Los Alamos NATIONAL LABORATORY

Parthenon: Adaptive Mesh Refinement for Exascale Astrophysics

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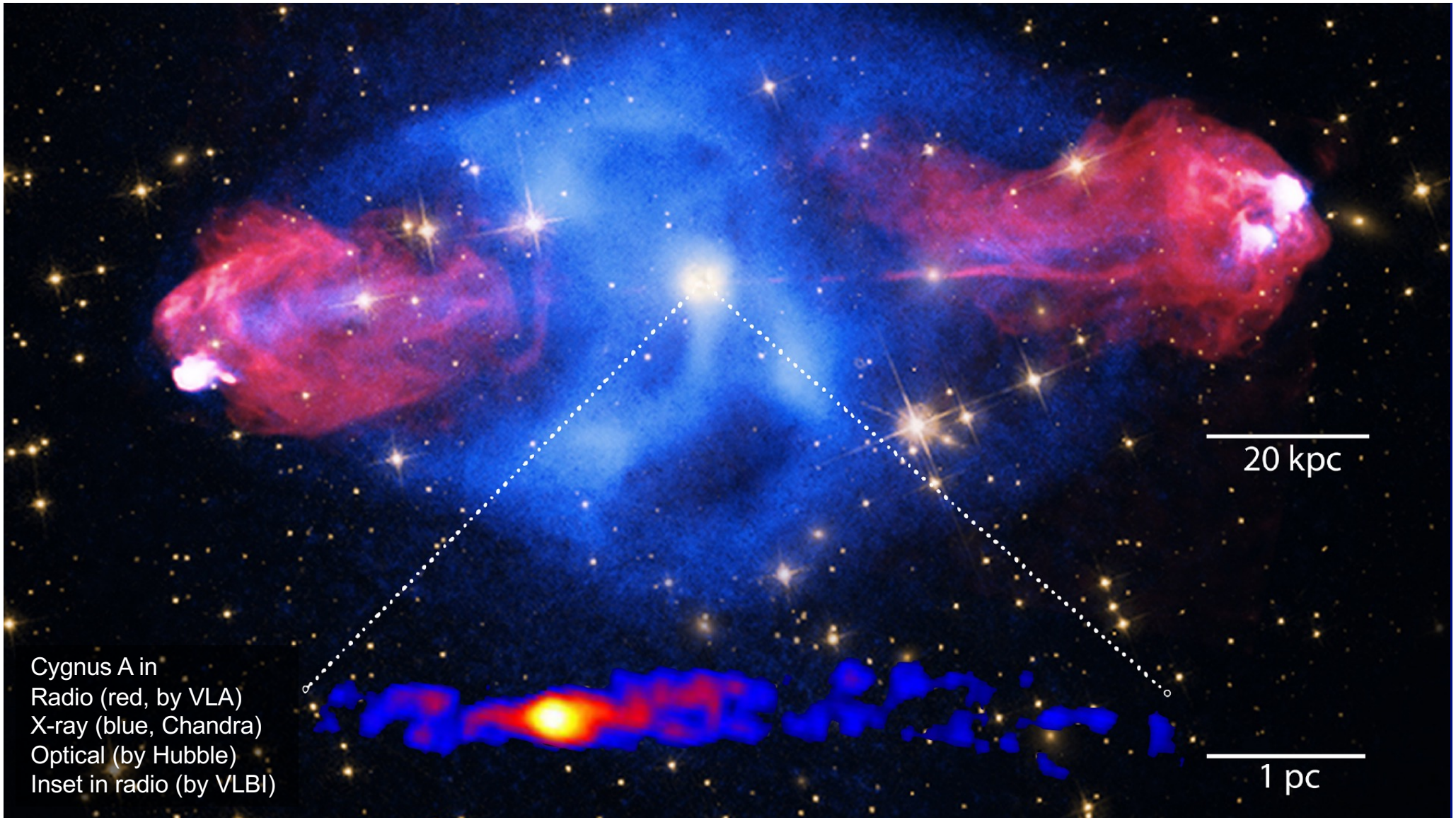
December 14th, 2023

LA-UR-23-33950


20 kpc
1 pc
Cygnus A in
Radio (red, by VLA)
X-ray (blue, Chandra)
Optical (by Hubble)
Inset in radio (by VLBI)

Pre-Exascale

Exascale Supercomputers

Key: Nvidia GPUs AMD GPUs Intel GPUs

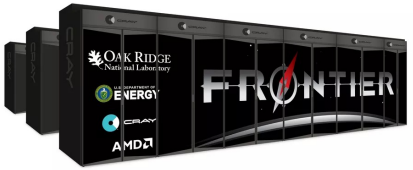
Fugaku
(Fujitsu ARM)

Summit
(Nvidia V100)

LUMI
(AMD MI250x)

Pre-Exascale

Exascale



Frontier
(AMD MI250x)

El Capitan
(AMD MI300A)

Aurora
(Intel Ponte Vecchio)

Jupiter
(Nvidia H200)

Finite Volume Method for MHD

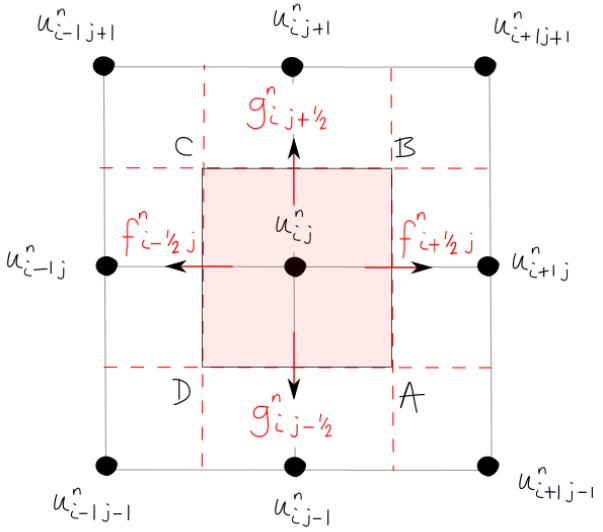
MHD Equations

$$\partial_t \rho + \nabla \cdot (\rho \boldsymbol{v}) = 0,$$

$$\partial_t (\rho \boldsymbol{v}) + \nabla \cdot (\rho \boldsymbol{v}\boldsymbol{v} - \boldsymbol{B}\boldsymbol{B} + P^* \mathbf{I}) = -\rho \, \boldsymbol{\nabla} \Phi,$$

$$\partial_t E + \nabla \cdot [(E + P^*)\boldsymbol{v} - \boldsymbol{B}(\boldsymbol{B} \cdot \boldsymbol{v})] = -\rho \, \boldsymbol{v} \cdot \nabla \Phi,$$

$$\partial_t \boldsymbol{B} + \nabla \cdot (\boldsymbol{v}\boldsymbol{B} - \boldsymbol{B}\boldsymbol{v}) = 0.$$



for each stage

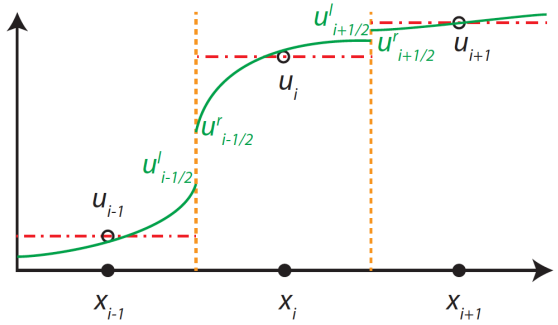
Convert Conserved Vars. to Primitives

Reconstruct Fluid State to Cell Faces

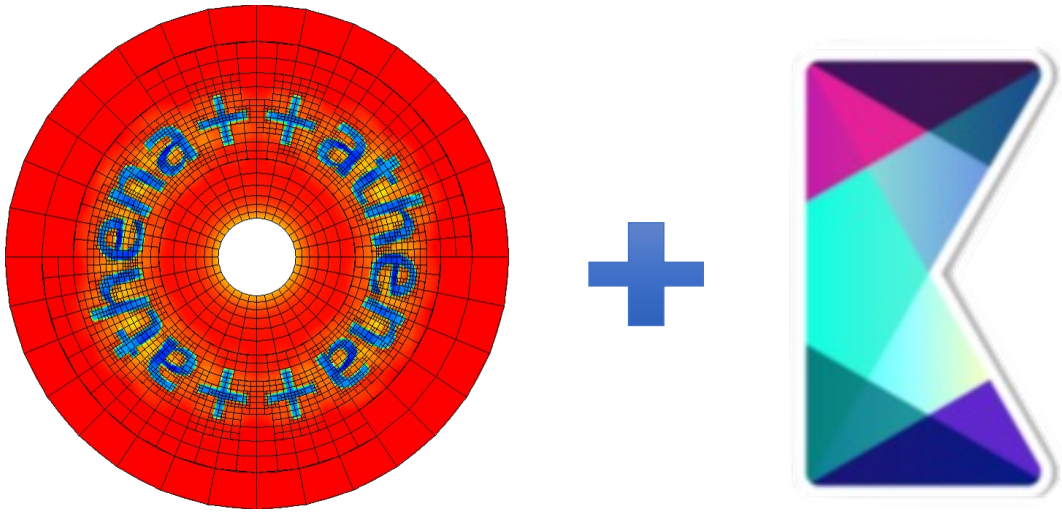
Solve Riemann Problem Across Faces for Fluxes

Add Flux Divergence to Conserved Vars.

