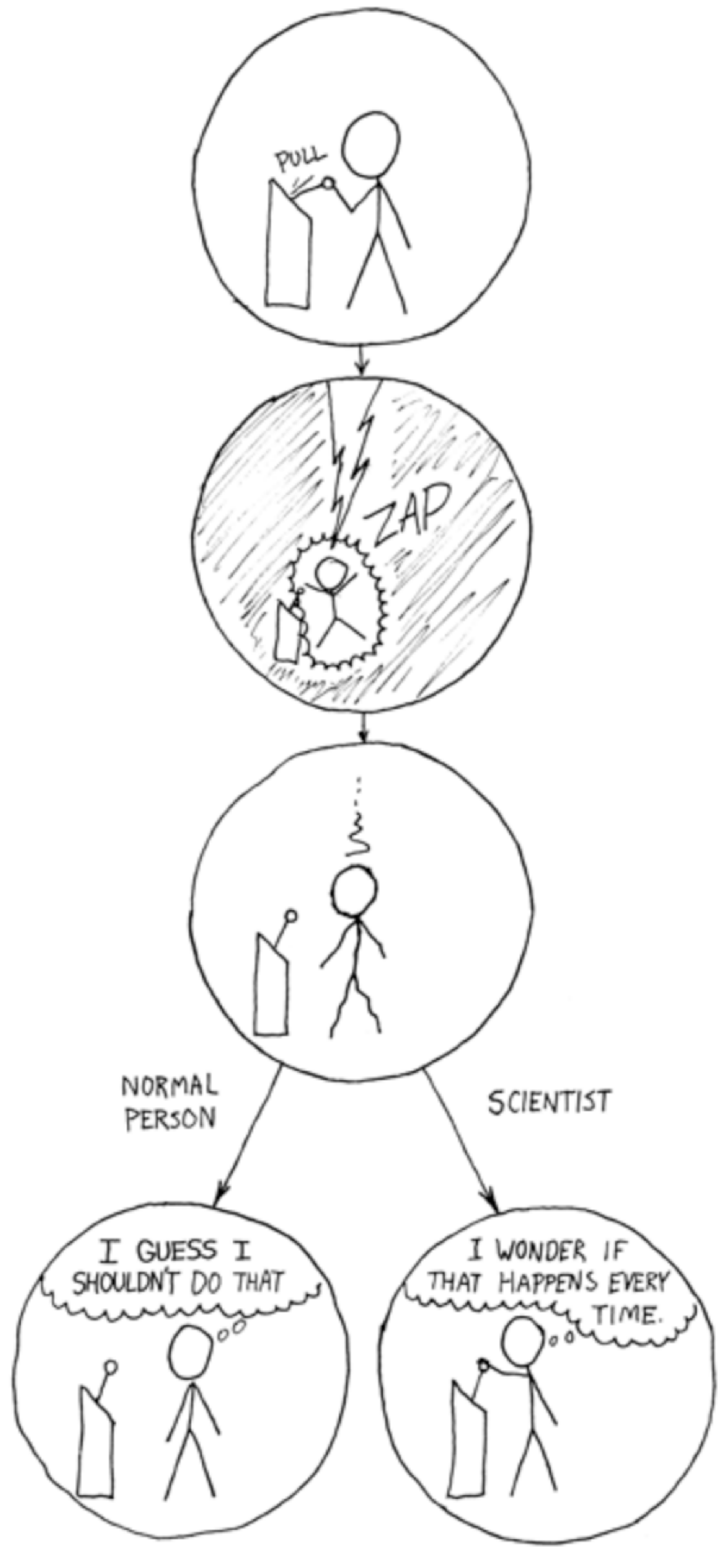
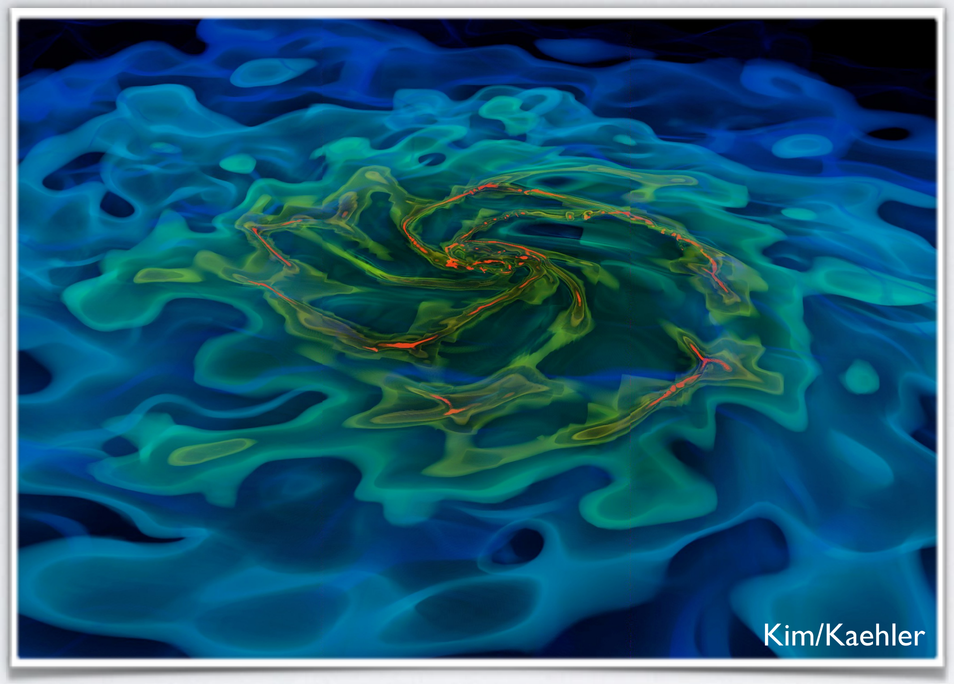

PULL
ZAP
NORMAL PERSON
SCIENTIST
I GUESS I SHOULDN'T DO THAT
I WONDER IF THAT HAPPENS EVERY TIME.

xkcd.com/242

Reproducibility: An Insight from the AGORA High-resolution Galaxy Simulations Comparison



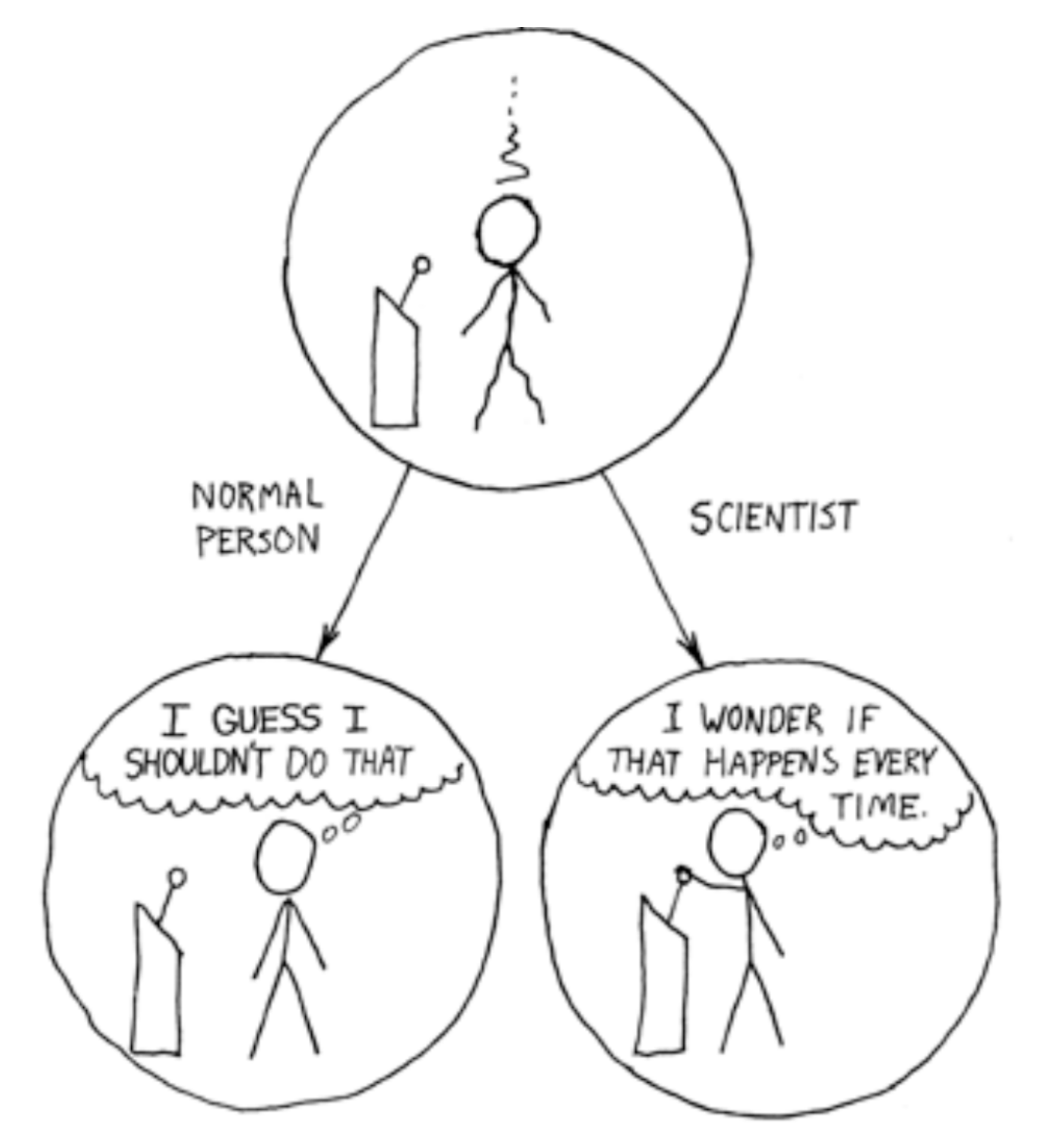
Ji-hoon Kim (SLAC/Stanford/KIPAC)

- Kim et al. for the AGORA Collaboration (2016, arXiv:1610.03066, ApJ submitted)
- Kim et al. for the AGORA Collaboration (2014, ApJS 210, 14)

Special thanks to: T. Abel (Stanford), O. Agertz (Surrey), N. Gnedin (Fermilab), R. Feldmann (Zurich), O. Hahn (Nice), B. Keller (McMaster), A. Lupi (IAP), P. Madau (UCSC), L. Mayer (Zurich), K. Nagamine (Osaka/UNLV), J. Primack (UCSC), B. Smith (Edinburgh), R. Teyssier (Zurich), M. Turk (NCSA), J. Wadsley (McMaster)

