VSB TECHNICAL UNIVERSITY OF OSTRAVA | IT4INNOVATIONS NATIONAL SUPERCOMPUTING CENTER

ENERGY EFFICIENCY ANALYSIS OF PARALLEL APPLICATIONS

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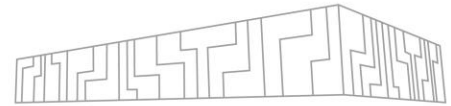
IT4Innovations

EUROPEAN UNION
European Structural and Investment Funds
Operational Programme Research,
Development and Education

MINISTRY OF EDUCATION, YOUTH AND SPORTS

ENERGY EFFICIENCY

$$EnergyEfficiency = \frac{Performance}{Power}$$



1] Measure performance

ENERGY EFFICIENCY - GREEN500

$$EnergyEfficiency = \frac{R_{max}}{\overline{P}(R_{max})}$$

- LINPACK Rmax/W
- FLOPs/W
- LUPs/W
- …

Green500 Data

Rank	TOP500 Rank	System	Cores	Rmax (PFlop/s)	Power (kW)	Energy Efficiency (GFlops/watts)
1	293	**Henri** - ThinkSystem SR670 V2, Intel Xeon Platinum 8362 32C 2.8GHz, NVIDIA H100 80GB PCIe, Infiniband HDR, Lenovo Flatiron Institute United States	8,288	2.88	44	65.396
2	44	**Frontier TDS** - HPE Cray EX235a, AMD Optimized 3rd Generation EPYC 64C 2GHz, AMD Instinct MI250X, Slingshot-11, HPE DOE/SC/Oak Ridge National Laboratory United States	120,832	19.20	309	62.684

11/2023

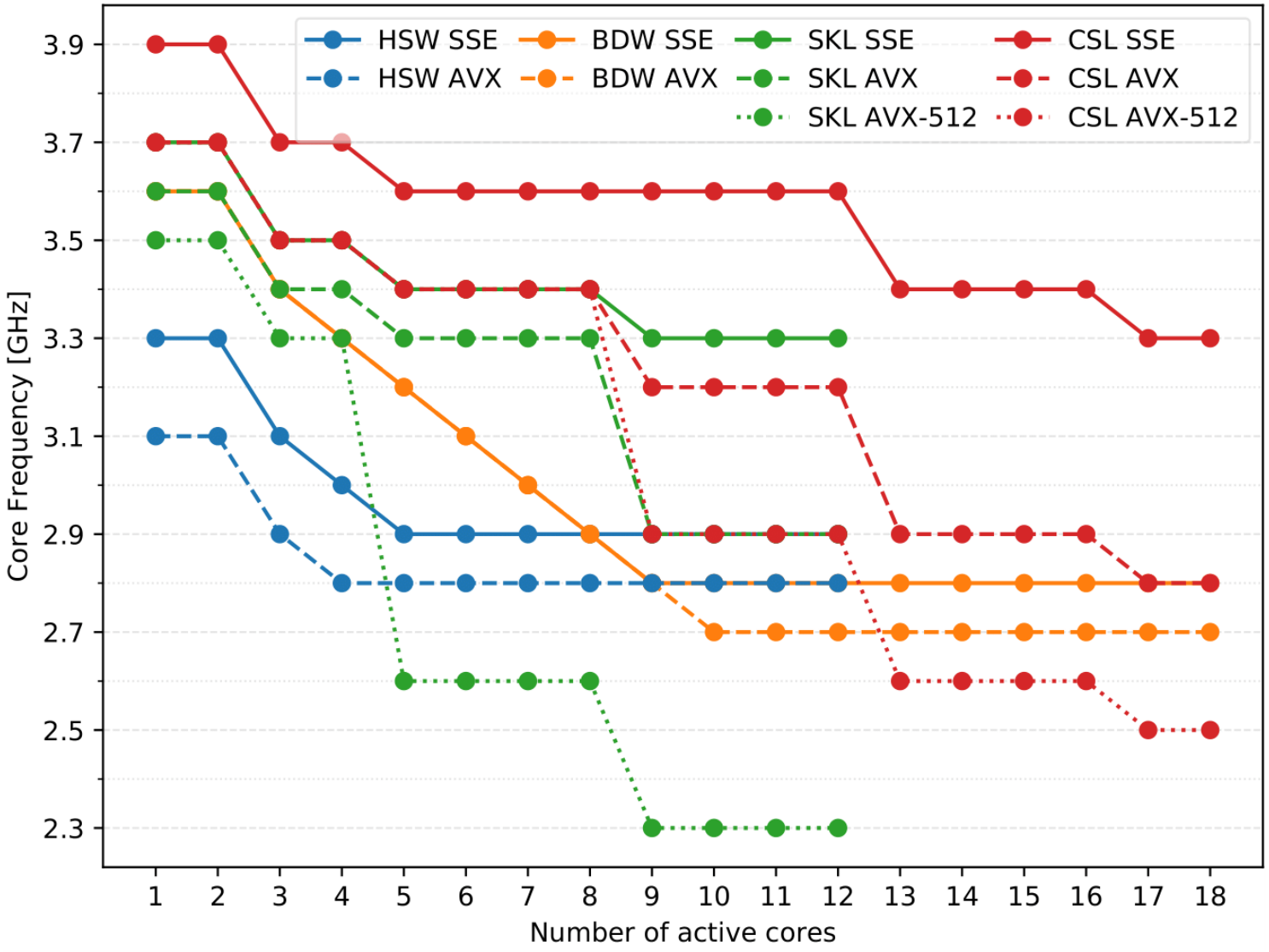
https://www.top500.org/files/green500/tutorial.pdf

PERFORMANCE

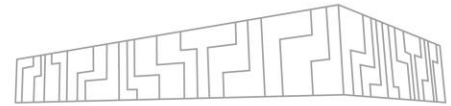
- Reported by the application (solver)
  - FLOPs, MLUPs, ...
- Evaluate FLOPs

event name	FLOPs/inst	#inst.	FLOPs
SCALAR_DOUBLE	1	7240374183451	9164881641636
SCALAR_SINGLE	1	154346452896	154346452896
128B_PACKED_DOUBLE	2	557726129284	1115452258568
128B_PACKED_SINGLE	4	254594513	1018378052
256B_PACKED_DOUBLE	4	2725451737	10901806948
256B_PACKED_SINGLE	8	0	0
512B_PACKED_DOUBLE	8	0	0
512B_PACKED_SINGLE	16	0	0
Runtime [s]	105.38	**Sum [FLOPs]**	8522093079915
		GFLOPs/s	80.87

INSTRUCTION SET vs FREQUENCY



HSW - Xeon E5-2680v3
BDW - Xeon E5-2697v4
SKL - Xeon Gold 6126
CSL - Xeon Gold 6240

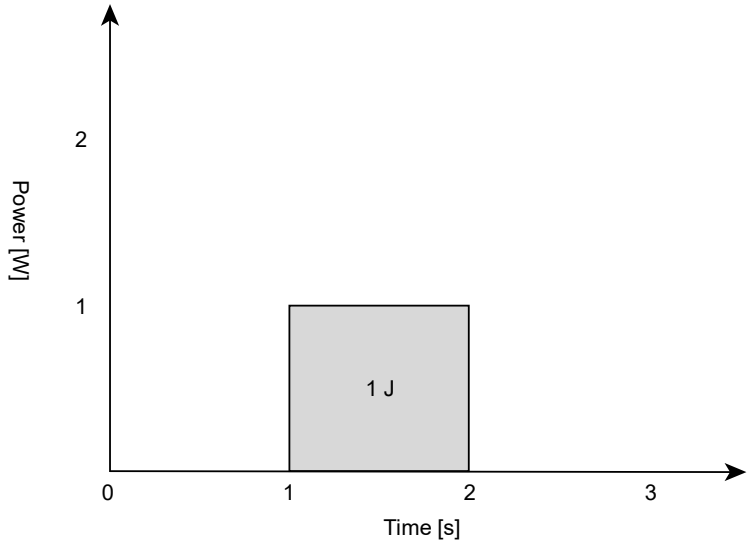


2] Measure energy

ENERGY

$$Energy = Power \times Time$$

- Power [W]
- 1 W * 1 s = 1 J
- 1 W * 1 h = 1 Wh = 3 600 J



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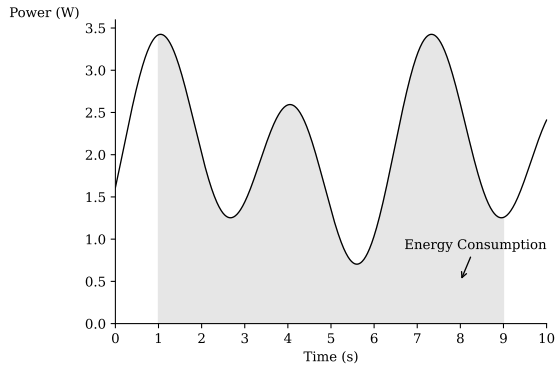

Img source, Luís Cruz (TU Delft)

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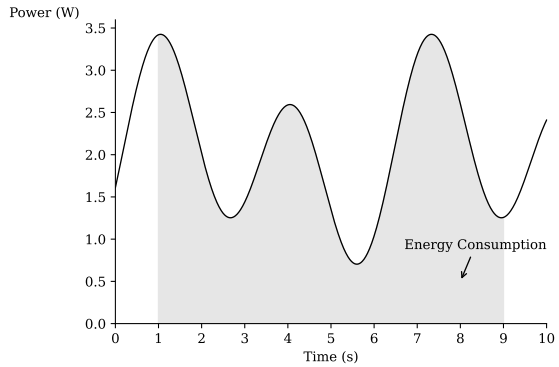

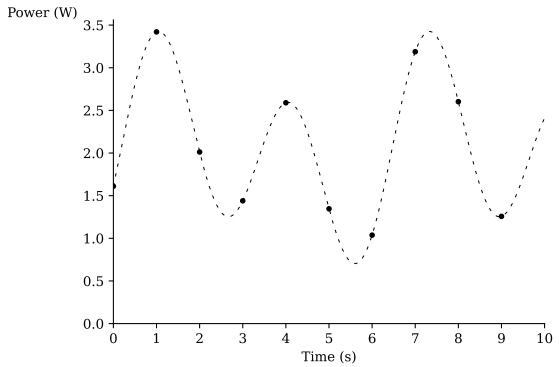

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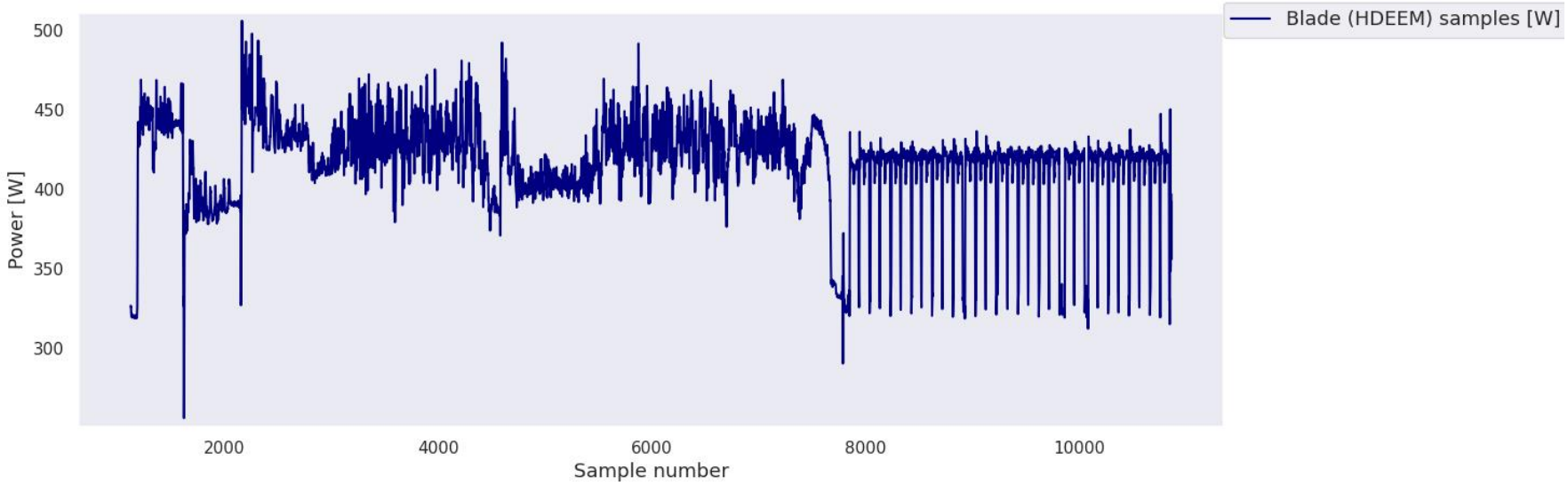

