Denoising and related inverse problems in astrophysics

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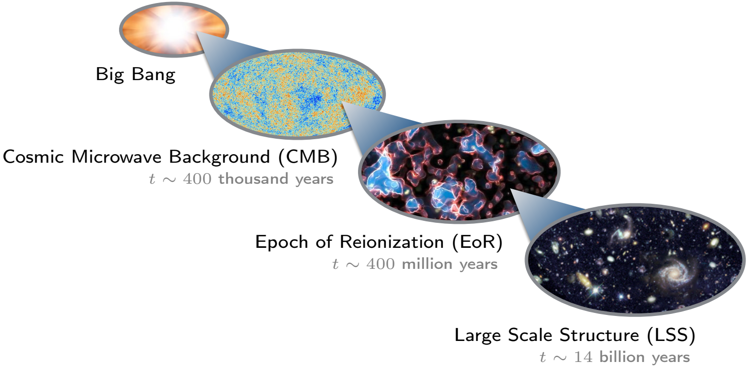
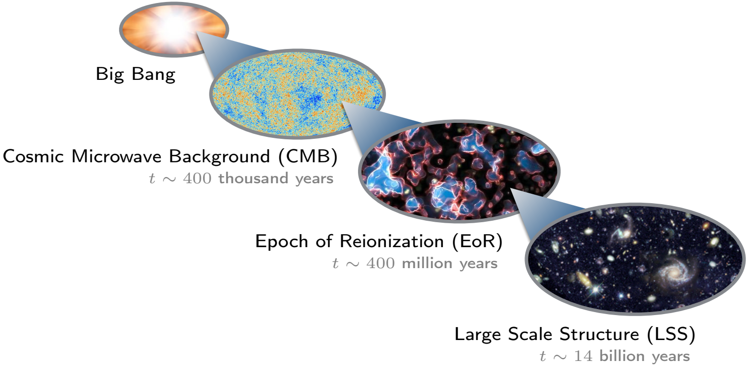
Signals and noise

"One person's noise is another's signal."


Big Bang
Cosmic Microwave Background (CMB)
$t \sim 400$ thousand years
Epoch of Reionization (EoR)
$t \sim 400$ million years
Large Scale Structure (LSS)
$t \sim 14$ billion years

Cosmic evolution

Signals and noise



Ill-posed denoising inverse problem:

$$\boxed{\boldsymbol{y} = \boldsymbol{x} + \boldsymbol{n}},$$

where $\boldsymbol{y}$ are observations, $\boldsymbol{x}$ is the underlying signal of interest, and $\boldsymbol{n}$ is noise.

Denoising and related inverse problems

Ill-posed denoising inverse problem:

$$\boxed{\boldsymbol{y} = \boldsymbol{x} + \boldsymbol{n}},$$

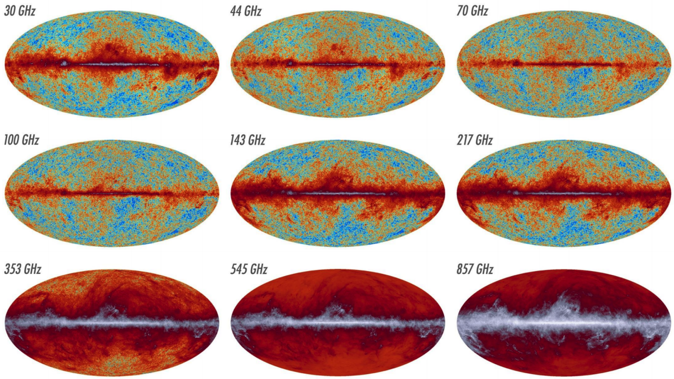
where $\boldsymbol{y}$ are observations, $\boldsymbol{x}$ is the underlying signal of interest, and $\boldsymbol{n}$ is noise.

Ill-posed inverse problem:

$$\boxed{\boldsymbol{y} = \boldsymbol{\Phi}\boldsymbol{x} + \boldsymbol{n}},$$

where $\boldsymbol{\Phi}$ is a linear (measurement) operator.

