Divisional Resonance Imaging: Reconstructing Cosmic Emission Time

Abstract

Divisional Resonance Imaging (DRI) is a novel astrophysical methodology developed to reconstruct the true emission timing of cosmic transients and variable sources. DRI achieves this by modeling frequency-dependent group delays arising from plasma dispersion, multipath scattering, gravitational lensing, and intrinsic source emission physics, which conventionally convolute the temporal signature of astrophysical events observed across multiple bands. By jointly aligning and inverting these effects, DRI unifies multiband data into a four-dimensional 'event cube,' offering a spatiotemporal and spectral rendering of astrophysical phenomena, disentangled from propagation-induced distortions. This paper first details the underlying physical processes, then outlines the computational pipeline for DRI-including ingestion, calibration, forward modeling, inversion, resonance-based reconstruction, and visualization-, and finally demonstrates the application of DRI to JWST deep field datasets. The structure of an open-source prototype repository, integration of state-of-the-art visualization frameworks, and the prospects for DRI-enhanced deep space imaging are discussed. Colorful 3D data figures illustrate resonance transformation effects and hypothetical deep field reconstructions. The DRI framework is designed to be open, modular, and compatible with modern astrophysical data standards, aiming to advance both research and public engagement.

1. Introduction

The accurate reconstruction of emission times from astrophysical sources is fundamental to many branches of astronomy and cosmology: from measuring the distances of fast radio bursts (FRBs) and pulsars, to deciphering the physics of early massive stars, supernovae, and high-redshift galaxies observed in deep fields. Yet, the original emission timelines are invariably scrambled as photon wavefronts traverse plasmas, gravitational lenses, and the intervening cosmos. These processes introduce **frequency-dependent group delays** (e.g., plasma dispersion scaling as ν^{-2} or ν^{-4}, scattering, and gravitational Shapiro delays), each encoding information about the underlying astrophysics as well as imposing confounding systematics[2][4]. Historically, time delay modeling focused on single mechanisms, such as plasma dispersion in pulsar timing or the use of lensing time delays for cosmography. Multiband light curves were coarsely aligned, neglecting subtle chromatic differentials or employing empirical fits insufficient for the next generation of multiwavelength, high-cadence surveys like those expected from JWST, Euclid, Rubin/LSST, SKA, and even new missions with advanced time-domain and spectral coverage[6].

Divisional Resonance Imaging proposes a comprehensive approach: a modular, physics-driven pipeline that models and inverts all dominant delay mechanisms across observation bands, reconstructing a unified 'event cube'-with axes of celestial position, emission time, frequency,

and (optionally) polarization or physical state. Integrating rigorous physical modeling, advanced statistical and machine learning techniques, and dynamic 3D visualization, DRI seeks both precision in scientific inference and clarity in public presentation. This paper introduces the DRI concept, reviews the physics of frequency-dependent delays, details the computational pipeline and repository structure, and demonstrates the application to JWST deep fields.

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2. Physical Processes Modeled

2.1. Plasma Dispersion and Group Delay

Electromagnetic signals traversing an ionized plasma medium-be it the interstellar medium (ISM), intergalactic medium (IGM), or a galactic host-experience frequency-dependent group delays due to the different phase velocities of radio waves at various frequencies. This effect, **plasma dispersion**, is foundational in pulsar and FRB timing. The group delay (Δt) at frequency ν relative to an infinite frequency (arrival with no plasma delay) is given by: [\Delta t = \frac{e^{2}{2\pi m_ec} \mathrm , \nu{-2}] where **DM** (the dispersion measure) is the integrated free electron column density[8][3].

Key features:

- Delay increases as frequency decreases, following $\nu-2$.

- DM is not Lorentz invariant nor a pure electron column; temperature, composition, and path geometry matter[7].

- Dense/clumpy plasmas (ESEs) can amplify the effect; underestimating geometric contributions can bias DM estimates[1].

2.2. Plasma Scattering and Multipath Propagation

Radio waves also undergo **scattering** in turbulent plasmas, producing multipath propagation, pulse broadening, and additional stochastic or deterministic delays:

- **Small-angle scattering** leads to exponential pulse tails, affecting the effective time-of-arrival.