ENERGY

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- Power [W]
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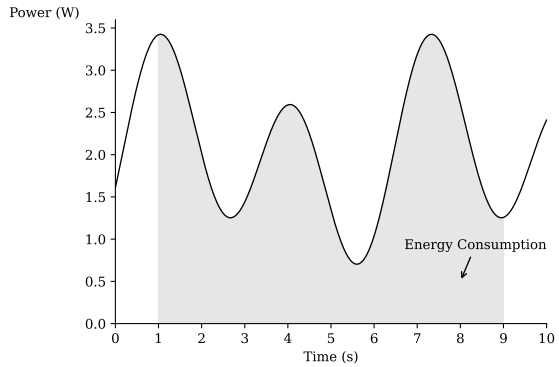
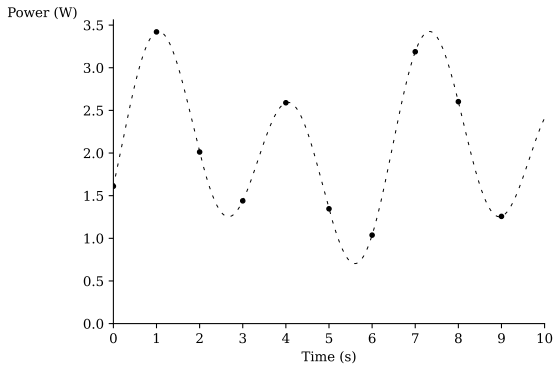
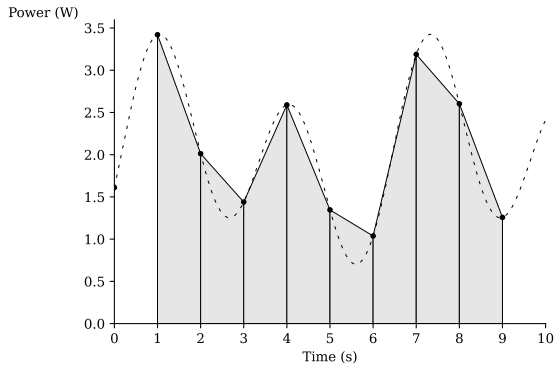
$$Energy(t) = \int_0^t Power(x)\,\mathrm{d}x \approx \frac{\sum_{i=0}^{n} PowerSample_i}{SamplingFrequency}$$







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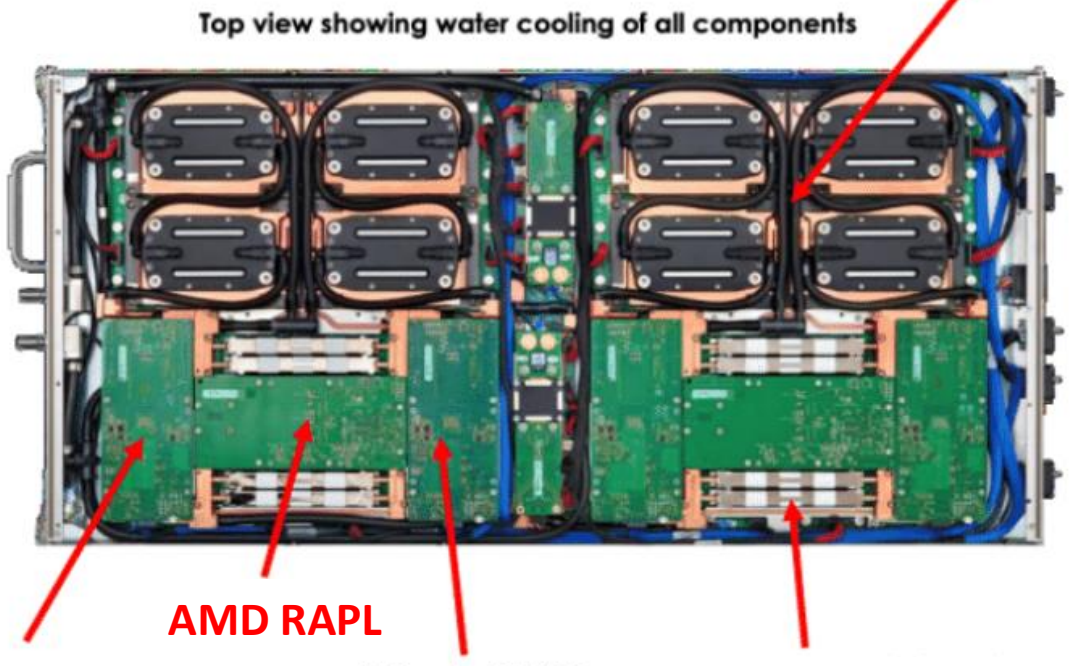
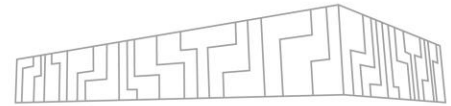
POWER MONITORING



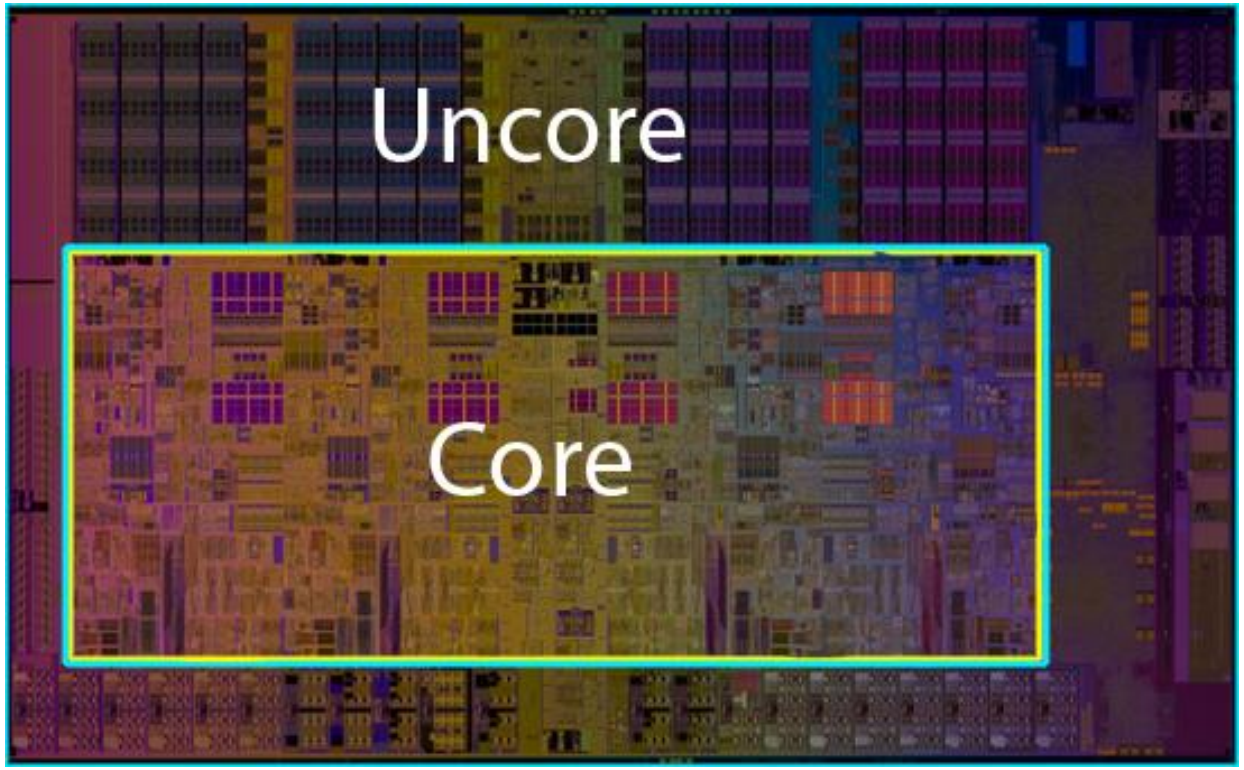
Images of HPE Cray, OLCF Frontier

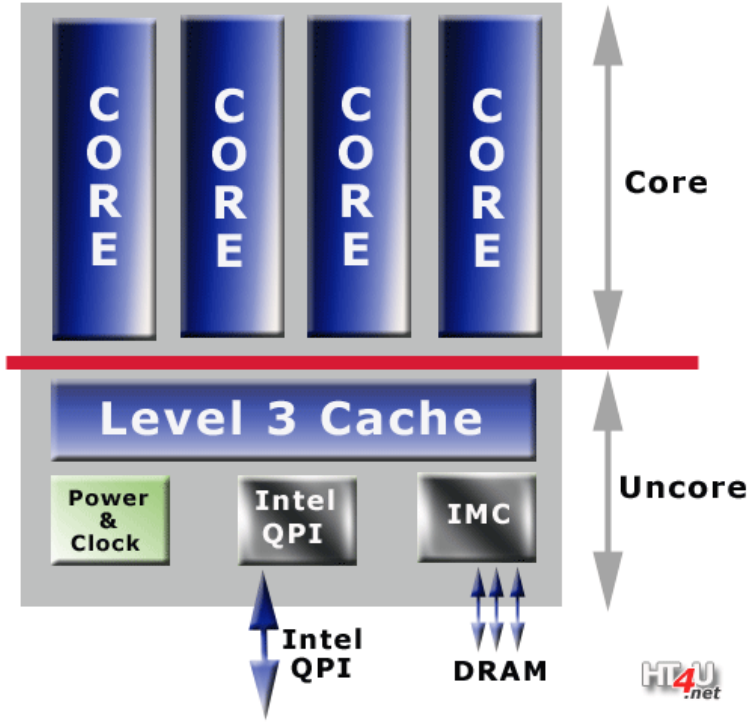


3] Know your hardware

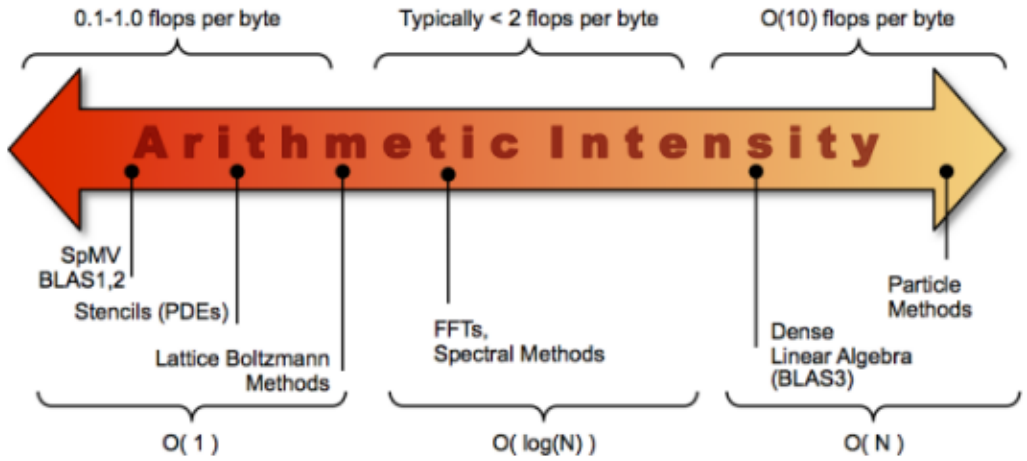
INTEL CPU UNCORE FREQUENCY

- MSR MSR_UNCORE_RATIO_LIMIT (0x620)
  - frequency of subsystems in the physical processor package that are shared by multiple processor cores
  - last level cache, on-chip ring interconnect or the integrated memory controllers, etc.
  - occupies approximately 30 % of a chip area

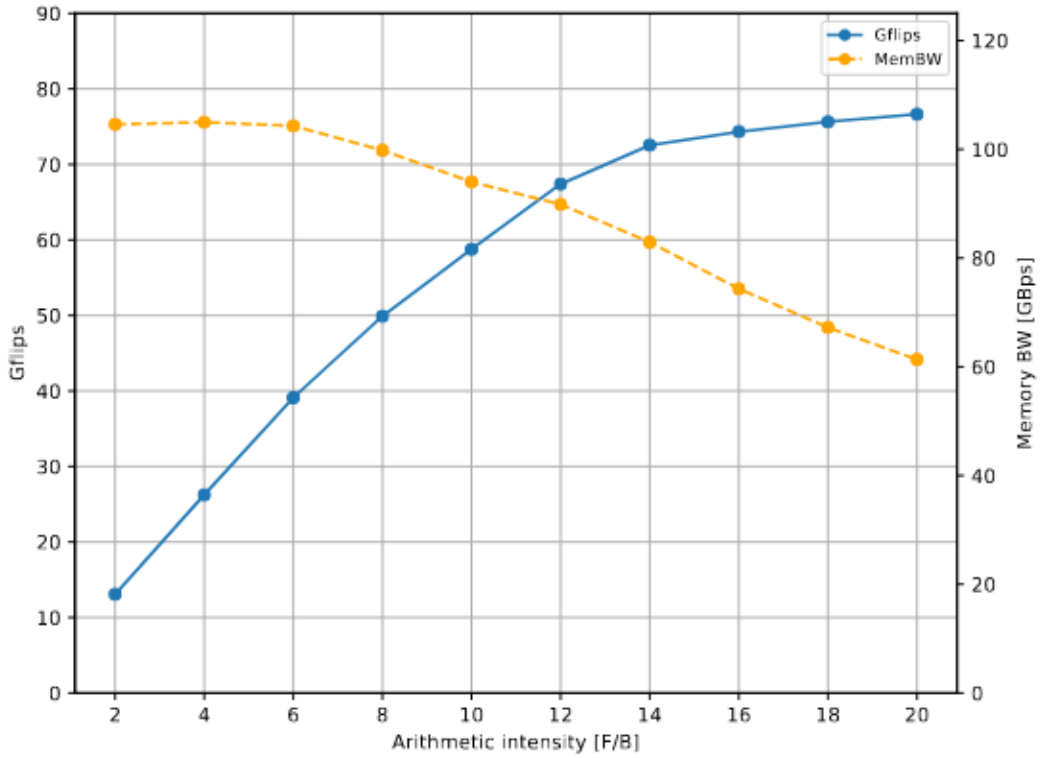




WORKLOAD BOUNDNESS



(a) Arrow presenting a range of applications of various arithmetic intensities [54].