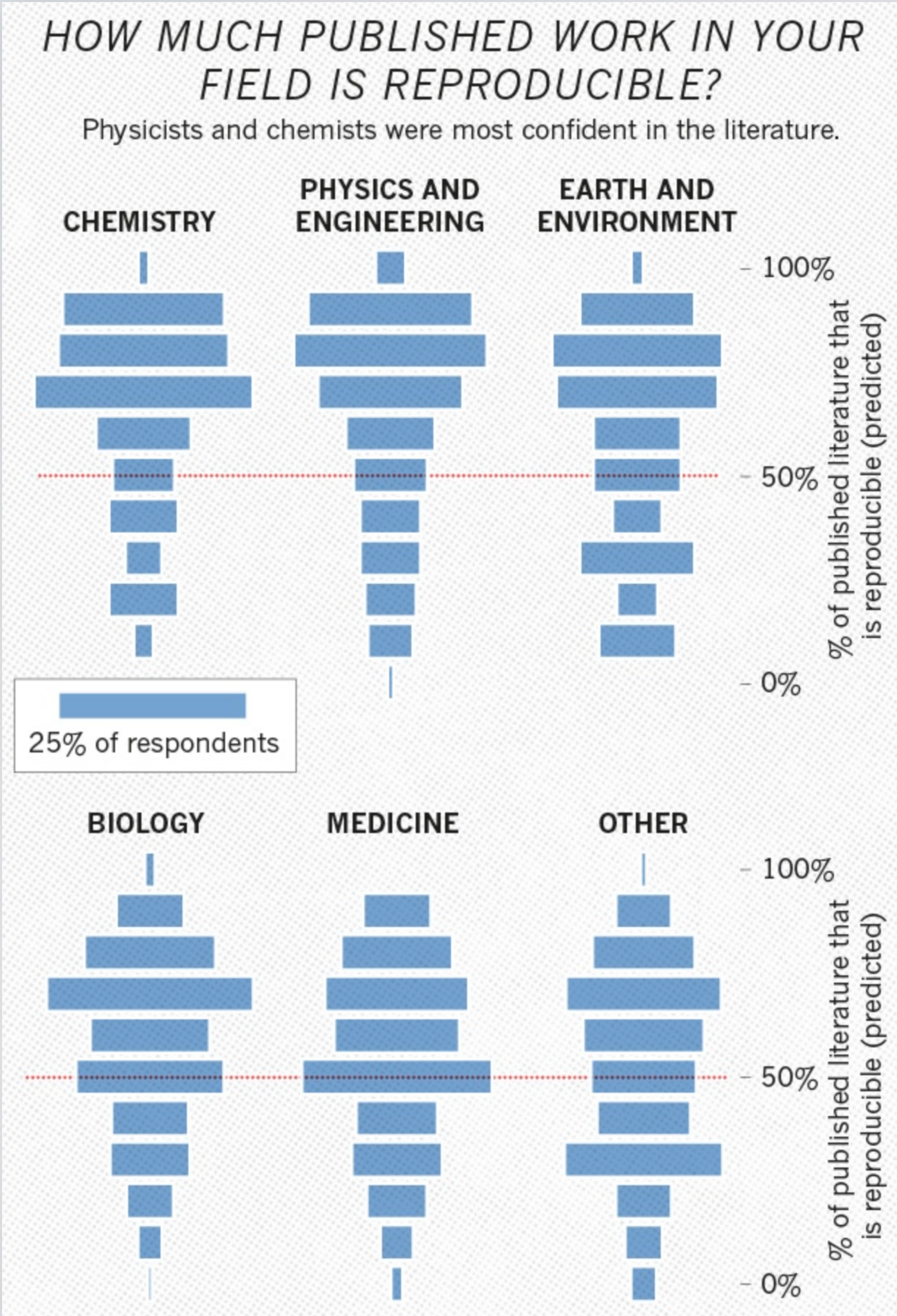
Fundamental Principle of Scientific Method

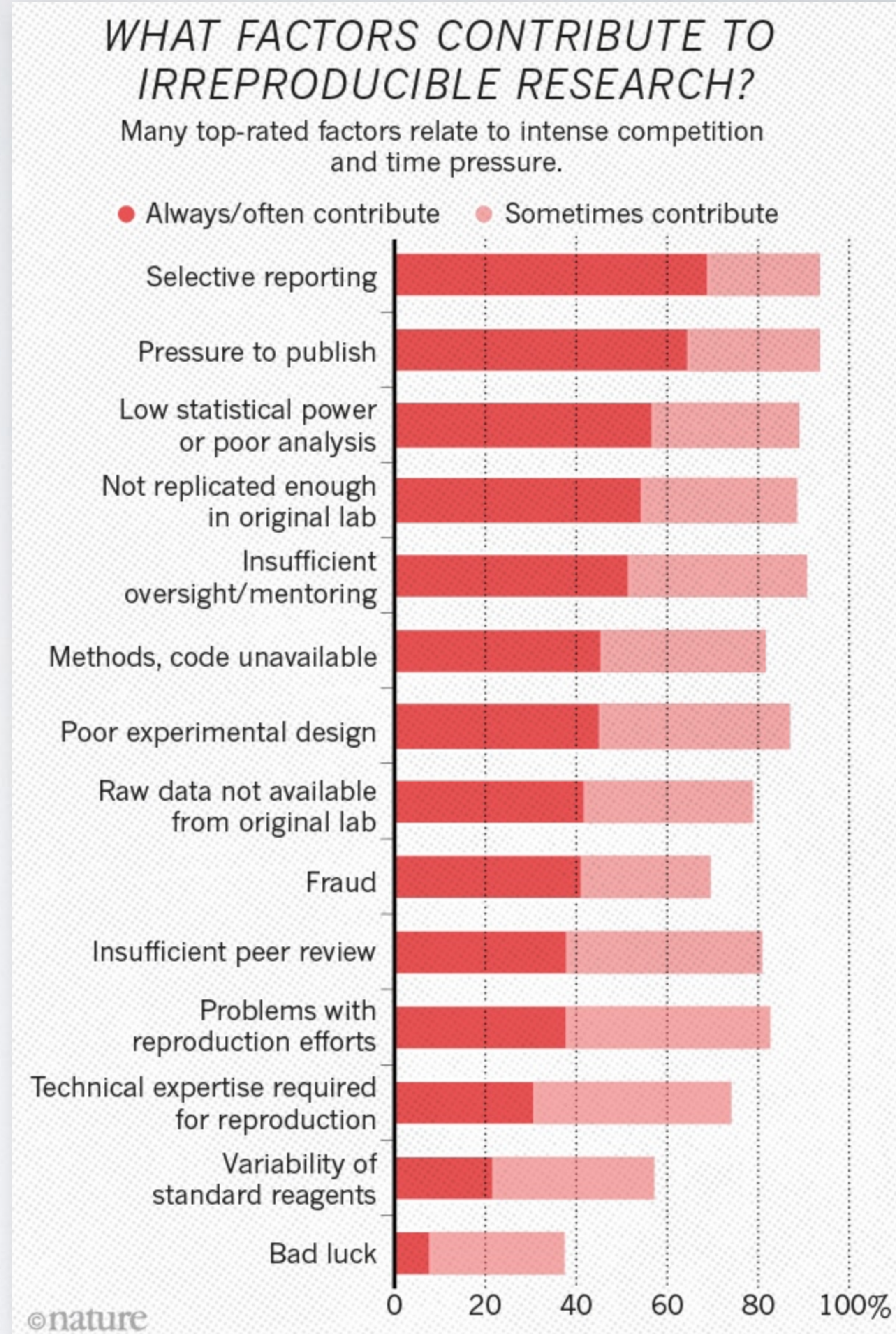
- Experiments must be reproducible to be established as knowledge.



xkcd.com/242

"Reproducibility Crisis" - *Nature* Magazine

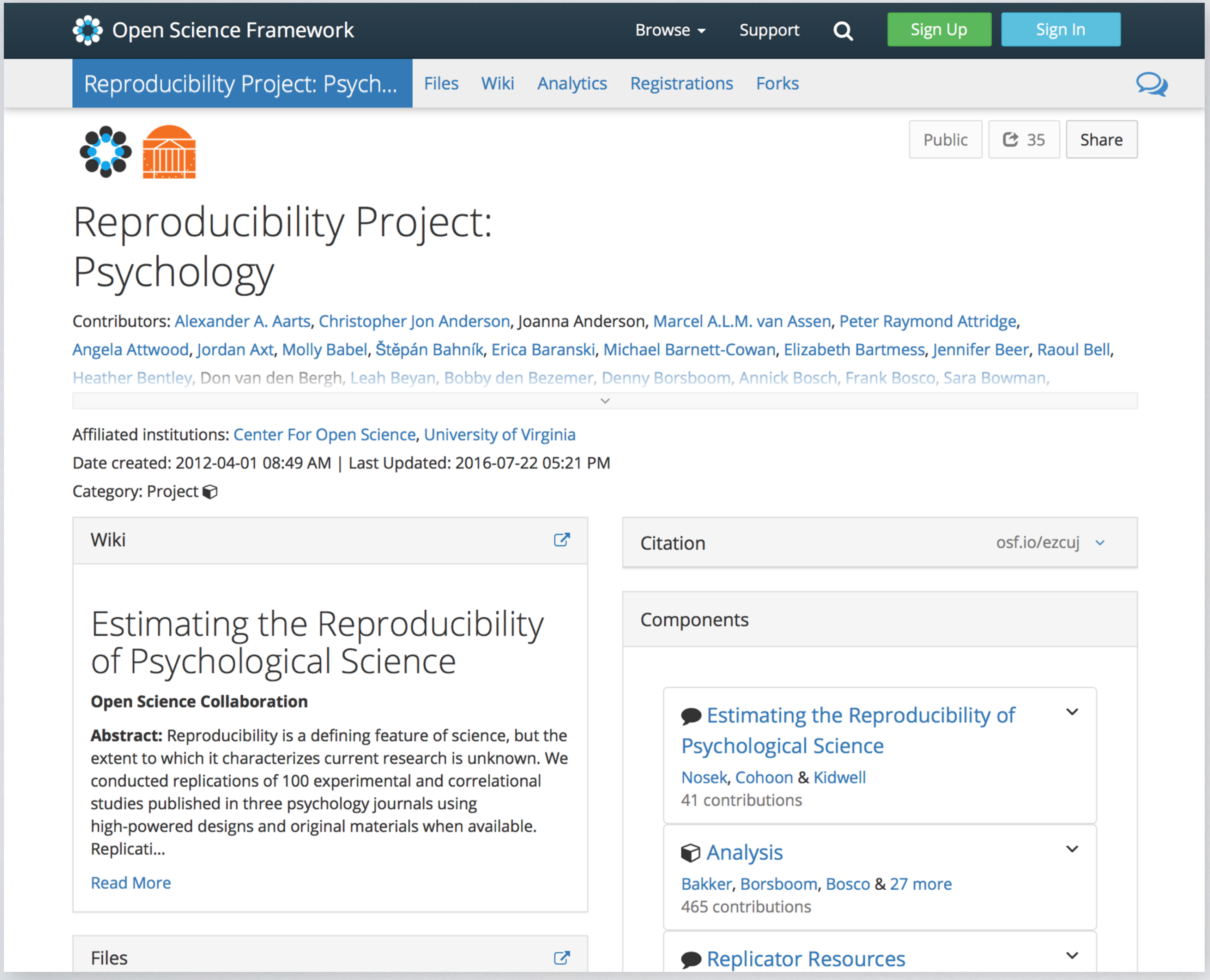




Nature Survey of 1576 researchers (2016)

How Other Fields Are Dealing With It

- e.g. Reproducibility Project: Psychology / Cancer Biology



Marshmallow experiment, pbs.org

http://osf.io/ezcuj

“Reproducibility Crisis” in Psychology

- Only 36% of replicated studies show statistically significant results.

