Quantum Assisted Secure Multiparty Computation

Manuel Batalha dos Santos

Thesis defense

16 January 2025

TÉCNICO LISBOA

Outline

Outline

- Motivation and outcomes

Outline

- Motivation and outcomes
- Quantum and classical oblivious transfer

Outline

- Motivation and outcomes
- Quantum and classical oblivious transfer
- Private phylogenetic trees

Outline

- Motivation and outcomes
- Quantum and classical oblivious transfer
- Private phylogenetic trees
- Quantum oblivious linear evaluation

Motivation

SMC

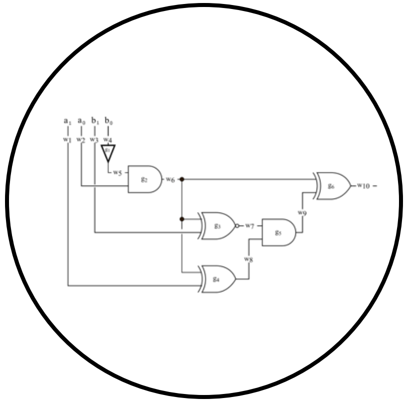
Motivation

SMC

Motivation

SMC

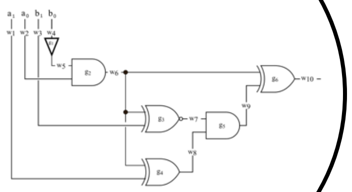
Boolean



Motivation

SMC

Boolean



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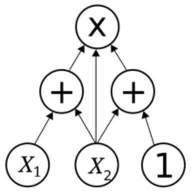
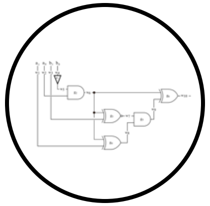
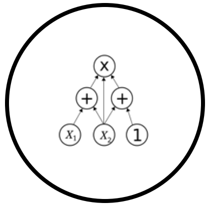


Motivation

SMC

Circuit



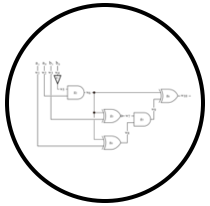


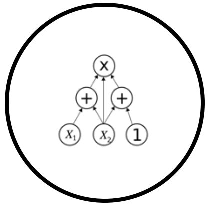
Motivation

SMC

Primitive

Circuit





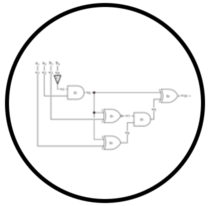
Motivation

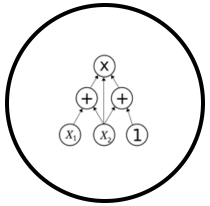
SMC

Primitive

Oblivious Transfer

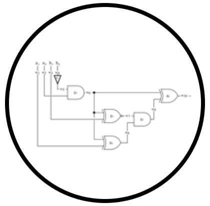
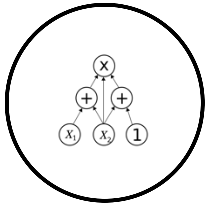
Circuit





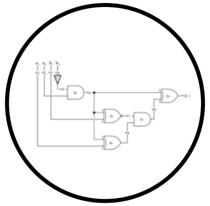
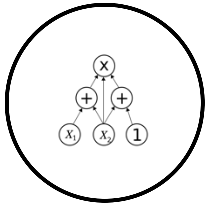
Motivation

SMC

Primitive	Oblivious Transfer	Oblivious Linear Evaluation
Circuit		

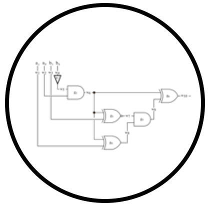
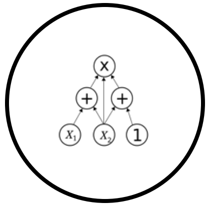
Motivation

SMC

	Classic	Classic
Primitive	Oblivious Transfer	Oblivious Linear Evaluation
Circuit		

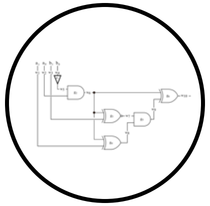
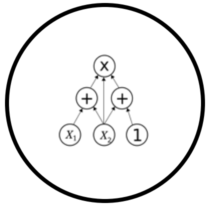
Motivation

SMC

	Quantum	Classic	Quantum	Classic
Primitive	Oblivious Transfer		Oblivious Linear Evaluation	
Circuit				

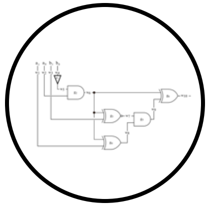
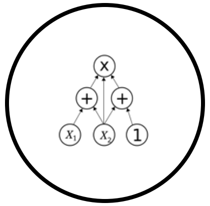
Motivation

SMC

	Quantum	Classic	Quantum	Classic
Primitive	[BBCS'91] Oblivious Transfer		Oblivious Linear Evaluation	
Circuit				

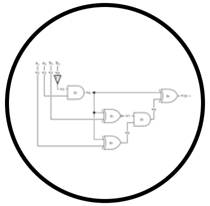
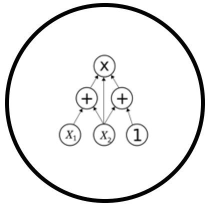
Motivation

SMC

	Quantum	Classic	Quantum	Classic
Primitive	[BBCS’91] [FS’09] [DFS+05] [WST’08] …	Oblivious Transfer	Oblivious Linear Evaluation	
Circuit				

Motivation

SMC

	Quantum		Classic	Quantum		Classic
Primitive	[BBCS'91] [FS'09] [DFS+05] [WST'08] …	Oblivious Transfer	[EGL'85] SimpleOT …		Oblivious Linear Evaluation	
Circuit						

Motivation

SMC

	Quantum		Classic	Quantum		Classic
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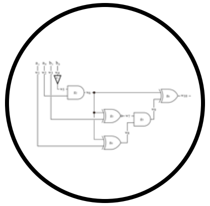
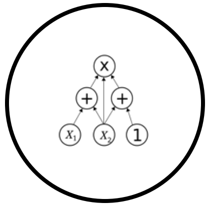
Circuit						

Motivation

SMC

Quantum | Classic | Quantum | Classic

Primitive

[BBCS’91]
[FS’09]
[DFS+05]
[WST’08] …

Oblivious Transfer

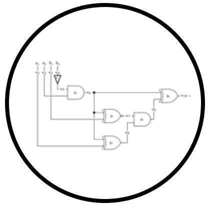
[EGL’85]
SimpleOT
…

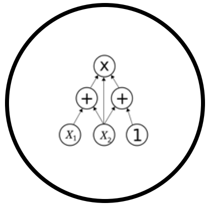
Review

[YAV’22]

Oblivious Linear Evaluation

Circuit





Motivation

SMC

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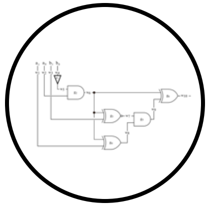
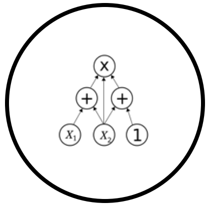
Circuit						

Motivation

SMC

	Quantum		Classic	Quantum		Classic
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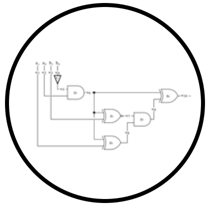
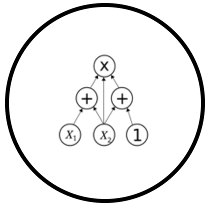
Circuit						

Motivation

SMC

Quantum | Classic

Primitive

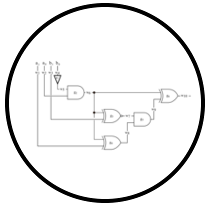
[BBCS'91]
[FS'09]
[DFS+05]
[WST'08] …

Oblivious Transfer

Review

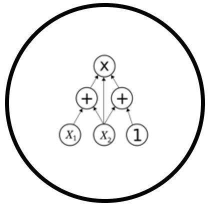
[EGL'85]
SimpleOT
…
libscapi
[YAV'22]

Circuit

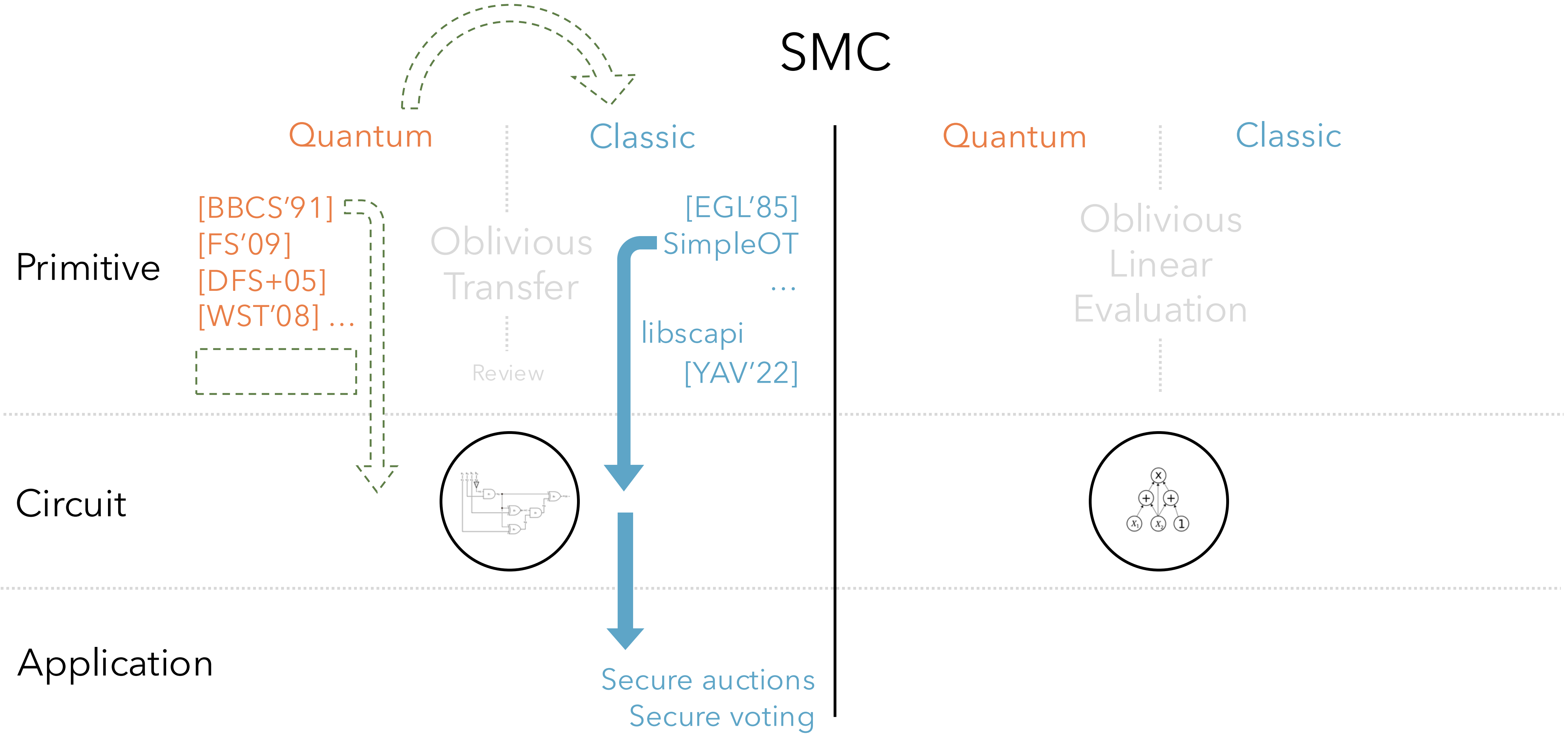


Quantum | Classic

Oblivious Linear Evaluation

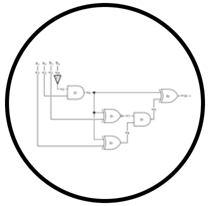
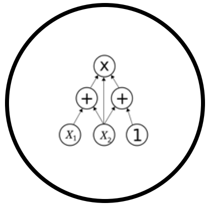


Motivation


SMC
Quantum
Classic
Quantum
Classic
Primitive
Circuit
Application
[BBCS'91]
[FS'09]
[DFS+05]
[WST'08] …
Oblivious Transfer
Review
[EGL'85]
SimpleOT
…
libscapi
[YAV'22]
Oblivious Linear Evaluation
Secure auctions
Secure voting

Motivation

SMC

	Quantum		Classic	Quantum		Classic
Primitive	[BBCS'91] [FS'09] [DFS+05] [WST'08] …	Oblivious Transfer Review	[EGL'85] SimpleOT … libscapi [YAV'22]		Oblivious Linear Evaluation	
Circuit						
Application			Secure auctions Secure voting			

Motivation

SMC

Quantum | Classic | Quantum | Classic

Primitive

[BBCS'91]
[FS'09]
[DFS+05]
[WST'08] …

Oblivious Transfer

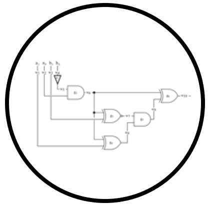
Review

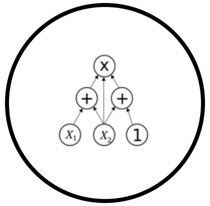
[EGL'85]
SimpleOT
…
libscapi
[YAV'22]

Oblivious Linear Evaluation

[NP'99]
TinyOLE
…

Circuit





Application

Secure auctions
Secure voting

Motivation

SMC

Quantum | Classic | Quantum | Classic

Primitive

[BBCS'91]
[FS'09]
[DFS+05]
[WST'08] …

Oblivious Transfer

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Oblivious Linear Evaluation

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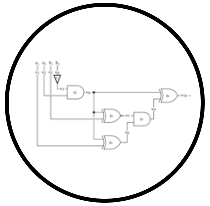
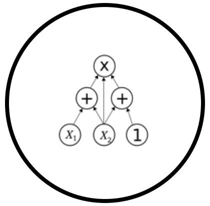
Circuit





Application

Secure auctions
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Motivation

SMC

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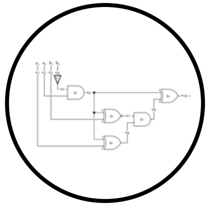
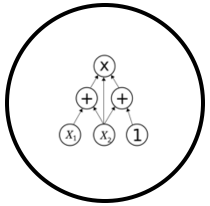
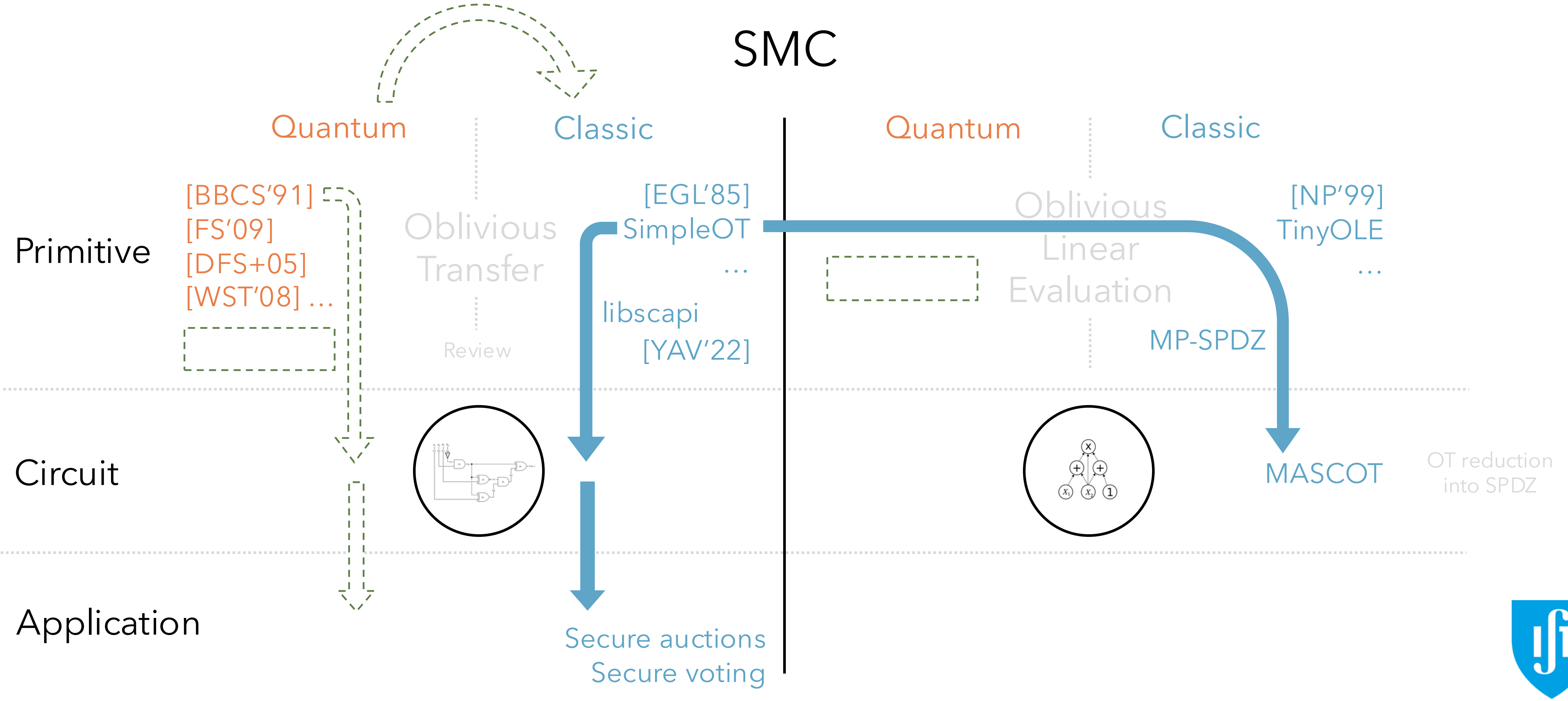
Circuit						MASCOT	OT reduction into SPDZ
Application			Secure auctions Secure voting				