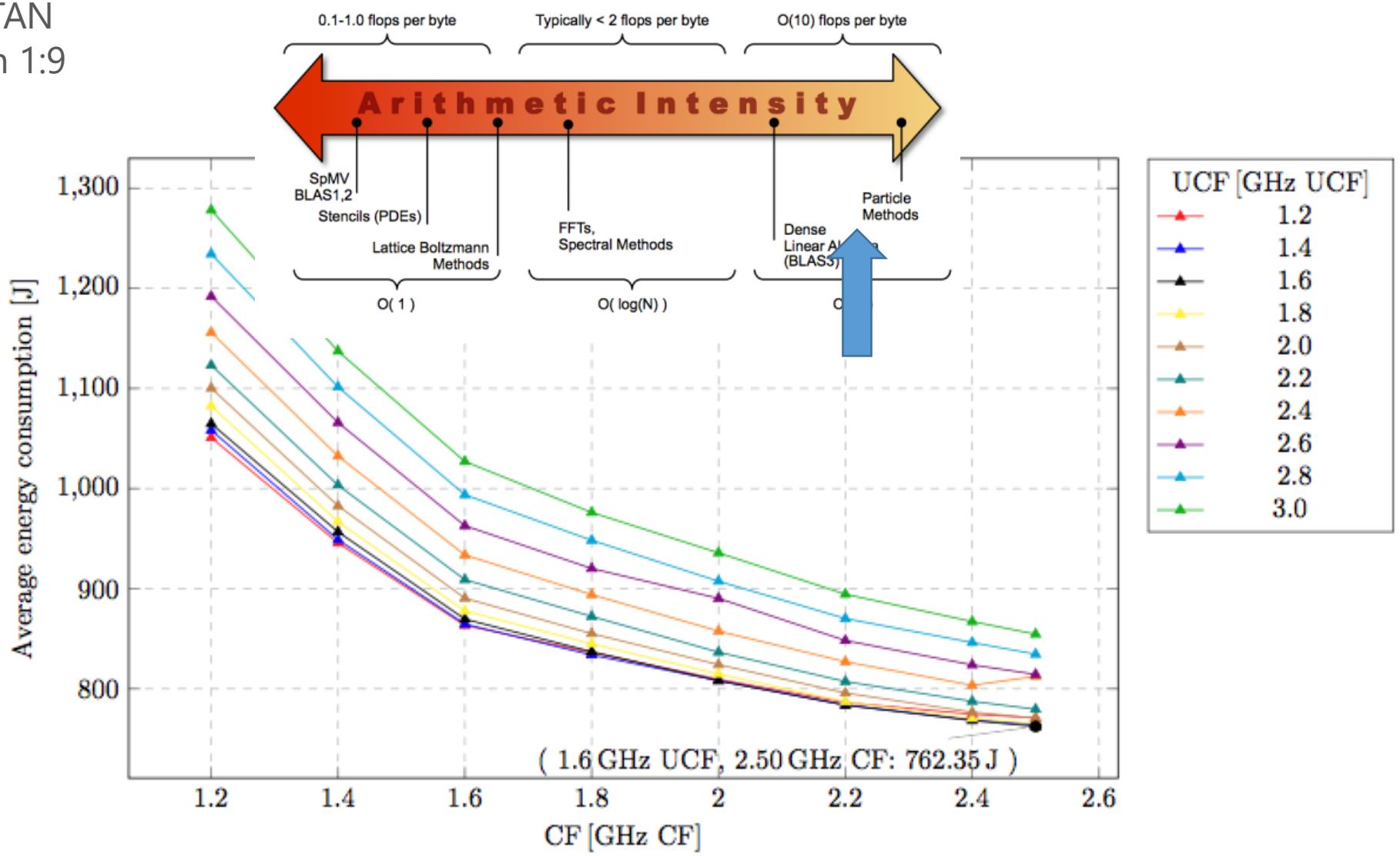


(b) Roofline model of the Intel Xeon Gold 6240 processor when executing a workload of AVX-512 instructions.

memory bound, compute bound, communication, I/O, etc.

