Accurate Analysis of SET effects on Flash-based FPGA System-on-a-Chip for Astrophysical Applications

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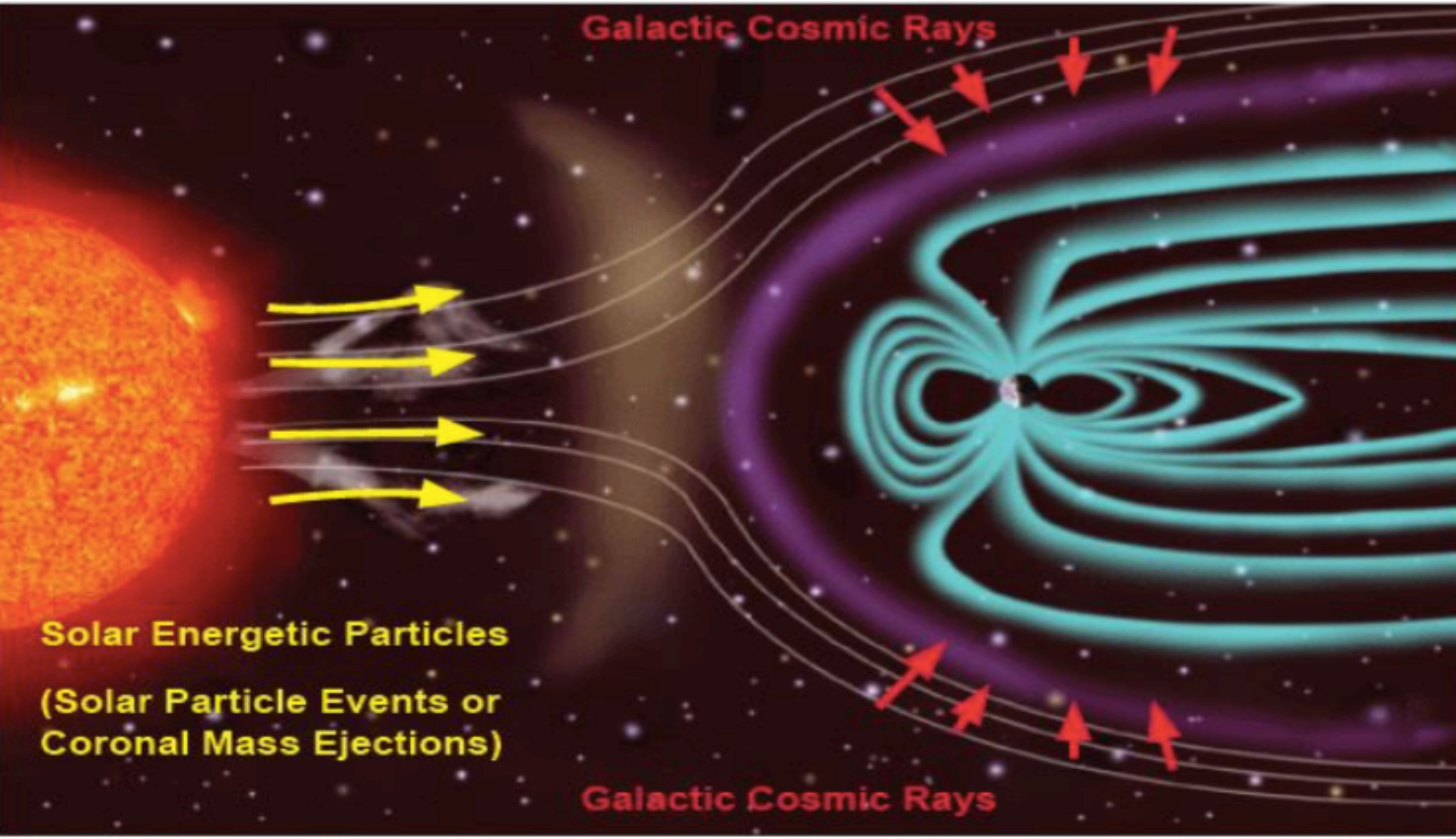
Outline

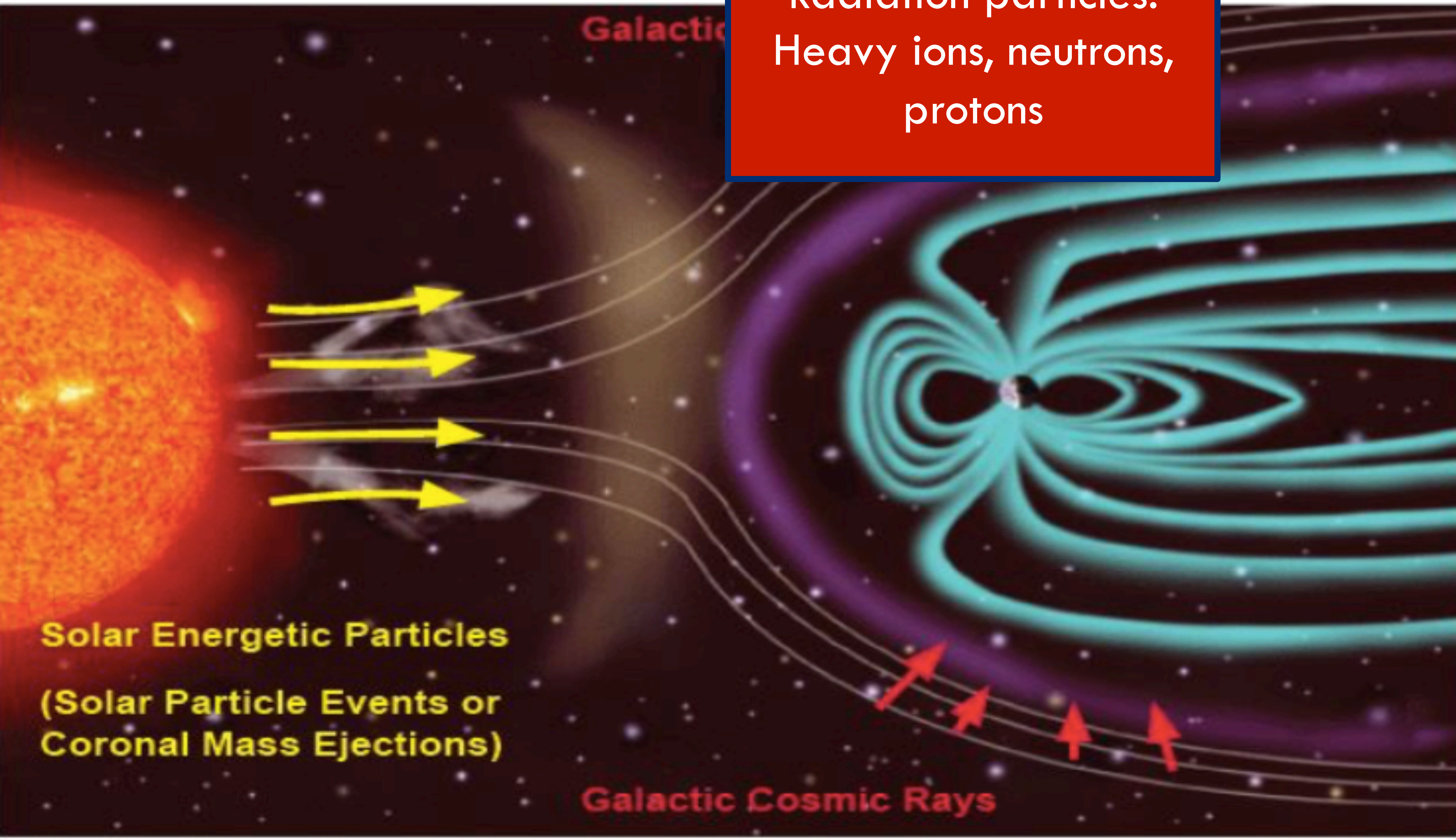
- SET effects on Flash-based FPGAs
- Single Event Transient Analysis (SETA) tool
  - Analysis
  - Mitigation
  - Experimental results
- Conclusions and future activities

SET effect


Galactic Cosmic Rays
Solar Energetic Particles
(Solar Particle Events or Coronal Mass Ejections)
Galactic Cosmic Rays

SET effect

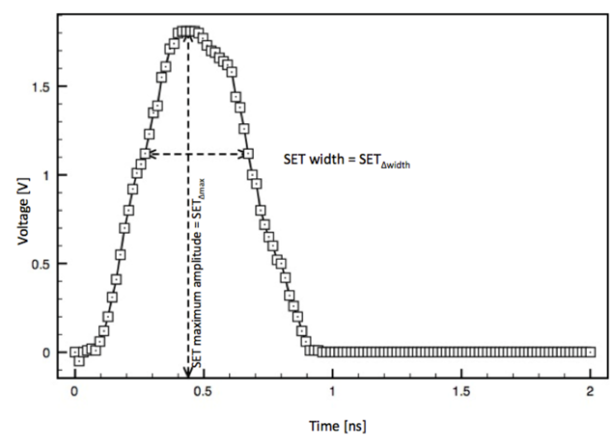
Radiation particles: Heavy ions, neutrons, protons



SET effect

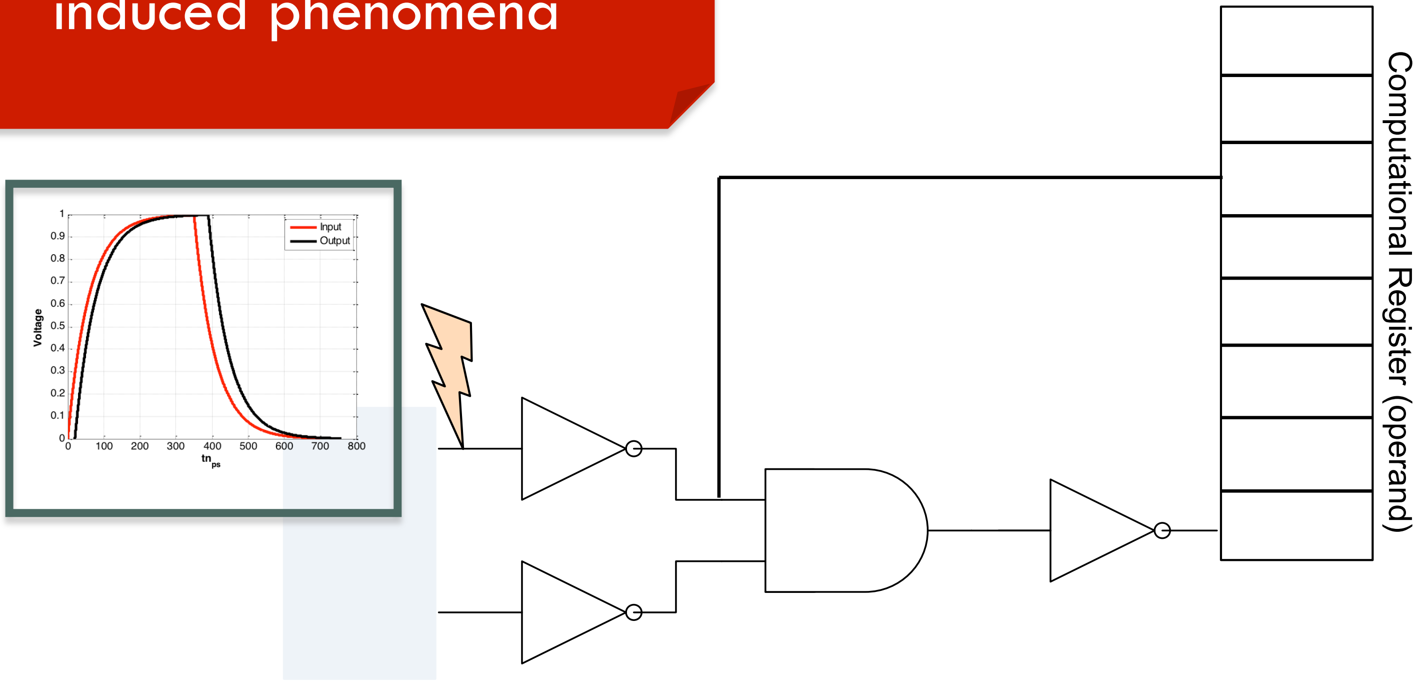
- A Single Event Transient (SET) is generated by the injunction of charge collection
  - A charged particle crosses a junction area
  - It generates an amount of current, provoking a “glitch”
  - SET can be indistinguishable from normal signal and exist for notable distances

SET width
SET amplitude
Rise ΔV/ΔT
Fall ΔV/ΔT



SET effect

Generation of the radiation-induced phenomena



SET effect

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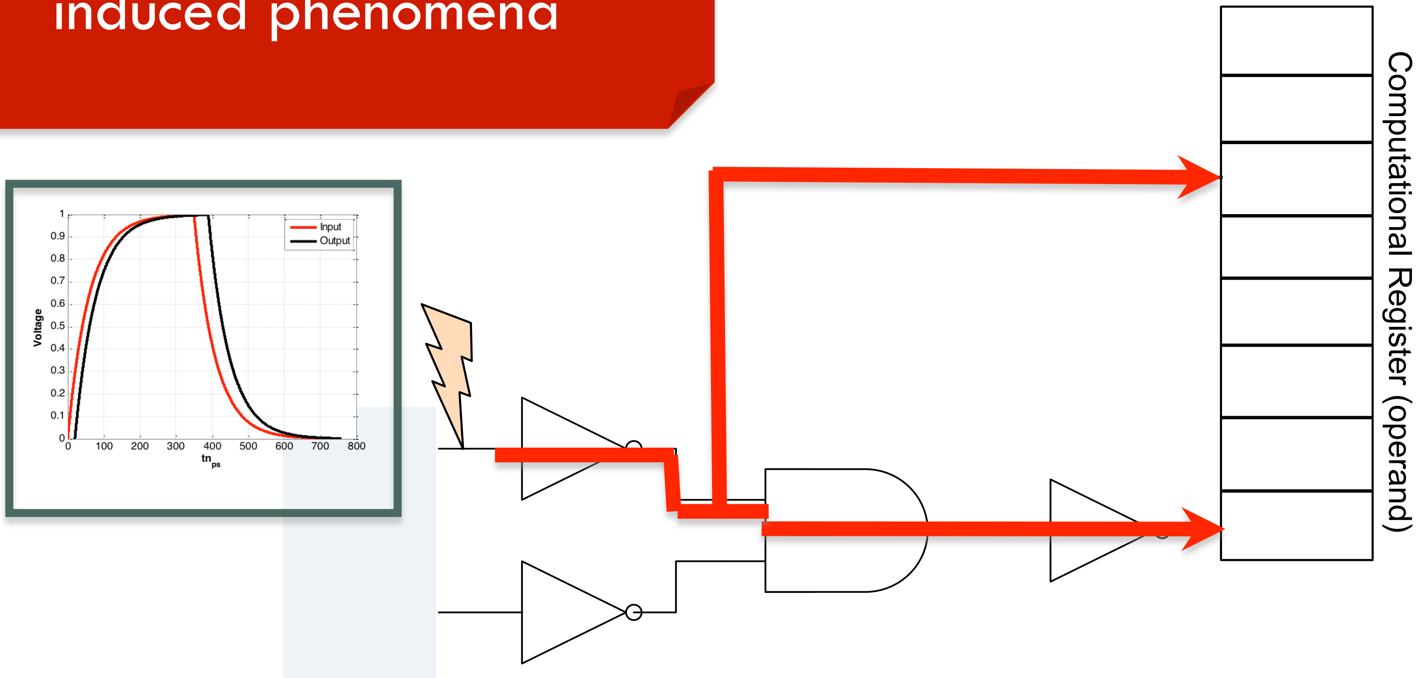
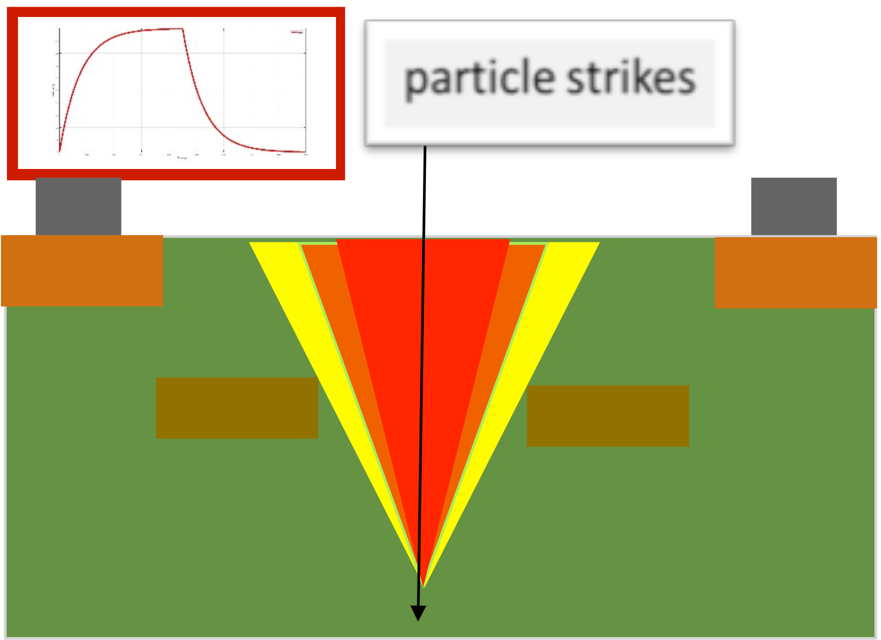
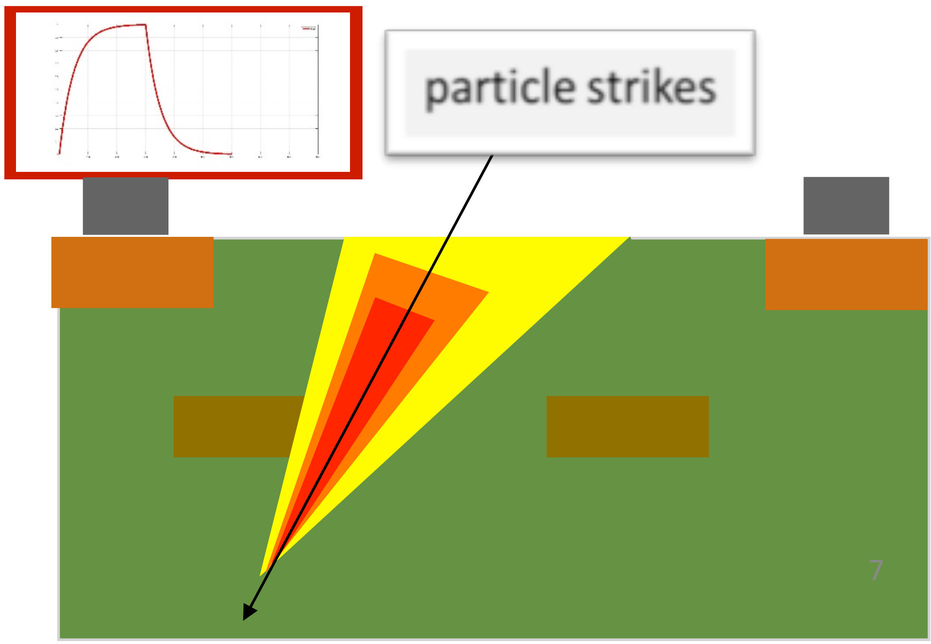