Motivation


SMC
Quantum
Classic
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[BBCS'91]
[FS'09]
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[WST'08] …
Oblivious Transfer
Review
[EGL'85]
SimpleOT
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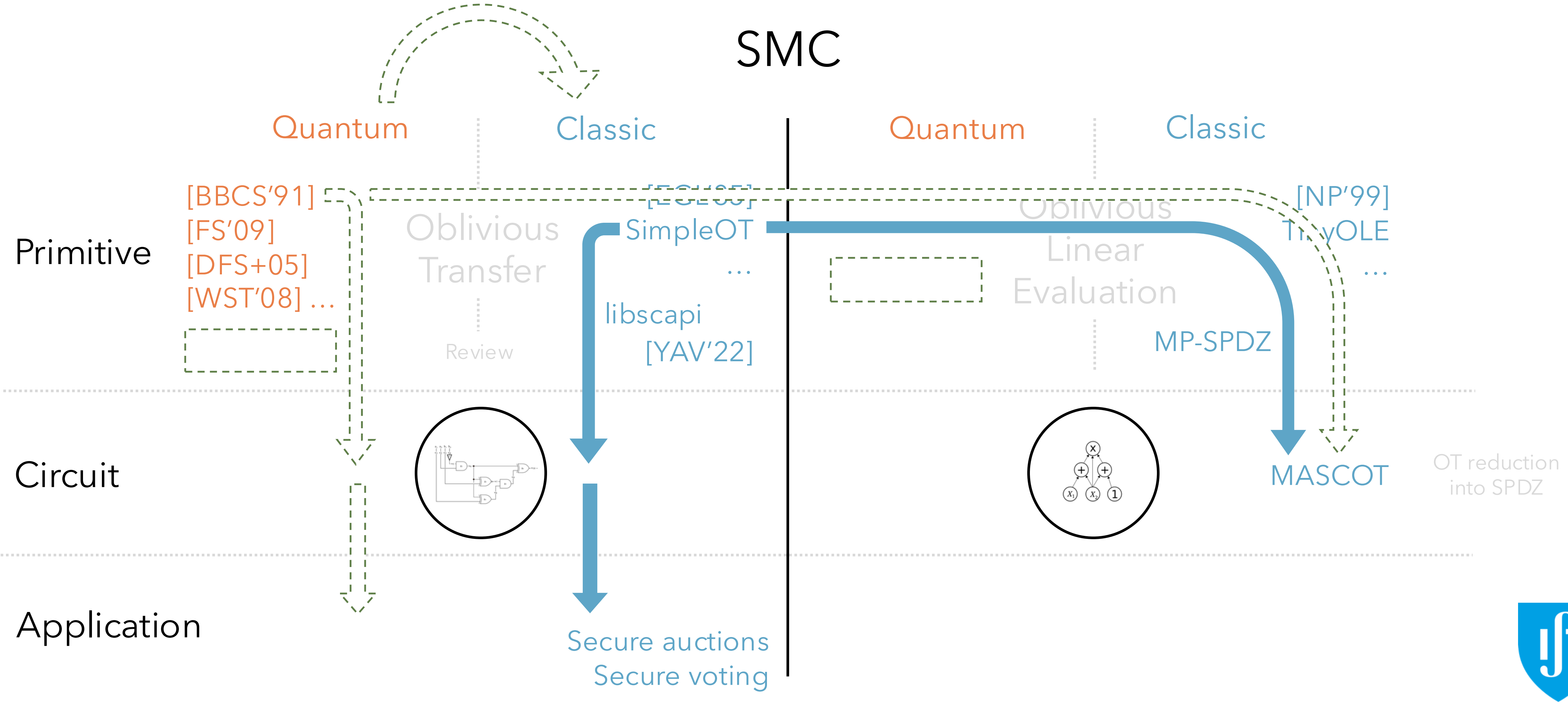
libscapi
[YAV'22]
Secure auctions
Secure voting
Oblivious Linear Evaluation
[NP'99]
TinyOLE
…
MP-SPDZ
MASCOT
OT reduction into SPDZ

Motivation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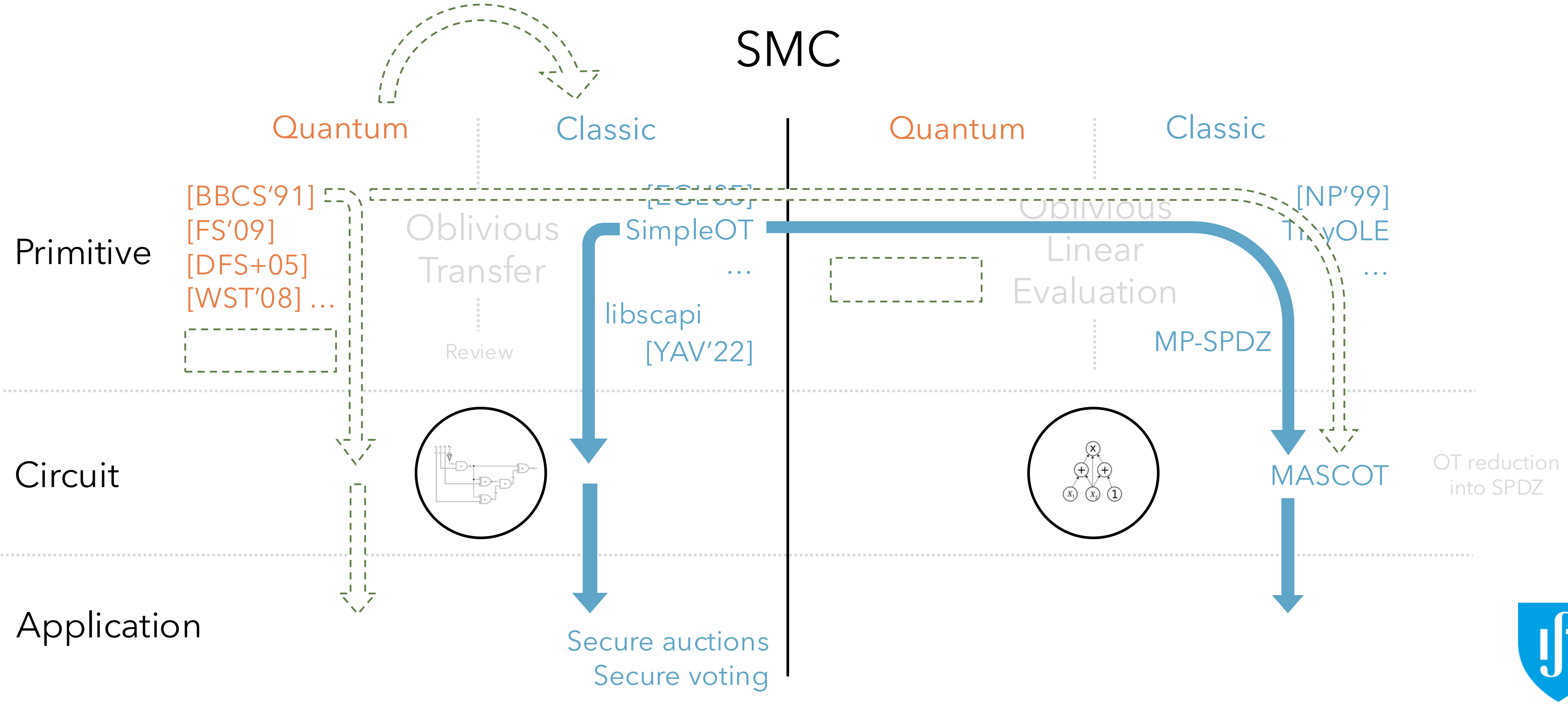
OT reduction into SPDZ

Motivation


SMC
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Linear
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MP-SPDZ
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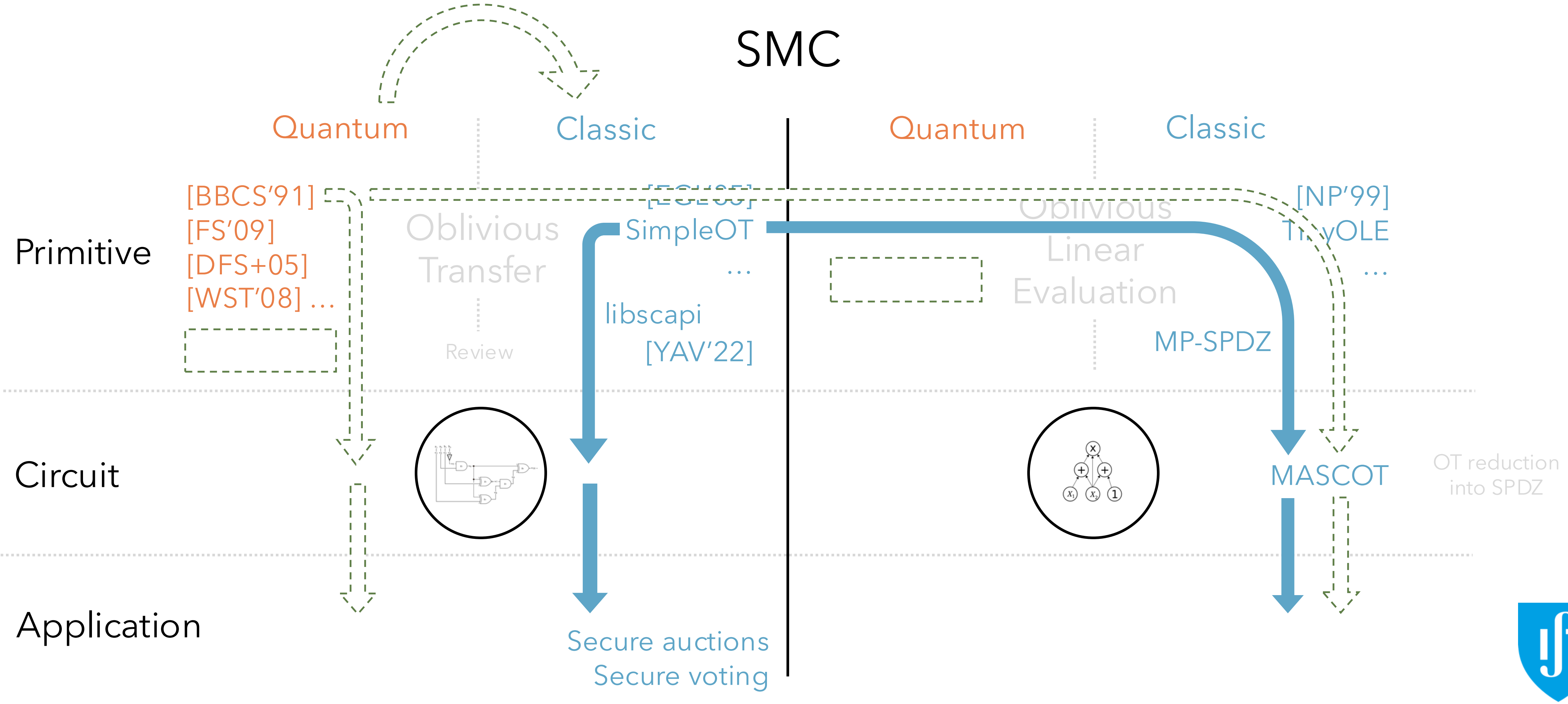
SMC
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Oblivious Transfer
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[YAV'22]
Secure auctions
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Oblivious Linear Evaluation
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MP-SPDZ
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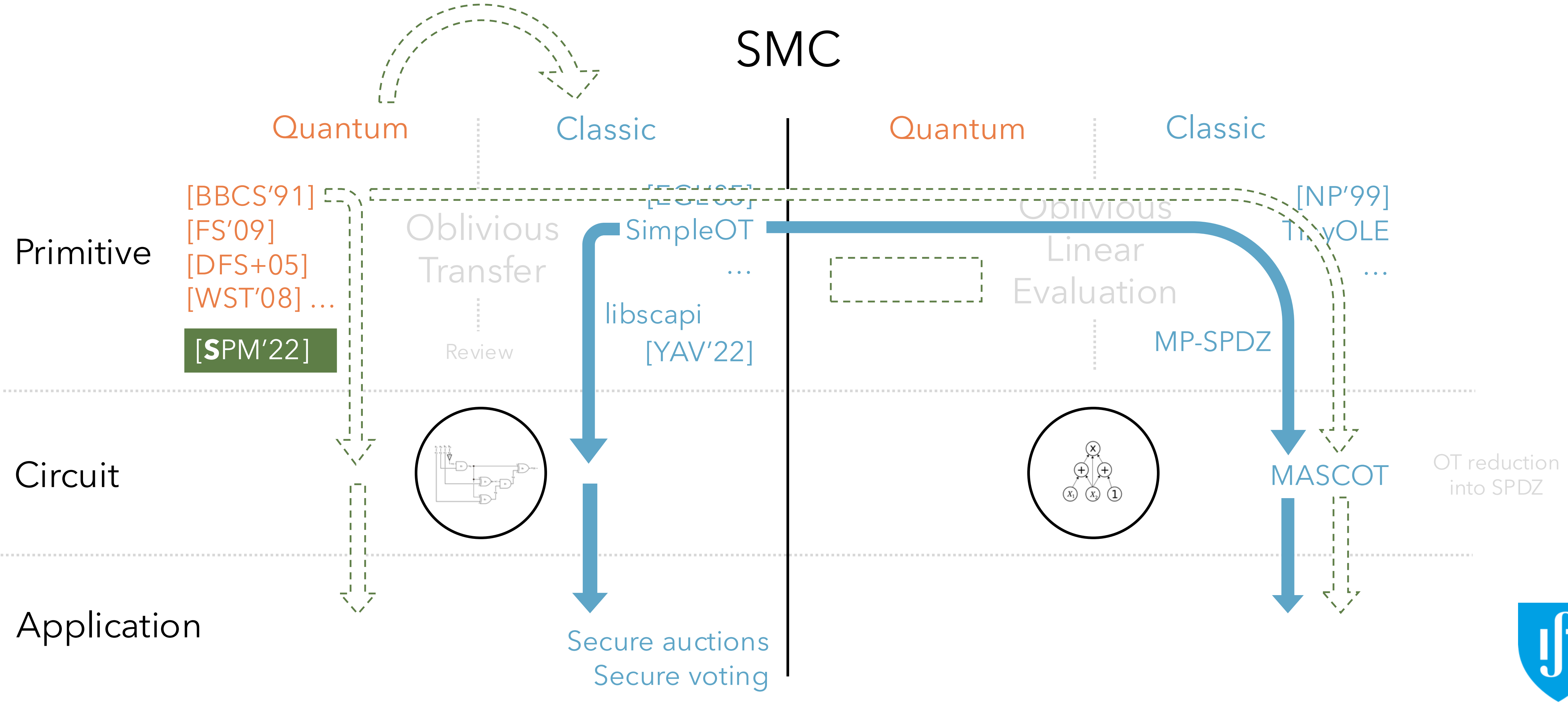
OT reduction into SPDZ

Outcomes


SMC
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Oblivious
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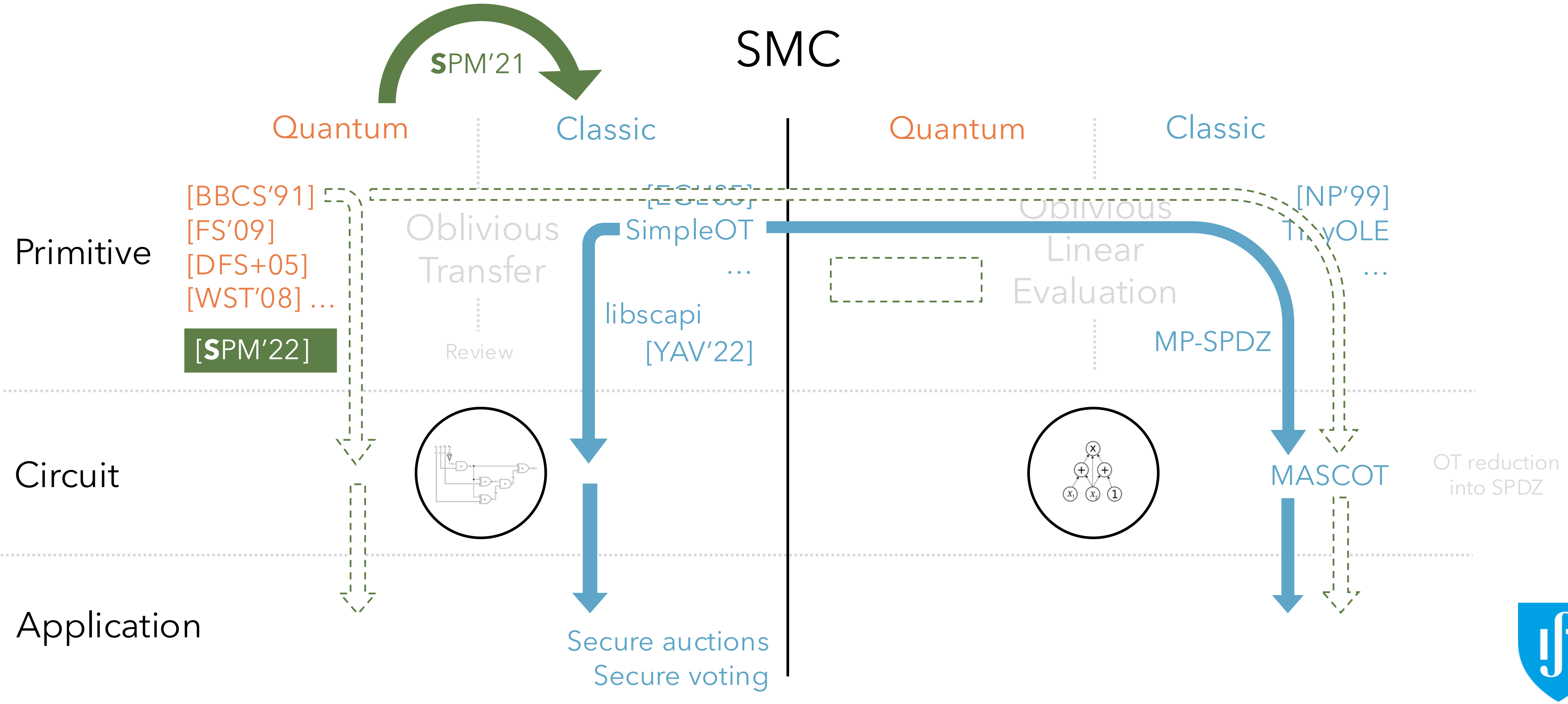
Outcomes