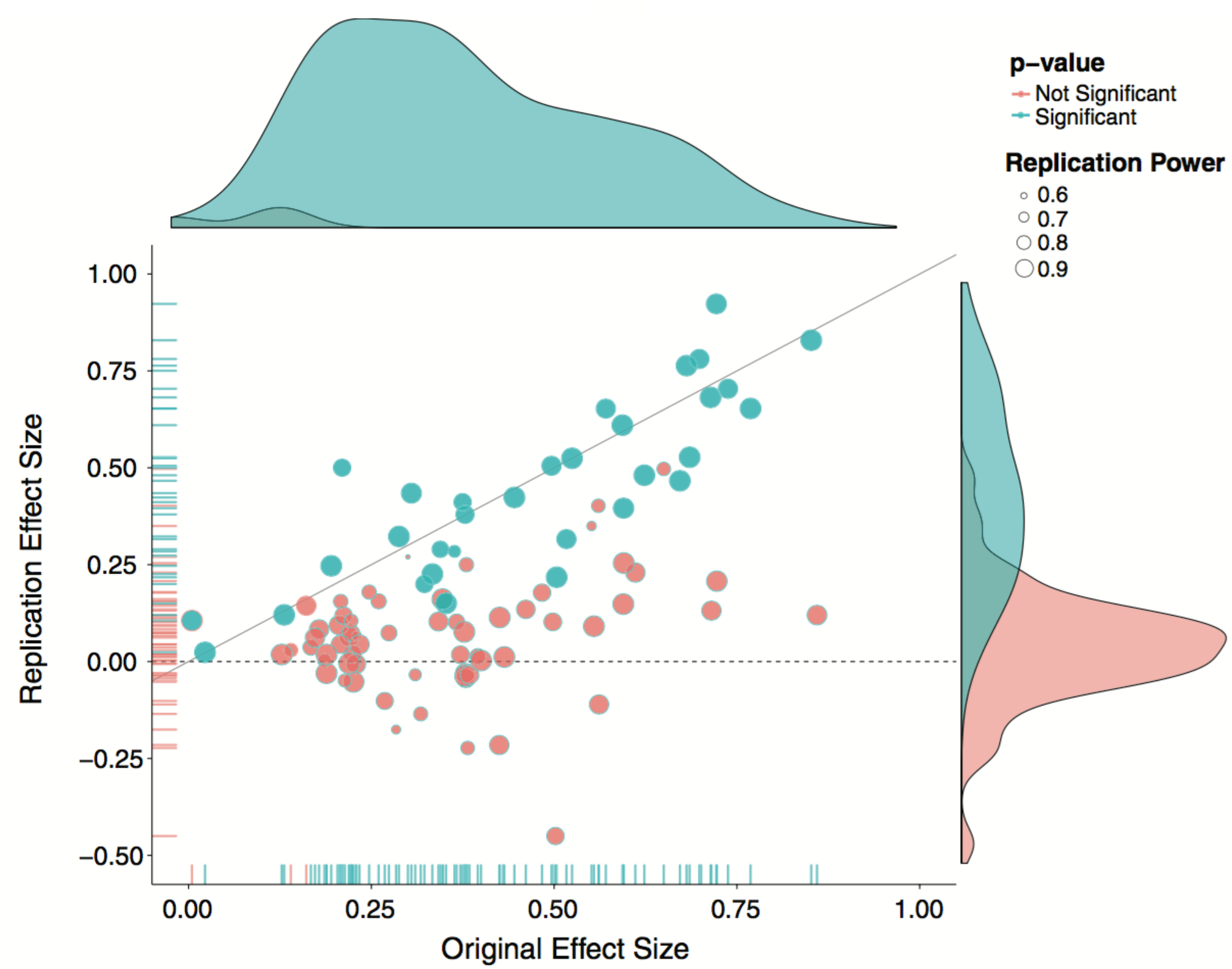
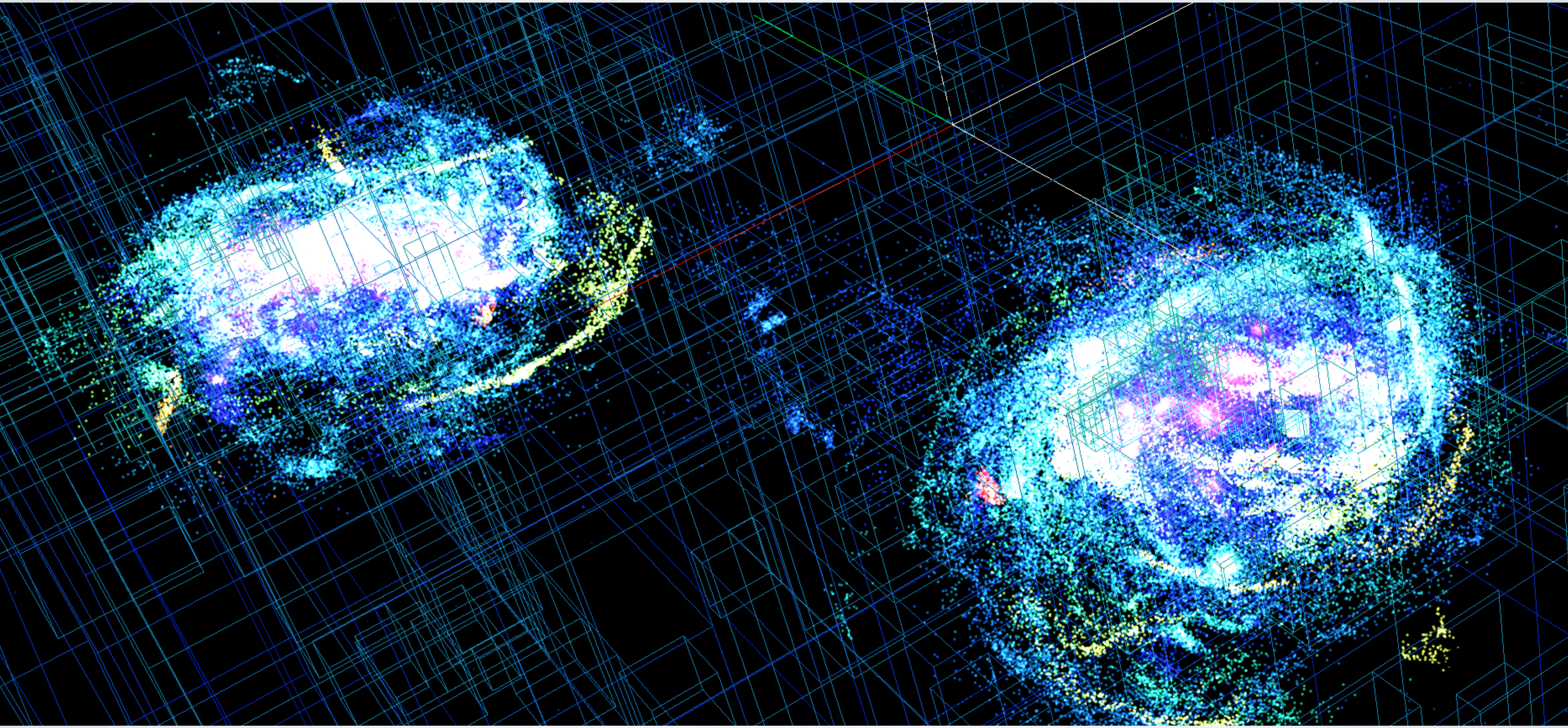


Fig. 3. Original study effect size versus replication effect size (correlation coefficients). Diagonal line represents replication effect size equal to original effect size. Dotted line represents replication effect size of 0. Points below the dotted line were effects in the opposite direction of the original. Density plots are separated by significant (blue) and nonsignificant (red) effects.

Nosek et al. for the Open Science Collaboration (2015, *Science*)

How About Galactic Astronomy?

- The success of our galaxy formation theory relies heavily on robust and reproducible numerical experiments.



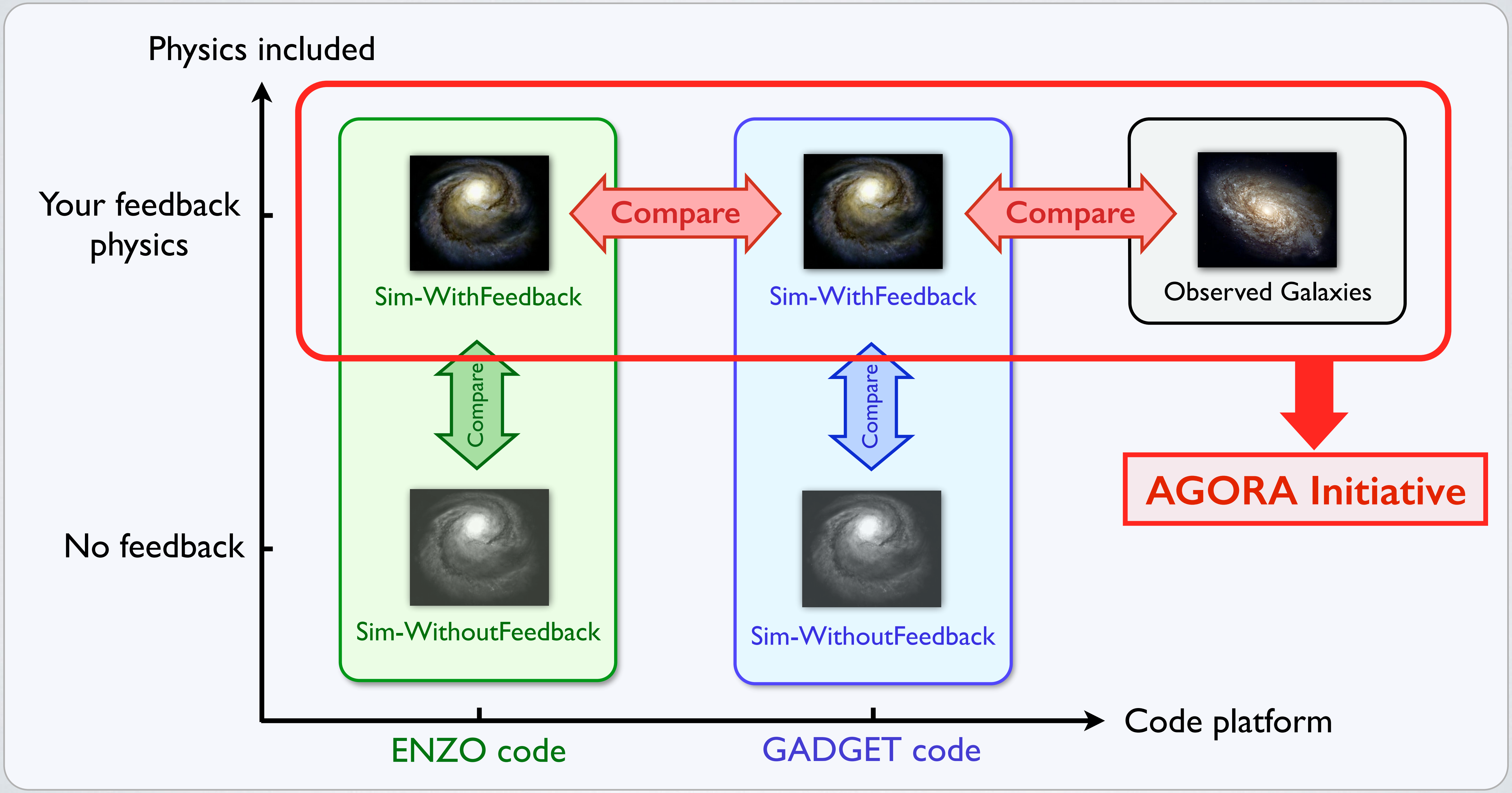
Binary galaxy merger, star clusters & adaptive mesh structure rendered, Kim et al. (2009, 2016b)

How About Galactic Astronomy?