*Additional Multiphysics

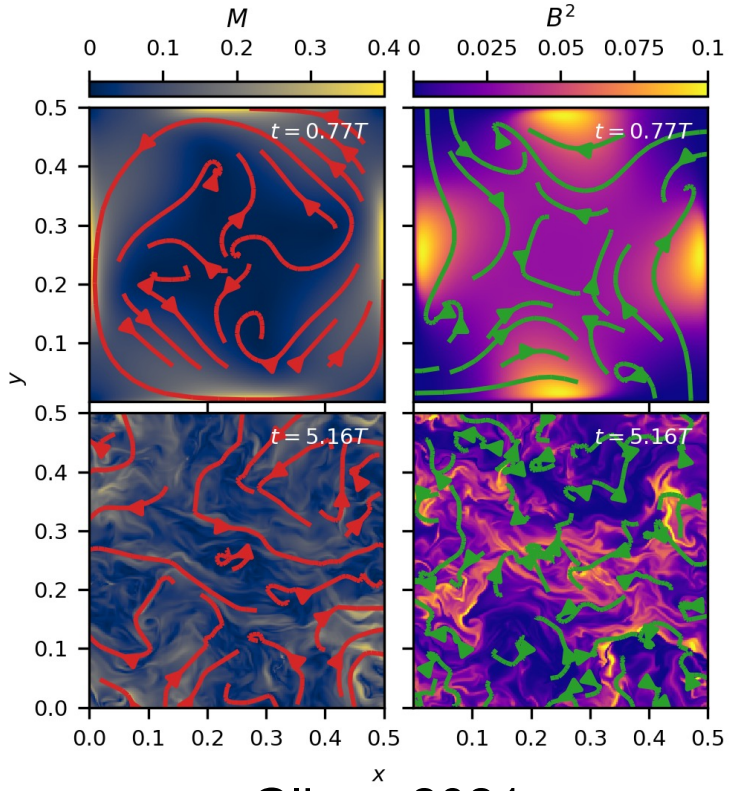


K-Athena: Kokkos Experiment for *Uniform* MHD

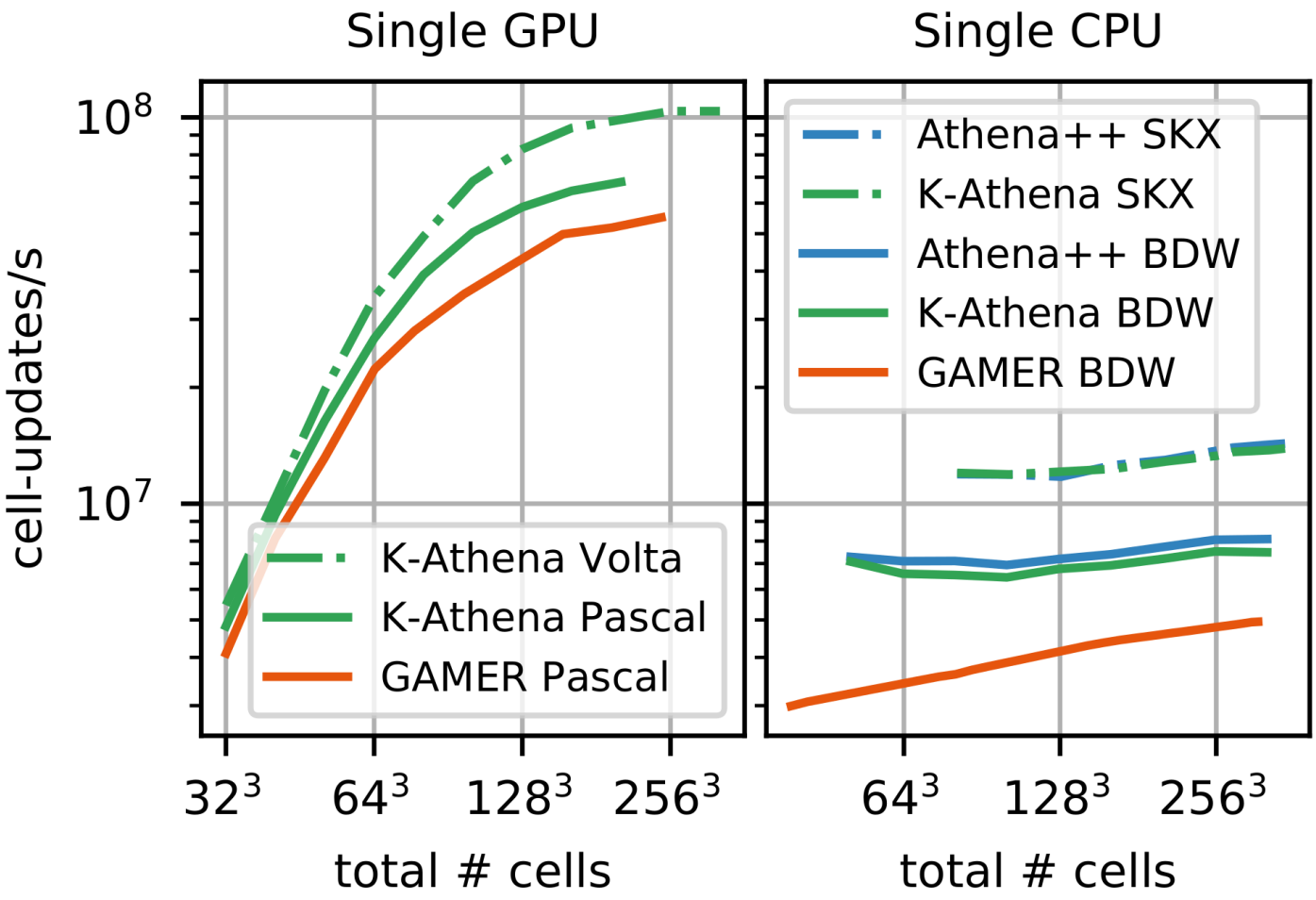


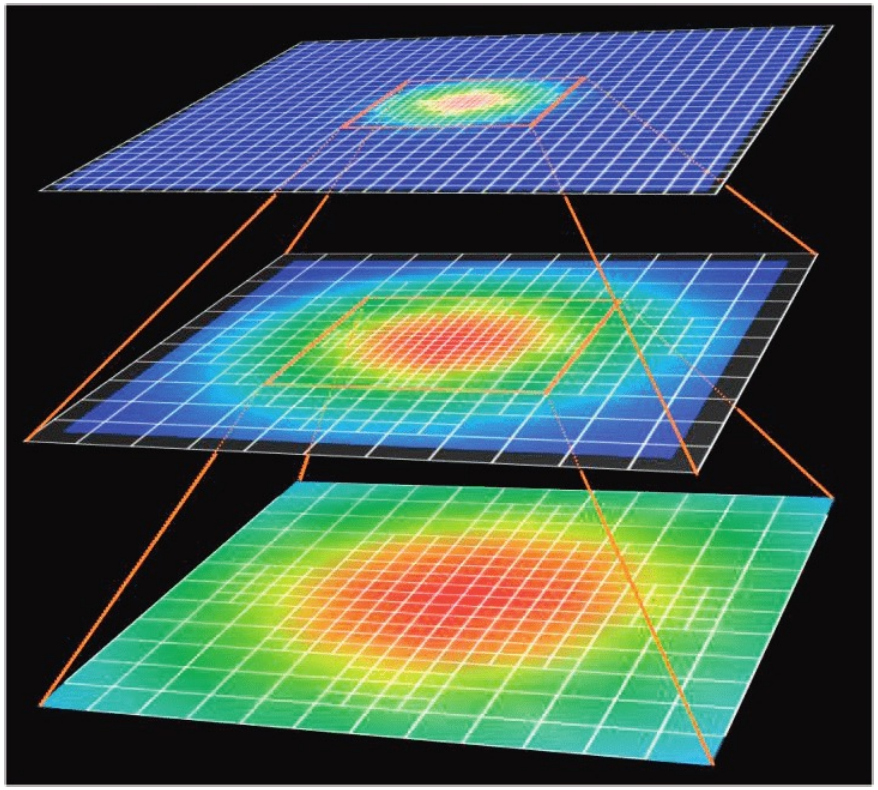
https://gitlab.com/pgrete/kathena
DOI: 10.1109/TPDS.2020.3010016