SMC
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[BBCS'91]
[FS'09]
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[WST'08] …
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Oblivious Transfer
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…
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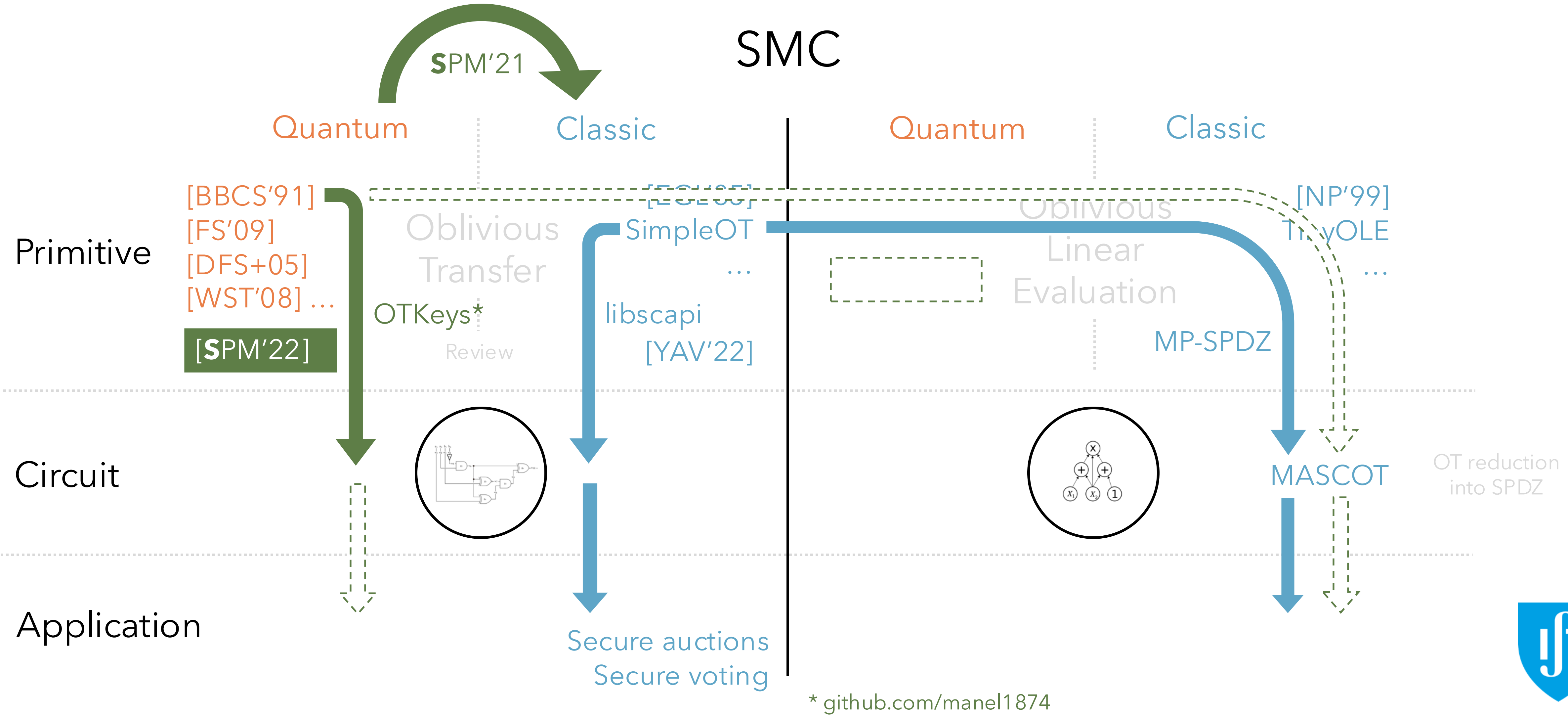
Outcomes


SMC
SPM'21
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Application
[BBCS'91]
[FS'09]
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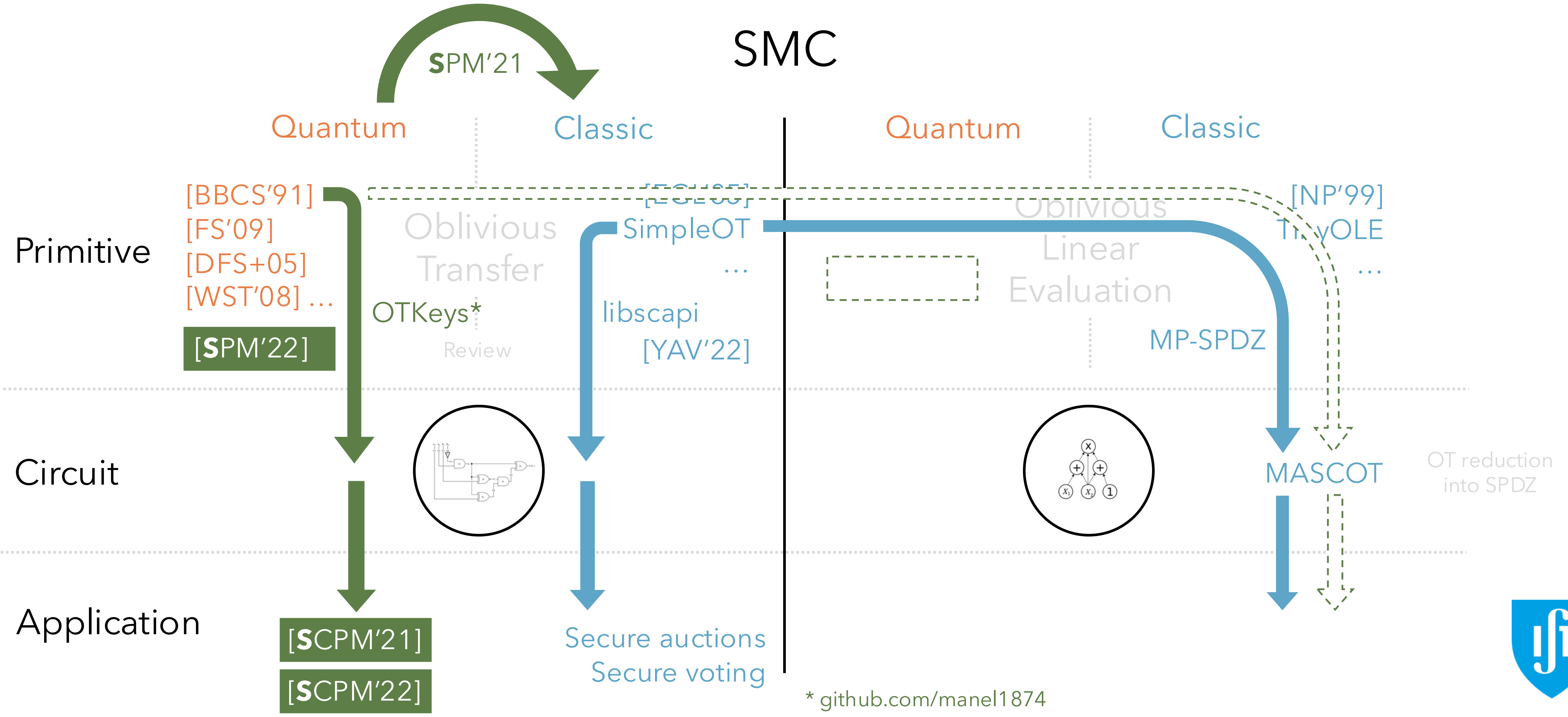
[WST'08] …
[SPM'22]
Oblivious Transfer
OTKeys*
Review
SimpleOT
…
libscapi
[YAV'22]
Oblivious Linear Evaluation
[NP'99]
…
MP-SPDZ
MASCOT
OT reduction into SPDZ
Secure auctions
Secure voting
* github.com/manel1874

Outcomes


SMC
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[BBCS'91]
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Oblivious Transfer
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Secure auctions
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Oblivious Linear Evaluation
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MP-SPDZ
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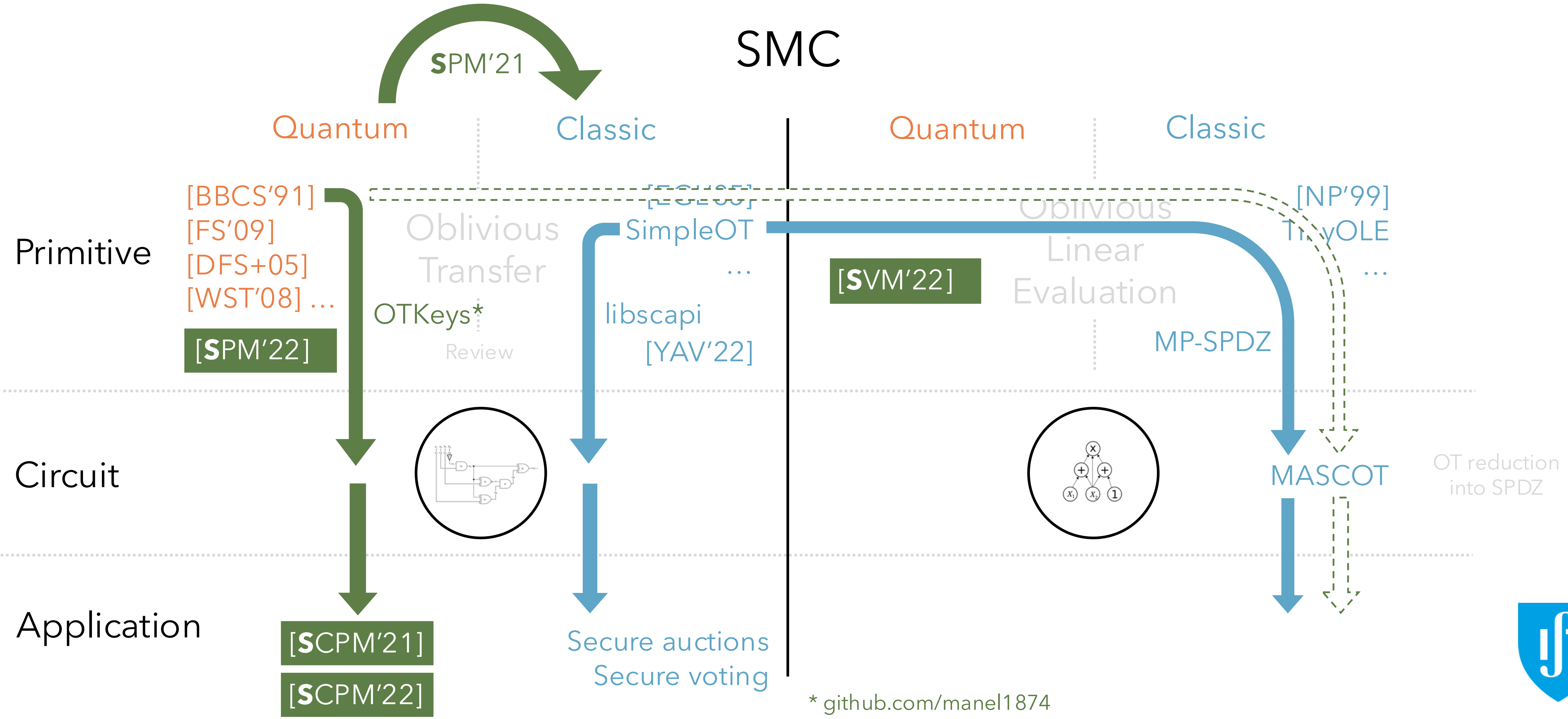
[SCPM'21]
[SCPM'22]
* github.com/manel1874

Outcomes



SMC
SPM'21
Quantum
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Quantum
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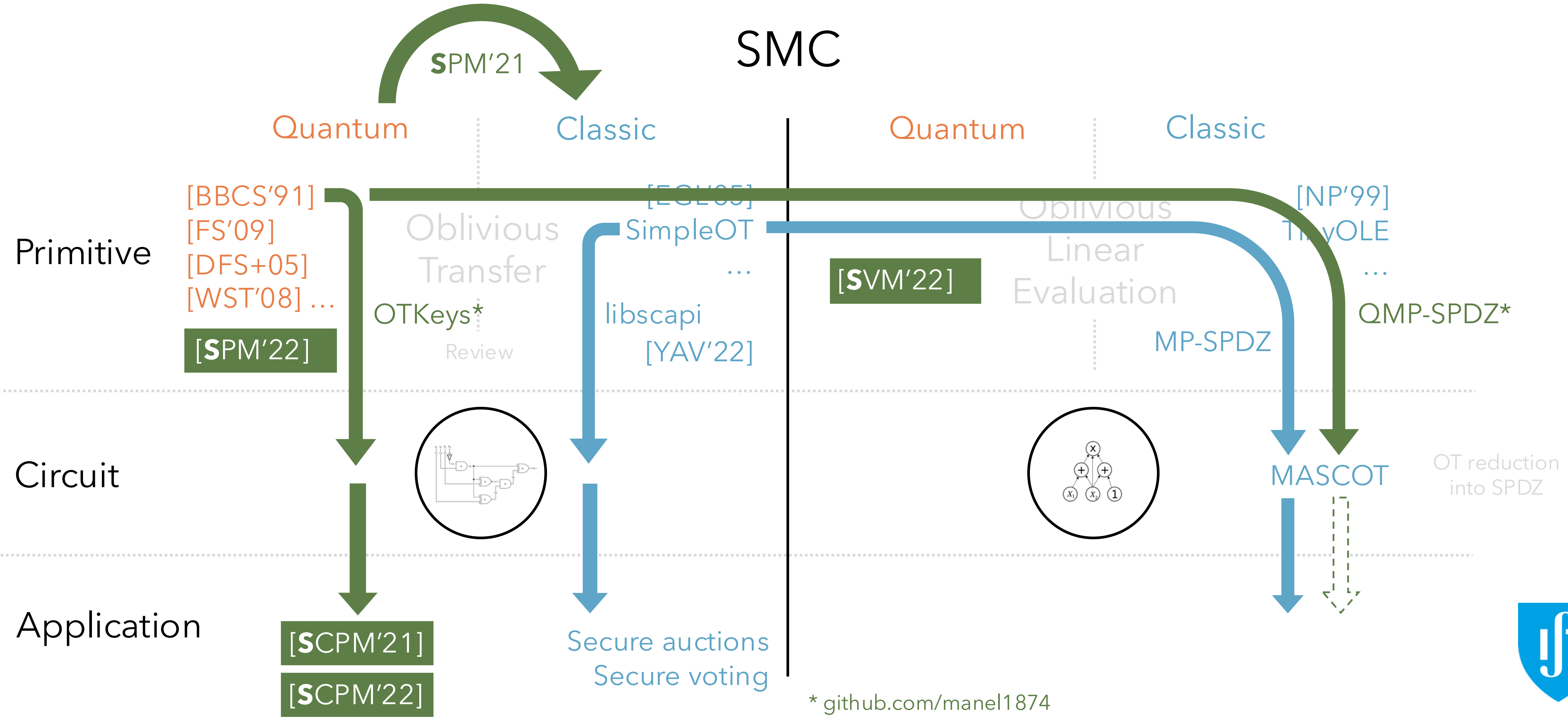
[BBCS'91]
[FS'09]
[DFS+05]
[WST'08] …
[SPM'22]
Oblivious Transfer
OTKeys*
Review
SimpleOT
…
libscapi
[YAV'22]
[SVM'22]
Linear
Evaluation
MP-SPDZ
[NP'99]
…
MASCOT
OT reduction into SPDZ
[SCPM'21]
[SCPM'22]
Secure auctions
Secure voting
* github.com/manel1874