SET effect

- Analysis and mitigation of the SEEs on Flash-based FPGAs
  - Type and radiation incidence angle
  - LET
  - Technology

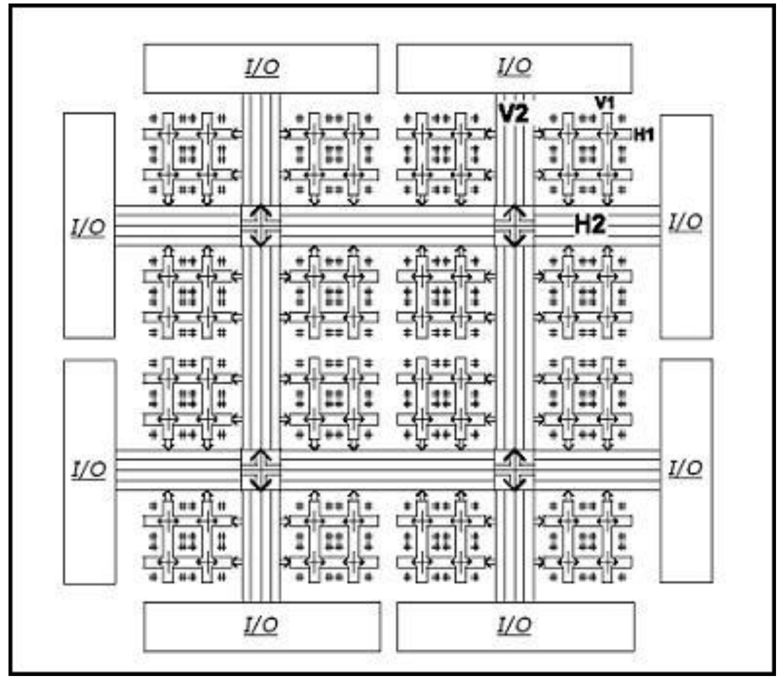




Circuits on Flash-based FPGAs

0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0

Flash configuration memory



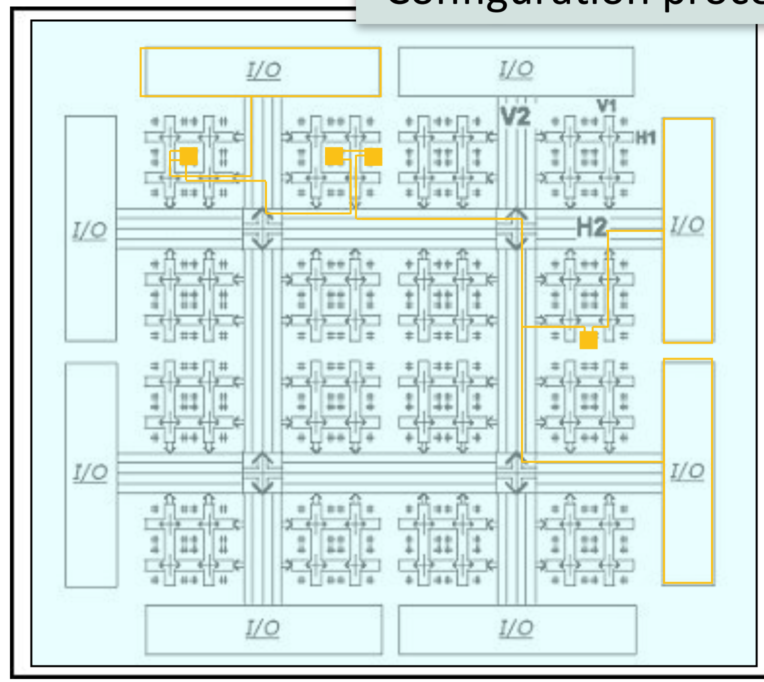
FPGA array

Circuits on Flash-based FPGAs

0	1	0	0	0	0
1	0	0	0	0	0
1	1	0	0	0	0
0	0	0	0	1	0
0	1	0	1	0	0
0	0	0	0	0	0

Flash configuration memory

Configuration process

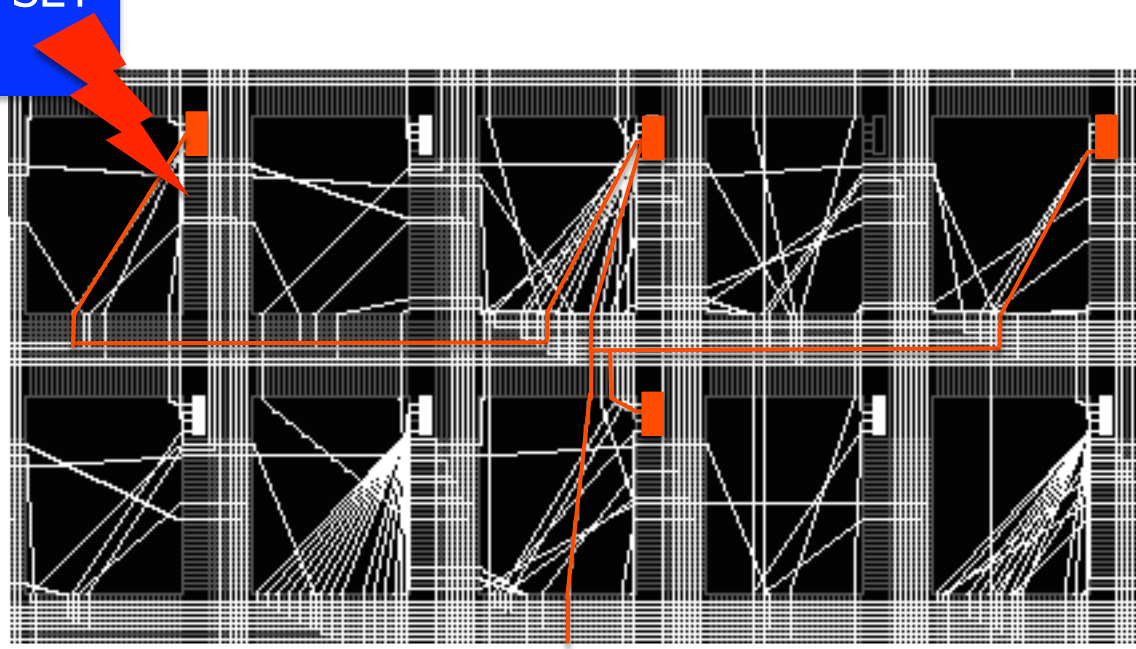


FPGA array

SET scenario

- Considering a place and route design on FPGA
  - Fixed logic cells
  - Defined number of routing segments

Source of SET



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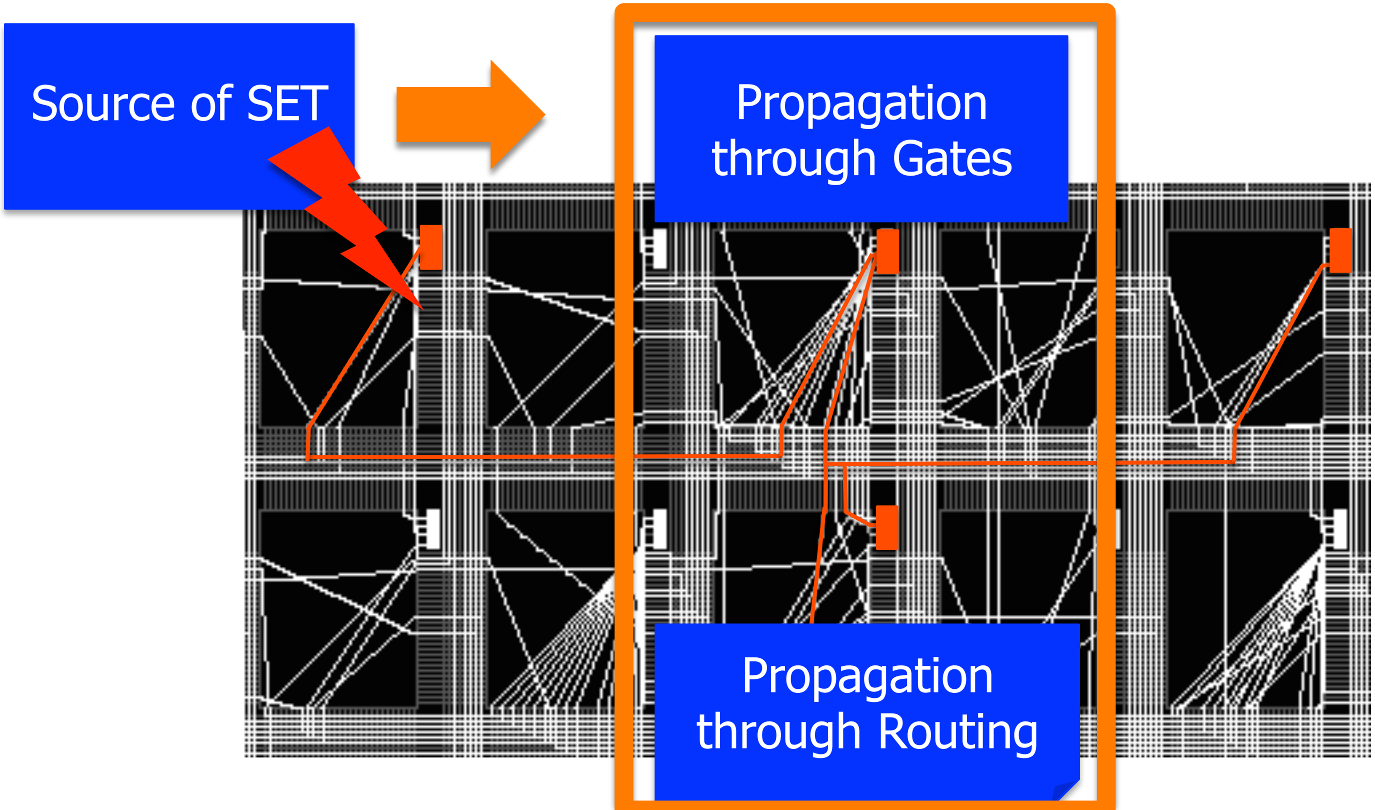

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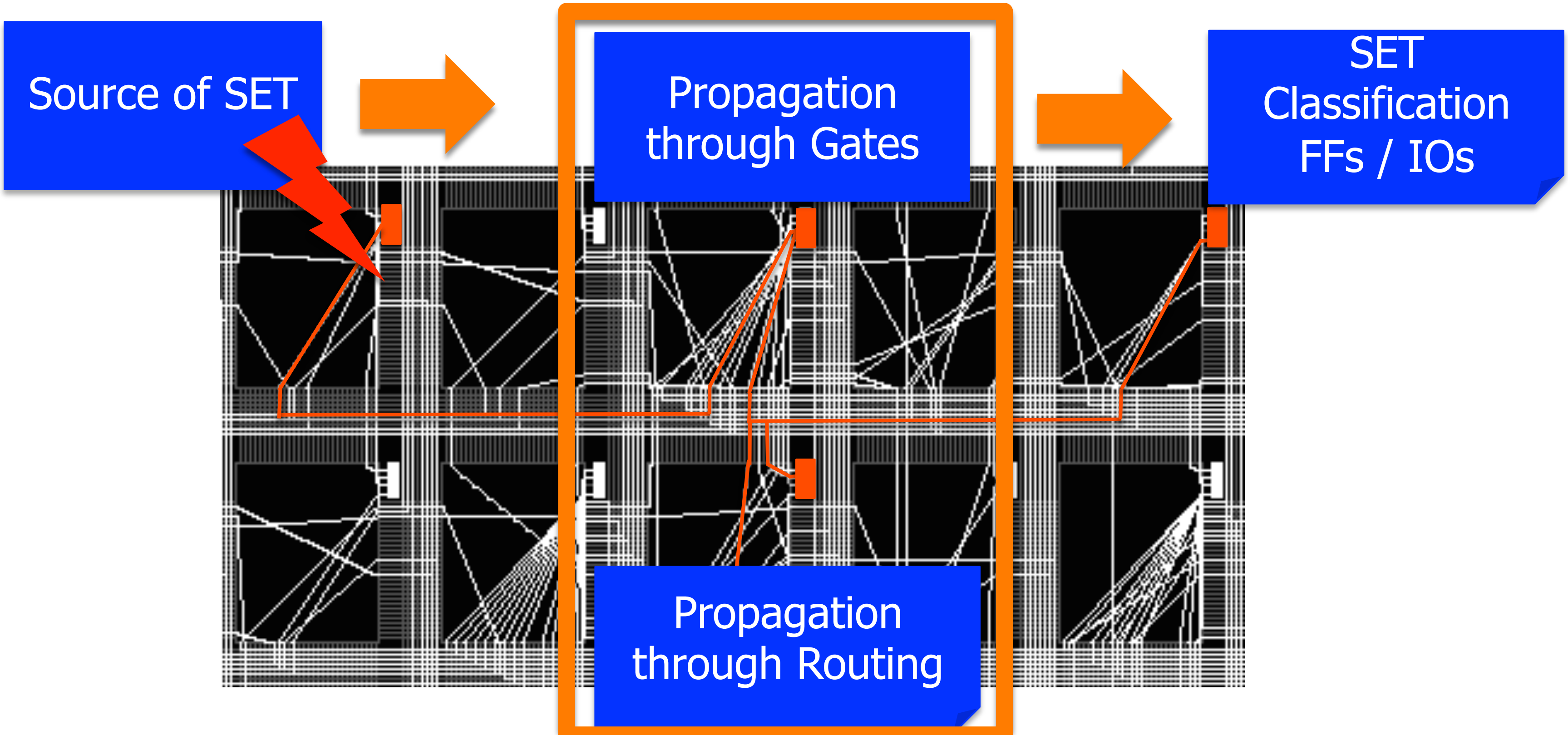