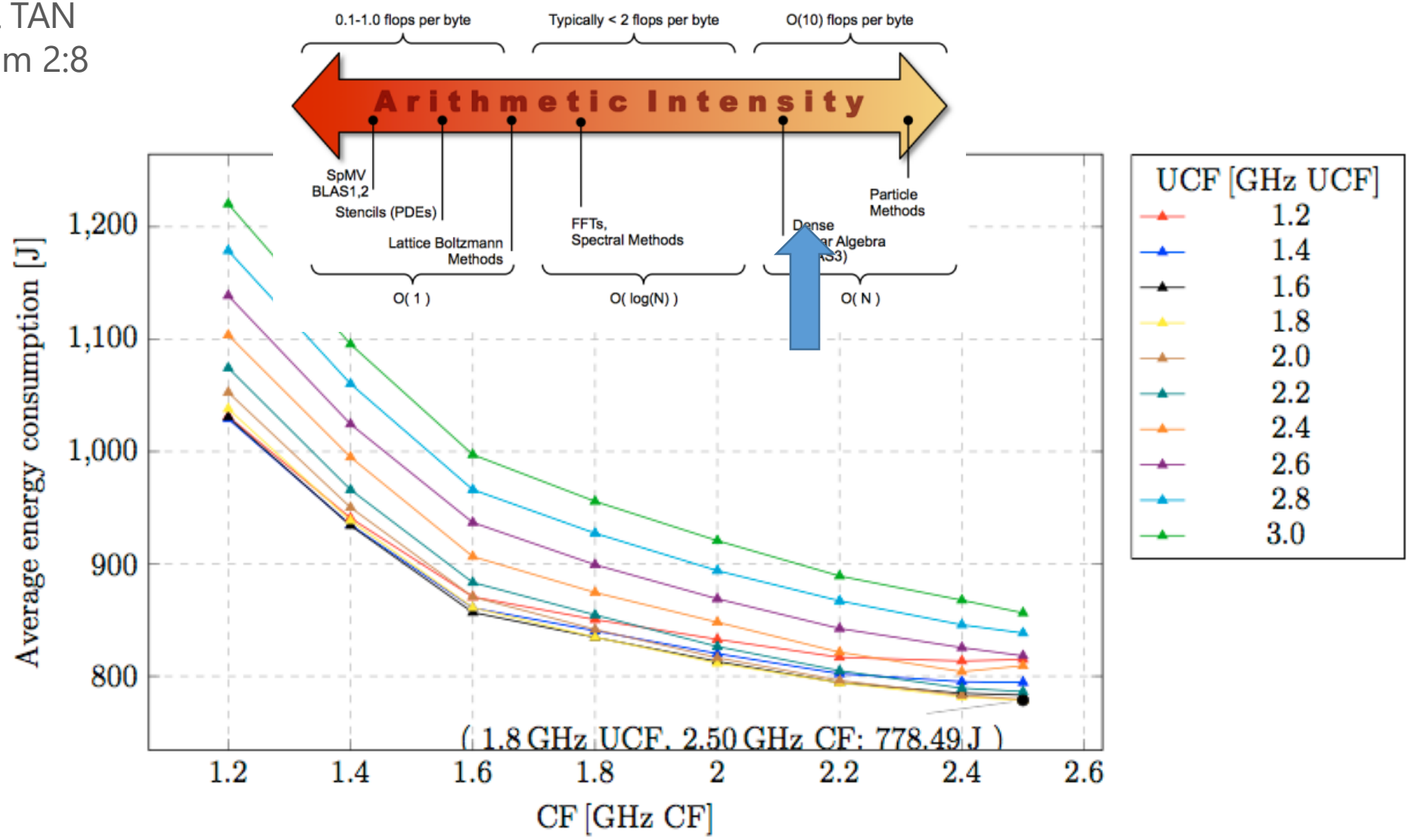
ARITHMETIC INTENSITY

GEMV & TAN
Ratio from 1:9



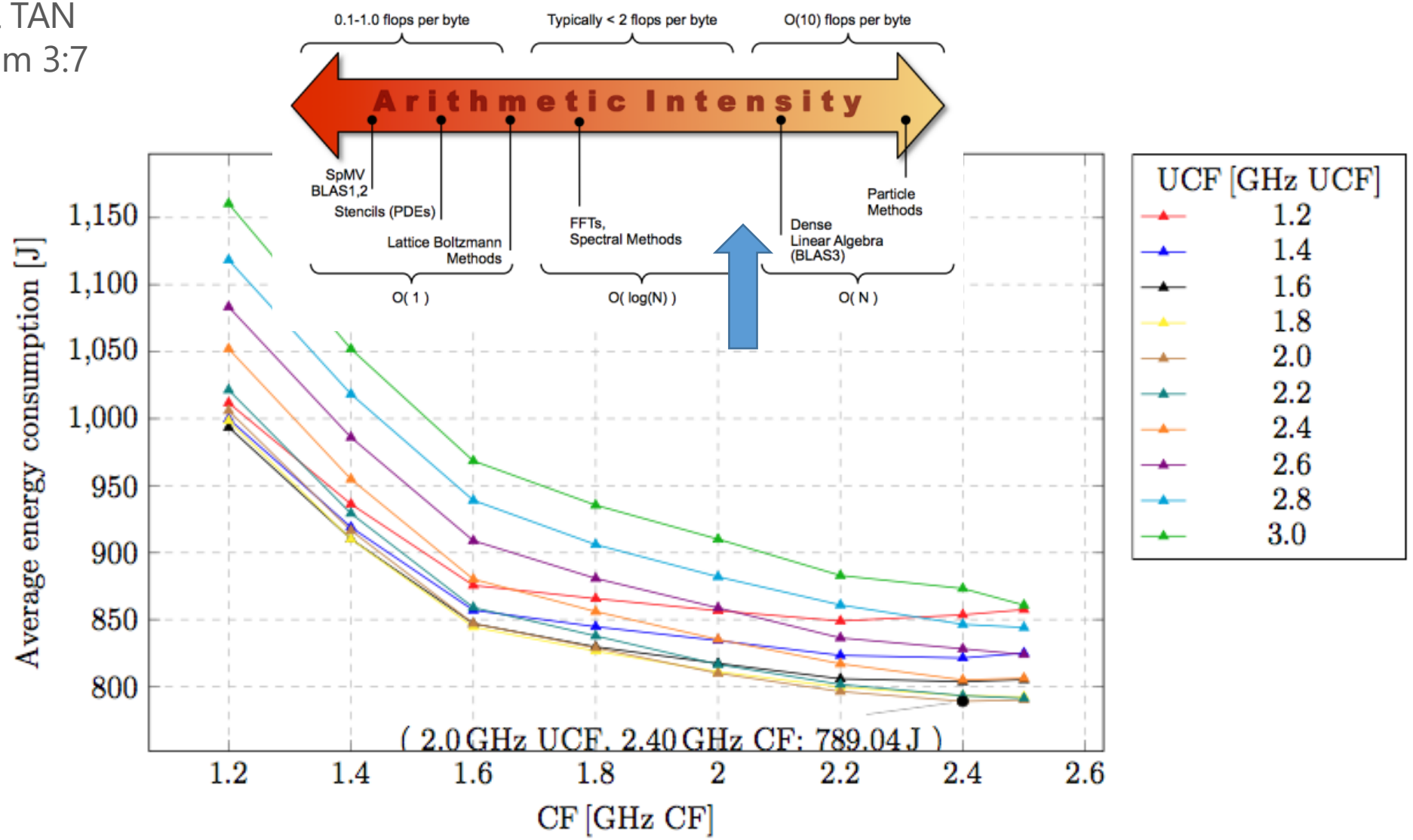
ARITHMETIC INTENSITY

GEMV & TAN
Ratio from 2:8



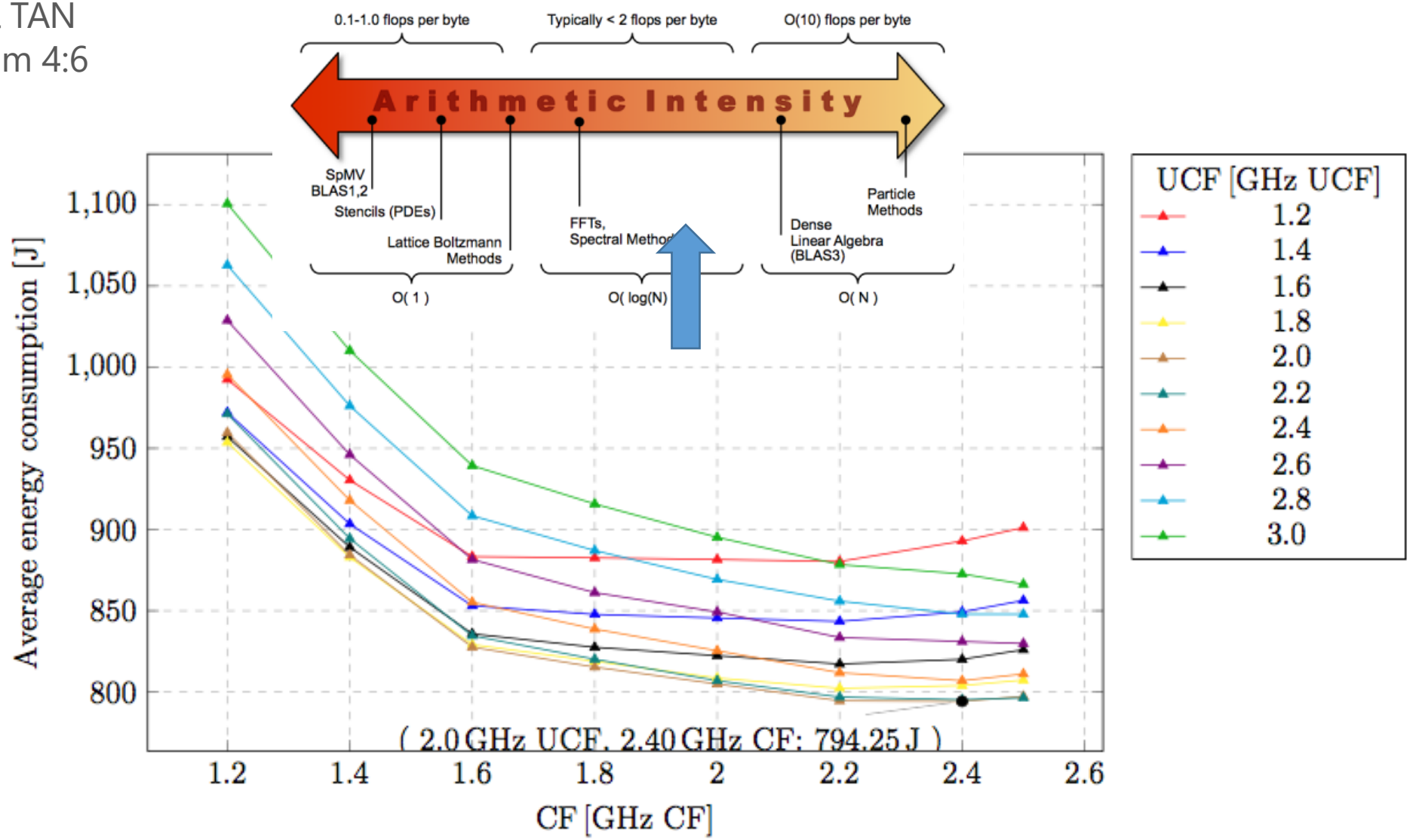
ARITHMETIC INTENSITY

GEMV & TAN
Ratio from 3:7



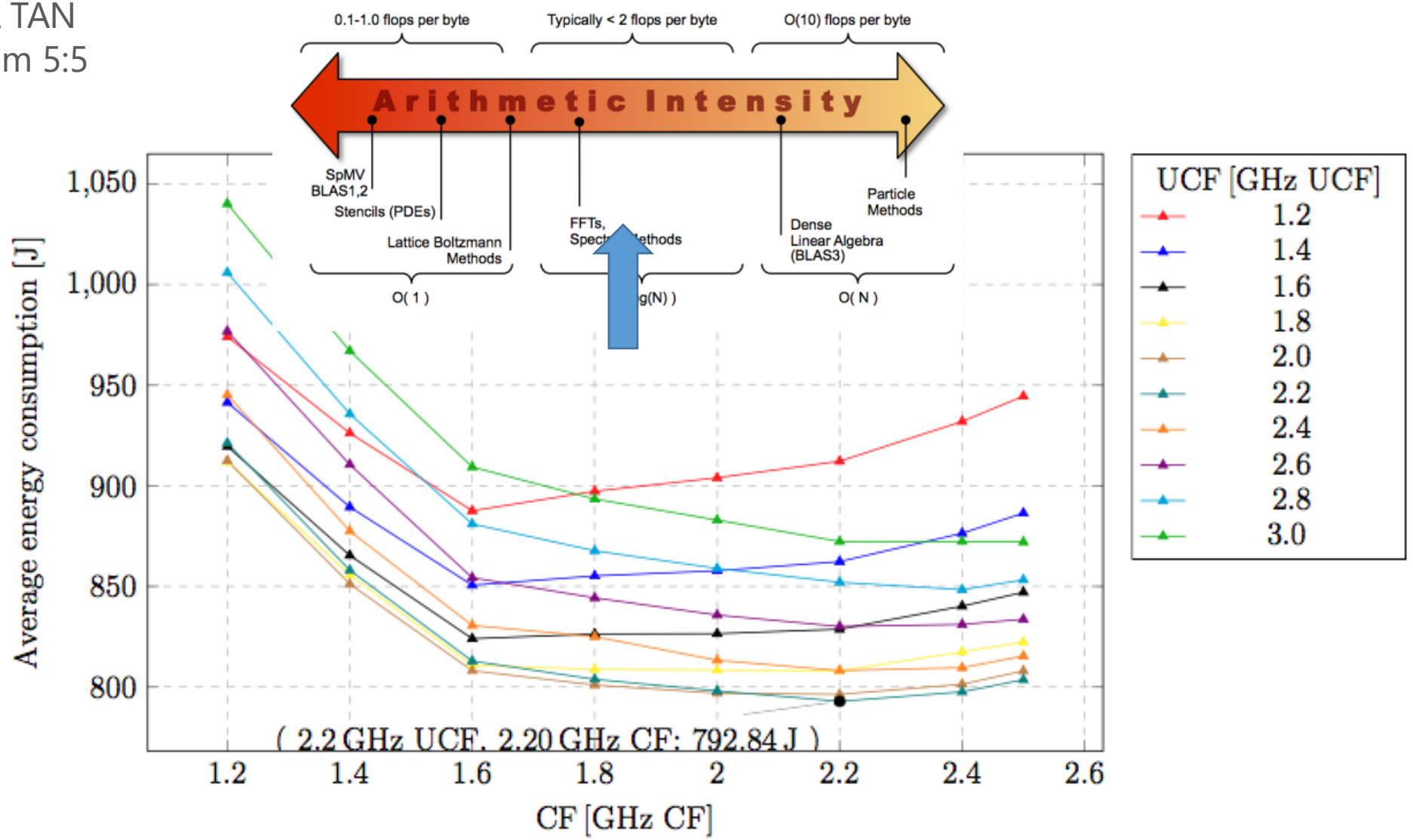
ARITHMETIC INTENSITY

GEMV & TAN
Ratio from 4:6



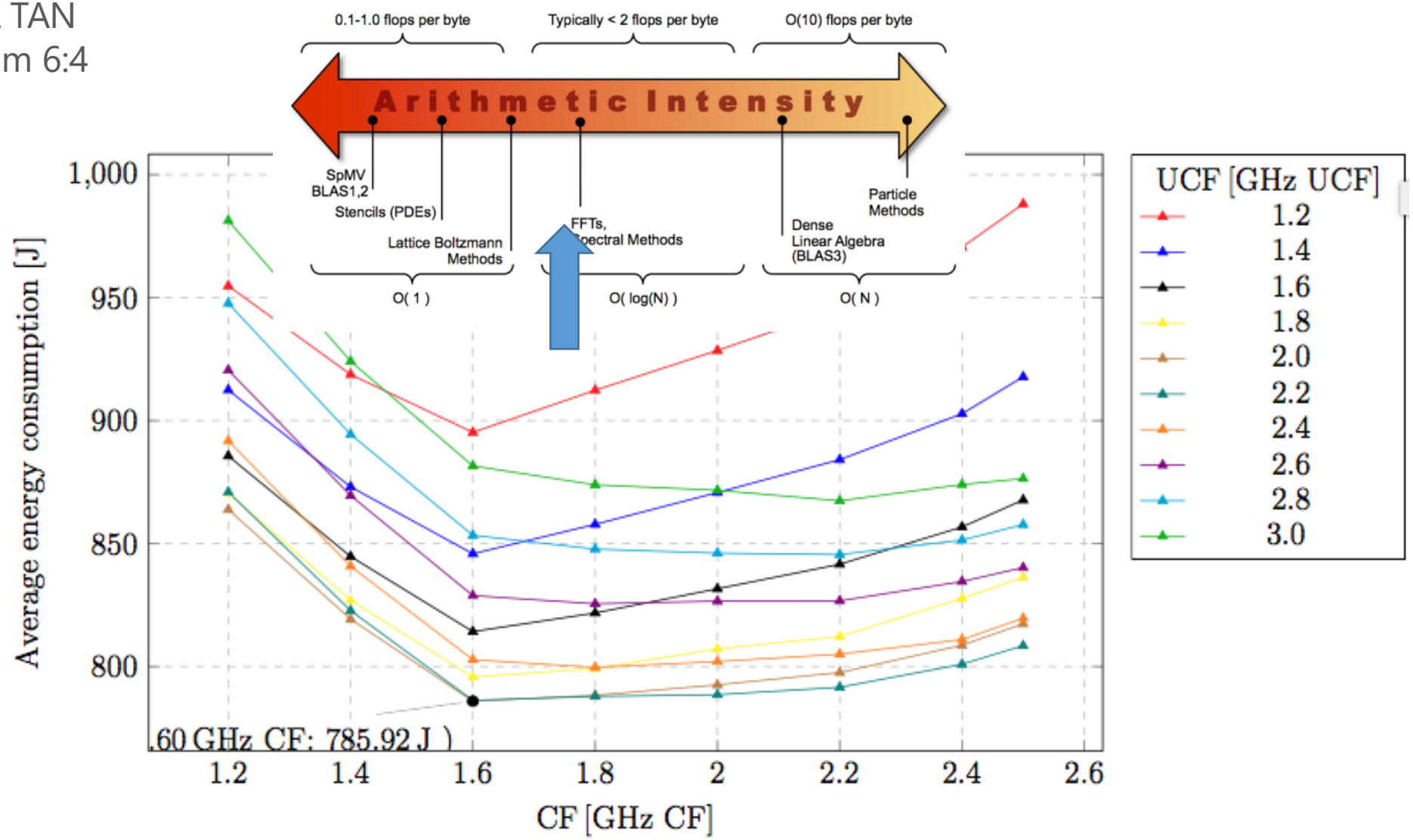
ARITHMETIC INTENSITY

GEMV & TAN
Ratio from 5:5



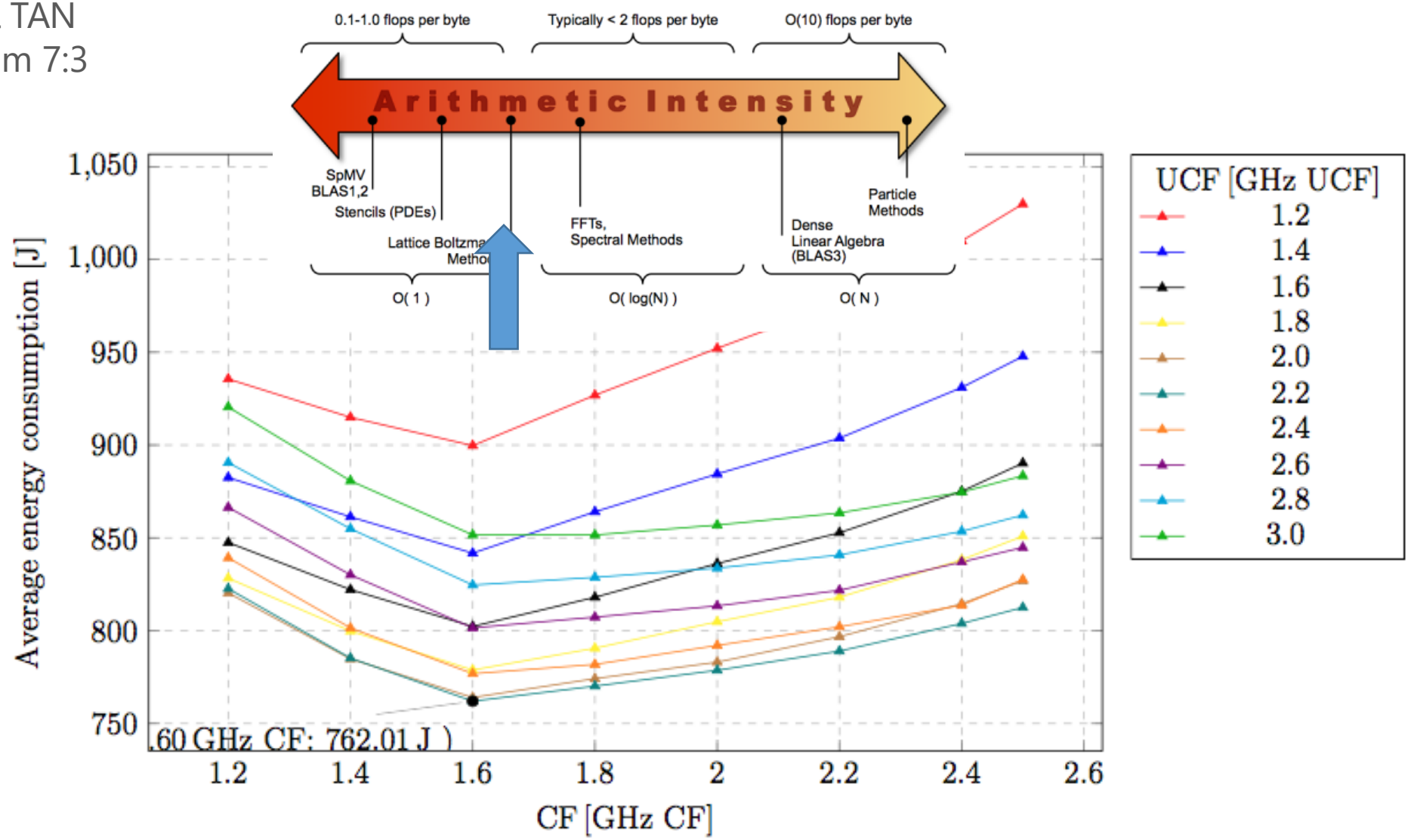
