
- 2016: 31% Women, 50% USA
- 2017: 42% Women, 46% USA
- 2018: 31% Women, 38% USA

We focus on supporting young scientists who are also skilled at developing community software instruments to obtain high-profile graduate fellowships (6), named postdoc fellowships (6), and tenure-stream positions (5).

MESA Funding Profile

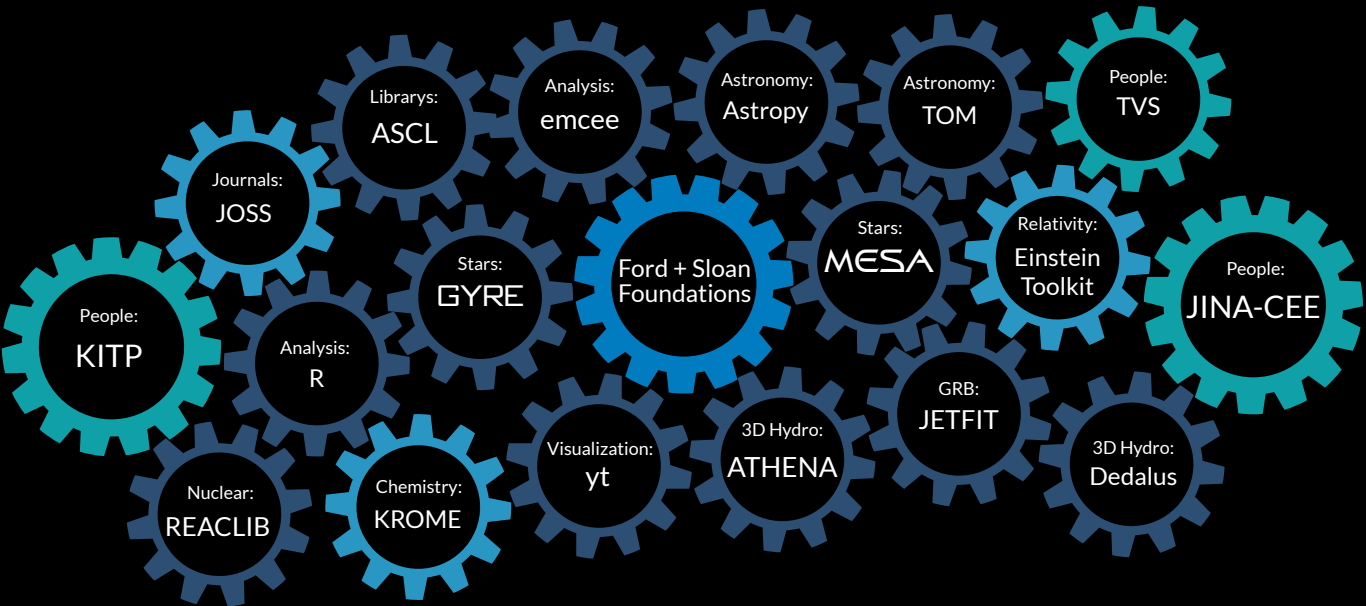| 2011	$0 - Failure[1]
2013	$500K for 3 years from NSF[2]
2017	$3M for 4 years from NSF[3]
2019	$35K from Ford/Sloan[3]
2020	TBD (New Opportunities)

[1]Lesson: Market community rather than source code.

[2]Lesson: Quantify and brand all aspects of the project.

[3]Lesson: Build an ecosystem.

Community-driven software and data ecosystems that accelerate new science.

Gaia LIGO SDSS Hubble JWST LSST TESS LCOGT NuSTAR

Librarys: ASCL

Analysis: emcee

Astronomy: Astropy

Astronomy: TOM

People: TVS

Journals: JOSS

Stars: GYRE

Ford + Sloan Foundations

Stars: MESA

Relativity: Einstein Toolkit

People: JINA-CEE

People: KITP

Analysis: R

Visualization: yt

3D Hydro: ATHENA

GRB: JETFIT

3D Hydro: Dedalus

Nuclear: REACLIB

Chemistry: KROME

Laboratory Astrophysics