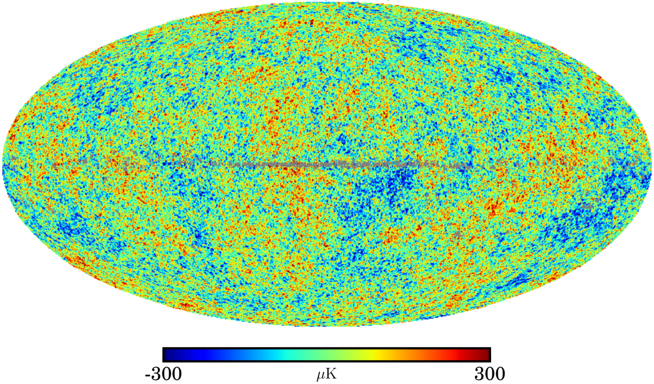
CMB foreground separation
Observations at different frequencies



CMB foreground separation

Recovered CMB map

SILC $(N = 1)$

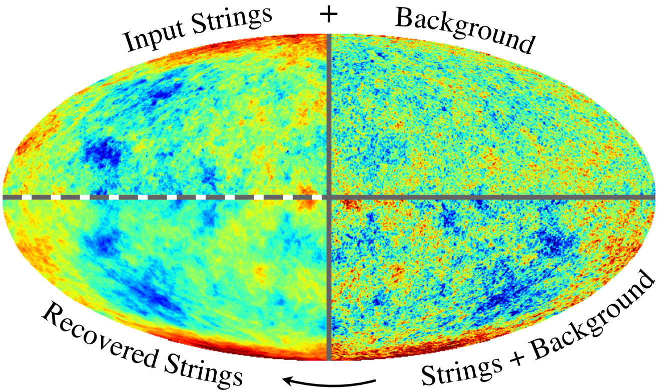


CMB foreground separation

Related papers

- Planck Collaboration IV (2018). Planck 2018 results. IV. Diffuse component separation. Astron. & Astrophys. arxiv:1807.06208
- K. K. Rogers, H. V. Peiris, B. Leistedt, J. D. McEwen, A. Pontzen (2016). Spin-SILC: CMB polarisation component separation with spin wavelets. Mon. Not. Roy. Astron. Soc.. arXiv:1605.01417
- K. K. Rogers, H. V. Peiris, B. Leistedt, J. D. McEwen, A. Pontzen (2016). SILC: a new Planck Internal Linear Combination CMB temperature map using directional wavelets. Mon. Not. Roy. Astron. Soc.. arXiv:1601.01322

Cosmic strings
Problem



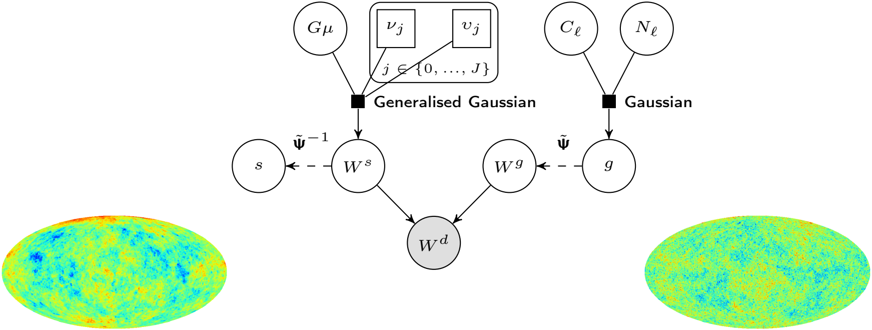


Figure: Hierarchical Bayesian model

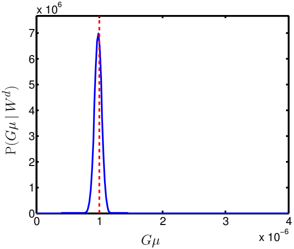
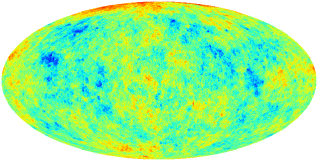


