Package ‘RScelestial’

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Type Package

Title Scelestial: Steiner Tree Based Single-Cell Lineage Tree Inference

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Description Scelestial infers a lineage tree from single-cell DNA mutation matrix. It generates a tree with approximately maximum parsimony through a Steiner tree approximation algorithm.

License GPL (>= 2)

Imports Rcpp (>= 1.0.1)

LinkingTo Rcpp

SystemRequirements C++11

RoxygenNote 7.1.1

Suggests igraph, knitr, rmarkdown

VignetteBuilder knitr, rmarkdown

Encoding UTF-8

NeedsCompilation yes

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.scelestial

Internal function for running scelestial algorithm.

Description

Internal function for running scelestial algorithm.

Usage

.scelestial(data, minK = 3L, maxK = 4L)

Arguments

data The data

minK, maxK Minimum and maximum number of vertices to be considered for k-restricted Steiner tree.

Value

The tree as well as missing value imputation
Internal function for generating synthetic single-cell data through simulation of tumor growth and evolution.

Usage

```r
.synthesis(
  sample,  # Number of samples
  site,    # Number of sites
  evolutionSteps,  # Number of non-root nodes in the evolutionary tree to be generated.
  mutationRate = 0.01,  # The rate of mutation on each evolutionary step in evolutionary tree synthesis.
  advantageIncreaseRatio = 1,  # A child node in the evolutionary tree is chosen for increase/decrease/keep its parent advantage with probabilities proportional to advantage.increase.ratio/advantage.decrease.ratio/advantage.keep.ratio.
  advantageDecreaseRatio = 10,
  advantageKeepRatio = 100,
  advantageIncreaseStep = 0.01,
  advantageDecreaseStep = 0.01,
  mvRate = 0.5,  # Rate of missing value to be added to the resulting sequences.
  fpRate = 0.2,  # Rate of false positive (0 -> 1) in the sequences.
  fnRate = 0.1,  # Rate of false negative (1 -> 0) in the sequences.
  seed = -1L  # The seed for randomization.
)
```

Arguments

- `sample`: Number of samples
- `site`: Number of sites
- `evolutionSteps`: Number of non-root nodes in the evolutionary tree to be generated.
- `mutationRate`: The rate of mutation on each evolutionary step in evolutionary tree synthesis.
- `advantageIncreaseRatio`, `advantageDecreaseRatio`, `advantageKeepRatio`: A child node in the evolutionary tree is chosen for increase/decrease/keep its parent advantage with probabilities proportional to `advantage.increase.ratio/advantage.decrease.ratio/advantage.keep.ratio`.
- `advantageIncreaseStep`, `advantageDecreaseStep`: The amount of increasing or decreasing the advantage of a cell relative to its parent.
- `mvRate`: Rate of missing value to be added to the resulting sequences.
- `fpRate`, `fnRate`: Rate of false positive (0 -> 1) and false negative (1 -> 0) in the sequences.
- `seed`: The seed for randomization.
The function returns a list. The list consists of

- sequence: A data frame representing result of sequencing. The data frame has a row for each locus and a column for each sample.
- true.sequence: The actual sequence for the sample before adding errors and missing values.
- true.clone: A list that stores index of sampled cells for each node in the evolutionary tree.
- true.tree: The evolutionary tree that the samples are sampled from. It is a data frame with src, dest, and len columns representing source, destination and weight of edges of the tree, respectively.

### Description
Conversion of ten-state sequencing matrix to 0/1-mutation matrix.

### Usage

```r
as.mutation.matrix(seq)
```

### Arguments

- **seq**: A dataframe representing the ten-state sequencing matrix. Elements of the matrix are the from "X/Y" for X and Y being nucleotides or "./." for missing value. Rows represent loci and columns represent samples.

### Value

A data frame with exactly the same size as the input seq matrix. The most abundant state in each loci (row) translated to 0, and the others are translated to 1. Missing values are translated to 3.

### Examples

```r
## A small 10-state matrix
seq = data.frame("C1" = c("C/C", "C/C"), "C2" = c("A/A", NA), "C3" = c("C/C", "A/A"))
## Convert it to mutation matrix
as.mutation.matrix(seq)
#   C1 C2 C3
# 1 0 1 0
# 2 1 3 0
```
### as.ten.state.matrix

**Conversion of 0/1 matrix to 10-state matrix**

**Description**

It converts 0 to A/A and 1 to C/C. 3 that represents missing values are converted to "./.".