SET Propagation through gates

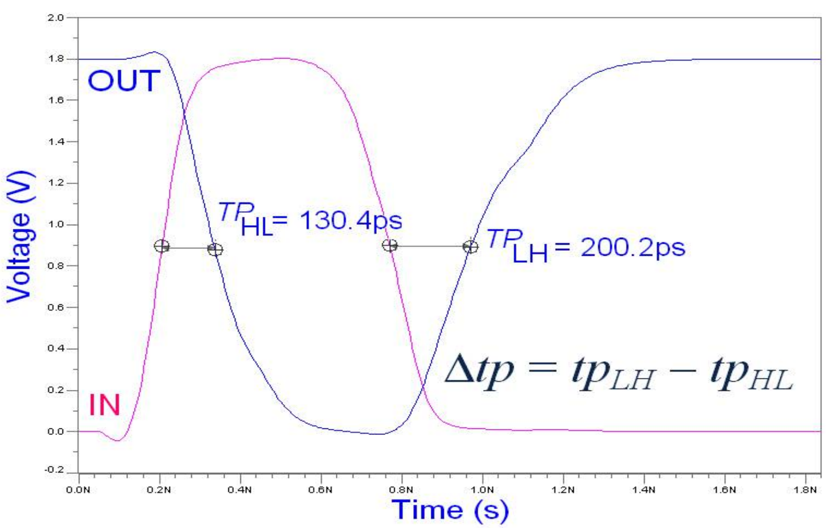
[Wirth et al, NSREC 2008]

Fist Region: If($\tau_n < k{*}tp$) then $\tau_{n+1} = 0$

Second Region: If ($\tau_n > (k+3){*}tp$) then $\tau_{n+1} = \tau_n + \Delta tp$

Third Region: If ($(k+1){*}tp < \tau_n < (k+3){*}tp$) then $\tau_{n+1} = (\tau_n^2 - tp^2)/\tau_n + \Delta tp$

Fourth Region: If ($k{*}tp < \tau_n < (k+1){*}tp$) then $\tau_{n+1} = (k+1){*}tp(1 - e^{(k-(\tau n/tp))}) + \Delta tp$



For a 1→0→1 transition Δtp is defined as:

$\Delta tp = tpHL - tpLH$

For a 0→1→0 transition Δtp is defined as:

$\Delta tp = tpLH - tpHL$

Source of SET
Propagation through gates
Propagation through routing
SET classification on FFs or IOs

SET Propagation through gates

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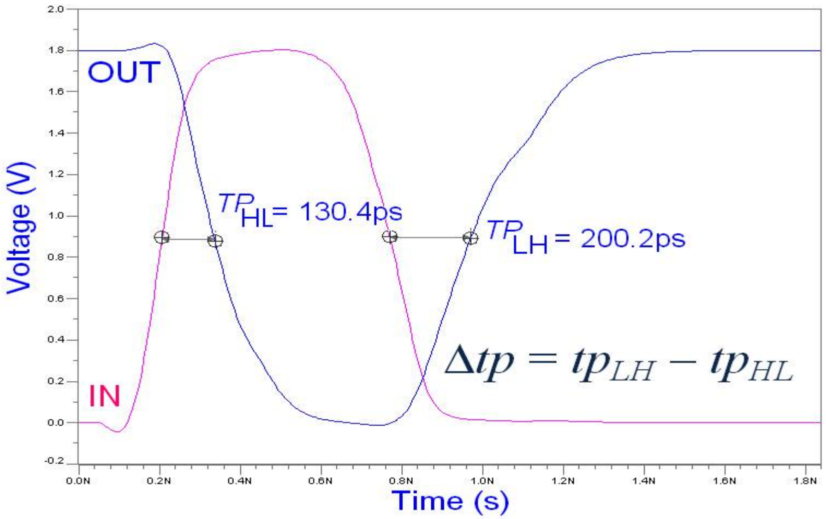

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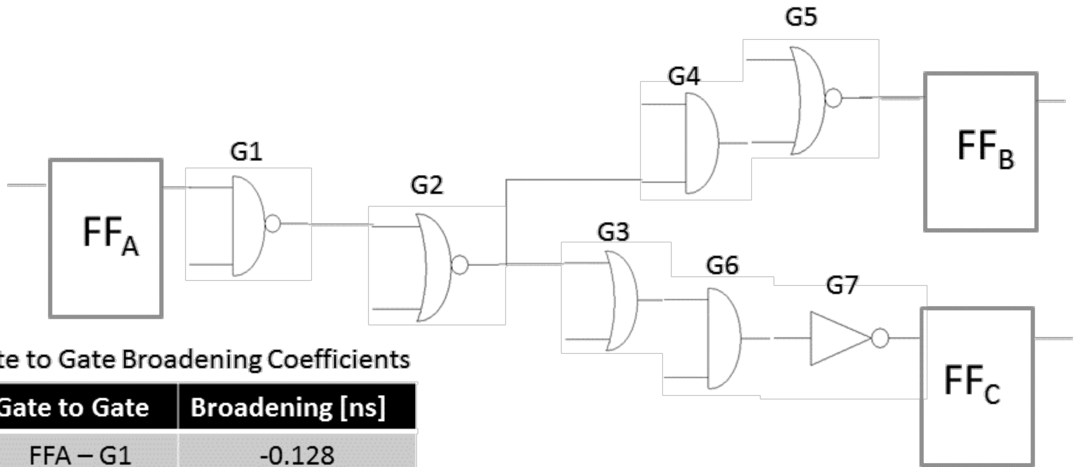
SET Propagation through routing

[Sterpone et al, RADECS 2014]



Gate to Gate Broadening Coefficients

Gate to Gate	Broadening [ns]
FFA – G1	-0.128
G1 – G2	0.458
G2 – G4	0.070
G2 – G3	-0.090
G3 – G6	0.480
G6 – G7	0.092
G7 - FFC	0.140
G4 – G5	-0.094
G5 - FFB	0.130

FFs maximal broadening pulses

Flip-Flop	Maximal Pulse [ns]
FFB	0.436
FFC	0.952

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SET Propagation through routing

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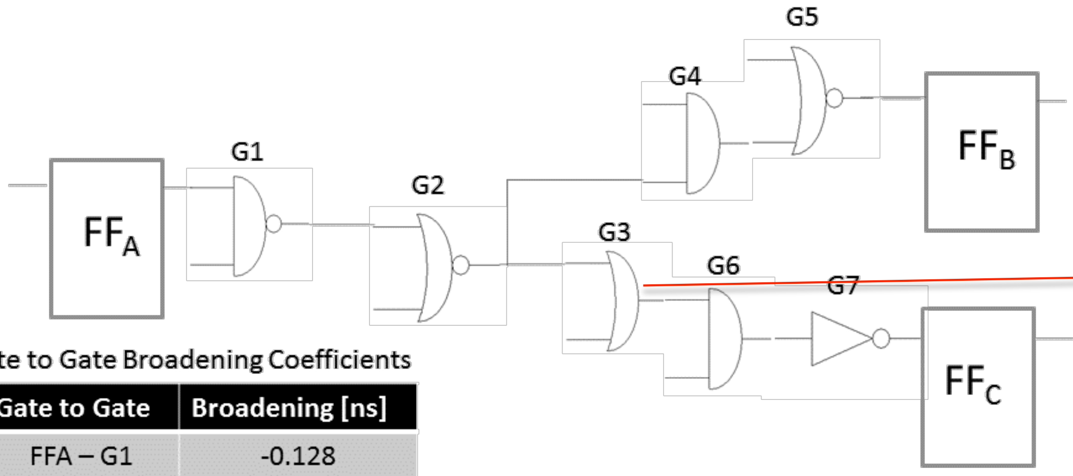

Propagation Induced Pulse Broadening

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SET Propagation through routing

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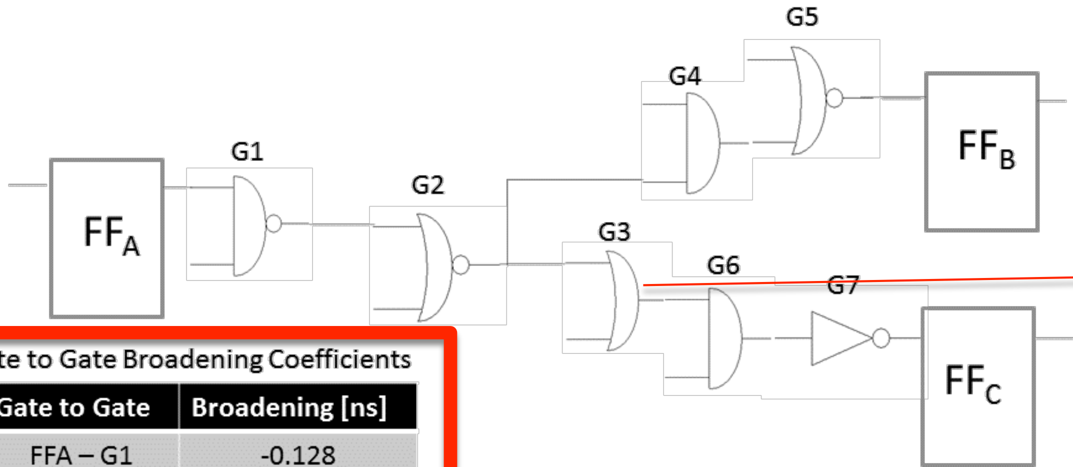

Propagation Induced Pulse Broadening

Gate to Gate Characterization

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- **Propagation through routing**
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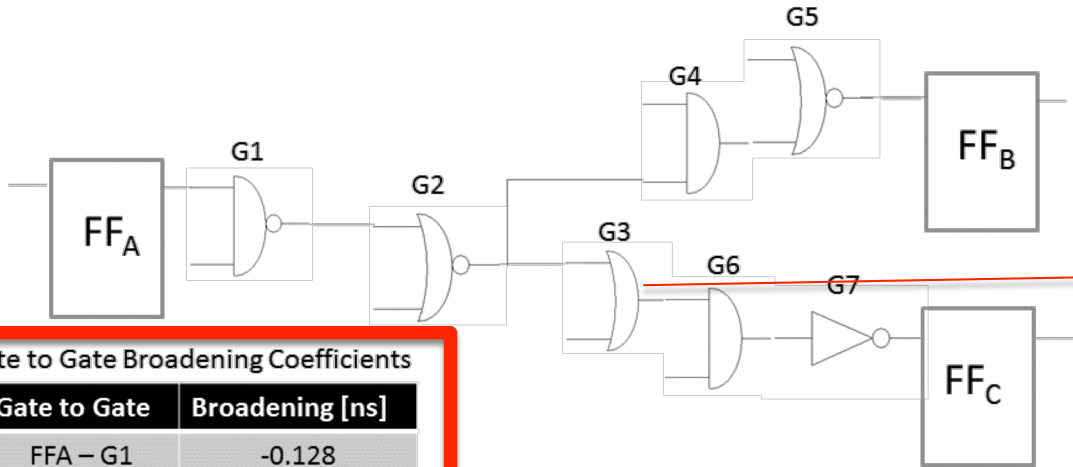
SET Propagation through routing

[Sterpone et al, RADECS 2014]



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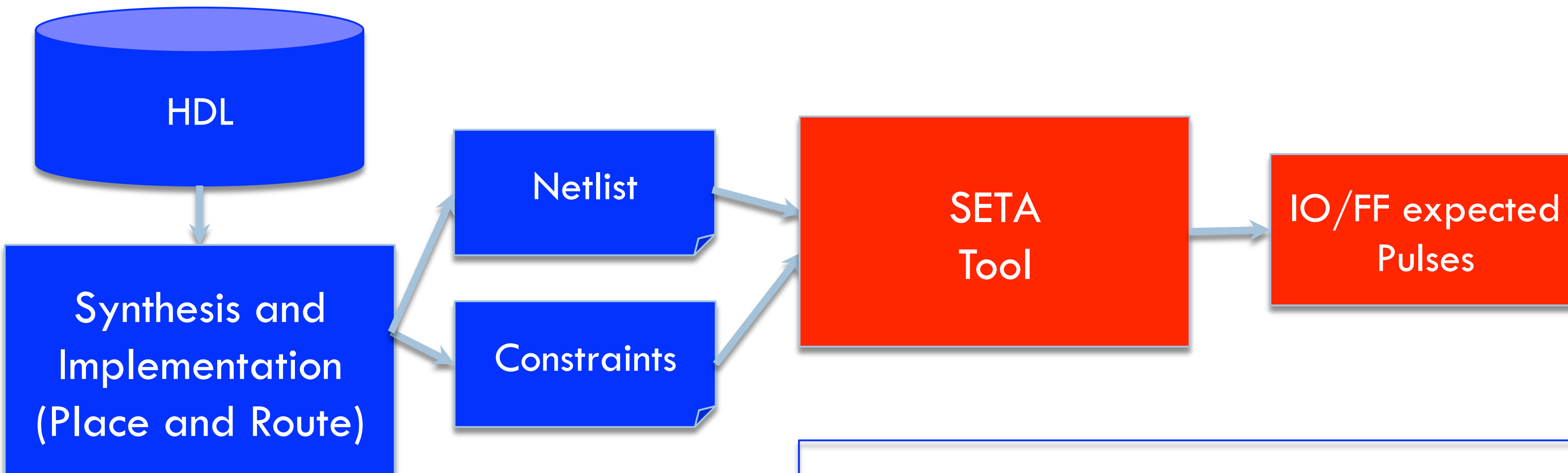
- **Source of SET**
- V **Propagation through gates**
- V **Propagation through routing**
- **SET classification on FFs or IOs**

SET classification on FFs and IOs

- A tool has been developed:
  - Single Event Transient Analyzer (SETA)



Source of SET
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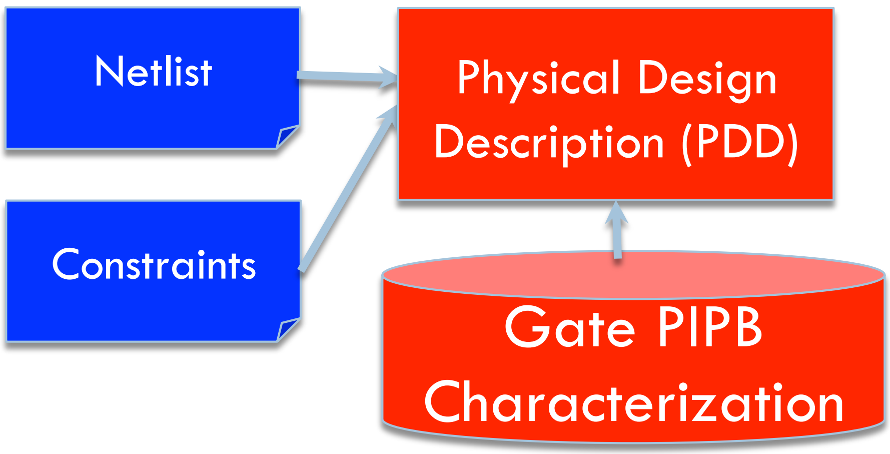
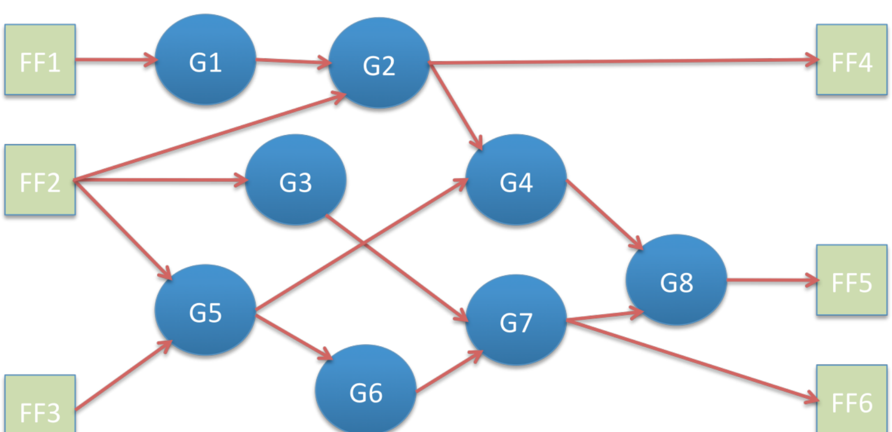
SETA tool