- The task of reproducing numerical experiments, or comparing simulations across platforms, has not received the highest priority.

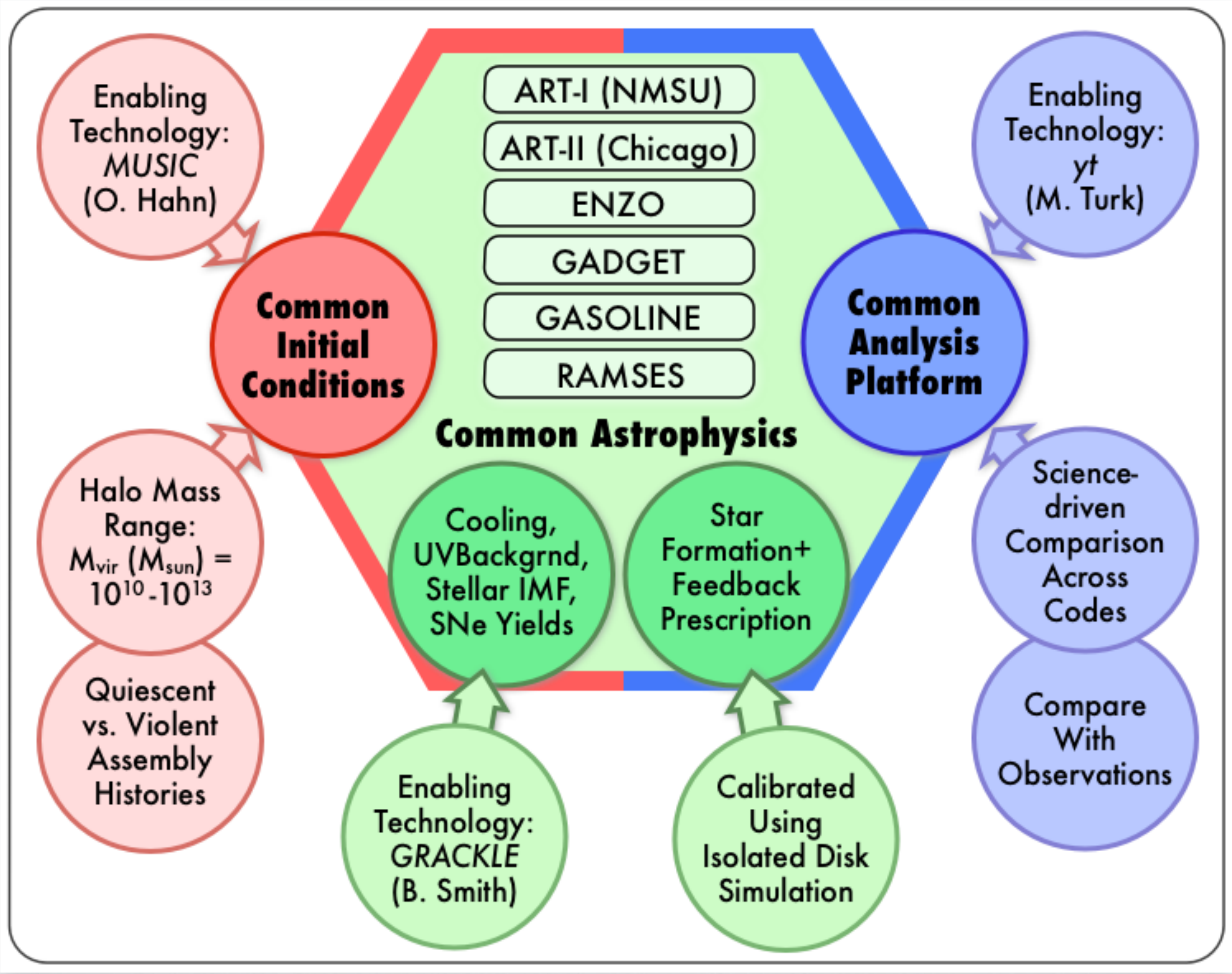
Reproducible Simulation Raises Realism

- To increase the predictive power of numerical simulations, and the field itself, let us compare simulations across code platforms.



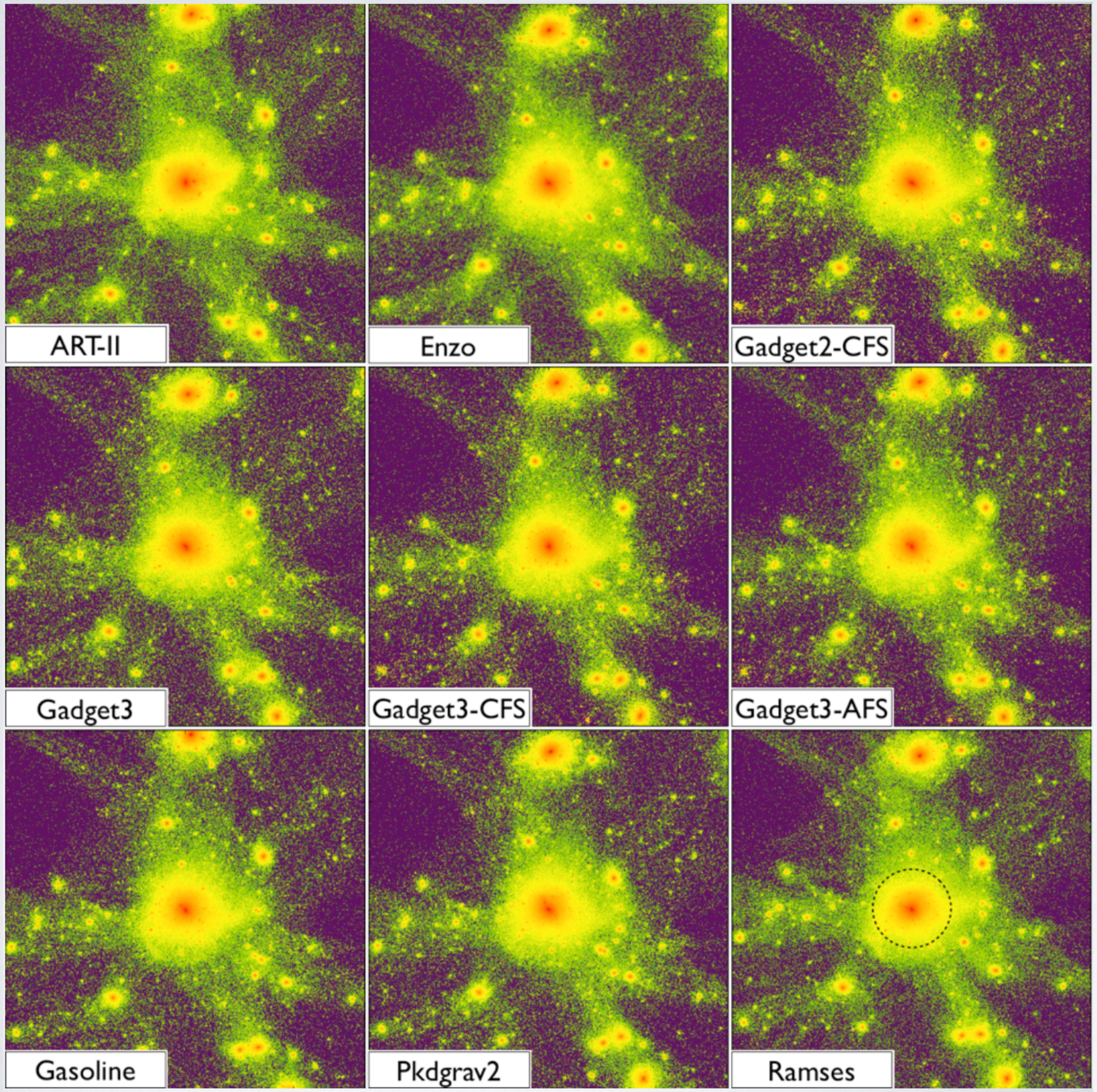
AGORA Comparison Infrastructure

- Includes key components necessary to run galaxy-scale simulations in a reproducible manner: code-independent and available to public



AGORA Dark Matter-Only Comparison

- Flagship paper with a proof-of-concept test (Kim et al. 2014)

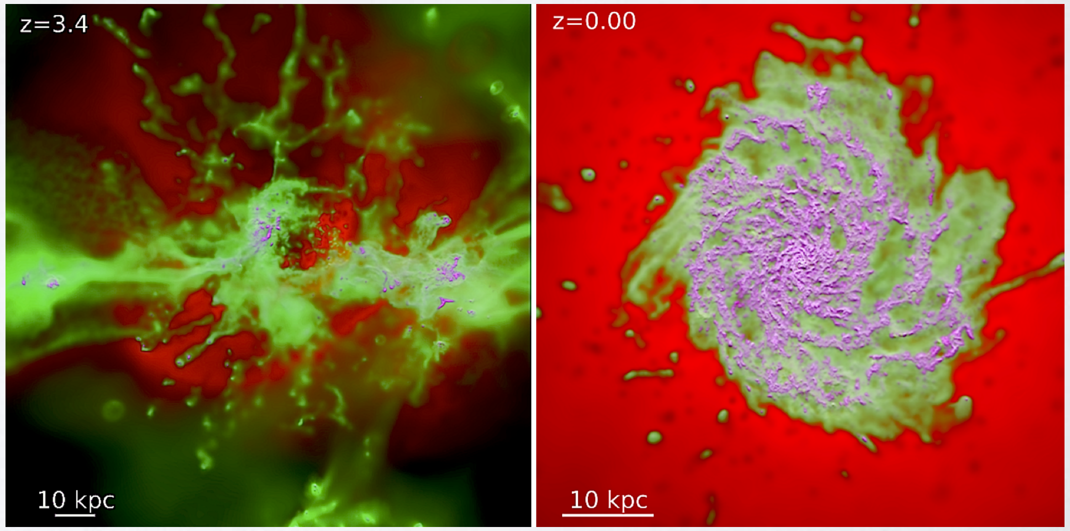


~10^{11} $M_\odot$ halo at z=0, projected DM density, Kim et al. (2014)

- Fully established comparison pipeline

- Runtime parameters identified that make codes compatible with one another

- Publicly available ICs are being used to build a library of AGORA simulations making future comparisons trivial