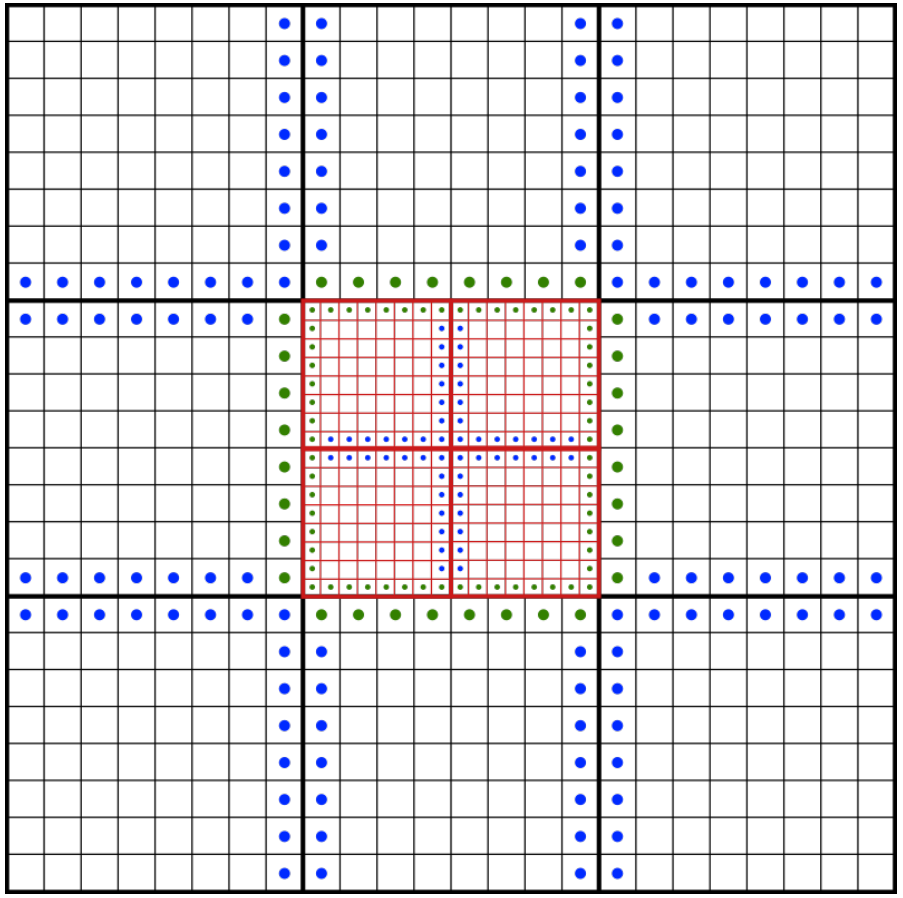
https://doi.org/10.1109/TPDS.2020.3010016



Glines 2021


Single GPU
Single CPU
cell-updates/s
10^8
10^7
K-Athena Volta
K-Athena Pascal
GAMER Pascal
Athena++ SKX
K-Athena SKX
Athena++ BDW
K-Athena BDW
GAMER BDW
32^3
64^3
128^3
256^3
total # cells
64^3
128^3
256^3
total # cells





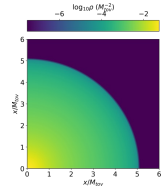
Adaptive Mesh Refinement
(Matsumoto 2014)

Parthenon: Exascale Adaptive Mesh Refinement

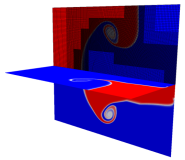
Oct-tree block-based AMR framework with Kokkos

- AMR for Cell-centered, Face-centered
- Basic coarse-grained tasking
- MPI communications
- IO via HDF5 (and soon OpenPMD/ADIOS)
- Particle Swarms
- Multigrid/BiCGSTAB Solver
- In-Situ analysis
  - ASCENT
  - Custom Analysis