Source of SET

V Propagation through gates

V Propagation through routing

SET classification on FFs or IOs

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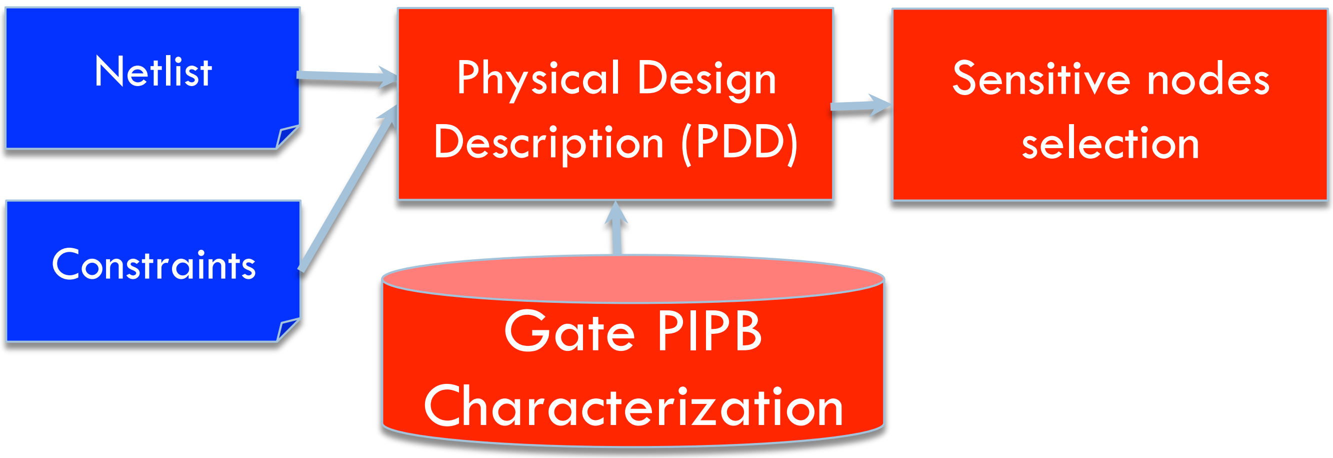

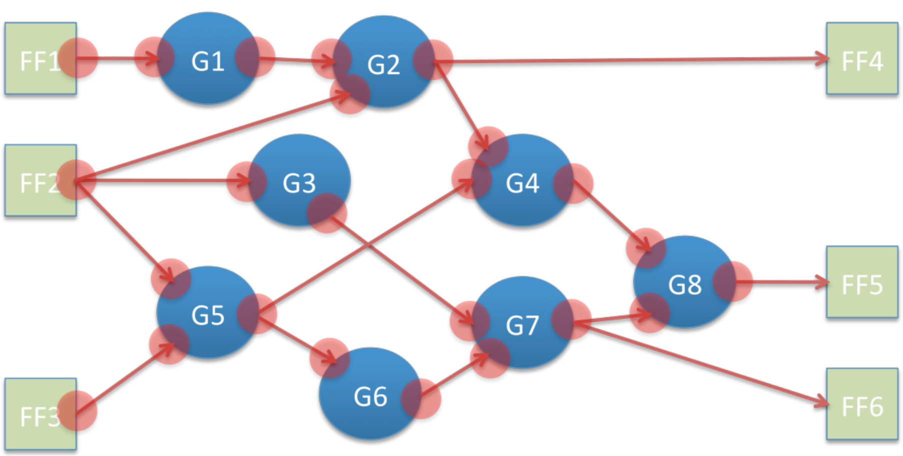

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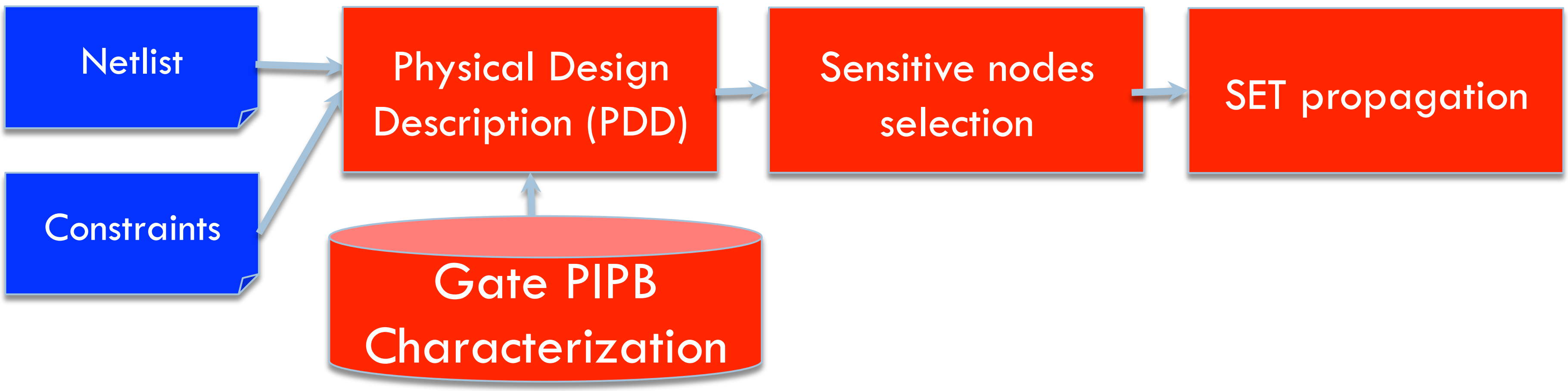

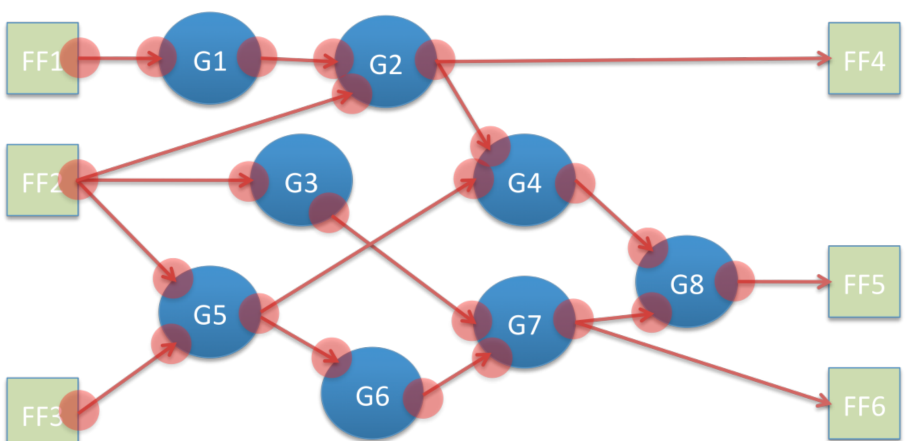

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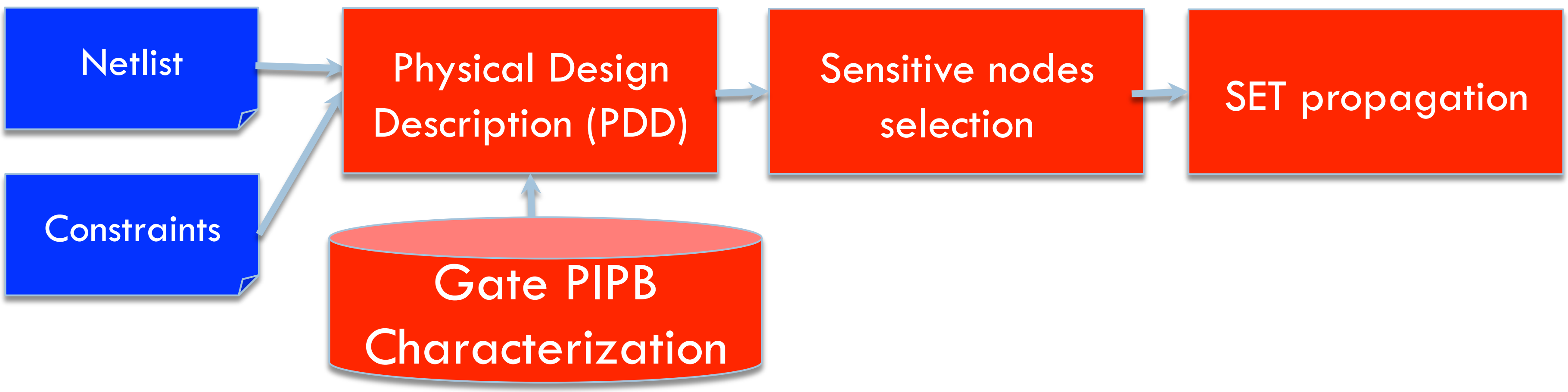

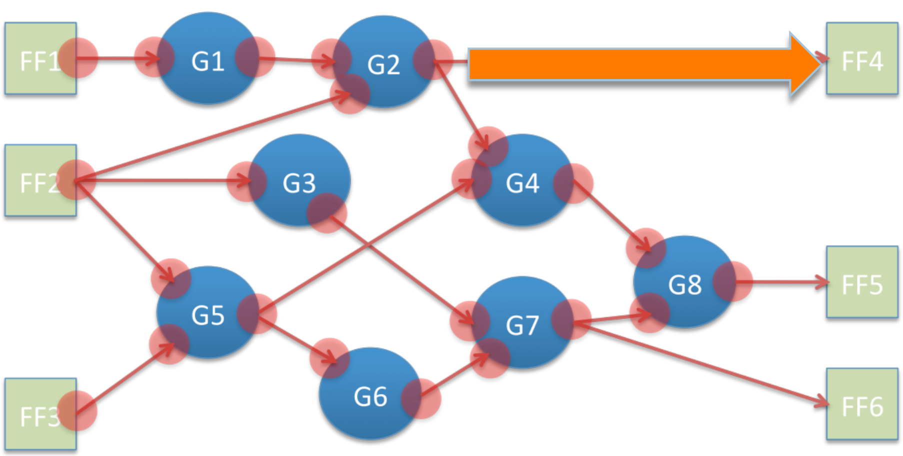

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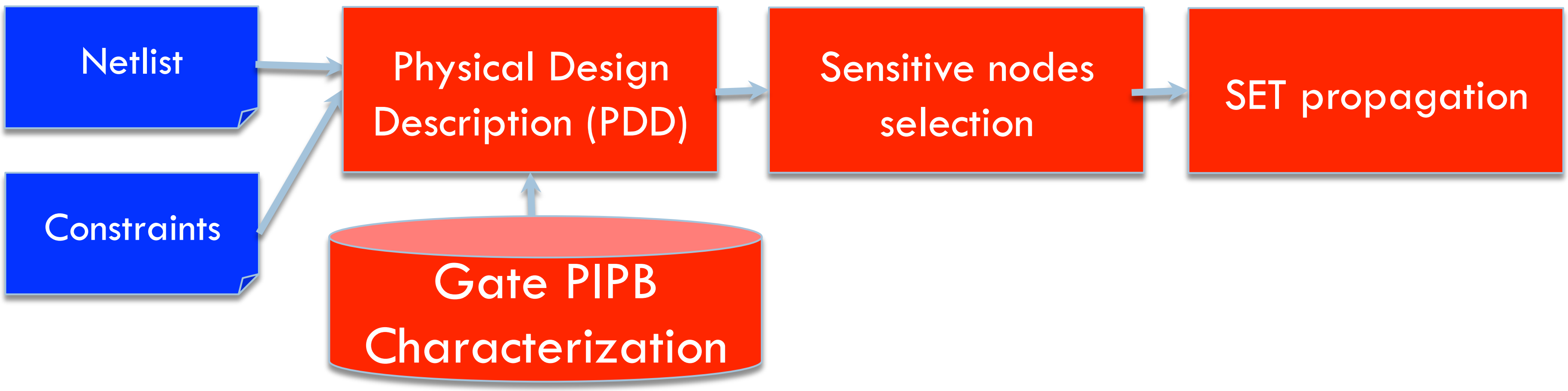
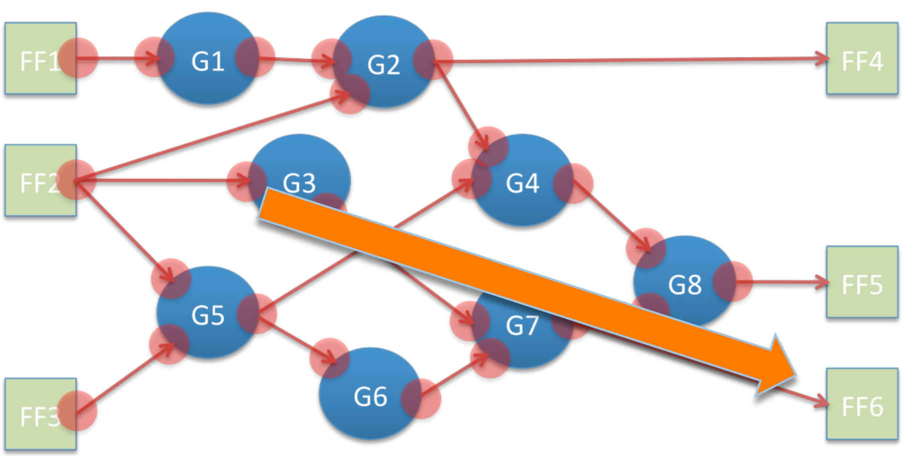




Source of SET
V Propagation through gates
V Propagation through routing
SET classification on FFs or IOs

SETA tool

Netlist

Constraints

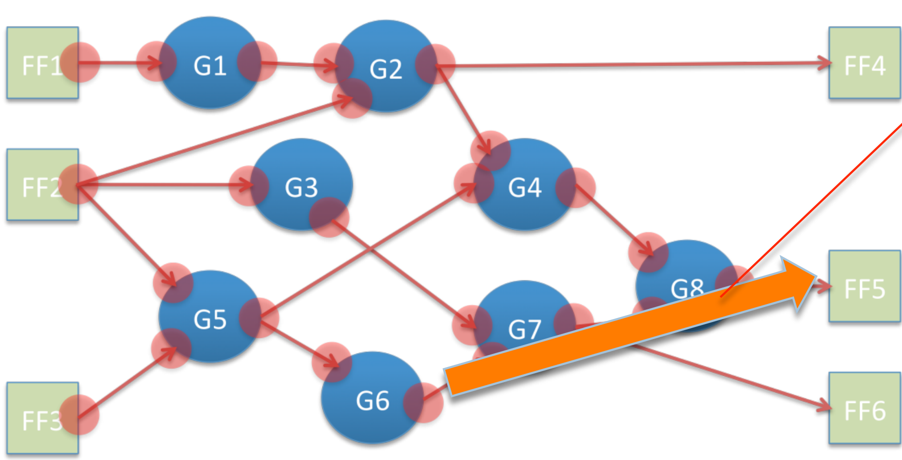
Physical Design Description (PDD)

Gate PIPB Characterization

Sensitive nodes selection

SET propagation

Propagation is performed up to “terminal” nodes (IOs / FFs)