ARITHMETIC INTENSITY

GEMV & TAN
Ratio from 6:4



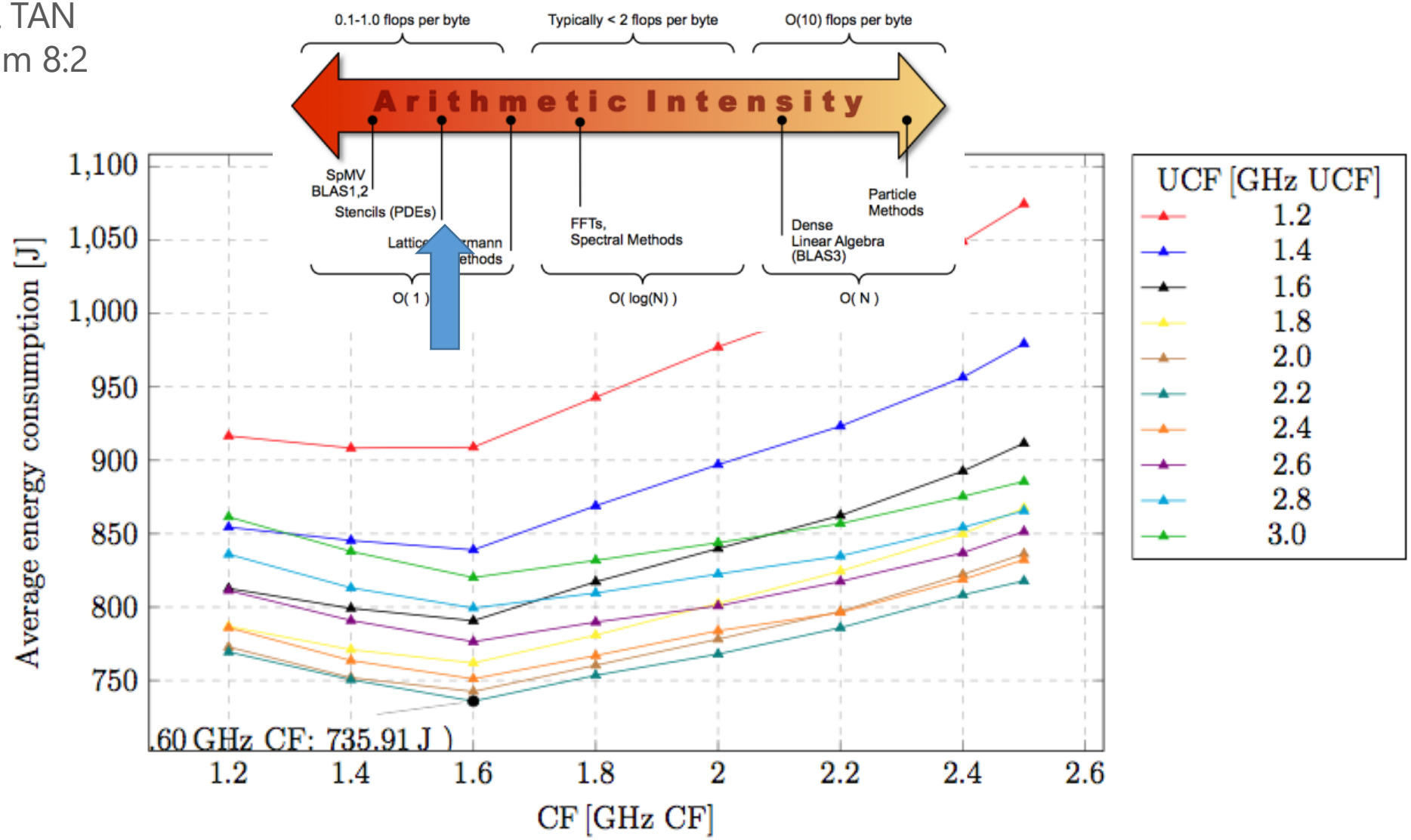
ARITHMETIC INTENSITY

GEMV & TAN
Ratio from 7:3



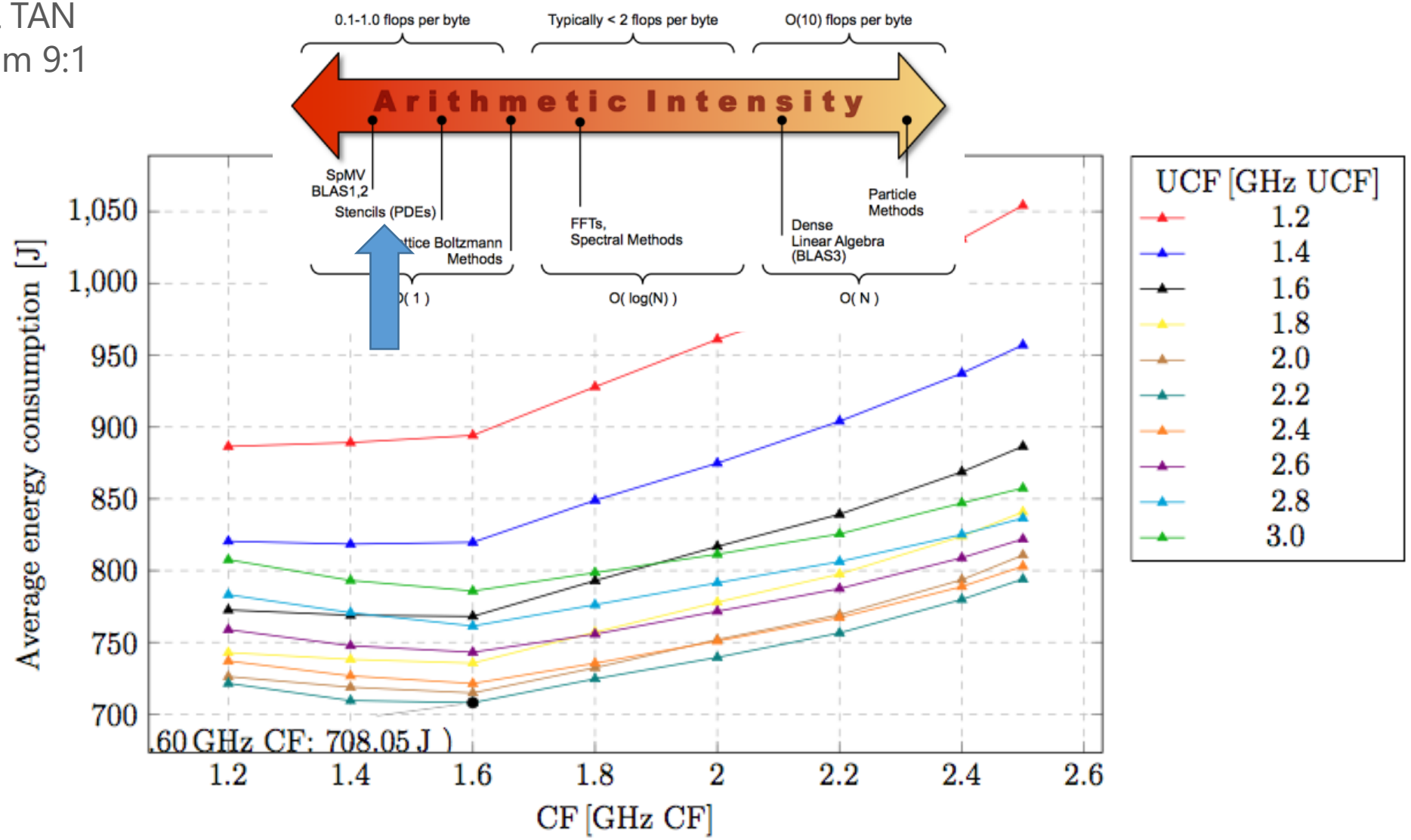
ARITHMETIC INTENSITY

GEMV & TAN
Ratio from 8:2

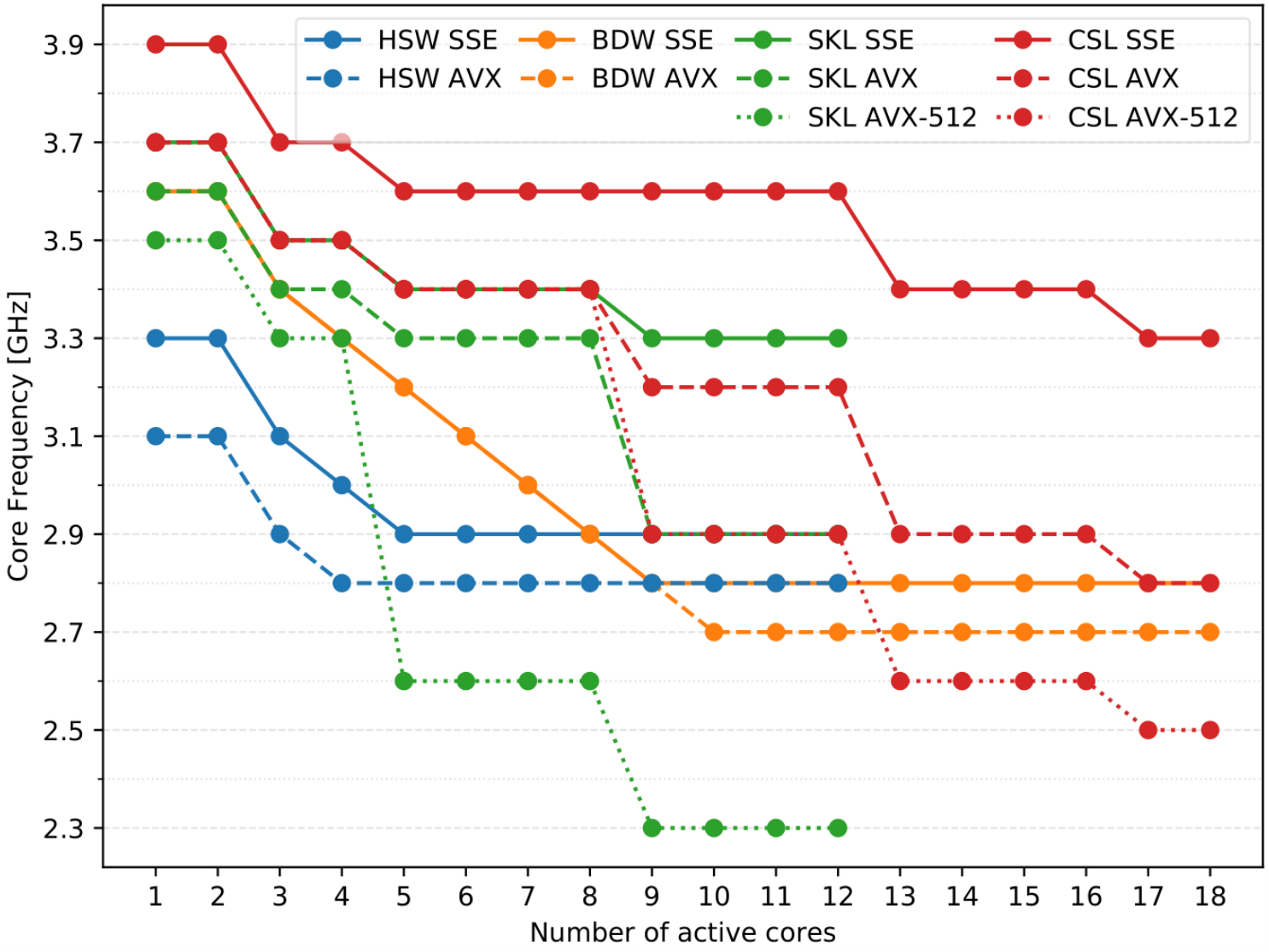


ARITHMETIC INTENSITY

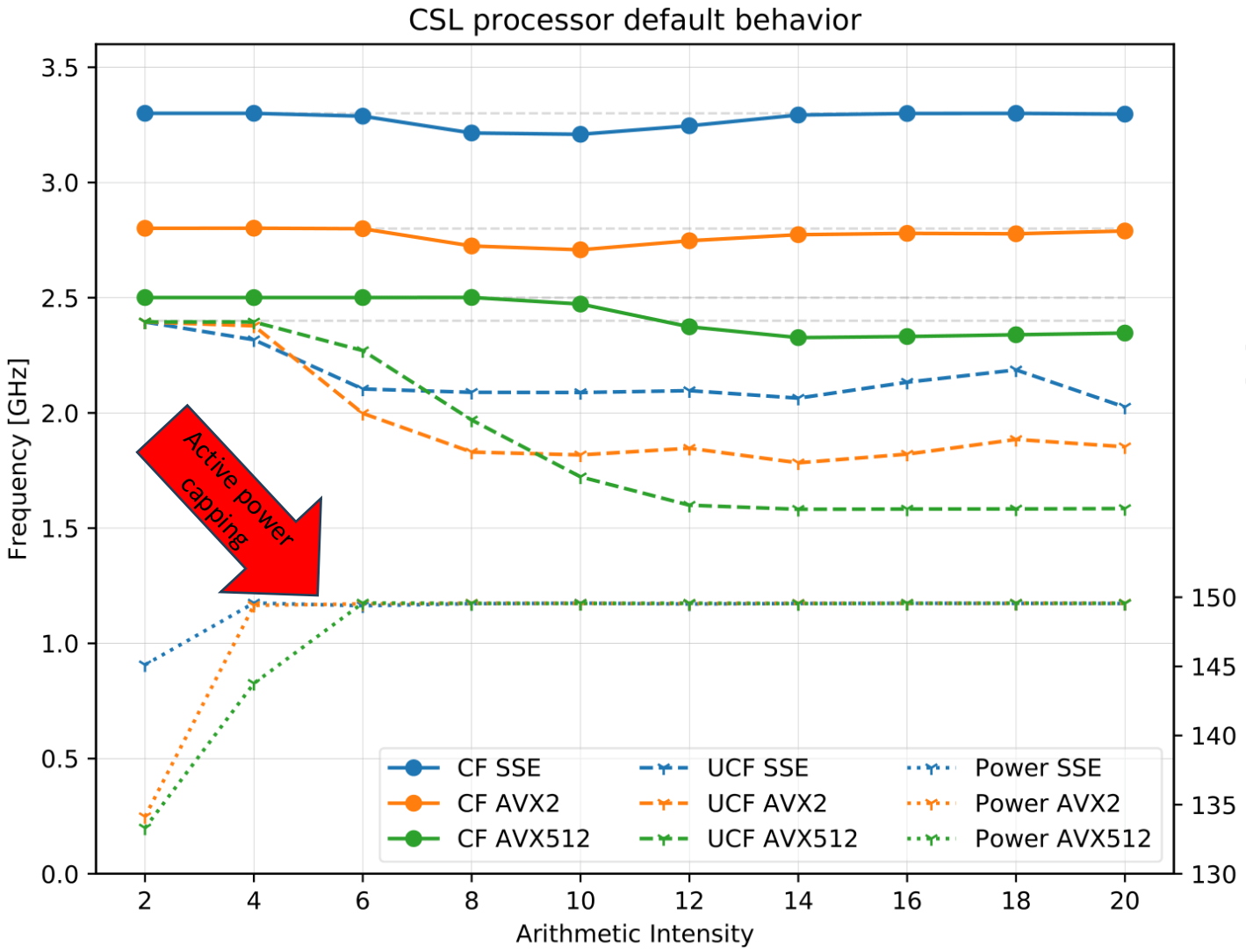
GEMV & TAN
Ratio from 9:1



MAXIMUM CORE FREQUENCY



CASCADELAKE CPU BEHAVIOR

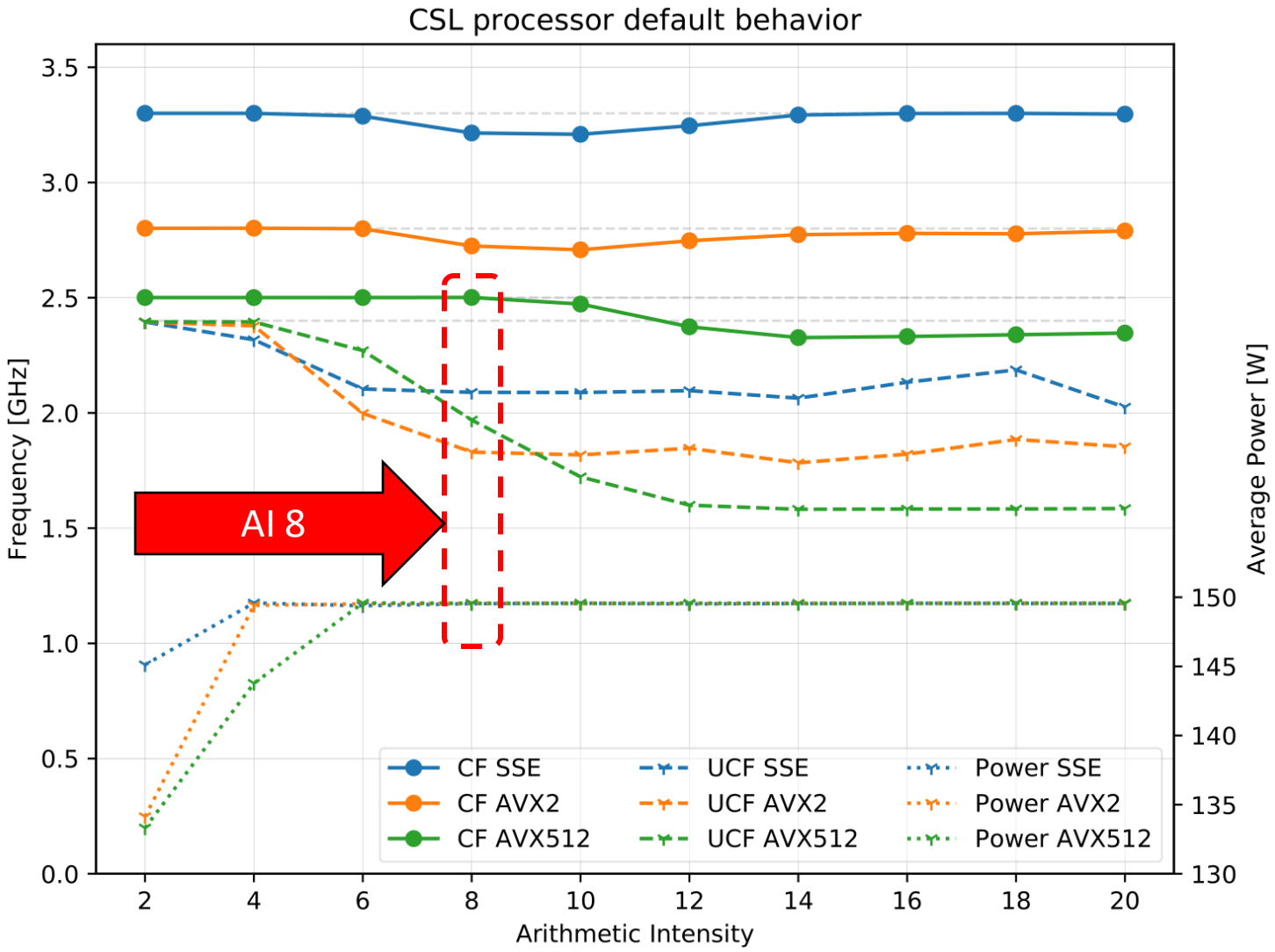


