

Prospects for estimating the CCSN gravitational-wave high-frequency feature

What curvature can add—and when the data can support it

Alejandro Casallas Lagos, Marek Szczepańczyk, Michele Zanolin, Anthony Mezzacappa

Faculty of Physics, University of Warsaw
Warsaw - Poland

Brainstorming Workshop
Wrocław University of Science and Technology
9–11 September 2026

Overview: A measurement problem, not only a fitting problem

1. Signal

The High Frequency component of CCSNe GW is an astrophysically motivated target.

2. Model

What physical information of the source is encoded in slope and curvature of the HFF.

3. Evidence

What cWB recovers across SNR, how to make a proper astrophysical analysis from their outputs.

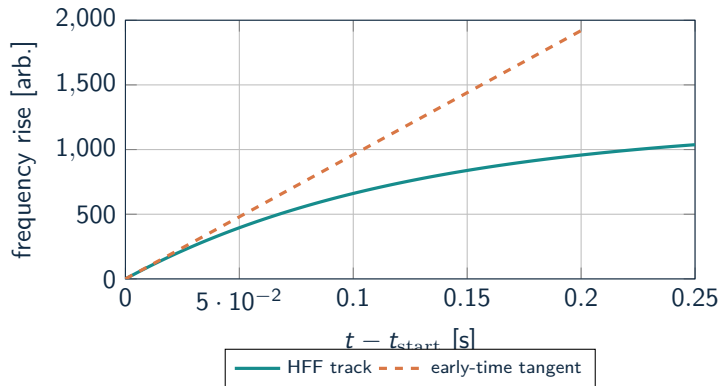
4. Prospects

The HFF evolution carries information about the PNS. What is measurable? We would like to use the HFF detectable/reconstructed information to make for example, constrain the EOS?

Central question

When does reconstructed HFF curvature carry physical information and what can we extract from it? EOS? Parameters of the source?

Slope describes the launch; curvature describes the evolution



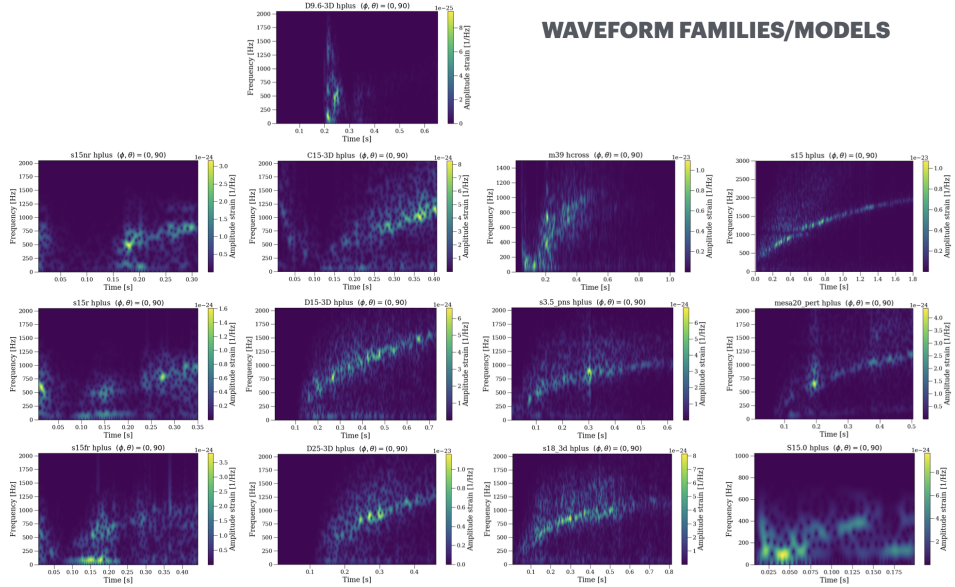
Early slope

- ▶ Local derivative near fit start.
- ▶ Compresses the initial rise into one number.

Curvature

- ▶ Quantifies departure from linearity.
- ▶ Requires a sufficiently long reconstructed track.