- Source of SET
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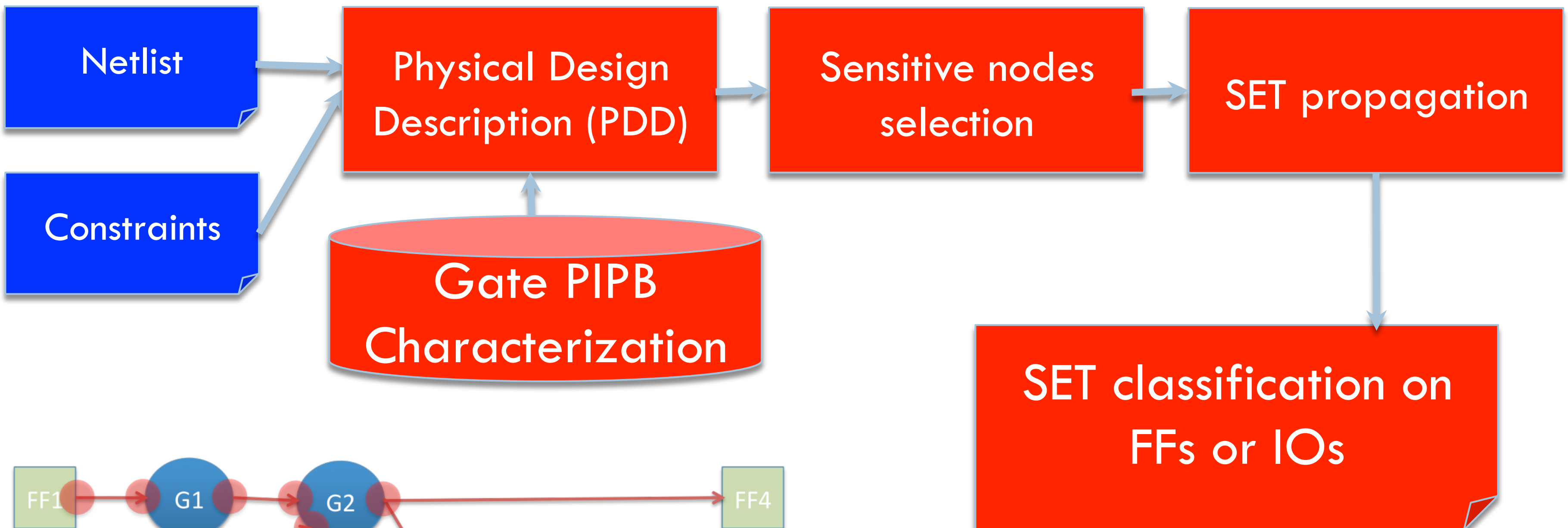
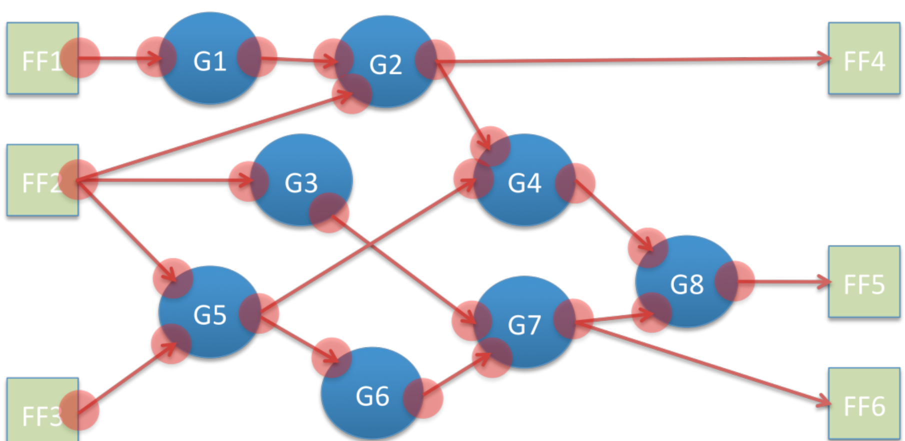
SETA tool





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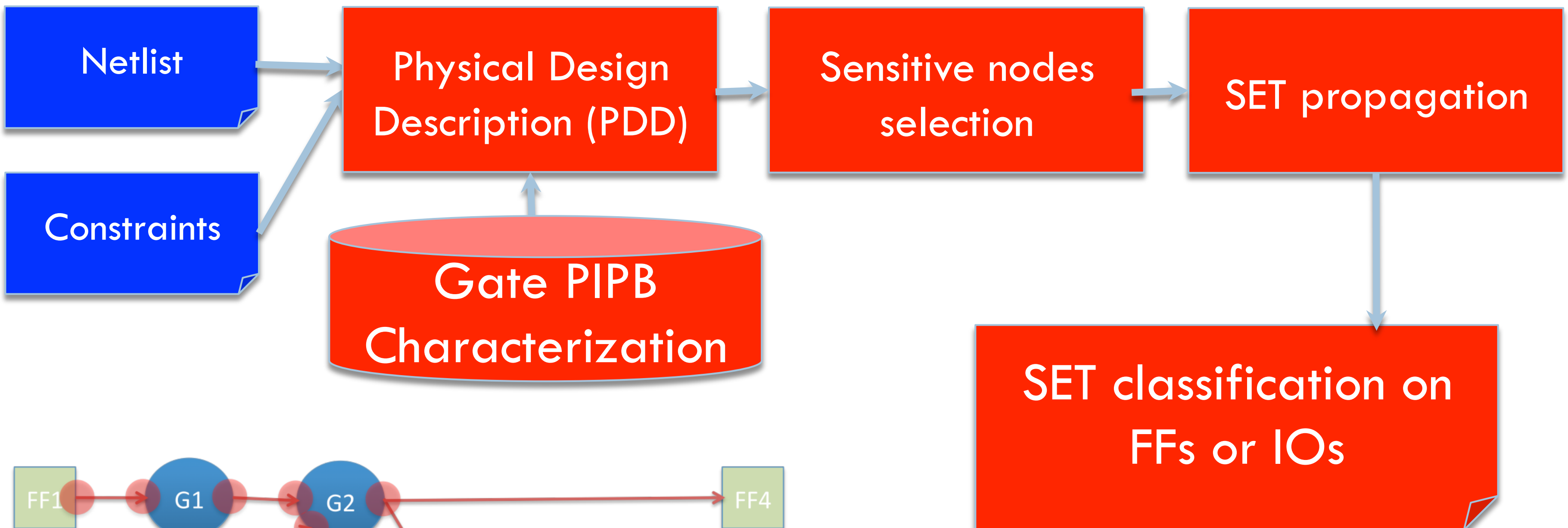
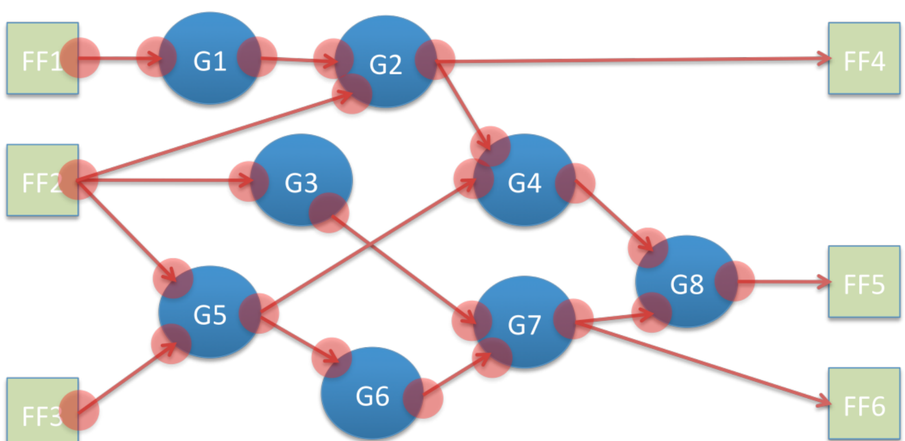


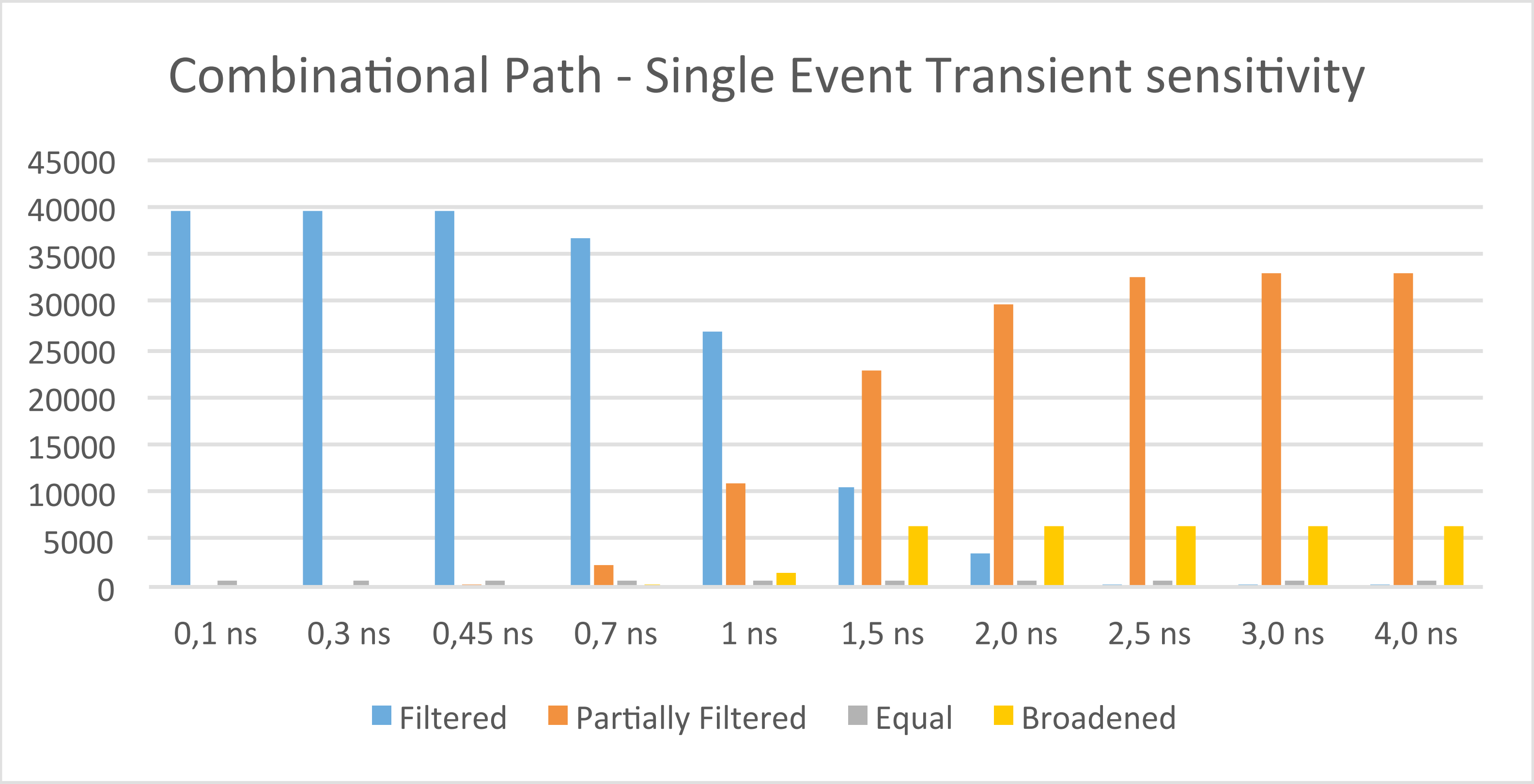


Source of SET
- V **Propagation through gates**
- V **Propagation through routing**
- V **SET classification on FFs or IOs**

SET classification on FFs and IOs

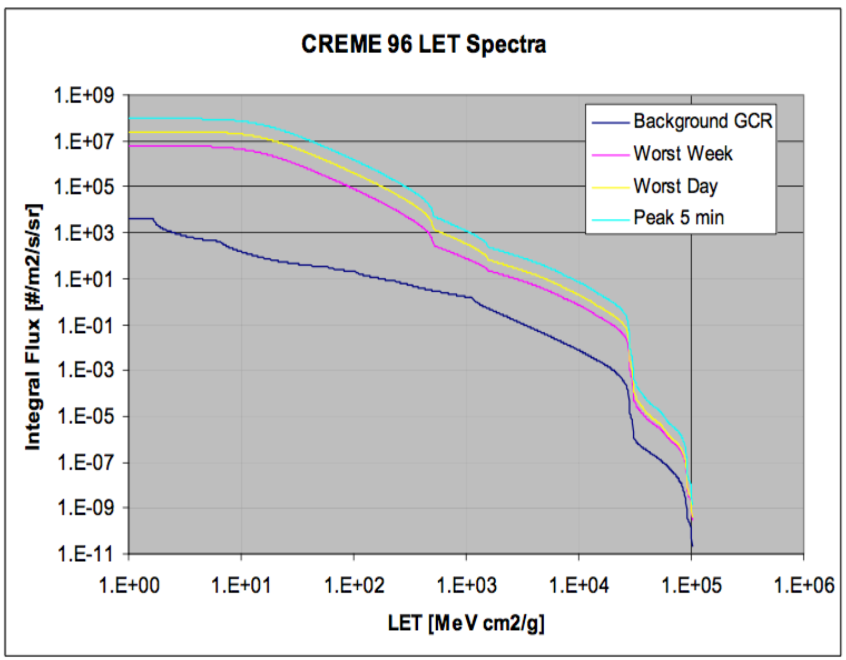
- The classification identifies the number of SET:
  - Totally filtered
  - Partially filtered
  - Equally propagated
  - Broadened

SETA results – EUCLID project



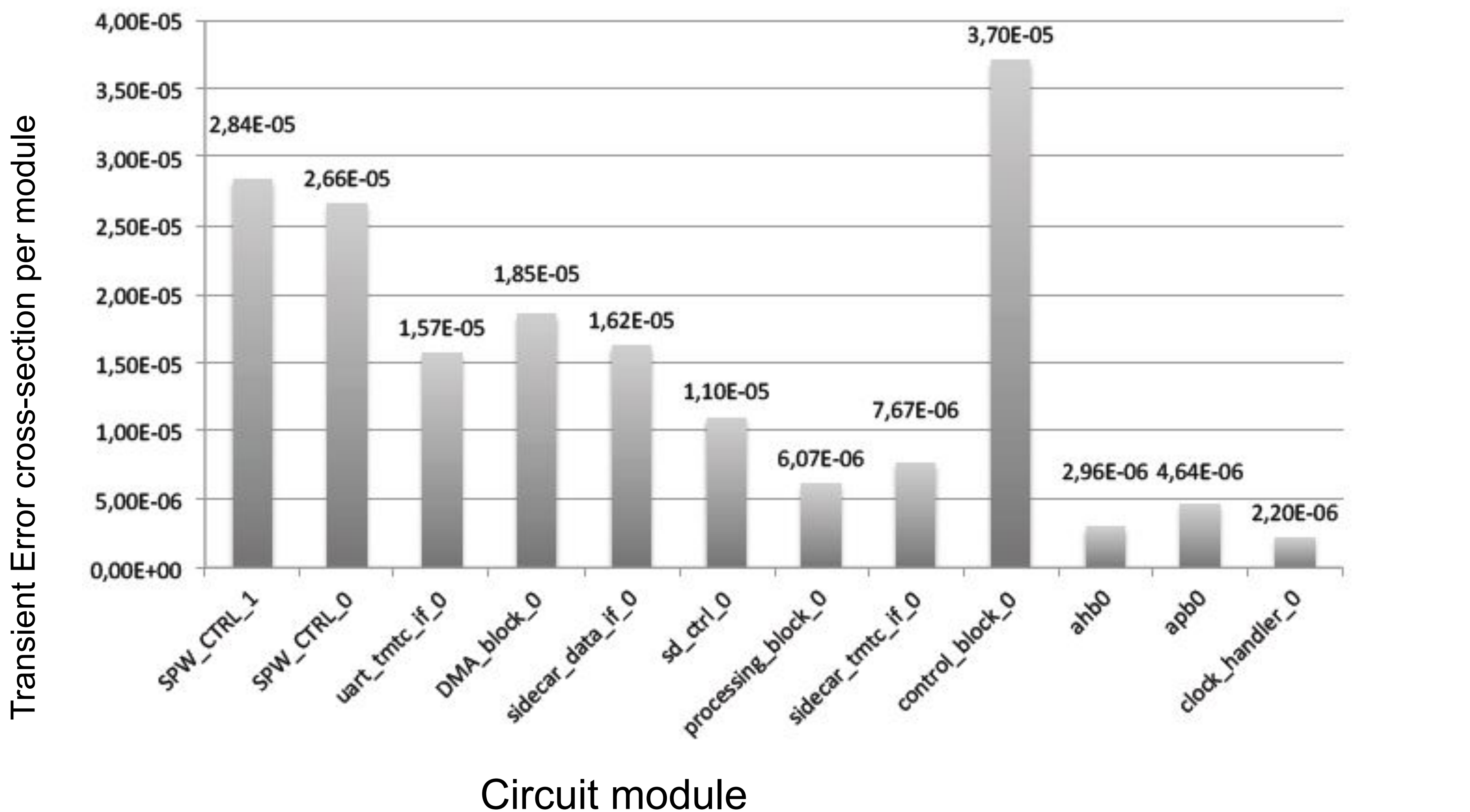
SETA results – EUCLID project

- Analysis of the integral fluency expected for the duration of the mission: expected EUCLID duration is 6.25 years
  - Linear Energy Transfer distribution calculated using CREME96



Resource	SET Normalized cross-section
Routing Segment	1.31E-10
VersaTile	2.60E-08

