Introduction to the Einstein Toolkit

Roland Haas, Steven R. Brandt, Peter Diener, Frank Löffler, others

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University of Illinois Urbana-Champaign

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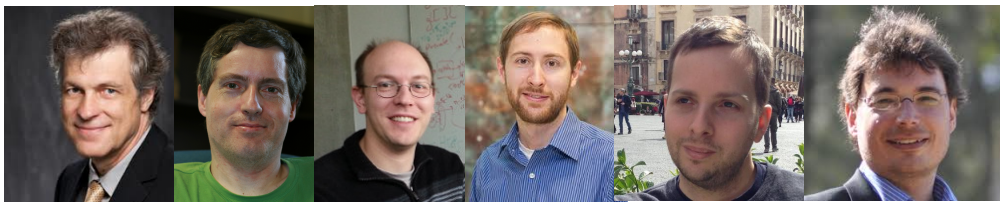
Einstein Toolkit

- Collection of scientific software components and tools to simulate and analyze general relativistic astrophysical systems
- Freely available as open source at http://www.einsteintoolkit.org
- Supported by NSF 2004157/2004044/2004311/2227105/2004879/2003893/2114582
- State-of-the-art set of tools for numerical relativity, open source
- Currently 421 members from 291 sites and 49 countries
- $>$ 481 publications, $>$ 58 theses building on these components (as of June 2024)
- Has been a SPEC benchmark twice, may be a third time.
- Received a Gorden-Bell prize (2001), and a Sydney-Fernbach Award (2006)
- Cactus appears in one science fiction story: "Black Torus Run"
- Regular, tested releases
- User support through various channels



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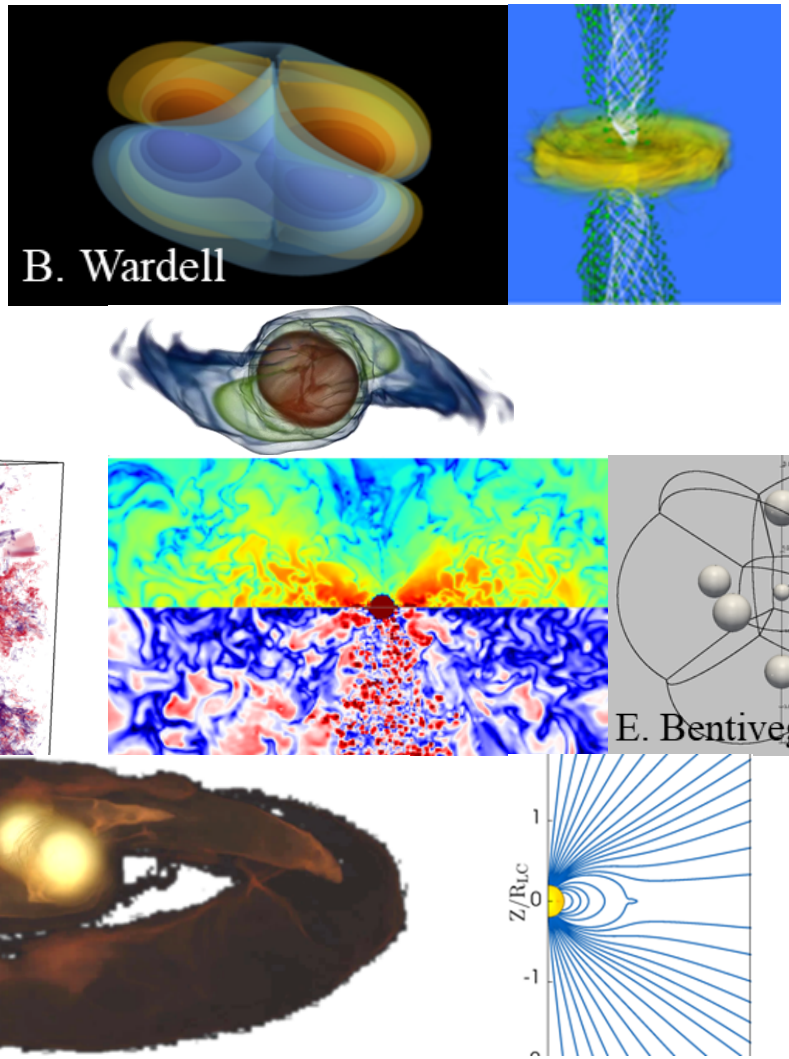
Einstein Toolkit

Science

- Binary Black Hole Mergers
- Neutron Star Mergers
- Supernovae
- Accretion Disks
- Boson Stars
- Hairy Black Holes
- Cosmic Censorship



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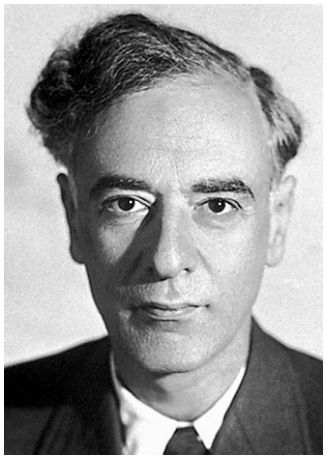
“Lev Landau” release

- named after *Lev Landau*
- 28th release, June 30, 2024
- release managers:
  - Steven R. Brandt
  - Roland Haas



- SLURM based multi-node tutorial server for live tutorials
- many new features:
  - NewRadX—builds on inclusion of CarpetX from the Meitner release
  - GRHayL-based IllinoisGRMHD—entropy evolution, tabulated EOS, and piecewise polytropes
  - Baikal(Vacuum)—NRPy 2.0
  - GRHayLHD(X)—now has a tabulated EOS
  - Kuibit—supports OpenPMD files generated by CarpetX

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Community Effort!

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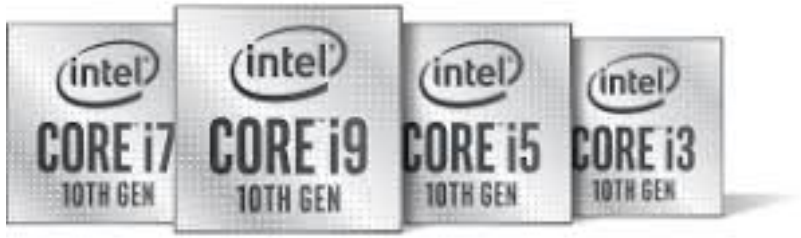
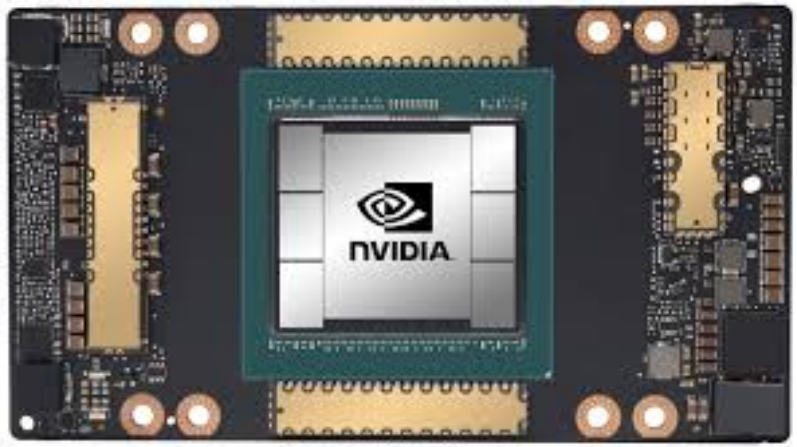
Why?

Computational Challenges

Computational Challenges

More and more diverse hardware





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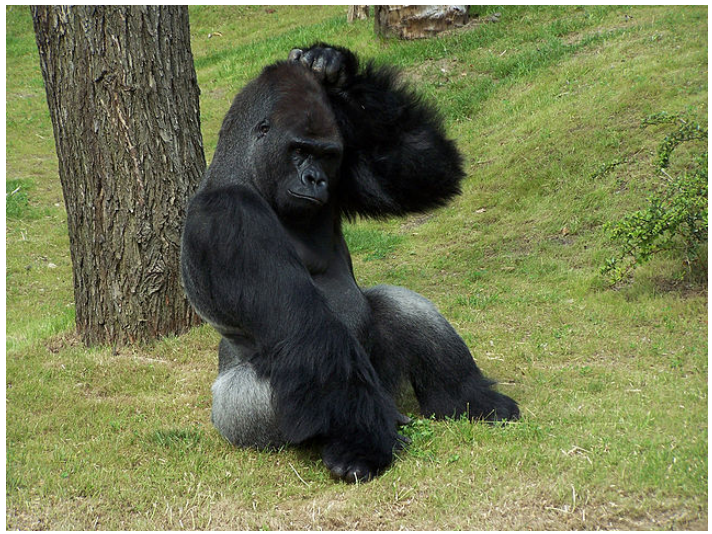
FRONTIER
OAK RIDGE National Laboratory
U.S. DEPARTMENT OF ENERGY
Hewlett Packard Enterprise
AMD

Computational Challenges

- Simulate cutting edge science
- Use latest numerical methods
- Make use of latest hardware
  - Cache



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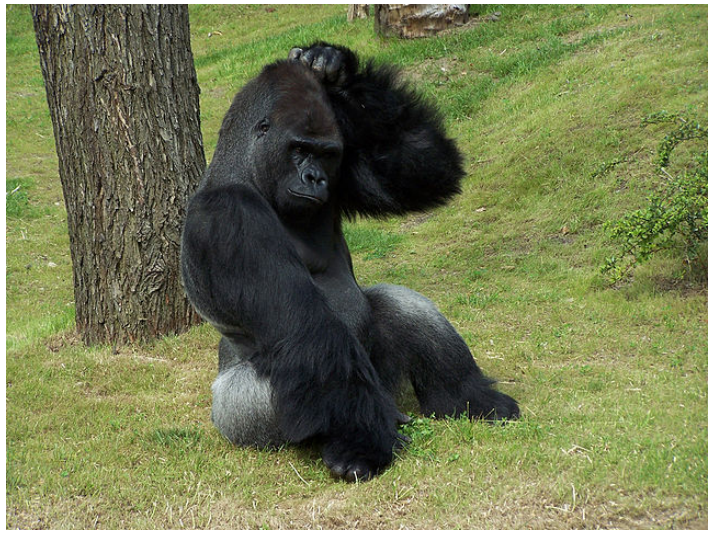
Computational Challenges

- Simulate cutting edge science
- Use latest numerical methods
- Make use of latest hardware
  - Cache
  - Vector



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Computational Challenges

- Simulate cutting edge science
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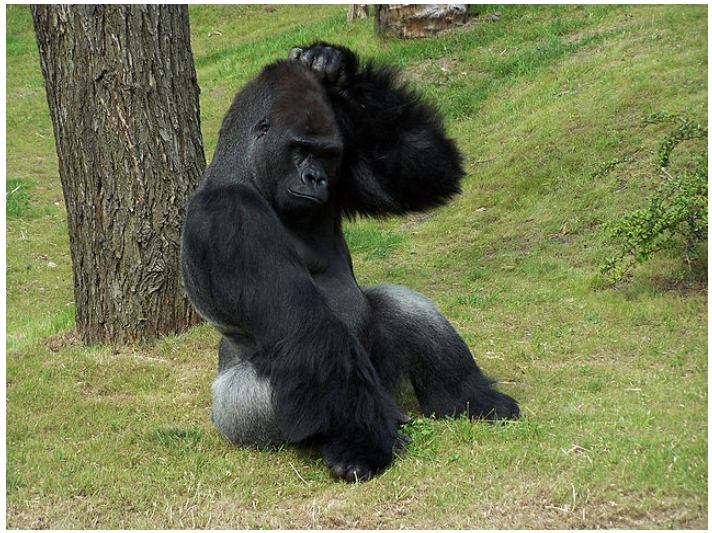
  - Accelerators



