Merger history from the critical event theory

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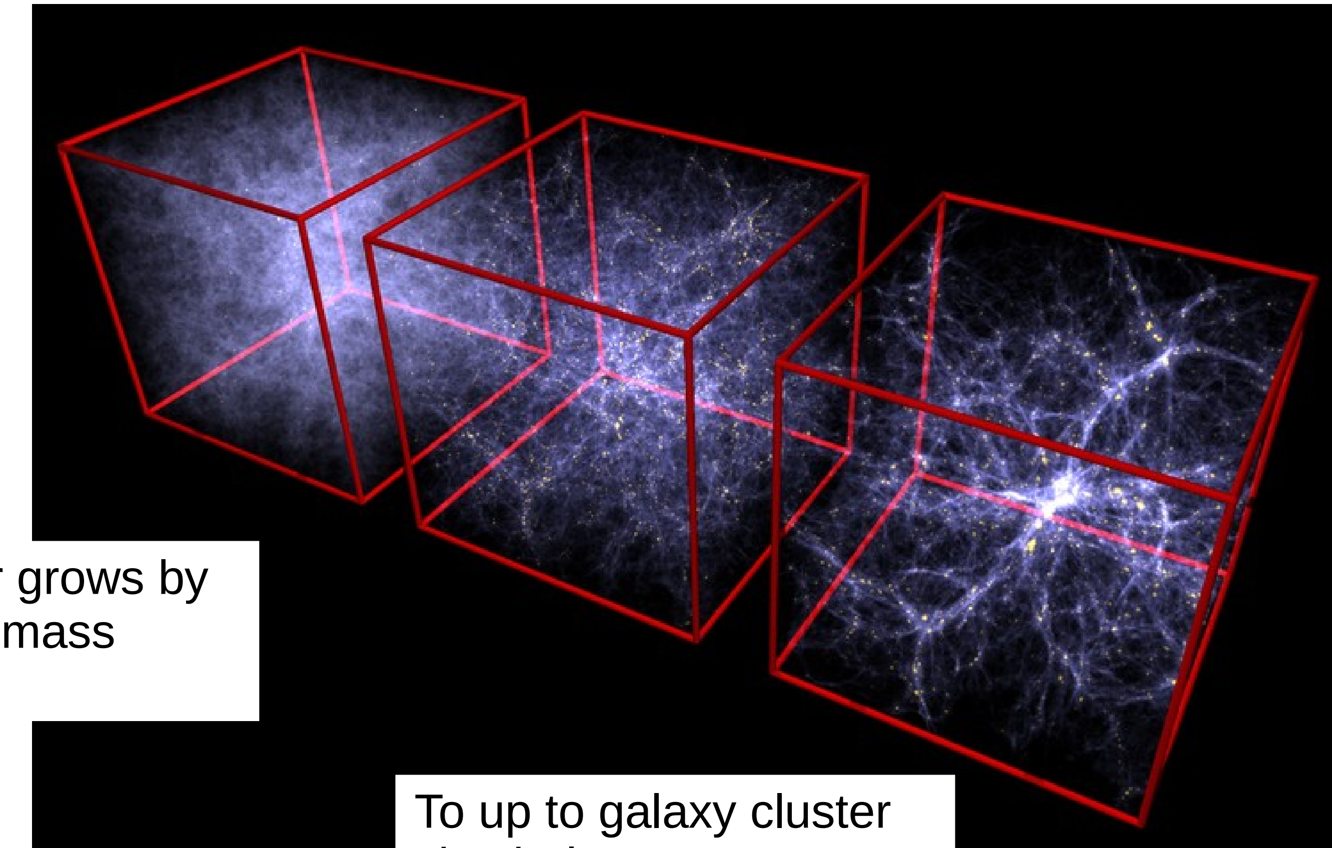
stemmed from: Eric Pharabod summer 2020 internship.

Hierarchical clustering in cosmic evolution

Evolution of the large-scale-structure proceeds hierarchically

From small first objects formed at high redshifts from small scale initial inhomogeneities