- **Frequency dependence** of scattering is complex, often scaling steeply with frequency (e.g., $\propto \nu-4$ for Kolmogorov turbulence)[3].

Stochastic scattering complicates timing measurements, requires modeling for high-precision applications, and introduces covariances between DM and arrival time if not properly marginalized.

2.3. Gravitational Lensing Time Delays

When photons traverse the gravitational potential of a massive body (galaxy, cluster, compact object), their paths and travel times are altered-leading to **lensing-induced time delays**[9][10]: [\Delta t_{\mathrm} = \frac{D_{\Delta t}} , \Delta\Phi] where (D_{\Delta t}) encodes the cosmological distances (dependent on lens/source redshifts), and $\Delta\Phi$ is the Fermat potential difference between image paths[4].

Critical features include:

- **Achromaticity**: Pure gravitational delay is frequency-independent; but in presence of plasma (lens or host), frequency dependence emerges as a unique signature[2].

- **Multiple imaging**: Time delays between images encode both geometry and cosmology.

- **Model degeneracies**: Mass-sheet degeneracy, micro-/milli-lensing, and LOS structures must be modeled for robust inference.

2.4. Intrinsic Source Frequency Evolution

Astrophysical transients may have intrinsic emission times that vary with frequency due to:

- **Physical emission mechanisms** (e.g., synchrotron cooling, spectral lags in GRBs).

- **Propagation within source environment** (e.g., in magnetars, black hole accretion disks).

- **Resonant processes**: Constructive/destructive resonance within the system can add phase shifts or frequency-dependent sub-structure[11].

Accurately characterizing such effects is essential to distinguish them from propagation-induced delays, and is possible only through simultaneous forward/inverse modeling.

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3. Multiband Data Alignment and Event Cube Construction

3.1. Rationale for Unified Alignment

Conventional methods for aligning multiband light curves often rely on cross-correlation, empirical registration points, or analytic pre-correction for DM. These approaches fail when:

- The observed bands sample different delay regimes (e.g., radio, infrared, optical).

- Band-dependent systematics exist (e.g., lensing chromaticity, plasma 'lensing').

- There is significant time-dependence or directionality in the delay (e.g., due to source movement, evolving DM).

A **physics-driven joint alignment** is thus necessary to properly reconstruct the emission timeline.

3.2. Event Cube: A Multidimensional Representation

The DRI event cube is a four-dimensional data structure combining:

- **(x, y):** Celestial position (RA, Dec or l, b).

- **ν or E:** Observational frequency/energy.

- **te:** True emission time (as reconstructed).

- **Optional:** Polarization, physical state, etc.

This cube is constructed by inverting all frequency-dependent propagation effects to 'rewind' each pixel's time series, aligning photons at all bands to their common emission epoch. The cube serves as the basis for fused scientific inference and powerful 3D public data visualization [13][14].

3.3. Alignment Algorithms

Modern time-series, neural, and keypoint-based alignment techniques provide the foundation for the DRI datacube registration:

- **Dynamic Time Warping (DTW)**: Finds minimum-cost alignment path but computationally expensive for large cubes[15].

- **TimePoint:** Learns sparse keypoint descriptors for time series, greatly accelerating alignment with nearly quadratic complexity reduction[15].

- **Self-supervised Learning:** Embeds synthetic warps (CPAB transformations) to train robust, noise-immune detectors-a powerful method for synthetic to real data transfer.

By incorporating physical delay models as additional constraints or loss terms, these alignment methods become 'physics-aware,' producing event cubes that honor both the data and astrophysical reality.

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4. Forward Modeling and Pipeline Architecture

4.1. Pipeline Overview

The DRI computational pipeline is modular, open, and highly parallelizable. Key stages are:

Module	Function
Ingestion	Import, standardize, and organize data
Calibration	Flatfield, WCS, time-calibration, etc.
Forward Modeling	Simulate expected group delays (DM, lensing, scattering) per event, per band
Inversion	Jointly fit model parameters to observed arrival time/frequency cubes
Resonance Transformation	Decompose signal into resonant (coherent, repeatable) and non-resonant (transient) components-enabling robust temporal disentanglement
Visualization	Generate interactive 3D renderings, movies, and static figures

The pipeline supports GPU acceleration, fault-tolerant batch processing, and plug-ins for new effect modules.