Outcomes



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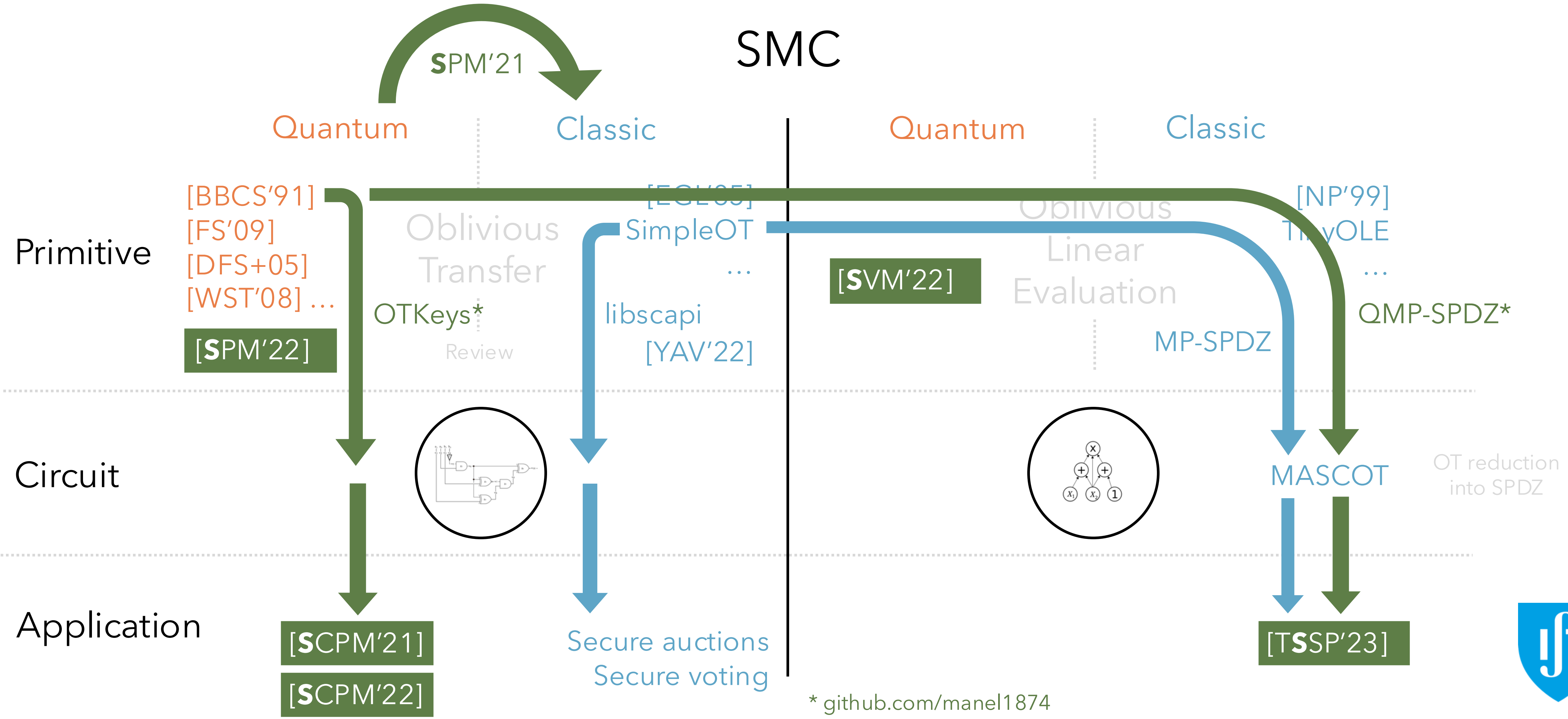
Outcomes


SMC
SPM'21
Quantum
Classic
Quantum
Classic
Primitive
[BBCS'91]
[FS'09]
[DFS+05]
[WST'08] …
[SPM'22]
Oblivious
Transfer
OTKeys*
Review
SimpleOT
…
libscapi
[YAV'22]
[SVM'22]
Oblivious
Linear
Evaluation
[NP'99]
…
QMP-SPDZ*
MP-SPDZ
Circuit
MASCOT
OT reduction
into SPDZ
Application
[SCPM'21]
[SCPM'22]
Secure auctions
Secure voting
[TSSP'23]
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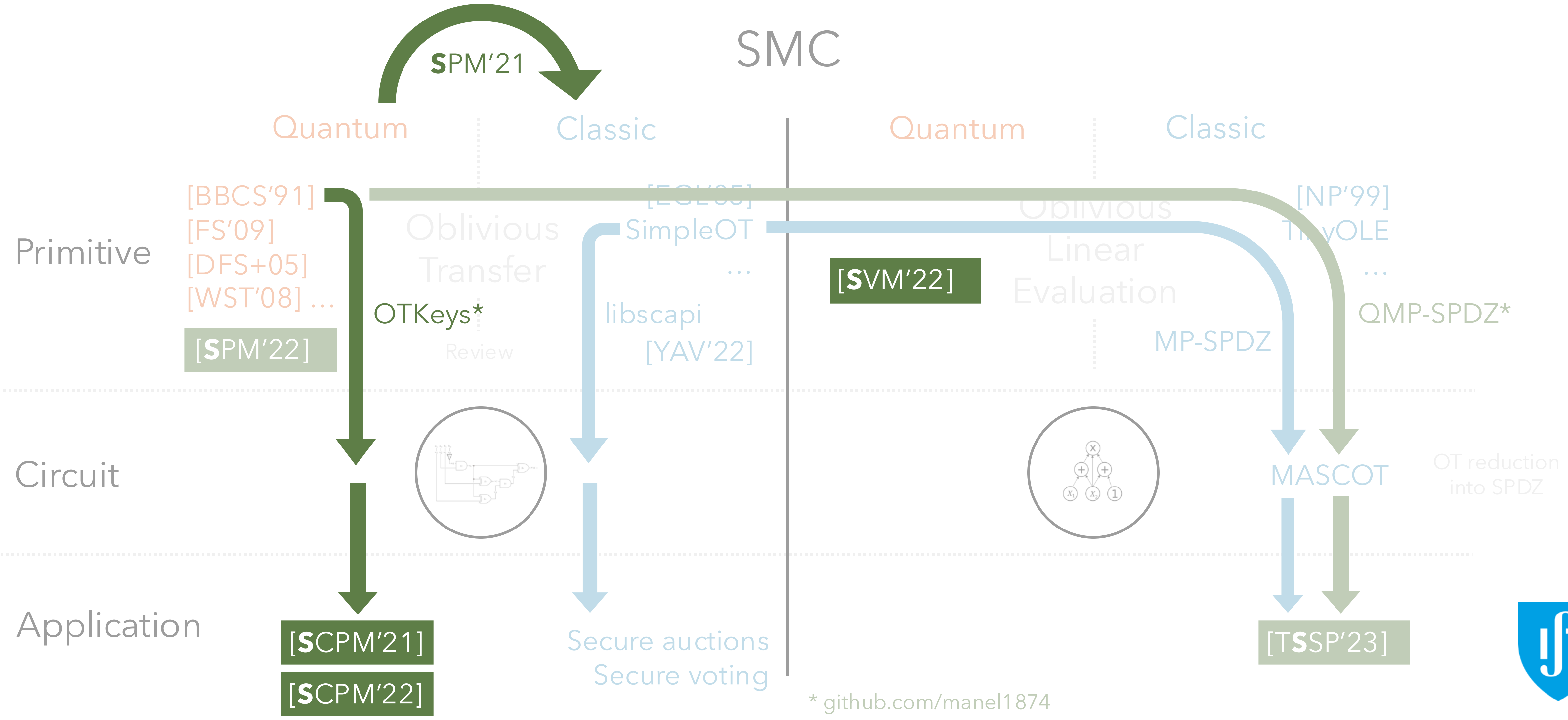

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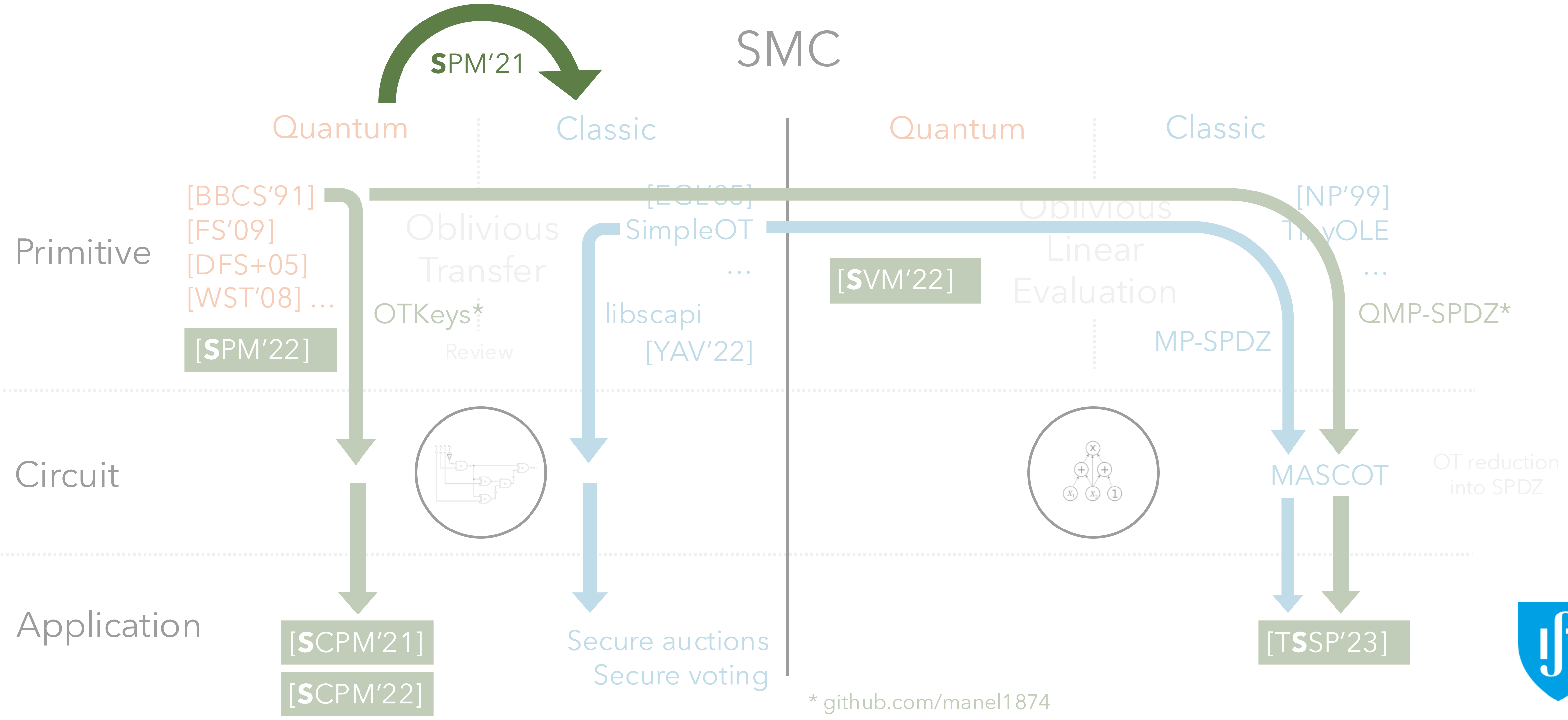
Quantum and classical OT



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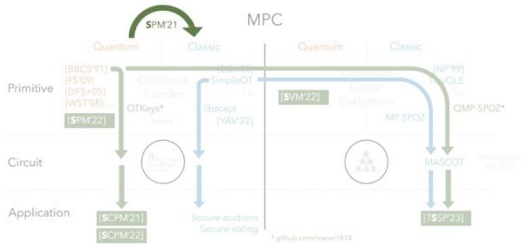
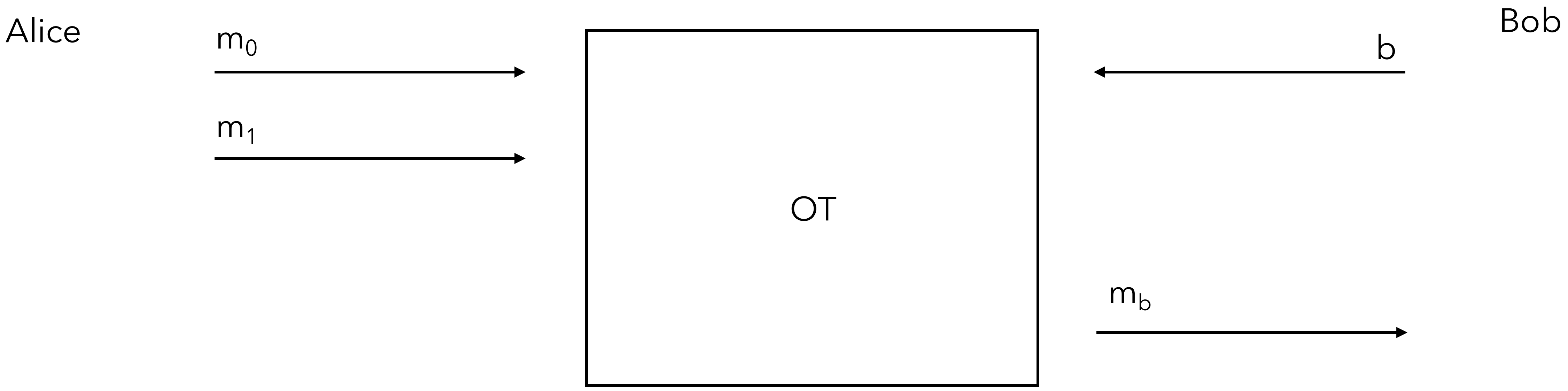
Oblivious Transfer





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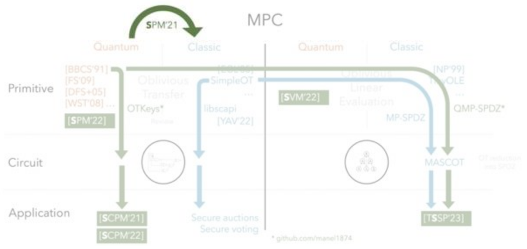

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...

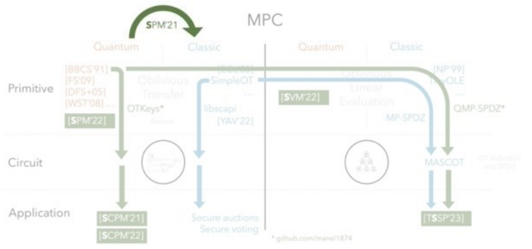
Classic

[EGL'85]
[BM'89]
[NP'01]
SimpleOT
...

No previous work

How can we compare?

Quantum and classical OT



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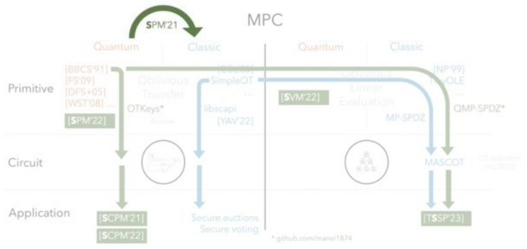
How can we compare?

Comparable structure?
Corresponding phases with same technology?
Any practical insight?

Quantum and classical OT



Quantum

[BBCS'91]

Offline phase → (Oblivious) key

Online phase

Classic

Base OT

OT Extension

Key ← Offline phase

Online phase

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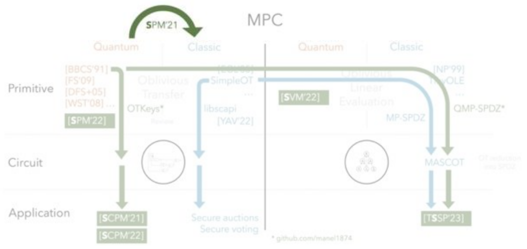
Quantum and classical OT



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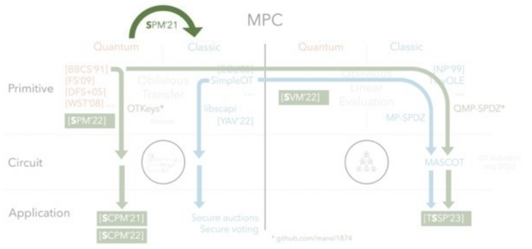

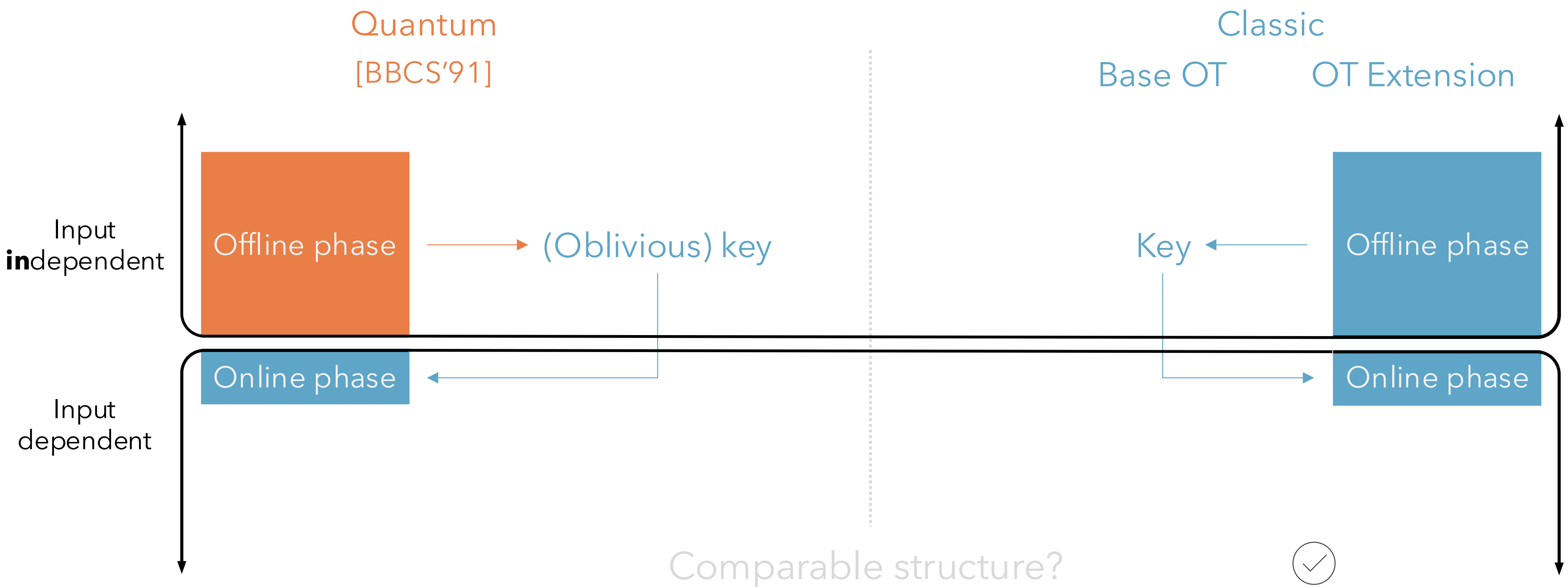

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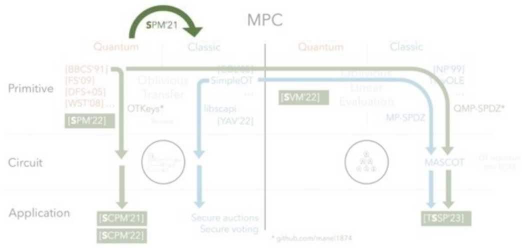
Corresponding phases with same technology? ✓
Any practical insight? ✓