**Usage**

```r
as.ten.state.matrix(mut)
```

**Arguments**

- `mut`  
  A dataframe representing the mutation matrix.

**Value**

A data frame with the exact size as `mut`, in which 0, 1 and 3 (or NAs) are replaced with "A/A", "C/C", and "./.", respectively.

**Note**

Note that following function does not provide inverse of as.mutation.matrix. It could be used to generate input for scelestial.

**Examples**

```r
## A small 0/1/NA mutation matrix
mut = data.frame("C1" = c(0, 0), "C2" = c(0, 3), "C3" = c(1, 0))
## Convert it to 10-state matrix
as.ten.state.matrix(mut)
# C1   C2   C3
# 1 A/A A/A C/C
# 2 A/A ./ A/A
```

---

### as.ten.state.matrix.from.node.seq

**Generates 10-state sequence matrix from name/10-char string matrix.**

**Description**

This function is used for conversion of results of internal scelestial result to 10-state sequence matrices.

**Usage**

```r
as.ten.state.matrix.from.node.seq(n.seq)
```
distance.matrix.scelestial

Calculates distance matrix for result of scelestial

distance.matrix.scelestial

Arguments

n.seq

A two column data frame. First column is the name of a node and the second column is a string representation of the sequencing result. Each element of the sequencing result is from a 10-state representation in which each state represented as a character according to the following encoding:

<table>
<thead>
<tr>
<th>One character representation</th>
<th>10-state representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;A&quot;</td>
<td>&quot;A/A&quot;,</td>
</tr>
<tr>
<td>&quot;T&quot;</td>
<td>&quot;T/T&quot;,</td>
</tr>
<tr>
<td>&quot;C&quot;</td>
<td>&quot;C/C&quot;,</td>
</tr>
<tr>
<td>&quot;G&quot;</td>
<td>&quot;G/G&quot;,</td>
</tr>
<tr>
<td>&quot;K&quot;</td>
<td>&quot;A/C&quot;,</td>
</tr>
<tr>
<td>&quot;L&quot;</td>
<td>&quot;A/G&quot;,</td>
</tr>
<tr>
<td>&quot;M&quot;</td>
<td>&quot;C/T&quot;,</td>
</tr>
<tr>
<td>&quot;N&quot;</td>
<td>&quot;C/G&quot;,</td>
</tr>
<tr>
<td>&quot;O&quot;</td>
<td>&quot;T/G&quot;,</td>
</tr>
<tr>
<td>&quot;P&quot;</td>
<td>&quot;T/A&quot;,</td>
</tr>
<tr>
<td>&quot;X&quot;</td>
<td>&quot;./.&quot;</td>
</tr>
</tbody>
</table>

Value

A 10-state sequence data frame with samples as columns and loci as rows. Elements of n.seq are translated to their 10-state representations.

Examples

```r
## A node sequence data frame
n.seq = data.frame("node" = c("C1", "C2"), "seq" = c("AKLTCXAAC", "AKKOCXAPC"))
## Convert it to ten state matrix
as.ten.state.matrix.from.node.seq(n.seq)
#    V1 V2 V3 V4 V5 V6 V7 V8 V9
# C1  A/A A/C A/G T/T C/C ././ A/A A/C C/C
# C2  A/A A/C A/C T/G C/C ././ A/A T/A C/C
```

distance.matrix.scelestial

Calculates distance matrix for result of scelestial

Description

Calculates distance matrix for result of scelestial

Usage

distance.matrix.scelestial(SP, normalize = TRUE)
distance.matrix.tree

Arguments

- **SP**: Output of `scelestial` function
- **normalize**: If true, sum of all elements of resulting table is added up to one.