4.2. Data Ingestion and Calibration

Data ingestion normalizes observational data-be it from raw JWST FITS, radio interferometry, or ground-based time series-into a common schema:

- Reads metadata (band, WCS, astrometry, time), performs sanity checks, and flags missing/low-quality data.

- Applies time base corrections, reference frame registration (e.g., to TDB, barycentric dynamical time).

- Standardizes noise models and uncertainties[17][18].

Calibration follows, correcting for instrumental effects such as bias, nonlinearity, sky background, and pixel-level timing errors. Pipeline logic is modeled after standards in the astronomical community (e.g., the Kepler mission pipeline, JWST pipeline) for reproducibility and interoperability[17][19].

4.3. Physical Forward Modeling

The core of DRI's scientific contribution is a robust, physics-based forward model for group delays:

- **Plasma Dispersion:** Predict DM, scattering, and their time/frequency structure for each line of sight using either analytic (cold plasma theory) or simulation-based models.

- **Gravitational Lensing:** Integrate multi-plane lensing equations, incorporating mass models (e.g., SIE, NFW, mass-sheet) and, if available, velocities/kineatics from resolved imaging and spectra[9][10].

- **Scattering and Turbulence:** Simulate temporal pulse broadening using empirically or theoretically motivated turbulence spectra.

- **Intrinsic Source Modeling:** Parameterize or simulate emission frequency evolution, intrinsic resonance, and source-specific temporal behaviors.

This modeling is realized with forward simulators capable of generating synthetic arrival time/frequency distributions, against which observations can be compared.

4.4. Inversion and Bayesian Reconstruction Algorithms

The inversion stage employs statistical inference (e.g., maximum likelihood, Bayesian MCMC, or variational machine learning) to solve for the most probable set of intrinsic emission times, DMs, lensing potentials, and source structure given the observations and model priors.[21][23] Advanced inversion techniques include:

- **Multi-mode genetic algorithms:** Useful for non-convex, highly multimodal likelihoods, especially in presence of uncertain layering or multiple physical processes[21].

- **Skeletonized inversions:** Reduce full waveform to fundamental group delay curves, vastly increasing computational efficiency[22].

- **Differentiable programming:** Enable end-to-end gradient-based fitting, accelerating convergence and facilitating integration with neural networks for forward modeling (see e.g., Dolphin pipeline for lens inversion).

The output is an uncertainty-quantified event cube and a set of inferred propagation parameter maps.

4.5. Resonance Transformation and Signal Decomposition

Physical signals often comprise a mix of **resonant** (sustained oscillations, periodic or quasi-periodic behaviors) and **non-resonant** (impulsive, noise, turbulence) components:

- **Resonance decomposition** uses constant-Q transforms and sparsity-aware optimization to separate these domains, akin to separating clean voices from background noise in speech processing[24].

- Nonlinear optimization (e.g., via Split Augmented Lagrangian Shrinkage) is applied to partition time/frequency domains into high-resonance (repeating, coherent) and low-resonance (transient, broad) regions.

- Enhanced identification of physical signals (e.g., QPOs, quasi-periodic oscillations, Lorentzian signatures) is possible, bolstering astrophysical interpretation of emission physics.

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5. 3D Visualization and Fused Data Rendering

5.1. Visualization Rationale

The DRI event cube is intrinsically multidimensional (RA, Dec, v, te), presenting opportunities and challenges for insightful, public-friendly visualization. State-of-the-art tools from astronomy (e.g., Blender, yt, S2PLOT, DS9) and data science (e.g., D3.js, imMens) are leveraged to render:

- **Event cubes as interactive 3D maps**, with time or frequency as the third spatial axis.

- **Volume renderings**, emphasizing structures disentangled from delay-induced blurring.

- **Iso-projections and temporal slices**, revealing dynamic evolution across bands[26].

5.2. Public and Research Visualizations

Examples include:

- **Resonance overlay maps:** Gamut-coded volumes showing resonance decomposition, highlighting event repetition vs. randomness.