Quantum and classical OT



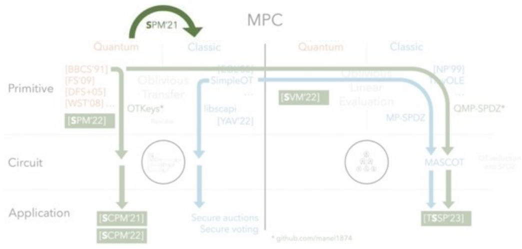
	Quantum [BBCS'91]	Classic: Base OT	Classic: OT Extension
"No" time constraint / Input **in**dependent	Offline phase → (Oblivious) key	Key	← Offline phase
Time constraint / Input dependent	Online phase ← (Oblivious) key	Key →	Online phase

Comparable structure? ✓

Corresponding phases with same technology? ✓

Any practical insight? ✓

Quantum and classical OT



Classic

Base OT

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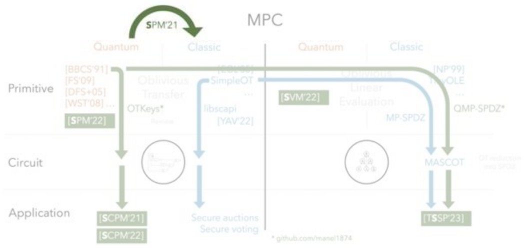
[BBCS’91]



Quantum and classical OT

Classic

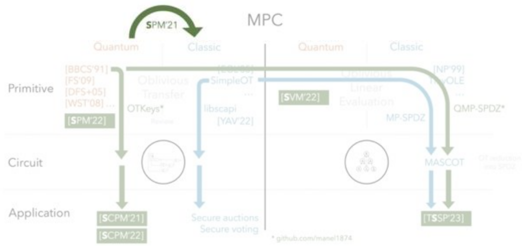
Base OT

OT Extension

Quantum

[BBCS’91]

Issue: PK operations



Quantum and classical OT

Classic

Base OT

OT Extension

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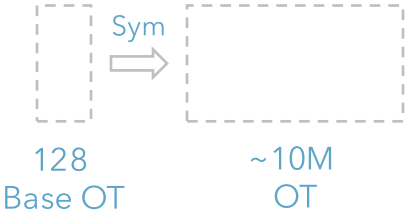

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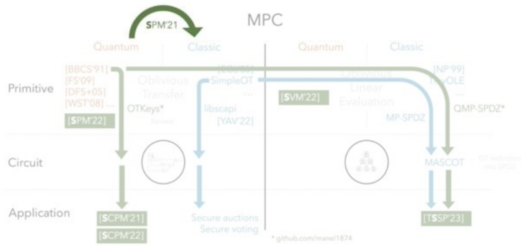


Classic

Base OT

	OT/s
[NP'01]	56
SimpleOT	1 375
NTRU-OT	728
Kyber-OT	41

<

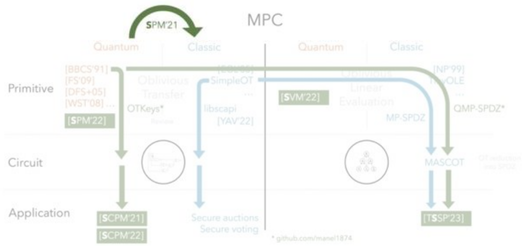
OT Extension

	10M OT
[ALSZ'13]	2.68 s
[KOS'15]	3.35 s

Quantum

[BBCS'91]

Quantum and classical OT



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OT Extension

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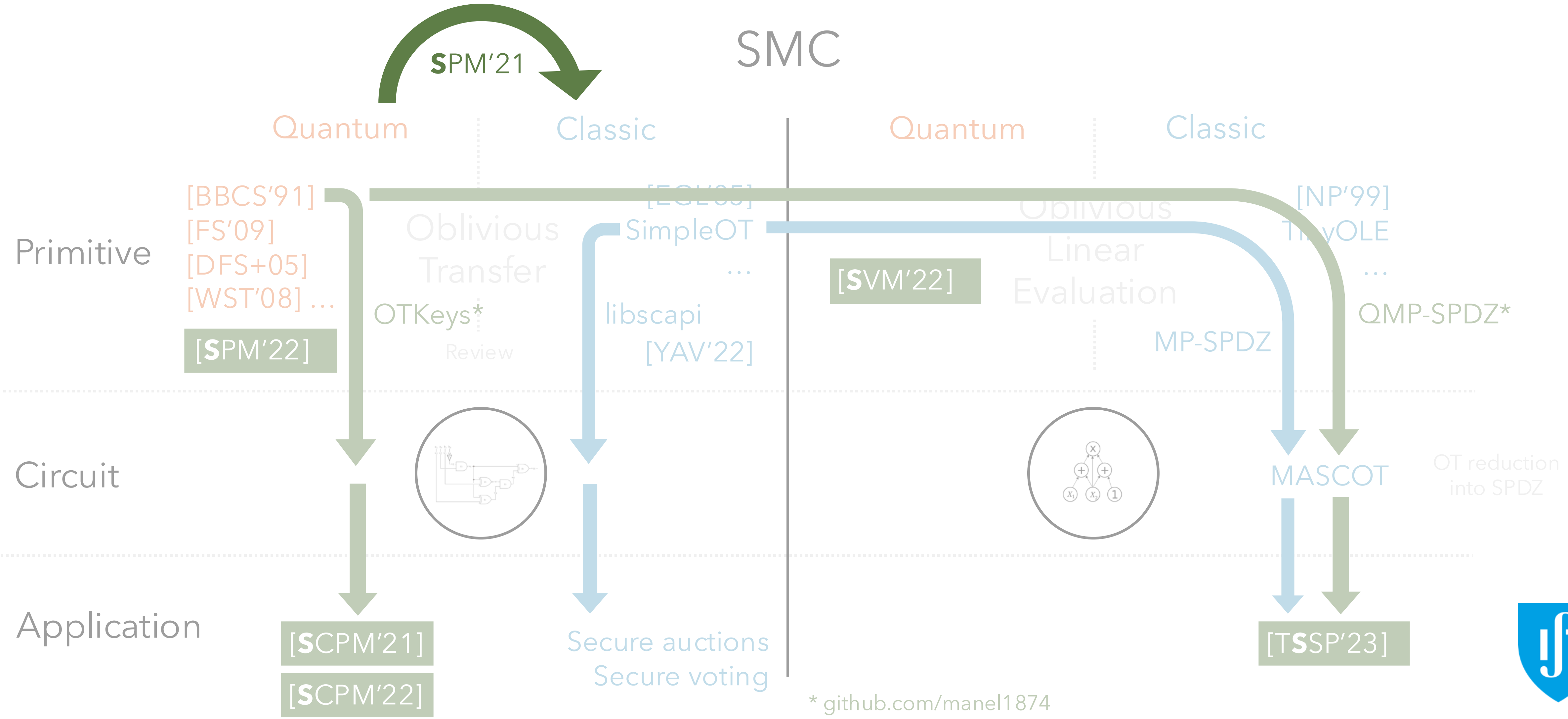
Online phase for m OTs

	Computation	Communication
[ALSZ'13]	$O^{ALSZ} - O^{BBCS} > m \log m$	$C^{ALSZ} - C^{BBCS} = 0$
[KOS'15]	$O^{KOS} - O^{BBCS} > m \log m + 5ml$	$C^{KOS} - C^{BBCS} \gtrsim 0$

BBCS

Quantum and classical OT



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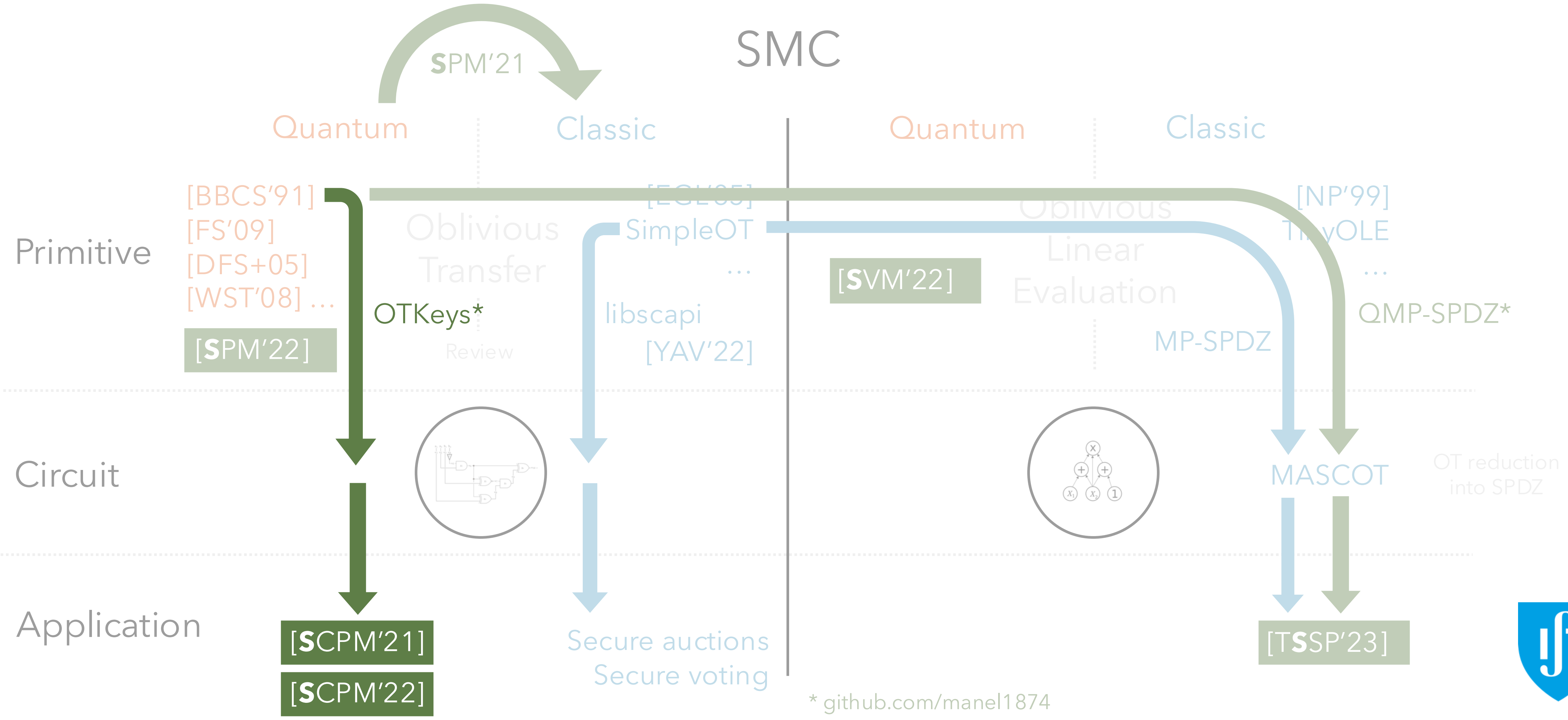
Private phylogenetic trees



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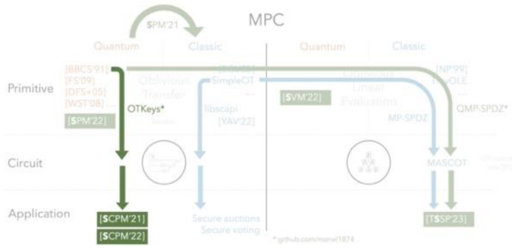
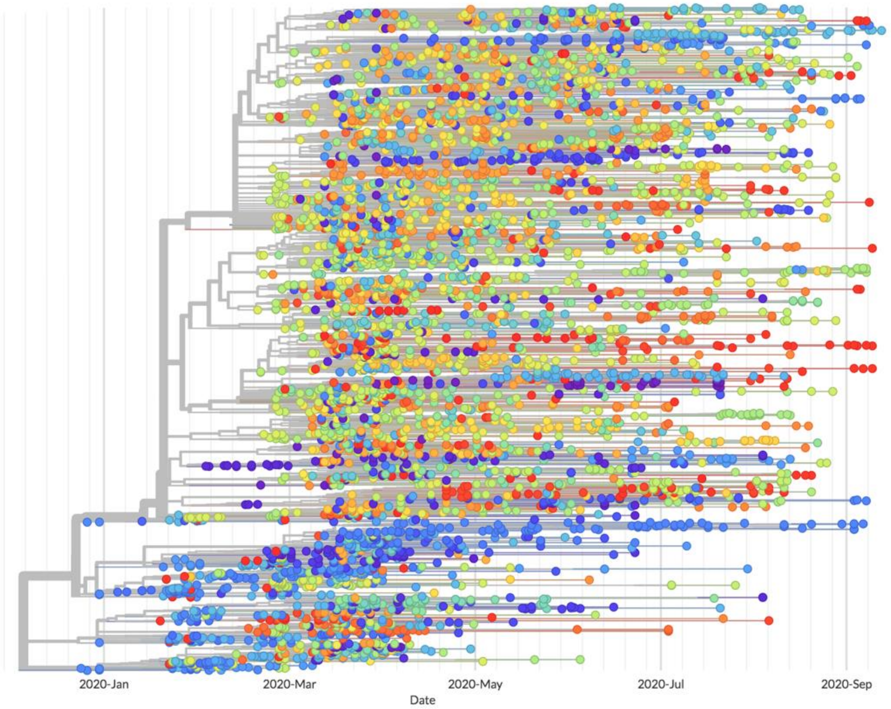


Shows the **evolutionary relationship** between **DNA** sequences in a **tree**.



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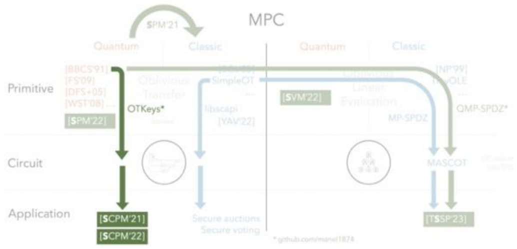
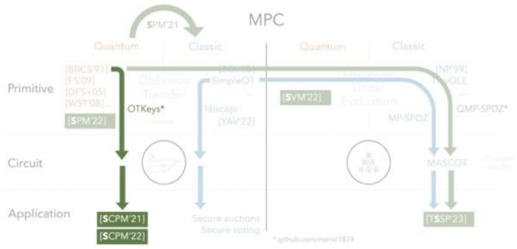


Results summary

- Tailored SMC protocol for phylogenetic trees algorithms

Private phylogenetic trees



Results summary

- Tailored SMC protocol for phylogenetic trees algorithms
- Classical implementation
  - CBMC-GC: circuit generation
  - MPC-Benchmark: yao protocol based on Libscapi
  - PHYLIP: phylogeny analysis

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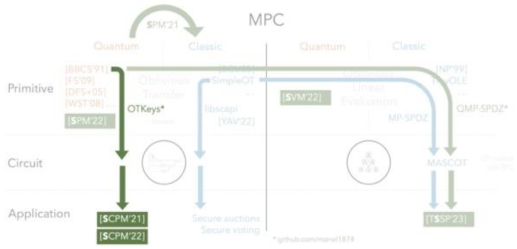

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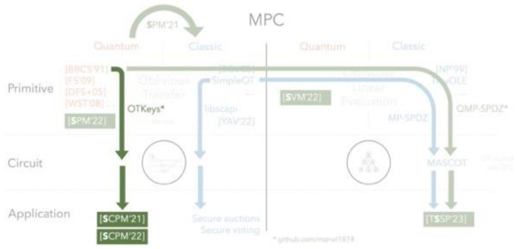
- Integrate BBCS based protocol into Libscapi

Private phylogenetic trees



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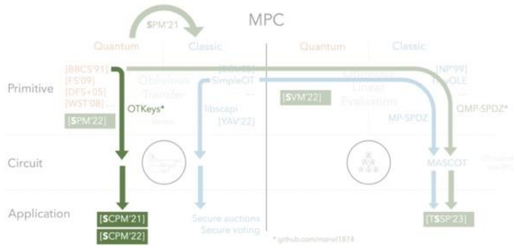
- Integrate BBCS based protocol into Libscapi
- Benchmark classical and quantum approaches

Performance evaluation



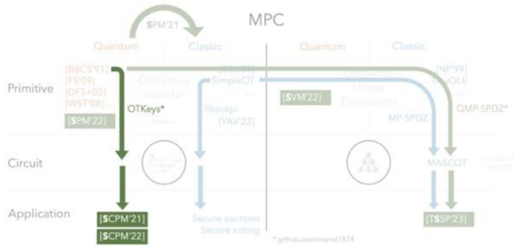
Setup:

- **3 parties:** VMs running Ubuntu 16.04.3
- **30** SARS-CoV-2 genome **sequences*** with **32 000 length**

Boolean circuit:

- ~3 minutes (CBMC-GC)
- ~2.2 million gates
- 128 000 input wires

*GISAID database



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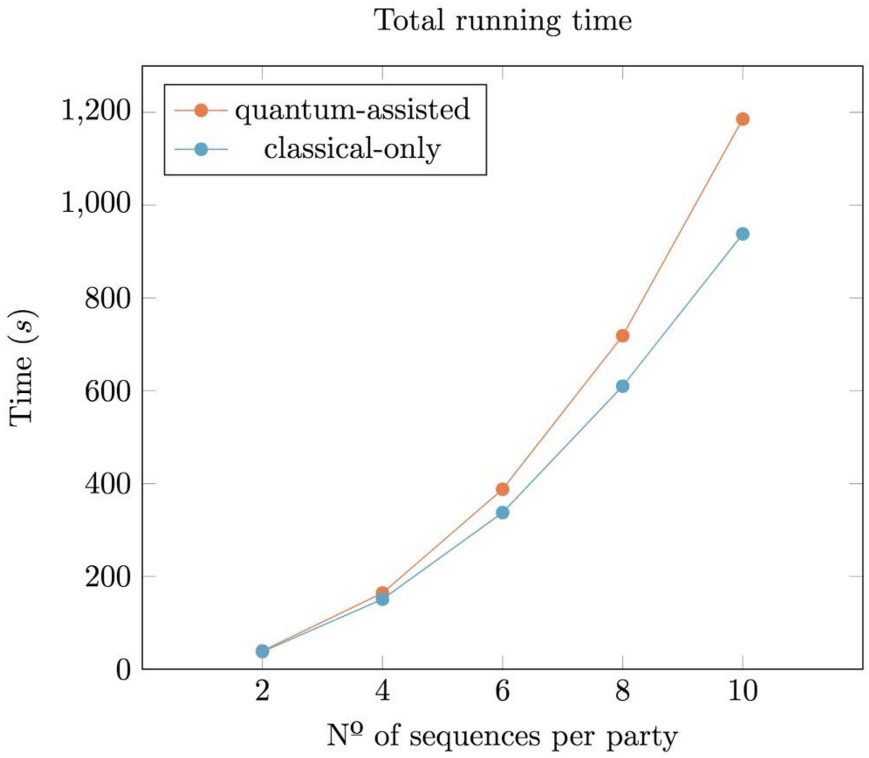