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Computational Challenges

- Simulate cutting edge science
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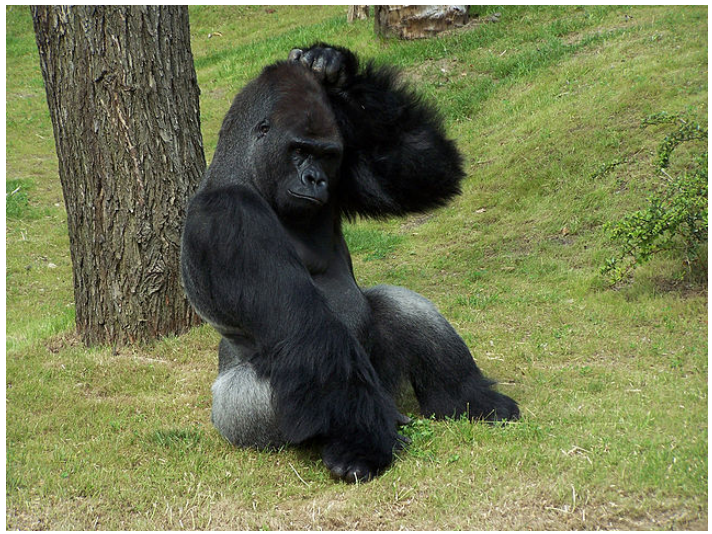
  - Cache
  - Vector
  - Accelerators
  - Scale to many cores



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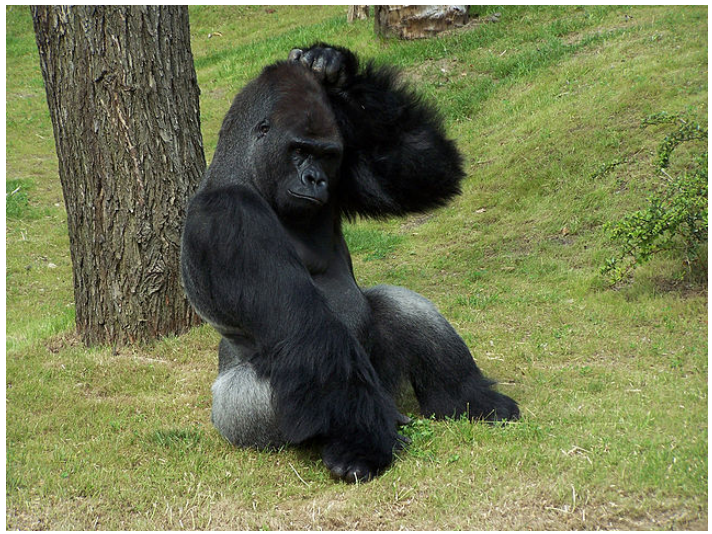

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Computational Challenges

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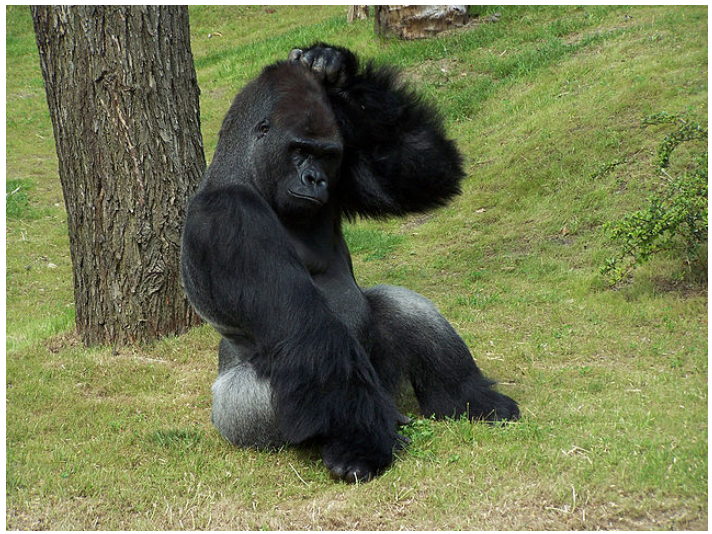
- Use latest numerical methods
- Make use of latest hardware
  - Cache
  - Vector
  - Accelerators
  - Scale to many cores
  - Scale to many nodes
  - Algorithms



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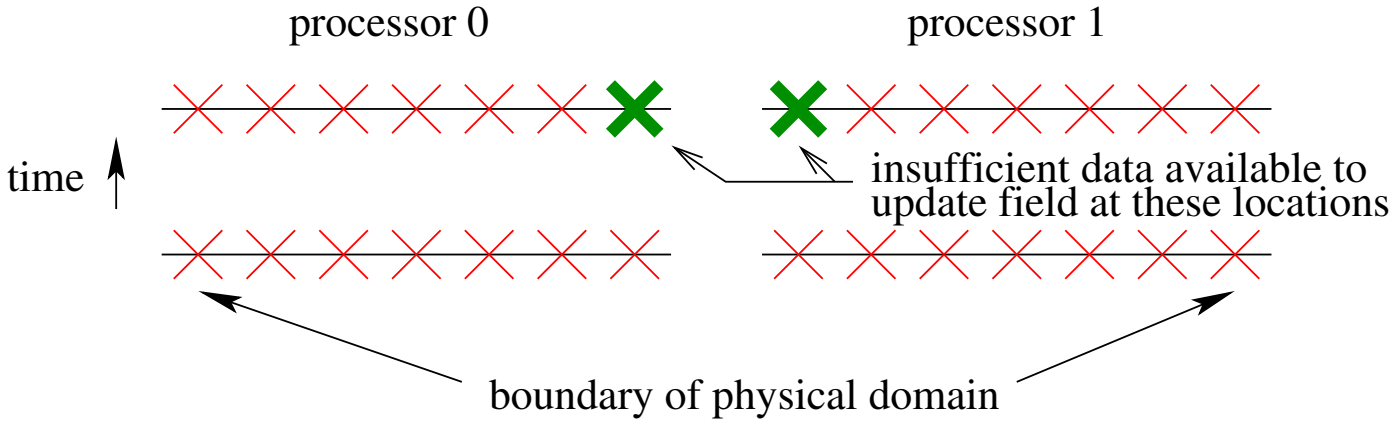
Computational Challenges

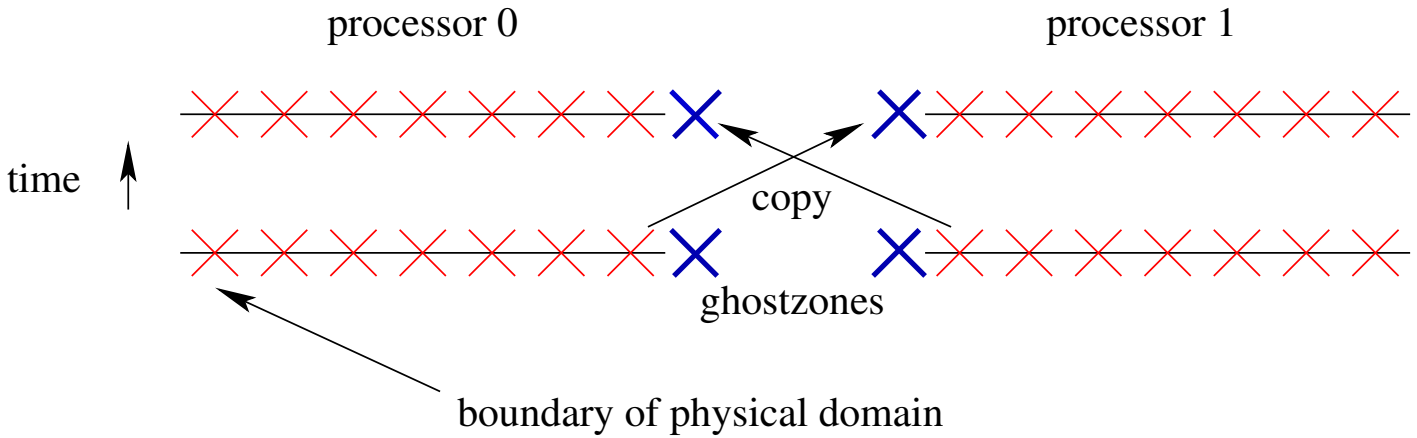
- Efficient use of all hardware is complex and tedious.
- Requires experts from different disciplines
- Requires good data layouts and APIs
- To ensure correctness, need good modularization on a number of levels and understanding of advanced programming concepts.
- Design and implementation needs to be carefully thought out in order to ensure extensibility and portability.

Domain Decomposition

Without Ghostzones:



With Ghostzones:



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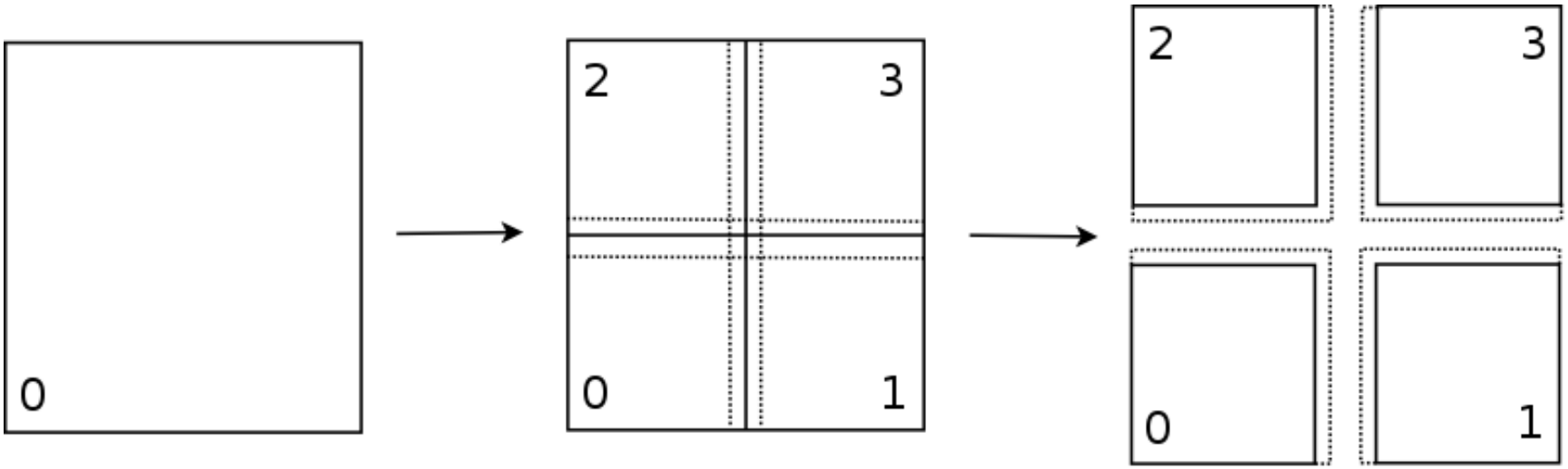
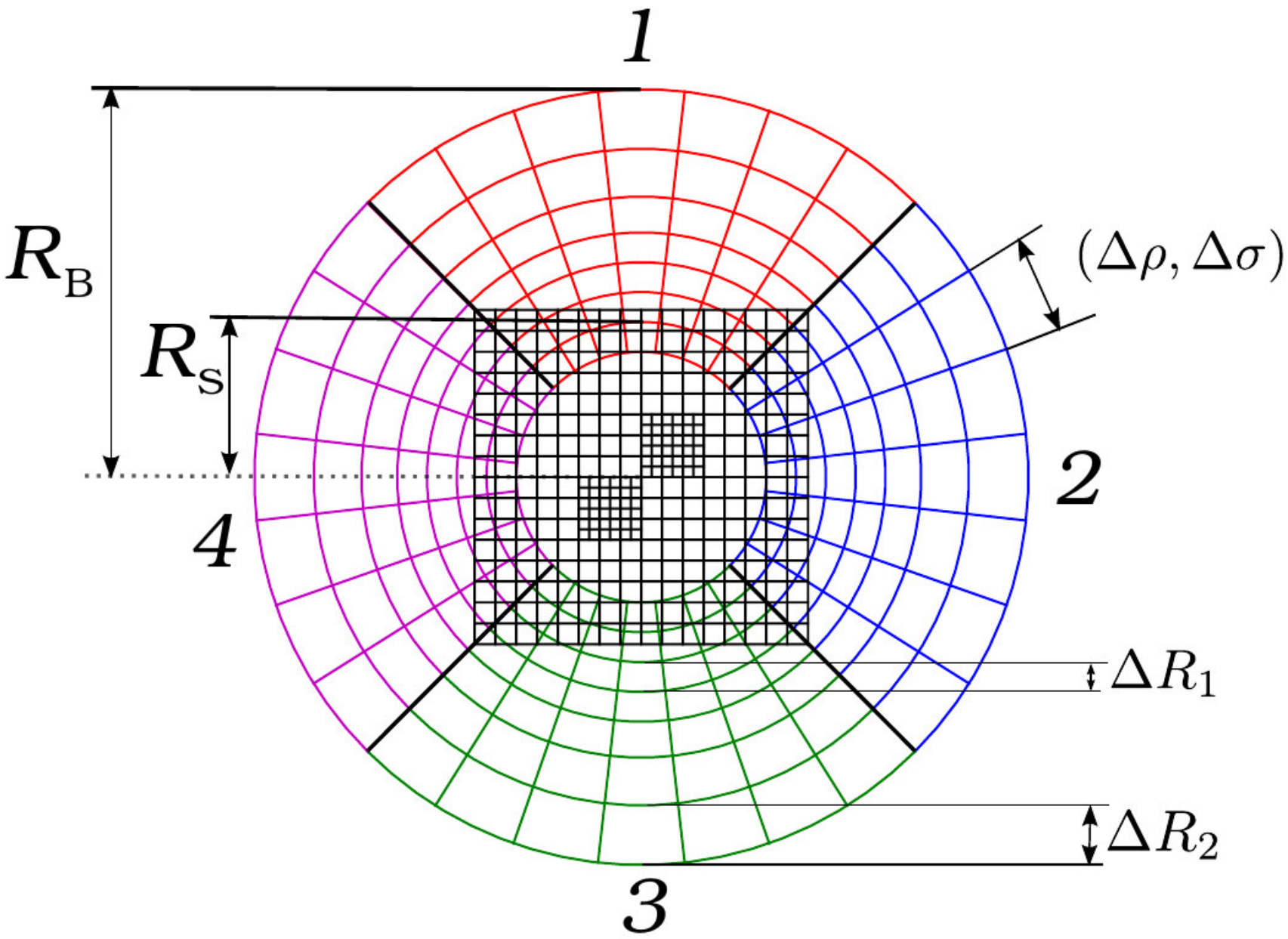
Domain decomposition