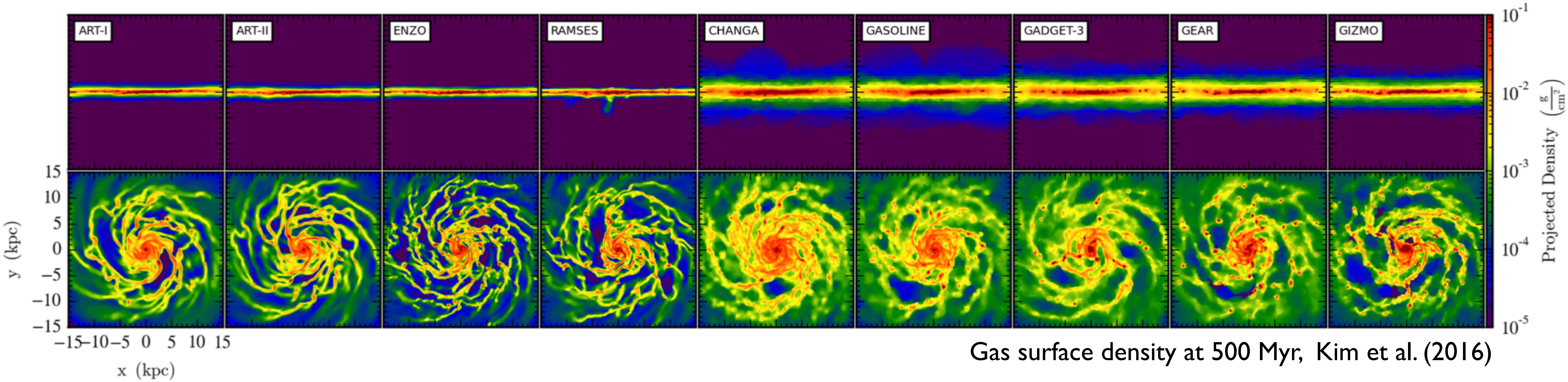
~10^{12} $M_\odot$ halo at z=0, AGORA IC used in *FIRE* Collaboration

Gravito-Hydrodynamics Comparison

- Second paper with an isolated MW-mass disk test (Kim et al. 2016)

  - Subgrid physics models such as Jeans pressure floor, star formation, supernova feedback energy, and metal production carefully constrained across code platforms

  - High spatial resolution to minimize dependence on a phenomenological model



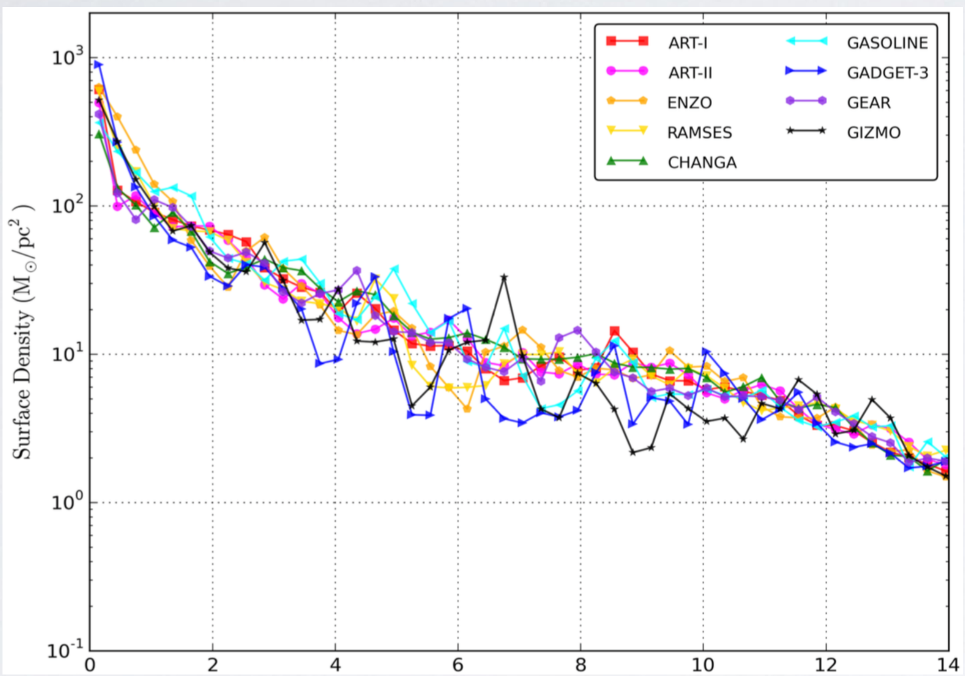
Gas surface density at 500 Myr, Kim et al. (2016)

Figure 2. The 500 Myr composite of gas surface densities from *Sim-noSF* with radiative gas cooling but without star formation or supernova feedback. Each frame is centered on the galactic center – location of maximum gas density within 1 kpc from the center of gas mass. For visualizations of the particle-based codes hereafter (Figures 1-3, 14-15, 32, 34, 35) – but not in any other analyses except these figures – yt uses an in-memory octree on which gas particles are deposited using smoothing kernels. See Section 5 for descriptions of participating codes in this comparison, and Section 6.1 for a detailed explanation of this figure. Compare with Figure 14. Simulations performed by: Daniel Ceverino (ART-I), Robert Feldmann (ART-II), Mike Butler (ENZO), Romain Teyssier (RAMSES), Spencer Wallace (CHANGA), Ben Keller (GASOLINE), Jun-Hwan Choi (GADGET-3), Yves Revaz (GEAR), and Alessandro Lupi (GIZMO). The full color version of this figure is available in the electronic edition. The high-resolution versions of this figure and article are available at the Project website, http://www.AGORAsimulations.org/.

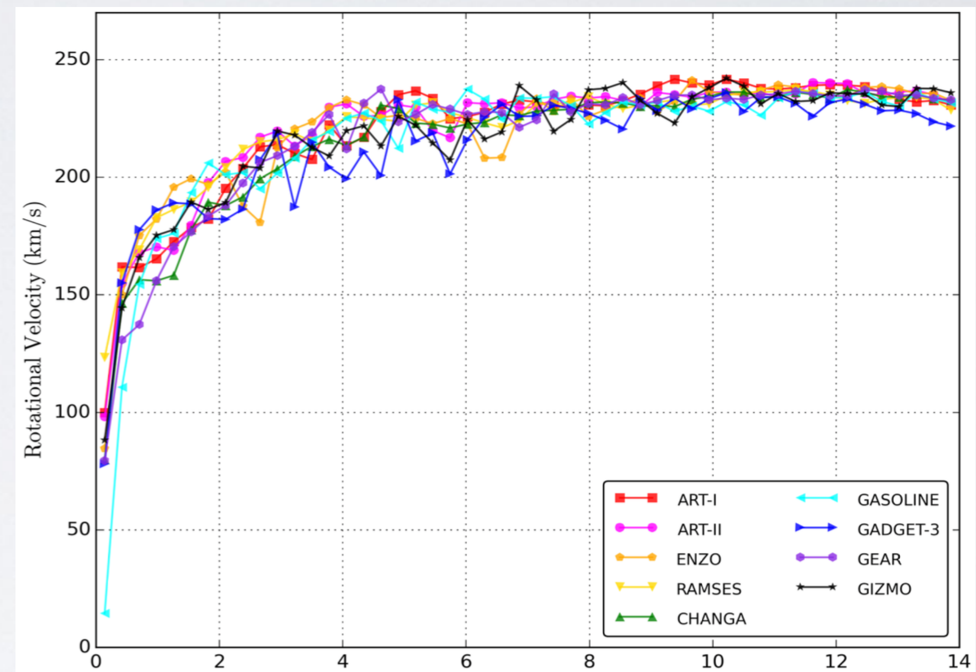
Convergence Among All 9 Codes

- Modern galaxy simulation codes agree very well with one another in many dimensions (agreement as good as within <10% at all radii).