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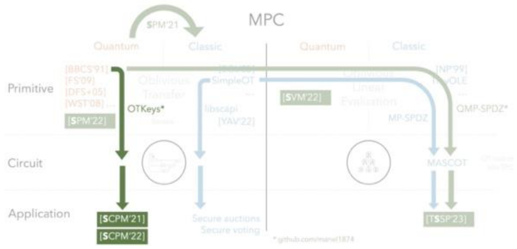

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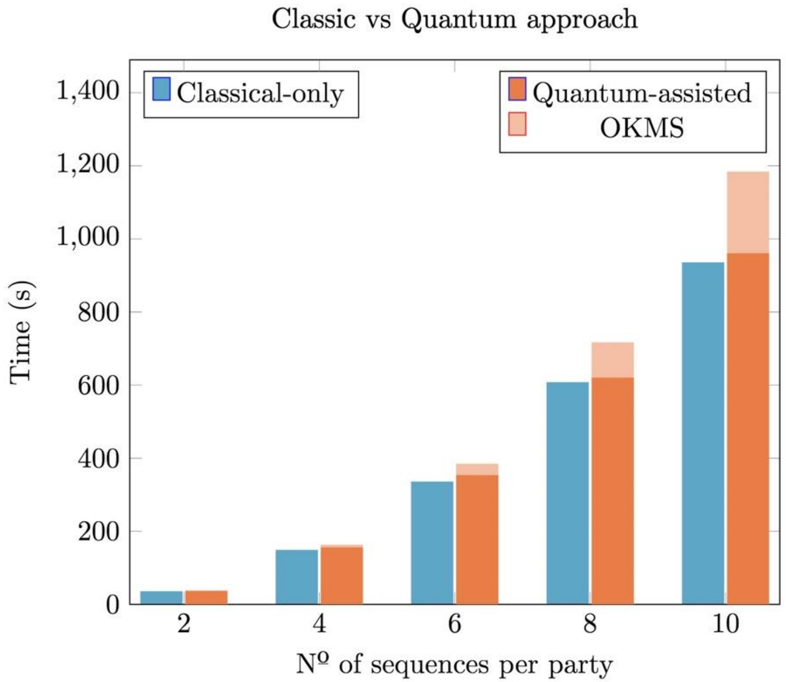

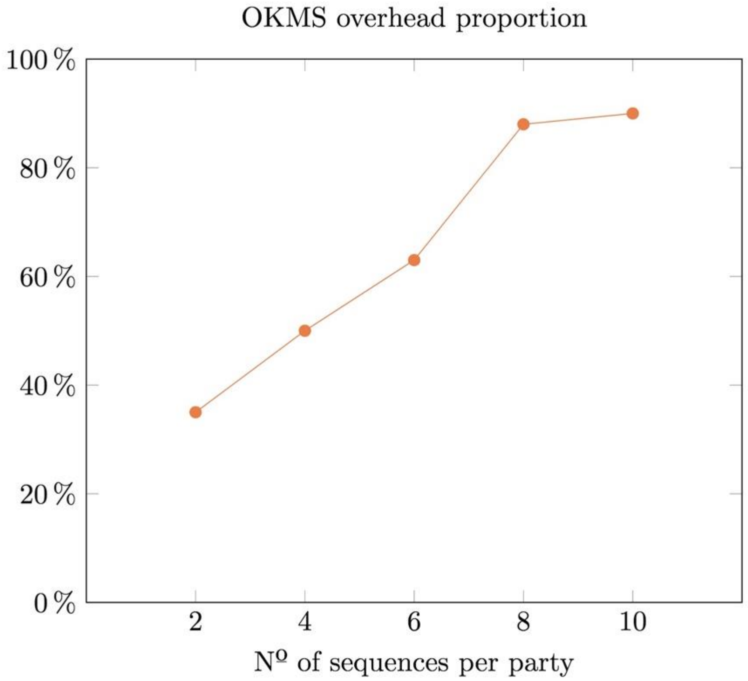

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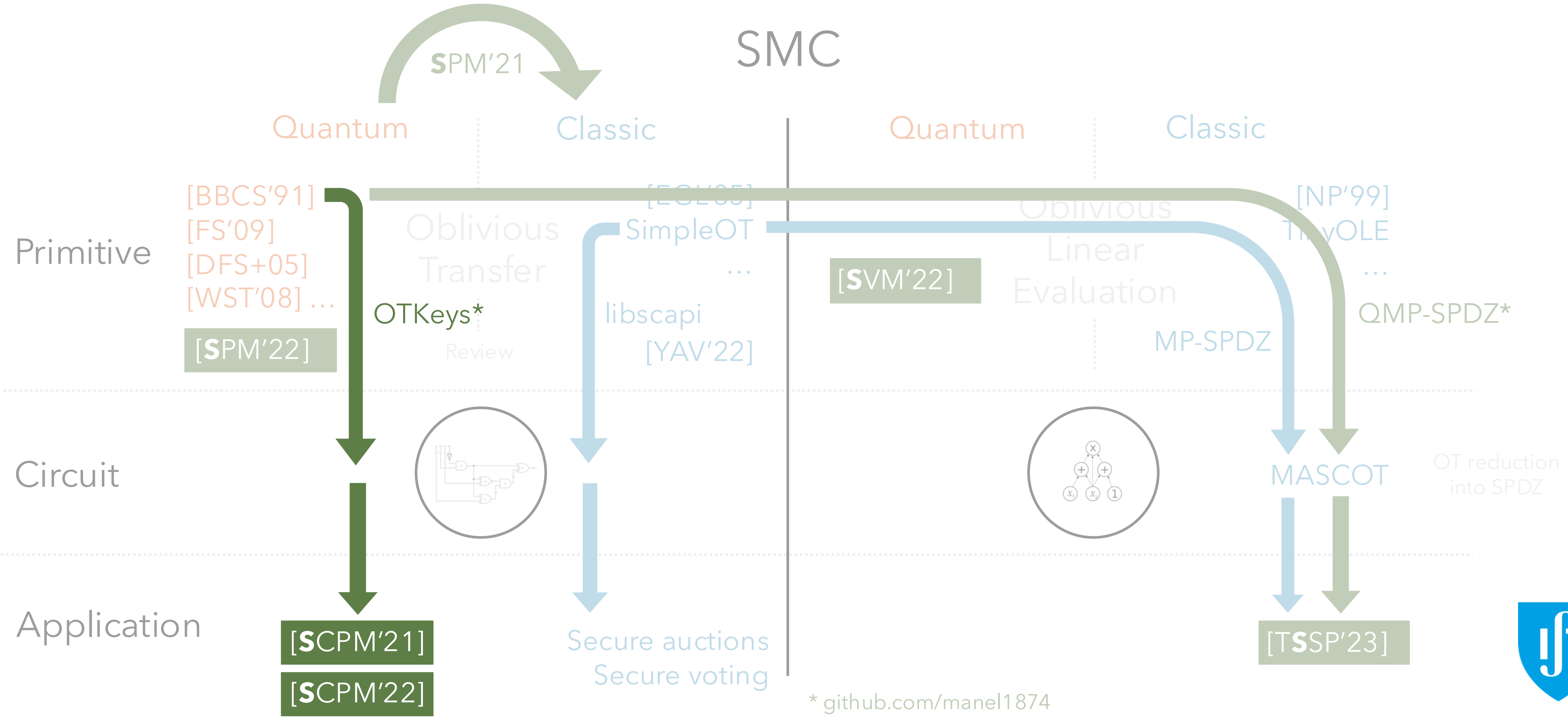
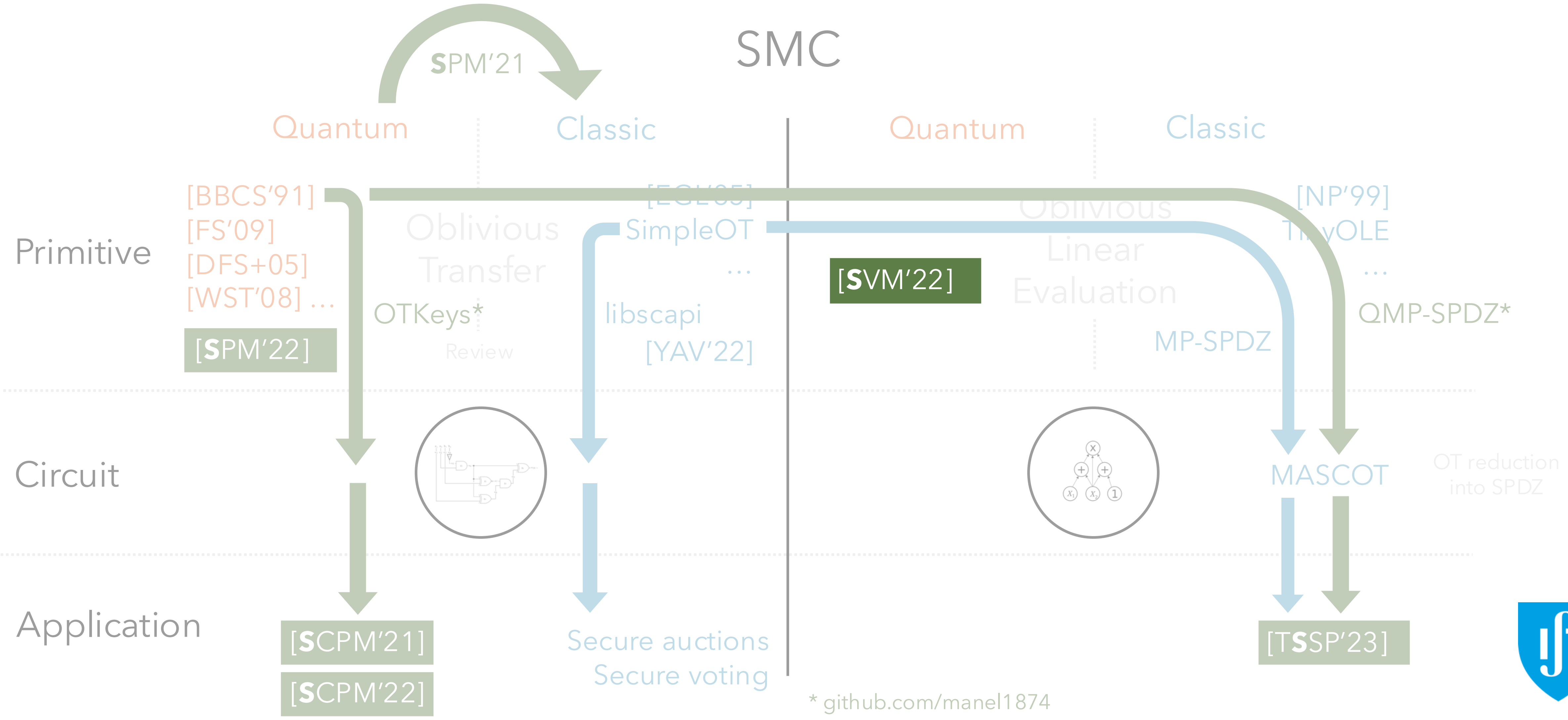


Quantum OLE



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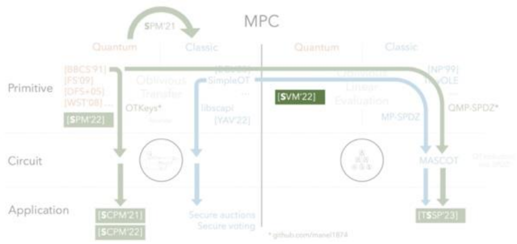
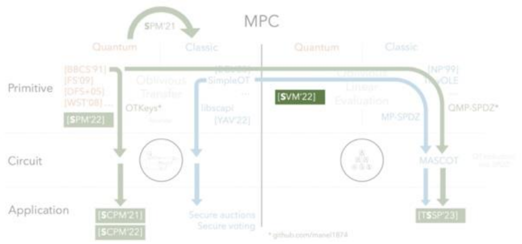
Quantum OLE

Results summary



- Oblivious Linear Evaluation (OLE)
- Vector OLE

Quantum OLE



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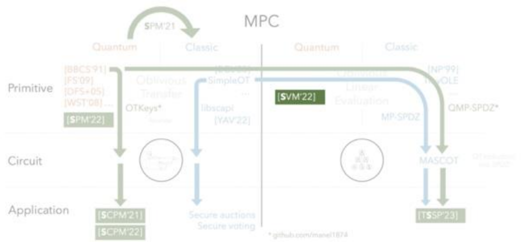

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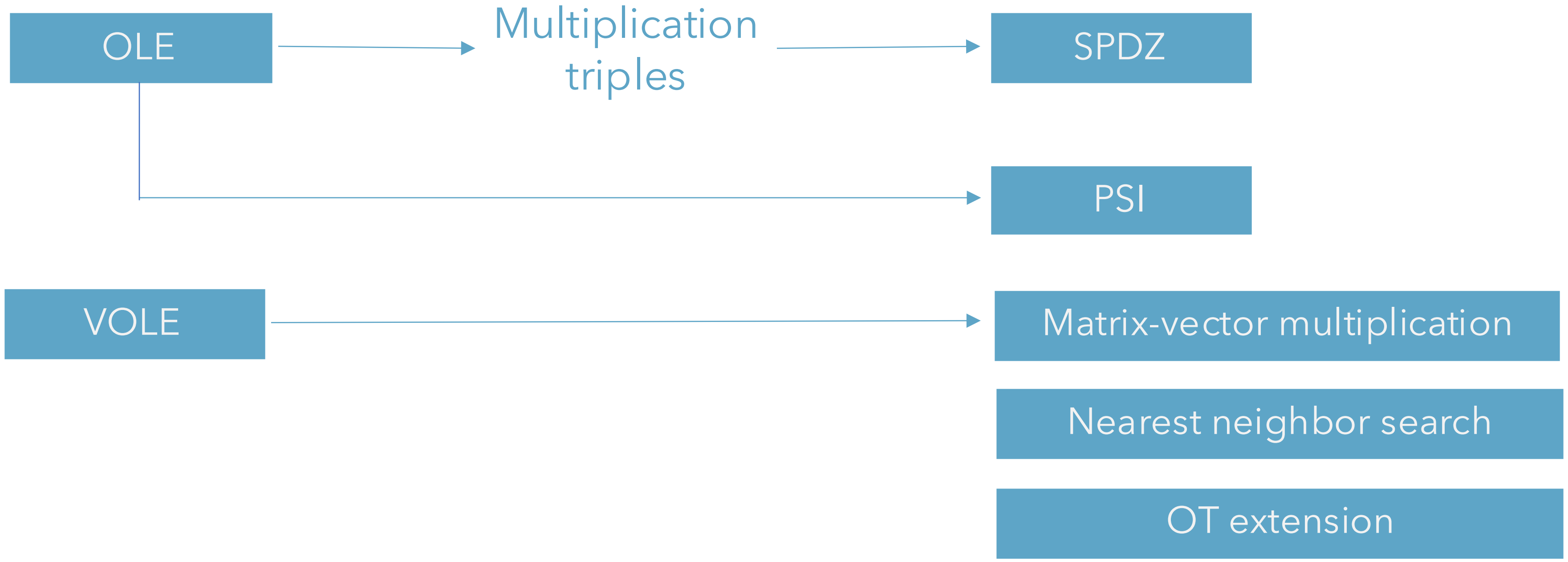

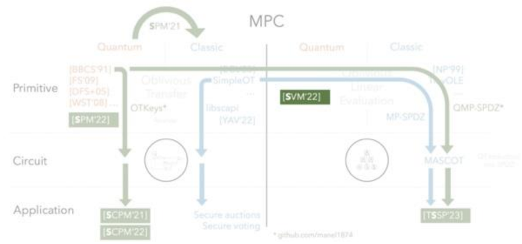

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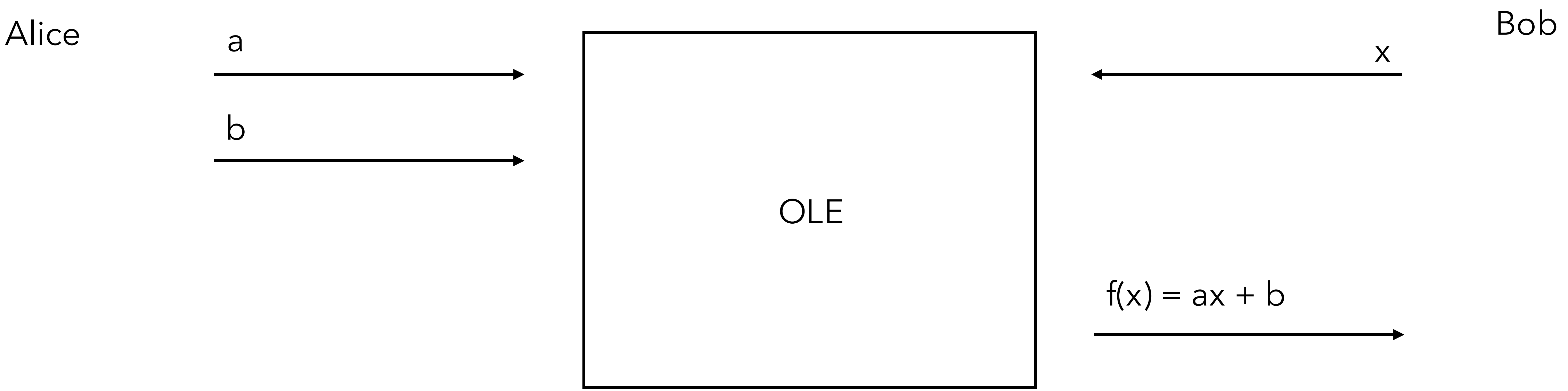