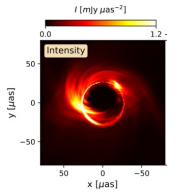
Phoebus
GRMHD
LANL+



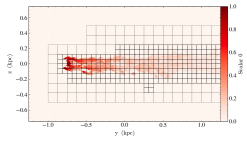
RIOT
Terrestrial Multiphysics
LANL



KHARMA
GRMHD
LANL, UIUC



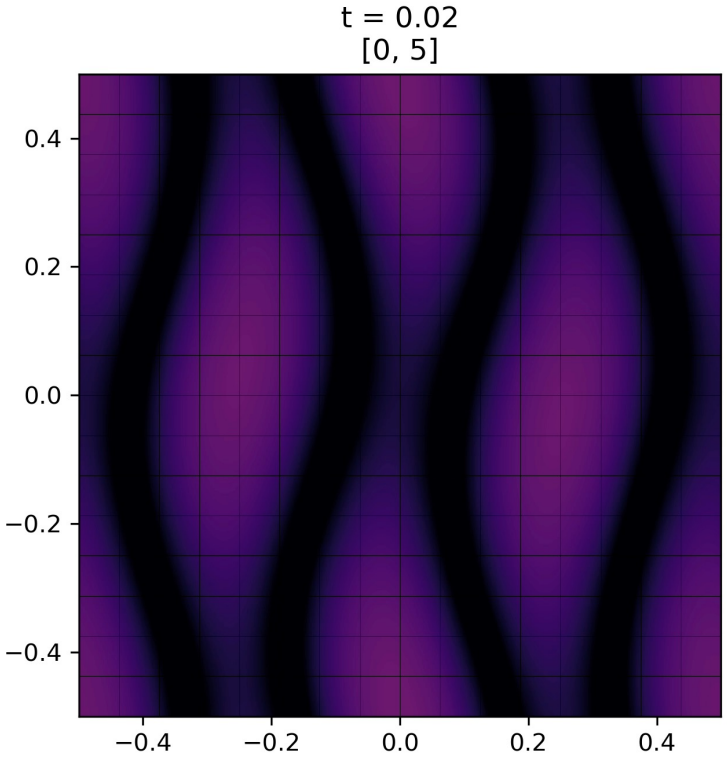
AthenaPK
MHD
MSU, LANL, Hamburg



*And more in development

Face-Centered Fields

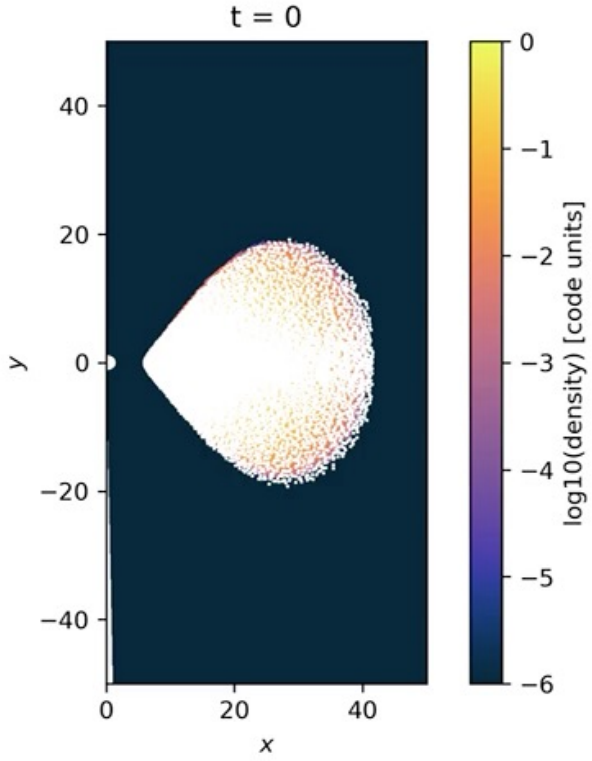
Orszag-Tang evolving **A** on faces



By Luke Roberts

Particle Swarms

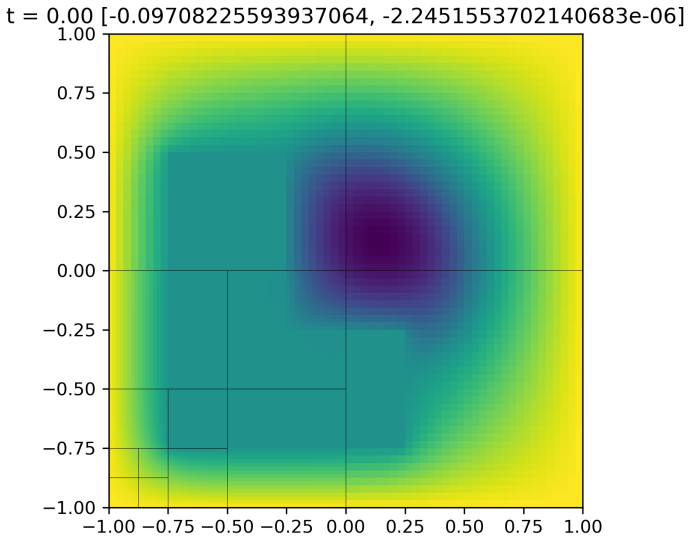
MHD Accretion Disk with Tracer Particles