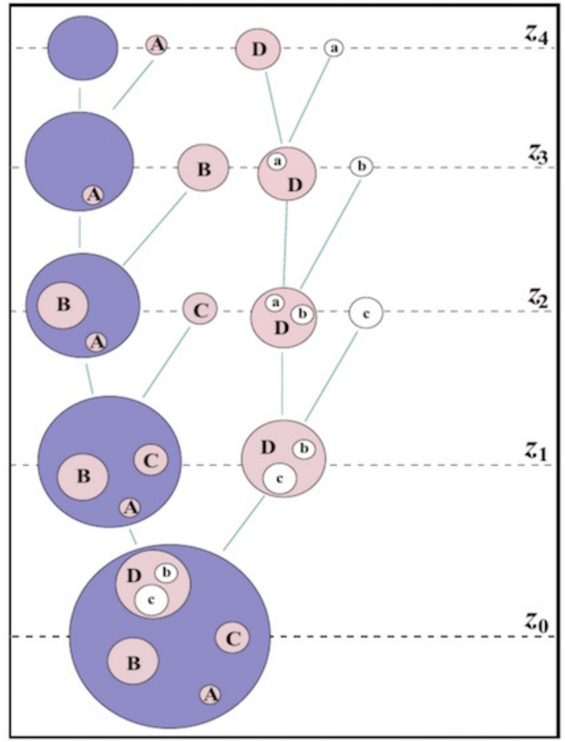


Through their grows by mergers and mass accumulation

To up to galaxy cluster size halos at present time of z=0

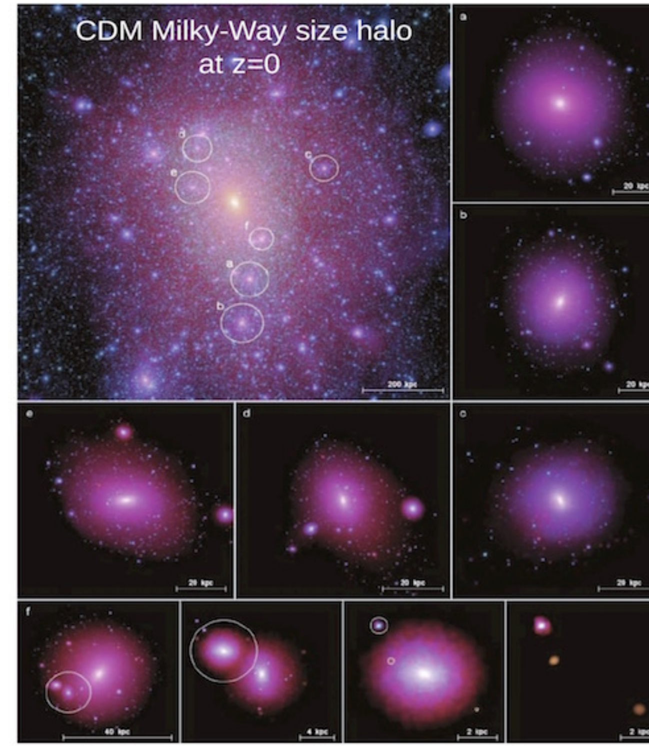
Halo merging during the evolution

Examples of galaxies merging
In NewHorizon simulations
(*Dubois et al, 2020*)



merger tree encodes the history of mergers from the halo.

Here we will be specially focused on the trunk of the tree



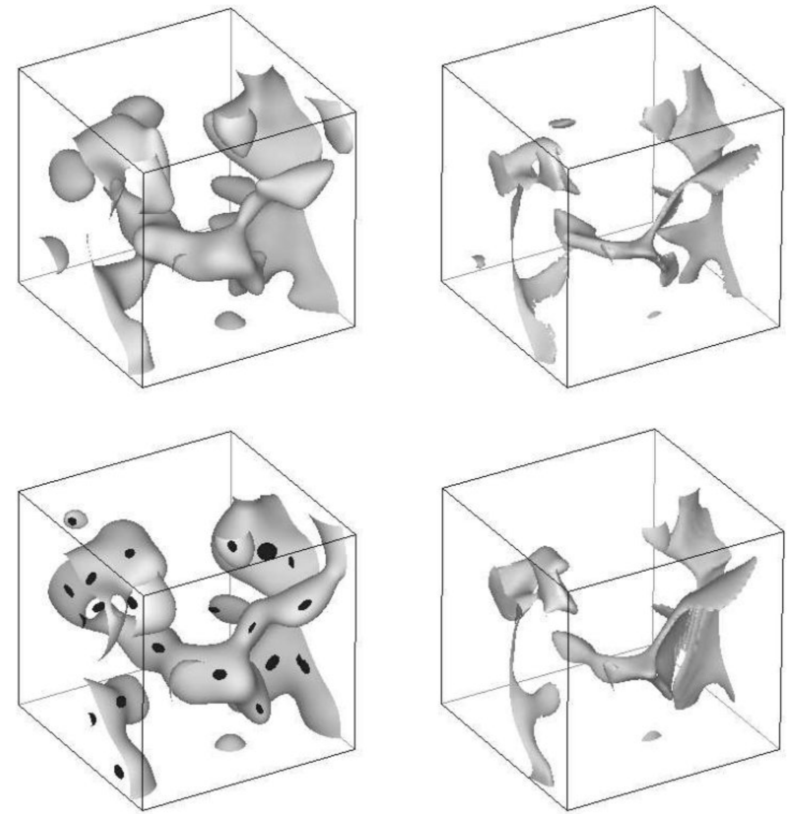
merger history may be imprinted in the substructure that is not fully mixed up in the final halo.

Understanding LSS from initial density field

- *Bond et al (BBKS) 1986* – maxima (peaks) as progenitors of halos, count of the critical points (maxima, minima, saddles), focus on peaks.
- *Bond, Kofman, Pogosyan, 1996* – Cosmic Web of filaments as bridges between peaks
- *Sousbie et al, 2008* – skeleton of the Cosmic Web
- *Codis et al, 2018* – connectivity of the filamentary Web, focus on saddle points

Underlying theme: study of critical points (extrema and saddles) at fixed smoothing scale R, that corresponds to the masses of the future halos. $\sigma(R,z)=1$ defines growing in z scale of nonlinearity.