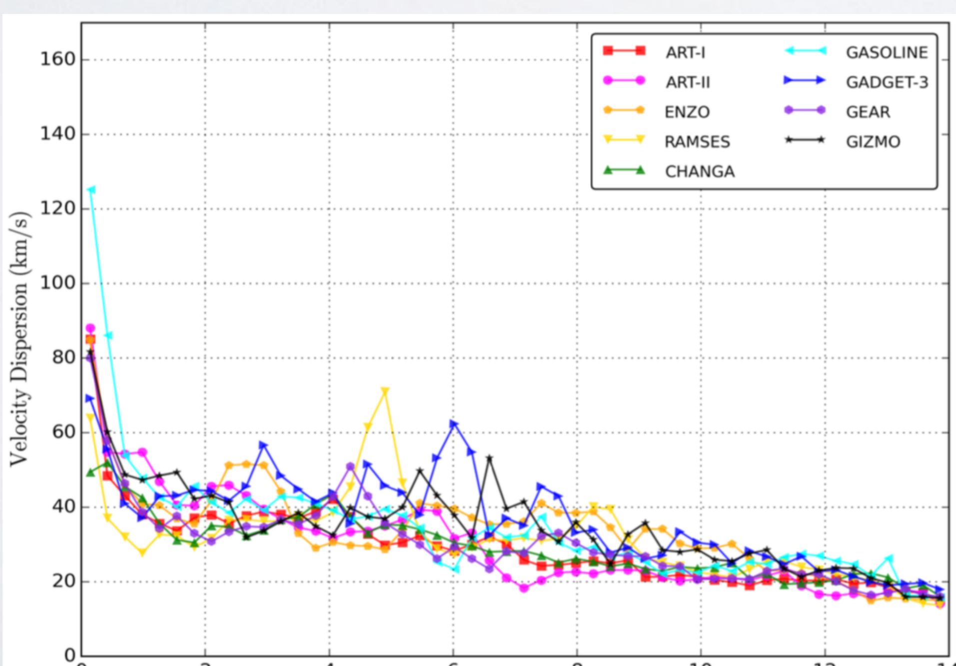
Surface density profile



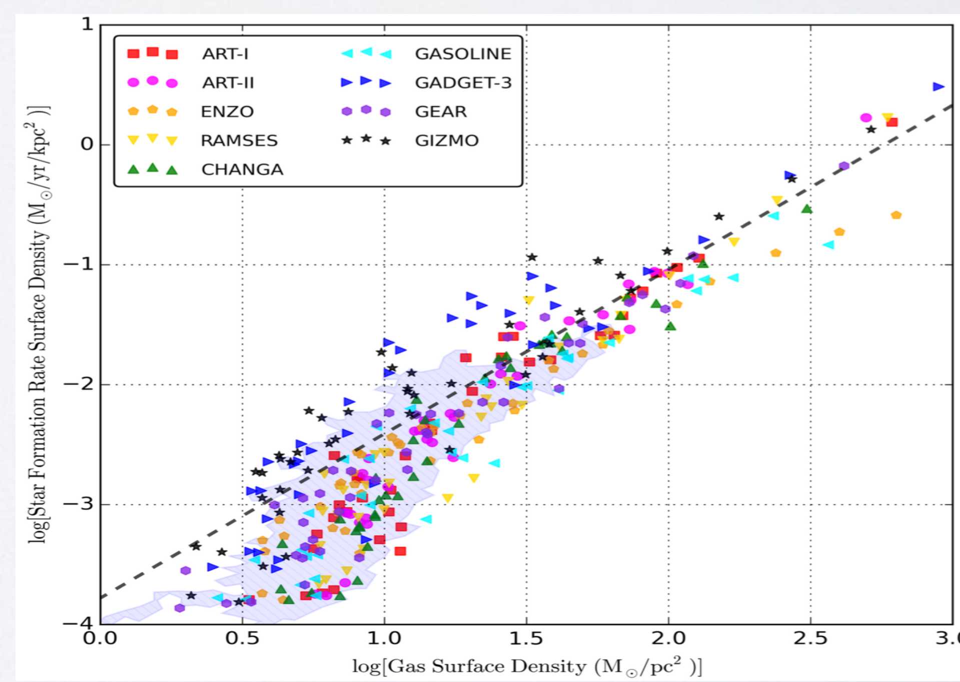
Rotation velocity profile



Velocity dispersion profile



Kennicutt-Schmidt relation

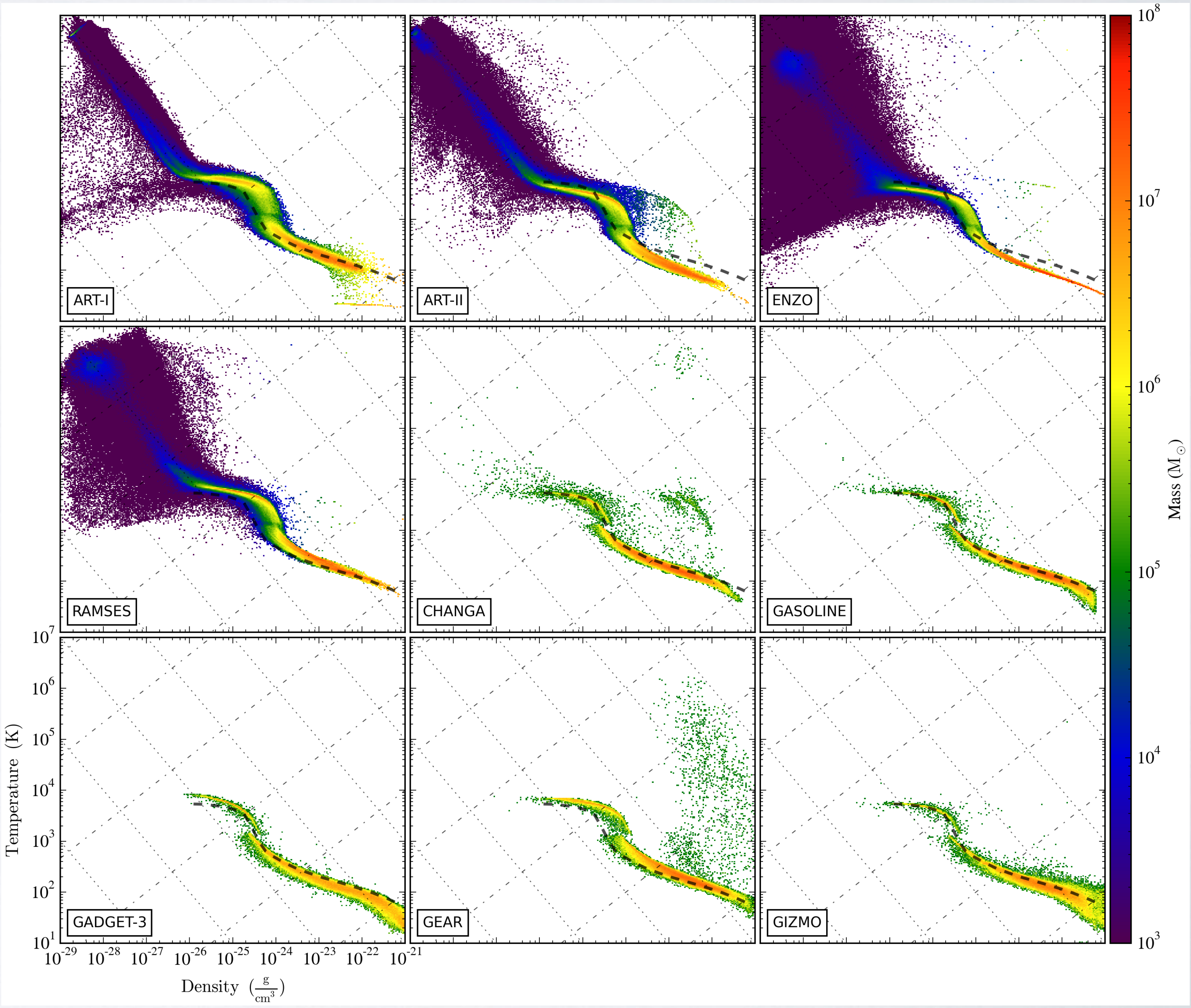


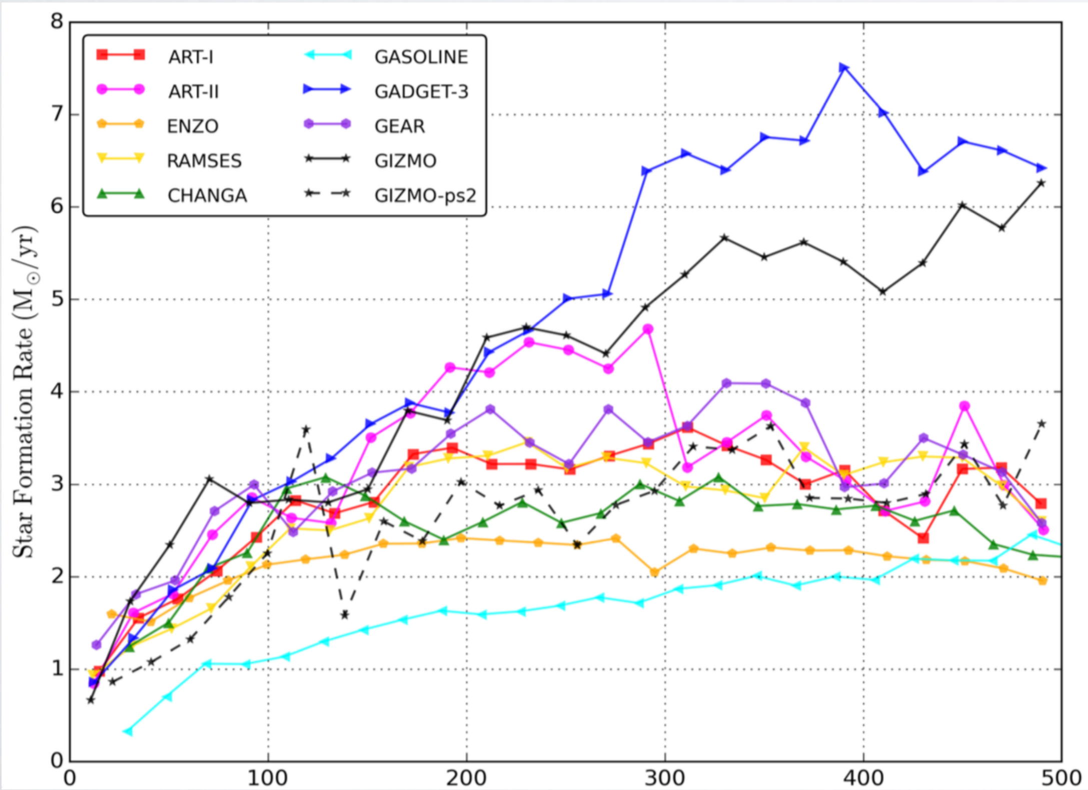
Convergence Among All 9 Codes

- Intrinsic code differences are small and generally dwarfed by variations in the implementation of the common subgrid physics.

→ Predictions made from a modern high-resolution galaxy formation simulation are likely robust and reproducible.

Density-temperature probability distribution function (PDF)



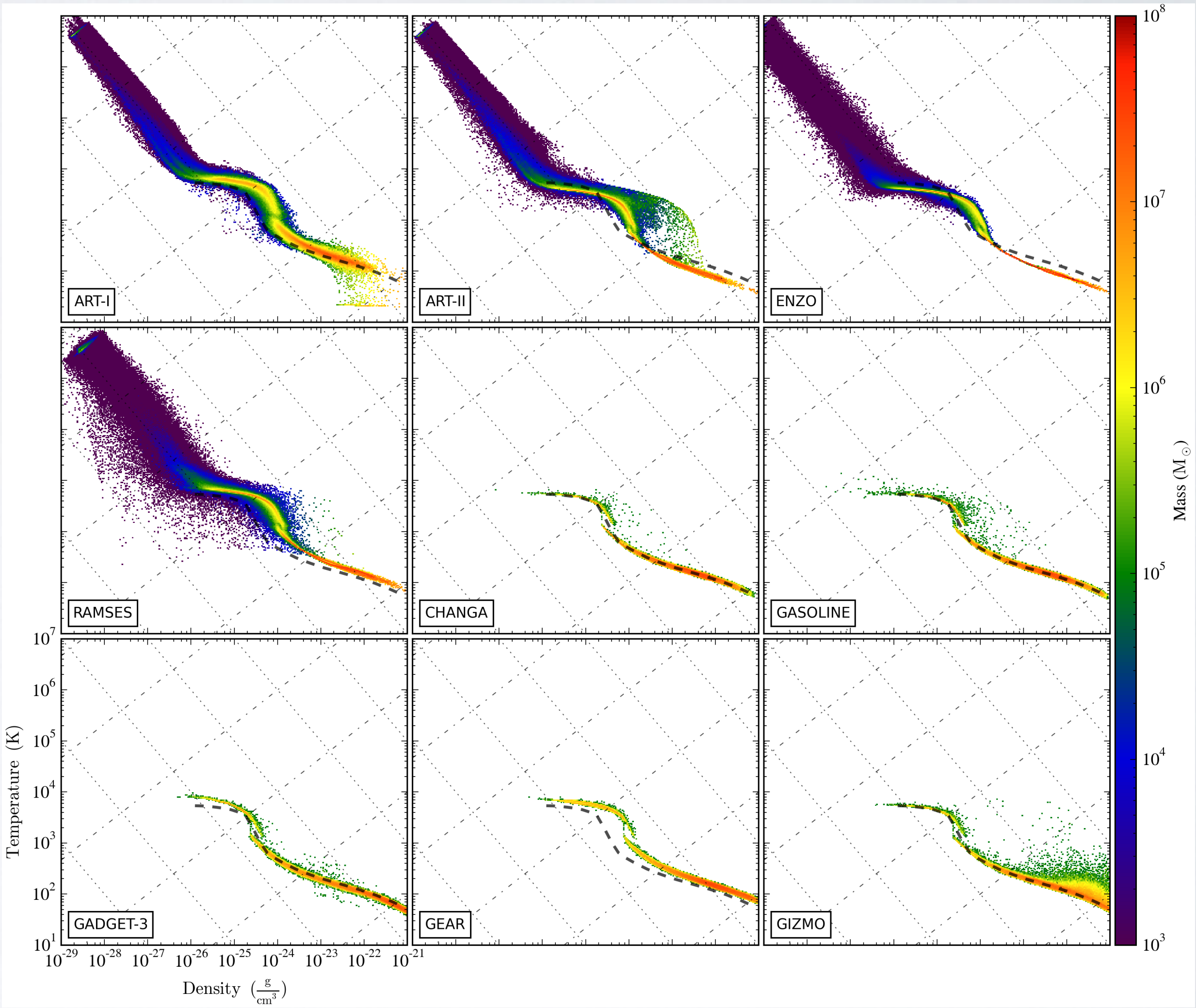


Galaxy-wide star formation rate

Great, but how did we get here?