SETA results – EUCLID project



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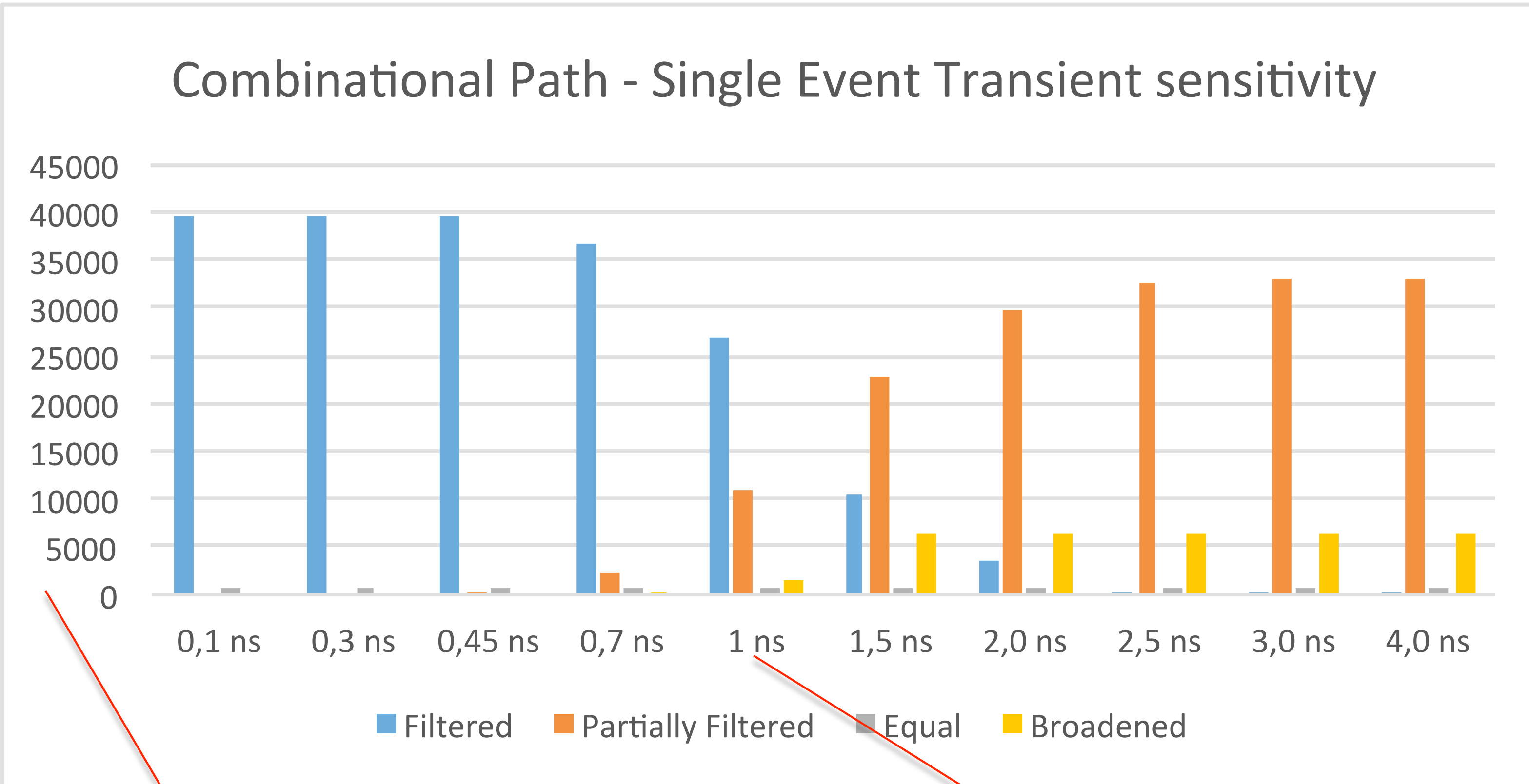


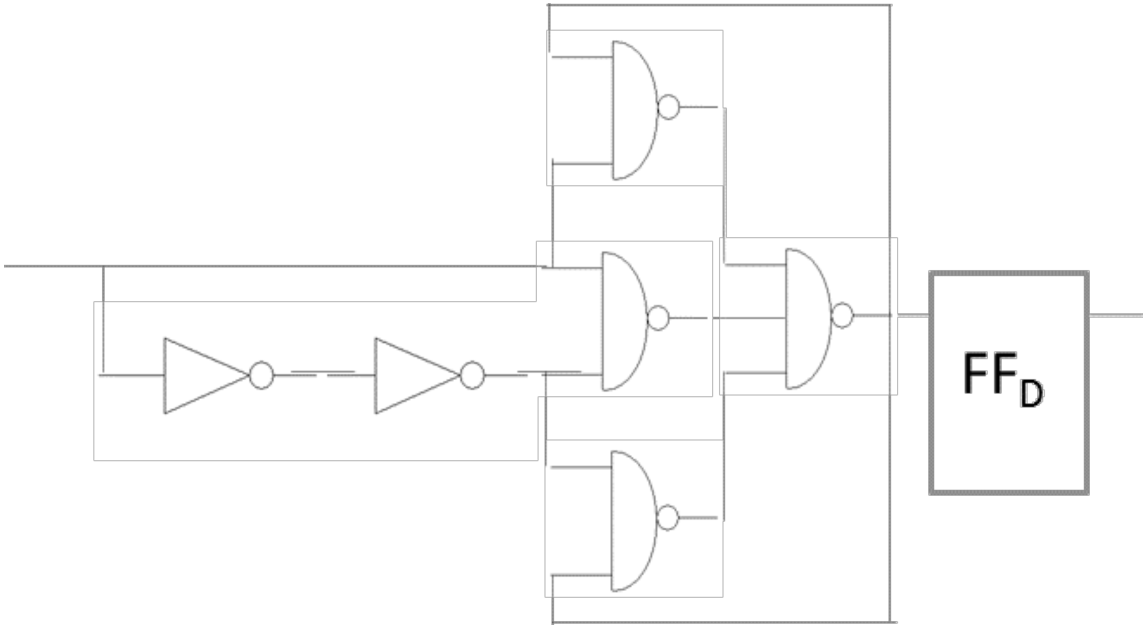
Total number of analyzed SET

Type of SET per injected pulse

SET: mitigation

[Sterpone and Du, IEEE ETS 2014]

- Selective guard gate (GG) mapper
  - Inserting a GG logic structure in the input of the selected FF



SET: mitigation solution 1

[Sterpone and Du, IEEE ETS 2014]

- Selective guard gate (GG) mapper
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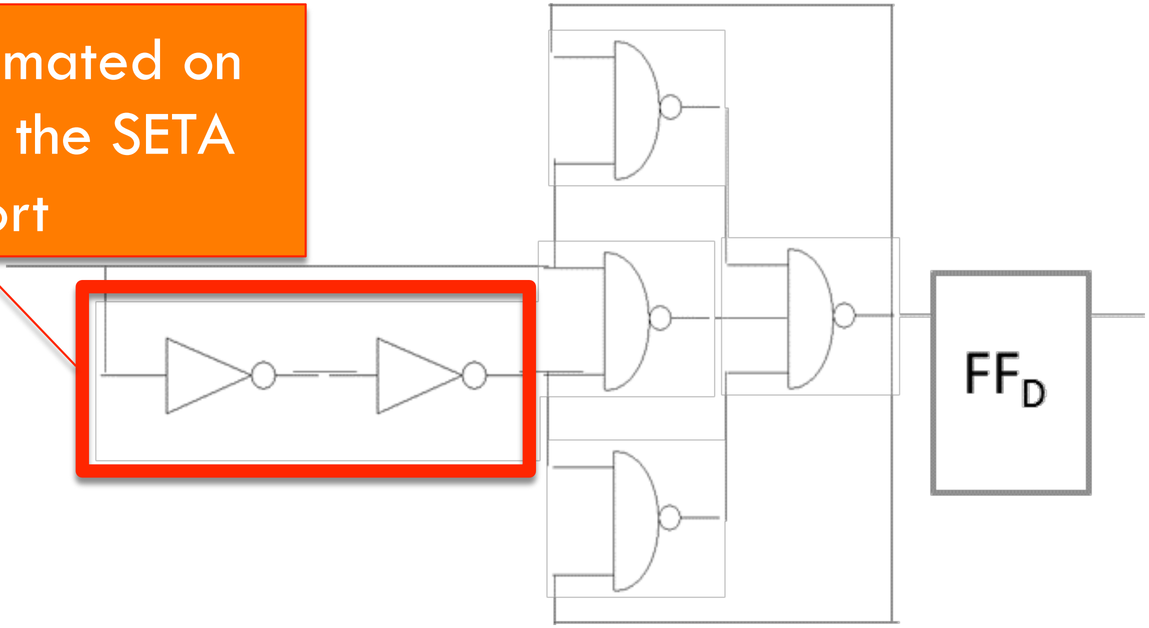
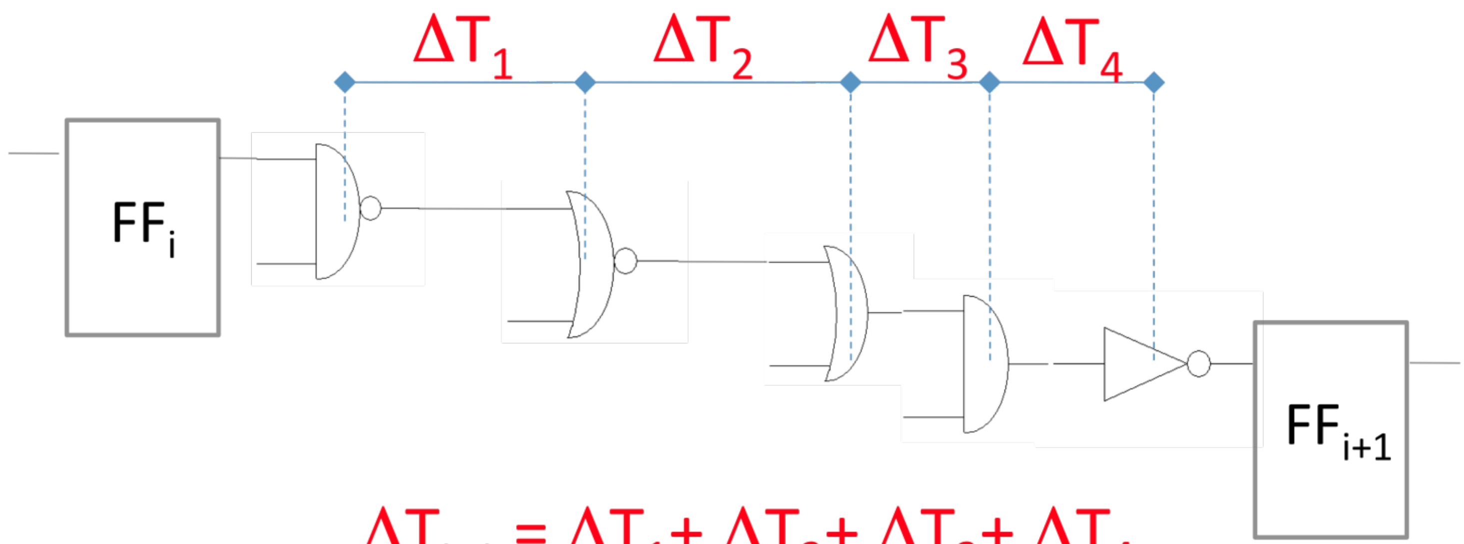
Filtering estimated on the basis of the SETA report



SET: mitigation solution 2

[Sterpone and Du, IEEE ETS 2014]

- Accurate placement acting on the critical paths
  - Distance between gates is modified in order to maximize the electrical filtering effect



$$\Delta T_{tot} = \Delta T_1 + \Delta T_2 + \Delta T_3 + \Delta T_4$$

SET: mitigation solution 2

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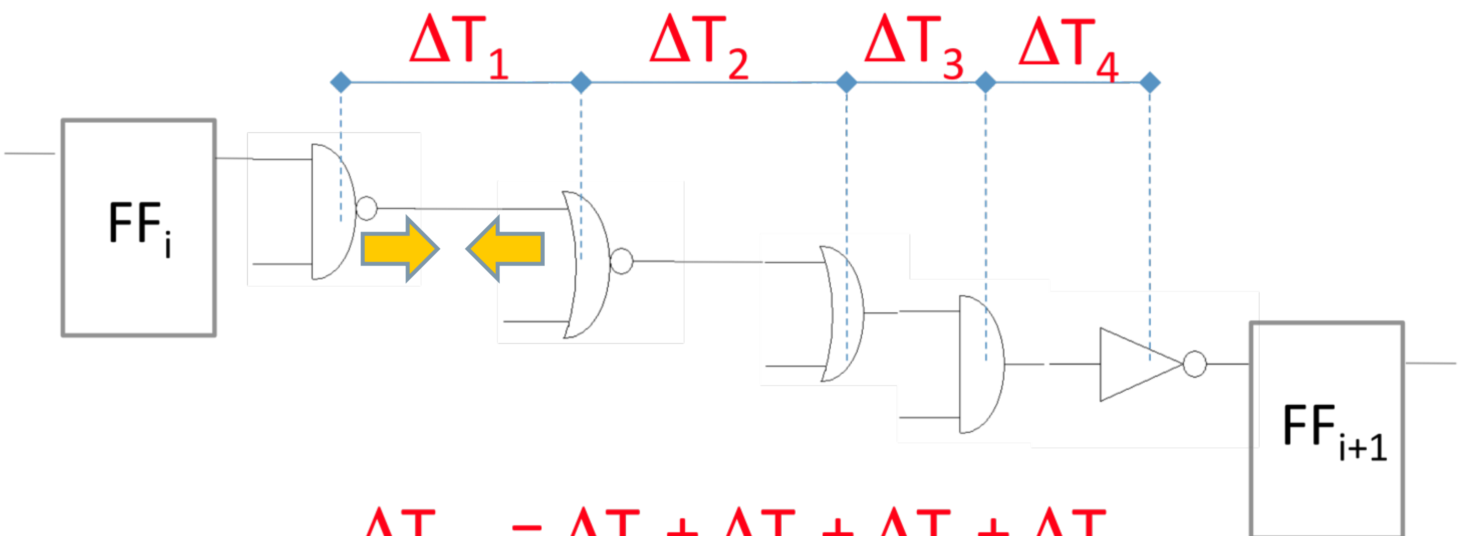

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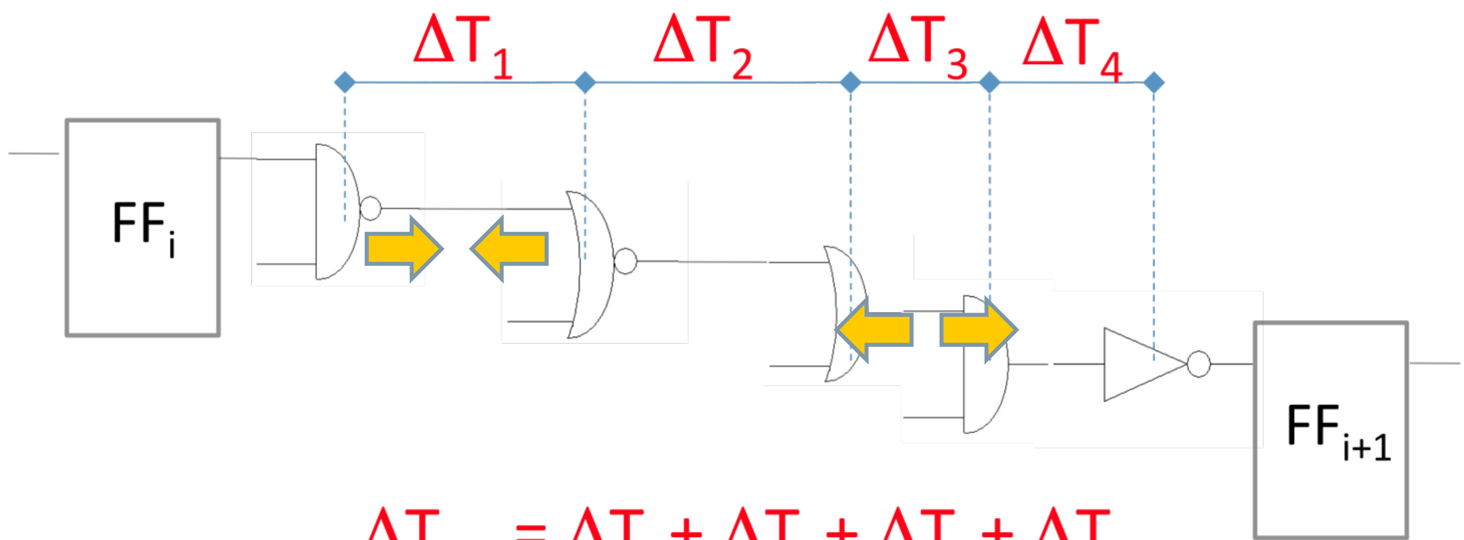