- Power capping system downscales CPU core and uncore frequencies to keep power consumption at the power limit
- Intel RAPL does not reflect the arithmetic intensity of the workload

Thermal Design Power

- Different e-e analysis results for a different power limit (default power limit = TDP)

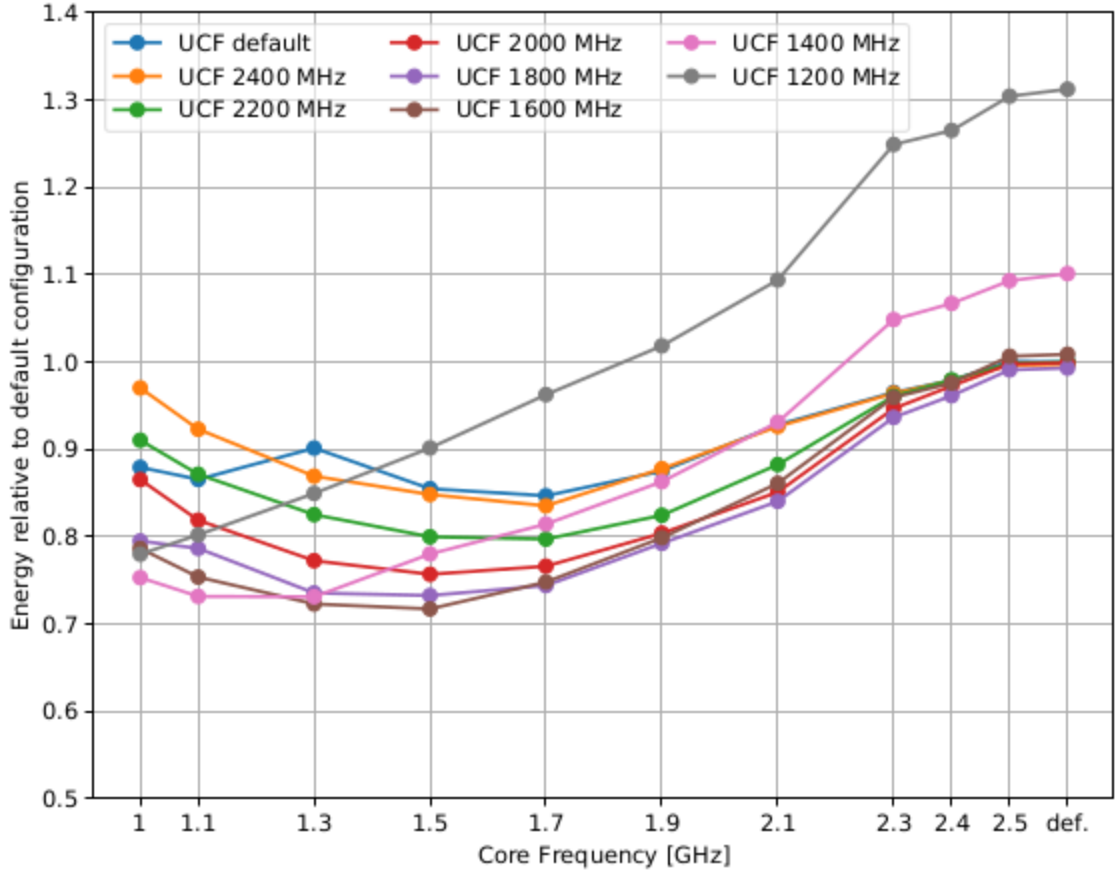
CASCADELAKE CPU BEHAVIOR



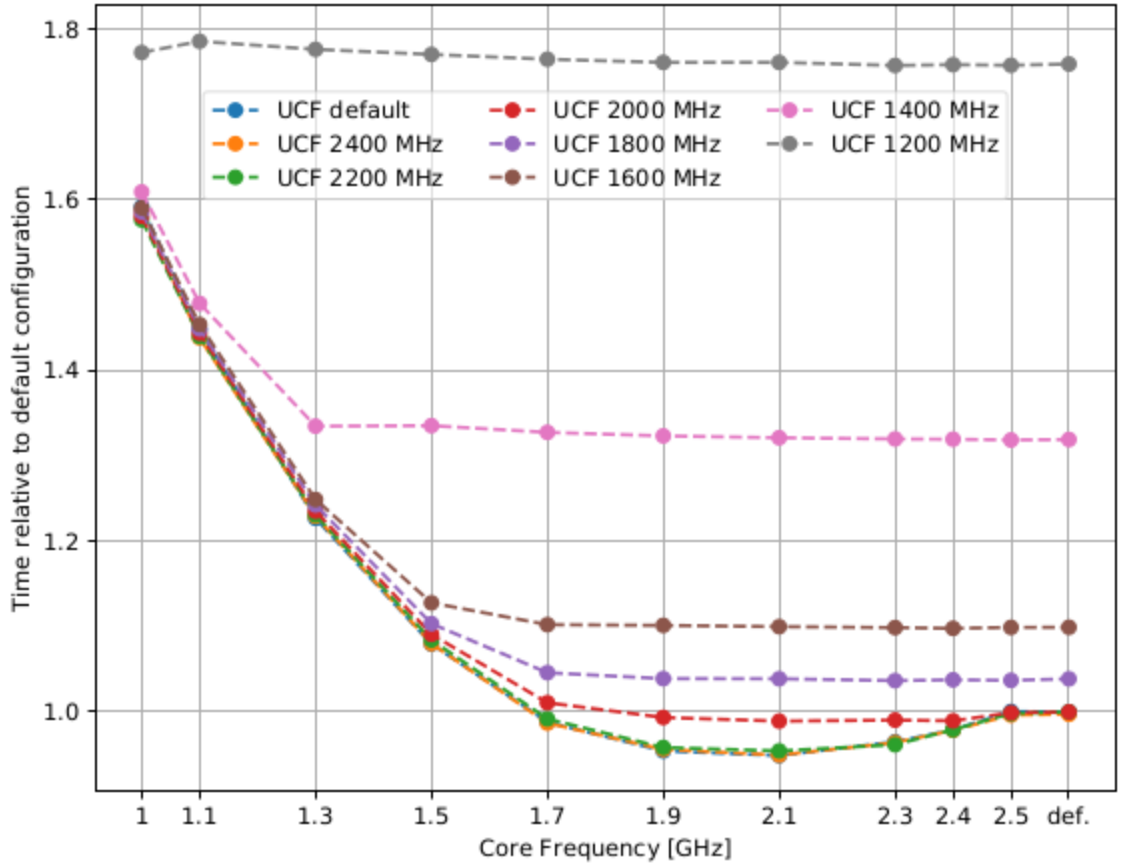
- AVX-512
- Arithmetic intensity 8
- RAPL keeps core frequency at its maximum while downscales uncore frequency