- Inter-code convergence achieved only after a Herculean effort by passionate participants, aided by many workshops and telecons.

October 2016

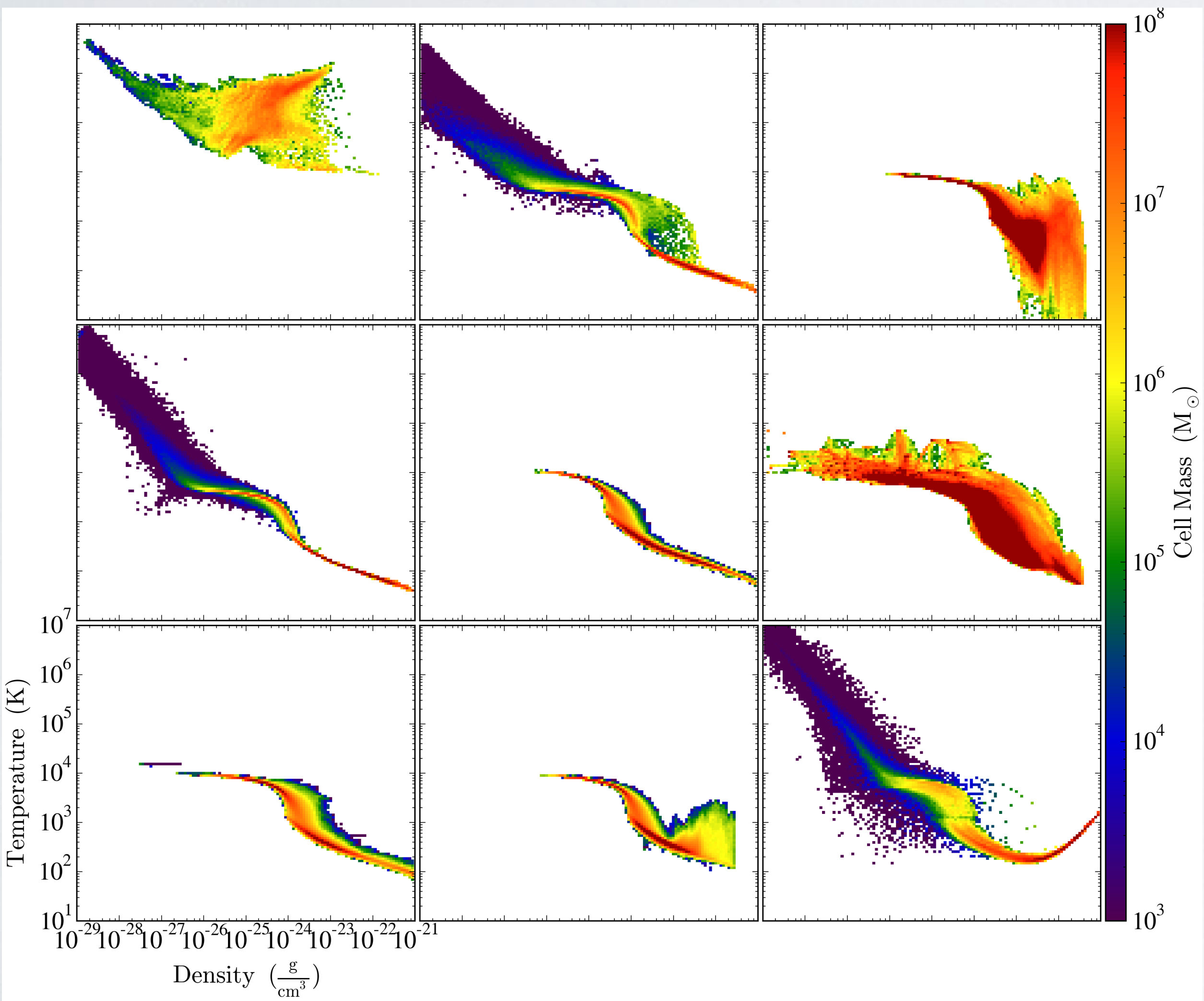


Density-temperature PDF (run with no star formation)

Great, but how did we get here?

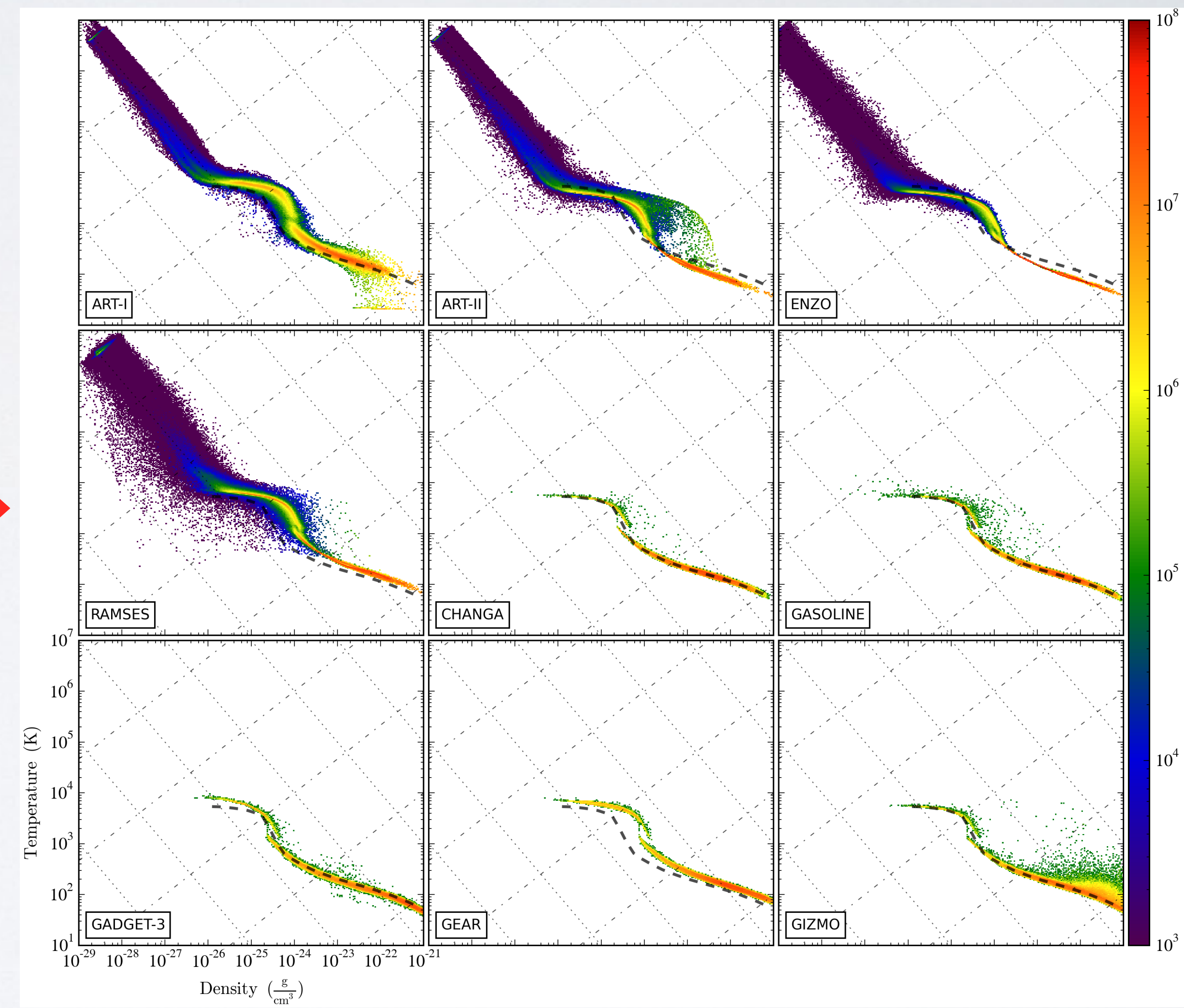
- Inter-code convergence achieved only after a Herculean effort by passionate participants, aided by many workshops and telecons.

July 2015



Density-temperature PDF (code order scrambled)

October 2016



Density-temperature PDF (run with no star formation)

Great, but how did we get here?

- Inter-code convergence achieved only after a Herculean effort by passionate participants, aided by many workshops and telecons.

7. DISCUSSION AND CONCLUSION

Through workshops and teleconferences, and via common languages and infrastructure built together, Project participants were able to better understand other codes, and improve their own. Participants found an optimal set of simulation parameters that makes their code to be best compatible with others. We came to understand how seemingly identical parameters differ in their meanings in different codes, and how seemingly different parameters have in fact identical meanings. In some comparisons, numerical errors were discovered and fixed in participating codes. The *AGORA* framework, now tested with the common physics and subgrid models, are serving as a launchpad to initiate *astrophysically-motivated* comparisons aimed at raising the predictive power of galaxy simulations, especially as we run the zoom-in cosmological simulations outlined in our flagship paper (Kim et al. 2014). In the coming years, we expect *AGORA* to continue to provide a sustainable and fertile platform on which numerical experiments are readily validated and cross-calibrated, and ambitious multi-platform collaborations are forged.

(1) Human errors fixed

→ (2) Runtime parameters found that make the codes compatible with one another

→ (3) Errors in (some) codes fixed

from Kim et al. (2016)

A Human Experiment In Itself

- We have founded an one-of-a-kind, open forum where numerical astrophysicists can talk to and learn from one another.