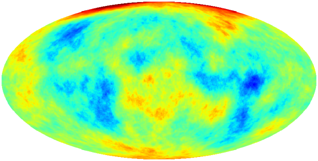
Figure: Posterior

Table: Bayes factors

$G\mu$ truth / 10^{-7}	Bayes factor $[\log_e]$
10.0	51.4
7.00	12.5
5.00	1.19
3.00	−3.87



(a) Ground truth



(b) Recovered

Figure: String map

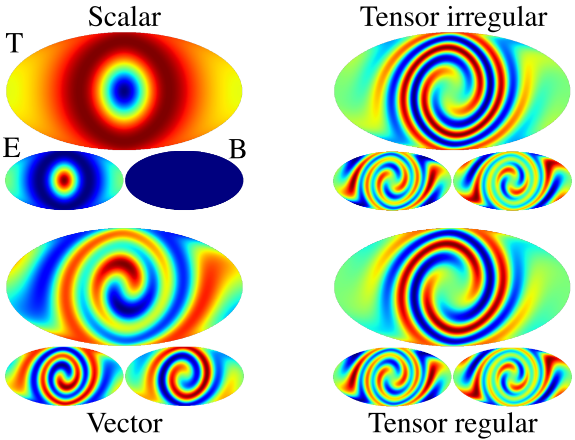
Cosmic strings

Related papers

- J. D. McEwen, S. M. Feeney, H. V. Peiris, Y. Wiaux, C. Ringeval, F. R. Bouchet (2017). Wavelet-Bayesian inference of cosmic strings embedded in the cosmic microwave background. Mon. Not. Roy. Astron. Soc.. arXiv:1611.10347
- Planck Collaboration XXV (2014). Planck 2013 results. XXV. Searches for cosmic strings and other topological defects. Astron. & Astrophys.. arXiv:1303.5085

Anisotropic cosmologies

Bianchi models of universal rotation



Anisotropic cosmologies

Related papers

- D. Saadeh, S. M. Feeney, A. Pontzen, H. V. Peiris, J. D. McEwen (2016). How isotropic is the universe?. Phys. Rev. Lett.. arXiv:1605.07178
- D. Saadeh, S. M. Feeney, A. Pontzen, H. V. Peiris, J. D. McEwen (2016). A framework for testing isotropy with the cosmic microwave background. Mon. Not. Roy. Astron. Soc.. arXiv:1604.01024
- Planck Collaboration XVIII (2016). Planck 2015 results. XVIII. Background geometry and topology of the Universe. Astron. & Astrophys.. arXiv:1502.01593
- Planck Collaboration XXVI (2014). Planck 2013 results. XXVI. Background geometry and topology of the Universe. Astron. & Astrophys.. arXiv:1303.5086
- J. D. McEwen, T. Josset, S. M. Feeney, H. V. Peiris, A. N. Lasenby (2013). Bayesian analysis of anisotropic cosmologies: Bianchi VII and WMAP. Mon. Not. Roy. Astron. Soc.. arXiv:1303.3409
- M. Bridges, J. D. McEwen, M. Cruz, M. P. Hobson, A. N. Lasenby, P. Vielva, E. Martinez-Gonzalez (2008). Bianchi VII signatures and the cold spot texture. Mon. Not. Roy. Astron. Soc.. arXiv:0712.1789
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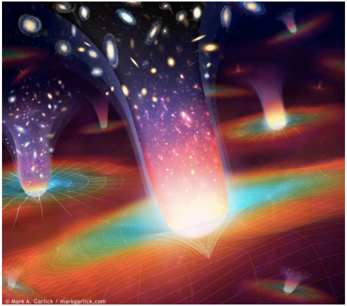
- J. D. McEwen, M. P. Hobson, A. N. Lasenby, D. J. Mortlock (2006). Non-Gaussianity detections in the Bianchi VII corrected WMAP 1-year data made with directional spherical wavelets. Mon. Not. Roy. Astron. Soc.. astro-ph/0510349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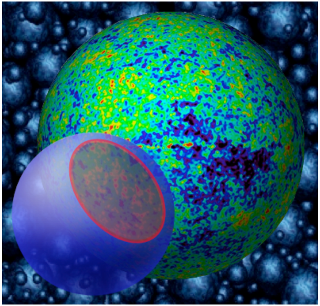
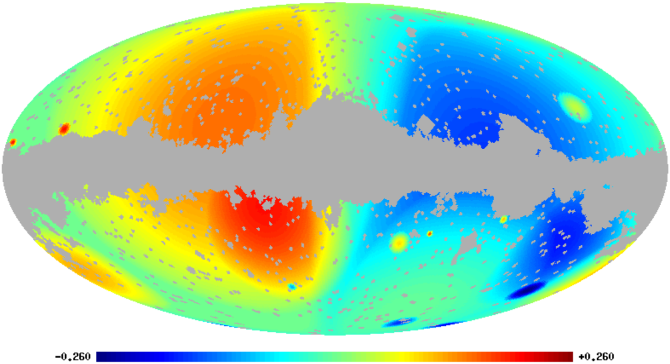
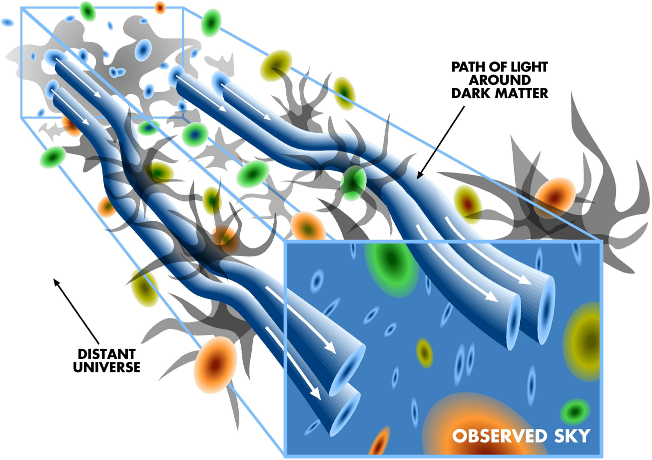