Value

The distance matrix

Examples

```r
## Synthesise an evolution
S = synthesis(10, 5, 20, seed=7)
## Run Scelestial
SC = scelestial(as.ten.state.matrix(S$sequence))
## Calculate the distance matrix
distance.matrix.scelestial(SC)
```

```
# C1 C10 C2 C3 C4
# C1 0.000000000 0.003512891 0.015222451 0.014051472 0.008196692
# C10 0.003512891 0.000000000 0.011709560 0.010538580 0.004683800
# C2 0.015222451 0.011709560 0.000000000 0.010538627 0.007025759
# C3 0.014051472 0.010538580 0.010538627 0.000000000 0.005854780
# C4 0.008196692 0.004683800 0.007025759 0.005854780 0.000000000
# C5 0.011709560 0.00819668 0.003512891 0.007025736 0.003512868
# C6 0.023419213 0.019906322 0.019906368 0.009367741 0.015222521
# C7 0.018735342 0.015222451 0.015222498 0.004683871 0.010538651
# C8 0.015222474 0.011709583 0.014051542 0.012888562 0.007025783
# C9 0.010538627 0.007025736 0.009367695 0.008196715 0.002341935
# C5 C6 C7 C8 C9
# C1 0.011709560 0.023419213 0.018735342 0.015222474 0.010538627
# C10 0.008196668 0.019906322 0.015222451 0.011709583 0.007025736
# C2 0.003512891 0.019906368 0.015222498 0.014051542 0.009367695
# C3 0.007025736 0.009367741 0.004683871 0.012888562 0.008196715
# C4 0.003512868 0.015222521 0.010538651 0.007025783 0.002341935
# C5 0.000000000 0.016393477 0.011709606 0.010538651 0.005854803
# C6 0.016393477 0.000000000 0.004683871 0.022248304 0.017564457
# C7 0.011709606 0.004683871 0.000000000 0.017564433 0.012880586
# C8 0.010538651 0.022248304 0.017564433 0.000000000 0.004683847
# C9 0.005854803 0.017564457 0.012880586 0.004683847 0.000000000
```

distance.matrix.tree

*Calculates distance matrix for a node on a tree.*

Description

It is used for internal purposes.

Usage

```r
distance.matrix.tree(graph, cell.names, tree.nodes, normalize = TRUE)
```
### Arguments

- **graph**: The tree
- **cell.names**: Name of the cells to be the row and column name of the resulting matrix
- **tree.nodes**: For each cell.name a tree node is stored in tree.nodes.
- **normalize**: If TRUE the resulting matrix is normalized.

### Value

A matrix with equal number of rows and columns, a row/column for each cell. Elements of matrix represent distance between cells on the graph.

### Examples

```r
## Synthesise an evolution
S = synthesis(10, 5, 20, seed=7)
## Run Scelestial
SC = scelestial(as.ten.state.matrix(S$sequence))
## Calculate the distance matrix
vertices <- rownames(SC$input);
distance.matrix.tree(SC$tree, vertices, vertices, normalize = TRUE)
```

```plaintext
# C1  C10  C2  C3  C4
# C1  0.000000000 0.003512891 0.015222451 0.014051472 0.008196692
# C10 0.003512891 0.000000000 0.011709560 0.010538580 0.004683800
# C2  0.015222451 0.011709560 0.000000000 0.010538627 0.007025759
# C3  0.014051472 0.010538580 0.010538627 0.000000000 0.005854780
# C4  0.008196692 0.004683800 0.007025759 0.005854780 0.000000000
# C5  0.011709560 0.008196668 0.003512891 0.007025736 0.003512868
# C6  0.023419213 0.019006322 0.019006368 0.009367741 0.015222521
# C7  0.018735342 0.015222451 0.015222498 0.004683871 0.010538651
# C8  0.015222474 0.011709583 0.014051542 0.012880562 0.007025783
# C9  0.010538627 0.007025736 0.009367695 0.008196715 0.002341935
# C5  0.011709560 0.023419213 0.018735342 0.015222474 0.010538627
# C10 0.008196668 0.019006322 0.015222451 0.011709583 0.007025736
# C2  0.003512891 0.019006368 0.015222498 0.014051542 0.009367695
# C3  0.007025736 0.009367741 0.004683871 0.012880562 0.008196715
# C4  0.003512868 0.015222521 0.010538651 0.007025783 0.002341935
# C5  0.000000000 0.016393477 0.011709606 0.010538651 0.005854803
# C6  0.016393477 0.000000000 0.004683871 0.022248304 0.017564457
# C7  0.011709606 0.004683871 0.000000000 0.017564433 0.012880586
# C8  0.010538651 0.022248304 0.017564433 0.000000000 0.004683847
# C9  0.005854803 0.017564457 0.012880586 0.004683847 0.000000000
```

### References

- distance.matrix.true.tree
  - Calculates distance matrix for a synthezited data
distance.matrix.true.tree

Description
Calculates distance matrix for a synthetized data

Usage

distance.matrix.true.tree(D, normalize = TRUE)

Arguments

D Output of synthesis function
normalize If true, sum of all elements of resulting table is added up to one.