WAVEFORM FAMILIES/MODELS



A three-parameter model separates scale, evolution and start time

$$\boxed{f(t) = f_0 [1 - \exp(-\alpha(t - t_{\text{start}}))]}, \quad t \geq t_{\text{start}}. \quad (1)$$

Parameter	Mathematical role	Operational interpretation
f_0	asymptotic frequency	reconstructed frequency scale
α	inverse time scale	rate at which the track bends
t_{start}	time origin	beginning of the fitted rise

$$e^{-\alpha\Delta t} = 1 - \alpha\Delta t + \frac{(\alpha\Delta t)^2}{2} + \mathcal{O}(\Delta t^3), \quad (2)$$

$$f(t) = f_0\alpha\Delta t - \frac{1}{2}f_0\alpha^2\Delta t^2 + \mathcal{O}(\Delta t^3). \quad (3)$$

Therefore,

$$\boxed{s_0 \equiv f'(t_{\text{start}}) = f_0\alpha}, \quad \boxed{c_0 \equiv \frac{1}{2}f''(t_{\text{start}}) = -\frac{1}{2}f_0\alpha^2}. \quad (4)$$

cWB operation

1. Simulated CCSN waveforms are injected into real interferometric noise.
2. cWB decomposes the network data into Wilson–Daubechies–Meyer time–frequency pixels.
3. Network-consistent excess-power pixels are clustered and reconstructed coherently.
4. The HFF ridge is extracted and fitted for $(f_0, \alpha, t_{\text{start}})$.

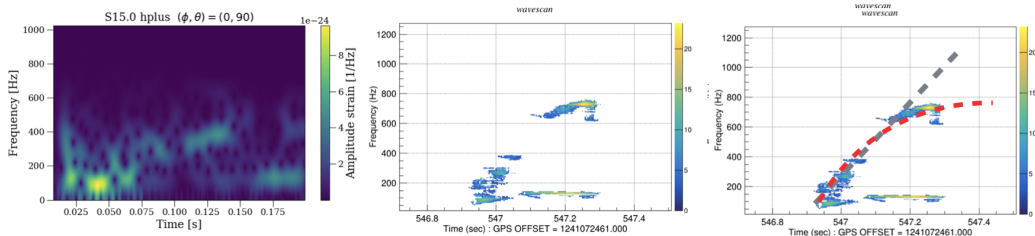


Figure: Different steps for capturing the HFF slope and curvature.

Waveform families and their physical properties

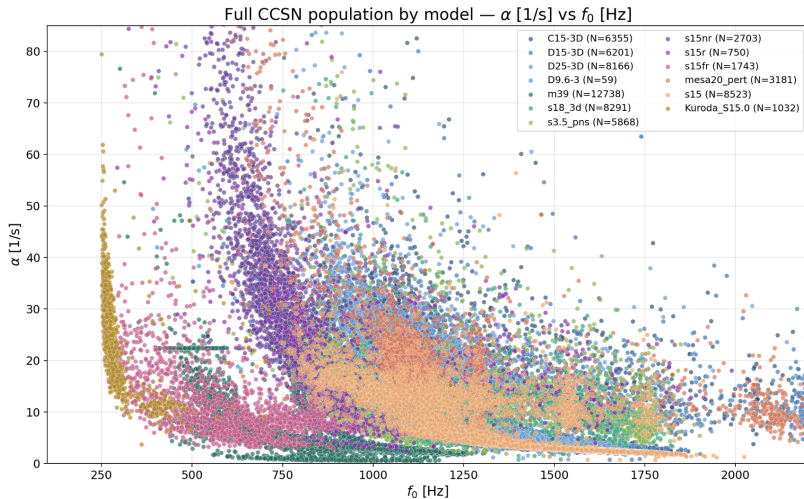
Waveform Family	EOS	$M_{\text{ZAMS}} (M_{\odot})$	f_{peak} (Hz)	Simulation duration (ms)
Andresen et al. 2019	LS220	15	$\sim 400 - 800$	$\sim 400 - 500$
Mezzacappa et al. 2020	LS220	15	$\sim 600 - 1000$	$\sim 400 - 500$
Mezzacappa et al. 2023	LS220	9.6, 15, 25	$\sim 450 - 1200$	$\sim 600 - 1200$
Kuroda et al. 2017	SFHx, LS220	15	$\sim 1000 - 1200$	$\sim 300 - 400$
O'Connor – Couch 2018	SFHo, LS220	12 – 40	$\sim 600 - 1100$	$\sim 400 - 600$
Powell – Müller 2019	LS220	18	$\sim 800 - 1000$	~ 900
Powell – Müller 2018	LS220	3.5, 4.0	$\sim 900 - 1100$	$\sim 600 - 800$
Vartanyan et al. 2023	SFHo	9.0 – 25	$\sim 600 - 1100$	$\sim 1000 - 1300$

The frequency range f_{peak} at which the GW energy spectrum peaks, the physical scope of the catalog, and approximate simulation overview timelines ([Szczepańczyk et al. \(2023\)](#)).