But: halos of different masses coexist at the same time. This calls for the hierarchy of smoothing scales. How this then relates to the time hierarchy?



initial density, smoothed

final density, smoothed

Peaks are anchors for the structures

Peaks become halos at late time

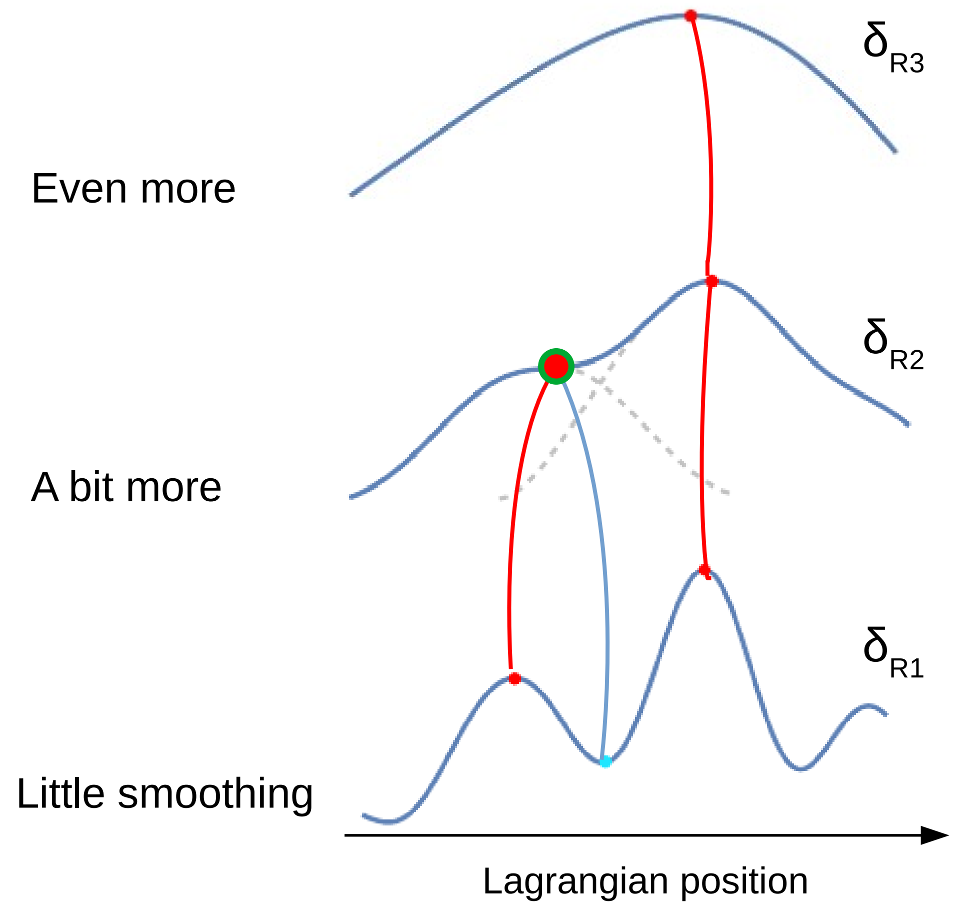
Critical events when smoothing varies

(*Hanami, 2001, Cadiou et al, 2020*)

Let us consider what happens with peaks as we continuously increase smoothing scale

In 1D example, some peaks survive, but others merge at some smoothing with a neighbouring minimum, in a critical event. In such event one peak disappears, and should be considered “merged” with the surviving peak (on the other side of the minima)

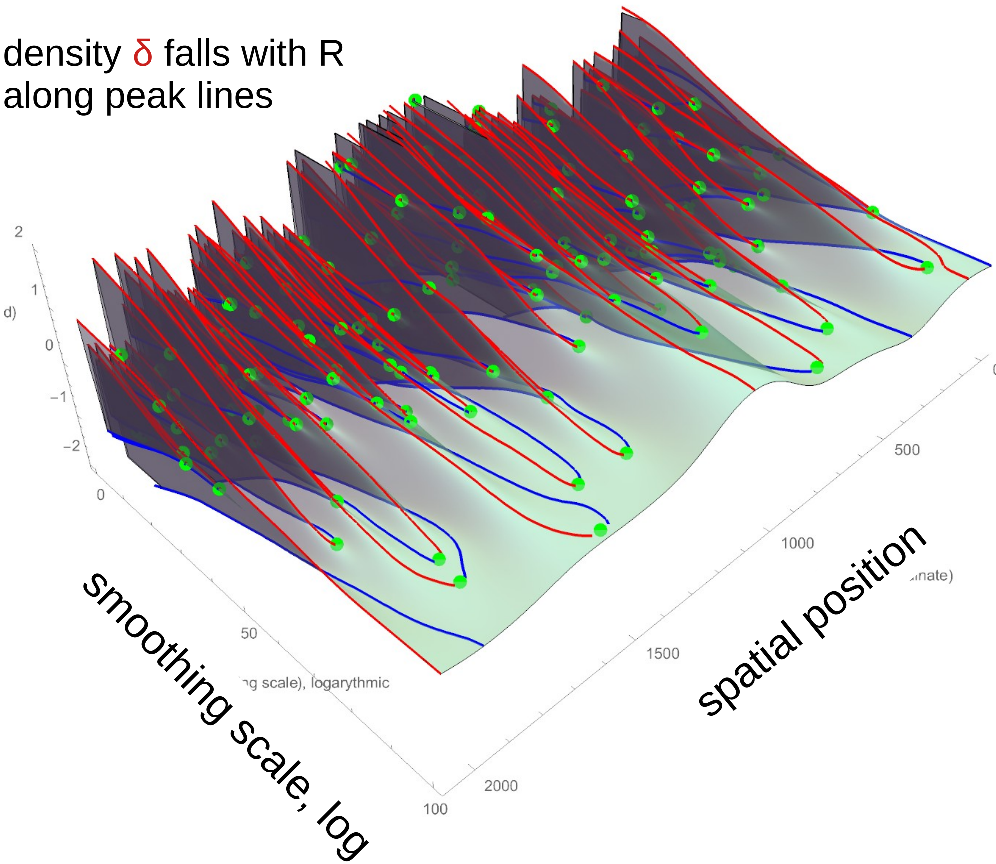
In 3D peaks merge not with minima, but with a saddle point of filamentary type. Actually, critical points can merge only with ones which signature of Hessian eigenvalues differ exactly by one: peaks with filametary saddles, voids (minima) with wall saddles, and filamentary and wall saddles between themselves.