-0.260
+0.260

- S. M. Feeney, M. C. Johnson, J. D. McEwen, D. J. Mortlock, H. V. Peiris (2013). Hierarchical Bayesian detection algorithm for early-Universe relics in the cosmic microwave background. Phys. Rev. D.. arXiv:1210.2725
- J. D. McEwen, S. M. Feeney, M. C. Johnson, H. V. Peiris (2012). Optimal filters for detecting cosmic bubble collisions. Phys. Rev. D.. arXiv:1202.2861
- J. D. McEwen, M. P. Hobson, A. N. Lasenby (2008). Optimal filters on the sphere. IEEE Trans. Sig. Proc.. astro-ph/0612688

Mass mapping

Weak gravitational lensing



[Credit: Tyson]

Mass mapping
Mass mapping is a linear inverse problem

- Cosmic shear ${}_2\gamma$ related to convergence ${}_0\kappa$ (integrated mass) by:

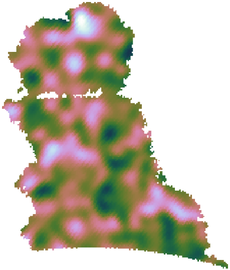
$$ {}_2\gamma = 2\eth^2 \left(\eth\bar{\eth} + \bar{\eth}\eth\right)^{-1} {}_0\kappa $$

Differential form

$$ {}_2\gamma(\boldsymbol{n}) = \int_{\mathbb{S}^2} \mathrm{d}\Omega(\boldsymbol{n}')\, {}_0\kappa(\boldsymbol{n}')(\mathcal{R}_{\boldsymbol{n}}\, {}_2\mathcal{K})(\boldsymbol{n}') $$

Integral form

- Mass mapping is a spherical inverse problem.
- Solve mass mapping problem in spherical setting, avoiding planar approximations (*e.g.* Wallis *et al.*).