Multiblock and refinement



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Computational Challenges

- Simulate cutting edge science
- Use latest numerical methods
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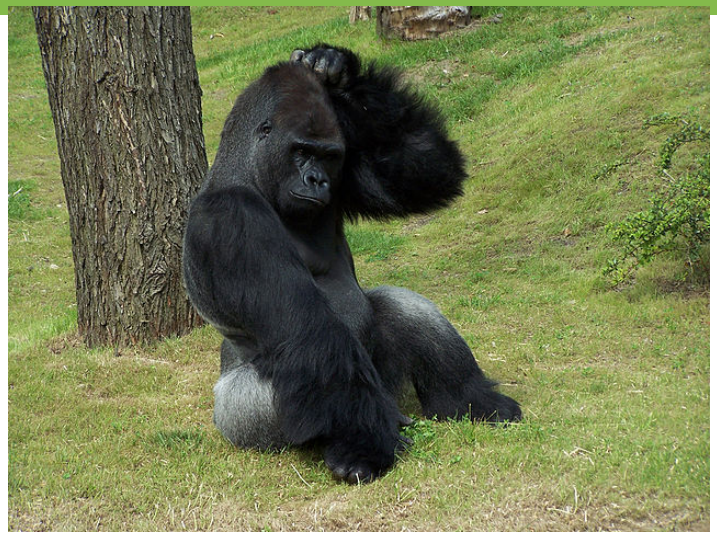
  - Vector (Kranc, NRPy)



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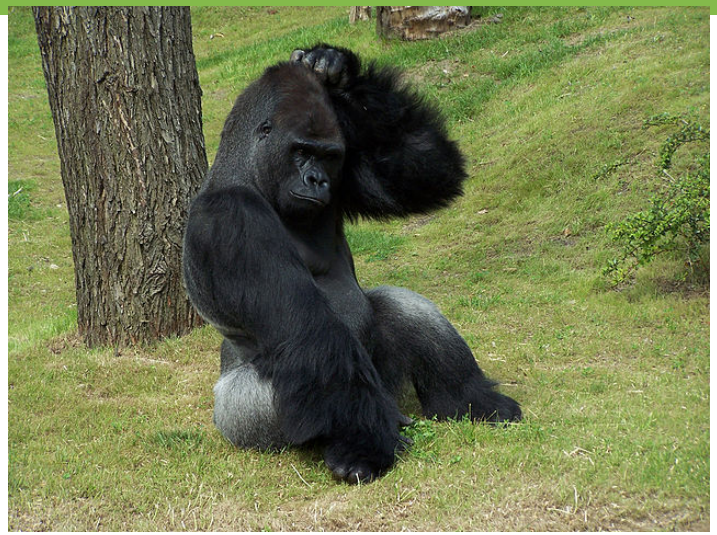

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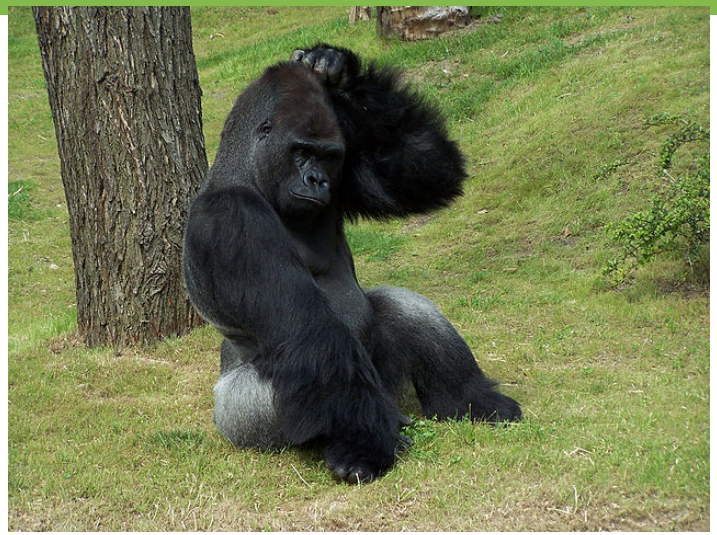

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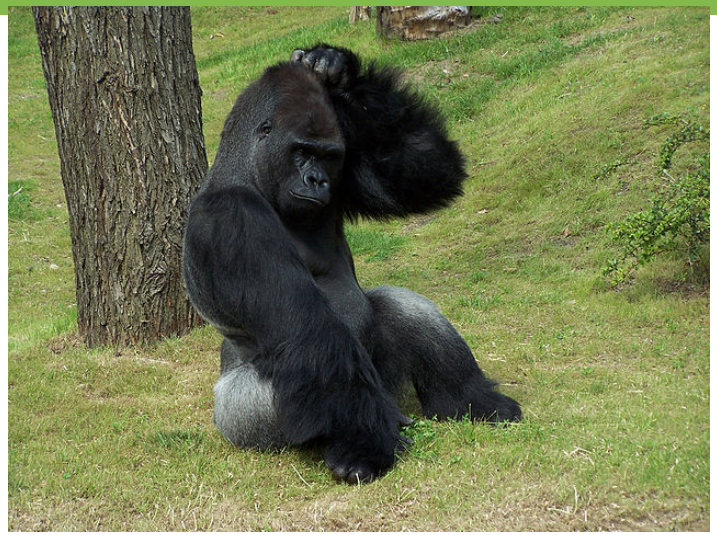

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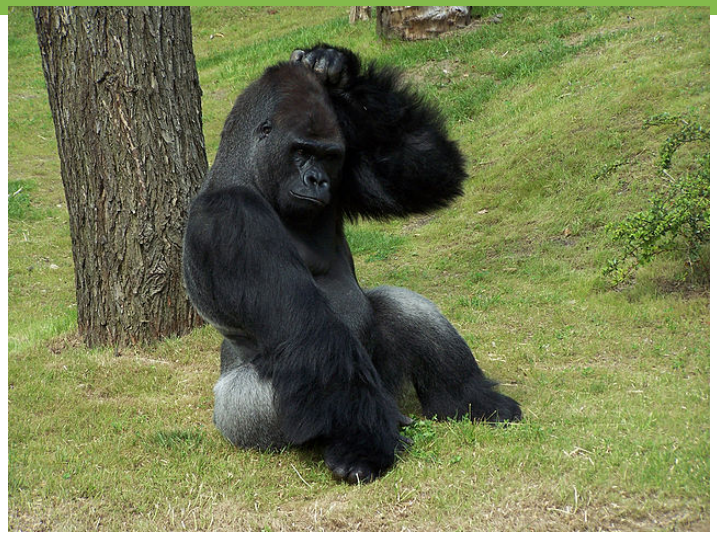

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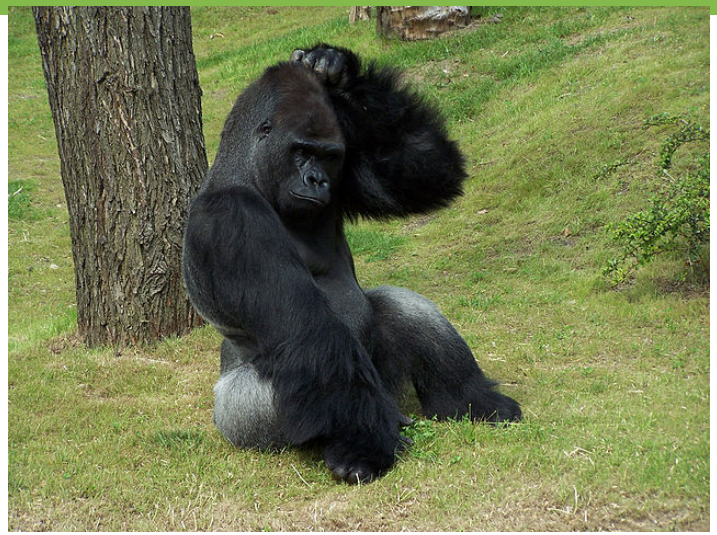

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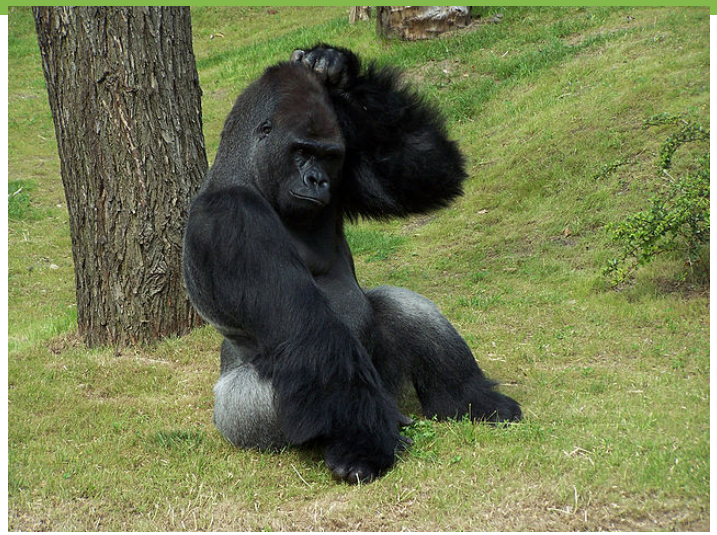