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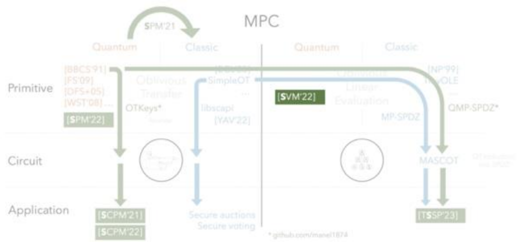

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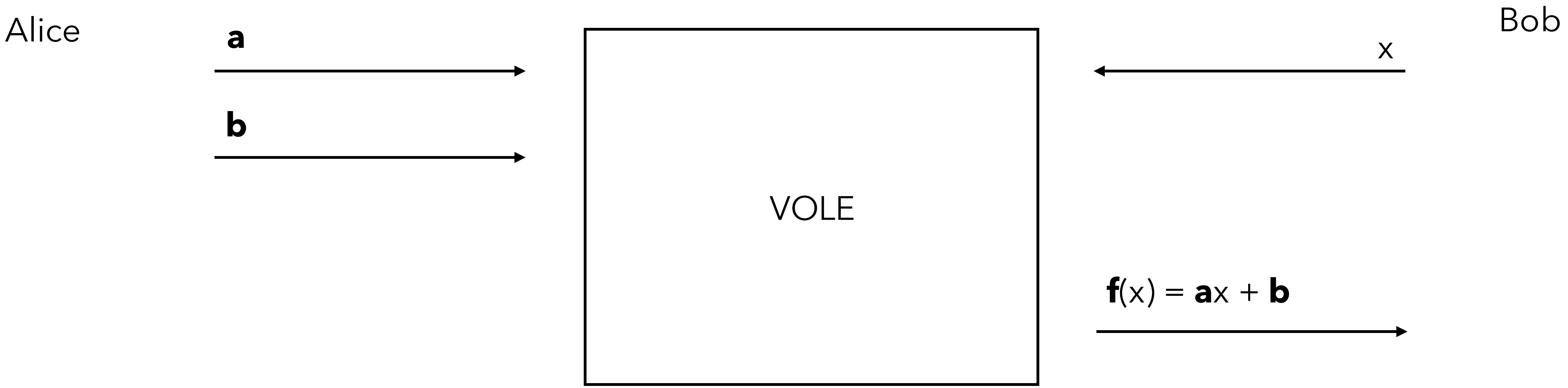
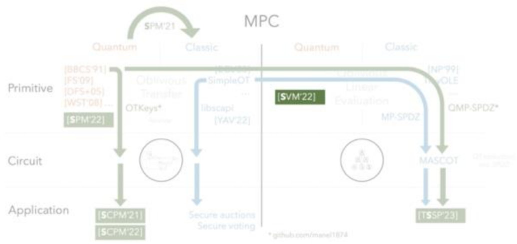
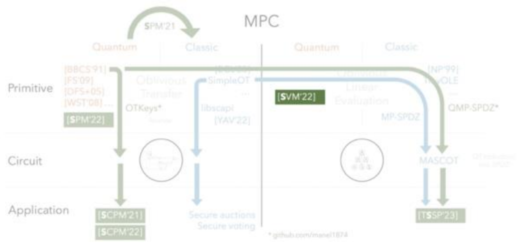


Quantum OLE | Main tool



In an Hilbert space of dimension d

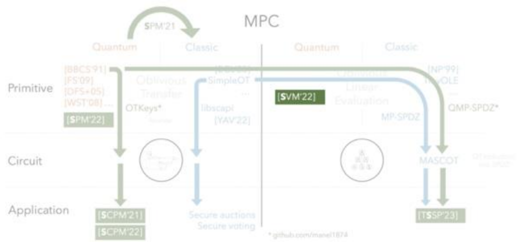
Quantum OLE | Main tool



In an Hilbert space of dimension *d*, there exists a set of MUBs

$$\{|e_r^x\rangle\}_{r\in\mathbb{Z}_d}$$

Quantum OLE | Main tool



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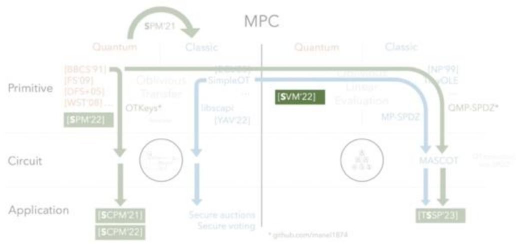
Definition:

$$\mathcal{B}_1 = \{|\phi_1\rangle, \ldots, |\phi_d\rangle\}$$

$$\mathcal{B}_0 = \{|\psi_1\rangle, \ldots, |\psi_d\rangle\}$$

$$|\langle\psi_i|\phi_j\rangle| = \frac{1}{\sqrt{d}}$$

Quantum OLE | Main tool



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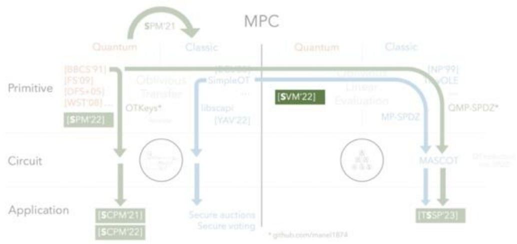

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which, upon the action of the Heisenberg-Weyl operators, V_a^b

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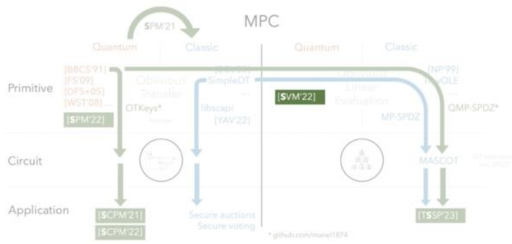

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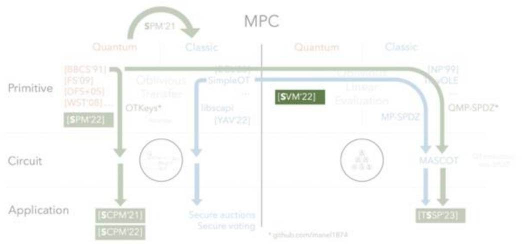
Quantum OLE | Main tool



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$$V_a^b\,|e_r^x\rangle = c_{a,b,x,r}\,\left|e^x_{ax-b+r}\right\rangle$$

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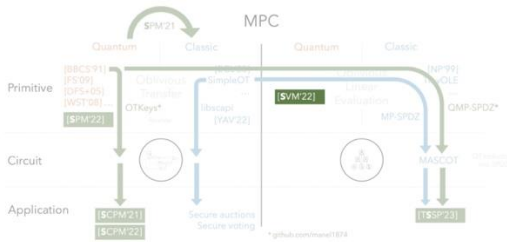
Quantum OLE | Main tool



In an Hilbert space of dimension *d*, there exists a set of MUBs

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which, upon the action of the Heisenberg-Weyl operators, V_a^b

$$V_a^b\,|e_r^x\rangle = c_{a,b,x,r}\,\left|e_{ax-b+r}^x\right\rangle$$

Alice, (a,b)

Bob, x

Definition:

$$\mathcal{B}_1 = \{|\phi_1\rangle, \ldots, |\phi_d\rangle\}$$

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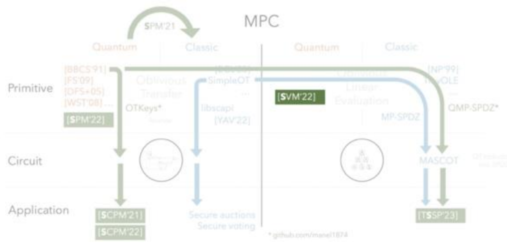

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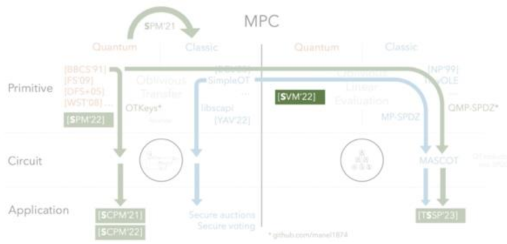
Alice, (a,b)

Bob, x

$|e_r^x\rangle$

Quantum OLE | Main tool



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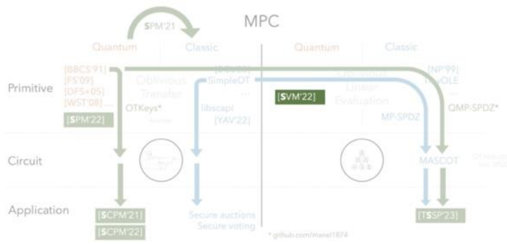
Alice, (a,b)

Bob, x

$$|e_r^x\rangle \longleftarrow |e_r^x\rangle$$

Quantum OLE | Main tool



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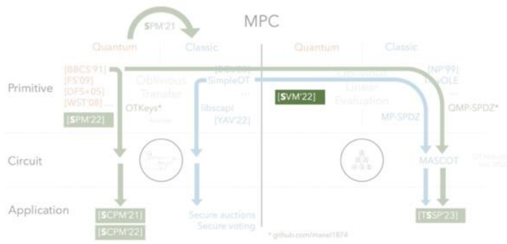
Alice, (a,b) — Bob, x

$|e_r^x\rangle \longleftarrow |e_r^x\rangle$

$V_a^b\,|e_r^x\rangle$

Quantum OLE | Main tool



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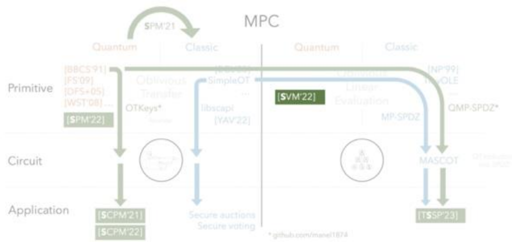

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Alice, (a,b) | Bob, x

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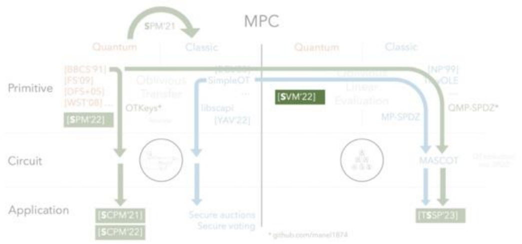
Quantum OLE | Main tool



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Alice, (a,b)

Bob, x

Attack:

$$|B_{a,b}\rangle \;=\; (\mathbb{1}\otimes V_a^b)\,|B_{0,0}\rangle$$

$|e_r^x\rangle$ ← ← $|e_r^x\rangle$

$|e_{ax-b+r}^x\rangle$ → → $|e_{ax-b+r}^x\rangle$

Definition:

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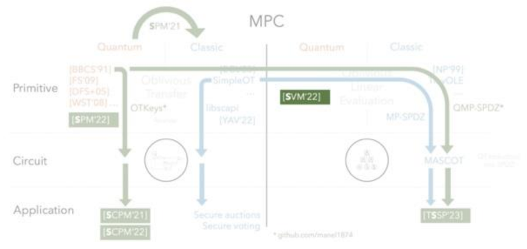
Quantum OLE | Main tool



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Alice, (a,b)

Bob, x

Attack:

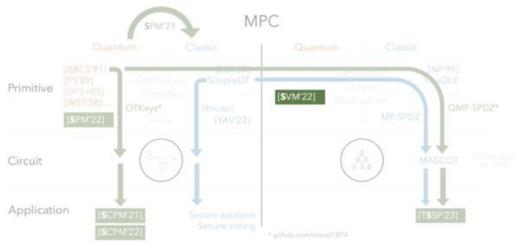
$|e_r^x\rangle$ ← ← $|e_r^x\rangle$

Commit-and-open phase

$|D_{a,b}\rangle = (1\otimes V_a^b)|D_{0,0}\rangle$

$|e_{ax-b+r}^x\rangle$ → → $|e_{ax-b+r}^x\rangle$

Quantum OLE | Protocol



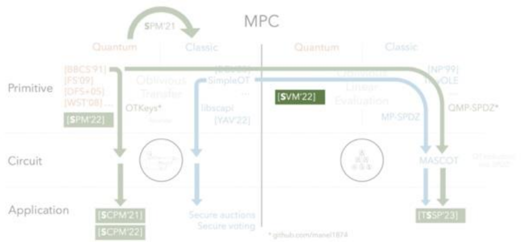
Alice, (a,b)

Bob, x

Quantum phase

Classical phase

Quantum OLE | Protocol



Quantum phase

Classical phase

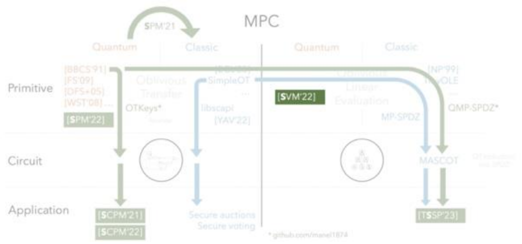
Alice, (a,b)

Bob, x

$i \in [m]$

$\left| e_{r_i}^{x_i^0} \right\rangle$

Quantum OLE | Protocol



Quantum phase

Classical phase

Alice, (a,b)

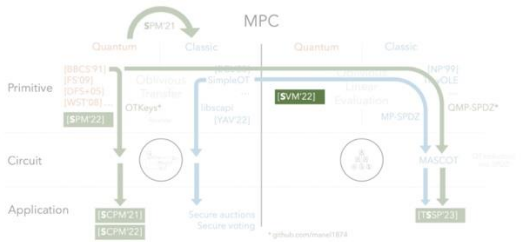
Bob, x

$i\in[m]$

$\left|e^{x_i^0}_{r_i}\right\rangle \longleftarrow \left|e^{x_i^0}_{r_i}\right\rangle$

$V^{b_i^0}_{a_i^0}\left|e^{x_i^0}_{r_i}\right\rangle$

Quantum OLE | Protocol



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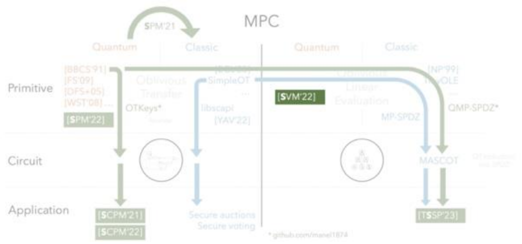
Quantum phase

Classical phase

Quantum OLE | Protocol



Alice, (a,b) Bob, x

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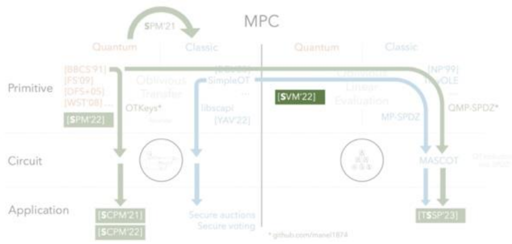
$\left|e^{x_i^0}_{r_i}\right\rangle \longleftarrow \left|e^{x_i^0}_{r_i}\right\rangle$

$\left|e^{x_i^0}_{a_i^0 x_i^0 - b_i^0 + r_i}\right\rangle$

Quantum phase

Classical phase

Quantum OLE | Protocol



Quantum phase

Alice, (a,b)

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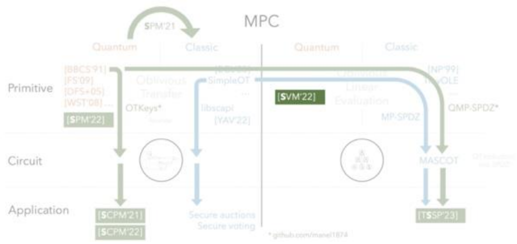
Commit-and-open phase

Classical phase

Quantum OLE | Protocol



Quantum phase

Classical phase

Alice, (a,b)

Bob, x

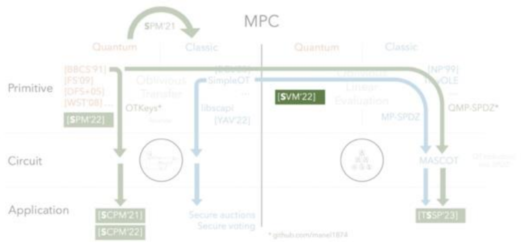
$i \in [m]$

$\left| e_{r_i}^{x_i^0} \right\rangle \longleftarrow \left| e_{r_i}^{x_i^0} \right\rangle$

$\left| e_{a_i^0 x_i^0 - b_i^0 + r_i}^{x_i^0} \right\rangle$

$\longleftarrow$ **Commit-and-open phase** $\longleftarrow$ $\texttt{commit}(i, x_i^0, r_i)_{i\in[m]}$

Quantum OLE | Protocol



Quantum phase

Classical phase

Alice, (a,b) — Bob, x

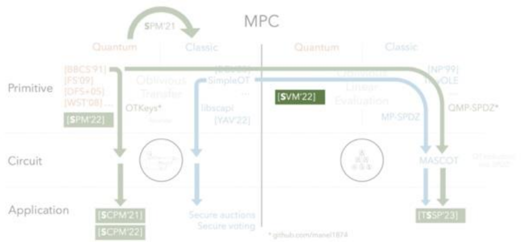
$i \in [m]$

$\left| e^{x_i^0}_{r_i} \right\rangle \longleftarrow \left| e^{x_i^0}_{r_i} \right\rangle$