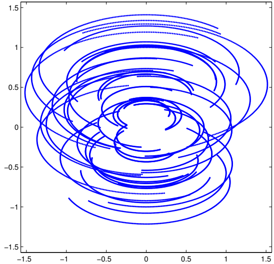
Mass mapping

Related papers

- M. A. Price, J. D. McEwen, L. Pratley, T. D. Kitching (2020). Sparse Bayesian mass-mapping with uncertainties: full-sky observations on the celestial sphere. Mon. Not. Roy. Astron. Soc., submitted. arXiv:2004.07855
- M. A. Price, J. D. McEwen, X. Cai, T. D. Kitching (2019). Sparse Bayesian mass-mapping with uncertainties: peak statistics and feature locations. Mon. Not. Roy. Astron. Soc.. arXiv:1812.04018
- M. A. Price, X. Cai, J. D. McEwen, M. Pereyra, T. D. Kitching (2019). Sparse Bayesian mass-mapping with uncertainties: local credible intervals. Mon. Not. Roy. Astron. Soc.. arXiv:1812.04017
- M. A. Price, J. D. McEwen, X. Cai, T. D. Kitching, C. G. R. Wallis (2019). Sparse Bayesian mass-mapping with uncertainties: hypothesis testing of structure. Mon. Not. Roy. Astron. Soc., submitted. arXiv:1812.04014
- C. G. R. Wallis, J. D. McEwen, T. D. Kitching, B. Leistedt, A. Plouviez (2017). Mapping dark matter on the celestial sphere with weak gravitational lensing. Mon. Not. Roy. Astron. Soc., submitted. arXiv:1703.09233

Radio interferometric imaging
Observational process

"Fourier"
Measurements



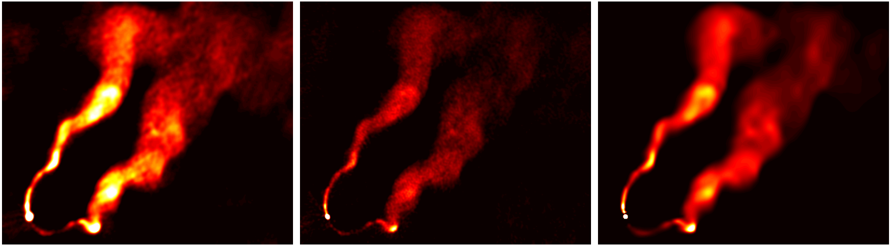
- Compressed sensing motivates sparse regularisation, imposing sparse prior in some representation $\boldsymbol{\alpha}$ (*e.g.* wavelets), where $\boldsymbol{x} = \boldsymbol{\Psi}\boldsymbol{\alpha}$:

$$\boldsymbol{\alpha}^\star = \arg\min_{\boldsymbol{\alpha}} \|\boldsymbol{\alpha}\|_1 \text{ s.t. } \|\boldsymbol{y} - \boldsymbol{\Phi}\boldsymbol{\Psi}\boldsymbol{\alpha}\|_2 \leq \epsilon$$

Synthesis framework

Radio interferometric imaging

PURIFY reconstruction of observations of 3C129 by the VLA

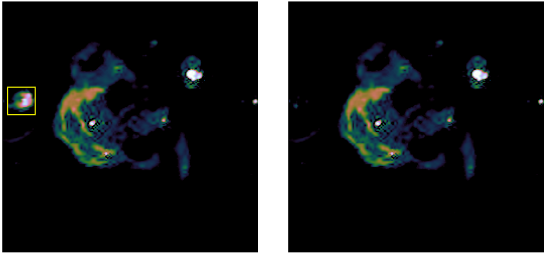


(a) CLEAN (natural); DR=220 (b) CLEAN (uniform); DR=495 (c) PURIFY; DR=969

Figure: 3C129 (Pratley, McEwen, *et al.* 2016)