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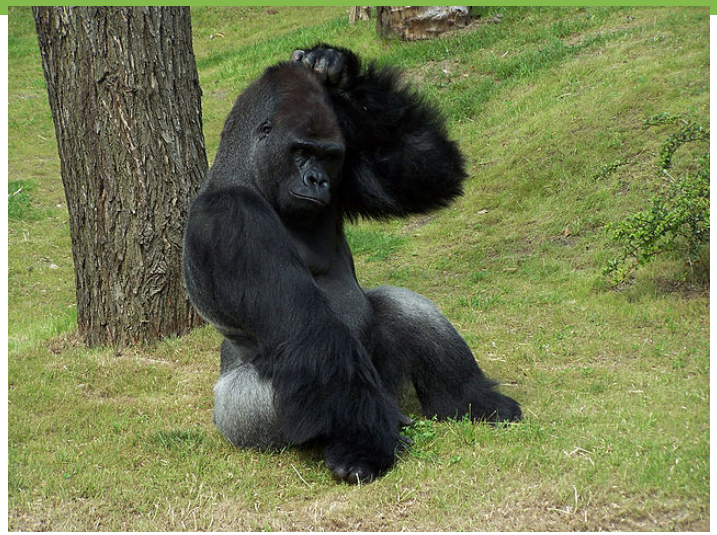

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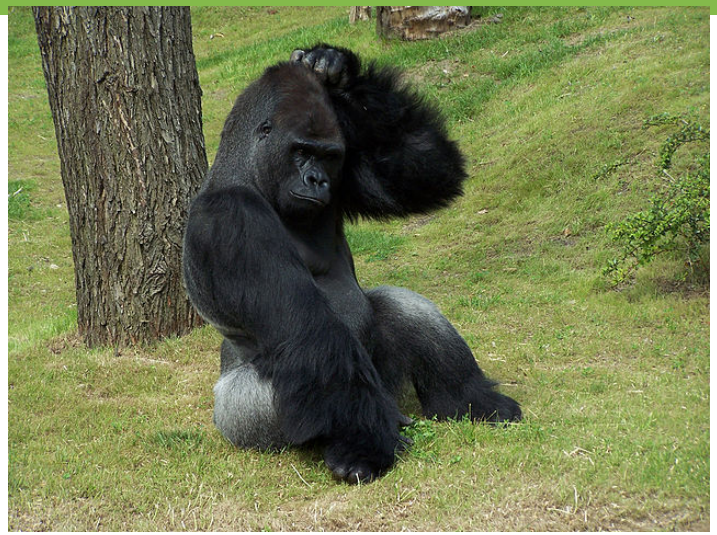

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  - Machine learning?
  - FPGA?
  - ASIC?
  - Neuromorphic processor?

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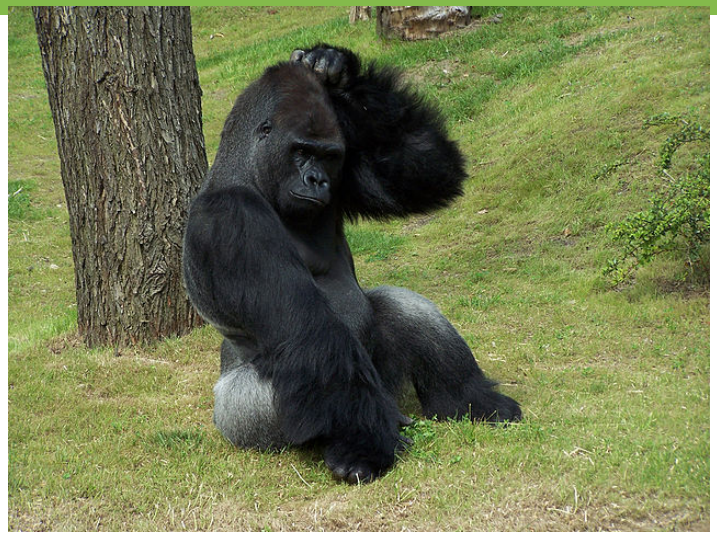
Computational Challenges



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  - Neuromorphic processor?
  - Q-bits?

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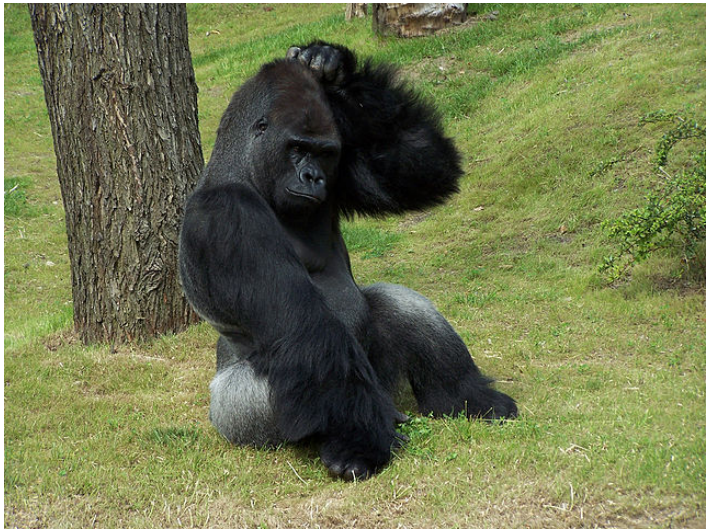
Computational Challenges

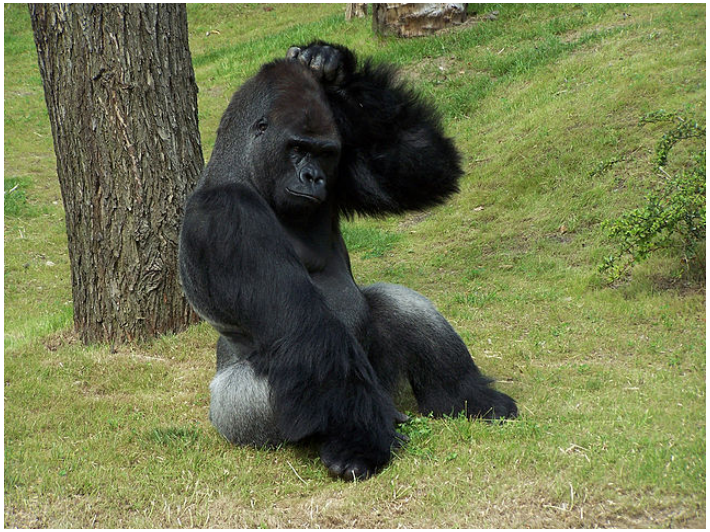
More Mundane Challenges



Computational Challenges

More Mundane Challenges

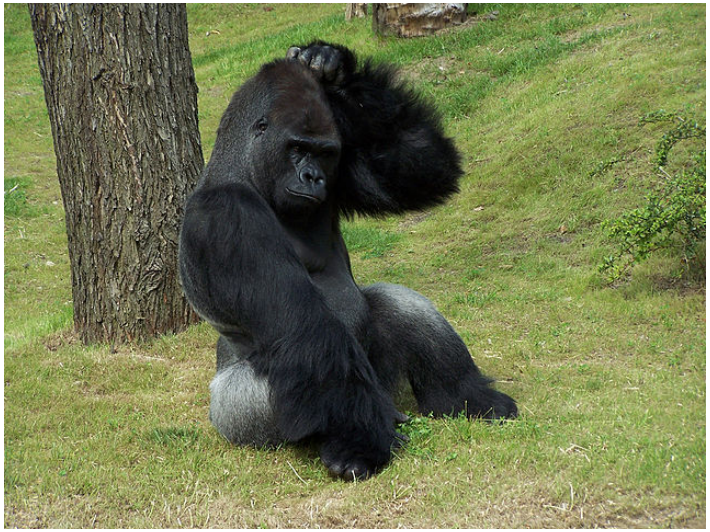
- Efficient I/O



Computational Challenges

More Mundane Challenges

- Efficient I/O
- HDF5



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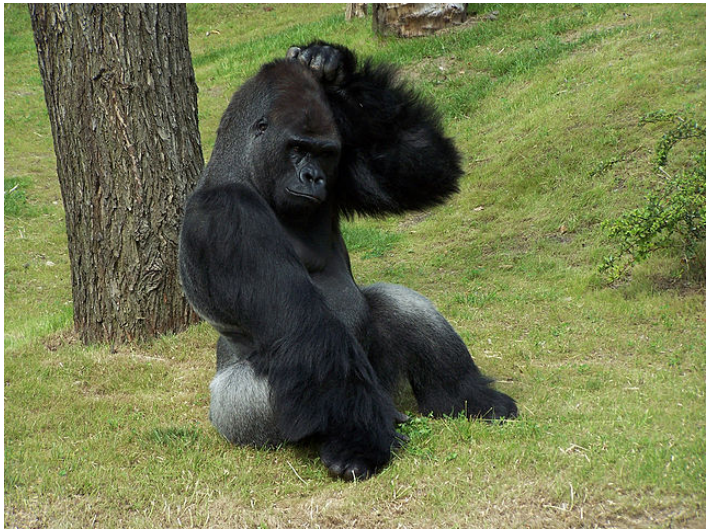
Computational Challenges

More Mundane Challenges

- Efficient I/O
- HDF5
- Checkpoint/Restart



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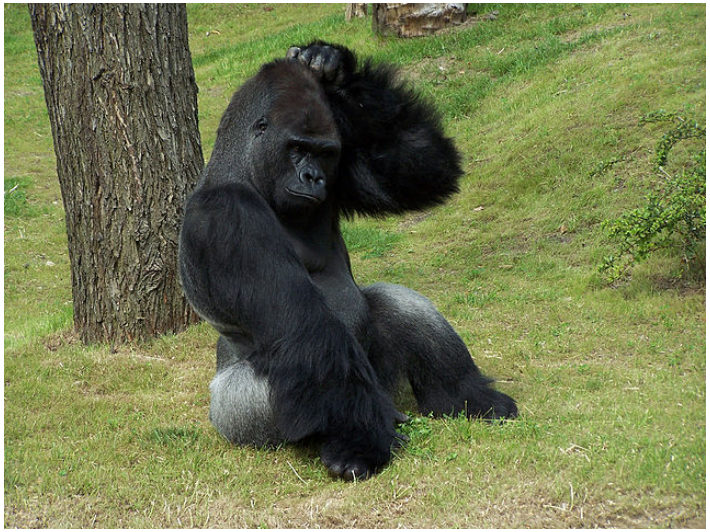
Computational Challenges

More Mundane Challenges

- Efficient I/O
- HDF5
- Checkpoint/Restart
- Parameter Parsing



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Computational Challenges

More Mundane Challenges

- Efficient I/O
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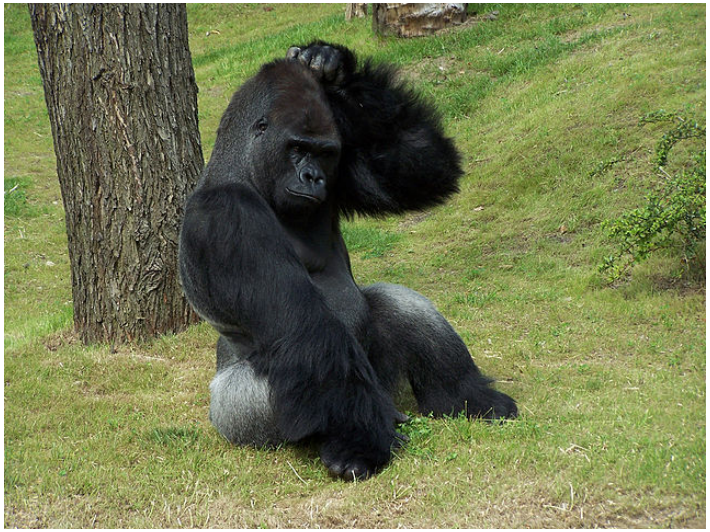
- Parameter Parsing
- Visualization