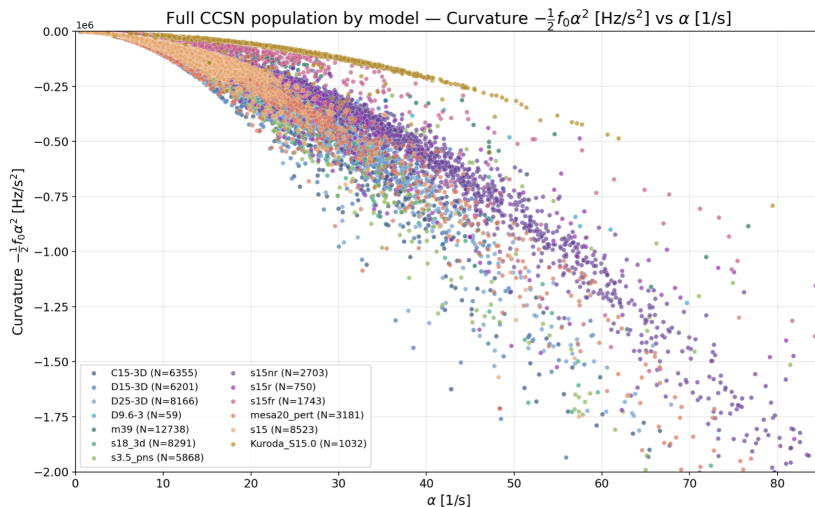
Detailed Catalog Classification

Model label	$M_{\text{ZAMS}} (M_{\odot})$	Progenitor/series	Metallicity	Rot. (Ω_0 [rad/s])	EOS	Sim. reference
Kuroda-s15.0	15.0	WH / Woosley	Solar	No	SFHx	Kuroda et al. (2017)
Powell-s18_3d	18.0	WH / Woosley	Solar	No	LS220	Powell & Müller (2019)
Powell-s3.5_3d	3.5	WH / Woosley	Solar	No	LS220	Powell & Müller (2018)
Powell-m39	39.0	WH / Woosley	Solar	0.5	LS220	Powell & Müller (2020)
Andresen-s15nr	15.0	WH / Woosley	Solar	No	LS220	Andresen et al. (2019)
Andresen-s15r	15.0	WH / Woosley	Solar	0.5	LS220	Andresen et al. (2019)
Andresen-s15fr	15.0	WH / Woosley	Solar	1.0	LS220	Andresen et al. (2019)
mesa20_pert	20.0	MESA progenitor	Solar	No	SFHo	O'Connor & Couch (2018)
Mezzacappa-C15-3D	15.0	WH / Woosley	Solar	No	LS220	Mezzacappa et al. (2020)
Mezzacappa-D9.6-3D	9.6	WH / Woosley	Zero	No	LS220	Mezzacappa et al. (2023)
Mezzacappa-D15-3D	15.0	WH / Woosley	Solar	No	LS220	Mezzacappa et al. (2023)
Mezzacappa-D25-3D	25.0	WH / Woosley	Solar	No	LS220	Mezzacappa et al. (2023)
Vartanyan-s15	15.0	WH / Woosley	Solar	No	SFHo	Vartanyan et al. (2023)