Radio interferometric imaging

Uncertainty quantification



(a) Recovered image (b) Surrogate with region removed

Figure: Supernova remnant W28

Reject null hypothesis

$\Rightarrow$ structure physical

Radio interferometric imaging
Deep learning

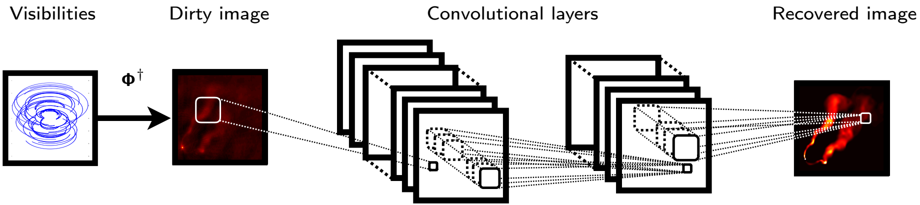


Figure: Deep learning architecture for interferometric imaging (Allam & McEwen, 2016)

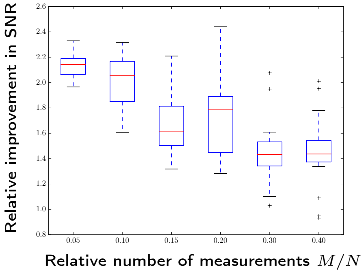
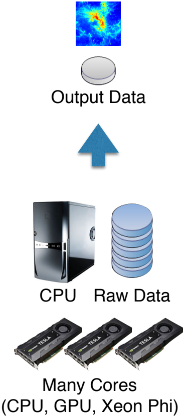


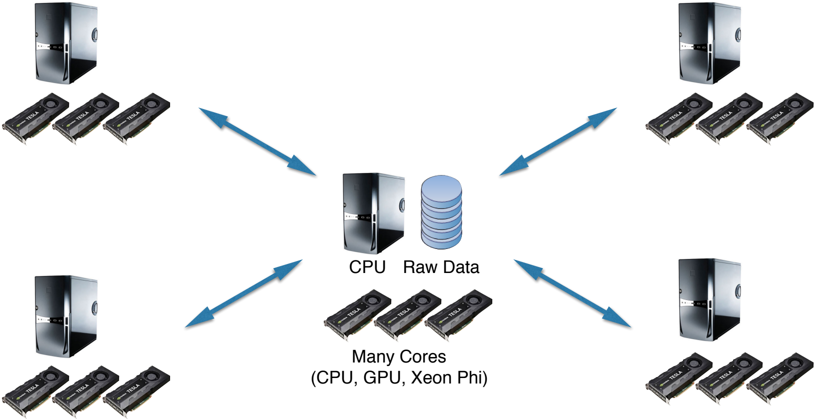
Figure: Improvement in signal-to-noise-ratio (SNR)



Output Data
CPU
Raw Data
Many Cores
(CPU, GPU, Xeon Phi)