Value
The distance matrix of the true tree.

Examples

## Synthesise an evolution
S = synthesis(10, 5, 20, seed=7)
## Calculating the distance matrix of the true tree.
distance.matrix.true.tree(S)
# C3 C6 C4 C2 C7
# C3 0.00000000 0.004587156 0.006880734 0.009174312 0.013761468
# C6 0.004587156 0.00000000 0.002293578 0.009174312 0.013761468
# C4 0.006880734 0.002293578 0.00000000 0.011467890 0.016055046
# C2 0.009174312 0.009174312 0.011467890 0.00000000 0.004587156
# C7 0.013761468 0.013761468 0.016055046 0.004587156 0.00000000
# C10 0.006880734 0.006880734 0.009174312 0.011467890 0.016055046
# C8 0.006880734 0.011467890 0.013761468 0.016055046 0.020642202
# C9 0.006880734 0.011467890 0.013761468 0.016055046 0.020642202
# C1 0.011467890 0.011467890 0.013761468 0.002293578 0.006880734
# C5 0.011467890 0.011467890 0.013761468 0.002293578 0.006880734
# C10 C8 C9 C1 C5
# C3 0.006880734 0.006880734 0.006880734 0.011467890 0.011467890
# C6 0.006880734 0.011467890 0.011467890 0.011467890 0.011467890
# C4 0.009174312 0.013761468 0.013761468 0.013761468 0.013761468
# C2 0.011467890 0.016055046 0.016055046 0.02293578 0.02293578
# C7 0.016055046 0.020642202 0.020642202 0.006880734 0.006880734
# C10 0.00000000 0.013761468 0.013761468 0.013761468 0.013761468
# C8 0.013761468 0.00000000 0.00000000 0.018348624 0.018348624
# C9 0.013761468 0.00000000 0.00000000 0.018348624 0.018348624
# C1 0.013761468 0.018348624 0.018348624 0.00000000 0.00000000
# C5 0.013761468 0.018348624 0.018348624 0.00000000 0.00000000
Li

**Bladder invasive single cell tumor dataset**

**Description**
Bladder invasive single cell tumor dataset

**Usage**
data(Li)

**Format**
Each column represent a cell and each row represent a locus. "./." represent the missing value, "A/A" the normal state and "C/C" the mutated state.

**Source**
QTL Archive

**References**

**Examples**
data(Li)

---

my.dfs

**Runs DFS on tree and calculates parent of each node as well as depth and upper-depth of nodes.**

**Description**
It is used for internal purposes.

**Usage**
my.dfs(graph, root = NULL)

**Arguments**

<table>
<thead>
<tr>
<th>Argument</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>graph</td>
<td>The tree</td>
</tr>
<tr>
<td>root</td>
<td>The starting node of DFS.</td>
</tr>
</tbody>
</table>
Value

a list with father representing the parent node, and balance.depth representing the distance between the node and the farthest node to it, as the elements.

Description

It is used for internal purposes.

Usage

my.general.dfs(
    nei,
    v,
    f,
    extra,
    in.call,
    mid.call.before,
    mid.call.after,
    out.call
)

Arguments

nei Neighbor list for each vertex
v Starting node
f Parent node
extra the shared object for the whole DFS
in.call First function to call
mid.call.before Function to call before calling child DFS
mid.call.after Function to call after calling child DFS
out.call Last function to call

Value

the extra parameter modified with in.call, mid.call.before, mid.call.after, and out.call functions
read.sequence.table  Read mutation table

Description

A simple read of a sequencing file.

Usage

read.sequence.table(file.name)

Arguments

file.name  Name of the file to be loaded

Value

A table representing the content of the file. First column of the file represents the row names.