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Computational Challenges

More Mundane Challenges

- Efficient I/O
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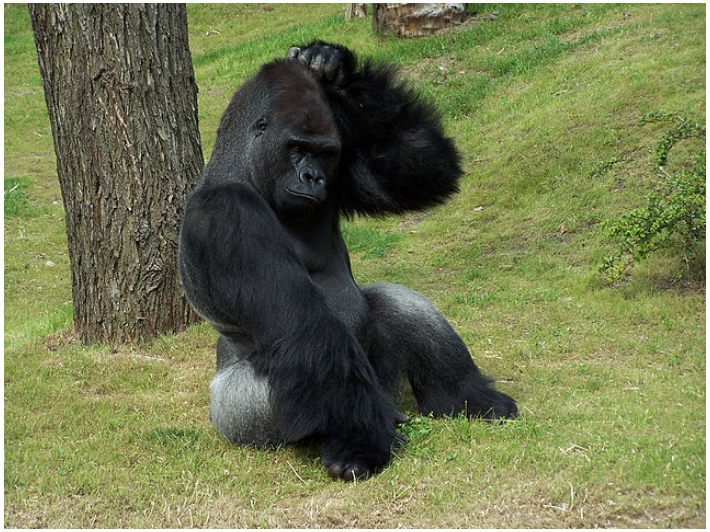
- Parameter Parsing
- Visualization
- Analysis



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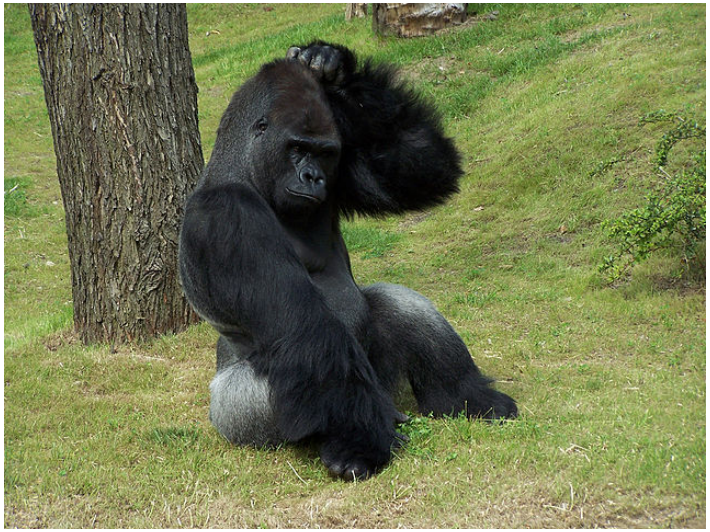

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Collaborative Challenges

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Collaborative Challenges

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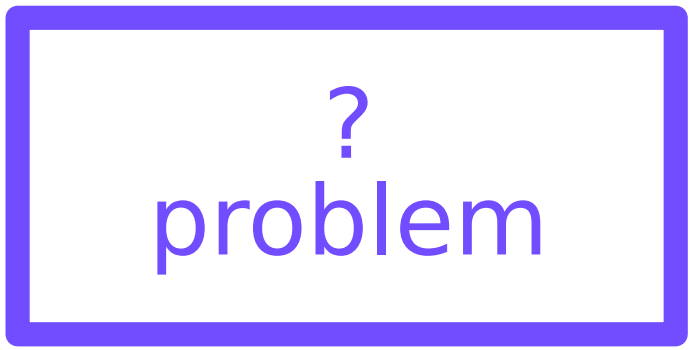
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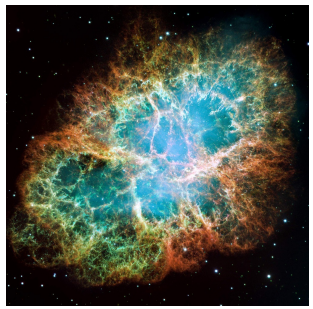

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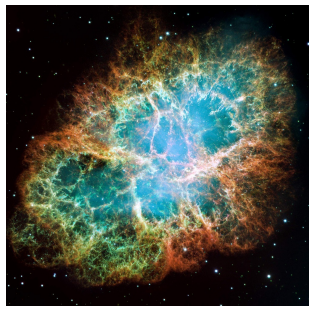

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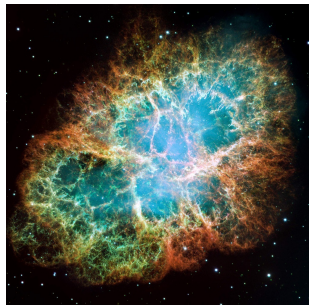
community



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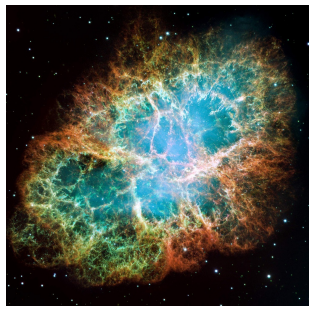

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SUBVERSION


git


mercurial


WWW

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Workshop

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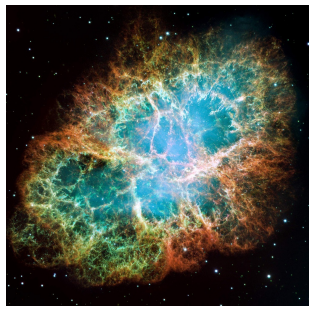

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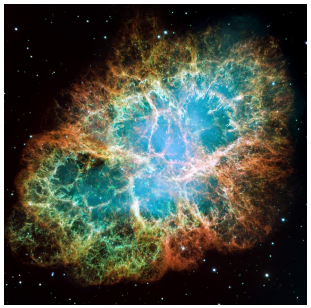

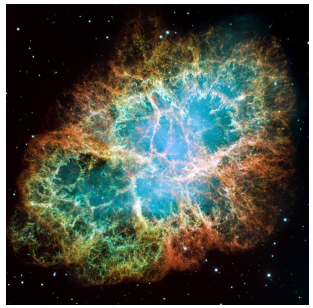

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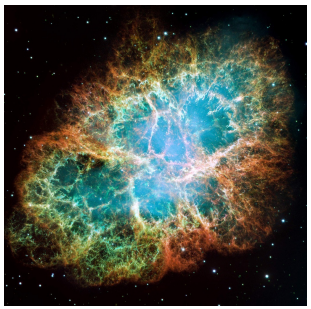

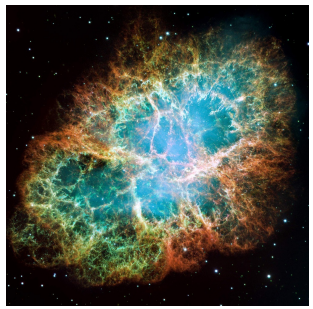

!
competition

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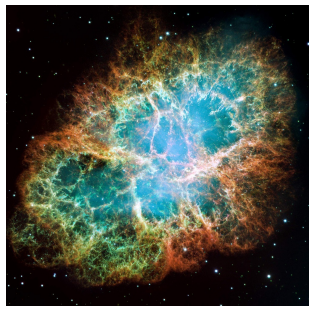
standards



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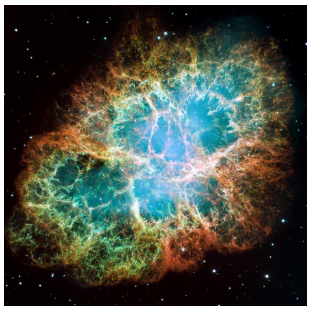

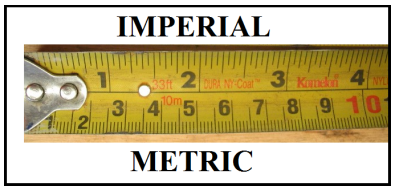

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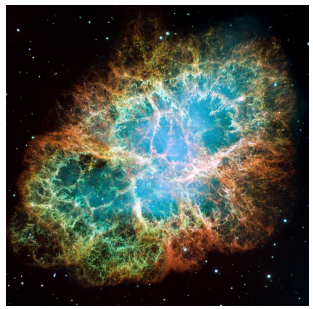

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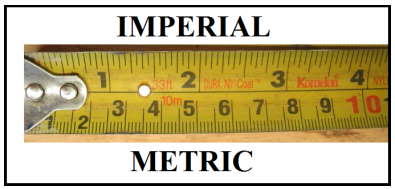

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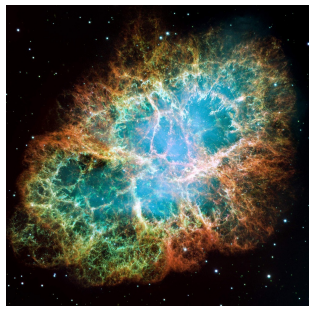

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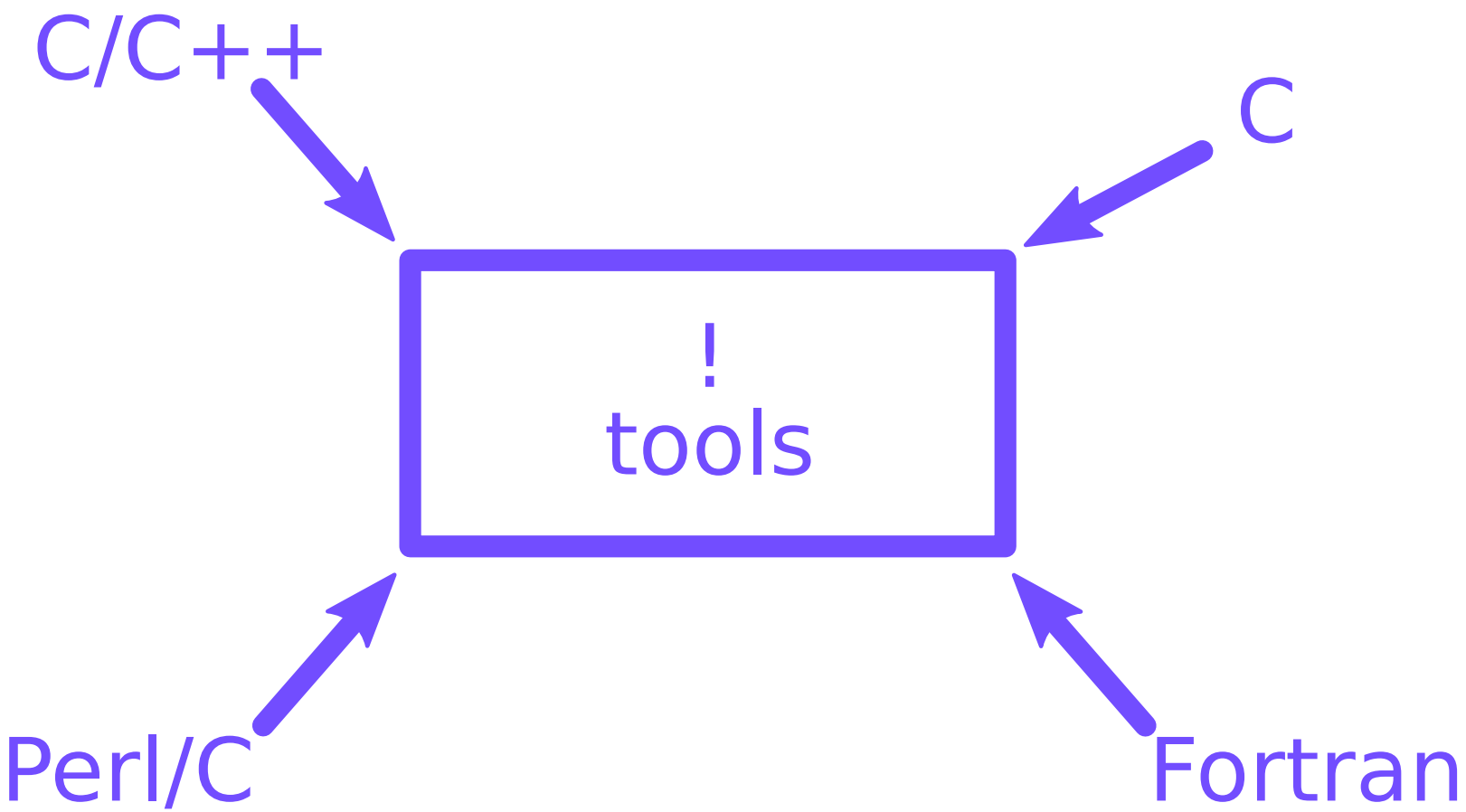