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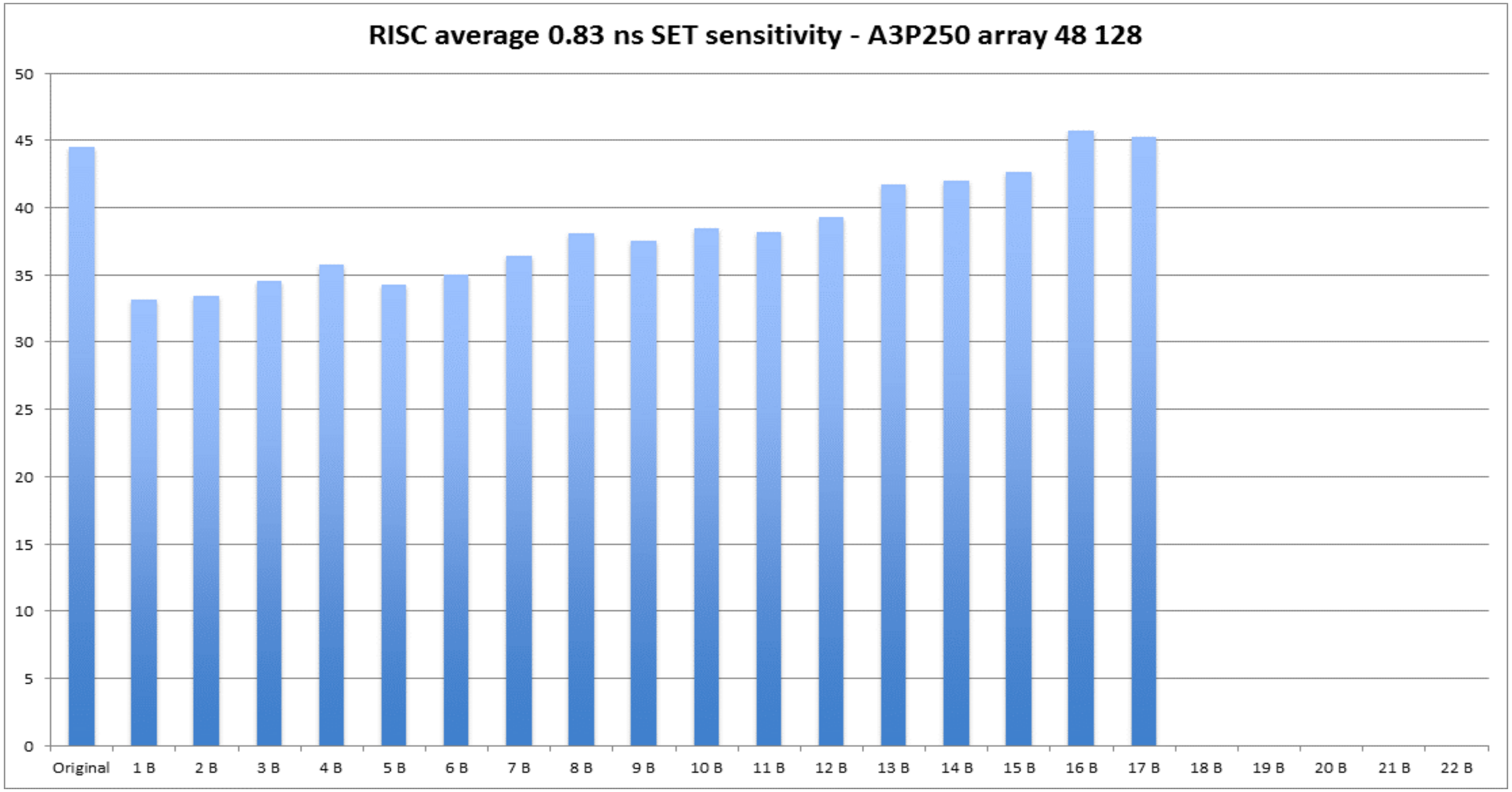
SET: mitigation results

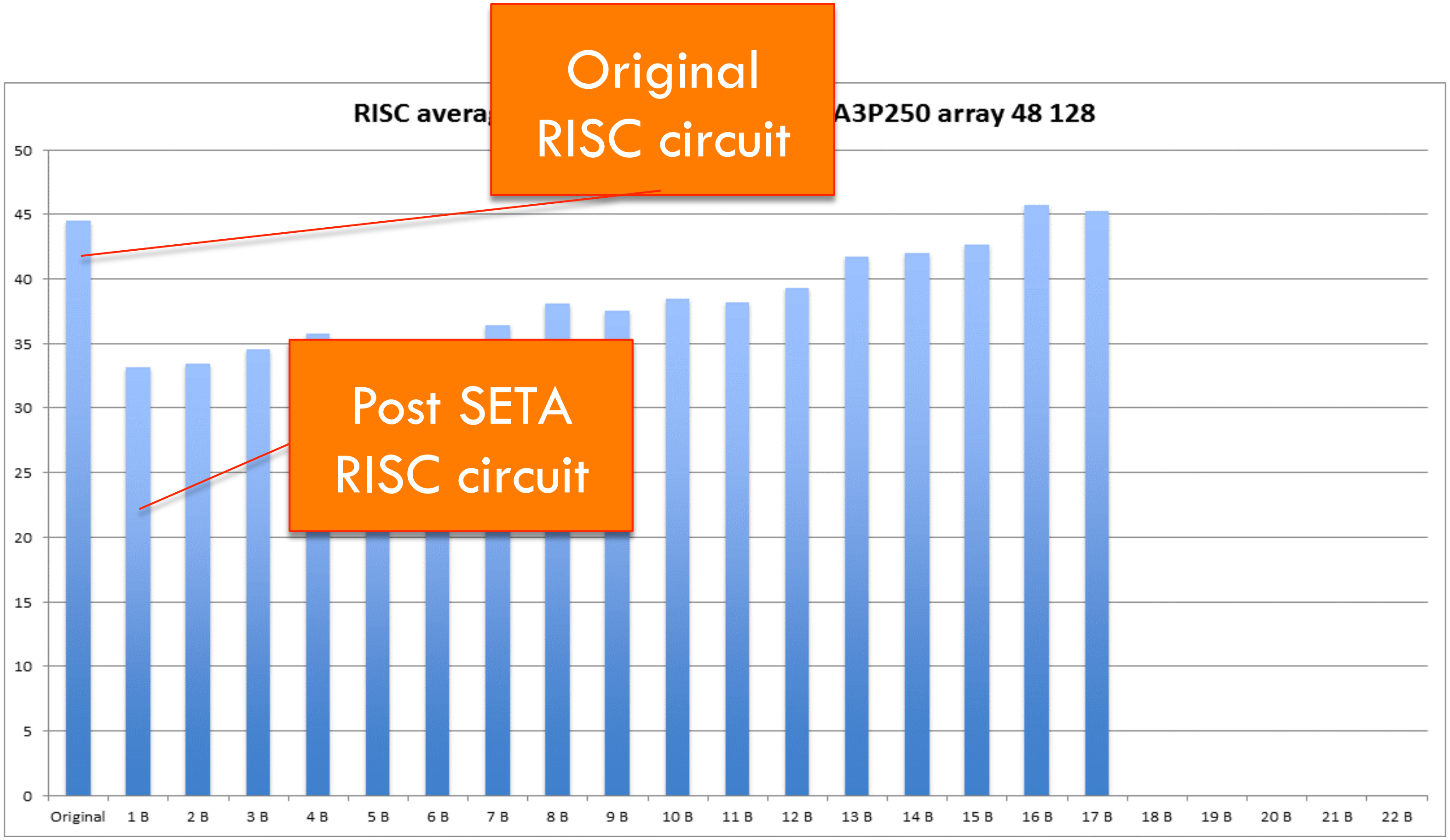
Average SET sensitivity



Different place and route constraints

SET: mitigation results

Average SET sensitivity



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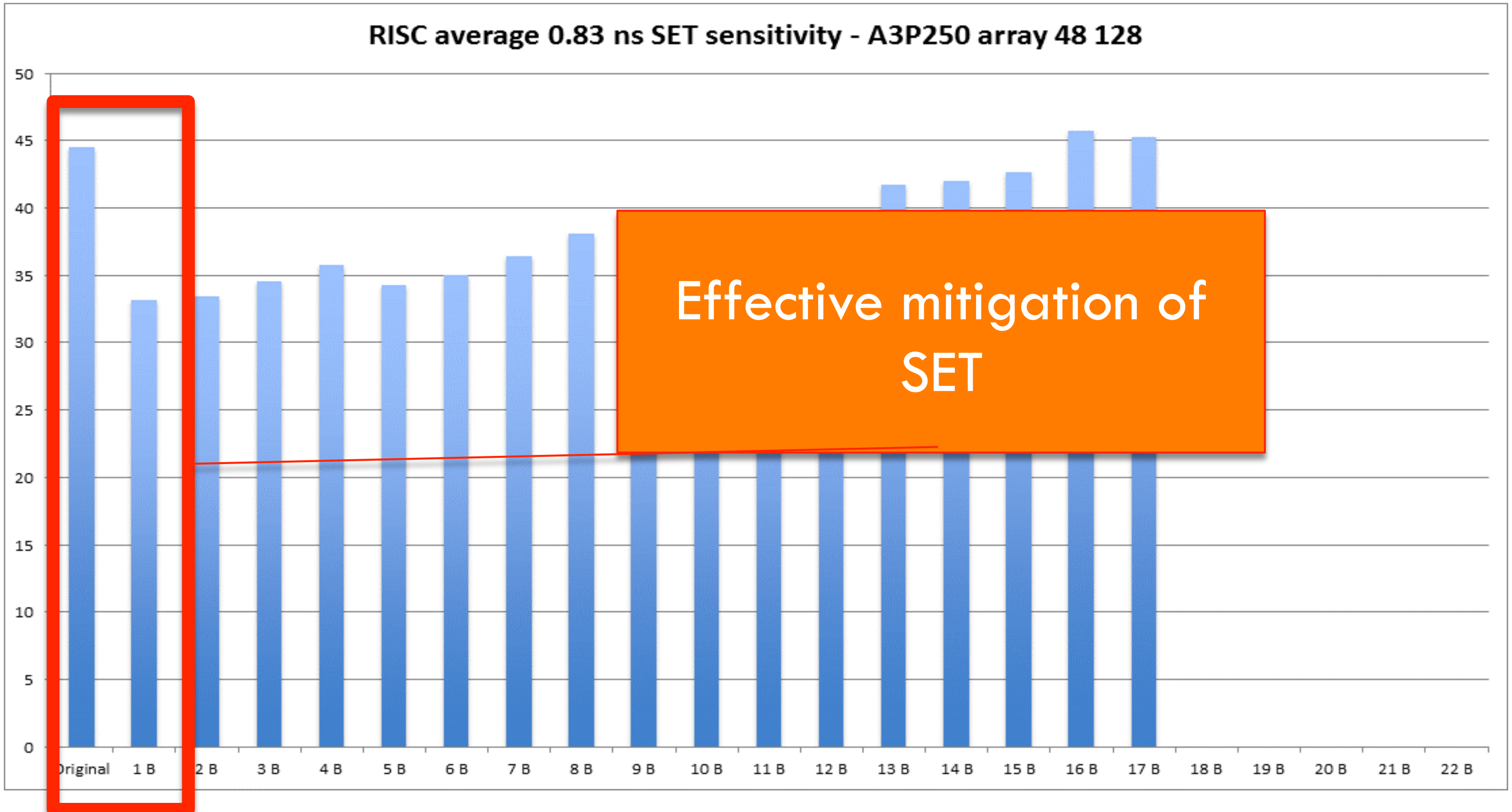

Different place and route constraints

SET: mitigation radiation test results

- Heavy ions test performed at the Cyclotron of the Université Catholique de Louvain (UCL)
  - Kripton ion with a fluence of 3.04E8 (particles)
  - Average flux 1E4 (particles/sec)
  - RISC working frequency of 20MHz on ProASIC3 A3P250

RISC processor version	SEE Cross-section [MeV cm^2/mg]
Unhardened	1.45E-9
Full TMR + GG	6.37E-10
Our Approach	3.12E-12

SET: in conclusion…

- SETA tools are available
  - Effective analysis of SET propagation
  - Effective overall SET mitigation

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  - Effective analysis of SET propagation
  - Effective overall SET mitigation

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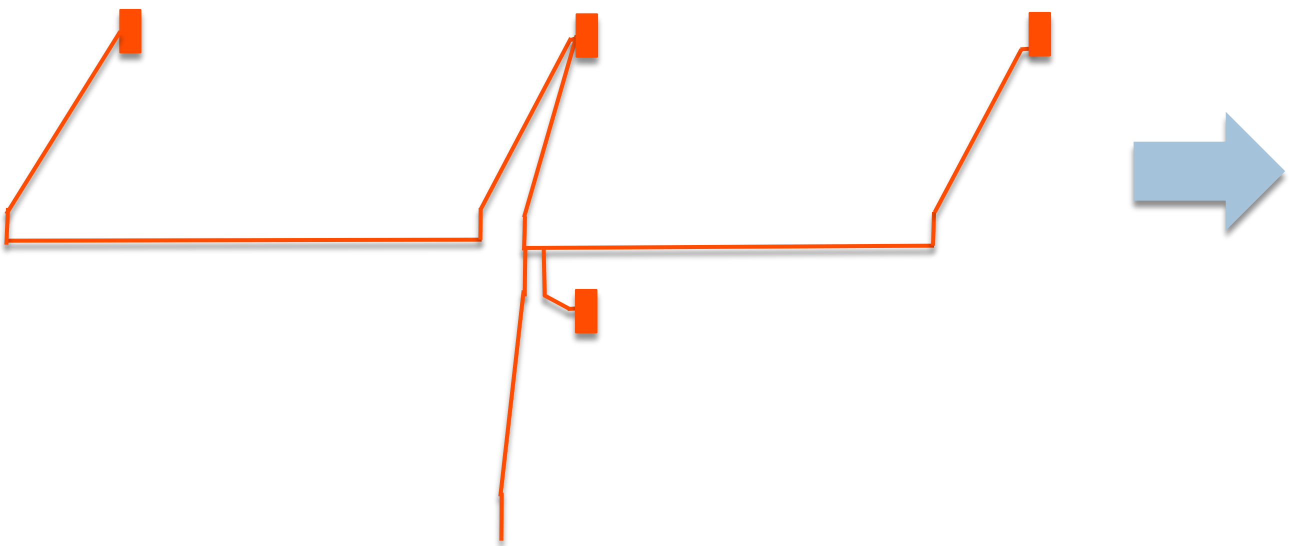
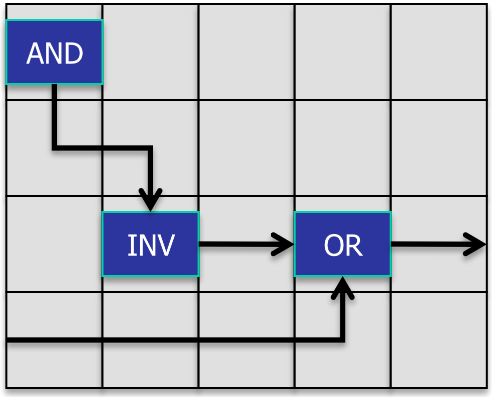
X **Source of SET**
V **Propagation through gates**
V **Propagation through routing**
V **SET classification on FFs or IOs**