Examples

# An example input without header could be like following:
# 1 C/C A/A A/A A/A
# 2 ./. A/A C/C C/C
# 3 C/C A/A C/C ./. 
# 4 A/A ./. ./. ./.
# 5 ./. A/A A/A A/A
#
# For this file you can run
read.sequence.table(system.file("extdata/sample1.txt", package="RScelestial"))

RScelestial  RScelestial: An R wrapper for scelestial algorithm for single-cell lineage tree reconstruction through an approximation algorithm based on Steiner tree problem

Description

This package provides a wrapper for the scelestial which is implemented in C++. The package contains function scelestial for running the algorithm and synthesis for tumor simulation for providing synthetic data.
Infer the single-cell phylogenetic tree

Description

Performs the Scelestial algorithm and calculates the phylogenetic tree reconstruction based on an approximation algorithm for Steiner tree problem.

Usage

scelestial(
  seq,
  mink = 3,
  maxk = 3,
  root.assign.method = c("none", "balance", "fix"),
  root = NULL,
  return.graph = FALSE
)

Arguments

seq  The sequence matrix. Rows represent loci and columns represent samples. Elements of the matrix represent 10-state genome sequencing results, or missing values. I.e each element is in the format "X/Y" where X and Y are from the set A, T, C, G. There is a special case "./." that represents the missing value.

mink  The minimum k used in the calculation of k-restricted Steiner trees. It is supposed to be 3.

maxk  The maximum k used in the calculation of k-restricted Steiner trees. When maxk=3, the approximation algorithm produces an 11/6-approximation result. Increasing k increases the running time as well as the approximation ratio of the algorithm. maxk should be not less than mink.

root.assign.method, root
root.assign.method is the method for choosing the root.

  • "none" for undirected tree,
  • "fix" for a tree with root as its root.
  • "balance" to let the root to be chosen to produce the most balanced tree.

return.graph  If TRUE, the actual graph through igraph library is generated and produced.

Value

Returns a list containing following elements:

  • tree: A data frame representing edges of the tree. tree$src is the source of the edge, tree$dest represents the destination of the edge, and tree$len represents its weight (evolutionary distance).
  • input: input sequences.
• sequence: inferred or imputed sequences for the tree nodes. If the node is already in the input, sequence represents its missing value imputation, in the case of presence of missing values, and if the node is not an input node, the sequence represents inferred sequence for the tree node.

• graph: graph. If the return.graph is TRUE, there is an element G that represents the graph from the igraph library.

Examples

```r
## simulates tumor evolution
S = synthesis(10, 10, 2, seed=7)
## convert to 10-state matrix
seq = as.ten.state.matrix(S$sequence)
## runs the scelestial to generate 4-restricted Steiner trees. It represents the tree and graph
SP = scelestial(seq, mink=3, maxk=4, return.graph = TRUE)
SP
## Expected output:
# $input
# node  sequence
#  1   0  AAXACAXAXX
#  2   1  AXXXAXAXAX
#  3   2  AXAXCAXAXA
#  4   3  AXXCAAXAXA
#  5   4  AXCCAAXAXA
#  6   5  AXCCXXAXAX
#  7   6  XACAXAXAXX
#  8   7  AAXXXXAXXX
#  9   8  AAXAXAXAXX
# 10   9  AAXAXXAXXX
#
# $sequence
# node  sequence
#  1   0  AAAACAAAAC
#  2   1  AACAAAAAAA
#  3   2  AAAACAAAAA
#  4   3  AACCCAAAAA
#  5   4  AACACAAAAA
#  6   5  AACACACAC
#  7   6  AACACACAC
#  8   7  AAAACAXAXA
#  9   8  AAAACAAAAA
# 10   9  AAAACACACA
# 11  10  AAAACACAC
# 12  16  AAAAAAAAA
# 13  18  ACACAAAAA
#
# $tree
# src dest len
#  1   9  10 4.00006
#  2   8  10 3.00006
#  3   7  10 2.50005
#  4   0  10 1.50003
```
### Description

This function simulates an evolution in a tumor through two phases: 1) simulation of evolution, 2) sampling.