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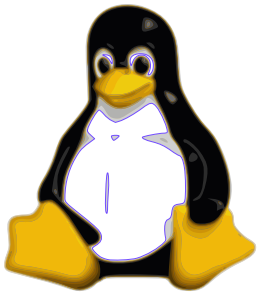
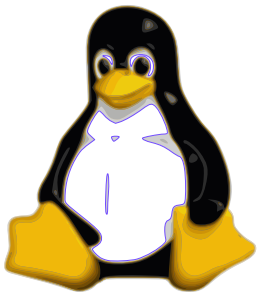


C/C++

C

!
tools



Perl/C

Fortran

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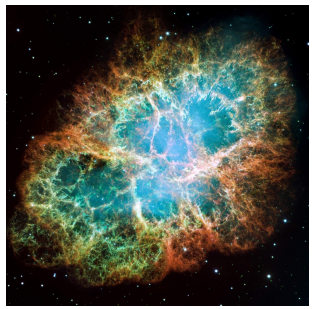

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group

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credit

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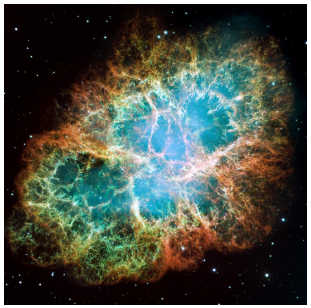
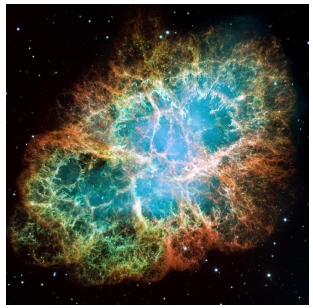
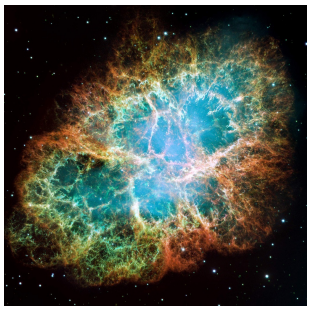
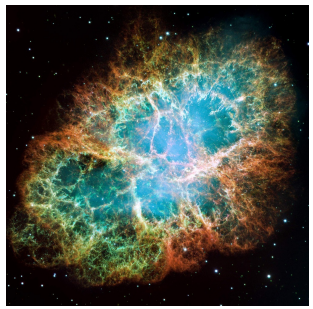

group

group

!
credit

group

group

Collaborative Challenges

How can we work together?

- Researchers in the USA
  - Arizona
  - Florida
  - Georgia
  - Louisiana
  - Illinois
  - Indiana
  - New York
  - Idaho
  - Tenessee
  - Texas
  - Pennsylvania
  - California
- In other countries
  - Canada
  - Netherlands
  - Germany
  - Italy
  - Ireland
  - Mexico
  - Portugal
  - Spain
  - Turkey
  - United Kingdom
  - and many more

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Einstein Toolkit

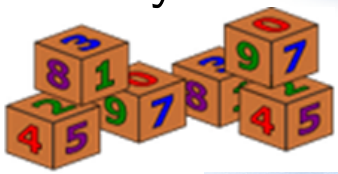
Goals:

- Community Driven
- Core computational tool for numerical astrophyscis
- General purpose tool!

Components:

- Cactus

- Simulation Factory



- Kranc
- NRPy
- Science Modules

Guiding Principles

- Open
- Community Driven
- Good interfaces
- Separation of physics from computational infrastructure
- Production ready
- High quality code

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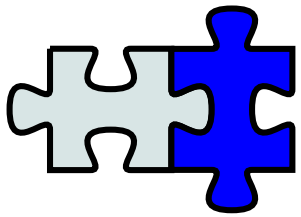
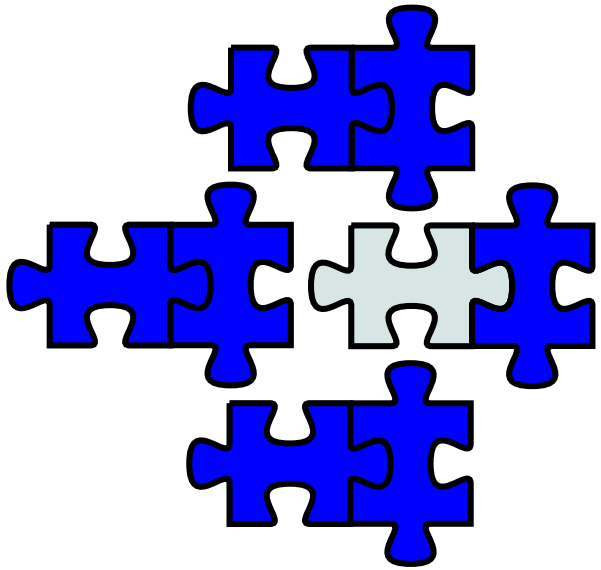
Einstein Toolkit as growing project

- Initially: some infrastructure, some application code



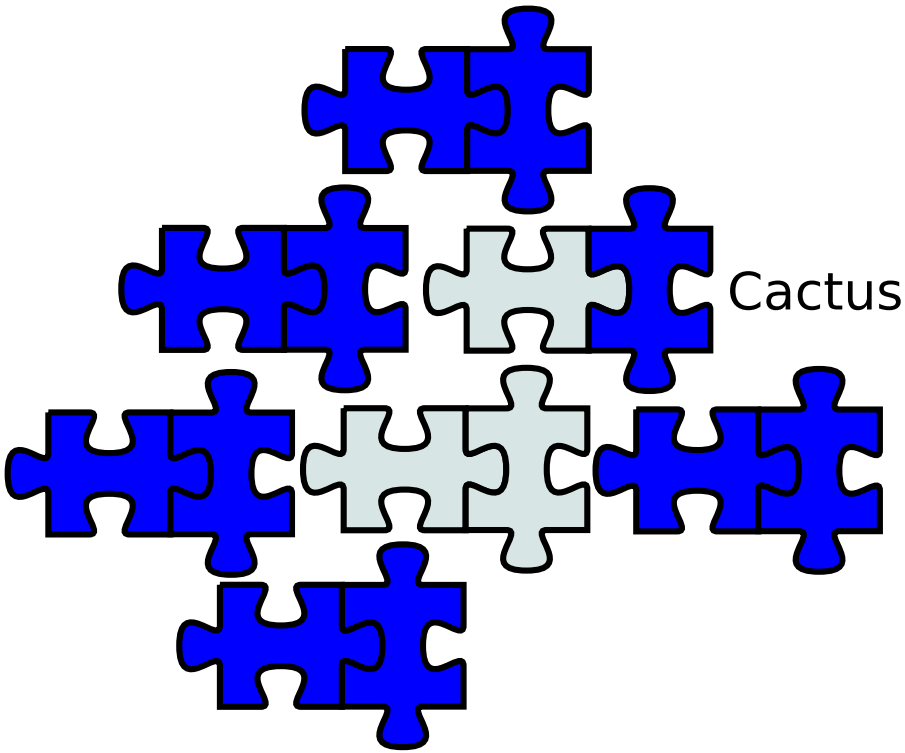
Einstein Toolkit as growing project

- Growing application suite



Einstein Toolkit as growing project

- Growing infrastructure "return"



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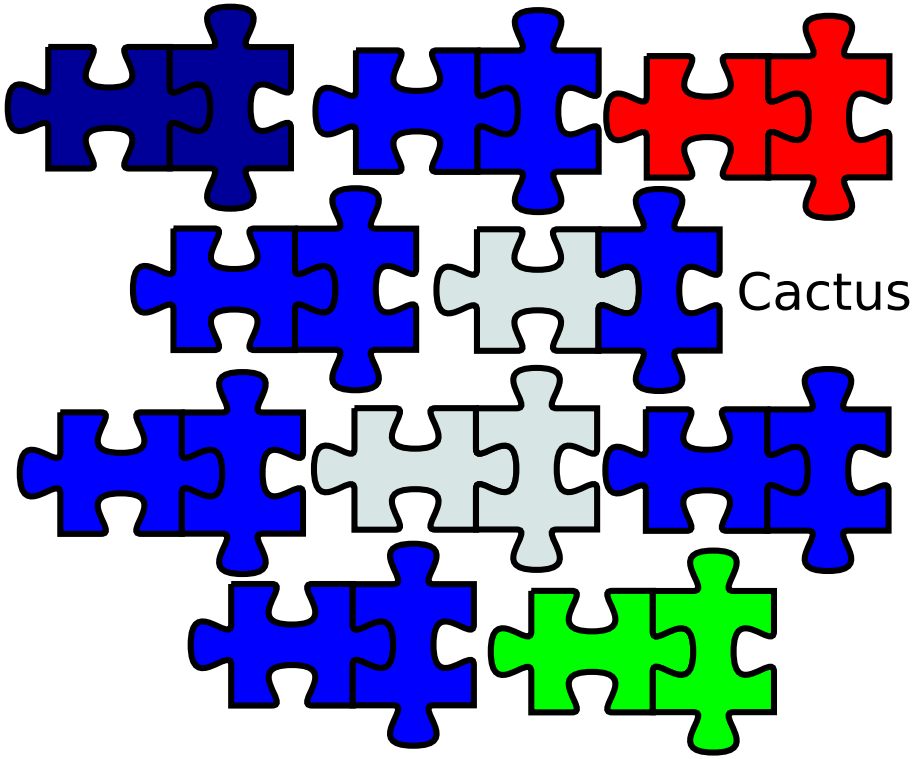
Einstein Toolkit as growing project

- Users from more fields of science



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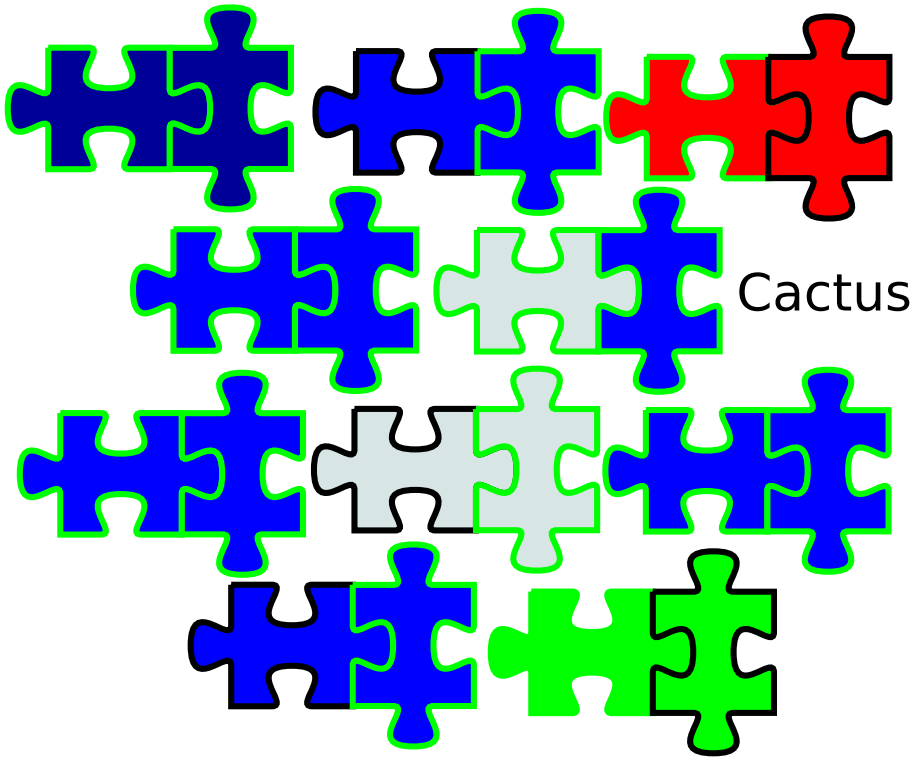
Einstein Toolkit as growing project