Physical Design Description

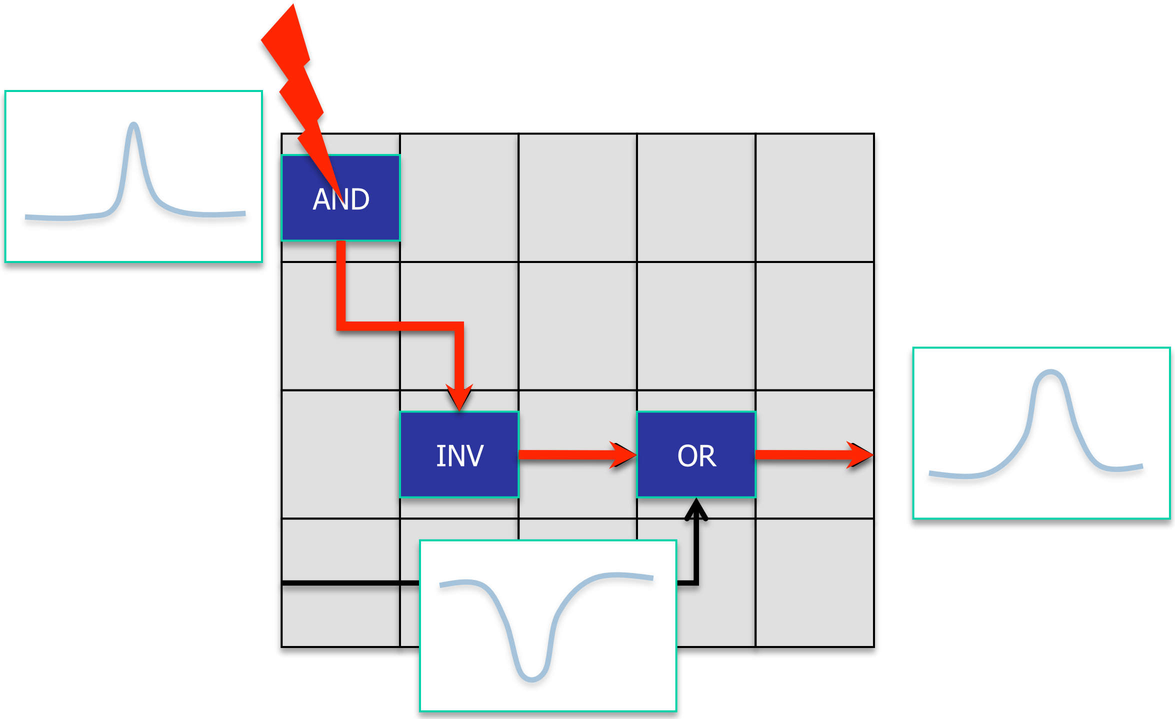
- The circuit is modeled as a graph
  - Cell functionality
  - Routing model





SET generation phenomena

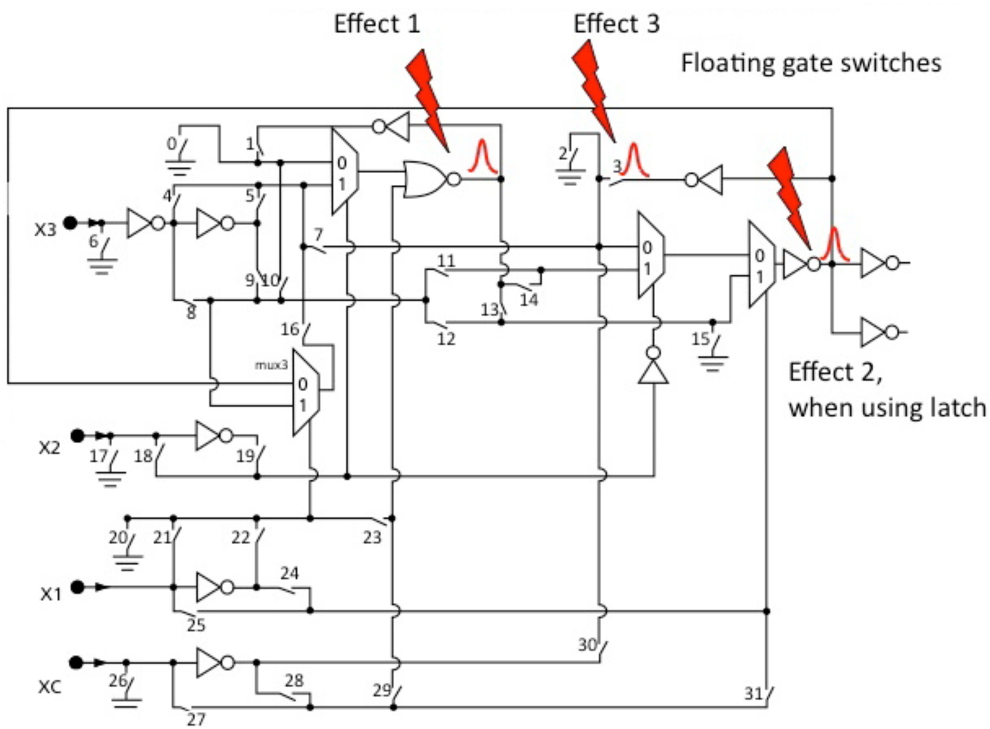
- Particle hitting a sensitive node
  - **Generate a SET pulse**
  - Propagates through the logic



SET generation phenomena

[Azimi, Du, Sterpone, Micro Rel, 2015]
[Azimi and Sterpone, IEEE DDECS 2016]

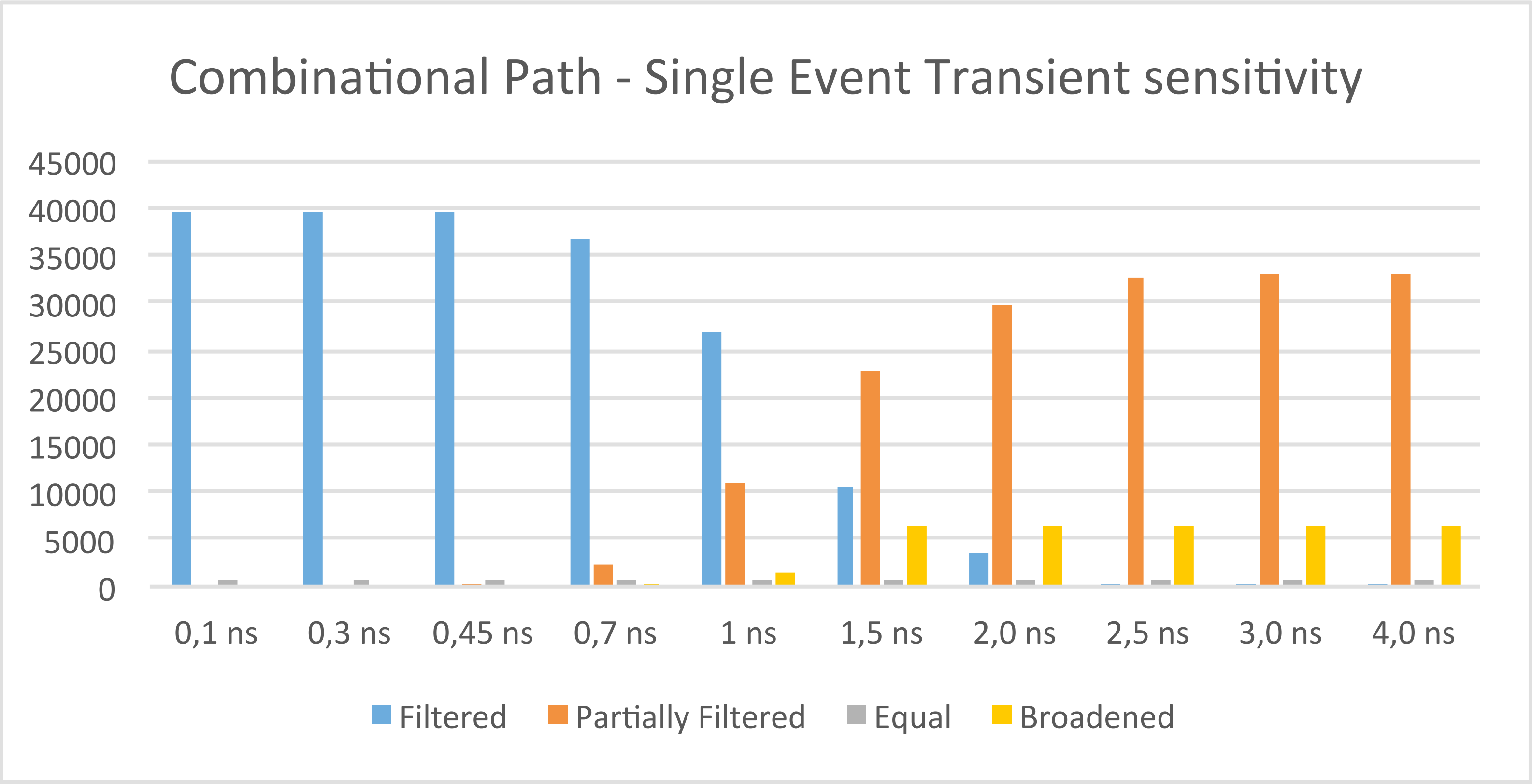
- SET generation is related to
  - Linear Energy Transfer (LET)
  - VersaTile architecture
  - Technology



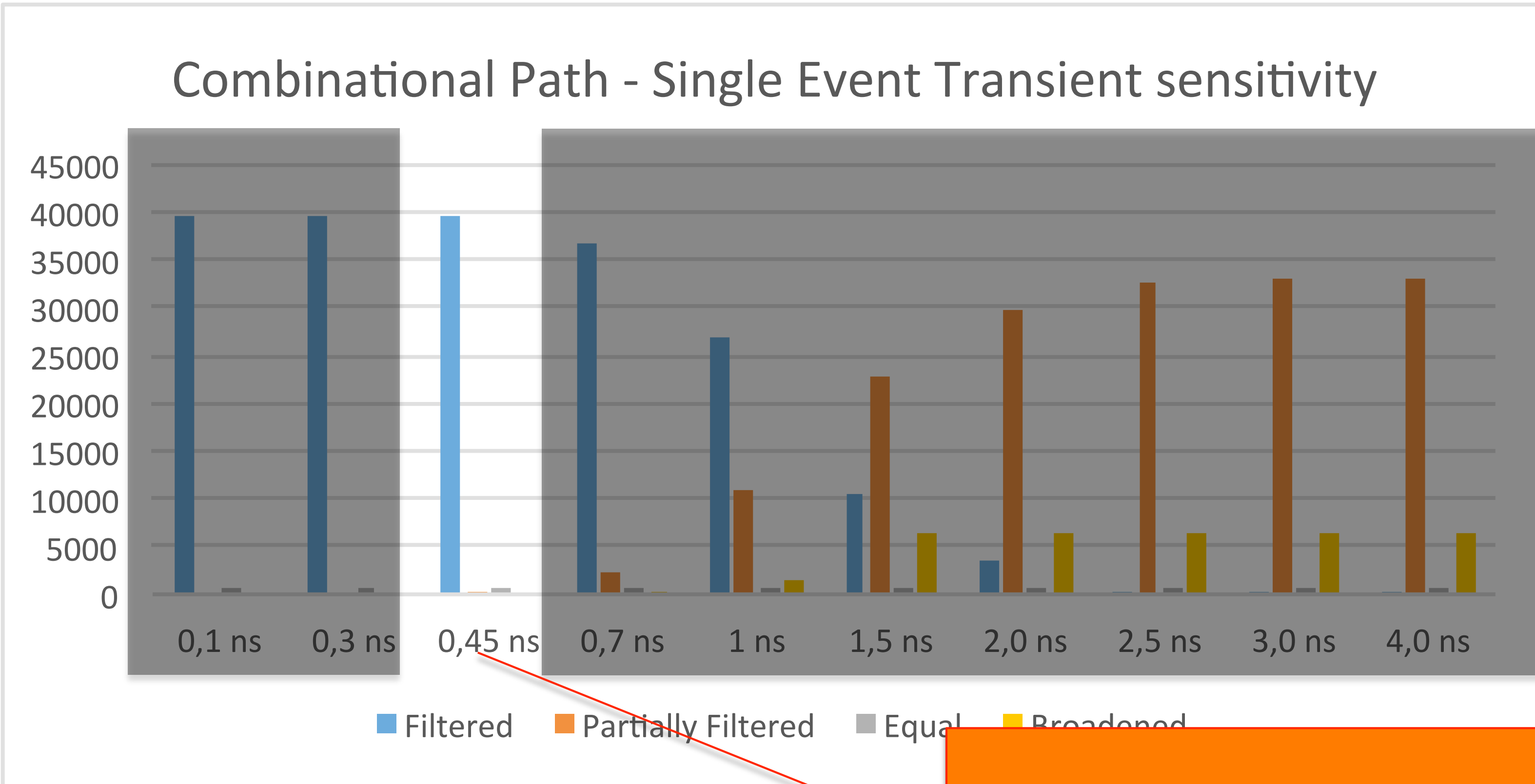
Why SET generation ?

- The type of source SET is mandatory to understand the exact type of propagation
  - Mitigation GG insertion is related to SET length
- It is necessary to establish the absolute SET count
  - Calculation of the realistic IOs/FFs error rate for the whole space mission duration

Why SET generation ?

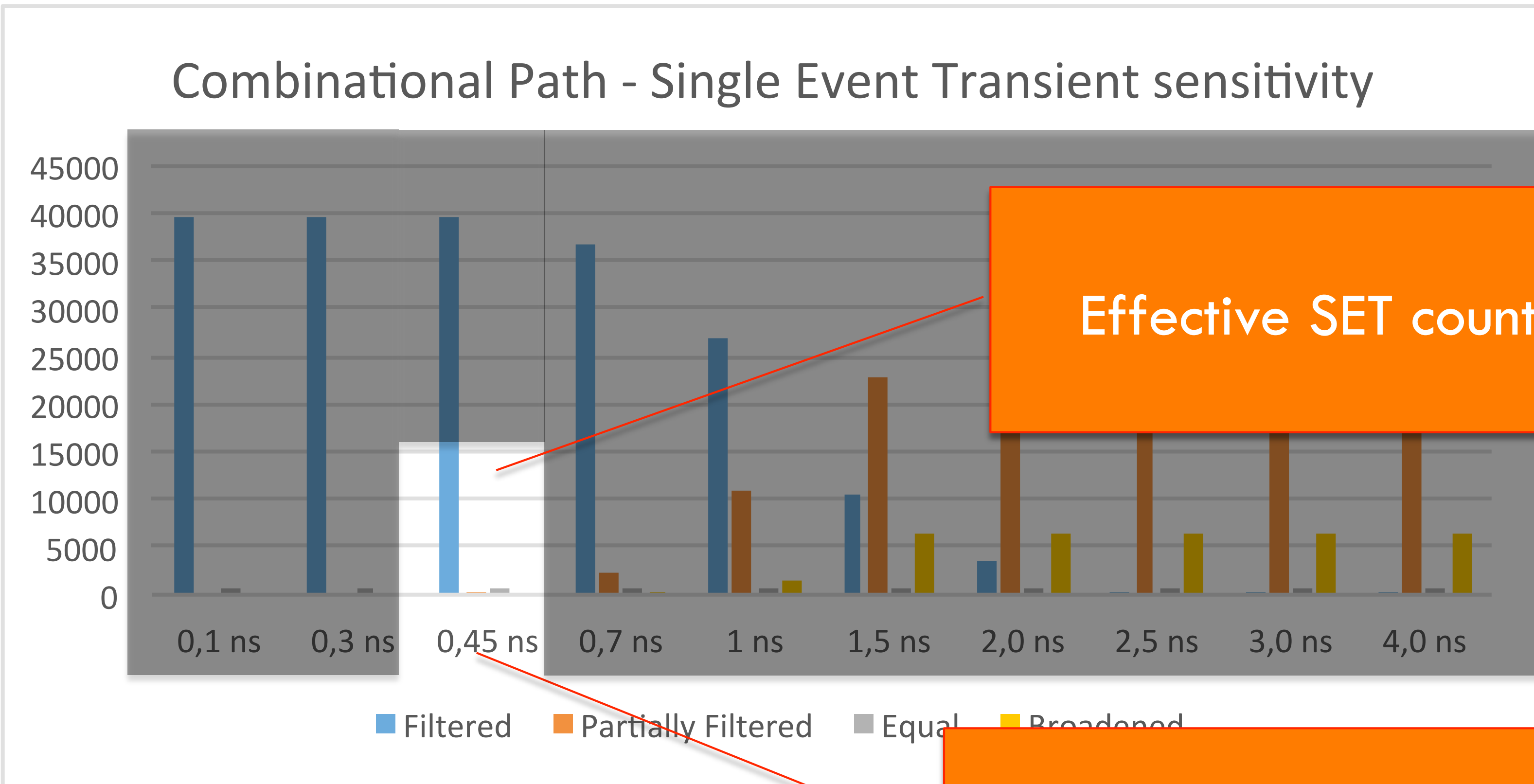


Identification of source SET length



Effective source SET designer must care

Identification of effective SET counts



Effective SET counts

Effective source SET designer must care

Thank you!

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