### Usage

```r
synthesis(
  sample,
  site,
  evolution.step,
  mutation.rate = 1,
  advantage.increase.ratio = 1,
  advantage.decrease.ratio = 10,
  advantage.keep.ratio = 100,
  advantage.increase.step = 0.01,
  advantage.decrease.step = 0.01,
  mv.rate = 0.5,
  fp.rate = 0.2,
  fn.rate = 0.1,
  seed = -1
)
```

### Arguments

- **sample**: Number of samples.
- **site**: number of sites (loci)
evolution.step  Number of evolutionary steps in the process of production of the evolutionary tree.

mutation.rate  The rate of mutation on each evolutionary step in evolutionary tree synthesis.

advantage.increase.ratio, advantage.decrease.ratio, advantage.keep.ratio
   A child node in the evolutionary tree is chosen for increase/decrease/keep its parent advantage with probabilities proportional to advantage.increase.ratio/advantage.decrease.ratio/advantage.keep.ratio.

advantage.increase.step, advantage.decrease.step
   The amount of increasing or decreasing the advantage of a cell relative to its parent.

mv.rate  Rate of missing value to be added to the resulting sequences.

fp.rate, fn.rate
   Rate of false positive (0 -> 1) and false negative (1 -> 0) in the sequences.

seed  The seed for randomization.

Details

The simulation of evolution starts with a single cell. Then for evolution.step steps, on each step a cell is selected for duplication. A new cell as its child is added to the evolutionary tree. To each node in the evolutionary tree an advantage is assigned representing its relative advantage in replication and in being sampled. Advantage of a node is calculated by increasing (decreasing) its parents advantage by advantage.increase.step (advantage.decrease.step) with probability proportional to advantage.increase.ratio (advantage.decrease.ratio). With a probability proportional to advantage.keep.ratio the advantage of a node is equal to its parent’s advantage.

Sequences for each node is build based on its parent’s sequence by adding some mutations. Mutations are added for each locus independently with rate mutation.rate.

In the sampling phase, sample cells are selected from the evolutionary tree nodes. Result of the sequencing process for a cell is determined by the sequence of the node in the evolutionary tree with addition of some random errors. Errors are result of applying some false positives with rate fp.rate, applying some false negatives with rate fn.rate, and adding some missing values with rate mv.rate.

Value

The function returns a list. The list consists of

- sequence: A data frame representing result of sequencing. The data frame has a row for each locus and a column for each sample.
- true.sequence: The actual sequence for the sample before adding errors and missing values.
- true.clone: A list that stores index of sampled cells for each node in the evolutionary tree.
- true.tree: The evolutionary tree that the samples are sampled from. It is a data frame with src, dest, and len columns representing source, destination and weight of edges of the tree, respectively.
Examples

```r
## generating a data set with 10 samples and 5 loci through simulation of
## 20-step evolution.
synthesis(10, 5, 20, seed=7)
## The result is
# $sequence
# C1 C2 C3 C4 C5
# L1  1  1  1  1  1
# L2  3  1  3  3  0
# L3  3  1  3  3  1
# L4  3  0  1  0  0
# L5  1  3  0  3  3
# L6  3  1  3  1  0
# L7  3  3  1  0  3
# L8  3  1  1  3  3
# L9  3  3  1  3  1
# L10 0  3  0  3  0
#
# $true.sequence
# C1 C2 C3 C4 C5
# L1  0  1  1  1  1
# L2  0  1  0  0  1
# L3  0  1  0  0  1
# L4  0  1  1  1  1
# L5  1  1  0  1  0
# L6  0  1  0  1  0
# L7  0  1  0  0  1
# L8  0  1  1  1  1
# L9  0  1  1  1  1
# L10 0  0  0  0  0
#
# $true.clone
# $true.clone[[1]]
# [1] 4
#
# $true.clone[[2]]
# [1] 1
#
# $true.clone[[3]]
# [1] 6
#
# $true.clone[[4]]
# [1] 10
#
# $true.clone[[5]]
# [1] 2
#
# $true.clone[[6]]
# [1] 3
#
# $true.clone[[7]]
# [1] 8 9
```
Plotting the tree

Description
Plotting the igraph tree created by scelestial.

Usage

```
tree.plot(graph, ...)
```

Arguments

- **graph**: Output of scelestial or the G element of the scelestial output.
- **...**: Parameters passing to the plot function
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