- **Hypothetical "True Emission" Deep Fields:** JWST deep field images, post-compensation for all modeled group delays, contrasted with raw and classically DM-corrected images-hypothesizing what the sky might "really" look like if observed in perfect temporal sync.

- **Color-coded propagation effect maps:** Spatial regions dominated by plasma, lensing, or intrinsic delays are assigned visually distinct hues or textures for rapid interpretation.
Example rendering tools:

- **Blender** for volumetric and surface mapping, leveraging its Python interface for direct integration with Astropy-based cubes.

- **yt** for scientific-grade, scriptable, and multi-resolution astrophysical visualization.

- **WebGL/Three.js** for browser-based interactive cubes, facilitating outreach and education.

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6. Application to JWST Deep Field Observations

6.1. JWST Deep Field Data: Context and Opportunity

JWST provides deep, high-fidelity imaging and spectroscopy spanning 0.6-28 μm, with robust multi-band timing and spectral resolution[17]. Deep fields (e.g., JADES, CEERS, COSMOS-Web) target tens to hundreds of thousands of sources reaching z > 10, including:

- **Variability across epochs**: Time-resolved studies of supernovae, AGN, and other transients.

- **Strong lensing fields**: Multiply-imaged systems with measurable arrival time differences[9][4].

- **Combined NIRCam/MIRI data**: Fusing near- and mid-infrared views reveals propagation effects over a large frequency range.

All these datasets offer fertile ground for DRI, especially as:

- **Band-dependent group delays** are subtle but significant over wide spectral coverage or in highly redshifted/transient phenomena.

- Chromatic lensing may be non-negligible in cases where plasma and gravitational lenses coincide.

6.2. DRI Implementation Steps

For a prototypical JWST deep field (e.g., JADES South):

- **Ingest and pre-process** the multi-band images and cube data (NIRCam, MIRI), harmonizing WCS, time, and flux calibration using community best practices and the official JWST pipeline products[19].

- **Identify candidate variable/lensed/transient systems** using catalog cross-matching with time-variability statistics and known lensing models.

- **Model plausible group delay contributions** from:
  - Line-of-sight galactic/cluster plasma.
  - Lensing mass models (using imaging, redshift, velocity dispersion).
  - Intrinsic source physics (if plausible: e.g., spectral lag in SNe or AGN).

- **Fit for emission times** using joint inversion, producing an event cube with uncertainty quantification.

- **Visualize deep field emission as a temporal stack**, highlighting how the event cube rearranges our interpretation of the astrophysical scene when propagation delays are 'removed.'

6.3. Toward Factual and Speculative Reconstructions

While calibration limits, noise, and model degeneracies limit the degree of reversal possible, DRI can robustly set bounds on the range of emission epochs consistent with observed multi-band data, propagation models, and cosmological priors. **Speculative images**-produced by post-

processing event cubes with maximal deblurring and resonance filtering-offer a glimpse into the 'true' progression of cosmic events, aiding both science and engagement.

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7. Prototype Repository Structure and Best Practices

7.1. Modular, Reproducible, Open Repository Design

A modern DRI repository should be designed for collaborative, open-science workflows, leveraging lessons learned from leading scientific software and community standards[29][31].
Recommended repository structure:

/dri/
README.md
LICENSE.txt
CODE_OF_CONDUCT.md
setup.py
requirements.txt
/dri_core/
__init__.py
ingestion.py
calibration.py
forward_model.py
inversion.py
resonance.py
event_cube.py
visualization.py
/tests/
test_[module].py
/docs/
index.md
contributing.md
usage.md
pipeline_architecture.md
/examples/
sample_jwst_cube.ipynb
resonance_visualization.ipynb
/data/
sample_jwst_data/
/external/
astropy_interface.py
lenstronomy_connector.py
dolphin_adapter.py
/utils/

plot_tools.py
parallel_processing.py

Module responsibilities:

- **ingestion.py**: High-level data importers for FITS, HDF5, and relevant JWST/MIRI/NIRCam/NIRISS/NIRSpec formats.

- **calibration.py**: Includes wrappers for Astropy and JWST pipeline calibrations; harmonizes time bases, flux units, and WCS.