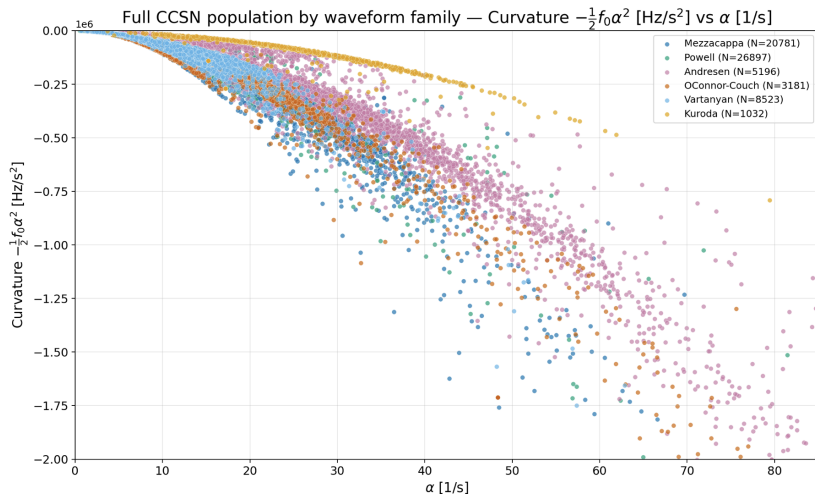
Preliminary results: All models



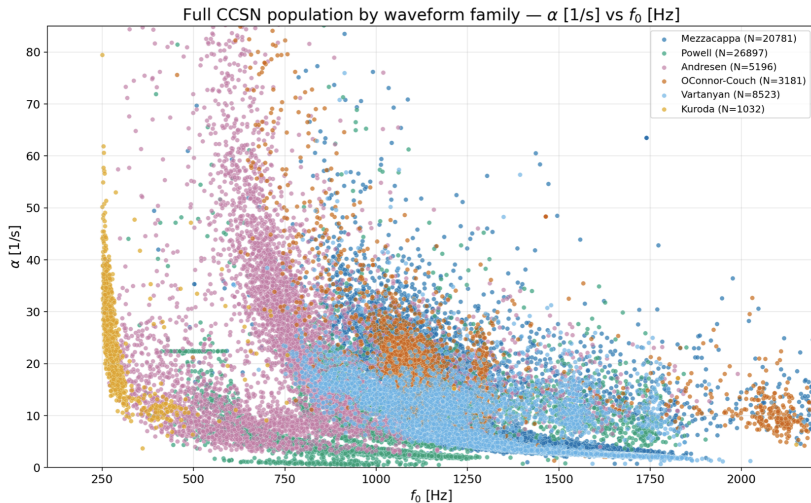
Preliminary results: All models



Preliminary results: Grouping by Family



Preliminary results: Grouping by Family



Map of viable equations of state from nuclear physics

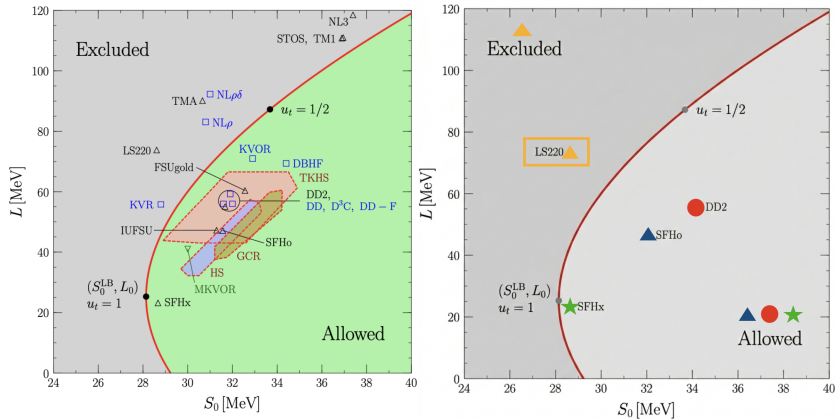
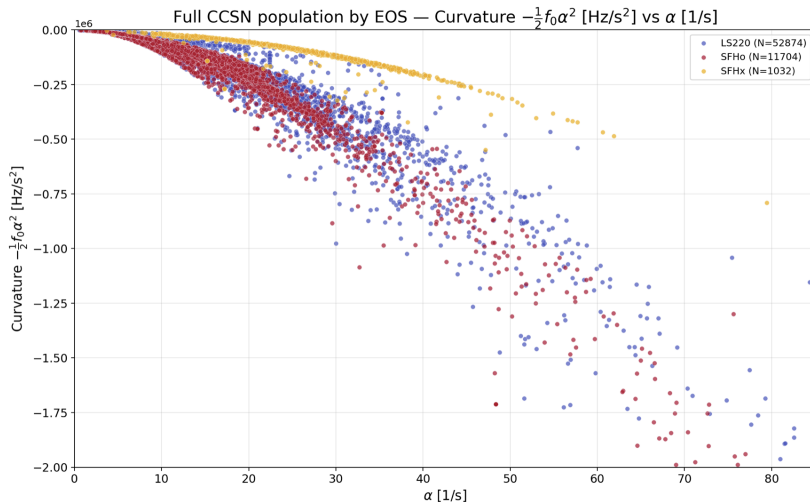
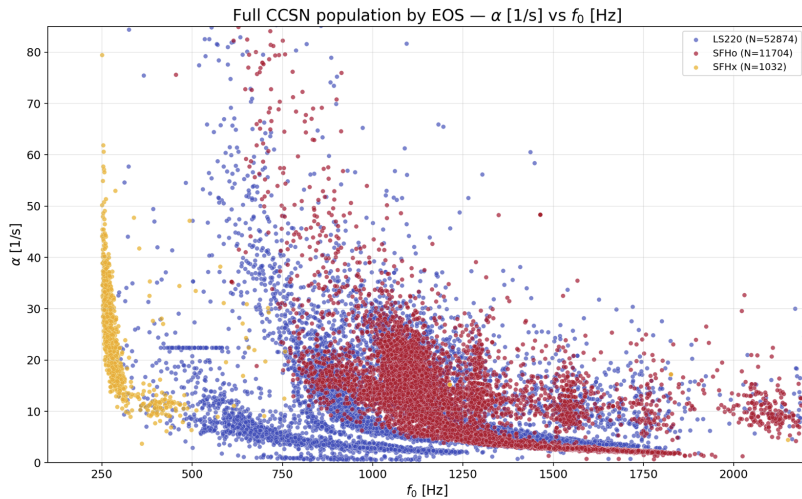