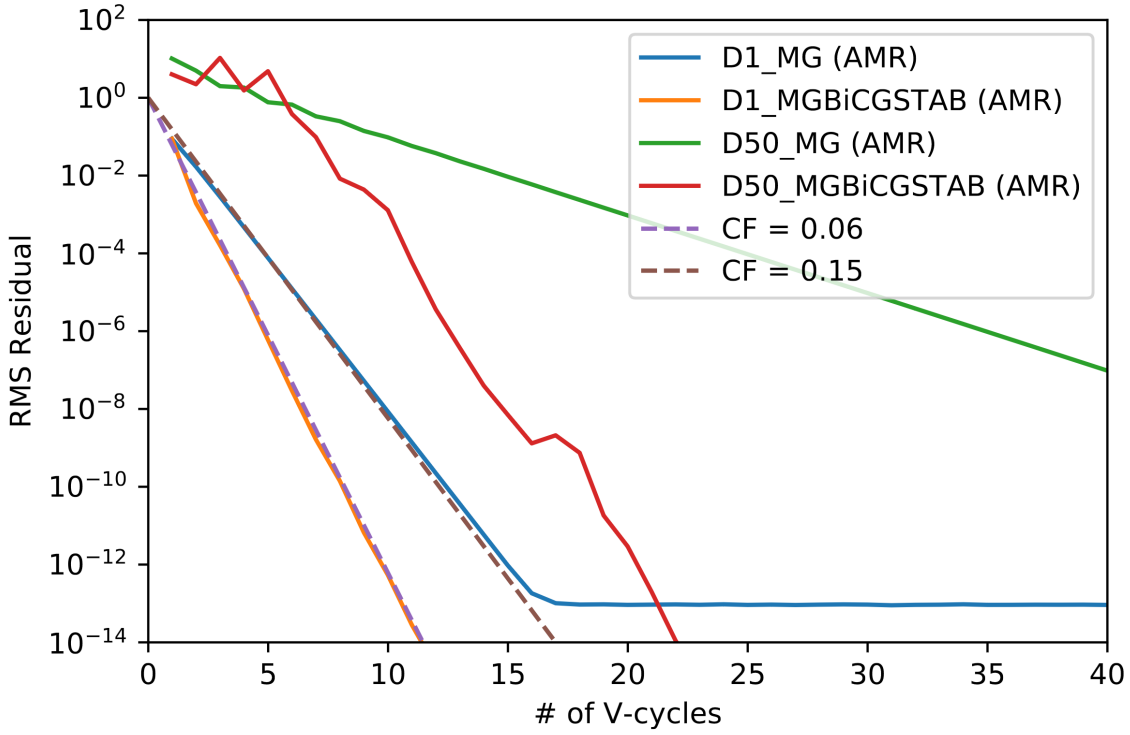
By Brandon Barker with PHOEBUS

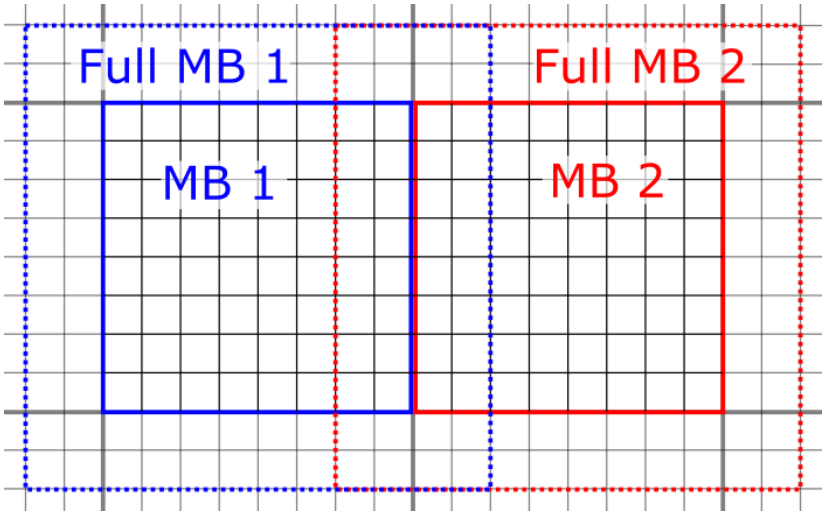
Multigrid/BiCGSTAB

$$\nabla \cdot D \nabla u = f$$

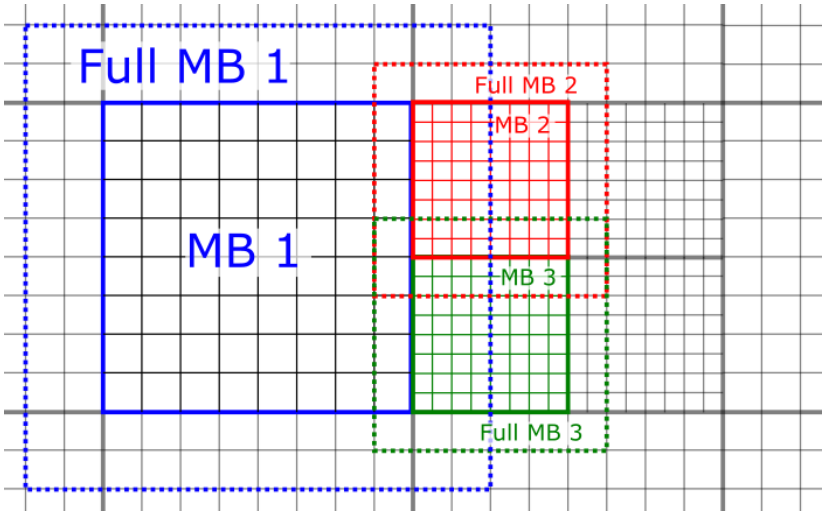


By Luke Roberts

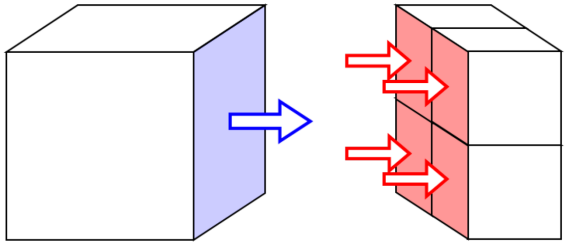




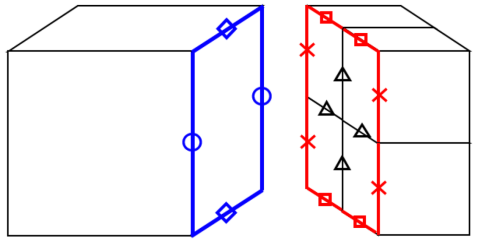
Same Level Halo Exchange



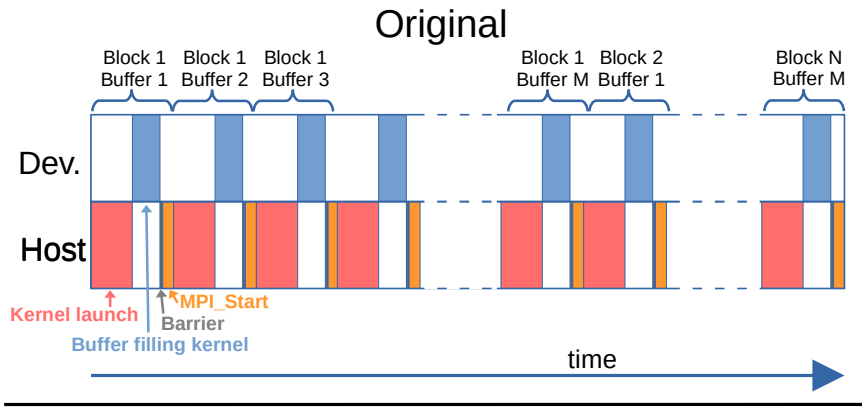
Between Levels Halo Exchange

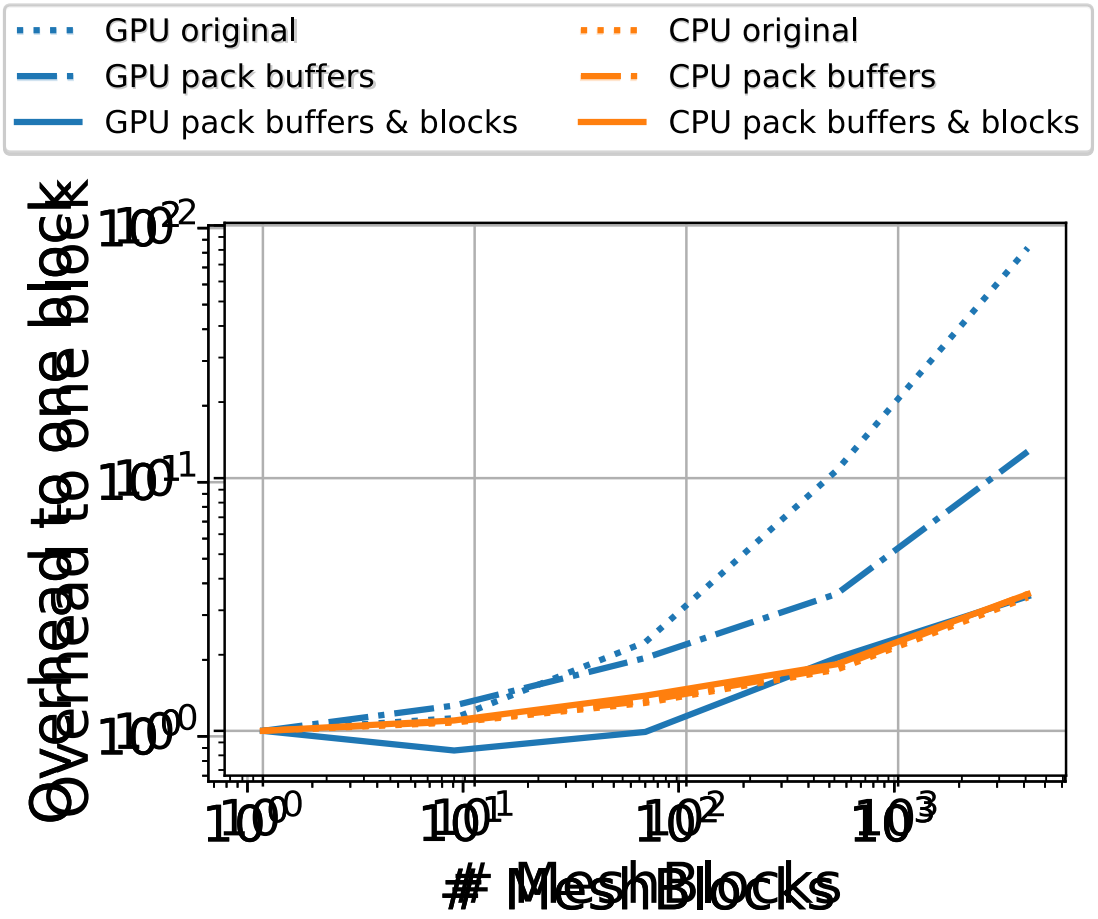


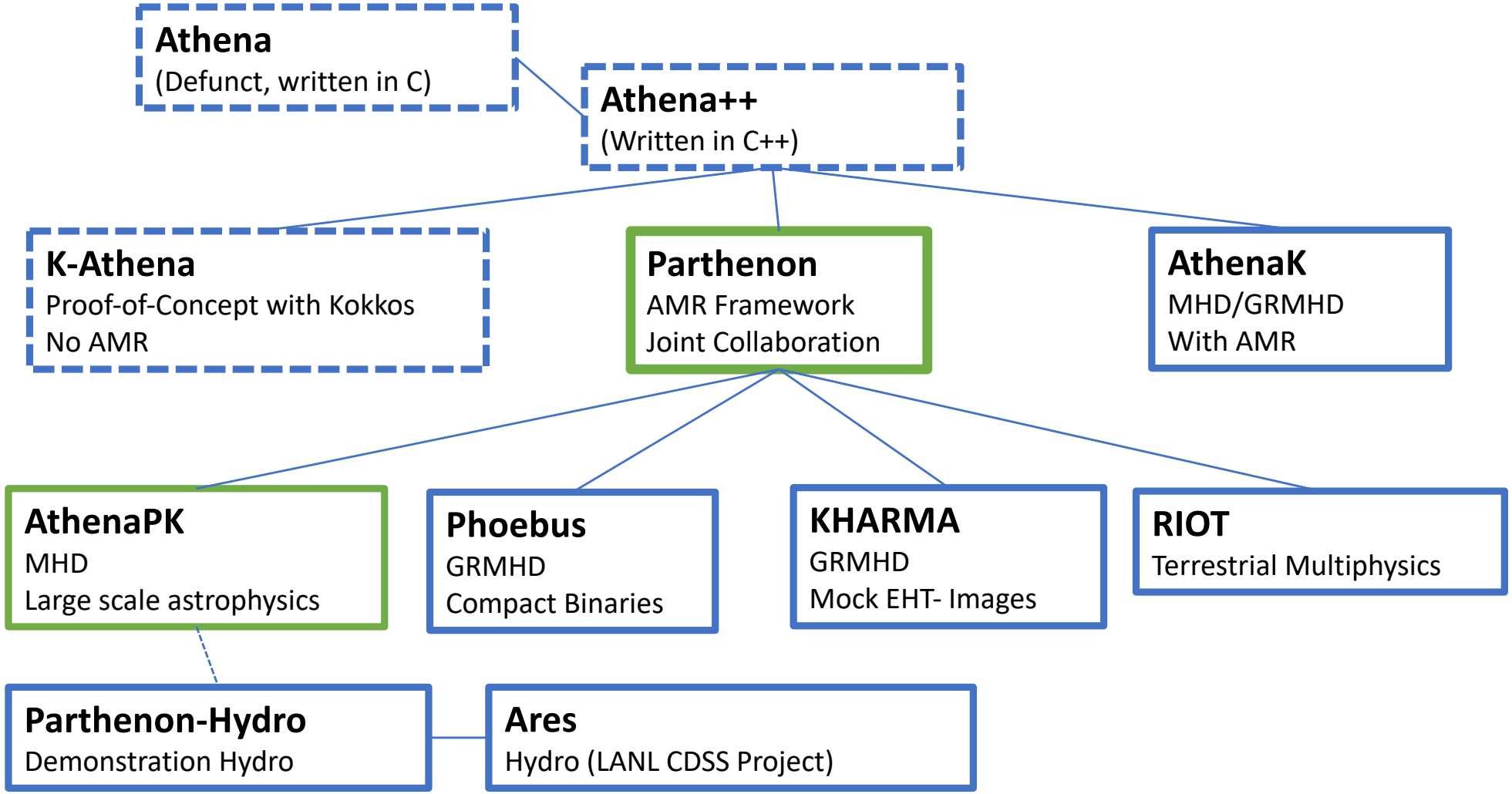
Flux Correction



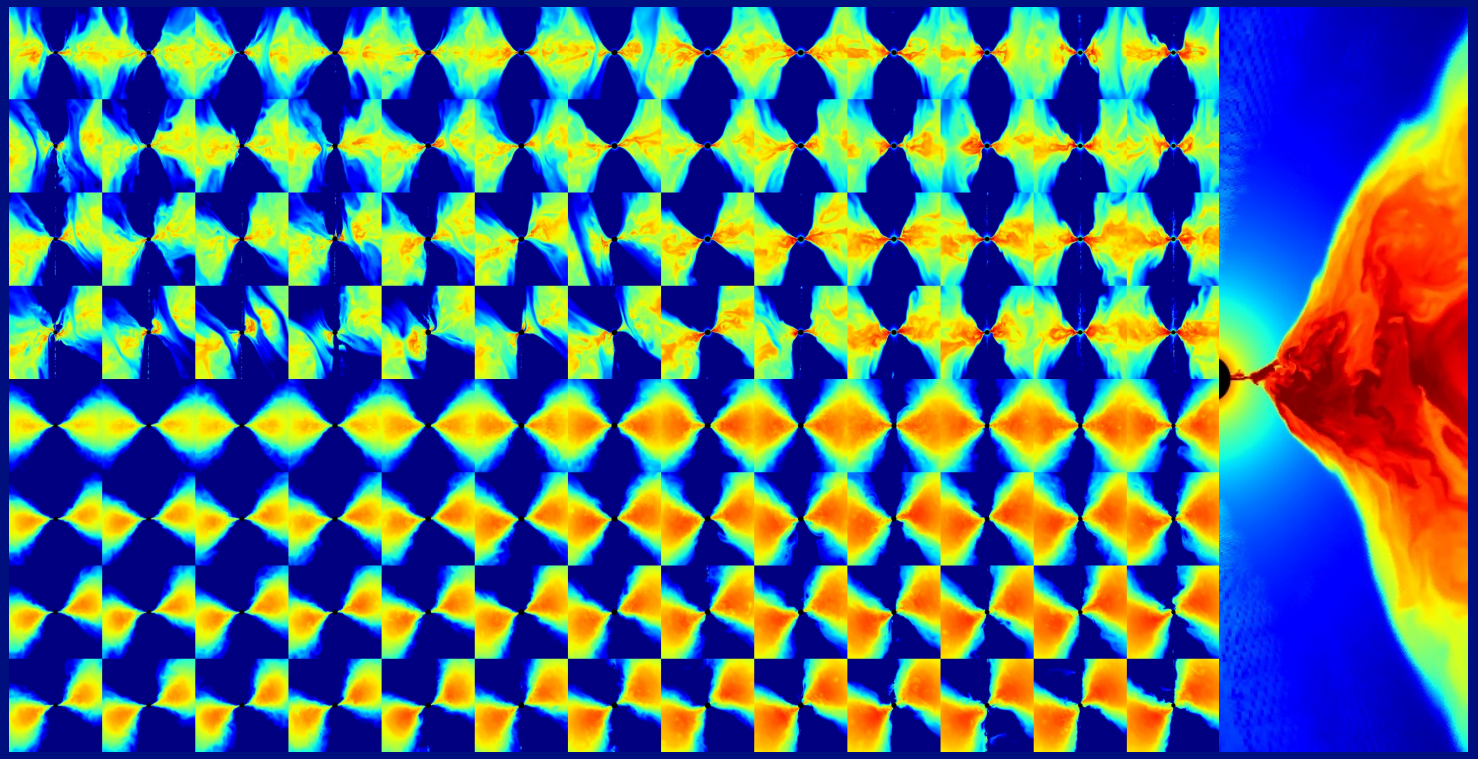
EMF Correction

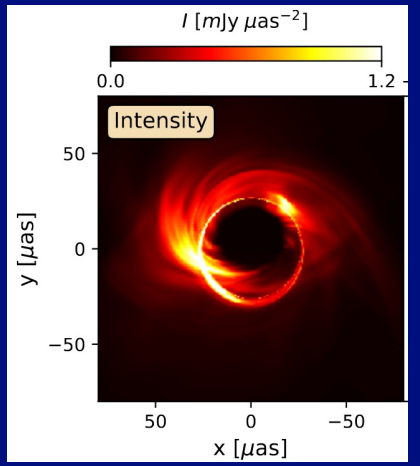

Original
Block 1 Buffer 1
Block 1 Buffer 2
Block 1 Buffer 3
Block 1 Buffer M
Block 2 Buffer 1
Block N Buffer M
Dev.
Host
Kernel launch
MPI_Start
Barrier
Buffer filling kernel
time


GPU original
GPU pack buffers
GPU pack buffers & blocks
CPU original
CPU pack buffers
CPU pack buffers & blocks
Overhead to one block
MeshBlocks


Athena
(Defunct, written in C)
Athena++
(Written in C++)
K-Athena
Proof-of-Concept with Kokkos
No AMR
Parthenon
AMR Framework
Joint Collaboration
AthenaK
MHD/GRMHD
With AMR
AthenaPK
MHD
Large scale astrophysics
Phoebus
GRMHD
Compact Binaries
KHARMA
GRMHD
Mock EHT- Images
RIOT
Terrestrial Multiphysics
Parthenon-Hydro
Demonstration Hydro
Ares
Hydro (LANL CDSS Project)