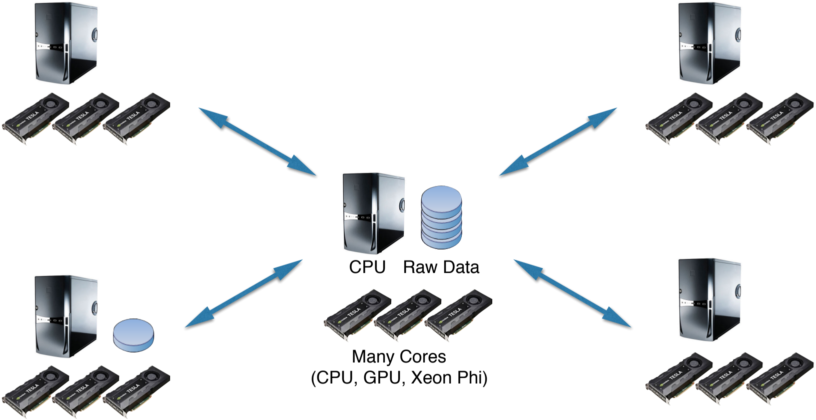
Radio interferometric imaging

Highly distributed and parallelized algorithms



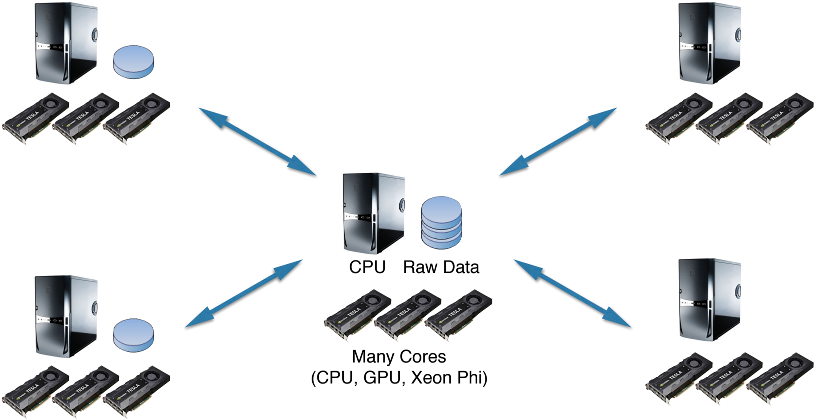
Radio interferometric imaging

Highly distributed and parallelized algorithms



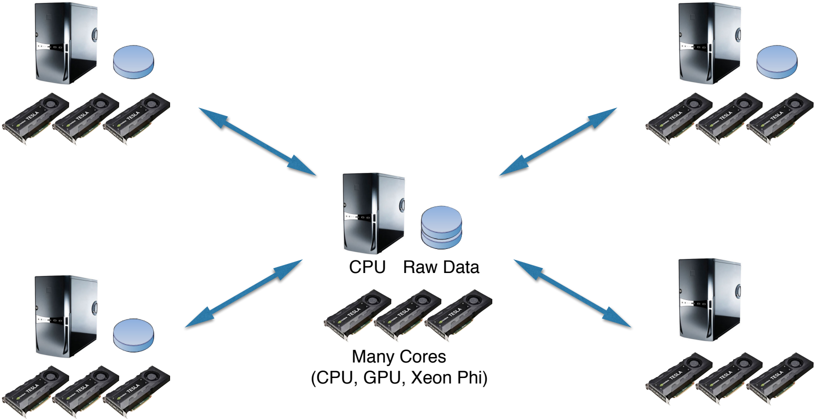
Radio interferometric imaging

Highly distributed and parallelized algorithms



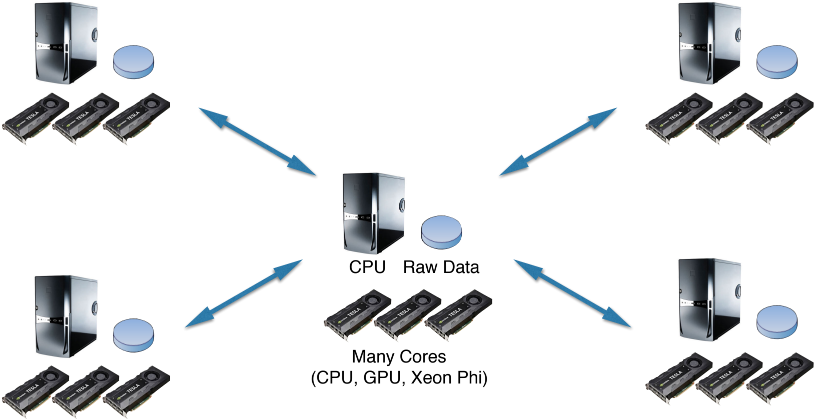
Radio interferometric imaging

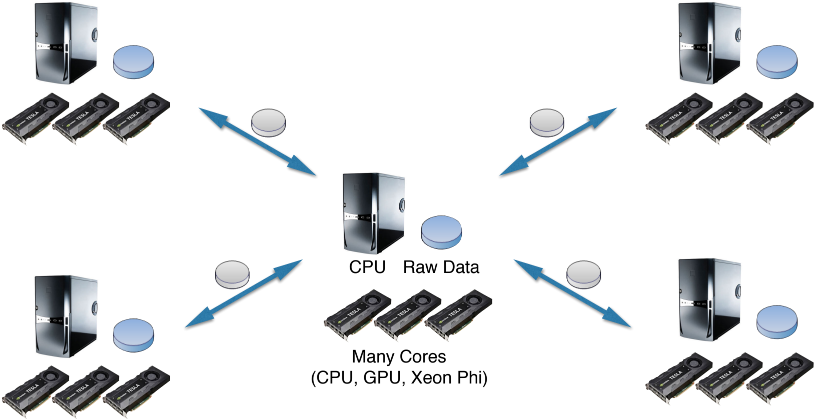
Highly distributed and parallelized algorithms