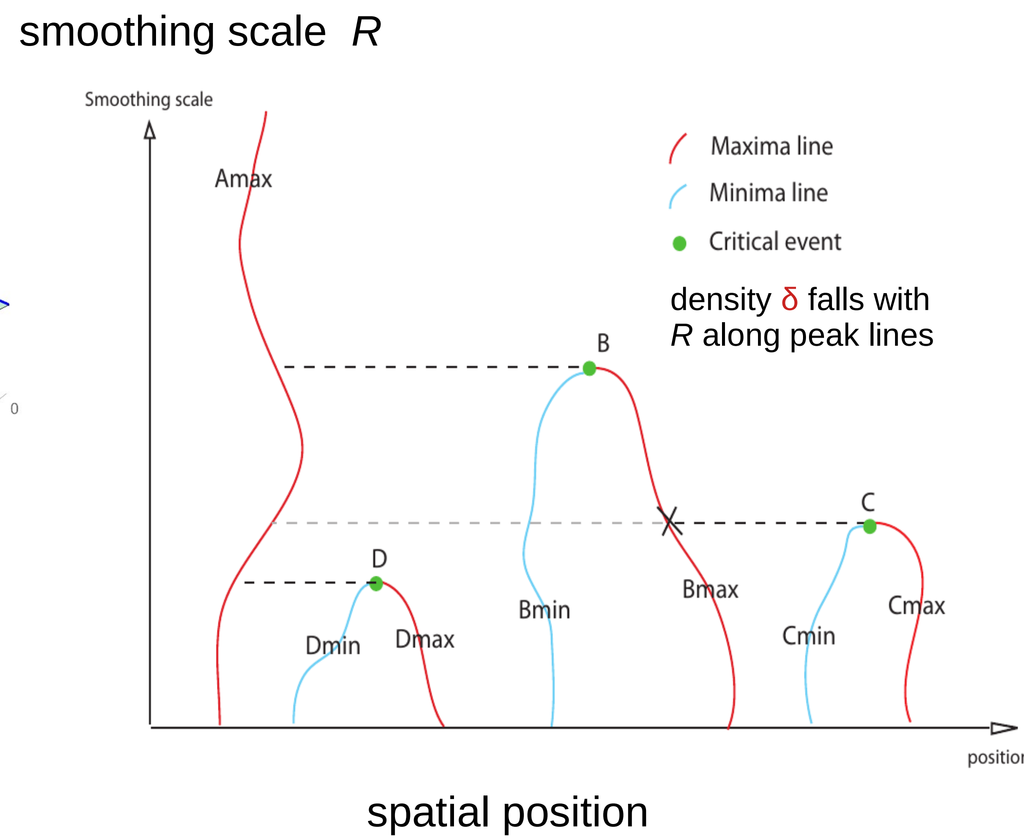


(1D) progression of critical points through critical events

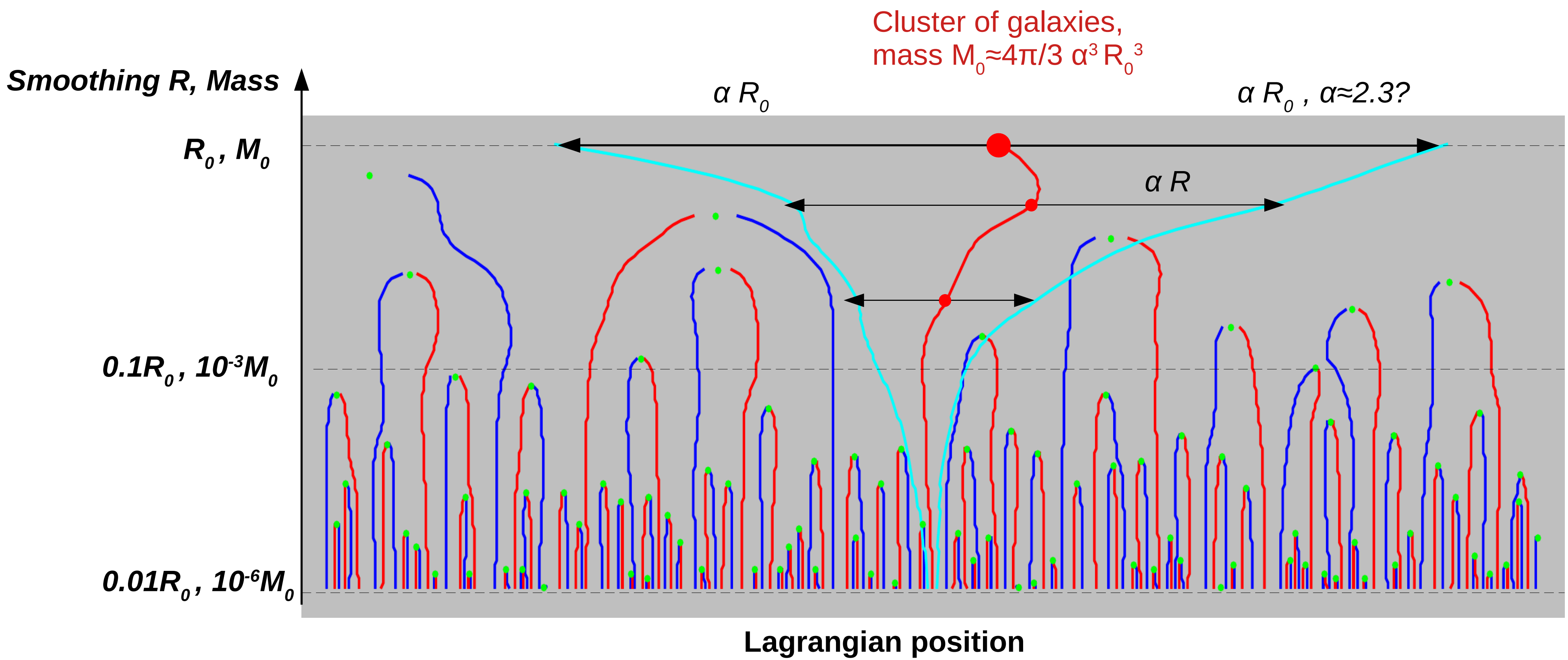
ND+1 space, density, N=1, Gaussian filter

ND+1 space, critical point tracks





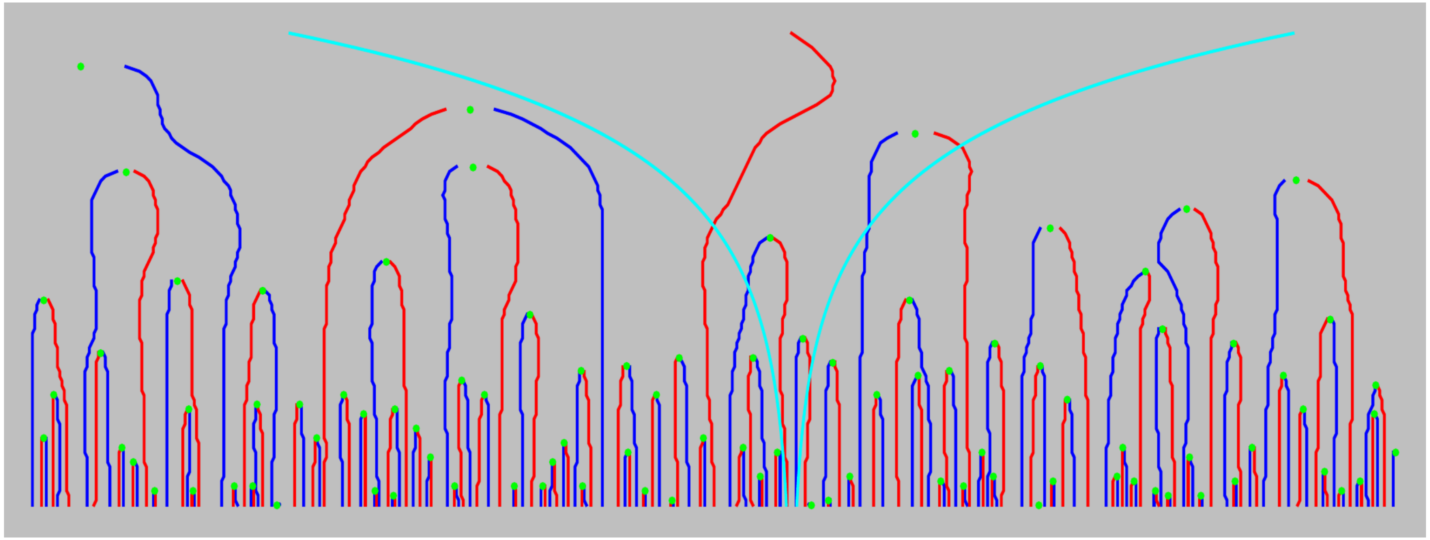
Past mass accumulation cone, merger capture cone



Points of note:

- Two regimes, a) monotonic accretion, b) merging crossing critical event
- Just several mergers as mass goes from 10^{-6} to 1 (say 10^9 M☼ to 10^{15} M☼)
- Critical events are near the boundary of the past mass cone. To capture all we may need to go to cone width $\beta R > \alpha R$, so β is to be calibrated

Past merger capture cone, simplified



Toward theoretical estimate of the merger rate, zero level (but Ok) approximation

- Build straight “capture cone” of cross-section *β R*, centered on the final Lagrangian position. *Its volume is equal to the volume of the tracking “capture” cone !*
- Count the number of critical events inside this cone – easy when critical event density is known. And it is ! (Cadiou et al 2020)
- This neglects correlations between the peaks and critical events (could ones repulse or attract the others ?) – but this can be corrected for at the next improvement step.