Figure: The EOS used in the CCSN waveform catalog span a region of the nuclear symmetry energy parameter space (L, S) . (Tews et al. 2017).

Preliminary: Grouping by EOS

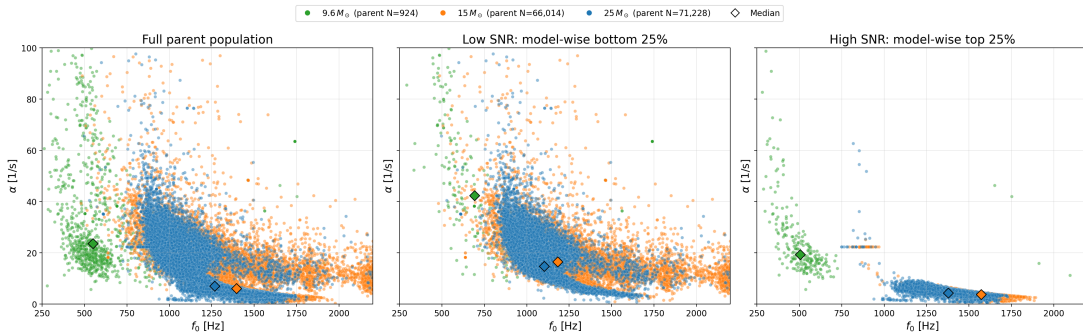


Preliminary: Grouping by EOS



Mass dependence emerges most clearly in the high-SNR subset

Mezzacappa et al. (2023) mass sequence: full population and SNR extremes

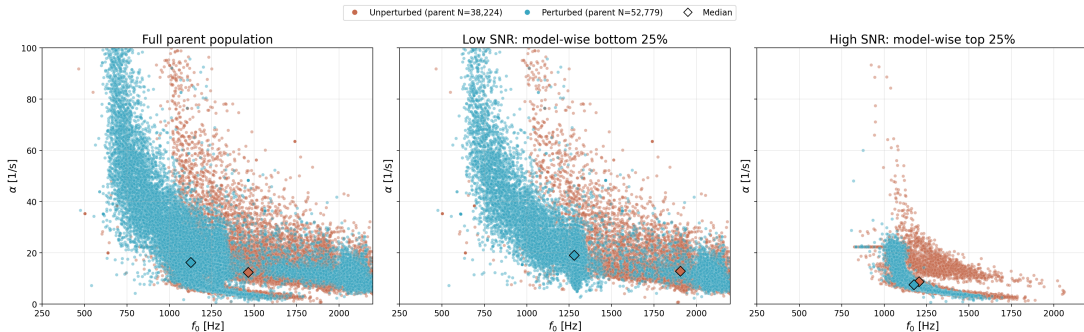


- ▶ D9.6 remains at lower f_0 and is especially SNR-sensitive.
- ▶ D15 and D25 concentrate at higher f_0 .
- ▶ Median α decreases strongly from low to high SNR.