CPU FREQUENCIES SCALING

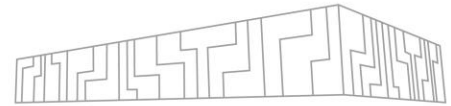
CPU energy



Time



- AVX-512, arithmetic intensity 8
- 1.9 GHz core frequency, 2.2 GHz uncore frequency
- => **18% CPU energy savings, 3.5% runtime improvement**
- => **15% node energy savings**



4] efficiency improvement

STATIC TUNING

Time

uncore [GHz] / core [GHz]	1.2	1.4	1.6	1.8	2	2.2	2.4
1.3	103.84	96.29	92.74	90.54	89.34	89.58	87.7
1.5	84.87	76.01	70.79	69.15	68.21	66.83	66.53
1.7	69.34	60.64	55.47	53.77	52.19	51.79	50.31
1.9	58.78	49.49	43.81	41.47	44.04	61.13	60.95
2.1	65.4	56.55	38.51	31.77	30.24	30.2	28.5
2.3	41.53	31.78	25.89	23.82	22.03	21.07	20.1
2.5	35.68	25.47	19.09	17.67	15.42	14.17	13.73
2.6	32.9	22.5	16.47	14.07	12.38	11.09	10.46
2.7	30.15	20.25	14.06	11.35	10.38	8.49	7.92
2.8	27.65	17.58	10.74	8.84	7	6.17	5.27
2.9	25.52	14.94	8.75	6.35	5.26	3.52	2.99
3	23.5	13.06	6.28	4.34	2.76	1.73	1.26
3.1	21.75	10.84	4.75	2.18	0.57	−0.55	−0.83
3.2	19.9	9.26	2.47	0.91	−1.2	−1.45	−1.6
3.3	18.49	7.83	1.02	−0.86	−1.64	−1.65	−1.56

Node energy (HDEEM)

uncore [GHz] / core [GHz]	1.2	1.4	1.6	1.8	2	2.2	2.4
1.3	9.27	7.86	8.48	9.52	12.78	17.55	21.76
1.5	3.25	0.77	0.08	1.32	4.45	7.73	12.26
1.7	−0.69	−3.28	−4.06	−3.09	−0.83	2.75	6.21
1.9	−3.29	−6.45	−7.76	−7.36	−2.46	12.82	17.32
2.1	−4.58	−8.1	−7.28	−9.93	−8	−5.2	−2.06
2.3	−5.86	−9.74	−11.49	−11.16	−9.55	−7.01	−4.11
2.5	−4.85	−9.3	−11.56	−10.84	−9.74	−7.62	−4.51
2.6	−4.69	−9.38	−11.42	−11.49	−10.09	−8.04	−5.16
2.7	−3.97	−8.39	−10.69	−11.09	−9.12	−7.62	−4.75
2.8	−3.14	−7.85	−10.74	−10.52	−9.34	−7.01	−4.43
2.9	−1.14	−6.46	−8.89	−9.17	−7.35	−5.87	−2.97
3	1.02	−4.35	−7.43	−7.3	−5.94	−3.81	−1.08
3.1	3.53	−2.43	−4.93	−5.44	−4.16	−2.43	−0.27
3.2	6.15	0.24	−3.04	−2.64	−2.24	−0.53	0.11
3.3	9.63	3.38	−0.46	−0.78	−0.3	0.16	0.46

STATIC TUNING

various performance degradation limits

various power monitoring systems

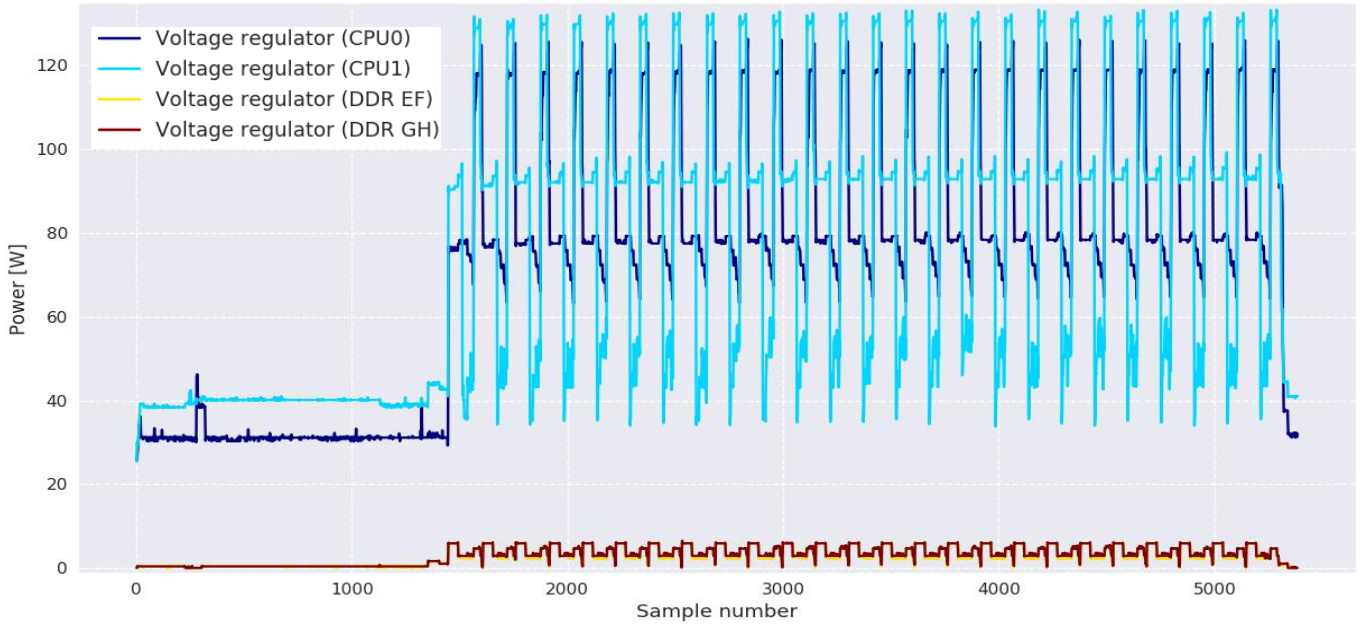
	default		-2 % limit	-5 % limit	-10 % limit	unlimited
Runtime [s]	257.07	**Performance penalty [%]**	2.18	4.34	8.84	25.9
Energy [kJ]		**Energy savings [%]**				
HDEEM	881.28	**HDEEM**	5.44	7.30	10.52	11.49
RAPL	668.07	**RAPL**	6.85	9.44	13.92	18.42
Eff. [MFLOPs/W]		**Eff. [MFLOPs/W]**				
HDEEM	10.40	**HDEEM**	11.00	11.22	11.62	11.75
RAPL	13.72	**RAPL**	14.73	15.15	15.94	16.81
		CPU configuration				
		Core freq. [GHz]	3.1	3.0	2.8	2.3
		Uncore freq. [GHz]	1.8	1.8	1.8	1.6

HW configuration tuning

READEX METHODOLOGY

READEX
Runtime Exploitation of Application Dynamism for Energy-efficient eXascale computing

- H2020 READEX, 2015-2018
- Complex parallel application has different requirements during execution, so it gives a possibility to be dynamically tuned for energy savings without performance penalty.



- Goal was to create a tools-aided methodology for automatic tuning of parallel applications. Dynamically adjust system parameters to actual resource requirements.

TECHNISCHE UNIVERSITÄT DRESDEN

NTNU

IT4Innovations national supercomputing center

NUI Galway OÉ Gaillimh

intel

gns

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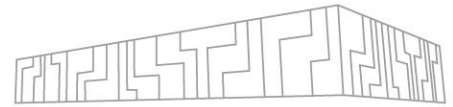
DYNAMICITY EXPLOITATION



```
void lbm(void) {
  // init application parameters
  // init mass
  for (int iter = 0; iter < NITER; iter++) { // phase region
    update_hallos();  // insignificant region

    propagate();      // significant region

    collide();        // significant region
  }
  // post-processing
  // store output
  // terminate application
}
```

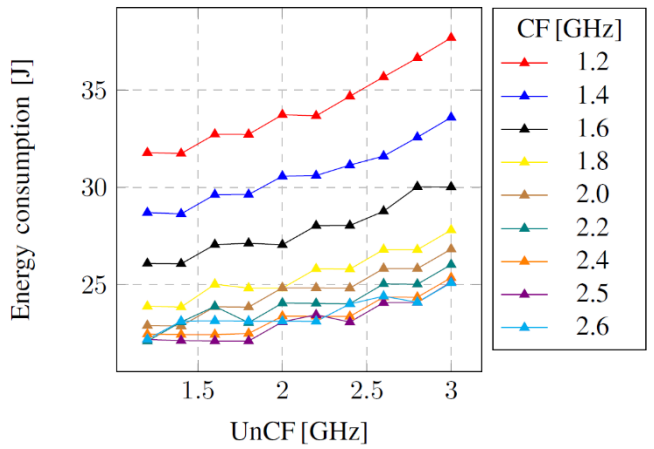
memory bound region
CPU core freq = 1.6 GHz

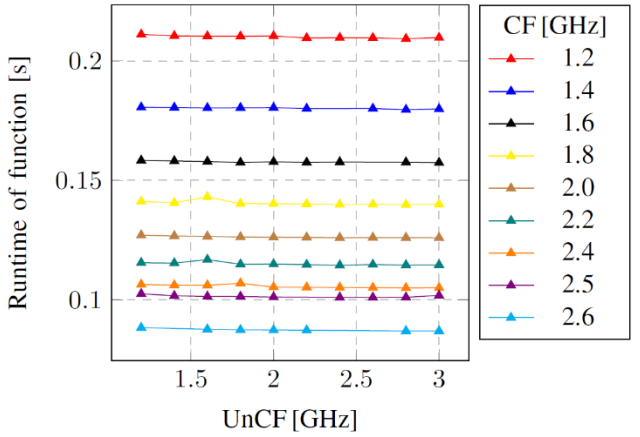
compute bound region
CPU core freq = 2.5 GHz

LATTICE BOLTZMANN BENCHMARK

Collide

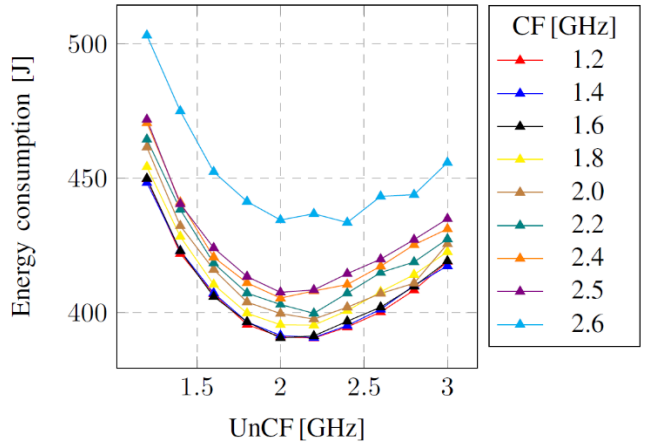
compute bound

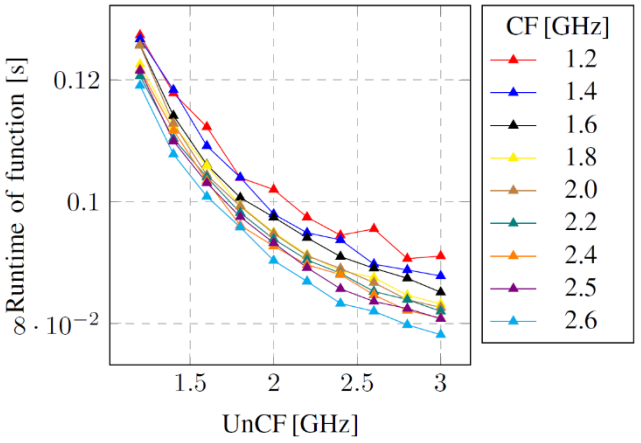




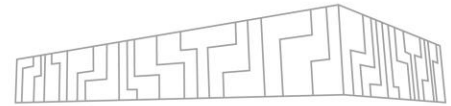
Propagate

memory bound





Default		Static savings		Dynamic savings	
time	energy	time	energy	time	energy
24 s	5.7 kJ	-11.6 %	7.8 %	**-1.5 %**	**19.8 %**