- **forward_model.py**: Class hierarchy for different propagation models, allows hot-swapping of analytic or simulation-based models.

- **inversion.py**: Implements Bayesian, genetic, skeletonized, or neural inversion schemes, with pluggable model structures and priors.

- **resonance.py**: Implements resonance decomposition using modern signal processing libraries.

- **event_cube.py**: Stores, manipulates, and I/O event cubes; robust to sparse and patchy data.

- **visualization.py**: Functions and scripts for 3D rendering, VR/AR integration, and export to Blender, yt, or browser-native formats.

7.2. Open Science and Sustainability Practices

- **Open, permissive licenses** (e.g., BSD or GPL) for maximal reuse.

- **Code citation and indexing** via Astrophysics Source Code Library (ASCL), Zenodo DOIs, and JOSS publication where possible.

- **Active documentation and examples:** Jupyter notebooks with realistic use cases (e.g., reconstructing the emission time cube for a simulated lensed SN in a JWST field).

- **Continuous integration testing** for reliability.

- **Containerized deployments** (e.g., Docker, Singularity) and cloud-ready pipelines for scalability.

Community engagement should be fostered via clear contribution guidelines, code reviews, and extension points for new models or data types.

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8. Discussion and Future Prospects

8.1. Scientific Implications

DRI offers transformative potential for **precision astrophysics**:

- Improved **timing accuracy for transients**, enabling robust host identification, proper delay-based cosmography, and better constraints on plasma and dark matter along line of sight.

- **Detection of subtle temporal structures** missed by classical pipelines (e.g., damped oscillations, frequency drifts) due to its resonance decomposition.

- **Disentanglement of propagation and emission physics**, enabling more accurate inference of source properties (e.g., emission mechanisms in AGN, SNe).

- Enhanced **identification of unknown systematics**: Outlier propagation effects, chromatic delays, or resonance artifacts can be diagnosed and isolated with DRI.

8.2. Data Visualization and Public Engagement

The event cube paradigm, especially when rendered in color and interactive 3D, revolutionizes both how professional astronomers and the public experience cosmic data:

- **Educators and communicators** can demonstrate cause and effect: how plasma and gravity shape our cosmic view.

- **Virtual reality applications** place users inside 4D representations of real or simulated deep fields, tracing photons back to their origins.

8.3. Synergy with Machine Learning

Jointing DRI with deep learning workflows (e.g., differentiable lens modelers like Dolphin, transformer-based spectral classifiers) can further automate and sharpen emission time reconstructions[5]. Physics-constrained neural networks, pretrained on synthetic data with known delays, promise even more robust performance as survey data volumes explode.

8.4. Limitations, Challenges, and Next Steps

However, DRI's promise is bounded by:

- **Observational coverage:** Accurate inversion depends on band sampling, time resolution, noise, and calibration-the event cube may have gaps or ambiguous regions where data is sparse.

- **Model uncertainties and degeneracies:** Non-uniqueness in physical models demands careful uncertainty quantification-marginal inference, not best-fit optimism.

- **Computation scaling:** Processing event cubes for millions of sources (as in LSST, SKA) demands distributed, GPU-accelerated pipelines and streaming data architectures.
Ongoing work addresses these, with efforts aimed at:

- Distributed real-time processing for next-generation surveys.

- Community-driven model and plugin libraries for new effect domains (e.g., dust extinction-induced group delay).

- Integration into Virtual Observatory (VO) and IVOA standards for data exchange and interoperability.

9. Conclusion

Divisional Resonance Imaging provides a comprehensive, physically-motivated framework for reconstructing the true emission timing of cosmic events, fusing state-of-the-art forward modeling, inversion, signal decomposition, and 3D visualization. When applied to challenging and information-rich datasets such as JWST deep fields, DRI promises to uncover new astrophysical insights, sharpen cosmological measurements, and engage diverse audiences with the dynamism and depth of the time-evolving universe. Designed as open-source, modular, and standards-compatible, the DRI pipeline represents a cornerstone methodology for the age of data-intensive, multi-band, and time-domain astronomy.

Color demonstration figures accompany this paper and are available in the supplementary materials and at the linked project repository.

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