Radio interferometric imaging

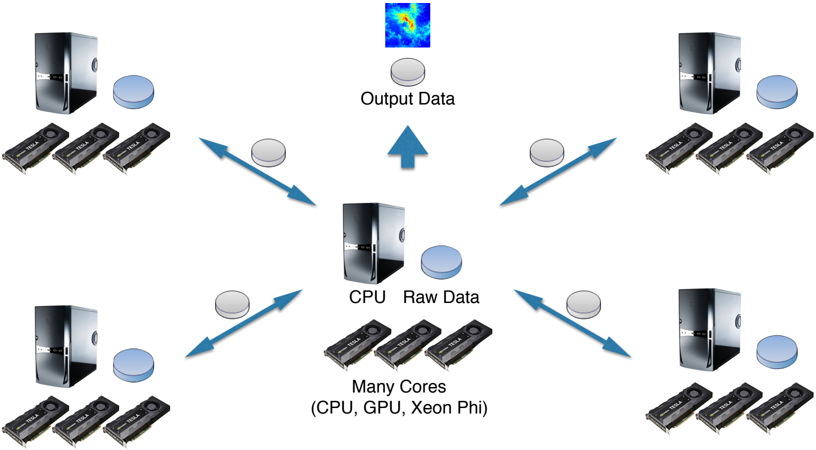
Highly distributed and parallelized algorithms




CPU
Raw Data
Many Cores
(CPU, GPU, Xeon Phi)

Radio interferometric imaging

Highly distributed and parallelized algorithms



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- L. Pratley, J. D. McEwen (2019). Sparse image reconstruction for the SPIDER optical interferometric telescope. Astrophys. J. Supp., submitted. https://arxiv.org/abs/arXiv:1903.05638
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- L. Pratley, J. D. McEwen, M. d'Avezac, X. Cai, D. Perez-Suarez, I. Christidi, R. Guichard (2019). Distributed and parallel sparse convex optimization for radio interferometry with PURIFY. Astron. Comput., submitted. https://arxiv.org/abs/arXiv:1903.04502
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Radio interferometric imaging
Related papers

- L. Pratley, M. Johnston-Hollitt, J. D. McEwen (2019). A fast and exact w-stacking and w-projection hybrid algorithm for wide-field interferometric imaging. Astrophys. J.. arXiv:1807.09239
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Radio interferometric imaging

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- A. Onose, R. E. Carrillo, A. Repetti, J. D. McEwen, J. -P. Thiran, J. -C. Pesquet, Y. Wiaux (2016). Scalable splitting algorithms for big-data interferometric imaging in the SKA era. Mon. Not. Roy. Astron. Soc.. arXiv:1601.04026
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- P. M. Sutter, B. D. Wandelt, J. D. McEwen, E. F. Bunn, A. Karakci, A. Korotkov, P. Timbie, G. S. Tucker, L. Zhang (2014). Probabilistic image reconstruction for radio interferometers. Mon. Not. Roy. Astron. Soc.. arXiv:1309.1469

Radio interferometric imaging

Related papers

- L. Wolz, F. B. Abdallah, R. E. Carrillo, Y. Wiaux, J. D. McEwen (2013). The varying- spread spectrum effect for radio interferometric imaging. Biomedical and Astronomical Signal Processing Frontiers (BASP). arXiv:1301.7259
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Radio interferometric imaging

Related papers

- J. D. McEwen, Y. Wiaux (2011). Compressed sensing for radio interferometric imaging: review and future direction. 18th IEEE International Conference on Image Processing (ICIP), invited contribution. arXiv:1110.6137
- J. D. McEwen, A. M. M. Scaife (2008). Simulating full-sky interferometric observations. Mon. Not. Roy. Astron. Soc.. arXiv:0803.2165