Merger number, in “zero” order

$$N_m = \int_{R_{in}}^{R_0} V_{capture}(R)dR \; n_{ce}(R|\mathrm{conditions}) \; .$$

4D density of critical events

R slice trough past cone

Correlations with peaks, …

Ignore conditions, take mean density of critical events (Cadiou et al, 2020)

$$\bar{n}_{ce}(R) = \frac{3R}{R_*^3 \tilde{R}^2} \left(1-\tilde{\gamma}^2\right) \frac{29\sqrt{15}-18\sqrt{10}}{1800\pi^2} \propto \frac{1}{R^4}$$

Estimate capture volume as tophat $V_{cone}(R) \approx 4\pi/3\, (\beta R)^3$, take power-law spectrum with index n for spectral parameters R_*, $\tilde{R}$, $\tilde{\gamma}$, and relate $R \sim M^{1/3}$

$$N_m = 0.16 \left(\frac{5+n}{2}\right)^{3/2} \left(\frac{\beta}{2.3}\right)^3 \ln\left(\frac{M_0}{M_{\rm in}}\right) \quad \begin{array}{ll} \approx 7 & M_0/M_{\rm in} = 10^6 \\ \approx 2.5 & M_0/M_{\rm in} = 100 \end{array}$$

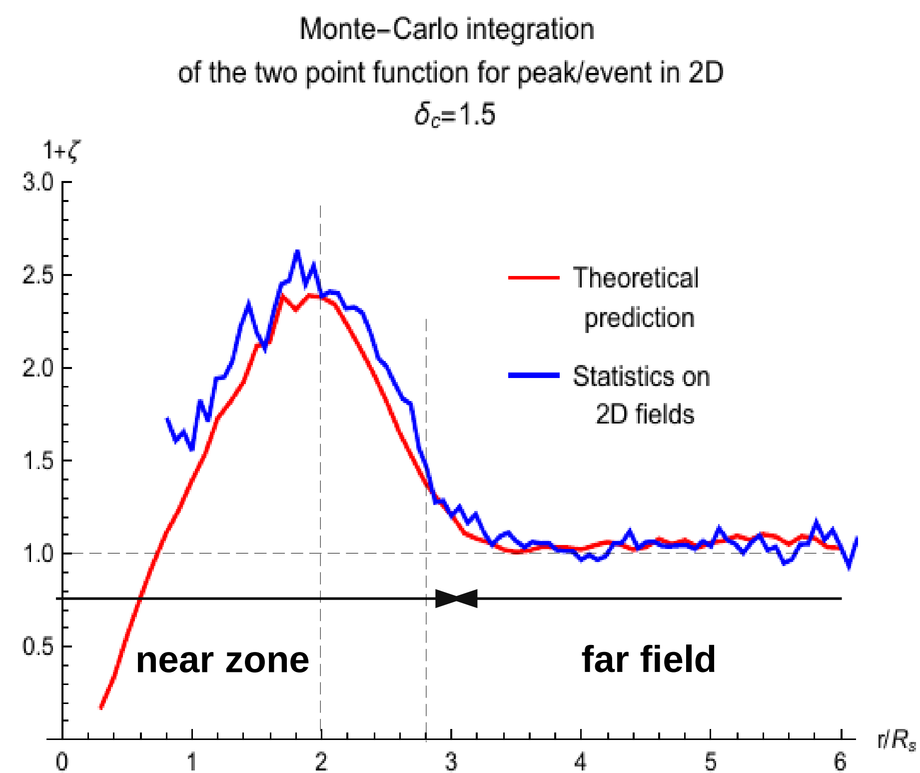
small

Capture zone size from peak – critical event correlations

Points of note:

- Preferred distance to the critical event from peak world line is *≈2R*, i.e near the boundary of the past mass cone, as we saw before
- Clear evidence of *far field*, where critical events do not know about peak presence, $\xi \approx 0$, and *near zone,* where they do.
- We argue that events within near zone are part of peak environment and these what should be counted (on average) as mergers.

  This gives $\beta \approx 2.8$
- 3D analysis is in progress



$\beta \approx 2.8$

Mass accumulation by mergers

$$M_m = \int_{R_{in}}^{R_0} V_{capture}(R)\ M_{ce}(R)\ dR\ n_{ce}(R|\mathrm{conditions})\,.$$

Critical event mass

Mass assignment to critical event is an interesting problem, but let us be naive and just take a top-hat prescription at *R*, $M_{ce}=4\pi/3\ (\alpha R)^3$ same as for the central cluster $M_0=4\pi/3\ (\alpha R_0)^3$. Then, the fraction of the mass accumulated in all mergers is finite and is given by

$$\frac{M_m}{M_0} = 0.16\left(\frac{5+n}{2}\right)^{3/2}\left(\frac{\beta}{2.3}\right)^3\left(1-\frac{M_{in}}{M_0}\right) \qquad \begin{array}{l}\approx 0.55 \quad \beta = 2.8 \;\; n=-2 \\ \approx 0.65 \quad \beta = 2.8 \;\; n=-1.5\end{array}$$