$\left| e^{x_i^0}_{a_i^0 x_i^0 - b_i^0 + r_i} \right\rangle$

$T \subset [m]$ **Commit-and-open phase** $\mathtt{commit}(i, x_i^0, r_i)_{i \in [m]}$

Quantum OLE | Protocol



Alice, (a,b) — Bob, x

Quantum phase

$i \in [m]$

$\left|e^{x_i^0}_{r_i}\right\rangle \longleftarrow \left|e^{x_i^0}_{r_i}\right\rangle$

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$T \subset [m]$

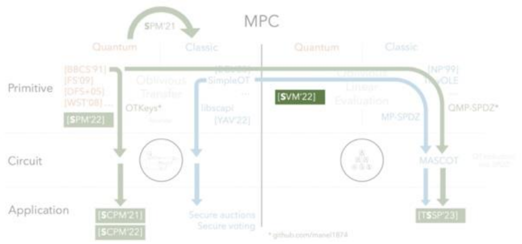
Commit-and-open phase

$\texttt{commit}(i, x_i^0, r_i)_{i\in[m]}$

$\texttt{open}(i, x_i^0, r_i)_{i\in T}$

Classical phase

Quantum OLE | Protocol



Quantum phase

Classical phase

Alice, (a,b) | Bob, x

$i \in [m]$

$\left| e^{x_i^0}_{r_i} \right\rangle \longleftarrow \left| e^{x_i^0}_{r_i} \right\rangle$

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$T \subset [m]$

Commit-and-open phase

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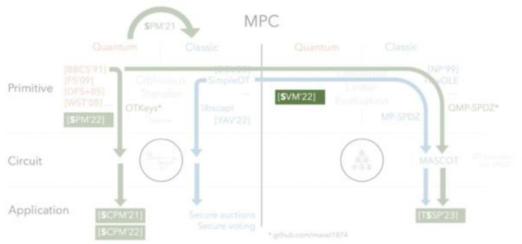
$\mathtt{open}(i, x_i^0, r_i)_{i \in T}$

$\left| e^{x_i^0}_{a_i^0 x_i^0 - b_i^0 + r_i} \right\rangle \longrightarrow$

Quantum OLE | Protocol



Quantum phase

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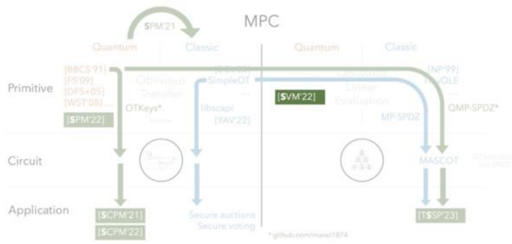
Classical phase

Quantum OLE | Protocol



Alice, (a,b) Bob, x

Quantum phase

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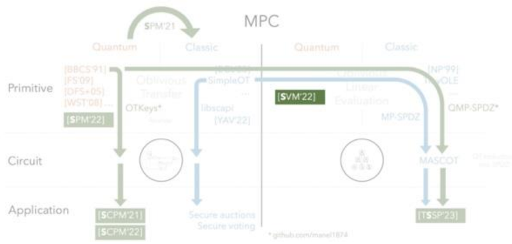
Classical phase

Derandomization:

n ROLE $\longrightarrow$ n OLE

Quantum OLE | Protocol



Quantum phase

Alice, (a,b) | Bob, x

$i \in [m]$

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Classical phase

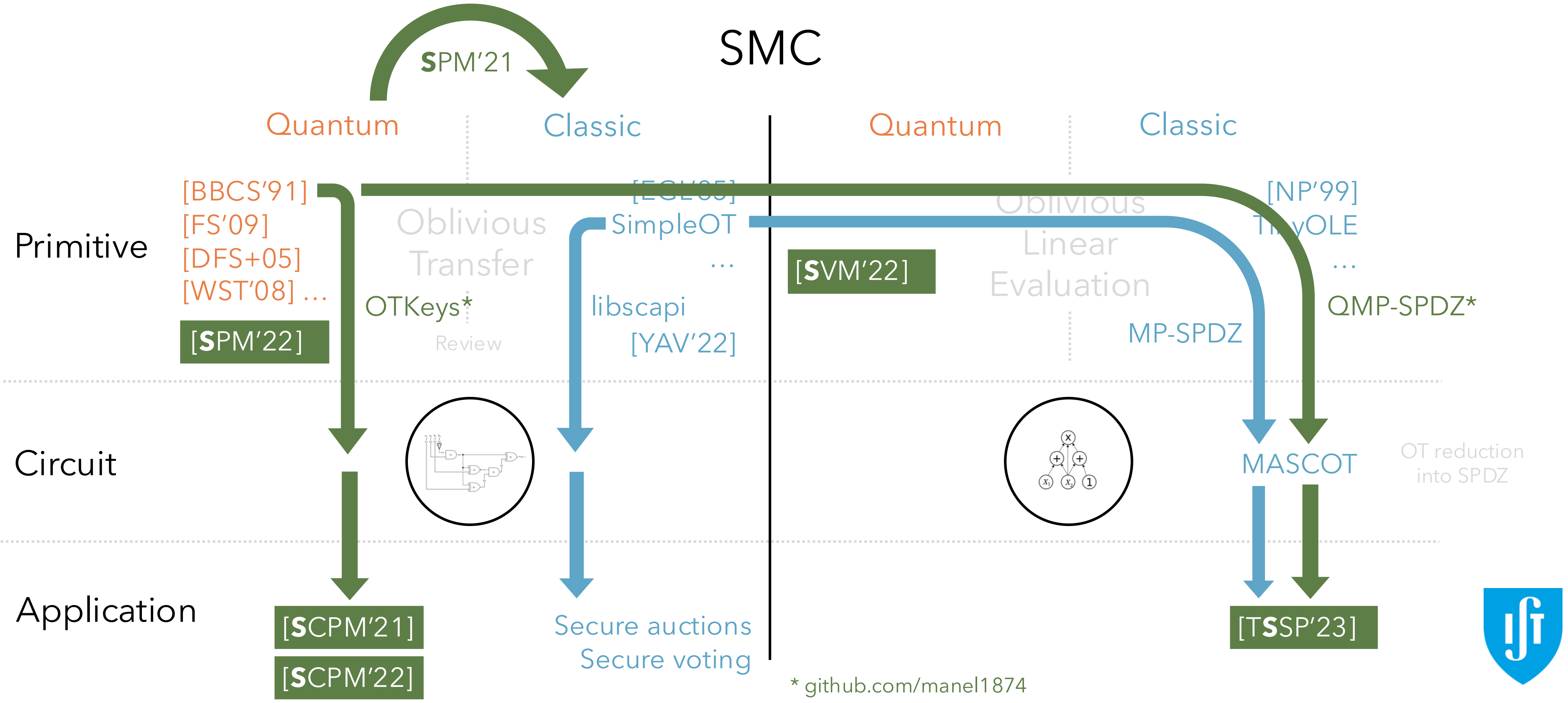
Derandomization:

n ROLE $\longrightarrow$ *n* OLE

Extraction: Privacy amplification + Combiner

n OLE $\longrightarrow$ *1* OLE

Future work



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[TSSP'23]
* github.com/manel1874

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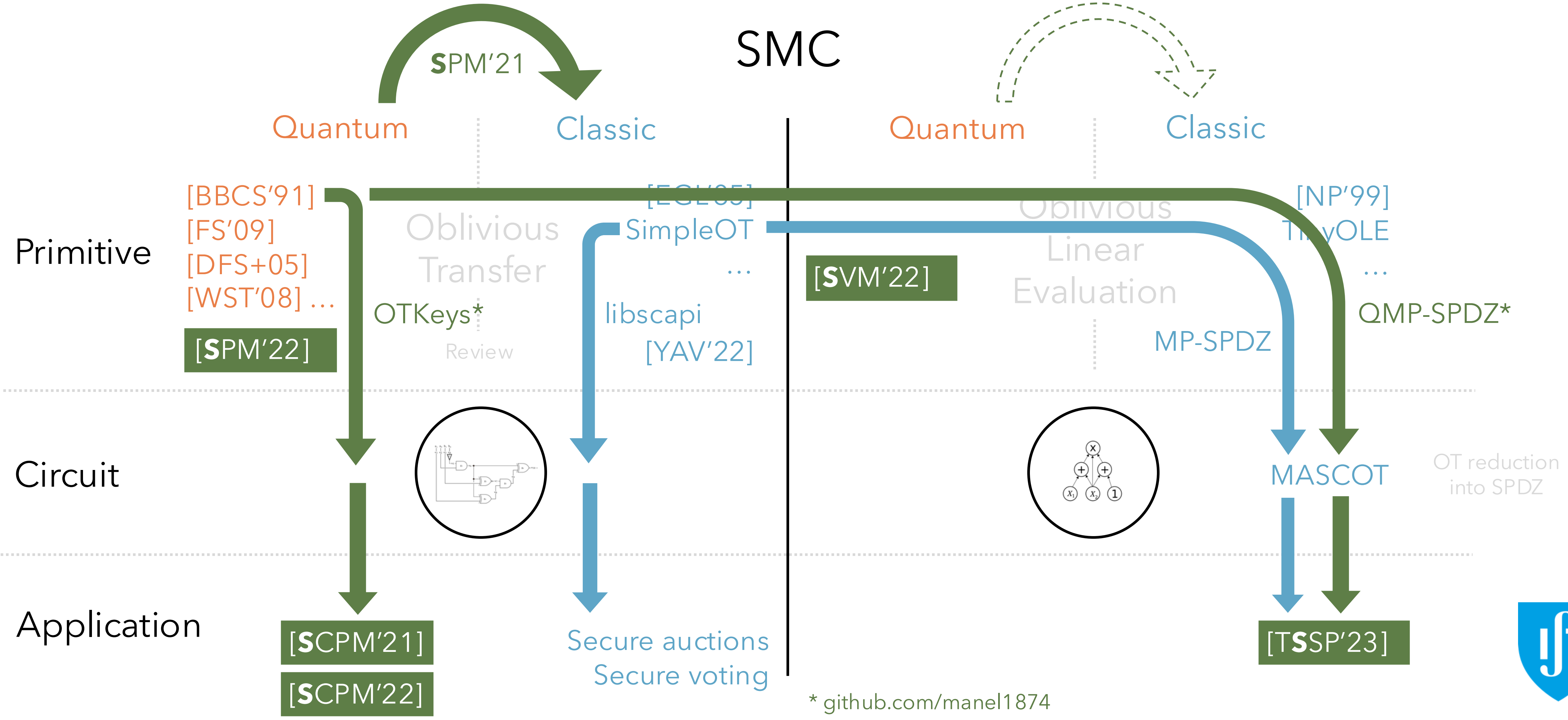
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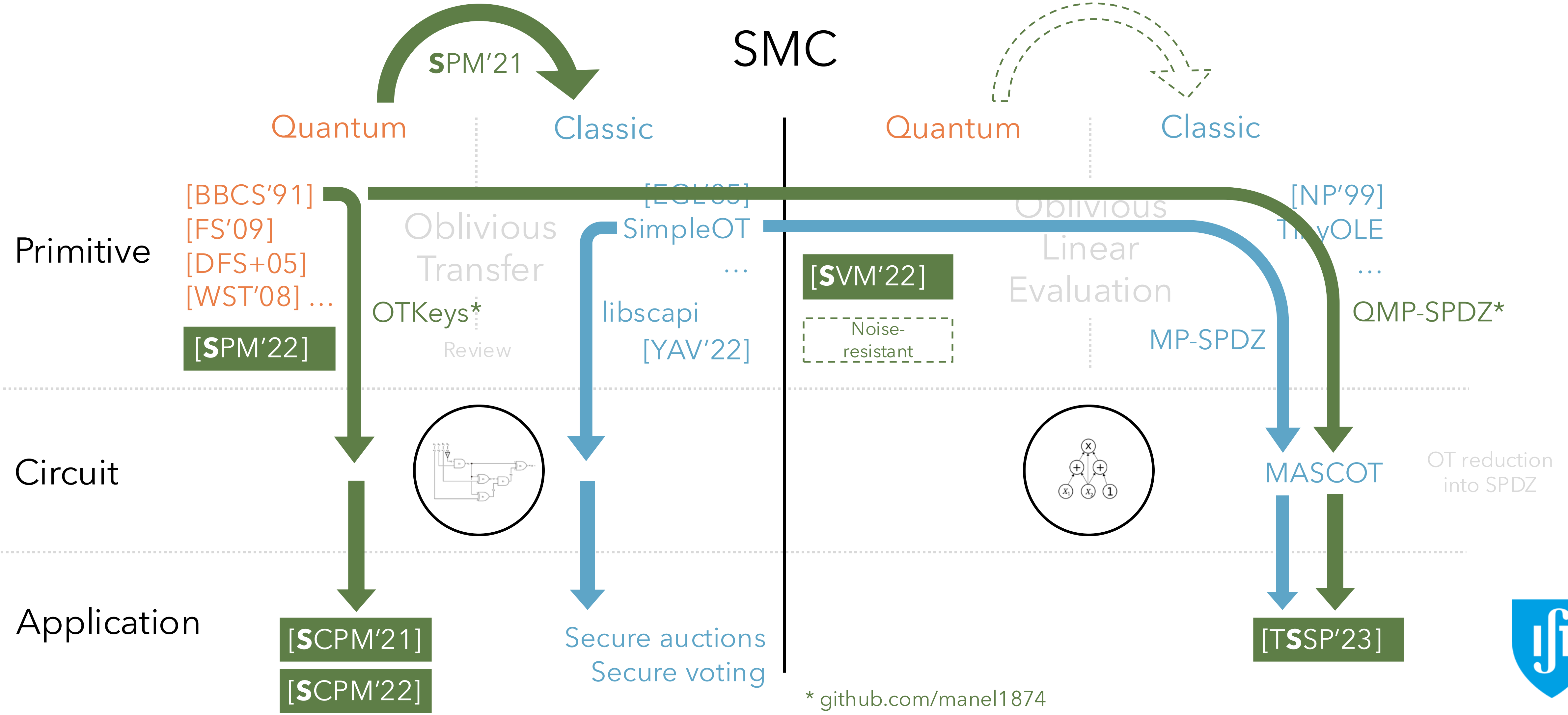

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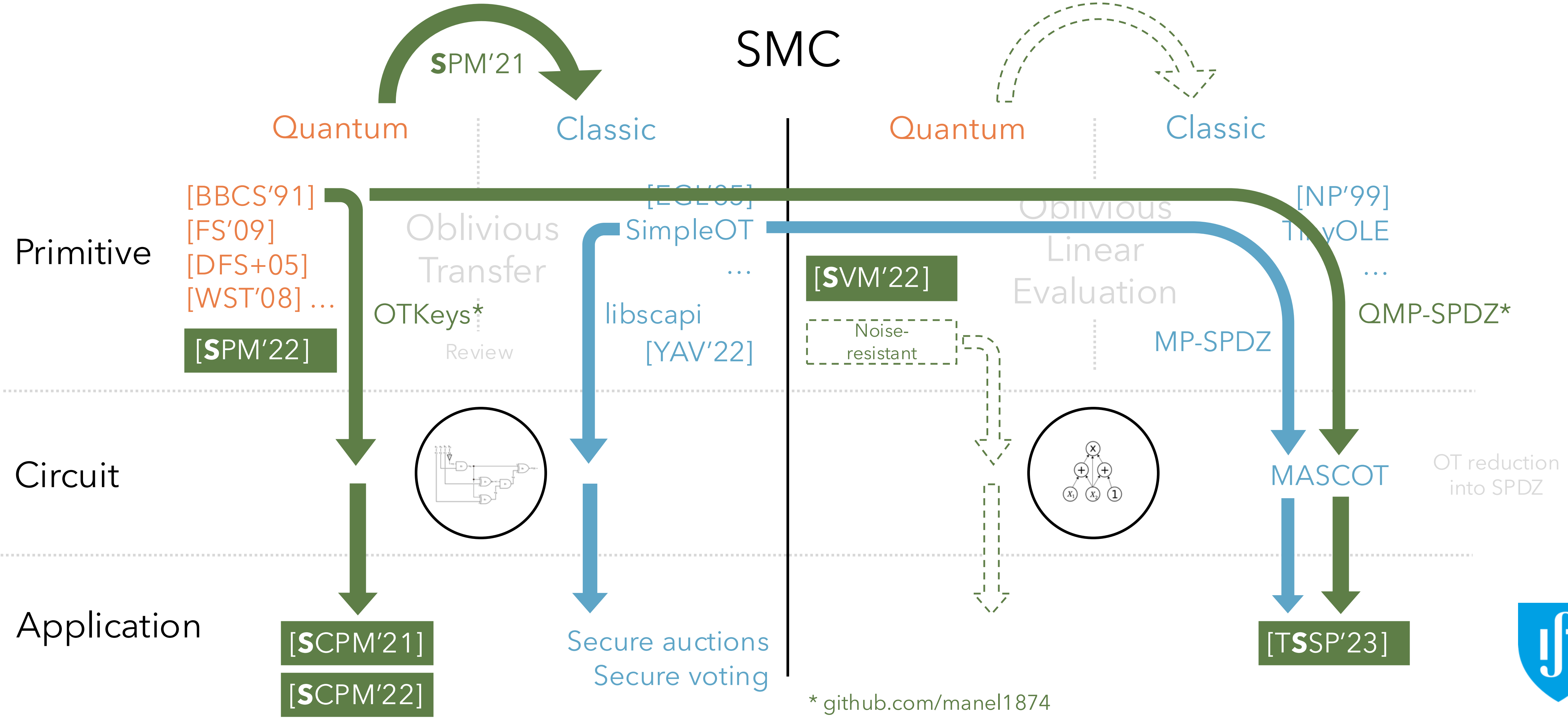
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* github.com/manel1874

Thank you

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Quantum Assisted Secure Multiparty Computation

Manuel Batalha dos Santos

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