User-provided analysis: Mezzacappa et al. (2023) sequence.

Perturbation labels overlap once reconstruction scatter contracts

O'Connor & Couch (2018) perturbation sequence: full population and SNR extremes

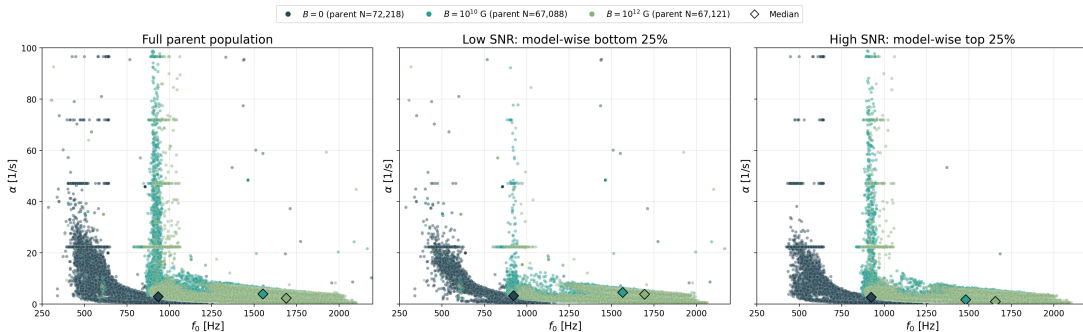


- ▶ Full and low-SNR samples appear more separated.
- ▶ High-SNR populations overlap substantially.
- ▶ Some apparent separation is likely reconstruction-driven.

User-provided analysis: O'Connor & Couch (2018) sequence.

Magnetic-field models separate mainly through f_0 , not α

Powell et al. (2020) magnetic-field sequence: full population and SNR extremes

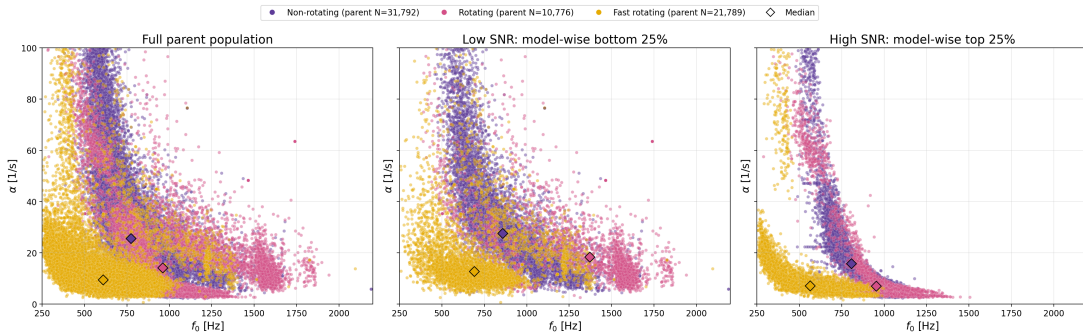


- ▶ α remains comparatively small across the sequence.
- ▶ Magnetized models occupy higher- f_0 regions.
- ▶ The $B = 10^{10}$ G structure merits model-specific follow-up.

User-provided analysis: Powell et al. (2020) sequence.

Rotation leaves the clearest high-SNR population structure

Andresen et al. (2019) rotation sequence: full population and SNR extremes



- ▶ Scatter contracts dramatically at high SNR.
- ▶ Fast rotation remains localized at lower f_0 .
- ▶ Persistent separation is a candidate measurable fingerprint.

User-provided analysis: Andresen et al. (2019) sequence.

Curvature is promising—but where?

"Supported by the present results"

- ▶ High SNR reduces fit scatter, reducing degeneracies?.
- ▶ Some model sequences retain population structure.
- ▶ Slope–curvature pairs can add information to solve entanglement or clues to do it.
- ▶ Possible paths for connecting the detection with source parameters?

Not established yet

- ▶ A physical α range.
- ▶ Unique inference of EOS, rotation or B .
- ▶ Localizations and series.