5] MERIC runtime system

MERIC RUNTIME SYSTEM

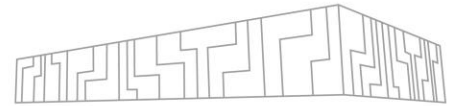
- MERIC runtime system provides dynamic application tuning
  - Lightweight & easy to install & easy to use
  - C/C++ API, Fortran module, Python module
  - MPI, OpenMP, CUDA parallelization
- Performance and power aware
- Support for a wide range of architectures
  - x86
  - IBM OpenPOWER
  - ARM
  - Nvidia/AMD GPUs
- Power monitoring systems
  - Intel/AMD RAPL
  - OCC
  - ATOS HDEEM
  - NVML
  - ROCm
  - HWMON *(Nvidia Grace, GraceHopper, AMD RAPL)*
  - A64FX

- **Application energy consumption measurement**
- **Application dynamism & energy efficiency behavior analysis**
- **Dynamic HW power knobs tuning for energy savings**
- **HW & SW power management co-design**

CPU freq, GPU freq,
memory freq, power limit,
#active CPU cores

https://code.it4i.cz/energy-efficiency/meric-suite/meric

SIMPLE ENERGY MEASUREMENT



mericStatic

```
$ mericStatic -e RAPL -- <application> [application parameters]
$ mericStatic –eval
```

OR

```
$ srun --overlap ./mericStatic -e RAPL,NVML -- ./application [application parameters] &
$ srun --overlap ./mericStatic -- stop
$ mericStatic –eval
```

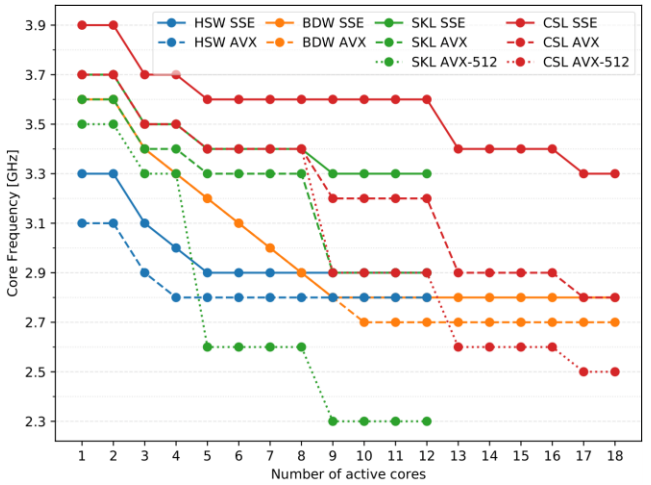
```
[nct00018@gs23r3b72 meric]$ mericStatic -e RAPL -- sleep 5
measurement_id : 36276003
[nct00018@gs23r3b72 meric]$ mericStatic -- eval
measurement_id : 36276003
Max Runtime [s] = 5.004
RAPL Energy consumption [J] = 1445.562


Total Energy consumption [J] = 1445.562
Total Energy consumption [Wh] = 0.402
```

ENERGY MEASUREMENT

		JUPITER	LUMI	Leonardo	MN5	Vega	MeluXina	Karolina	Discoverer	Deucalion
AMD CPU	intel_rapl kernel module									
	amd_energy kernel module									
	msr_safe kernel module									
	perf									
Intel CPU	intel_rapl kernel module									
	msr_safe kernel module									
	perf									
A64FX	perf									
Nvidia GPU	NVML									
AMD GPU	ROCm									
GraceHopper	HWMON									

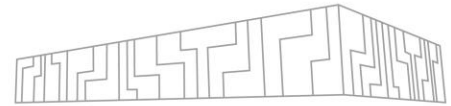
SYSTEM INFO 1/2

Detailed information about available hardware



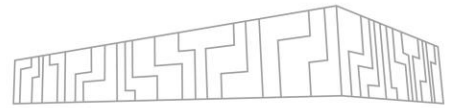

```
$ systemInfo
# SYSTEM INFORMATION
    CPU name:           Intel(R) Xeon(R) Gold 6240 CPU @ 2.60GHz
    Sockets per node: 2
    Cores per socket: 18
    Threads per core: 1

# CPU FREQUENCIES
    Current scaling driver:      acpi-cpufreq
    Current scaling governor:    performance
    Available governors:         conservative ondemand userspace powersave performance
    Hardware controlled P-State: disabled
    Turbo CPU core frequencies:  3900000(2) 3700000(4) 3600000(8) 3600000(12) 3400000(16) 3300000(18)
kHz(#cores)
    Nominal CPU core frequency:  2600000 kHz
    Min CPU core frequency:      1000000 kHz
    Available CPU core frequencies:  2601000 2600000 2500000 2400000 2300000 2100000 2000000 1900000
1800000 1700000 1600000 1500000 1300000 1200000 1100000 1000000 kHz
    Max CPU uncore frequency:    2400000 kHz
    Min CPU uncore frequency:    1200000 kHz
...
```

SYSTEM INFO 2/2



```
...
# CPU POWER LIMITS
    RAPL time window unit: 976.562 us
    PKG max power limit:   376 W
    PKG min power limit:   69 W
    DRAM max power limit:  26.75 W
    DRAM min power limit:  4.5 W

# DEFAULT CPU POWER LIMITS
    PKG power limit #1: enabled + clamping disabled
    PKG power limit #1: 150 W
    PKG time window #1: 1 s
    PKG power limit #2: enabled + clamping enabled
    PKG power limit #2: 180 W
    PKG time window #2: 0.000976562 s
    DRAM power limit:   disabled + clamping disabled
    DRAM power limit:   0 W
    DRAM time window:   0.000976562 s

# AVAILABLE POWER MONITORING SYSTEMS
    RAPL
    HDEEM
```

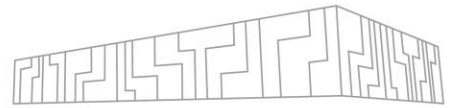
ANALYSIS WITHOUT HW TUNING



- Performance (FLOPs) evaluation
- Energy consumption
  - node energy consumption
  - CPU+GPU energy performance counters
- Energy efficiency
- Carbon footprint
- Vectorization ratio
- CPU (core/uncore) frequency
- Memory bandwidth
- Computation intensity
- Power consumption timeline

- Various hardware platforms, various power monitoring systems

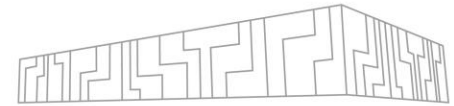
ADDITIONAL ANALYSIS STEPS



- Application instrumentation
- Default HW configuration execution
- Multiple executions of the application in a variety of HW configurations
- Evaluation of the trace files

- Various power limits

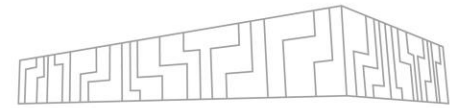
LIBRARY API



Instrumentation

```
int main(int argc, char **argv)
{
MERIC_Init();
MERIC_MeasureStart("A");
do_work_A(2);
MERIC_MeasureStop("A");

MERIC_MeasureStart("B");
do_work_B(5);
MERIC_MeasureStop("B");

MERIC_Close();
return 0;
}
```

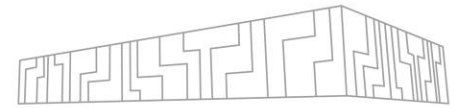
APPLICATION ANALYSIS



- Manual exhaustive state-space-search (old-fashioned way)
- MERICwrapper will identify the optimal configuration from the data

```
export MERIC_OUTPUT_DIR="MERICdir"
export MERIC_MEASUREMENT=RAPL
for CF in 30 25 20
do
   for UCF in 24 22 20
   do
      export MERIC_FREQUENCY=$CF"00MHz"
      export MERIC_UNCORE_FREQUENCY=$UCF"00MHz"
      LD_PRELOAD=libmpi_sbi.so mpirun ./a_sbi.out --app_param
   done
done
$MERIC_PATH/bin/wrapper -a $MERIC_OUTPUT_DIR -m RAPL
```

APPLICATION TUNING



- Automatized state-space-search using MERICwrapper

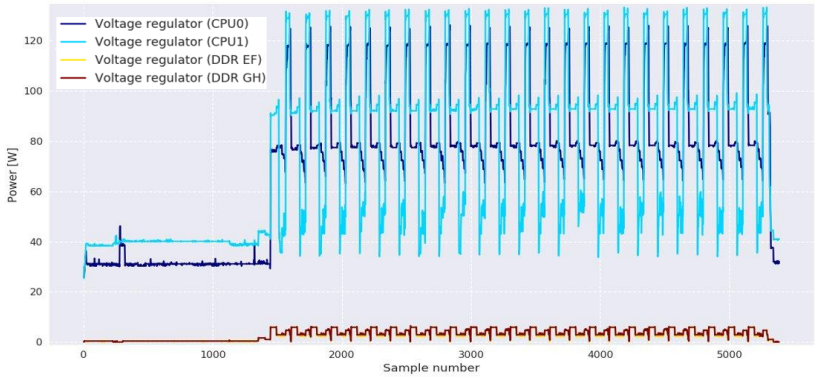
```
$ $MERIC_PATH/bin/wrapper -s config.json -- ./a_meric.out
```

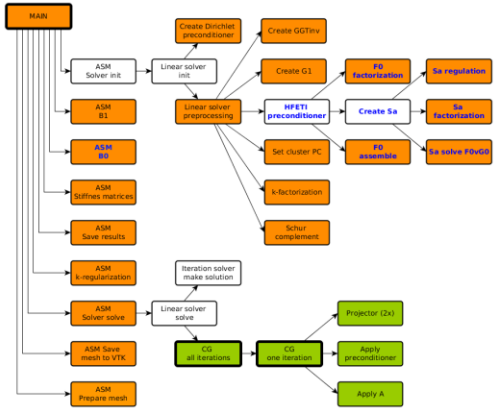
```
$ $MERIC_PATH/bin/wrapper -s config.json -- \
LD_PRELOAD=libmpi_meric.so mpirun ./a_meric.out --app_param
```

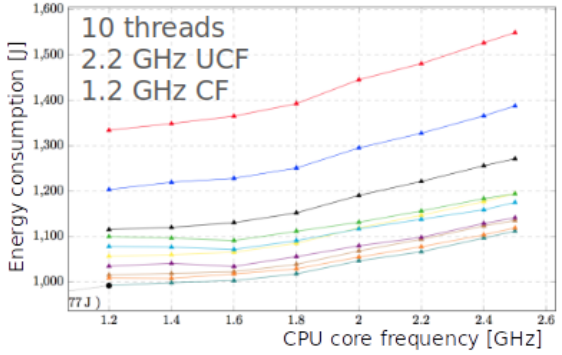
- Configuration file specifies what
  - HW configurations to test
  - State-space-search algorithm
  - Used energy measurement mode
  - MERIC output configuration

RADAR VISUALIZER

- *Visualisation of applicatin behavior in various configuration*
- Tables
  - Overall application evaluation
  - Summary of nested regions' behavior
  - Each region behavior description
- Heatmaps
- Plots
- Samples timeline
- Trace timeline
- Call-path graph







	Default settings	Default values	Best static configuration	Static savings	Dynamic savings
Runtime of function [s], Job info - rapl	3.0GHz, 2.5GHz	1.97s	3.0GHz, 2.5GHz	0.00s (0.00%)	0.015s of 1.97s (0.76%)
Energy summary, COUNTERS - rapl:	3.0GHz, 2.5GHz	800.37	2.4GHz, 2.5GHz	19.70 (2.46%)	46.52 of 780.67 (5.96%)
Run-time change with the energy optimal settings	+0.14s (107.04 % of default time)				

Uncore freq [GHz] / Core freq [GHz]	1.2	1.4	1.6	1.8	2.0	2.2	2.4	2.6	2.8	3.0
1.2	13,200.02	12,717.1	12,621.78	12,410.62	12,380.68	12,507.38	12,774.16	13,108.6	13,604.2	14,040.8
1.4	13,161.9	12,597.78	12,125.18	12,065.52	12,074.54	12,173.36	12,312.24	12,802.26	13,095.84	13,450.8
1.6	13,320.66	12,640.76	12,256.22	12,033.62	11,966.36	11,992.7	12,372.04	12,579.22	13,126.44	13,370.24
1.8	13,878.04	13,082.66	12,700.92	12,457.08	12,373.86	12,445.98	12,574.6	12,831.82	13,081.62	13,296.04
2	14,218.58	13,327.12	12,902.62	12,544.82	12,456.82	12,494.8	12,680.32	13,038.86	13,207.38	13,474.8
2.2	14,625.62	13,849.58	13,240.14	12,851	12,760.98	12,802.24	12,993.44	13,260.38	13,497.6	13,767.62
2.4	15,083.2	14,412.62	13,568.68	13,447.18	12,973.38	13,238.6	13,332.7	13,388.7	13,777.68	14,030.66
2.5	15,554.96	14,465.2	13,991	13,553.84	13,300.24	13,354.46	13,472.36	14,179.16	14,083.06	14,231.3

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