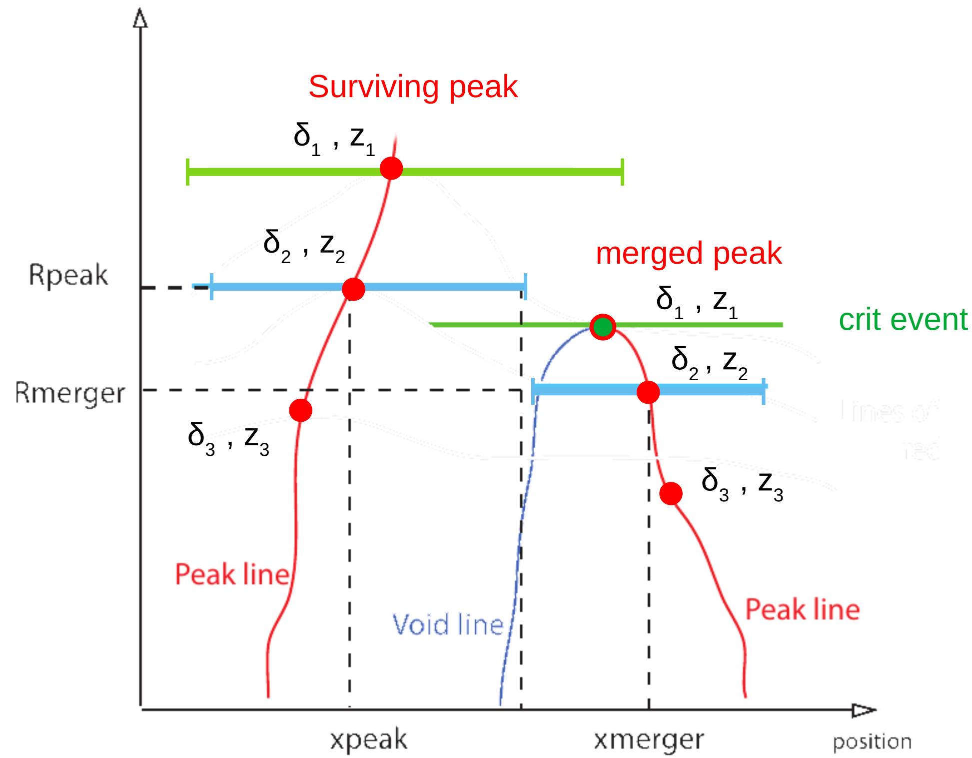
Point of note: here we were not guaranteed to get $M_m/M_0 < 1$. At the same time, for mass count to be "within a factor of two" may not be good enough, so we need to study mass assignment in more detail

Mass assignment: numerical, “double pointer” method

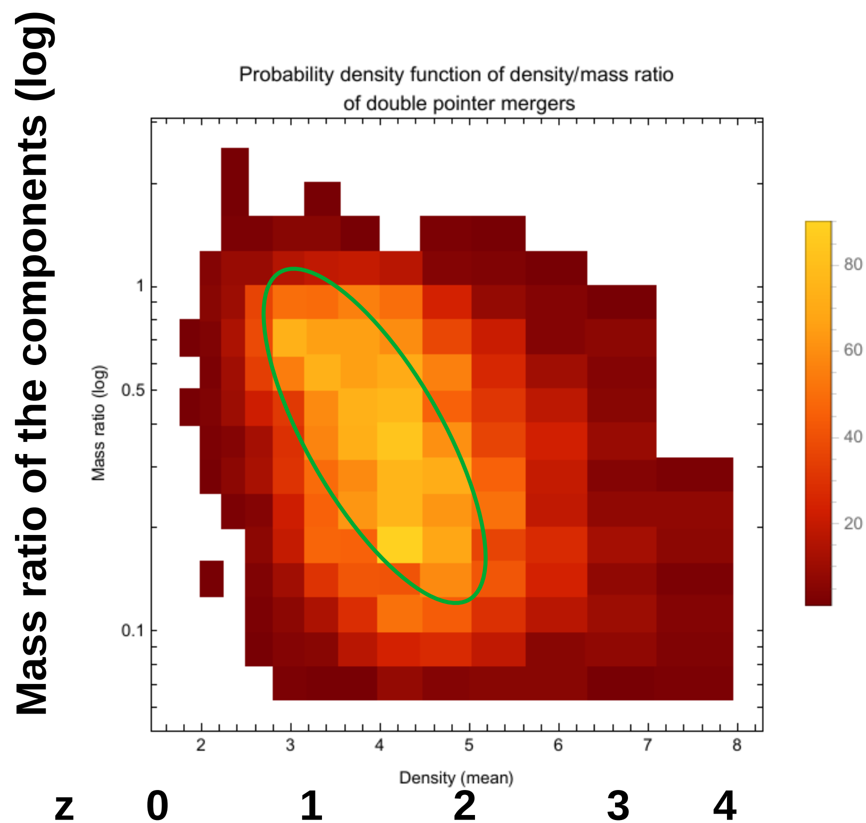
- How to assign time (z) and masses to the merger ?
- There is no general correspondence between smoothing scale R and redshift z
- Except along the peak lines, where one can use spherical collapse model to related density to z

$$1 + z = \delta/\delta_c$$

- So one can establish points of equal time on peak “world lines”. They are points of equal density
- Mergers occur at equal time, we use that to relate smoothing scales. i.e. masses of surviving and merging peak/halo
- In “double pointer” method we step back to find time when Lagrangian regions of two peaks just start to overlap. These are then their masses.
- Thus we can count merger events, together with masses of components
- Easy in 1D, working on 2D and 3D