- Most modules open-source, but not necessarily all



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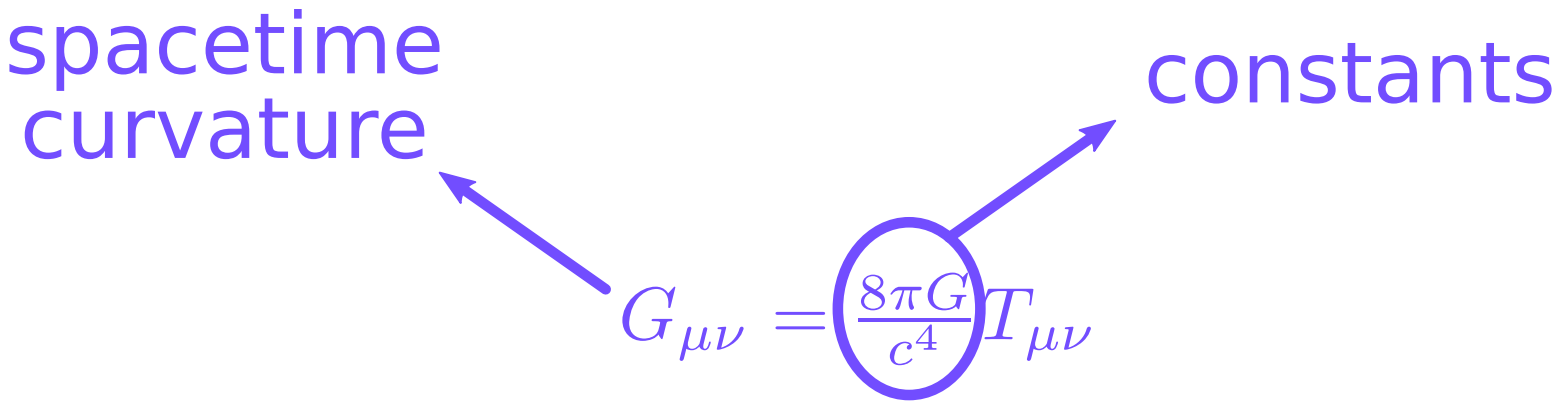
Base Modules

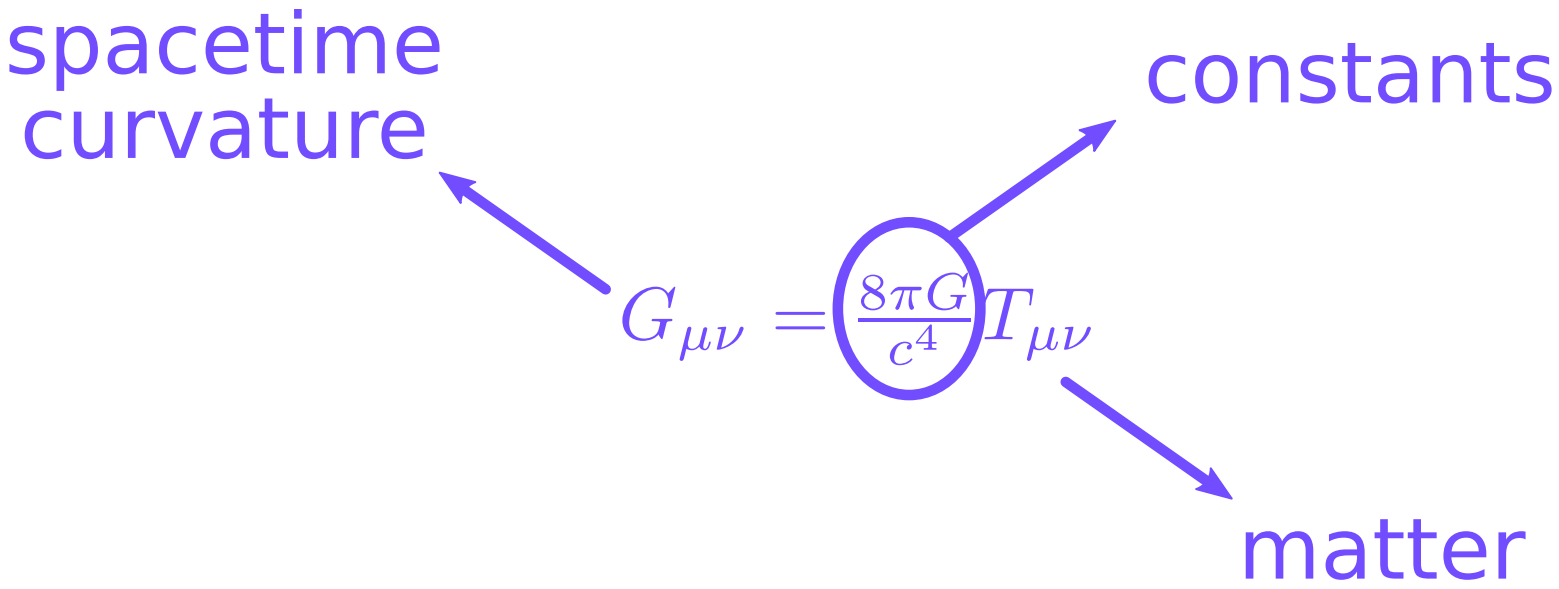
The Einstein Equations

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

spacetime curvature

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$


spacetime
curvature
constants
$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$



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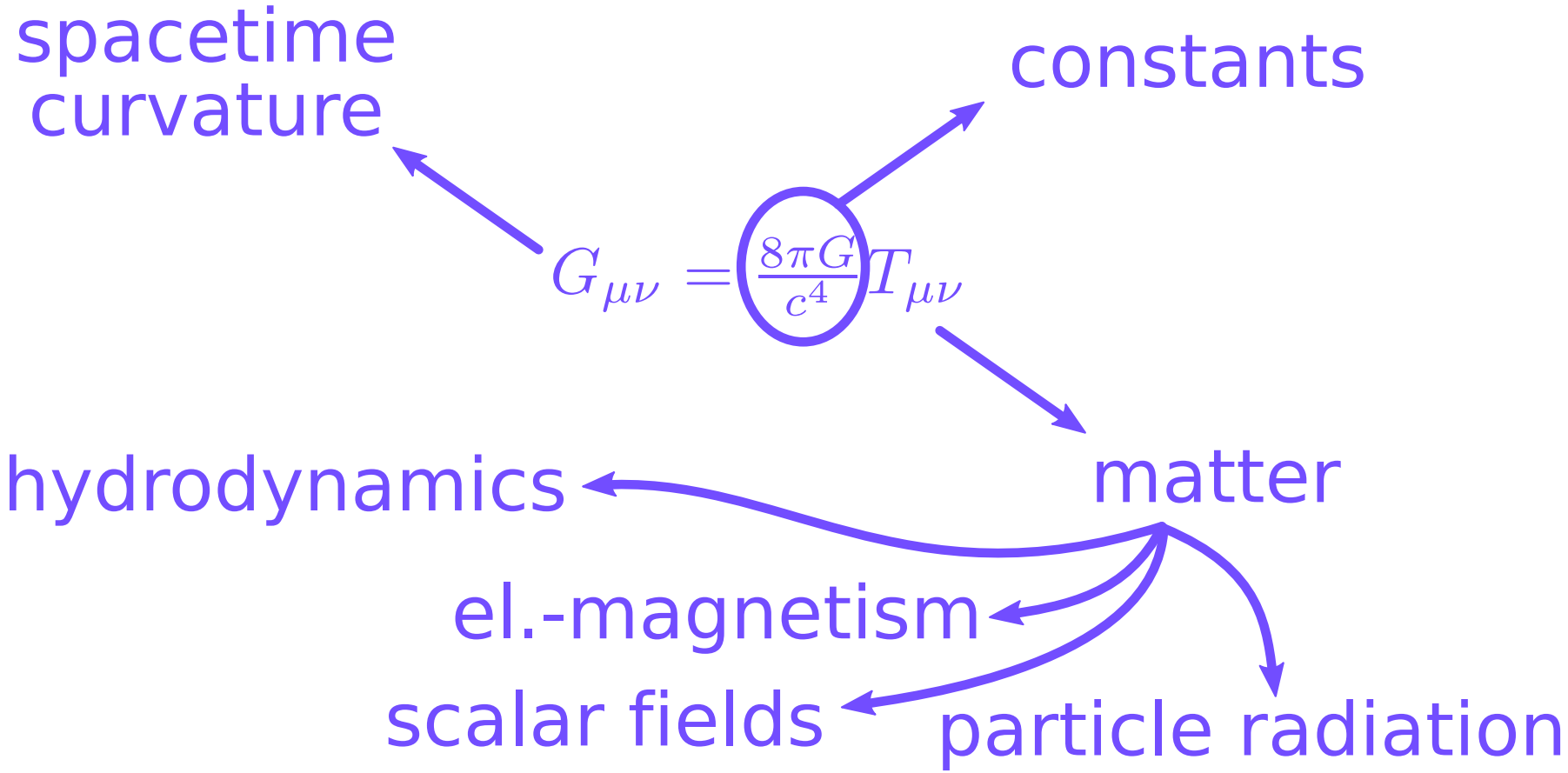

spacetime
curvature
constants
$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$
hydrodynamics
matter
el.-magnetism
scalar fields
particle radiation