INCITE 2022 (Gammie): Black Hole Acc. Disks for EHT

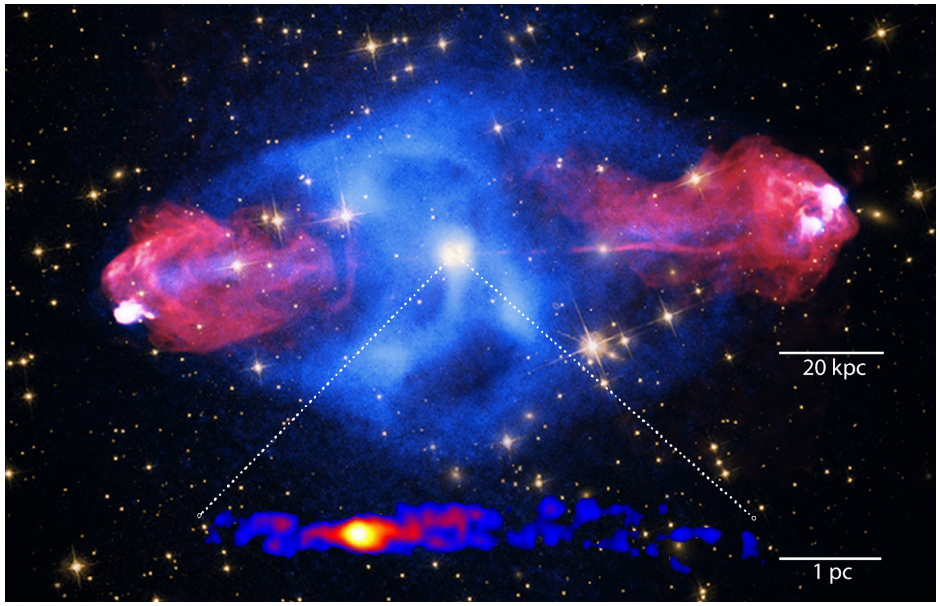




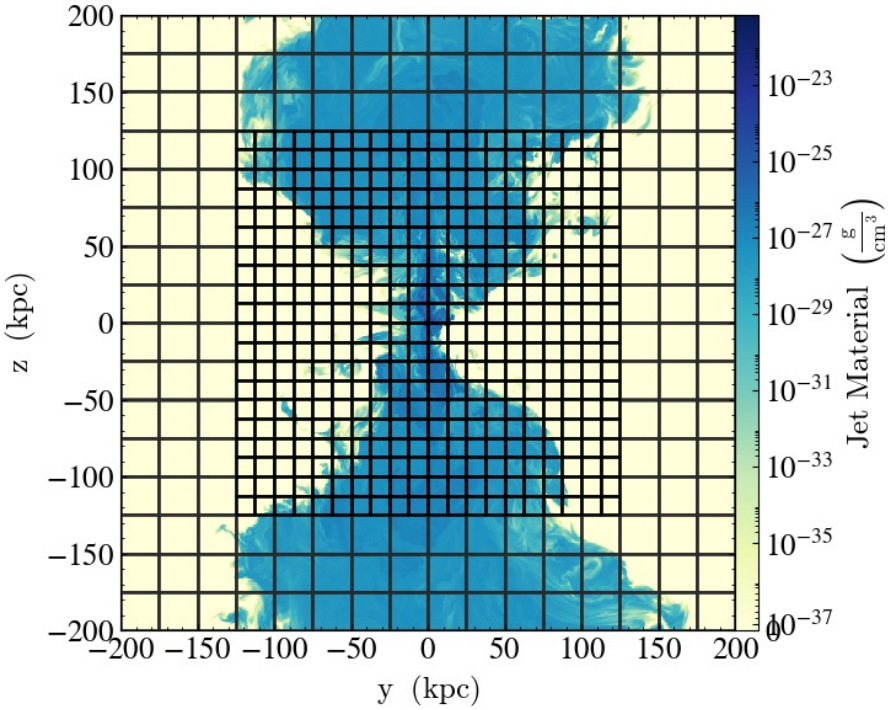
By Ben Prather with KHARMA on Summit

INCITE 2023-2024 (O'Shea): XMAGNET

eXascale simulations of Magnetized AGN feedback and Energetics with Turbulence



Cygnus A



Mesh Structure of XMAGNET on Frontier with AthenaPK

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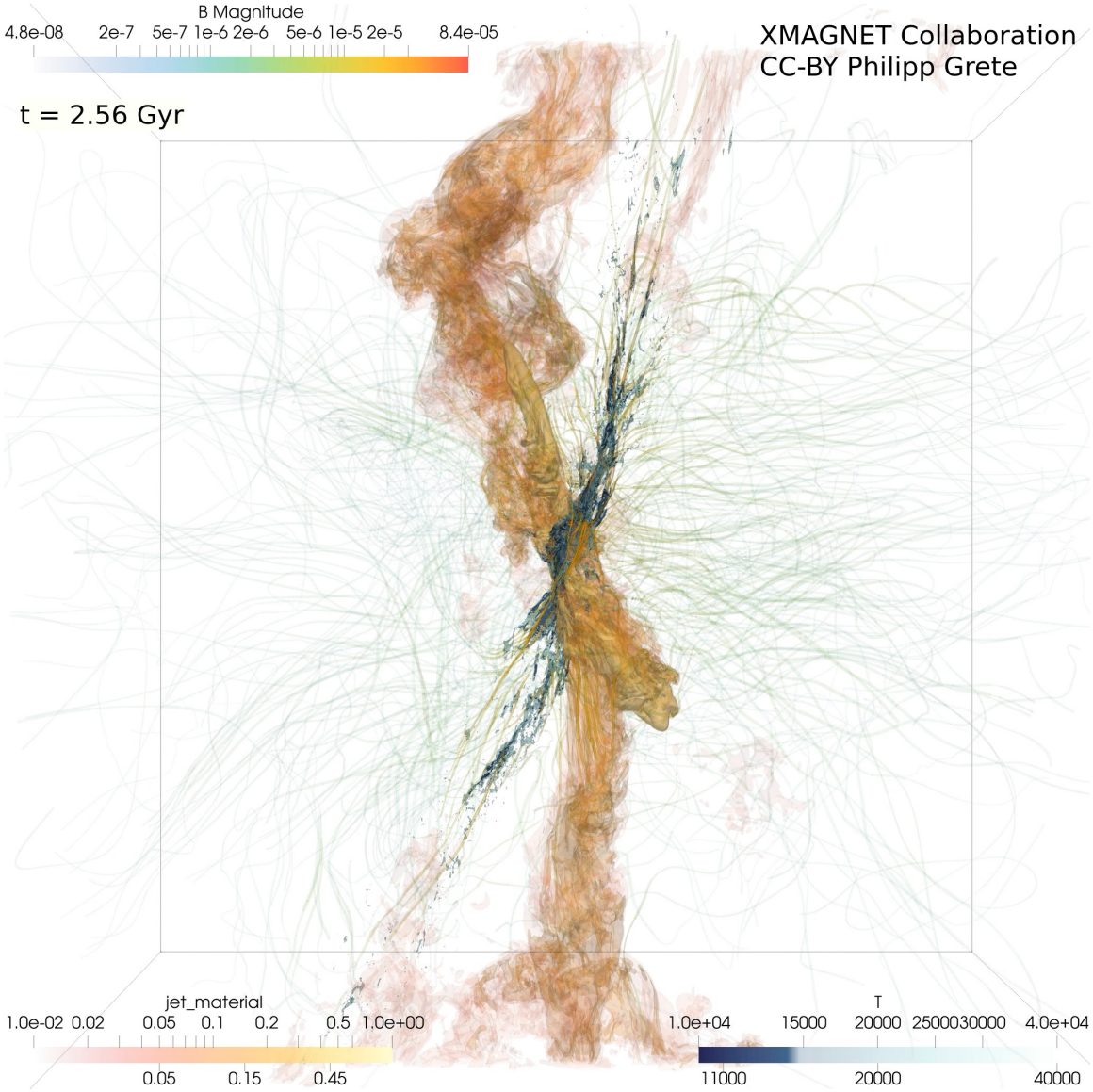
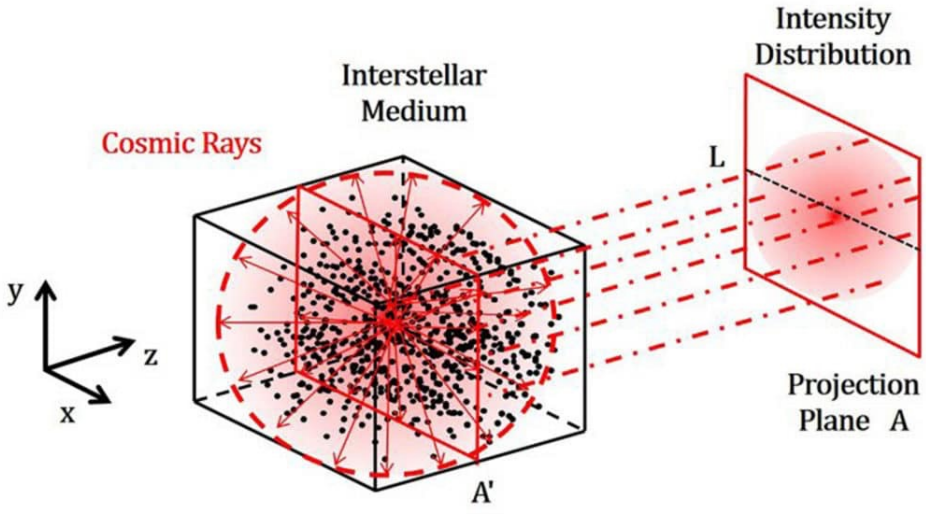
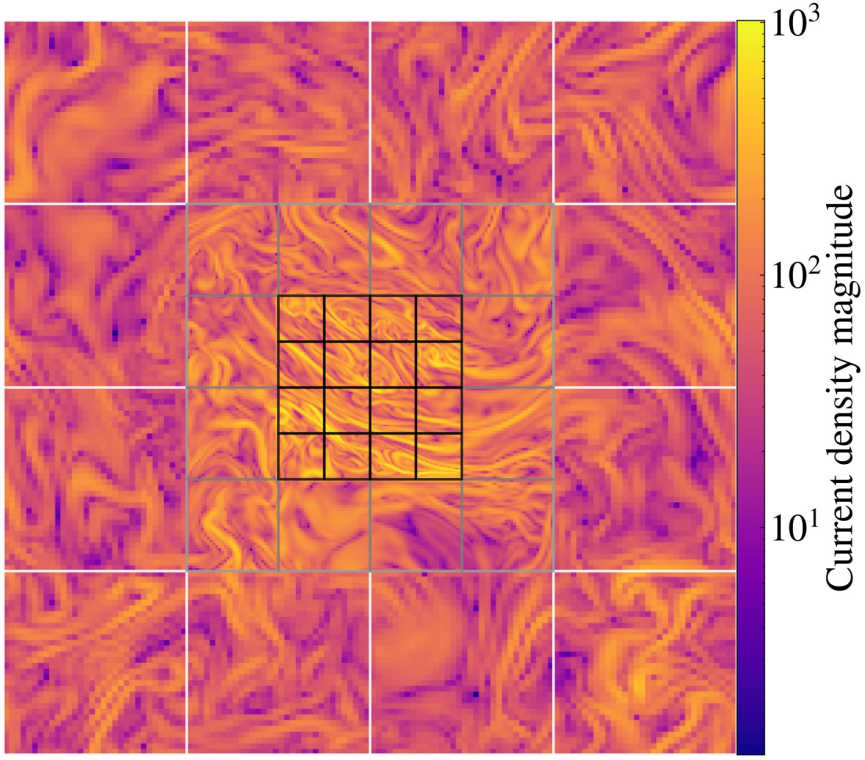