THE *AGORA* HIGH-RESOLUTION GALAXY SIMULATIONS COMPARISON PROJECT. II: ISOLATED DISK TEST

JI-HOON KIM[1,2,3,4], OSCAR AGERTZ[5,6], ROMAIN TEYSSIER[7], MICHAEL J. BUTLER[8,†,‡], DANIEL CEVERINO[9,†,‡], JUN-HWAN CHOI[10,†,‡], ROBERT FELDMANN[7,11,†], BEN W. KELLER[12,†,‡], ALESSANDRO LUPI[13,†,‡], THOMAS QUINN[14,†,‡], YVES REVAZ[15,†,‡], SPENCER WALLACE[14,†], NICKOLAY Y. GNEDIN[16,17,18,‡], SAMUEL N. LEITNER[19,‡], SIJING SHEN[20,‡], BRITTON D. SMITH[21,‡], ROBERT THOMPSON[22,‡], MATTHEW J. TURK[23,‡], TOM ABEL[1,2], KENZA S. ARRAKI[24], SAMANTHA M. BENINCASA[12], SUKANYA CHAKRABARTI[25], COLIN DEGRAF[20], AVISHAI DEKEL[26], NATHAN J. GOLDBAUM[22], PHILIP F. HOPKINS[3], CAMERON B. HUMMELS[3], ANATOLY KLYPIN[24], HUI LI[27], PIERO MADAU[28,13], NIR MANDELKER[29,26], LUCIO MAYER[7], KENTARO NAGAMINE[30,31], SARAH NICKERSON[7], BRIAN W. O'SHEA[32], JOEL R. PRIMACK[33], SANTI ROCA-FÀBREGA[26], VADIM SEMENOV[17], IKKOH SHIMIZU[30], CHRISTINE M. SIMPSON[34], KEITA TODOROKI[35], JAMES W. WADSLEY[12], AND JOHN H. WISE[36] FOR THE *AGORA* COLLABORATION[37]

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[25]School of Physics and Astronomy, Rochester Institute of Technology, Rochester, NY 14623, USA

Kim et al. (2016)

A Human Experiment In Itself

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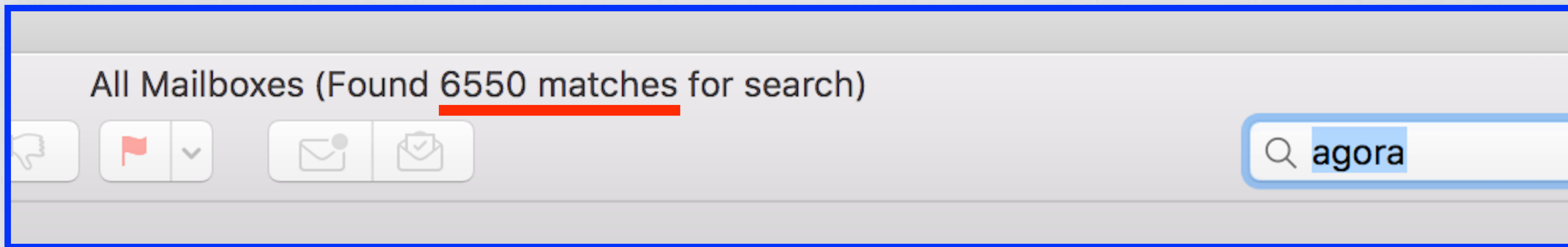
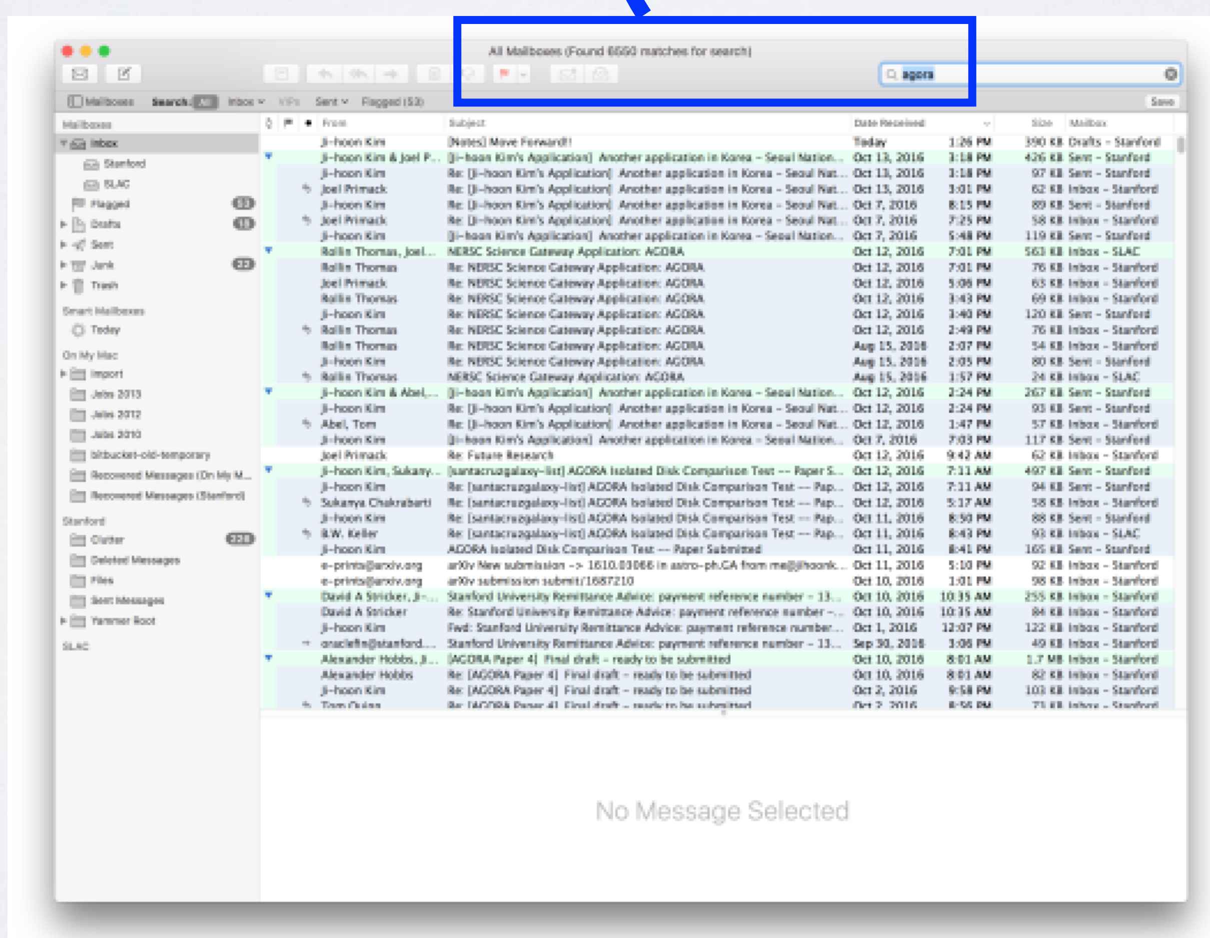




My mailbox,
October 2016

Conclusion

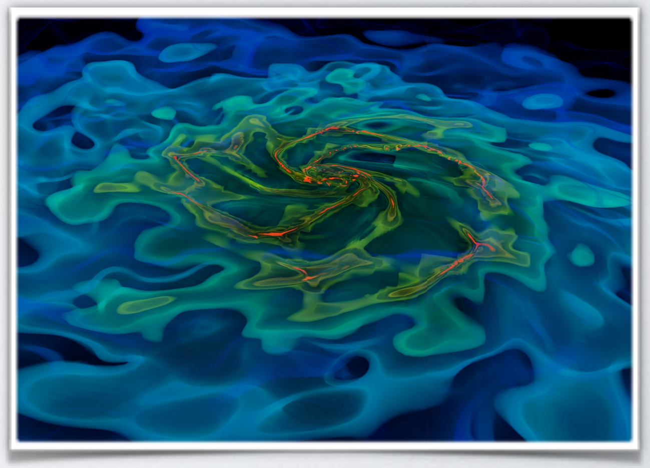
- We strive to promote collaborative and reproducible research in the numerical galaxy formation community.

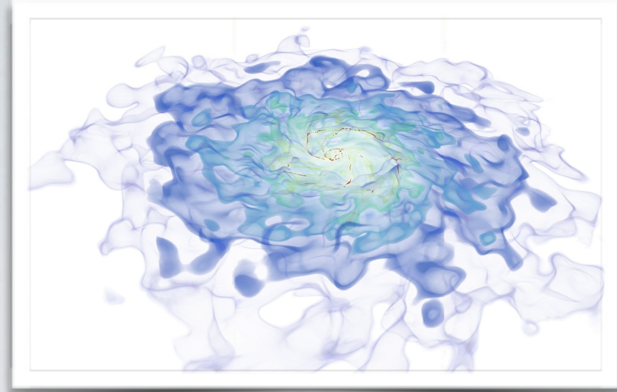
- Goals and challenges

AGORA aims to increase the predictive power of numerical simulations through a multi-platform approach.

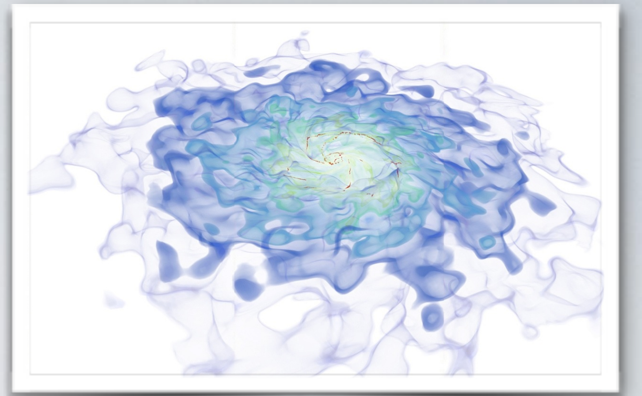
- New possibilities

AGORA offers a unique opportunity to validate answers to long-standing problems in galaxy formation.





Thank you!



Supplemental Slides

AGORA

A High-resolution Galaxy Simulations Comparison Initiative: www.AGORAsimulations.org

AGORA Project: Goal and Team

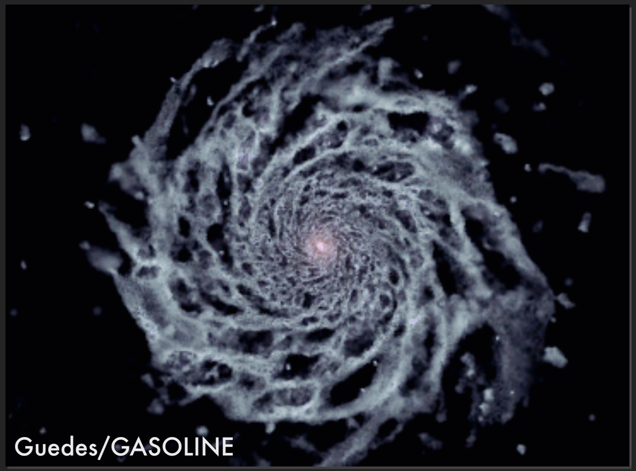
- GOAL: A collaborative, multi-code platform to raise the realism and predictive power of high-res galaxy simulations

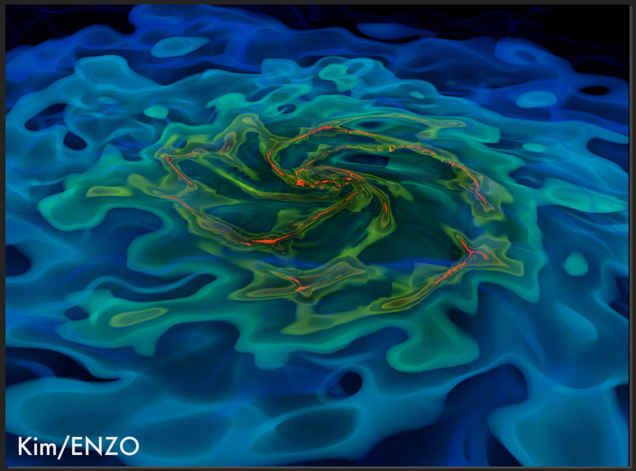
- TEAM
  - 140+ participants from 60+ institutions, 10/2016
  - 10+ groups each with variations of 9+ codes
  - 5 conferences & 11 web conferences organized
  - Project Coordinator: Ji-hoon Kim (Stanford/SLAC)

- DATA SHARING: Initial conditions, astrophysics modules, analysis software, and simulation outputs all to be public

- RESULTS
  - Flagship paper by Kim et al. (2014, ApJS)
  - Second paper by Kim et al. (2016, ApJ submitted)

High-res Galaxy Simulation





Variation of the official AGORA intro slide (credit: Kim & Governato) / Project funded in part by: