Enabling Millimeter Computing

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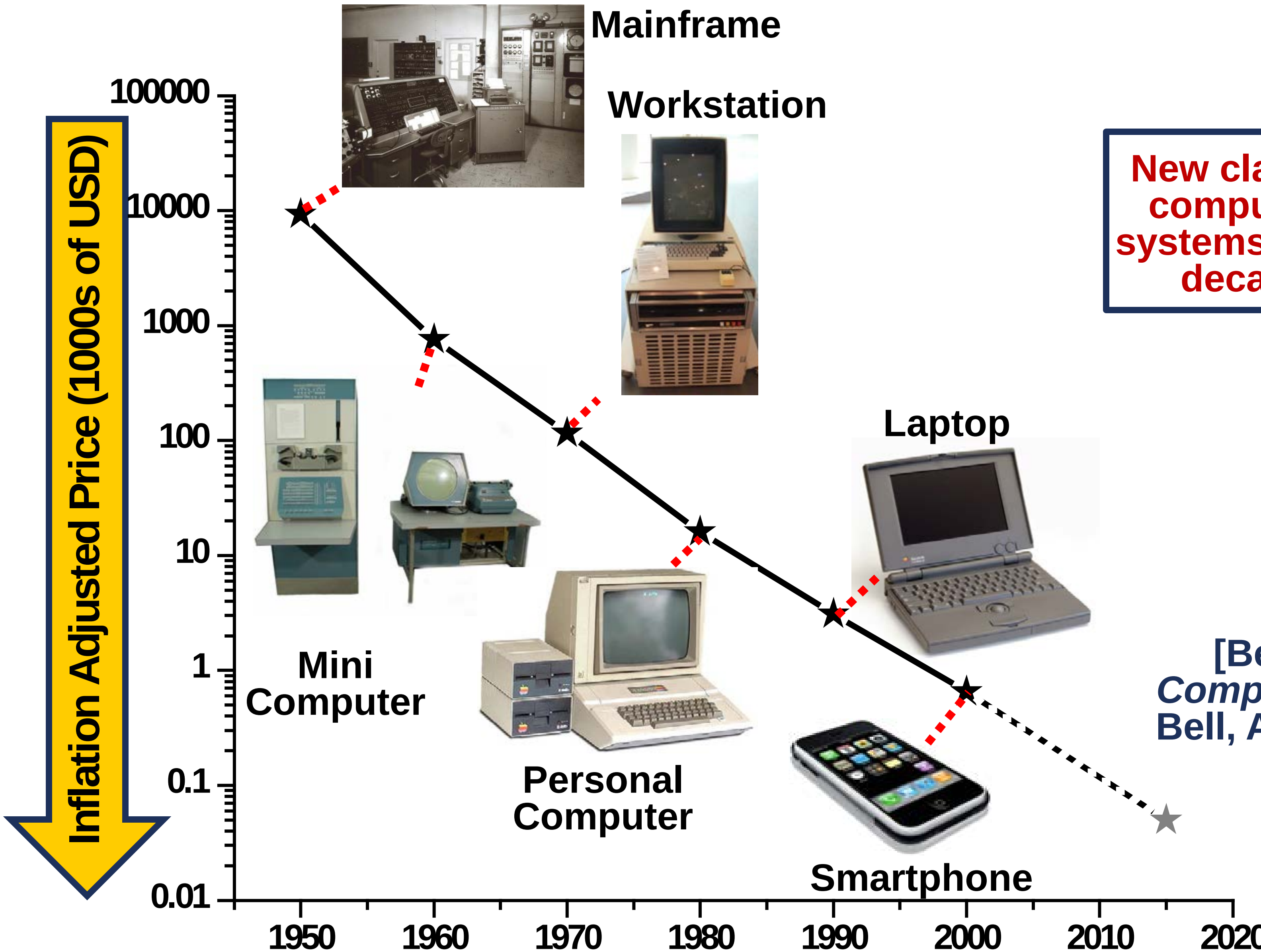
Joint work with David Blaauw

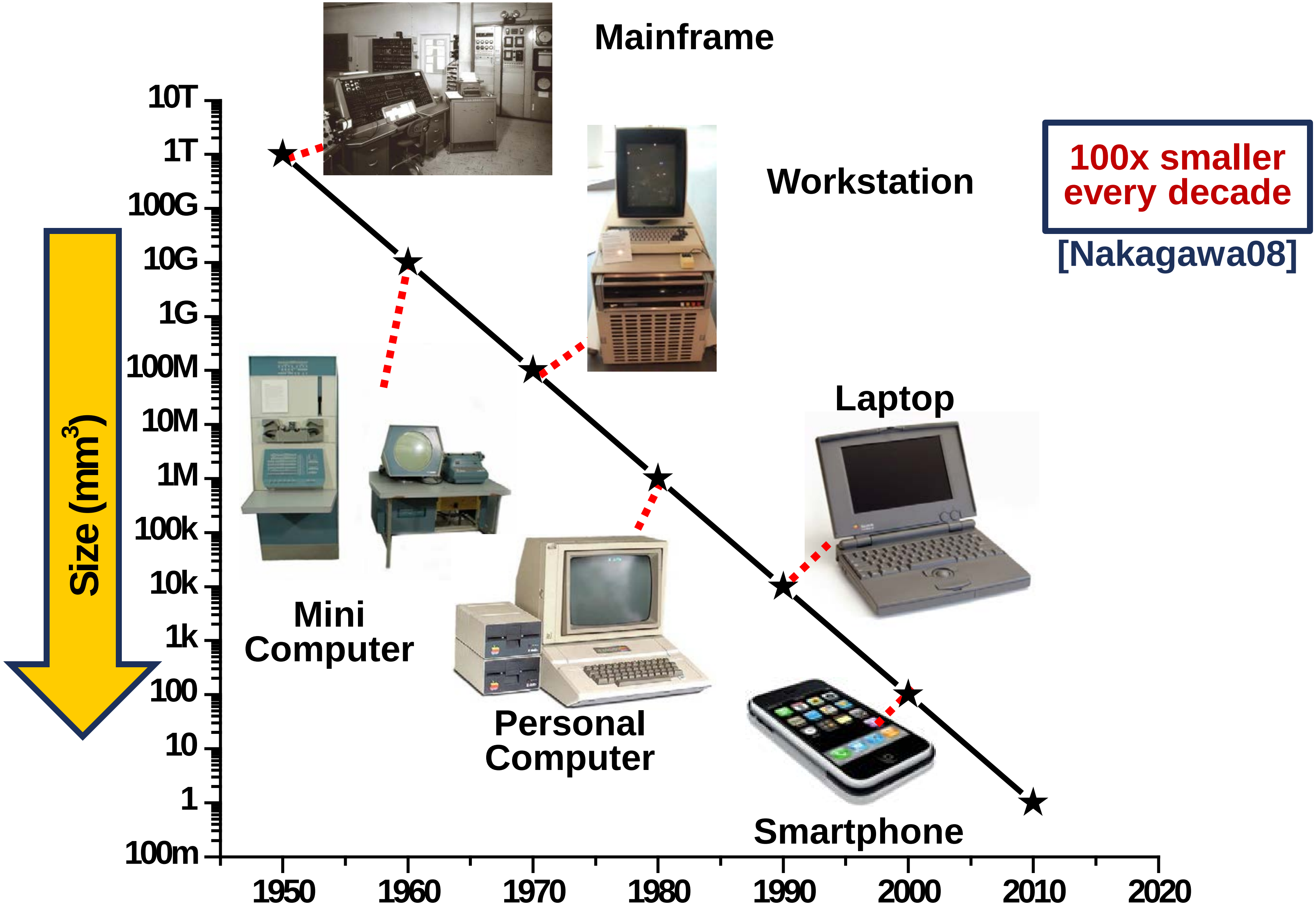
Bell's Law



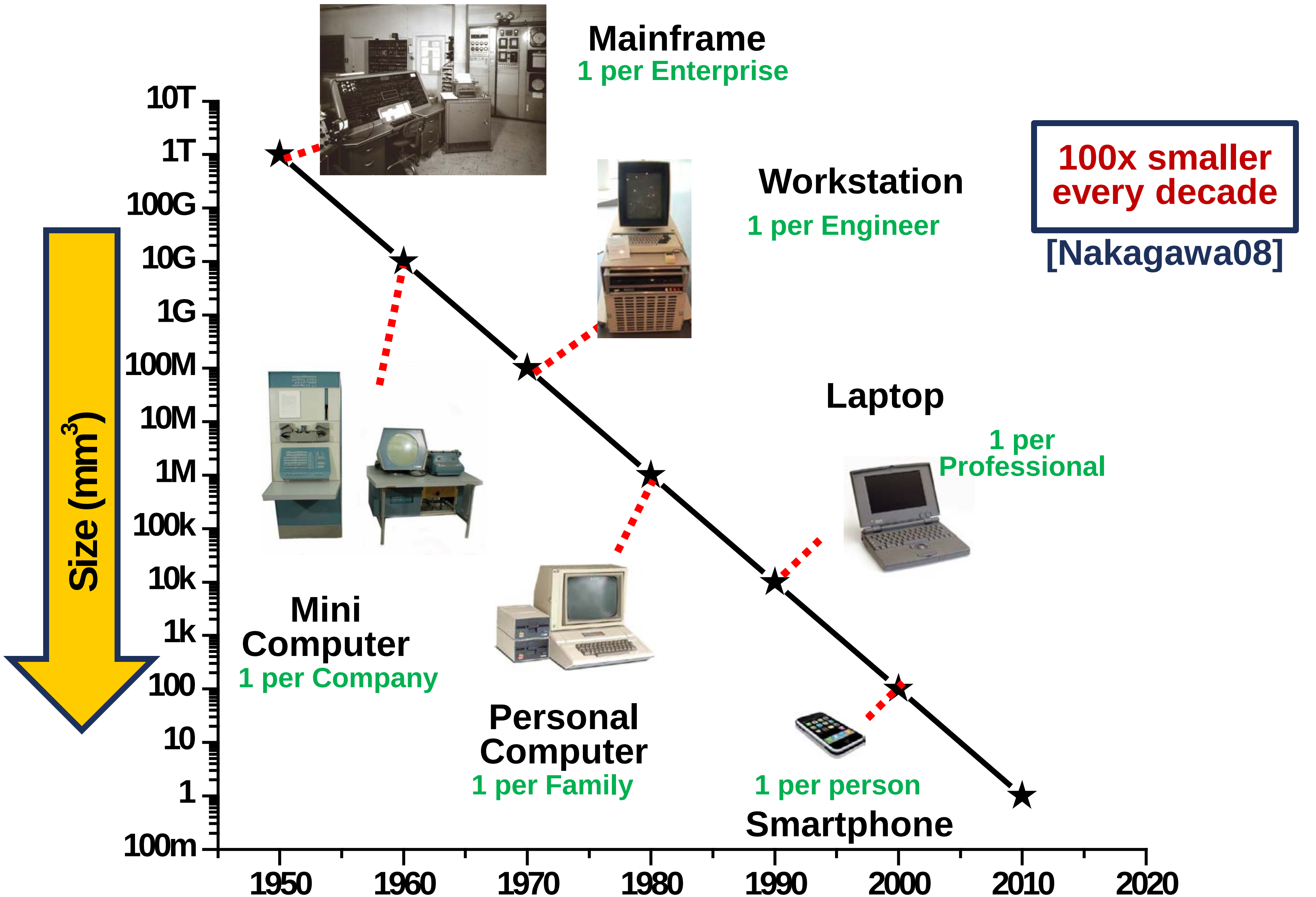
New class of computing systems every decade

[Bell et al. *Computer, 1971*, Bell, ACM, 2008]

Bell's Law – Corollary



Bell's Law – Production Volume



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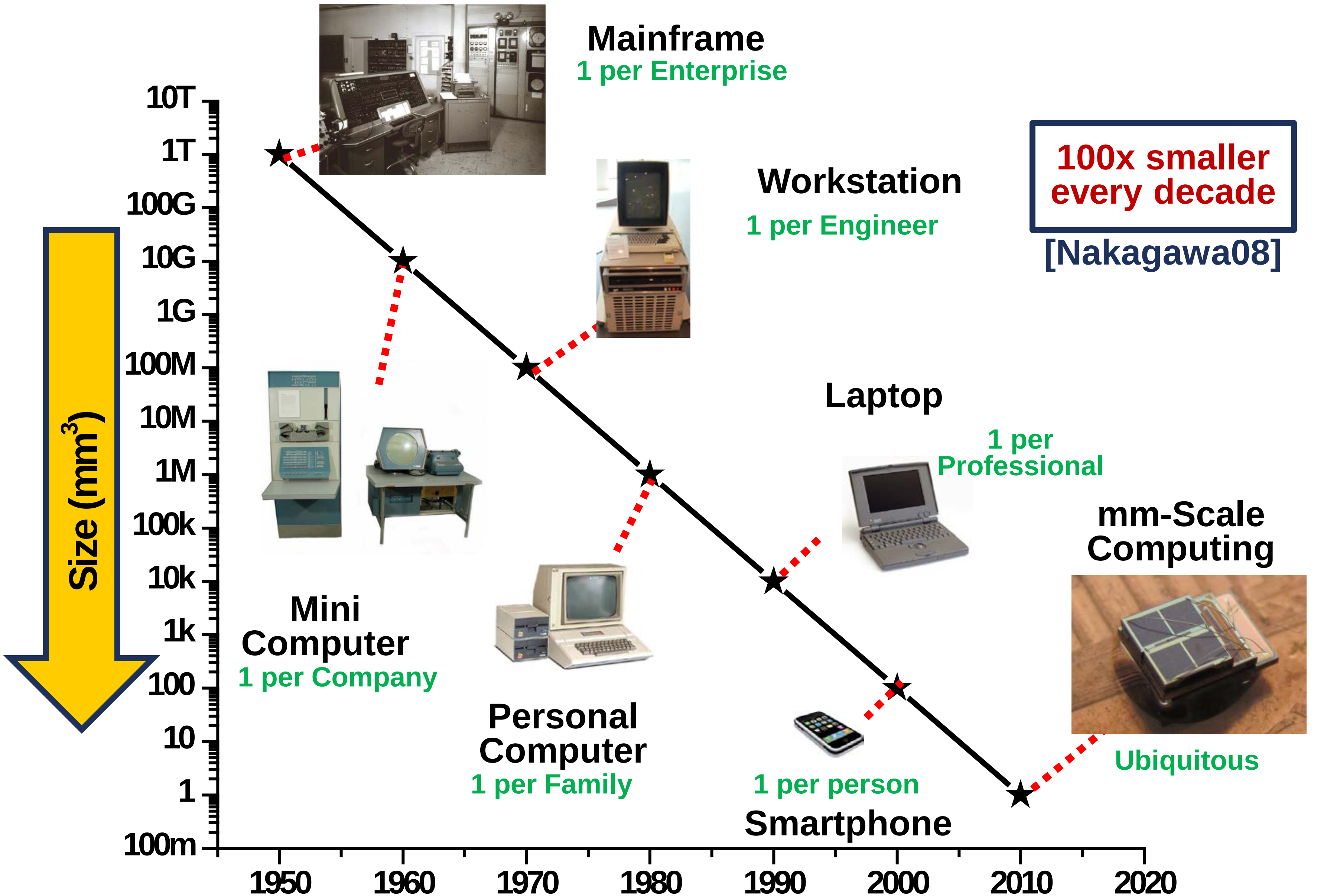
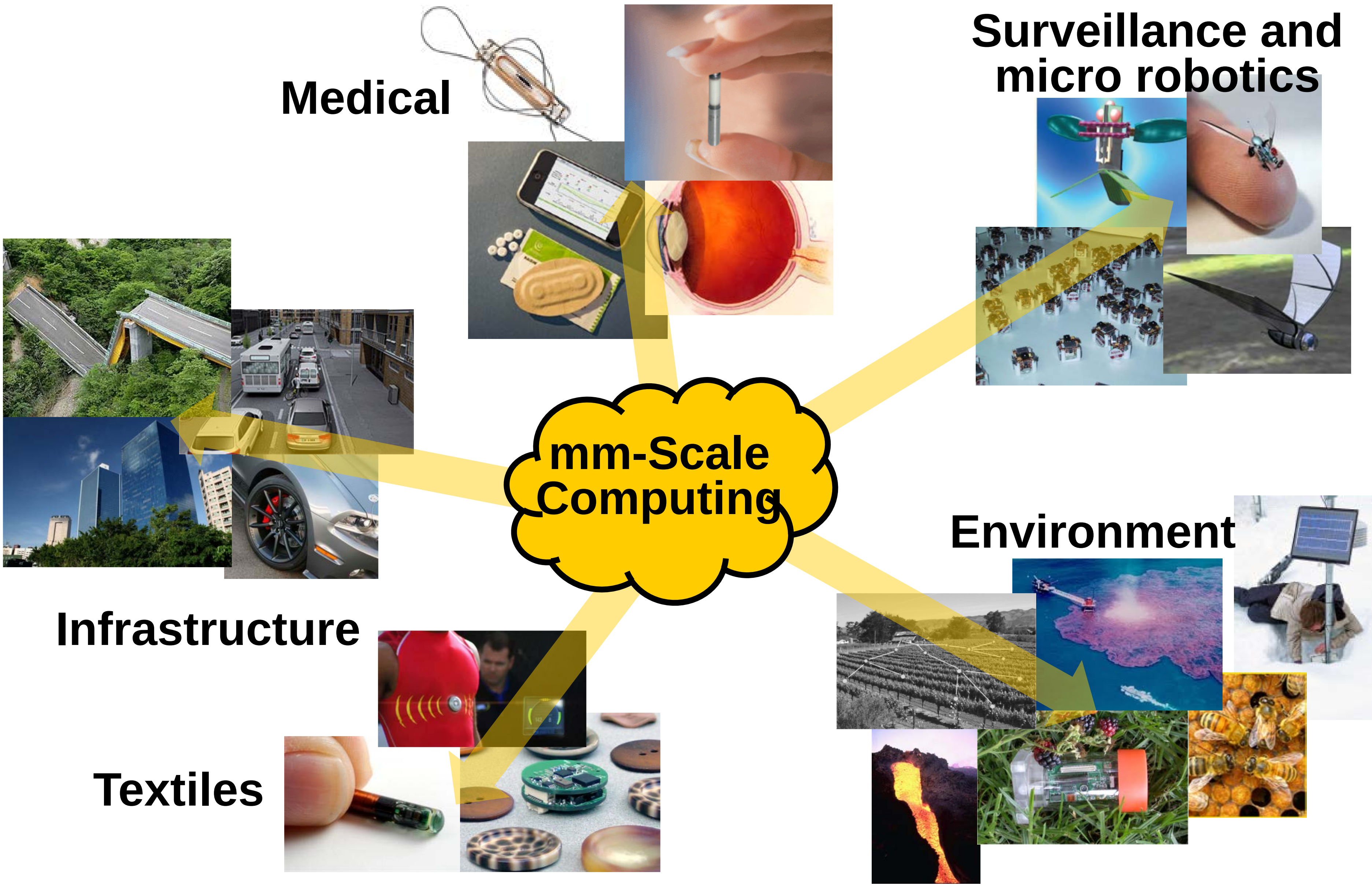
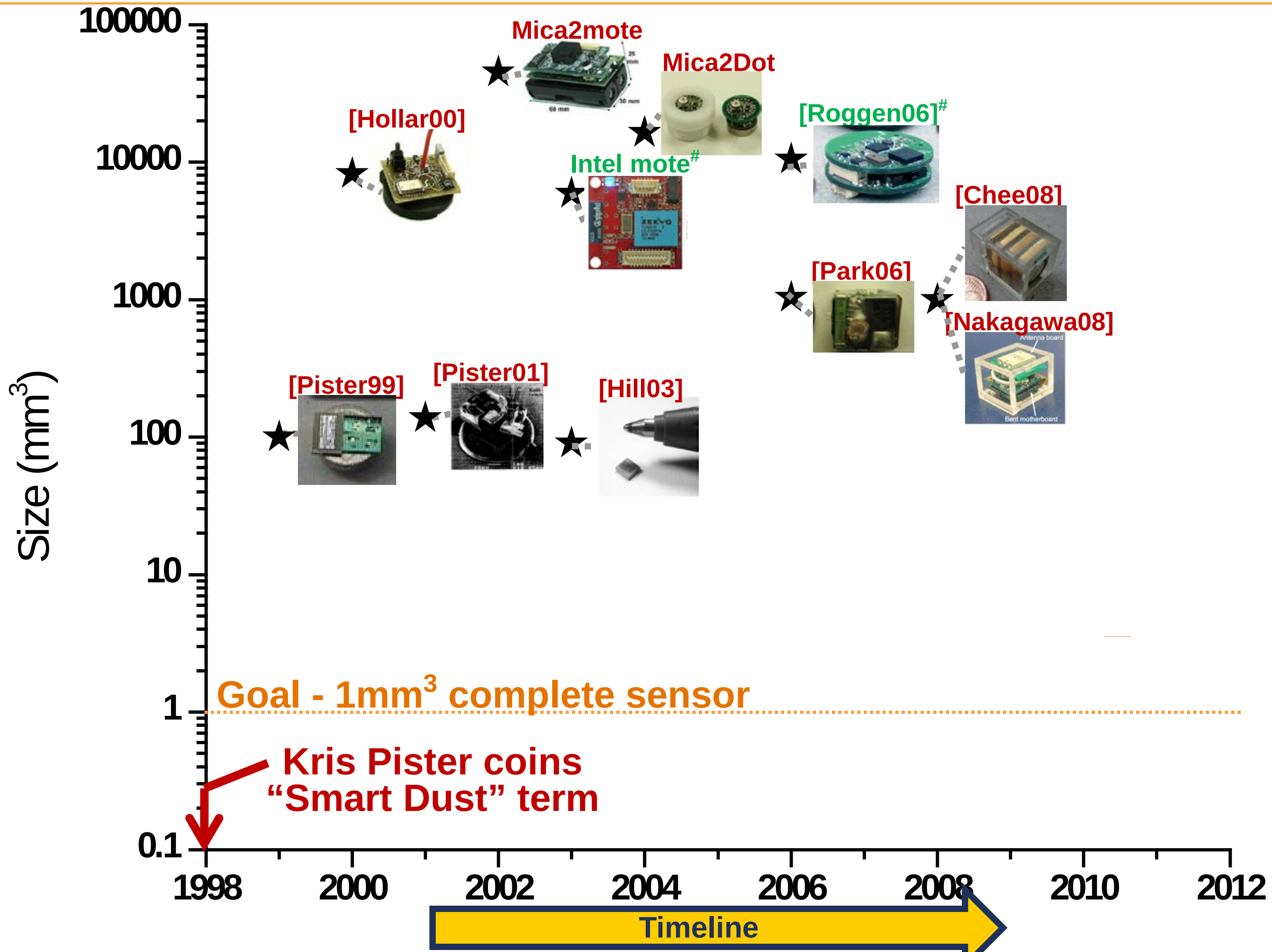


mm-Computing: Application Areas



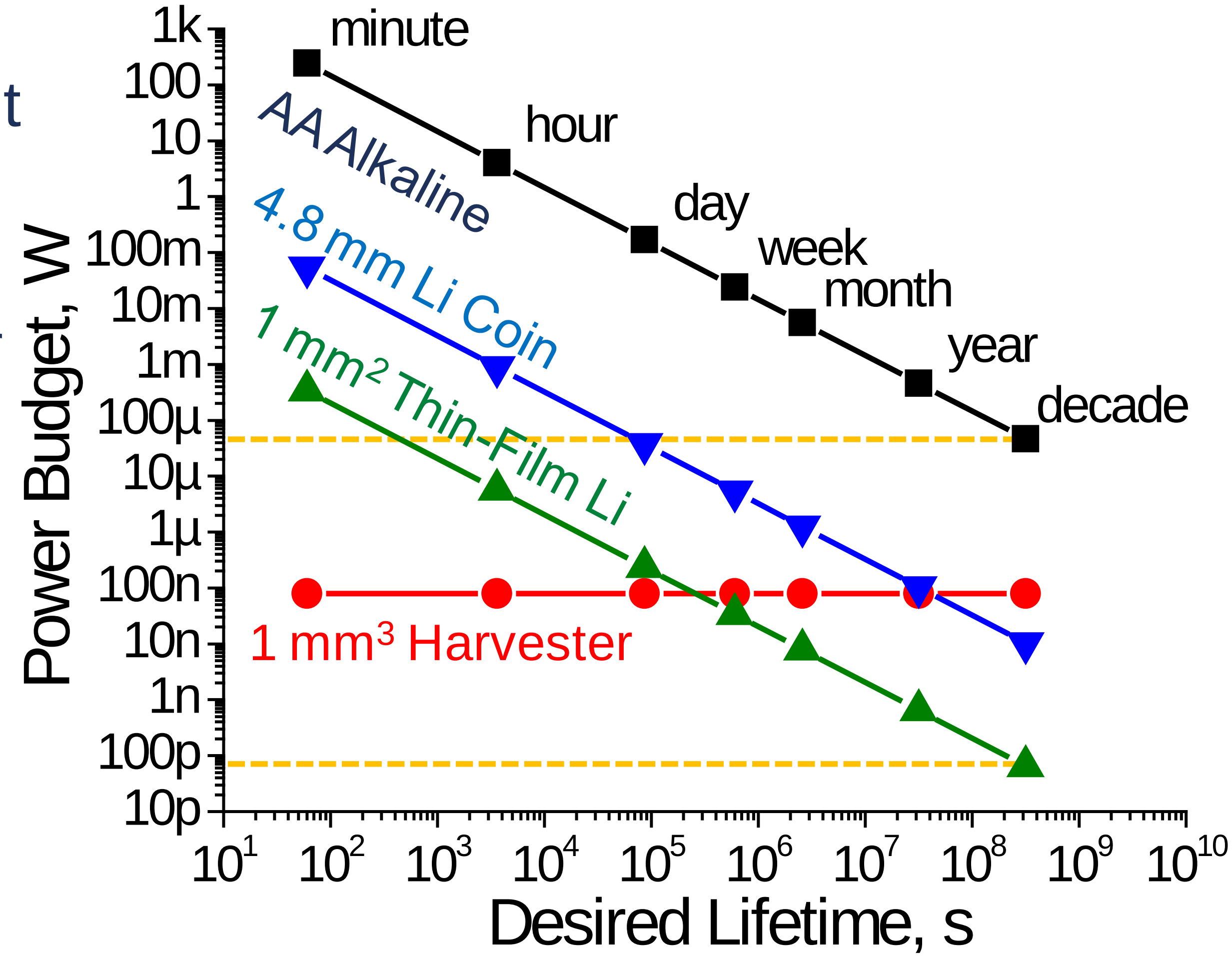
Where Are We?



100000
10000
1000
100
10
1
0.1
Size (mm3)
Mica2mote
Mica2Dot
[Hollar00]
[Roggen06]#
Intel mote#
[Chee08]
[Park06]
[Nakagawa08]
[Pister99]
[Pister01]
[Hill03]
Goal - 1mm3 complete sensor
Kris Pister coins
"Smart Dust" term
1998
2000
2002
2004
2006
2008
2010
2012
Timeline

Why aren't we further along?

- Long device lifetime vs. small form factor
- The 3 most important things in miniaturization:
  - Power, Power, Power
- Circuits just are not there yet

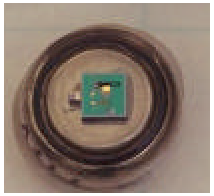


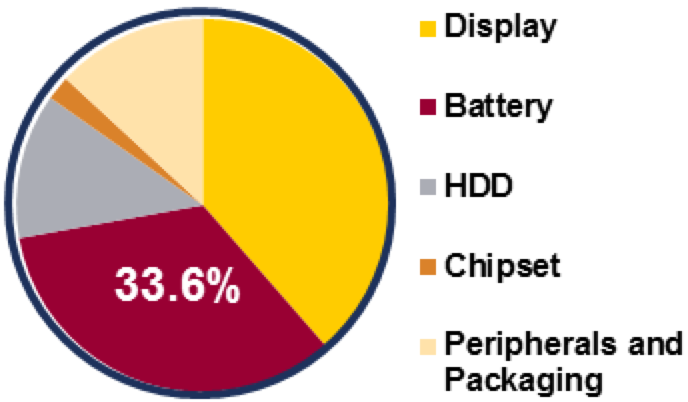
Reducing Size

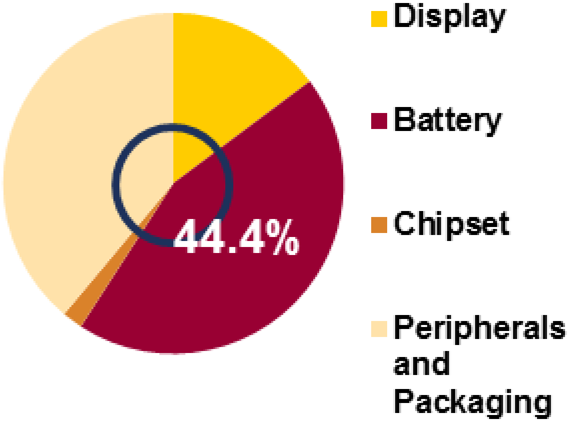
Laptop – 24,500cm^3

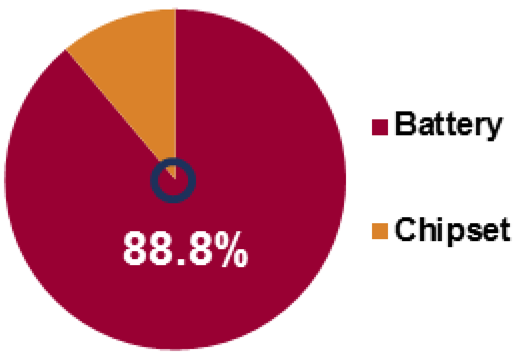
Smartphone – 63cm^3

Micro-mote – 63mm^3 [Pister2000]





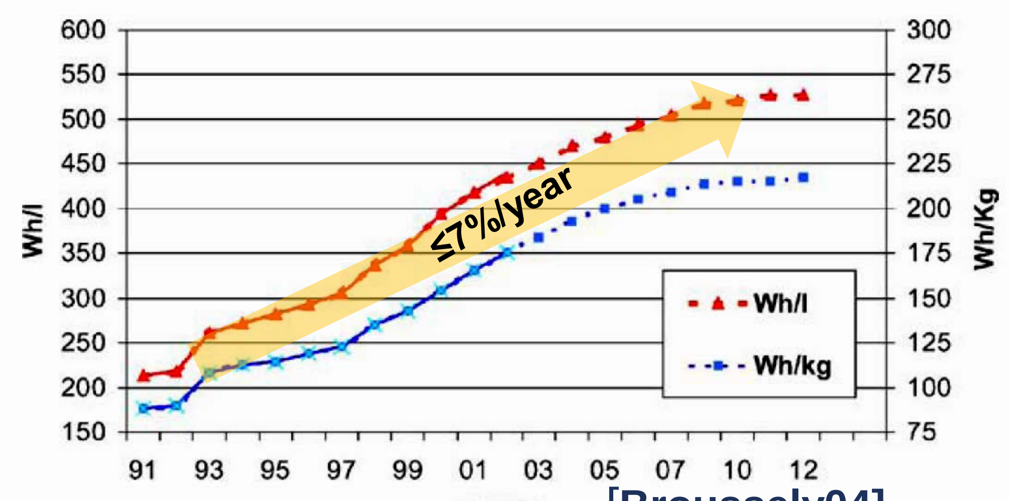




- Solving the battery size bottleneck:
  - Improve battery capacity
  - Add harvesting
  - Reduce power draw

Battery Trends

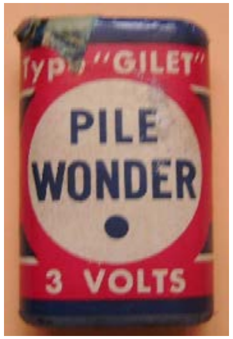
- New battery chemistries are rare
  - Li-ion ≤7%/year expected improvement (energy density)
- Energy capacity limited by safety and cost



[Broussely04]

1896 Columbia Dry Cell Zinc Carbon Battery

1956 Eveready Alkaline Battery ~72mAh



1960 Zinc Carbon Battery 1100 mAh

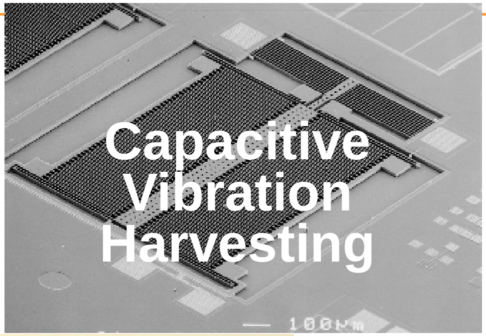
1961 Nickel CadmiumBattery 1100 mAh

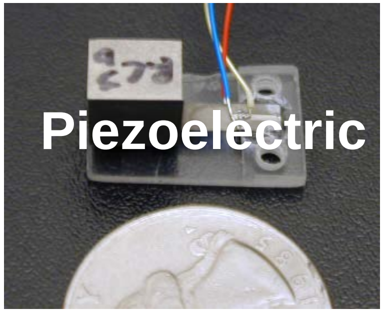
1989 Lithium Iron Disulfide Battery 3100 mAh

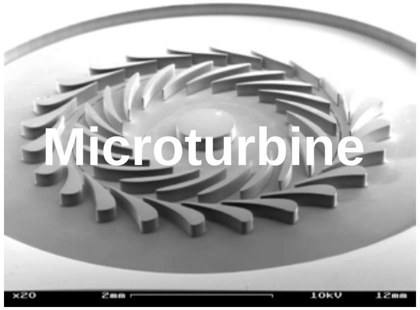
1992 Rechargeable Alkaline Battery 2000 mAh

2005 LSD NiMH Battery 2300 mAh

Energy Harvesting

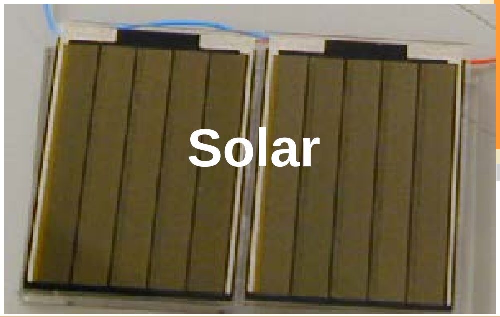






	μW/cm^3
Photovoltaic (outside)	15,000#
Air flow	380
Vibration	200
Temperature	40#
Pressure Var.	17
Photovoltaic (inside)	10#

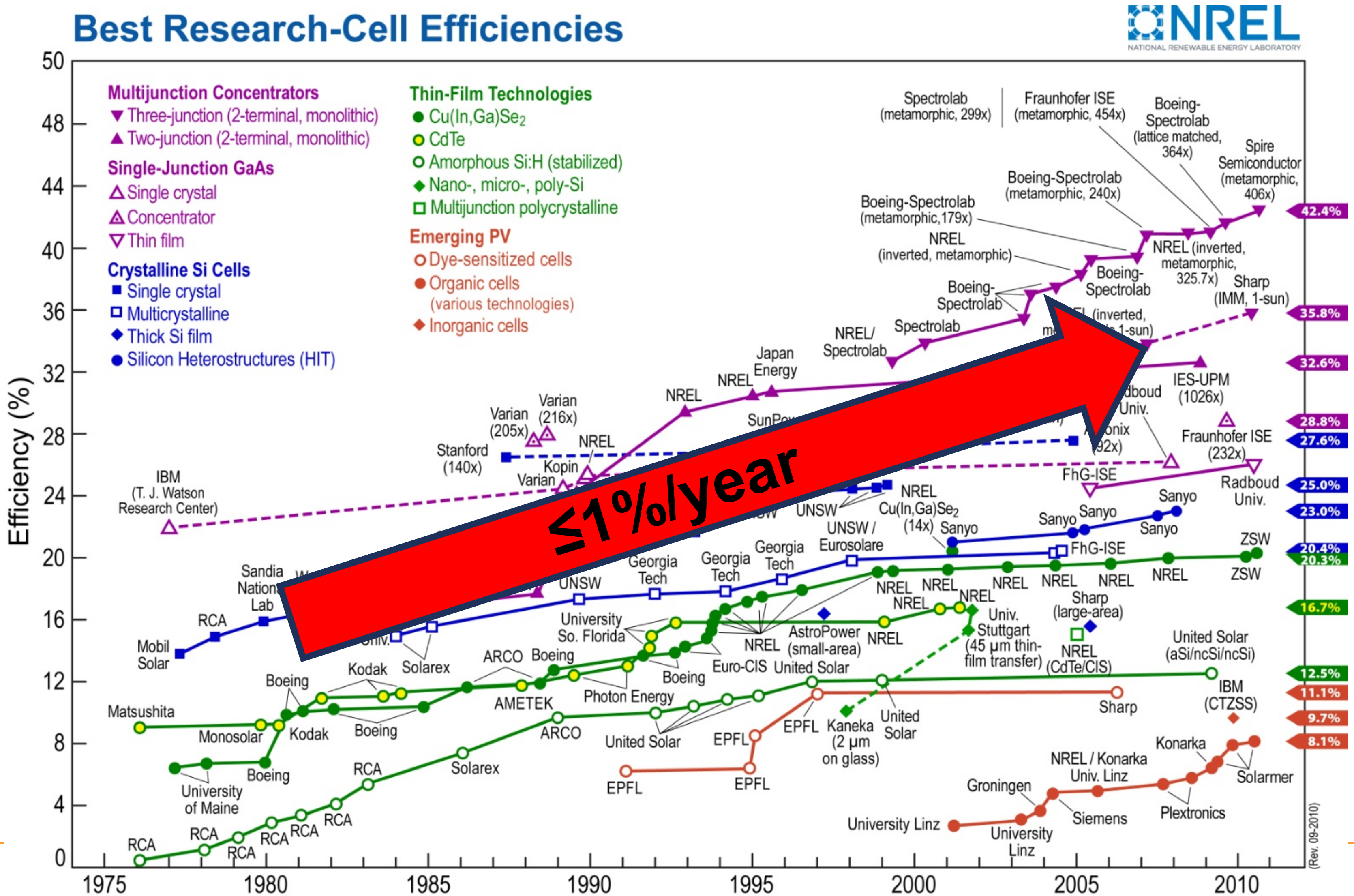
fundamental metric is μW/cm^2



[Courtesy: Jan Rabaey, S. Roundy]

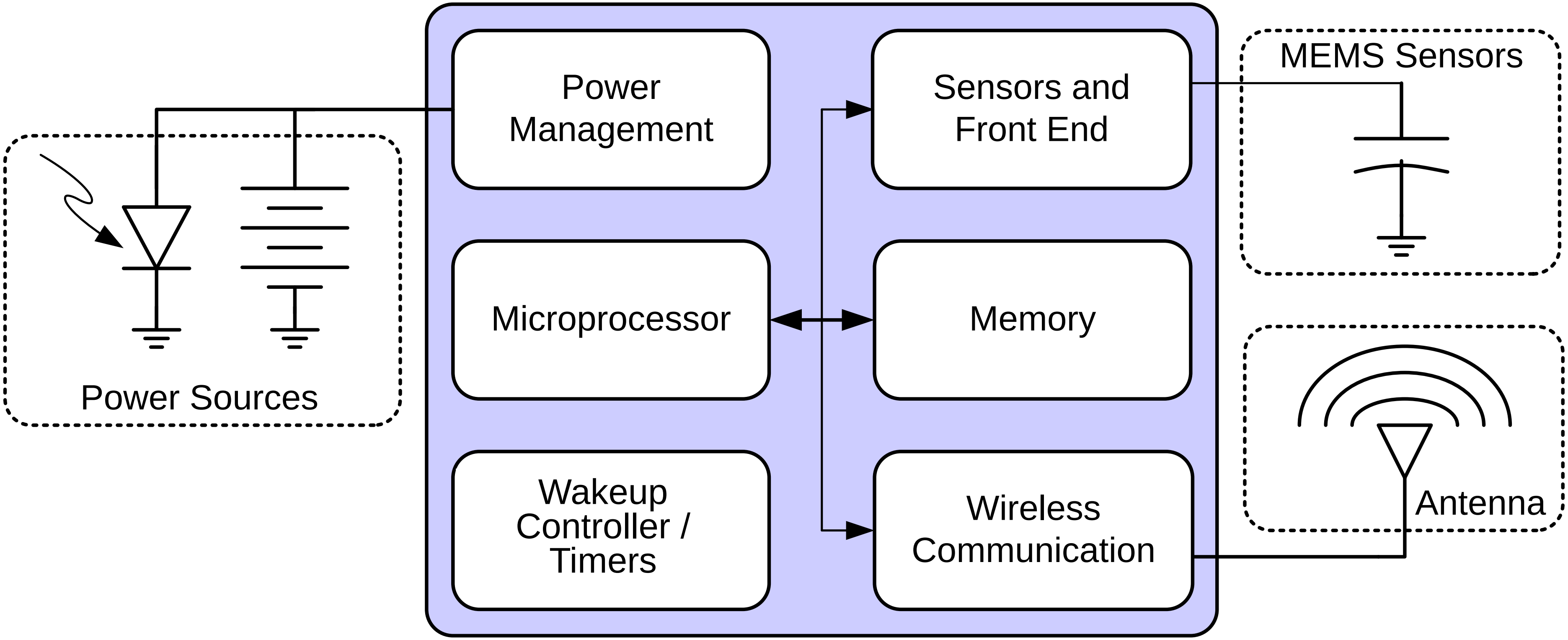
Harvesting Improvements Limited

- Energy harvester efficiency gains are modest
- Fundamentally limited by harvesting source



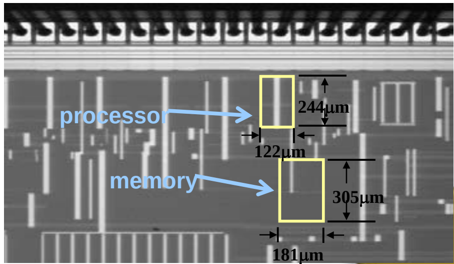
mm^3: How Do We Get There

- Microsystem functions include sensing, processing, storage, and transmission
- All components must be re-examined to fit within power envelope defined by power sources and power management

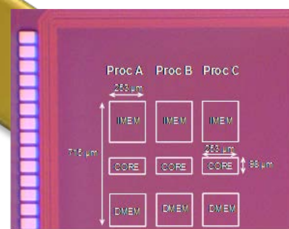


Past Michigan Sensor Designs

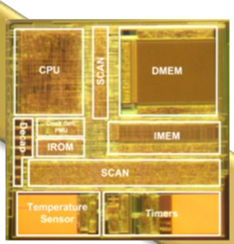
Subliminal 1 Design (2006)
-0.13 μm CMOS
-investigate Vmin
-2.60 μW/MHz



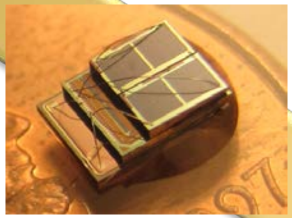
Phoenix 1 Design (2008)
- 0.18 μm CMOS
- Minimize sleep current
- 2.8 μW/MHz / 30pW sleep power



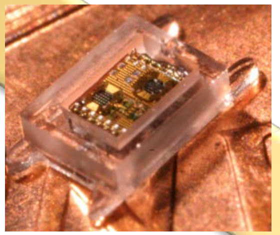
Subliminal 2 Design (2007)
- 0.13 μm CMOS
- Study variability effects
- 3.5 μW/MHz



Phoenix 2 Design (2010)
- 0.18 μm CMOS
- Commercial ARM M3 Core
- Solar harvesting / PMU
-28 μW/MHz



IOPM (2011)
- 0.18 μm CMOS
- MEMS/CDC
- Solar / PMU
- Wireless comm



mm^3: How Do We Get There

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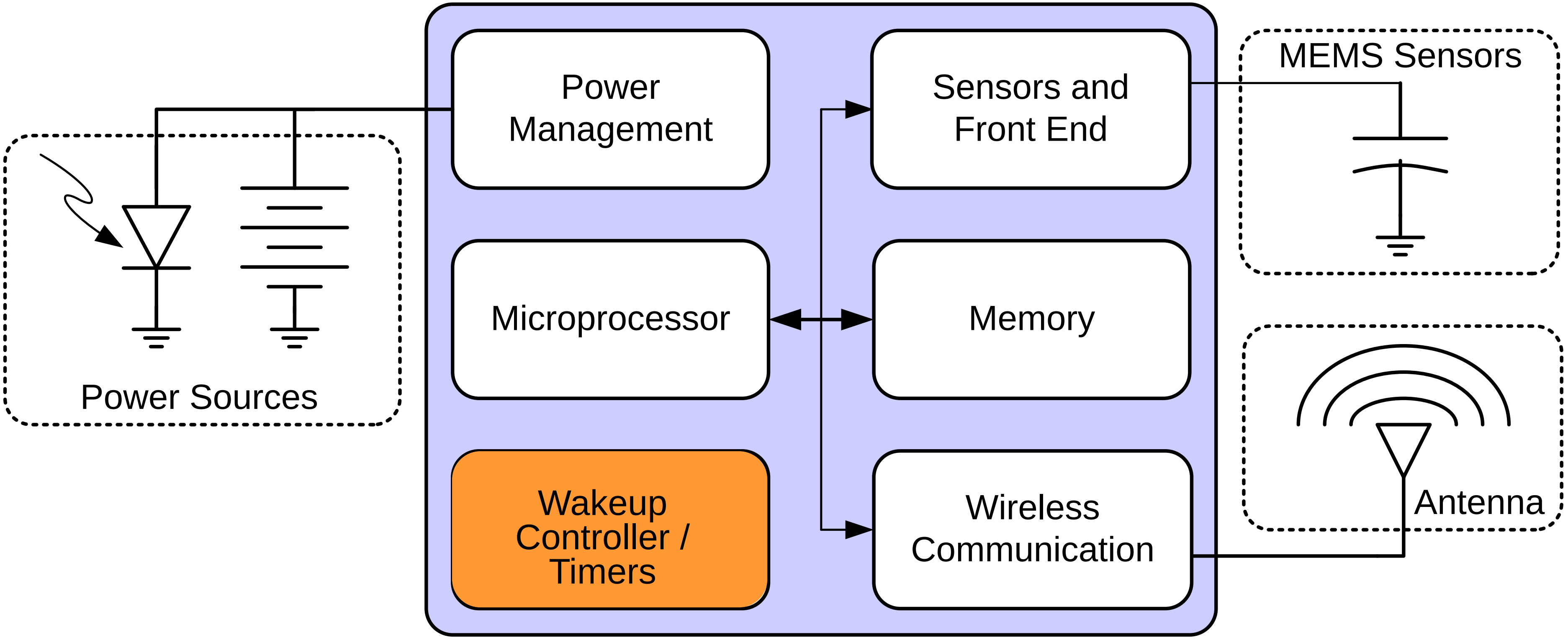
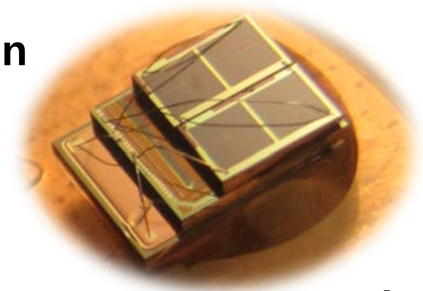
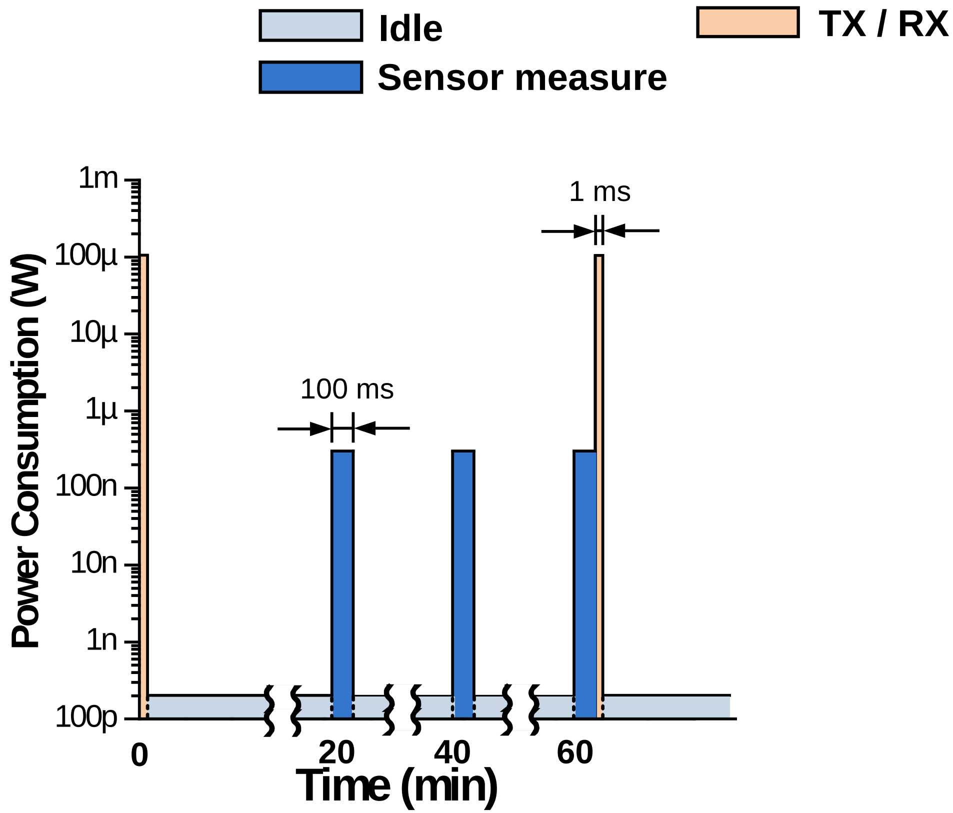


Why Timers Are So Important

Base Station



Sensor Node

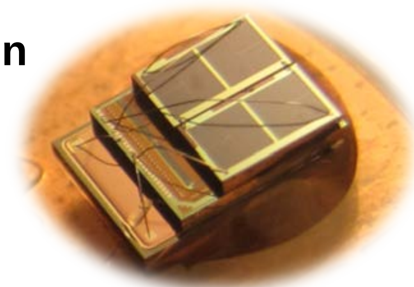


Power consumptions in various modes of ULP sensor

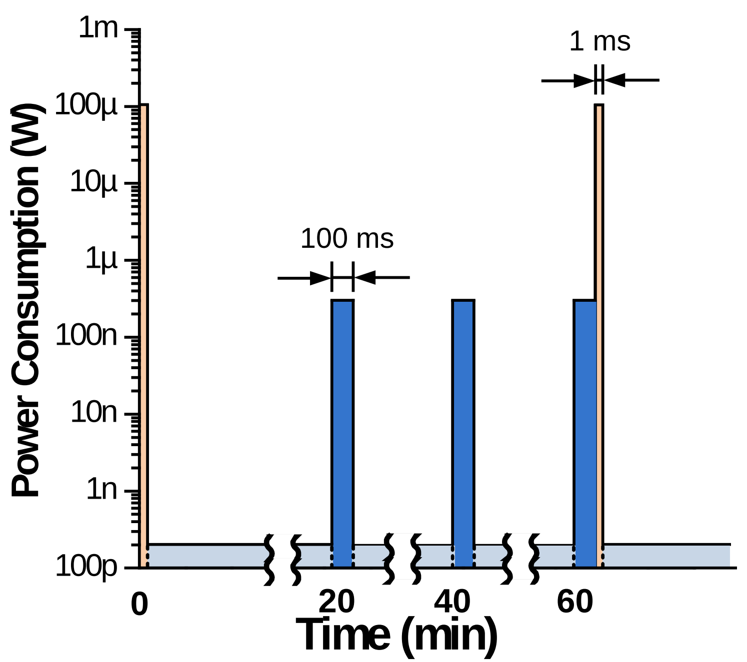
- Asymmetric RF communication does not require precise timing

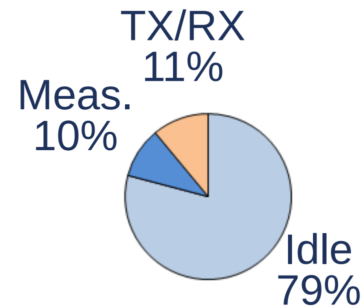
Why Timers Are So Important

Base Station



Sensor Node





Energy

0.91 µJ/hr

Power consumptions in various modes of ULP sensor

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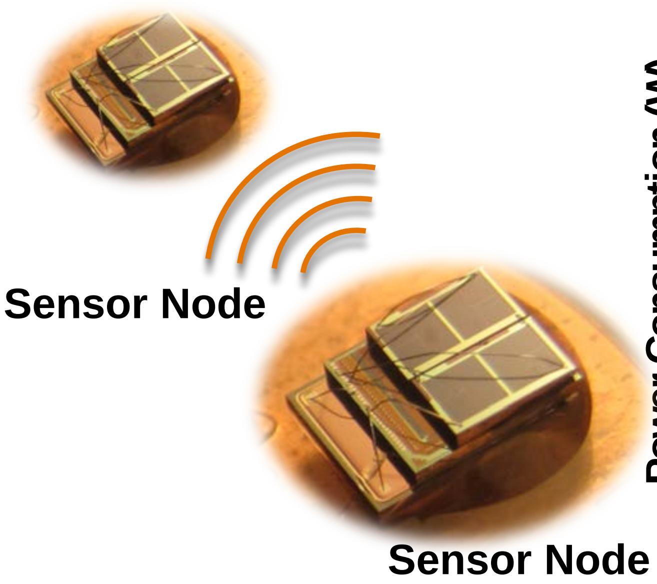

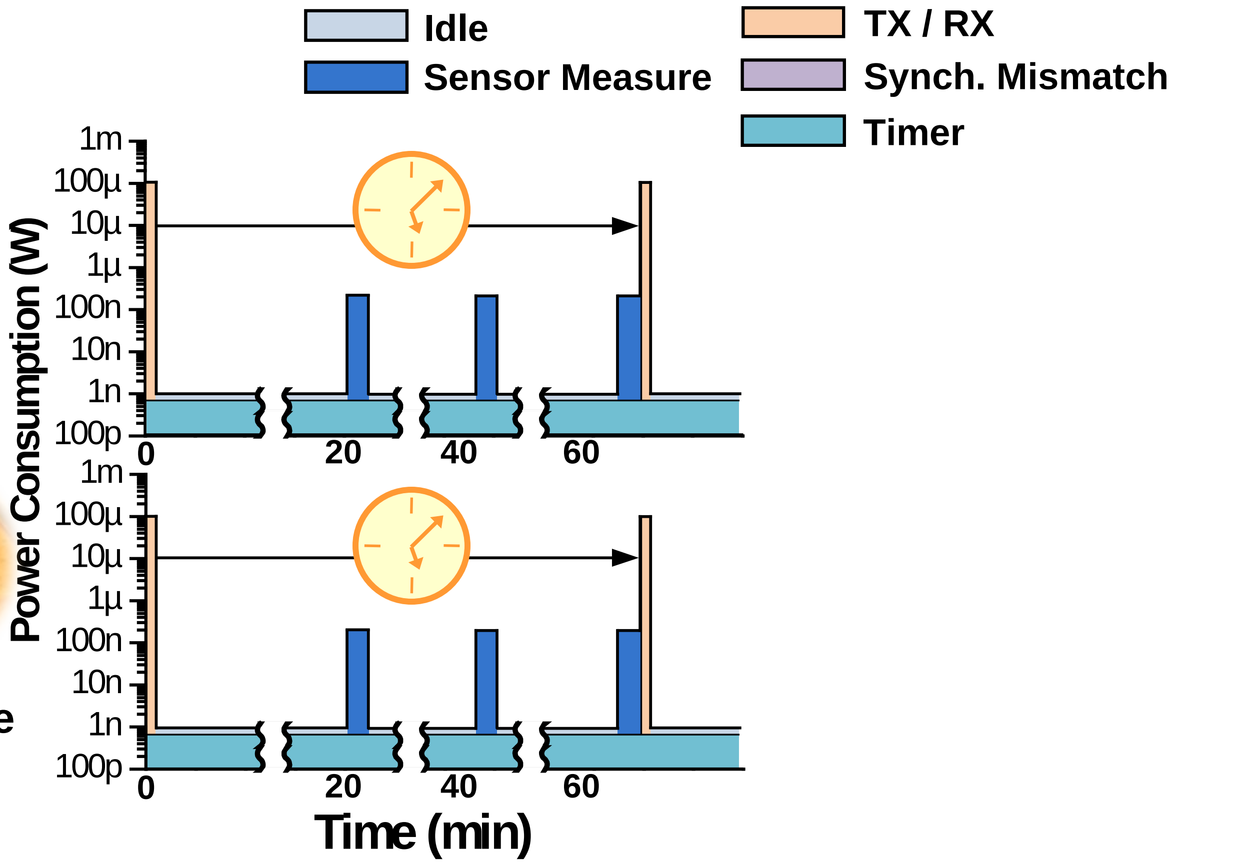

Power consumptions in various modes of ULP sensor

- Asymmetric RF communication does not require precise timing
- Symmetric RF communication requires precise timing
- Energy penalty for mismatch can dominate energy budget

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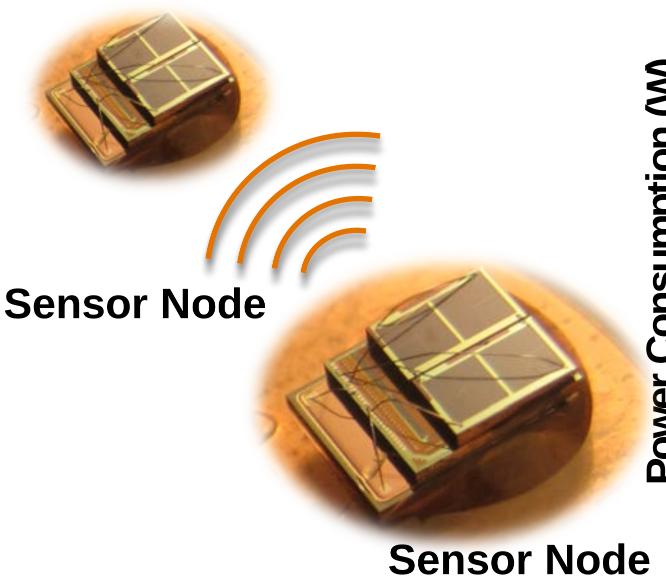

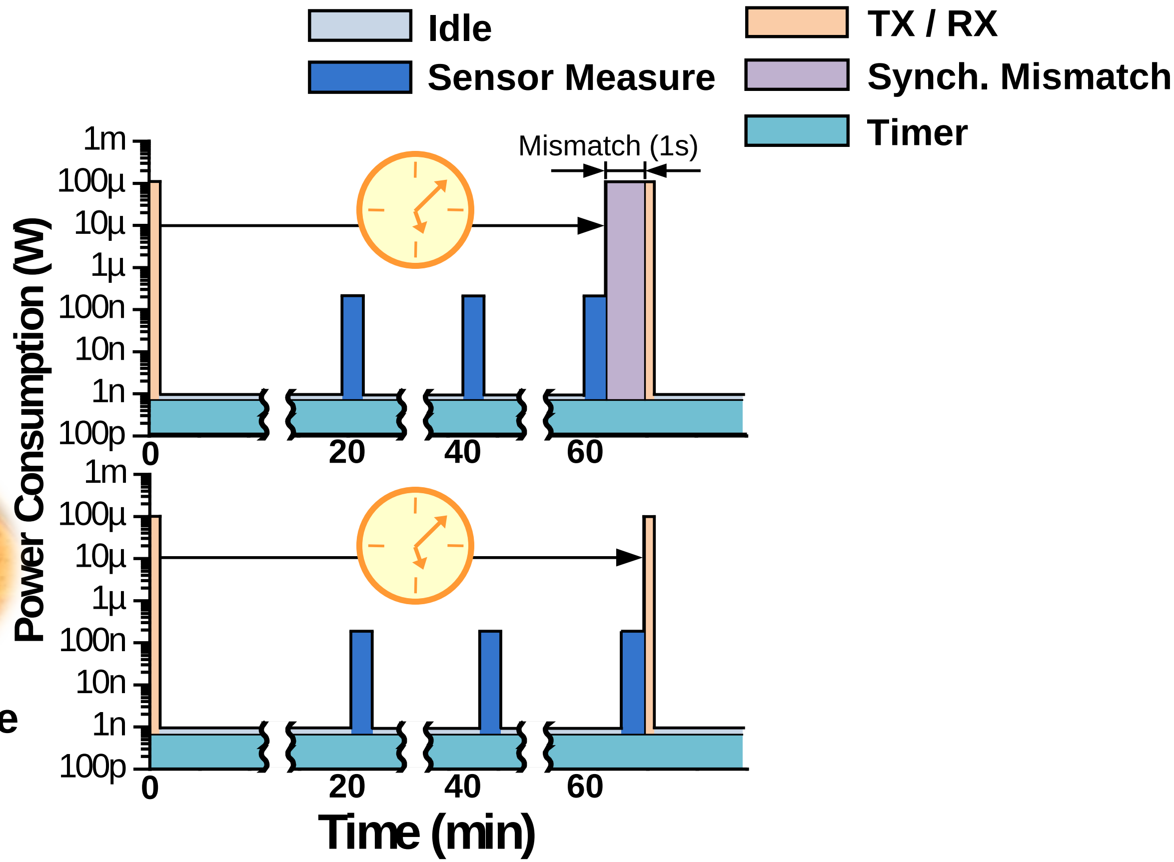

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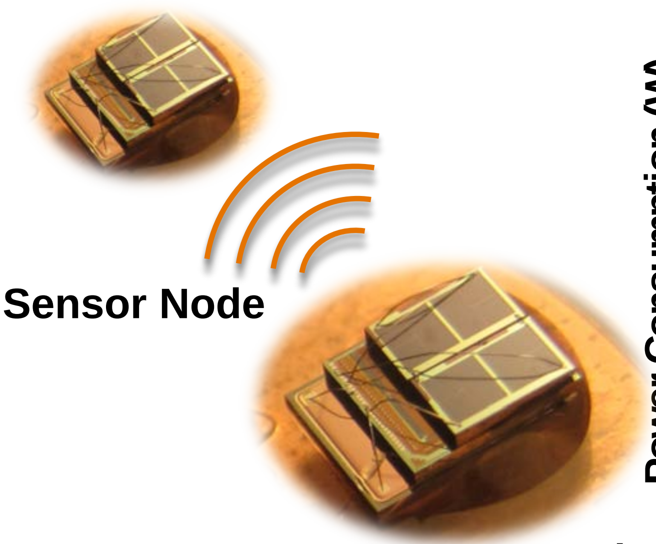

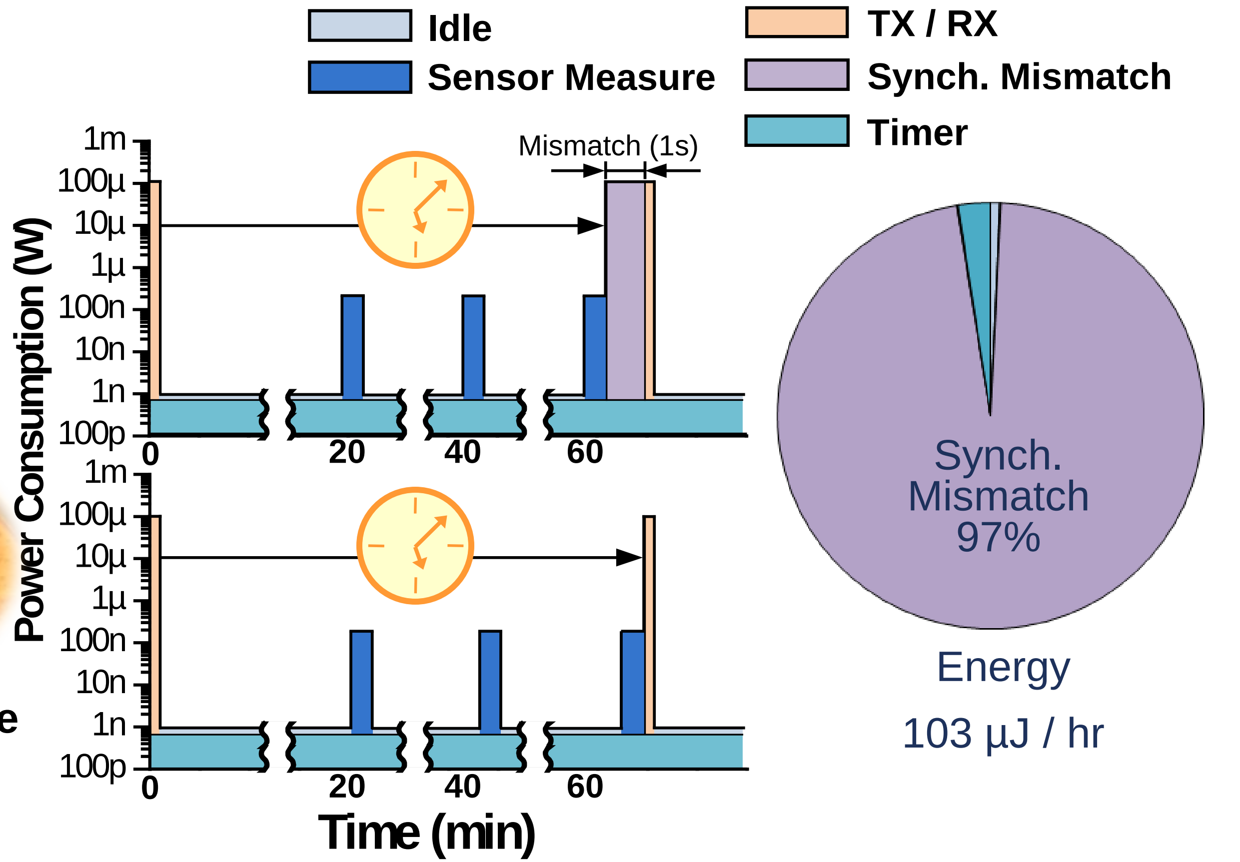

Power consumptions in various modes of ULP sensor

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Keeping Time with Picowatts

- Crystal oscillators bulky and power hungry
- RC oscillators preferable, exhibit accuracy vs. power tradeoff

Low power commercial crystal oscillator ~120nW

[Ref: Micro Crystal Switzerland RV-2123-C2]

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Low power commercial crystal oscillator ~120nW

[Ref: Micro Crystal Switzerland RV-2123-C2]

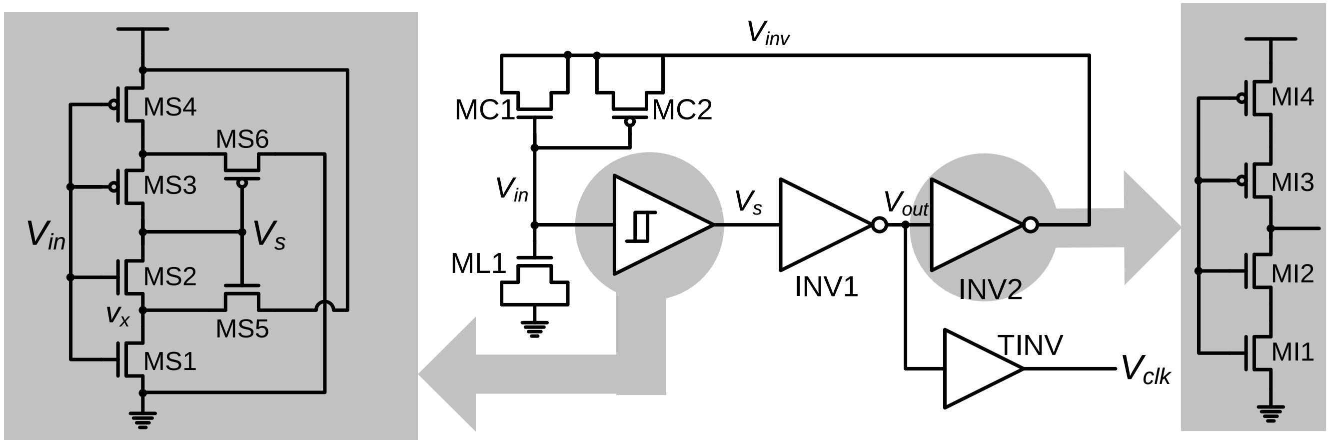
Gate leakage current based timer

<1pW, < 1Hz@300mV

But….

1400ppm Jitter

1600ppm/ºC



Keeping Time with Picowatts

- Crystal oscillators bulky and power hungry
- RC oscillators preferable, exhibit accuracy vs. power tradeoff
- Still a need for improved accuracy at ~nW

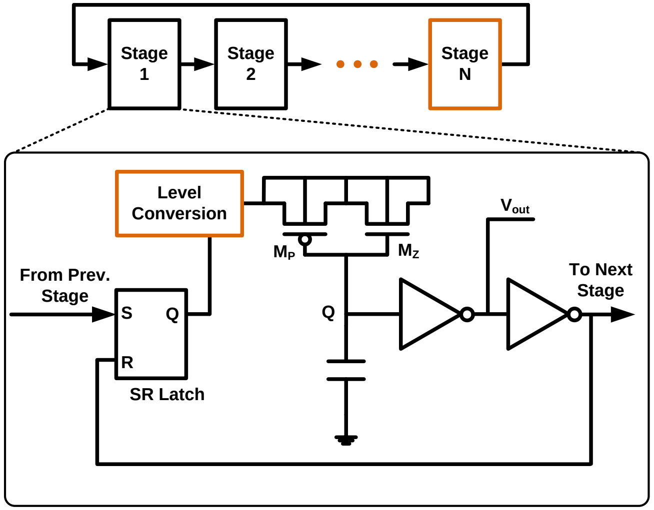
Low power commercial crystal oscillator ~120nW

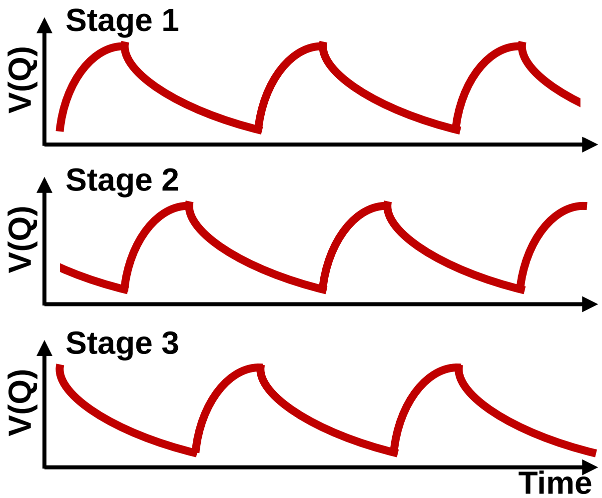
[Ref: Micro Crystal Switzerland RV-2123-C2]

Multi-stage Gate Leakage Timer with Temperature Compensation

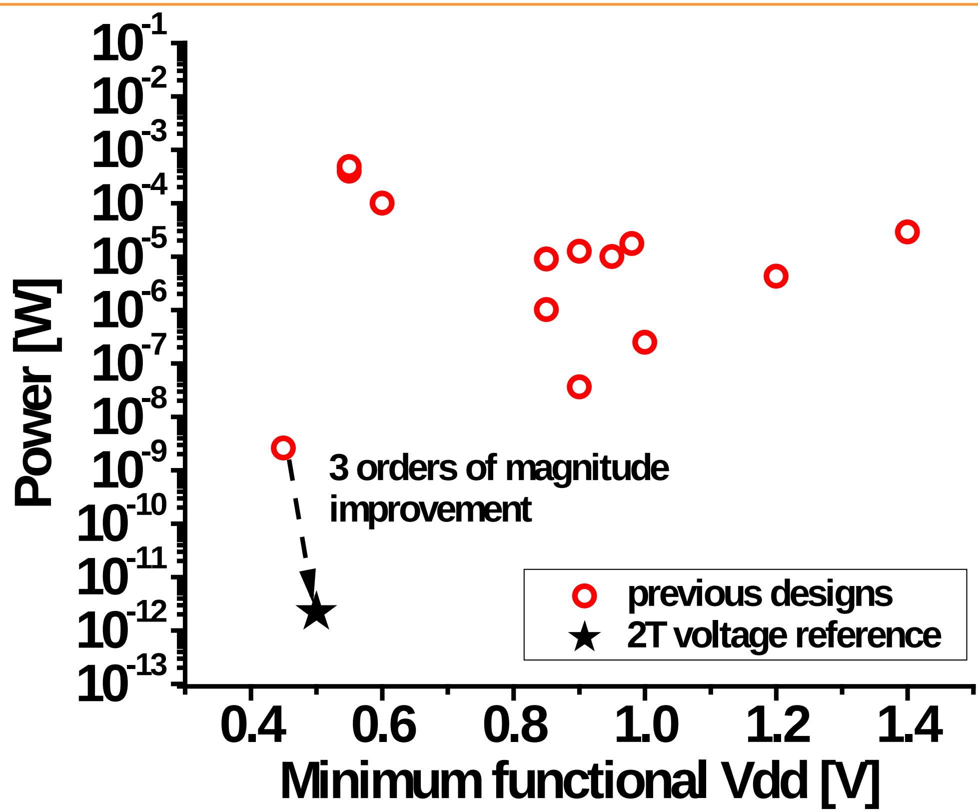
660pW power

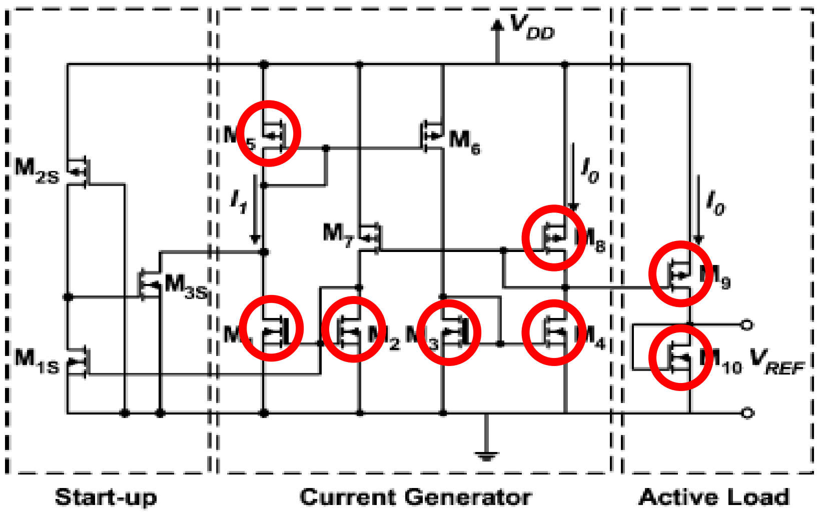
but…
275ppm jitter
31ppm/°C temp variation





Previous Voltage Reference Designs

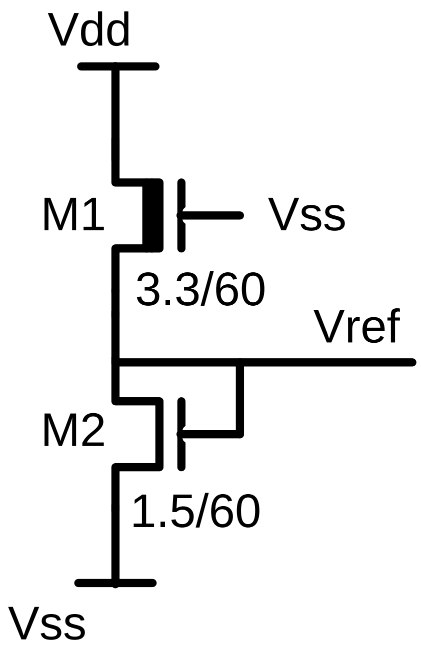


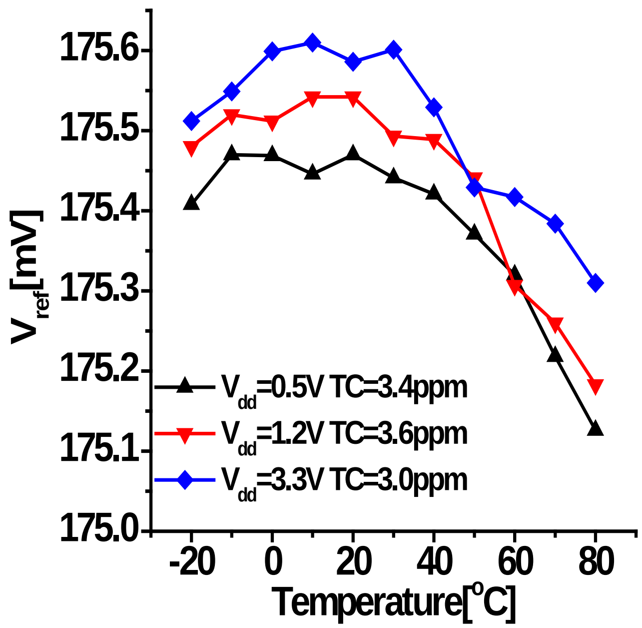


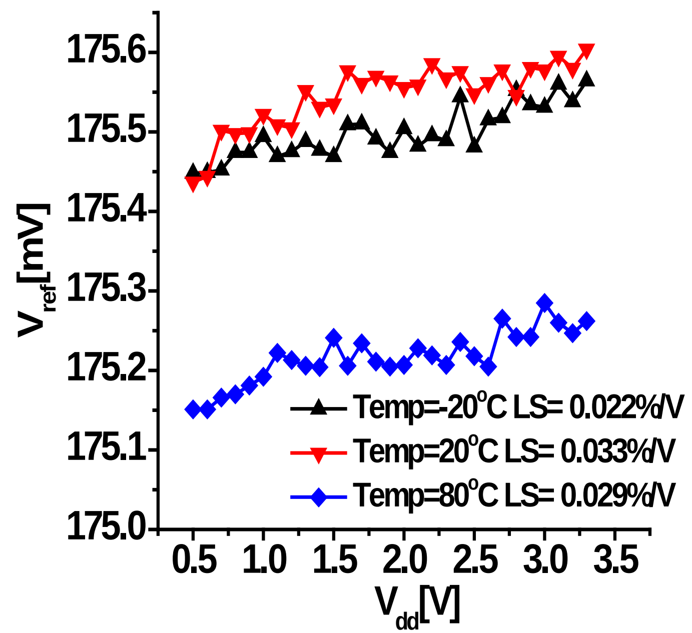
36nW design

- Voltage references used in regulators, timers, radios
- Previous work
  - Consumes 100-1000X more power
  - Typically needs higher supply voltage
- Reasons: transistors in saturated region (power & headroom)

pW Voltage Reference



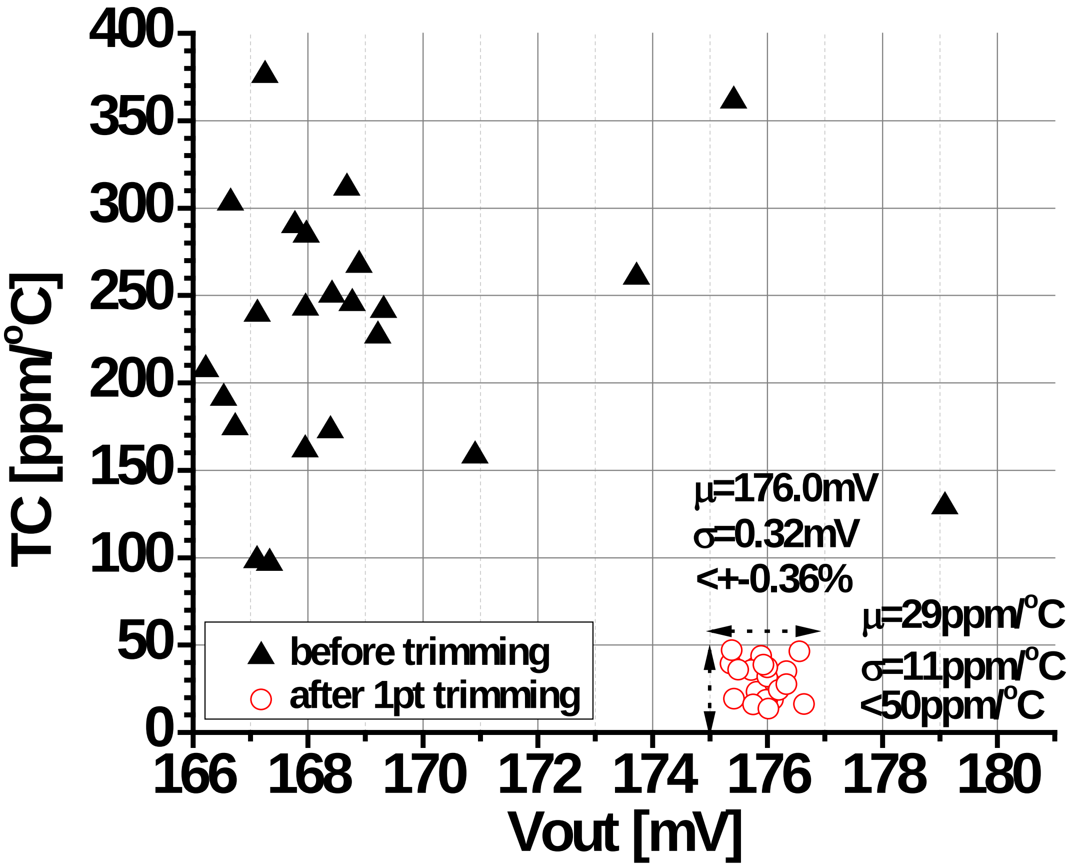




- VDD_{min} = 0.5V
- Power = 2.3pW
- TC=19.4ppm/°C
- LS=0.033%/V
- PSRR = -70dB at 100kHz
- Area = 1350μm²

- New design achieves
  - Ultra-low power down to 2.2pW at Vdd=0.5V
  - Good TC, LS, PSRR, excellent footprint, power

Tightening Variability

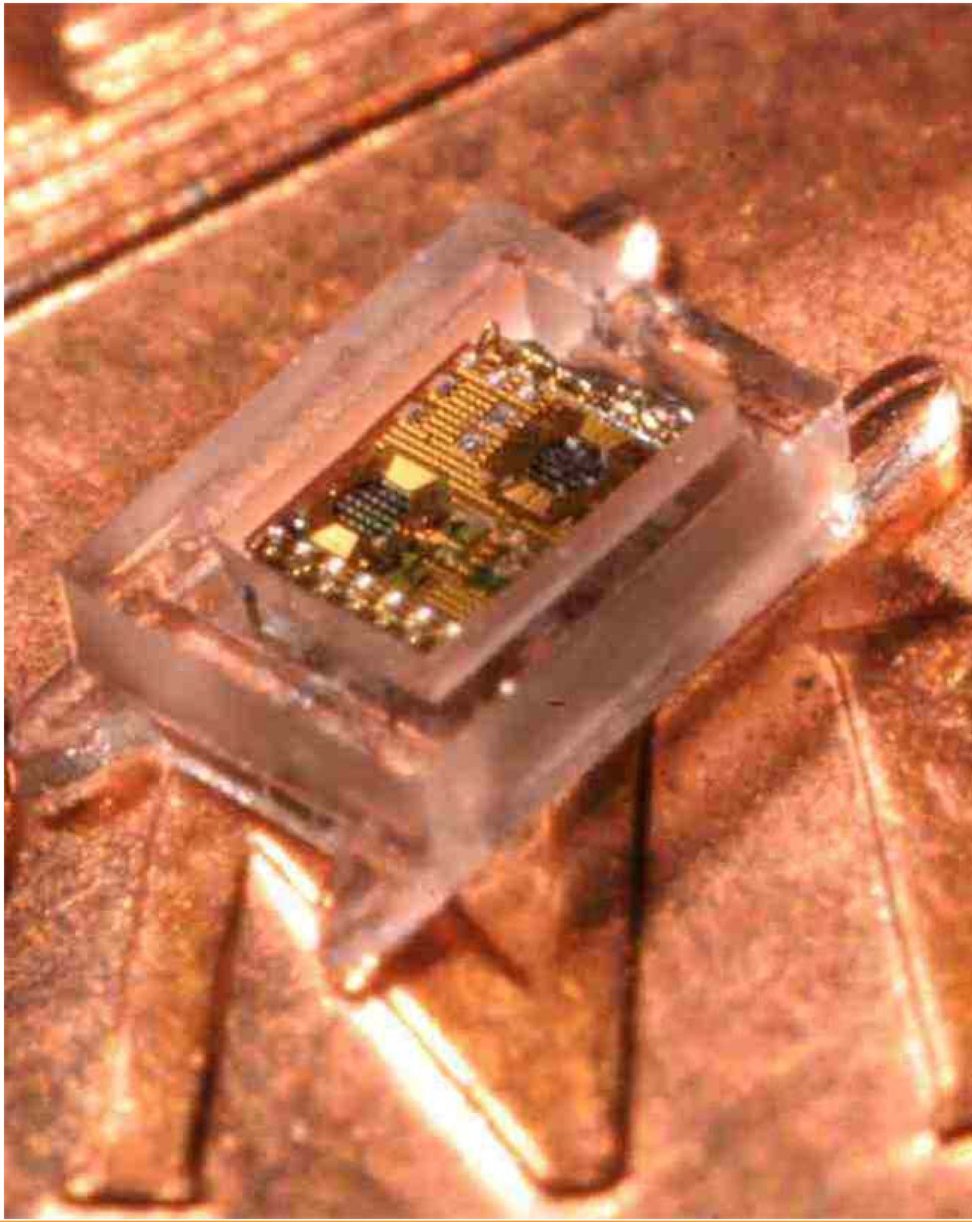


- 1-pt temp trimming over 25 dies

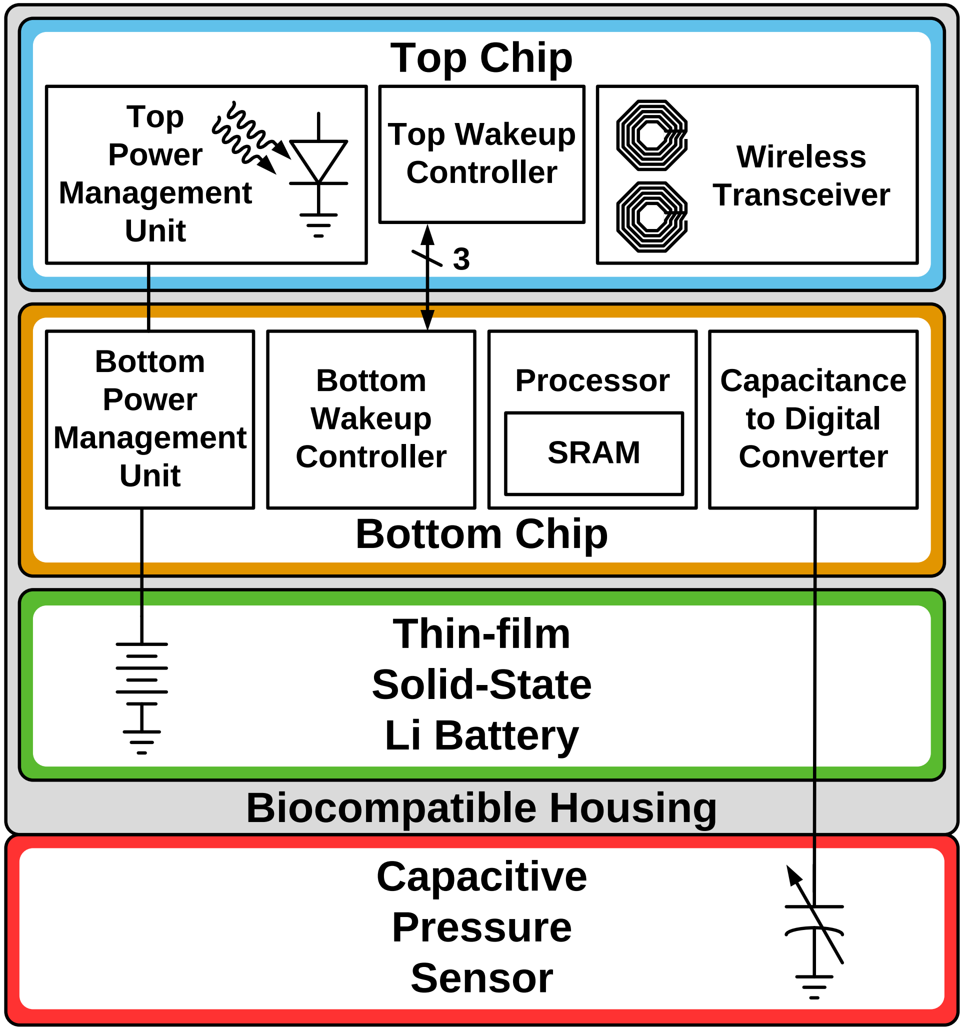
↓TC and V_{out} spread by 9.6X and 9.8X
25 dies: TC<50ppm, ±0.36% Vout

1.5 mm^3 Intraocular Pressure Monitor

- Continuous IOP monitoring
- Wireless communication
- Energy-autonomy
- Device components
  - Solar cell
  - Wireless transceiver
  - Cap to digital converter
  - Processor and memory
  - Power delivery
  - Thin-film Li battery
  - MEMS capacitive sensor
  - Biocompatible housing [Haque, Wise]

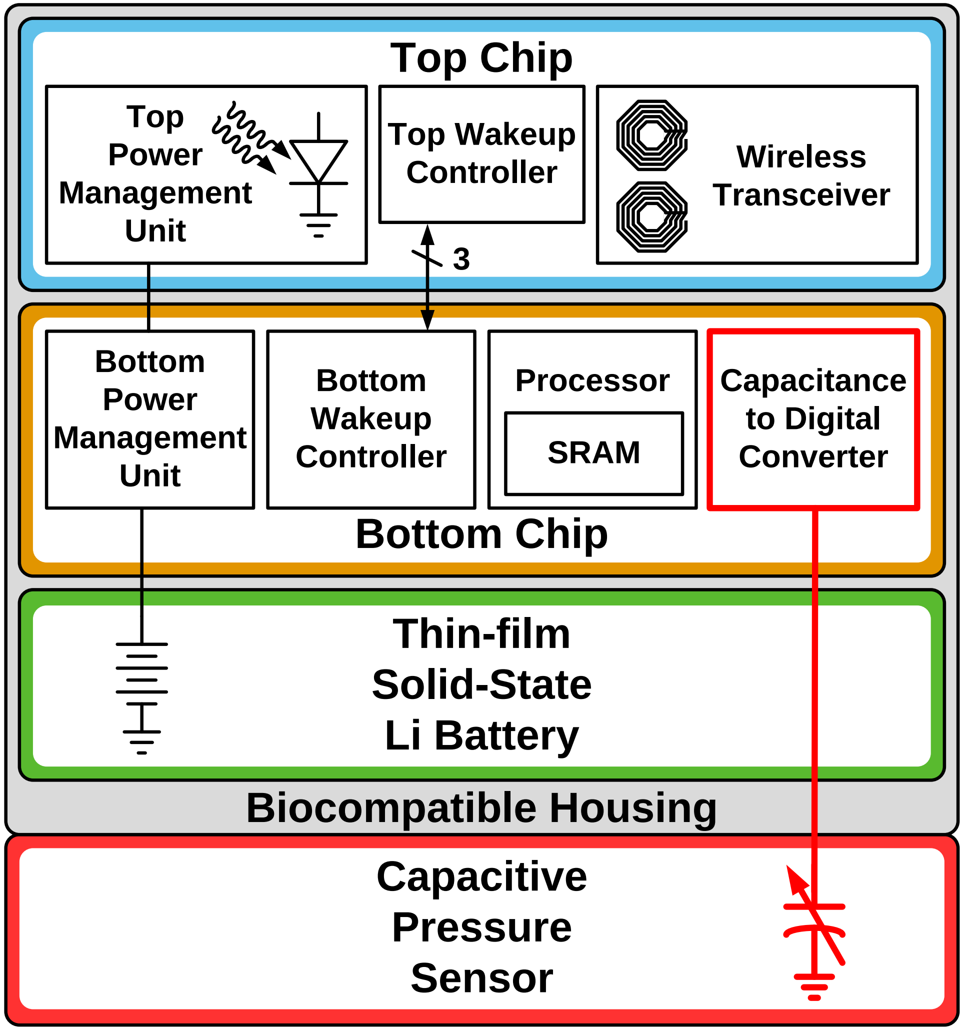


IOP Monitor Block Diagram



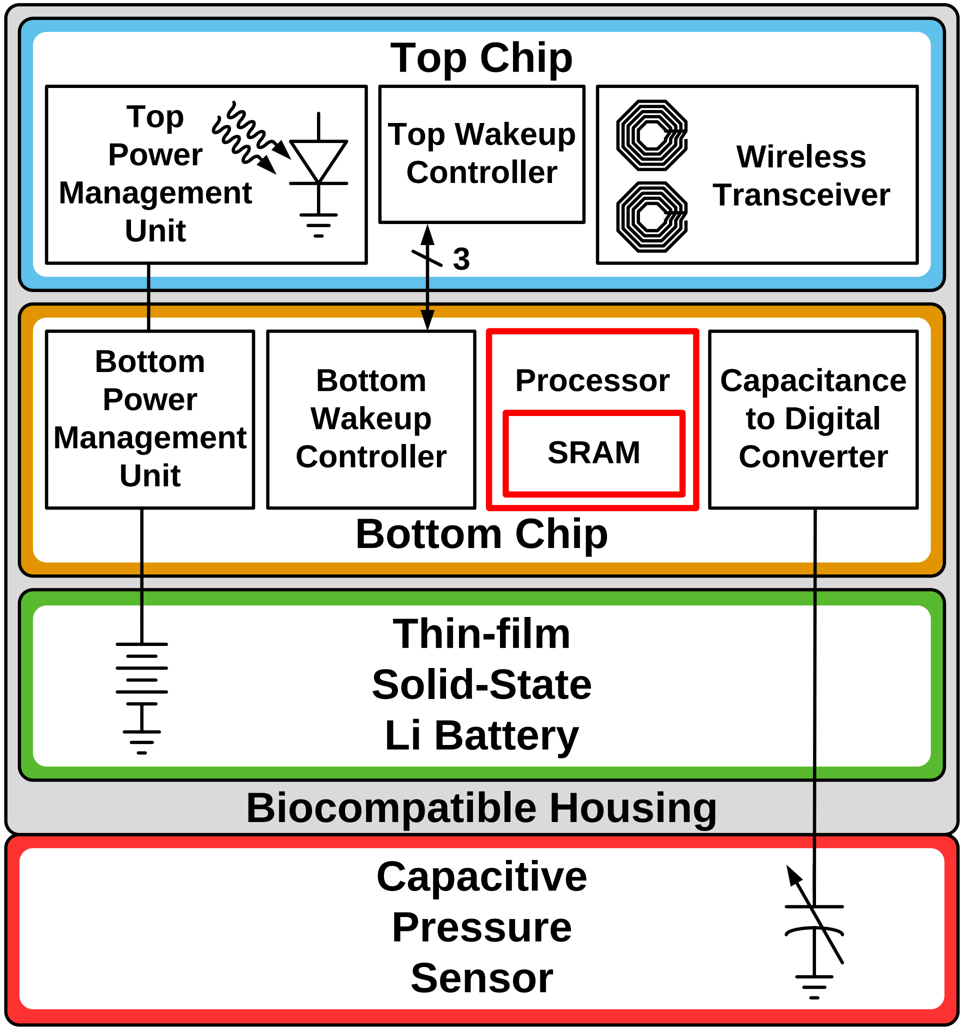
- Cross sectional view of microsystem

Usage Model Example



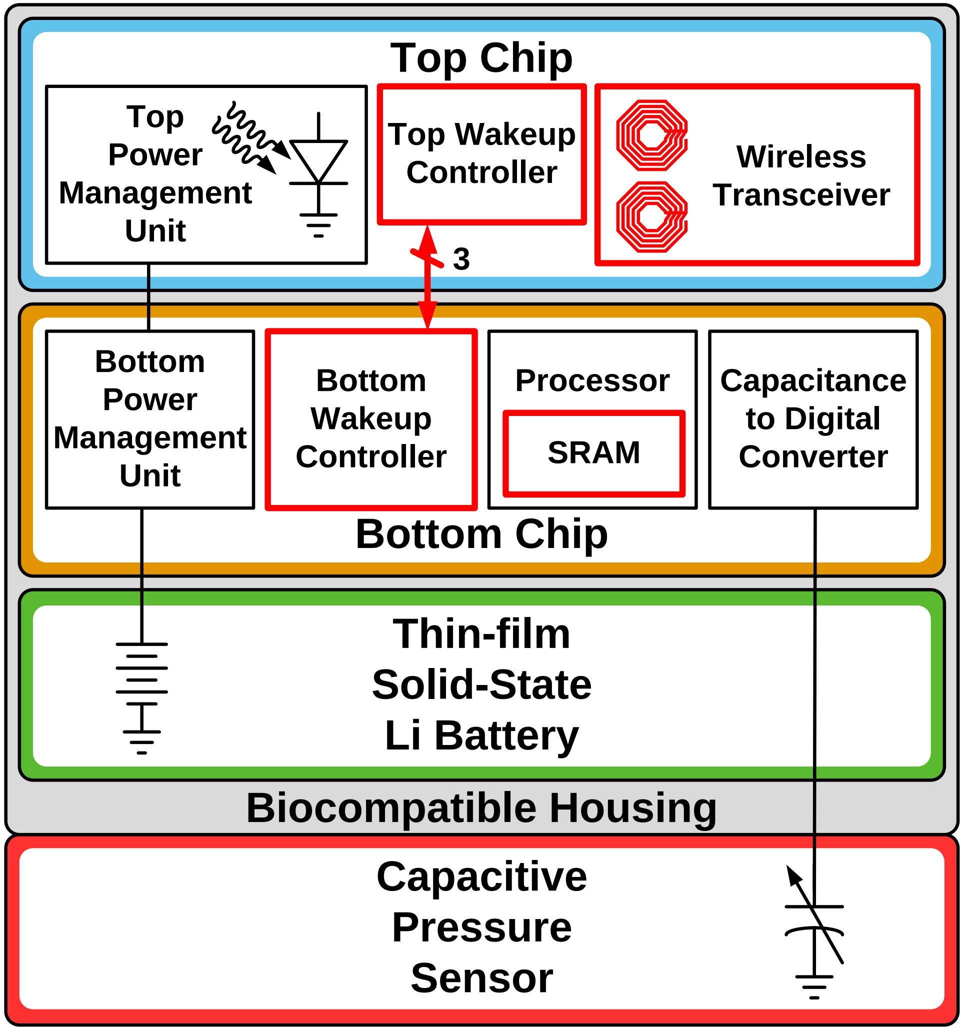
- CDC converts pressure to a digital value
- Stores IOP data to a memory mapped location

Usage Model Example



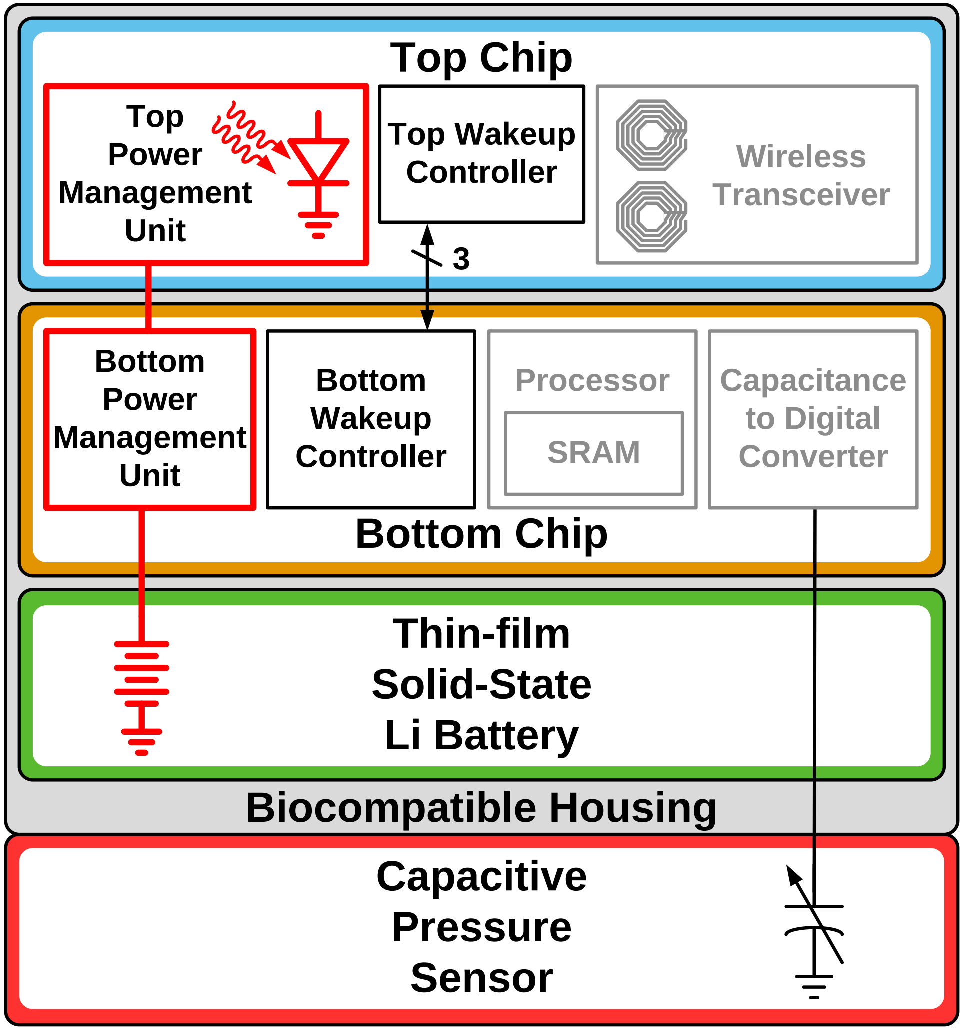
- Processor extracts medical information from IOP data
- Stores its result into SRAM

Usage Model Example



- User wirelessly queries microsystem
- Responds by retrieving and transmitting data

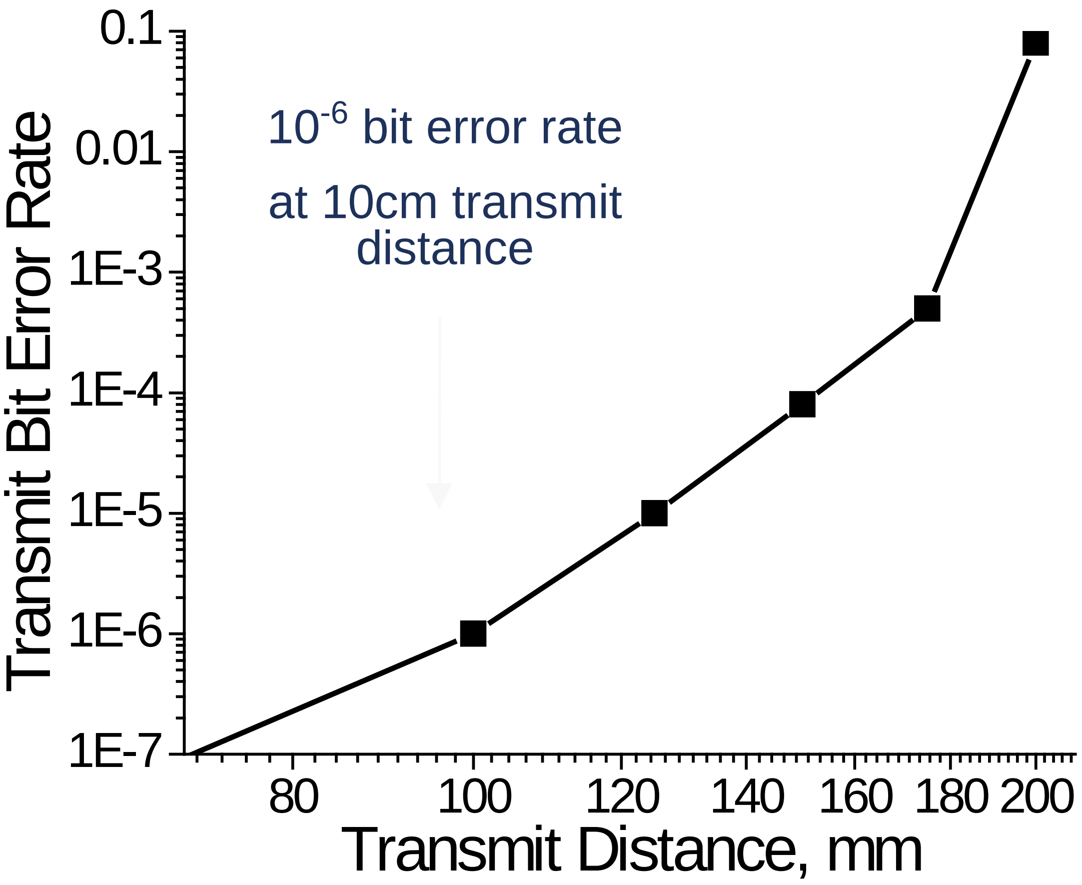
Standby Mode



- Energy harvesting and low-load power management
- Data stored in SRAM

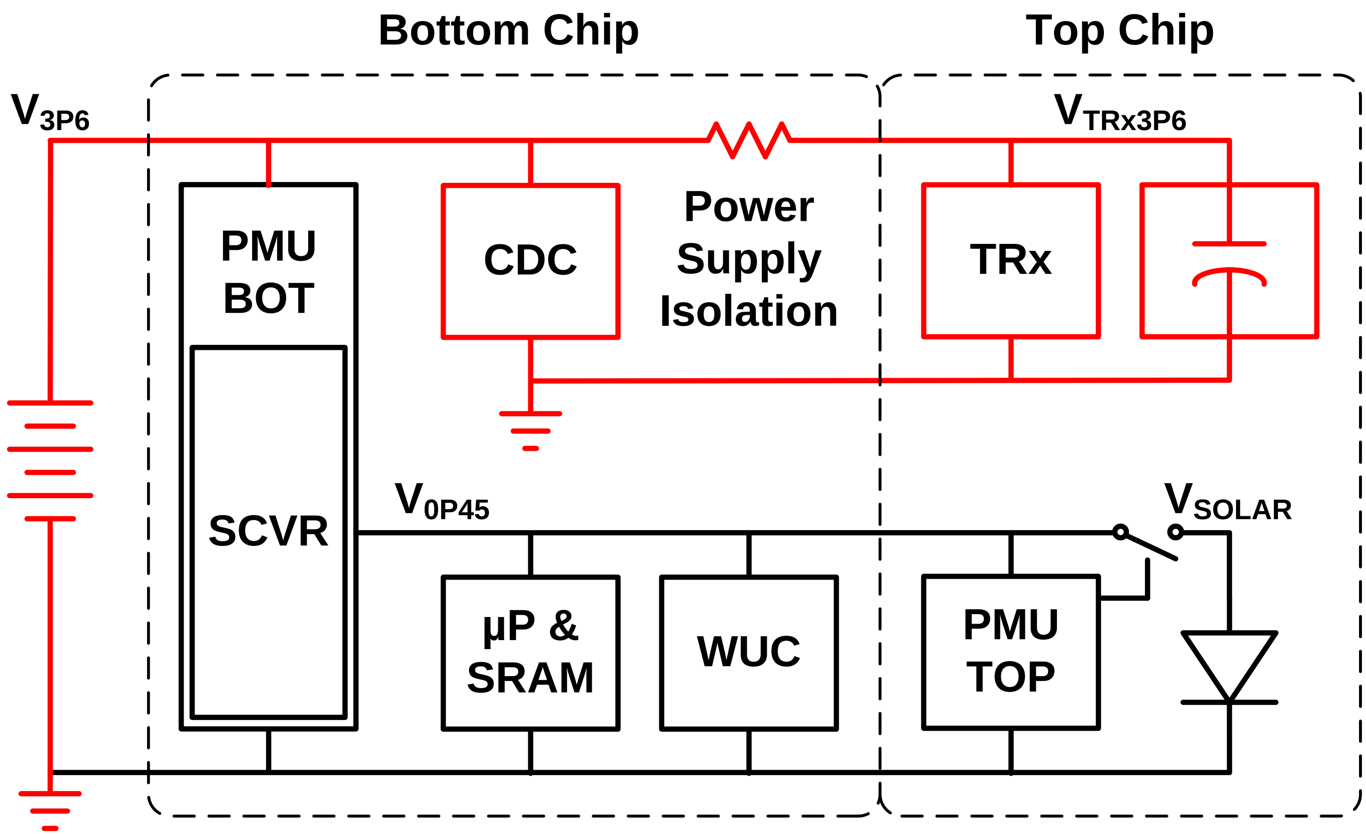
IOP Transmitter

- Main radio challenge: very small coils
- FSK receiver with dual-resonator LC tanks
- Transmitter sends 1 bit (100ns), drawing from 1.6nF decap, recovers droop (~100us) then sends another bit
- Transmit media is 0.5 mm saline + air
- Transmitter: 4.7nJ/bit, improves upon prior implantable work



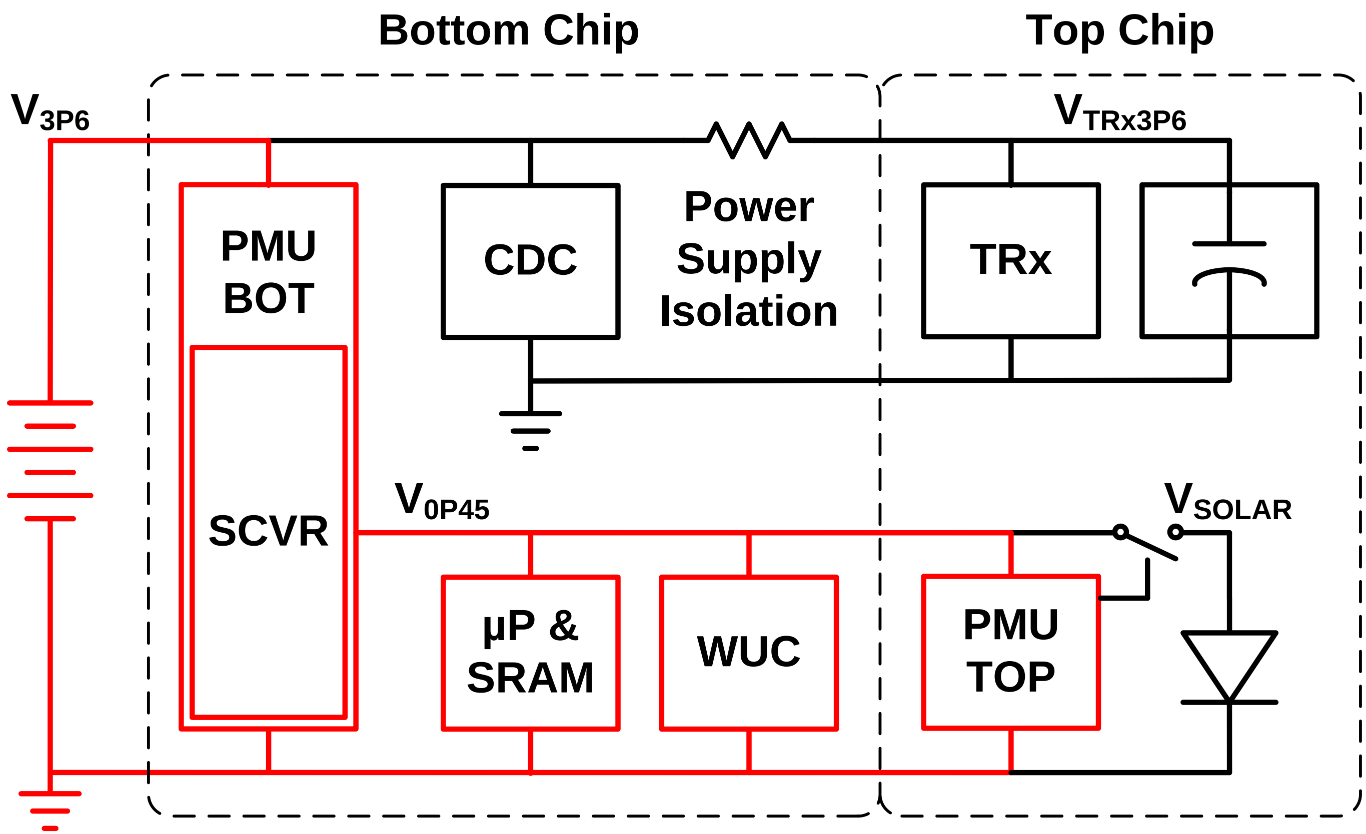
Power Delivery and Management

- Battery powers CDC and wireless TRx
- Isolated local TRx power supply prevents catastrophic V_{DD} drop
- CDC and TRx designed with high-V_{TH} thick-t_{OX} IO devices and no bias currents for low leakage during standby mode



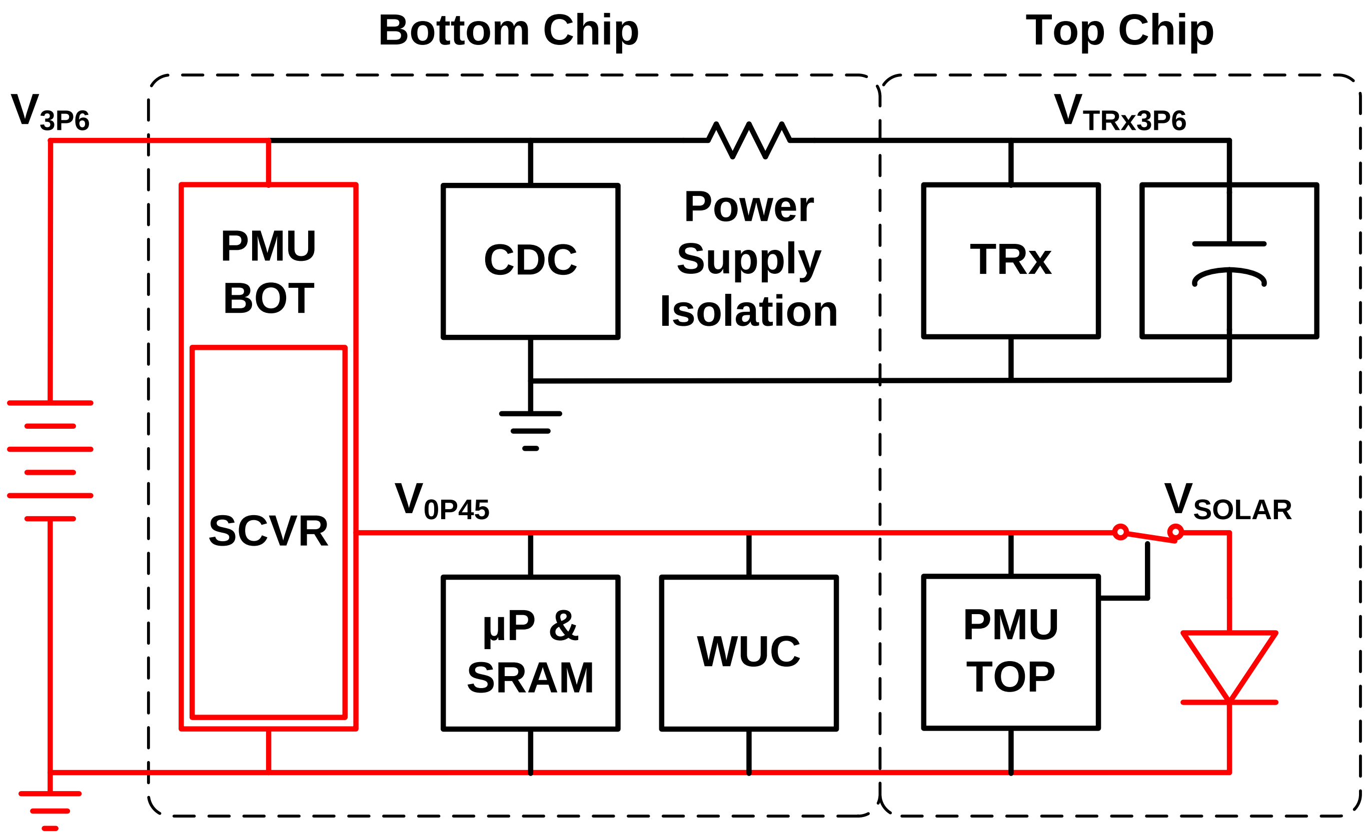
Power Delivery and Management

- 8:1 Switch Cap Voltage Regulator (SCVR) delivers 0.45 V
- µP is power gated in standby mode and uses logic devices
- SRAM and WUC use IO devices for low standby leakage
- SCVR clock is reduced to 50 Hz clock in standby mode

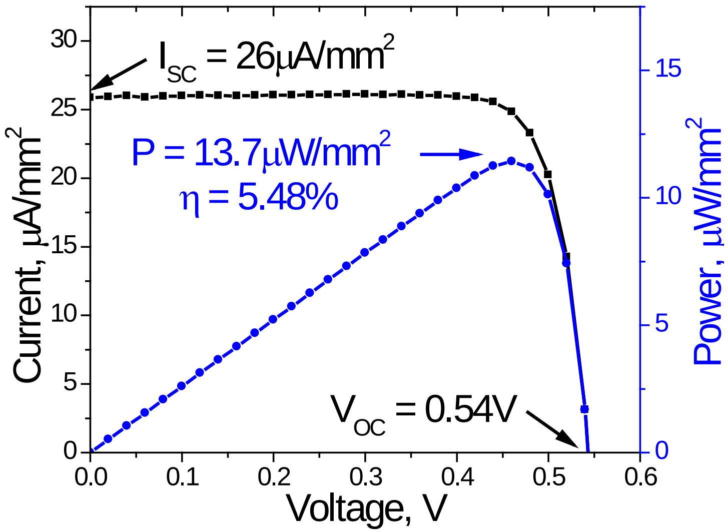


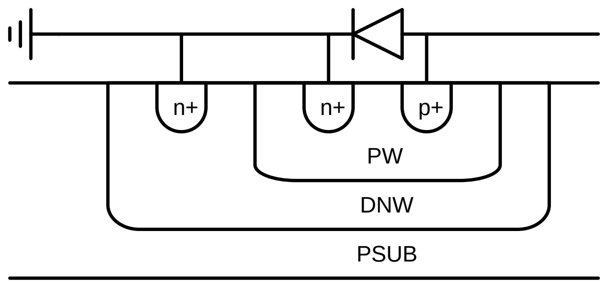
Power Delivery and Management

- Solar cell connected when open circuit V_{SOLAR} exceeds V_{0P45}
  - Check voltage on solar cell with small replica
  - Compare using clocked comparator
- SCVR up-converts solar energy to recharge battery



Power Sources

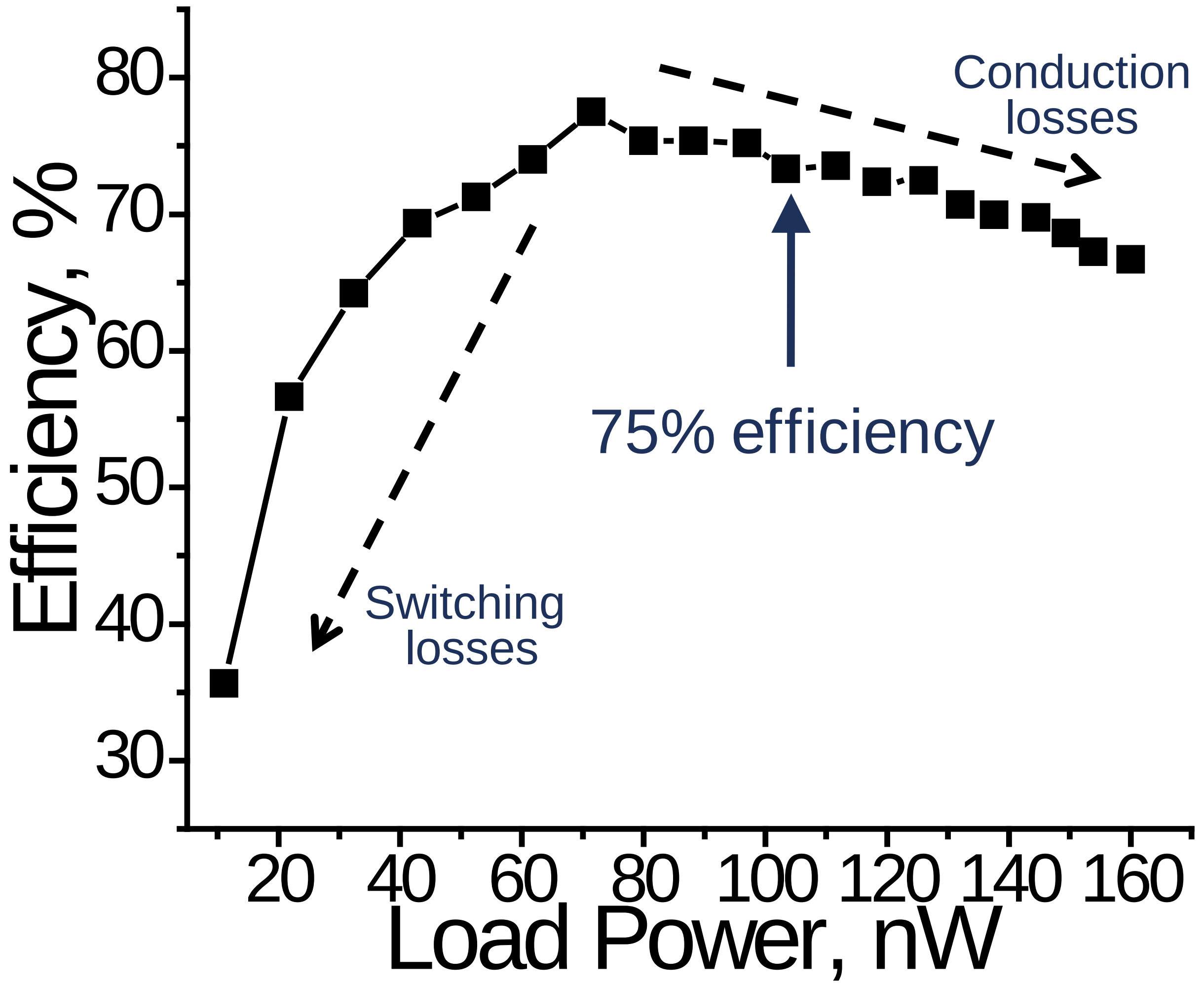




- 0.07 mm² solar cell
- 0.18 μm CMOS
- No post-processing
- 5% solar efficiency

- Cymbet thin-film Li battery
- 1 mm² custom size
- 1μAh capacity
- 40μW peak power

SCVR Measurements



- 75% efficiency with 90 nW processor load in active mode
- 40% efficiency with 72 pW load in standby mode

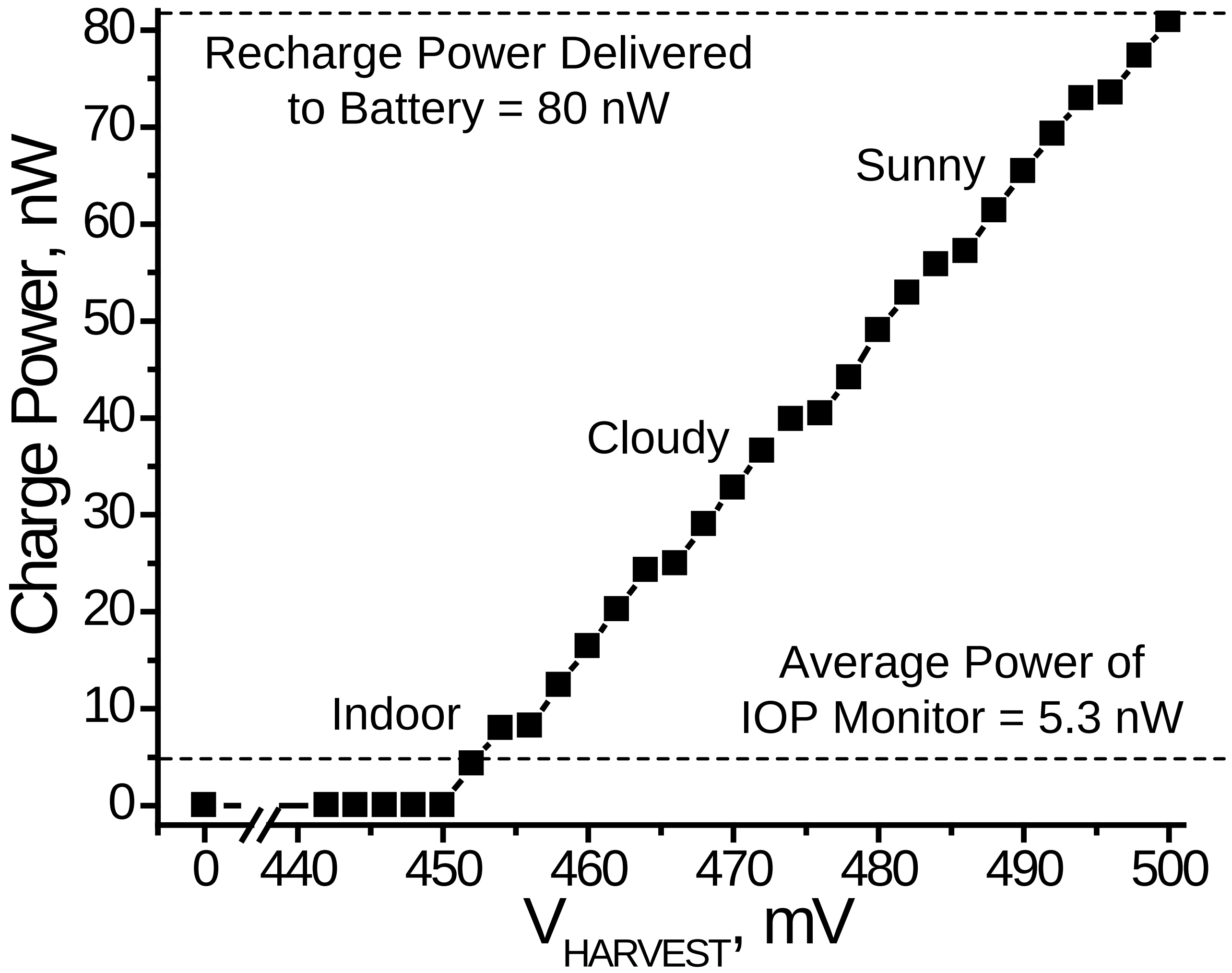
IOP Monitor Power Consumption

- Measure IOP every 15 minutes
- DSP with 10k processor cycles @ 100 kHz per measurement
- Daily wireless transmission of 1344b raw IOP data

Active Mode	**Power**	**Time/Day**	**Energy/Day**
CDC	7.0 µW	19.2 sec	**134.8 µJ**
Transceiver	47.0 mW	134.4 µsec	**6.3 µJ**
SCVR	116.9 nW	19.2 sec	**2.2 µJ**
• µP @ 100 kHz	90.0 nW	19.2 sec	**1.7 µJ**
Standby Mode	**Power**	**Time/Day**	**Energy/Day**
CDC	172.8 pW	24 hours	**14.9 µJ**
Transceiver	3.3 nW	24 hours	**285.1 µJ**
SCVR	174.8 pW	24 hours	**15.1 µJ**
• 4kb SRAM	9.8 pW	24 hours	**846.7 nJ**
• WUC	62.0 pW	24 hours	**5.2 µJ**

5.3 nW average power → 1 month lifetime with no harvesting

PMU Measurements



- Energy autonomous operation with 1.5 hours of sunlight or 10 hours of indoor lighting per day

Leveraging Ideas for Other Domains

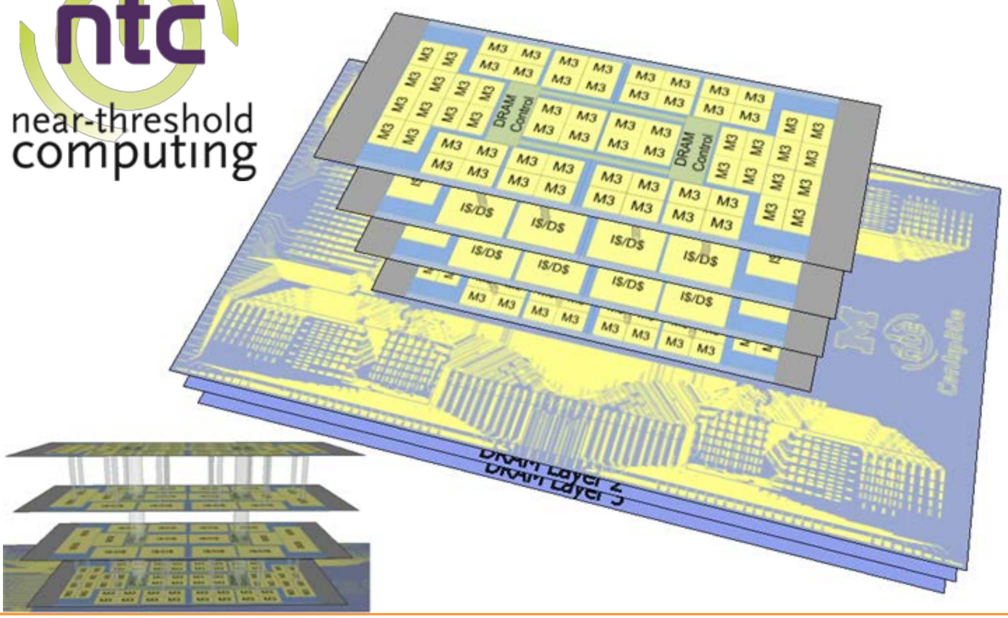
3D NTC

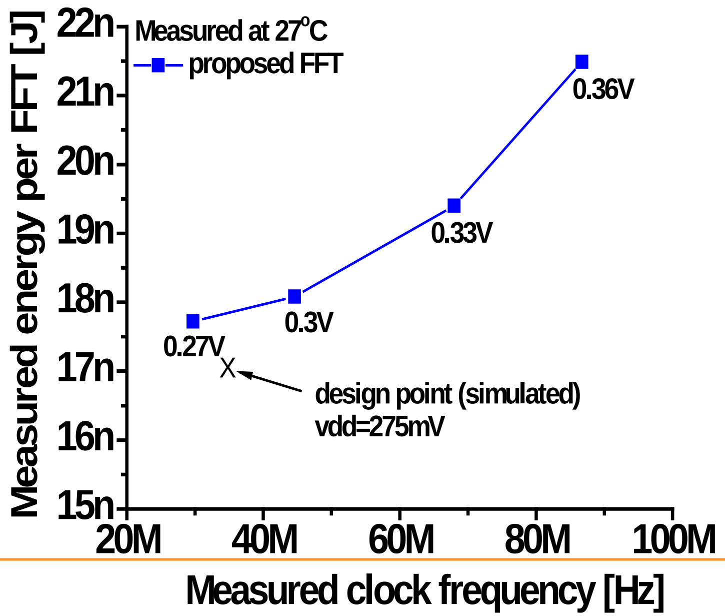
- Centip3De, 7-layer 128-core system with stacked DRAM
- NTC: 5-10 GOPS/W general purpose in 130LP

ULP DSP

- FFT accelerator with record energy efficiency (ISSCC11)
  - 15.8nJ/FFT @ 240MS/s
- Aggressive pipelining to drive down Vmin and Emin
- Minimize leaky memory

ntc near-threshold computing





Conclusions

- Applications of mm-scale computing are endless and often unimaginable today
  - But first the hardware must get there
- Power minimization is paramount
  - Few nW power budget
  - Re-think entire sensor system from bottom up
- For the next decade: **nanowatt challenge**
  - Trickle up effect to servers, mobile platforms
- Acknowledgements:
  - Many UM grad students