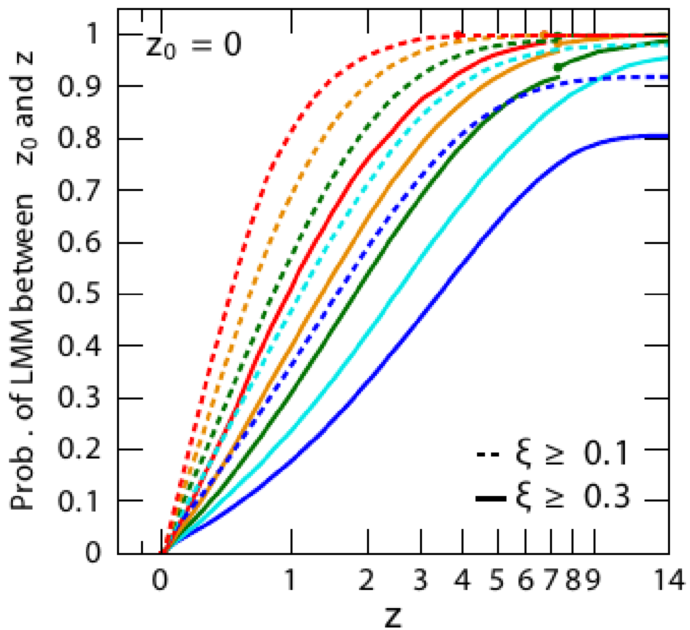


Distribution of mergers in z and mass

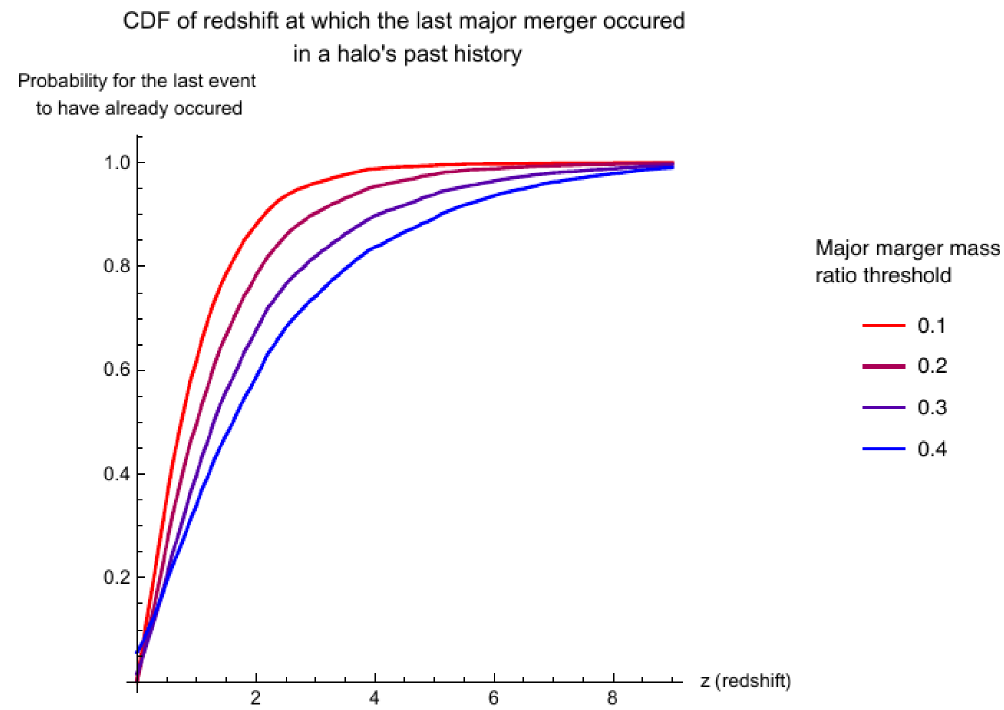


Caution: this is a 1D result !

Probablity of a past major merger for a halo at z=0



Millenium/ II simulations (Fakhouri et al, 2010)



Caution: this is a 1D result !

conclusions

- We are developing program of modelling halo merger history from the first principles, using critical event theory
- Critical event theory allows realistic theoretical estimates of the number of mergers halo with a given properties experience on average, as well as mass distribution of its progenitors.
- General understanding is obtained already from simple estimates. We see how the number of mergers of a typical halo over astrophysical relevant lifetime is “few” (≤ 10)
- Which will be improved with numerical studies of correlations between critical events and peaks.
- Numerical simulations of critical event process allows us to calibrate theoretical estimates, including going from lower dimensions to 3D.
- Numerical simulations currently have been accomplished in 1D and, partially, in 2D. 3D case is a work in progress.