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

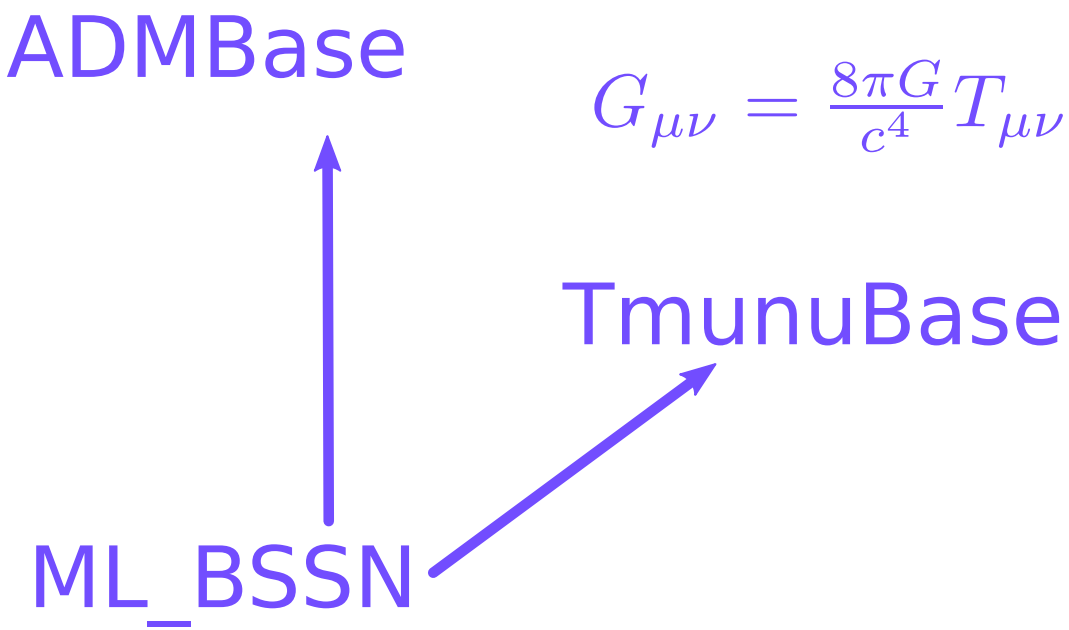
ADMBase

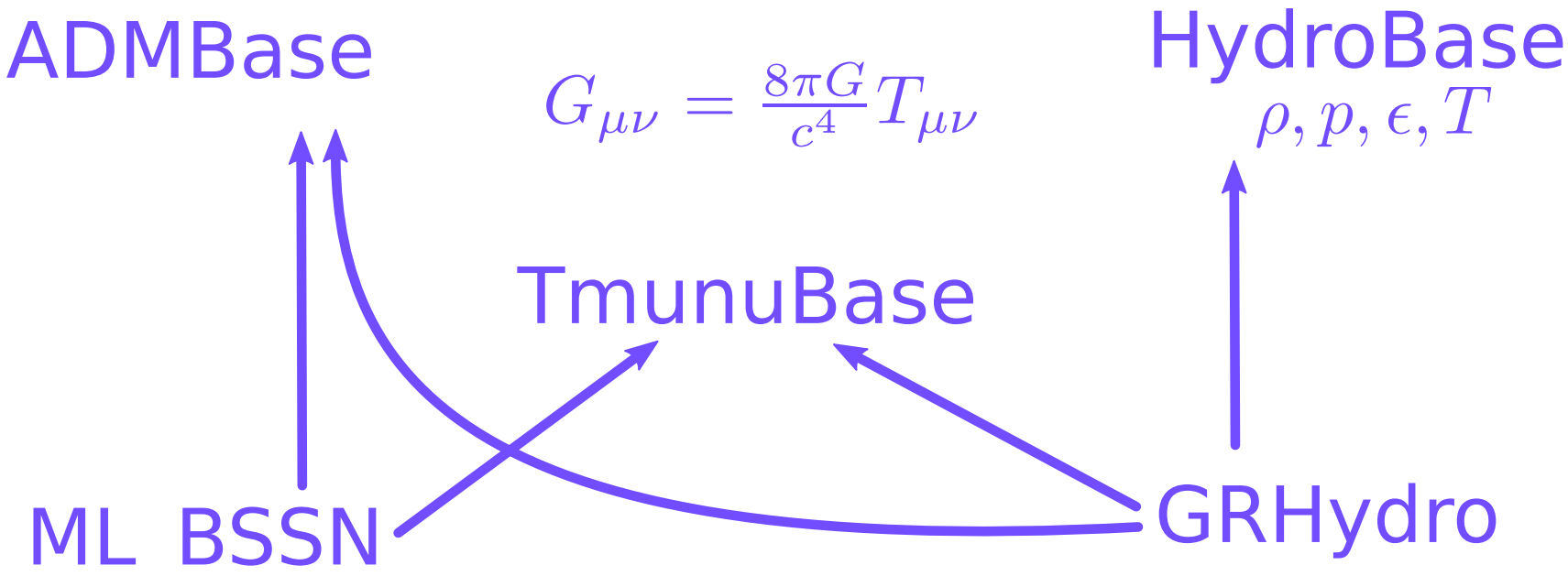
$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

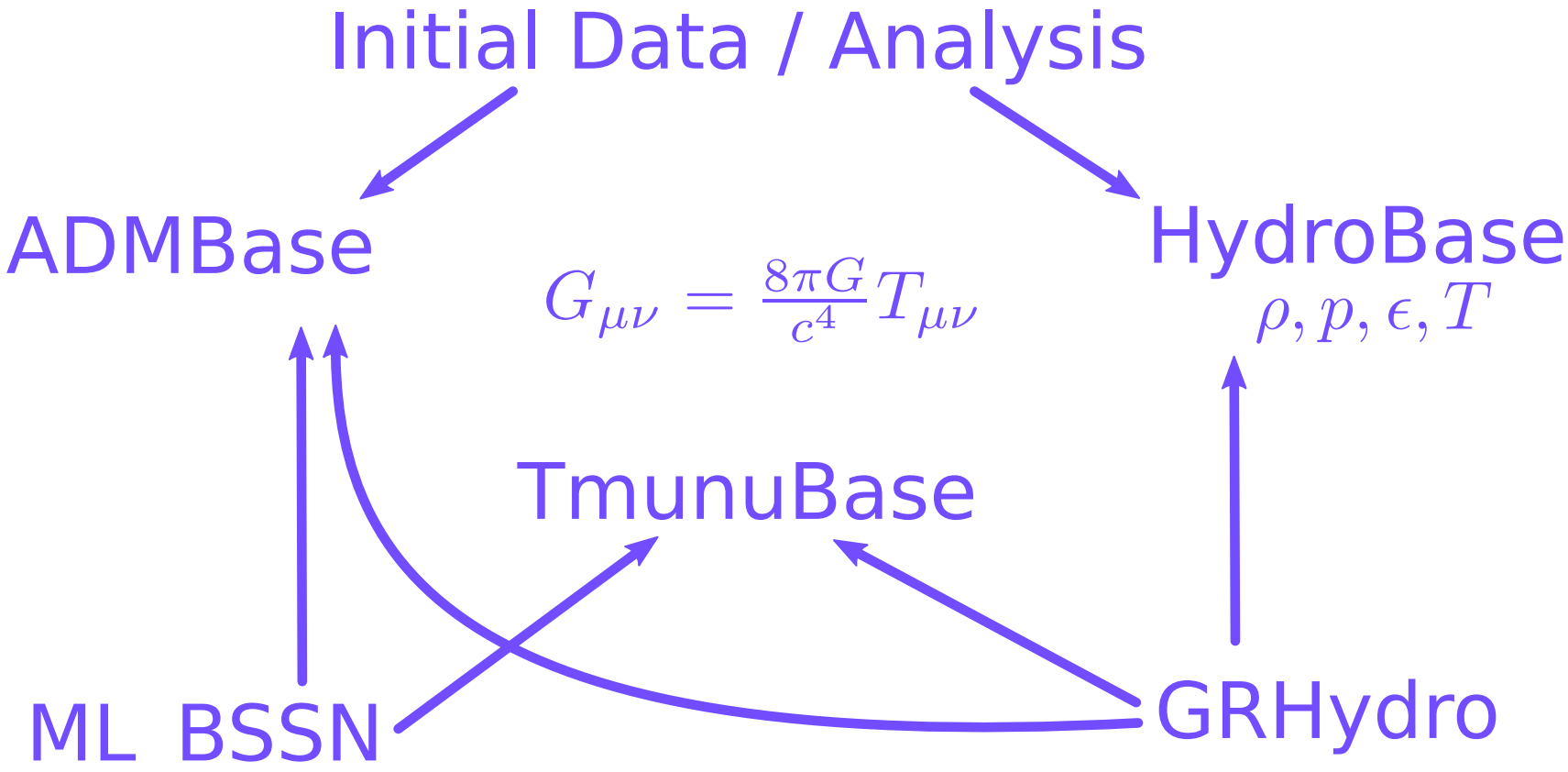
ADMBase

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

TmunuBase


ADMBase
$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$
TmunuBase
ML_BSSN


ADMBase
$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$
HydroBase
ρ, p, ϵ, T
TmunuBase
ML_BSSN
GRHydro



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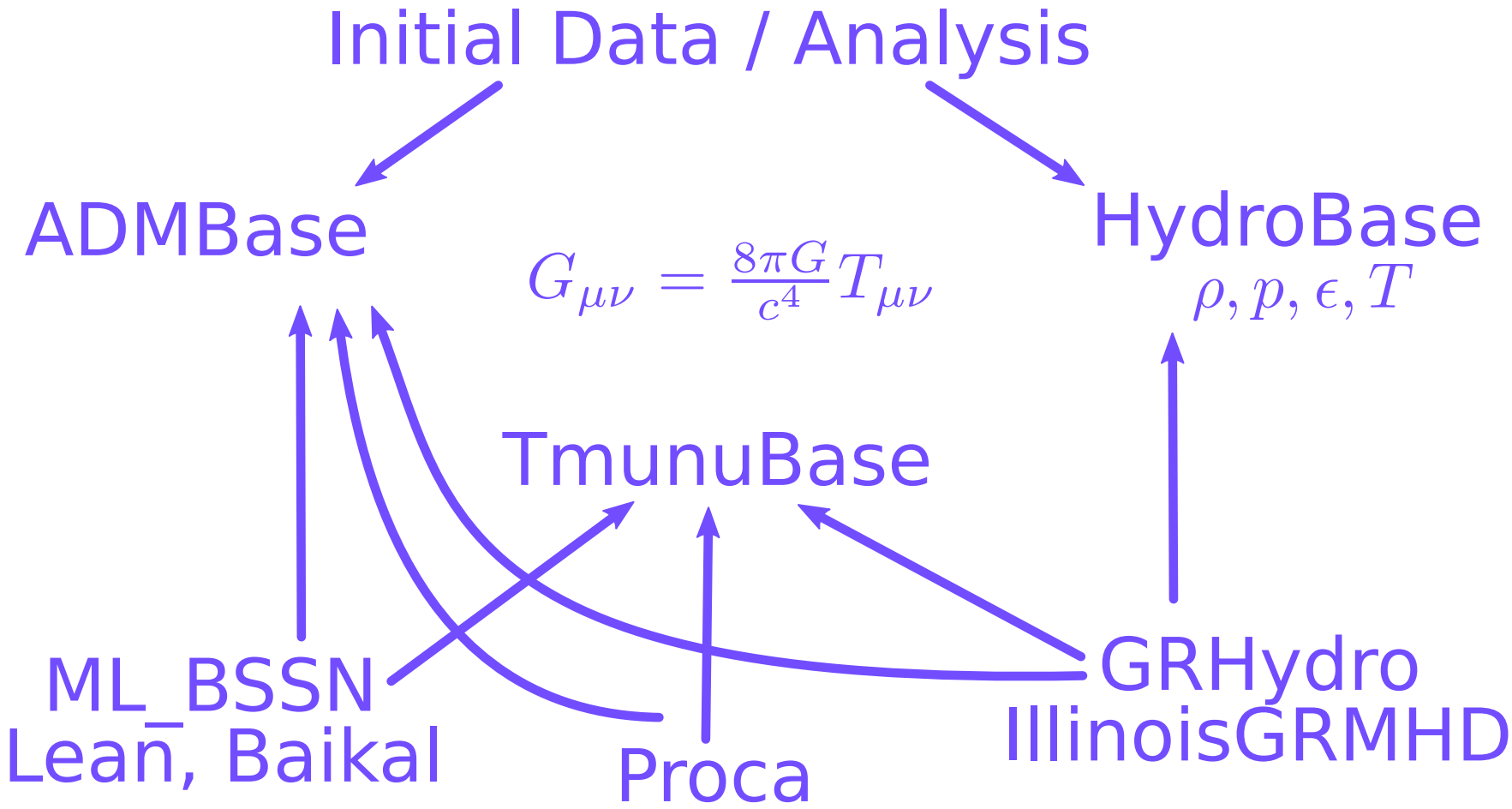

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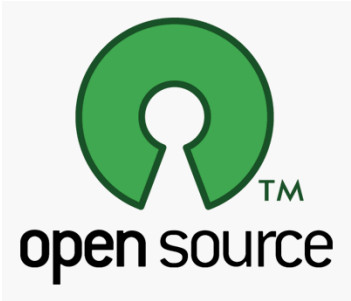
Guiding Principles

- Open, community-driven software development
- Separation of **physics** software and **computational** infrastructure
- Stable interfaces, allowing extensions
- Simplify usage where possible:
  - Doing science >> Running a simulation
  - Students need to know a lot about physics (meaningful initial conditions, numerical stability, accuracy/resolution, have patience, have curiosity, develop a "gut feeling" for what is right ...)
  - Einstein Toolkit **cannot** give that, **however**: Open codes that are easy to use allow to concentrate on these things!



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Credits, Citations

In academics: citations, citations, citations!
For Einstein Toolkit:

- Open and free source
- No **requirement** to cite anything
- However: **requested** to cite
  - The DOI doi:10.5281/zenodo.3350841
  - Maybe the ET or Cactus papers
  - Some papers for the components list a few as well
  - List published on website and manage through publication database
- Soon: auto-generate list of citations during simulation run

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Vision

Cutting Edge / Future

- New Driver Thorn: CarpetX (Meitner Release)
- New Hydro Thorn: AsterX (Next Release?)
- New Boundary Thorn: NewRadX (Landau Release)
- GRHayL thorns (Meitner, Landau, etc...)
- Python Code Generator: Full thorn output from NRPy
- Kerr background support in SelfForce1D (Soon?)

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Summary

Einstein Toolkit

- http://www.einsteintoolkit.org/
- Tools for high-performance computing in numerical relativity
- Open Source
- World-wide, open Community
- Used in high-end research

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Supported By

The Einstein Toolkit is supported by
NSF 2004157/2004044/2004311/2004879/2003893, NSF 1550551/1550461/1550436/1550514 Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

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