B Magnitude
4.8e-08 2e-7 5e-7 1e-6 2e-6 5e-6 1e-5 2e-5 8.4e-05
XMAGNET Collaboration
CC-BY Philipp Grete
t = 2.56 Gyr
jet_material
1.0e-02 0.02 0.05 0.1 0.2 0.5 1.0e+00
0.05 0.15 0.45
T
1.0e+04 15000 20000 2500030000 4.0e+04
11000 20000 40000

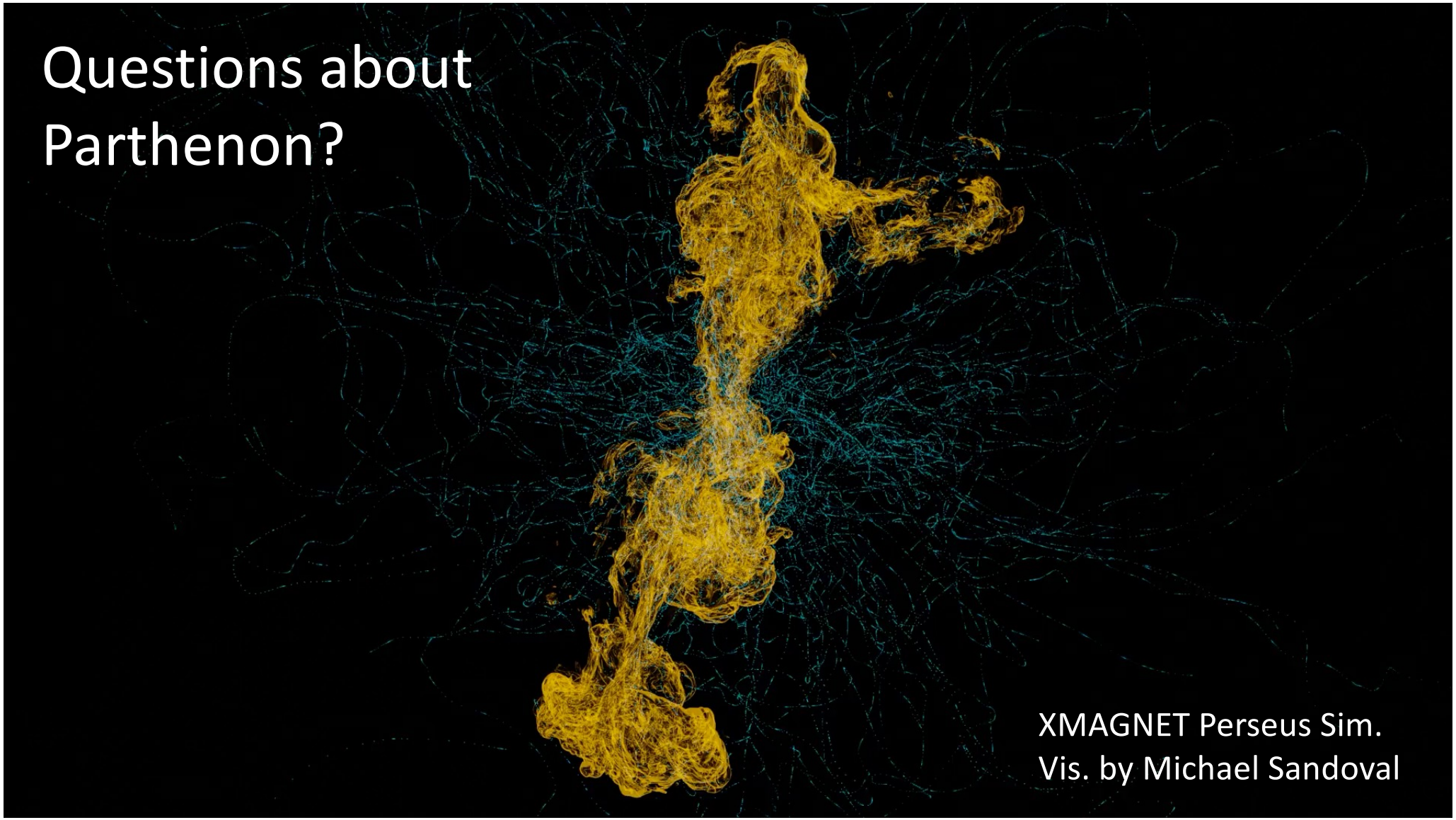
INCITE 2024 (Fielding): CR Transport and MHD Turbulence





MHD Turbulence with AthenaPK by Philipp Grete

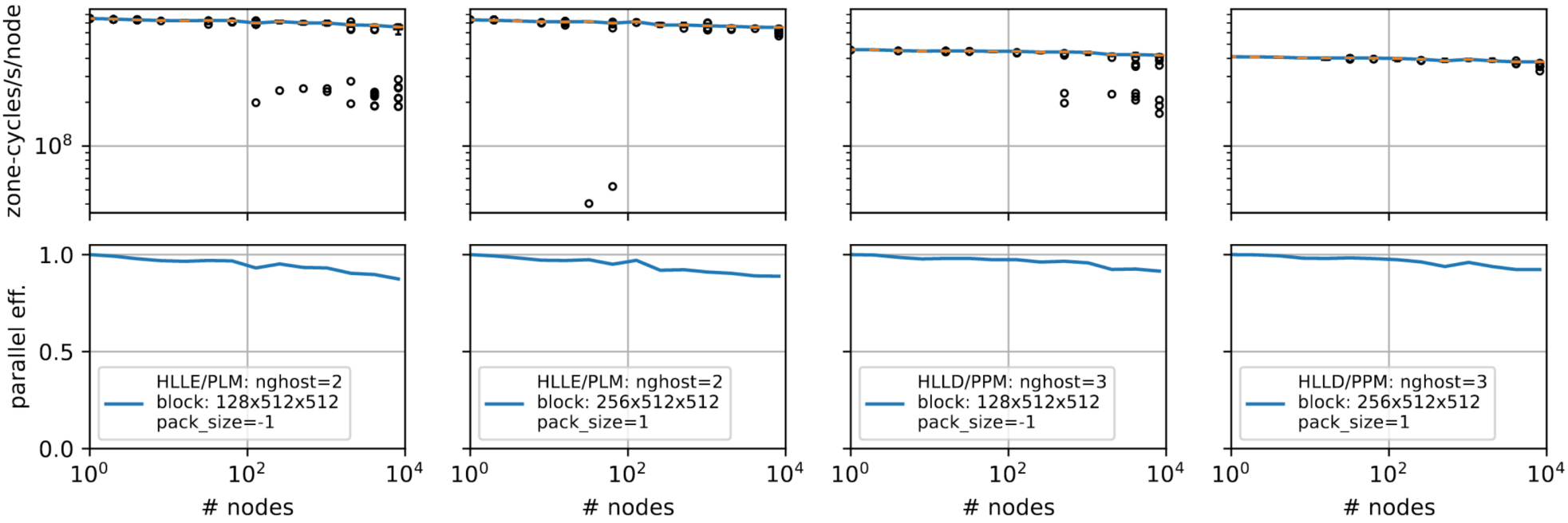
Questions about Parthenon?



XMAGNET Perseus Sim.
Vis. by Michael Sandoval

Extra Slides

Performance on Frontier



How to loop over a 3D Meshblock?